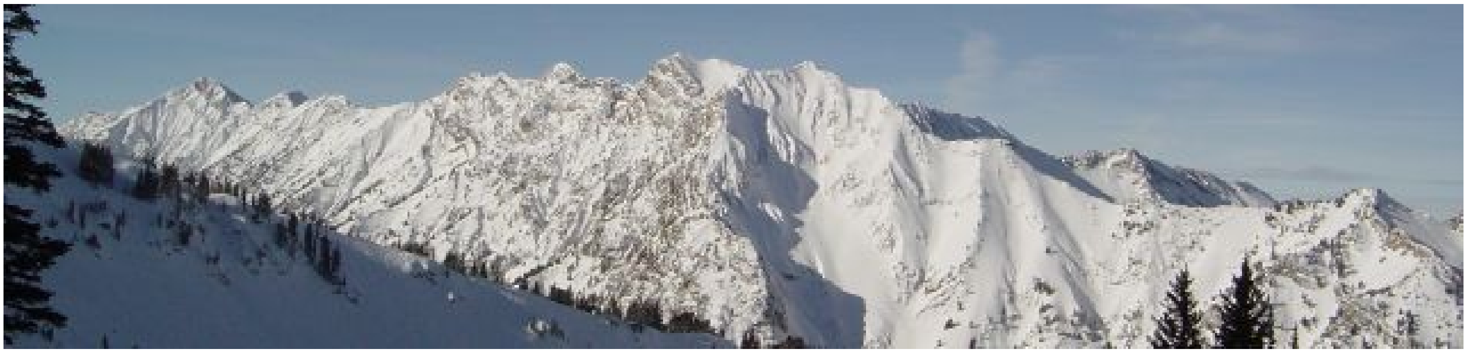
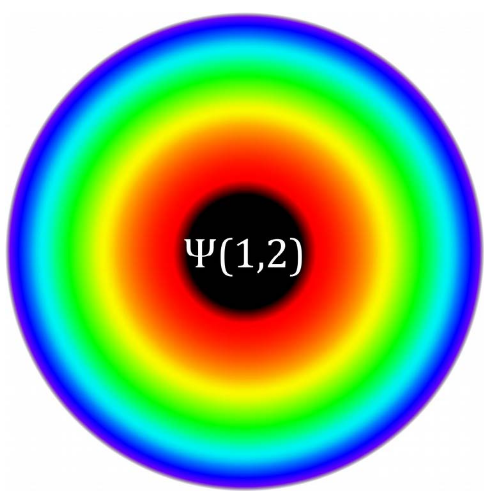
PQE–2026



The 55th Winter Colloquium on the PHYSICS of QUANTUM ELECTRONICS

January 5-9, 2026 — Snowbird, Utah, USA



PQE–2026

The 55th Winter Colloquium on the Physics of Quantum Electronics

January 5-9, 2026
Snowbird, Utah, USA

Organizing Committee:

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Distinguished Professor
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Preface

To all of our PQE friends,

Welcome back! PQE-2026 is underway, and this year promises to be truly special. Following the successful and joyous celebrations of our previous "gathering of the clan"! we're thrilled to gather once again for another unforgettable PQE experience. In particular we look forward seeing you at the Sunday evening reception!

We can again enjoy gathering in Golden Cliff at 6:00PM in January 4th with colleagues, forge new friendships, celebrate the spirit of PQE, and 100 years of quantum mechanics.

Behind the scenes of this conference lies a team of remarkable individuals. Our heartfelt gratitude goes first and foremost to the session organizers:

> Jon Pendry, Mikhail Lukin, Gerd Leuchs, Vitaly Kocharovsky, Dmitry Budker, Susanne Yelin, Shaul Mukamel, Alexei Sokolov, Wolfgang Schleich, Gadi Eisenstein, Richard Miles, Zubin Jacob, Ebrahim Karimi, Adam Kaufman, Vladimir Shalev, Alexandra Boltasseva, Ralf Rohlsberger, Franco Nori, Eugene Polzik, Marianna Safronova, Ernst Rusel, Lan Yang, James Thomspson, Mikhail ivanov, Olga Smirnova, Jorge Rocca, J. Gary Eden, Richard Sandberg, Dana Anderson, Ido Kaminer, Thomas Smith, Mathew Pelton, Philip Hemmer, Renbao Liu, Vladislav Yakovlev, Vladimir Malinovsky, Michael Tobar, Nir Davidson, Pavel Polynkin and Weng Chow.

These champions handpicked and arranged the majority of sessions, shaping the very core of this event, and heroically navigated every scheduling challenge.

The organizing committee also deserves immense praise. Their foresight and tireless efforts ensured that potential problems were nipped in the bud, and we sincerely thank them for their invaluable contributions.

And last but not least, our warm thanks extend to the exceptional staff at Snowbird. We owe a debt of gratitude to Jim Dixon, Jared Jentzsch, Mike Weing, Matt Miller, and Lindsey Perlman for their unwavering support on every crucial facet of this conference. So now, go forth and enjoy Snowbird! The slopes beckon with exceptional powder, and the physics, as always, promises to be truly exhilarating.

Marlan O. Scully

Contents

1 Schedule

The conference takes place on January 4-9, 2026. The program consists of two parts: the technical sessions are on Monday through Friday *mornings and evenings*, January 4–9; and the poster session with dinner is on Thursday afternoon, January 8. All events take place in the Cliff Lodge at Snowbird.

Event	**When and Where**
Reception	Sunday evening, January 4 Time: 6:00 p.m. Room: Golden Cliff Notes: Includes pizza and crudités buffet dinner.
Continental Breakfast	Monday-Friday mornings, January 4-9 Time: 7:00 a.m. Room: Ballroom 2 Notes: Includes coffee and tea, juice, and pastries.
Technical Sessions	Monday-Friday, January 4-9 Time: 7:30 a.m. – 1:00 p.m., 7:00 p.m. – 10:30 p.m. Rooms: Ballrooms 1 and 2 Magpie Rooms A and B Wasatch Room A (Level L1). Notes: The technical sessions occur morning and evening. Your afternoons are free to enjoy the atmosphere. See the program for information about rooms for individual talks.
Poster Session and Buffet Dinner	Thursday evening, January 8 Time: 5:30 p.m. – 7:00 p.m. Room: Ballroom 2 and 3 Notes: Posters may be set up starting Wednesday morning, January 7. The “official” session is listed above, and includes a buffet dinner.

2 Location

All conference events are in the Cliff Lodge at Snowbird. Please refer to the diagrams on the next page to determine the location of the various conference events.

Most events are on level B in the Cliff Lodge. For reference, this is the level with the automobile entry-way, and the bell desk. The hotel reception desk is on level L. Level L is directly above level L1.

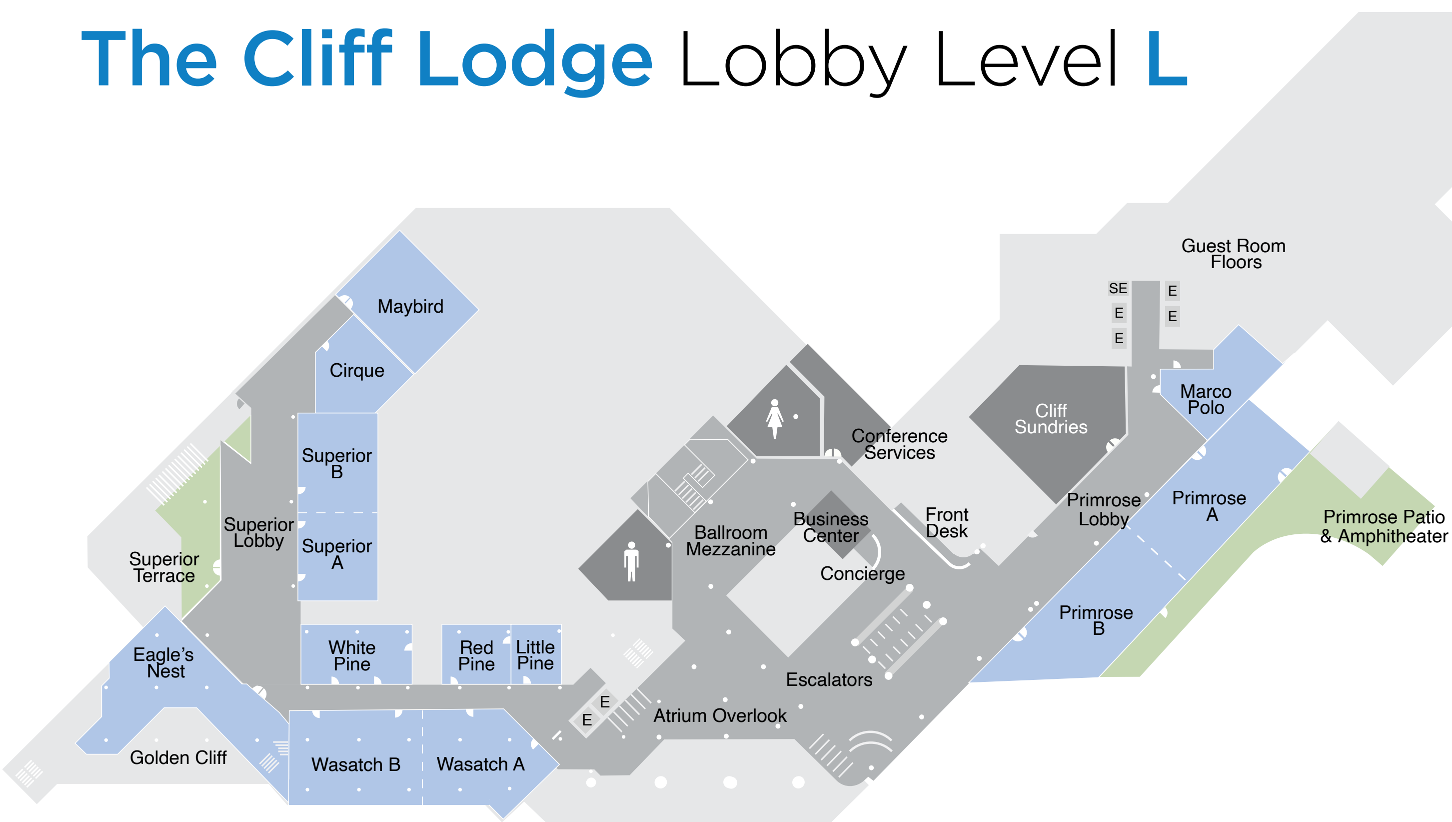
- Reception (Sunday evening): Golden Cliff room, Cliff Lodge level L1.
- Plenary sessions: Ballrooms 1 and 2, Cliff Lodge level L1.
- Breakout session 1: Ballroom 1, Cliff Lodge level L1.
- Breakout sessions 2 and 3: Magpie rooms, Cliff Lodge level L1.
- Breakout session 4: Wasatch A room, Cliff Lodge level L.
- Poster Session (Thursday afternoon): Ballroom 3, Cliff Lodge level L1.

To reach the Snowbird Center, or other parts of Snowbird Village, it is common to take the exit on the West end of the Cliff Lodge, and walk across the snow to Snowbird Center. The Center is the building where the gentle “Chickadee” chair lift terminates. It may also be possible to take a Snowbird Village shuttle to other parts of the resort. You can ask about this at the concierge or bell desks.

A map of Snowbird Village follows the diagrams of the Cliff Lodge.

The Cliff Lodge Lower Level L1

The Cliff Lodge Lobby Level L



Snowbird Village Map

CLIFF LODGE

Aerie Restaurant
Aerie Lounge & Sushi Bar
(A private club for members)
Atrium Restaurant
Boot Teck Bootfitting (winter only)
Camp Snowbird Children's Center
Cliff Spa, Salon & Spa Shop
Cliff Sundries
Cliff Sports (winter only)
Cliff Sports Gear Rental, Tuning & Repair (winter only)
Conference Center
Keyhole Junction
Keyhole Cantina
(A private club for members)
Marco Polo's Silk Road Treasures
Superior Snacks

SNOWBIRD CENTER

Activity Center
Aerial Tram
Alpine Slide (summer only)
Baked & Brewed at the Bird
Birdfeeder
Bungy Tramp (summer only)
Canyon Designs
Center Sundries & Pharmacy
Cottonwood Canyons Realty
Christy Sports & Gear Rental
Event Center (summer only)
Forklift Restaurant
General Gritt's Grocery & Deli
Meeting Rooms
Pier 49 San Francisco Sourdough Pizza
Powder Shots/Superior Photo
Rendezvous Restaurant (winter only)
O Zone-The Oakley Store
Superior Ski Tuning and Repair (winter only)
Ticket Sales
Legend Demo Center (winter only)
Steak Pit Restaurant
Tram Club
(A private club for members.)
Wasatch Powderbird Guides (winter only)
Wine & Liquor Store
Wings

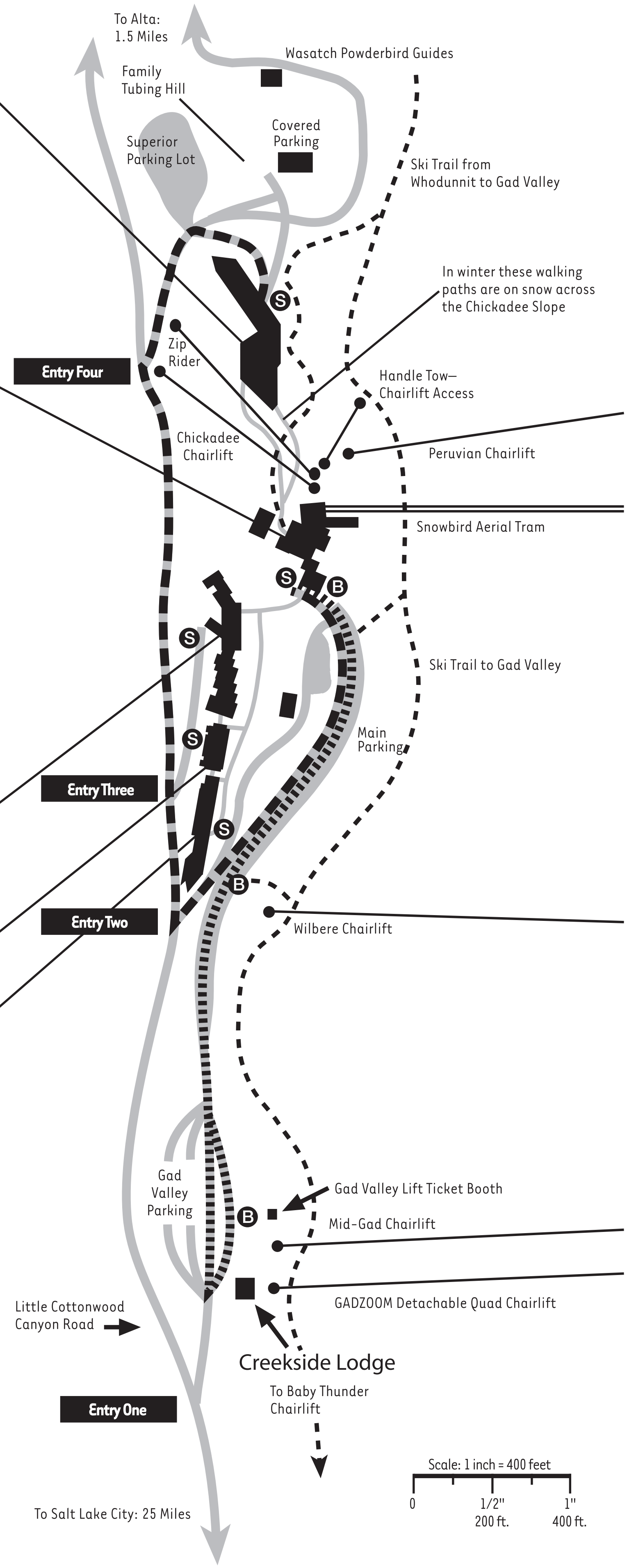
LODGE AT SNOWBIRD

Aspen Room
Lodge Bistro
Lodge Bistro Lounge
(A private club for members)

THE INN

IRON BLOSAM LODGE

Wildflower Restaurant
Wildflower Lounge (winter only)
(A private club for members)



Ⓢ Resort Shuttle stops

Resort Shuttle routes— Operates on an as needed basis from 5 p.m. nightly. Call Ext. 5034

Ⓑ B.A.S.S. Shuttle stops

B.A.S.S. Shuttle routes— please check the posted schedules for arrival and departure times. Operates from 8 a.m. to 5 p.m. daily.

Walking path between lodges
Snowbird is a pedestrian village. Cars are not necessary once you arrive.

3 Information for Participants

3.1 Eating

The conference provides dinner on Sunday and Thursday evenings, and breakfast on Monday through Friday mornings. All other meals are the responsibility of the participants.

A continental breakfast of coffee and tea, pastries, juice, yogurt and fruit will be provided each morning at 7:00 before the first plenary session. The breakfast will be in Ballroom 2. A buffet dinner will be provided during the poster session on Thursday evening. This will commence at 5:30 p.m. in Ballroom 2.

Many participants choose to eat hot breakfast and lunch each day in the Atrium restaurant, on level L1 of the Cliff Lodge, just outside the ballrooms. This restaurant serves sandwiches and other lunch fare in the spectacular setting of the Cliff Lodge atrium. The other lunch possibilities in the Cliff Lodge are the SeventyOne restaurant on level L2, and the Steak Pit at the Snowbird Center. In Snowbird Center, there are several lunch possibilities, including the Forklift restaurant, the Rendezvous cafeteria, and a fresh pizza oven. Also in Snowbird Center is a small grocery store called General Gritts located on the lower level.

For dinner, there are a large number of restaurants spanning the entire range from bar food to fine dining, as well as several àpres ski possibilities. There will be a dining guide in your hotel room, or the concierge at the Cliff Lodge level L can provide you with one.

3.2 Entertainment

It goes without saying that one of the most common afternoon entertainments during the conference is skiing. Many people ask if there is any discount for lift tickets for conference attendees. PQE attendees should show either a lodging card or a name badge to receive the discount. The lodging card is issued to guests when they check in. The card will identify them as being with the PQE conference. The name badges that you receive at registration may work as well.

If you want more variety, you can also ski at the Alta ski resort – just a few miles up Little Cottonwood Canyon from Snowbird. You can get a combined lift ticket, and reach Alta via Snowbird lifts (weather permitting). Or, you can ride the UTA bus (at Snowbird Center, or the East end of the Cliff Lodge, level 1) for free. Alta is one of the few ski resorts in the country that does not allow snow-boarding, so plan only to ski there.

If you stay in the Cliff Lodge, you can ski on the Chickadee lift (between the Cliff Lodge and Snowbird Center) for free. Just tell the vendor at the lift ticket window in the Cliff Lodge level 1 that you have a room in the Cliff Lodge and want a free Chickadee pass.

For accurate and detailed information, refer to https://www.snowbird.com.

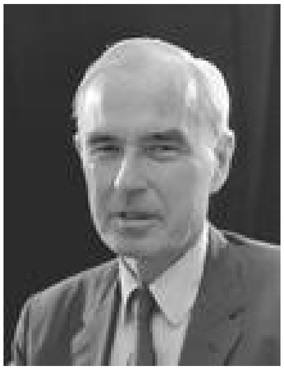
3.3 Information for Speakers

- Please try to attend as many sessions as possible. This means staying through Friday evening. No one likes for their audience to be only the other speakers. The only way the meeting can work is if all participants attend as many talks as possible.

- Talk duration:
  - Plenary talks are 30 minutes, including questions and laptop setup.
  - Invited talks are 20 minutes, including questions and laptop setup.
- The meeting rooms will have LCD projectors (aka beamers). Computers are not provided. Please plan to use your own computer or share with another person in your session.
- The LCD projectors (aka beamers) that are provided have standard XGA (1024x768) interfaces, some have 1080p. If you have a higher resolution laptop, please adjust it accordingly. The connector is a standard HDMI connector. If you have a Macintosh computer that needs an adapter, please do not forget to bring it.
- If you plan to use your computer with the LCD projectors that are provided, please learn to use your computer before your talk begins. The sessions must proceed on time, so the time for configuring your laptop must be included in your speaking time. The conference organizers cannot usually know how to connect your computer for you.

PQE-2026 Website https://pqeconference.com

4 Lamb Award



The Willis E. Lamb Award for Laser Science and Quantum Optics

The Willis E. Lamb Award for Laser Science and Quantum Optics is presented annually for outstanding contributions to the field. The award honors Willis E. Lamb, Jr., famous laser scientist and 1955 winner of the Nobel Prize in physics, who gave us many seminal insights and served as our guide in so many areas of physics and technology.

The award is sponsored by the Physics of Quantum Electronics (PQE) conference and presented at its Winter Colloquium in Snowbird, Utah. This award will be presented at PQE-2026 at 10:50 a.m. on Tuesday morning, January 6, 2026. The 2026 winners are:

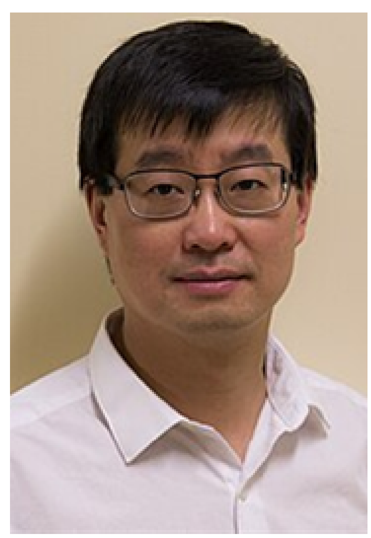
Weng W. Chow, Sandia National Laboratories
For pioneering work in the many body physics of semiconductor lasers.

Richard Miles, Texas A&M University
For path breaking research on the laser diagnostics of aerodynamic plasmas.

Jun Ye, University of Colorado at Boulder
For ground breaking research in atomic clock physics.

Weng W. Chow

Richard Milesn



Jun Ye

More information: https://www.lambaward.org/

5 Program

There are three sessions each day, Monday through Friday. Each session consists of several plenary talks, followed by four parallel breakout sessions. The first session begins at 7:30 a.m. each morning, following the continental breakfast. After the first breakout session there will be a coffee break, then the second plenary session will begin. The second breakout session ends at 1:00 p.m. The third plenary session starts at 7:00 p.m. each evening.

All plenary talks are in Ballrooms 1 and 2. The four breakout sessions are in Ballroom 1, Magpie A, Magpie B, and Wasatch A. These rooms are shown on the maps of the Cliff Lodge on page 4.

The following five pages show a block-diagram guide to the sessions, one for each day. After that is a detailed listing of all the talks.

5.1 Block diagrams of sessions

Monday, January 5, 2026

Time				
7:00	**Continental Breakfast**— *Ballroom 1 and 2*			
7:30	**Morning Plenary Session 1**— *Ballroom 1 and 2*			
9:10	Invited Session: **Quantum Thermodynamics** *Ballroom 1*	Invited Session: **Space-time Metamaterials** *Magpie A*	Invited Session: **Atom Arrays I** *Magpie B*	Invited Session: **Nanophotonics** *Wasatch A*
10:30	**Coffee Break**— *Ballroom 2*			
10:50	**Morning Plenary Session 2**— *Ballroom 1 and 2*			
12:00	Invited Session: **Coherence in Spontaneous Emission** *Ballroom 1*	Invited Session: **Quantum Advantage: Cold atoms and Cavity QED** *Magpie A*	Invited Session: **Quantum Networks I** *Magpie B*	Invited Session: **Topological Features** *Wasatch A*
13:00	**Afternoon is free**			
19:00	**Evening Plenary Session**— *Ballroom 1 and 2*			
20:30	**Coffee Break**— *Ballroom 2*			
20:50	Invited Session: **Gravitational Waves, Dark Matter, Photons...** *Ballroom 1*	Invited Session: **Quantum and Bio** *Magpie A*	Invited Session: **Novel Molecular Spectroscopies with Quantum Light** *Magpie B*	Invited Session: **Ultrafast Optics and Cohrence Phenomena** *Wasatch A*

Tuesday, January 6, 2026

Time				
7:00	**Continental Breakfast**— *Ballroom 1 and 2*			
7:30	**Morning Plenary Session 1**— *Ballroom 1 and 2*			
9:10	Invited Session: **Frontiers of Atom Optics I** *Ballroom 1*	Invited Session: **Nuclear Clock** *Magpie A*	Invited Session: **Semiconductor Lasers I** *Magpie B*	Invited Session: **Quantum Sensors** *Wasatch A*
10:30	**Coffee Break**— *Ballroom 2*			
10:50	**Morning Plenary Session 2**— *Ballroom 1 and 2*			
12:00	Invited Session: **Quantum State and Nonlinear Optics enabled Measurements of Gases and Plasmas** *Ballroom 1*	Invited Session: **Cold Atoms** *Magpie A*	Invited Session: **Quantum Detectors, Sensors and Amplifiers** *Magpie B*	Invited Session: **Quasi-particles in Semiconductor Heterostructures** *Wasatch A*
13:00	**Afternoon is free**			
19:00	**Evening Plenary Session**— *Ballroom 1 and 2*			
20:30	**Coffee Break**— *Ballroom 2*			
20:50	Invited Session: **Frontiers of Quantum Imaging** *Ballroom 1*	Invited Session: **Atomic Arrays II** *Magpie A*	Invited Session: **Meta-Quantum and Near-Zero Materials I** *Magpie B*	Invited Session: **Quantum X-ray Optics** *Wasatch A*

Wednesday, January 7, 2026

Time				
7:00	**Continental Breakfast**— *Ballroom 1 and 2*			
7:30	**Morning Plenary Session 1**— *Ballroom 1 and 2*			
9:10	Invited Session: **Quantum Circuits, Quantum Information, and Quantum Open Systems** *Ballroom 1*	Invited Session: **Controlling Electrons with Ultrashort Pulses** *Magpie A*	Invited Session: **Semiconductor Lasers II** *Magpie B*	Invited Session: **Frontiers of Atom Optics II** *Wasatch A*
10:30	**Coffee Break**— *Ballroom 2*			
10:50	**Lamb Award**— *Ballroom 1 and 2*			
11:20	**Morning Plenary Session 2**— *Ballroom 1 and 2*			
12:00	Invited Session: **Quantum Sensing Beyond Standard Quantum Limits** *Ballroom 1*	Invited Session: **Meta-Quantum and Near-Zero Materials II** *Magpie A*	Invited Session: **Chirality I** *Magpie B*	Invited Session: **Applications of Utrafast Structured Laser Beams** *Wasatch A*
13:00	**Afternoon is free**			
19:00	**Evening Plenary Session**— *Ballroom 1 and 2*			
20:30	**Coffee Break**— *Ballroom 2*			
20:50	Invited Session: **Quantum Technologies for New Physics Discoveries** *Ballroom 1*	Invited Session: **Atom Intereferometry and Space** *Magpie A*	Invited Session: **Quantum Sensing I** *Magpie B*	Invited Session: **Quantum Nuclear Optics** *Wasatch A*

Thursday, January 8, 2026

Time				
7:00	**Continental Breakfast**— *Ballroom 1 and 2*			
7:30	**Morning Plenary Session 1**— *Ballroom 1 and 2*			
9:10	Invited Session: **Enhanced Quantum Metrology using Cavity-QED** *Ballroom 1*	Invited Session: **Attosecond Quantum Optics** *Magpie A*	Invited Session: **IFE Target Engagement and Design** *Magpie B*	Invited Session: **X-ray Optics** *Wasatch A*
10:30	**Coffee Break**— *Ballroom 2*			
10:50	**Morning Plenary Session 2**— *Ballroom 1 and 2*			
12:00	Invited Session: **Excimer Laser Development** *Ballroom 1*	Invited Session: **Chirality II** *Magpie A*	Invited Session: **Frontiers of Sensing and Signal Processing** *Magpie B*	Invited Session: **Quantum Networks II** *Wasatch A*
13:00	**Afternoon is free**			
17:00	**Poster Session and Buffet Dinner**— *Ballroom 1 and 2*			
19:00	**Evening Plenary Session**— *Ballroom 1 and 2*			
20:30	**Coffee Break**— *Ballroom 2*			
20:50	Invited Session: **Multiparticle Interference for Quantum Sensing** *Ballroom 1*	Invited Session: **Challenges with MJ Class Laser Systems for Inertial Fusion Energy** *Magpie A*	Invited Session: **Unconventional Platforms for Entanglement: High Energies and Ultrafast Timescales** *Magpie B*	Invited Session: **Optical Devices** *Wasatch A*

Friday, January 9, 2026

Time				
7:00	**Continental Breakfast**— *Ballroom 1 and 2*			
7:30	**Morning Plenary Session 1**— *Ballroom 1 and 2*			
9:10	Invited Session: **Quantum and Nano Photonics** *Ballroom 1*	Invited Session: **Nanodiamond and Sensors** *Magpie A*	Invited Session: **From Quantum to Life** *Magpie B*	Invited Session: **Attosecond Spectroscopy: from Classical to Quantum** *Wasatch A*
10:30	**Coffee Break**— *Ballroom 2*			
10:50	**Morning Plenary Session 2**— *Ballroom 1 and 2*			
12:00	Invited Session: **Superradiant Maser-Laser** *Ballroom 1*	Invited Session: **Cold Atoms** *Magpie A*	Invited Session: **Frontiers of Quantum Optics II** *Magpie B*	Invited Session: **Laser Spectroscopy** *Wasatch A*
13:00	**Afternoon is free**			
19:00	**Evening Plenary Session**— *Ballroom 1 and 2*			
20:30	**Coffee Break**— *Ballroom 2*			
20:50	Invited Session: **Quantum Technologies to test Fundamental Physics** *Ballroom 1*	Invited Session: **Quantum Sensing II** *Magpie A*	Invited Session: **Controlling Coherence in Photonic Networks** *Magpie B*	Invited Session: **Frontiers of Quantum Optics III** *Wasatch A*

5.2 List of all sessions in detail

Monday, January 5, 2026

Monday Morning Plenary Session 1

Location: Ballrooms 1 and 2 — Olga Kocharovskaya, Chair

7:30 **Marlan Scully**, *Texas A&M University*, “Quantum Advantage in Thermodynamics” [268]

8:00 **John Pendry**, *Imperial College London*, “Energy and entropy content of time-dependent metamaterials” [225]

8:30 **Mikhail Lukin**, *Harvard University*, “New frontier of quantum computing” [**??**]

Monday Morning Invited Session 1

Breakout Session 1: *Quantum Thermodynamics*

Location: Ballrooms 1 — Marlan Scully, Chair

9:10 **Yusef Maleki**, *Texas A&M University*, “Quantum Heat Engine as a Sensor and Beyond: Insights from Fisher Information” [193]

9:30 **Anatoly Svidzinsky**, *Texas A&M University*, “Quantum evolution of mixed states, vacuum entanglement and performance of quantum heat engines” [291]

9:50 **Hui Wang**, *Texas A&M University*, “Quantum Heat Engines Driven by Multilevel Quantum Coherence” [302]

10:10 **Barnabas Kim**, *Texas A&M University*, “Heat Engine in Quantum Engineering: Coherence and Entanglement as resources” [163]

Breakout Session 2: *Space-time Metamaterials*

Location: Magpie A — John Pendry, Chair

9:10 **Bumki Min**, *Korea Advanced Institute of Science & Technology*, “Unified framework for classical and quantum light-matter interactions in photonic time crystals” [202]

9:30 **Jingdi Zhang**, *Hong Kong University of Science and Technology*, “Terahertz wave amplification by a time-boundary-modulated Huygens’ metasurface” [317]

9:50 **Francesco Monticone**, *Cornell University*, “Space-time nonlocal metamaterials” [205]

10:10 **Yonatan Sivan**, *Ben-Gurion University*, “Single-cycle optical nonlinearity of transparent conducting oxides explained” [280]

Breakout Session 3: *Atom Arrays I*

Location: Magpie B — Mikhail Lukin, Chair

9:10 **Andrew Jayich**, *University of California, Santa Barbara*, “Cryogenic ion trapping of atomic and molecular ions for precision measurements” [153]

9:30 **Trent Graham**, *University of Wisconsin at Madison*, “Rydberg gates in a neutral atom array using single-photon excitation” [130]

9:50 **Norbert Linke**, *Duke University*, “Hybrid quantum simulation and city-scale quantum networking with trapped ions” [186]

10:10 **Alexey Gorshkov**, *JQI, NIST/University of Maryland*, “Readout-Free Majority Decoding via Asymmetric Rydberg Antiblockade” [129]

Breakout Session 4: *Nanophotonics*

Location: Wasatch A — Markus Raschke, Chair

9:10 **Markus Raschke**, *University of Colorado, Boulder*, "Ultrafast nano-imaging and tip-enhanced control of electronic coherence in 2D semiconductors" [244]

9:30 **Kejie Fang**, *University of Illinois Urbana-Champaign*, "High-performance nonlinear photonics for quantum information and networking" [115]

9:50 **Souvik Biswas**, *Stanford University and University of Michgan*, "Diamond as a Platform for Scalable Quantum Networks" [76]

10:10 **Cheng Guo**, *The University of Texas at Austin*, "Transport Measurements of Majorization Order for Wave Coherence" [134]

Monday Morning Plenary Session 2

Location: Ballrooms 1 and 2 — Vitaly Kocharovsky, Chair

10:50 **Gerd Leuchs**, *MPL*, "The Atom and the Vacuum" [182]

11:20 **Kazimierz Rzążewski**, *CFT PAN*, "The Hybrid Sampling Method for the Statistics of a Bose Gas" [257]

Monday Morning Invited Session 2

Breakout Session 1: *Coherence in Spontaneous Emission*

Location: Ballrooms 1 — Gerd Leuchs, Chair

12:00 **Rocio Jauregui**, *Universidad Nacional Autonoma de Mexico*, "Effects of collective coupling and center of mass motion on the light scattered by driven multilevel atoms" [152]

12:20 **Martin Fischer**, *Max Planck Institute for the Science of Light*, "Spatial coherence of single photons in spontaneous emission from a single atom" [118]

12:40 **Shuo Sun**, *University of Colorado Boulder*, "Resonance fluorescence of a strongly driven two-level system with dynamically modulated frequency" [288]

Breakout Session 2: *Quantum Advantage: Cold atoms and Cavity QED*

Location: Magpie A — Vitaly Kocharovsky, Chair

12:00 **Vitaly Kocharovsky**, *Texas A&M University*, "Hafnian master theorem and quantum supremacy" [173]

12:20 **Raj Patel**, *Imperial College*, "Gaussian Boson Sampling with Displacements" [221]

12:40 **Changhun Oh**, *KAIST*, "Classical algorithm for simulating experimental Gaussian boson sampling" [216]

Breakout Session 3: *Quantum Networks I*

Location: Magpie B — John Howell, Chair

12:00 **John Howell**, *Chapman University*, "Super Bandwidth Deconvolution Signal Reconstruction" [**??**]

12:20 **Thomas Walther**, *TU Darmstadt*, "Alice, Bob, ... and Friends: What's next for the Darmstadt Quantum Key Distribution Network" [301]

12:40 **Ephraim Shahmoon**, *Weizmann Institute of Science*, "Quantum light-matter interfaces with tweezer atomic arrays" [272]

Breakout Session 4: *Topological Features*

Location: Wasatch A — Andrei Afanasev, Chair

12:00 **Andrei Afanasev**, *George Washington University*, “Nondiffractive Spin Skyrmions of the Vortex Cores in Electromagnetic and Acoustic Waves” [64]

12:20 **Evgenii Narimanov**, *Purdue University*, “Hyperbolic Quantum Procesor” [213]

12:40 **Pankaj Jha**, *Syracuse University*, “Iron-Based Topological Superconductors for Single-Photon Detection” [154]

Monday Evening Plenary Session

Location: Ballrooms 1 and 2 — Birgitta Whaley, Chair

19:00 **Dmitry Budker**, *Helmholtz Institute Mainz, JGU Mainz, and UC Berkeley*, “Gravitational Waves, Dark Matter, Photons... More ways to explore fundamental questions” [85]

19:30 **Susanne F. Yelin**, *Harvard University*, “Unleashing Analog Quantum Computing” [314]

20:00 **Shaul Mukamel**, *University of California, Irvine*, “Monitoring of elementary molecular events with quantum and X-ray light” [209]

Monday Evening Invited Session

Breakout Session 1: *Gravitational Waves, Dark Matter, Photons...*

Location: Ballrooms 1 — Dmitry Budker, Chair

20:50 **Derek F. Jackson Kimball**, *California State University - East Bay*, “Levitated Ferromagnetic Gyroscopes for Fundamental Physics” [165]

21:10 **Vera M. Schäfer**, *Max-Planck-Institut für Kernphysik*, “Searching for a variation of the fine structure constant with highly charged ions” [264]

21:30 **Szymon Pustelny**, *Jagiellonian University in Krakow/Harvard University*, “Constraining long range spin gravity coupling using nuclear magnetic resonance” [239]

21:50 **Alexander Sushkov**, *Johns Hopkins University*, “Quantum metrology of macroscopic spin ensembles” [289]

22:10 **Arne Wickenbrock**, *Johannes Gutenberg University, Mainz*, “Searching dark matter with hyperpolarized spin ensembles” [306]

Breakout Session 2: *Quantum and Bio*

Location: Magpie A — Susanne F. Yelin, Chair

20:50 **Peter Maurer**, *University of Chicago*, “A fluorescent-protein spin qubit” [197]

21:10 **Jonah Peter**, *Harvard University*, “Enabling Ultrastrong Chiral Light-Matter Interactions With Chiral Superradiance” [226]

21:30 **Nishad Maskara**, *MIT*, “Fast simulation of fermions with reconfigurable qubits” [196]

21:50 **Jack Harris**, *Yale University*, “Cavity optomechanics in a levitated drops of superfluid helium” [**??**]

22:10 **Quanwei Li**, *University of California*, “Photon statistics in photosynthetic light harvesting” [183]

Breakout Session 3: *Novel Molecular Spectroscopies with Quantum Light*

Location: Magpie B — Shaul Mukamel, Chair

20:50 **Birgitta Whaley**, *University of California, Berkeley*, "Quantum light spectroscopies for probing photosynthetic systems" [305]

21:10 **Felipe Herrara**, *USACH, Chile*, "Theory of vacuum-assisted chemical reactions in infrared cavities" [142]

21:30 **Michael Reitz**, *UCSD*, "Nonlinear semiclassical spectroscopy of ultrafast molecular polariton dynamics" [**??**]

21:50 **Oumeng Zhang**, *Texas A&M University*, "Quantum-bound-guided single-molecule orientation localization microscopy" [318]

22:10 **Zhenhuan Yi**, *Texas A&M University*, "Generating Coherent States of Photonic Dimers" [315]

Breakout Session 4: *Ultrafast Optics and Cohrence Phenomena*

Location: Wasatch A — Alexei V. Sokolov, Chair

20:50 **Deniz Yavuz**, *University of Wisconsin - Madison*, "Quantum statistics of radiation in collective spontaneous emission" [313]

21:10 **Dmitri Voronine**, *University of South Florida, USA*, "Novel approaches to nanoscale imaging of 2D materials and micro(nano)plastics" [300]

21:30 **Alma Fernández**, *Texas A&M University*, "Optical Coherence Microscopy: Applications to Agriculture" [116]

21:50 **Dong Hee Son**, *Texas A&M University*, "Superradiance and hot electrons from strongly quantum-confined perovskite quantum dots" [285]

22:10 **Alexei V. Sokolov**, *Texas A&M University*, "Quantum Molecular Coherence for Chemical Sensing and Fusion Energy" [284]

Tuesday, January 6, 2026

Tuesday Morning Plenary Session 1

Location: Ballrooms 1 and 2 — Ron Folman, Chair

7:30 **Wolfgang Schleich**, *Ulm University*, "Interference at work" [266]

8:00 **Jun Ye**, *JILA/NIST/University of Colorado*, "Nuclear clock: recent developments" [**??**]

8:30 **Massaya Notomi**, *NTT Research Lab*, "Chiral topology and nonlinearity in non-Hermitian nanophotonics" [**??**]

Tuesday Morning Invited Session 1

Breakout Session 1: *Frontiers of Atom Optics I*

Location: Ballrooms 1 — Wolfgang Schleich, Chair

9:10 **Peter Asenbaum**, *IQOQI Vienna*, "Gravity in quantum systems: From atoms to macroscopic objects" [70]

9:30 **Ron Folman**, *Ben-Gurion University of the Negev*, "Experiments at the interface of general relativity and quantum mechanics" [120]

9:50 **Jannik Str"ohle**, *Ulm University*, "The Einstein Equivalence Principle and the Quantum Galileo Interferometer" [286]

10:10 **Barbara Platzer**, *University of Vienna*, "Embracing instability: preparing macroscopic quantum states in the dark" [231]

Breakout Session 2: *Nuclear Clock*

Location: Magpie A — Jun Ye, Chair

9:10 **Eric Hudson**, *University of California, Los Angeles*, “Nuclear clocks: What now?” [150]

9:30 **Andrei Derevianko**, *University of Nevada, Reno*, “Sub-100 MHz accurate $^{e}xt229$Th nuclear clock frequencies in solid-state and trapped ion platforms” [106]

9:50 **Keerthan Subramanian**, *Johannes Gutenberg University, Mainz*, “A solid-state continuous-wave laser at 148.4 nm for driving the $^{e}xt229m$Th nuclear transition” [287]

10:10 **Victor V. Flambaum**, *University of New South Wales, Sydeny*, “Nuclear Clocks and the Search for New Physics” [119]

Breakout Session 3: *Semiconductor Lasers I*

Location: Magpie B — Massaya Notomi, Chair

9:10 **John Bowers**, *University of California, Santa Barbara*, “Heterogeneously-Integrated Lasers on Thin Film Lithium Niobate” [84]

9:30 **Frédéric Grillot**, *Laval University, Canada*, “Quantum Homodyne Tomography Application to Ultra-Narrow Linewidth Semiconductor Lasers” [132]

9:50 **Alexander Dikopoltsev**, *ETH Zurich*, “Liquid Light Dynamics in Synthetic Dimensions: a New Class of Frequency Combs” [108]

10:10 **Jesper Mørk**, *Technical University of Denmark*, “Sub-Wavelength Semiconductor Nanocavities for Nanoscale Light Sources” [206]

Breakout Session 4: *Quantum Sensors*

Location: Wasatch A — Mikhail Lukin, Chair

9:10 **Ania Bleszynski Jayich**, *University of California Santa Barbara*, “Engineering interacting spins in the solid-state for quantum sensing” [77]

9:30 **Andrei Faraon**, *California Institute of Technoloy*, “Quantum nano-photonics with rare-earth ions” [**??**]

9:50 **Shimon Kolkowitz**, *University of California, Berkeley*, “Gravitational wave detection with space-based optical lattice clocks” [174]

10:10 **Igor Pikovski**, *Stevens Institute of Technology and Stockholm University*, “Towards superpositions of proper time in atomic clocks and quantum networks” [228]

Tuesday Morning Plenary Session 2

Location: Ballrooms 1 and 2 — Olga Kocharovskaya, Chair

10:50 **Marlan Scully**, *Texas A&M University*, “Presentation of the 2026 Willis E. Lamb Award for Laser Science and Quantum Optics” [**??**]

11:20 **Richard Miles**, *Texas A&M University*, “Unravelling Turbulence with Laser Pumped, Time Delayed Quantum State Emission” [200]

Tuesday Morning Invited Session 2

Breakout Session 1: *Quantum State and Nonlinear Optics enabled Measurements of Gases and Plasmas*

Location: Ballrooms 1 — Richard Miles, Chair

12:00 **Arthur Dogariu**, *Texas A&M University and Princeton University*, "Quantum States in Thermodynamical Non-equilibrium Unveiled by Coherent Raman" [109]

12:20 **Mikhail N. Shneider**, *Princeton University*, "Bragg Amplification of Weak Laser Radiation in Optical Lattices in a Gas" [278]

12:40 **Alexandros Gerakis**, *Luxembourg Institute of Science & Technology*, "Reshaping and Probing Velocity Distribution Functions of Neutral and Charged Species with Chirped Optical Lattices" [125]

Breakout Session 2: *Cold Atoms*

Location: Magpie A — Kaden Hazzard, Chair

12:00 **Kaden Hazzard**, *Rice University*, "Observing paraparticles in ultracold Rydberg atoms" [139]

12:20 **Aaron Young**, *Harvard*, "Quantum simulation of the Hubbard model: pseudogap, charge order, and beyond" [316]

12:40 **Theodor Lukin Yelin**, *JILA, University of Colorado*, "Entanglement-Enhanced Metrology in a Neutral Atom Array" [**??**]

Breakout Session 3: *Quantum Detectors, Sensors and Amplifiers*

Location: Magpie B — Zubin Jacob, Chair

12:00 **Shyam Shankar**, *University of Texas at Austin*, "Advancing Josephson parametric amplifiers for scalable high-fidelity readout of solid-state qubits" [275]

12:20 **Zubin Jacob**, *Purdue University*, "Neural bolometers for thermal imaging" [**??**]

12:40 **Mahdi Hosseini**, *Northwestern University*, "Nonlinear Dynamics in Macroscopic Levitation for Enhanced Inertial Sensing and Tests of Semiclassical Gravity" [147]

Breakout Session 4: *Quasi-particles in Semiconductor Heterostructures*

Location: Wasatch A — Leonid Butov, Chair

12:00 **Leonid Butov**, *University of California San Diego*, "Indirect excitons in heterostructures" [89]

12:20 **Cun-Zheng Ning**, *Shenzhen Tech University*, "The Quadruplon: Evidence for a New Quasi-Particle in a 2D Monolayer Semiconductor Through Ultrafast Pump-Probe Experiments" [214]

12:40 **Igor Bondarev**, *North Carolina Central University*, "Charged Bosons Made of Fermions in Laser-Excited Semiconductor-Metal Heterostructures" [80]

Tuesday Evening Plenary Session

Location: Ballrooms 1 and 2 — Federico Capasso, Chair

19:00 **Ebrahim Karimi**, *Chapman University*, "Characterising Entangled Structured Photons for Quantum Imaging Applications" [159]

19:30 **Adam Kaufman**, *JILA, University of Colorado at Boulder*, "A new platform for programmable Hubbard systems" [162]

20:00 **Vladimir Shalaev**, *Purdue University*, "Engineering Light with Space-Time Metamaterials" [274]

Tuesday Evening Invited Session

Breakout Session 1: *Frontiers of Quantum Imaging*

Location: Ballrooms 1 — Ebrahim Karimi, Chair

20:50 **Andrew Jordan**, *Chapman University*, "Direct measurement of the quantum pseudo-distribution via its generating function" [155]

21:10 **Milena D'Angelo**, *Universit'a degli Studi di Bari*, "Correlation imaging, from 3D to hyperspectral" [101]

21:30 **Alessio D'Errico**, *University of Ottawa*, "Imaging the quantum state of biphotons" [102]

21:50 **Benjamin Sussman**, *National Research Council Canada*, "Ultrafast Quantum Photonics: Beating Decoherence with Fast Light Pulses" [290]

22:10 **Yingwen Zhang**, *Chapman University*, "Light-field microscope using entangled photons" [321]

Breakout Session 2: *Atomic Arrays II*

Location: Magpie A — Adam Kaufman, Chair

20:50 **Jake Covey**, *University of Illinois Urbana-Champaign*, "Distributed quantum science with neutral atom arrays" [99]

21:10 **Danial Shadmany**, *Stanford University*, "A 600-site cavity array: expanding the neutral atom array toolbox" [271]

21:30 **Hengyun Zhou**, *QuEra Computing*, "Transversal Architectures for Neutral Atom Logical Quantum Computation" [324]

21:50 **Alexey Lukin**, *QuEra*, "Improved two-qubit gate fidelities for neutral-atom quantum computers" [**??**]

22:10 **Zhenjie Yan**, *Columbia University*, "Cavity-Enabled Measurements and Interactions in Neutral Atom Quantum Processors" [309]

Breakout Session 3: *Meta-Quantum and Near-Zero Materials I*

Location: Magpie B — Vladimir Shalaev, Chair

20:50 **Federico Capasso**, *Harvard*, "From Classical to Quantum Metasurfaces for Multiphoton Interferometry" [92]

21:10 **David Miller**, *Stanford University*, "Self-configuring spectral filters by mapping time to space" [201]

21:30 **Mark Brongersma**, *Stanford University*, "Creating dynamic antennas and metasurfaces with 2D quantum materials" [**??**]

21:50 **Joshua Caldwell**, *Vanderbilt*, "Employing Phonon Polaritons and ENZ Polaritons in Enhanced Thermal Transport" [90]

22:10 **Howard Lee**, *University of California, Irvine*, "Active and Nonlinear Epsilon-Near-Zero Photonics" [**??**]

Breakout Session 4: *Quantum X-ray Optics*

Location: Wasatch A — Ralf Röhlsberger, Chair

20:50 **Ralf Röhlsberger**, *Helmholtz Institute Jena and DESY Hamburg*, "Anomalous Nuclear Forward Scattering under Intense XFEL Excitation" [248]

21:10 **Jörg Evers**, *MPI for Nuclear Physics, Heidelberg*, "Single-shot Mössbauer spectroscopy at X-ray free-electron lasers" [113]

21:30 **Joachim von Zanthier**, *University Erlangen-Nürnberg*, "New results of incoherent diffraction imaging (IDI) for x-ray structure analysis" [299]

21:50 **James M. Baxter**, *SLAC National Accelerator Laboratory*, "Spontaneous parametric down conversion of X-rays at LCLS XFEL" [**??**]

22:10 **Konstantin Beyer**, *Stevens Institute of Technology*, "One-sided Witnesses for the Quantumness of Gravitational Dynamics" [75]

Wednesday, January 7, 2026

Wednesday Morning Plenary Session 1

Location: Ballrooms 1 and 2 — Anatoly Svidzinsky, Chair

7:30 **Franco Nori**, *RIKEN and Univ. of Michigan*, "A few recent results on superconducting qubits" [215]

8:00 **Peter Hommelhoff**, *LMU Munich and FAU Erlangen*, "New control over electrons with ultrashort laser and non-classical fields" [146]

8:30 **Weng Chow**, *Sandia National Laboratory*, "Semiconductor lasers for conventional and quantum applications" [96]

Wednesday Morning Invited Session 1

Breakout Session 1: *Quantum Circuits, Quantum Information, and Quantum Open Systems*

Location: Ballrooms 1 — Franco Nori, Chair

9:10 **Sahin Ozdemir**, *Saint Louis University*, "Non-Hermiticity as a Resource in Photonics" [218]

9:30 **Clemens Gneiting**, *RIKEN, Japan*, "Quantum error correction in bosonic systems" [127]

9:50 **Rodrigo Cortinas**, *Google Quantum AI*, "Quantum computation of molecular geometry via many-body nuclear spin echoes" [97]

10:10 **Andy Schang**, *University of Waterloo*, "Observation of Genuine Tripartite Non-Gaussian Entanglement from a Superconducting Three-Photon Spontaneous Parametric Down-Conversion Source" [265]

Breakout Session 2: *Controlling Electrons with Ultrashort Pulses*

Location: Magpie A — Peter Hommelhoff, Chair

9:10 **Christian Heide**, *University of Central Florida*, "Designing Quantum Materials with Lightwaves: Coherent Floquet Control and Raman-Force Phase Engineering" [**??**]

9:30 **Shawn Sederberg**, *Simon Fraser University*, "Field-driven currents in solids with few-cycle mid-infrared pulses" [269]

9:50 **Uwe Thumm**, *Kansas State University*, "Photoelectron – residual-ion entanglement in angle-differential attosecond time-reolved shake-up ionization" [292]

10:10 **Luca Argenti**, *University of Central Florida*, "Time-Dependent Close Coupling on the heels of attosecond electron dynamics" [69]

Breakout Session 3: *Semiconductor Lasers II*

Location: Magpie B — John Bowers, Chair

9:10 **Nima Nader**, *NIST, Boulder*, "Stimulated Brillouin Scattering in InGaP-on-insulator waveguides" [210]

9:30 **Sebastian Klembdt**, *Würzburg University*, "Topological Lasers: From Electrical Injection and Novel Organic Emitters" [168]

9:50 **Richard Mirin**, *University of California, Santa Barbara*, "Integrated Semiconductor Lasers For Quantum Systems" [203]

10:10 **David Burghoff**, *University of Texas at Austin*, "Liquid combs: broadband light with equidistance and without stability" [87]

Breakout Session 4: *Frontiers of Atom Optics II*

Location: Wasatch A — Wolfgang Schleich, Chair

9:10 **Frank Narducci**, *Naval Postgraduate School*, "A T^3 interferometer and the pit and the pendulum" [212]

9:30 **Alexander Bott**, *Ulm University*, "Atomic diffraction from single-photon transitions in gravity and Standard-Model extensions" [82]

9:50 **Denys I. Bondar**, *Tulane University*, "Quantum Pythagoras: Entanglement Generation via Tunneling and Black-Hole Analogs" [79]

10:10 **Georgi Gary Rozenman**, *Massachusetts Institute of Technology*, "Hydrodynamic Aharonov-Bohm Effect, Time-Varying Vortex-Induced Phases, and Rotating Black-Hole Analogues" [253]

Wednesday Morning Plenary Session 2

Location: Ballrooms 1 and 2 — Kaden Hazzard, Chair

10:50 **Eugene Polzik**, *Niels Bohr Institute, Copenhagen University*, "Quantum sensing beyond standard quantum limits"

11:20 **Alexandra Boltasseva**, *Purdue University*, "Epsilon Near Zero Effects and Applications" [78]

Wednesday Morning Invited Session 2

Breakout Session 1: *Quantum Sensing Beyond Standard Quantum Limits*

Location: Ballrooms 1 — Eugene Polzik, Chair

12:00 **Yang Yang**, *JILA, University of Colorado*, "Spin-squeezed clock for beyond the standard quantum limit performance at 1 imes10^{-18}" [312]

12:20 **Klemens Hammerer**, *Innsbruck University, IQOQI Innsbruck*, "Quantum enhanced atomic clocks without spin squeezing" [135]

12:40 **Johannes Borregaard**, *Harvard University*, "Quantum computing enhanced imaging" [81]

Breakout Session 2: *Meta-Quantum and Near-Zero Materials II*

Location: Magpie A — Alexandra Boltasseva, Chair

12:00 **Nathaniel Kinsey**, *Saint Louis University*, "Origins of Nonlinearities at Epsilon-Near-Zero and its Influence on Applications" [166]

12:20 **Marcello Ferrera**, *Heriot-Watt University*, "Time-varying photonics in transparent conductors" [117]

12:40 **Alexander Khanikaev**, *UCF*, "Leveraging symmetries for control of classical and quantum light in topological metasurfaces" [**??**]

Breakout Session 3: *Chirality I*

Location: Magpie B — Olga Smirnova, Chair

12:00 **Loren Greenman**, *Kanzas University*, "Multiphoton Photoelectron Circular Dichroism via Time-Dependent Perturbation Theory: Revealing Principles of Chirality with Attosecond XUV Imaging" [131]

12:20 **Davide Facciala**, *CNR Milan*, "Probing attosecond chiral multi-electron dynamics via enantio-sensitive interferometry" [114]

12:40 **Nikolay Golubev**, *University of Arizona*, "Control of quantum dynamics using stimulated Raman adiabatic passage technique" [128]

Breakout Session 4: *Applications of Utrafast Structured Laser Beams*

Location: Wasatch A — Pavel Polynkin, Chair

12:00 **Pavel Polynkin**, *University of Arizona*, "Curved air waveguides using intense designer laser beams" [233]

12:20 **Francois Courvoisier**, *Marie and Louis Pasteur University, CNRS, FEMTO-ST institute*, "Physics and applications of femtosecond higher-order Bessel beam interaction with dielectrics" [98]

12:40 **Aurelien Houard**, *LOA - Ecole Polytechnique*, "Spatio-temporal shaping of laser filaments in air" [149]

Wednesday Evening Plenary Session

Location: Ballrooms 1 and 2 — Frank Narducci, Chair

19:00 **Marianna Safronova**, *University of Delaware*, "Quantum Technologies for New Physics Discoveries" [259]

19:30 **Ernst Rusel**, *University of Hannover*, "Quantum gases in microgravity: new perspectives for ground based research" [256]

20:00 **Lan Yang**, *Washington University in St. Louis*, "When Light Listens: New Frontiers at the Intersection of Cavity Optomechanics and Photoacoustic Spectroscopy" [311]

Wednesday Evening Invited Session

Breakout Session 1: *Quantum Technologies for New Physics Discoveries*

Location: Ballrooms 1 — Marianna Safronova, Chair

20:50 **Piet O. Schmidt**, *Physikalisch-Technische Bundesanstalt*, "Highly Charged Ion Clocks to Test Fundamental Physics" [267]

21:10 **José R. Crespo López-Urrutia**, *Max-Planck-Institut für Kernphysik, Heidelberg, Germany*, "Towards frequency metrology in the extreme ultraviolet range with trapped highly charged ions" [189]

21:30 **Harikrishnan Ramani**, *University of Delaware*, "Searches for dark matter with precise electric field sensors" [241]

21:50 **Andrew Ludlow**, *National Institute of Standards and Technology*, "Next-generation timekeeping with optical lattice clocks" [190]

22:10 **Christian Sanner**, *Colorado State University*, "Testing relativity with a cryogenic ytterbium ion clock" [263]

Breakout Session 2: *Atom Intereferometry and Space*

Location: Magpie A — Ernst Rusel, Chair

20:50 **Arnaud Landragin**, *LTE, Observatoire de Paris, Université PSL*, "High sensitivity and accuracy with a large area cold atom gyroscope" [179]

21:10 **Tim Kovachy**, *Northwestern University*, "A Surprising Systematic Effect from the Interplay of Spontaneous Emission and Many-Pulse Atom Interferometry" [176]

21:30 **Kai Frye-Arndt**, *Leibniz University Hannover*, "Diffraction-induced apparent self-focussing and transplant of Bose-Einstein condensates in absorption imaging" [121]

21:50 **Zack Pagel**, *Infleqtion*, "Quantum Gravity Gradiometry from Space: A Pathfinder Mission with NASA" [219]

22:10 **Jan Michael Rost**, *Max Planck Institute for the Physics of Complex Systems, Desden, Germany*, "Is Physics Timeless ?" [251]

Breakout Session 3: *Quantum Sensing I*

Location: Magpie B — Lan Yang, Chair

20:50 **Zheshen Zhang**, *University of Michigan*, "Quantum Sensing based on Centralized and Distributed Entanglement" [322]

21:10 **Kyungtae Kim**, *JILA*, "Optical Lattic Clocks: physics and applications" [164]

21:30 **Chong Zu**, *Washington University in St. Louis*, "Quantum Sensors in 2D Materials: Opportunities and Challenges" [326]

21:50 **Andy Mounce**, *Sandia National Laboratory*, "Quantum sensing with quantum defects" [207]

22:10 **Tian-Xing Zheng**, *The University of Chicago*, "A Molecular Qubit Scaffolded on a Hexagonal Boron Nitride Surface" [323]

Breakout Session 4: *Quantum Nuclear Optics*

Location: Wasatch A — Olga Kocharovskaya, Chair

20:50 **Yuri Shvyd'ko**, *Argonne National Laboratory*, "Advances in 45-Scandium nuclear clock research" [**??**]

21:10 **Sharon Shwartz**, *Bar-Ilan University*, "Direct ghost tomography for 3D X-ray fluorescence imaging" [279]

21:30 **Wen-Te Liao**, *National Central University*, "Gravitational Photon Echo using Thorium-229 nuclear clock transition" [184]

21:50 **Olga Kocharovskaya**, *Texas A&M University*, "Quantum memory for hard X-ray photons in the stationary nuclear absorbers" [172]

22:10 **Xiwen Zhang**, *Texas A&M University*, "Quantum memory for hard X-ray photons with reduced mechanical complexity" [320]

Thursday, January 8, 2026

Thursday Morning Plenary Session 1

Location: Ballrooms 1 and 2 — Carmen Menoni, Chair

7:30 **James Thompson**, *JILA, NIST and University of Colorado, Boulder*, "Photon mediated interactions for quantum sensing and simulation" [**??**]

8:00 **Mikhail Ivanov**, *Max Born Institute*, "Attosecond Quantum Optics and Tortured Super-Radiance" [151]

8:30 **Conner Galloway**, *Xcimer Energy, Inc.*, "A high-energy excimer-Raman-Brillouin laser system for inertial fusion energy" [**??**]

Thursday Morning Invited Session 1

Breakout Session 1: *Enhanced Quantum Metrology using Cavity-QED*

Location: Ballrooms 1 — James Thompson, Chair

9:10 **Chengyi Luo**, *California Institute of Technology*, "Extending Ramsey coherence of solid-state spins via cavity-mediated interactions" [191]

9:30 **Gustavo Velez**, *Massachusetts Institute of Technology*, "Quantum-amplified spectroscopy on an optical clock transition" [297]

9:50 **Raphael Kaubruegger**, *JILA and University of Colorado Boulder*, "Lieb-Mattis states for robust entangled differential phase sensing: prospects for implementation in cavities" [161]

10:10 **Guglielmo Panelli**, *Stanford University*, "Excitation of the Strontium clock state with megahertz Rabi frequency and a new platform for quantum-enhanced sensing" [220]

Breakout Session 2: *Attosecond Quantum Optics*

Location: Magpie A — Mikhail Ivanov, Chair

9:10 **Denis Seletskiy**, *University of New Mexico*, "Time-Domain Measurement of Few-Cycle Two-Mode Squeezed State" [270]

9:30 **Carlos Trallero**, *University of Connecticut*, "Single photon attosecond interferometry" [294]

9:50 **Michael Krueger**, *Technion*, "Quantum tomography of nonperturbative harmonic light from solids" [177]

10:10 **Mohammed Hassan**, *University of Arizona*, "Ultrafast Quantum Optics" [137]

Breakout Session 3: *IFE Target Engagement and Design*

Location: Magpie B — Jorge Rocca, Chair

9:10 **Felicie Albert**, *Lawrence Livermore National Laboratory*, "LaserNetUS: the first five years of scientific discovery" [66]

9:30 **Bedros Afeyan**, *Polymath Research Inc.*, "Enabling Inertial Fusion Energy (IFE) by Controlling Nonlinear Optical Instabilities Using Spike Trains of Uneven Duration and Delay (STUD Pulses)" [65]

9:50 **Camille Samulski**, *Los Alamos National Laboratory*, "Polar Direct Drive Target Design for a 10MJ Laser Inertial Fusion Energy Facility" [261]

10:10 **Jorge Rocca**, *Colorado State Univesity*, "Physics of ion acceleration in nanowire arrays irradiated with ultrashort laser pulses of relativistic intensity" [247]

Breakout Session 4: *X-ray Optics*

Location: Wasatch A — Arvinder Sandhu, Chair

9:10 **Arvinder Sandhu**, *University of Arizona*, "Commissioning of femtosecond hard x-source at ASU CXFEL facility" [**??**]

9:30 **Zain Abhari**, *University of Wisconsin - Madison*, "Stimulated Emission in the Hard X-ray Regime for X-ray Coherent Attosecond Pulse Pair Spectroscopy" [62]

9:50 **Phay Ho**, *Argonne National Laboratory*, "Indistinguishability and Quantum Pathways in Nonlinear Resonant X-ray Scattering" [143]

10:10 **Justin Peatross**, *Brigham Young University*, "Polarization of Nonlinear Thomson Scattering" [223]

Thursday Morning Plenary Session 2

Location: Ballrooms 1 and 2 — J. Gary Eden, Chair

10:50 **Paul Hoff**, *Xcimer Energy, Inc.*, "The Excimer Laser: Its Development and Evolution" [144]

11:20 **Olga Smirnova**, *Max Born Institute*, "Enantio-sensitive molecular compass" [282]

Thursday Morning Invited Session 2

Breakout Session 1: *Excimer Laser Development*

Location: Ballrooms 1 — J. Gary Eden, Chair

12:00 **Mike Campbell**, *University of California, San Diego*, "Laser Systems for Inertial Fusion: Requirements, Challenges and Opportunities" [91]

12:20 **J. Gary Eden**, *University of Illinois, Texas A&M University*, "A Brief Overview of the Discovery, Critical Parameters, and Scaling of the Rare-gas Halide Excimer Lasers" [112]

12:40 **Sophia Malko**, *Princeton University*, "Role of the Nernst Effect in magneto-inertial plama" [**??**]

Breakout Session 2: *Chirality II*

Location: Magpie A — Olga Smirnova, Chair

12:00 **David Ayuso**, *Imperial College London*, "Towards microfluidic chips for efficient chiral recognition" [71]

12:20 **Vladimiro Mujica**, *Arizona State University*, "Surface Chirality Sensors Based on Spin-Dependent van der Waals Interactions and CISS-Induced Spinterface Effects" [208]

12:40 **Andrés Ordóñez**, *Freie Universität Berlin*, "Non-Dichroic Enantio-Sensitive Chiroptical Spectroscopy" [217]

Breakout Session 3: *Frontiers of Sensing and Signal Processing*

Location: Magpie B — Dana Z. Anderson, Chair

12:00 **Dana Z. Anderson**, *Infleqtion, Louisville CO, and JILA, University of Colorado Boulder*, "Atomtricity: From Field Theory to Atom Transistors" [**??**]

12:20 **Shengwang Du**, *Purdue University*, "Quantum-Enhanced Nonlinearities for Scalable All-Optical Neural Networks" [111]

12:40 **Sergey V. Polyakov**, *NIST*, "Robust, Scalable, and Low-Noise Phase Stabilization for Next-Generation Quantum Networks" [232]

Breakout Session 4: *Quantum Networks II*

Location: Wasatch A — Michael Kolodrubetz, Chair

12:00 **John J. Prevost**, *University of Austin at San Antonio*, “Next generation quantum memories with Rydberg technology” [236]

12:20 **Akbar Safari**, *University of Wisconsin-Madison*, “Efficient generation of single photons and atom-photon entanglement in a quantum network node” [258]

12:40 **Michael Kolodrubetz**, *University of Texas at Dallas*, “Geometry and Topology in Cavity QED” [175]

Thursday Evening Plenary Session

Location: Ballrooms 1 and 2 — David A. Reis, Chair

19:00 **Yanhua Shih**, *University of Maryland, Baltimore County*, “From Ghost Frequency Comb to Quantum Ghost Frequency Comb” [277]

19:30 **Siegfried Glenzer**, *SLAC National Accelerator Laboratory and Stanford University*, “Advancing inertial fusion energy using ultra-high peak power X-rays” [126]

20:00 **Ido Kaminer**, *Technion - Israel Institute of Technology*, “Quantum Optics and Entanglement at the Extremes” [**??**]

Thursday Evening Invited Session

Breakout Session 1: *Multiparticle Interference for Quantum Sensing*

Location: Ballrooms 1 — Thomas A. Smith, Chair

20:50 **Melissa A. Guidry**, *MIT-LIGO*, “Heisenberg scaling in a continuous-wave interferometer” [133]

21:10 **Thomas A. Smith**, *Naval Air Warfare Center, Aircraft Division*, “Nontrivial intensity correlations with coherent continuous-wave lasers” [283]

21:30 **Mary F. Locke**, *Naval Air Warfare Center, Aircraft Division*, “Two-atom correlations in a continuous cold atom beam” [188]

21:50 **Emanuele Galiffi**, *The University of Texas at Austin*, “Multiphoton Hong-Ou-Mandel Interference from Classical Light in a Time-Varying Medium” [122]

22:10 **Ivan Burenkov**, *Joint Quantum Institute at NIST*, “Towards robust detector tomography” [86]

Breakout Session 2: *Challenges with MJ Class Laser Systems for Inertial Fusion Energy*

Location: Magpie A — Richard L. Sandberg, Chair

20:50 **Carmen Menoni**, *Colorado State University*, “Optical coatings for MJ Lasers” [**??**]

21:10 **Robert Kirkwood**, *Consultant at Xcimer Energy, Inc.*, “The Promise and Challenges of Ion Wave Plasma Optics for Enabling Laser Driven Fusion Energy” [167]

21:30 **Richard L. Sandberg**, *Brigham Young University*, “Understanding nanometer structure-performance relation of foams for inertial fusion energy” [262]

21:50 **Pravesh Patel**, *Focused Energy Inc.*, “Focused Energy’s Path to Inertial Fusion Energy: Status and Challenges” [**??**]

22:10 **Gabriele Benincasa**, *Texas A&M University*, “Experimental study of laser plasma instabilities with broadband laser pulses at the GSI PHELIX laser facility” [74]

Breakout Session 3: *Unconventional Platforms for Entanglement: High Energies and Ultrafast Timescales*

Location: Magpie B — Ido Kaminer, Chair

20:50 **Claus Ropers**, *Max Planck Institute for Multidisciplinary Sciences & University of Göttingen*, "Free-Electron Quantum Optics:? Coherent Control, Correlations, and Entanglement" [250]

21:10 **Philipp Haslinger**, *VCQ - Atominstitut - USTEM Technische Universität Wien*, "Entanglement in Electron Microscopy" [136]

21:30 **David A. Reis**, *Stanford University*, "Transduction of squeezed light from infrared to x rays" [**??**]

21:50 **Aviv Karnieli**, *Technion - Israel Institute of Technology*, "Towards observation of entanglement in free-electron pairs and free-electron-bound electron systems" [160]

22:10 **Nicholas Rivera**, *Cornell University*, "Controlling quantum correlations of bright multimode light sources" [246]

Breakout Session 4: *Optical Devices*

Location: Wasatch A — Axel Hoffmann, Chair

20:50 **Frances Ligler**, *Texas A&M University*, "The road to an optical biosensor based on quantum photonics" [185]

21:10 **Selim Shahriar**, *Northwestern University*, "Demonstration of a Rb-based Mode-Locking Free Subluminal Ring Laser Gyroscope" [273]

21:30 **Axel Hoffmann**, *University of Illinois Urbana-Champaign*, "Hybrid Magnon Modes" [145]

21:50 **Stephen Cronin**, *University of Southern California*, "Probing the Real and Imaginary Dielectric Response of the Electric Double Layer using Surface Plasmon Resonance Nanostructures" [100]

22:10 **Gerhard Klimeck**, *Purdue University*, "Quantitative Quantum Device Design and Optimization to increase THz Radiation Power" [170]

Friday, January 9, 2026

Friday Morning Plenary Session 1

Location: Ballrooms 1 and 2 — Alexei V. Sokolov, Chair

7:30 **Matthew Pelton**, *University of Maryland, Baltimore County*, "Strong light-matter coupling at the nanoscale for quantum photonics" [224]

8:00 **Philip Hemmer**, *Texas A&M University*, "Nanodiamonds and quantum sensing" [140]

8:30 **Vladislav Yakovlev**, *Texas A&M University*, "Quantum Biomechanics" [**??**]

Friday Morning Invited Session 1

Breakout Session 1: *Quantum and Nano Photonics*

Location: Ballrooms 1 — Matthew Pelton, Chair

9:10 **Arka Majumdar**, *University of Washington*, "Integrated Nanophotonics with Colloidal Materials" [192]

9:30 **Lee Bassett**, *University of Pennsylvania*, "Engineering quantum defects in colloidal nanocrystals" [**??**]

9:50 **Alexey Belyanin**, *Texas A&M University*, "Nanophotonics for coherent control of topological electron states" [73]

10:10 **Yuri Rostovtsev**, *University of North Texas*, "Correlated quantum fields generated by vacuum fields" [252]

Breakout Session 2: *Nanodiamond and Sensors*

Location: Magpie A — Philip Hemmer, Chair

9:10 **Milos Nesladek**, *University Hasselt*, "Nanoscale thermometry on the neural-cell plasma membrane using NV-nanodiamond " [**??**]

9:30 **Peter J. Burke**, *University of California, Irvine*, "Mitochondria in quantum sensing: Effect of photobleaching and phototoxicity" [88]

9:50 **Peter Pauzauskie**, *University of Washington*, "Solid state laser refrigeration of nanoscale plasmonic sensors probed via Raman spectroscopy" [222]

10:10 **Gurudev Dutt**, *University of Pittsburgh*, "Toward Macroscopic Quantum Superpositions with Magnetically Levitated Diamond Crystals" [**??**]

Breakout Session 3: *From Quantum to Life*

Location: Magpie B — Vladislav Yakovlev, Chair

9:10 **Igor Lednev**, *University at Albany, State University of New York*, "Raman Spectroscopy and Machine Learning for Biomedical Applications" [181]

9:30 **Layla Pires**, *Texas A&M University*, "Multiphoton melanin-mediated energy transfer enables ocular melanoma eradication" [229]

9:50 **Dylan Almeida**, *University of California, Berkeley*, "Photon Correlation Measurements of Fluorescence as a Probe of Quantum Coherence in Multi-Chromophoric Systems" [68]

10:10 **Michelle B. Requena**, *Texas A&M University*, "Spin Exchange, Molecular Energy Transfer, and Photoreactions for Destroying Cancer Cells and Microorganisms and Overcoming Antibiotic Resistance " [245]

Breakout Session 4: *Attosecond Spectroscopy: from Classical to Quantum*

Location: Wasatch A — Mikhail Ivanov, Chair

9:10 **Omer Kneller**, *Regensburg University*, "Lightwave Engineering of Excitonic States in an Atomically Thin Semiconductor" [171]

9:30 **Noa Yaffe**, *Weizmann Institute of Science*, "Attosecond transient absorption with quantum-structured fluctuations" [308]

9:50 **Hamed Merdji**, *Ecole Polytechnique*, "Quantum-optical nature of ultrafast high-harmonic generation in semiconductors" [199]

10:10 **David Purschke**, *Laboratory for Laser Energetics*, "Disorder-driven decoherence in the attosecond dynamics of amorphized silicon" [238]

Friday Morning Plenary Session 2

Location: Ballrooms 1 and 2 — Robert Usselman, Chair

10:50 **Dominik Schneble**, *Stony Brook University*, "Exploring super- and subradiant dynamics with matter-wave quantum emitters" [**??**]

11:20 **Vanderlei S. Bagnato**, *University of São Paulo and Texas A&M University*, "The revival of the Superfluid or decaying to a thermal gas during relaxation of a far-from equilibrium Bose-Einstein Condensate" [72]

Friday Morning Invited Session 2

Breakout Session 1: *Superradiant Maser-Laser*

Location: Ballrooms 1 — Dominik Schneble, Chair

12:00 **Yuimaru Kubo**, *Okinawa Institute of Science and Technology*, "A near-quantum limited diamond maser amplifier operating at millikelvin temperatures" [**??**]

12:20 **Daan M. Arroo**, *Imperial College London*, "Towards broadband, high dynamic-range diamond maser amplifiers" [**??**]

12:40 **Ren-Bao Liu**, *Chinese University of Hong Kong*, "Superradiant lasing from a quantum many-body emitter" [187]

Breakout Session 2: *Cold Atoms*

Location: Magpie A — Vanderlei S. Bagnato, Chair

12:00 **Thu Hac Huong Le**, *National Institute of Advanced Industrial Science and Technology, Japan*, "Metasurfaces in Laser Cooling and Trapping of Atoms Towards Miniaturized Cold Atom Platforms" [180]

12:20 **Wenchao Ge**, *University of Rhode Island*, "Double Quantum-Enhanced Sensing of Displacements with Trapped-ion Crystals" [123]

12:40 **Philippe Bouyer**, *Univ. Amsterdam and Technical Univ. Eindhoven*, "Atom Interferometry Beyond Its Limits" [83]

Breakout Session 3: *Frontiers of Quantum Optics II*

Location: Magpie B — John J. Prevost, Chair

12:00 **Robert Usselman**, *Florida Institute of Technology*, "Biological Systems as Functional Quantum Sensors" [**??**]

12:20 **Daniel I. Herman**, *Sandia National Laboratories*, "Dual-comb spectroscopy with quantum states of light" [141]

12:40 **Jared Weidman**, *Michigan State University*, "Quantum electron dynamics of molecules in cavities" [304]

Breakout Session 4: *Laser Spectroscopy*

Location: Wasatch A — Aart Verhoef, Chair

12:00 **Dmitry Kurouski**, *Texas A&M University*, "Raman Spectroscopy in Digital Farming" [178]

12:20 **Konstantin Dorfman**, *Hainan University*, "High precision spectroscopy with metasurfaces" [110]

12:40 **Aart Verhoef**, *Texas A&M University*, "Super-resolved multiphoton microscopy with double enhancement achieves sub-100 nm resolution" [298]

Friday Evening Plenary Session

Location: Ballrooms 1 and 2 — Boubacar Kanté, Chair

19:00 **Michael Tobar**, *The University of Western Australia*, "Electric Land'e g-Factor and Pseudo-Angular Momentum: A Symmetry-Based Dual Reformulation of Electric Dipole Moments and the Stark Effect" [293]

19:30 **Vladimir Malinovsky**, *DEVCOM Army Research Laboratory*, "Quantum Control as a Unifying Principle for Sensing, Metrology, and Computation" [194]

20:00 **Nir Davidson**, *Weizmann Institute of Science*, "Complex bands and topology with coupled lasers" [103]

Friday Evening Invited Session

Breakout Session 1: *Quantum Technologies to test Fundamental Physics*

Location: Ballrooms 1 — Michael Tobar, Chair

20:50 **Andrew Geraci**, *Northwestern University*, "Optomechanical sensors for dark matter, axions and high frequency gravitational waves" [124]

21:10 **John Davis**, *University of Alberta*, "Sensing Gravitational Waves and Dark Matter with Superfluid Helium" [105]

21:30 **Ben McAllister**, *Swinburne University of Technology*, "Quantum Sensing Above and Below Ground: ORGAN and CELLAR" [198]

21:50 **Aaron Chou**, *Fermilab*, "Targeting the QCD axion with qubit-based electronics" [**??**]

22:10 **Elizabeth Ruddy**, *Yale University, University of Colorado Boulder*, "Quantum sensing to accelerate the axion dark matter search" [255]

Breakout Session 2: *Quantum Sensing II*

Location: Magpie A — Vladimir Malinovsky, Chair

20:50 **Michael Romalis**, *Princeton University*, "Nuclear spin comagnetometer gyroscopes with $^{e}xt21$Ne" [249]

21:10 **Victor Acosta**, *University of New Mexico*, "Optical nuclear magnetic resonance spectroscopy of solid-state spins" [63]

21:30 **Emily Davis**, *New York University*, "Spin squeezing in an ensemble of nitrogen-vacancy centers in diamond" [104]

21:50 **Onur Hosten**, *Institute of Science and Technology, Austria*, "Control, sensing and gravitational coupling of milligram pendulums: towards interfacing quantum and gravity" [148]

22:10 **Georg Raithel**, *University of Michigan*, "Sagnac Tractor Atom Interferometer on a Photonic Integrated Circuit" [240]

Breakout Session 3: *Controlling Coherence in Photonic Networks*

Location: Magpie B — Nir Davidson, Chair

20:50 **Boubacar Kanté**, *University of California, Berkeley*, "Arbitrary fractional quantization in Dirac systems and scale-invariant lasers" [157]

21:10 **Sebastian Klembdt**, *Würzburg University*, "Polariton Lattices, Higher-Order Topology, and Artifical Gauge Fields" [169]

21:30 **Lida Xu**, *University of Maryland*, "Nonlinear topological photonics: from frequency combs and harmonic generation to emergent phenomena" [307]

21:50 **Arthur Montanari**, *Northwestern University*, "Disorder-Promoted Synchronization and Coherence in Coupled Laser Networks" [204]

22:10 **Alexander Cerjan**, *Sandia*, "Classifying topology in nonlinear photonic systems" [94]

Breakout Session 4: *Frontiers of Quantum Optics III*

Location: Wasatch A — Steven F. DiMarco, Chair

20:50 **Steven F. DiMarco**, *Texas A&M University*, "Quantum Ocean: Resetting Ocean Science with Applications of Quantum Sensors, Materials, Networks" [107]

21:10 **Yi Rao**, *Utah State University*, "Polariton-Modulated Singlet Fission in Cavity" [243]

21:30 **Sebastián C. Carrasco**, *DEVCOM Army Research Laboratory*, "Dynamic Population Suppression for Two-Photon Excitation" [93]

21:50 **Sebastian Klembdt**, *Würzburg University*, "Polariton Lattices, Higher-Order Topology, and Artifical Gauge Fields" [169]

22:10 **M. Tuan Trinh**, *Utah State University*, "Quantum Coherent State of Plasmon-exciton Strong Coupling in a Nanocavity" [295]

5.3 Poster session

Adel Ali, *Texas A&M University*
"Fermionic Dicke phase transition in Circuit Quantum Magnetostatics" [67]

Gabriele Benincasa, *Texas A&M University*
"Experimental study of laser plasma instabilities with broadband laser pulses at the GSI PHELIX laser facility" [74]

Sheila Chauwinoir, *Texas A&M University*
"Extreme-Value Statistics of Soliton Dynamics: Validating Model for Robust Inertial-Confinement Fusion Design" [95]

Ayla Hazrathosseini, *Texas A&M University*
"Entanglement in Diamond Color Centers for Quantum Technologies" [138]

Kunwar Kalra, *Texas A&M University*
"Universal lower bound on the computational complexity of Gaussian boson sampling" [156]

Christos Karapoulitidis, *Stevens Institute of Technology*
"Distinguishing Semi-Classical and Quantum Models of Proper Time with Atomic Clocks" [158]

Amber Manspeaker, *Naval Air Warfare Center, Aircraft Division*
"Is the GFC the result of Intensity Fluctuation Correlation?" [195]

Nathan G. Phillips, *Texas A&M University*
"Fluorescence Imaging of Vibrationally Excited Molecular Oxygen using an Optical Parametric Oscillator" [227]

Robert Randolph, *Texas A&M University*
"Development of an Active Atomic Vapor Filter Utilizing Quantum Resonance Enhanced Four Wave Mixing" [242]

Georgi Gary Rozenman, *Massachusetts Institute of Technology*
"Optical Emulation of Quantum Systems Using Pulsed Lasers and Classical Optics" [254]

Samuel Sahel-Schackis, *SLAC National Accelerator Laboratory*
"Investigation of the effects of nanoscale facets on catalytic activity in photo-driven nanosystems" [260]

Zhijie Shi, *Huazhong University of Science and Technology*
"Low-Energy Femtosecond LIBS Enabled by Mie-Resonance-Induced Field Enhancement" [276]

AmirAli VanakiFarahani, *Texas A&M University*
"Hybrid Pumping of Excimer Lasers as a Candidate Architecture for Fusion Drivers" [296]

Cooper Watson, *Texas A&M University*
"Review of the Quantum Boltzmann Equation" [303]

Fan Yang, *Texas A&M University*
"Coherence-Enhanced Open Quantum Battery" [319]

Wenzhuo Zhang, *Texas A&M University*
"Quantum evolution of mixed states and efficiency of quantum heat engines" [319]

Shiyao Zhu, *Zhejiang University*
"Realizing the Haldane Model in Thermal Atoms" [325]

6 List of Participants

Zain Abhari, *University of Wisconsin - Madison*
Thursday morning invited session 1, abstract on page [62]
"*Stimulated Emission in the Hard X-ray Regime for X-ray Coherent Attosecond Pulse Pair Spectroscopy*"

Victor Acosta, *University of New Mexico*
Friday evening invited session, abstract on page [63]
"*Optical nuclear magnetic resonance spectroscopy of solid-state spins*"

Andrei Afanasev, *George Washington University*
Monday morning invited session 2, abstract on page [64]
"*Nondiffractive Spin Skyrmions of the Vortex Cores in Electromagnetic and Acoustic Waves*"

Bedros Afeyan, *Polymath Research Inc.*
Thursday morning invited session 1, abstract on page [65]
"*Enabling Inertial Fusion Energy (IFE) by Controlling Nonlinear Optical Instabilities Using Spike Trains of Uneven Duration and Delay (STUD Pulses)*"

Felicie Albert, *Lawrence Livermore National Laboratory*
Thursday morning invited session 1, abstract on page [66]
"*LaserNetUS: the first five years of scientific discovery*"

Adel Ali, *Texas A&M University*
Poster session, abstract on page [67]
"*Fermionic Dicke phase transition in Circuit Quantum Magnetostatics*"

Dylan Almeida, *University of California, Berkeley*
Friday morning invited session 1, abstract on page [68]
"*Photon Correlation Measurements of Fluorescence as a Probe of Quantum Coherence in Multi-Chromophoric Systems*"

Dana Z. Anderson, *Infleqtion, Louisville CO, and JILA, University of Colorado Boulder*
Thursday morning invited session 2, abstract on page [**??**]
"*Atomtricity: From Field Theory to Atom Transistors*"

Luca Argenti, *University of Central Florida*
Wednesday morning invited session 1, abstract on page [69]
"*Time-Dependent Close Coupling on the heels of attosecond electron dynamics*"

Daan M. Arroo, *Imperial College London*
Friday morning invited session 2, abstract on page [**??**]
"*Towards broadband, high dynamic-range diamond maser amplifiers*"

Peter Asenbaum, *IQOQI Vienna*
Tuesday morning invited session 1, abstract on page [70]
"*Gravity in quantum systems: From atoms to macroscopic objects*"

David Ayuso, *Imperial College London*
Thursday morning invited session 2, abstract on page [71]
"*Towards microfluidic chips for efficient chiral recognition*"

Vanderlei S. Bagnato, *University of São Paulo and Texas A&M University*
Friday morning plenary session 2, abstract on page [72]
"*The revival of the Superfluid or decaying to a thermal gas during relaxation of a far-from equilibrium Bose-Einstein Condensate*"

Lee Bassett, *University of Pennsylvania*
Friday morning invited session 1, abstract on page [**??**]
"*Engineering quantum defects in colloidal nanocrystals*"

James M. Baxter, *SLAC National Accelerator Laboratory*
Tuesday evening invited session, abstract on page [**??**]
"*Spontaneous parametric down conversion of X-rays at LCLS XFEL*"

Alexey Belyanin, *Texas A&M University*
Friday morning invited session 1, abstract on page [73]
"*Nanophotonics for coherent control of topological electron states*"

Gabriele Benincasa, *Texas A&M University*
Thursday evening invited session, abstract on page [74]
"*Experimental study of laser plasma instabilities with broadband laser pulses at the GSI PHELIX laser facility*"

Konstantin Beyer, *Stevens Institute of Technology*
Tuesday evening invited session, abstract on page [75]
"*One-sided Witnesses for the Quantumness of Gravitational Dynamics*"

Souvik Biswas, *Stanford University and University of Michgan*
Monday morning invited session 1, abstract on page [76]
"*Diamond as a Platform for Scalable Quantum Networks*"

Ania Bleszynski Jayich, *University of California Santa Barbara*
Tuesday morning invited session 1, abstract on page [77]
"*Engineering interacting spins in the solid-state for quantum sensing*"

Alexandra Boltasseva, *Purdue University*
Wednesday morning plenary session 2, abstract on page [78]
"*Epsilon Near Zero Effects and Applications*"

Denys I. Bondar, *Tulane University*
Wednesday morning invited session 1, abstract on page [79]
"*Quantum Pythagoras: Entanglement Generation via Tunneling and Black-Hole Analogs*"

Igor Bondarev, *North Carolina Central University*
Tuesday morning invited session 2, abstract on page [80]
"*Charged Bosons Made of Fermions in Laser-Excited Semiconductor-Metal Heterostructures*"

Johannes Borregaard, *Harvard University*
Wednesday morning invited session 2, abstract on page [81]
"*Quantum computing enhanced imaging*"

Alexander Bott, *Ulm University*
Wednesday morning invited session 1, abstract on page [82]
"*Atomic diffraction from single-photon transitions in gravity and Standard-Model extensions*"

Philippe Bouyer, *Univ. Amsterdam and Technical Univ. Eindhoven*
Friday morning invited session 2, abstract on page [83]
"*Atom Interferometry Beyond Its Limits*"

John Bowers, *University of California, Santa Barbara*
Tuesday morning invited session 1, abstract on page [84]
"*Heterogeneously-Integrated Lasers on Thin Film Lithium Niobate*"

Mark Brongersma, *Stanford University*
Tuesday evening invited session, abstract on page [**??**]
"*Creating dynamic antennas and metasurfaces with 2D quantum materials*"

Dmitry Budker, *Helmholtz Institute Mainz, JGU Mainz, and UC Berkeley*
Monday evening plenary session, abstract on page [85]
"*Gravitational Waves, Dark Matter, Photons... More ways to explore fundamental questions*"

Ivan Burenkov, *Joint Quantum Institute at NIST*
Thursday evening invited session, abstract on page [86]
"*Towards robust detector tomography*"

David Burghoff, *University of Texas at Austin*
Wednesday morning invited session 1, abstract on page [87]
"*Liquid combs: broadband light with equidistance and without stability*"

Peter J. Burke, *University of California, Irvine*
Friday morning invited session 1, abstract on page [88]
"*Mitochondria in quantum sensing: Effect of photobleaching and phototoxicity*"

Leonid Butov, *University of California San Diego*
Tuesday morning invited session 2, abstract on page [89]
"*Indirect excitons in heterostructures*"

Joshua Caldwell, *Vanderbilt*
Tuesday evening invited session, abstract on page [90]
"*Employing Phonon Polaritons and ENZ Polaritons in Enhanced Thermal Transport*"

Mike Campbell, *University of California, San Diego*
Thursday morning invited session 2, abstract on page [91]
"*Laser Systems for Inertial Fusion: Requirements, Challenges and Opportunities*"

Federico Capasso, *Harvard*
Tuesday evening invited session, abstract on page [92]
"*From Classical to Quantum Metasurfaces for Multiphoton Interferometry*"

Sebastián C. Carrasco, *DEVCOM Army Research Laboratory*
Friday evening invited session, abstract on page [93]
"*Dynamic Population Suppression for Two-Photon Excitation*"

Alexander Cerjan, *Sandia*
Friday evening invited session, abstract on page [94]
"*Classifying topology in nonlinear photonic systems*"

Sheila Chauwinoir, *Texas A&M University*
Poster session, abstract on page [95]
"*Extreme-Value Statistics of Soliton Dynamics: Validating Model for Robust Inertial-Confinement Fusion Design*"

Aaron Chou, *Fermilab*
Friday evening invited session, abstract on page [**??**]
"*Targeting the QCD axion with qubit-based electronics*"

Weng Chow, *Sandia National Laboratory*
Wednesday morning plenary session 1, abstract on page [96]
"*Semiconductor lasers for conventional and quantum applications*"

Rodrigo Cortinas, *Google Quantum AI*
Wednesday morning invited session 1, abstract on page [97]
"*Quantum computation of molecular geometry via many-body nuclear spin echoes*"

Francois Courvoisier, *Marie and Louis Pasteur University, CNRS, FEMTO-ST institute*
Wednesday morning invited session 2, abstract on page [98]
"*Physics and applications of femtosecond higher-order Bessel beam interaction with dielectrics*"

Jake Covey, *University of Illinois Urbana-Champaign*
Tuesday evening invited session, abstract on page [99]
"*Distributed quantum science with neutral atom arrays*"

Stephen Cronin, *University of Southern California*
Thursday evening invited session, abstract on page [100]
"*Probing the Real and Imaginary Dielectric Response of the Electric Double Layer using Surface Plasmon Resonance Nanostructures*"

Milena D'Angelo, *Universit'a degli Studi di Bari*
Tuesday evening invited session, abstract on page [101]
"*Correlation imaging, from 3D to hyperspectral*"

Alessio D'Errico, *University of Ottawa*
Tuesday evening invited session, abstract on page [102]
"*Imaging the quantum state of biphotons*"

Nir Davidson, *Weizmann Institute of Science*
Friday evening plenary session, abstract on page [103]
"*Complex bands and topology with coupled lasers*"

Emily Davis, *New York University*
Friday evening invited session, abstract on page [104]
"*Spin squeezing in an ensemble of nitrogen-vacancy centers in diamond*"

John Davis, *University of Alberta*
Friday evening invited session, abstract on page [105]
"*Sensing Gravitational Waves and Dark Matter with Superfluid Helium*"

Andrei Derevianko, *University of Nevada, Reno*
Tuesday morning invited session 1, abstract on page [106]
"*Sub-100 MHz accurate* ^{e}*xt229Th nuclear clock frequencies in solid-state and trapped ion platforms*"

Steven F. DiMarco, *Texas A&M University*
Friday evening invited session, abstract on page [107]
"*Quantum Ocean: Resetting Ocean Science with Applications of Quantum Sensors, Materials, Networks*"

Alexander Dikopoltsev, *ETH Zurich*
Tuesday morning invited session 1, abstract on page [108]
"*Liquid Light Dynamics in Synthetic Dimensions: a New Class of Frequency Combs*"

Arthur Dogariu, *Texas A&M University and Princeton University*
Tuesday morning invited session 2, abstract on page [109]
"*Quantum States in Thermodynamical Non-equilibrium Unveiled by Coherent Raman*"

Konstantin Dorfman, *Hainan University*
Friday morning invited session 2, abstract on page [110]
"*High precision spectroscopy with metasurfaces*"

Shengwang Du, *Purdue University*
Thursday morning invited session 2, abstract on page [111]
"*Quantum-Enhanced Nonlinearities for Scalable All-Optical Neural Networks*"

Gurudev Dutt, *University of Pittsburgh*
Friday morning invited session 1, abstract on page [**??**]
"*Toward Macroscopic Quantum Superpositions with Magnetically Levitated Diamond Crystals*"

J. Gary Eden, *University of Illinois, Texas A&M University*
Thursday morning invited session 2, abstract on page [112]
"*A Brief Overview of the Discovery, Critical Parameters, and Scaling of the Rare-gas Halide Excimer Lasers*"

Jörg Evers, *MPI for Nuclear Physics, Heidelberg*
Tuesday evening invited session, abstract on page [113]
"*Single-shot Mössbauer spectroscopy at X-ray free-electron lasers*"

Davide Facciala, *CNR Milan*
Wednesday morning invited session 2, abstract on page [114]
"*Probing attosecond chiral multi-electron dynamics via enantio-sensitive interferometry*"

Kejie Fang, *University of Illinois Urbana-Champaign*
Monday morning invited session 1, abstract on page [115]
"*High-performance nonlinear photonics for quantum information and networking*"

Andrei Faraon, *California Institute of Technoloy*
Tuesday morning invited session 1, abstract on page [**??**]
"*Quantum nano-photonics with rare-earth ions*"

Alma Fernández, *Texas A&M University*
Monday evening invited session, abstract on page [116]
"*Optical Coherence Microscopy: Applications to Agriculture*"

Marcello Ferrera, *Heriot-Watt University*
Wednesday morning invited session 2, abstract on page [117]
"*Time-varying photonics in transparent conductors*"

Martin Fischer, *Max Planck Institute for the Science of Light*
Monday morning invited session 2, abstract on page [118]
"*Spatial coherence of single photons in spontaneous emission from a single atom*"

Victor V. Flambaum, *University of New South Wales, Sydeny*
Tuesday morning invited session 1, abstract on page [119]
"*Nuclear Clocks and the Search for New Physics*"

Ron Folman, *Ben-Gurion University of the Negev*
Tuesday morning invited session 1, abstract on page [120]
"*Experiments at the interface of general relativity and quantum mechanics*"

Kai Frye-Arndt, *Leibniz University Hannover*
Wednesday evening invited session, abstract on page [121]
"*Diffraction-induced apparent self-focussing and transplant of Bose-Einstein condensates in absorption imaging*"

Emanuele Galiffi, *The University of Texas at Austin*
Thursday evening invited session, abstract on page [122]
"*Multiphoton Hong-Ou-Mandel Interference from Classical Light in a Time-Varying Medium*"

Conner Galloway, *Xcimer Energy, Inc.*
Thursday morning plenary session 1, abstract on page [**??**]
"*A high-energy excimer-Raman-Brillouin laser system for inertial fusion energy*"

Wenchao Ge, *University of Rhode Island*
Friday morning invited session 2, abstract on page [123]
"*Double Quantum-Enhanced Sensing of Displacements with Trapped-ion Crystals*"

Andrew Geraci, *Northwestern University*
Friday evening invited session, abstract on page [124]
"*Optomechanical sensors for dark matter, axions and high frequency gravitational waves*"

Alexandros Gerakis, *Luxembourg Institute of Science & Technology*
Tuesday morning invited session 2, abstract on page [125]
"*Reshaping and Probing Velocity Distribution Functions of Neutral and Charged Species with Chirped Optical Lattices*"

Siegfried Glenzer, *SLAC National Accelerator Laboratory and Stanford University*
Thursday evening plenary session, abstract on page [126]
"*Advancing inertial fusion energy using ultra-high peak power X-rays*"

Clemens Gneiting, *RIKEN, Japan*
Wednesday morning invited session 1, abstract on page [127]
"*Quantum error correction in bosonic systems*"

Nikolay Golubev, *University of Arizona*
Wednesday morning invited session 2, abstract on page [128]
"*Control of quantum dynamics using stimulated Raman adiabatic passage technique*"

Alexey Gorshkov, *JQI, NIST/University of Maryland*
Monday morning invited session 1, abstract on page [129]
"*Readout-Free Majority Decoding via Asymmetric Rydberg Antiblockade*"

Trent Graham, *University of Wisconsin at Madison*
Monday morning invited session 1, abstract on page [130]
"*Rydberg gates in a neutral atom array using single-photon excitation*"

Loren Greenman, *Kanzas University*
Wednesday morning invited session 2, abstract on page [131]
"*Multiphoton Photoelectron Circular Dichroism via Time-Dependent Perturbation Theory: Revealing Principles of Chirality with Attosecond XUV Imaging*"

Frédéric Grillot, *Laval University, Canada*
Tuesday morning invited session 1, abstract on page [132]
"*Quantum Homodyne Tomography Application to Ultra-Narrow Linewidth Semiconductor Lasers*"

Melissa A. Guidry, *MIT-LIGO*
Thursday evening invited session, abstract on page [133]
"*Heisenberg scaling in a continuous-wave interferometer*"

Cheng Guo, *The University of Texas at Austin*
Monday morning invited session 1, abstract on page [134]
"*Transport Measurements of Majorization Order for Wave Coherence*"

Klemens Hammerer, *Innsbruck University, IQOQI Innsbruck*
Wednesday morning invited session 2, abstract on page [135]
"*Quantum enhanced atomic clocks without spin squeezing*"

Jack Harris, *Yale University*
Monday evening invited session, abstract on page [**??**]
"*Cavity optomechanics in a levitated drops of superfluid helium*"

Philipp Haslinger, *VCQ - Atominstitut - USTEM Technische Universität Wien*
Thursday evening invited session, abstract on page [136]
"*Entanglement in Electron Microscopy*"

Mohammed Hassan, *University of Arizona*
Thursday morning invited session 1, abstract on page [137]
"*Ultrafast Quantum Optics*"

Ayla Hazrathosseini, *Texas A&M University*
Poster session, abstract on page [138]
"*Entanglement in Diamond Color Centers for Quantum Technologies*"

Kaden Hazzard, *Rice University*
Tuesday morning invited session 2, abstract on page [139]
"*Observing paraparticles in ultracold Rydberg atoms*"

Christian Heide, *University of Central Florida*
Wednesday morning invited session 1, abstract on page [**??**]
"*Designing Quantum Materials with Lightwaves: Coherent Floquet Control and Raman-Force Phase Engineering*"

Philip Hemmer, *Texas A&M University*
Friday morning plenary session 1, abstract on page [140]
"*Nanodiamonds and quantum sensing*"

Daniel I. Herman, *Sandia National Laboratories*
Friday morning invited session 2, abstract on page [141]
"*Dual-comb spectroscopy with quantum states of light*"

Felipe Herrara, *USACH, Chile*
Monday evening invited session, abstract on page [142]
"*Theory of vacuum-assisted chemical reactions in infrared cavities*"

Phay Ho, *Argonne National Laboratory*
Thursday morning invited session 1, abstract on page [143]
"*Indistinguishability and Quantum Pathways in Nonlinear Resonant X-ray Scattering*"

Paul Hoff, *Xcimer Energy, Inc.*
Thursday morning plenary session 2, abstract on page [144]
"*The Excimer Laser: Its Development and Evolution*"

Axel Hoffmann, *University of Illinois Urbana-Champaign*
Thursday evening invited session, abstract on page [145]
"*Hybrid Magnon Modes*"

Peter Hommelhoff, *LMU Munich and FAU Erlangen*
Wednesday morning plenary session 1, abstract on page [146]
"*New control over electrons with ultrashort laser and non-classical fields*"

Mahdi Hosseini, *Northwestern University*
Tuesday morning invited session 2, abstract on page [147]
"*Nonlinear Dynamics in Macroscopic Levitation for Enhanced Inertial Sensing and Tests of Semiclassical Gravity*"

Onur Hosten, *Institute of Science and Technology, Austria*
Friday evening invited session, abstract on page [148]
"*Control, sensing and gravitational coupling of milligram pendulums: towards interfacing quantum and gravity*"

Aurelien Houard, *LOA - Ecole Polytechnique*
Wednesday morning invited session 2, abstract on page [149]
"*Spatio-temporal shaping of laser filaments in air*"

John Howell, *Chapman University*
Monday morning invited session 2, abstract on page [**??**]
"*Super Bandwidth Deconvolution Signal Reconstruction*"

Eric Hudson, *University of California, Los Angeles*
Tuesday morning invited session 1, abstract on page [150]
"*Nuclear clocks: What now?*"

Mikhail Ivanov, *Max Born Institute*
Thursday morning plenary session 1, abstract on page [151]
"*Attosecond Quantum Optics and Tortured Super-Radiance*"

Zubin Jacob, *Purdue University*
Tuesday morning invited session 2, abstract on page [**??**]
"*Neural bolometers for thermal imaging*"

Rocio Jauregui, *Universidad Nacional Autonoma de Mexico*
Monday morning invited session 2, abstract on page [152]
"*Effects of collective coupling and center of mass motion on the light scattered by driven multilevel atoms*"

Andrew Jayich, *University of California, Santa Barbara*
Monday morning invited session 1, abstract on page [153]
"*Cryogenic ion trapping of atomic and molecular ions for precision measurements*"

Pankaj Jha, *Syracuse University*
Monday morning invited session 2, abstract on page [154]
"*Iron-Based Topological Superconductors for Single-Photon Detection*"

Andrew Jordan, *Chapman University*
Tuesday evening invited session, abstract on page [155]
"*Direct measurement of the quantum pseudo-distribution via its generating function*"

Kunwar Kalra, *Texas A&M University*
Poster session, abstract on page [156]
"*Universal lower bound on the computational complexity of Gaussian boson sampling*"

Ido Kaminer, *Technion - Israel Institute of Technology*
Thursday evening plenary session, abstract on page [**??**]
"*Quantum Optics and Entanglement at the Extremes*"

Boubacar Kanté, *University of California, Berkeley*
Friday evening invited session, abstract on page [157]
"*Arbitrary fractional quantization in Dirac systems and scale-invariant lasers*"

Christos Karapoulitidis, *Stevens Institute of Technology*
Poster session, abstract on page [158]
"*Distinguishing Semi-Classical and Quantum Models of Proper Time with Atomic Clocks*"

Ebrahim Karimi, *Chapman University*
Tuesday evening plenary session, abstract on page [159]
"*Characterising Entangled Structured Photons for Quantum Imaging Applications*"

Aviv Karnieli, *Technion - Israel Institute of Technology*
Thursday evening invited session, abstract on page [160]
"*Towards observation of entanglement in free-electron pairs and free-electron-bound electron systems*"

Raphael Kaubruegger, *JILA and University of Colorado Boulder*
Thursday morning invited session 1, abstract on page [161]

"*Lieb-Mattis states for robust entangled differential phase sensing: prospects for implementation in cavities*"

Adam Kaufman, *JILA, University of Colorado at Boulder*
Tuesday evening plenary session, abstract on page [162]
"*A new platform for programmable Hubbard systems*"

Alexander Khanikaev, *UCF*
Wednesday morning invited session 2, abstract on page [**??**]
"*Leveraging symmetries for control of classical and quantum light in topological metasurfaces*"

Barnabas Kim, *Texas A&M University*
Monday morning invited session 1, abstract on page [163]
"*Heat Engine in Quantum Engineering: Coherence and Entanglement as resources*"

Kyungtae Kim, *JILA*
Wednesday evening invited session, abstract on page [164]
"*Optical Lattic Clocks: physics and applications*"

Derek F. Jackson Kimball, *California State University - East Bay*
Monday evening invited session, abstract on page [165]
"*Levitated Ferromagnetic Gyroscopes for Fundamental Physics*"

Nathaniel Kinsey, *Saint Louis University*
Wednesday morning invited session 2, abstract on page [166]
"*Origins of Nonlinearities at Epsilon-Near-Zero and its Influence on Applications*"

Robert Kirkwood, *Consultant at Xcimer Energy, Inc.*
Thursday evening invited session, abstract on page [167]
"*The Promise and Challenges of Ion Wave Plasma Optics for Enabling Laser Driven Fusion Energy*"

Sebastian Klembdt, *Würzburg University*
Wednesday morning invited session 1, abstract on page [168]
"*Topological Lasers: From Electrical Injection and Novel Organic Emitters*"

Gerhard Klimeck, *Purdue University*
Thursday evening invited session, abstract on page [170]
"*Quantitative Quantum Device Design and Optimization to increase THz Radiation Power*"

Omer Kneller, *Regensburg University*
Friday morning invited session 1, abstract on page [171]
"*Lightwave Engineering of Excitonic States in an Atomically Thin Semiconductor*"

Olga Kocharovskaya, *Texas A&M University*
Wednesday evening invited session, abstract on page [172]
"*Quantum memory for hard X-ray photons in the stationary nuclear absorbers*"

Vitaly Kocharovsky, *Texas A&M University*
Monday morning invited session 2, abstract on page [173]
"*Hafnian master theorem and quantum supremacy*"

Shimon Kolkowitz, *University of California, Berkeley*
Tuesday morning invited session 1, abstract on page [174]
"*Gravitational wave detection with space-based optical lattice clocks*"

Michael Kolodrubetz, *University of Texas at Dallas*
Thursday morning invited session 2, abstract on page [175]
"*Geometry and Topology in Cavity QED*"

Tim Kovachy, *Northwestern University*
Wednesday evening invited session, abstract on page [176]
"*A Surprising Systematic Effect from the Interplay of Spontaneous Emission and Many-Pulse Atom Interferometry*"

Michael Krueger, *Technion*
Thursday morning invited session 1, abstract on page [177]
"*Quantum tomography of nonperturbative harmonic light from solids*"

Yuimaru Kubo, *Okinawa Institute of Science and Technology*
Friday morning invited session 2, abstract on page [**??**]
"*A near-quantum limited diamond maser amplifier operating at millikelvin temperatures*"

Dmitry Kurouski, *Texas A&M University*
Friday morning invited session 2, abstract on page [178]
"*Raman Spectroscopy in Digital Farming*"

Arnaud Landragin, *LTE, Observatoire de Paris, Université PSL*
Wednesday evening invited session, abstract on page [179]
"*High sensitivity and accuracy with a large area cold atom gyroscope*"

Thu Hac Huong Le, *National Institute of Advanced Industrial Science and Technology, Japan*
Friday morning invited session 2, abstract on page [180]
"*Metasurfaces in Laser Cooling and Trapping of Atoms Towards Miniaturized Cold Atom Platforms*"

Igor Lednev, *University at Albany, State University of New York*
Friday morning invited session 1, abstract on page [181]
"*Raman Spectroscopy and Machine Learning for Biomedical Applications*"

Howard Lee, *University of California, Irvine*
Tuesday evening invited session, abstract on page [**??**]
"*Active and Nonlinear Epsilon-Near-Zero Photonics*"

Gerd Leuchs, *MPL*
Monday morning plenary session 2, abstract on page [182]
"*The Atom and the Vacuum*"

Quanwei Li, *University of California*
Monday evening invited session, abstract on page [183]
"*Photon statistics in photosynthetic light harvesting*"

Wen-Te Liao, *National Central University*
Wednesday evening invited session, abstract on page [184]
"*Gravitational Photon Echo using Thorium-229 nuclear clock transition*"

Frances Ligler, *Texas A&M University*
Thursday evening invited session, abstract on page [185]
"*The road to an optical biosensor based on quantum photonics*"

Norbert Linke, *Duke University*
Monday morning invited session 1, abstract on page [186]
"*Hybrid quantum simulation and city-scale quantum networking with trapped ions*"

Ren-Bao Liu, *Chinese University of Hong Kong*
Friday morning invited session 2, abstract on page [187]
"*Superradiant lasing from a quantum many-body emitter*"

Mary F. Locke, *Naval Air Warfare Center, Aircraft Division*
Thursday evening invited session, abstract on page [188]
"*Two-atom correlations in a continuous cold atom beam*"

José R. Crespo López-Urrutia, *Max-Planck-Institut für Kernphysik, Heidelberg, Germany*
Wednesday evening invited session, abstract on page [189]
"*Towards frequency metrology in the extreme ultraviolet range with trapped highly charged ions*"

Andrew Ludlow, *National Institute of Standards and Technology*
Wednesday evening invited session, abstract on page [190]
"*Next-generation timekeeping with optical lattice clocks*"

Alexey Lukin, *QuEra*
Tuesday evening invited session, abstract on page [**??**]
"*Improved two-qubit gate fidelities for neutral-atom quantum computers*"

Mikhail Lukin, *Harvard University*
Monday morning plenary session 1, abstract on page [**??**]
"*New frontier of quantum computing*"

Chengyi Luo, *California Institute of Technology*
Thursday morning invited session 1, abstract on page [191]
"*Extending Ramsey coherence of solid-state spins via cavity-mediated interactions*"

Arka Majumdar, *University of Washington*
Friday morning invited session 1, abstract on page [192]
"*Integrated Nanophotonics with Colloidal Materials*"

Yusef Maleki, *Texas A&M University*
Monday morning invited session 1, abstract on page [193]
"*Quantum Heat Engine as a Sensor and Beyond: Insights from Fisher Information*"

Vladimir Malinovsky, *DEVCOM Army Research Laboratory*
Friday evening plenary session, abstract on page [194]
"*Quantum Control as a Unifying Principle for Sensing, Metrology, and Computation*"

Sophia Malko, *Princeton University*
Thursday morning invited session 2, abstract on page [**??**]
"*Role of the Nernst Effect in magneto-inertial plama*"

Amber Manspeaker, *Naval Air Warfare Center, Aircraft Division*
Poster session, abstract on page [195]
"*Is the GFC the result of Intensity Fluctuation Correlation?*"

Nishad Maskara, *MIT*
Monday evening invited session, abstract on page [196]
"*Fast simulation of fermions with reconfigurable qubits*"

Peter Maurer, *University of Chicago*
Monday evening invited session, abstract on page [197]
"*A fluorescent-protein spin qubit*"

Ben McAllister, *Swinburne University of Technology*
Friday evening invited session, abstract on page [198]
"*Quantum Sensing Above and Below Ground: ORGAN and CELLAR*"

Carmen Menoni, *Colorado State University*
Thursday evening invited session, abstract on page [**??**]
"*Optical coatings for MJ Lasers*"

Hamed Merdji, *Ecole Polytechnique*
Friday morning invited session 1, abstract on page [199]
"*Quantum-optical nature of ultrafast high-harmonic generation in semiconductors*"

Richard Miles, *Texas A&M University*
Tuesday morning plenary session 2, abstract on page [200]
"*Unravelling Turbulence with Laser Pumped, Time Delayed Quantum State Emission*"

David Miller, *Stanford University*
Tuesday evening invited session, abstract on page [201]
"*Self-configuring spectral filters by mapping time to space*"

Bumki Min, *Korea Advanced Institute of Science & Technology*
Monday morning invited session 1, abstract on page [202]
"*Unified framework for classical and quantum light-matter interactions in photonic time crystals*"

Richard Mirin, *University of California, Santa Barbara*
Wednesday morning invited session 1, abstract on page [203]
"*Integrated Semiconductor Lasers For Quantum Systems*"

Arthur Montanari, *Northwestern University*
Friday evening invited session, abstract on page [204]
"*Disorder-Promoted Synchronization and Coherence in Coupled Laser Networks*"

Francesco Monticone, *Cornell University*
Monday morning invited session 1, abstract on page [205]
"*Space-time nonlocal metamaterials*"

Jesper Mørk, *Technical University of Denmark*
Tuesday morning invited session 1, abstract on page [206]
"*Sub-Wavelength Semiconductor Nanocavities for Nanoscale Light Sources*"

Andy Mounce, *Sandia National Laboratory*
Wednesday evening invited session, abstract on page [207]
"*Quantum sensing with quantum defects*"

Vladimiro Mujica, *Arizona State University*
Thursday morning invited session 2, abstract on page [208]
"*Surface Chirality Sensors Based on Spin-Dependent van der Waals Interactions and CISS-Induced Spinterface Effects*"

Shaul Mukamel, *University of California, Irvine*
Monday evening plenary session, abstract on page [209]
"*Monitoring of elementary molecular events with quantum and X-ray light*"

Nima Nader, *NIST, Boulder*
Wednesday morning invited session 1, abstract on page [210]
"*Stimulated Brillouin Scattering in InGaP-on-insulator waveguides*"

Frank Narducci, *Naval Postgraduate School*
Wednesday morning invited session 1, abstract on page [212]
"*A T^3 interferometer and the pit and the pendulum*"

Evgenii Narimanov, *Purdue University*
Monday morning invited session 2, abstract on page [213]
"*Hyperbolic Quantum Procesor*"

Milos Nesladek, *University Hasselt*
Friday morning invited session 1, abstract on page [**??**]
"*Nanoscale thermometry on the neural-cell plasma membrane using NV-nanodiamond* "

Cun-Zheng Ning, *Shenzhen Tech University*
Tuesday morning invited session 2, abstract on page [214]
"*The Quadruplon: Evidence for a New Quasi-Particle in a 2D Monolayer Semiconductor Through Ultrafast Pump-Probe Experiments*"

Franco Nori, *RIKEN and Univ. of Michigan*
Wednesday morning plenary session 1, abstract on page [215]
"*A few recent results on superconducting qubits*"

Massaya Notomi, *NTT Research Lab*
Tuesday morning plenary session 1, abstract on page [**??**]
"*Chiral topology and nonlinearity in non-Hermitian nanophotonics*"

Changhun Oh, *KAIST*
Monday morning invited session 2, abstract on page [216]
"*Classical algorithm for simulating experimental Gaussian boson sampling*"

Andrés Ordóñez, *Freie Universität Berlin*
Thursday morning invited session 2, abstract on page [217]
"*Non-Dichroic Enantio-Sensitive Chiroptical Spectroscopy*"

Sahin Ozdemir, *Saint Louis University*
Wednesday morning invited session 1, abstract on page [218]
"*Non-Hermiticity as a Resource in Photonics*"

Zack Pagel, *Infleqtion*
Wednesday evening invited session, abstract on page [219]
"*Quantum Gravity Gradiometry from Space: A Pathfinder Mission with NASA*"

Guglielmo Panelli, *Stanford University*
Thursday morning invited session 1, abstract on page [220]
"*Excitation of the Strontium clock state with megahertz Rabi frequency and a new platform for quantum-enhanced sensing*"

Pravesh Patel, *Focused Energy Inc.*
Thursday evening invited session, abstract on page [**??**]
"*Focused Energy's Path to Inertial Fusion Energy: Status and Challenges*"

Raj Patel, *Imperial College*
Monday morning invited session 2, abstract on page [221]
"*Gaussian Boson Sampling with Displacements*"

Peter Pauzauskie, *University of Washington*
Friday morning invited session 1, abstract on page [222]
"*Solid state laser refrigeration of nanoscale plasmonic sensors probed via Raman spectroscopy*"

Justin Peatross, *Brigham Young University*
Thursday morning invited session 1, abstract on page [223]
"*Polarization of Nonlinear Thomson Scattering*"

Matthew Pelton, *University of Maryland, Baltimore County*
Friday morning plenary session 1, abstract on page [224]
"*Strong light-matter coupling at the nanoscale for quantum photonics*"

John Pendry, *Imperial College London*
Monday morning plenary session 1, abstract on page [225]
"*Energy and entropy content of time-dependent metamaterials*"

Jonah Peter, *Harvard University*
Monday evening invited session, abstract on page [226]
"*Enabling Ultrastrong Chiral Light-Matter Interactions With Chiral Superradiance*"

Nathan G. Phillips, *Texas A&M University*
Poster session, abstract on page [227]
"*Fluorescence Imaging of Vibrationally Excited Molecular Oxygen using an Optical Parametric Oscillator*"

Igor Pikovski, *Stevens Institute of Technology and Stockholm University*
Tuesday morning invited session 1, abstract on page [228]
"*Towards superpositions of proper time in atomic clocks and quantum networks*"

Layla Pires, *Texas A&M University*
Friday morning invited session 1, abstract on page [229]
"*Multiphoton melanin-mediated energy transfer enables ocular melanoma eradication*"

Barbara Platzer, *University of Vienna*
Tuesday morning invited session 1, abstract on page [231]
"*Embracing instability: preparing macroscopic quantum states in the dark*"

Sergey V. Polyakov, *NIST*
Thursday morning invited session 2, abstract on page [232]
"*Robust, Scalable, and Low-Noise Phase Stabilization for Next-Generation Quantum Networks*"

Pavel Polynkin, *University of Arizona*
Wednesday morning invited session 2, abstract on page [233]
"*Curved air waveguides using intense designer laser beams*"

Eugene Polzik, *Niels Bohr Institute, Copenhagen University*
Wednesday morning plenary session 2, abstract on page [235]
"*Quantum sensing beyond standard quantum limits*"

John J. Prevost, *University of Austin at San Antonio*
Thursday morning invited session 2, abstract on page [236]
"*Next generation quantum memories with Rydberg technology*"

David Purschke, *Laboratory for Laser Energetics*
Friday morning invited session 1, abstract on page [238]
"*Disorder-driven decoherence in the attosecond dynamics of amorphized silicon*"

Szymon Pustelny, *Jagiellonian University in Krakow/Harvard University*
Monday evening invited session, abstract on page [239]
"*Constraining long range spin gravity coupling using nuclear magnetic resonance*"

Georg Raithel, *University of Michigan*
Friday evening invited session, abstract on page [240]
"*Sagnac Tractor Atom Interferometer on a Photonic Integrated Circuit*"

Harikrishnan Ramani, *University of Delaware*
Wednesday evening invited session, abstract on page [241]
"*Searches for dark matter with precise electric field sensors*"

Robert Randolph, *Texas A&M University*
Poster session, abstract on page [242]
"*Development of an Active Atomic Vapor Filter Utilizing Quantum Resonance Enhanced Four Wave Mixing*"

Yi Rao, *Utah State University*
Friday evening invited session, abstract on page [243]
"*Polariton-Modulated Singlet Fission in Cavity*"

Markus Raschke, *University of Colorado, Boulder*
Monday morning invited session 1, abstract on page [244]
"*Ultrafast nano-imaging and tip-enhanced control of electronic coherence in 2D semiconductors*"

David A. Reis, *Stanford University*
Thursday evening invited session, abstract on page [**??**]
"*Transduction of squeezed light from infrared to x rays*"

Michael Reitz, *UCSD*
Monday evening invited session, abstract on page [**??**]
"*Nonlinear semiclassical spectroscopy of ultrafast molecular polariton dynamics*"

Michelle B. Requena, *Texas A&M University*
Friday morning invited session 1, abstract on page [245]
"*Spin Exchange, Molecular Energy Transfer, and Photoreactions for Destroying Cancer Cells and Microorganisms and Overcoming Antibiotic Resistance* "

Nicholas Rivera, *Cornell University*
Thursday evening invited session, abstract on page [246]
"*Controlling quantum correlations of bright multimode light sources*"

Jorge Rocca, *Colorado State Univesity*
Thursday morning invited session 1, abstract on page [247]
"*Physics of ion acceleration in nanowire arrays irradiated with ultrashort laser pulses of relativistic intensity*"

Ralf Röhlsberger, *Helmholtz Institute Jena and DESY Hamburg*
Tuesday evening invited session, abstract on page [248]
"*Anomalous Nuclear Forward Scattering under Intense XFEL Excitation*"

Michael Romalis, *Princeton University*
Friday evening invited session, abstract on page [249]
"*Nuclear spin comagnetometer gyroscopes with* $^{e}xt21Ne$"

Claus Ropers, *Max Planck Institute for Multidisciplinary Sciences & University of Göttingen*
Thursday evening invited session, abstract on page [250]
"*Free-Electron Quantum Optics:? Coherent Control, Correlations, and Entanglement*"

Jan Michael Rost, *Max Planck Institute for the Physics of Complex Systems, Desden, Germany*
Wednesday evening invited session, abstract on page [251]
"*Is Physics Timeless ?*"

Yuri Rostovtsev, *University of North Texas*
Friday morning invited session 1, abstract on page [252]
"*Correlated quantum fields generated by vacuum fields*"

Georgi Gary Rozenman, *Massachusetts Institute of Technology*
Wednesday morning invited session 1, abstract on page [253]
"*Hydrodynamic Aharonov-Bohm Effect, Time-Varying Vortex-Induced Phases, and Rotating Black-Hole Analogues*"

Poster session, abstract on page [254]
"*Optical Emulation of Quantum Systems Using Pulsed Lasers and Classical Optics*"

Elizabeth Ruddy, *Yale University, University of Colorado Boulder*
Friday evening invited session, abstract on page [255]
"*Quantum sensing to accelerate the axion dark matter search*"

Ernst Rusel, *University of Hannover*
Wednesday evening plenary session, abstract on page [256]
"*Quantum gases in microgravity: new perspectives for ground based research*"

Kazimierz Rzążewski, *CFT PAN*
Monday morning plenary session 2, abstract on page [257]
"*The Hybrid Sampling Method for the Statistics of a Bose Gas*"

Akbar Safari, *University of Wisconsin-Madison*
Thursday morning invited session 2, abstract on page [258]
"*Efficient generation of single photons and atom-photon entanglement in a quantum network node*"

Marianna Safronova, *University of Delaware*
Wednesday evening plenary session, abstract on page [259]
"*Quantum Technologies for New Physics Discoveries*"

Samuel Sahel-Schackis, *SLAC National Accelerator Laboratory*
Poster session, abstract on page [260]
"*Investigation of the effects of nanoscale facets on catalytic activity in photo-driven nanosystems*"

Camille Samulski, *Los Alamos National Laboratory*
Thursday morning invited session 1, abstract on page [261]
"*Polar Direct Drive Target Design for a 10MJ Laser Inertial Fusion Energy Facility*"

Richard L. Sandberg, *Brigham Young University*
Thursday evening invited session, abstract on page [262]
"*Understanding nanometer structure-performance relation of foams for inertial fusion energy*"

Arvinder Sandhu, *University of Arizona*
Thursday morning invited session 1, abstract on page [**??**]
"*Commissioning of femtosecond hard x-source at ASU CXFEL facility*"

Christian Sanner, *Colorado State University*
Wednesday evening invited session, abstract on page [263]
"*Testing relativity with a cryogenic ytterbium ion clock*"

Vera M. Schäfer, *Max-Planck-Institut für Kernphysik*
Monday evening invited session, abstract on page [264]
"*Searching for a variation of the fine structure constant with highly charged ions*"

Andy Schang, *University of Waterloo*
Wednesday morning invited session 1, abstract on page [265]
"*Observation of Genuine Tripartite Non-Gaussian Entanglement from a Superconducting Three-Photon Spontaneous Parametric Down-Conversion Source*"

Wolfgang Schleich, *Ulm University*
Tuesday morning plenary session 1, abstract on page [266]
"*Interference at work*"

Piet O. Schmidt, *Physikalisch-Technische Bundesanstalt*
Wednesday evening invited session, abstract on page [267]
"*Highly Charged Ion Clocks to Test Fundamental Physics*"

Dominik Schneble, *Stony Brook University*
Friday morning plenary session 2, abstract on page [**??**]
"*Exploring super- and subradiant dynamics with matter-wave quantum emitters*"

James Scully, *International Captain, American Airlines*
No Presentation

Marlan Scully, *Texas A&M University*
Monday morning plenary session 1, abstract on page [268]
"*Quantum Advantage in Thermodynamics*"

Shawn Sederberg, *Simon Fraser University*
Wednesday morning invited session 1, abstract on page [269]
"*Field-driven currents in solids with few-cycle mid-infrared pulses*"

Denis Seletskiy, *University of New Mexico*
Thursday morning invited session 1, abstract on page [270]
"*Time-Domain Measurement of Few-Cycle Two-Mode Squeezed State*"

Danial Shadmany, *Stanford University*
Tuesday evening invited session, abstract on page [271]
"*A 600-site cavity array: expanding the neutral atom array toolbox*"

Ephraim Shahmoon, *Weizmann Institute of Science*
Monday morning invited session 2, abstract on page [272]
"*Quantum light-matter interfaces with tweezer atomic arrays*"

Selim Shahriar, *Northwestern University*
Thursday evening invited session, abstract on page [273]
"*Demonstration of a Rb-based Mode-Locking Free Subluminal Ring Laser Gyroscope*"

Vladimir Shalaev, *Purdue University*
Tuesday evening plenary session, abstract on page [274]
"*Engineering Light with Space-Time Metamaterials*"

Shyam Shankar, *University of Texas at Austin*
Tuesday morning invited session 2, abstract on page [275]
"*Advancing Josephson parametric amplifiers for scalable high-fidelity readout of solid-state qubits*"

Zhijie Shi, *Huazhong University of Science and Technology*
Poster session, abstract on page [276]
"*Low-Energy Femtosecond LIBS Enabled by Mie-Resonance-Induced Field Enhancement*"

Yanhua Shih, *University of Maryland, Baltimore County*
Thursday evening plenary session, abstract on page [277]
"*From Ghost Frequency Comb to Quantum Ghost Frequency Comb*"

Mikhail N. Shneider, *Princeton University*
Tuesday morning invited session 2, abstract on page [278]
"*Bragg Amplification of Weak Laser Radiation in Optical Lattices in a Gas*"

Yuri Shvyd'ko, *Argonne National Laboratory*
Wednesday evening invited session, abstract on page [**??**]
"*Advances in 45-Scandium nuclear clock research*"

Sharon Shwartz, *Bar-Ilan University*
Wednesday evening invited session, abstract on page [279]
"*Direct ghost tomography for 3D X-ray fluorescence imaging*"

Yonatan Sivan, *Ben-Gurion University*
Monday morning invited session 1, abstract on page [280]
"*Single-cycle optical nonlinearity of transparent conducting oxides explained*"

Poster session, abstract on page [**??**]
"*Photoluminescence from metlas—(all) arguments resolved*"

Olga Smirnova, *Max Born Institute*
Thursday morning plenary session 2, abstract on page [282]
"*Enantio-sensitive molecular compass*"

Thomas A. Smith, *Naval Air Warfare Center, Aircraft Division*
Thursday evening invited session, abstract on page [283]
"*Nontrivial intensity correlations with coherent continuous-wave lasers*"

Alexei V. Sokolov, *Texas A&M University*
Monday evening invited session, abstract on page [284]
"*Quantum Molecular Coherence for Chemical Sensing and Fusion Energy*"

Dong Hee Son, *Texas A&M University*
Monday evening invited session, abstract on page [285]
"*Superradiance and hot electrons from strongly quantum-confined perovskite quantum dots*"

Jannik Str"ohle, *Ulm University*
Tuesday morning invited session 1, abstract on page [286]
"*The Einstein Equivalence Principle and the Quantum Galileo Interferometer*"

Keerthan Subramanian, *Johannes Gutenberg University, Mainz*
Tuesday morning invited session 1, abstract on page [287]
"*A solid-state continuous-wave laser at 148.4 nm for driving the $^{e}xt229mTh$ nuclear transition*"

Shuo Sun, *University of Colorado Boulder*
Monday morning invited session 2, abstract on page [288]
"*Resonance fluorescence of a strongly driven two-level system with dynamically modulated frequency*"

Alexander Sushkov, *Johns Hopkins University*
Monday evening invited session, abstract on page [289]
"*Quantum metrology of macroscopic spin ensembles*"

Benjamin Sussman, *National Research Council Canada*
Tuesday evening invited session, abstract on page [290]
"*Ultrafast Quantum Photonics: Beating Decoherence with Fast Light Pulses*"

Anatoly Svidzinsky, *Texas A&M University*
Monday morning invited session 1, abstract on page [291]
"*Quantum evolution of mixed states, vacuum entanglement and performance of quantum heat engines*"

James Thompson, *JILA, NIST and University of Colorado, Boulder*
Thursday morning plenary session 1, abstract on page [**??**]
"*Photon mediated interactions for quantum sensing and simulation*"

Uwe Thumm, *Kansas State University*
Wednesday morning invited session 1, abstract on page [292]
"*Photoelectron – residual-ion entanglement in angle-differential attosecond time-reolved shake-up ionization*"

Michael Tobar, *The University of Western Australia*
Friday evening plenary session, abstract on page [293]
"*Electric Land'e g-Factor and Pseudo-Angular Momentum: A Symmetry-Based Dual Reformulation of Electric Dipole Moments and the Stark Effect*"

Carlos Trallero, *University of Connecticut*
Thursday morning invited session 1, abstract on page [294]
"*Single photon attosecond interferometry*"

M. Tuan Trinh, *Utah State University*
Friday evening invited session, abstract on page [295]
"*Quantum Coherent State of Plasmon-exciton Strong Coupling in a Nanocavity*"

Robert Usselman, *Florida Institute of Technology*
Friday morning invited session 2, abstract on page [**??**]
"*Biological Systems as Functional Quantum Sensors*"

AmirAli VanakiFarahani, *Texas A&M University*
Poster session, abstract on page [296]
"*Hybrid Pumping of Excimer Lasers as a Candidate Architecture for Fusion Drivers*"

Gustavo Velez, *Massachusetts Institute of Technology*
Thursday morning invited session 1, abstract on page [297]
"*Quantum-amplified spectroscopy on an optical clock transition*"

Aart Verhoef, *Texas A&M University*
Friday morning invited session 2, abstract on page [298]
"*Super-resolved multiphoton microscopy with double enhancement achieves sub-100 nm resolution*"

Joachim von Zanthier, *University Erlangen-Nürnberg*
Tuesday evening invited session, abstract on page [299]
"*New results of incoherent diffraction imaging (IDI) for x-ray structure analysis*"

Dmitri Voronine, *University of South Florida, USA*
Monday evening invited session, abstract on page [300]
"*Novel approaches to nanoscale imaging of 2D materials and micro(nano)plastics*"

Thomas Walther, *TU Darmstadt*
Monday morning invited session 2, abstract on page [301]
"*Alice, Bob, ... and Friends: What's next for the Darmstadt Quantum Key Distribution Network*"

Hui Wang, *Texas A&M University*
Monday morning invited session 1, abstract on page [302]
"*Quantum Heat Engines Driven by Multilevel Quantum Coherence*"

Cooper Watson, *Texas A&M University*
Poster session, abstract on page [303]
"*Review of the Quantum Boltzmann Equation*"

Jared Weidman, *Michigan State University*
Friday morning invited session 2, abstract on page [304]
"*Quantum electron dynamics of molecules in cavities*"

Birgitta Whaley, *University of California, Berkeley*
Monday evening invited session, abstract on page [305]
"*Quantum light spectroscopies for probing photosynthetic systems*"

Arne Wickenbrock, *Johannes Gutenberg University, Mainz*
Monday evening invited session, abstract on page [306]
"*Searching dark matter with hyperpolarized spin ensembles*"

Lida Xu, *University of Maryland*
Friday evening invited session, abstract on page [307]
"*Nonlinear topological photonics: from frequency combs and harmonic generation to emergent phenomena*"

Noa Yaffe, *Weizmann Institute of Science*
Friday morning invited session 1, abstract on page [308]
"*Attosecond transient absorption with quantum-structured fluctuations*"

Vladislav Yakovlev, *Texas A&M University*
Friday morning plenary session 1, abstract on page [**??**]
"*Quantum Biomechanics*"

Zhenjie Yan, *Columbia University*
Tuesday evening invited session, abstract on page [309]
"*Cavity-Enabled Measurements and Interactions in Neutral Atom Quantum Processors*"

Fan Yang, *Texas A&M University*
Poster session, abstract on page [319]
"*Coherence-Enhanced Open Quantum Battery*"

Lan Yang, *Washington University in St. Louis*
Wednesday evening plenary session, abstract on page [311]
"*When Light Listens: New Frontiers at the Intersection of Cavity Optomechanics and Photoacoustic Spectroscopy*"

Yang Yang, *JILA, University of Colorado*
Wednesday morning invited session 2, abstract on page [312]
"*Spin-squeezed clock for beyond the standard quantum limit performance at 1 imes10*$^{-18}$"

Deniz Yavuz, *University of Wisconsin - Madison*
Monday evening invited session, abstract on page [313]
"*Quantum statistics of radiation in collective spontaneous emission*"

Jun Ye, *JILA/NIST/University of Colorado*
Tuesday morning plenary session 1, abstract on page [**??**]
"*Nuclear clock: recent developments*"

Susanne F. Yelin, *Harvard University*
Monday evening plenary session, abstract on page [314]
"*Unleashing Analog Quantum Computing*"

Theodor Lukin Yelin, *JILA, University of Colorado*
Tuesday morning invited session 2, abstract on page [**??**]
"*Entanglement-Enhanced Metrology in a Neutral Atom Array*"

Zhenhuan Yi, *Texas A&M University*
Monday evening invited session, abstract on page [315]
"*Generating Coherent States of Photonic Dimers*"

Aaron Young, *Harvard*
Tuesday morning invited session 2, abstract on page [316]
"*Quantum simulation of the Hubbard model: pseudogap, charge order, and beyond*"

Jingdi Zhang, *Hong Kong University of Science and Technology*
Monday morning invited session 1, abstract on page [317]
"*Terahertz wave amplification by a time-boundary-modulated Huygens' metasurface*"

Oumeng Zhang, *Texas A&M University*
Monday evening invited session, abstract on page [318]
"*Quantum-bound-guided single-molecule orientation localization microscopy*"

Wenzhuo Zhang, *Texas A&M University*
Poster session, abstract on page [319]
"*Quantum evolution of mixed states and efficiency of quantum heat engines*"

Xiwen Zhang, *Texas A&M University*
Wednesday evening invited session, abstract on page [320]
"*Quantum memory for hard X-ray photons with reduced mechanical complexity*"

Yingwen Zhang, *Chapman University*
Tuesday evening invited session, abstract on page [321]
"*Light-field microscope using entangled photons*"

Zheshen Zhang, *University of Michigan*
Wednesday evening invited session, abstract on page [322]
"*Quantum Sensing based on Centralized and Distributed Entanglement*"

Tian-Xing Zheng, *The University of Chicago*
Wednesday evening invited session, abstract on page [323]
"*A Molecular Qubit Scaffolded on a Hexagonal Boron Nitride Surface*"

Hengyun Zhou, *QuEra Computing*
Tuesday evening invited session, abstract on page [324]
"*Transversal Architectures for Neutral Atom Logical Quantum Computation*"

Shiyao Zhu, *Zhejiang University*
Poster session, abstract on page [325]
"*Realizing the Haldane Model in Thermal Atoms*"

Chong Zu, *Washington University in St. Louis*
Wednesday evening invited session, abstract on page [326]
"*Quantum Sensors in 2D Materials: Opportunities and Challenges*"

7 Abstracts

The following pages contain the abstracts submitted by the participants.

Speaker: Zain Abhari, *University of Wisconsin - Madison*

Session: X-ray Optics

Schedule: Thursday morning invited session 1

Stimulated Emission in the Hard X-ray Regime for X-ray Coherent Attosecond Pulse Pair Spectroscopy

Zain Abhari[1]

Thomas M. Linker[2], Ichiro Inoue[3], Uwe Bergmann[1]

1. *Department of Physics, University of Wisconsin – Madison, Madison, WI 53706, USA*
2. *Stanford Pulse Institute, SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA*
3. *RIKEN Spring-8 Center, Sayo-cho, Sayo-gun, Hyogo 679-5148, Japan*

Advancing our understanding of electron dynamics and electronic structure—key to explaining chemical and biological functions—requires ultrashort X-ray pulses and techniques to enhance weak signals. Recent years have seen significant progress in the development of ultrafast X-ray sources and methods, and our research focuses on the development and application of new nonlinear spectroscopy and new X-ray sources by way of stimulated X-ray emission at Ångström wavelengths. In this talk I will discuss X-ray Coherent Attosecond Pulse-Pair Spectroscopy (X-CAPPS), a new X-ray interferometry method that opens the 480 attosecond to 5.2 femtosecond delay window using stimulated Cu K□ emission to generate coherent pulse pairs. Interference signals collected by two sequential Bragg spectrometers allow precise measurements of amplitude and phase changes induced by a sample. Importantly, X-CAPPS requires no XFEL optics or pulse modifications, making it deployable at existing facilities. This approach enables Ångström-scale, attosecond-resolved studies of ultrafast electronic and structural dynamics.

Optical nuclear magnetic resonance spectroscopy of solid-state spins

We investigate the use of ^{13}C nuclear spins in diamond as a candidate system for nuclear magnetic resonance (NMR) based rotation sensing. The high density and relatively weak gyromagnetic ratio of ^{13}C nuclear spins afford favorable properties for rotation sensing, including relatively long spin dephasing times and robustness against ambient field and temperature fluctuations. Moreover, ^{13}C spins in diamond can be initialized to a high degree of spin polarization using optical and microwave interrogation. However, detection of ^{13}C NMR in diamond has so far relied on inductive detection, which has relatively poor sensitivity at the low magnetic fields required for rotation sensing.

Here, we demonstrate a technique that takes advantage of microwave-swept “Landau-Zener” crossover resonances to transfer spin quanta between Nitrogen-Vacancy (NV) electron spins and ^{13}C nuclear spins via their transverse hyperfine interaction, allowing for both optical hyperpolarization and readout. We perform optically-detected ^{13}C Ramsey spectroscopy and realize a ^{13}C-spin-dependent fluorescence contrast approaching 1%, with dephasing time $T_2^* \simeq 2$ ms. We study the magnetic field dependence of the optical readout and find good performance for magnetic fields below 10 mT. Our method can be interpreted as a type of repetitive readout where each NV center is used to read out the spin state of hundreds of ^{13}C nuclei before nuclear spin relaxation processes dominate. We show that this property offers a commensurate improvement in sensitivity compared to gyroscopes based on the ^{14}N nuclear spins associated with NV centers.

Nondiffractive Spin Skyrmions of the Vortex Cores in Electromagnetic and Acoustic Waves

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We provide an account of newly observed three-dimensional spin skyrmions found near phase singularities of both optical and acoustic vortex beams. While beams' intensity profiles expand during propagation due to diffraction, certain polarization features near phase singularities maintain constant transverse spatial dimensions, the property noticed for optical vortices [1], and dark fringes in the interference patterns of light [2] or sound [3].

Defining a "spin alignment parameter" for the beam propagating in z-direction as

$$\chi_{TL}(\boldsymbol{s}) = |s_\perp|^2 - s_z^2,$$

where ***s*** is a unit vector along the spin direction, we analyze spin dynamics of the propagating beams, with predictions shown in Fig.1. These calculated spin textures can be identified as skyrmions of propagation-independent transverse size. Such novel spin structures were recently discovered experimentally in optical [4-5] and acoustic vortices [6].

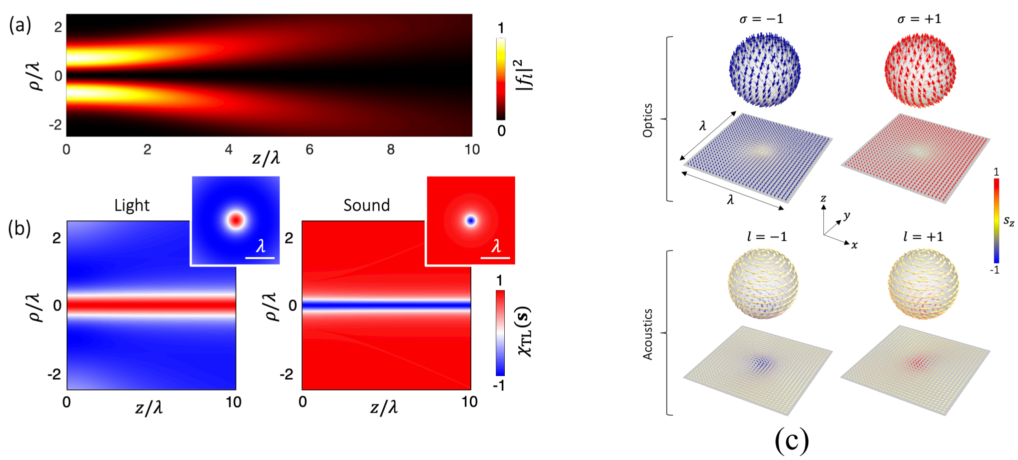

Fig. 1. (a) A diffracting intensity pattern of a vortex beam with OAM=1; (b) Calculated non-diffracting profiles of the spin alignment parameter $\chi_{TL}(\boldsymbol{s})$ for the light and sound in the longitudinal and transverse planes; (c) skyrmionic spin patterns.

References

[1]. A. Afanasev, J.J. Kingsley-Smith, F.J. Rodríguez-Fortuño, and A.V. Zayats, *Advanced Photonics Nexus* **2**, 026001 (2023).
[2]. A. Vernon, A. Kille, F. Rodríguez-Fortuño, and A. Afanasev, *Optica* **11**, 120 (2024).
[3]. A. Kille and A. Afanasev, Phys. Rev. **B109**, 184305 (2024).
[4]. N. Mata-Cervera, D. K. Sharma, Y. Shen, R. Paniagua- Dominguez, and M. A. Porras, Phys. Rev. Lett. **135**, 033805 (2025).
[5]. N. Mata-Cervera, et al. arXiv preprint arXiv:2509.06555 (2025).
[6]. E. Annenkova, A. Afanasev, and E. Brasselet, Universal nondiffractive topological spin textures in vortex cores of light and sound, submitted to *Physical Review Letters* (Oct. 2025).

Enabling Inertial Fusion Energy (IFE) by Controlling Nonlinear Optical Instabilities Using Spike Trains of Uneven Duration and Delay (STUD Pulses)

B. Afeyan, Polymath Research Inc., Palo Alto, CA

IFE requires the generation of sufficient inward pressure at the ablation surface of a D-T fueled target to implode its core to sufficiently high temperatures and densities to trigger a thermonuclear outward propagating burn wave that heats sufficient cold dense fuel outside the core to generate overall yields in exess of the input electrical energy supplied to drive the multiple MJ class lasers in the first place. If the laser absorption outside the ablation surface is disrupted and rendered inefficient, the rest stand no chance of success. Chief among the causes of this persistent disruption or flawed coupling from SHIVA to NIF are nonlinear optical instabilities in the coronal plasmas of laser-fusion targets.

The STUD pulse program is a set of strategies to combat all nonlinear optical instabilities and plasma self-organization processes in coronal plasmas of laser-fusion targets. It requires sub-ps pulse shaping for pulses that last for 10's of ns. How this is designed and implemented in specific circumstances with high frequency plasma mode instabilities such as Resonance Absorption (RA), Stimulated Raman Scattering (SRS), Two Plasman Decay (TPD), Driven KEEN waves, as well as for low frequency plasma mode processes such as Stimulated Brillouin Scattering and Crossed-Beam Energy Transfer (CBET) will be highlighted. The use of ML and reduced order models can play a crucial role in the implementation of the STUD pulse program, together with advanced plasma kinetic modelling algorithms such as BARS (Bidirectional Adaptive Refinement Scheme) in PIC or Vlasov codes. Equally crucial would be the use of high rep rated lasers if they gave rise to reproducible laser-plasma conditions where many STUD pulse configurations could be sampled, and STUD pulses 10's of 1000's of spikes optimized.

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LaserNetUS: the first five years of scientific discovery

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o*n behalf of the LaserNetUS Network*

LaserNetUS was launched in 2018, with a mission to advance and promote intense ultrafast laser science and applications. Since its inception, the network has transformed the landscape of high-power and high-intensity laser research, and it has grown into a community of over 1300 users. Additionally, it promotes worldwide collaborations and provides scientists, students, and underrepresented communities with broad access to unique facilities and enabling technologies. LaserNetUS has gone through 7 cycles of open calls for proposals, and over 180 unique experiments have been successfully executed across the network.

This talk will present the scientific achievements across the LaserNetUS over the first years of operation, with emphasis on secondary source development and applications. The breadth of laser parameters in pulse energy (from sub-Joule to a few kilojoules), pulse duration (from about 10 femtoseconds to 10s of nanoseconds) and repetition rate (up to 10 Hz) have enabled unique discoveries and applications in plasma-based particle acceleration, high energy density science, fusion energy, magnetic field generation, and plasma diagnostics. The talk will further present perspectives on the future of the network and how it can continue to stimulate high impact science in plasma physics, as well as in other scientific disciplines, medicine or industry.

Fig 1. *The 13 facilities of LaserNetUS*

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Fermionic Dicke phase transition in Circuit Quantum Magnetostatics

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Strong light–matter interaction lies at the core of cavity quantum electrodynamics (CQED), where quantized cavity modes are coupled to matter via electric-field operators. In the strong-coupling regime, CQED models have revealed new routes to engineer interactions, ordering phenomena, and transport far beyond bare Coulomb forces. In mesoscopic and synthetic systems, vector potentials themselves—even in nominally field-free geometries—can control quantum phases, as in the Aharonov–Bohm effect and its modern realizations in solid-state and cold-atom platforms. Here we develop a gauge-invariant, analytically tractable framework in which a quantized gauge field mediates effective, tunable interactions among mobile particles, while avoiding pathologies associated with no-go theorems tied to the diamagnetic term. We develop exactly solvable models of coupled flux–matter systems within the framework of cavity quantum magnetostatics (CQM), where a quantized transverse magnetic near field—generated, for example, by a deeply subwavelength LC resonator—couples minimally to mobile charges via their orbital motion. In this setting, the LC circuit plays a passive cavity-like role and need not be controlled or read out as a qubit. The CQM paradigm differs qualitatively from standard cavity QED: the leading light–matter coupling is orbital (magnetic) rather than electric dipole, selection rules are governed by angular momentum instead of polarization charge, and collective many-body effects emerge from an exactly derived current–current interaction channel mediated by the quantized flux. The Dicke phase transition can occur in this system even when the diamagnetic term is retained. This persistence of the transition stems from the fermionic nature of the particles coupled to the cavity, in contrast to the effective hard-boson emitters in standard CQED architectures.

We show that the paradigm of nonlocal coupling via a quantized Aharonov–Bohm effect naturally extends to more general architectures with quantized real or synthetic gauge fields, beyond strictly field-free toroidal configurations, thereby enabling more practical implementations. As a conceptual example, we consider a two-dimensional electron system embedded in a quantized magnetic flux that can exist in a superposition of flux states, leading to an effective nonlocal electron–electron coupling that may drive a superconducting instability.

Photon Correlation Measurements of Fluorescence as a Probe of Quantum Coherence in Multi-Chromophoric Systems

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November 24, 2025

The second-order correlation function $g^{(2)}(\tau)$ has long been recognized as a way to characterize the behavior of molecular emitters as well as the quantum nature of light. A growing interest in detecting quantum coherence in multi-chromophoric systems, such as conjugated polymers and light-harvesting complexes, has led to investigations of photon correlation measurements as a probe of the internal dynamics. In this work we theoretically investigate the $g^{(2)}(\tau)$ of fluorescence from a multi-chromophoric system modeled as a chain of N identical coupled two-level systems, under conditions of weak excitation by both incoherent and coherent light, including dephasing and collective emission effects. Our analysis explores how the incoming light source, number of emitters, coupling between these, their dephasing, and any collective emission influence the fluorescent photon statistics, providing a theoretical framework for interpreting fluorescent $g^{(2)}(\tau)$ measurements of multi-chromophoric systems.

Time-Dependent Close Coupling on the heels of attosecond electron dynamics

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Attosecond science is instrumental in resolving in time the photoionization and coherent electronic excitation of atoms, molecules, and solids [1]. In this context, *ab initio* time-dependent close-coupling (TDCC) wavefunction-based methods are essential to describe processes shaped by multiple excitations and photofragment entanglement. In the first part of this talk, I will show how Rainbow RABBITT [2] reveals a full 2π phase excursion near the argon $3s^{-1}4p$ state [3], characteristic of complex-q Fano profiles [4]. In the second part, I will illustrate an example of two-particle interference in the time-resolved two-photon double ionization of neon [5]. Depending on the spin state of the residual ion, the process generates photoelectron pairs with definite even or odd exchange symmetry, which is mapped onto the interference fringes of their joint energy distribution. Molecular scaling remains a major challenge. In the third part, I will present recent results obtained with ASTRA [6] (AttoSecond TRAnsitions), an *ab initio* CC molecular code based on high-order transition density matrices between correlated ionic states. I will illustrate a recent study of the sequential XUV-pump IR-probe double ionization of C_2H_4, conducted by combining ASTRA and surface-hopping methods [7] to account for both nuclear dynamics and resonantly-enhanced multiphoton ionization processes [8].

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[1] F Vismarra *et al*., Nat. Chem. **16**, 2017 (2024).
[2] V Gruson *et al.*, Science **354**, 734 (2016).
[3] S Luo *et al.*, Phys. Rev. Res. **6**, 043271 (2024).
[4] A Jiménez Galán *et al*., Phys. Rev. A **93**, 023429 (2016).
[5] S. Chattopadhyay *et al.*, Phys. Rev. A **108**, 013114 (2023); *ibid.* **110**, 013106 (2024).
[6] J M. Randazzo *et al*., Phys. Rev. Res. **5**, 043115 (2023).
[7] L Fransén *et al.*, J. Phys. Chem. A **128**, 1457 (2024).
[8] C Marante *et al.*, *under review*

Gravity in quantum systems: From atoms to macroscopic objects

Peter Asenbaum

IQOQI Vienna, Austrian Academy of Sciences

Gravity remains largely unexplored at the quantum level. A prime system to study is quantum states with small and large spatial extension. Sophisticated atom-optics techniques have allowed precise measurements of gravity in the small-extension regime, such as equivalence principle tests with quantum states [1]. More recently, we have accessed the large-extension regime and performed the first non-classical gravitational measurements [2]. In these experiments, laser pulses create meter-scale superpositions of single atoms that freely fall along fountain trajectories for several seconds.

The next frontier is to create and control *two* massive particles in quantum states with sufficient spatial extension to probe gravity-mediated entanglement. To achieve this, we aim to translate atom-optics techniques to macroscopic particles, i.e., implementing highly coherent interactions with laser pulses as well as precisely controlled fountain trajectories for sufficient drift time in free fall. These developments will hopefully open a path toward testing the quantum nature of gravity.

[1] Asenbaum/Overstreet et al. Phys. Rev. Lett. **125**, 191101 (2020)

[2] Overstreet/Asenbaum et al. Science **375**, 226(2022)

Towards microfluidic chips for efficient chiral recognition

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Apart from their well-established roles in nanotechnology and drug discovery, *small* chiral molecules are emerging as biomarkers for early-stage diagnosis, prognosis, and personalised medicine [1]. However, unlocking the biomedical potential of small-molecule chiral detection requires being able to detect small variations in the concentration of a highly diluted biomarker (e.g. D-serine [1]) in a biological sample containing a large excess of the opposite enantiomer (L-serine). Traditional optical methods, namely polarimetry and circular dichroism, lack the sensitivity to resolve such differences, whereas chemical methods involving chromatographic columns or sophisticated analysis are not sufficiently general, rapid, and cost-effective [1].

The possibility of shaping light in 3D to shape the electronic response of chiral molecules on ultrafast timescales creates an opportunity to overcome these limitations [2]. Locally chiral light [3-6], where the tip of the electric-field vector draws a chiral Lissajous figure in time [3], can drive ultrafast electronic currents inside the molecules that interact with the chiral molecular potential in a highly enantiosensitive manner. It allows us to enhance the enantiosensitivity of traditional chiral spectroscopy from 0.1% up to 100% [3-6].

In this presentation, I will show how we can engineer compact microfluidic platforms to create locally chiral light inside their microchannels carrying liquid samples. Our ideas are supported by state-of-the-art numerical simulations showing that bringing the high chiral sensitivity from free-space optics [3-6] to confined microfluidic environments is very feasible. This creates an opportunity for designing compact microfluidic technology for efficient chiral recognition in the liquid phase, the natural environment of biological samples.

[1] Y. Liu et al, *Nat. Rev. Chem.* **7**, 355 (2023)
[2] D. Ayuso et al, *Phys. Chem. Chem. Phys* **24**, 26962 (2022)
[3] D. Ayuso et al, *Nat. Photon.* **13**, 866 (2019)
[4] D. Ayuso et al, *Nat. Commun.* **12**, 3951 (2021)
[5] J. Vogwell et al, *Science Advances* **9**, eadj1429 (2023)
[6] N. Mayer et al, *Nat. Photon.* **18**, 1155 (2024)

The revival of the Superfluid or decaying to a thermal gas during relaxation of a far-from equilibrium Bose-Einstein Condensate

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BME- Texas A&M - College Station - TX - USA

Understanding the initial conditions that drive many-body quantum systems out of equilibrium is essential for getting into their thermalization dynamics. In this work [1,2,3,4], we identify two excitation regimes that lead a trapped Bose–Einstein condensate into turbulence regime evolving resulting in distinct final states. In the subcritical regime, the condensate partially reemerges after turbulence, whereas in the supercritical regime it dissolves completely into a thermal state. Despite these differences, both cases exhibit relaxation stages with common features: a direct energy cascade, the emergence of a nonthermal fixed point (characterized by identical scaling exponents), a prethermalization plateau, and eventual thermalization. Our results show that turbulence relaxation develops independently of the system's initial conditions or its ultimate state. At late times, both regimes display universal scaling dynamics consistent with predictions from wave turbulence theory. Finally, by analyzing the time evolution of the condensate's momentum distribution center of mass, we demonstrate how kinetic-energy dominance reflects the thermalized nature of the final states in each regime. The present results advance the field by showing that thermalization in far-from-equilibrium quantum systems follows universal relaxation dynamics, even when final states differ, thereby deepening our understanding on time evolution of many bodies quantum system thermalization. We shall present a new possible interpretation for pre-thermalization as well as an analysis of the construction of the coherent length during the last stage of thermalization of the system. Work done in cooperation with: , Sarah Sab, Michelle M Armijos, Arnol G Orozco, and Amilson Fritch. Acknowledgement**:** *GURI, CRI, CPRIT-grant RR220054, FAPESP-CEPID/CEPOF and FAPESP*

1. M. A. Moreno-Armijos et al - Phys. Rev. Lett. 134. 023401 (2025)
2. L. Madeira et al - Proc. Nat, Acad. Sci. -PNAS 121, 24044828121 (2024)
3. A. D. Garcia-Orozco et al - Phys. Rev. A 106, 023314(2022)
4. S. Sab et al – Submitted for publication (2025)

Nanophotonics for coherent control of topological electron states

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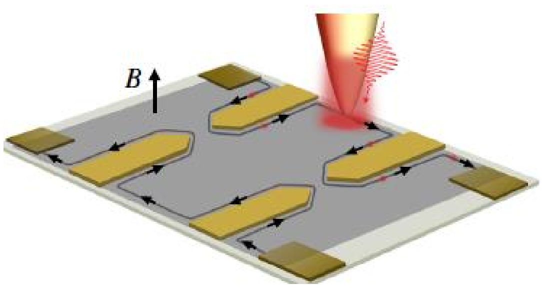
[2]Department of Electrical and Electronic Engineering, Ariel University, Israel

Current-carrying chiral edge states in quantum Hall systems are topologically protected and exhibit fascinating properties typically studied using electron transport. Here we show that electron occupation, current, and coherence in the chiral edge states can be selectively probed and controlled by terahertz or infrared radiation with single-quasiparticle sensitivity without destroying quantum Hall effect in the bulk. Out of several material systems that we study, graphene provides a particularly versatile platform enabling valley-selective optical excitations into a given edge state. The underlying physical mechanism is the inevitable violation of adiabaticity and inversion symmetry breaking for electron states near the edge. This leads to the formation of Landau-level-specific and valley-specific absorbance spectral peaks that are spectrally well separated from each other and from absorption by the bulk states, and have different polarization selection rules. Furthermore, inversion symmetry breaking enables coherent driving of chiral edge photocurrents due to second-order nonlinear optical rectification which becomes allowed in the electric-dipole approximation. The shape of an incident single-photon state controls the quantum state of an excited electron, offering new opportunities for optoelectronic control, quantum Hall interferometry, and quantum gates.



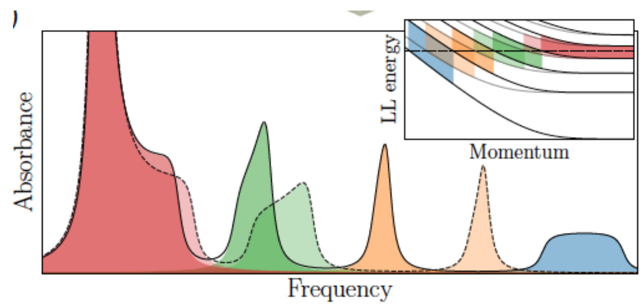


Fig. 1. Left: Schematic of a nanotip-enabled optical excitation of chiral edge states in a typical quantum Hall interferometer. Right: An example of dimensionless 2D absorbance spectra showing well-separated spectral peaks corresponding to the excitation of specific edge states and different valleys: K valley states (solid line) and K' valley (dashed line). Inset: dispersion of electron eigenenergies and optical transitions corresponding to different part of the absorption spectra, indicated by the same color coding. Dashed line denotes the chemical potential below which all states are occupied.

References:

A. Singh, M. Sebastian, M. Tokman, and A. Belyanin, Coherent optical control of quantum Hall edge states, Phys. Rev. B 110, 085405 (2024).

A. Singh, M. Sebastian, M. Tokman, and A. Belyanin, Valley resolved optical spectroscopy and coherent excitation of quantum Hall edge states in graphene, Phys. Rev. B 112, 125414 (2025).

Experimental study of laser plasma instabilities with broadband laser pulses at the GSI PHELIX laser facility

C Kanstein[1], F Wasser[2,3] S¸ Zähter[2], S Atzeni[2], G Benincasa[4], G Cristoforetti[4], G Erdogdu[2], M Fischer[5], L A Gizzi[4], K Glize[6], S J Grimm[5], J Hornung[7], E Hume[4,8], P Köster[4], S Kuschel[5], T Meffert[9], F Neufeld[5], P Neumayer[7,9], K L Nguyen[2], W Theobald[2,10], V Winter[1], N Woolsey[8], K Zarrouk[5], X Zhao[8], V Bagnoud[1,7] and M Roth[2,5]

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Abstract

We present first experimental data obtained at the recently commissioned experimental platform to compare laser plasma instabilities (LPIs) driven by monochromatic and broad spectral bandwidth (≈ 0.5%) laser pulses with a wavelength of around 527 nm. The evaluation of LPIs at 10^15 W cm^-2 is shown by utilizing a full aperture backscatter diagnostic and side scatter diagnostics. For a broad bandwidth, our study indicates a suppression of stimulated Brillouin back- and side scattering as well as of the two plasmon decay instability, but an increase of stimulated Raman side scattering. An increase in both temperature and numbers of hot electrons is also identified by direct and indirect measurements.

One-sided Witnesses for the Quantumness of Gravitational Dynamics

Konstantin Beyer, M. S. Kim, Igor Pikovski

Quantum information concepts are opening new possibilities for probing quantum aspects of gravity in table-top experiments. Existing proposals typically aim to demonstrate that gravity can act as a quantum channel by detecting entanglement generated between two interacting systems, which requires measurements on both of them [1, 2].

We introduce a different class of tests for the quantum nature of the gravitational interaction that relies on measurements of only a single probe system, while the interacting partner remains unmeasured [3]. Our method is based on the notion of verifiable quantum memory: if the local dynamics of the probe reveal nonclassical memory effects that cannot arise from any classical interaction, then the coupling must be quantum [4].

This enables the first one-sided verification of the quantumness of gravity and provides a complementary quantum signature beyond existing two-sided approaches. We further show that the asymmetric structure of our scheme offers experimental advantages. For instance, in the case of gravitationally coupled oscillators, the probe can be small and fully quantum-controllable, while the second system may be much heavier and merely needs to be prepared close to its ground state.

Our results extend the range of possible tabletop tests of quantum gravity and clarify how decisive signatures of a quantum gravitational interaction can be obtained using measurements on a single system.

[1] Sougato Bose, Anupam Mazumdar, Gavin W. Morley, Hendrik Ulbricht, Marko Toroš, Mauro Paternostro, Andrew A. Geraci, Peter F. Barker, M. S. Kim, and Gerard Milburn. Spin Entanglement Witness for Quantum Gravity. *Physical Review Letters*, 119(24):240401, December 2017.

[2] C. Marletto and V. Vedral. Gravitationally Induced Entanglement between Two Massive Particles is Sufficient Evidence of Quantum Effects in Gravity. *Physical Review Letters*, 119(24):240402, December 2017.

[3] Konstantin Beyer, M. S. Kim, and Igor Pikovski. A One-sided Witness for the Quantumness of Gravitational Dynamics, July 2025. arXiv:2507.15588 [quant-ph].

[4] Charlotte Bäcker, Konstantin Beyer, and Walter T. Strunz. Local Disclosure of Quantum Memory in Non-Markovian Dynamics. *Physical Review Letters*, 132(6):060402, February 2024.

Speaker: Souvik Biswas, *Stanford University and University of Michgan*
Session: Nanophotonics
Schedule: Monday morning invited session 1

Diamond as a Platform for Scalable Quantum Networks

Optically active spin defects in solid-state systems are promising building blocks for next-generation quantum networks. Diamond has emerged as a leading platform, with nitrogen- and silicon-vacancy centers serving as the primary candidates to date. However, nitrogen-vacancy centers suffer from low quantum efficiency, while silicon-vacancy centers require stringent cryogenic conditions (~100 mK), limiting scalability. The tin-vacancy center has recently emerged as a compelling alternative, offering high quantum efficiency, robust spin coherence, and inversion-symmetry-based protection against environmental noise – properties that collectively make it well suited for scalable photonic integration.

In this talk, I will present our first demonstration of coherent spin control in the tin-vacancy qubit, showing robust operation at elevated temperatures around 2 K. I will discuss the relevant electronic level structure and its role in enabling efficient spin readout. I will then describe the realization of single-shot electron spin readout with fidelities of 87.4%, which can be improved to 98.5% using conditional readout, and emphasize the importance of identifying and characterizing the dominant dephasing channels in this system. Finally, I will discuss how monolithically integrated diamond photonic devices can further enhance readout fidelities, paving the way toward efficient spin-photon interfaces for scalable quantum networks.

Engineering interacting spins in the solid-state for quantum sensing

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The diamond nitrogen vacancy (NV) center spin qubit is a uniquely versatile quantum sensor that offers a path towards truly nanoscale magnetic imaging with high sensitivity over a wide range of temperatures and applications targets. Here I discuss NV-based scanned magnetic imaging experiments as applied to condensed matter systems, in particular focusing on a new sensing modality for probing dynamics. These experiments, as well as all others to date, have primarily leveraged either single NV centers or ensembles of non-interacting NV centers. I then discuss the challenges, prospects, and experimental progress towards leveraging strongly-interacting spin ensembles for entanglement-enhanced quantum sensing.

Epsilon Near Zero Effects and Applications

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Transparent conducting oxides (TCOs) and other low-loss epsilon-near-zero (ENZ) materials that support near-zero-index (NZI) bahavior demonstrate exceptional optical properties, enhancing both linear and nonlinear optical response. TCO optical properties can be passively (statically) tailored and dynamically tuned on ultrafast time scales. We demonstrate great control in varying the ENZ response of TCOs such as aluminum- and gallium-doped zinc oxide and yttrium doped cadmium oxide both in the optical and mid-infrared spectral ranges. We also investigate the strong modification of both nanoantenna resonance and quantum emitter properties when combined with an NZI substrate. Employing the Berreman modes of a metal and AZO films, we demonstrate variable switching speeds of an optically-pumped structure. The nonlinear capabilities of undoped ZnO for all optical switching and third harmonic generation are also discussed. We explore the possibility of realizing photonic time crystals and investigate the fastest material responses in TCOs. Our studies pave the way to novel phenomena and device design with ultrafast tunable and tailorable materials.

Quantum Pythagoras: Entanglement Generation via Tunneling and Black-Hole Analogs

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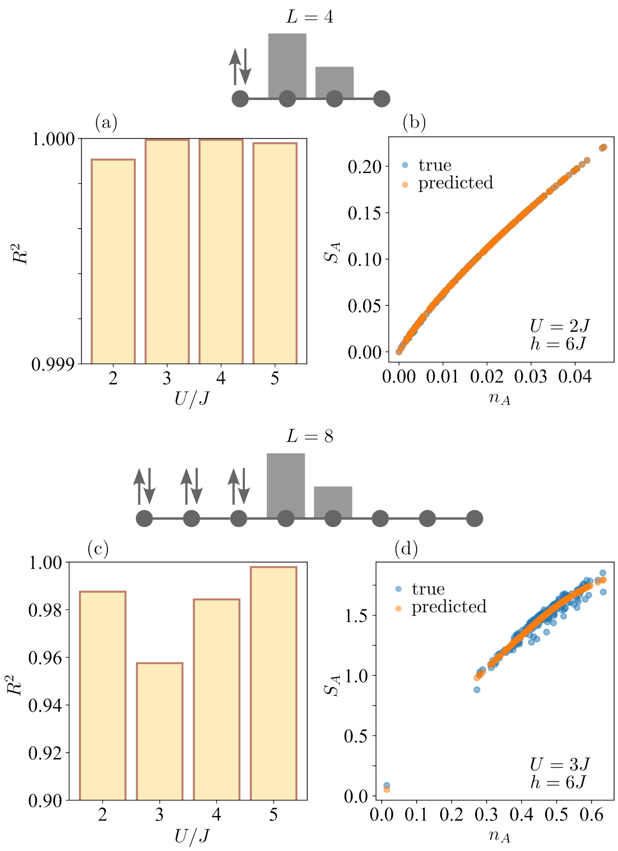

FIG. 1: KAN prediction accuracy for the functional relationship $S_A(U, n_A)$. (a, c) Coefficient of determination R^2 as a function of on-site interaction strength U for system configurations $L = 4$, $N = 2$ and $L = 8$, $N = 6$ respectively, with barrier height $h = 8J$. (b, d) Comparison between true (blue circles) and KAN-predicted (orange circles) values of $S_A(n_A)$ for the parameter sets with the lowest R^2 values: (b) $L = 4$, $N = 2$, $U = 2J$, $h = 6J$ and (d) $L = 8$, $N = 6$, $U = 3J$, $h = 6J$. The lattice diagrams show the system setup with fermions initially localized on the left and external potential barriers (gray boxes) acting on two central sites.

Quantum tunneling is one of the oldest concepts in quantum physics and is often considered a well-understood phenomenon. Yet even a single triangular ("Quantum Pythagoras") barrier produces a surprising wealth of physics. In his famous textbook, Landau showed that in one-dimensional single-particle systems, the tunneling probability is identical for left- and right-incident waves, independent of the barrier shape. We demonstrate that interactions overturn this symmetry and give rise to a diverse set of new effects when tunneling through a triangular barrier.

Entanglement entropy is a fundamental measure of quantum correlations and a key resource underpinning advances in quantum information and many-body physics. We uncover a universal relationship between bipartite entanglement entropy and particle number after the barrier in a one-dimensional Fermi-Hubbard system with an external asymmetric potential [arXiv:2507.19731]. Using Kolmogorov-Arnold Networks (KAN) —a novel machine learning architecture—we learn this relationship across a broad range of interaction strengths with near-perfect predictive accuracy. Furthermore, we propose a simple analytical binary-entropy-like expression that quantitatively captures the observed correlation for fixed parameters. Our findings open new avenues for characterizing quantum correlations in transport phenomena and provide a powerful framework for predicting entanglement evolution in quantum systems.

We also investigate interaction-driven directional transport of ultracold bosons in a one-dimensional optical lattice featuring an asymmetric triangular potential barrier. Using exact diagonalization of the Bose–Hubbard model, we show that repulsive interactions enable strongly unidirectional tunneling: particles initialized on one side of the barrier propagate across it, while the reverse process is nearly completely suppressed.

Charged Bosons Made of Fermions in Laser-Excited Semiconductor-Metal Heterostructures

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Laser excited quasi-2D heterostructures of transition metal dichalcogenides (TMDCs) have been shown to allow for quite a few higher-order excitonic bound states such as trions (charged excitons), biexcitons (neutral excitonic molecules), charged biexcitons, and more [1-5]. Such a large variety of coupled electron-hole quasiparticle excitations opens the door to a variety of new laser-driven phenomena in these systems, including metal-insulator transitions, Bose-Einstein condensation (BEC), and even unconventional superconductivity [6-10]. Recently [5,10], a doubly charged excitonic complex was reported experimentally in laser excited bilayer TMDCs in accord with theory predictions—the quaternion, a tightly bound complex of a free charge carrier in the top layer coupled to a like-charge trion in the bottom layer—provided that the entire heterostructure is placed close to a metallic surface to screen the excessive repulsive interaction in the system. Because such quaternions carry two net charges and are also bosonic, their BEC would be a superfluid and so also a Schafroth superconductor [11]. We develop a theoretical framework to explain the latest experimental observations of the Zeeman effect for quaternions in perpendicular magnetostatic field [10]. Our theory is based on group theoretical analysis and spin-Hamiltonian formalism. We show that the quaternion ground state is the spin-triplet to exhibit a quadratic magnetic field shift like that known for hydrogen-like atoms. In addition to prospective laser-driven BEC and superconductivity of bosonic quaternion excitations, another fascinating possibility we discuss for quaternions is that, as they are charged bosons, they could form bosonic Wigner crystal. Such a light-induced quasiparticle crystal would be an ‘atom-like’ supersolid inside of the crystalline material. Wigner crystallization is controlled by the ratio of the Coulomb repulsion energy to the average single-particle kinetic energy of an ensemble of charge carriers [12,13]. Due to the double charge and quadruple mass as compared to electrons, this ratio is at least 10 times greater for quaternions, suggesting higher crystallization temperature (T_c) than $T_c \sim 10$ K reported for quasi-2D electrons in monolayer TMDCs [14]. Higher T_c implies higher T of Wigner solid-liquid phase transition, in which case one could also expect high-T BEC and light-induced superconductivity of quaternions, accordingly.

Acknowledgments: This research is supported by the U.S. ARO collaborative grant No. W911NF-24-1-0237.

[1] I.V.Bondarev and M.R.Vladimirova, Complexes of dipolar excitons in layered quasi-2D nanostructures, Phys. Rev. B 97, 165419 (2018).
[2] E.Liu, *et al.*, Exciton-polaron Rydberg states in monolayer $MoSe_2$ & WSe_2, Nat. Commun. 12, 6131 (2021).
[3] I.V.Bondarev, O.L.Berman, R.Ya.Kezerashvili, and Yu.E.Lozovik, Crystal phases of charged interlayer excitons in van der Waals heterostructures, Commun. Phys. (Nature) 4, 134 (2021).
[4] X.Sun, *et al.*, Enhanced interactions of interlayer excitons in free-standing bilayers, Nature 610, 478 (2022).
[5] Z.Sun, *et al.*, Charged bosons made of fermions in bilayer structures with strong metallic screening, Nano Lett. 21, 7669 (2021).
[6] Y.N.Joglekar, A.V.Balatsky, and S.Das Sarma, Wigner supersolid of excitons in electron-hole bilayers, Phys. Rev. B 74, 233302 (2006).
[7] L.Ma, *et al.*, Strongly correlated excitonic insulator in atomic double layers, Nature 598, 585 (2021).
[8] I.V.Bondarev and Yu.E.Lozovik, Magnetic-field-induced Wigner crystallization of charged interlayer excitons in van der Waals heterostructures, Commun. Phys. (Nature) 5, 315 (2022).
[9] D.Erkensten, S.Brem, R.Perea-Causin, and E.Malić, Stability of Wigner crystals and Mott insulators in twisted moiré structures, Phys. Rev. B 110, 155132 (2024).
[10] Q.Wan, *et al.*, Light-induced electron pairing in a bilayer structure, Rep. on Progress in Physics, *in print*.
[11] M.Schafroth, Theory of superconductivity, Phys. Rev. 96, 1442 (1954).
[12] P.M.Platzman and H.Fukuyama, Phase diagram of the 2D electron liquid, Phys. Rev. B 10, 3150 (1974).
[13] I.V.Bondarev, A.Boltasseva, J.B.Khurgin, and V.M.Shalaev, Crystallization of the transdimensional electron liquid, arXiv:2503.05165 (7 Mar 2025).
[14] T.Smolenski, *et al.*, Signatures of Wigner crystal of electrons in a monolayer semiconductor, Nature 595, 53 (2021); Y. Zhou, *et al.*, Bilayer Wigner crystals in a TMDC heterostructure, *ibid.* 595, 48 (2021).

Title: Quantum computing enhanced imaging

Abstract: High-resolution optical imaging underpins applications from exoplanet detection and satellite monitoring to molecular imaging. Classical methods rely on tomographic reconstruction and post-processing to remove background noise, which comes with prohibitive measurement overhead and stability requirements for weak sources. In this talk, I will introduce a fundamentally different approach that replaces tomographic analysis with direct quantum processing of photonic information. Building on recent demonstrations of coherent photon-to-qubit transduction, asynchronously arriving photons can be stored in quantum memories and interfered through quantum algorithms to remove background noise without tomographic reconstruction. Applied to exoplanet imaging, our estimates show several-orders-of-magnitude improvement under realistic conditions using quantum circuits of only hundreds of gates and tens of qubits. The approach generalizes to similar tasks within adaptive optics, molecular imaging, and space awareness, opening new opportunities for quantum-enhanced imaging with near term quantum computers.

Speaker: Alexander Bott, *Ulm University*

Session: Frontiers of Atom Optics II

Schedule: Wednesday morning invited session 1

Atomic diffraction from single-photon transitions in gravity and Standard-Model extensions

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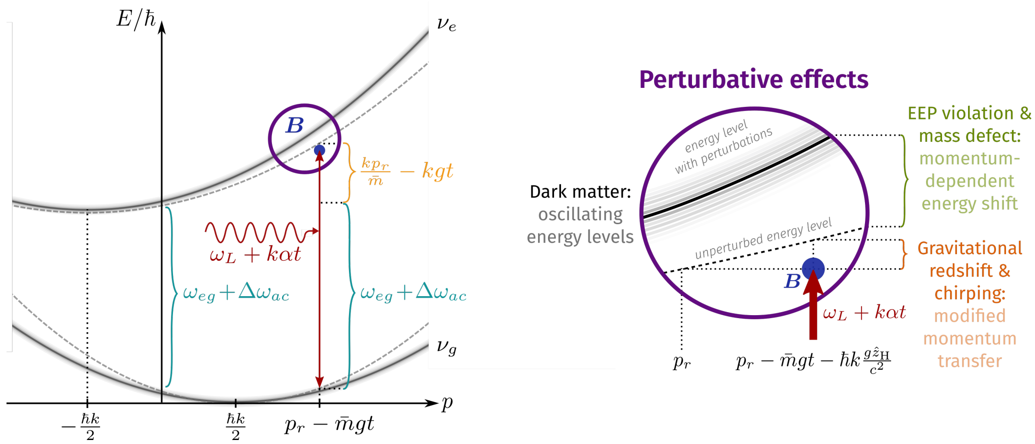
Single-photon transitions are one of the key technologies for designing and operating very-long-baseline atom interferometers tailored for terrestrial gravitational-wave [1] and dark-matter detection [2]. Since such setups aim at the detection of relativistic and beyond-Standard-Model physics, the analysis of interferometric phases as well as of atomic diffraction must be performed to this precision and including these effects.

This talk features our analysis of atomic diffraction by magnetically induced single-photon transitions in gravity [3]. We consider a number of perturbative effects, including Standard-Model extensions modeling dark matter as well as Einstein-equivalence-principle violations [4]. We furthermore take into account relativistic effects like the coupling of internal to center-of-mass degrees of freedom, induced by the mass defect, as well as the gravitational redshift of the diffracting light pulse [5]. We also discuss the role of chirping of the light pulse required by terrestrial setups, with special emphasis on the associated modified momentum transfer for single-photon transitions.



Perturbations to the resonant single-photon transition in an energy-momentum diagram in the co-rotating frame

[1] M. Abe, P. Adamson, M. Borcean, et al. *Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100)*, Quantum Sci. Technol. **6**, 044003 (2021)

[2] L. Badurina, V. Gibson, C. McCabe, and J. Mitchell *Ultralight dark matter searches at the sub-Hz frontier with atom multigradiometry*, Phys. Rev. D **107**, 055002 (2023)

[3] A. Bott, F. Di Pumpo and E. Giese *Atomic diffraction from single-photon transitions in gravity and Standard-Model extensions*, AVS Quantum Sci. **5**, 044402 (2023)

[4] F. Di Pumpo, A. Friedrich, A. Geyer, C. Ufrecht, and E. Giese *Light propagation and atom interferometry in gravity and dilaton fields*, Phys. Rev. D **105**, 084065 (2022)

[5] F. Di Pumpo, C. Ufrecht, A. Friedrich, E. Giese, W. P. Schleich, and W. G. Unruh *Gravitational redshift tests with atomic clocks and atom interferometers*, PRX Quantum **2**, 040333 (2021)

Speaker: Philippe Bouyer, *Univ. Amsterdam and Technical Univ. Eindhoven*

Session: Cold Atoms

Schedule: Friday morning invited session 2

Atom Interferometry Beyond Its Limits

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***Abstract*— Atom interferometry is entering a new regime of sensitivity and scale, enabling precision measurements of gravity, inertia, and spacetime far beyond previous limits. Advances in long-baseline architectures, high-flux atom sources, and microgravity platforms demonstrate that coherent matter waves can probe low-frequency gravitational signals and environmental mass dynamics with unprecedented precision. Building on these developments, continental-scale quantum gravimetry infrastructures are emerging, linking gravimeters, gradiometers, and future long-baseline interferometers into synchronised hybrid sensing infrastructures. Beyond applied gravimetry, these systems open a realistic pathway to exploring foundational physics, including smooth-collapse mechanisms for macroscopic quantum states.**

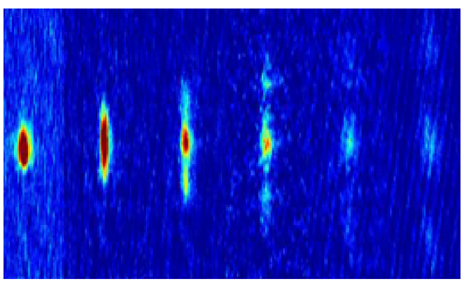

Fig. 1. Atom interferometry in microgravity

Atom interferometry has progressed from controlled laboratory experiments to a versatile tool capable of probing gravity, geophysics, and fundamental physics at exceptional levels of sensitivity. The maturation of long-baseline instruments, advanced atom-optical techniques, and microgravity platforms now positions atom interferometers to operate in regimes previously accessible only to very large optical interferometers.

A key milestone in this evolution is the Matter-wave laser Interferometric Gravitation Antenna (MIGA), now in advanced commissioning. This 150-m underground instrument is designed to achieve stable long-baseline operation, multi-axis interferometry, and precise strain and gravity-gradient extraction in a complex natural environment. Early results are expected to confirm the potential of matter-wave detectors to access the low-frequency gravitational spectrum while simultaneously providing high-resolution geophysical data. These demonstrations are a mandatory step to demonstrate the feasibility of matter-wave observatories as core components of future gravitational instrumentation.

Parallel progress in multi-dimensional atom optics, cavity-assisted beam splitters, and high-brightness atomic sources is expanding achievable interrogation times and operational flexibility. Microgravity infrastructures; such as compact Einstein-elevator platforms times; bridge the gap between terrestrial setups and future space missions, enabling sensitivities comparable to kilometre-scale laser interferometers. These developments collectively establish the technological foundations for next-generation gravity sensing.

Building on this momentum, efforts are underway to establish quantum gravimetry infrastructure that make use of cold-atom gravimeters, gravity gradiometers, and long-baseline interferometers across continental scales. Together, these instruments can provide real-time monitoring of hydrological and geological mass redistribution, improved early-warning capabilities for natural hazards, enhanced inertial navigation, and access to low-frequency gravitational signals. Initiatives such as EQuIP-G extend this approach by developing deployable, on-demand gravimetry services capable of bringing laboratory-grade performance to field and industrial environments.

In addition to their applied value, these emerging infrastructures offer a powerful platform for probing the interface of quantum mechanics and gravitation. The combination of long interrogation times, low-noise environments, and advanced quantum states provides sensitivity to gravitational self-energy, gravity-induced phase diffusion, and proposed smooth-collapse mechanisms for macroscopic spatial superpositions. Such experiments could begin to test collapse scenarios at mass scales far below those required for full wavefunction reduction, opening an experimental path toward understanding whether gravity plays a role in the loss of quantum coherence at large scales.

Atom interferometry is thus poised to move beyond its current limits, enabling both large-area sensing infrastructures and fundamental tests of gravity's influence on quantum coherence. Instruments like MIGA, combined with microgravity techniques and coordinated quantum sensor networks, form the foundations of future gravitational observatories, and may ultimately reveal new physics at the intersection of quantum mechanics and spacetime.

References

[1] Pelluet, C., Arguel, R., Rabault, M. et al. Atom interferometry in an Einstein Elevator. Nat Commun 16, 4812 (2025). https://doi.org/10.1038/s41467-025-60042-7

[2] Abend S., Allard, B., et al. Terrestrial Very-Long-Baseline Atom Interferometry: Workshop Summary. arXiv:2310.0818 (2023). https://doi.org/10.48550/arXiv.2310.08183

[3] Cassens C., Meyer-Hoppe, B., et al. Entanglement-Enhanced Atomic Gravimeter. Phys. Rev. X 15, 011029 (2025) https://doi.org/10.1103/PhysRevX.15.011029

[4] Howl R., Penrose R., and Fuentes I. New Journal of Physics, 21(4):043047, (2019) https://doi.org/10.1088/1367-2630/ab104a

Heterogeneously-Integrated Lasers on Thin Film Lithium Niobate

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We demonstrate a versatile heterogeneous integration platform unifying III-V gain with thin-film lithium niobate (TFLN) photonic circuits to create high-performance lasers with integrated functionality[1-4]. This advance overcomes the critical barrier to fully integrated photonic systems by combining optical gain, low-loss cavities, and phase control on a single chip. Fig. 1 shows the wafer and devices used to integrate lasers on TFLN. We present two distinct laser architectures: a distributed feedback laser achieving 11.0 kHz intrinsic linewidth and 4.0 mW in-fiber power through self-injection locking to a high-Q TFLN resonator, and a Vernier ring laser exhibiting 44 nm continuous tuning range with >40 dB side-mode suppression ratio (Fig 2). Crucially, the heterogeneous integration of the gain

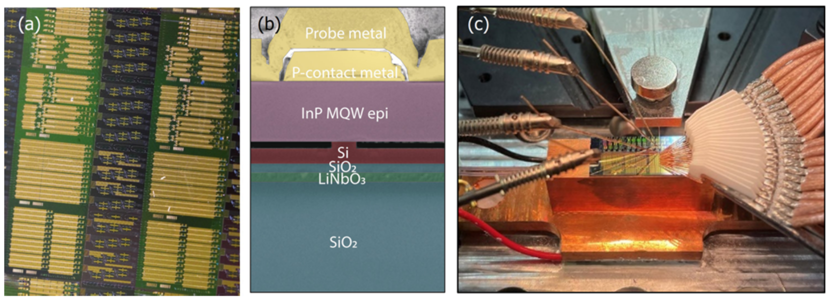

Fig. 1. A) Photo of TFLN PIC wafer. B) Colorized SEM image of structure. C) Photo of PIC under test.

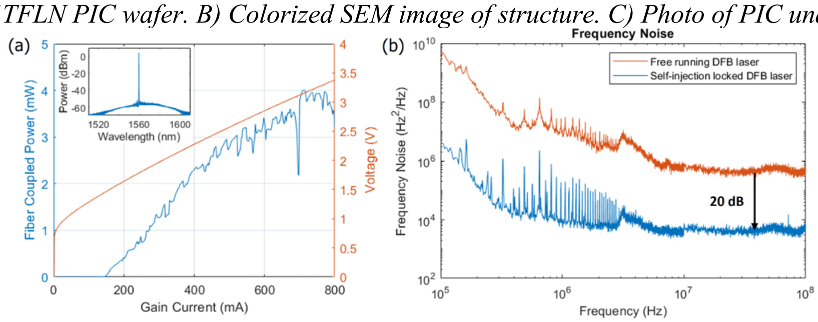

Fig. 2 A) LIV Curve of DFB laser. B) Frequency noise of free running laser and self injection locked laser.

section with TFLN's components provides a promising path to implementing direct intracavity modulation, which is a functionality that typically requires discrete components}. This inherent capability makes our platform a foundational advancement for future compact, robust systems in coherent communications, ultrafast optical metrology, quantum photonic processors, and microwave photonic systems operating at GHz bandwidths, marking a significant advancement toward complete photonic system integration.

The authors acknowledge a fruitful collaboration with Chang Lin's group at University of Rochester and Kerry Vahala's group at Caltech.

[1] John E. Bowers, Mingxiao Li, et al. , "Heterogeneous Integration of Semiconductor Lasers on Thin-Film Lithium Niobate", Invited paper, CLEO 2025.
[2] Mingxiao Li, Lin Chang, Lue Wu, Jeremy Staffa, Jingwei Ling, Usman A. Javid, Yang He, Raymond Lopez-rios, Shixin Xue, Theodore J. Morin, Boqiang Shen, Heming Wang, Siwei Zeng, Lin Zhu, Kerry J. Vahala, John E. Bowers, Qiang Lin, "Integrated Pockels Laser" Nature Communications 13, Article number: 5344 (2022).
[3] Shixin Xue, Mingxiao Li, Raymond Lopez-rios, Jingwei Ling, Zhengdong Gao, Qili Hu, Tian Qiu, Jeremy Staffa, Lin Chang, Heming Wang, Chao Xiang, John E. Bowers, and Qiang Lin "Pockels Laser Directly Driving Ultrafast Optical Metrology" Light Sci Appl 14, 209 (2025). https://doi.org/10.1038/s41377-025-01872-4
[4] Changhao Han, Mingxiao Li, Chen Shang, Joel Guo and John E. Bowers, "Integrated Laser Technologies for Artificial Intelligence Applications" Invited paper Optics Express (2025)

Gravitational Waves, Dark Matter, Photons…

More ways to explore fundamental questions

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The advent of new experimental techniques (the proverbial "new eyes on the universe") and refinement of the proven ones gives us hope to find answers to the "elephant-in-the-room" questions of the origins of the matter-antimatter asymmetry, dark matter, and the fundamental symmetries and their violation.

We will discuss a selection of ongoing experiments searching for specific types of ultralight bosonic dark matter (UBDM) and high-frequency gravitational waves (in particular, by the GravNet collaboration [1]). Modern quantum sensors [2], including those based on spin [3], are essential for these searches.

We will also emphasize the utility of "couch experiments", in which existing data, often collected for unrelated purposes, are analyzed in search of "new physics".

References

[1] https://www.pi.uni-bonn.de/gravnet/en/homepage

[2] Quantum Science and Technology: Focus on Quantum Sensors for New-Physics Discoveries, guest-edited by Marianna Safronova and Dmitry Budker. Editorial**:** Quantum technologies and the elephants; *Quantum Sci. Technol.* **6** 040401(2021); DOI 10.1088/2058-9565/ac01f0

[3] Derek F. Jackson Kimball, Dmitry Budker, Timothy E. Chupp, Andrew A. Geraci, Shimon Kolkowitz, Jaideep T. Singh, and Alexander O. Sushkov, Probing fundamental physics with spin-based quantum sensors, Phys. Rev. A **108**, 010101 (2023)

Speaker: Ivan Burenkov, *Joint Quantum Institute at NIST*

Session: Multiparticle Interference for Quantum Sensing

Schedule: Thursday evening invited session

Towards robust detector tomography

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Abstract: Photon-number-resolving (PNR) detectors are now commercially available; however, to unlock the advanced quantum algorithms based on PNR, robust and reliable characterization is required. This work is the first attempt at a methodological comparison of the reliability of different tomographic algorithms.

For practical use in quantum information science [1-3], the output of a PNR or quasi-PNR detector should be calibrated to accurately represent the input state. Quantum measurement tomography yields a positive operator-valued measure (POVM), which relates the detector's response to the number of photons incident on the detector [4,5]. Experimentally, PNR detector tomography is often performed with attenuated coherent states because it is hard to generate high Fock states. Experimentally measured photon number statistics are mathematically related to the matrix product of the known input state probability matrix of input states and the unknown POVM matrix. Due to statistical errors, reconstruction of the unknown POWM is not a trivial task. We implement and compare the least-squares (LS) error minimization algorithm, the maximum likelihood estimation (MLE) algorithm, as well as a Bayesian inference detector tomography.

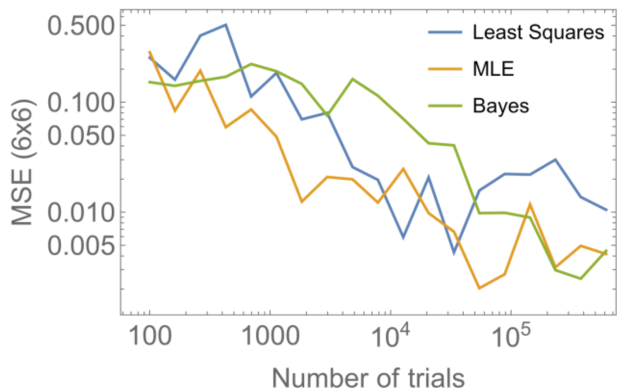

Fig. 1 Performance of different tomographic algorithms on synthetic data.

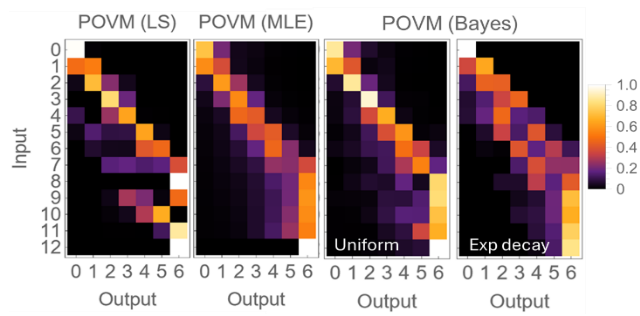

Fig. 2 Comparison of POVMs obtained from experimental data

First, we test that all algorithms perform well on synthetic data, for both ideal and non-ideal detectors, i.e. where POVM can be significantly non-diagonal, but known. For example, Fig. 1 shows preliminary results for the idealized PNR detector with a system detection efficiency of 90 % and a maximum PNR of 5 photons. Plotted are the mean squared errors (MSEs) of POVMs reconstructed by different algorithms from synthetic data as a function of the number of trials. MSE is calculated for the square part of the POVM matrix corresponding to the input and output number of photons from 0 to 5. Fluctuations in MSE are due to random error resulting from the finite size of a simulated statistical sample. We see a reduction in MSE for an increasing number of simulated trials using synthetic data.

We proceed to the comparison of POVM reconstructions of a commercial detector, specifically a PNR camera pixel, with the a priori unknown POVM. We perform 10000 experimental trials and compute the output statistics for coherent state input with a range of photon fluxes, i.e., in the regime where synthetic data converges well. Fig. 2 shows POVMs obtained from the same experimental data but with different tomographic algorithms. These POVMs are significantly distinct from each other but describe the experimental data with similar estimated accuracy. The exact cause of the inconsistency between the algorithms is currently under investigation.

In this work, we confirm that while various detector tomography algorithms are expected to extract POVM well, the results obtained from commercial detectors significantly diverge and require further analysis. Before this issue is settled, all PNR data from such devices should be used with extreme caution.

[1] S. V. Polyakov et al. J. Mod. Opt. **56**, 1045–1052 (2009)
[2] C.J. Chunnilall, *et al.* Opt. Eng. **53**, 081910 (2014)
[3] M. Barbieri, PRX Q **3**, 010202 (2022)
[4] J. S. Lundeen, *et al.*, Nat. Phys. **5**, 27–30 (2009)
[5] F. Piacentini, *et al.*, Opt. Lett. **40**, 1548–1551 (2015)

Liquid combs: broadband light with equidistance and without stability

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In this talk, we will introduce our results[1] establishing the existence of liquid combs: broadband optical states that retain spectral equidistance even though their phases wander in time. By engineering semiconductor quantum cascade lasers (QCLs) for low dispersion and tailored gain curvature, we observe regimes where intermodal phase differences evolve in unison, so every pair of modes experiences the same instantaneous frequency fluctuations. To verify coherence rigorously in these broad-beatnote states, we develop self-referenced and frequency-resolved variants of SWIFTS[2] that compare correlation spectra to spectrum products across the entire beatnote; their agreement at each radio frequency demonstrates persistent equidistance despite repetition-rate fluctuations.

We realize liquid combs in two chip-scale platforms spanning more than an order of magnitude in frequency: a mid-infrared InGaAs/AlInAs QCL with an integrated double-chirped mirror and a terahertz GaAs/AlGaAs QCL with distributed resonant-loss disks that shape gain curvature. In both devices, the broad-beatnote regime yields highly uniform, significantly wider spectra than FM-comb counterparts (including a mid-IR bandwidth around 123 cm^{-1}) while maintaining high first-order coherence. Frequency-resolved SWIFTS measurements show the correlation spectrum and spectrum product co-track across the beatnote, and extracted phases reveal uniform, nonlinear modal phase evolution that distinguishes liquid combs from incoherent multimode emission.

A mean-field theory for active bidirectional cavities explains liquid-comb formation as a continuation of the FM-comb (extendon) state when dispersion is pushed below its optimum and/or gain curvature increases: intensity becomes time-varying, but spectral equidistance—and thus mutual coherence—survives. This phenomenon arises from the fast component of the optical gain suppressing intensity fluctuations faster than all other timescales[3]. Because liquid combs naturally access wider bandwidths and exhibit uniform phase variations, they enable computational or experimental phase correction for multiheterodyne spectroscopy and open flexible pathways to broadband, structured light sources for sensing, metrology, and communications.

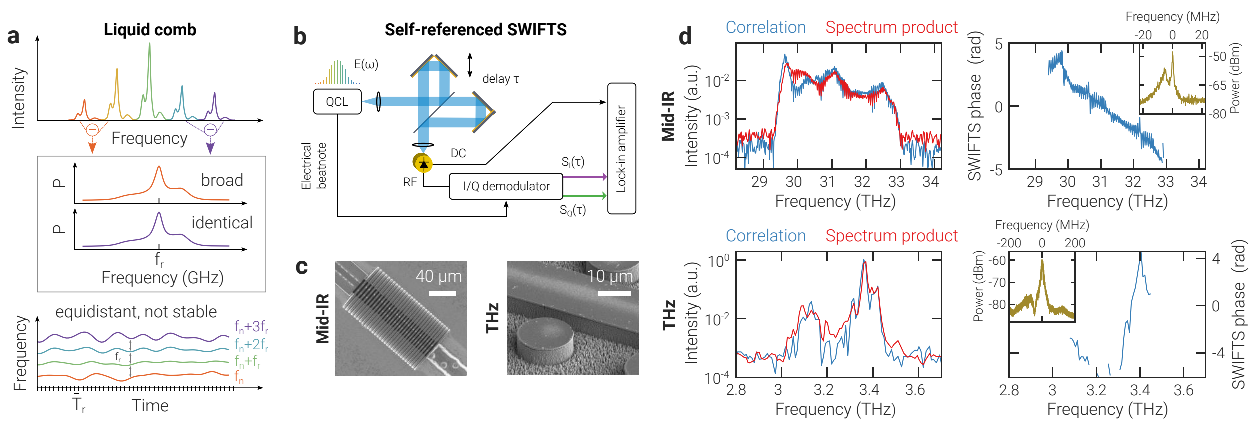

Figure 1. a. Basic concept of a liquid comb, which maintains equidistance and coherence but not stability. b. Schematic of a self-referenced SWIFTS scheme that can partially demonstrate coherence. c. SEMs of lasers used in this work. **b,c.** Bandwidth limits as a function of gain curvature, which is linear in effective gain bandwidth. **d.** Experimental results establishing the coherence and FM nature of these devices, in both the MIR and THz bands.

[1] M. Roy, T. Zeng, Z. Xiao, C. Dong, S. Addamane, Q. Hu, and D. Burghoff, "Liquid combs: broadband light with equidistance and without stability," (2025).
[2] D. Burghoff, Y. Yang, D.J. Hayton, J.-R. Gao, J.L. Reno, and Q. Hu, "Evaluating the coherence and time-domain profile of quantum cascade laser frequency combs," Opt. Express **23**(2), 1190 (2015).
[3] A. Dikopoltsev, I. Heckelmann, M. Bertrand, M. Beck, G. Scalari, O. Zilberberg, and J. Faist, "Collective quench dynamics of active photonic lattices in synthetic dimensions," Nat. Phys. **21**(7), 1134–1140 (2025).

Mitochondria in quantum sensing: Effect of photobleaching and phototoxicity

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In this talk we will cover the issue of quantum sensing in mitochondria, including temperature sensing and "hot mitochondria".

We will present our empirical data on phototoxicity and photobleaching [1] that need to be taken into account to avoid any artifacts in quantum NV sensors of mitochondrial temperature.

[1] Lee, C. H., Wallace, D. C., & Burke, P. J. (2024). Photobleaching and phototoxicity of mitochondria in live cell fluorescent super-resolution microscopy. *Mitochondrial Communications*, *2*, 38-47.

Indirect excitons in heterostructures

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Spatially indirect excitons (IXs), also known as interlayer excitons, are formed by electrons and holes in separated layers in a heterostructure (HS). Due to the layer separation, the IX lifetimes are orders of magnitude longer than lifetimes of spatially direct excitons. The long lifetimes allow IXs to cool below the temperature of quantum degeneracy and form quantum bosonic states. We present recent results in quantum IX systems. In GaAs HS, we present the Mott transition in excitonic Bose polarons [1]. In van der Waals HS, we present the efficient IX transport with anomalously high diffusivity, orders of magnitude higher than diffusivities found in earlier studies of exciton transport in van der Waals heterostructures [2].

The PL and PLE studies were supported by DOE award DE-FG02-07ER46449, the van der Waals HS manufacturing and data analysis were supported by NSF Grants 1905478 and 2516006, the GaAs HS growth was supported by Gordon and Betty Moore Foundation Grant GBMF9615 and NSF Grant DMR 2011750.

[1] E.A. Szwed, B. Vermilyea, D.J. Choksy, Zhiwen Zhou, M.M. Fogler, L.V. Butov, K.W. Baldwin, L.N. Pfeiffer, Mott transition in excitonic Bose polarons, arXiv:2504.07227 (2025).

[2] Zhiwen Zhou, W.J. Brunner, E.A. Szwed, H. Henstridge, L.H. Fowler-Gerace, L.V. Butov, Efficient transport of indirect excitons in a van der Waals heterostructure, arXiv:2507.04556 (2025).

Employing Phonon Polaritons and ENZ Polaritons in Enhanced Thermal Transport

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Abstract

The field of nanophotonics is based on the ability to confine light to sub-diffractional dimensions. In the infrared, this requires compression of the wavelength to length scales well below that of the free-space values. While traditional dielectric materials do not exhibit indices of refraction large enough in non-dispersive media to realize such compression, the implementation of polaritons, quasi-particles comprised of oscillating charges and photons, enable such opportunities. Two predominant forms, the plasmon and phonon polariton have found significant attention in recent years, with the former relying on the coupling of free charge carriers in a conductor, while the latter the polar lattice oscillations of a crystal, with light. Further, employing deeply sub-diffractional thickness films of polaritonic media can also provide the opportunity to realize epsilon near zero (ENZ) polaritons, which offer a highly confined, non-dispersive resonance within a planar film. Gang Chen's original theory work theoretically predicted the potential large benefits of phonon polaritons for enhancing thermal transport at the nanoscale. This concept has been of distinct interest at the intersection of the research fields of nanophotonics and thermal transport ever since, but has experimental validation has been limited. Here, we report on experimental investigations demonstrating that phonon polaritons can significantly enhance thermal conductivity under steady state conditions when they can be launched in sufficient number densities, as well as provide the opportunity for ultrafast thermal transport across hetero-interfaces. In the former, we demonstrate that by coating one end of a 3C-SiC nanowire or boron nitride nanotube with gold, that near-field thermal emission from the gold can efficiently launch phonon polaritons, which provides >20% and >50% enhancements in thermal conductivity at room and cryogenic temperatures, respectively, with contributions from these nanophotonic modes up to ~6-10 W/mK. In the latter work, thermal interactions between gold radiating pads and hyperbolic modes within either a layered hyperbolic metamaterial (HMM) comprised of the plasmonic semiconductor CdO or flakes of isotopically enriched hBN provide the opportunity to direct thermal energy across the gold-HMM interface at picosecond timescales, much faster than thermal dissipation through conductive channels would provide. This effort involves a unique ultrafast pump-probe spectroscopy technique that enables spectral resolution of vibrational modes with sub-picosecond temporal resolution. This technique relies on a frequency-tunable mid-infrared probe pulse, allowing us to directly interface with polaritonic heat carriers, thereby providing a direct assessment of their temporal propagation within nanoscale material systems. Further, it was recently demonstrated that such excitations even allow for ultrafast thermal transport across a solid-state dielectric gap, moving the field of near-field radiative heat transfer away from purely vacuum gap systems. These results provide a new path for novel design of polaritonic devices with far-reaching applications at the intersection of thermal transport and photonics where structure and vibrational selection rules allow for the transduction of thermal energy at speeds faster than diffusion, leveraging this heat flux as a source for photonic communication, novel thermal dissipation strategies for power electronics, as well as overcoming the traditional reductions in thermal conductivity observed at nano- to atomic-scale dimensions.

Abstract for PQE 2026 conference

Title: Laser Systems for Inertial Fusion: Requirements, Challenges and Opportunities

Abstract: The demonstration of ignition and scientific gain greater than one on the National Ignition Facility (NIF) has created significant interest in the development of Inertial Fusion Energy (IFE). The challenging requirements for average power, beam quality, efficiency, and cost for the lasers for commercially viable IFE, the present state of the field and the proposed research program will be presented.

Dr . E Michael Campbell

University of California-San Diego

President, Fusion Power Associates

From Classical to Quantum Metasurfaces for Multiphoton Interferometry

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Multiphoton interference and entanglement are fundamental to quantum information science, but necessary extensions to higher-dimensional systems remain challenging due to imperfections and complexity of scaling conventional optical setups.

Here we demonstrate a generalized Hong-Ou-Mandel effect using metasurfaces and graph theory, enabling controlled multi-photon bunching, antibunching, and entanglement across parallel matrix-encoded spatial modes.[1] Our theoretical framework rigorously predicts the device's behavior and facilitates the design of dual graphs representing both metasurface-based multiport interferometer designs and the complex non-classical correlations they generate. Experimentally, we show that a single-layer metasurface induces strong multiphoton interference simultaneously across multiple Jones matrix–encoded diffraction orders—violating the classical limit and effectively implementing higher-order Hadamard interferometers.

These results highlight the potential of metasurface-based quantum graphs for scalable, low-decoherence quantum information infrastructure.

1. Kerolos M. A. Yousef, Marco D'Alessandro, Matthew Yeh, Neil Sinclair, Marko Loncar Federico Capasso *Science* **389**, 416 (2025)

Dynamic Population Suppression for Two-Photon Excitation

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We present a new quantum control technique to generate two-photon excitation while suppressing single-photon excitation. Our technique employs oscillatory modulated pulses with zero area and out-of-phase fields to enable the intermediate state population's dynamic elimination (DE) [1]. The technique shares features with adiabatic elimination (AE) approaches that work within the limits of large detuning and intense pulses to suppress single-photon excitation. The fundamental difference is that our technique works in resonance and presents remarkable robustness to variations in single-photon detuning Δ with fidelity corrections scaling as Δ^4. Its simplicity, universality, and wide-ranging applicability make it an attractive solution for various fields, including color centers in solids where detuning errors are a limiting factor for sensing applications [2]. Finally, we will discuss other applications of the technique, such as creating perfectly entangling gates in neutral atoms [3].

References

1. Carrasco, S. C., Lourette, S., Sola, I. & Malinovsky, V. S. Dynamically Enhanced Two-Photon Spectroscopy. *Phys. Rev. Lett.* **134,** 163601 (2025).
2. Lourette, S. *et al.* Ramsey interferometry of nuclear spins in diamond using stimulated Raman adiabatic passage. *Quantum Sci. Technol.* **10,** 015032 (2024).
3. Carrasco, S. C., Chathanathil, J., Malinovskaya, S. A., Sola, I. & Malinovsky, V. S. (in preparation).

Classifying topology in nonlinear photonic systems

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Photonic topological insulators exhibit bulk-boundary correspondence, which requires that boundary-localized states appear at the interface formed between topologically distinct insulating materials. However, many topological photonic devices can exhibit nonlinearities, which raises a subtle but critical problem as these are generally local, prohibiting the application of topological band theory to classify the resulting system. Here, we use a local theory of topological materials to resolve bulk-boundary correspondence in heterostructures containing nonlinear materials. In particular, we construct the heterostructure's spectral localizer, a composite operator based on the system's real-space description that provides a local marker for the system's topology and a corresponding local measure of its topological protection; both quantities are independent of the material's bulk band gap (or lack thereof). Using this framework, we demonstrate how to classify the topology of solitons, as well as show how nonlinearities can enable reconfigurable topological routing in exciton-polariton lattices.

Acknowledgement: SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Extreme-Value Statistics of Soliton Dynamics: Validating Model for Robust Inertial-Confinement Fusion Design

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Extreme events [1,2], defined by both rarity and high impact, are inherently difficult to characterize, as their low occurrence rates limit conventional statistical analysis and hinder robust predictive modeling. Developing controlled laboratory platforms capable of generating such events with tailored statistical properties is therefore important for advancing extreme-event science and for improving the reliability of high-power laser systems, including those used in inertial-confinement fusion (ICF). Here, we demonstrate that ultrafast nonlinear fiber optics provides an effective framework for this purpose. By employing ultrashort pulses undergoing soliton transformations in highly nonlinear fibers, we realize a compact system with finely tunable parameters capable of producing extreme optical events at megahertz rates.

By adjusting the input-pulse and fiber parameters, we access a regime in which extreme soliton peak-power outputs occur only a few times across several million readouts. In this regime, we verify that peak-power fluctuations of spectrally shifted solitons form an independent and identically distributed (i.i.d.) sequence, permitting application of classical extreme-value theory [3,4], which states that any sample of i.i.d. variables must converge in its extreme-value statistics to one of three possible distributions: Gumbel, Fréchet, or Weibull. Under these conditions, the soliton extremes closely follow the Gumbel distribution, with small but statistically significant deviations indicating an increased likelihood of rare, high-intensity events driven by nonlinear soliton dynamics.

These results establish a high-rate, fiber-based testbed for controlled generation and benchmarking of extreme events. The platform enables systematic studies of rare-event dynamics and provides a route toward high-resolution metrology of optical fluctuations. Future extensions to broader laser statistical sources, such as optical amplifiers, will allow controlled noise engineering and improved modeling of extreme-event risks in high-power laser systems, including those used in ICF.

References

[1] S. Coles, *An introduction to statistical modeling of extreme events* (Springer, Berlin, 2001).
[2] M. R. Leadbetter, G. Lindgren, H. Rootzén, *Extremes and Related Properties of Random Sequences and Processes* (Springer, New York, 1983).
[3] A. M. Zheltikov, A. V. Sokolov, Z. Yi, G. S. Agarwal, J. G. Eden, and M. O. Scully, "Beam instability of broadband stochastic laser fields," *Applied Physics B* **130**, 191 (2024).
[4] A. M. Zheltikov, "Extreme-value statistics in nonlinear optics," *Optics Letters* **49**, 2665–2668 (2024).

Semiconductor lasers for conventional and quantum applications

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ABSTRACT

This talk will give an overview of the state-of-the-art with semiconductor lasers. Semiconductor lasers are important in our daily lives. They are present in phones, cars, CD/DVD players, printers, … Billions are in use today and millions have to be manufactured and improved yearly to satisfy demands.

While fabrication and engineering of semiconductor lasers are complicated, the underlying physics is concise. This talk will also show that much of the behaviors may be understood (and importantly predicted) from $\wp \cdot E$, $e^2/4\pi\varepsilon_0 r$ and $\{c_k, c_{k'}^\dagger\}$. Also discussed are the differences between AMO laser physics and semiconductor laser physics.

Quantum computation of molecular geometry via many-body nuclear spin echoes

Rodrigo G. Cortiñas
Google Quantum AI

Quantum-information-inspired experiments in nuclear magnetic resonance spectroscopy may yield a pathway towards determining molecular structure and properties that are otherwise challenging to learn. We measure out-of-time-ordered correlators (OTOCs) on two organic molecules suspended in a nematic liquid crystal, and investigate the utility of this data in performing structural learning tasks. We use OTOC measurements to augment molecular dynamics models, and to correct for known approximations in the underlying force fields. We demonstrate the utility of OTOCs in these models by estimating the mean ortho-meta H-H distance of toluene and the mean dihedral angle of 3-5-dimethylbiphenyl, achieving similar accuracy and precision to independent spectroscopic measurements of both quantities. To ameliorate the apparent exponential classical cost of interpreting the above OTOC data, we simulate the molecular OTOCs on a Willow superconducting quantum processor, using AlphaEvolve-optimized quantum circuits and arbitrary-angle fermionic simulation gates. We implement novel zero-noise extrapolation techniques based on the Pauli pathing model of operator dynamics, to repeat the learning experiments with root-meansquare error 0.05 over all circuits used. Our work highlights a computational protocol to interpret many-body echoes from nuclear magnetic systems using low resource quantum computation.

Physics and applications of femtosecond higher-order Bessel beam interaction with dielectrics

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Abstract: Femtosecond nondiffracting beams, tightly focused inside dielectrics, bring exciting new opportunities to generate high energy density matter over significant distances. Particle-In-Cell simulations and experiments reveal the underlying mechanisms. We demonstrate a novel regime of single-shot extrusion of matter with tubular ultrafast pulses with radial polarization.

Non-diffracting Bessel beams can be usefully exploited to generate high-aspect ratio nano-voids inside glass or in deep inside sapphire. However, the sequence leading to void formation with Bessel beams remained hitherto unclear. A key aspect is the energy density effectively deposited during laser-matter interaction, into the laser-generated nano-plasma. Conventional modeling of the Bessel-beam interaction within dielectrics are unable to fit with experimental diagnostics. We have recently developed a Particle-In-Cell model that successfully overcomes these limitations [1]. This reveals that resonance absorption is one of the key physical phenomena that lead to exceptionally high energy density , which reaches MJ/cm^3, well in the HED regime [2]. It is possible to create this high energy density regime over length of several cm using only tabletop femtosecond lasers. This opens new avenues for developing high-energy-density physics within solids.

The extreme localization has been further exploited using radially-polarized first-order Bessel beams. They generate empty cylindrical plasmas (Fig. 1[left]). Figure 1 (right) shows the result of the single-shot interaction with sapphire exit surface: a vertically standing, high aspect ratio, nano-pillar has emerged from the sapphire sample. We have confirmed the different regimes of the process of laser-induced extrusion using Transmission Electron Microscopy, demonstrating that the nano-pillar is a mono-crystal that has not undergone any phase change.

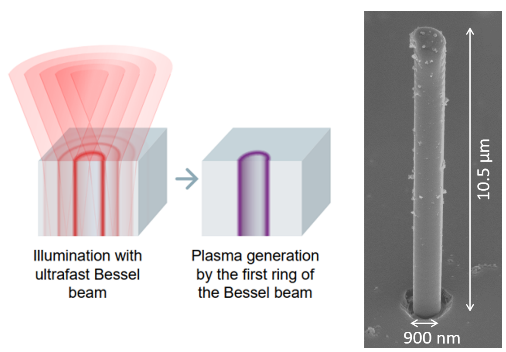

Fig. 1. (left) Cylindrical plasma formation concept. (right) Scanning Electron Microscopy image of a nano-pillar generated via laser-induced extrusion [3].

References

1. P. Charpin, K. Ardaneh, B. Morel, R. Giust, F. Courvoisier, ”Simulation of laser-induced ionization in wide bandgap solid dielectrics with a particle-in-cell code,” Opt. Express **32**, 10175-10189 (2024).
2. K. Ardaneh, R. Meyer, M. Hassan, R. Giust, B. Morel, A. Couairon, G. Bonnaud, F. Courvoisier, ”Femtosecond laser-induced sub-wavelength plasma inside dielectrics: I. Field enhancement,” Phys. Plasma **29**, 072715 (2022).
3. V. V. Belloni, M. Hassan, L. Furfaro, R. Giust, A.-M. Seydoux-Guillaume, S. Sao-Joao, F. Courvoisier, ”Single Shot Generation of High-Aspect-Ratio Nano-Rods from Sapphire by Ultrafast First Order Bessel Beam,” Laser Photonics Rev. **18**, 2300687 (2024).

Speaker: Jake Covey, *University of Illinois Urbana-Champaign*
Session: Atomic Arrays II
Schedule: Tuesday evening invited session

Title: Distributed quantum science with neutral atom arrays

Abstract: The realization of fast and high-fidelity entanglement between separated arrays of neutral atoms would enable a host of new opportunities in quantum communication, distributed quantum sensing, and modular quantum computation. In this talk, I will describe two approaches we are pursuing to generate fast and high-fidelity remote entanglement. In the first approach, we have demonstrated a photonic interconnect based on high-fidelity entanglement of the metastable nuclear spin-1/2 qubit in ytterbium-171 and a telecom-band photon with time-bin encoding. We have realized an atom-photon Bell state fidelity of 0.95 when correcting for atomic measurement errors. As an extension of this work, I will describe a second system based on ytterbium-171 atom arrays in a near-concentric optical cavity. We anticipate the ability to generate atom-atom Bell pairs with fidelity approaching 0.99 and rate of 10^4 ebits/sec using this telecom photonic interface. In the second approach, I will introduce a novel technique for transporting large tweezer arrays over 200 mm within a single vacuum chamber via a microscope objective mounted on an air-bearing linear motion stage. I will describe our vision for modular quantum computation based on an array of atom arrays.

Probing the Real and Imaginary Dielectric Response of the Electric Double Layer using Surface Plasmon Resonance Nanostructures

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Abstract

We will present a new approach for studying the electrochemical double layer (EDL) at electrode/electrolyte interfaces that exploits the surface sensitivity of the plasmon resonance phenomenon. Here, we use surface plasmon resonant (SPR) metal gratings to probe the local response of ionic liquids (IL) and aqueous electrolytes at electrode interfaces. This is observed as a shift in the resonant angle of the grating (i.e., $\Delta\phi$) that can be related to the change in the local index of refraction of the electrolyte (i.e., Δn_{local}). This highly sensitive method provides a minimum resolution of $\Delta n = 0.001$ and a time resolution in the range of 1-2 μsec. The electrostatic accumulation of ions in solution induces local index changes to the gratings over the extent of the electrical double layer (EDL) thickness. We use finite difference time domain (FDTD) simulations to relate the observed shifts in the plasmon resonance ($\Delta\phi$) and change in reflection (ΔR) to the change in the local index of refraction (Δn_{local}) of the electrolyte and the thickness of the EDL (Δh). Simultaneously using the wavelength and intensity shift of the resonance enables us to determine both the effective thickness (Δh) and Δn of the double layer. We believe this technique can be applied more broadly, enabling the dynamics related to potential-induced ordering and rearrangement of ionic species at electrode-solution interfaces to be distinguished from the bulk solution response. This technique allows us to investigate the unusual effect of dielectric screening (i.e., Debye screening) observed at high ion concentrations, a subject of recent debate. By observing voltage-induced changes in the SPR, we can directly examine the dielectric screening capability of the electrochemical double layer. Contrary to standard Debye-Hickel theory, we see a dramatic drop in the double layer's ability to screen charge at high ion concentrations.

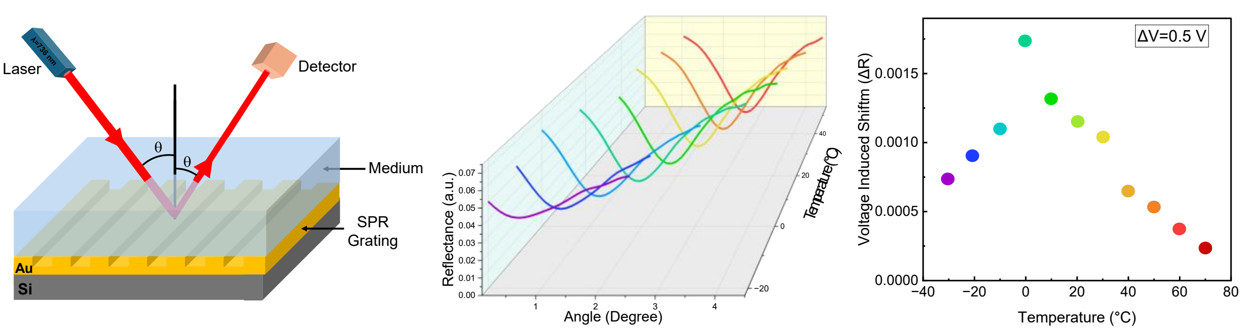

Figure: (a) Schematic diagram of the angle-dependent photoreflectance measurement setup on a corrugated grating structure. (b) Reflectance vs. angle spectra taken at various temperatures and (c) voltage-induced shift in the plasmon resonance plotted as a function of temperature using ionic liquid [EMIM][TFSI].

Correlation imaging, from 3D to hyperspectral

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Plenoptic or lightfiled imaging is a recently developed imaging modality enabling both to modify the focused plane of acquired images, in post-processing, and to perform scanning-free 3D imaging. The key is to retrieve both spatial and directional information about light from the scene of interest.

In conventional lightifield cameras, the effective potential of the technique is intrinsically limited by the strong trade-off between plenoptic capabilities (DOF extension and 3D imaging) and image resolution; this is issue is typically addressed with signal processing and AI. Still, the fast 3D imaging capability is attracting increasing attention.

We have proposed and developed a novel approach to plenoptic imaging, named correlation plenoptic imaging (CPI) [1,2], which enables addressing the intrinsic resolution versus depth of field (DOF) trade-off by exploiting the peculiar spatio-temporal correlations of both chaotic light and entangled photons.

In this talk, we will present the main experimental achievements in CPI: from the first proof-of-principle demonstration of its diffraction-limited plenoptic imaging capability, to the implementation in the realm of microscopy, where diffraction-limited resolution has been combined with a 6x DOF improvement.

We shall also present recent advances in correlation imaging modalities which are expected to enable scanning-free high-resolution hyperspectral imaging [3], 3D imaging and microscopy [3-6], as well as tracking of moving samples; we demonstrate an advantage by at least one order of magnitude over typical tradeoffs such as resolution versus DOF, in 3D imaging, and spatial versus spectral resolution, in hyperspectral imaging. Both entangled light beams and chaotic light are employed, depending on the specific application scenario.

Speed-up enabled by both SPAD arrays and AI denoising approaches shall also be presented, demonstrating the effective capability of the presented approaches to effectively compete with state of the art devices, while overcoming their intrinsic limitations.

References

[1] F.V. Pepe, F. Di Lena, A. Mazzilli, G. Scarcelli, M. D'Angelo, Diffraction-Limited Plenoptic Imaging with Correlated Light, Physical Review Letters 119, 243602 (2017)
[2] M. D'Angelo, F.V. Pepe, A. Garuccio, G. Scarcelli, Correlation Plenoptic Imaging, Physical Review Letters 116, 223602 (2016)
[3] G. Masssaro, F.V. Pepe, M. D’Angelo, Correlation Hyperspectral Imaging, Physical Review Letters (2024)
[4] Massaro, G., Mos, P., Vasiukov, S. et al. Correlated-photon imaging at 10 volumetric images per second, Scientific Reports 13, 12813 (2023)
[5] C. Abbattista,…, M. D’Angelo. Toward quantum 3D imaging devices. Applied Sciences 11, 6414 (2021)
[6] G. Massaro, D. Giannella, A. Scagliola, F.V. Pepe, M. D’Angelo, Light-field microscopy with correlated beams for high-resolution volumetric imaging. Scientific Reports 12, 16823 (2022)

Imaging the quantum state of biphotons

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High-dimensional biphoton states are promising resources for quantum applications, ranging from high-dimensional quantum communication to quantum imaging. A key challenge is fully characterizing these states, which is typically time-consuming and not scalable when using projective measurement approaches. Fortunately, advancements in camera technology allow for recording photons' position and time of arrival with nanosecond resolution, enabling new techniques for reconstructing strongly correlated two-photon states [1,2]. This innovation significantly enhances both the efficiency and accuracy of quantum state tomography. We demonstrate the bi-photon phase retrieval using interferometric [1] and non-interferometric [2] strategies. The latter approach is adopted for two-photon states generated via spontaneous parametric down-conversion, where the spatial-correlation structure allows for a simplified description of free-space propagation and, thus, the use of phase-reconstruction techniques based on diffraction measurements. This scheme applies to the diffraction of a bi-photon state through a sample, allowing us to characterize the sample itself. We demonstrate that when a phase object is placed in the image plane of the source, diffraction through the sample can be extracted from the correlations between the two entangled photons. Moreover, by applying phase-retrieval algorithms, we achieve a twofold enhancement in phase reconstruction due to the two-photon nature of the source [3].

We will also review recent results of imaging studies where the separability in sum and difference coordinates of biphoton states is lost, due to walk-off effects in the crystal, and scattering through random and ordered media.

References

1. D. Zia, N. Dehghan, A. D'Errico, F. Sciarrino, E. Karimi, "Interferometric imaging of amplitude and phase of spatial biphoton states," Nature Photonics 17, 1009-1016 (2023).
2. N. Dehghan, A. D'Errico, F. Di Colandrea, and E. Karimi, "Biphoton state reconstruction via phase retrieval methods," Optica 11, 1115-1123 (2024).
3. N. Dehghan, A. D'Errico, Y. Zhang and E. Karimi, "Diffraction of correlated biphotons through transparent samples," arXiv preprint arXiv:2410.22635 (2024).

Complex bands and topology with coupled lasers

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Complex coupling in periodic laser arrays leads to complex bands, where the real part corresponds to the dispersion relation of the band w(k) and the imaginary part corresponds to k-dependent loss. By precisely tuning the complex coupling and the array geometry we engineer the complex bands to generate unique topological lasing states. We demonstrate how lasing at Dirac points in a hexagonal laser lattice can lead to Klein tunneling of coherence through a barrier, how complex Hermitian coupling can generate artificial gauge fields and edge states. Finally, we characterize the effects of quenches disorder and hints to KT Physic in coupled laser arrays.

Spin squeezing in an ensemble of nitrogen-vacancy centers in diamond

Spin squeezed states provide a seminal example of how the structure of quantum mechanical correlations can be controlled to produce metrologically useful entanglement. Such squeezed states have been demonstrated in a wide variety of artificial quantum systems ranging from atoms in optical cavities to trapped ion crystals. By contrast, despite their numerous advantages as practical sensors, spin ensembles in solid-state materials have yet to be controlled with sufficient precision to generate targeted entanglement such as spin squeezing. In this work, we present the first experimental demonstration of spin squeezing in a solid-state spin system. Our experiments are performed on a strongly-interacting ensemble of nitrogen-vacancy (NV) color centers in diamond at room temperature and squeezing (-0.5 pm 0.1 dB) is generated by the native magnetic dipole-dipole interaction between NVs. In order to generate and detect squeezing in a solid-state spin system, we overcome a number of key challenges of broad experimental and theoretical interest. First, we develop a novel approach, using interaction-enabled noise spectroscopy, to characterize the quantum projection noise in our system without directly resolving the spin probability distribution. Second, noting that the random positioning of spin defects severely limits the generation of spin squeezing, we implement a pair of strategies aimed at isolating the dynamics of a relatively ordered sub-ensemble of NV centers. Our results open the door to entanglement-enhanced metrology using macroscopic ensembles of optically-active spins in solids.

Sensing Gravitational Waves and Dark Matter with Superfluid Helium

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Motivated by the experiments of DeLorenzo and Schwab [1], along with theoretical predictions for coupling of acoustic resonators to dark matter [2], we have embarked on an effort to build small-scale detectors of gravitational waves and ultra-light dark matter using superfluid helium resonators [3-4]. The core idea is to build a Weber bar, which resonantly enhances the strain signal from these sources, but with the added feature that at low-temperatures helium remains a liquid, enabling tuning of the acoustic resonance frequency. Coupled with the vanishing acoustic losses in the superfluid state of helium [1], this makes superfluid helium resonators the ideal acoustic detectors. Readout is performed using modern cavity electromechanics, furthering the toolbox of advanced techniques to measure and control these acoustic detectors.

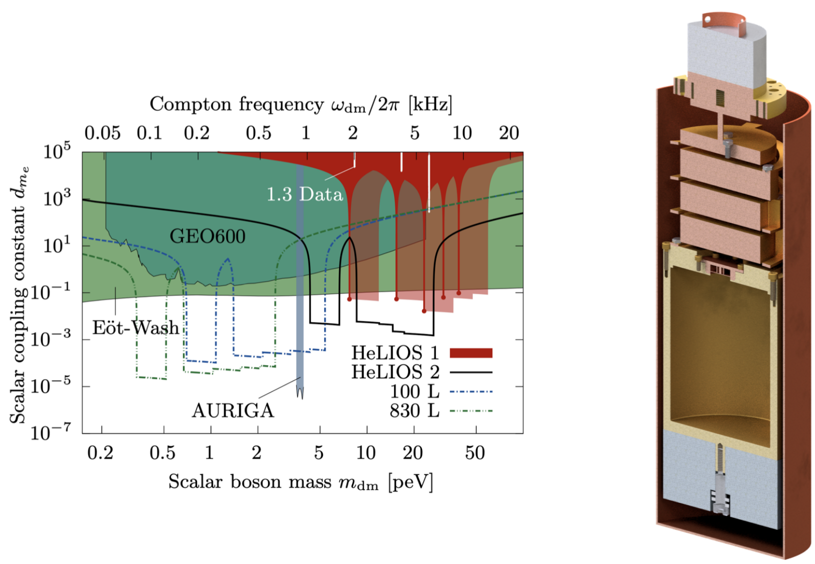

FIGURE 1. (a) Preliminary data from the HeLIOS 1.3 detector, along with projections for HeLIOS 2.0 and beyond, for coupling to scalar dark matter. (b) Cross-section of the HeLIOS 2.0 detector, composed of 0.9 liters of helium, with improved scalar and vector dark matter coupling.

[1] L.A. De Lorenzo and K.C. Schwab, Ultra-high Q acoustic resonance in superfluid ^{4}He, J. Low Temp. Phys. 186, 233 (2017).
[2] J. Manley, D.J. Wilson, R. Stump, D. Grin, and S. Singh, Searching for scalar dark matter with compact mechanical resonators, Phys. Rev. Lett. 124, 151301 (2020).
[3] Prototype superfluid gravitational wave detector, V. Vadakkumbatt, M. Hirschel, J. Manley, T.J. Clark S. Singh and J.P. Davis, Phys. Rev. D 104, 082001 (2021).
[4] HeLIOS: The superfluid helium ultralight dark matter detector, M. Hirschel, V. Vadakkumbatt, N.P. Baker, F.M. Schweizer, J.C. Sankey, S. Singh and J.P. Davis, Phys. Rev. D 109, 095011 (2024).

Sub-100 MHz accurate ^{229}Th nuclear clock frequencies in solid-state and trapped ion platforms

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The low-energy isomer transition in ^{229}Th underpins a new class of optical frequency standards—nuclear clocks—that promise exceptional stability and sensitivity to beyond-standard-model physics. While this transition has now been driven with lasers in several solid-state hosts, the nuclear "tick" is not a universal constant of nature: its observed frequency depends on the electronic environment of the ^{229}Th nucleus. We quantify these host-dependent frequency offsets by computing the isomer (chemical) shift arising from the change in nuclear charge distribution between the ground and isomeric states [1].

We combine relativistic many-body atomic structure calculations for Th ions with periodic density-functional theory (DFT) for Th-doped and Th-containing crystals. A key theoretical finding is that the dominant contribution to the isomer shift in solids comes not from the naive contact density at the nucleus but from electronic "relaxation" of the deeply bound core orbitals, which then modifies the effective potential seen by $l \neq 0$ valence band orbitals centered on Th. We show how this relaxation can be captured by expressing the valence-band isomer shift as a linear combination of Th^{3+} orbital isomer shifts, weighted by Th-projected integrated partial densities of states obtained from solid-state DFT calculations.

Taking the high-precision measurement of the nuclear clock transition frequency in $^{229}Th:CaF_2$ as a reference [C. Zhang et al., Nature 633, 63 (2024)], we use our method to relate this solid-state result to other platforms:

$$\begin{aligned} \omega_{\text{clk}}\,(\text{solid state}) &= 2{,}020{,}407{,}384(40)\ \text{MHz}, \\ \omega_{\text{clk}}(\text{Th}^{4+}) &= 2{,}020{,}407{,}648(70)\ \text{MHz}, \\ \omega_{\text{clk}}(\text{Th}^{3+}) &= 2{,}020{,}407{,}114(70)\ \text{MHz}, \end{aligned}$$

and infer a bare nuclear transition energy of $\omega_{\text{nuc}} = 8.272(22)$ eV. For a broad set of high-bandgap hosts we find valence-band isomer shifts at the ∼−250 MHz level with a spread of order 60–80 MHz across realistic doping sites and materials. This defines a practical ∼80 MHz search window for high-resolution VUV spectroscopy of solid-state nuclear-clock candidates and provides a quantitative bridge between solid-state and trapped-ion ^{229}Th nuclear clocks.

Reference:

1. U. C. Perera, H. W. T. Morgan, E. R. Hudson, and A. Derevianko, Host-Dependent Frequency Offsets in ^{229}Th Nuclear Clockwork, Phys. Rev. Lett. **135**, 123001 (2025).

Quantum Ocean: Resetting Ocean Science with Applications of Quantum Sensors, Materials, Networks

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Advancements in quantum technology, sensing, and computation have the potential to provide observational solutions of the subsurface ocean with unprecedented accuracy and precision, which will advance understanding, innovation, and lead to improved prediction of the natural world. Identifying, developing, and applying those quantum sensors and measurement techniques to improve the accuracy and precision of EOV's, underwater imaging, navigation, and communication is the key to usher in a new era of quantum ocean observing systems that can improve predictions of long- (climate) and short-term (weather) processes that will benefit human society by improving resiliency, sustainability, and well-being. We report on our recent activities to develop ocean specific techniques for in situ measurement of temperature, salinity, specific density, and other essential ocean variables of salt water. These techniques include the potential application of *NV nanodiamonds* (integrated into fiber-optic probes), *Raman spectroscopy* (through *SERS*), *Brillouin spectroscopy* to measure temperature, salinity, and pressure and dissolved gases (e.g. oxygen) and dissolved organic materials (particularly photosynthetically active materials). Additional techniques considered include *Quantum Imaging with Undetected Photons (QIUP)* and *Quantum Ghost Imaging (QGI),* which can allow the integration with single-molecule (SM) fluorescence microscopy to achieve high-resolution tracking of materials, e.g. on the ocean floor and interior, and *Bose-Einstein condensates* for deep-sea navigational applications (where traditional GPS is not possible).

Liquid Light Dynamics in Synthetic Dimensions: a New Class of Frequency Combs

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The dynamics of light in the frequency domain underpin many advances in metrology and communications. Among the most remarkable states is the optical frequency comb—broadband light with equally spaced frequencies that can be viewed as a lattice in a synthetic frequency dimension. Various coupling schemes have been proposed to engineer such lattices [1], but most remain linear and lack self-sustaining mechanisms for steady-state operation.

Recent progress in semiconductor-based combs has revealed a qualitatively new regime: when the gain recovery becomes the fastest timescale [2], light dynamics change radically [3–6]. The optical field behaves as a *liquid*, where fast gain saturation enforces coherence and suppresses fluctuations [7,8]. I will discuss how this "liquid light" enables exploration of the full synthetic frequency lattice, realizing coherent states inaccessible to linear systems. This approach points toward a new class of frequency combs—self-organized, robust, and dynamically controllable—rooted in the hydrodynamics of light itself [8].

References

[1] Yu, Danying, et al. "Comprehensive review on developments of synthetic dimensions." Photonics Insights 4.2 (2025).
[2] U. Senica, A. Dikopoltsev, et al., "Frequency-Modulated Combs via Field-Enhancing Tapered Waveguides", Laser Photonics Rev, 2300472 (2023).
[3] J. B. Khurgin, et al. "Coherent frequency combs produced by self frequency modulation in quantum cascade lasers." APL 104.8 (2014).
[4] N. Opačak, et al., "Theory of frequency-modulated combs in lasers with spatial hole burning, dispersion, and Kerr nonlinearity" Phys. Rev. Lett. 123, 243902 (2019).
[5] D. Burghoff, "Unravelling the origin of frequency modulated combs using active cavity mean-field theory." Optica 7.12 (2020): 1781-1787.
[6] M. Piccardo, et al. "Frequency combs induced by phase turbulence." Nature 582.7812 (2020): 360-364.
[7] A. Dikopoltsev, et al. "Collective quench dynamics of active photonic lattices in synthetic dimensions." Nature Physics (2025): 1-7.
[8] I. Heckelmann*, M. Bertrand*, A. Dikopoltsev*, et al., "Quantum walk comb in a fast gain laser", Science 382, 434-438 (2023).

Quantum States in Thermodynamical Non-equilibrium Unveiled by Coherent Raman

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Abstract: For more than a half century, Coherent Anti-Stokes Raman Scattering (CARS) has been successfully used to measure the temperature in gases in plasmas by identifying the Maxwell-Boltzmann distribution of the vibrational and rotational modes of the constituent molecules. Hybrid fs/ps CARS [1] allows for probing rovibrational population distributions and inferring the vibrational and rotational temperatures in a single laser shot. This capability offers not only identification of thermodynamic non-equilibrium in the system, but it also enables monitoring the dynamics of the of vibrational and rotational temperature with high temporal resolution. Figs. 1 (a) and (b) show an example of thermodynamic non-equilibrium between the rotational and vibrational states manifested in fs/ps CARS spectra acquired in a plasma discharge. Under highly non-equilibrium conditions, typical of hypersonic flows, low temperature plasmas, or laser filaments, an overpopulation of the higher vibrationally excited levels can occur, such that the non-equilibrium takes places not only between the rotational (and hence translational) and vibrational modes, but also between the vibrational modes which no longer follow a Maxwell-Boltzmann distribution. As an example, Fig. 1 (c) and (d) show a rotational CARS spectrum measured in the boundary layer (c) and a vibrational spectrum measured behind a normal shock (d) in a Mach 6 hypersonic flow [2] which cannot be fitted using single Boltzmann-based distribution. We are also reporting significant non-equilibrium non-Boltzmann distribution in nanosecond plasma discharges and in laser induced filaments [3]. In such cases, we can no longer assign a classical thermodynamics-based temperature, and the gas properties are more accurately captured by the distribution of its quantized energy levels. Since the temperature cannot be defined unambiguously, the non-equilibrium condition is better characterized by the population distribution instead of temperature.

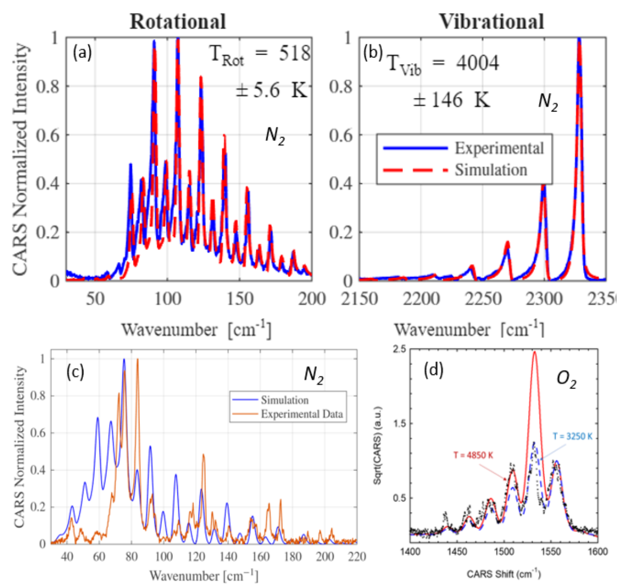

Fig. 1: CARS spectra showing (a) rotational and (b) vibrational temperatures in non-equilibrium plasmas, and non-Boltzmann energy distributions in (c) rotational and (d) vibrational measurements in hypersonic flows.

[1] D. Pestov et al, “Optimizing the Laser Pulse Configuration for Coherent Raman Spectroscopy,” Science 316, 265 (2007).
[2] J. J. Anaya et al, “Interferometry Analysis and CARS Measurements of Nonequilibrium in Hypersonic Oxygen/Argon and pure Oxygen Flows,” Exp. Fluids 65, 64 (2024).
[3] R. Rosser et al, “Non-equilibrium temperature dynamics in a femtosecond filament using Hybrid Coherent Anti-Stokes Raman Scattering,” Opt. Lett. 50, 6638 (2025).

High precision spectroscopy with metasurfaces

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Abstract

We will present the metasurfaces as a platform for optical spectroscopy. Relying on the local orientation of nanostructures, Pancharatnam–Berry (PB) metasurfaces are currently enabling a new generation of polarization sensitive optical devices. A systematical mesoscopic description of topological metasurfaces is developed, providing a deeper understanding of the physical mechanisms leading to the polarization-dependent breaking of translational symmetry in contrast with propagation phase effects. Our theoretical model, which allows clear understanding of PB phase is proven in an experimental measurement involving Mach-Zehnder interferometric setup. We next demonstrate that the reconstruction of a multidimensional nonlinear polarization response of a nanomaterial can be achieved in a single heterodyne measurement by active manipulation of the polarization states of incident light. Using multidimensional spectroscopy, we show the possibility to track both stationary and transient delocalized charge distributions via detecting plasmonic populations and coherences. We further present a strategy for generating arbitrary polarization in the broadband regime, relying solely on the PB phase. The orientation of the metamolecules provides a new degree of freedom to control both the amplitude and phase of right- and left-circular polarization components. We experimentally demonstrated that the polarization of the scattered light can cover the entire Poincare sphere by merely tuning the metamolecule orientation. Finally, we explore the absorption spectra of a metasurface coupled to a quantum phonon bath using the time dependent variational principle and the flexible multi D2 Davydov trial states. In the strong coupling regime, it significantly influences dissipation dynamics. Additionally, a phonon bath with a selected number of strongly coupled modes near the phonon center line substantially narrows the absorption spectrum linewidth by controlling dissipation through a few phonon channels.

References

1. Z. Gao, S. Golla, R. Sawant, V. Osipov, G. Briere, S. Vezian, B. Damilano, P. Genevet, and K. E. Dorfman, Nanophotonics 9, 4711 (2020).
2. Z. Gao, P. Genevet, Guixin Li, and K. E. Dorfman, Phys. Rev. B 104, 054303 (2021).
3. Z. Gao, Z. Su, Q. Song, P. Genevet, and K.E. Dorfman, Nanophotonics 12, 569–577 (2022).
4. Z. Gao, W. Zhao, X. Gao, A. Chen, W. Ye, Q. Song, P. Genevet, and K.E. Dorfman, Nanoletters 25, 5565 (2025).
5. Z. Jiang, K. Sun, Y. Zhao, and K.E. Dorfman, Nanophotonics 14, 2345 (2025).

Quantum-Enhanced Nonlinearities for Scalable All-Optical Neural Networks

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All-optical neural networks (AONNs) promise a revolutionary shift in artificial intelligence hardware by exploiting the wave nature of light for ultrafast speed and massive intrinsic parallelism. However, achieving true scalability for deep networks has been fundamentally limited by the high power requirements of conventional optical components used to implement the essential nonlinear activation functions. We present an ultralow-power scheme for engineering nonlinear activation based on a three-level Λ-type quantum system realized in a thermal rubidium (Rb) vapor cell [1]. By leveraging controlled quantum interference between dual, comparable-intensity laser fields, we gain precise control over the medium's nonlinear response. This approach yields a two-channel, Multi-Input Multi-Output (MIMO) nonlinear activation unit that exhibits both self- and cross-nonlinearities—a significant advancement over single-channel designs. We theoretically model and experimentally demonstrate a system that supports tunable activation behaviors, including Sigmoid and Rectified Linear Unit (ReLU) functions. The system operates at an unprecedentedly low power threshold, achieving an operational power consumption of just 17 μW per neuron. These performance metrics confirm the technical feasibility of scaling to deep AONNs with millions of optical neurons, requiring less than 20 W of total optical power. Finally, we demonstrate the all-optical measurement of gradient-like signals using a backward-propagating beam, a critical capability that paves the way for the realization of fully all-optical training and backpropagation within deep photonic computing architectures. This work establishes a scalable, energy-efficient, and dynamically reconfigurable quantum-optical platform for the next generation of AI hardware.

[1] Ruben Canora, Xinzhe Xu, Ziqi Niu, Hadiseh Alaeian, and Shengwang Du, "Engineering nonlinear activation functions for all-optical neural networks via quantum interference," Opt. Express **33**, 52458 (2025)

A BRIEF OVERVIEW OF THE DISCOVERY, CRITICAL PARAMETERS, AND SCALING OF THE RARE-GAS HALIDE EXCIMER LASERS

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ABSTRACT

Lasing from a rare gas-halide molecule (XeBr) was first reported by the Naval Research Laboratory in the Spring of 1975. Shortly thereafter, the KrF (248 nm), XeCl (308 nm), KrCl (222 nm), XeF (351,353 nm) and ArF (193 nm) lasers were also discovered. In the following decade, scaling of the XeCl and KrF pulse energies to ~5 kJ and 1-3 μs pulse widths was demonstrated. Since the mid-1980s, emphasis has been placed on laser spectroscopic probing of the optical and kinetic (collisional) processes most responsible for laser performance. This talk will describe several highlights of the past 50 years in the scientific and engineering development of this family of ultraviolet lasers that has become a leading contender in the race to develop an optical driver for laser fusion energy (LFE).

Single-shot Mössbauer spectroscopy at X-ray free-electron lasers

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Mössbauer spectroscopy is widely used to study structure and dynamics of matter with a remarkably high energy resolution, provided by the narrow resonance line widths. However, theory and experiment so far are focused on the linear low-excitation regime with on average less than one resonant exciting photon per incident X-ray pulse, owing to a restriction of the experimentally available resonant photon flux.

This situation has changed with the availability of X-ray free electron lasers, which may provide a large number of photons within the nuclear linewidth - either on average, or per pulse. A first experiment demonstrated superradiance with up to 70 signal photons per X-ray pulse [1]. Further progress towards the high-excitation regime recently became possible with high-repetition-rate self-seeded hard X-ray free electron lasers, and is expected to open up several qualitatively new lines of research with Mössbauer nuclei. One of them is the exploration of ultra-narrow Mössbauer resonances, which has already been realized with the recent direct resonant X-ray excitation of the Mössbauer clock transition in ^{45}Sc [2], and which is based on the high average number of resonant photons.

In a parallel development, the ^{57}Fe EuXFEL collaboration (led by R. Röhlsberger and J. Evers) has established nuclear resonance scattering on ^{57}Fe in a series of experiments at the European X-ray free electron laser Germany. In these experiments, up to several hundreds of signal photons were observed following a single x-ray excitation.

In this talk, I will discuss single-shot Mössbauer spectroscopy as a second application of NRS at XFELs, which relies on the high number of resonant photons per pulse in order to alleviate the need for time averaging [3]. I will introduce our approach, which uses machine learning techniques to also including repetitions with lower signal photon number into the single-shot analysis. Then, I will demonstrate its feasibility using data from a recent experiment at European XFEL.

[1] A. I. Chumakov *et al.*, *Superradiance of an ensemble of nuclei excited by a free electron laser*, Nature Physics **14** (2018) 261.

[2] Y. Shvyd'ko *et al.*, *Resonant x-ray excitation of the nuclear clock isomer ^{45}Sc*, Nature 622 (2023) 471.

[3] M. Gerharz *et. al*, *Single-shot sorting of Mössbauer time-domain data at X-ray free electron lasers*, arXiv:2509.15833 [quant-ph].

Probing attosecond chiral multi-electron dynamics via enantio-sensitive interferometry

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Probing chiral-specific electron dynamics on attosecond timescales represents a frontier in ultrafast science. However, measurements are hindered by rapid electronic decoherence of the prepared electronic wave packet and the challenge of isolating correlated multi-electron dynamics from the dominant single-active-electron channels.

Here, we experimentally demonstrate a coherent interferometric technique using a seeded free-electron laser (FEL) to probe these dynamics with enantio-sensitive and attosecond resolution. The approach [1,2] uses a phase-locked, orthogonally polarized two-color (ω, 2ω) field. By photoionizing the prototypical chiral molecule propylene oxide, we isolate a prompt, laser-assisted, enantio-sensitive Auger–Meitner decay pathway that interferes with a direct photoionization reference. Realizing this scheme required a light source combining high spectral purity, VUV photon energies, and attosecond-level phase stability, a capability provided by the seeded FEL FERMI [3,4].

With this experiment, we are able to directly extract a characteristic molecular phase that exhibits a π-shift between opposite enantiomers and resolves dynamics with a precision of ∼40 attoseconds. This method selectively enhances ultrafast multi-electron correlations while suppressing slower sequential processes, providing a new window into the internal helicity and sub-femtosecond current dynamics inherent to chiral systems.

[1] P. V. Demekhin et al. Phys. Rev. Lett. 121, 253201 (2018)
[2] A. F. Ordonez and O. Smirnova, PCCP, 24, 7264, (2022)
[3] E. Allaria et al. Nature Photonics 6, 699–704 (2012)
[4] K. C Prince et al. Nature Photonics 10, 176–179 (2016)

High-performance nonlinear photonics for quantum information and networking

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Optical quantum information processing and quantum networking critically depend on optical nonlinearities. We introduce a high-performance nonlinear photonics platform based on the III–V semiconductor indium gallium phosphide (InGaP), which features a record-high nonlinearity-to-loss ratio and enables unprecedented capabilities for quantum information and networking. We demonstrate a nonlinear Bell-state analyzer employing a high-efficiency nonlinear microcavity and use it to perform high-fidelity quantum teleportation. Such nanophotonics-enhanced nonlinear Bell-state analyzers can improve quantum networking by suppressing multiphoton errors when non-deterministic entangled photon sources are used. In addition, we demonstrate high-performance quantum frequency conversion (QFC) between the telecom and visible bands using unpoled InGaP nanophotonic waveguides with programmable phase-matching control. This approach simultaneously satisfies multiple critical requirements for QFC by combining high efficiency, low power consumption, bidirectional operation, and effective noise suppression within a scalable platform. Furthermore, we leverage this high-performance QFC to realize magnetic-free quantum optical nonreciprocity, encompassing both isolation and circulation. The demonstration of quantum optical nonreciprocity in a scalable photonic platform paves the way toward directional quantum communication and noise-resilient quantum networks.

[1] J. Akin, Y. Zhao, P. G. Kwiat, E. A. Goldschmidt, and K. Fang, "Faithful quantum teleportation via a nanophotonic nonlinear Bell state analyzer", Phys. Rev. Lett. 134, 160802 (2025).
[2] K. Fang and E. A. Goldschmidt, "Fidelity and efficiency analysis for heralded entanglement swapping in lossy channels: linear and nonlinear optical approaches", Phys. Rev. A 111, 062618 (2025).
[3] J. Hu, H. Yuan, J. Akin, A.K.M.N. Haque, Y. Zhao, and K. Fang, "High-performance quantum frequency conversion using programmable unpoled nanophotonic waveguides", arXiv:2510.16696 (2025).
[4] J. Akin, Y. Zhao, A.K.M.N. Haque, and K. Fang, "Perspectives on epitaxial InGaP for quantum and nonlinear optics", Applied Physics Letters 125, 260501 (2024).
[5] J. Akin, Y. Zhao, Y. Misra, A.K.M.N. Haque, and K. Fang, "InGaP $\chi^{(2)}$ integrated photonics platform for broadband, ultra-efficient nonlinear conversion and entangled photon generation", Light: Science & Applications 13:290 (2024).
[6]. M. Zhao and K. Fang, "InGaP quantum nanophotonic integrated circuits with 1.5% nonlinearity-to-loss ratio", Optica 9, 258-263 (2022).

Optical Coherence Microscopy: Applications to Agriculture

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Optical Coherence Tomography (OCT) was invented in the 1990's [1] as a technique ideally suited to non-invasively obtain 3 dimensional images of the structure at the back of the eye. Soon, this technology was translated to clinical applications in ophthalmology [2]. Later developments allowed to extend OCT imaging to other medical fields. One of the limitations of OCT is that while it provides a uniform resolution in the axial direction, the transverse resolution depends on the focusing conditions, quickly degrading away from the focal plane. A solution to this issue was found in the application of Bessel-like beams [3], however alignment sensitivity of the axicon lens used to generate the Bessel beam hampered adoption of this technique. We have demonstrated a fiber-integrated approach to robustly generate a Bessel-like beam, and applied it to OCT, showing a 2-fold improvement of the transverse resolution and 4-fold improvement of the depth-of-focus of tomograms [4].

We have applied this technique to obtain high resolution tomograms of sorghum [5] and cotton [6] seeds, showing the ability of OCT to provide phenotypical information relevant to plant breeding programs [5] and seed quality assessment [6]. We have obtained precise measurements of seed coat thickness of sorghum seeds, a trait that is relevant for storage and processing of these seeds. Many seeds, among those cotton seeds, are treated with anti-fungal or anti-microbial coatings to prevent infections during storage or upon germination. However, during the coating process, damages to the seeds will be masked, requiring a higher seeding rate upon planting. OCT can reveal damage to the seed below the coating in a quick measurement, allowing to efficiently remove damaged seed. We also found that the morphology of the seed coat observed from cotton seeds is an important factor in seed viability, allowing for even more sophisticated seed selection.

Another area where OCT can provide relevant information for agricultural applications is in the assessment of soil aggregate structure. Fertile soils are composed of a mixture of inorganic and organic materials, and the organic and inorganic materials often form composite structures known as soil aggregates. Soil aggregates have improved water retention capacity compared to loose particulates, as the aggregates exhibit intricate pore networks. Besides water retention, the pore networks also provide additional surface area to support improved microbial activity. Existing methods to measure aggregate porosity are limited in their ability to accurately quantify the pore volume, due to limitations in resolution and sensitivity. For small aggregates, we demonstrate OCT provides a means to accurately measure porosity and pore connectivity with a resolution well beyond other techniques.

Finally, we apply OCT to identify insect larvae within wheat stems. This novel application will allow us to not only obtain in-field quantification of infestation levels, but also to track infestation dynamics. Potentially this will allow to discover the mechanics behind plant resistance or susceptibility to insect pests and improve strategies for long-lasting resistance.

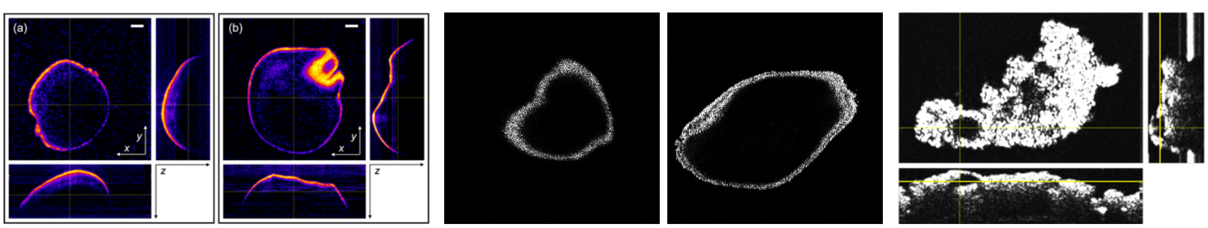

Fig. 1. OCT measurements of sorghum (left) and cotton seed structure (center) and soil aggregates (right). The grayscale contrast in the aggregate image was adjusted to improve contrast between material (bright) and voids (black). Internal voids are clearly observed, showing the porous nature of the aggregate.

References

[1] D. Huang, et al., *Science* **254**, 1178 (1991), A. Fercher, et al., *Am. J. Ophthalmology* **116**, 113 (1993)
[2] A. Fercher, *Z. Med. Phys.* **20**, 251 2010
[3] R. Leitgeb, et al., *Opt. Lett.* **31**, 2450 (2006)
[4] D. Sen, et al., *Biomed. Opt. Express* **12**, 7327 (2021)
[5] D. Sen, et al., *Sensors* **23**, 707 (2023)
[6] B. Henrich, et al., *ASA, CSSA, SSSA International Annual Meeting*, Abstract no. 151077 (2023)

Time-varying photonics in transparent conductors

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Over the past decade, transparent conductive oxides (TCOs) have emerged as a focal point in photonics research owing to their exceptional linear and nonlinear optical properties, which extend far beyond traditional electro-optic applications such as photovoltaics and touch-screen technologies [1]. When operated near their characteristic crossover wavelength, these materials exhibit epsilon-near-zero (ENZ) behaviour, effectively decoupling the electric and magnetic fields and thereby enabling remarkable nonlinear phenomena including wavefront freezing and super-coupling [2]. Notably, TCOs have demonstrated the strongest nonlinear responses among solid-state materials—supporting on-chip modulation and frequency conversion within device footprints spanning from 100 nm to 1 mm [3–5]. This pronounced nonlinearity is commonly attributed to a slow-light effect associated with the extreme dispersion of these near-zero-index (NZI) materials [6]. Another key feature is the intrinsic bandwidth of their nonlinear response, which, though not yet completely understood, exhibits ultrafast dynamics on the order of tens of femtoseconds [7]. Within this framework, NZI TCOs can be regarded as nearly ideal time-varying systems, offering unprecedented opportunities for the control of spatio-spectral properties of propagating radiation [8] and for the development of emerging applications in quantum technologies [9]. This presentation will examine the interplay among these fundamental aspects and highlight recent results showing that a low-index environment can profoundly modify quantum-dot emission [10], enable ultrafast and complete polarisation control in time-varying flat systems [11], and realise the first purely spatio-temporal metamaterial with unprecedented control over photon energy and momentum [12].

[1] W. Jaffray, et al., *Transparent conducting oxides: from all-dielectric plasmonics to a new paradigm in integrated photonics*, **Adv. Opt. Phot**. 14 (2), 148-208 (2022).
[2] I. Liberal, N. Engheta, *Near-zero refractive index photonics*. **Nat. Phot**. 11, 149–158 (2017).
[3] W. Jaffray, et al., *High-Order Nonlinear Frequency Conversion in Transparent Conducting Oxide Thin Films*, **Adv. Opt. Mater**., 12 2401249 (2024)
[4] W. Jaffray, et al., *Near-zero-index ultra-fast pulse characterization*, **Nat. Commun**. 13 (1), 3536 (2022).
[5] W Jaffray, et al., *Engineering waveguide nonlinear effective length via low index thin films* **Adv. Opt. Mater**. 12 (16), 2303199
[6] J.B. Khurgin, et al., *Adiabatic frequency shifting in epsilon-near-zero materials: the role of group velocity*, **Optica** 7 (3), 226 231 (2020).
[7] E. Lustig, et al., *Time-refraction optics with single cycle modulation*, **Nanophotonics**, 12, 2221 (2023)
[8] W. Jaffray, et al. *Spatio-spectral optical fission in time-varying subwavelength layers*. **Nature Photonics** 19, 558–566 (2025)
[9] I. Liberal, A. Alù, N. Engheta, *Zero-index metamaterials for classical and quantum light*, **Appl. Phys. Lett.** 120, 260401 (2022)
[10] W. Jaffray, et al. All-optical polarization control in time-varying low-index films via plasma symmetry breaking. https://doi.org/10.48550/arXiv.2510.06985
[11] S. Stengel, et al. *Quantum dots emission enhancement via coupling with an epsilon-near-zero sublayer*. https://doi.org/10.48550/arXiv.2509.09477
[12] W. Jaffray, et al. *Spatio-Temporal Photonic Metalattice*. https://doi.org/10.48550/arXiv.2510.09273

Spatial coherence of single photons in spontaneous emission from a single atom

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The spontaneous emission of a photon by an atom is thought to be initiated by quantum uncertainties, e.g. the uncertainties of the vacuum field in the plane waves impinging on the single atom. We investigate the notion that these plane waves interfere at the position of the atom to generate a single random electric field which stimulates the atomic decay and, therefore, the emission of a photon. In our experiment we trap a single atom at the focal point of a deep parabolic mirror. This enables us to collect photons emitted by the atom under spontaneous emission with close to all $\vec{k}$-vectors. We separate two half spaces of the emission profile with a D-shaped mirror and match the corresponding areas with a modified Mach-Zehnder interferometer. By modulating the path length of one of the interferometer arms, we can show that the light generated by spontaneous emission from a single atom shows spatial coherence. Other than in a related experiment[1] this setup does not modify the mode spectrum of free space. Simultaneously correlating the two output arms of the interferometer exhibits clear antibunching, showing, that only a single photon is present in the apparatus at any given time.

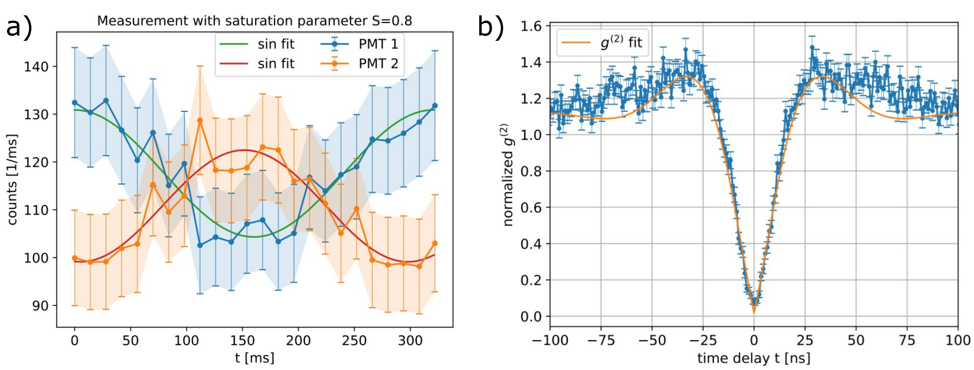

Figure 1: a) Interference signal of the two detectors at the output of the interferometer. The interference of the emission of the atom into the two half spaces is clearly visible. b) The signal on the two detectors shows antibunching showing that the interference signal originates from single photons.

From the interference fringes, observed in our experiment, we can conclude that the spontaneous emission shows spatial coherence between the two separated halves.

[1] Eschner, J. *et al.*, Nature **413**, 495–498 (2001).

Nuclear Clocks and the Search for New Physics

V.V. Flambaum

The isomeric transition in ^{229}Th - recently laser-excited by multiple groups - opens a path to a nuclear clock with accuracy competitive with, and potentially exceeding, the best optical atomic clocks. The nuclear clock can be realised using different charge states - Th^{+}, Th^{2+}, Th^{3+}, and Th^{4+} - each exhibiting distinct frequency shifts due to electron-nucleus interactions [1]. In effect, these represent different clocks, each with unique properties and precision limits.

The surrounding electrons strongly mediate excitation and decay via the electronic-bridge mechanism and can modify both transition probability and lifetime by orders of magnitude [2]. The clock performance is influenced by external perturbations, such as ion-trapping fields and blackbody radiation [3]. A “stretched-state” scheme suppresses leading-order electron–nucleus entanglement and mitigates key systematic effects [4].

The ^{229}Th transition is exceptionally sensitive to physics beyond the Standard Model: spatial/temporal variation of fundamental constants (α, quark masses, Λ_{QCD}) [5], ultralight dark-matter couplings to gluons and nucleons [6], and violations of Lorentz invariance and Einstein’s equivalence principle [7]. For orders enhancement factors relative to electronic transitions, together with frequency-ratio networks linking nuclear and atomic references, enable stringent, model-aware constraints.

[1]V.A. Dzuba, V.V. Flambaum, *Phys .Rev. Lett.* **131**, 263002 (2023).
[2]S.G. Porsev, V.V. Flambaum, E. Peik, C. Tamm, Phys. Rev. Lett.105,182501 (2010); S.G.Porsev, V.V. Flambaum*, Phys. Rev. A***81**, 042516 (2010). V.A. Dzuba, V.V. Flambaum, Phys.Rev.A111,L041103 (2025);A111, 053109 (2025);A112,023103 (2025).
[3] V. V. Flambaum}, V. A. Dzuba, E. Peik, Phys. Rev. A 112, 023103, 2025.
[4] C. J. Campbell, A. G.Radnaev, A. Kuzmich, V. A. Dzuba, V. V. Flambaum, and A. Derevianko, Phys.Rev.Lett.108, 120802 (2012).
[5] V. V. Flambaum, Phys. Rev. Lett. 97, 092502 (2006). E. Litvinova, H. Feldmeier, J. Dobaczewski & V. V. Flambaum, *Phys. Rev. C* **79**, 064303 (2009).J. C. Berengut, V. A. Dzuba, V. V. Flambaum, S. G. Porsev, *Phys. Rev. Lett.* **102**, 210801 (2009). P. Fadeev, J. C. Berengut, V. V. Flambaum, *Phys. Rev. A* **102**, 052833 (2020). V. V. Flambaum, A. J. Mansour, JHEP 2025, arxiv 2508.07266
[6] Y. V. Stadnik, V. V. Flambaum, *Phys. Rev. Lett.* **115**, 201301 (2015).
[7] V. V. Flambaum, *Phys. Rev. Lett.* **117**, 072501 (2016).

Experiments at the interface of general relativity and quantum mechanics

Ron Folman and the Atom Chip Group, Ben-Gurion University of the Negev

The two pillars of modern physics are the theories of General Relativity (GR) and Quantum Mechanics (QM). After decades of theoretical attempts to unify these two pillars under one theoretical framework (often referred to as quantum-gravity), these pillars remain independent. To some this situation is so unnatural, that they claim it actually hints that at least one of the theories is wrong in some fundamental way. As technology in quantum-optics labs improves, new experiments – working at the interface of these two theories – can be realized. Such experiments will hopefully provide new insights that will eventually allow for the sought-after unification to be finally achieved.

In this talk, I will present three experiments conducted at this interface, two already realized and one planned. The first involves clock interferometry, in which a single clock in a spatial superposition experiences two different proper times due to gravitationally induced red shift [1-3]. The second involves the observation of the Einsteinian equivalence principle, measured in the quantum domain [4]. While the first two were realized with atoms, the third involves massive objects, specifically, nano-diamonds [5]. Leaping by ten orders of magnitude in mass relative to the atomic experiments, the third experiment makes use of so-called active mass, where not only the gravitational field of Earth needs to be taken into account.

The experiments are based on Stern-Gerlach interferometry [6]. Time permitting, I will be happy to also address more technical questions. For example, interesting issues concerning decoherence arise [7,8].

[1] Y. Margalit et al., A self-interfering clock as a "which path" witness, Science 349, 1205 (2015).

[2] Zhifan Zhou et al., Quantum complementarity of clocks in the context of general relativity, Classical and quantum gravity 35, 185003 (2018).

[3] Zhifan Zhou et al., Geometric phase amplification in a clock interferometer for enhanced metrology, Science advances 11, adr6893 (2025).

[4] Or Dobkowski, Barak Trok, Peter Skakunenko, Yonathan Japha, David Groswasser, Maxim Efremov, Chiara Marletto, Ivette Fuentes, Roger Penrose, Vlatko Vedral, Wolfgang P. Schleich, Ron Folman, Observation of the quantum equivalence principle for matter-waves, ArXiv:2502.14535 (2025).

[5] Y. Margalit et al., Realization of a complete Stern-Gerlach interferometer: Towards a test of quantum gravity, Science advances 7, eabg2879 (2021).

[6] O. Amit et al., T3 Stern-Gerlach matter-wave interferometer, Phys. Rev. Lett. 123, 083601 (2019).

[7] Y. Japha and R. Folman, Role of rotations in Stern-Gerlach interferometry with massive objects, Phys. Rev. Lett. 130, 113602 (2023).

[8] C. Henkel and R. Folman, Universal limit on quantum spatial superpositions with massive objects due to phonons, Phys. Rev. A 110, 042221 (2024) – Editor's choice.

Diffraction-induced apparent self-focussing and transplant of Bose-Einstein condensates in absorption imaging

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Absorption imaging is a standard technique for determining the atom number and spatial distribution in ultracold ensembles. For this, the atoms are illuminated with a beam of light, the atoms attenuate the light and the resulting shadow is imaged onto a camera sensor.

We show, through experiments and Rayleigh–Sommerfeld diffraction simulations, that accurate reconstruction of both the cloud's position along the imaging axis and its transverse density profile can be significantly affected by diffraction and refraction – especially for dense samples such as Bose–Einstein condensates (BECs). We observe that diffraction produces regions darker than the immediate post-cloud shadow, giving the false impression of a sharper density profile. This effect originates from detuning of the imaging beam, which introduces refraction and causes the BEC to act as a lens whose curvature is determined by its density distribution. The dominant parameters are the Thomas–Fermi radius of the condensate and the imaging laser detuning, which determines the complex refractive index.

Our findings affect temperature measurements of ultracold atoms and precision applications that rely on accurate knowledge of spatial atomic distributions, such as point-source atom interferometry [1]. Additionally, the excellent control over the shape of the atomic cloud and the refractive index provides a perfect testbed to study specimen-induced aberrations in optical imaging [2].

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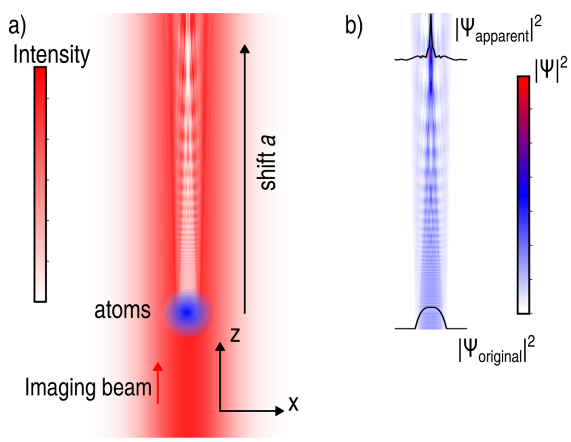

Figure 1: a) An imaging beam (red) illuminates a BEC (blue), which both absorbs and refracts the light. The resulting transmission function generates a pronounced diffraction pattern downstream of the cloud. Notably, the minimum intensity does not occur directly behind the atoms but at a finite propagation distance a. b) At every position z, the apparent atomic density $|\Psi|^2$ is inferred from the local absorption signal. At the true cloud position, this reconstruction matches the original transverse density $|\Psi_{\text{original}}|^2$. At distance a, however, diffraction causes the inferred density to peak sharply and appear significantly narrower than the real distribution.

[1] Dickerson et al. "Multiaxis Inertial Sensing with Long-Time Point Source Atom Interferometry". In: *Physical Review Letters* 111.8 (2013). DOI: 10.1103/PhysRevLett.111.083001.

[2] Török, S. J. Hewlett, and P. Varga. "The role of specimen-induced spherical aberration in confocal microscopy". In: *Journal of Microscopy* (1997). DOI: 10.1046/j.1365-2818.1997.2440802.x.

Multiphoton Hong-Ou-Mandel Interference from Classical Light in a Time-Varying Medium

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Hong–Ou–Mandel interference is a hallmark of quantum optics and a distinctive signature of quantum light interacting with spatial photonic structures. Here, we show that a simple time-varying structure—a temporally modulated homogeneous medium—can produce analogous quantum correlations starting from classical light. Building on our recent theoretical and experimental work on the photonics of temporal interfaces, i.e. sudden variations in the dielectric properties of homogeneous materials [1–3], we develop a quantum model to investigate analytically and semi-analytically the temporal analog of the celebrated Hong–Ou–Mandel effect, and compute the resulting generation of NOON states and their quantum statistics. We identify the origin of these correlations as the nontrivial interference between counterpropagating coherent states and the superpositions of entangled photon pairs produced by the interaction of the vacuum with the time-modulated background. Our results outline a feasible experimental route toward realizing nonclassical interference from classical light in time-modulated dielectric platforms and can be further generalized to multimode and nondegenerate pump–probe configurations.

References

[1] Galiffi, E., Xu, G., Yin, S., Moussa, H., Ra’di, Y., & Alù, A. (2023). Broadband coherent wave control through photonic collisions at time interfaces. *Nature Physics*, *19*(11), 1703-1708.

[2] Moussa, H., Xu, G., Yin, S., Galiffi, E., Ra’di, Y., & Alù, A. (2023). Observation of temporal reflection and broadband frequency translation at photonic time interfaces. *Nature Physics*, *19*(6), 863-868.

[3] Stefanini, L., Galiffi, E., Yin, S., Singh, S., Solís, D. M., Engheta, N., ... & Alù, A. (2025). Theory and Experimental Observation of Scattering by a Space-Time Corner. *Physical Review Letters*, *135*(11), 113802.

Double Quantum-Enhanced Sensing of Displacements with Trapped-ion Crystals

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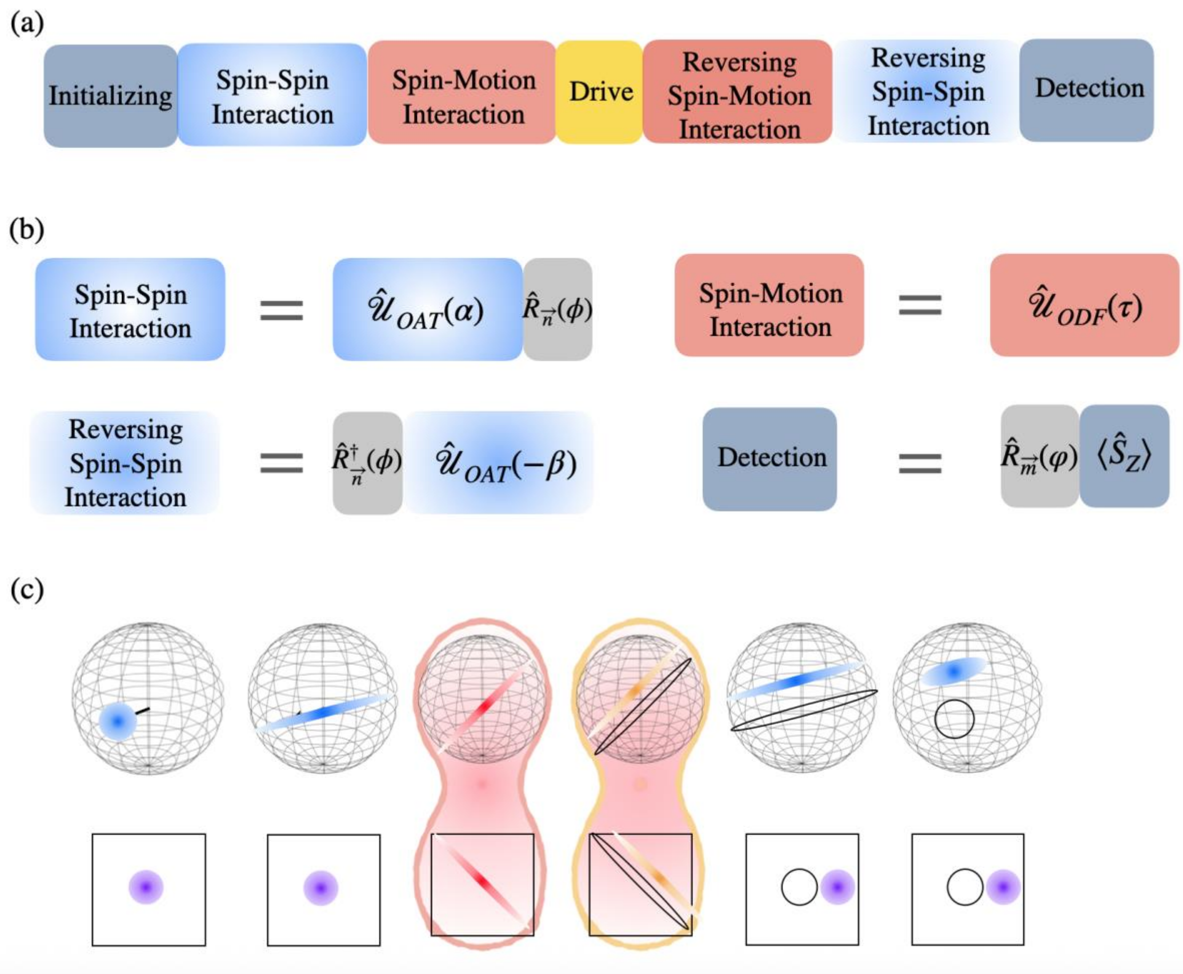
The vibrational motions of trapped ions have been demonstrated as quantum-enhanced sensors to detect extremely weak forces and electric fields. Further improvements could enable searches for dark matter. Here, we present a general quantum sensing protocol to enhance the ability of trapped-ion crystals to detect displacements and electric fields by exploiting both spin-motion entanglement and spin-spin entanglement. To optimally extract spin rotational sensitivity, we implement a time reversal sequence. We show an optimal enhancement of over 10 dB in displacement sensing under practical considerations. Our protocol can be applied to many different platforms, including Rydberg atoms, cold atoms, and polar molecules.



Optomechanical sensors for dark matter, axions and high frequency gravitational waves

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Optomechanical sensors have achieved levels of sensitivity enabling the detection of gravitational waves, and have advanced into the quantum-limited regime limited by the measurement imprecision associated with shot noise or the backaction from radiation pressure shot noise. Quantum techniques based on entanglement such as squeezing have provided a route for improved sensitivity beyond the standard quantum limit. Optomechanical detectors also have been identified as a means to search for dark matter over a wide range of energy and mass scales as well as to search for gravitational waves at high frequency. In this talk I will present new experimental constraints on ultralight scalar dark matter using cryogenic optical cavities [1].

Optically levitated particles exhibit extreme decoupling from the environment, making them excellent sensors of small forces, torques, or accelerations. I will also discuss progress on our efforts towards using high-aspect-ratio plate-like levitated optomechanical sensors to search for high frequency gravitational waves above the frequency band accessible by ground-based laser interferometer observatories [2,3,4] and describe new prospects for using levitated optomechanics to search for ultralight dark matter [5].

[1] “Demonstration that differential length changes of optical cavities are a sensitive probe for ultralight dark matter”, Tejas Deshpande, Andra Ionescu, Nicholas Miller, Zhiyuan Wang, Gerald Gabrielse, Andrew A. Geraci, and Tim Kovachy, Phys. Rev. Lett. - Accepted 13 November, 2025

[2] “Optical trapping of high-aspect-ratio NaYF hexagonal prisms for kHz-MHz gravitational wave detectors” George Winstone, Zhiyuan Wang, Shelby Klomp, Greg Felsted, Andrew Laeuger, Daniel Grass, Nancy Aggarwal, Jacob Sprague, Peter J. Pauzauskie, Shane L. Larson, Vicky Kalogera, Andrew A. Geraci, *Phys. Rev. Lett.* 129, 053604 (2022).

[3] “Optimal displacement detection of arbitrarily shaped levitated dielectric objects using optical radiation”, Shaun Laing, Shelby Klomp, George Winstone, Alexey Grinin, Andrew Dana, Zhiyuan Wang, Kevin Seca Widyatmodjo, James Bateman, Andrew A. Geraci, arxiv: *arXiv:2409.00782* (2024).

[4] “Simulating the Galactic population of axion clouds around stellar-origin black holes: Gravitational wave signals in the 10–100 kHz band”, Jacob R. Sprague, Shane L. Larson, Zhiyuan Wang, Shelby Klomp, Andrew Laeuger, George Winstone, Nancy Aggarwal, Andrew A. Geraci, Vicky Kalogera (LSD Collaboration), Phys. Rev. D 110, 123025 (2024).

[5] “Searching for Ultralight Dark Matter with MOLeQuTE: a Massive Optically Levitated Quantum Tabletop Experiment”, Louis Hamaide, Hannah Banks, Peter Barker and Andrew A. Geraci (arxiv, Dec. 2025).

Reshaping and Probing Velocity Distribution Functions of Neutral and Charged Species with Chirped Optical Lattices

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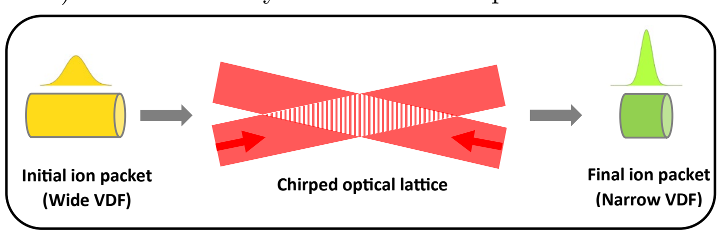
Intense, chirped optical lattices are currently at the wavefront of neutral and plasma flow diagnostics as well as matter manipulation with optical forces. Chirped optical lattices offer a versatile, non-intrusive platform for the diagnostics, control and manipulation of the velocity distribution function (VDF) of particles, ranging from atoms and molecules to nanoparticles and antimatter. The ultimate aim is to gain a fundamental understanding of the particle-optical lattice interaction and exploit it to a) perform cutting-edge non-intrusive diagnostics and b) to enable the coherent control of the translational motion of the particles which can result in "exotic" VDFs, which are difficult to be attained by other means.

Chirped optical lattices have recently enabled single-shot Rayleigh–Brillouin scattering (CRBS) measurements in both neutral and plasma flows, providing a powerful route to non-intrusive, high–spatiotemporal–resolution diagnostics. By imprinting a controlled frequency chirp onto the interfering pump beams, the resulting optical lattice sweeps across the different velocity manifolds of the VDF, thus enabling its characterization within the probed medium, regardless of its shape, in a single laser shot of ~200 ns. In neutral gases, single shot CRBS has been used to extract flow velocity[1], temperature, and bulk transport properties, even in high-speed or strongly non-equilibrium environments. In weakly ionized plasmas, CRBS further enables simultaneous probing of neutral[2] and charged[3] species within the plasma. These advances establish chirped optical lattices as a versatile platform for next-generation laser diagnostics in complex fluid and plasma systems.

To this day, intense optical lattices have been utilized to control the motion of neutral species, either by accelerating them or by decelerating them: neutral atoms or molecules are drawn (due to the optical dipole force) to the intensity maxima of an optical interference pattern to form an optical lattice; by changing in time the velocity of the lattice, i.e. by chirping its frequency and thus velocity, the particles that are "riding" the lattice obtain the same final velocity and thus particle manipulation can be achieved.



Conceptual schematic of velocity distribution narrowing using a chirped optical lattice.

In this talk we will present working progress towards developing custom made instrumentation to deliver chirped optical pulses and the subsequent utilization of these pulses to perform neutral gas and plasma diagnostics, as well as ionic beam VDF reshaping for use in mass spectrometry.

References:

[1] Gerakis, A., Bak, J., Randolph R., and Shneider, M.N., "Seedless nonresonant gas-flow velocimetry with single-shot coherent Rayleigh-Brillouin scattering", *Manuscript accepted for publication in Physical Review Applied*

[2] Randolph R., Flores Alfaro, G., Suzuki, S., Bak, J., Hara, K., and Gerakis, A., "Density and translational temperature measurements of neutral atoms in a glow discharge using coherent Rayleigh scattering", *Manuscript accepted for publication in Plasma Sources Science & Technology*

[3] Flores Alfaro, G., Shneider, M.N., and Gerakis, A. "Analysis of an induced Langmuir wave by ponderomotive forces and its applicability for plasma diagnostics." Physics of Plasmas 31, no. 9 (2024).

Abstract for presentation the 55th Winter Colloquium on the Physics of Quantum Electronics, Snowbird, Utah

Advancing inertial fusion energy using ultra-high peak power X-rays

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Abstract:
The demonstration of energy gain by nuclear fusion in the laboratory and its industrial utilization as an unlimited energy source has been a grand challenge for physicists and engineers for 70 years. This vision has shifted closer to reality after the successful demonstration of multi-megajoule energy yield from deuterium-tritium plasmas in indirectly driven inertial confinement fusion implosions on the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory. These experiments exceed fusion powers of 100 PW in a single event, vastly exceeding human’s total annual power capability by a factor of 5,000. This achievement came after increasing the fusion energy yield by a factor of 3,000 since the first experiments on the NIF about a decade ago. Currently, several avenues towards power generation by fusion ignition and high fusion yield are beginning to emerge where efforts towards laser and target technology developments have been launched recently through the U.S. DOE’s IFE-STAR and FIRE programs.

A leading target design for delivering high fusion yield at repetition rates of seconds uses laser-driven polymer foam capsules wetted with liquid nuclear fuels. Current target and fusion power plant design studies urgently need data on the Equation of State (EoS) and validation of simulations of the adiabat and hydrodynamic stability at megabar to gigabar pressures. For this purpose, we have launched a new program at SLAC to deliver these data by performing high precision experiments with powerful X-ray sources. Precision data are required because the fusion capsule design must be robust to the presence of radiation cooling from polymer ions. Further, plastic capsules were abandoned earlier on the NIF and replaced by diamond ablators due to stability issues that will aim to be overcome in future fusion power applications.

In this talk, I will present new elements of the U.S. IFE program and discuss recent results that provide critical experimental tests of our ability to design IFE implosions for future fusion power plants.

Quantum error correction in bosonic systems

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Bosonic systems offer unique opportunities for the protection of quantum information. They combine the hardware-efficient encoding of quantum information in the large Hilbert spaces of harmonic oscillators with a strong bias towards photon loss errors, allowing tailored code designs. In addition, bosonic encodings are particularly suitable for autonomous quantum error correction, where an engineered environment substitutes the measurement-feedback loop of the standard approach. While traditional bosonic codes, such as cat, binomial, and Gottesman-Kitaev-Preskill (GKP) codes, are built upon these premises, recent advances, partly enabled by machine learning, have shown the potential for further improvement. I will demonstrate this with three bosonic codes that have been optimized towards performance and experiment-friendly implementation [1-3]. Moreover, I will show how monitoring the engineered environment can further improve the performance.

[1] Y. Zeng, Z.-Y. Zhou, E. Rinaldi, C. Gneiting, F. Nori, *Approximate Autonomous Quantum Error Correction with Reinforcement Learning*, PRL 131, 050601 (2023)

[2] Y. Zeng, W. Qin, Y.-H. Chen, C. Gneiting, F. Nori, *Neural-Network-Based Design of Approximate Gottesman-Kitaev-Preskill Code*, PRL 134, 060601 (2025)

[3] Y. Zeng, F. Quijandría, C. Gneiting, F. Nori, *Quantum Error Correction with Superpositions of Squeezed Fock States*, arXiv:2510.04209

Control of Quantum Dynamics Using the Stimulated Raman Adiabatic Passage Technique

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The coherent control of dynamics in quantum systems has been at the forefront of physics research for decades. Among the various approaches developed for quantum control, the Stimulated Raman Adiabatic Passage (STIRAP) technique stands out for its robustness against experimental imperfections and its ability to facilitate complete population transfer without populating intermediate states. This work theoretically investigates possibilities of using the STIRAP and its variants to control a coherent superposition of quantum states. We present a generalization of the so-called fractional STIRAP (f-STIRAP), demonstrating precise control over the mixing ratio of quantum states in the wave packet. In contrast to conventional f-STIRAP, designed to drive a system from an eigenstate into a coherent superposition, our scheme enables arbitrary control over the composition of an already existing superposition state. We demonstrate that an approximate version of this technique—where analytically designed laser pulses with composite envelopes are replaced by simple Gaussian pulses—achieves comparable performance in controlling the dynamics of the wave packet. A limiting case of this scheme, utilizing two pulses with identical Gaussian envelopes and tuned delay and relative phase, is also explored, revealing experimentally accessible pathways for manipulating quantum coherence. We apply our developed techniques to control the ultrafast charge migration in the spin-orbit split ground electronic states of xenon cation via intermediate valence- and core-excited states. Finally, we propose concrete experimental realizations of the developed control schemes in combination with attosecond transient absorption spectroscopy as a method to probe the system.

Readout-Free Majority Decoding via Asymmetric Rydberg Antiblockade

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Classical readout and feedback delays for quantum error correction represent a significant bottleneck in neutral atom quantum computing architectures. We present a constant-time multi-qubit Rydberg protocol that enables readout-free majority vote decoding for $N \geq 3$ input bits encoded in the electronic hyperfine levels of N Rydberg atoms. Our protocol adds to the landscape of gates enabled by either asymmetric interactions or Rydberg antiblockade, where interaction-induced energy shifts are precisely tracked and utilized and asymmetric, and requires only global laser controls. We perform a detailed noise analysis, estimating gate errors from various sources and proposing potential mitigation methods. Finally, we explore applications to measurement-free quantum error correction, where our protocol can be used to achieve low-latency decoding for a broad class of passive quantum memories.

Rydberg gates in a neutral atom array using single-photon excitation

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In recent years, great progress has been made in improving Rydberg-mediated controlled-Z gates (CZ gates) in neutral atom arrays. This progress has been mainly due to advances in gate protocols and technical improvements such as reduced laser noise. In alkali atoms, most CZ gate demonstrations use two-photon excitation to the Rydberg state. Although two-photon excitation has been used to obtain a high CZ gate fidelity, the fidelity will be limited by intermediate state scattering and differential light shifts on the ground and Rydberg states. One way to circumvent these limitations is to use single-photon Rydberg excitation with UV light. This strategy remedies intermediate state scattering and greatly reduces differential light shifts, but also requires excitation to a $np_{3/2}$ state. Performing high-fidelity CZ gates using these states requires several strategies to address the additional magnetic sub-states and the increased electric field sensitivity of $np3/2$-states. I will describe our theoretical and experimental methods to shift-out extra magnetic sub-states using polarized microwaves and use of microwave dressing to reduce DC electric field shifts. I will present our preliminary gate results and discuss how such single-photon excitation schemes can be extended to two-species atom arrays. I will also give an update on our general progress and architecture for a neutral atom quantum computer.

This work was supported by LPS/ARO and Infleqtion.

Multiphoton Photoelectron Circular Dichroism via Time-Dependent Perturbation Theory: Revealing Principles of Chirality with Attosecond XUV Imaging

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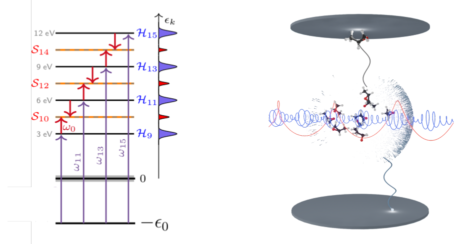
Recently, my group has presented a time-dependent perturbation theory approach to calculating photoelectron circular dichroism in the multiphoton regime [1, 2]. This framework leverages quantum chemistry and molecular scattering theory to describe all relevant states including continuum states at high levels of accuracy. Here, I present evidence that this method works for calculating PECD that may be compared with experiments. I will show a recent example that combines our calculations with a state-of-the-art experiment employing attosecond circularly polarized XUV pulses [3, 4]. I will also show that the technique not only works, but it reveals a physical structure underneath these complicated chiral signals. Finally, I will outline the next computations that will bring us closer to closing completely the theory-experiment loop. †



(a) (b)

Figure 1: Multiphoton PECD via the RABBITT scheme. (a) Scheme and energy levels involved. (b) Schematic for attosecond XUV realization with momentum imaging.

References

[1] R. E. Goetz, C. P. Koch, and L. Greenman, “Quantum control of photoelectron circular dichroism”, Phys. Rev. Lett. **122**, 013204 (2019).

[2] R. E. Goetz, C. P. Koch, and L. Greenman, “Perfect control of photoelectron anisotropy for randomly oriented ensembles of molecules by xuv rempi and polarization shaping”, J. Chem. Phys. **151**, 074106 (2019).

[3] M. Han, J.-B. Ji, A. Blech, R. E. Goetz, C. Allison, L. Greenman, C. P. Koch, and H. J. Wörner, “Attosecond control and measurement of chiral photoionization dynamics”, Nature **645**, 95–100 (2025).

[4] R. E. Goetz, A. Blech, C. Allison, C. P. Koch, and L. Greenman, “Continuum-electron interferometry for enhancement of photoelectron circular dichroism and measurement of bound, free, and mixed contributions to chiral response”, Phys. Rev. Res. **7**, L032036 (2025).

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Quantum Homodyne Tomography
Application to Ultra-Narrow Linewidth Semiconductor Lasers

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Continuous-variable quantum communications provide a promising pathway toward practical quantum information transfer by exploiting the continuous quadratures of the electromagnetic field. Unlike discrete-variable protocols based on single-photon detection, continuous-variable approaches are compatible with standard telecommunication technologies, enabling room-temperature operation and seamless integration within existing optical-fiber networks [1]. In this context, achieving sensitivities below the shot-noise limit remains a central challenge. Squeezed states, which reduce quantum noise in one quadrature at the expense of the conjugate one, represent a key resource for enhanced communication performance, improved sensing capabilities, and scalable continuous-variable quantum information processing [2].
Although squeezed states are commonly generated through nonlinear processes such as parametric down-conversion or four-wave mixing, quiet optoelectronic sources such as semiconductor lasers have also been shown to exhibit nonclassical light under appropriate pumping conditions [3,4]. In this work, we present an experimental framework for full quantum homodyne tomography of optical fields emitted by an ultra-narrow-linewidth semiconductor laser. The setup is validated using vacuum and coherent states, which provide benchmarks for phase control, homodyne detection fidelity, and noise calibration [5]. Two complementary reconstruction techniques namely the inverse Radon transform and maximum-likelihood estimation are implemented to recover the Wigner function and evaluate the quantum properties of the measured states.
This platform lays the groundwork for future investigations into quantum-noise suppression and potential nonclassical emission from semiconductor lasers, particularly in the quiet-pump regime. The approach is directly applicable to the development of continuous-variable quantum key distribution transmitters and to the broader integration of semiconductor devices into advanced quantum-optical technologies.

References
[1] V. C. Usenko et al., arXiv:2501.12801 (2025).
[2] F. Grosshans and P. Grangier, Phys. Rev. Lett. (2002).
[3] S. Machida, Y. Yamamoto, Y. Itaya, Phys. Rev. Lett. (1987).
[4] S. Zhao et al., Phys. Rev. Research (2024).
[5] J. Wright, Lecture 22: Introduction to Quantum Tomography (2015).

Heisenberg scaling in a continuous-wave interferometer [1]

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Continuous-wave (CW) interferometry has underlain key experiments in precision measurement science: from the Michelson-Morley search for a luminiferous ether to the modern interferometers that enable gravitational-wave detection. By introducing quantum resources as the interferometer input states and co-designing the measurement scheme, one can accelerate the rate at which measurement precision improves, surpassing what is achievable with classical light alone. In particular, the use of appropriate quantum states allows access to Heisenberg scaling—a quadratic enhancement over the best possible classical scaling [2-6]. While this regime has been reached in pulsed experiments [7-11], a continuous-wave demonstration has remained elusive, for two reasons. The first: it has been theorized that injecting squeezed vacuum into each interferometer input port can in principle, *i.e.* for some unknown measurement and estimator, achieve Heisenberg scaling for static phase estimation [12]. In practice, it is the estimation of a time-varying signal that is more relevant; more importantly, the measurement and estimator must be known concretely. The second challenge is that the quantum states are fragile such that the experiment must be designed to minimize optical loss while maintaining full phase locking. In this work [1], we address these challenges and present, to our knowledge, the first CW interferometric system whose resource efficiency approaches the Heisenberg limit. Conceptually, the scheme is straightforward: a Mach–Zehnder interferometer driven by two squeezed-light sources, combined with a nonlinear estimator acting on the resulting homodyne signal to recover a differential phase modulation applied to the interferometer.

[1] H. A. Loughlin, et al. arXiv preprint arXiv:2509.25384 (2025).
[2] B. Yurke, S. L. McCall, and J. R. Klauder, Phys. Rev. A 33, 4033 (1986).
[3] M. J. Holland and K. Burnett, Phys. Rev. Lett. 71, 1355 (1993).
[4] V. Giovannetti, S. Lloyd, and L. Maccone, Phys. Rev. Lett. 96, 010401 (2006).
[5] L. Pezzé and A. Smerzi, Phys. Rev. Lett. 102, 100401 (2009).
[6] L. Pezzé, A. Smerzi, M. K. Oberthaler, R. Schmied, and P. Treutlein, Rev. Mod. Phys. 90, 035005 (2018).
[7] D. Leibfried, M. D. Barrett, T. Schaetz, J. Britton, J. Chiaverini, W. M. Itano, J. D. Jost, C. Langer, and D. J. Wineland, Science 304, 1476 (2004).
[8] F. Sun, B. Liu, Y. Gong, Y. Huang, Z. Ou, and G. Guo, Europhysics Letters 82, 24001 (2008).
[9] T. Monz, P. Schindler, J. T. Barreiro, M. Chwalla, D. Nigg, W. A. Coish, M. Harlander, W. Hänsel, M. Hennrich, and R. Blatt, Phys. Rev. Lett. 106, 130506 (2011).
[10] S. Daryanoosh, S. Slussarenko, D. W. Berry, H. M. Wise- man, and G. J. Pryde, Nature Communications 9, 4606 (2018).
[11] R. Shaniv, T. Manovitz, Y. Shapira, N. Akerman, and R. Ozeri, Phys. Rev. Lett. 120, 243603 (2018).
[12] M. D. Lang and C. M. Caves, Physical Review A 90, 025802 (2014).

Transport Measurements of Majorization Order for Wave Coherence

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Wave coherence is fundamental to physics, underpinning phenomena such as interference, diffraction, and scattering. Comparing wave coherence is a key issue in coherence theory. While various coherence measures exist, the majorization order has emerged as a promising approach, offering mathematical advantages including finer granularity and clear algebraic and geometric interpretations. However, the unique physical effects and direct experimental measurements of this majorization order have remained unclear.

In this presentation, I will reveal the fundamental consequences of the majorization order in transport measurements, including power distribution, absorption, transmission, and reflection. I will show that these measurements precisely preserve the majorization order under unitary control, distinguishing it from other measures such as entropy order. Consequently, these effects enable direct experimental characterization of the majorization order. These findings underscore the crucial role of the majorization order in transport phenomena and coherence theory.

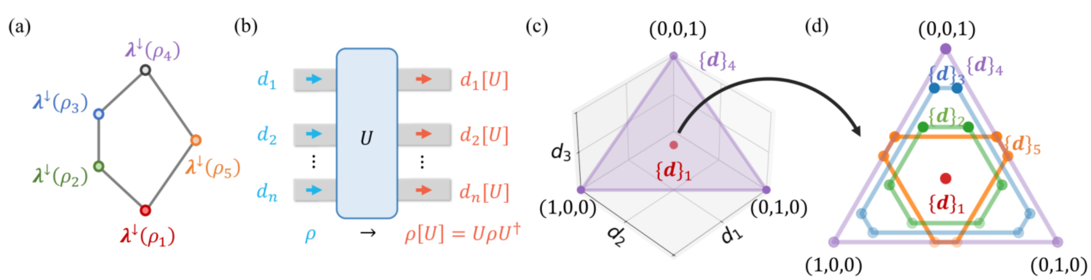

Fig. 1. (a) Hasse diagram for $\boldsymbol{\lambda}^{\downarrow}(\rho_1)$ to $\boldsymbol{\lambda}^{\downarrow}(\rho_5)$. An edge indicates a strict majorization relation between the lower and upper vertices. (b) Scheme of unitary control. The power distribution $\boldsymbol{d}(\rho) \rightarrow \boldsymbol{d}(U\rho U^{\dagger})$. (c,d) $\{\boldsymbol{d}\}$ for ρ_1 to ρ_5. (c) A 3D plot. (d) Boundaries of each set $\{\boldsymbol{d}\}$ in the plane.

References

1. C. Guo and S. Fan, "Majorization theory for unitary control of optical absorption and emission," PRL 130, 146202 (2023).

2. C. Guo, and S. Fan, "Unitary control of partially coherent waves. I. Absorption," PRB 110, 035430 (2024).

3. C. Guo, and S. Fan, "Unitary control of partially coherent waves. II. Transmission or reflection," PRB 110, 035431 (2024).

4. C. Guo, D. A. B. Miller, and S. Fan, "Transport measurements of majorization order for wave coherence," PRL 135, 053801 (2025).

Title: Quantum enhanced atomic clocks without spin squeezing

Speaker: Klemens Hammerer, Innsbruck University and IQOQI Innsbruck

Abstract: I will discuss strategies to improve the stability of optical atomic clocks in regimes where long Ramsey interrogation times are constrained by spontaneous emission, even on ultranarrow optical transitions. We identify classes of entangled states that provide optimal gain beyond the projection-noise limit and approach the fundamental precision bounds set by the available coherence. These states differ markedly from standard spin-squeezed states and are instead strongly non-Gaussian collective spin states, even in the presence of decoherence. I will outline how such states can, in principle, be generated using one-axis-twisting dynamics and how they enable quantum enhancement in conditions relevant to state-of-the-art optical clocks.

T. Kielinski, P.O. Schmidt, K. Hammerer, Science Advances, Vol. 10, No. 43, 2024
T. Kielinski, K. Hammerer, arXiv:2505.04287, Report on Progress in Physics

Entanglement in Electron Microscopy

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The emerging capability to generate, manipulate, and detect entanglement [1, 2] inside a transmission electron microscope (TEM) opens new avenues for quantum electron optics and high mass matter-wave interferometry[5].

I will present our recent experiment demonstrating entanglement between free electrons and photons using a coincidence-imaging approach [2, 3]. In this work, electron-photon pairs are generated via cathodoluminescence inside a TEM. Coincidence imaging [4], also known as ghost imaging, is used to reconstruct near- and far-field ghost images of a periodic transmission mask. By measuring position and momentum correlations of the electron-photon pairs, we observe a violation of the classical uncertainty bound, thereby demonstrating continuous-variable entanglement in position and momentum space.

In the second part of the talk, I will outline how electrons can act as high-momentum beam splitters for levitated nanoparticles, enabling high-mass matter-wave interferometry [5].

When a single electron undergoes Bragg diffraction at a free-falling nanoparticle, momentum conservation imprints a superposition of Bragg momenta onto the relative electron-nanoparticle coordinate, entangling their wave functions. Imaging the electron interferogram maps the nanoparticle onto a superposition of Bragg momenta, as if it were diffracted by its own crystal lattice. This produces a coherent momentum splitting roughly 1000 times larger than that achievable with two-photon recoils in conventional standing-wave gratings.
As a result, nanoparticle self-interference can be observed within drastically shorter interference times in a time-domain Talbot interferometer configuration, significantly relaxing source requirements and mitigating decoherence from residual gas and thermal radiation [5]. These short time scales also enable recapture of the nanoparticle within its initial trapping volume, facilitating reuse and allowing for rapid experimental duty cycles.

[1] J Henke, H Jeng, M Sivis, C Ropers, Observation of quantum entanglement between free electrons and photons, arXiv:2504.13047
[2] A Preimesberger, S Bogdanov, IC Bicket, P Rembold, P Haslinger, Experimental Verification of Electron-Photon Entanglement, arXiv:2504.13163
[3] P Rembold, S Beltrán-Romero, A Preimesberger, S Bogdanov, I Bicket, , N Friis, E Agudelo, D Rätzel, P Haslinger, State-agnostic approach to certifying electron-photon entanglement in electron microscopy, Quantum Sci. Technol. 10, 045003 (2025)
[4] S Bogdanov, A Preimesberger, H Mishra, D Hornof, T Spielauer, F Thajer, M Maurer, P Falb, L Stöger, T Schachinger, F Bleicher, M Seifner, I Bicket, P Haslinger, Ghost Imaging with Free Electron-Photon Pairs , arXiv:2509.14950
[5] S Nimmrichter, D Rätzel, IC Bicket, MS Seifner, P Haslinger, Electron-Enabled Nanoparticle Diffraction, Physical Review Letters 135 (17), 173601 (2025)

Ultrafast Quantum Optics

Mohammed Hassan

University of Arizona

Advancements in quantum optics and squeezed light generation have transformed various domains of quantum science and technology[1-5]. However, real-time quantum dynamics remain an underexplored frontier. Here, we extend quantum optics into the ultrafast regime[6], providing direct experimental evidence that quantum uncertainty is not a static constraint but evolves dynamically with the system's state and interactions. Using ultrafast squeezed light generated via a four-wave mixing nonlinear process[7,8], we observe the temporal dynamics of amplitude uncertainty, demonstrating that quantum uncertainty is a controllable and tunable physical quantity. This offers new insights into fundamental quantum mechanics in real time. Additionally, we demonstrate control over the quantum state of light by switching between amplitude and phase squeezing. Our ability to generate and manipulate ultrafast squeezed light waveforms with attosecond resolution unlocks exciting possibilities for quantum technologies, including petahertz-scale secure quantum communication, quantum computing, and ultrafast spectroscopy. We also introduce an ultrafast quantum encryption protocol leveraging squeezed light for secure digital communication at unprecedented speeds. This work paves the way for exploring quantum uncertainty dynamics and establishes the foundation for the emerging field of ultrafast quantum optics[6].

References

[1] Loudon, R. & Knight, P. L. *Journal of modern optics* **34**, 709-759, (1987).
[2] Jia, W. *et al. Science* **385**, 1318-1321, (2024).
[3] Andersen, U. L., Gehring, T., Marquardt, C. & Leuchs, G. *Physica Scripta* **91**, 053001, (2016).
[4] Aasi, J. *et al. Classical and quantum gravity* **32**, 074001, (2015).
[5] Abbott, B. P. *et al. Phys. Rev. Lett.* **116**, 061102, (2016).
[6] Sennary, M. *et al. Light: Science & Applications* **14**, 350, (2025).
[7] Slusher, R. E., Hollberg, L., Yurke, B., Mertz, J. & Valley, J. *Phys. Rev. Lett.* **55**, 2409, (1985).
[8] Scully, M. O. & Zubairy, M. S. in *Squeezing via nonlinear optical processes* Ch. 4, 460-486 (Cambridge university press, 2001).

Entanglement in Diamond Color Centers for Quantum Technologies

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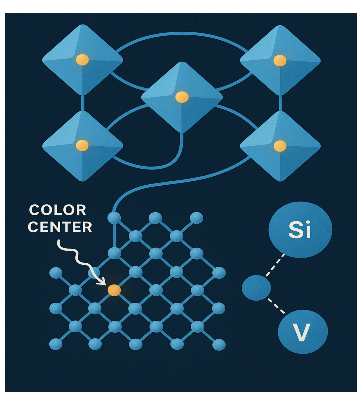
Nanodiamonds, hosting optically addressable color centers, such as the nitrogen-vacancy (NV) and silicon-vacancy (SiV), represent a promising solid-state platform for quantum technologies. These systems exhibit a unique combination of room temperature operation, photostability, biocompatibility, and single-photon sensitivity. This enables their dual application as nanoscale quantum sensors for detecting magnetic, electric, and thermal fields with sub-nanometer precision, and as a scalable hardware platform for few-qubit processors within sub 20 nm crystals.

This work explores the integration of these capabilities by employing deterministically implanted, entangled NV centers to function simultaneously as long-lived qubits and sensitive probes. This synergy allows quantum algorithms to directly enhance sensing tasks, such as probing neuronal ion channel dynamics via quantum gradiometry, with the potential to surpass classical sensitivity limits. A significant obstacle to this vision is the requirement for low-energy, uniform ion implantation across nanodiamond surfaces, a challenge unmet by conventional methods. To address this, we have developed a custom plasma immersion ion implanter, which reduces fabrication turnaround time from weeks to under an hour. Together, these advances in material design and quantum-enabled application establish nanodiamonds as a unifying technology with transformative potential for neuroscience, precision medicine, and quantum information science.



References:

1. Philip Hemmer, "Quantum sensing with Nanodiamond", Optical sensing and precision metrology, PC133800B, 2025, HTTPS://DOI.ORG/10.1117/12.3054211.
2. Philip Hemmer and Carmen Gomes, "Single proteins under a diamond spotlight", Science, 6 Mar 2015, Vol 347, Issue 6226, pp. 1072-1073, DOI: 10.1126/science.aaa7440.
3. Takuya F. Segawa, Ryuji Igarashi, "A magnetic resonance perspective", progress in nuclear magnetic resonance spectroscopy, 2023, 134-135, DOI.ORG/10.1016/J.PNMRS.2022.12.001.

Observing paraparticles in ultracold Rydberg atoms

Kaden Hazzard
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Abstract

Exchange statistics is a fundamental characteristic of both fundamental particles and quasiparticles, and is conventionally thought to be constrained to give either fermions or bosons. I will discuss recent research in our group that has shown other exchange statistics are possible (beyond already-known anyons, which are restricted to two dimensions), and their properties. I will also describe our efforts to find practical ways to observe paraparticles experimentally using quantum simulations with Rydberg atoms in tweezer arrays, quantum computers, and real materials.

Quantum sensing with nanodiamonds

Philip Hemmer

IQSE/Texas A&M University

Abstract: Nanodiamond color centers like the nitrogen-vacancy (NV) have shown much promise for nanoscale sensing of magnetic and electric fields and temperature. To realize these promises it is necessary to optimally engineer the properties of the nanodiamonds containing these NVs. This includes size of the nanodiamonds, proximity of NVs to the diamond surface, charge stability, and when possible, degree of quantum entanglement. In this talk I will review recent advances in the fabrication of NVs, and other magnetic color centers in diamond, as well as both top-down and bottom-up approaches to producing high quality nanodiamonds. Emphasis will be on techniques that can easily scale to large quantities.

Physics of Quantum Electronics (January 2026)

Presenter: **Daniel Isaac Herman,** [1] Jerome Genest, [2] and Scott Diddams[3]

Affiliation: Sandia National Laboratories, Albuquerque, NM, USA

Title: Dual-comb spectroscopy with quantum states of light

Abstract:

Dual optical frequency comb systems enable precision atomic and molecular sensing applications including atmospheric monitoring, high-speed chemical analysis and femtosecond time transfer. In this talk, we review the basics of dual-comb measurements and discuss some real-world use-cases for dual-comb sensors including quantification of agricultural gas emissions. After motivating the use of dual-combs for industrial applications, we will discuss the quantum nature of dual-comb measurements and learn how to use quantum states of light to improve dual-comb metrology. By viewing dual-comb interferometry as a time-domain quantum measurement, we can identify multiple routes towards quantum enhanced dual-comb measurements. Specifically we will discuss measurements with relevance to spectroscopy, optical timing and tomography with quantum dual-comb systems.

Theory of vacuum-assisted chemical reactions in infrared cavities

Felipe Herrera
Universidad de Santiago de Chile

Abstract

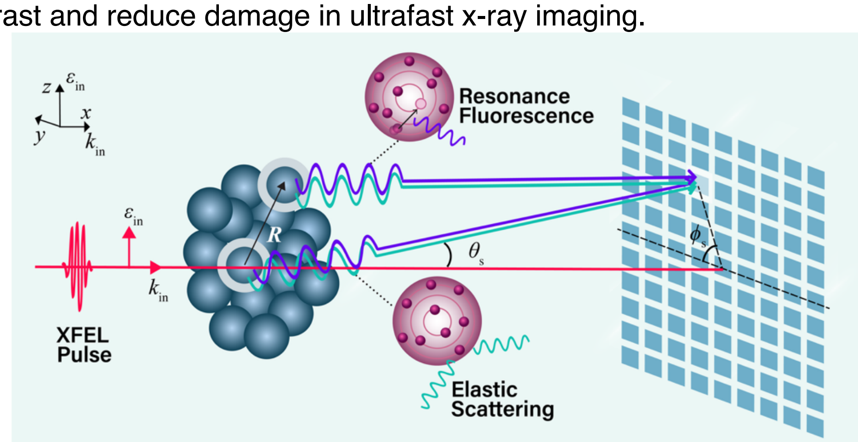
The measured rate constant of several chemical reactions inside infrared cavities at room temperature have been shown to deviate significantly from standard out-of-cavity values in the high-cooperativity regime of cavity QED, with a frequency dependence of the deviations that closely follows infrared absorption features of the reactant molecules [1]. Canonical thermalization theory based on stationary Gibbs states predicts no change in reactivity inside a cavity for an ensemble of reacting molecules, in conflict with experimental observations. To address this gap, we developed two microscopic cavity QED models of chemical reactivity that show resonant modifications of the vibrational occupation of reactive modes due to strong light-matter interaction with the cavity vacuum field. The first model is based on a local Lindblad quantum master equation with a nonlinear vibrational Hamiltonian that describes an ensemble of N bimolecular reactions that form urethane in liquid phase [2]. Resonant deviations from canonical occupation statistics due to light-matter coherence are demonstrated in the large N limit, with a size scaling that suggests disorder protection of fluctuations. The second reactivity model simplifies the system Hamiltonian to remove vibrational nonlinearities, but generalizes the quantum master equation to include non-secular terms and bath-induced light-matter coherences. Rigorous analytical solutions for small N demonstrate that resonant deviations from the canonical Gibbs state of the coupled system are responsible for modifications of chemical reactivity in strong coupling [3], suggesting that more general treatments of quantum thermalization [5] are needed to reconcile theory and experiments in the field of cavity chemistry. Finally, we discuss recent predictions of quantum nuclear wavepacket dynamics leading to bond dissociation in exotic regimes of ultrastrong light-matter coupling in infrared cavities [5,6].

[1] K. Nagarajan, A. Thomas, T. W. Ebbesen, JACS 143, 16877-16889, 2021.
[2] W. Ahn, J. F. Triana, F. Recabal, F. Herrera, B. Simpkins, Science 380, 1165, 2023.
[3] F. Recabal, A. Rubio Lopez, J. Schachenmayer, F. Herrera, arXiv 2025.
[4] A. S. Trushechkin, M Merkli, JD Cresser, J Anders. *AVS Quantum Science* 4, 1, 2022.
[5] J. F. Triana, F. Herrera, J. Chem. Phys. 162, 134103, 2025.
[6] J. F. Triana, F. Herrera, arXiv:2511.17278, 2025.

Indistinguishability and Quantum Pathways in Nonlinear Resonant X-ray Scattering

Phay J. Ho
Argonne National Laboratory

Nonlinear x-ray scattering is emerging as a powerful mechanism for enhancing ultrafast diffraction beyond limits set by photoionization and electronic bleaching [1]. Ultrashort resonant x-ray pulses can drive electronic dynamics on attosecond time scales, generating transient core-hole configurations whose scattering signatures deviate strongly from the linear, single-photon regime [2]. Motivated by recent observations of nonlinear resonance enhancement in rapidly ionizing Xe nanoparticles [3] and Rabi-driven excitation reversal in Ne that suppresses absorption while boosting coherent scattering [4], we developed a time-dependent QED framework [4-7] to describe x-ray resonant absorption, emission, scattering, and coherent dynamics in atoms and clusters. Our theory shows how strong-field resonant driving opens interference pathways that extend ground-state contrast and amplify the effective structure factor far beyond linear scaling. Only a subset of these pathways remains indistinguishable and contributes to first-order interference, with fringe visibility governed by pulse area, polarization geometry, and the initial electronic state. In the linear limit, resonant channels yield the highest fringe contrast and a differential signal resembling a structure factor, but with substantially enhanced photon counts relative to non-resonant scattering. These effects can be exploited to enhance contrast and reduce damage in ultrafast x-ray imaging.



References

1. R. Neutze, et. al., Potential for biomolecular imaging with femtosecond x-ray pulses, Nature 406, 752 (2000).
2. P. J. Ho, et. al., The role of transient resonances for ultra-fast imaging of single sucrose nanoclusters, Nature Communications 11, 167 (2020).
3. S. Kuschel, et. al., Enhanced ultrafast x-ray diffraction through transient resonances, Nature Comm. 16, 847 (2025).
4. A. Ulmer, et. al., Nonlinear reversal of photo-excitation on the attosecond time scale improves ultrafast x-ray diffraction images, submitted, arXiv:2506.19394 (2025).
5. A. Venkatesh and P. J. Ho, Effect of Rabi dynamics in resonant x-ray scattering of intense attosecond pulses, Phys. Rev. A 111, L021101 (2025).
6. A. Venkatesh and P. J. Ho, Theory of resonant x-ray scattering with ultrafast intense pulses, Phys. Rev. A 111, 023101 (2025).
7. A. Venkatesh and P. J. Ho, Quantum Interference in Two-Atom Resonant X-ray Scattering of an Intense Attosecond Pulse, arXiv:2506.06585 (2025).

The Excimer Laser: Its Development and Evolution

Paul Hoff

Abstract

The impetus, physics, and technical challenges leading to the initial demonstration of the excimer laser will be reviewed along with the physics behind its evolution leading to its dominant roles in medical applications, lithography, defense, and finally laser fusion.

Hybrid Magnon Modes

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Magnons readily interact with a wide variety of different excitations, including microwave and optical photons, phonons, and other magnons. Such hybrid magnon dynamic excitations have recently gained increased interest due to their potential impact on coherent information processing [1]. This in turn opens new pathways for hybrid quantum information systems [2–4]. I will discuss specific examples and strategies, where we developed fully integrated devices that form the essential building blocks for more complex integrated coherent quantum systems. Towards this end, we demonstrated strong magnon-photon coupling in scalable coplanar devices using coplanar superconducting microwave photon resonators [5]. Based on this concept we have shown how two magnon resonators can be coupled over macroscopic distances, and using local time-resolved detection, we demonstrate coherent, Rabi-like, energy exchange between them [6]. Conversely, photons in two separate coplanar waveguides can be transmitted in a directional manner via nonreciprocal coupling to magnons [7]. Lastly, I will show how a superconducting qubit can be used for sensitively detecting magnon populations over a broad dynamic range [8]. These measurements illustrate the potential of using magnons for coherently controlled interactions ultimately even in the single quantum limit.

This work was supported by the U.S. Department of Energy, Office of Science, Materials Sciences and Engineering Division under Contract No. DE-SC0022060.

References

[1] Y. Li,,*et al.*, J. Appl. Phys. **128**, 130902 (2020).
[2] D. D. Awschalom, *et al.*, IEEE Quantum Engin. **2**, 5500836 (2021).
[3] Y. Li, *et al.*, 2022 IEEE Intern. Electr. Dev. Meeting, 14.6.1 (2022).
[4] Z. Jiang, *et al.*, “Appl. Phys. Lett. **123**, 130501 (2023).
[5] Y. Li, *et al.*, Phys. Rev. Lett. **123**, 107701 (2019).
[6] M. Song, *et al.*, Nat. Commun. **16**, 3649 (2025).
[7] Y. Li, *et al.*, Appl. Phys. Lett. **123,** 022406 (2023).
[8] S. Rani, *et al.*, Phys. Rev. Appl. **23**, 064032 (2025).

New control over electrons with ultrashort laser and non-classical fields

D. Lesko[1, 2], J. Heimerl[1], T. Weitz[1, 2], J. Pölloth[1], Weizhe Li[1], S. Nöcker[1, 2], F. López-Hoffmann[1], T. Volk[1], C. Hüttner[1], T. Pröbster[1], S. Meier[1], C. Heide[1, 3], S. Wittigschlager[1], A. Rasputnyi[4], A. Herzig[5], L. Seiffert[5], T. Fennel[5], M. Chekhova[1, 4], O. Neufeld[6], P. Hommelhoff[1, 2, 4]

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We will discuss how we can use intense ultrashort laser fields and bright squeezed vacuum to steer electrons. We will discuss this in two different settings.

(1) Photo-emitted electrons at the surface of metal needle tips can be driven strongly such that they behave exactly like strongly-driven electrons in high harmonic and attosecond pulse generation from atoms: They may be driven back within an optical period to scatter elastically off the metal surface. This happens in the fast-decaying optical nearfield, leading to new CEP-dependant spectral features even in the direct electrons. When driven with bright squeezed vacuum, we find that the electrons inherit the counting statistics of the driving light. Furthermore, they form high energy spectra, too, albeit without a clear plateau. When we post-select on the BSV photon number in each shot, a plateau is revealed, showing that the electron may serve as an ultrafast sensor for the driving light.

(2) When driven by few-cycle light fields, electrons inside of graphene have been shown to undergo intraband dynamics in conjunction with Landau-Zener interband transitions, leading to Landau-Zener-Stückelberg-Majorana interferometry. We will show that we can extract band structure information based on this interferometric approach. In addition, we will also show that we can light-dress graphene with a circularly-polarized laser field to form a Floquet topological insulator state (FTI), which we probe with the linearly polarized second harmonic. We will show the anomalous Hall effect and circular dichroism in the FTI state.

Nonlinear Dynamics in Macroscopic Levitation for Enhanced Inertial Sensing and Tests of Semiclassical Gravity

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Abstract: We present a novel platform for high-sensitivity inertial sensing, based on the ultra-low loss levitation of millimeter-scale dielectric quartz particles in a diamagnetic trap [1]. Our system reveals rich nonlinear dynamics, including mode coupling and partial energy recurrences, echoing the paradigmatic Fermi–Pasta–Ulam–Tsingou (FPUT) physics. Despite operating at room temperature, we observe exceptionally low dissipation rates ($< 4 \times 10^{-6}$ Hz) and a positive largest Lyapunov exponent (~0.0095 s^{-1}), indicating long-lived coherent oscillations and weak chaos.

This work has two key implications for quantum sensing and fundamental physics:

- Accelerometry: The levitated particle shows an intrinsic acceleration sensitivity of approximately 6.2×10^{-11} g/√Hz, without relying on active feedback or power-hungry control: the trap is constructed from a static configuration of permanent magnets. This passive, low-dissipation architecture suggests a path to compact, high-performance inertial sensors, leveraging nonlinear dynamics to boost sensitivity and bandwidth, and potentially surpassing limits of linear resonators.
- Testbed for Semiclassical Gravity: The combination of macroscopic mass, long coherence times, and nonlinear behavior opens a compelling avenue for probing physics beyond standard quantum mechanics. In particular, such a levitated system could be adapted to test predictions of the Schrödinger–Newton equation, a nonlinear modification that introduces gravitational self-interaction in the quantum evolution of a massive body. By engineering low-frequency motion and exploiting the weak damping of our levitated particles, one can enhance the timescales and mass regimes where a small deviation from linear quantum dynamics might become detectable.

In summary, our results demonstrate that macroscopic levitation, traditionally viewed as a classical platform, can reach a regime of ultralow damping and coherent nonlinear motion that is directly relevant for inertial sensing. Simultaneously, the system can be considered as a promising experimental toolbox for exploring the intersection of quantum mechanics and gravity — for example, testing whether semiclassical gravitational models like the Schrödinger–Newton equation leave measurable imprints in the dynamics of a levitated mass.

Acknowledgement: This work is supported by DARPA YFA, grant number D24AP00326-00 and W.M. Keck Foundation.

Reference.

1. Mehrdad M. Sourki, Wisdom Boinde, Ali N. Amiri, Mahdi Hosseini, "Nonlinear Dynamics and Fermi-Pasta-Ulam-Tsingou Recurrences in Macroscopic Ultra-low Loss Levitation", arXiv:2510.09490 [physics.app-ph] 2025.

Control, sensing and gravitational coupling of milligram pendulums: towards interfacing quantum and gravity

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Can we test the quantum mechanical nature of gravitational fields? Milligram-scale optomechanical experiments present a frontier for bridging quantum mechanics and gravitational physics by aiming to strike a balance between 1) making gravitational couplings of the controlled objects dominant and 2) making the motions of these objects quantum noise dominated. Required systems necessitate low-frequency dynamics that is typically considered quantum-unfriendly, but seems to be needed to achieve a large figure-of-merit in the problem, quantifying the ability to generate quantum entanglement gravitationally.

In this talk, I will first focus on our 1-milligram suspended torsional pendulum operating at 18 Hz, and the successful laser cooling of its motion to 240~microkelvins. I will elucidate the resulting boost in the quantum coherence length of this pendulum, benchmarking a remarkable quantum-gravity figure-of-merit with a vast improvement potential [1]. I will outline a path towards gravitational entanglement utilizing our zig-zag optical cavities [2] to boost the interactions of light and torsional pendulums. I will conclude with the ongoing effort of achieving gravitationally-limited coupling between two free running ~1 milligram pendulums – aiming to push observable inter-particle gravitational couplings down by 3 orders of magnitude.

References

[1] “1-milligram torsional pendulum for experiments at the quantum-gravity interface”, S. Agafonova, P. Rossello, M. Mekonnen, O. Hosten, arXiv:2408.09445 (2024).
[2] “A zigzag optical cavity for sensing and controlling torsional motion”, S. Agafonova, U. Mishra , F. Diorico , and O. Hosten, *Phys. Rev. Research* **6**, 013141. (2024)

Spatio-temporal shaping of laser filaments in air

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Laser filamentation is a nonlinear phenomenon observed during the propagation of femtosecond laser pulses with GW-peak-power in air. It results in the self-contraction of the beam, maintaining a very high intensity in a thin channel with an almost constant radius over many Rayleigh lengths, and leaves a plasma channel in the wake of the laser pulse. This spectacular effect can be obtained at a long distance and could be very used for remote applications requiring high laser intensity such as the laser lightning rod [1], laser telecommunication through fog [2,3] and for the generation of secondary radiations in the THz or UV range.

In a recent experiment we demonstrated that the flying focus technique could be used to control the velocity and direction of the ionization front of a filament produced in air [4]. These tailored filaments can emit THz radiation in any direction relative to their propagation axis. The emission angle can be adjusted by changing the input chirp of the laser pulse [5]. With superluminal ionization velocities $v > c$, the features of the filament THz radiation correspond to Cherenkov radiation produced not by a charged particle, but by a dipole or a quasiparticle moving in a dielectric medium at a velocity higher than the light velocity [6].

References

1. A. Houard, P. Walch, *et al.,* Laser guided lightning, Nat. Photonics **17**, 231 (2023).
2. N. Jhajj, E. W. Rosenthal, R. Birnbaum, *et al.,* Demonstration of Long-Lived High-Power Optical Waveguides in Air, Phys. Rev. X **4**, 011027 (2014).
3. G. Schimmel, T. Produit, D. Mongin *et al.,* Optica **5**, 1338 (2018).
4. D. H. Froula, *et al.,* Spatiotemporal control of laser intensity, Nat. Photon **12**, 262–265 (2018).
5. S. Fu, B. Groussin, Y. Liu, A. Mysyrowicz, V. Tikhonchuk, A. Houard, Steering Laser-Produced THz Radiation in Air with Superluminal Ionization Fronts, Phys. Rev. Lett. **134**, 045001 (2025).
6. B. Malaca, *et al.,* "Coherence and superradiance from a plasma-based quasiparticle accelerator," Nat. Photon. **18**, 39 (2024).

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Nuclear clocks: What now?
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In 1976 Kroger and Reich established the existence of a low-lying nuclear excited state in ^{229}Th through the spectroscopy of γ rays emitted following the α decay of ^{233}U. The prospects of a laser-accessible nuclear transition touched off a flurry of proposals to utilize this apparently unique nuclear transition as a sensitive probe of both nuclear structure and chemical environment, to constrain physics beyond the Standard Model, and to construct a clock with unprecedented performance. Unfortunately, Kroger and Reich could only tell us that the transition energy was less than about 100 eV and therefore scientists have spent the intervening 48 years searching for the thorium nuclear transition.

Last year, there was a breakthrough in this search and the nuclear transition was finally laser excited in Th:CaF_2 [1,2] at PTB and JILA, and in Th:$LiSrAlF_6$ [3], ThF_4 [4], and ThO_2 [5] at UCLA. With this new data, a clearer theoretical picture of the nuclear-electronic couplings in the solid-state hosts is emerging [6-8]. In this talk, we will summarize the current understanding of these systems and highlight the new opportunities they suggest for optimizing nuclear clock performance. This work was funded by the NSF, DARPA, and ARO.

1. J. Tiedau et al., Phys. Rev. Lett. 132, 182501 (2024)
2. C. Zhang et al., Nature 633, 63 (2024)
3. R. Elwell et al., Phys. Rev. Lett. 133, 013201 (2024)
4. C. Zhang et al., Nature 636, 603 (2024)
5. R. Elwell et al., Nature (in press) (arXiv:2506.03018)
6. H. Morgan et al., Phys. Rev. Lett. 134, 253801 (2025)
7. U. Perera et al., Phys. Rev. Lett. 135, 123001 (2025)
8. J. Terhune et al., Phys. Rev. Res. 7, L022062 (2025)

Attosecond Quantum Optics and Tortured Super-Radiance

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The last few years have seen a revolution in our understanding of attosecond nonlinear optics such as high harmonic generation: we have started to appreciate that highly non-equilibrium quantum dynamics of matter can endow its nonlinear optical response with distinct quantum properties.

I will present some of our latest results describing how quantum dynamics of even simple material systems, such as small molecules and solids, can be tailored to generate quantum states of light. In small molecules, the interplay of ultrafast electronic excitation and nuclear dynamics can be used to turn the generated harmonics into the Schroedinger cats. The same can be attempted in solids, where one can also try to squeeze the quantum states of the generated harmonics.

Turning to atomic gases, one can take advantage of the strong classical driving field to generate multiple excitations, setting up conditions for Dicke super-radiance. What would happen if these atoms are placed inside a cavity which is far detuned from the atomic line, so that atoms are strongly discouraged from emitting the frequencies they normally do, while being constantly excited by a strong classical field? We find that when placed inside such a torture chamber, the atoms form strongly correlated many-body state that tunes its energy to the cavity resonance. The released super-radiance then develops distinctly quantum properties leading to the generation of a multi-mode squeezed state. Time resolving the generated emission clearly shows how the atomic ensemble undergoes a phase transition from many uncorrelated, even if phase-locked, excitations to a correlated many-body state.

Effects of collective coupling and center of mass motion on the light scattered by driven multilevel atoms

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A systematic analysis of the cooperative effects arising in driven systems composed of multilevel atoms coupled via a common electromagnetic environment is presented. It is based on an interplay between dressed states induced by the driving field and photon exchanges, and collective decay channels. Special interest is given to the case of four-wave mixing induced by a pair of lasers acting on an atomic pair with internal levels in the diamond configuration. Three regions of operation are identified: (i) laser-dominated, (ii) intermediate, and (iii) dipole-dominated. Photonic correlation functions of the scattered light are evaluated. They exhibit a transition from a Lorentz-like dependence on the two-photon detuning—with general features that can be obtained in an isolated atom scheme—to a two-peaked distribution when the dipole-dipole interactions become relevant. For weak Rabi frequencies whose value is smaller than the highest collective decay rate, the atoms are trapped inside their ground state as they approach each other. The anisotropy of the dipole-dipole interaction and its wave nature are shown to be essential to understand the behavior of the photon correlations. Signatures of these processes are identified for existing experimental realizations including effects of the center of mass motion of the atoms.

Title

Cryogenic ion trapping of atomic and molecular ions for precision measurements

Abstract

We are establishing an molecular spectroscopy experiment of radium-bearing molecules. These molecules have exceptional sensitivity to time reversal symmetry (T) violation, which is at the heart of two issues: the abundance of antimatter over matter in the Universe and the Strong CP (charge conjugation and parity symmetries) problem. An ion trap is well-suited to working with radioactive species as they can be used very efficiently. They can be trapped for a long time and a single particle can be measured very precisely. We need a cryogenic environment for molecules for the molecules that could be used to study T violations to prevent black body remixing of rotational levels. We report on progress trapping such molecules and preparing for quantum logic spectroscopy to both measure their structure and ultimately control the molecules.

Iron-Based Topological Superconductors for Single-Photon Detection

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Here, we present our preliminary experimental results on photodetection in the iron-based topological superconductor $FeTe_xSe_{1-x}$ (also known as Fe(Te,Se)). Single crystals of Fe(Te,Se) were exfoliated and transferred onto a Si/SiO_2 substrate using a conventional dry-transfer method. Using the 2-probe method, we observed a superconducting transition at $T_c \sim 10.5$ K in a sub-10 nm-thick Fe(Te,Se) microwire. Next, we observed photodetection up to 6K with a photon count rate reaching a few million counts/s.

Direct measurement of the quantum pseudo-distribution via its generating function

Andrew Jordan
Chapman University

We demonstrate how the quantum mechanical pseudo-distribution of observable properties can be directly measured. An experimental proposal is given to directly find the pseudo-distribution via a conditional moment generating function measurement. While the pseudo-distribution can be extracted from the data in a theory agnostic way, when applying quantum mechanical formalism in the weak measurement limit, it is shown that the predicted pseudo-distribution is identified with the conditional Kirkwood-Dirac pseudo-distribution.

Universal lower bound on the computational complexity of Gaussian boson sampling

Kunwar Kalra and Vitaly Kocharovsky

Texas A&M University

Gaussian boson sampling from a many-body system of bosons (photons [1-3] or atoms [4,5]) is one of the leading experimental schemes capable of demonstrating quantum advantage of quantum simulations over classical computers. This is because the joint probability distribution of sampled boson numbers is given by a hafnian of a matrix associated with the covariance matrix of creation and annihilation boson operators and such a hafnian is hard to compute when the covariance matrix has negative eigenvalues, say, due to bosons being in the squeezed quantum states.

However, losses and other sources of classical noise hide squeezing under classically simulatable Gaussian displacement fluctuations and suppress the negative eigenvalues. This makes it possible for the recently found classical algorithm [6] to efficiently simulate boson sampling if the number of squeezed photons in the quantum resource of complexity becomes relatively small, less or about fifty. Physical meaning and estimate of the size of this nontrivial quantum resource of complexity remain unknown. Its size was evaluated only by ad hoc numerical convex optimization.

We find and prove analytically that there is a universal lower bound on the quantum-resource size. It equals the number of bosons associated with the negative eigenvalues of the covariance matrix. They correspond to the most squeezed minor axes of a multi-dimensional ellipsoid of Wigner quasi-probability distribution. This result provides a clear physical meaning and a very simple way to estimate the size of the quantum resource of complexity. We present results of numerical analysis of this lower bound, which is quite close to the exact value given by convex optimization, and reveal some of its remarkable properties. This analysis poses several interesting open questions.

References

1. H.-S. Zhong et al., Phase-Programmable Gaussian Boson Sampling Using Stimulated Squeezed Light, PRL **127**, 180502, 2021.

2. L. S. Madsen et al., Quantum computational advantage with a programmable photonic processor, Nature **606**, 75–81 (2022).

3. H.-L. Liu et al., Robust quantum computational advantage with programmable 3050-photon Gaussian boson sampling, arXiv:2508.09092v2 [quant-ph] 13 Aug 2025.

4. V. V. Kocharovsky, Vl. V. Kocharovsky, and S. V. Tarasov, Atomic boson sampling in a Bose-Einstein-condensed gas, Phys. Rev. A **106**, No. 6, 063312, 2022.

5. V. V. Kocharovsky, Hybrid Boson Sampling, Entropy **26**(11), 926, 2024.

6. C. Oh, M. Liu, Y. Alexeev, B. Fefferman, and L. Jiang, Classical algorithm for simulating experimental Gaussian boson sampling, Nature Phys. **20**, 1461-1468, 2024.

Title: Arbitrary fractional quantization in Dirac systems and scale-invariant lasers

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Abstract- Coherent light sources play a fundamental role in science and technology. Fundamental challenges have prevented the true "scaling" of light sources. For example, efficiently scaling the power of lasers has always come at the cost of single mode operation, a question that has been investigated, without success, since the invention of lasers in 1958. In the first part of the talk, I will propose a solution to this question with a "scale-invariant" laser, the Berkeley Surface Emitting Laser (BerkSEL), that remains single mode irrespective of its cavity size. I will show that the strategy discovered goes beyond the Schawlow-Townes two-mirror approach that is used by all existing lasers. In the second part of the talk, I will discuss our recent discovery of arbitrary fractional quantization in Dirac system and discuss its relation to scale-invariant BerkSELs.

Bio- Boubacar Kanté is the Chenming Hu Professor of Electrical Engineering and Computer Sciences (EECS) at the University of California Berkeley and a faculty scientist at the Materials Science Division (MSD) of the Lawrence Berkeley National Laboratory (LBNL). He is also a co-Director of the Berkeley Emerging Technology Research Center (BETR). He received a Ph.D degree in Engineering/Physics from "Université Paris-Saclay" (Orsay-France) in 2010. He was assistant professor and then associate professor of Electrical and Computer Engineering (ECE) at UC San Diego from 2013to 2018. His research interests include wave-matter interaction and optoelectronics.

Distinguishing Semi-Classical and Quantum Models of Proper Time with Atomic Clocks.

Christos Karapoulitidis,* Konstantin Beyer,* Jun Ye,† Shimon Kolkowitz,‡ and Igor Pikovski§

Today's best optical lattice clocks reach fractional frequency uncertainties at the 10^{-19} level, enabling the direct observation of gravitational redshift over millimeter-scale height differences [1, 2], pushing into a regime where the interplay between quantum mechanics and relativity becomes directly testable. Yet, these redshift measurements only probe the gravitational field at classically localized points, whereas many experimental demonstrations of gravitationally induced phases, such as neutron interferometry [3] or atomic fountains [4], remain fully compatible with gravity acting as a classical Newtonian background.

Previous proposals [5, 6] explored how gravitational time dilation could leave imprints on quantum systems that also carry an internal or clock degree of freedom. Most notably, they predicted a loss of visibility when a clock is placed in spatial superposition. While this phenomenon is fundamentally incompatible with semiclassical proper-time evolutions, its experimental observation remains challenging, as it requires meter-scale superpositions and seconds-long coherence times.

Here [7], we revisit the problem by focusing only on frequency measurements in atomic clocks and quantum control of position and internal states. We introduce a Hamiltonian formulation that extrapolates between semiclassical and quantum descriptions of the gravitational redshift terms. It captures the post-Newtonian evolution of quantum systems with possible semi-classical contributions, describing physically distinct possibilities: a genuinely quantum interaction capable of entangling internal and external degrees of freedom of clocks; and semi-classical models which are not necessarily ruled out by current redshift measurements.

We show that these scenarios lead to qualitatively different gravitational phase shifts, which become apparent when the system is subjected to specific spectroscopic control sequences. Importantly, the level of quantum control now available in state-of-the-art optical lattice clocks [8] brings these distinguishing signatures within the reach of upcoming experiments, and can thus probe for the first time the post-Newtonian coupling of mass to gravity in the quantum domain.

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[1] T. Bothwell, C. J. Kennedy, A. Aeppli, D. Kedar, J. M. Robinson, E. Oelker, A. Staron, and J. Ye, Resolving the gravitational redshift within a millimeter atomic sample, Nature **602**, 420 (2022).
[2] X. Zheng, J. Dolde, V. Lochab, B. N. Merriman, H. Li, and S. Kolkowitz, High precision differential clock comparisons with a multiplexed optical lattice clock, Physical Review Letters 10.1038/s41586-021-04344-y (2021).
[3] R. Colella, A. W. Overhauser, and S. A. Werner, Observation of gravitationally induced quantum interference, Physical Review Letters **34**, 1472 (1975).
[4] C. Overstreet, P. Asenbaum, J. Curti, M. Kim, and M. A. Kasevich, Observation of a gravitational aharonov-bohm effect, Science **375**, 226 (2022).
[5] M. Zych, F. Costa, I. Pikovski, and Č. Brukner, Quantum interferometric visibility as a witness of general relativistic proper time, Nature communications **2**, 505 (2011).
[6] I. Pikovski, M. Zych, F. Costa, and Č. Brukner, Time dilation in quantum systems and decoherence, New Journal of Physics **19**, 025011 (2017).
[7] C. Karapoulitidis, K. Beyer, J. Ye, S. Kolkowitz, and I. Pikovski, Distinguishing semi-classical and quantum models of proper time with atomic clocks (2025), in preparation.
[8] K. Kim, A. Aeppli, W. Warfield, A. Chu, A. M. Rey, and J. Ye, Atomic coherence of 2 minutes and instability of 1.5×10^{-18} at 1 s in a wannier-stark lattice clock, Phys. Rev. Lett. **135**, 103601 (2025).

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Characterising Entangled Structured Photons for Quantum Imaging Applications

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Quantum entanglement lies at the heart of many fundamental questions in quantum mechanics and serves as a powerful resource for emerging quantum technologies, playing a central role in demonstrations of quantum advantage and quantum supremacy. The most widely used platform for generating entangled photons is spontaneous parametric down-conversion (SPDC)—a probabilistic process occurring in nonlinear optical crystals. Although SPDC has been extensively studied, its underlying complexity has often been overestimated, and most experiments rely on the thin-crystal approximation [1]. As a result, quantum-state characterisation has traditionally been restricted to a limited set of photonic degrees of freedom, such as polarisation, time–energy, position–momentum, and orbital angular momentum. This limitation stems from both the intrinsic complexity of multi-photon quantum states and the exponential scaling of conventional quantum-state tomography.

We have recently developed a suite of advanced techniques for determining multi-photon quantum states based on digital holography and phase-retrieval algorithms, using multi-photon coincidence measurements [2,3]. These methods enable direct reconstruction of biphoton quantum states—including full phase-matching information—with high precision and on timescales that are orders of magnitude shorter than those required by traditional projective measurements. Building on this capability, we have also engineered and rigorously characterised more complex entangled quantum states [4,5] for applications in quantum imaging [6] and high-dimensional quantum information processing, including non-local computation [7] and quantum-enhanced imaging [8-10].

References

1. S.P. Walborn, C.H. Monken, S. Pádua, and P.S. Ribeiro, “Spatial correlations in parametric down-conversion,” *Physics Reports* **495**, 87-139 (2010).
2. D. Zia, N. Dehghan, A. D’Errico, F. Sciarrino, and E. Karimi, “Interferometric imaging of amplitude and phase of spatial biphoton states,” *Nature Photonics* **17**, 1009-1016 (2023).
3. N. Dehghan, A. D'Errico, F. Di Colandrea, and E. Karimi, “Biphoton State Reconstruction via Phase Retrieval Methods,” *Optica* **11**, 1115 (2024).
4. X Gao, Y Zhang, A D’Errico, A Sit, K Heshami, E Karimi, “Full spatial characterization of entangled structured photons,” *Physical Review Letters* **132**, 063802 (2024).
5. X. Gao, D. Paneru, F. Di Colandrea, Y. Zhang, and E. Karimi, “Generation of the complete Bell basis via Hong-Ou-Mandel interference of vector modes,” *Physical Review A* **112**, 012215 (2025).
6. F Grenapin, D Paneru, A D’Errico, V Grillo, G Leuchs, and E Karimi, “Superresolution Enhancement in Biphoton Spatial-Mode Demultiplexing,” *Physical Review Applied* **20**, 024077 (2023).
7. D Paneru, F Di Colandrea, A D’Errico, and E Karimi “Nonlocal transfer of high-dimensional unitary operations,” *Quantum* **9**, 1855 (2025).
8. Y. Zhang, D. England, N. Lupu-Gladstein, F. Bouchard, G. Thekkadath, P. J. Bustard, E. Karimi, and B Sussman “Quantum-Enhanced Beam Tracking Surpassing the Heisenberg Uncertainty Limit,” *Physical Review Letters* **134**, 190804 (2025).
9. Y Zhang, PA Moreau, D England, E Karimi, B Sussman, Quantitative phase gradient microscopy with spatially entangled photons, *in press* (2025).
10. N Dehghan, A D’Errico, Y Zhang, B Sussman, E Karimi, Diffraction of correlated biphotons through transparent samples, arXiv:2410.22635 (2024).

Towards observation of entanglement in free-electron pairs and free-electron—bound electron systems

Free-electron quantum optics [1] is an emerging field that harnesses the quantum-coherent interactions of free-electron wavepackets with light and matter. It offers powerful opportunities for probing quantum correlations on ultrafast timescales and at deep-subwavelength resolutions. Central to the field is the entanglement between free electrons and photons [2], recently demonstrated experimentally [3-5].

Beyond electron–photon entanglement, theory has predicted additional forms of quantum correlations: entanglement between free electrons and bound electrons [6,7], generated by charge–dipole interactions at deep-subwavelength distances; and entanglement between pairs of free electrons [8], arising from long-range Coulomb interactions. Experimental evidence of classical correlations between free-electron pairs has only recently been reported [9,10], though conclusive detection of residual entanglement remains outstanding [8]. Likewise, experimental observation of free-electron—bound-electron entanglement is still an open challenge being pursued [11,12].

In this talk, I will show that entangled free-electron pairs leave a distinctive imprint on the emitted light—an imprint that depends on their underlying entangled quantum state. This mechanism enables a new form of superradiant and subradiant emission by free electrons [13], opening a path toward probing free-electron entanglement through optical measurements. Building on this prediction, I will outline a recent experimental effort demonstrating that Coulomb-entangled electron pairs, when driven by an external laser, exhibit characteristic two-dimensional quantum-walk–like patterns in their energy correlations [8], which are distinctly different than the ones for electron pairs in a separable state. Finally, in the context of free-electron—bound-electron interactions, I will discuss how engineered electromagnetic environments can significantly enhance the interaction strength [14,15], bringing closer the first experimental observation of free-electron—bound-electron entanglement.

References

[1] R. Ruimy, et al., *Nat. Phys.* **21,** 193 (2025).
[2] O. Kfir, *Phys. Rev. Lett.* **123**, 103602 (2019).
[3] G. Arend, et al., *Nat. Phys.* **21,** 1855 (2025).
[4] Henke et al, arXiv :2504.13047 (2025)
[5] Rembold et al, arXiv :2502.19536 (2025)
[6] R. Ruimy, et al., *Phys. Rev. Lett.* **126,** 233403 (2021).
[7] Z. Zhao, et al., *Phys. Rev. Lett.* **126,** 233402 (2021).
[8] O. Tziperman, et al., arXiv:2505.03707 (2025).
[9] R. Haindl, et al., *Nat. Phys.* **19,** 1410 (2023).
[10] S. Meier, et al., *Nat. Phys.* **19,** 1402 (2023).
[11] Kolb et al, arXiv:2509.13904 (2025).
[12] Grzesik et al, arXiv:2508.13112 (2025).
[13] Karnieli et al, *Phys. Rev. Lett.* **127**, 060403 (2021).
[14] Karnieli et al, *Sci. Adv.* 9, add2349 (2023).
[15] Grzesik et al, in preparation (2025)

Lieb–Mattis states for robust entangled differential phase sensing:

prospects for implementation in cavities

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Abstract

Developing sensors with large particle numbers N that can resolve subtle physical effects is a central goal in precision measurement science. Entangled quantum sensors can surpass the standard quantum limit, where the signal variance scales as $1/N$, and approach the Heisenberg limit with variance scaling as $1/N^2$. However, entangled states are typically more sensitive to noise, especially common-mode noise such as magnetic field fluctuations, control phase noise, or vibrations in atomic interferometers. We propose a two-node entanglement-enhanced quantum sensor network for differential signal estimation that intrinsically rejects common-mode noise while remaining robust against local, uncorrelated noise. This architecture enables sensitivities approaching the Heisenberg limit. We investigate two state preparation strategies: (i) unitary entanglement generation analogous to bosonic two-mode squeezing, yielding Heisenberg scaling; and (ii) dissipative preparation via collective emission into a shared cavity mode, offering a $\sqrt{N}$ improvement over the standard quantum limit. Numerical simulations confirm that both protocols remain effective under realistic conditions, supporting scalable quantum-enhanced sensing in the presence of dominant common-mode noise.

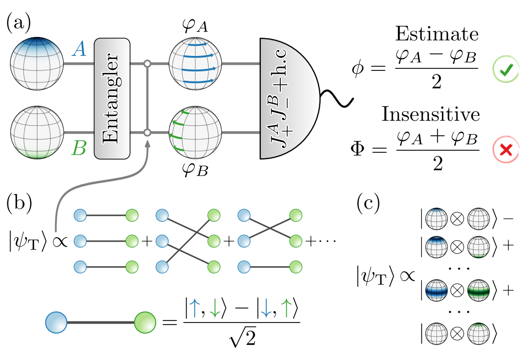

Figure 1: (a) Schematic illustration of the differential phase sensing protocol. Atoms in ensembles A (B) are initially prepared in their respective excited (ground) states, followed by an entangling operation. Each ensemble then acquires a distinct phase φ_A and φ_B. A joint measurement estimates the differential phase ϕ with high precision while remaining insensitive to common-phase fluctuations Φ. (b) The target state after entangling, $|\psi_T\rangle$, is an entangled Lieb–Mattis state that can be viewed as a permutation-symmetric superposition over all configurations where each atom in A forms a singlet with an atom in B. (c) In the Dicke basis of the individual ensembles, represented by their Wigner distributions, this state is an equal superposition, with alternating signs, of all Dicke-state pairs where the number of excited atoms in A equals the number of ground-state atoms in B.

A new platform for programmable Hubbard systems

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Abstract

I will describe a new experimental platform based on optical tweezer arrays, optical lattices, and alkaline-earth atoms that enables a new approach to producing and controlling ultracold atomic systems for studies of Hubbard models and their extensions.

Heat Engine in Quantum Engineering:
Coherence and Entanglement as resources

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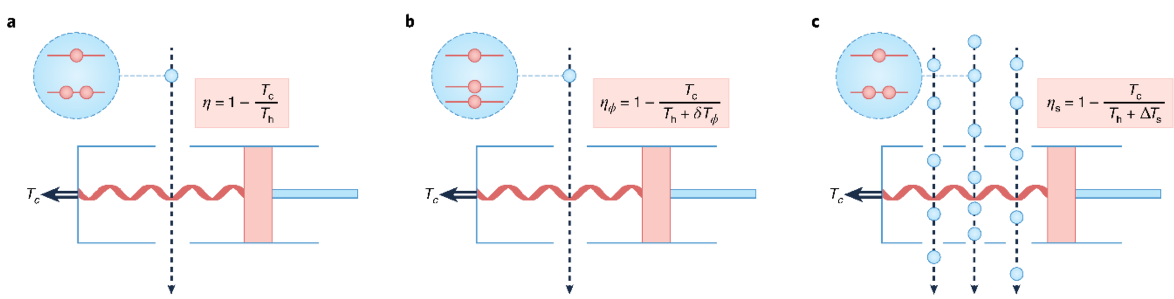
Thermodynamics can be viewed as an emergent theory where macroscopic behaviors are manifested by the underlying microscopic processes.[1] Since the equilibrium of thermodynamic behaviors of "quantum" systems are governed by the 'same' thermodynamic laws as classical systems, some quantumness should be specified in quantum thermodynamics. Even a heat engine with a single atom[2] can be described as a thermal system, and its thermal behavior is described by traditional thermodynamics.

In the recent development of resource theory,[3] coherence and entanglement are considered new types of resources, which may provide such quantumness in thermal systems. Phaseonium (atoms with coherence of internal states),[4] superradiance (multi-atom coherent state)[5] and two entangled atoms[6] are examples of coherent (entangled) fuels, which can show super-efficiency beyond the Carnot limit. Furthermore, these systems can open a quantum engineering era based on a 'quantum' heat engine with coherence and entanglement as new kinds of resources.[3,7]



Photonic quantum engine. **a.** Photon-Carnot engine, which can show maximum efficiency as Carnot limit, $\eta = 1 - T_c/T_h$. **b.** With atomic coherence, the efficiency can be improved and may exceed the Carnot limit. **c.** With superradiance made by an ensemble of coherent atoms, the efficiency can be almost 1, which might be considered a *perfect* photonic heat engine, though it doesn't violate the entropy increasement law.

[1] S. Vinjanampathy and J. Anders, "Quantum thermodynamics", Cont. Phy. 57, 545 (2016); P. Ván, "Nonequilibrium thermodynamics: emergent and fundamental", Phil. Trans. R. Soc. A 378, 20200066. (2020).
[2] J. Roßnagel, S. Dawkins, K. Tolazzi, O. Abah, E. Lutz, F. Schmidt-Kaler, and K. Singer, "A single-atom heat engine", Science 352, 325 (2016).
[3] A. Streitsov, G. Adesso, M. Bplenio, "Quantum coherence as a resource", RMP 89, 041003 (2017).
[4] M. Scully, M. Zubairy, G. Agarwal, H. Walther, "Extracting Work from a Single Heat Bath via Vanishing Quantum Coherence", Science 299, 862 (2003).
[5] M. Kim, M. Scully, and A. Svidzinsky, "A supercharged photonic quantum heat engine", ibid, **16**, 669 (2022); J. Kim, S. Oh, D. Yang, J. Kim, M. Lee, and K. An, "A photonic quantum engine driven by superradiance", Nat. Phot. **16**, 707 (2022).
[6] C. Feyisa and H. Jen, "A Photonic engine fueled by entangled two atoms", NJP 26, 033038 (2024); Another example of the usage of entanglement is in J. Rovny, S. Kolkowitz & N. de Leon, "Multi-qubit nanoscale sensing with entanglement as a resource", Nature 647, 876 (2025).
[7] N. Myers, O. Abah, and S. Deffner, "Quantum thermodynamic device: From theoretical proposals to experimental reality", AVS Quantum Science 4, 027101 (2022).

[PQE 2026]

Title: Optical lattice clocks: physics and applications

Authors: Kyungtae Kim, Dahyeon Lee, Alexander Aeppli, William Warfield, Kai Zhou, Ben Lewis, Zoey Hu, Jun Ye

Optical lattice clocks continue to push the boundaries of our understanding and control of atom-light and atom-atom interactions, now achieving fractional frequency uncertainties below 10^-18. This level of precision provides superior timekeeping capabilities, driving progress toward the redefinition of the second. These clocks also serve as sensors for fundamental physics studies, such as measuring gravitational time dilation at sub-millimeter length scales. In this talk, I will present our Sr optical lattice clock experiments at JILA. From the frequency standard perspective, we contribute to the global effort toward redefining the second. We have compared our clock to other optical atomic clocks at NIST over a fiber network. By comparing the JILA ultrastable cryogenic silicon reference cavity and NIST maser against Sr, this network has also enabled ongoing effort for the contribution to the global time scale and future optical time scales. We continue to advance the Sr clock performance. As we use more atoms to reduce quantum projection noise, many-body interactions introduce decoherence and frequency shifts. We have characterized the physical processes that perturb atomic coherence, pushing its limit to 2 minutes

Levitated Ferromagnetic Gyroscopes for Fundamental Physics

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Levitated ferromagnetic gyroscopes (LFGs) – ferromagnets whose angular momentum is dominated by oriented electron spins – offer a new route to ultra-low-noise torque sensors [1,2]. Here we introduce the LFG concept, its precession/libration dynamics, and projected sensitivities, then survey applications to fundamental physics: searches for exotic spin-dependent forces [2], broadband searches for ultralight dark matter [3], and even tests to measure whether intrinsic spin experiences Lense–Thirring and de Sitter precession in the same manner as orbital angular momentum [4]. I will also highlight recent experimental progress – direct observation of gyroscopic spin–rotation coupling in a levitated ferromagnet [5] which validates a key ingredient of the LFG picture and informs near-term designs. Finally, I will outline our own experimental plan to develop an electrodynamic (Paul) trap for levitation of electrically charged ferromagnets: using the interaction with the electric charge to control center-of-mass motion while using the rotational motion (precession/libration) to sense torques from magnetic fields or exotic fields.

[1] Derek F. Jackson Kimball, Alexander O. Sushkov, and Dmitry Budker, *Precessing Ferromagnetic Needle Magnetometer*, Phys. Rev. Lett. **116**, 190801 (2016).
[2] Pavel Fadeev, Chris Timberlake, Tao Wang, Andrea Vinante, Y. B. Band, Dmitry Budker, Alexander O. Sushkov, Hendrik Ulbricht, and Derek F. Jackson Kimball, *Ferromagnetic gyroscopes for tests of fundamental physics*, Quantum Science and Technology **6**, 024006 (2021).
[3] Saarik Kalia, Dmitry Budker, Derek F. Jackson Kimball, Wei Ji, Zhen Liu, Alexander O. Sushkov, Chris Timberlake, Hendrik Ulbricht, Andrea Vinante, and Tao Wang, *Ultralight dark matter detection with levitated ferromagnets*, Phys. Rev. D **110**, 115029 (2024).
[4] Pavel Fadeev, Tao Wang, Y. B. Band, Dmitry Budker, Peter W. Graham, Alexander O. Sushkov, and Derek F. Jackson Kimball, *Gravity Probe Spin: Prospects for measuring general-relativistic precession of intrinsic spin using a ferromagnetic gyroscope*, Phys. Rev. D **103**, 044056 (2021).
[5] Felix Ahrens and Andrea Vinante, *Observation of gyroscopic coupling in a non-spinning levitated ferromagnet*, arXiv:2504.13744 (2025).

Origins of Nonlinearities at Epsilon-Near-Zero and its Influence on Applications

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Since initial works in 2015 [1-3], the exploration of nonlinear optical effects in the epsilon-near-zero (ENZ) regime of materials has become a focus area of research in the broader study of nanophotonics and light-matter interaction. Building from initial demonstrations of enhanced harmonic generation and refractive index modulation in transparent conducting oxides at ENZ, the community has expanded the breadth, understanding, and potential application of these effects [4]. More recently, the ability of ENZ nonlinearities to generate exceptionally large (order of unity) changes in index on picosecond or less time scales is driving an interest in the area of time varying photonics as well as potential applications in tunable devices and metasurfaces [5]. As we continue to explore these fields, it is crucial to remember that not all nonlinearities are created equal, and the strength and efficiency of a given process relies upon many parameters including excitation conditions and material properties. Driven to explain questions that arose from our own experimental results, we sought to develop a robust and intuitive description for the nonlinear processes in ENZ films to verify experiments and guide future studies. In this presentation I will summarize our description of fast and slow nonlinear processes in ENZ [6,7]. We will highlight the difference between each process, the physical origin of the nonlinearity, and the relative magnitudes of fast and slow effects under the assumption of many cycle optical pulses (e.g. > 10 fs). We will conclude with a short outlook of how both fast and slow processes are driving a search for applications of ENZ effects from our team in low-threshold nonlinear systems, ultrafast pulse characterization, and nonlocal nonlinear processes. We hope that highlighting the difference between nonlinear processes that may - on the surface - seem connected, will help to guide the field as further research is pursued.

[1] N. Kinsey et al, Optica, 2(7), 616-622, 2015.
[2] A. Capretti et al, ACS Photon. 2(11) 1584-1594, 2015.
[3] A. Capretti et al, Opt. Lett. 40(7), 1500-1503, 2015.
[4] D. Fomra et al, Appl. Phys. Rev. 11(1), 011317, 2014.
[5] E. Galiffi et al, Adv. Photon. 4(1), 014002, 2022.
[6] R. Secondo et al, Opt. Mater. Express, 10(7), 1545-1560, 2020.
[7] J. B. Khurgin, M. Clerici, and N. Kinsey, Laser & Photon. Rev. 15(2), 20002691, 2021.

The Promise and Challenges of Ion Wave Plasma Optics for Enabling Laser Driven Fusion Energy

Robert Kirkwood (Consultant), Patrick Poole (LLNL), Scott Wilks (LLNL), Tom Chapman (LLNL), Lin Yin (LANL), Brian Albright (LANL)

In the decade and a half since NIF began operation many developments with plasma optics created with ion acoustic waves via stimulated Brillouin scattering (SBS) have shown promise to provide solutions for delivering the multi-mega Joule pulses needed for IFE [1]. In the intervening years experimentally validated models have shown that even simple linear descriptions of stimulated ion waves [1,2] could describe scattered power due to the cross beam energy transfer (CBET) inferred in some hohlraum targets at NIF [3]. These models have now allowed accurate designs of plasma optics with impressive performance, including a 20 beam plasma combiner that set the record for UV energy in a ns pulse in a single laser beam [1,4], an optic to improve beam focal quality [1], and a plasma wave plate to effectively control polarization at high fluence [5]. The linear wave models have further suggested CBET in plasmas could produce final optics that survive the extreme radiation of fusion, and pulse compressors that meet the needs of fast ignition (FI) if plasma waves remain linear [1]. Yet more recent experiments have both provided precise validation of the linear wave model of CBET [6] at low scattered power, and also confirmed there are many cases of interest where non-linearities in scattered power occur [6-8]. Most recently advances in VPIC simulations that describe non-linear ion motion in the presence of binary collisions [9] have succeeded in accurately describing some observed non-linearities in the scattered power as being due ion heating by the plasma waves modifying the background plasma conditions [10]. This advance now promises to enable accurate designs of plasma optics for IFE in a wider range of conditions and applications. This talk will summarize the state of this emerging IFE technology.

[1] R. K. Kirkwood, et al. Appl. Phys. Lett. 120, 200501 (2022).
[2] E. Williams, et al, Phys. Plasmas 11, 231–244 (2004), W. L. Kruer et al, Phys. Plasmas 3, 382 (1996)., P. Michel et al., *Phys. Rev. Lett.* 102, 025004 (2009)
[3] P. Michel, et al Phys. Plasmas 17, 056305 (2010), L. A. Pickworth Phys. Plasmas 27, 102702 (2020).
[4] R. K. Kirkwood, et al. Nat. Phys. 14, 80, JANUARY 2018, R. K. Kirkwood, et al Phys. Plasmas 25, 056701 (2018).
[5] D. Turnbull, et al Phys. Rev. Lett. 116, 205001 (2016).
[6] D. Turnbull, et al, Plasma Phys. Controlled Fusion 60, 054017 (2018)
[7] A. L. Kritcher, et al PHYSICAL REVIEW E **106**, 025201 (2022)
[8] R. K. Kirkwood Phys. Rev. Lett. 89 21 215003 (2002) and Phys. Plasmas12 112701 (2005).
[9] L. Yin et al Phys. Plasmas 30, 102703 (2023)
[10] A. M. Hansen, et al Phys. Rev. Lett. 126, 075002 (2021), A. M. Hansen, et al Plasma Phys. Control. Fusion 64 (2022) 034003.

Topological Lasers: From Electrical Injection and Novel Organic Emitters

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Topological lasers exploit protected photonic states to enable robust and scalable coherent light sources. In this talk, I discuss recent progress in topological laser architectures based on coupled photonic lattices, highlighting experimental realizations of topological insulator vertical-cavity laser arrays. Emphasis is placed on advances toward electrically injected topological lasers and lasing from topological defect states, paving the way for practical device integration. In addition, emerging opportunities enabled by novel organic emitter materials are addressed, offering new pathways to engineer gain, non-Hermiticity, and hybrid light-matter interactions in topological laser platforms.

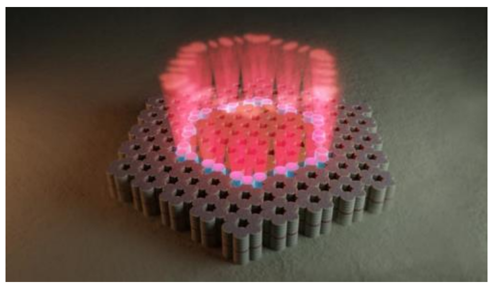

Fig. 1: Schematic drawing of a topological vertical-cavity surface-emitting laser array.

References

[1] M. Rechtsman et al., Nature **496**, 196–200 (2013).

[2] M. Hafezi et al., Nat. Photon. **7**, 1001–1005 (2013).

[3] S. Klembt et al., Nature **562**, 552–556 (2018)

[4] A. Dikopoltsev et al., Science **373**, 1514–1517 (2021).

[5] P. Gagel, et al., Nano Lett. **24**, 6538–6544 (2024).

[6] J. Düreth et al., arXiv:2511.13958 (2025).

[7] S. Widmann et al, arXiv:2506.13521 (2025). (accepted in Nat. Commun.)

Polariton Lattices, Higher-Order Topology, and Artificial Gauge Fields

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Exciton-polariton lattices provide a versatile platform for realizing synthetic quantum matter with engineered topology and interactions. I present recent work on topological photonic systems based on coupled microresonators operating in the strong light-matter coupling regime, including the first experimental demonstration of an exciton-polariton topological insulator with chiral edge states [4]. Higher-order topological phases can support localized corner modes in two-dimensional lattices are discussed, with a focus on robustness against fabrication imperfections and the application of spectral localizer techniques to classify local topology. Finally, I explore the use of polarization degrees of freedom to implement artificial gauge fields and realize spin-dependent topological transport, opening routes toward spin quantum Hall physics of light [7].

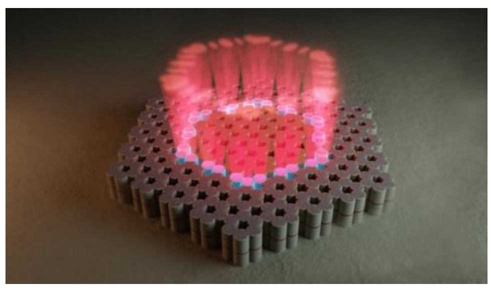

Fig. 1: Schematic drawing of a topological vertical-cavity surface-emitting laser array.

References

[1] M. Rechtsman et al., Nature **496**, 196–200 (2013).

[2] M. Hafezi et al., Nat. Photon. **7**, 1001–1005 (2013).

[3] S. Klembt et al., Nature **562**, 552–556 (2018)

[4] A. Dikopoltsev et al., Science **373**, 1514–1517 (2021).

[5] P. Gagel, et al., Nano Lett. **24**, 6538–6544 (2024).

[6] J. Düreth et al., arXiv:2511.13958 (2025).

[7] S. Widmann et al, arXiv:2506.13521 (2025). (accepted in Nat. Commun.)

Quantitative Quantum Device Design and Optimization to increase THz Radiation Power

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The interest in stronger THz radiation sources continues to rise for a variety of applications. Resonant tunneling diodes (RTDs) have been explored for this purpose for decades since the early 1990s. An industrial strength NEGF-based simulation engine (NEMO) has been developed since 1994 and demonstrated quantitative design for InP-based RTDs [1]. Recently triple-barrier RTDs (TBRTD) have found renewed interest and revealed additional degrees of freedom to optimize peak-to-valley ratios (PVR) for increased power extraction [2]. NEMO enables the modeling of realistically extended devices with highly non-parabolic material properties and full energy and momentum space integration. This work optimizes the TBRTD devices to increase the peak-to-valley-ratio, insert the realistic I-V curves into a full time-dependent circuit simulation to optimize THz emission.

Fig 1a depicts the prototype TBRTD [2] under a high bias. Fig 1b depicts 2 current density traces as a function of energy for two different transverse momenta k. The higher transverse momentum trace is not a simple translation from the k=0 trace and shows significantly different spectral features. The nature of three wells (emitter notch, well-1 and well-2) create a complex interaction of multiple states with different transverse energy dispersions resulting in complex transmission coefficients including Fano-resonances.

We will present the design approaches, changes in the quantum capacitance and the current voltage characteristic due to internal charge accumulation and their consequences in full, non-linear time-dependent circuit simulations.

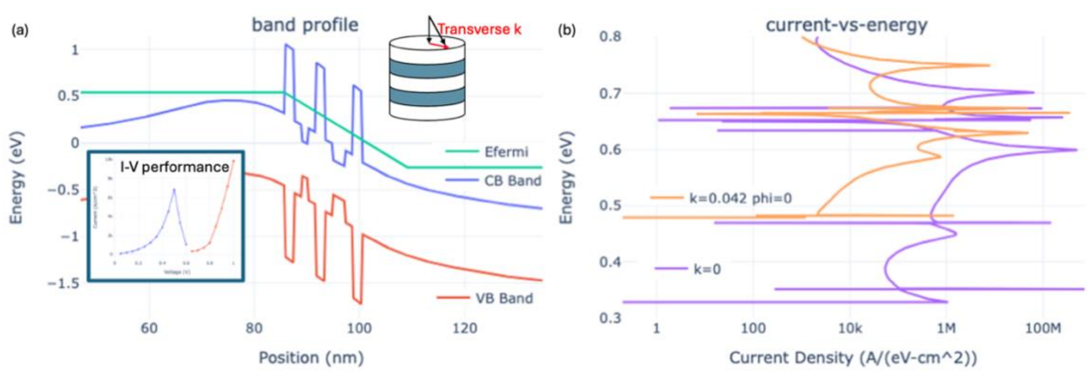

Fig.1: (a) Band edge diagram of the nominal TBRTD. Insert left – full I-V. Insert right layer stack with direct k=0 and lateral k momentum sketch. (b) Current density J(E,k) as a function of energy for two different transverse momenta. The spectral features such as broad and very narrow as well as Fano resonances are visible. The spectral features change dramatically with the transverse electron momentum. Simple effective mass models cannot capture these features created by the non-parabolic material properties and complex triple well interactions. Full k-integration within an atomistic Hamiltonian is needed to obtain a correct I-V characteristic.

[1] R. Bowen, Gerhard Klimeck, Roger Lake, William Frensley, Ted Moise, **"Quantitative Simulation of A Resonant Tunneling Diode",** J. of Appl. Phys. 81, 3207 (1997)
[2] Enes Mutlu, *et al.*, "Experimental and Theoretical Investigation of Collector Spacer and Doping Profile on Triple-Barrier Resonant Tunneling Diodes", Phys. Status Solidi A, Vol. 221, pg. 862 (2023)

Lightwave Engineering of Excitonic States in an Atomically Thin Semiconductor

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Coherently shaping excitonic states paves the way for novel optoelectronics and quantum information processing [1-4]. Yet, their femtosecond-scale coherence time [5] substantially constrains coherent control. We demonstrate lightwave engineering of excitonic states by employing intense, phase-stable multi-THz fields, resonant with the 1*s*-2*p* transition in a monolayer of $MoSe_2$ (Fig. 1a). The excitonic system is driven into multiple Rabi oscillations that occur during a single cycle of light, shaping its quantum states during its coherence time (Fig. 1b). We probe the dynamics by injecting excitons into the 1*s* state with femtosecond NIR pulses and detect the resulting high-order sideband (HSB) radiation [6-10] (Fig. 1c). The HSB signal, measured at increasing driving strengths (Fig. 1d-i), captures subcycle oscillations along with surprising emission minima during the NIR-THz temporal overlap. We reproduce these findings by advanced quantum-dynamic cluster expansion simulations, as well as a reduced 1*s*-2*p* two-level model that captures the dominant role of this sub-system, even at extreme driving conditions.

The origin of the observations is elucidated by a two-level Floquet analysis. In this picture, the NIR-THz delay can be considered as sampling different Rabi frequencies of a cw-like resonant drive. In the Floquet emission spectrum (Fig. 1j), the lowest order Floquet states (near 400 THz) undergo an Autler-Townes (AT) splitting, measured by Δ. At increasing drives, higher order Floquet sidebands replicate the AT splitting of the original system and generate a periodic sequence of avoided crossings, resulting in an oscillating pattern of Δ. When $\Delta \approx \omega_0$ the gap between all Floquet states is resonant to the multi-THz driving frequency, drastically increasing HSB emission. Correspondingly, HSB minima capture the instances where the system is transiently driven out of this enhancement window. Our results establish an exciting new route to shape many-body quantum correlations by integrating concepts from lightwave electronics, attosecond science, and atomic physics. The application of lightwave engineering with high repetition rate (170 kHz) lasers, establishes a path to its future integration with quantum optics by resolving the emitted photon statistics.

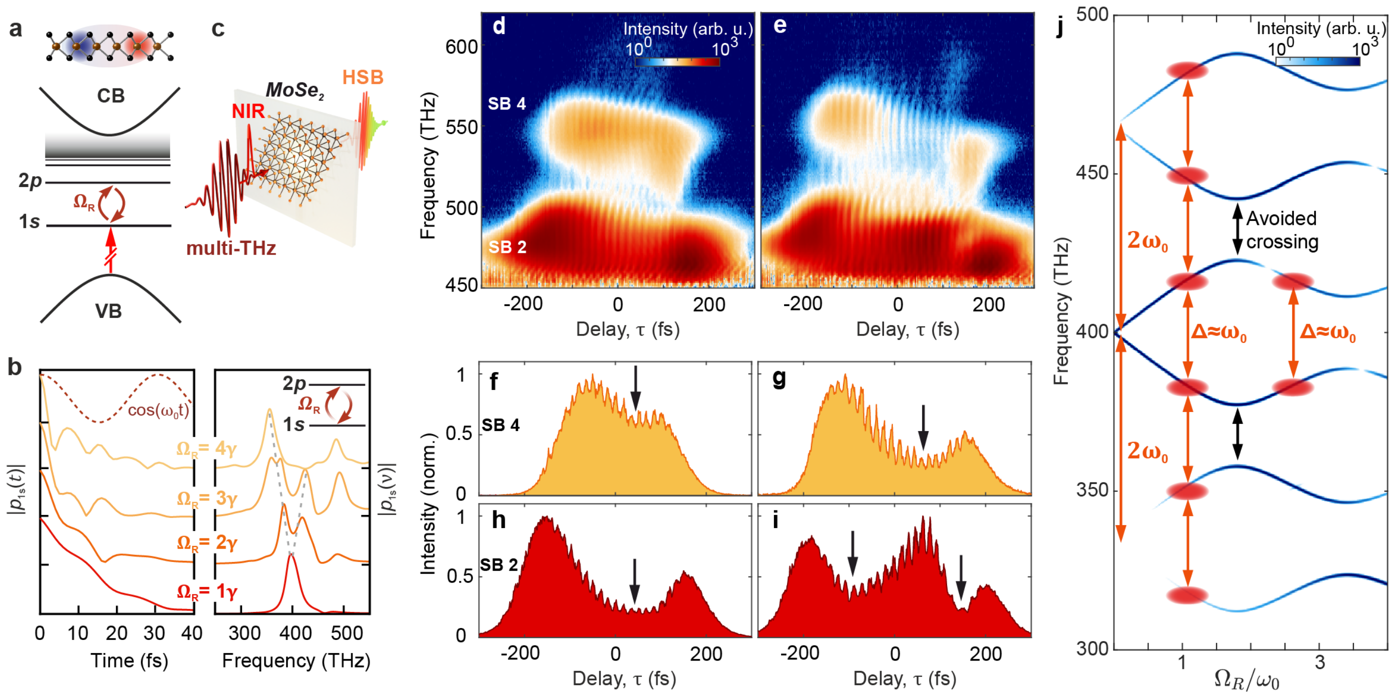

Figure 1 | Lightwave engineering of monolayer excitonic states. a, The excitonic 1*s*-2*p* transition is driven by a resonant multi-THz field, at a Rabi frequency Ω_R. **b**, Simulated two-level spectro-temporal evolution of the induced polarization by the 1*s* state (P_{1s}) for increasing ratios of Ω_R/γ, (γ: decoherence rate). An optical cycle of the resonant driving field is shown (dashed red). ω_0: 1*s*-2*p* resonance frequency. Visible Rabi oscillations only appear as the Rabi frequency exceeds the decoherence rate, leading to subcycle oscillations and generating HSB. Dashed gray guides mark the linear splitting expected within the Autler-Townes (AT) picture. The curves are artificially offset for clarity. **c**, Experimental scheme. A weak NIR femtosecond pulse resonantly prepares excitons in the 1*s* state in monolayer $MoSe_2$ and the dynamics are captured by HSB measurements. **d-i**, HSB measurements at peak electric field strength of (d) 3.0 MV/cm, and (e) 4.0 MV/cm. Corresponding spectrally integrated intensity of the second-order (red shaded, bottom row) and fourth-order (yellow shaded, top row) sidebands. Arrows indicate the positions of intensity minima in the sideband signals. **j**, Floquet analysis of the emission by the 1*s*-2*p* two-level system. Floquet sidebands appear at $2\omega_0$ intervals. Δ represents the frequency gap between inequivalent Floquet quasi-energies. HSB is enhanced when $\Delta \approx \omega_0$, driving transitions across the entire Floquet branch to lie within the multi-THz pulse bandwidth (red shading).

[1] E. J. Sie et al., Science **355**, 1066 (2017).
[2] C. K.Yong et al., Nat. Mater. **18**, 1065 (2019).
[3] K. Q. Lin et al., Nat. Phys. **15**, 242 (2019).
[4] Y. Kobayashi, Nat. Phys. **19**, 171 (2023).
[5] C. Poellmann et al., Nat. Mater. **14**, 889 (2015).
[6] B. Zaks et al., Nature **483**, 580 (2012).
[7] F. Langer et al., Nature **533**, 225 (2016).
[9] M. Borsch et al., Science **370**, 1204 (2020).
[10] J. Freudenstein et al., Nature **610**, 290 (2022).

Quantum memory for hard X-ray photons in the stationary nuclear absorbers

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Hard X-ray - nuclear interfaces offer unique potential advantages over optical-atomic systems for room temperature, solid-state quantum information processing, including lower background noise, tighter photon focusing, larger bandwidth, larger emitters densities, and exceptionally high resonance qualities.

Quantum memories, enabling reliable storage and retrieval of quantum states of light in atomic medium are required for the long-distance quantum networks, synchronization of different processes in quantum computation and realization of on-demand single photon sources. While several memory protocols have been realized for optical photon qubits, the storage of hard X-ray photons has remained an outstanding challenge. Recently, nuclear quantum memory has been demonstrated for the first time in hard X-ray range in a set of synchronously moving nuclear absorbers [1]. However, on-demand retrievals of stored photons in such a setup has not been achieved. In this work we consider two protocols for realization of on-demand quantum memory in the stationary absorbers (which extend the optical gradient echo memory and atomic frequency comb techniques to the hard-X-ray range) and evaluate the feasibility of their experimental demonstration [2,3].

[1] S. Velten, L. Bocklage, X. Zhang, K. Schlage, A. Panchwanee, I. Sergeev, O. Leupold, A.I. Chumakov, O. Kocharovskaya, R. Röhlsberger, *Science Advances* **10**, eadn9825 (2024).
[2] E. Kuznetsova, X. Zhang, Yu. Shvyd'ko, M.O. Scully, O. Kocharovskaya, *Phys. Rev. Lett.* **133**, 193401 (2024).
[3] Y. Shi, X. Zhang, Yu. Shvyd'ko, O. Kocharovskaya, On-demand Zeeman nuclear frequency comb quantum memory, arxiv.org/abs/2508.18645

Hafnian master theorem and quantum supremacy

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Many-body quantum systems possess quantum supremacy over classical computers. It is related to quantum processes which description is #P-complex, i.e., cannot be computed in polynomial time. We disclose the nature of quantum supremacy via the hafnian technique based on the Hafnian Master Theorem found in [1,2]. It provides a generating function for hafnians - the matrix functions which, in the general case, are #P-hard to compute. Amazingly, this generating function is easily computable in polynomial time.

We show universality of the hafnian technique for addressing every #P-complex problem (in accord with Toda's theorem on a polynomial-time reduction relative to a #P oracle) [3,4]. We unveil the mystery of quantum supremacy that is no more complex than a multivariate Fourier series integration. For instance, we elaborate on quantum advantage of the atomic, photonic and hybrid boson sampling [5-7] as an example of quantum simulation.

References

1. V. V. Kocharovsky, Vl. V. Kocharovsky, and S. V. Tarasov, The Hafnian Master Theorem, Linear Algebra and Its Applications **651**, 144-161, 2022.

2. V. V. Kocharovsky, Vl. V. Kocharovsky, and S. V. Tarasov, Atomic boson sampling in a Bose-Einstein-condensed gas, Phys. Rev. A **106**, No. 6, 063312, 2022.

3. V. V. Kocharovsky, Universal nature of quantum supremacy, J. Phys.: Conf. Ser. **2894**, 012002, 2024 (6 pages, open access); DOI: 10.1088/1742-6596/2894/1/012002.

4. V. V. Kocharovsky, Vl. V. Kocharovsky, S. V. Tarasov, Unification of the Nature's Complexities via a Matrix Permanent—Critical Phenomena, Fractals, Quantum Computing, #P-Complexity, Entropy **22**, 322, 2020.

5. V. V. Kocharovsky, Vl. V. Kocharovsky, W. D. Shannon, and S. V. Tarasov, Towards the Simplest Model of Quantum Supremacy: Atomic Boson Sampling in a Box Trap. Entropy 25(12), **1584**, 2023.

6. V. V. Kocharovsky, Hybrid Boson Sampling, Entropy **26**(11), 926, 2024.

7. V. Kocharovsky, Boson Sampling from a Multimode Cavity Containing Bose-Einstein Condensate, 2025 IEEE International Conference on Quantum Computing and Engineering (QCE) **01**, 1063-1068, 2025; DOI: 10.1109/QCE65121.2025.00118.

Gravitational wave detection with space-based optical lattice clocks

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With optical lattice clock comparisons beginning to reach fractional frequency precisions of 10^{-20} and below $[1-4]$, they are now approaching the level of performance required to measure the Doppler shifts of space-craft induced by gravitational waves [5]. In this talk I will present the motivations for gravitational wave detection with a network of space-based optical lattice clocks, and will explain the basic operating principles and design considerations for such a detector. I will present recent work analyzing detector capabilities and performance requirements, including the pulse sequences and data processing protocols for detecting and localizing a specific gravitational wave event. Finally, I will present our recent progress and future plans for experimentally testing and validating these concepts with a testbed consisting of a tabletop network of strontium optical lattice clocks.

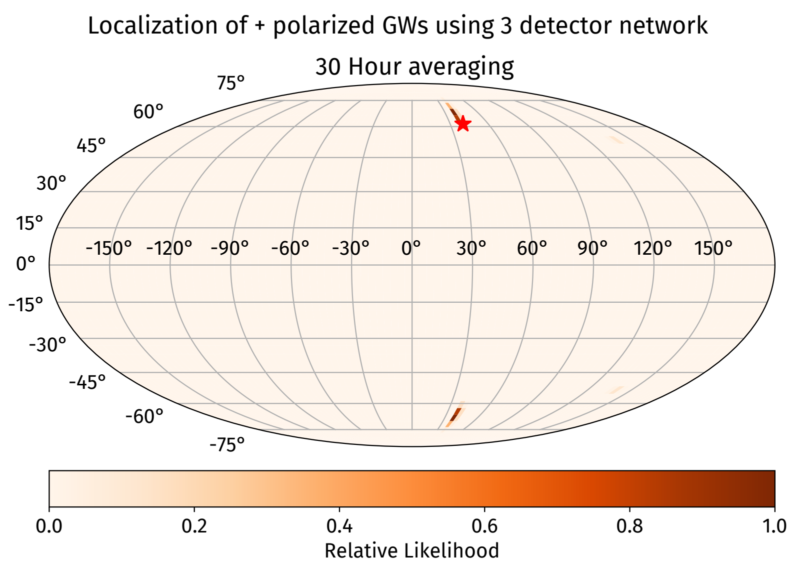

Figure 1: Sky map showing simulated localization of a monochromatic, + polarized gravitational wave source after 30 hours of averaging using a hypothetical network of 3 space-based optical lattice clock detectors. The red star shows the true location of the simulated source. Here each detector consists of two drag-free spacecraft, each with an optical lattice clock on board, linked across a single optical baseline, with similar atom numbers, laser powers, and pulse sequences as described in Ref. [5]. The simulated data and analysis are preliminary and this figure is as yet unpublished.

[1] X. Zheng, J. Dolde, V. Lochab, B.N. Merriman, H. Li, and S. Kolkowitz, "Differential clock comparisons with a multiplexed optical lattice clock," *Nature* **602**, 425-430 (2022).
[2] T. Bothwell, C.J. Kennedy, A. Aeppli, D. Kedar, J.M. Robinson, E. Oelker, A. Staron, and J. Ye, "Resolving the gravitational redshift across a millimetre-scale atomic sample," *Nature* **602**, 420-424 (2022).
[3] X. Zheng, J. Dolde, M.C. Cambria, H.M. Lim, and S. Kolkowitz, "A lab-based test of the gravitational redshift with a miniature clock network," *Nature Communications*, **14** 4886 (2023).
[4] K. Kim, A. Aeppli, W. Warfield, A. Chu, A.M. Rey, and J. Ye, "Atomic coherence of 2 minutes and instability of 1.5×10^{-18} at 1 s in a Wannier-Stark lattice clock," *PRL* **135**, 103601 (2025).
[5] S. Kolkowitz, I. Pikovski, N. Langellier, M.D. Lukin, R.L. Walsworth, and J. Ye, "Gravitational wave detection with optical lattice atomic clocks," *Physical Review D* **94**, 124043 (2016).

Geometry and Topology in Cavity QED

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Topological properties of physical systems occur in a wide variety of settings, with robust measurable characteristics that depend on dimensionality, symmetries, and non-equilibrium drive. In this talk, I discuss two recent projects where we have studied the role of topology in cavity QED. In the first project, I introduce a topological phase known as the anomalous Floquet photon pump (AFPP) whose natural topological response involves quantized conversion of photons from one frequency to another. I discuss its connection to a more famous topological phase – the anomalous Floquet insulator – and introduce a very simple model for realizing the AFPP using a time-dependent Jaynes-Cummings Hamiltonian. In the second project, I consider the prospect of using topological edge modes in photonic cavity arrays to mediate long-range coupling between qubits. I show that an infinite-range RKKY-type interaction is mediated by topological edge modes in a photon Chern insulator and with magnitude that is unaffected by the distance between qubits. Away from perturbatively weak coupling of the qubits to the photons, I show that robust interactions persist with non-vanishing fidelity, suggesting a potential route to use topological edge modes for increasingly robust qubit-qubit interactions.

A Surprising Systematic Effect from the Interplay of Spontaneous Emission and Many-Pulse Atom Interferometry

Tim Kovachy, Department of Physics and Astronomy and Center for Fundamental Physics, Northwestern University

The field of light-pulse atom interferometry is rapidly advancing. An especially active area of growth is long-baseline atom interferometry. Motivated by goals such as dark matter searches, gravitational wave detection, and fundamental tests of gravity and of quantum mechanics, multiple terrestrial instruments at the 10-meter scale and beyond are being developed around the world [1]. The community is also investigating prospects for atom interferometers with even longer baselines in space [2].

For these detectors to achieve their scientific goals, hundreds to thousands of laser pulses will need to be applied to amplify the response of the interferometer phase to signals of interest [1, 2]. In this talk, I will describe experimental and simulation studies of a surprising systematic effect that can emerge from the interplay of these many-pulse atom interferometers and spontaneous emission [3]. The effect manifests as a spurious interference signal which can have large fringe visibility, in some cases obscuring the signal the instrument aims to measure. I will explain why this effect occurs and present a method to suppress it [3]. Since spontaneous emission is ubiquitous in quantum systems, the same effect may become relevant for a wide range of quantum sensors as advances in quantum control techniques enable increasingly complex pulse sequences to boost sensitivity.

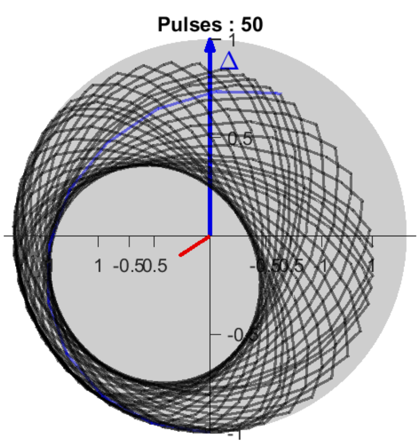

Figure: Bloch sphere visualization of the states (black arcs) of atoms that have undergone spontaneous emission at different times during the interferometer sequence and been manipulated by subsequent pulses. For the example pulse sequence here, these atoms have a nonzero average coherence, yielding a large spurious interference signal.

[1] S. Abend et al., *AVS Quantum Science* **6**, 024701 (2024).

[2] Y. A. El-Neaj et al., *EPJ Quantum Techno*logy **7**, 6 (2020).

[3] Y. Wang et al., *Physical Review Letters* **133**, 243403 (2024).

Quantum tomography of nonperturbative harmonic light from solids

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The intersection of quantum and extreme nonlinear optics leads to fascinating phenomena in the emerging field of extreme nonlinear quantum optics. While high-harmonic generation (HHG) has gained significant interest as a non-perturbative light-matter interaction, and quantum optics explores subtle interactions between quantas of light and matter, combining these fields challenges conventional assumptions about the quantum nature of light in nonlinear processes [1-3].

A main gap in the field remains measuring the quantum state of light generated by non-perturbative nonlinear processes, which requires a sub-cycle quantum light tomography approach. Our research bridges this gap by presenting the first complete measurement of the quantum state of light from a non-perturbative nonlinear process. We measure (Fig. 1(a)) the quantum state of the 3rd harmonic driven by a mid-infrared laser out of highly ordered pyrolytic graphite (HOPG). The emitted harmonic is in the visible regime, where the quantum efficiency of detectors is sufficiently high for homodyne tomography. The vanishing bandgap of HOPG generates a non-perturbative 3rd harmonic, which we characterize in a novel homodyne scheme. This scheme mixes the signal with a strong, phase-locked coherent state local oscillator (LO), derived from a zinc oxide (ZnO) crystal. The ZnO generates a perturbative third harmonic LO that shares the same properties as the signal except its quantum light state. This allows reconstruction of the signal's Wigner function (Fig. 1(b)), revealing non-classical characteristics includind anti-squeezing and traces of squeezing (Fig. 1(c)).

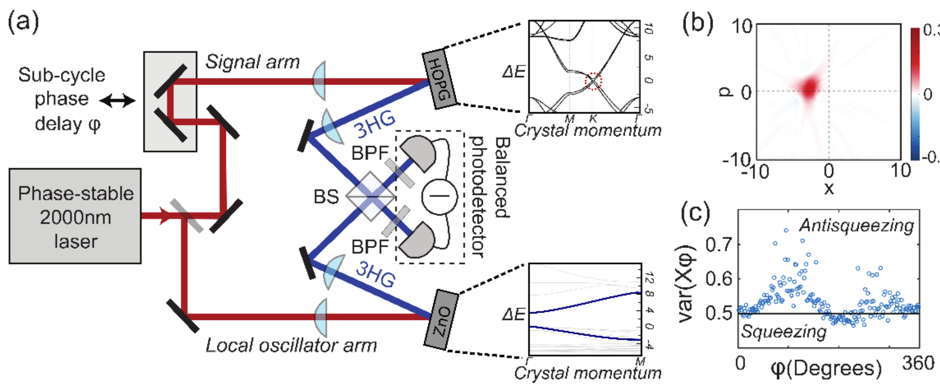

Figure 1. Homodyne measurement of non-perturbative harmonic. (a) Experimental setup: Two 3rd harmonic pulses, non-perturbative (HOPG) and perturbative (ZnO), generated by a 2 µm femtosecond laser and interfere in a homodyne scheme measuring the signal as a function of sub-cycle phase delay φ (BS: 50:50 beam splitter, BPF: bandpass filter). Insets: band structures. (b) Measured Wigner function. (c) Quadratures variance as a function of φ, showing anti-squeezing and slight squeezing.

In conclusion, our work provides a novel method to study non-perturbative HHG in solid-state materials. The measurement and comparison of the quantum properties of light generated by perturbative and non-perturbative processes will shed new light on the fundamental light-matter interactions in solid-state HHG. We envision the generation of non-classical femtosecond and attosecond light pulses in the ultraviolet and extreme ultraviolet using HHG, opening up new frontiers for quantum optics.

References

[1] A. Gorlach, et al., Nat. Phys. 19, 1689 (2023).
[2] A. Rasputnyi et al., Nat. Phys. 20, 1960 (2024).
[3] D. Theidel et al., PRX Quantum 5, 0403195 (2024).

Raman Spectroscopy in Digital Farming

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Abstract:

Plant pathogens, including viruses, bacteria, and fungi, cause massive crop losses around the world. Abiotic stresses, such as drought, salinity and nutritional deficiencies are even more detrimental. Timely diagnostics of plant diseases and abiotic stresses can be used to provide site- and doze-specific treatment of plants. In addition to the direct economic impact, this “smart agriculture” can help minimizing the effect of farming on the environment. Mounting evidence demonstrates that vibrational spectroscopy, which includes Raman (RS) and infrared spectroscopies (IR), can be used to detect and identify biotic and abiotic stresses in plants. These findings indicate that RS and IR can be used for in-field surveillance of the plant health. Surface-enhanced RS (SERS) has also been used for direct detection of plant stressors, offering advantages over traditional spectroscopies. Finally, all three of these technologies have applications in phenotyping and studying composition of crops. Such noninvasive, non-destructive, and chemical-free diagnostics is set to revolutionize crop agriculture globally. This review critically discusses the most recent findings of RS-based sensing of biotic and abiotic stresses, as well as the use of RS for nutritional analysis of foods.

High sensitivity and accuracy with a large area cold atom gyroscope

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LTE, Observatoire de Paris, Université PSL, Sorbonne Université, Université de Lille, LNE and CNRS, 61 avenue de l'Observatoire, 75014 Paris, France.

Abstract:

We present a measurement of the rotation rate using a large-area (11 cm²) cold atom interferometer based on a four-pulse Raman configuration. It offers both high sensitivity and high accuracy. We interrogate the atoms in a fountain-type four-pulse Raman configuration, thereby achieving a symmetrical double-loop geometry folded in space, sensitive to the Sagnac phase induced by the Earth's rotation. Such a configuration makes it insensitive to acceleration [1]. We performed atomic phase shift measurements along the two horizontal axes in different orientations of the platform supporting the experiment relative to true north. We obtained a concordance of around 20 ppm between the experimental measurement of the Sagnac effect and that predicted from the experimental parameters. This corresponds to a twenty-five-fold improvement in the measurement of the Sagnac effect with matter waves compared to previous results[2].

This cold atom gyroscope represents the state-of-the-art in sensitivity, with a long-term stability of of 3.10^{-10} $rad.s^{-1}$ thanks to methods that efficiently average the sampling inertial noise in this type of cold atom sensor. It relies on both real-time compensation of vibration noise on Raman phase noise and interleaved methods [3]. Such methods can be essential in applications requiring high sensitivity in a short time frame and being limited by the detection noise, ultimately by the quantum projection noise. We will present alternative methods of real-time vibration compensation, demonstrated on the gyroscope, which can also be used for such applications and in particular for space interferometers in which the atoms have no velocity relative to the diffraction lasers.

[1] "Tailoring multi-loop atom interferometers with adjustable momentum transfer", L. A. Sidorenkov, R. Gautier, M. Altorio, R. Geiger, A. Landragin, Phys. Rev. Lett. 125, 213201 (2020).
[2] "Accurate measurement of the Sagnac effect for matter waves", R. Gautier, M. Guessoum, L. A. Sidorenkov, Q. Bouton, A. Landragin, R. Geiger, Science Advances, Vol. 8, no. 23, eabn8009 (2022).
[3] "Interleaved Atom Interferometry for High Sensitivity Inertial Measurements", D. Savoie, M. Altorio, B. Fang, L.
A. Sidorenkov, R. Geiger, A. Landragin, Science Advances, Vol. 4, no. 12, eaau7948 (2018).

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Metasurfaces in Laser Cooling and Trapping of Atoms Towards Miniaturized Cold Atom Platforms

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This study proposes and experimentally validates a compact scheme for preparing arrays of individual cold atoms using flat optics based on the geometric-phase metasurfaces. Our approach leverages the ability of metastructures to control the phase, amplitude, and polarization of light at subwavelength resolution to produce the tailored wavefronts required for magneto-optical trapping (MOT) and dipole optical trapping (ODT) of alkali-metal atoms. By replacing conventional bulky optical elements with planar metasurfaces, the proposed system enables the efficient generation and manipulation of atomic arrays within a highly compact platform.

Arrays of individual cold neutral atoms have emerged as powerful platforms for quantum metrology, computation, and networking owing to their long coherence times, scalability, and reconfigurability. However, further miniaturization of atom-trapping systems is hindered by the size and complexity of conventional optical components employed in the magneto-optical trap (MOT) and the optical dipole trap (ODT) configurations. To address this limitation, we introduce a metasurface-based design that performs all essential optical functions—beam shaping, focusing, and polarization control—within a single flat element. In this scheme, a Pancharatnam–Berry (PB) phase or geometric metasurface is used to simultaneously manipulates circular polarization states and spatial phase profiles to generate diffraction wavefronts required for the magneto-optical cooling of alkali-metal atoms. The cooled atoms are then arranged into periodic arrays using holographically generated optical tweezers produced by a metasurface hologram. This approach demonstrates that metasurfaces can efficiently generate and control atom-trapping fields without auxiliary optics, providing enhanced stability and scalability. The integration of metasurface-based MOT and ODT systems thus represents a significant step toward compact, robust quantum platforms for applications in quantum information processing, precision metrology, and fundamental atomic physics.

Raman Spectroscopy and Machine Learning for Biomedical Applications

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University at Albany, State University of New York

Raman spectroscopy combined with artificial intelligence is uniquely suitable for characterizing complex heterogeneous systems. This approach is widely utilized for probing the structure and (bio)chemical composition of samples that is important for many practical applications including material science, pharmaceutical industry, etc. Here, we will discuss a great potential of Raman spectroscopies for disease diagnostics including the development of screening saliva and blood tests for Alzheimer's disease (AD) and Sjögren's disease (SjD). This approach was also utilized successfully for Duchenne Muscular Dystrophy detection in blood serum of mice. Raman microspectroscopy of individual red blood cells was demonstrated to differentiate patients with Celiac disease relative to healthy controls. Using animal models allows for conducting longitudinal studies of disease progression within a few months and evaluate the potential of the diagnostics at the early stages of the disease.

The recent success of mRNA-based COVID-19 vaccines has highlighted the potential of RNA-based therapeutics. However, using RNA-based therapeutics is limited by special storage conditions needed to keep RNA stable. For example, an improper temperature control results in the loss of approximately half of the vaccines distributed worldwide. The current methods used for assessing the quality of vaccines are labor-intensive, require specialized training and laboratory environments, and are resource-intensive and time-consuming. Notably, these methods cannot be performed in situ and require the destruction of samples before analysis. We have developed the first nondestructive, in situ method based on deep–UV resonance Raman (DUVRR) spectroscopy for probing the stability of mRNA vaccines. Specifically, a vaccine model was subjected to controlled degradation using RNase A or through aging at room temperature. The degradation of mRNA was confirmed using a cell transfection test and by gel electrophoresis. Under both settings, DUVRR spectroscopy successfully revealed mRNA degradation signs of the vaccine model.

The Atom and the Vacuum

Gerd Leuchs
Max Planck Institure for the Science of Light

Abstract

The vacuum stimulates the atom to decay. In this sense the vacuum determines the dynamics of the atom and the atom probes the properties of the vacuum. By using appropriate boundary conditions, the vacuum can be modified affecting the observed lifetime. We focussed on the coherence properties of the radiation emitted by a single trapped atom and the extend to which it depends on the details of the experiment.

Poster Presentation

Title: Photon statistics in photosynthetic light harvesting

Authors: **Quanwei Li**[1,2], Liwen Ko[1,2], K. Birgitta Whaley[1,2]*, and Graham R. Fleming[1,2,3]*

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Abstract:
Photosynthesis *in vivo* is driven by sunlight, an ultra-weak incoherent thermal source. However, most experiments and theories have studied photosynthetic light harvesting driven by strong coherent laser sources. The quantum states of light are characterized by their photon statistics, in addition to classical properties such as intensity and frequency spectrum. Here, we report experiments that investigate how photon statistics affect a natural photosynthetic system and vice versa [1]. Employing a home-built time-resolved quantum light spectroscopy setup [2], we directly compare how single photons and pseudothermal light from spontaneous parametric down conversion drive light harvesting in the light-harvesting 2 complex from a purple bacterium. We find that the fluorescence lifetime and quantum efficiency are unchanged while the fluorescence photon statistics are dramatically different, resembling that of the incident light, implying that the dynamics do not fundamentally modify the photon statistics. This represents a step towards clarification of the similarities and differences between photosynthetic light harvesting in laboratory and in natural sunlight conditions.

References:
[1] Quanwei Li, Liwen Ko, K. Birgitta Whaley, and Graham R. Fleming. “Comparing photosynthetic light harvesting of single photons and pseudothermal light under ultraweak illumination”. ***Sci. Adv.*** **11**, eadz2616 (2025)

[2] Quanwei Li, Kaydren Orcutt, Robert L. Cook, Javier Sabines-Chesterking, Ashley L. Tong, Gabriela S. Schlau-Cohen, Xiang Zhang, Graham R. Fleming & K. Birgitta Whaley. “Single-photon absorption and emission from a natural photosynthetic complex”. ***Nature***, **619**, 300–304 (2023).

Gravitational Photon Echo using Thorium-229 nuclear clock transition

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A gravitationally induced photon echo based on the 8.4 eV Thorium-229 nuclear clock transition on Earth is theoretically investigated. With an exceptionally narrow linewidth of approximately 1 mHz and a high quality factor in the order of 10^{19}, the Thorium-229 clock transition enables the exploitation of gravitational redshift effects at millimeter-scale altitude variations. A height difference between two Thorium-229-doped targets results in a mode spacing between their respective nuclear absorption lines. Based on this picture, we explore the generation of a coherent photon echo driven by the gravitational frequency shift, either within a single extended target or across multiple remote samples. Furthermore, we will discuss strategies for the control and storage of the gravitationally induced photon echo. **[1]**.

References

[1] W.-T. Liao & S. Ahrens, arXiv:2507.00533 (2025).

The road to an optical biosensor based on quantum photonics.

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Historically, an optical biosensor has included a recognition biomolecule that generates an optical signal upon target binding and a portable optoelectronic device that measures the signal. Conventionally, the recognition molecule is immobilized on an optically active surface that generates a signal upon target binding. Looking at these biosensors the perspective of decades of development is intriguing. Instead of adding a sample to a biosensor, we can now add recognition molecules to the sample and detect spectral changes using cell phone optics. Furthermore, imaging capabilities suggest that we can analyze larger areas, such as thousands of cells in complex arrangements, without generating “average values”. Most importantly, the detector can be both portable and remote from the recognition molecules and without any direct contact with the sample. For the first time, we can envision continuous, long-term measurements in living cells, three-dimensional tissues, and even intact animals. Quantum optics are already being implemented for illumination of two-dimensional areas at subsurface depths. What is needed before these approaches can be used for optical biosensing? What are barriers to decreased cost, portability, and simplicity of use? Perhaps more importantly, what are the motivations for overcoming these barriers?

Hybrid quantum simulation and city-scale quantum networking with trapped ions

Norbert Linke
Duke University

Abstract

High-energy physics models are computationally challenging due to the bosonic Hilbert space and the complex interactions involved. Trapped-ions are a powerful platform for quantum computing but mapping boson modes to qubits is costly. The motional modes of trapped ions are a quantum resource that can be used directly for the efficient simulation of bosons. We describe first results from an analog-digital hybrid quantum simulation of the Yukawa model that employs digital gates and qubits in combination with motional modes along multiple directions [1].

Secondly, we present a quantum network node based on Strontium ions that emit photons at 1092 nm with a polarization state that is entangled with a meta-stable D-level qubit in the emitting ion. The wavelength transmits through optical fiber with moderate loss allowing for quantum network links of a few kilometers for a city-scale quantum network. We present the first set of results from this experiment transmitting the photons over commercial optical fiber, 2.8 km in length, deployed in the field, stretching between two buildings in a downtown area [2].

[1] A. Than et al., arXiv:2509.11477

[2] M. Zalewski et al., arXiv:2506.11257

Superradiant lasing from a quantum many-body emitter

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In conventional lasers, the emitters are typically incoherent, radiating photons independently; in superradiant lasers, many coherent emitters radiate photons collectively, but they essentially do not interact with each other. Here, we present the concept of quantum many-body laser (QMBL), in which the emitters interact coherently and radiate collectively. To prove the concept of QMBL, we consider the Lipkin-Meshkov-Glick (LMG) model as a quantum many-body emitter, in which the all-to-all one-axis twisting interaction between many spin-1/2's causes quantum squeezing of the spins. Through the collective interaction between the spins and the cavity field, the quantum squeezing within the spins is transferred to the light during collective emission, leading to a squeezed superradiant laser. We identify three distinct phases of the pumped LMG system in a cavity (see Fig. 1), namely, a non-lasing normal phase, a superradiant lasing phase, and a bistable phase. In the bistable phase, the system can jump between the lasing state and the thermal state of photons through a first-order transition. In both lasing phases, the spin-spin interactions induce correlated fluctuations in the amplitude and phase of the collective spins and photons, that is, the number-phase squeezing. Several experimental platforms currently available in laboratories could be used to realize a quantum many-body laser, including defect spins in solid system and Rydberg atoms. This work illustrates the concept of using pumped quantum many-body emitters to generate bright quantum light with quantum correlations beyond conventional optical coherence, which can facilitate the study of nonlinear optics in the quantum realm and novel quantum technologies.

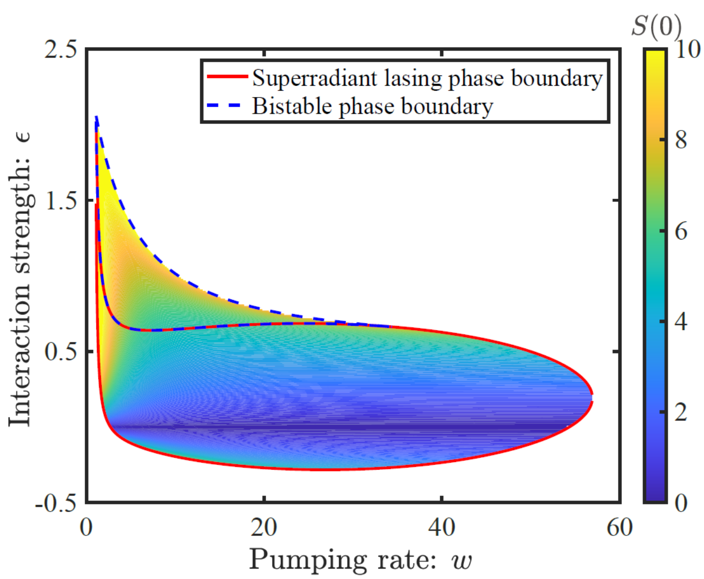

Figure 1. Phase diagram of a quantum-many body lasing system and the squeezing in different regions as a function of the pump rate and the spin-spin interaction strength in the LMG model.

This work was done in collaboration with Dawu Xiao and Chong Chen and was supported by the National Natural Science Foundation of China/Hong Kong RGC Collaborative Research Scheme (Project CRS_CUHK401/22) and the New Cornerstone Science Foundation.

Two-atom correlations in a continuous cold atom beam

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A two-atom interferometer introduces two different yet indistinguishable alternatives for randomly paired atoms to create a joint atom-detection event. The superposition of the two-atom amplitude yields features that are distinctly different, and in common configurations, preferable, to traditional atom interferometry: (1) two-atom interference is still observable when the time delay of the interferometer is greater than the coherence time of the atom beam and (2) two-atom interference may eliminate phase noises, including background, variation, turbulence and Raman laser induced phase noises; thereby allowing for higher sensitivity and stability for sensing applications. In the case of ultra-cold atom clouds, observation of two-atom interference can be readily achieved due to the long de Broglie wavelength compared to the distance between atoms at such low temperatures, as well as the large number of atoms that can be observed within a typical measurement. However, for sensing applications, an atom interferometer based on a continuous atom source is preferable. Unfortunately, such a source generally results in low atom-number density and short coherence lengths which introduces additional challenges.

We present an experimental demonstration of second-order temporal and spatial correlations for a continuous cold atom beam, analogous to the Hanbury Brown and Twiss (HBT) experiment in the 1950s. Although the beam is derived from a pure 2D magneto-optical trap, which limits both the atom density and temperature, fluctuation correlations are observed through two-atom joint-detection events at separate space-time locations.

Towards frequency metrology with trapped highly charged ions

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Abstract: A plethora of forbidden transitions of various multipolarities can be found in many isoelectronic sequences that are realizable with highly charged ions. Moreover, such transitions span an energy range extending up to X rays. This enables frequency metrology in the extreme ultraviolet region, where electronic states with larger quantum electrodynamics effects, nuclear-size contributions and greater sensitivity to new physics can be accessed. For this purpose, we are working on exciting cold trapped highly charged ions using an extreme ultraviolet frequency comb based on high harmonic generation.

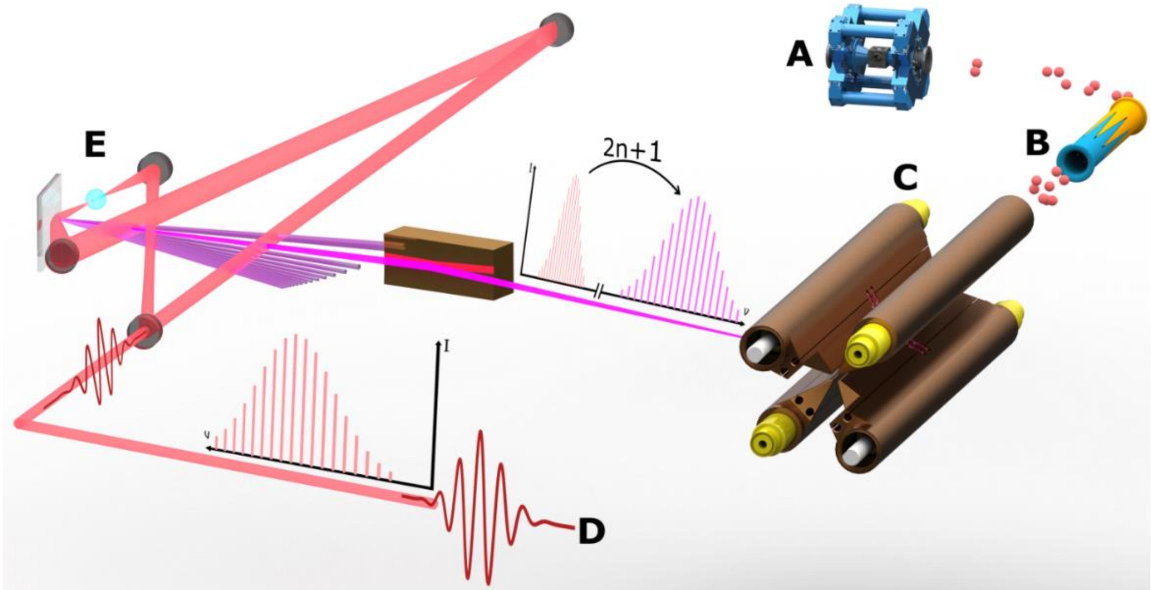

Figure 1. Sketch of our experiment combining trapped highly charged ions and a XUV frequency comb: (A) electron beam ion trap for generation of highly charged ions; (B) pulsed decelerating buncher for slowing down and transfer of the ions to the (C) superconducting RF trap; (D) XUV frequency comb produced in an (E) enhancement cavity where high-harmonic generation from an infrared frequency comb occurs at 100 MHz repetition rate is used to excite the trapped ions.

[1] Kozlov, M. G., et al., Rev. Mod. Phys. **90**, 045005 (2018)
[2] Schüssler, R. X, et al., Nature **581**, 42 (2020)
[3] Lyu, C., et al., Phys. Rev. Lett. **125** 093201 (2020)
[4] Rehbehn, N. H., et al., Phys. Rev. Lett. **131**, 161803 (2023)
[5] Schmöger, L., et al., Science **347**, 1233 (2015)
[6] Micke, P., et al., Nature **578**, 60 (2020)
[7] King, S. A., et al., Phys. Rev. X **11**, 041049 (2021)
[8] King, S.A., et al. Nature **611**, 43 (2022)
[9] Cheung, C., et al., Phys. Rev. Lett. **135**, 093002 (2025)
[10] Spieß L. J., et al., Phys. Rev. Lett. **135**, 043002 (2025)
[11] Wilzewski, A., et al., Phys. Rev. Lett. 134, 233002 (2025)
[12] Nauta, J. et al., Opt. Express **29**, 2624 (2021)
[13] Stark J. et al., Rev. Sci. Instrum. **92**, 083203 (2021)
[14] Rüffert, L. A., et al., Phys. Rev. A **110**, 063110 (2024)

Next-generation timekeeping with optical lattice clocks

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Optical lattice clocks rely on thousands of ultracold atoms confined in the Lamb-Dicke regime via an optical lattice to realize unprecedented timekeeping capability. For several years, lattice clocks have reported systematic uncertainty at the 10^{-18} fractional frequency level, making them viable tools for testing general relativity. We describe the recent development and measurements of a transportable ytterbium optical lattice clock, towards a test of the relativistic gravitational redshift at new levels of precision. We have operated the lattice clock on a Colorado mountain summit at elevation >4000 m, and in order to measure the redshift, have made preliminary efforts to link the clock to a low-elevation reference clock. Looking ahead to even more precise tests of fundamental physics, we also describe recent activity to realize next-generation clock uncertainty in the lab, towards the goal of 10^{-20} fractional frequency.

Extending Ramsey coherence of solid-state spins via cavity-mediated interactions

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Ensembles of two-level systems are foundational for quantum technologies. A fundamental property of any ensemble is the Ramsey coherence time T_2^*, generally set by the inhomogeneous linewidth and limiting the performance of clocks, sensors, and memories. Here we use $^{171}Yb^{3+}$ spins in $CaWO_4$ coupled to a microwave resonator to engineer unitary cavity-mediated interactions that generate one-axis twisting dynamics and open a many-body energy gap, suppressing inhomogeneous dephasing. Leveraging this mechanism, we show extension of T_2^* from $52(3)\ \mu$s to $3.3(2)$ ms and realize an echo-free microwave spin memory with on-demand optical readout. The extended coherence enabled by the spin-exchange interaction opens a previously inaccessible space of applications requiring millisecond or longer T_2^*, including quantum sensors and spin quantum memories for superconducting qubits.

Integrated Nanophotonics with Colloidal Materials

A key obstacle for all quantum information science and engineering platforms is their lack of scalability. The discovery of emergent quantum phenomena and their applications in active photonic quantum technologies have been dominated by work with single atoms, self-assembled quantum dots, or single solid-state defects. Unfortunately, scaling these systems to many quantum nodes remains a significant challenge. Solution-processed quantum materials are uniquely positioned to address this challenge, but the quantum properties of these materials have remained generally inferior to those of solid-state emitters or atoms. Additionally, systematic integration of solution-processed materials with dielectric nanophotonic structures has been rare compared to other solid-state systems. In this talk I will describe our recent effors to integrate solution processed materials to nanophotonic cavities. Additionally, I will talk about making metasurfaces out of these materials, and observing signature of few photon nonlinearity.

Bio: Prof. Arka Majumdar is a professor in the departments of Electrical and Computer Engineering and Physics at the University of Washington (UW). He is also a visiting scientist in Meta Reality Labs (2025-current). He received B. Tech. from IIT-Kharagpur (2007), where he was honored with the President's Gold Medal. He completed his MS (2009) and Ph.D. (2012) in Electrical Engineering at Stanford University. He spent one year at the University of California, Berkeley (2012-13), and then in Intel Labs (2013-14) as postdoc before joining UW. His research interests include developing a hybrid nanophotonic platform using emerging material systems for optical information science, imaging, and microscopy. Prof. Majumdar is the recipient of multiple Young Investigator Awards from the AFOSR (2015), NSF (2019), ONR (2020) and DARPA (2021), Intel early career faculty award (2015), Amazon Catalyst Award (2016), Alfred P. Sloan fellowship (2018), UW college of engineering outstanding junior faculty award (2020), iCANX Young Scientist Award (2021), IIT-Kharagpur Young Alumni Achiever Award (2022), DARPA Director's Award (2023), and Rising star of light award (2023). He is an Optica (2024) and SPIE (2025) fellow. He is co-founder and technical advisor of Tunoptix, a startup commercializing software defined meta-optics.

Quantum Heat Engine as a Sensor and Beyond: Insights from Fisher Information

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Quantum thermodynamic devices, such as coherence-assisted heat engines and quantum batteries, exhibit performance features that surpass classical limits. This talk introduces a unified framework showing how Fisher information and quantum-state geometry govern both energy conversion and sensing capabilities. For coherence-assisted quantum heat engines [see Figure 1], we show that atomic coherence imprints a measurable phase on cavity photon statistics and derive quantum Cramér–Rao bounds for optimal phase and temperature estimation. We derive geometric bounds for quantum batteries, using Fisher information, that link stored energy and charging power to the Bures length, yielding sine-of-length and range-sine laws that constrain all unitary and noisy dynamics. Applying these bounds to an m-photon charger–battery interaction, we identify the conditions under which evolution saturates the quantum speed limit, certifying genuine quantum advantage. Together, these results demonstrate that Fisher information provides a unifying resource that shapes the limits and capabilities of quantum energy devices.

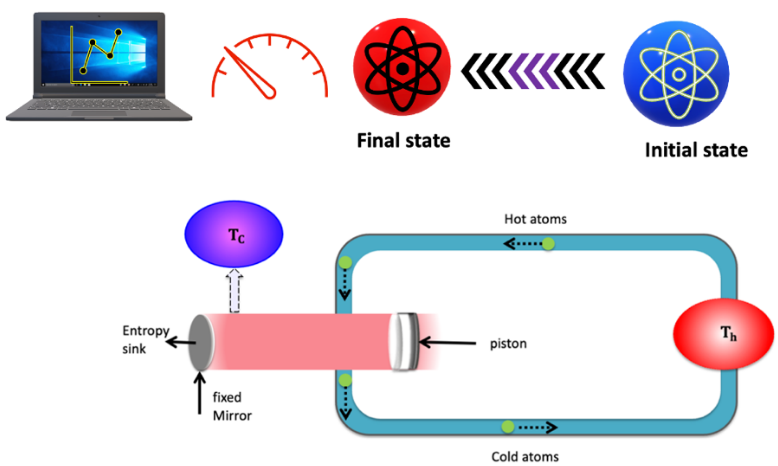

Figure 1. Quantum sensing protocol via a quantum heat engine. The top panel illustrates the general quantum sensing workflow. The bottom panel depicts a quantum heat engine device operated as a sensor.

Quantum Control as a Unifying Principle for Sensing, Metrology, and Computation

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Quantum control provides a unifying framework for advancing quantum sensing, precision metrology, and quantum information processing. In this talk, we will highlight several recent developments demonstrating how carefully engineered control protocols enable enhanced robustness, noise resilience, and metrological gain across multiple quantum platforms.

First, we will discuss pulse-area–resilient and adiabatic control techniques developed for solid-state quantum sensors based on nitrogen–vacancy (NV) centers in diamond. NV centers offer a versatile platform for gyroscopes, magnetometers, and clocks operating across a wide range of environmental conditions. Our earlier work established a rotation sensor based on ^{14}N nuclear spins using all-optical initialization/readout and double-quantum Ramsey interferometry [1], but long-term stability remained limited by magnetic-field fluctuations, temperature drift, and RF pulse errors. To address these limitations, we developed two robust protocols—STIRAP-based adiabatic control [2] and a dynamical elimination technique using modulated zero-pulse-area fields [3]—that suppress sensitivity to single-photon excitation errors while preserving two-photon coherence. We will present theoretical performance analyses and experimental demonstrations showing improved state-preparation fidelities and stable Ramsey fringes. We will also summarize our recent realization of a temperature-compensated NV spin clock [4], which achieves nearly an order-of-magnitude reduction in thermal drift through combined electronic–nuclear control and optimized two-tone readout.

Next, we will briefly describe a rapid adiabatic passage method for generating spin-squeezed states and Dicke states under an engineered one-axis-twisting Hamiltonian [5]. This protocol efficiently accesses metrologically optimal entangled states, maintains robustness to drive imperfections, and exhibits favorable time scaling for systems of up to $n \sim 10^3$ atoms. These states enable phase sensitivities surpassing the standard quantum limit and approaching the Heisenberg limit.

Finally, we will present a new Rydberg-based entangling-gate mechanism using modulated zero-pulse-area control fields [6]. This technique dynamically suppresses Rydberg population while exploiting Rydberg–Rydberg interactions to accumulate a controlled phase, enabling single-step, perfectly entangling phase gates for arbitrary blockade strengths, eliminating finite-blockade errors even when the Rabi frequency approaches or exceeds the interaction energy. Its simplicity and generality make it well-suited for scalable neutral-atom quantum computing architectures.

Together, these results illustrate how quantum control can be leveraged to enhance both the performance and practicality of next-generation quantum sensors and quantum information processors.

[1] A. Jarmola, S. Lourette, V. M. Acosta, et al., Sci. Adv. 7, eabl3840 (2021).
[2] S. Lourette, A. Jarmola, J. Chathanathil, et al., Quan. Sci. Tech. 10, 015032 (2024).
[3] S. C. Carrasco, S. Lourette, I. Sola, V. S. Malinovsky, Phys. Rev. Lett. 134, 163601 (2025).
[4] S. Lourette, A. Jarmola, J. Chathanathil, et al., to be published.
[5] S. C. Carrasco, M. H. Goerz, S. A. Malinovskaya, et al., Phys. Rev. Lett., 132, 153603 (2024).
[6] S. C. Carrasco, J. Chathanathil, S. A.Malinovskaya, et al., to be published.

Is the GFC the result of Intensity Fluctuation Correlation?

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The recently discovered the ghost frequency comb (GFC) is of both fundamental and practical interest, with demonstrations of having applications in LiDAR as well as non-local time transfer. A 50% contrast GFC has been observed in relation to the temporal correlation of a CW laser with 500,000 modes. This second-order measurement was made by splitting the CW laser to two point-like photodetectors and temporally correlating the respective outputs. Due to the nature of the experiment, the GFC would be classically described as intensity fluctuation correlations; however, the intensity fluctuations of a laser consisting of half a million modes would be extremely low. The 500,000 mode laser is equivalent to an ensemble average, resulting in a maximum intensity fluctuation on the order of 10^{-3} compared to the mean intensity value, and thus insignificant.

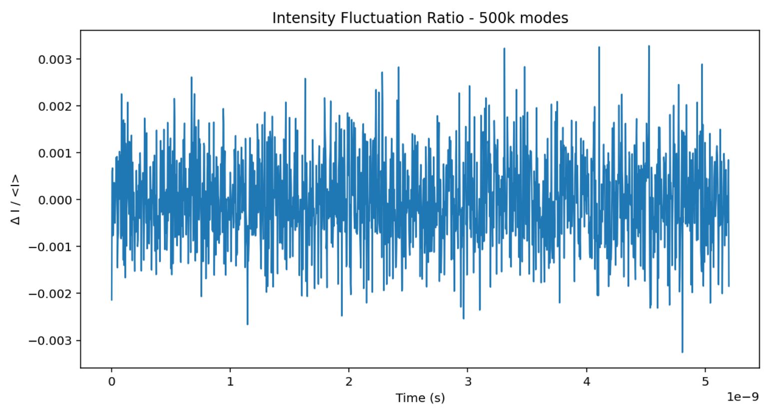

Figure 1: Numerical simulation of intensity fluctuations for a CW fiber laser with half a million cavity modes. In this simulation, the wavelength is around 1550 nm ($\nu \sim 2 \times 10^{14}$ Hz), and the mode spacing is 17 KHz where each mode has a random phase. In this simulation, 50 GHz sampling rate is applied to simulate 20 ps detection time averaging.

Based on the calculated intensity fluctuations, the intensity fluctuation correlation would be on the order of 10^{-6}. This raises the question: is the GFC the result of intensity fluctuation correlations?

In this poster, we present a numerical simulation of a 500,000 mode CW laser to find the intensity fluctuations relative to the mean intensity, as well as the intensity fluctuation correlations. The simulation was developed to mimic the experiment that found 50% contrast to show the contribution classical intensity fluctuation correlations make to the GFC contrast. Such a simulation raises the question whether the ghost frequency comb can be described as intensity fluctuations.

Title: Fast simulation of fermions with reconfigurable qubits

Abstract: Performing large-scale, accurate quantum simulations of many-fermion systems is a central challenge in quantum science, with applications in chemistry, materials, and high-energy physics. Despite significant progress, realizing generic fermionic algorithms with qubit systems incurs significant space-time overhead, scaling as O(N) for N fermionic modes. Here we present a method for faster fermionic simulation with asymptotic space-time overhead of O(log(N)) in the worst case, and O(1) for circuits with additional structure, including important subroutines like the fermionic fast Fourier transform. This exponential reduction is achieved by using reconfigurable quantum systems with non-local connectivity, mid-circuit measurement, and classical feedforward, to generate dynamical fermion-to-qubit mappings. We apply this technique to achieve efficient compilation for key simulation tasks, including Hamiltonian simulation of the sparse Sachdev-Ye-Kitaev model and plane-wave quantum chemistry simulations, as well as free-fermion state-preparation. Moreover, we show that the algorithms themselves can be adapted to use only the O(1)-overhead structures to further reduce resource overhead. These techniques can lower gate counts by orders of magnitude for practical system sizes and are natively compatible with error corrected computation, making them ideal for early fault-tolerant quantum devices. Our results tightly bound the computational gap between fermionic and qubit models and open new directions in quantum simulation algorithm design and implementation.

A fluorescent-protein spin qubit

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Optically-addressable spin quantum bits (qubits) form the foundation of several key quantum technologies with applications ranging from communication to sensing. Traditionally, the engineering of such quantum technologies has been focused on solid-state systems, such as nitrogen vacancy centers in diamond. However, biomolecules, such as proteins, have so far not been investigated as a potential qubit platform. Nevertheless, proteins would offer distinct advantages over conventional approaches and new avenues towards qubit engineering. In this talk, I will discuss our recently developed optically addressable protein-based spin qubit encoded in the metastable triplet state of an enhanced yellow fluorescent protein (EYFP) [1]. My discussion will start with the introduction of a novel fluorescent spin readout technique based on optically activated delayed fluorescence (OADF), allowing us to readout the spin with up to 40% contrast. Using coherent microwave control of the EYFP spin at liquid-nitrogen temperatures, we measure a spin-lattice relaxation time of (141±5) μs, a (16±2) μs coherence time under Carr-Purcell-Meiboom-Gill (CPMG) decoupling, and predict an oscillating (AC) magnetic field sensitivity of 183 fT mol½ Hz-½. We express the qubit in mammalian cells, maintaining contrast and coherent control despite the complex intracellular environment. Finally, we demonstrate optically-detected magnetic resonance at room temperature in aqueous solution and measure a static (DC) field sensitivity with an upper bound of 93 pT mol½ Hz-½. The demonstrated work establishes fluorescent proteins as a versatile and biocompatible platform for quantum sensing, opening new possibilities for bio-integrated quantum technologies.

[1] J. S. Feder, B. S. Soloway, S. Verma, Z. Z. Geng, S. Wang, B. Kifle, E. G. Riendeau, Y. Tsaturyan, L. R. Weiss, M. Xie, J. Huang, A. Esser-Kahn, L. Gagliardi, D. D. Awschalom, P. C. Maurer, A fluorescent-protein spin qubit, Nature 645, 73–79 (2025).

Quantum Sensing Above and Below Ground: ORGAN and CELLAR

Dr Ben T. McAllister
Swinburne University of Technology

Abstract. Quantum microwave sensors are increasingly being deployed in a variety of disparate contexts to probe new regions of parameter space in fundamental physics. In this talk I will present two examples situated literally above and below ground.

Above ground, the ORGAN program forms Australia's axion haloscope initiative, using high-Q microwave cavities in strong magnetic fields to convert axion dark matter into detectable photons. The current iterations of ORGAN operate with quantum-limited microwave measurement chains. R&D is on-going to extend ORGAN's sensitivity through squeezed-state readout, superconducting resonators, and microwave single photon detection schemes. These efforts make ORGAN a proving ground for quantum-enhanced sensing methods aimed at detecting some of the faintest electromagnetic signals accessible in fundamental physics experiments. I will report on the current status and progress of ORGAN.

Below ground, I will introduce CELLAR, a new deep underground cryogenic platform at the Stawell Underground Physics Laboratory designed for ultra-low-noise quantum sensing. CELLAR's combination of sub-10 mK cryogenics and more than a kilometre of rock overburden enables studies of superconducting quantum devices with dramatically suppressed cosmic ray backgrounds. This provides a unique opportunity for quantum-enhanced searches for high-frequency gravitational waves (MAGE, GravNet), low mass dark matter, precision timing technologies, and systematic investigations of radiation-induced decoherence mechanisms in quantum electronics.

Together, ORGAN and CELLAR showcase how quantum sensors can operate and unlock new possibilities in a range of environments, offering complementary pathways toward ultra-sensitive measurements in fundamental physics.

Quantum-optical nature of ultrafast high-harmonic generation in semiconductors

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High harmonic generation (HHG) has the potential to overcome some bottlenecks of the 2nd quantum revolution. Indeed, HHG can potentially generate many modes, high dimension, quantum states of broadband light spanning many octaves (from telecom down to visible/UV and even extreme UV spectral range) [1]. What is the strategy behind? Well, instead of freezing the quantum system in temperature, our strategy is based on freezing the system in time using ultrafast strong optical fields. Indeed, high harmonics of the driving light are emitted as attosecond burst of light, well before main decoherence channels of the system occur.

Recently, independent theoretical investigations predicted non-classical effects in this strong field laser driven process [1-3]. After few years of debate, we have reported the first experimental demonstration of the presence of non-classicality and squeezing in HHG generated on various semiconductor samples (Si, ZnO, GaAs, CdTe) [4,5]. Thorough photon statistics analysis shows that harmonics are emitted as near single-mode displaced squeezed state. Further, the high harmonic generation process can be finely controlled in spatial, spectral phase with high and complex dimensionality such as topology from beams that carry orbital angular momentum. This semiconductor-based quantum light source is a highly promising candidate for applications in the broad field of quantum information science and engineering, gaining possible quantum advantage. As an example, I will report on perspectives in condensed matter systems such as spin sensitivity of the quantum light states in cadmium telluride. These new non-classical properties extend current quantum photonic resources. To further illustrate that, I may present our first experimental investigation on the quantum non-gaussianity of the HHG source and more recent results on position-momentum correlations.

Overall, the HHG source is a quantum newcomer, opening fundamental questions and industrial perspectives in quantum information science such as quantum metrology and quantum information science.

REFERENCES

[1] Gorlach, et al. "The quantum-optical nature of high harmonic generation." Nature communications 11.1 (2020): 4598.
[2] Gombkötő et al. "Quantum-optical description of photon statistics and cross correlations in high-order harmonic generation." Phys. Rev. A 04.3 (2021): 033703.
[3] Cruz-Rodriguez et al. "Quantum phenomena in attosecond science." Nature Rev. Phys. (2024): 1-14.
*[4] Theidel et al. "Evidence of the quantum-optical nature of high-harmonic generation." Phys. Rev. X Quantum **5** (2024): 040319.* DOI: https://doi.org/10.1103/PRXQuantum.5.040319
[5] Theidel et al., "Observation of a displaced squeezed state in high-harmonic generation" Phys. Rev. Research 7 (3), 033223. DOI: https://doi.org/10.1103/6r6n-pxfp

Unravelling Turbulence with Laser Pumped, Time Delayed Quantum State Emission

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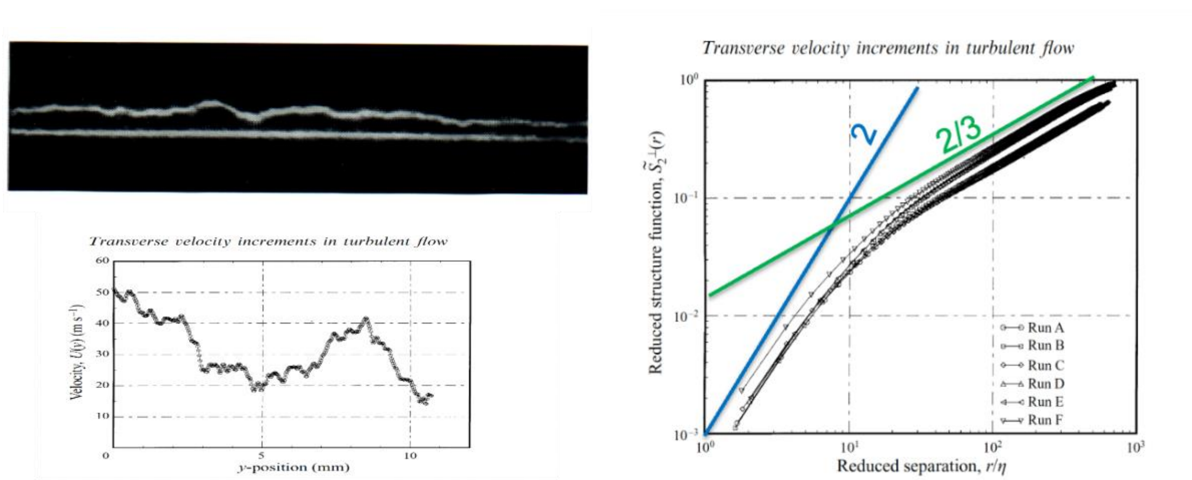
Heisenberg said "When I meet God, I am going to ask him two questions: why relativity? And why turbulence? I really believe he will have an answer for the first"

Understanding and controlling turbulence are critical areas of focus for aerospace, since the transition from laminar to turbulence dramatically changes the heating and drag of a flight vehicle, and turbulence disrupts light propagation through the atmosphere, limiting celestial navigation, long range imaging, directed energy defense, and optical communication. Turbulence comes in many forms and many scales, ranging from many kilometers to sub millimeters. Characterization of turbulence involves the measurement of both spatial and temporal fluctuations over a relevant range of scales and time intervals. Through the development of pulsed laser driven nonlinear optical excitation of molecular quantum states, molecular tagging velocimetry (MTV) has emerged as a highly effective method for the simultaneous, temporally resolved measurement of multiple turbulent scales. These methods follow the motion of the molecules and enable the acquisition of quantitative data characterizing the turbulence and, for high speed flows, turbulent shear and turbulent boundary layers. For "fully developed" turbulence, energy is transferred from the large scales to smaller scales and finally to viscous dissipation following the well-known self-similarity law first proposed by Kolmogorov (K41). It predicts a 2/3 scaling of the spatial second order structure function through the self-similar inertial subrange. Scaling in the dissipation range is quadratic. Modifications of that scaling occur due to intermittency, but the overall scaling closely follows K41. The figures below show MTV measurements of those scaling ranges.



Turbulent vertical air flow tagged and analyzed by RELIEF tracking of vibrationally tagged oxygen.

Three methods for the measuement of turbulence will be discussed: Raman Exciation plus Laser Induced Electronic Fluorescence (RELIEF), Femtosecond Laser Electronic Excitation Tagging (FLEET), and Nitric-oxide ionization induced Flow Tagging and Imaging (NiiFTI). The first two function in air, tagging oxygen and nitrogen, respectively. NiiFTI requires a small percentage of nitric-oxide, which is present in hypersonic flows due to shock induced chemical reactions.

Self-configuring spectral filters by mapping time to space

David A. B. Miller, C. Roques-Carmes, C. G. Valdez, A. R. Kroo, M. Vlk, S. Fan, and O. Solgaard
Stanford University

Meshes of integrated Mach-Zehnder interferometers (MZIs) have shown an impressive range of programmable and self-configuring optical functions for light in different spatial modes [1,2]. Though we have had many interesting and useful integrated optical spectral filters based on concepts like unbalanced interferometers, resonators, and recirculating meshes that enable programmable rings, the simple programming and self-configuration possible with "forward-only" meshes has not so far been available for spectral filtering. Now we show, both theoretically [3] and in first experiments [4], a flexible and powerful way of exploiting such meshes for fully programmable and self-configuring spectral filters.

The key concept is to use an array of waveguides of different lengths, and so of different time delays, to map different frequencies into different spatial patterns or input vectors for a self-configuring MZI mesh (Fig. 1). This time-space or frequency-space mapping allows the many interesting and powerful ideas demonstrated with such meshes for spatial beams to be transferred into time and/or frequency.

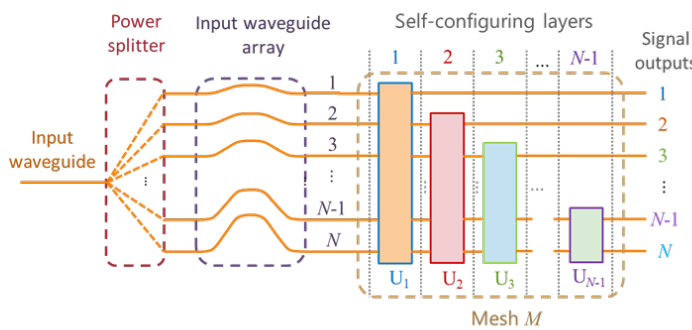


Fig. 1. Block diagram of a programmable and self-configuring spectrometer formed by adding a power splitter and a waveguide array in front of a Mach-Zehnder interferometer mesh.

In addition to conventional and fully programmable filtering operations, the approach offers self-configuring filters that tune themselves to the wavelength of interest, filters that can reject multiple arbitrarily chosen frequencies automatically, and filters that simultaneously and separately perform multiple filter functions. Proposed extensions allow very narrow line filtering without resonators (and without limitations from resonator Q-factors) with relatively small meshes and measurement and separation of partially coherent light into its mutually incoherent components. The key underlying principle of mapping time to space suggests many other interesting spectral devices may be possible even with optical structures that are not themselves intrinsically dispersive.

1. D. A. B. Miller, "Self-configuring universal linear optical component," Photon. Res. **1**, 1–15 (2013).
2. W. Bogaerts, D. Pérez, J. Capmany, D. A. B. Miller, J. Poon, D. Englund, F. Morichetti, and A. Melloni, "Programmable photonic circuits," Nature **586**, 207–216 (2020).
3. D. A. B. Miller, C. Roques-Carmes, C. G. Valdez, A. R. Kroo, M. Vlk, S. Fan, and O. Solgaard, "Universal programmable and self-configuring optical filter," Optica **12**, 1417–1426 (2025).
4. C. G. Valdez, A. R. Kroo, M. Vlk, C. Roques-Carmes, S. Fan, D. A. B. Miller, and O. Solgaard, "Programmable Optical Filters Based on Feed-Forward Photonic Meshes," (2025). http://arxiv.org/abs/2509.12059

Unified framework for classical and quantum light–matter interactions in photonic time crystals

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Photonic temporal crystals (PTCs), media with permittivity modulated periodically in time, open a dynamic route to controlling spontaneous emission beyond spatial photonic crystals. Building on the pioneering insights of Purcell [1] and Yablonovitch [2], and the more recent advances in time-varying photonics by Halevi and Pendry [3–5], we develop a unified theory that bridges non-Hermitian classical electrodynamics and quantum field quantization in temporally modulated media.

Using a Floquet–Maxwell framework, temporal modulation produces momentum gaps bounded by exceptional points and nonorthogonal eigenmodes, leading to a pronounced enhancement of the spontaneous-emission decay rate at the gap frequency. The enhancement originates from the Petermann factor, which compensates the steep band-edge slope and quantifies the nonorthogonality of Floquet modes [6–9]. Moreover, the same non-Hermitian mixing yields a nonequilibrium channel of spontaneous emission excitation, in which an atom is promoted to an excited state while emitting a photon [9].

Extending to the quantum regime, we formulate a Bogoliubov–de Gennes (BdG) description in which photon annihilation and creation operators hybridize through photon–quasiparticle mixing, characterized by a squeezing parameter [10]. The classical field amplification in PTCs thus corresponds to a localization–delocalization transition in a Floquet-synthetic lattice, where coupling a two-level atom to delocalized in-gap modes drives its Rabi oscillations into an irreversible half-and-half mixed state [11]. This framework unifies the Purcell–Yablonovitch paradigm of spatial emission control with the emerging paradigm of dynamic, time-varying photonics, providing a foundation for nonequilibrium quantum electrodynamics in temporally structured media.

[1] E. M. Purcell, Phys. Rev. 69, 674 (1946).
[2] E. Yablonovitch, Phys. Rev. Lett. 58, 2059 (1987).
[3] J. R. Reyes-Ayona, P. Halevi, Appl. Phys. Lett. 107, 074101 (2015).
[4] E. Galiffi, P. A. Huidobro, J. B. Pendry, Phys. Rev. Lett. 123, 206101 (2019).
[5] J. B. Pendry, E. Galiffi, P. A. Huidobro, J. Opt. Soc. Am. B 38, 3360 (2021).
[6] N. Wang, Z.-Q. Zhang, C. T. Chan, Phys. Rev. B 98, 085142 (2018).
[7] J. Park, B. Min, Opt. Lett. 46, 484 (2021).
[8] J. Park et al., Sci. Adv. 8, eabo6220 (2022).
[9] J. Park et al., Phys. Rev. Lett. 135, 133801 (2025).
[10] Y. Kim et al., in preparation
[11] J. Bae et al., to appear in Nat. Comm.

Integrated Semiconductor Lasers For Quantum Systems

Richard Mirin, University of California Santa Barbara and NIST

Abstract: We will discuss developments in integrated semiconductor lasers that can be used for addressing quantum systems operating at wavelengths less than 1000 nm. Distributed feedback lasers utilizing an InGaAs quantum well heterostructure wafer-bonded to a tantalum pentoxide photonic integrated circuit will be presented.

Heterogeneous materials integration of III-V semiconductors with other materials such as silicon[1], silicon nitride [2], and lithium niobate[3] is core technology for the realization of chip-scale semiconductor lasers with photonic integrated circuits, as well as for improved performance metrics. Nearly all the work in this area has focused on integration with silicon photonics, with the goal of developing high-performance semiconductor lasers for high-speed communications at wavelengths around 1310 nm and 1550 nm. However, there is an increasing interest in high-performance (especially narrow linewidth) semiconductor lasers with low size, weight, and power for quantum systems such compact clocks. In this talk, we will describe the development of integrated semiconductor lasers that use heterogeneously integrated III-V semiconductor gain regions, with InGaAs quantum wells that emit at 980 nm, with tantalum pentoxide photonic integrated circuits [4]. Progress towards monolithic optical parametric oscillators will be discussed.

[1] A.W. Fang, H. Park, O. Cohen, R. Jones, M.J. Paniccia, and J.E. Bowers, "Electrically pumped hybrid AlGaInAs-silicon evanescent laser," Opt. Express 14, 9203-9210 (2006).
[2] C. Xiang, W. Jin, J. Guo, J.D. Peters, M. J. Kennedy, J. Selvidge, P.A. Morton, and J.E. Bowers, "Narrow-linewidth III-V/Si/Si_3N_4 laser using multilayer heterogeneous integration," Optica **7**, 20-21 (2020).
[3] M. Li, C. Xiang, J. Guo, J. Peters, M. Dumont, S. Xue, J. Staffa, Q. Hu, Z. Gao, Q. Lin, and J.E. Bowers, "Heterogeneously-integrated lasers on thin film lithium niobate," Nanophotonics 14(26): 4739–4748 (2025).
[4] N. Nader, E.J. Stanton, G.M. Brodnik, N. Jahan, S.C. Weight, L.M. Williams, A.E. Dorche, K.L. Silverman, S.W Nam, S.B. Papp, and R.P. Mirin, "Heterogeneous tantala photonic integrated circuits for sub-micron wavelength applications," Optica **12**, 585-593 (2025).

Disorder-Promoted Synchronization and Coherence in Coupled Laser Networks

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Coupled lasers offer a promising approach to scaling the power output of photonic devices for applications demanding high frequency precision and beam coherence. However, maintaining coherence among lasers remains a fundamental challenge due to desynchronizing instabilities arising from time delay in the optical coupling. In this talk, we will depart from the conventional notion that disorder is detrimental to synchronization and instead propose an interpretable mechanism through which heterogeneity in the laser parameters can be harnessed to promote synchronization. Our approach allows for *stabilization of pre-specified synchronous states* that, while abundant, are often unstable in systems of identical lasers. The results show that stable synchronization enabling coherence can be frequently achieved by introducing intermediate levels of random mismatches in any of several laser constructive parameters. This talk will establish a principled framework for enhancing coherence in large laser networks and other coupled oscillator systems, offering a robust strategy for power scaling and synchronization.

Reference: Barioni AED, Montanari AN, Motter AE. Interpretable Disorder-Promoted Synchronization and Coherence in Coupled Laser Networks. *Physical Review Letters*, 135:197401 (2025).

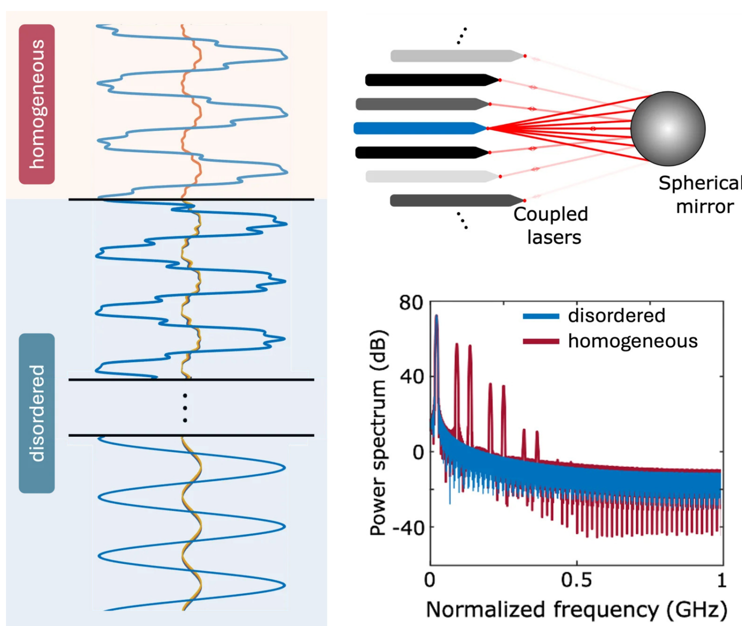

Figure 1: For a laser array externally coupled through a spherical mirror, we show the time series of the electric fields as the lasers transition from a homogeneous configuration to a disordered configuration. For the homogeneous configuration, the lasers synchronize at a limit cycle with zero phase shift but distorted waveforms, whereas the disordered configuration outputs sinusoidal waves with constant, but negligible, phase shifts among lasers. The small-amplitude signals indicate the imaginary component of the individual fields E_j, while the high-amplitude signal represents the combined field $E = \sum_j E_j$. The power spectrum of the combined steady-state field E shows that the disordered configuration attains a narrower linewidth compared to the homogeneous configuration.

Space-time nonlocal metamaterials

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In recent years, significant research efforts have been devoted to exploring new wave phenomena and enabling novel forms of wave control by relaxing traditional assumptions, including those of time-invariance [1-3] and spatial locality [4]. In this talk, I will discuss our recent work in this area and present new results on extreme wave effects enabled by the interplay between time modulation, frequency dispersion (temporal nonlocality), and spatial dispersion (spatial nonlocality), including the emergence of ultra-wide "momentum bandgaps" (Fig. 1) and new opportunities for efficient, ultra-broadband electromagnetic absorption and amplification [5-8].

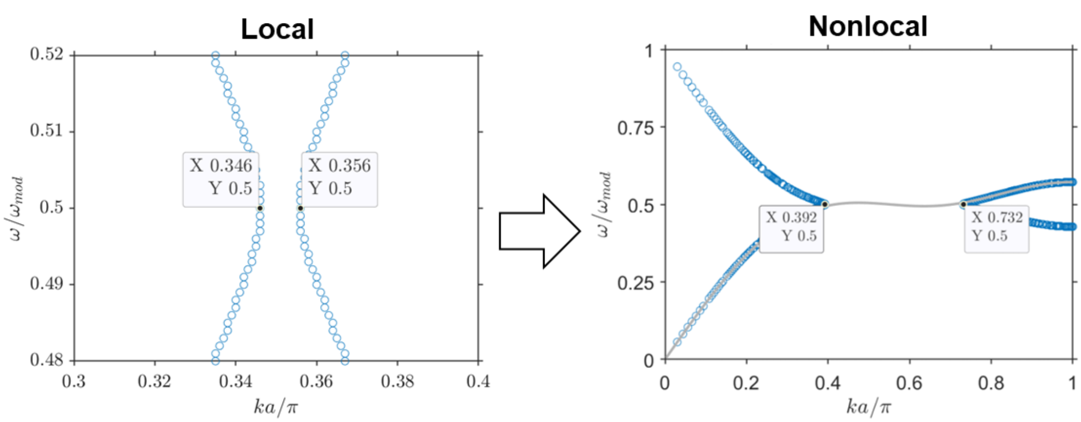

Fig. 1. Orders-of-magnitude widening of momentum bandgaps is achievable in nonlocality engineered time-varying systems.

References

[1] E. Galiffi, et al. "Photonics of time-varying media," Advanced Photonics 4, 014002-014002 (2022).
[2] Z. Hayran, and F. Monticone, "Using time-varying systems to challenge fundamental limitations in electromagnetics: Overview and summary of applications," IEEE Antennas and Propagation Magazine 65, 29-38 (2023).
[3] T. T. Koutserimpas and F. Monticone, "Time-varying media, dispersion, and the principle of causality," Opt. Mater. Express 14, 1222-1236 (2024).
[4] F. Monticone, A. Mortensen, et al. "Nonlocality in photonic materials and metamaterials: roadmap," Optical Materials Express 15, 1544-1709 (2025).
[5] M. Ciabattoni, Z. Hayran, and F. Monticone, "Observation of broadband super-absorption of electromagnetic waves through space-time symmetry breaking," Science Advances 11 (2025).
[6] Z. Hayran, J. B. Pendry, P. P. Iyer, F. Monticone, "Pulse-driven photonic transitions and nonreciprocity in space-time modulated nonlocal metasurfaces" under review (2025).
[7] M. Ciabattoni, and F. Monticone, "Enhancing momentum bandgaps with nonlocality," in preparation (2025).
[8] M. Ciabattoni and F. Monticone, "Nonlocal time-varying microwave systems," in preparation (2025).

Sub-Wavelength Semiconductor Nanocavities for Nanoscale Light Sources

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We present recent advances in the development of sub-wavelength semiconductor nanocavities and their application in nanolasers and nanoLEDs. By leveraging bowtie-shaped geometries, we demonstrate optical confinement significantly below the diffraction-limited mode volume, defined as $(\lambda/2n)^3$, where λ is the wavelength and n the refractive index. This extreme confinement enables strong light-matter interaction with nanoscale active regions positioned at the cavity's optical hotspot. Using buried heterostructures integrated into conventional line-defect photonic crystal cavities, we have achieved laser threshold currents below 1 μA. Further reduction of the mode volume suggests the possibility of threshold currents approaching 100 nA. More significantly, such designs pave the way toward near-unity quantum efficiency. In this talk, we present recent experimental breakthroughs and discuss the opportunities and fundamental limits associated with enhanced light-matter coupling in semiconductor nanocavities.

Quantum sensing with quantum defects

Andy Mounce

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Quantum defects are lattice vacancies, substitutions, interstitials, or combinations of the these that have promising properties for quantum information sciences: single photon emission, long coherence times, and the ability to be integrated into photonic devices. Nitrogen vacancies have been the go-to quantum defect for quantum sensing in the past decade, with applications such as sensing of quantum materials or currents in electronic devices. In this presentation, I will show our work within the realm of quantum defects for fundamental and applied sciences, including magnetic imaging for electronic device failure detection [1, 2], diamond fabrication for integrated quantum sensing [3], open-source quantum hardware for quantum defect control [4], and the potential for boron vacancy in hBN as a quantum sensor.

[1] Basso, L., *et al.* " Wide-field microwave magnetic field imaging with nitrogen-vacancy centers in diamond" Journal of Applied Physics **137**, 124401 (2025).
[2] Kehayias, Pauli, et al. "Fault Localization in a Microfabricated Surface Ion Trap using Diamond Nitrogen-Vacancy Center Magnetometry." *Applied Physics Letters* 25, 125 (2025).
[3] Basso, Luca, *et al.* "Fabrication of thin diamond membranes by Ne+ implantation." *Giant* **17**, 100238 (2024).
[4] Riendeau, Emmeline G., *et al.* “Quantum Instrumentation Control Kit -- Defect Arbitrary Waveform Generator (QICK-DAWG): A Quantum Sensing Control Framework for Quantum Defects.” *arXiv*:2311.18253 (2023)

Surface Chirality Sensors Based on Spin-Dependent van der Waals Interactions and CISS-Induced Spinterface Effects.

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Abstract.

Spin polarization involved in the Chiral-Induced Spin Selectivity (CISS) can be used in the design of surface chirality sensors (SCS). The physical reason is that spin transfer at an interface composed of a surface and adsorbed enantiomer-specific chiral molecules, exhibits a dynamics that can lead to a combination of spinterface effects and the onset of spin-dependent van der Waals (vdW) interactions. This combination can lead to surface chiral discrimination, an effect with deep consequences in spintronics, spin-dependent chemistry, the pharmacological industry, and the design of molecular sensors.

In this contribution, we will explore a theoretical model for spinterface effects, which are due to the combination of magnetic and electrical responses at the interface, and also for spin-dependent vdW interactions, which are directly related to the CISS effect. Both phenomena are connected to surface chiral discrimination in different distance-dependent domains going from the physisorption to the chemisorption regimes. We will also explore the consequences of the combination of these interactions in Dynamic Nuclear Polarization, a transfer mechanism of electron-nuclear spin polarization in chiral interfaces that can have important consequences in Quantum Information Sciences.

Monitoring of elementary molecular events with quantum and X-ray light

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Novel X-ray pulse sources from free-electron lasers and high-harmonic generation setups enable the monitoring of elementary events molecular such as the ultrafast passage through conical intersections on unprecedented temporal, spatial and energetic scales. The attosecond duration of X-ray pulses, their large bandwidth, and the atomic selectivity of core X-ray excitations offer new windows into photochemical processes. Coherent control protocols are employed to manipulate and optimize the nuclear wavepacket passage through conical intersections. We show how the Orbital Angular Momentum of twisted X-ray light can be leveraged to detect vibronic coherences and time evolving chirality emerging at conical intersections due to the bifurcation of molecular wavepackets.

Employing quantum light in multidimensional spectroscopy is opening up many exciting opportunities to enhance the signal-to-noise ratio, improve the combined temporal, spatial, and spectral resolutions, and simplify nonlinear optical signals by selecting desired transition pathways in second and third order signals. We show how photoelectron signals generated by time-energy entangled photon pairs can monitor ultrafast excited state dynamics of molecules with high joint spectral and temporal resolutions, not subjected to the Fourier uncertainty limitation of classical light. Two-entangled-photon absorption scales linearly with the pump intensity, allowing the study of fragile biological samples with low photon fluxes, and quantum interferometry can enhance the signals.

Stimulated Brillouin Scattering in InGaP-on-insulator waveguides

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Yuyang Xue,[1,2,*] **Lisa-Sophie Haerteis,**[2] **Zixuan Wang,**[1] **Kevin L. Silverman,**[1] **Richard P. Mirin,**[1] **Glenn Solomon,**[3] **and Andreas Boes**[2]
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Abstract: We report on the simulation, fabrication, and optical testing of InGaP-on-SiO_2 waveguides for Stimulated Brillouin Scattering operating at 1550 nm. High refractive index and low optical losses of the InGaP can enable ultra-high Brillouin gain.

Introduction

Stimulated Brillouin Scattering (SBS) is a third-order nonlinear ($\chi^{(3)}$) interaction between optical and acoustic waves, in which the optical fields both generate and are scattered by the acoustic wave. The scattered light inherits the narrow linewidth of the acoustic mode (in the order of tens of megahertz), desired for applications such as narrow-linewidth lasers, filters and sensors [1-3]. In this work, we present an InGaP-on-SiO_2 platform for backward (counter-propagating) SBS pumped at 1550 nm, where the InGaP waveguide core provides a large third-order nonlinearity, wide bandgap of 1.9 eV that avoids two-photon absorption, high refractive index of 3.14, and low acoustic velocity.

Design, Fabrication and testing

We use the open-source finite element software NumBAT to calculate the SBS gain of air-cladded $In_{0.48}Ga_{0.52}P$ on insulator (SiO_2) waveguides at 1550 nm. Both counter-propagating optical waves are in TE mode, suitable for backward intra-modal SBS. To find the waveguide geometry with highest Brillouin gain, we simulate the optical modes (Fig. 1a) and mechanical modes (Fig. 1b) of the device geometry, which are used to calculate the Brillouin gain via the mode overlap integral. The results that fulfill the intra-modal SBS requirement are plotted in Fig. 1c for waveguide heights and widths in the ranges of 150-400 nm and 350-700 nm, respectively.

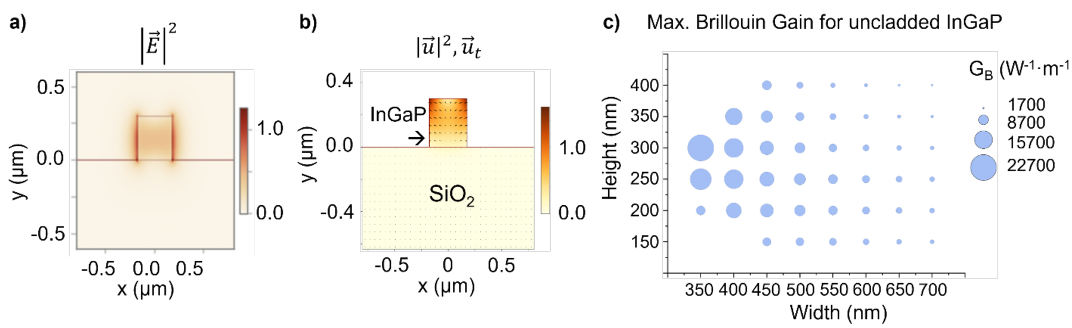

Figure 1. Simulated device cross section with **a)** optical mode (TE_{00}) and **b)** mechanical mode where highest Brillouin gain was found. **c)** Highest Brillouin gain values for backward intra-modal SBS at 1550 nm plotted against waveguide height and width. The values are calculated for an optical quality factor of 1000.

In recent years, we have developed the InGaP-on-SiO_2 platform as a low-loss photonics for efficient third-order nonlinear processes. Here, we fabricate 260 nm thick air-clad InGaP-on-SiO_2 waveguides following the process developed in [4], optimized for the SBS process. To characterize the Brillouin gain spectrum, the straight waveguides are measured with a double intensity-modulated pump-probe setup using a lock-in amplifier [5], where the optical pump wavelength is around 1550 nm. Fig. 2b shows the initial measurement result for a waveguide designed with 9.5 mm length and 880 nm width. We observe a Brillouin shift of 9.43 GHz with an estimated FWHM of 38.2 MHz using a Lorentzian fit, which results in a Q-factor of 250. Our experiment agrees well with a simulated 9.57 GHz Brillouin shift. The peak at 10.8 GHz is identified as resulting from SBS process in the input and output SMF-28 fibers [5]. The background oscillation might be caused by other nonlinear optical effects, such as cross-phase modulation.

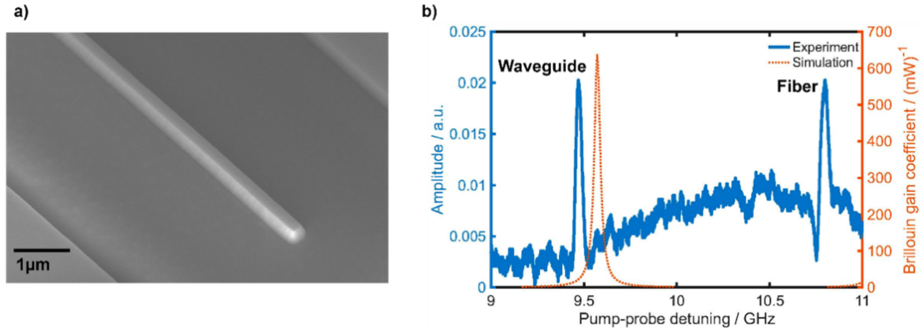

Figure 2. **a)** SEM image of a tapered section. **b)** Initial pump-probe measurement of the Brillouin gain spectrum showing a Brillouin peak at 9.43 GHz and fiber peak at 10.8 GHz (blue). The graph includes the simulated Brillouin peak at 9.57 GHz (orange) and the gain value is calculated to be 636 $W^{-1}m^{-1}$ for a mechanical quality factor of 250.

References

[1] Eggleton, Benjamin J., et al. "Brillouin integrated photonics." *Nature Photonics* 13.10 (2019): 664-677.

[2] Eggleton, Benjamin J., Christopher G. Poulton, and Ravi Pant. "Inducing and harnessing stimulated Brillouin scattering in photonic integrated circuits." *Advances in Optics and Photonics* 5.4 (2013): 536-587.

[3] Wolff, Christian, et al. "Brillouin scattering—theory and experiment: tutorial." *Journal of the Optical Society of America B* 38.4 (2021): 1243-1269.

[4] Ahler, L. C., et al. "Second-order nonlinear frequency conversion in InGaP-on-insulator waveguides," Opt. Lett. 50, 3652-3655 (2025)

[5] Haerteis, L., et al. "Suspended Z-cut lithium niobate waveguides for stimulated Brillouin scattering," in *APL Photonics*, vol. 10, no. 9, pp. 096112, 2025.

A T^3 interferometer and the pit and the pendulum

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In this talk, I will describe two experiments involving light pulse atom interferometers. The first interferometer is based on the use of magnetic field gradients to change the phase sensitivity from T^2 to a T^3 scaling. Early results are depicted in Figure 1 (left), showing the expected chirp in the interference frequency when the results are plotted as a function of T. Subsequent measurements have proven that this result is difficult to reproduce. We very precisely model the magnetic field inside our chamber, in both the vertical and the radial directions, and explore the impact of the field on the closure of the interferometer. The second experiment involves the measurement of the period of a Foucault pendulum using a tall atom interferometer. I will present the results of our feasibility study, focusing on our introduction of a novel sensitivity function to characterize perturbations in gravitational acceleration.

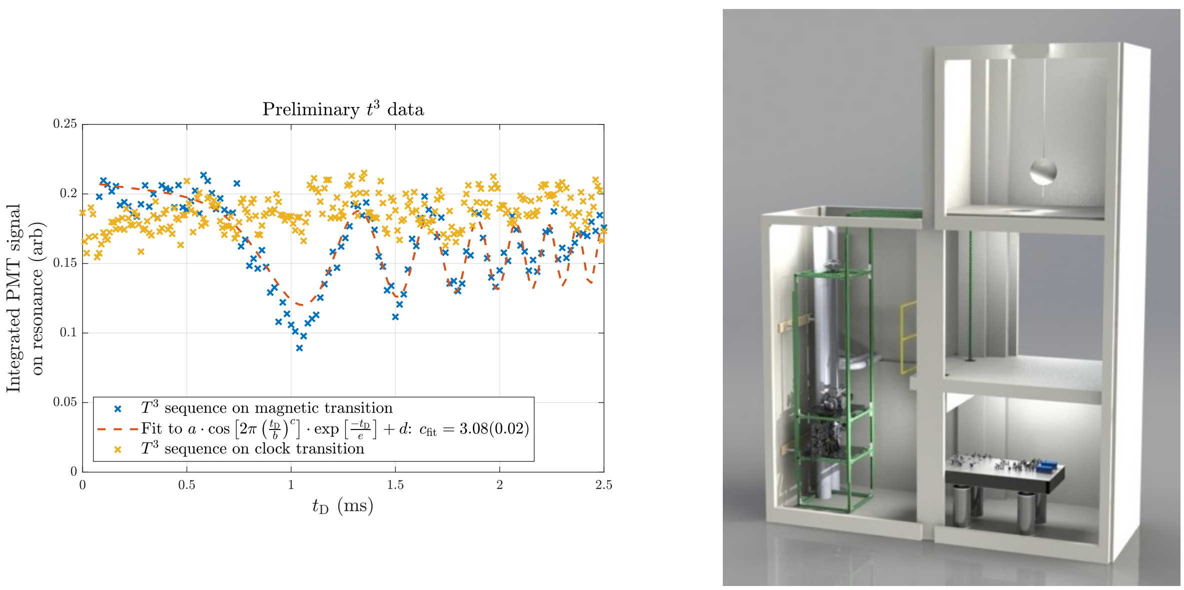

Figure 1 (left) Preliminary data showing T^3 scaling. (right) Solidworks depiction of the proposed experiment.

Hyperbolic Quantum Processor.

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Achieving strong, coherent interactions between qubits separated by large distances is central to advancing quantum technologies—from the design of next-generation quantum computers, to new platforms for quantum simulations, to the realization of large-scale quantum optical networks. Yet, the fundamental mismatch between the spatial dimensions of quantum emitters and the photon wavelength imposes severe limits on transmitting entanglement over long distances.

In this work [1] we demonstrate that long-range qubit entanglement can be realized when interactions are mediated by optical polariton waves in hyperbolic materials, enabled by the phenomenon of Hyperbolic Super-Resonance [1]. In this regime, quantum gate fidelities exceeding 99% are attainable using qubits based on well-established deep donors in silicon, with interactions mediated by polariton fields in substrates such as hexagonal boron nitride (hBN).

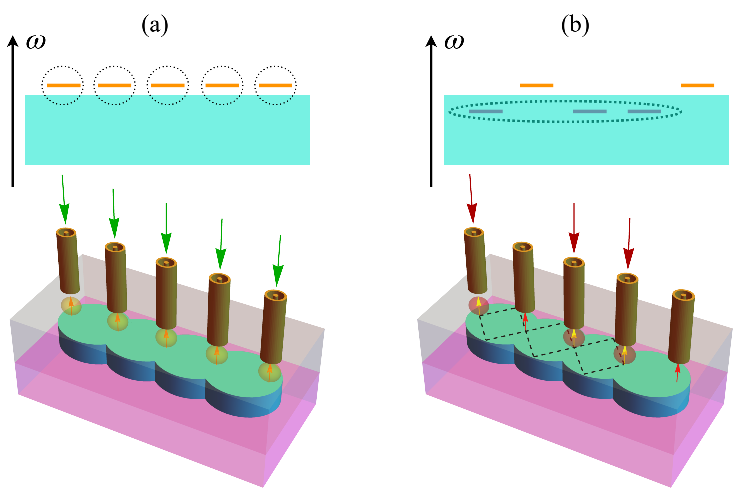

Fig. 1. Hyperbolic Quantum Processor operation. Panel (a): the quantum transition frequencies for all qubits (e.g. chalcogen donor atoms in the silicon layer at the top surface of the *h*BN hyperbolic resonator) are beyond the hyperbolic frequency band. Control fields at qubit transition frequency in the nano-waveguides coupled to selected qubits (yellow "clouds"), force the desired single qubit operations. Panel (b): off-resonance control fields (red clouds) applied to selected qubits, down-shift the qubit transition frequencies to the hyperbolic band, which leads to strong dipole-dipole interactions and the resulting entanglement.

References

1. E. E. Narimanov and E.A. Demler, Hyperbolic Quantum Processor. *https://arxiv.org/abs/2412.14098*
2. C. R. Pidgeon and B. N. Murdin, Silicon as a model ion trap: Time domain measurements of donor Rydberg states. Proc. Nat. Acad. Sci. **105** (31), 10649–10653 (2008).

The Quadruplon: Evidence for a New Quasi-Particle in a 2D Monolayer Semiconductor Through Ultrafast Pump-Probe Experiments

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The concept of quasiparticles in semiconductors plays a fundamentally important role in understanding physical processes and optical properties and in photonic device applications. In the cases of quasi-particles with three and four constituting particles (electrons and/or holes), the conventional understanding is the formation of trions (or charged excitons) in the former case and bi-excitons in the latter. But exactly what is a trion or charged exciton? Is there anything beyond the bi-exciton in the case of two electrons and two holes? These questions are rarely asked, much less studied in the existing literature until our recent papers [1-3]. In our presentation, these questions will be examined in detail experimentally using pump-probe spectroscopy and theoretically using microscopic theories based on Bethe-Salpeter equation and quantum cluster expansion techniques [1]. The answers are supervising. We will show that in either case, there are new entities (quasi-particles) [1,2] or new understanding [3] that have not been studied so far. Especially, we will show that there is a pure many-body splitting [3] between a genuine trion and a charged exciton, which are conventionally thought to be the same and indistinguishable. In the case of four-particle situation, we show that there is a new quasi-particle which corresponds to an irreducible four-particle complex we call quadruplon [1,2] that is distinct from a bi-exciton.

References:

[1] Jiacheng Tang, Cun-Zheng Ning, Theoretical prediction of the quadruplon in a monolayer semiconductor, *Phys. Rev. B*, **111**, L161409 (2025)

[2] Jiacheng Tang, Cun-Zheng Ning, Hao Sun, Qiyao Zhang, Xingcan Dai, Zhen Wang, The quadruplon in a monolayer semiconductor, *eLight*, **5**, 3(2025)

[3] Jiacheng Tang, Cun-Zheng Ning, Many-Body Configurational Spectral Splitting between a Trion and a Charged Exciton in a Monolayer Semiconductor, *ACS Nano*, 19, 11091-11099 (2025)

A few recent results on superconducting qubits: (1) one photon simultaneously exciting two qubits; (2) strong coupling between a single photon and a two-photon Fock state; and (3) Thouless pumping.

Franco Nori [1,2]

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This talk will cover several experimental and theoretical results on superconducting qubits.

(1) We investigated a superconducting circuit composed of two flux qubits ultrastrongly coupled to a common *LC* resonator. Owing to the large anharmonicity of the flux qubits, the system can be described well by a generalized Dicke Hamiltonian containing spin–spin interaction terms. We observed an avoided level crossing providing evidence of the exotic interaction that allows the simultaneous excitation of two artificial atoms by absorbing one photon from the resonator. This multi-atom ultrastrongly coupled system opens the door to studying novel processes for quantum optics and quantum-information tasks on a chip. A.F. Kockum et al., *Deterministic quantum nonlinear optics with single atoms and virtual photons,* Phys. Rev. A **95**, 063849 (2017). [PDF][Link][arXiv] L. Garziano, V. Macri, R. Stassi, O. Di Stefano, F. Nori, S. Savasta, *One Photon Can Simultaneously Excite Two or More Atoms,* Phys. Rev. Lett. **117**, 043601 (2016). [PDF][Link][arXiv][Suppl. Info.]; A. Tomonaga, R. Stassi, H. Mukai, F. Nori, F. Yoshihara, J.S. Tsai, *Spectral properties of two superconducting artificial atoms coupled to a resonator in the ultrastrong coupling regime,* Nature Communications **16**, 5294 (2025). [PDF][Link][arXiv]

(**2)** We report an experimental observation of the strong coupling between a single-photon and a two-photon Fock state in an ultrastrongly-coupled circuit-QED system. The ultrastrong light–matter interaction breaks the excitation number conservation, and an external flux bias breaks the parity conservation. The combined effect of the two enables the strong one–two-photon coupling. Quantum Rabi-like avoided level-crossing is resolved when tuning the two-photon resonance frequency of the first mode across the single-photon resonance frequency of the second mode. Within this new photonic regime, we observe thresholdless 2nd-harmonic generation for a mean photon number in the resonator below one. These results represent a step towards a new regime of quantum nonlinear optics, where individual photons can deterministically and coherently interact with each other in the absence of any stimulating field.
S.P. Wang, A. Mercurio, A. Ridolfo, Y. Wang, M. Chen, W. Wang, Y. Liu, H. Sun, T. Li, F. Nori, S. Savasta, J.Q. You, *Strong coupling between a single-photon and a two-photon Fock state,* Nature Communications **16**, 8730 (2025). [PDF][Link][arXiv][Suppl. Info.]

(3) I will summarize experimental observations of the competition and interplay between Thouless pumping and disorder on a 41-qubit superconducting quantum processor. This highly controllable system provides a valuable quantum simulating platform for studying various aspects of topological physics in the presence of disorder. Y. Liu, Y.R. Zhang, … , F. Nori, K. Xu, H. Fan, *Interplay between disorder and topology in Thouless pumping on a super-conducting quantum processor,* Nature Communications **16**, 108 (2025). [PDF][Link][arXiv][Suppl. Info.]

Classical algorithm for simulating experimental Gaussian boson sampling

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Gaussian boson sampling is a promising candidate for demonstrating experimental quantum advantage, and there have been many experiments to perform large-scale Gaussian boson sampling to claim the quantum advantage. Even though they suffer from a large amount of photon loss, the experiments claim a tremendous computational advantage (at least 100 years) over the state-of-the-art supercomputer. In this talk, we present a classical algorithm that takes advantage of a large loss rate to significantly reduce the computational cost to simulate the experimental Gaussian boson sampling. The main observation is that when photon loss occurs, many of the input photons become thermalized so that they can be efficiently simulated. Based on the observation, we construct a classical algorithm using a newly proposed quantum-optical decomposition of lossy Gaussian state and the matrix product state method. Using the algorithm, we simulate most of the state-of-the-art Gaussian boson sampling experiments, generate 10 million samples in around 1 hour using up to 288 GPUs, and demonstrate that our classical sampler outperforms the experimental Gaussian boson sampler. We also analytically prove the scaling of our classical algorithm as the system size grows. The details can be found in Ref. [1]

[1] C. Oh, M. Liu, Y. Alexeev, B. Fefferman, and L. Jiang, Nature Physics **20,** 1461-1468 (2024)

Non-Dichroic Enantio-Sensitive Chiroptical Spectroscopy

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Chiroptical effects using circularly polarized light produce signals that change sign when switching either molecular handedness (enantiosensitivity) or light helicity (circular dichroism). Here, we break this enantiosensitive-and-dichroic paradigm by measuring a new type of chiroptical signal which is enantiosensitive but not dichroic, as predicted in *Ordonez & Smirnova, Phys. Chem. Chem. Phys. 24, 7264 (2022)*. We photoionize chiral molecules using a strong laser field and detect the three-dimensional photoelectron momentum distribution (PMD). The Non-Dichroic, Enantio-Sensitive (NoDES) asymmetry is encoded in octupolar and higher multipolar terms in the PMD, appearing in multiphoton ionization with elliptical or cross-polarized two-color fields. We identify the NoDES signal with the A_u irrep of the D_{2h} point group of the PMD and provide a protocol to extract it using two velocity-map imaging projections. Our simulations agree with our measurements and show that this effect is universal, extending from the two-photon to the strong-field ionization regime. This robustness of the enantiosensitivity with respect to the relative phase between the orthogonal components of the ionizing field represents an example of symmetry protection. It opens unexplored opportunities for imaging ultrafast dynamics in chiral molecules, such as enantiosensitive photoelectron spectroscopy with bright squeezed vacuum states.

Non-Hermiticity as a Resource in Photonics

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Recent years have seen tremendous progress in the experimental implementations of concepts rooted in non-Hermitian physics. This progress has led to a host of new intriguing results in optics with promising potential applications. One of the most notable properties of non-Hermitian systems is the emergence of spectral degeneracies known as exceptional points (EPs) whose presence leads to nontrivial physics with interesting features. In this talk, I will present the progress in our experimental and theoretical studies towards a better understanding of non-Hermitian processes in different platforms in particular in photonics with a focus on sensing – one of the most debated topics in non-Hermitian photonics with many contradicting results. I will end the talk with a discussion of some of the opportunities and challenges in photonics research within the framework of non-Hermitian optics.

Quantum Gravity Gradiometry from Space: A Pathfinder Mission with NASA

Zack Pagel
Infleqtion

Gravity measurements from NASA's Gravity Recovery and Climate Explorer (GRACE) mission are the second most cited data set in all of NASA Earth Science. As classical technologies are nearing physical limits to their performance, new technologies are required to meet next-generation demands outlined in NASA's most recent Earth Science Decadal Survey. NASA's Jet Propulsion Laboratory (JPL) is leading the Quantum Gravity Gradiometer Pathfinder (QGGPf) mission to demonstrate quantum gravity sensing using Bose Einstein condenstates. The target performance of 100 mE/$\sqrt{\mathrm{Hz}}$ is well beyond terrestrial quantum state-of-the-art instruments, and the demonstration will serve as a pathfinder mission for future earth science and fundamental physics missions. Infleqtion is partnering with JPL to deliver the atomic physics package and the laser and optical system on QGGPf, with a target launch date in 2030. The talk will discuss background and motivation for the mission as well as the overall technical approach and key requirements.

Excitation of the Strontium clock state with megahertz Rabi frequency and a new platform for quantum-enhanced sensing

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Optical clocks have reached unprecedented levels of stability and accuracy over the past decade, enabling searches for new physics, and are poised to redefine the second. These clocks operate at the fundamental noise limit imposed by quantum state projection - the standard quantum limit. This limit can be surpassed with squeezing, often achieved using the interaction between an atomic ensemble and light in a high-finesse optical cavity, leading to orders of magnitude improvement in sensor sensitivity [1]. Further improvement of clocks and other quantum sensors via squeezing has been a long-standing goal of precision measurement science, with recent successes demonstrating enhanced performance of an optical lattice clock [2] and enhanced momentum-state readout in an atom interferometer [3]. Here we describe our spin squeezing platform for Strontium-based devices. Using ensembles of ^{88}Sr atoms in a high-finesse optical cavity, we employ a quantum nondemolition measurement scheme that is immune to cavity length fluctuations and free of probe AC Stark shift effects. Combined with a novel Doppler- and recoil-free excitation method for clock state manipulation, our platform is capable of achieving $>$ 20 dB of quantum enhancement in clock performance.

[1] O. Hosten, N. J. Engelsen, R. Krishnakumar, and M. A. Kasevich, Measurement noise 100 times lower than the quantum-projection limit using entangled atoms, Nature **529**, 505 (2016).
[2] Y. A. Yang, M. Miklos, Y. M. Tso, S. Kraus, J. Hur, and J. Ye, Clock precision beyond the standard quantum limit at 10^{-18} level, Phys. Rev. Lett. **135**, 193202 (2025).
[3] G. P. Greve, C. Luo, B. Wu, and J. K. Thompson, Entanglement-enhanced matter-wave interferometry in a high-finesse cavity, Nature **610**, 472 (2022).

Title: Gaussian Boson Sampling with Displacements

Abstract: Gaussian Boson Sampling (GBS) is a primary candidate for demonstrating quantum computational advantage; however, achieving the high photon numbers required for this advantage is experimentally constrained by the difficulty of producing highly squeezed states. In this talk, I explore GBS with displacements, a protocol that aims to circumvent experimental limitations by introducing coherent states to readily increase photon number.

The primary focus of the talk will be the computational complexity implications of this modification. By mapping the output probabilities to the matching polynomial, we identify a complexity transition: while high displacement or non-negative graph outputs allow for efficient classical simulation, a distinct low-displacement regime preserves arguments for quantum advantage. I will present numerical quantifications of where this transition occurs. Finally, I will briefly discuss the practical utility of this protocol, demonstrating how adding displacement can surprisingly enhance success rates for Max-Clique search in lossy, limited-squeezing environments.

Authors: Peter Pauzauskie, Andy Feng (University of Washington)

Title:
Solid state laser refrigeration of nanoscale plasmonic sensors probed via Raman spectroscopy

Abstract:
Surface enhanced Raman spectroscopy (SERS) is a powerful approach for the rapid detection of a wide range of molecular analytes that are important in the context of both environmental sensing and human health. While surface plasmons in nanostructures are known to increase Raman signals by several orders of magnitude, surface plasmons also concentrate absorbed laser energy, leading to local photothermal heating that can shift plasmonic resonances and degrade temperature-sensitive molecules. Photothermal heating has been shown not only to change the shape, and therefore plasmonic resonances, of gold nanostructures, but also to cause the thermal degradation of molecular analytes. In this presentation I will share recent experimental results demonstrating that quantum electronic transitions of ytterbium ions within ceramic host crystals can realize solid-state laser refrigeration [1,2] of plasmonic gold nanosensors during the collection of SERS data sets. Measurements based on ratiometric Stokes/anti-Stokes Raman spectroscopy indicate that laser cooling can reduce the temperature of plasmonic gold nanocrystals by approximately 10K below their steady state operating temperatures, opening new pathways for mitigating photothermal heating for a wide range of quantum electronic sensors [3,4].

[1] Roder, P. B.; Smith, B. E.; Zhou, X.; Crane, M. J.; Pauzauskie, P. J., Laser refrigeration of hydrothermal nanocrystals in physiological media. Proceedings of the National Academy of Sciences 2015, 112 (49), 15024-15029.
[2] Pant, A.; Xia, X.; Davis, E. J.; Pauzauskie, P. J., Solid-state laser refrigeration of a composite semiconductor Yb:YLiF4 optomechanical resonator. Nature Communications 2020, 11 (1), 3235.
[3] Luntz-Martin, D. R.; Felsted, R. G.; Dadras, S.; Pauzauskie, P. J.; Vamivakas, A. N., Laser refrigeration of optically levitated sodium yttrium fluoride nanocrystals. Opt. Lett. 2021, 46 (15), 3797-3800.
[4] Felsted, R. G.; Chun, J.; Schenter, G. K.; Bard, A. B.; Xia, X.; Pauzauskie, P. J., Mediation of Colloidal Encounter Dynamics by Surface Roughness. Physical Review Letters 2025, 134 (8), 088201.

Polarization of Nonlinear Thomson Scattering

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We characterize nonlinear Thomson scattering from free electrons in an intense laser focus [1]. In addition, we analyse the polarization of the 2nd and 3rd harmonic scattered photons. The setup is shown in the Fig. 1. Electrons are donated from low-density helium, ionized during the rising edge of 800 nm, 40 fs, 50 mJ, 10 Hz laser. We use single-photon counting and gather statistics from hundreds of laser shots at each emission angle around the full emission sphere.

The peak intensity in the laser focus is 2×10^{18} W/cm^2, which causes electrons to move relativistically and execute a well-known figure-8 trajectory when subjected to linearly polarized laser light [2]. Fig. 1 shows calculated and measured 2nd harmonic scattered photons. Measurements are highlighted around the equator of the emission sphere when the laser propagation is aligned along the poles of the sphere. The longer dimension of the electron figure-8 trajectory gives rise to scattered light with azimuthal polarization, while the perpendicular dimension of the trajectory produces longitudinal polarization. An asymmetry between emission into the `northern' and `southern' hemispheres arises because electrons move in the same direction on both ends of the figure 8 while crossing in the middle.

To characterize the polarization state of the scattered harmonics, it is insufficient to measure photon counts through a polarizer oriented along preselected orthogonal dimensions (i.e. azimuthal vs. longitudinal). In this case, the relative phase between the two polarization components remains undetermined. We pin down the polarization state through additional measurements. At each angle, the polarization of the scattered light is found to be close to linear, in agreement with theoretical predictions. The adjacent lobes in the 2nd-harmonic angular emission pattern for azimuthal polarization are out of phase by 180°, leaving two lobes in phase with and two lobes out of phase with the longitudinal polarization. The polarization angle for maximum transmission of the combined light is shown in Fig. 1P.

This work is supported by the National Science Foundation under grant No. 2207737.

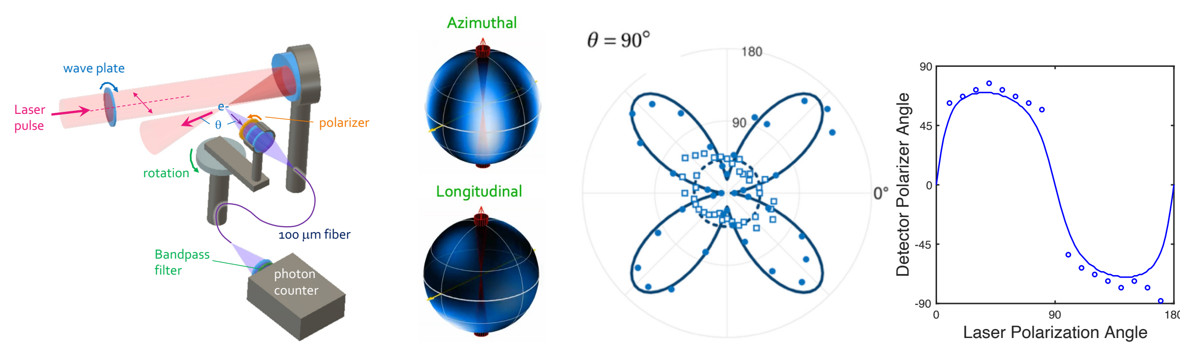

Fig. 1 Experimental setup (left), computed far-field 2nd-harmonic emission polarization-resolved along latitude (upper center left) and longitude (lower center left) dimensions, measured polarization-resolved 2nd-harmonic emission around equator (center right), measured polarization angle of combined 2nd-harmonic light.

[1] M. Romero, L. Robins, A. Stevens, N. Sá, Y. Sun, M. Ware, and J. Peatross, "Nonlinear Thomson scattering: velocity asymmetry inherent in electron figure-8 Motion," Optics Express 19, 33950-33961 (2024).
[2] E. S. Sarachik and G. T. Schappert, "Classical Theory of the Scattering of Intense Laser Radiation by Free Electrons," Phys. Rev. D 1, 2738-2753 (1970).

Strong light-matter coupling at the nanoscale for quantum photonics

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Coupling optical transitions to a single mode of an optical cavity has the potential to enable nonlinear-optical applications at the single-photon level and quantum information transduction. These applications arise both in the strong-coupling regime and in the induced-transparency (or high-cooperativity) regimes, which both require coupling strengths to be large compared to decoherence rates of the emitter and of the cavity photons. In photonic cavities, the diffraction limit places a minimum on the mode volume and thus a maximum on the coupling strength; strong coupling in these cavities therefore generally requires operation at cryogenic temperatures when small numbers of emitters are involved. Using plasmonic nanocavities overcomes this restriction, enabling high cooperativity and strong coupling at room temperature with as little as a single emitter.

We have previously demonstrated the potential for room-temperature strong coupling using a single colloidal quantum dot (QD) coupled to a gap-plasmon nanocavity. Initial demonstrations involved random assembly of single QDs in the gap between a metal nanoparticle and a metal film, or formation of a nanocavity between a metal film and a scanning-probe tip. These demonstrations thus either achieved strong coupling with very low yield, or one QD at a time.

To produce macroscopic numbers of strongly-coupled structures with high yield, we have emplyed a chemically-directed assembly method illustrated in Figure 1. The ends of chemically synthesized gold bipyramids (AuBPs) are selectively functionalized with molecules that have azide terminal groups, and the colloidal QDs are functionalized with molecules containing dibenzo-cyclooctyne (DBCO). A catalyst-free click reaction between the molecules leads to controlled AuBP-QD assemblies. Approximately 25% of the assemblies formed consist of a QD between the ends of a pair of AuBPs. Many of those AuBP-QD-AuBP assemblies show induced transparency, with coupling strengths of approximately 45 meV. Future directions will involve the use of larger metal nanoparticles and smaller QDs to further increase coupling strengths into the strong-coupling regime and the development of techniques to separate the target AuBP-QD-AuBP assemblies from the byproducts of unlinked particles and assemblies of different sizes.

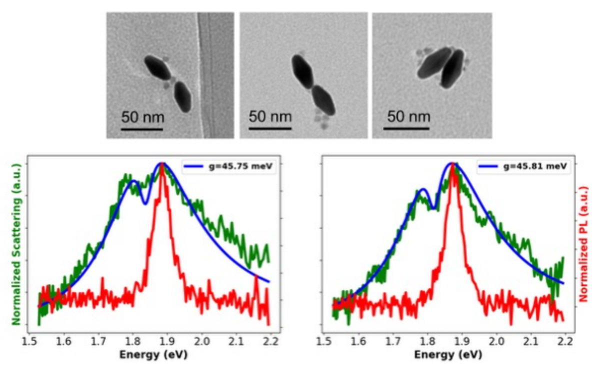

Figure 1: Assemblies of gold bipyramids (AuBPs) with quantum dots (QDs) for strong coupling. Top: TEM images of different representative assemblies. The target assembly is a pair of end-to-end bipyramids with a single QD between their tips. Bottom: Photoluminescence (red) and scattering (green) from typical assemblies showing induced transparency. The dip in the scattering spectrum is a signature of intermediate copling. Blue lines are fits to a coupled-oscillator model that gives the indicated coupling strengths.

Energy and entropy content of time-dependent metamaterials

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Abstract

Time dependent metamaterials, sometimes known as space-time crystals, can obey PT symmetry with a Hamiltonian whose eigenvalues are real. In contrast to static systems eigenstates do not have definite energy and eigenvalues are not associated with energy, rather some other quantity depending on the system. Nevertheless eigenstates have an expectation value for their energy and also for the number of photons. I shall explore whether it is possible to define a 'ground state' for these systems, what is the minimum energy expectation of this state and whether it is possible to find an eigenstate of a PT symmetric system with zero photon content. PT systems can be regarded as Carnot engines as they are reversible; they therefore conserve entropy. The consequences of entropy conservation will be explored.

Enabling Ultrastrong Chiral Light-Matter Interactions With Chiral Superradiance

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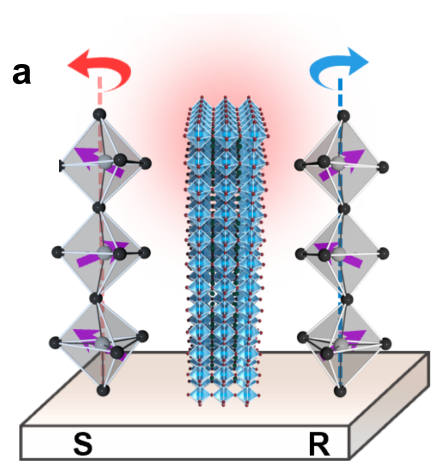
The interaction of chiral materials with circularly polarized light enables fundamentally important spectroscopic techniques including circular dichroism, optical rotation, and circularly polarized luminescence. However, these phenomena, as well as other traditional chiral light-matter interactions, are inherently weak because they rely on the magnetic dipole interaction which is higher-order in the multi-pole expansion. In this talk, I will explain how cooperative enhancement via quantum coherence can be used to amplify chiral light-matter interactions by orders of magnitude. In doing so, I will present the first experimental demonstration of "chiral superradiance"—in which the circular polarization of the superradiant light is determined by the handedness of the radiating chiral material[1]. First predicted theoretically for ultracold atoms[2,3], I will present a new model for chiral superradiance at room temperature and in the solid-state. This model shows excellent agreement with our experimental measurements on hybrid organic-inorganic chiral perovskites. Our results demonstrate the transition from unpolarized spontaneous emission to circularly polarized chiral superradiance, thereby revealing promising new directions for chirality-controlled quantum spin-optical applications at room-temperature.

[1] QW*, JSP*, HR*+ arXiv:2506.22786
[2] JSP+ Phys. Rev. R 6, 023200 (2024).
[3] JSP+ Phys. Rev. A 109, 043525 (2024).



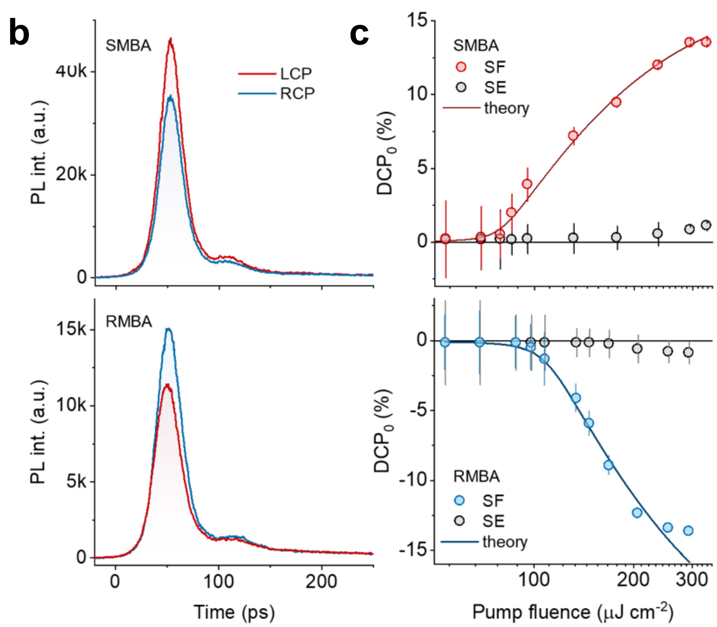


*Fig. 1: (**a**) Schematic drawing of dipole orientations in left-handed (SMBA) and right-handed (RMBA) hybrid organic-inorganic chiral perovskites. (**b**) Photoluminescence (PL) intensities for left-handed (LCP) and right-handed (RCP) circularly polarized light in the superradiant regime. (**c**) Peak degree of circular polarization (DCP$_0$) measured during superradiance/superfluorescence (SF; colored points), spontaneous emission (SE; grey points), and calculated theoretically for SF (colored lines).*

Fluorescence Imaging of Vibrationally Excited Molecular Oxygen using an Optical Parametric Oscillator

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Residual amounts of vibrationally excited molecular oxygen exist in flames, plasmas, and high-enthalpy environments wherein the $B\ ^3\Sigma_g^- - X\ ^3\Sigma_u^-$ spin- and symmetry-allowed Schumann–Runge electronic transition is active in the UV region [1]. The pair of overlapping rotational lines in the $(v', v'') = (0, 6)$ and $(2, 7)$ vibrational bands shown in Fig. 2 were studied in a propane flame using laser-induced fluorescence (LIF). These lines allow for future two-line thermometry experiments [2], [3] to be performed using the setup described herein.

An Nd:YAG pumped injection-seeded optical parametric oscillator (OPO) was built for narrow linewidth operation. Since unseeded OPOs amplify background fluctuations in the electromagnetic field, they are characterized by a broad gain profile not suited to single-line rovibronic spectroscopy [4]. For this reason, a seeded configuration was constructed using a tunable narrow linewidth CW laser source. Following the OPO, a sum frequency generation mixing process was used to reach the required UV wavelengths.

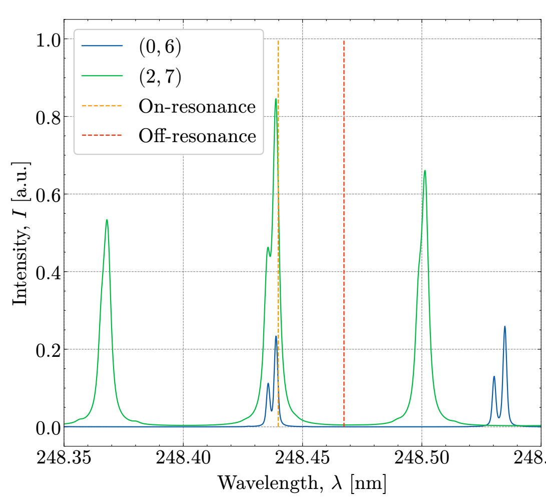


Fig. 2: Absorption features of the $(0, 6)$ and $(2, 7)$ bands of O_2 at 1500 K, 101 325 Pa. Doppler, natural, collisional, and predissociation broadening effects are simulated. On- and off-resonance seed wavelengths are shown at 248.44 nm and 248.47 nm respectively.

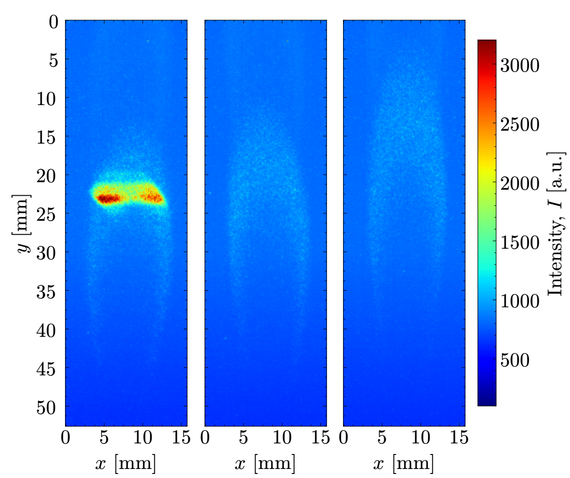


Fig. 1: On-resonance seeded (left), on-resonance unseeded (center), and off-resonance seeded (right) LIF signal. The on- and off-resonance seed wavelengths are 248.44 nm and 248.47 nm respectively. Background natural emission from the flame is visible in all three cases.

A general-purpose diatomic spectroscopy code was developed to identify candidate line overlaps and simulate the theoretical absorption spectra of the targeted rotational lines. Figure 1 shows the LIF signal collected during on-resonance seeded operation, on-resonance unseeded operation, and off-resonance seeded operation. Single-shot images at a gate width of 20 ns were collected and capture the high vibrational quantum number emission pathways with $v' \geq 7$. Future work capturing the emission spectra in an oxy-methane flame is planned. This work was supported by the Office of Naval Research (ONR) under award number N00024-23-1-2458.

[1] P. H. Krupenie, *Journal of Physical and Chemical Reference Data*, no. 2, pp. 423–534, 1972.

[2] J. H. Grinstead et al., *Applied Physics B*, no. 6, pp. 393–396, 1993.

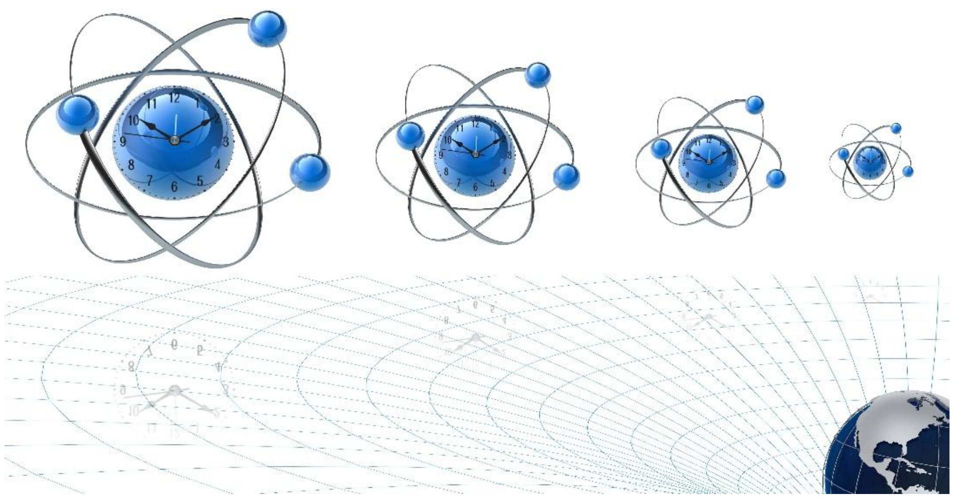
[3] J. H. Grinstead et al., *Applied Optics*, no. 24, p. 5501, 1995.

[4] R. Boyd, *Nonlinear Optics*, 4th ed. 2020.

Towards superpositions of proper time in atomic clocks and quantum networks

Igor Pikovski

Can quantum systems evolve in superposition of different proper times? According to standard quantum theory, this should occur in a relativistic and post-Newtonian treatment of the quantum dynamics of clocks, causing entanglement and decoherence [1,2]. But such behavior has not yet been observed in experiments. Here I will discuss how quantum proper time interference can be achieved in trapped ion clocks [3] and networks of entangled atoms [4]. These offer promising platforms to probe how time dilation and quantum superpositions intertwine, shedding light on fundamental principles of quantum theory in a new regime. I will also discuss how quantum networks of three or more entangled clocks [5] can probe the linearity, unitarity and validity of the Born rule of quantum theory in the presence of curved space-time.



[1] M. Zych, F. Costa, I. Pikovski and Č. Brukner. "Quantum interferometric visibility as a witness of a general relativistic proper time." *Nature Communications* 2, 505 (2011)

[2] I. Pikovski, M. Zych, F. Costa and Č. Brukner. "Universal decoherence due to gravitational time dilation." *Nature Physics* 11, 668–672 (2015)

[3] G. Sorci, J. Foo, D. Leibfried, C. Sanner, and I. Pikovski. "Quantum signatures of proper time in optical ion clocks." *Preprint:* arXiv:2509.09573

[4] J. Borregaard and I. Pikovski. "Testing quantum theory on curved space-time with quantum networks." *Physical Review Research* 7, 023192 (2025)

[5] J. P. Covey, I. Pikovski and J. Borregaard. "Probing curved spacetime with a distributed atomic processor clock." *PRX Quantum* 6, 030310 (2025)

Multiphoton melanin-mediated energy transfer enables ocular melanoma eradication

Layla Pires, Shireen Khattak, Sebastiao Pratavieira, Carla Calcada, Renan Romano, Yeni Yucel, Vanderlei S Bagnato, Cristina Kurachi, Brian C Wilson

Photodynamic therapy (PDT) utilizes light, a photosensitizer, and oxygen to selectively induce cell death. Uveal melanoma (UM) is the most common ocular tumor in adults and represents a huge clinical unmet need, with 50% of patients developing metastatic disease and a median survival of 13 months post-metastatic diagnosis. Clinical trials using linear PDT have demonstrated high efficacy, achieving partial or complete regression in ~80% of non-pigmented UM cases. However, in pigmented tumors, the same treatment failed in >90% of the cases. This failure is attributed to the broad absorption spectrum of melanin, which acts as an optical shield preventing therapeutic light from reaching the deeper tumor layers and activating the photosensitizer. *We hypothesize that utilizing femtosecond Near-Infrared (NIR) non-linear excitation would overcome melanin's high linear absorption, enabling deep light penetration such that both pigmented and non-pigmented tumors would be equally susceptible to treatment.*

The studies were carried out in clonal pigmented and non-pigmented melanoma cells, utilizing two photosensitizers: a two-photon engineered compound, Oxdime, with $\sigma_{2p}{\sim}17{,}000\ GM$ and a clinically approved photosensitizer with a $\sigma_{2p}{\sim}50\ GM$. When cells were treated with Oxdime and a femtosecond-pulsed laser at 910nm, minimal differences were observed in cell death, Oxdime photobleaching rates, and ROS generation between the pigmented and non-pigmented cell lines. Surprisingly, when studies were carried out using Visudyne and 865nm excitation, the pigmented cells were significantly more susceptible to the treatment than the non-pigmented cells. In addition, Visudyne photobleaching and ROS generation were observed only in the pigmented cells. This data indicates a melanin-sensitized excitation mechanism, in which melanin absorbs femtosecond pulses via broadband multi-photon absorption and transfers the energy to the photosensitizer. This coupling effectively bypasses the photosensitizer's low two-photon cross-section. In this case, the melanin-mediated shielding effect is inverted and converted into a therapeutic mechanism.

To validate these findings, the treatment was applied in pigmented and non-pigmented conjunctival melanomas *in vivo*. Visudyne-mediated two-photon PDT resulted in the complete eradication of pigmented tumors while no response was observed in non-pigmented melanomas, a direct reversal of the standard PDT clinical outcome. Furthermore, the confined therapeutic volume of non-linear excitation prevents off-target damage to surrounding tissue, preserving vision. These results represent a groundbreaking advance in light-based therapies, demonstrating that the optical properties of endogenous pigment can be exploited to overcome the fundamental limitations of linear PDT, turning the primary cause of treatment failure into the mechanism of success.

Embracing instability: preparing macroscopic quantum states in the dark

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Optical levitation of nano-scale objects is a promising candidate for preparing large quantum superposition states and realizing diffraction experiments of massive objects. A central limitation of optical trapping is that absorption of the trapping light by the levitated particle causes heating of internal degrees of freedom. The raised internal temperature increases decoherence via blackbody radiation and limits the range of materials that can be levitated at low pressures without damage. We are developing an experimental setup that can remove this limitation by preparing pure quantum states of motion of levitated objects with minimal heating. The core idea is to stabilize and cool a levitated nanoparticle at the intensity minimum of an optical potential using feedback control based on quantum limited optical position readout. This implies that the particle will be stabilized at the unstable point of an optical field, resulting in intrinsically different dynamics than in harmonic traps. The state expansion of the nanoparticle motion is accelerated by an inverted harmonic potential, which promises new approaches for preparing macroscopic quantum states.

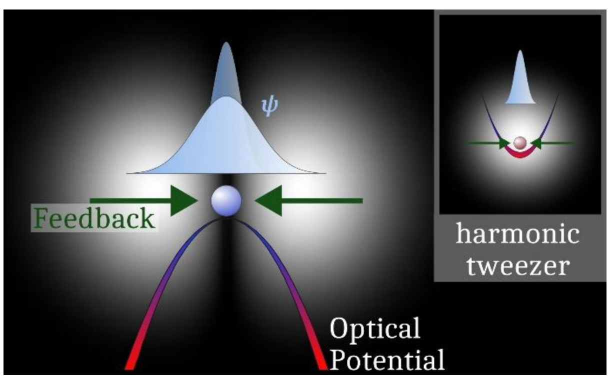

Figure 1: **Artistic sketch of the dark trap.** A charged silica nanoparticle is stabilized in the dark centre of a TEM-10 laser mode, experiencing a repulsive optical potential and minimal internal heating. Electronic feedback based on optical position readout stabilizes, cools, and purifies the motion of the particle. The steady state is enlarged due to the repulsive potential. **Inset:** The confining, harmonic case: Feedback cooling close to the ground state has been demonstrated, but absorption of the trapping laser results in internal heating causing decoherence.

References:

[1] Dago et al., Stabilizing nanoparticles in the intensity minimum: feedback levitation on an inverted potential. *Optics Express* Bd. 32, p. 45133 (2024)

[2] Magrini et al., Real-time optimal quantum control of mechanical motion at room temperature. *Nature* Bd. 595, p. 373–377 (2021)

[3] Neumeier et al., Fast quantum interference of a nanoparticle via optical potential control. *Proc Natl Acad Sci USA* Bd 122 (2024)

[4] Maurer et al., Quantum theory of light interaction with a Lorenz-Mie particle: Optical detection and three-dimensional ground-state cooling. *Phys. Rev. A* 108, 033714 (2022)

Robust, Scalable, and Low-Noise Phase Stabilization for Next-Generation Quantum Networks

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National Institute of Standards and Technology, USA

Optical phase stability is essential for advanced faint-light applications, especially quantum networks. These networks utilize single photons and other fragile quantum states for distributing entanglement and exchanging quantum bits, which are foundational to protocols like entanglement swapping and quantum-repeater enabled long-distance communication. Despite the convenience of optical fibers, environmental disturbances introduce significant and unpredictable phase variations.

While fibers are convenient for optical communications, temperature fluctuations and acoustic noise result in large phase fluctuations over time. This problem is known in classical networks, and multiple solutions exist to measure and cancel phase instability effects. Typically, to extract a phase reference, strong classical light is used as a probe signal. However, strong probe signals introduce broadband noise into faint quantum channels affecting both time-division-multiplexed (TDM) and wavelength-division-multiplexed solutions (WDM). Further, even a small spectral detuning of probe channels results in significant residual phase fluctuations in target (quantum) channels. Here we demonstrate two novel and scalable phase stabilization methods for metropolitan sized quantum networks and obtain a 120 km phase stabilized channel with residual sub-femtosecond phase fluctuations while limiting noise in the payload channel to lower than 0.2 rad RMS.

Our TDM method takes advantage of adaptive quantum measurement and enjoys quantum Fisher information advantage. It is based on coherent state displacement, single-photon counting measurements. Note that single photon detectors are required for most quantum protocols, and they can readily be shared for phase stabilization. Here we achieve up to 2dB of Fisher information advantage over the most optimal classical (homodyne) detection, which allows the use of just 700,000 photons/sec (at the receiving detector) for phase measurements. With a 50% duty factor, there is plenty of “dark” time for the payload in the channel. In a TDM channel, double Rayleigh back-scattering results in up to -50~dB of phase reference signal leaking into the payload time, resulting in <<100 crosstalk photons per second.

The new WDM method uses two DWDM-detuned channels and classical detection. One channel is used for regular phase stabilization and it provides feedback information that corrects phase in several adjacent DWDM channels. However, adjacent DWDM channels are not perfectly stabilized, even when the detuning between the two is just 100 GHz! Therefore, we use one more channel to classically measure residual phase error. This signal can be used as feed-forward stabilization for target (quantum) channels that remain completely dark. Interestingly, this method allows for a long-term, persistent phase stabilization of both fiber spools (stable over an hour) and deployed fiber (stable over a minute). With a combined output optical power of 550 pW in feedback and feedforward channels approximately 100(5) photons/s of inelastic scattering noise were detected in the payload channel. Due to the higher optical power in the feedback channel (500 pW), it contributes approximately 95(5) photons/s, whereas feedforward channel (50 pW) accounts for only 4(1) photons/s. By back propagating the receiver losses we estimate noise at the end of the fiber due to classical-to-dark channel crosstalk as ≈500 photons/s.

In conclusion, we demonstrate two methods for quantum-compatible phase stabilization in long fiber links. In both cases we stabilize a 120 km deployed fiber link to within 0.2 rad RMS (or 0.15 fs) for longer than a minute while reducing crosstalk in the target channel by several orders of magnitude than heretofore possible. In both cases, we may be limited by the coherence length of our stable laser, not the feedback scheme. In addition, experiments with long fiber spools demonstrate that our method can stabilize links for hours at a time if polarization control is implemented together with the phase stabilization.

Curved air waveguides using intense designer laser beams

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Various applications of intense, ultrashort-pulse laser beams benefit from advanced techniques that force light beams to deviate from their usual behavior, namely from traveling along straight paths at the speed of light. Those techniques involve a judicious shaping of the available degrees of freedom of the lightwave – the spatial and temporal profile, topology, and polarization. The nonlinear character of pulse propagation and the oftentimes complex response of the propagation medium to its intense fields challenge the design and implementation of spatiotemporal structures tailored to the application. Here we present experimental results on using advanced beam shaping for the generation of curved optical waveguides in ambient air.

It has been found that intense, ultrashort laser pulses, propagating in air, leave behind air-density perturbations that have millisecond-scale lifetime [1,2]. By pre-shaping the leading beam, an air waveguide can be created for another pulsed or continuous-wave laser that follows [3-4]. The air waveguides demonstrated so far have been straight. In a separate development, a beam-shaping strategy has been devised that forces a laser beam to propagate along an arbitrary trajectory in a linear transparent medium [5]. The generalization of this approach to doughnut-shaped beams has been demonstrated in the context of guiding microscopic particles in a liquid [6]. Here, we present recent results on the realization of this beam-shaping strategy with ultra-intense, ultrashort laser pulses and the use of these beams for waveguiding another laser beam along a parabolic trajectory in air. Our results are summarized in Figure 1. The waveguide-generating Titanium-Sapphire laser system emits 40 femtosecond-long laser pulses with 30 mJ energy per pulse at a repetition rate of ten pulses per second. The laser beam is shaped according to the strategy outlined in [6]. The shaped beam produces a bottle-like pattern of ionization in air that follows a parabolic trajectory, deviating from a straight line by about one millimeter over an about 20-centimeter-long propagation path. The energy deposited into the air by the laser beam drives an axially imploding shockwave that reaches the center of the doughnut-shaped beam pattern about 50 to 100 nanoseconds after the pulse has passed. At that point, another six nanosecond-long, weaker laser pulse (the probe) at 532 nm wavelength is coupled into the generated air waveguide and imaged at the exit from the waveguide on a CCD camera for analysis. The waveguiding of the probe beam along a curved trajectory is evident and is shown in Figure 1(C,D). The applications of curved air waveguides include acceleration of charged particles, remote sensing, and directed energy.

This work was supported by by the Office of Naval Research under the award number N00014-21-1-2469 and by the US Office Under the Secretary of Defense for Research and Engineering, Joint Directed Energy Transition Office (JDETO). JB acknowledges the support from the SMART scholarship by the US Air Force Research Laboratory and the graduate fellowship by the Directed Energy Professional Society. PP acknowledges helpful discussions with Zhigang Chen and Nikolaos K. Efremidis.

References

[1] Y.-H. Cheng, J. K. Wahlstrand, N. Jhajj, and H. M. Milchberg, "The effect of long timescale gas dynamics on femtosecond filamentation," Opt. Express **21**, 4740 (2013)
[2] O. Lahav, L. Levi, I. Orr, R. A. Nemirovsky, J. Nemirovsky, I. Kaminer, M. Segev, and O. Cohen, "Long-lived waveguides and sound-wave generation by laser filamentation," Phys. Rev. A **90**, 021801(R) (2014)
[3] N. Jhajj, E. W. Rosenthal, R. Birnbaum, J. K. Wahlstrand, and H. M. Milchberg, "Demonstration of long-lived high-power optical waveguides in air," Phys. Rev. X **4**, 011027 (2014)

[4] S. Fu, B. Mahieu, A. Mysyrowicz, and A. Huard, "Femtosecond filamentation of optical vortices for the generation of optical air waveguides," Opt. Lett. **47**, 5228 (2022)
[5] I. D. Chremmos, Z. Chen, D. N. Christodoulides, and N. K. Efremidis, "Bessel-like optical beams with arbitrary trajectories," Opt. Lett. **37**, 5003 (2012)
[6] J. Zhao, I. D. Chremmos, D. Song, D. N. Christodoulides, N. K. Efremidis, and Z. Chen, "Curved singular beams for three-dimensional particle manipulation," Sci. Rep. 5:12086 (2015)

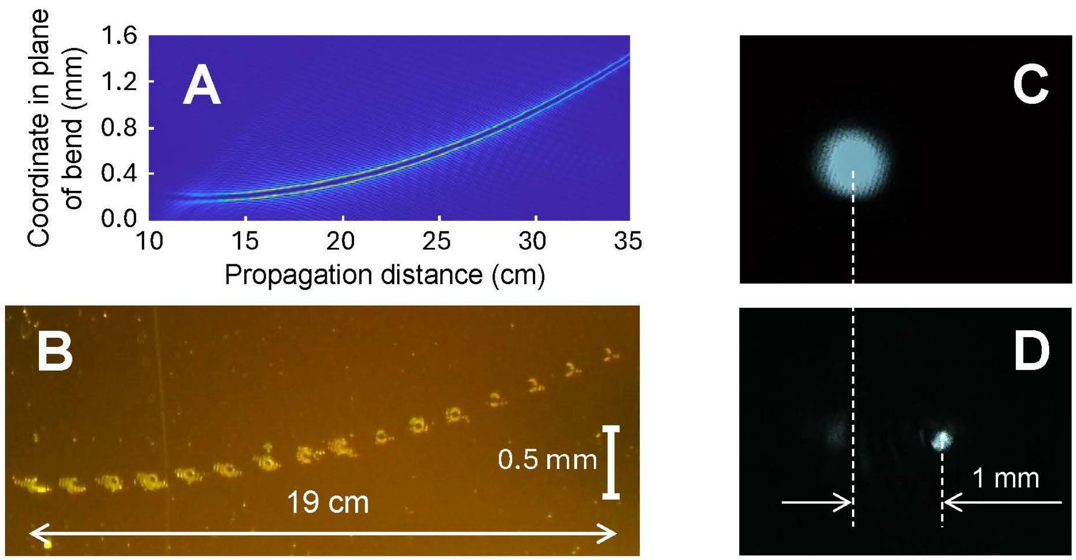

Figure 1. Slice of the intensity in the curvature plane, computed assuming linear beam propagation, i.e., neglecting the influence of air nonlinearity and ionization (A). Single-shot burns produced by the beam on a gold-coated silicon wafer along the beam path (B). Probe-beam intensity patterns imaged at the exit from the curved air waveguide (at z ≈ 20 cm) on a CCD camera with the waveguiding beam off (C) and on (D).

Quantum sensing beyond standard quantum limits

Eugene S. Polzik, Niels Bohr Institute, Copenhagen University

Abstract:
Standard quantum limits of sensing and metrology are set by an interplay between quantum noise of the sensor, quantum noise of the meter and the back action of the meter on the sensor. Engineering multipartite entanglement between the sensor and the meter and generation of non-classical states of the meter and the sensor allows for suppression of all those sources of quantum noise and for achieving sensitivity to fields and forces beyond standard quantum limits in a range of applications. I will review our recent efforts in applying those principles to magnetometry, magnetic induction tomography and interferometry.

Next generation quantum memories with Rydberg technology

John J. Prevost

University of Austin at San Antonio

Building a large-scale quantum network remains challenging. Quantum nodes must interface with light for remote entanglement generation (REG), and long distances require quantum repeaters to extend entanglement across intermediate links. Because REG is probabilistic, long-lived quantum memories are needed, while entanglement swapping requires deterministic logic at nodes and repeaters. Limited fidelity over multiple links necessitates stochastic entanglement purification, and active error correction is ultimately essential for maintaining coherence.

The DLCZ protocol demonstrated that atomic ensembles could serve as repeater nodes, generating entanglement via spontaneous Raman emission, where a photon emission is correlated with a collective spin excitation. Entanglement is established for each link through single-photon detection that erases which-way information.

Individual neutral atoms, especially Rydberg atoms, offer additional advantages, including efficient light-matter interfaces (potentially at telecom wavelengths), long coherence times, multi-qubit processing, scalability, and high-fidelity mid-circuit readout.

This project will involve numerically simulating the DLCZ protocol with Rydberg ensembles in a cavity. By exploiting superatom dynamics along with techniques of optimal control theory, we will explore for improved theoretical protocols to enhance entanglement distribution rates and robustness. Key performance metrics will include link and collection efficiency, memory lifetime, and multimode capacity, with efficient multiplexing making simple quantum repeaters feasible beyond the limits of direct transmission.

Bio for Dr. Prevost

Dr. John “Jeff” Prevost is an Endowed Associate Professor in Electrical and Computer Engineering at UT San Antonio. He earned degrees in economics and electrical engineering and completed his Ph.D. in electrical engineering after nearly two decades in the tech industry, where he served as Director of Product Development, Director of Information Systems, and Chief Technical Officer.

In 2015, Dr. Prevost co-founded UTSA’s Open Cloud Institute (OCI), initially serving as Assistant Director and Chief Research Officer. He became Executive Director in 2021, leading initiatives in cloud and edge computing through seminars, workshops, internships, and collaborative research. That same year, he was appointed VP for Secure Cloud Architecture at the Cyber Manufacturing Innovation Institute (CyManII), where he co-leads the Shared Research and Development Infrastructure team, developing secure cloud-to-edge systems connecting manufacturers and researchers nationwide.

His research focuses on quantum information science and engineering, particularly quantum networking and applied quantum algorithms. Teaching interests include quantum information theory and quantum sensing, enriched by his industry experience. Dr. Prevost aims to position San Antonio and Texas as leading hubs for quantum engineering and related technologies.

Disorder-driven decoherence in the attosecond dynamics of amorphized silicon

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Recently, there has been a flurry of interest in the area of attosecond quantum optics, which aims to combine the so-called quantum advantage in metrology and information with the attosecond precision enabled by ultrashort laser pulses. While research has shown that extreme quantum light—*bright-squeezed vacuum*—can be used to control high-harmonic generation [1] and distribute entanglement over a broad range of frequencies [2], little attention has been paid to the role of decoherence in strong-field quantum optical processes. This stems in part from the lack of a general understanding into the nature of decoherence in the sub-cycle dynamics of electron-hole pairs. Here, we study high-harmonic generation in silicon amorphized by ion implantation (Fig. 1a) and show how disorder is imprinted onto the roll off of the HHG spectrum (Fig. 1b) [3]. Our observations are modelled using the semiconductor Wannier equations (Fig. 1c), a real-space approach to attosecond quantum dynamics that we show naturally captures the role of disorder in damping the coherence of electron-hole pairs [4]. We further use HHG to estimate the length scale of medium-range order and observe remnant structure of the cubic lattice not visible with conventional probes. While here, we study an extreme case (complete lack of long-range order), we discuss how real-space dephasing arises even in a perfect crystal [5].

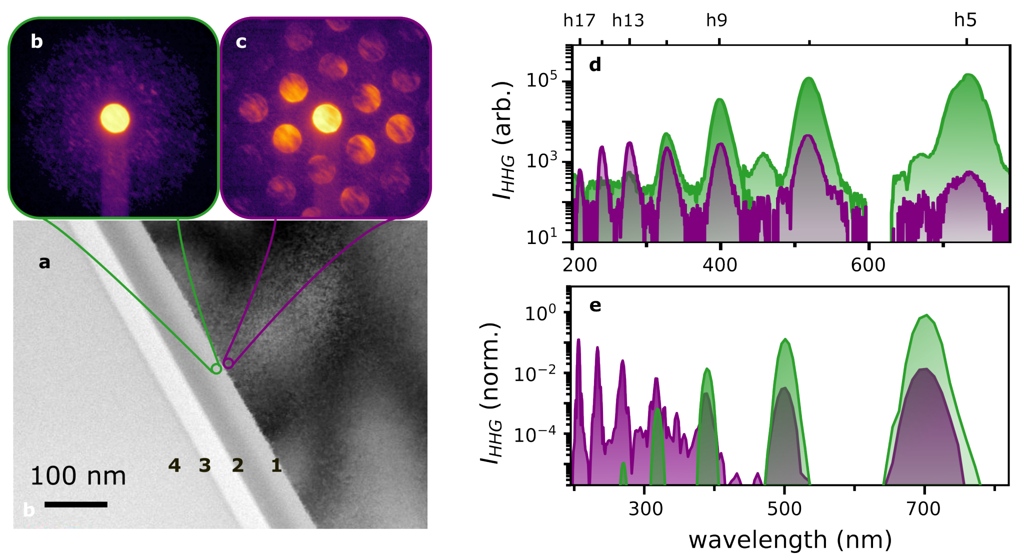

Figure 1, a. Transmission-electron microscope image of an amorphized silicon lamella excavated from the crystalline surface. Convergent-beam electron diffraction patterns of **b.** the amorphous layer and **c.** the crystalline substrate. **d.** Experimentally measured HHG spectra in crystalline silicon (purple) and amorphous silicon (green). **e.** Calculated HHG spectra from crystalline silicon and amorphous silicon, with a real-space decoherence term.

5. References

[1] S. Lemieux *et al.* "Photon bunching in high-harmonic emission controlled by quantum light," Nature Photonics **19**, 767-771 (2025)
[2] N. Boroumand *et al.* "Quantum engineering of high harmonic generation," arXiv:2505.22536
[3] D. N. Purschke *et al.* "Giant enhancement of attosecond tunnel ionization competes with disorder-driven decoherence in silicon," arXiv:2511.14678 (2025)
[4] G. G. Brown *et al.* "Real-space perspective on dephasing in solid-state high harmonic generation," Physical Review Research **6,** 43005 (2024)
[5] A. Cárdenas *et al.* "Effects of zero-point motion in the high harmonic generation spectrum in solids," arXiv:2512:01712 (2025)

Constraining long-range spin-gravity coupling using nuclear magnetic resonance

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The Standard Model of particle physics, while extremely successful, does not account for key cosmological observations such as dark matter, the matter–antimatter asymmetry, or the Universe's accelerating expansion. These open questions provide strong motivation to search for new fundamental interactions. Many theoretical frameworks beyond the Standard Model predict the existence of new, light spin-0 bosons, such as axion-like particles, which are also well-motivated dark matter candidates. The exchange of such particles could generate a new long-range, spin-dependent force that can be described as a coupling between a particle's intrinsic spin and gravity. An observable consequence would be an anomalous precession of spins in the Earth's gravitational field.

The detection of such a subtle signal presents a significant experimental challenge, requiring highly sensitive measurements of spin dynamics. Our approach utilizes zero- to ultralow-field (ZULF) nuclear magnetic resonance (NMR), a technique that is not only promising for chemical spectroscopy but also for precision measurements. In the ZULF regime, the evolution of nuclear spins is governed by internal, indirect spin–spin couplings (J-coupling), which produce narrow NMR spectral lines (<100 mHz) with a good signal-to-noise ratio (~100). When subjected to a magnetic field, these lines may split, and any anomalies in their positions relative to gravity could signal new physics.

However, in such systems, a major systematic effect arises from residual magnetic fields, which can induce effects many orders of magnitude stronger than the expected spin–gravity coupling. To address this, our apparatus combines multi-layer magnetic shielding with comagnetometry techniques to suppress magnetic-field noise.

In this talk, we present recent advances in our search for spin–gravity (monopole–dipole) coupling using the ZULF NMR technique.

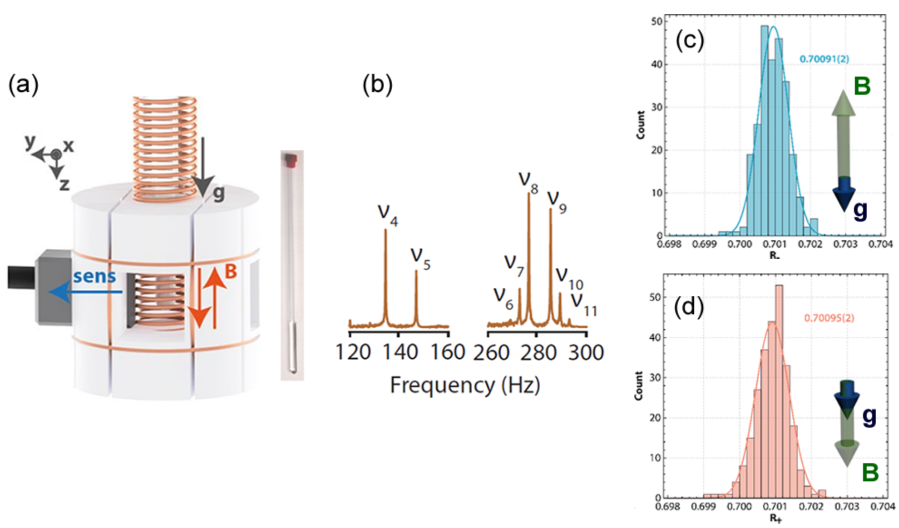

Fig. 1. Schematic of the experimental setup and methodology. (a) Core of the setup showing the magnetic sensor, coil system, liquid sample, and field orientations used for measurements. (b) ZULF NMR spectrum displaying the spectral lines employed in the spin–gravity measurements. (c, d) Statistics of the splitting ratio for parallel (c) and antiparallel (d) orientations of the magnetic and gravitational field.

Sagnac Tractor Atom Interferometer on a Photonic Integrated Circuit

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(Dated: November 5, 2025)

Abstract. We study the theory of and propose an experimental design for a Sagnac tractor atom interferometer based on a photonic integrated circuit (PIC). The atoms are trapped in counter-rotating azimuthal optical lattices, formed by interfering evanescent fields of laser modes injected into circular PIC waveguides. We develop quantum models for the radial and azimuthal dynamics of the interfering atoms in adiabatic frames, which provide computational efficiency. The theory is applied to an exemplary PIC, for which we first compute field modes and atom trapping potentials for ^{87}Rb. We then evaluate non-adiabaticity, fidelity and sensitivity of the exemplary PIC.

In atom interferometry (AI), matter-wave interference of cold atoms is used to test fundamental principles of physics and to perform precise measurements of fundamental constants. Using massive atoms instead of photons leads to short de Broglie wavelengths, as compared to optical wavelengths, which in turn yield high sensitivity to gravity and inertial forces. The recently proposed method of tractor atom interferometry (TAI) [1–3] is a candidate to achieve high sensitivity with a small footprint. In TAI, atoms are trapped in three-dimensional (3D) potentials throughout the entire AI sequence. The atoms are shuttled in the 3D-confining tractor traps along user-programmed paths, which define the AI configuration. In TAI, the atoms have zero external spatial degrees of freedom. The uninterrupted 3D trapping ensures closure, and enables long holding times and complex multi-loop paths. In this report, we propose a Sagnac TAI on a compact PIC platform, with the goal of creating a rotation-sensing device that offers a favorable combination of low SWaP and high rotation sensitivity.

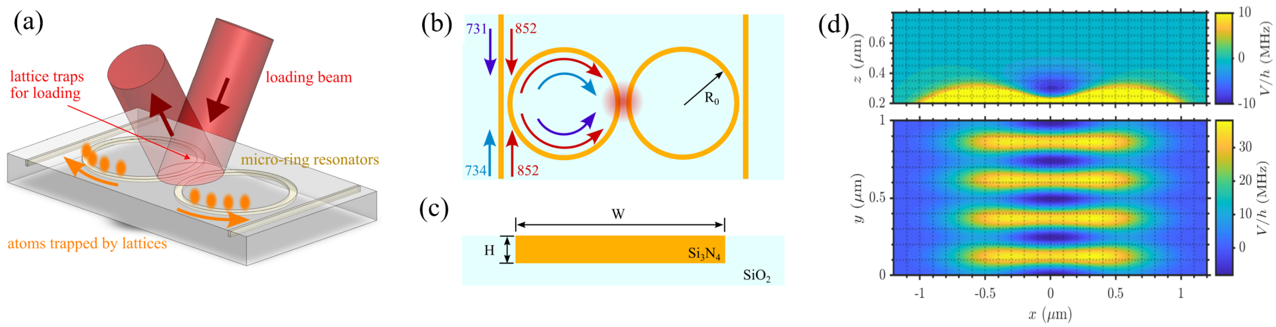

FIG. 1. (a) Two micro-ring resonators side by side on a photonic chip. A BEC loading beam is partially reflected by the top surface of the chip, forming pancake-shaped traps that coherently load azimuthal lattices located above the ring resonators. (b) Top-down view of the PIC considered in this presentation. Counter-propagating pairs of red-detuned (852 nm) modes form optical lattices above the PIC for azimuthal tractor control. Two blue-detuned modes (734 nm and 731 nm) repel the atoms from the waveguide and reinforce radial confinement. The red shaded area between two rings is the atom loading area. All wavelengths are vacuum wavelengths. (c) Cross-section through the PIC waveguides. Parameters are $R_0 = 600\,\mu\text{m}$, $H = 0.09\,\mu\text{m}$, and $W = 1.8\,\mu\text{m}$. The light blue shading represents silicon dioxide (SiO_2), and the yellow is silicon nitride (Si_3N_4). (d) Vertical (top) and in-plane cuts of the trapping potentials for ^{87}Rb atoms.

In the presentation, we will introduce theoretical models suitable to evaluate possible PIC designs, sketched in Figs. 1 (a-c). A specific PIC design and corresponding tractor trapping potentials for ^{87}Rb BECs, shown in Fig. 1 (d), will then be discussed in some detail. Quantum simulations for the design promise a sensitivity of $\delta\Omega \approx 10\,\text{nrad/s}/\sqrt{\text{Hz}}$ for rotation sensing, with improvements possible with larger Sagnac areas, parallelization of multiple, identical PIC-TAIs on a single chip, and potentially with spin squeezing.

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REFERENCES

[1] Georg Raithel, Alisher Duspayev, Bineet Dash, Sebastián C Carrasco, Michael H Goerz, Vladan Vuletić, and Vladimir S Malinovsky, "Principles of tractor atom interferometry," Quantum Science and Technology **8**, 014001 (2022).
[2] A Duspayev and G Raithel, "Tractor atom interferometry," Phys. Rev. A (Coll. Park.) **104** (2021).
[3] Bineet Dash, Michael H. Goerz, Alisher Duspayev, Sebastián C. Carrasco, Vladimir S. Malinovsky, and Georg Raithel, "Rotation sensing using tractor atom interferometry," AVS Quantum Science **6**, 014407 (2024).

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Title: Searches for dark matter with precise electric field sensors.

Abstract

Extensions to the Standard Model of particle physics abound in feebly coupled particles that generate extremely small electric and magnetic fields. Examples include axions, dark photons, and millicharged particles, all of which are theoretically well-motivated dark matter candidates but remain difficult to probe with conventional searches. In this talk, I will show that recent advances in precision atomic and molecular physics provide a natural pathway to detect such particles through their minute electromagnetic signatures. In particular, I will demonstrate how ion traps, electron traps, and Gauss-law tests together can achieve sensitivity to the QCD axion dark-matter line and probe millicharged particles at levels far below the projected reach of even future beam-dump and collider experiments.

Development of an Active Atomic Vapor Filter Utilizing Quantum Resonance Enhanced Four Wave Mixing

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Abstract

Atomic resonance filters utilize the transition lines of an atomic vapor to produce an ultranarrow ($\sim$ 1 GHz) bandpass filter with a high acceptance angle. The technology can be applied to various remote sensing applications including lidar which must discern a weak signal against a large continuum background. This work describes the development of an active atomic resonance filter to convert collimated green light at 532 nm to collimated blue light at 420 nm. The inputted green beam co-propagates through a rubidium vapor with two CW idler beams at 795 nm and 1320 nm. This mixing process generates the collimated blue beam due to the resonances between the 5S, 5P, 10S, and 6P states of rubidium. The narrow frequency range required of the pumps for resonance means the green beam can be tuned so only a portion of the signal spectrum influences the blue signal's intensity.

Here the intensity of the blue signal beam is characterized under various pump beam detunings, intensities, and polarizations using a coherent green beam. Notably, the blue signal is strongest with linearly polarized pump beams detuned $1 - 5$ GHz from resonance in vapor pressures between $\sim 0.8 - 1.5$ mTorr when the vapor is contained in a 70 mm cell. This work also demonstrates up-converting spatially incoherent images from green to blue light. Potential conversion mechanisms are discussed including three-photon coherence and amplified spontaneous emission. The work also discusses applications to lidar, methods to reduce energy pooling, and ways to further increase the conversion efficiency between green and blue photons.

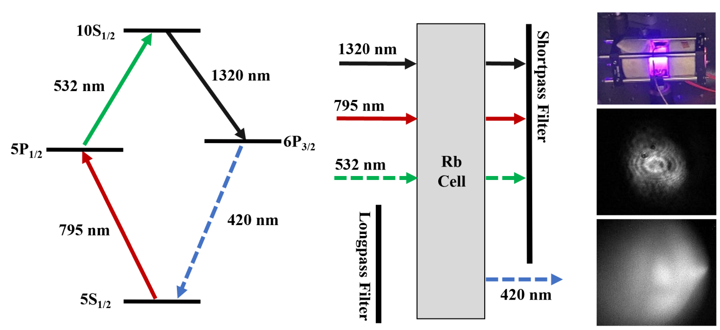

Figure 1: Energy level schematic and conceptual illustration of atomic resonance filter. Right-most images show fluorescence from the cell, the beam profile of a coherent blue signal, and image up-conversion of the letter "A".

References

[1] R. T. Randolph, E. Finberg, R. B. Miles, Green to Blue Light Conversion Through Resonant Four Wave Mixing in Rubidium Vapor. [Manuscript submitted for publication.]

[2] J. A. Gelbwachs, Atomic resonance filters (1988). doi:10.1109/3.963.

[3] M. Minden, H. Bruesselbach, Detection of 532-nm frequency-doubled Nd:YAG radiation in an active rubidium atomic resonance filter, Opt. Lett. 15 (1990) 384–386. doi:10.1364/OL.15.000384.

[4] A. Vernier, S. Franke-Arnold, E. Riis, A. S. Arnold, Enhanced frequency up-conversion in rb vapor, Optics Express 18 (2010). doi:10.1364/oe.18.017020.

Polariton-Modulated Singlet Fission in Cavity

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Numerous materials have been assessed in the hope of maximizing the energy conversion performance of solar cells. Under the single-band approximation, a detailed balance analysis yields a maximum efficiency of 30% assuming a band gap of 1.12 eV when the solar cell is in thermal equilibrium with a heat bath at 300K. Over the last forty years, many techniques have been developed to circumvent the Shockely-Queisser principle. Due to the complicated multi-step nature of singlet fission, several competing processes may severely deteriorate its overall product yield. A polariton is a quasiparticle that results from coupling between an electromagnetic wave, such as light, and a dipole carrying excitation in matter. Polaritons inherit the wavelike nature of light while maintaining local molecular interactions and structure. When the cavity mode is tuned to coincide in energy with a specific molecular excitation, the molecule's excited state and cavity's light field mix, or strongly couple, to form two new hybrid polariton states. This process is analogous to two atomic orbitals mixing to form molecular orbitals with new properties. Polaritons can therefore be created without pumping the cavity with external light. Here we fabricated a polariton cavity to manipulate singlet fission of hexacene and pentacene thin films. From time-resolved measurements, it is found that the coupling of exciton and photon depends on the thickness of the films. At a maximal thickness of the Rabi coupling, both the rates of singlet fission were enhanced. These results could not be explained by the existing theory.

Ultrafast nano-imaging and tip-enhanced control of electronic coherence in 2D semiconductors

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Understanding and ultimately controlling the properties of quantum materials and their coupled degrees of freedom will require counteracting the effects of dissipation and dephasing. This necessitates imaging the elementary excitations on their natural time and length scales. To achieve this goal, we developed scanning probe microscopies with ultrafast and shaped laser pulses for multiscale coherent spatio-temporal optical nano-imaging. In corresponding ultrafast movies, we resolve the fundamental quantum dynamics down to the few-femtosecond regime with nanometer spatial resolution.

Specifically, in 2D materials and their heterostructures, the emergent electronic, spin, and other quantum properties are controlled by the underlying interlayer coupling and associated charge and energy transfer dynamics. These processes are sensitive to interlayer distance and crystallographic orientation, which are in turn affected by defects, grain boundaries, and other nanoscale heterogeneities. In this talk, I will present the use of adiabatic plasmonic nanofocused four-wave mixing (FWM) [1] to image the coherent electron dynamics in monolayer WSe_2 resolving nanoscale heterogeneities in dephasing ranging from $T_2 < 5$ fs to $T_2 > 60$ fs on length scales of 50-100 nm [2]. Further, in combination with Purcell-enhanced nano-cavity clock spectroscopy [3] in WSe_2/graphene heterostructures we identify interlayer energy transfer dynamics at times scales of 350 fs [4]. Beyond the fundamental understanding to the competition between intrinsic and extrinsic effects on excitation lifetimes and coherence, we discover a new regime of nonlinear nano-optics at the interplay of spatial coherence and disorder-induced scattering.

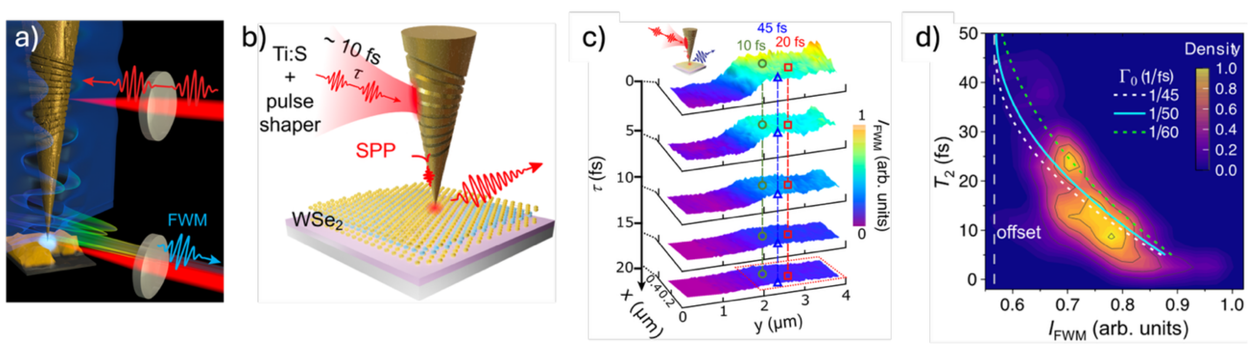

Fig. 1. ***a****-illustration of adiabatic nano-focusing of few-fs pulses with pulse-shaper and MIIPS controlled pulse replica for interferometric nano-localized FWM spatio-temporal coherent spectroscopy;* ***b****-application to 2D semiconductors probing exciton coherence, its spatial heterogeneity, and relation to local defects and strain;* ***c****-spatio-temporal variation of dephasing time ranging from < 5fs to >60 fs on length scales of 50-100 nm;* ***d****-unusual anti-correlation of coherence time T_2 with FWM signal intensity as a result of defect induced decoherence within the coherence area defined by spatial extent of the tip-confined optical near-field defining a new regime of nonlinear nano-optics.*

References

[1] T. Jiang, et al., "Ultrafast coherent nonlinear nano-optics and nano-imaging of graphene", *Nature Nanotechnology* **14**, 838 (2019).
[2] W. Luo, et al., "Ultrafast nano-imaging of electronic coherence in monolayer WSe_2" *Nano Lett.* **23**, 1767 (2023).
[3] M. A. May, et al., "Nanocavity clock spectroscopy: resolving competing exciton dynamics in WSe_2/$MoSe_2$ heterobilayers", *Nano Lett.* **21**, 522 (2020).
[4] W. Luo, et al. "Nonlinear nano-imaging of interlayer coupling in 2D graphene-semiconductor heterostructures", *Small* 2307345 (2024).

Spin Exchange, Molecular Energy Transfer, and Photoreactions for Destroying Cancer Cells and Microorganisms and Overcoming Antibiotic Resistance

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At the atomic and molecular level, all phenomena are governed by quantum effects, and certain interactions can influence how cells respond to reactive species, altering their equilibrium and leading to cell death. These reactions are particularly important for targeting tumor cells and achieving effective microbiological control. Molecular energy transfer processes that induce spin-state changes are especially noteworthy for these purposes. Through non-radiative energy transfer, we can generate reactive species that can destroy tumors. Even more intriguing is that, with precise molecular engineering, we can target microorganisms, eliminate them, or, most importantly, overcome their resistance to antibiotics. These fundamental mechanisms, when precisely controlled, provide the foundation for advanced and highly effective therapeutic strategies rooted in optical and quantum principles. This presentation will review the theoretical underpinnings of these mechanisms and highlight their application in the treatment of cancer and the control of infections. Furthermore, we will outline the basis for new therapeutic strategies.

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Controlling quantum correlations of bright multimode light sources

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Laser light is typically understood classically, in terms of wave solutions of the Maxwell equations. We often neglecting quantum effects with bright laser light because the relative fluctuations in intensity and phase of a coherent state are small when the number of photons is large. However, it is this small residual quantum noise and its dynamics that determine the noise properties of a laser sources, and thus controlling the quantum statistical properties of bright states of light is critical for applications in imaging and spectroscopy that demand high sensitivity.

I will present a new paradigm for controlling the quantum noise properties of bright states of light which exploits the fact that any nonlinear optical system imposes a multimode Bogoliubov transformation on the input quantum noise. In this paradigm, we use programmable input waveshaping and output mode filtering to steer this transformation to optimally reduce the fluctuations in any property of interest. This can be seen as a form of laser stabilization based on the control of complex multimode quantum correlations that naturally emerge when intense spatiotemporal pulses propagate in nonlinear media. We present two examples of this paradigm.

In one example, we will show how spectral dynamics of intense femtosecond pulses in single-mode optical fiber leads to a surprising decoupling of the output intensity fluctuations from input fluctuations induced by a combination of spectral correlations and stimulated Raman scattering of solitons, enabling a new regime of sub-Poissonian light generation [1]. In a second example, we show by that exploiting quantum correlations between spatial modes in a multimode fiber, it is possible to simultaneously control the classical spatial intensity and the quantum noise by means of a programmable spatial light modulator, strongly reducing intensity fluctuations in a region of a beam while keeping the intensity fluctuations fixed [2]. Critical to these developments is a new computational framework we have developed for predicting the quantum noise dynamics of intense light states, with complex input noise properties, in regimes of strongly multimode nonlinear optics [1,3].

[1] Zia Uddin, Shiekh, Nicholas Rivera, Devin Seyler, Jamison Sloan, Yannick Salamin, Charles Roques-Carmes, Shutao Xu, Michelle Y. Sander, Ido Kaminer, and Marin Soljačić. "Noise-immune quantum correlations of intense light." *Nature Photonics* (2025): 1-7.

[2] Sloan, Jamison, Michael Horodynski, Shiekh Zia Uddin, Yannick Salamin, Michael Birk, Pavel Sidorenko, Ido Kaminer, Marin Soljačić, and Nicholas Rivera. "Programmable control of the spatiotemporal quantum noise of light." *arXiv preprint arXiv:2509.03482* (2025).

[3] Rivera, Nicholas, Shiekh Zia Uddin, Jamison Sloan, and Marin Soljačić. "Ultra-broadband and passive stabilization of ultrafast light sources by quantum light injection." *Nanophotonics* 14, no. 11 (2025): 1857-1864.

Physics of ion acceleration in nanowire arrays irradiated with ultrashort laser pulses of relativistic intensity

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The efficient conversion of laser pulse energy into kinetic energy of MeV ions is demanded by applications that include new inertial fusion energy schemes. Laser-irradiated nanowire arrays act as efficient ion micro-accelerators in which the laser energy can be nearly totally absorbed and efficiently converted into kinetic energy of high energy ions . The resulting high energy ions induce nuclear fusion reactions, producing high energy neutrons [1] and alpha particles [2]. The understanding of these processes if crucial to improve the efficiency of these targets for their use in inertial fusion energy schemes.

Here we present results of the measurement of energy spectrum and angular distribution of accelerated protons and particle-in-cell simulations from which the fraction of laser energy converted into ion kinetic energy can be estimated. Measurement were conducted for polyethylene (CH_2) and nickel nanowire array targets irradiated with ultrahigh contrast laser femtosecond pulses from the Petawatt-class laser ALEPH. An array of seven Thomson parabola ion spectrometers and CR-39 ion detectors were place at different angles respect to the target normal. The results are compared with those obtained irradiating flat solid targets from the same materials. We demonstrate that while in flat solid targets ions are accelerated predominantly in the target normal direction by the well know mechanism of transverse normal sheet acceleration (TNSA), in nanowire arrays ions are also accelerated radially along the target plane. Radial acceleration is shown to result from the formation of a charge sheet surrounding each of the nanowires. The observation of this new radial ion acceleration mechanism is in agreement with our earlier prediction using 3-D particle-in-cell simulations [3].

Work conducted for the RISE IFE hub with the support of the U.S. Department of Energy (DOE), Office of Science, Fusion Energy Sciences, under Award No. DE-SC0024882: IFE-STAR, and a DoD Vannevar Bush Faculty Fellowship ONR award N000142012842, using facilities supported by LaserNet US grant US DE- SC0021246

[1] A. Curtis et al. , "Micro-scale fusion in dense relativistic nanowire array plasmas," Nat. Communication. **9**, 1077 (2018).
[2] M. S. Schollmeier, et al., "Investigation of Proton Beam-Driven Fusion Reactions Generated by an Ultra-Short Petawatt-Scale Laser Pulse," Laser Part. Beams, ID 2404263 (2022)
[3] J.J. Rocca et al., “Ultra-intense femtosecond laser interactions with aligned nanostructures” Optica, **11**, 437, (2024)

Anomalous Nuclear Forward Scattering under Intense XFEL Excitation

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Nuclear resonant scattering of hard x-rays is a powerful probe of coherent processes in matter, yet its response to intense, femtosecond x-ray pulses remains largely unexplored. Here, we report systematic measurements of nuclear forward scattering (NFS) from ^{57}Fe Mössbauer nuclei at the European XFEL, revealing robust and reproducible deviations from conventional NFS theory under high-flux excitation. Three types of "anomalies" were identified:

1) an apparent reduction of the effective sample thickness as compared to its physical thickness,
2) sensitivity of nuclear forward scattering to the spatial distribution of attenuators placed up- and downstream of the sample, and
3) a pronounced small-angle broadening of the delayed forward scattering (nuclear small-angle X-ray scattering).

Using monochromatization and polarization control, we show that these effects vanish under spectrally narrow and low-flux conditions, but grow with increasing X-ray fluence. Multi-thickness modeling and time-resolved analyzer scans reveal that the anomalies correlate with pulse intensity and evolve on 100 ns - timescales .
Our results establish a new nonlinear regime of nuclear x-ray optics, in which the collective response of Mössbauer nuclei couples to transient sample or field inhomogeneities induced by intense XFEL pulses.

Nuclear spin comagnetometer gyroscopes with ^{21}Ne

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Nuclear spin comagnetometers offer exceptional precision in measurements of spin energy levels and exhibit long-term stability, making them powerful tools for probing spin-dependent physics beyond the Standard Model as well as for inertial rotation sensing. I will describe recent progress in the development of nuclear spin co-magnetometers using ^{21}Ne atoms which are preferred because of their low polarizability and small magnetic moment. We have developed two types of co-magnetometers, one based on magnetic field self-compensation using a SERF Rb magnetometer [1] and another based on free precession of nuclear spins detected with a Rb magnetometer using π-pulse decoupling [2]. Self-compensating magnetometers can achieve lowest angle-random-walk, similar to atom interferometer gyroscopes, but suffer from long-term drift [3,4]. In contrast, free spin-precession gyroscopes have very good long term stability and can achieve bias drift in the navigational range of <1 mdeg/hour [5]. I will discuss interesting physics effects observed in the development of the co-magnetometer, including long-range scalar and dipolar interactions between nuclear spins, suppression of quadrupolar frequency splitting for ^{21}Ne, and Overhauser effect observed in Rb vapor under microwave field illumination. Compact spin-precession gyroscopes offer significant potential for practical navigation applications as well as for searches for new spin-dependent forces.

[1] T. W. Kornack, R. K. Ghosh, and M. V. Romalis, Phys. Rev. Lett. **95**, 230801 (2005).
[2] M. E. Limes, D. Sheng, and M. V. Romalis, Phys. Rev. Lett. **120**, 033401 (2018).
[3] K. Wei *et al*, Phys. Rev. Lett. **130**, 063201 (2023)
[4] J. Wang, J. Lee, H. Loughlin, M. Hedges, M. V. Romalis, Phys. Rev. A **111**, 053103 (2025).
[5] S. Zhang, J. Wang, G. Sun, J. J. van de Wetering, M.V. Romalis, arxiv:2509.13486

Free-Electron Quantum Optics: Coherent Control, Correlations, and Entanglement

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Free electrons enable coherent interactions with optical near fields at nanometer spatial and femtosecond to attosecond temporal scales, providing a new interface between electron microscopy and quantum optics. Recent experiments establish free-electron quantum optics as a framework for coherent electron control, quantum readout, and correlated dynamics involving photons and electrons. This presentation presents selected works from our group in this field.

In particular, free-electron homodyne detection enables phase-sensitive readout of optically induced electron wave-function modulations [1]. Complementary approaches based on cavity-mediated inelastic electron–photon scattering generate correlated electron–photon pairs [2], while coincidence measurements demonstrate electron-heralded nonclassical photon number states [3]. Following a variety of theoretical proposals involving entangled free electrons and photons (see, e.g., Refs. [4-6]), recently, the first experimental observations of free-electron–photon entanglement have been made [7,8].

Beyond single-electron physics, Coulomb interactions in ultrashort electron pulses generate strong electron–electron correlations. We characterized Coulomb-correlated electron number states in electron microscope beams [9], while phase-space–resolved measurement reveal femtosecond and attosecond few-electron correlations [10]. Taken together, these works illustrate how free-electron quantum optics enables controlled preparation, readout, and correlation of quantum states of electrons and photons on ultrafast and nanoscale length scales.

References

[1] J. H. Gaida *et al.*, “Attosecond electron microscopy by free-electron homodyne detection”, *Nature Photonics* **18**, 509–515 (2024).
[2] A. Feist *et al.*, “Cavity-mediated electron-photon pairs”, Science 377, 777–780 (2022).
[3] A. Arend *et al.*, “Electrons herald non-classical light“, *Nature Physics* **21**, 1855–1862 (2025).
[4] O. Kfir, “Entanglements of Electrons and Cavity Photons in the Strong-Coupling Regime”, Phys. Rev. Lett. **123**,103602 (2019),
[5] G. Baranes *et al.*, “Free electrons can induce entanglement between photons”, npj Quant. Inf. **8**, 32 (2022)
[6] J.W. Henke *et al.,* “Probing electron-photon entanglement using a quantum eraser”, Phys. Rev. A **111**, 012610 (2025)
[7] J.-W. Henke *et al.*, “Observation of quantum entanglement between free electrons and photons”, arXiv:2504.13047(2025).
[8] A. Preimesberger et al., “Experimental Verification of Electron-Photon Entanglement”, arXiv:2504.13163 (2025).
[9] R. Haindl *et al.*, “Coulomb-correlated electron number states in a transmission electron microscope beam”, *Nature Physics* **19**, 1410–1419 (2020).
[10] R. Haindl *et al.*, “Femtosecond and Attosecond Phase-Space Correlations in Few-Particle Photoelectron Pulses”, Phys. Rev. Lett. **135**, 165002 (2025).

Is Physics Timeless ?

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ABSTRACT

To find a common origin for different concepts used in the mathematical description of nature has been a lasting motivation to evolve theory in physics. Here, we argue that time and temperature originate from a stationary global entangled state of a system and its environment. Time evolution emerges in the relation of system and environment when separating them [1]. Imaginary relational time gives rise to temperature and the canonical ensemble for the system, if the global state is maximally entangled [2].

[1] **Sebastian Gemsheim,** Jan M. Rost, ***Phys. Rev. Lett.,*** 131, 140202 *(2023).*

[2] **Sebastian Gemsheim,** Jan M. Rost, ***Phys. Rev. D,*** 109, L121701 *(2024).*

Correlated quantum fields generated by vacuum fields

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This talk is to explore various techniques to manipulate populations in quantum systems by applying tailored optical pulses included even vacuum fields. The techniques are based on interactions between adiabaticaly changing quantum fields with the quantum systems. The obtained results will be beneficial to the fields of atomic and molecular physics, quantum electronics, and nonlinear physics. In particular, these new techniques will be important for developing quantum sensors, quantum information systems. The quantum fields created and emitted can be used for quantum communications.

Propagationofquantumfieldinteractingwithsingletwo-levelorthree-levelatomshasbeen studied. Using the Gaussian quantum mode functions, we calculate evolution of the quantum state that includes atomic and field variable. We demonstrated the phase acquired by single-photon propagation [1,2], which can be of great importance for long-range quantum communications. The results can be used for controlling quantum field propagation, and for design of optical elements such as a quantum prism and a quantum lens.

The vacuum field can be strongly modified by the cavity, and in particular, the "vacuum" field can have a chirped frequency modulation that it can be a part of adiabatic rapid passage together with classical drive field. The action of the classical and "vacuum" or quantum field can result in the generation of the quantum fields with controllable parameters. Such QED cavity can be used to generate strongly correlated quantum fields that can be of interest for quantum sensing, spectroscopy at the single photon level, quantum teleportation, and other applications for quantum information.

[1] Yuri Rostovtsev, Jacob Emerick, Anil Patnaik, "The refractive index of a single atom ex perienced by a single photon", Results in Optics, 2023. DOI: 10.1016/j.rio.2023.100568

[2] https://sciencefeatured.com/2024/01/24/light-particle-meets-atom-revolutionizes-communication/

[3] Y. Rostovtsev, J. Emerick, and A. Patnaik, Correlated quantum photon states generated by vacuum fields, The European Physical Journal Special Topics **(in press)** (2025).

[4] J. Emerick, T. Harborth, A. Patnaik, and Y. Rostovtsev, The refractive index of a single three-level atom: Quantum state separator, The European Physical Journal Special Topics, 1 (2025).

[5] J. Emerick, A. K. Patnaik, and Y. Rostovtsev, The refractive index of a single three-level atom experienced by a single photon, Frontiers in Quantum Science and Technology **4**, 1546480 (2025).

[6] T. Harborth and Y. Rostovtsev, Refraction of the two-photon multimode field via a three-level atom, Entropy **27**, 10.3390/e27010071 (2025).

Hydrodynamic Aharonov–Bohm Effect, Time-Varying Vortex-Induced Phases, and Rotating Black-Hole Analogues*

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Emulation has become a powerful tool in quantum physics, allowing us to reproduce key quantum phenomena in controlled, often classical, platforms where measurements are faster, tunable, and experimentally accessible [1]. By recreating the underlying mathematics rather than relying on inherently fragile quantum states, these analog systems offer insight into quantum behavior otherwise difficult to probe directly [2].

Hydrodynamic quantum analogues provide a macroscopic wave platform on which concepts from quantum mechanics and gravitation can be studied in accessible settings [3]. In particular, Couder walkers can be used to observe quantum-like effects such as quantized orbital states, tunneling-like transitions, double-slit interference, and emergent quantum-like statistics [4].

We first present a hydrodynamic analogue of the Aharonov–Bohm (AB) effect, in which the droplets acquire a circulation-dependent phase while propagating around a localized vortex, even in regions where the local vorticity vanishes. We resolve AB-type interference patterns and directly measure the resulting phase shifts in Wigner phase space.

Next, we examine time-varying vortex-induced phases, highlighting the emergence of higher-order geometric contributions such as the Kennard cubic phase, whose magnitude scales with the cube of the effective propagation time. By introducing temporal modulation into the background flow, we map out this non-linear phase structure and compare it against simplified quantum wavepacket models.

Finally, we demonstrate how these techniques extend to rotating black-hole analogues. By tailoring radial and azimuthal flow profiles, we construct hydrodynamic analogues of effective curved space–times that capture both weak-field gravito-electromagnetic behavior and strong-field rotating black-hole characteristics, including frame dragging and ergoregion-like domains. Together, these results establish a unified platform for exploring AB phases, time-dependent phases, and rotating space–time analogues in the laboratory.

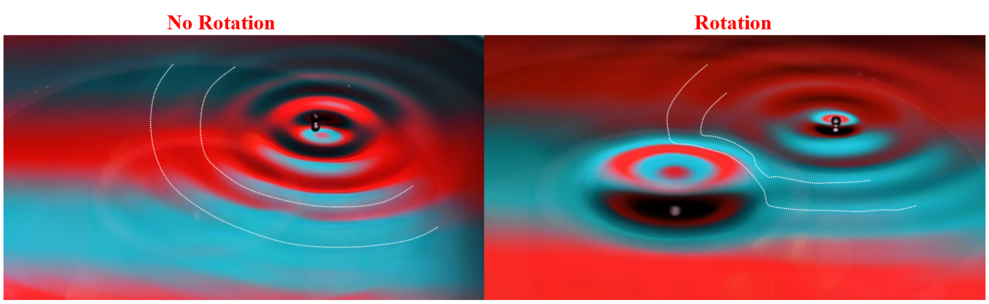

Figure 1: The Aharonov–Bohm effect in a pilot-wave hydrodynamic apparatus. When the vortex is off (left), the walker's path shows clear long-term memory. When the vortex is activated (right), distinct memory disturbances appear, revealing the hydrodynamic analogue of the AB phase.

References

[1] E. Arbel et al., "Optical emulation of quantum state tomography and Bell test—A novel undergraduate experiment," *Results in Optics* 21, 100847 (2025).

[2] G. G. Rozenman et al., "Observation of a phase space horizon with surface gravity water waves," *Communications Physics* 7, 165 (2024).

[3] J. W. M. Bush and O. U. Anand, "Hydrodynamic quantum analogs." Reports on progress in physics 84.1 (2020).

[4] J. W. M. Bush, "Pilot-wave hydrodynamics." Annual Review of Fluid Mechanics 47.1 (2015).

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Optical Emulation of Quantum Systems Using Pulsed Lasers and Classical Optics

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Emulation has become a central paradigm in contemporary quantum science, enabling the investigation of quantum phenomena using controllable classical platforms that faithfully reproduce the mathematical and operational structure of quantum theory. Rather than relying on fragile single-photon sources or intrinsically quantum hardware, such emulators implement quantum protocols at the level of state preparation, measurement, and statistical inference, offering rapid data acquisition, tunability, and conceptual transparency.

In this work, we present a unified optical framework for the emulation of quantum systems using pulsed laser sources and linear optical elements. By encoding information in polarization, phase, and measurement basis choice, classical coherent pulses are used to replicate the protocol flow of foundational quantum experiments, including quantum state tomography, Bell inequality tests, and quantum key distribution schemes such as BB84, B92, and the six-state protocol. Although the underlying light field remains classical, the experimental observables are processed through the same mathematical machinery as in genuine quantum implementations.

We show that polarization-randomized pulsed sources, when analyzed using standard tomographic reconstruction techniques, yield density matrices that are algebraically identical to those associated with entangled quantum states. Measurements performed across multiple polarization bases reveal off-diagonal coherence terms and correlation structures that mirror those of ideal Bell states. Similarly, correlation measurements conducted within the Clauser–Horne–Shimony–Holt (CHSH) framework produce violations of classical bounds at the level of inferred Bell parameters, reflecting protocol-level quantum correlations rather than claims of nonlocal ontology.

Extending beyond foundational tests, the same optical emulation platform enables the systematic study of quantum communication protocols. We demonstrate that BB84, B92, and six-state quantum key distribution schemes can be faithfully implemented using classical pulses by preserving the essential features of basis choice, state overlap, sifting, and disturbance under intercept–resend strategies. This approach allows the quantitative investigation of error rates, information leakage, and protocol robustness using accessible laboratory hardware while maintaining full compatibility with quantum information theoretic analysis.

Taken together, these results establish classical optical emulation as a powerful and versatile tool for exploring quantum optics, quantum information, and quantum cryptography. By disentangling the operational structure of quantum protocols from the physical realization of single quanta, this framework provides a bridge between abstract quantum theory and experimentally accessible systems, with applications ranging from undergraduate education to rapid prototyping of quantum communication architectures.

References

[1] J. S. Bell, “On the Einstein–Podolsky–Rosen paradox,” *Physics* **1**, 195 (1964).

[2] S. P. Gandelman, A. Maslennikov, and G. G. Rozenman, “Hands-on quantum cryptography: Experimentation with the B92 protocol using pulsed lasers,” *Photonics* **12**(3), (2025).

[3] E. Arbel *et al.*, “Optical emulation of quantum state tomography and Bell test—A novel undergraduate experiment,” *Results in Optics* **21**, 100847 (2025).

[4] Y. Bloom *et al.*, “Quantum cryptography—A simplified undergraduate experiment and simulation,” *Physics* **4**, 104 (2022).

[5] S. P. Gandelman and G. G. Rozenman, “Emulation of the six-state quantum key distribution protocol with pulsed lasers,” *arXiv preprint* arXiv:2511.13413 (2025).

Quantum sensing to accelerate the axion dark matter search

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Cavity-based axion dark matter searches, which probe for a weak narrowband microwave signal at an unknown frequency, can be enhanced by quantum sensing techniques. These haloscope experiments operate in the regime where zero-temperature vacuum fluctuations limit the rate at which detectors can scan the axion parameter space. As such, they stand to benefit from measurements that evade the quantum noise penalty, either by using non-classical microwave states or by employing single-photon counting [1,2]. A central challenge to implementing these measurements is that they require Josephson circuitry which must be physically isolated from the strong magnetic field of the detector.

Here, we demonstrate a remote measurement scheme that uses static hybridization to overcome the physical separation between the detection cavity and the Josephson circuitry. We couple one mode of a Josephson parametric converter (JPC) through a 50 cm coaxial cable to a 3D microwave cavity, and we parametrically couple the resulting normal modes to a readout mode of the JPC. By using the JPC as a frequency-converter, we swap the state of the cavity with the readout mode. This (ideally noiseless) type of operation could be used to swap microwave photons from a tunable detection cavity to a fixed-frequency readout cavity used for single-photon counting protocols [2]. Alternatively, using the JPC for both frequency-conversion and gain, we realize a quantum non-demolition measurement which increases both the peak visibility and the bandwidth of our detector, resulting in more than ten-fold scan rate enhancement over the quantum-limited scan rate.

[1] K. M. Backes, *et al.,* A quantum-enhanced search for dark matter axions, Nature 590, 238 (2020).
[2] A. V. Dixit, *et al.,* Searching for Dark Matter with a Superconducting Qubit, Phys. Rev. Lett. 126, 141302 (2021).

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Quantum gases in microgravity: new perspectives for ground based research

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Abstract

Free-fall allows to study quantum degenerate gases in new, text-book like settings. Moreover, extending free fall promise to boost the sensitivity and accuracy of inertial matter-wave interferometers. These sensors are employed in fundamental physics as well as are studied for applications in navigation or geodesy. Atom interferometers have been demonstrated aboard the chinese space station. So far, apart from experiments in space aboard sounding rockets and the international space station, we took benefit of the microgravity environment in the Bremen drop tower. New perspectives arise in elevators such as the Bremen Gravitower as well as the Einstein elevator in Hannover, providing many experimental runs per day. We exploit them to study for the first time quantum degenerate mixtures in microgravity on ground and perform interferometry on extended time scales.

The Hybrid Sampling Method for the Statistics of a Bose Gas

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While the statistical properties of an ideal Bose gas are well understood, accounting for interaction induced corrections remains a challenging and unresolved problem. We propose a fundamentally different approach: instead of calculating partition functions, we construct models of the canonical and microcanonical ensembles directly. Previously, to this end, we developed two sampling techniques—one based on the classical field approximation and the other on Fock State Sampling (FSS). Each method offers significant advantages but also suffers from critical limitations: the classical field approach is plagued by ultraviolet divergence, while FSS neglects changes to the condensate wave function. In this talk, we introduce a new Hybrid Sampling method that overcomes these issues, combining the strengths of both earlier approaches while avoiding their respective shortcomings.

Efficient generation of single photons and atom-photon entanglement in a quantum network node

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We demonstrate an efficient neutral-atom quantum networking node based on a parabolic mirror that both collects and mode-matches single photons emitted by a trapped atom directly into a single-mode fiber. The core optomechanics are realized with millimeter-scale optics (see the figure) that are pre-aligned and bonded on a rigid platform inside the vacuum chamber, with all modes interfaced to fibers accessible outside the vacuum, yielding a compact and robust plug-and-play node. We measure an overall photon collection and detection efficiency of 3.6% after the single-mode fiber, significantly exceeding typical values obtained with large external high-NA objectives and approaching the limit set by the mirror's numerical aperture. The single photons have high purity indicated by the measured $g^{(2)}(0) = 0.006 \pm 0.006$. Using this node, we generate atom–photon entangled states with a raw Bell-state fidelity of 0.93 ± 0.05, and an inferred fidelity of ≈0.98 after correcting for atom-state measurement errors. Our results show that cavity-free neutral-atom nodes can achieve both high efficiency and high entanglement fidelity, providing a practical building block for scalable quantum repeaters and distributed quantum information processing with neutral atoms.

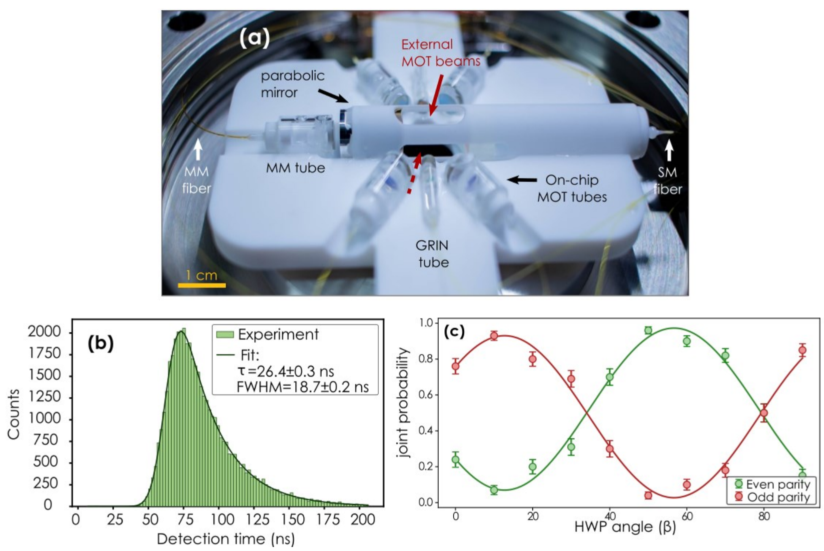

Figure. (a) The on-chip assembly as the core of the setup for single atom trapping and single photon generation. All the on-chip optics are pre-aligned and interfaced with optical fibers. (b) Histogram of the single-photon detection time with a decay time of 26.4 ns as expected from the lifetime of the excited state. (c) parity oscillations in the z-basis indicating atom-photon correlation in polarization basis.

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Quantum Technologies for New Physics Discoveries

Marianna Safronova

University of Delaware

Advances in AMO quantum sensing and the discovery potential they offer need advances in atomic theory. Robust, scalable, and high-precision theoretical tools are essential not only for interpreting current new physics searches, but also for identifying promising systems, transitions, and measurement strategies that maximize sensitivity to new physics. I will review the remarkable recent progress in atomic theory, highlighting its numerous applications to new physics searches spurred by enhanced computational capabilities, including development of clocks with highly charged ions. Recent developments include large-scale high-performance computing, the transformation of research codes into widely accessible software, the open sharing of data through a community portal, and the application of machine learning in atomic theory.

Investigation of the effects of nanoscale facets on catalytic activity in photo-driven nanosystems

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Nanoparticles exhibit extraordinary catalytic activity due to their high surface area, tunable morphology, and unique electronic properties. Among these, facets and surface defects play a pivotal role in enhancing photocatalytic reactions. In this study, we investigate the nanoscale mechanisms governing charge-driven photocatalytic processes on single, isolated cubic gold nanoparticles (AuNPs) in a time-resolved optical pump and X-ray probe scheme at the Maloja instrument at SwissFEL. Coherent diffractive imaging (CDI) patterns are classified per a convolutional neural network (CNN) according to the nanoparticle orientations. A three-dimensional reconstruction based on the Memetic Phase Retrieval algorithm is then used to resolve the full 3D morphology of each nanoparticle. These structural maps are correlated with the three-dimensional momentum distributions of hydrogen ion species emitted from the same particles, retrieved through an Abel inversion of the velocity map imaging (VMI) data. This multimodal correlation reveals orientation-dependent ion emission and facet-specific reactivity, indicating that local near-field enhancement at high-index facets governs the efficiency of photocatalytic charge transfer. By linking structural and dynamical observables on a particle-by-particle level, this approach provides unprecedented insight into the interplay between morphology, local fields, and catalytic function in nanoscale photocatalysis.

This work was supported by the U.S. Department of Energy, Office of Science, Basic Energy Sciences, under Contract No. DE-SC0063.

Polar Direct Drive Target Design for a 10MJ Laser Inertial Fusion Energy Facility

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The future of inertial fusion energy (IFE) as a viable green energy source requires development in all areas from target manufacturing to power plant operation. Therefore, a polar direct drive spherical target fielded on a facility at sufficient powers for maximal power production by neutron deposition is a viable avenue for future high rep-rate experimental platforms. Using Los Alamos National Laboratory's (LANL) xRage radiation hydrodynamics simulation code benchmarked against experiments using the common model framework (CMF), our design is intended for use on a 10MJ laser facility. Specifically, our design is rooted in the high repetition-rate two sided illimitation concept from Xcimer Energy adapted for a direct drive only target. We are using shaped, time dependent energy profiles and exploring the impacts of implosion symmetry and target design on the estimated yield. This work is intended to map the laser requirements, target robustness, physics impacts, and target manufacturing need for a polar direct drive target design intended for IFE.

This work is supported by the U.S. Department of Energy (DOE), Office of Science, Fusion Energy Sciences, FWP No. 0024882: IFE-STAR. This work was supported by the U.S. Department of Energy through the Los Alamos National Laboratory. Los Alamos National Laboratory is operated by Triad National Security, LLC, for the National Nuclear Security Administration of U.S. Department of Energy (Contract No. 89233218CNA000001).

Understanding nanometer structure-performance relation of foams for inertial fusion energy

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Within the RISE Inertial Fusion Energy – Science and Technology Accelerated Research (IFE-STAR) Hub, we are seeking to develop aerogel and 3D printed foams for inertial fusion energy (IFE) fuel capsules. It is proposed that these foams could improve IFE implosion symmetry and control of the deuterium and tritium fuels in the capsules. These nanostructured foams provide designer density and controllable dynamic response. The RISE hub has been working with General Atomics (GA) and Lawrence Livermore National Laboratories (LLNL) to characterize these foams statically at nanometer scale in three dimensions and dynamical during laser shock experiments. It is imperative that these novel foams can be modeled correctly in hydrodynamic models so that the capsules can be optimized for IFE yield. We utilize x-ray light sources such as the Advanced Photon Source at Argonne National Laboratory and the Linac Coherent Light Source – Matter in Extreme Conditions instrument at SLAC National Accelerator Laboratory to characterize these foams. Here, we will present the results of multiple x-ray imaging experiments to determine the nanometer scale structure and dynamic response of aerogel IFE foams from GA and two photon polymerized 3D printed foams from LLNL. We are currently seeking to constrain xRAGE and FLASH hydrodynamic models of these foams to improve the accuracy of the designed high-yield experiments for direct drive IFE. The accuracy of these models will be critical for developing IFE schemes that will inform fusion pilot plant designs.

Acknowledgements: This research was performed on APS beam time award (DOI: https://doi.org/10.46936/APS-191046/60014810) from the Advanced Photon Source, a U.S. Department of Energy (DOE) Office of Science user facility operated for the DOE Office of Science by Argonne National Laboratory under Contract No. DE-AC02-06CH11357. Use of the Linac Coherent Light Source (LCLS) at the SLAC National Accelerator Laboratory, U.S. Department of Energy (DOE), Funding from Office of Science, Fusion Energy Sciences, under Award No. DE-SC 0024882: IFE-STAR issued as SLAC FWP 101126 through the IFE RISE Hub partnership; Laboratory Directed Research and Development Director's Fellowship (20200744PRD1); U.S. Department of Energy (DOE) Office of Science, Office of Fusion Energy Sciences, under the Early Career Award, 2019; iHMX and Conventional High Explosives Grand Challenge Programs; NNSA grants (DE-NA0003914, DE-NA0004134, DE-NA0003856); DOE grants (DE-SC0020229, DE-SC0019329); NSF grants (PHY-2020249, PHY-2206380)

PQE2026

Christian Sanner

Session “Quantum technologies for new physics discoveries”

Title:
Testing relativity with a cryogenic ytterbium ion clock

Abstract:
Optical clocks based on atoms and ions probe relativistic effects with unprecedented sensitivity. By performing clock spectroscopy on a single ytterbium ion in a cryogenic environment we have full quantum control over all internal and external degrees of freedom and expect strongly improved coherence times. This makes it possible to realize novel tests of relativity in a regime where superpositions of proper time emerge.

Searching for a variation of the fine structure constant with highly charged ions

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Precision spectroscopy of atomic transitions is a promising tool to test our understanding of fundamental physics and search for new physics beyond the standard model. Combining the excellent precision achievable with single trapped ion clocks with the enhanced sensitivities to relativistic effects in highly charged ions (HCIs) [1, 2] yields an ideal platform to search for a variation of the fine structure constant α - a possibility predicted for example by models for ultralight bosonic dark matter [3, 4]. I will present the TwinTrap experiment, where we plan to perform direct simultaneous spectroscopy on two complementary highly charged ions - Cf^{15+} and Cf^{17+} - via quantum logic spectroscopy [5, 6], and monitor the ration of these two frequencies to search for a variation of α. I will present our progress on the design and construction of the experimental apparatus comprising of two identical cryogenic vacuum systems and an EBIT and ion beamline for production and delivery of the HCIs.

[1] Berengut, J. C. *et al., Phys. Rev. Lett.*, 105:120801 (2010).

[2] Kozlov, M. G. *et al., Rev.Mod.Phys.*, 90:045005 (2018).

[3] Safronova, M. S. *et al., Rev.Mod.Phys.*, 90:025008 (2018).

[4] Filzinger, M. *et al., Phys Rev Lett.*, 130:253001 (2023).

[5] Schmidt, P. *et al., Science*, 309:5735 (2005).

[6] Micke, P. *et al., Nature*, 578:60–65 (2020).

Observation of Genuine Tripartite Non-Gaussian Entanglement from a Superconducting Three-Photon Spontaneous Parametric Down-Conversion Source

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The generation of entangled photons through Spontaneous Parametric Down-Conversion (SPDC) is a critical resource for many key experiments and technologies in the domain of quantum optics. Historically, SPDC was limited to the generation of photon pairs. However, the use of the strong nonlinearities in circuit quantum electrodynamics has recently enabled the observation of Three-Photon SPDC (3P-SPDC). Despite great interest in the entanglement structure of the resultant states, entanglement between photon triplets produced by a 3P-SPDC source has still has not been confirmed. Here, we report on the observation of genuine tripartite non-Gaussian entanglement in the steady-state output field of a 3P-SPDC source consisting of a superconducting parametric cavity coupled to a transmission line. We study this non-Gaussian tripartite entanglement using an entanglement witness built from three-mode correlation functions, observing a maximum violation of the bound by 15 standard deviations of the statistical noise. Furthermore, we find strong agreement between the observed and the analytically predicted scaling of the entanglement witness.

Interference at work

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The central ingredient of quantum mechanics is *interference* which explains the distinct difference between the classical and the quantum world. We show [1] that at the very heart of the CHSH inequality and the GHZ states is the difference between the sum of *probability amplitudes* and the sum of *probabilities*. In the field of signal processing it is well known, that the phase of the Fourier transform is more important, than the amplitude. We transfer the concept of the associated phase-only reconstruction [2] to quantum mechanics as illustrated by the figure. A third example of the power of interference is the familiar Landau-Zener effect. We demonstrate that the exponential transition probability originates [3] from a logarithmic phase singularity. Finally, we analyze an atom interferometer realized by the group of R. Folman to test [4] the Einstein-Equivalence Principle.

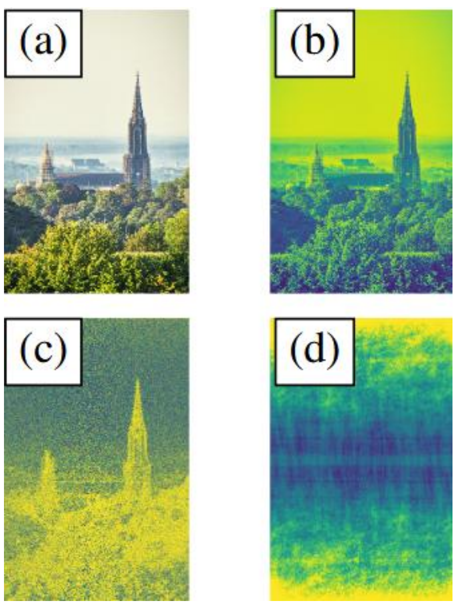

Fig: Phase-only (c) and amplitude-only (d) reconstructions illustrated for the Ulm minster (a). The inverse of the Fourier transform of (a) yields (b), which is identical to (a).

References:

[1] A. Schellhorn, J. Seiler and W.P. Schleich, *The role of interference in quantum correlations,* Phys. Rev. Research (accepted)

[2] A. Knoll, L. Cohen and W.P. Schleich, *Interference in phase space and phase-only reconstruction,* Phys. Rev. A (accepted)

[3] E. P. Glasbrenner, D. Fabian and W.P. Schleich, *A logarithmic phase singularity at the heart of Landau- Zener transitions* (to be published)

[4] O. Dobkowski, B. Trok, P. Skakunenko, Y. Japha, D. Groswasser, M. Efremov, C. Marletto, I. Fuentes Guridi, R. Penrose, V. Vedral, W. P. Schleich and R. Folman, *Observation of quantum free fall and the consistency with the equivalence principle* (to be published)

Highly Charged Ion Clocks to Test Fundamental Physics

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The extreme electronic properties of highly charged ions (HCI) render them highly sensitive probes for testing fundamental physical theories. The same properties reduce systematic frequency shifts, making HCI excellent optical clock candidates [1]. The technical challenges that hindered the development of such clocks have now all been overcome, starting with their extraction from a hot plasma and sympathetic cooling in a linear Paul trap, readout of their internal state via quantum logic spectroscopy, and finally the preparation of the HCI in the ground state of motion of the trap. Here, we present the first operation of an atomic clock based on an HCI (Ar^{13+} in our case) and a full evaluation of systematic frequency shifts of the employed $^2P_{1/2}$-$^2P_{3/2}$ fine-structure transition at 442 nm [2]. The achieved uncertainty is almost eight orders of magnitude lower than any previous frequency measurements using HCI and comparable to other optical clocks. One of the main features of quantum logic spectroscopy is the flexibility of the investigated species. This allowed us to perform isotope shift spectroscopy of the $^2P_0$-$^2P_1$ fine-structure transition at 569 nm in Ca^{14+} ions. In a large theory-experiment collaboration, we combined this data with improved measurements of the Ca^+ $^2S_{1/2}$-$^2D_{5/2}$ clock transition at 729 nm, new isotope mass measurements, and highly accurate calculations of the 2nd order mass shift. The resulting King plot exhibits a large ($> 1000\sigma$) nonlinearity, expected to be dominated by nuclear polarizability. Using this data, we put the currently most stringent bound on a hypothetical 5th force coupling neutrons and electrons [3]. This demonstrates the suitability of HCI as references for high-accuracy optical clocks and to probe for physics beyond the standard model.
A next-generation HCI optical clock may be based on Ni^{12+}, which offers an excited state lifetime of ≈ 20 s. By developing efficient search strategies with quantum logic techniques [4] and precise atomic structure calculations [5], we identified the logic and clock transitions in this species within just a few hours of searching.

References

1. M. G. Kozlov *et al.*, Rev. Mod. Phys. **90**, 045005 (2018).
2. S. A. King *et al.*, Nature 611, 43 (2022).
3. A. Wilzewski *et al.*, Phys. Rev. Lett. 134, 233002 (2025).
4. S. Chen *et al.*, Phys. Rev. Appl. 22, 054059 (2024).
5. C. Cheung *et al.*, Phys. Rev. Lett. 135, 093002 (2025).

Quantum Advantage in Thermodynamics

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Quantum coherence, squeezing and entanglement are new types of resources in quantum era which led to rapid development of quantum sensors, quantum heat engines and quantum batteries. The latter possess features which are not possible in the classical counterparts and serve as platforms for studying thermodynamics in the quantum regime. For example, quantum heat engine performance can be improved beyond the classical Carnot limit (determined by the ratio of reservoir temperatures) by using a heat source with a small bit of coherence [1] (Fig. 1a). A photonic quantum engine driven by superradiance employing a single heat reservoir composed of atoms and photonic vacuum has been realized experimentally [2] (Fig. 1b). A quantum battery is another example of a quantum system which utilizes quantum properties, such as coherence, entanglement, and superradiance, to enhance energy charging rates, stabilize stored energy, and optimize work extraction.

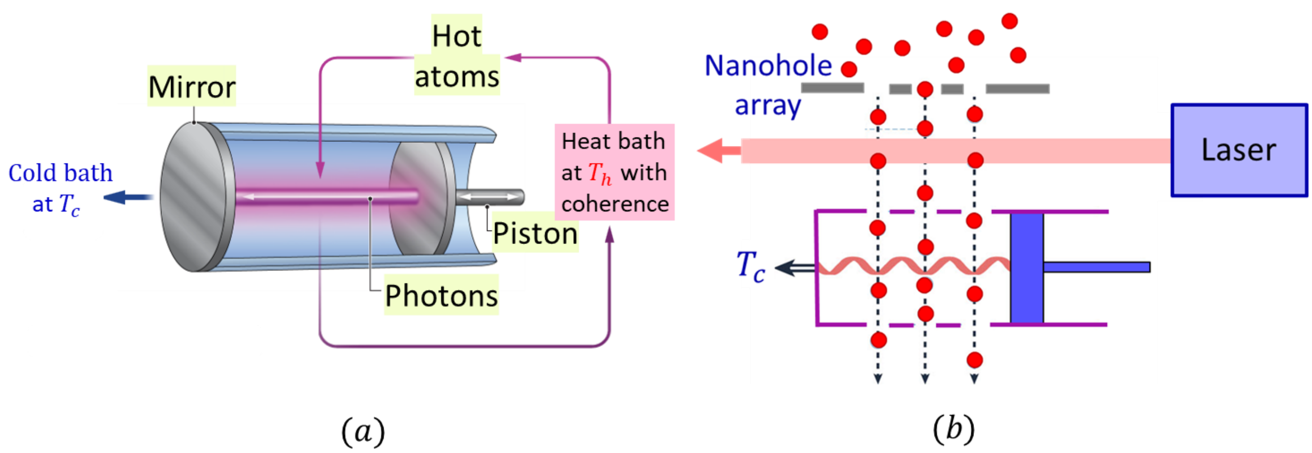

Figure 1: (a) Quantum photonic heat engine. An optical cavity is confined between two mirrors, of which one is a piston. The piston generates useful work on expansion, which is driven by radiation pressure of photons emitted by hot atoms. This photon gas is subsequently cooled to T_c, and the cold gas is compressed. This is waste work. The ratio of waste work to useful work is the maximum efficiency for a classical Carnot heat engine. A quantum heat engine can surpass this Carnot limit by using a heat source with a small bit of coherence in the hot atoms. (b) Superradiant quantum engine in which superradiant atomic ensemble serves as a non-thermal reservoir. The engine's working fluid is photon gas exerting pressure on cavity mirrors. The engine works between a superradiant state and an effective thermal state of atoms. This led to about a 40-fold increase in the effective engine temperature, resulting in near-unity engine efficiency [2].

[1] M.O. Scully and W. Unruh, *One hundred years of quantum mechanics*, Science **390**, 998 (2025).

[2] J. Kim *et al., A photonic quantum engine driven by superradiance,* Nature Photonics **16**, 707 (2022).

Field-driven currents in solids with few-cycle mid-infrared pulses

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Few-cycle, carrier-envelop-phase (CEP) stable pulses enable currents to be injected into materials on sub-cycle timescales [1]. A smaller photon energy with respect to the bandgap energy of the material results in deeper sub-cycle temporal confinement of the resulting currents. Whereas visible light pulses enable currents to be injected into dielectrics on a sub-cycle scale, near- to mid-infrared pulses enable similar confinement in semiconductors. In general, fine control over the various degrees of freedom of the incident light (temporal structure, spatial structure, polarization, orbital angular momentum, quantum character) can be transferred to the currents that are introduced to the material [2,3].

The first part of this presentation will provide an overview of 3 platforms for generating few-cycle, carrier-envelop-phase (CEP) stable pulses containing spectral content spanning 1.2 µm – 3.0 µm. The first source is a commercially available laser oscillator with integrated post-compression.

In the second approach, relatively long pulses (100 – 150 fs) generated from an optical parametric amplifier are applied to a series of crystalline TiO_2 substrates. In these substrates, the pulses experience a combination of self-phase modulation, plasma formation, and linear dispersion. Optimization of the intensity of the pulse entering each crystal enables the pulse to temporally self-compress by a factor of approximately 2 per substrate. We demonstrate seven-fold pulse compression to 2 optical cycles using 3 TiO_2 substrates, without the need for additional dispersion compensating optics.

The third approach is based on applying octave-spanning pulses produced by nonlinear compression of Ti:Sapph pulses to intra-pulse difference frequency generation. Using this approach, we achieve 8-10% conversion efficiency in a beta barium borate (BBO) crystal and demonstrate that the entire super-octave-spanning spectrum from 1.2 µm – beyond 2.6 µm is passively CEP stable.

The application of these sources to optical-field-driven currents in solids, electric field sampling, and nonlinear processes in nanostructures will be discussed in the latter half of the presentation. The talk will conclude with an outlook on the development of few-cycle, CEP stable, spatially isolated magnetic impulses at the 100 T scale.

References:

[1] S. Sederberg et al, "Attosecond optoelectronic field measurement in solids," Nature Comm. **11**:430 (2020).
[2] S. Sederberg et al, "Vectorized optoelectronic control and metrology in a semiconductor," Nature Photon. **14**, 680-685 (2020).
[3] K. Jana et al, "Reconfigurable electronic circuits for magnetic fields controlled by structured light," Nature Photon. **15**, 622-626 (2021).

Time-Domain Measurement of Few-Cycle Two-Mode Squeezed State

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In this work we report direct reconstruction of a time-domain few-cycle bright two-mode squeezed state, which we term bright entangled beams (BEBs). BEBs are generated through parametric downconversion from a 3-mm BBO crystal (Type I phase-matching), excited by a 9-fs 650nm pump from a noncollinear optical parametric amplifier. BEBs have different center wavelengths and k-vectors, and are carefully prepared in a single spatio-temporal mode (Schmidt number < 1.04). A frequency-domain amplitude and phase of both daughter beams is readout from an f-2f interferometer on a single-shot basis [1]. This information, together with the knowledge of the spectral envelope of a single-mode representation of BEBs, allows for an unambiguous and direct reconstruction of electric field distributions of both beams in the time domain (Fig. 1A). For both, expected thermal statistics of the individually-measured daughters results in washed out information about their respective carriers waves, only supported by their 10-fs temporal envelopes. In addition these individual measurements, we also show their superposition (Fig 1B). A superposition of the field measurements between two daughters of the BEB now reveals a quantum correlations in the pronounced dynamics, where variance oscillates between squeezing and antisqueezing at the carrier frequency of the pump. Thus, field measurement performed on the BEBs does not distinguish between the daughters, revealing the underlying fundamental structure of quantum correlations of the field, manifested in a single-mode squeezed vacuum, captured here for the first time. Access to quantum-correlated twin beams and field measurements promises to open new paths in studying ultrafast quantum optics.

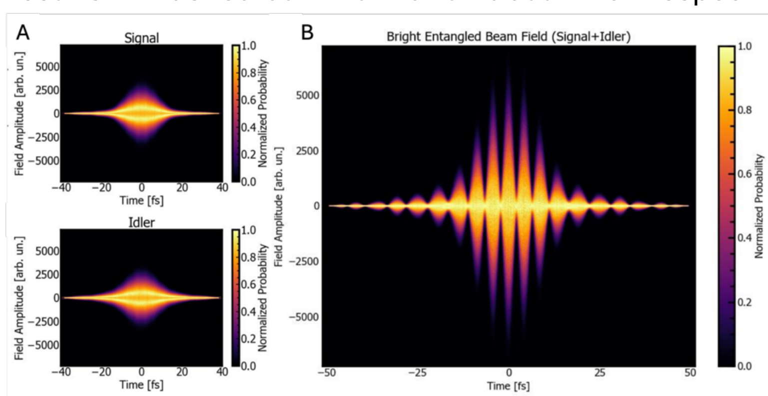

Figure 1: *Measured time-domain field distributions of 10-fs signal and idler pulses (panel A) and their field superposition (panel B)*

[1] P. Cusson, S. Virally, D. V. Seletskiy, Carrier-envelope phase correlations in few-cycle bright twin beams. International Conference on Ultrafast Phenomena (UP 2024). Optica Technical Digest. Optica Publishing Group, Barcelona, Spain (2024). Optica. Th-4A

A 600-site cavity array: expanding the neutral atom array toolbox

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Abstract

Neutral atom arrays have emerged as a promising platform for quantum information processing with the realization of high two-qubit gate fidelities and system sizes nearing 10,000 atoms. Scaling to the yet-larger systems believed to be necessary for useful, fault-tolerant applications, however, appears challenging in a single apparatus. In this talk, I will outline the development of a next-generation neutral atom array system consisting of an array of hundreds of optical cavities. This so-called "cavity array" functions similarly to a tweezer array in spirit, but with every atom strongly coupled to its own cavity with greater-than-unity cooperativity. I will both sketch the promise of the platform – which includes power enhancement, faster readout speeds, and multiplexed cavity networking – and also elucidate the primary technical limitations on scaling and performance. In short, the advent of cavity arrays promises to enable a new class of experiments in the regime of "many-cavity QED," where many single atoms interact and entangle with many single photons.

Quantum light-matter interfaces with tweezer atomic arrays

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Efficient interfacing of tweezer atomic arrays to light is crucial for a variety of applications based on these platforms: from state-readout and quantum networks to the generation of entangled states of light. Nevertheless, such efficient interfacing is severely limited in typical tweezer arrays due to large scattering losses to non-paraxial lattice diffraction orders. I will describe several solutions for this basic problem, which all rely on collective physics of radiation. First, we derive a general formalism, showing that the quantum interface efficiency of the atom array is universally given by its reflectivity to light [1]. We then apply this principle to develop solutions for efficient interfacing: (i) eliminating the scattering losses by destructive interference between different array layers [2]; (ii) designing a multibeam mode that naturally couples to the array [3]; (iii) enhancing the coupling over the losses using a cavity [4]. For all these solutions, we derive analytical theories and design principles, showing favorable scalings with the number of array atoms.

[1] Y. Solomons, R. Ben-Maimon and E. Shahmoon, PRX Quantum 5, 020329 (2024).

[2] R. Ben-Maimon, Y. Solomons, N. Davidson, O. Firstenberg, and E. Shahmoon, Phys. Rev. Lett. 135, 033601 (2025).

[3] Y. Solomons*, R. Ben-Maimon*, Arpit Behera*, O. Firstenberg, N. Davidson, and E. Shahmoon, arXiv:2510.23398

[4] Y. Solomons, I. Shani, O. Firstenberg, N. Davidson, and E. Shahmoon, Phys. Rev. Research 6 , L042070 (2024).

Demonstration of a Rb-based Mode-Locking Free Subluminal Ring Laser Gyroscope

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Ring laser gyroscopes (RLG) is considered to be one of the most accurate types of rotation sensors. An RLG consists of two counter-propagating lasers in the same cavity. Due to the Sagnac effect, the frequency of each laser is shifted by equal and opposite amounts in the presence of rotation around an axis perpendicular to the plane of the cavity. In a conventional RLG, the frequencies of the counter-propagating lasers are degenerate in the absence of rotation. The most widely used RLG makes use of Helium-Neon lasers [1]. In such an RLG, gain competition between the counter-propagating lasers is prevented due to the presence of two different isotopes of Neon, and by operating the lasers close to the threshold. One of the limitations of such an RLG is that the frequencies continue to remain degenerate for rotation rates smaller than a certain value, which is known as the lock-in effect [1]. This can potentially limit the minimum measurable rotation rate (MMRR). This constraint can be circumvented, for example, by dithering the apparatus, thereby creating a bias rotation rate beyond the lock-in range. Such a process limits the MMRR to the precision of the bias caused by various effects such as the noise in the power supply, and adds additional complexity to the device. An alternative approach is using non-degenerate longitudinal modes for different directions. However, this approach cannot be employed in HeNe RLGs, because the difference between the peaks of the gain for the two isotopes of Neon is much smaller than the free-spectral-range (FSR) of the cavity. In this talk, we will describe a ring laser based on Raman gain in ^{85}Rb vapor facilitating non-degenerate operation, thus eliminating the mode-locking effect. This is made possible due to several factors: (a) Raman gain occurs primarily in the direction of the Raman pump, (b) The gain peak can be controlled by changing the frequency of the Raman pump, (c) Two different gain cells are used for two directions, and (d) Polarizing beam splitters are used to prevent the Raman pump for one direction from interacting with the gain cell for the other direction. For an RLG, the scale-factor (SF), defined as the ratio between the frequency shift and the rotation rate, is predicted to be proportional to the inverse of the group index [2]. The group index in Raman lasers is greater than unity, making it a subluminal laser [3]. On the other hand, the Schawlow-Townes Linewidth (STL) is also predicted to be proportional to the inverse of the square of the group index [4]. The MMMR is directly proportional to the minimum measurable frequency shift (MMFS), which is proportional to the square-root of the STL [1]. Thus, the MMRR is expected to be independent of the group index. We have demonstrate measurement of rotation using a non-degenerate subluminal RLG and shown that the scale factor is indeed proportional to the inverse of the group index. This result is also important for a superluminal version of such an RLG, for which the scale factor is expected to be very high, since the group index can be vanishingly small, and for which the STL is predicted to be independent of the group index [2]. As a result, the MMRR for a superluminal RLG is expected to be much smaller than that for a conventional RLG, by the factor of the inverse of the group index [5].

[1] W. W. Chow et al. "The ring laser gyro," Rev. Mod. Phys. 57, 61 (1985).
[2] M.S. Shahriar et al. "Ultrahigh enhancement in absolute and relative rotation sensing using fast and slow light," Phys. Rev. A 75, 053807 (2007).
[3] J. Yablon et al. "Demonstration of a highly subluminal laser with suppression of cavity length sensitivity by nearly three orders of magnitude," Opt. Express 25, 30327-30335 (2017).
[4] C. Henry, "Theory of the Linewidth of Semiconductor Lasers," IEEE J. Quantum Electron. 18(2), 259–264 (1982)
[5] Z. Zhou, R. Zhu, N. Condon, D. Hileman, J. Bonacum and S.M. Shahriar, "Bi-directional Superluminal Ring Lasers without Cross-talk and Gain Competition," Appl. Phys. Lett. 120, 251105 (2022).

Engineering Light with Space-Time Metamaterials

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We discuss new optical phenomena enabled by metamaterials with properties engineered in both space and time. We show that near-zero index (NZI) regime in such 4D metamaterials can help to enable the extreme optics with superb properties.

Advancing Josephson parametric amplifiers for scalable high-fidelity readout of solid-state qubits

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High-fidelity qubit readout is a critical requirement for scaling solid-state quantum processors, requiring amplifiers that approach the quantum noise limit while remaining robust and scalable. Josephson Parametric Amplifiers (JPAs) have become indispensable in this context, enabling rapid, ultra-low-noise measurement of solid-state qubits. In this talk, I will present recent work in my group on the development of next-generation JPAs. First [1], I will introduce amplifiers based on new Josephson junctions called Josephson Junction Field-Effect Transistors (JJFETs) fabricated from InAs-Al heterostructures, which offer improved power handling compared to conventional Al/AlOx junctions. Second [2], I will describe techniques for extending JPA operation to higher frequencies; to enable operation near 1 K. Together, these developments provide a path toward robust, quantum-limited amplification for large-scale quantum information processing.

[1] Z. Hao et al., Appl. Phys. Lett. 124, 254003, (2024).

[2] Z. Hao et al., arXiv:2508.11137.

Low-Energy Femtosecond LIBS Enabled by Mie-Resonance-Induced Field Enhancement

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Femtosecond laser-induced breakdown spectroscopy (fs-LIBS) has attracted increasing attention for material analysis owing to its minimal thermal effects and high spatial precision. Here, we demonstrate that dielectric particles with dimensions comparable to the laser wavelength can induce strong local field enhancement through optically driven Mie resonances, enabling plasma generation at unprecedentedly low energies. Numerical simulations reveal that low-index ellipsoidal particles exhibit significant near-field amplification depending on their size and aspect ratio. A Ti: sapphire fs-LIBS system was developed to analyze dust deposition on outdoor high-voltage insulators as a representative case. A Ti: sapphire fs-LIBS system was developed to analyze dust deposition on outdoor high-voltage insulators as a representative case. The relationships between laser parameters and signal characteristics—including spectral intensity, signal-to-noise ratio, and ablation line width—were systematically investigated. Experimental results show that dust particles provide self-localized field enhancement, allowing detectable LIBS emission at pulse energies below 500 nJ. This work demonstrates the feasibility of low-energy fs-LIBS for real-time, in-situ surface dust analysis and provides guidance for optimizing laser parameters in field environments.

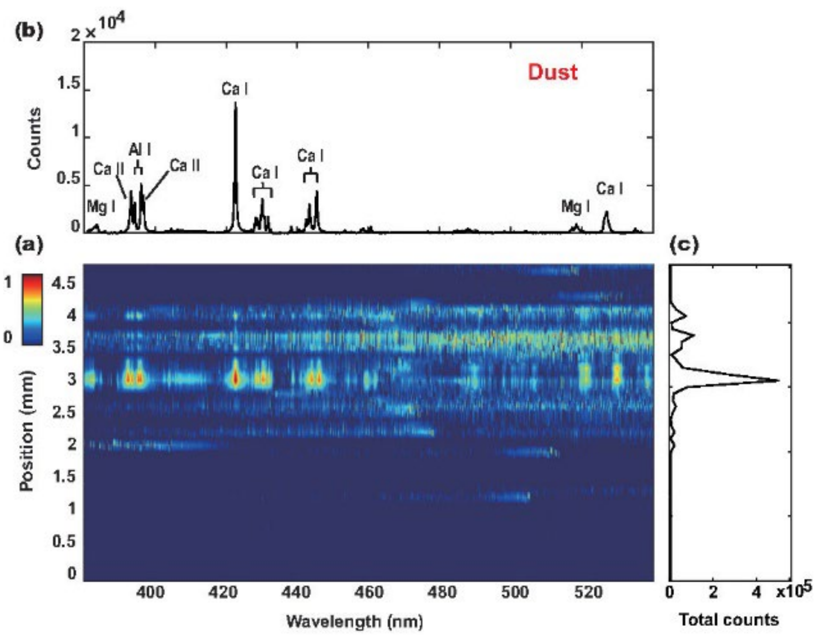

Fig. 1 Femtosecond laser-induced breakdown spectrum. (a) The fs-LIBS spectrum at different positions during line scanning of dust and ceramic substrates, respectively. (b) The fs-LIBS spectra, integrated along the position axis. (c) and (f) The fs-LIBS intensity at different positions, integrated along the position axis.

From Ghost Frequency Comb to Quantum Ghost Frequency Comb

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Recent experimental observation of ghost frequency comb (GFC) has attracted much attention from both fundamental and practical perspectives. The 50% contrast GFC is observed from the temporal correlation measurement of a continuous wave (CW) laser beam that is produced from a 10 km optical fiber cavity with half a million cavity modes:

$$g^{(2)}(\tau) = 1 + \frac{\sin^2(N\omega_b\tau/2)}{N^2\sin^2(\omega_b\tau/2)} \tag{1}$$

where ω_b is the *beat* frequency between neighboring cavity-modes, N is the total number of cavity-modes, and $\tau \equiv \tau_1 - \tau_2 = (t_1 - t_2) - (r_1 - r_2)/c$.

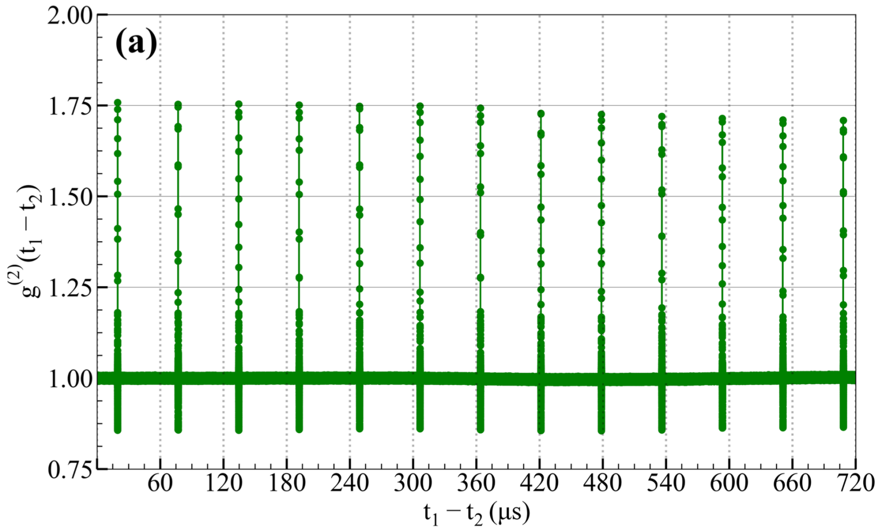

Figure 1: Recent experimental observation of 50% contrast GFC from the correlation measurement of a CW laser beam, which is produced from a 10 km optical fiber cavity with half-million cavity modes.

The 50% contrast of the GFC has been criticized and may not be considered a quantum correlation according to Bell's criterion ($\geq 71\%$).

Is it possible to create 100% contrast comb-like second-order coherence function $g^{(2)}(\tau)$? This talk gives a positive answer: 100% contrast quantum ghost frequency comb (QGFC) correlation can be produced from the following entangled coherent state

$$|\Psi\rangle = \prod_{s,i} \delta\left(\omega_s + \omega_i - \omega_0\right) \delta\left(\mathbf{k}_s + \mathbf{k}_i - \mathbf{k}_0\right) |\alpha_s(\mathbf{k}_s)\rangle |\alpha_i(\mathbf{k}_i)\rangle \tag{2}$$

where $|\Psi\rangle$ is a *vector* in the coherent state space. Adapting from Spontaneous Parametric Down-conversion (SPDC), in Eq. (2), we use s and i label the two entangled coherent states $|\alpha_s(\mathbf{k}_s)\rangle$ and $|\alpha_i(\mathbf{k}_i)\rangle$; ω_j and $\mathbf{k}_j$, for $j = s, i$, are the frequency and wavevector of the signal (s), idler (i), ω_0 and $\mathbf{k}_0$ are constants. The 100% contrast QGFC, i.e., the second-order temporal correlation of the entangled signal-idler laser beams, is easily calculated:

$$g^{(2)}(\tau) = \frac{\sin^2\left(N\,\omega_b\tau/2\right)}{N^2\sin^2\left(\omega_b\tau/2\right)}. \tag{3}$$

This talk will discuss the physics and applications of GFC and QGFC.

Bragg Amplification of Weak Laser Radiation in Optical Lattices in a Gas

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We considered the self-consistent interaction of interfering laser beams in a gas, which forms a traveling or static optical lattice depending on the frequencies of the beams. We studied the nonlinear interaction between an optical lattice and a gas based on the Maxwell equations for laser fields and the Boltzmann kinetic equation for the gas [1]. The Boltzmann equation considers the spatial periodic ponderomotive force acting on the polarizing gas molecules within the interference region of the counter-propagating laser beams. As a result of the induced perturbation in gas density (and therefore the index of refraction), a static or traveling Bragg lattice forms, which results in feedback of laser radiation. The main cause-and-effect relationship of this interaction between the optical lattice and the gas is as follows: *Optical Lattice* $\rightarrow \Delta N \rightarrow \Delta n \rightarrow$ *Bragg reflection* $\rightarrow$ *Laser intensities* $\rightarrow$ *Optical Lattice*. Here, ΔN is the gas density perturbation and Δn is the perturbation of the index of refraction.

The strength of the interaction depends on the optical lattice phase velocity. If the relative intensities of opposite laser beams are very different then the amplification of weaker beams is possible. Note that this is not an example of amplification in the literal sense, such as Raman amplification of a laser beam in a plasma medium involving plasma oscillations [2]. This is the redistribution of photons, when Bragg-reflected photons from one beam contribute to the photon flux of another laser beam.

One possible practical application of such "amplification" is the amplification of single-pass laser radiation in remote air lasing [3]. To achieve this, we propose superimposing powerful laser radiation of the same frequency onto the weak radiation from the air-lasing region. This creates a remote optical grating and a periodic disturbance in the refractive index of the air, enabling Bragg amplification of the air-laser radiation. This approach is illustrated schematically in Fig. 1.

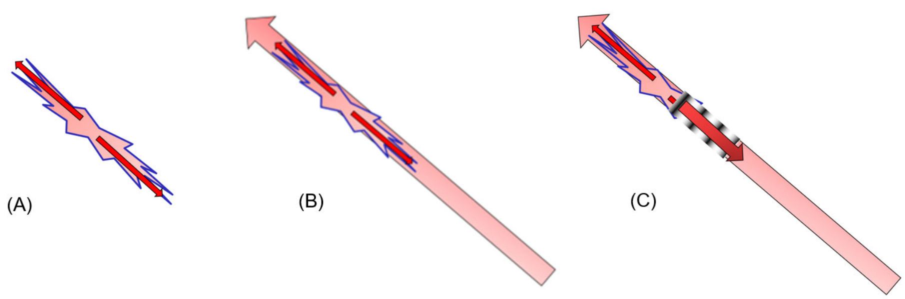

Figure 1. (A) Low-intensity remote air laser [3]; (B) 'Backward' low-intensity air laser beam superimposed with 'pump upward' powerful laser beam of the same wavelength; (C) Formation of a remote interference pattern (optical lattice), resulting in amplification of the 'backward' laser beam via Bragg scattering.

References

1. M.N. Shneider, P.F. Barker, Optics Communications **284**, 1238 (2011)
2. V.M. Malkin, G. Shvets, N.J. Fisch, Phys. Rev. Lett. **82**, 4448 (1999)
3. A. Dogariu, J.B.Michael, M.O. Scully, R.B. Miles, Science, **331**, 442 (2011)

Direct ghost tomography for 3D X-ray fluorescence imaging

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X-ray fluorescence (XRF) is one of the most powerful non-destructive probes of composition we have. From basic materials science to industrial inspection and cultural-heritage studies, it offers a direct elemental "fingerprint" with excellent sensitivity. Yet there is a stubborn bottleneck built into the method: fluorescence is essentially unidirectional, so XRF imaging has traditionally meant raster scanning. Every point must be visited, one by one. For complex samples this is slow and for three-dimensional XRF tomography it becomes prohibitive, because every voxel must be measured at every projection angle. In practice, acquisition time not physics sets the limit.

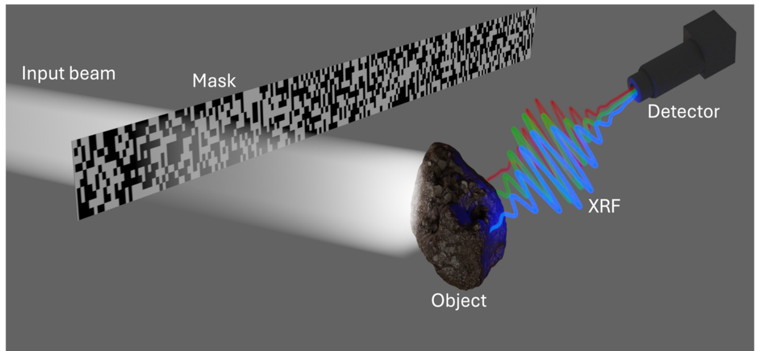

Fig 1: Schematic of the experimental setup.

Here we experimentally demonstrate X-ray fluorescence ghost tomography (XRFGT), a route that breaks this scanning barrier. The simple experimental setup is shown in Fig 1. The key is to exploit what most real fluorescence objects share: sparsity, especially in 3D, only a small fraction of voxels carries elemental contrast. By combining compressive ghost imaging with a direct reconstruction strategy that retrieves the full 3D elemental distribution straight from bucket signals, we reduce the number of required measurements by orders of magnitude. In our proof-of-concept, a volume of 2,824,080 voxels is reconstructed from only 900 measurements for each angle, cutting acquisition time by a factor of 21.5 without sacrificing the elemental information that makes XRF unique. The isosurface reconstruction of our object is shown in Fig.2.

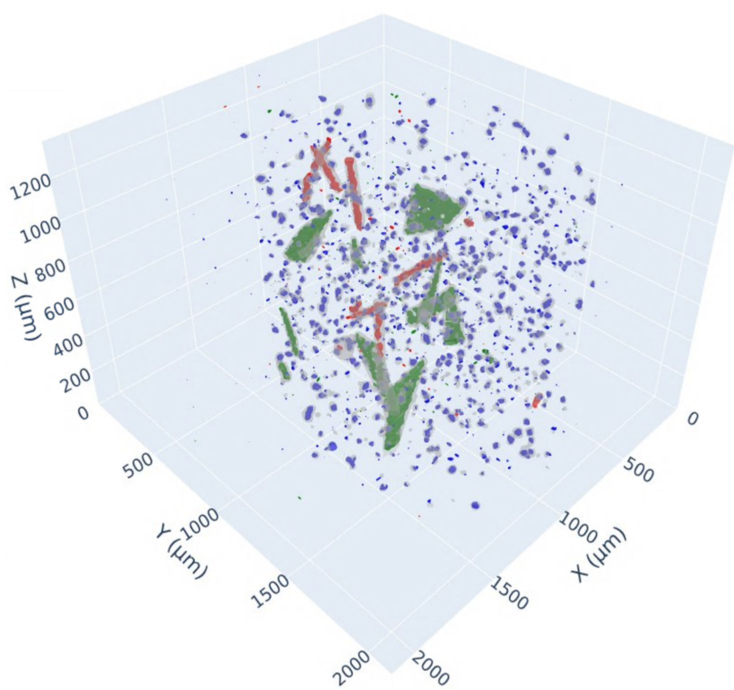

Fig 2: Isosurface of Ag, Cu, Zr particles in cured glue with XRF elemental classification reconstructed with only 900 realizations.

XRFGT therefore turns XRF tomography from a slow, point-by-point procedure into a scalable imaging modality. It opens the door to routine 3D elemental imaging of complex objects, and positions XRF to meet the demands of next-generation studies of heterogeneous, multi-component materials.

Single-cycle optical nonlinearity of transparent conducting oxides explained

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Abstract: We provide a quantitative model for the electro-optic response of transparent conducting oxides to single cycle intense pulses. We show that the interplay between spatio-temporal aspects of absorption, stimulated emission and multi-photon absorption can explain the weaker-than-before nonlinear response observed in experiments, as well as on the unexplained relaxation dynamics.

Time-reversal (sometimes referred to as time-reflection), time refraction and temporal photonic crystals are exotic nonlinear optical effects that attracted a lot of interest and debates in recent years. The challenge associated with realizing these effects in experiment is the need for a strong and rapid changes to the material permittivity. Transparent conducting oxides were identified as the most promising candidate materials to enable these manipulations due to their associated extremely large optical nonlinearity, reaching 100's of percent of the refractive index/permittivity [1].

After a decade of extensive experiments, a comprehensive quantitative theoretical (Boltzmann-based) description of their electronic, thermal and optical response was obtained in [2]; it revealed the cumulative (absorptive) thermal nature of their optical nonlinearity, and quantified its strength correctly in terms of the total energy in the electron sub-system. Yet, the model in [2] was capable of explaining experiments done with pulse durations of a few picosecond down to 50-100 femtosecond, but is unsuitable to describe the dynamics due to intense *single-cycle* illumination. Such extremely short illumination is needed to probe the claims of instantaneous turn-on of the optical response [1] as well as the femtosecond scale turn-off dynamics required for the realization of temporal photonic crystals. In particular, the formulation of [2] is not suitable to model the unexpectedly-short 50-100 femtosecond decay rate of the transmission observed in [3].

To meet this challenge, we have extended the formulation of [2] by switching to the density matrix formulation. This approach treats (previously-ignored) coherent aspects of the photon-electron interactions and allows accounting for coherent control schemes via phase manipulations of the incoming pulses. We find that stimulated emission approaches absorption levels at high intensities, yet, the system only reaches partial transparency (see Fig. 1(a)) due to the absence of population inversion in the remainder of the conduction band. In that regard, stimulated emission gives rise to a weaker nonlinearity (see Fig. 1(b)), but cannot invert its sign.

We then characterize the thermalization occurring under the extreme non-equilibrium conditions in the non-parabolic and narrow conduction band, and provide a simple theory that captures its new features (see Fig. 1(c)). Finally, we show that electron-phonon interactions are too weak to explain the observed fast transmission relaxation, but that a (multi-photon) absorption of valence band electrons (modelled via DFT), and spatial dynamics and substrate effects can explain experimental findings. Our approach paves the way for quantitative modelling of time-varying photonics and coherent wave control on few-femtosecond timescales in these systems.

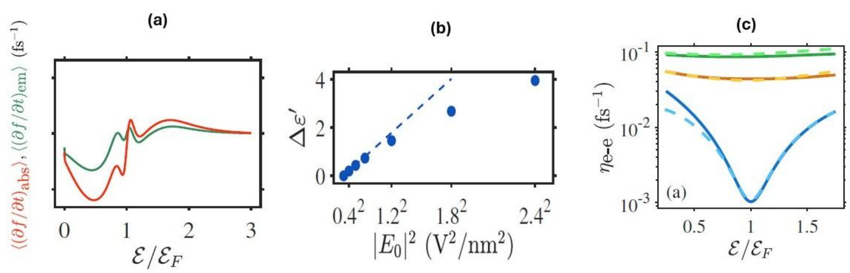

Fig. 1. (a) A comparison of the strengths of absorption and stimulated emission of an ITO particle under illumination by strong single cycle pulse. (b) The associated changes of the ITO permittivity as a function of illumination strength. (c) The e-e relaxation rate (solid) and its analytic approximated form (dashed) for various time cross-sections.

References

[1] R. Tirole *et al.*, Nature Physics 19, 999 (2023).
[2] S. Sarkar, I.W. Un, Y. Sivan, Phys. Rev. Appl. 19, 014005 (2023). I.W. Un, S. Sarkar, Y. Sivan, Phys. Rev. Appl., 19, 044043 (2023).
[3] Lustig *et al.*, Nanophotonics 12, 2221-2230 (2023).

Photoluminescence from metals – (all) arguments resolved

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Abstract: We provide a single line analytic theory for (nonlinear) photoluminescence from illuminated metal nanostructures under CW and pulsed illumination which allows us to explain a long series of seemingly contradicting experimental reports. We then describe a new set of measurements which provide detailed experimental evidence supporting our subtle novel predictions.

Photoluminescence (PL) from metals is one of the most fundamental aspects of light-matter interactions – it involves the 2-step process in which an incoming photon gets absorbed in a material, and consequently emitted spontaneously. In the context of metals, this phenomenon was disputed for many decades, with contradicting experimental reports on every possible aspect – the emission statistics (fermionic/bosonic, thermal/non-thermal), its dependence on electric field (polynomial/power law with integer/non-integer exponent), on structure size (grows/decreases with increasing size), its quantum efficiency, the underlying microscopic mechanism (electronic Raman scattering/simple recombination) etc. etc. [1]. These radically different behaviours were not accompanied by a complete theory because of the lack of knowledge of the hard-to-calculate electron non-equilibrium distribution under illumination.

Here, we remedy this problem by providing a complete quantitative theory for this important, decades-old, yet unresolved problem of (nonlinear) photoluminescence (PL) from metals for both continuous-wave (CW) and pulsed illumination. Based on our the *steady-state* non-equilibrium electron distribution in metals [2], we first compute the electron and lattice temperatures and the emission from metals illuminated by *CW* light [3]. This solution reveals what is to our knowledge, the first ever explanation of the dependence of the metal emission on the electric field, and its dependence on the electron temperature; we show that the emission is a primarily *non-thermal* phenomenon, and identify the unique signatures of the deviation from thermal equilibrium on the emission spectra and electric field dependence. The theory is then shown to match experimental data and used to clarify open questions associated with the use of the PL as a temperatre probe.

We then analyze *transient* nonlinear PL following illumination by intense *ultrashort pulses*. Our detailed calculations and a simplified heuristic model enable us to elucidate the crossover from the non-thermal emission characteristic of weak (CW-like) illumination to thermal emission occurring after illumination by strong shorter pulses [4]. Specifically, we identify the characteristics of nonthermal and thermal emission in the transient emission spectra and its dependence on the illumination frequency and intensity. These findings, specifically, the weak 3 photon absorption, were then verified in measurements from various sets of Au rods (see Fig. 1(a)). In that regard, our work puts to rest the many decades-long arguments on the statistics and electric field dependence of the emission [1].

Finally, based on the extension of our point-emission theory [3,4] to macroscopic bodies using the extension of the local Kirchhoff's law to non-equilibrium distributions [5], we reconcile seemingly contradicting behaviour of the PL as a function of the metal structure size (for nanospheres and nanofilms), see Fig. 1(b)-(d) [6].

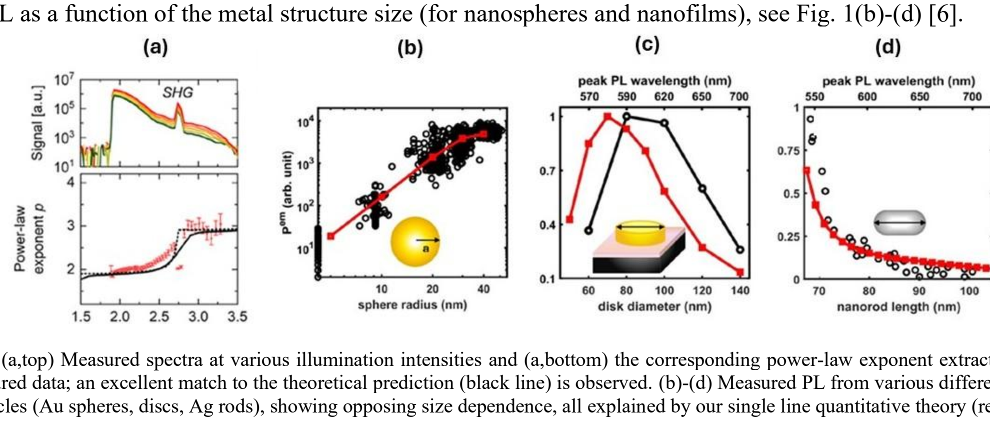

Figure 1: (a,top) Measured spectra at various illumination intensities and (a,bottom) the corresponding power-law exponent extracted from the measured data; an excellent match to the theoretical prediction (black line) is observed. (b)-(d) Measured PL from various different metal nanoparticles (Au spheres, discs, Ag rods), showing opposing size dependence, all explained by our single line quantitative theory (red).

References

[1] G. Baffou, ACS Nano 15, 5785 (2021).
[2] Y. Dubi, Y. Sivan, Light: Science & Applications 8, 89 (2019). Y. Sivan *et al.*, Faraday Discussion 214, 215 (2019).
[3] Y. Sivan, Y. Dubi, ACS Nano 15, 8724 (2021).
[4] Y. Sivan, I.W. Un, I. Kalyan, K. Lin, J. Lupton, S. Bange, ACS Nano 17, 11439 (2023).
[5] J.-J. Greffet *et al.*, Phys. Rev. X, 8, 021008 (2018). A. Pelous-Loirette, J.-J. Greffet, ACS Nano 18, 31823 (2024).
[6] I. Kalyan, I.W. Un, G. Rosolen, N. Shitrit, Y. Sivan, ACS Nano 19, 29181 (2025).

Enantio-sensitive molecular compass

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Chirality describes the asymmetry between an object and its mirror image and manifests itself in diverse functionalities across all scales of matter - from molecules and aggregates to thin films and bulk chiral materials. A particularly intriguing example is chirality-induced spin selectivity (CISS), where chiral structures orient electron spins enantio-sensitively. Despite extensive research, the fundamental origin of spin-chirality coupling, the unexpectedly large magnitude of the CISS effect, and the possible role of electromagnetic fields in it remain unclear.

We show [1] that any excited or photoionized chiral molecule behaves like an enantio-sensitive molecular compass. Its internal "compass axis" is locked to the molecular geometry itself — not to any external field. Remarkably, this compass effect arises even under isotropic illumination, where light provides no preferred direction. Just as a traditional compass needle aligns with Earth's magnetic field, the molecular compass aligns the electron spin with a built-in geometric direction inside the molecule — a direction defined by its handedness. In this way, the molecule generates its own "chiral north," guiding the electron spin without any magnetic interaction. In a single chiral molecule fixed in space, this compass causes the emitted or excited electron's spin to orient differently for left- and right-handed forms of the same molecule — exactly the kind of enantio-sensitive spin polarization observed in the CISS effect. In randomly oriented chiral molecules and under isotropic illumination the enantio-sensitive molecular compass enables a phenomenon central to CISS: locking of the photoelectron spin orientation to molecular geometry. It shows that chiral molecules can sustain time-odd correlations whereas achiral molecules cannot.

New spin-sensitive phenomena also arise in the interaction of chiral molecules with photon spin. We show that molecular chirality mediates the coupling between photon spin and electron spin in photoionization of randomly oriented molecules and induces a triple orientational lock, where molecular structure, electron and photon spin orientations are correlated in an enantio-sensitive way. Specifically, we identify a universal spin–torque mechanism in which the Berry curvature of a chiral molecule, activated by the photon spin of the incident light, exerts a torque on the photoelectron spin. This mechanism represents the second fundamental pathway of chiral spin–photon coupling, complementary to the enantio-sensitive molecular-compass effect. While enantio-sensitive molecular compass identifies a direction of spin-polarization of photoelectron imposed by chiral molecule, the spin torque rotates the photoelectron spin around the photon-spin direction and away from the compass axis. Our geometric framework connecting Berry curvature to electron spin polarization provides foundation for linking the CISS effect to topological properties of electron response.

References

[1] P. M. Flores et al, arxiv 2505.22433

Nontrivial intensity correlations with coherent continuous-wave lasers

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In addition to the well-known, strong correlations present when measuring entangled photon pairs, nontrivial intensity correlations are also known to be present in light that is in a thermal state. These correlations were first demonstrated by Hanbury Brown and Twiss in the 1950s, but there have been recent advances in correlation-based interferometers. These new interferometers have benefits such as fully visible interference when measuring beyond the coherence length of the light and through degraded conditions such as optical turbulence. However, the wide angle of divergence present in thermal light sources greatly reduces the amount of light that reaches the detectors, especially over large distances or lossy environments.

Traditional interferometers benefit from using well-collimated continuous-wave (CW) lasers, thus allowing for a high rate of detection over large distances. A question arises: Can we observe intensity correlations from CW lasers? When initially considering this, one is reminded that such lasers are approximated as coherent states and are often considered a "non-correlated state." In this talk we discuss how CW lasers can still be used to produce nontrivial intensity correlations for applications in correlation-based interferometers. For this we investigate multiple configurations including intensity correlation measurements from a pair of superimposed independent CW laser beams and intensity correlations from a single multi-longitudinal-mode laser, labeled as a ghost frequency comb.

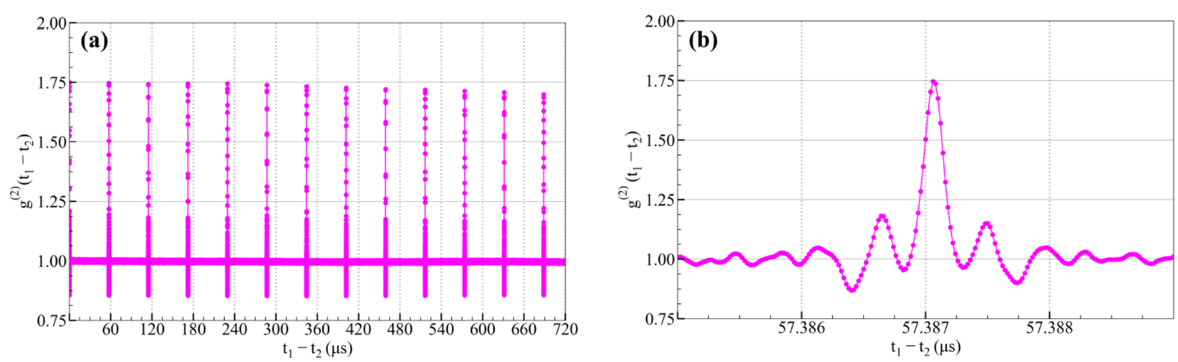

Figure 1: Measured intensity correlation from a single CW laser containing 500,000 longitudinal modes. a) Even though the laser is operating in CW mode, the correlation results in a pulse-train analogous to that of a frequency comb. b) A closer look at the second correlation peak.

Quantum Molecular Coherence

for Chemical Sensing and Fusion Energy

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Abstract

Quantum coherence corresponds to a situation where atoms or molecules of a sample are prepared in a coherent superposition of eigenstates. Atomic coherence lies at the core of fascinating phenomena such as electromagnetically induced transparency, lasing without inversion, slow light, and is used in laser cooling of atoms, manipulation and storage of quantum states *etc*. Recent work has shown that an increased and cleverly manipulated molecular coherence leads to comparably interesting consequences. For example, it leads to an enhanced sensitivity and speed in spectroscopic chemical-specific imaging. Additional improvements in signal-to-noise ratio can come from the use of properly engineered non-classical states of light, particularly in scenarios where the applied laser power is limited, as is often the case when working with biological samples and/or utilizing plasmonic nano-structures for micro- and nano-spectroscopy. These unique tools, based on molecular coherence, quantum optics and plasmonic nano-antennas, show promise to areas ranging from life sciences to materials research, addressing the structure and function of systems extending from bio-molecules to cells and organisms, and to topological and reduced-dimensionality materials.

Quantum molecular coherence prepared and maximized in a single-species molecular medium, solid or gaseous, leads to a technique termed molecular modulation, which produces ultra-broadband radiation, allowing arbitrary ultrafast space- and time-tailored optical field synthesis. Another remarkable example is the use of molecular coherence for the purpose of combining high-power laser beams through stimulated Raman scattering - a technique adopted by the excimer laser driven inertial-confinement fusion community.

* A large number of people have contributed to this work; I will give proper acknowledgements during my presentation. I want to give special thanks to Marlan Scully, Aleksei Zheltikov and Zhenhuan Yi.

Superradiance and hot electrons from strongly quantum-confined perovskite quantum dots

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Imposing strong quantum confinement in lead halide perovskite nanocrystals enhances the electronic interactions of charge carriers within each nanocrystal and promotes the delocalization of the exciton wavefunction between nanocrystals in closely packed quantum dot assemblies. Such enhanced intra- and inter-quantum dot electronic (or excitonic) coupling in the strong confinement regime can improve the performance of perovskite quantum dots as sources of hot electrons and superradiant photon emitters. This presentation will discuss (i) the generation of hot electrons via Auger hot electron upconversion mediated via spin-exchange interaction in strongly quantum-confined $CsPbBr_3$ nanocrystals doped with Mn^{2+}[1], and (ii) superradiance from superlattices of $CsPbBr_3$ quantum dots. [2]

[1] C.-W. Wang, X. Liu, T. Qiao, M. Khurana, A. V. Akimov, D. H. Son "Photoemission of the Upconverted Hot Electrons in Mn-doped $CsPbBr_3$ Nanocrystals" *Nano Lett.* **2022**. *16, 6753-6759*

[2] L. Luo, X.Tang, J. Park, C.-W. Wang, M. Park, M. Khurana, A. Singh, J. Cheon, A. Belyanin, A. V. Sokolov and D. H. Son, "Polarized Superradiance from CsPbBr3 Quantum Dot Superlattice with Controlled Inter-dot Electronic Couplings" *Nano Letters* **2025**. *128, 5, 2062–2069*

The Einstein Equivalence Principle and the Quantum Galileo Interferometer

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The Equivalence Principle is a corner stone of general relativity, and its decisive role in the birth of this pillar of modern physics was summarized by Albert Einstein in 1922 by the Gedanken experiment: *"If a man falls freely, he would not feel his weight"* [1]. This observation rests on the identity of inertial and gravitational mass, known already to Galileo Galilei, and led Einstein to the Weak Equivalence Principle: *locally a constant gravitational field is indistinguishable from a constant acceleration.* This impossibility of distinguishing between a frame with gravity and one that is accelerated implies that the laws of physics must be identical in these two systems.

Testing the Einstein Equivalence Principle (EEP) the Colella-Overhauser-Werner experiment with neutrons in 1975 [2] has shown that gravity induces a measurable phase shift; the Kasevich–Chu Interferometer [3] achieves the same using a standing electromagnetic field instead of a crystal lattice. In a freely falling frame, the Kasevich–Chu phase shift arises from the laser chirp and remains invariant under transformation back to the lab frame, reflecting the EEP for electromagnetic waves.

We analyze the Quantum Galileo Interferometer (QGI) [4] that contrasts a magnetically levitated "at-rest" branch with a freely falling branch, yielding a Kennard-phase shift. In this way the QGI indeed probes the EEP for matter waves.

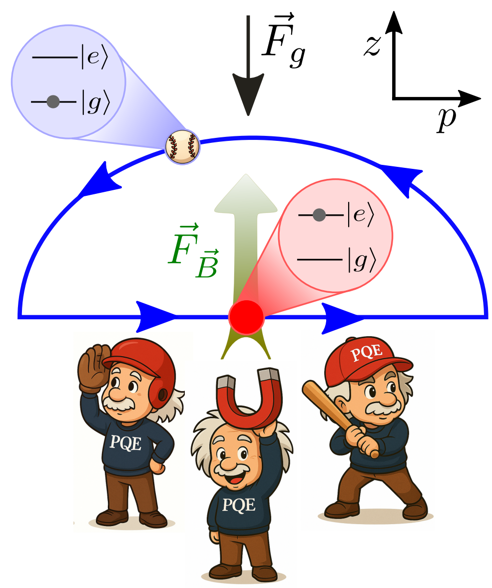

Fig. 1: QGI in phase space (z/p): the force $\vec{F}_{\vec{B}}$ due to the magnetic field gradient (green) compensates the gravitational force $\vec{F}_g$ (black), resulting in the levitation of the atoms in the magnetic sensitive excited state (red), while the atoms in the magnetically insensitive ground state (blue) are launched into free fall by the first beam splitter ("baseball-racket Einstein") and recombined by the second beam splitter ("baseball-glove Einstein").

[1] Y. A. Ono, Phys. Today **35**, 45 (1982).
[2] R. Colella, A. W. Overhauser, and S. A. Werner, Phys. Rev. Lett. **34**, 1472 (1975).
[3] M. Kasevich and S. Chu, Phys. Rev. Lett. **67**, 181 (1991).
[4] O. Dobkowski, et. al., arXiv:2502.14535 (2025).

A solid-state continuous-wave laser at 148.4 nm for driving the ^{229m}Th nuclear transition

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In the entire nuclear energy landscape, the ^{229m}Th nuclear isomer stands out as an anomaly with an unusually low energy. The laser excitation of this isomer[1,2,3] has ushered in a new era which is expected to significantly influence the next generation of portable, high-accuracy optical clocks and fundamental physics. The excitation wavelength at 148.4 nm lies in the Vacuum Ultra-Violet (VUV) region of the spectrum making the development of continuous laser sources of high spectral purity a challenge. Apart from pulsed sources based on Four-wave-mixing (FWM) and XUV combs used for the first nuclear excitations, continuous sources based on FWM in Cd vapor[4] and random quasi-phase matching (QPM) in a solid state crystal SBO[5] have been demonstrated.

As part of the NuQuant project we aim to develop an all solid-state continuous wave laser at 148.4 nm based on second harmonic generation (SHG) in $BaMgF_4$ (BMF). BMF possesses three factors[6] which make it a suitable candidate for this task (i) transparency at 148.4 nm (ii) non-vanishing second order non-linearity and (iii) ferroelectric properties making it amenable to periodic poling (pp) to achieve quasi-phase matching (QPM). However, SHG at these wavelengths has a coherence length on the order of $1\mu m$ making poling challenging. So far ppBMF with 9$^{\text{th}}$ order poling has been achieved, which shows SHG at 148.4 nm. In order to reach reasonable powers, ppBMF is placed in an enhancement resonator for intracavity SHG and progress towards this goal is presented. The projected powers are sufficient to drive the nuclear transition in Th doped crystals as well as single ions.

This work is supported by BMBF Quantum Futur II Grant ”NuQuant” under grant agreement no FKZ 13N16295A.

References

1. J. Tiedau, et al. PRL 132.18 (2024): 182501
2. R. Elwell et al., PRL 133.1 (2024): 013201
3. C. Zhang et al., Nature 633, 633.8028 (2024): 63
4. Q. Xiao, et al. arXiv:2507.19449 (2025)
5. V. Lal, et al. arXiv:2507.17719 (2025)
6. E.G. Villora et al., Optics Express, 17.15 (2009): 12362

Resonance fluorescence of a strongly driven two-level system with dynamically modulated frequency

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When a two-level atom interacts with a strong optical field, its bare states are split into doublets or "dressed states" separated by the Rabi frequency. This phenomenon gives rise to the Mollow triplet in the resonance fluorescence spectrum, a fundamental phenomenon in quantum optics. Beyond the Mollow triplet, new physics emerges when a two-level system is subjected to bichromatic or polychromatic driving fields, leading to diverse nonlinear and multiphoton dynamics in the interaction between light and matter.

In this talk, I will present the first experimental study of the resonance fluorescence when a microwave frequency field is strongly driving the transition between two atom-light dressed states of the same energy ladder. We employ a single self-assembled InAs quantum dot as the two-level system. The quantum dot is simultaneously driven by a laser near resonant with its optical transition and a surface acoustic wave near resonant with the optical Rabi frequency. We observe emission spectra significantly altered from the standard Mollow triplet, including the dynamical cancellation of the spontaneous emission at the atomic frequency, a feature previously seen only with bichromatic optical driving. The observed spectra are well explained by a theoretical model incorporating the hybridization of the atom, optical field, and acoustic field. We also observe the Bloch-Siegert shift and the Coherent Destruction of Tunneling via optical resonance fluorescence, a phenomenon that has only been observed in the microwave domain before.

Beyond its significance in quantum optics, our device enables the optical cooling of acoustic phonons mediated by a single two-level system. By measuring the full emission spectrum of the doubly dressed quantum dot under various laser amplitudes and detuning, we experimentally explored the optimal conditions for phonon cooling. Our results provide new insights into quantum interactions among single atoms, light, and sound in the strong driving limit, paving the way for advances in nonclassical light and sound generation, quantum transduction, and hybrid quantum systems.

Reference:

Y. Zhan, Z. Wang, R. P. Mirin, K. L. Silverman, S. Sun, "Dynamical Acoustic Control of Resonance Fluorescence from a Strongly Driven Two-Level System", arXiv:2509.25847.

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Title:

Quantum metrology of macroscopic spin ensembles

Abstract:

Quantum effects are usually observed and utilized in microscopic systems, where qubits can be manipulated and measured with precise control. However, for sensing and metrology, there is a clear benefit to using large qubit ensembles. There is an inherent tension between the sensitivity afforded by large-scale experiments and the ability to use quantum protocols, since quantum phenomena are rapidly swamped by classical noise as the system size is scaled up. Our quantum-limited macroscopic nuclear magnetic resonance (NMR) detection platform mitigates this trade-off. This apparatus performs magnetic-resonance spectroscopy of intrinsic quantum spin fluctuations in mole-scale ensembles, without any external excitation. This enables truly non-invasive magnetic resonance spectroscopy and precision searches for new fundamental physics.

Ultrafast Quantum Photonics: Beating Decoherence with Fast Light Pulses

Ben Sussman
National Research Council & University of Ottawa

Ultrafast optical pulses - femtoseconds to picoseconds in duration - are gaining interest for quantum processing due to their potential to encode information in brief time-bins, overcoming rapid decoherence.
The development of essential components for optical quantum technologies will be discussed, including a single photon switch based on the optical Kerr effect in single-mode fibres and a single photon memory based on fibre cavities. The switch controls single photon routing without adding noise, while the memory addresses a key scaling challenge by temporarily storing quantum states without loss of coherence, enabling quantum process synchronization.
Application of these components in photonic quantum processing and quantum sensing will be discussed, including random walks and more general processing, as well as quantum enhanced ranging and approaches to imaging and spectroscopy using correlated photons.

Quantum evolution of mixed states, vacuum entanglement and performance of quantum heat engines

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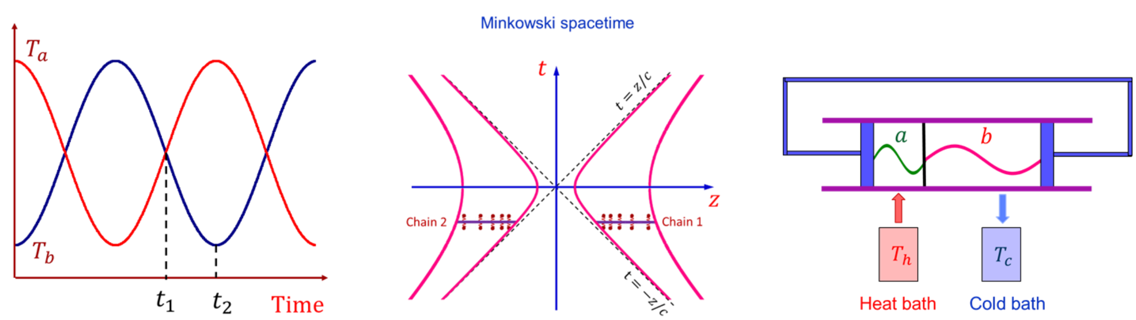
We introduce a technique for calculating the density operator time evolution for isolated systems along the lines of Heisenberg representation of quantum mechanics. Using this technique, we find the exact solution for the quantum evolution of two coupled harmonic oscillators initially prepared in thermal, coherent and two-mode squeezed states. We show that such systems exhibit interesting quantum dynamics (Fig. 1a).

Interaction of a uniformly accelerated oscillator chain with Rindler photons present in Minkowski vacuum is similar to that of coupled harmonic oscillators in thermal states. Due to vacuum entanglement two oscillator chains accelerated in causally disconnected regions (Fig. 1b) become excited in a correlated fashion by absorbing Rindler photons [1]. During evolution, vacuum entanglement is transferred to the entanglement of the oscillator chains.

A photonic quantum heat engine (QHE) composed of two optical cavities (Fig. 1c) can be modeled as coupled harmonic oscillators with time-dependent frequencies. Photons in the cavities become correlated during the engine operation. We show that the work done by such an engine is maximum if at the end of the cycle the oscillators swap numbers of excitations which can be achieved when the engine operates under the condition of parametric resonance. We also show that Carnot formula yields limiting efficiency for QHEs under general assumptions without quantum coherence.



(a) (b) (c)

Figure 1: (a) Effective temperature of two coupled harmonic oscillators a and b as a function of time initially prepared in thermal states with different temperatures. Due to correlation induced in the process of energy exchange oscillators swap their thermal states. (b) Two identical harmonic oscillator chains are accelerated in the opposite Rindler wedges through Minkowski vacuum and become excited in correlated fashion by absorbing Rindler photons. (c) Photonic quantum heat engine composed of two optical cavities with different frequencies coupled via a partially transmitting common mirror. Outside mirrors can move and act as a piston of the engine. The working fluid of the engine is photon gas in the cavities which exerts radiation pressure on the mirrors and can do mechanical work on the surroundings.

[1] A.A. Svidzinsky, M.O. Scully, and W. Unruh, Phys. Rev. D **111**, 045022 (2025).

Photoelectron -- residual-ion entanglement in angle-differential attosecond time-reolved shake-up ionization

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Distinguishing direct and shake-up ionization resulting in ground-state and excited He^+ residual ions, we examined the effects of the correlated photoemission dynamics on the photoelectron phase accumulation as a function of the XUV–IR pulse delay and observable photoelectron detection direction and kinetic energy.

Streaked photoelectron (PE) emission spectra access the correlated dynamics of PEs and residual target electrons with attosecond temporal resolution. We calculated *ab initio* single [1]- and *double* [2] - ionization spectra for photoemission from He atoms by colinearly polarized ultrashort XUV and assisting delayed femtosecond IR pulses (Fig. 1) [1,2].

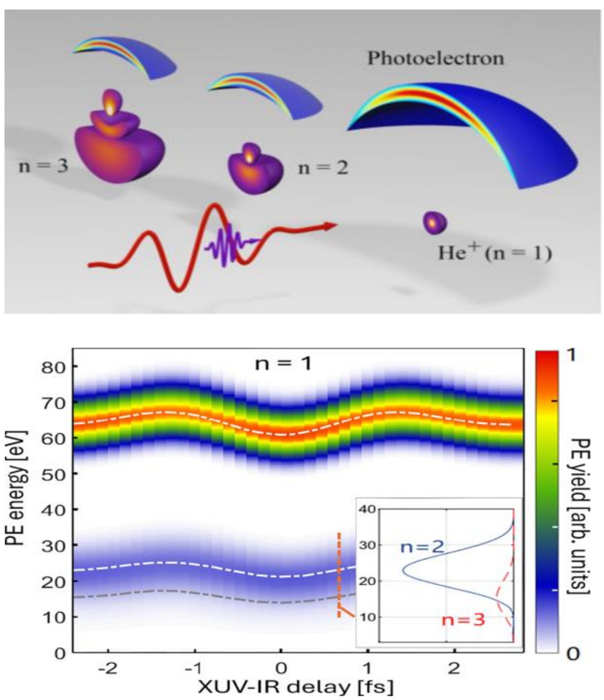

Figure 1. Top: Streaked direct (n = 1) and shake-up (n = 2, 3) single ionization of He. *Ab initio* PE-wave-packet probability densities 4 fs after the XUV-pulse center reached the nucleus for an XUV-IR pulse delay of −1/4 IR period. Not to scale. Bottom: Streaked spectra for an XUV photon energy of 90 eV. Centers of energy for direct and n = 2 shake-up emission are shown as white dash- dotted lines, and as the gray dash-dotted line for n = 3 shake-up. Inset: line-outs of the yields.

We tracked the evolution of the residual ion in relative streaking delays. For emission along the pulse-polarization directions in the n = 2 (3) shake-up channels, our relative streaking delays [1] are in very good (fair) agreement with the experimental and theoretical results in [3]. In addition, they reveal a strong photoemission-direction dependence for shake-up ionization due to the dominant coupling between the PE and evolving residual-ion dipole (Fig. 2) [1].

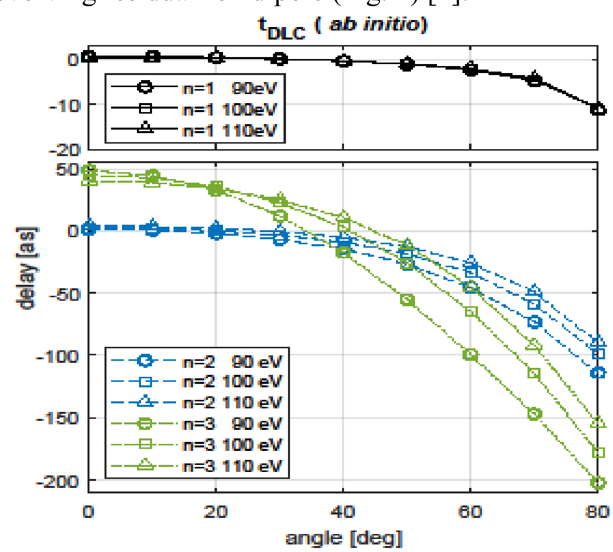

Figure 2. Angle- and energy-resolved absolute DLC de-lays for direct (n = 1) and n = 2, 3 shake-up ionization of helium for XUV-pulse photon energies of 90, 100, and 110 eV as functions of the PE-detection direction.

References
[1] H Shi,U Thumm, Phys. Rev. A **111**, 013119 (2025)
[2] A Liu, U. Thumm, Phys. Rev. Lett. **115**, 183002 (2015).
[3] M Ossiander *et al.,* Nat. Phys. **13**, 280 (2017)

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Electric Landé g-Factor and Pseudo-Angular Momentum: A Symmetry-Based Dual Reformulation of Electric Dipole Moments and the Stark Effect

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Electric dipole moments (EDMs) are sensitive probes of fundamental symmetries and central to searches for physics beyond the Standard Model. Unifying magnetic and electric dipole phenomena under electromagnetic duality, we develop a symmetry-based description of EDMs in analogue to the Zeeman effect. Exploiting the hidden $O(4) \simeq SU(2) \times SU(2)$ dynamical symmetry of the Coulomb problem, we show that the linear Stark effect in hydrogen is governed by Runge-Lenz vector, $\hat{\vec{A}}$, which couples directly to an external electric field. This naturally leads to the definition of a *pseudo-angular momentum* operator $\hat{\vec{J}}_p$ determined by $\hat{\vec{A}}$, and an *electric Landé factor* g_E, such that within a principal manifold n, the position operator along the field direction can be written as $\hat{z}|_n = \frac{3}{2} n a_0 \, \hat{J}_{p,z}/\hbar$, and the electric dipole operator as $\hat{\vec{d}} = e\hat{\vec{r}} = g_E \, d_B \hat{\vec{J}}_p/\hbar$, where a_0 is the Bohr radius and $g_E = \frac{3}{2}n$. Identifying the dual electric unit as the Bohr electric dipole moment, $d_B = \frac{2\mu_B}{c\alpha} = \frac{e\hbar}{m_e c\alpha} = ea_0$, establishes a direct correspondence to the Bohr magneton. Importantly, g_E incorporates not only the field-induced EDM but also any intrinsic EDM, $\hat{\vec{d}}_{int}$, that may arise from symmetry-violating interactions, although to date such contributions have been far too small to measure. For $n = 2$, Stark mixing of the $2s$ and $2p_{m=0}$ orbitals produces states with permanent EDMs $\langle d_2 \rangle = \pm 3 d_B$ ($g_E = 3$).

Constructing a dual Ohanian analogue of the Stark effect with respect to the Zeeman effect [1], we identify the microscopic polarization field of the wavefunction, $\vec{P}(\vec{r})$, which exhibits nonzero curl ($\nabla \times \vec{P} \neq 0$), defining an *effective bound magnetic probability current*, $\vec{J}_m = -\epsilon_0^{-1} \nabla \times \vec{P}$. From this, the electric dipole follows as, $\langle \hat{\vec{d}} \rangle = -\frac{\epsilon_0}{2} \int \vec{r} \times \vec{J}_m \, d^3 r = g_E^{(S)} d_{\rm int} \langle \hat{\vec{S}}_p \rangle/\hbar + g_E d_B \langle \hat{\vec{J}}_p \rangle/\hbar$, where $g_E^{(S)} = 2$. The intrinsic term is expressed in terms of a *pseudo-spin* operator $\hat{\vec{S}}_p$, which emerges naturally from the Dirac spinor formulation of the electron and satisfies the standard $SU(2)$ commutation relations. In this framework, $\hat{\vec{S}}_p$ encodes any intrinsic EDM contribution, while $\hat{\vec{J}}_p$ describes the dynamical pseudo–angular momentum generated by orbital motion and Runge–Lenz symmetry.

The same description extends beyond atomic physics to axion electrodynamics [2]. Within this dual structure, the $\vec{E} \cdot \vec{B}$ interaction generates pseudo–magnetic current signatures that mirror those obtained from our formalism. We show that a magnetic moment interacting with an axion field directly produces an electric dipole moment, which allows new strategies for precision measurements to search for light axion dark matter.

[1] Hans C. Ohanian. What is spin? *American Journal of Physics*, 54(6):500–505, 06 1986.

[2] Michael E. Tobar, Ben T. McAllister, and Maxim Goryachev. Modified axion electrodynamics as impressed electromagnetic sources through oscillating background polarization and magnetization. *Physics of the Dark Universe*, 26:100339, 2019.

Single photon attosecond interferometry

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University of Connecticut

Through a very stable attosecond interferometer we are now able capable of measuring XUV pulses interfering with a temporal precision of 3zs and perform single photon measurements. This allows us to measure the XUV fields in quadrature and determine correlations and photon statistics. We discuss possible squeeze states of the XUV.

Quantum Coherent State of Plasmon-exciton Strong Coupling in a Nanocavity

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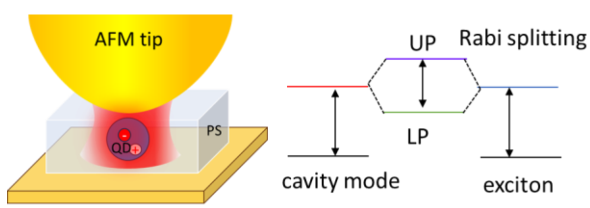
A strong coupling between excitons and plasmons in a nanocavity gives rise to hybrid quantum eigenstates known as plexcitons (or plasmon–exciton polaritons).[1–3] This emergent quantum state of light-matter enables exciting opportunities in quantum optics, including single-photon sources for quantum information processing, quantum bits, and ultrafast photonic switches.[4,5] Here, we report the observation of a plexciton generated through strong coupling between excitons in a single perovskite quantum dot in a plasmonic nanocavity. The nanocavity is formed between a gold AFM tip and a gold substrate. Using a femtosecond laser at 800 nm, we excite the $MAPbBr_3$ quantum dot via two-photon absorption, generating excitons that strongly couple with localized plasmons to form plexcitons. This coupling results in distinct upper and lower polariton branches, exhibiting a Rabi splitting energy up to 250 meV at room temperature. By controlling tip-sample distance and excitation light polarization, we can tune the nanocavity resonance and, consequently, the exciton–plasmon coupling strength.



References

1. Park, K. D. *et al.* Tip-enhanced strong coupling spectroscopy, imaging, and control of a single quantum emitter. *Sci Adv* **5**, eaav5931 (2019).
2. Hennessy, K. *et al.* Quantum nature of a strongly coupled single quantum dot–cavity system. *Nature 2006 445:7130* **445**, 896–899 (2007).
3. Yoshle, T. *et al.* Vacuum Rabi splitting with a single quantum dot in a photonic crystal nanocavity. *Nature 2004 432:7014* **432**, 200–203 (2004).
4. Hu, S. *et al.* Robust consistent single quantum dot strong coupling in plasmonic nanocavities. *Nature Communications 2024 15:1* **15**, 1–8 (2024).
5. Bhuyan, R. *et al.* The Rise and Current Status of Polaritonic Photochemistry and Photophysics. *Chem Rev* **123**, 10877–10919 (2023).

Abstract for PQE 2026

Title: *Hybrid Pumping of Excimer Lasers as a Candidate Architecture for Fusion Drivers*

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Inertial confinement fusion (ICF) requires laser drivers that can operate efficiently and repeatedly at high power levels suitable for generating extreme plasma conditions necessary for fusion. While existing laser systems can achieve the peak energies required for ignition-scale experiments, their excitation methods impose fundamental limitations on efficiency, scalability, and repetition rate. Equivalently, conventional electron-beam–pumped excimer lasers rely on relativistic electrons whose energies greatly exceed the excitation thresholds of the laser medium, resulting in significant ionization losses and inefficient energy utilization.

This work investigates a hybrid electromagnetic–electron pumping method for high-power pulsed gas lasers, with a focus on krypton-fluoride (KrF) excimer systems. In this approach, plasma generation and electron heating are treated as independent, controllable processes: a low-energy electron source sustains plasma density, while an electromagnetic field heats electrons into the excitation-dominant energy range. The method is studied computationally using Boltzmann modeling with the $BOLSIG^+$ solver and validated electron-impact cross-section data from the LXCat database.

Electron energy distribution functions, mean electron energies, and reaction rates are calculated over a broad range of reduced electric fields. The results show that maintaining electron energies in the 9–14 eV range maximizes excitation while suppressing ionization losses, demonstrating that hybrid pumping is intrinsically more efficient than traditional electron-beam excitation. These findings establish a physics-based pathway for improving efficiency while supporting scalable energy deposition. Ongoing experimental work on a hybrid-pumped ArXe system will serve as validation, with future extension to a hybrid-pumped KrF laser aimed at increasing output energy in parallel with peak power.

Quantum-amplified spectroscopy on an optical clock transition

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Optical lattice clocks (OLCs) are at the forefront of precision metrology [1–6], operating near a standard quantum limit (SQL) set by quantum noise [4, 7]. Harnessing quantum entanglement offers a promising route to surpass this limit [8–15], yet there remain practical roadblocks concerning scalability and measurement resolution requirements [16]. In this talk, I will present our recent work in which we demonstrate quantum-amplified time-reversal spectroscopy on an optical clock transition that achieves directly measured 2.4(7) dB metrological gain, and 4.0(8) dB improvement in laser noise sensitivity beyond SQL. We implement the signal amplification using time reversed interaction (SATIN) protocol [17, 18] to achieve this amplification. Furthermore, we adapt the holonomic-quantum-gate concept [19] to develop a novel Rabi-type "global-phase spectroscopy" that utilizes the detuning-sensitive global Aharanov-Anandan phase [20]. Our technique is not limited by measurement resolution, scales easily owing to the global nature of entangling interaction, and exhibits high resilience to typical experimental imperfections.

[1] A. D. Ludlow, M. M. Boyd, J. Ye, E. Peik, and P. O. Schmidt, Rev. Mod. Phys. **87**, 637 (2015).

[2] I. Ushijima, M. Takamoto, M. Das, T. Ohkubo, and H. Katori, Nature Photonics **9**, 185 (2015).

[3] E. Oelker, R. B. Hutson, C. J. Kennedy, L. Sonderhouse, T. Bothwell, A. Goban, D. Kedar, C. Sanner, J. M. Robinson, G. E. Marti, D. G. Matei, T. Legero, M. Giunta, R. Holzwarth, F. Riehle, U. Sterr, and J. Ye, Nature Photonics **13**, 714 (2019).

[4] M. Schioppo, R. C. Brown, W. F. McGrew, N. Hinkley, R. J. Fasano, K. Beloy, T. H. Yoon, G. Milani, D. Nicolodi, J. A. Sherman, N. B. Phillips, C. W. Oates, and A. D. Ludlow, Nature Photonics **11**, 48 (2017).

[5] J. Li, X.-Y. Cui, Z.-P. Jia, D.-Q. Kong, H.-W. Yu, X.-Q. Zhu, X.-Y. Liu, D.-Z. Wang, X. Zhang, X.-Y. Huang, M.-Y. Zhu, Y.-M. Yang, Y. Hu, X.-P. Liu, X.-M. Zhai, P. Liu, X. Jiang, P. Xu, H.-N. Dai, Y.-A. Chen, and J.-W. Pan, Metrologia **61**, 015006 (2024).

[6] J. M. Robinson, M. Miklos, Y. M. Tso, C. J. Kennedy, T. Bothwell, D. Kedar, J. K. Thompson, and J. Ye, Nature Physics **20**, 208 (2024).

[7] X. Zheng, J. Dolde, V. Lochab, B. N. Merriman, H. Li, and S. Kolkowitz, Nature **602**, 425 (2022).

[8] L. Pezzè, A. Smerzi, M. K. Oberthaler, R. Schmied, and P. Treutlein, Rev. Mod. Phys. **90**, 035005 (2018).

[9] T. Monz, P. Schindler, J. T. Barreiro, M. Chwalla, D. Nigg, W. A. Coish, M. Harlander, W. Hänsel, M. Hennrich, and R. Blatt, Phys. Rev. Lett. **106**, 130506 (2011).

[10] I. Pogorelov, T. Feldker, C. D. Marciniak, L. Postler, G. Jacob, O. Krieglsteiner, V. Podlesnic, M. Meth, V. Negnevitsky, M. Stadler, B. Höfer, C. Wächter, K. Lakhmanskiy, R. Blatt, P. Schindler, and T. Monz, PRX Quantum **2**, 020343 (2021).

[11] D. Leibfried, E. Knill, S. Seidelin, J. Britton, R. B. Blakestad, J. Chiaverini, D. B. Hume, W. M. Itano, J. D. Jost, C. Langer, R. Ozeri, R. Reichle, and D. J. Wineland, Nature **438**, 639 (2005).

[12] A. Cao, W. J. Eckner, T. Lukin Yelin, A. W. Young, S. Jandura, L. Yan, K. Kim, G. Pupillo, J. Ye, N. Darkwah Oppong, and A. M. Kaufman, Nature **634**, 315 (2024).

[13] M. Kitagawa and M. Ueda, Phys. Rev. A **47**, 5138 (1993).

[14] B. Yurke, S. L. McCall, and J. R. Klauder, Phys. Rev. A **33**, 4033 (1986).

[15] D. J. Wineland, J. J. Bollinger, W. M. Itano, and D. J. Heinzen, Phys. Rev. A **50**, 67 (1994).

[16] F. Fröwis, P. Sekatski, and W. Dür, Phys. Rev. Lett. **116**, 090801 (2016).

[17] E. Davis, G. Bentsen, and M. Schleier-Smith, Phys. Rev. Lett. **116**, 053601 (2016).

[18] S. Colombo, E. Pedrozo-Peñafiel, A. F. Adiyatullin, Z. Li, E. Mendez, C. Shu, and V. Vuletić, Nature Physics **18**, 925 (2022).

[19] E. Sjöqvist, Physics Letters A **380**, 65 (2016).

[20] Y. Aharonov and J. Anandan, Phys. Rev. Lett. **58**, 1593 (1987).

Super-resolved multiphoton microscopy with double enhancement achieves sub-100 nm resolution.

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Laser scanning multiphoton microscopy allows imaging deep in samples, as the nonlinearity causes the excitation to be strongly confined in the axial direction, that is, multiphoton microscopy comes with intrinsic sectioning of the signal. However, the resolution in laser scanning microscopy is given by how tightly one can focus the beam, which is the so-called Abbe limit, given by the wavelength λ, divided by twice the numerical aperture NA of the focusing element (objective). Thus, compared to single photon excited microscopy, the two-photon excited microscopy worsens the resolution by a factor $\sqrt{2}$. To overcome the Abbe resolution limit, several approaches have been developed for single photon excited microscopy [1–5]. Of those methods, structured illumination microscopy [2] and image scanning microscopy (ISM) [4] can be applied with virtually any fluorescent marker, which makes them the most widely applicable super-resolution methods. ISM is implemented with laser scanning confocal microscopy, and recently it was demonstrated to be applicable to two- and three photon microscopy [6], achieving deep imaging with a resolution better than what is achieved with confocal microscopy. It was shown previously that ISM can be combined with super-resolution optical fluctuation imaging (SOFI) to achieve further resolution enhancement [7].

In this work we demonstrate the resolution enhancement of 2-photon ISM-SOFI experimentally and show the utility of this approach for various imaging scenarios. The left panels of Fig. 1 show the subsequent enhancement of 2P ISM, 2P ISM-SOFI and 2P ISM 4^{th} order SOFI. We use the system to image fixed biological samples. The right panels of Fig. 1 show the enhancement of ISM SOFI over ISM images obtained from mouse brain tissue with quantum dots labelling tubulin filaments.

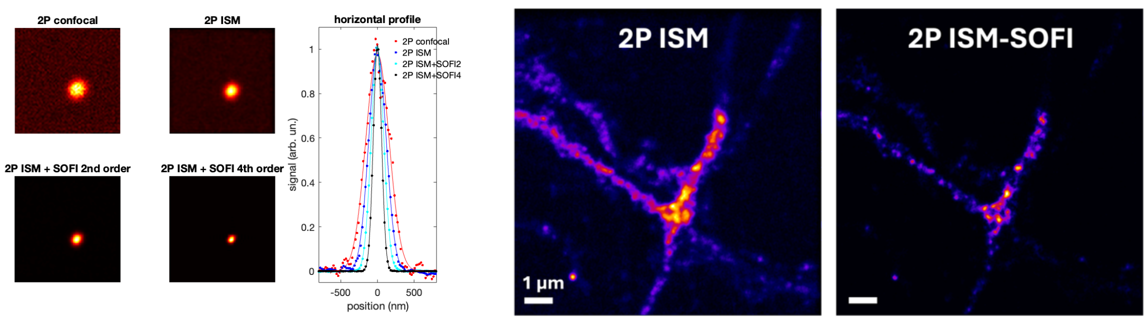

Fig. 1. 2P ISM-SOFI imaging performance. Left: Successive enhancement of 2P ISM, 2P ISM SOFI and 2P ISM 4^{th} order SOFI over 2P confocal imaging. 2P ISM 4^{th} order SOFI allows to achieve <100 nm resolution when including image deconvolution. Right: Enhancement of 2P ISM SOFI imaging over 2P ISM imaging for fixed mouse brain tissue with QD625 labeled tubulin fibers.

4. References

1. S. Hell, J. Wichmann, "Breaking the diffraction resolution limit by stimulated emission: stimulated-emission-depletion fluorescence microscopy," Opt. Lett. 19, 11, 780 (1994); E. Betzig, et al., "Imaging intracellular fluorescent proteins at nanometer resolution," Science 313, 5793, 1642 (2006)
2. A. Alva, et al., "Fluorescence fluctuation-based super-resolution microscopy: Basic concepts for an easy start,"Journal of Microscopy 288, 3, 218 (2022)
3. M. Gustafsson, "Surpassing the lateral resolution limit by a factor of two using structured illumination microscopy," J. Microsc. 198, 2, 82 (2000)
4. C. Müller, J. Enderlein, "Image scanning microscopy," Phys. Rev. Lett. 104, 198101 (2010)
5. F. Ströhl, C. Kaminski, Frontiers in structured illumination microscopy, Optica 3, 6, 667 (2016)
6. A. Classen, et al., "Three Photon Excited Image Scanning Microscopy for in-Depth Super-Resolution Studies of Biological Samples," PRX Life 2 033010 (2024)
7. A. Sroda, et al., "SOFISM: Super-resolution optical fluctuation image scanning microscopy," Optica 7, 1308 (2020)

New results of incoherent diffraction imaging (IDI) for x-ray structure analysis

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For more than 100 years, coherent X-rays have been used in crystallography to determine the structure of proteins and molecules via *Coherent Diffraction Imaging* (CDI) [1]. Recently, it was proposed that also incoherent fluorescence light can be utilized to resolve the atomic distribution of crystalized proteins or even single molecules, an approach termed *Incoherent Diffraction Imaging* (IDI) [2].

In order to make use of incoherent fluorescence light for x-ray structure analysis, the spatial second-order photon correlations $g^{(2)}(r_1,r_2)$ must be determined instead of the coherently scattered intensity. Like in the landmark experiment by Hanbury Brown and Twiss to overcome atmospheric fluctuations in astronomy [3,4], this eliminates the phase fluctuations of fluorescence via a two-photon interference process.

However, measuring $g^{(2)}(r_1,r_2)$ requires recording the photons within their coherence time, i.e., within the lifetime of inner core transitions of the investigated atoms. With the latter being on the order of fs or below, this is beyond the temporal resolution capabilities of current detectors. An alternative is using fs-pulses of advanced FEL sources.

We implemented IDI for the first time at the European XFEL, Hamburg, with pulses of ~10fs duration producing Kα-fluorescence of copper at 8 keV stemming from two spots on a thin copper foil, after splitting the incoming FEL beam into two beams by use of a transmission phase grating [5]. In a recent follow-up experiment we further retrieved the form factor of copper nanocubes of size ~88nm with 20nm resolution, extending IDI to the destructive single-particle regime [6]. Here, we observed unexpectedly a sharp drop in visibility of $g^{(2)}(r_1,r_2)$ above an incident photon fluence of 10^2 J/cm^2 per pulse, most likely resulting from amplified spontaneous emission (ASE).

To circumvent this problem, one could employ in the future fluorescence photons from Mössbauer transitions, with lifetimes on the order of 100 ns. Here, up to 900 photons per pulse have been observed at FEL facilities recently [7]. This is too low to produce ASE while at the same time ensures high visibilities of $g^{(2)}(r_1,r_2)$ due to the ultra-long lifetimes.

References

1. A. Barty, J. Küpper, H. N. Chapman, Annu. Rev. Phys. Chem. 64, 415 (2013) and references therein.
2. A. Classen, K. Ayyer, H. N. Chapman, R. Röhlsberger, J. von Zanthier, Phys. Rev. Lett. 119, 053401 (2017).
3. R. Hanbury Brown and R. Q. Twiss, Nature 178, 1046 (1956).
4. R. Hanbury Brown and R. Q. Twiss, Nature 177, 27 (1956).
5. F. Trost et al., Phys. Rev. Lett. 130, 173201 (2023) (Editors suggestion, also Featured in *Physics*).
6. T. Wollweber et al., arXiv: 2512.06110.
7. M. Gerharz et al., arXiv:2509.15833

Novel approaches to nanoscale imaging of 2D materials and micro(nano)plastics

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ABSTRACT

Nanoscale chemical imaging of micro- and nano-plastics (MNPs) in the environment and human patients has been a challenge due to weak spectroscopic signals of small sample volumes and limited spatial resolution of the conventional MNP characterization approaches. Novel approaches based on the combination of scanning probe microscopy (SPM) and optical spectroscopic methods such as photoluminescence/fluorescence and Raman scattering have been developed for rapid minimally invasive optical imaging of 2D materials and MNPs. Pressure-induced effects lead to signal enhancement via exciton funneling and charge transfer in the plasmonic gap-mode quantum tunneling regime. Tip-enhanced Raman scattering (TERS) has been optimized for the gapless mode imaging. These novel materials-specific approaches take advantage of the specific molecular and atomic transitions to maximize the signal enhancement and sensitivity to MNPs that include a variety of minerals, pigments and organic biopolymers. The optimization of experimental parameters and throughput of TERS are based on the interplay of the electromagnetic and chemical enhancement mechanisms. Sub-sampling strategies and tip-sample distance (TSD) are optimized to achieve the fast and reliable imaging analysis.

Alice, Bob, … and Friends: What's next for the Darmstadt Quantum Key Distribution Network

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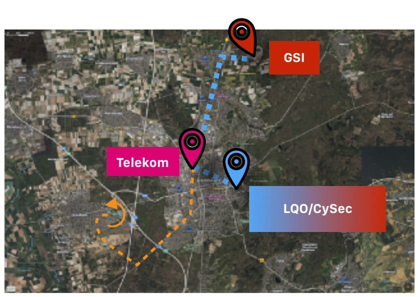
Quantum key distribution (QKD) is one of the possible solutions to maintain data privacy when quantum computers will render today's public-key cryptography insufficient. For a broad deployment of QKD, scalable and robust systems are necessary. Scalability can be achieved by using star-shaped networks in combination with entanglement-based QKD protocols. A single untrusted source in the center serves all connected network parties to exchange a key. We implemented a city-wide QKD network comprised of four users employing a time-bin variant of the BBM92 protocol. Scaling up to 100 users is possible.

Based on our prior works [1-3], we distributed our receiver units among four labs within Darmstadt and connected them via deployed fibers operated by Deutsche Telekom and TU Darmstadt. Furthermore, we implemented post-quantum secure authentication schemes for the public channel as well as full error correction, privacy amplification and software based clock recovery. In our talk, we discuss our results and give an outlook on future work, where we plan to switch to a Photonic Chip based light source.

[1] E. Fitzke et al., PRX 3 (2022) 020341;
[2] T. Dolejsky et al. Europ. Phys. J. Spec. Top. 232 (2023) 3553;
[3] J. Kaltwasser et al., Physical Review A 109 (2024) 012618;



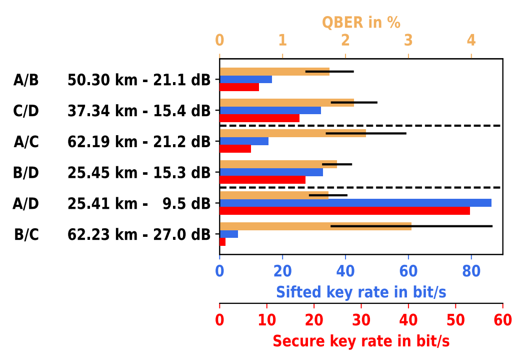


Figure: The Darmstadt Quantum Key Distribution Network (left). Sifted and secure key rates as well as the quantum bit error (QBER) rate for alle possible QKD connections within our 4-party network (right). In principle distances up to 150 km are possible.

Quantum Heat Engines Driven by Multilevel Quantum Coherence

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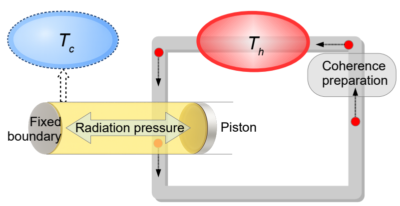
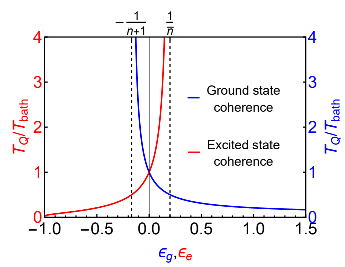
Quantum thermodynamics explores how quantum properties such as coherence and entanglement enable energy conversion processes beyond classical efficiency limits, with quantum heat engines providing a central platform for studying these effects. Building on this foundation, we extend the cavity QED photo-Carnot engine of Ref. [1], schematically illustrated in Fig. 1(a), to atoms with engineered internal coherence that interact with a cavity field whose radiation pressure can perform mechanical work. Unlike earlier three-level atomic schemes, consisting of one excited and two nearly degenerate ground states that support a single coherence channel and thus operate only in heating or cooling modes [1], our model incorporates both ground- and excited-state coherences, enabling smooth transitions between heating, cooling, and cancellation.



(a)



(b)

Fig. 1: (a) Quantum photo-Carnot engine schematic. Atoms with engineered internal coherence interact with the cavity field through radiation pressure, enabling tunable optical heating and cooling. (b)Calculated T_Q/T_{bath} as a function of the coherence parameters ε_g and ε_e, where ground-state (blue) and excited-state (red) coherences act as independent control knobs that produce heating or cooling.

We introduce a four-level configuration with two ground and two excited states, allowing ground- and excited-state coherences to be tuned within a single system. The resulting effective temperature,

$$T_Q = \frac{\hbar\omega}{k_B \ln\left[\frac{(\bar{n}+1)(1+\varepsilon_g)}{\bar{n}(1+\varepsilon_e)}\right]}. \tag{1}$$

shows that each coherence channel independently controls heating or cooling: varying ε_g or ε_e shifts T_Q above or below T_{bath}, with both limits reducing to the classical case when the corresponding coherence vanishes. When both coherences are present, their combined action enables smooth switching between heating, cooling, and near-cancellation within a single photonic platform. Coherence-modified temperatures enter the Carnot relation, giving an effective efficiency that can exceed the classical value when part of the internal energy cost is stored in coherence. Using T_Q in place of bath temperature redefines the thermal gradient driving work extraction, linking laser-like interference effects to tunable thermal biases in quantum engines.

These results show that coherence acts as a genuine thermodynamic variable capable of reshaping the thermal gradient that drives work extraction. Such coherence-controlled thermal response can be realized with existing cavity-QED platforms, with rubidium atoms offering the most direct implementation. NV centers, quantum dots, and circuit-QED systems provide additional platforms for observing coherence-driven heating, cooling, and cancellation.

References

1. M. O. Scully *et al.*, 'Extracting work from a single heat bath via vanishing quantum coherence', *Science* **299**, 862 (2003).
2. D. Turkpence and O. E. Mustecaplioglu, 'Quantum fuel with multilevel atomic coherence for ultrahigh specific work in a photonic carnot engine', *Phys. Rev. E* **93**, 012145 (2016).

Review of the Quantum Boltzmann Equation (Poster)

Cooper Watson

The quantum Boltzmann equation (QBE), first emerging from the quantum extension of Boltzmann's classical transport theory by Uehling and Uhlenbeck and later reformulated within the nonequilibrium Green-function developments of Kadanoff–Baym and Keldysh, stands as the central kinetic framework for describing quantum many-body relaxation. It underlies the modern treatment of semiconductor transport, ultracold gases, and plasma kinetics. However, the standard derivations of the QBE reveal a subtle but persistent gap: ladder-operator constructions typically appeal to Wick factorization without exhibiting the complete algebraic structure of contractions, while Green-function approaches compress the same underlying information into Born-level self-energies whose operator origin becomes obscured. The Golden Rule derivation is pedagogically simpler and yields the correct physical result for dilute gases, but the full Wick's theorem derivation is the mathematically precise way to connect the quantum many-body Hamiltonian to the kinetic equation.

In this review, we provide a unified and explicit derivation of the QBE, demonstrating a one-to-one correspondence between the twelve Wick contractions in the operator formalism and the associated Keldysh contractions that generate the second-order self-energy. The mapping clarifies the emergence of $|U(k-p)|^2$, Bose/Pauli factors, and momentum conservation, strengthening the microscopic foundation of the QBE and enabling systematic extensions to quantum noise and higher-order correlation dynamics.

Quantum electron dynamics of molecules in cavities

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Strong light-matter coupling between molecules and optical cavities offers new opportunities to control chemical reactivity and to enable applications in quantum information science. Theoretical methods play a key role in explaining these phenomena and guiding experimental design. Quantum electrodynamics (QED) electronic structure methods combine rigorous molecular electronic structure theory with a quantized light-matter coupling Hamiltonian. In particular, QED configuration interaction (QED-CI) theory solves the electronic states using CI techniques while incorporating molecule-photon coupling through the Pauli-Fierz Hamiltonian. QED-CI provides the foundation for real-time polaritonic dynamics via QED time-dependent CI (QED-TDCI), which propagates the polaritonic wavefunction in the presence of a classical driving field. Here, we present recent developments in QED-CI for applications in polaritonic dynamics, focusing on how truncation of the electronic subspace impacts the accuracy of QED-CI energies and properties. We also apply the TDCI methodology to artificial molecular systems used as qubits, demonstrating strategies for optimizing two-qubit gates in electrons-on-helium systems.

Quantum light spectroscopies for probing photosynthetic systems

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Photosynthetic light harvesting in vivo displays near unit quantum efficiency under ultra-weak illumination conditions. A new generation of experimental and theoretical studies using quantum light sources and coincidence counting on photosynthetic systems now allows explicit study of the absorption of individual photons and the dynamical processes following such events. These studies include correlation measurements of incident and fluorescent photons that can reveal the effect of photon statistics on photosynthesis, witness the presence of excitonic and vibrational coherence in the excited state dynamics, and allow microscopic measurements of quantum efficiency at the level of single photons that is relevant to natural conditions in which this is optimized. I shall summarize recent developments, with discussion of the possible roles of entangled photons and illustration of how these techniques and related theoretical studies can probe the spatiotemporal dynamics of photosynthesis in new and fundamental ways.

Searching dark matter with hyperpolarized spin ensembles

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Axion-like particles (ALPs) arise from well-motivated extensions to the Standard Model and could account for dark matter. ALP dark matter would manifest as a field oscillating at an (as of yet) unknown frequency. The frequency depends linearly on the ALP mass which is plausibly ranging from 10^{-22} to $10\,\mathrm{eV}/c^2$. This motivates broadband search approaches. Furthermore, dark matter couples differently to different standard model particles, photons, gluons, electrons, protons and neutrons. The stochastic signatures of ALP dark matter in our galaxy [1] would manifest with different amplitude spectra [2] considering the different couplings. Searching for gradient-coupled ALP dark matter with hyperpolarized spin ensembles is the idea behind the Cosmic Spin Precession experiment [3, 4]. Dark matter consisting of low mass ALPs, corresponding to oscillation frequencies around 100 Hz and below can be effectively searched for with vapor cells containing gaseous noble gas ensembles with nuclear spins. Furthermore, the nuclear spin can be initialized and read-out using overlapped alkali ensembles. We used two such polarization-optimized comagnetometers [5] calibrated regularly to ALP signatures [6] to search for dark matter in an interferometric configuration. In this configuration we leveraged the anticipated spatio-temporal coherence properties of the ALP field and probed all ALP-gradient-spin interactions covering a mass range of nine orders of magnitude. No significant evidence of an ALP signal was found and we placed new upper limits on the ALP-neutron, ALP-proton and ALP-electron couplings reaching below $g_{aNN} < 10^{-9}\,\mathrm{GeV}^{-1}$, $g_{aPP} < 10^{-7}\,\mathrm{GeV}^{-1}$ and $g_{aee} < 10^{-6}\,\mathrm{GeV}^{-1}$, respectively. These limits improve upon previous laboratory constraints for neutron and proton couplings by up to three orders of magnitude.
The results are summarized in [7]. I am going to discuss this experiment and present our ongoing work to increase the range of our spin-based dark matter searches.

[1] G. P. Centers, J. W. Blanchard, J. Conrad, N. L. Figueroa, A. Garcon, *et al.*, Nat. Commun. **12**, 7321 (2021).
[2] A. V. Gramolin, A. Wickenbrock, D. Aybas, H. Bekker, D. Budker, G. P. Centers, N. L. Figueroa, D. F. Jackson Kimball, and A. O. Sushkov, Physical Review D **105**, 035029 (2022).
[3] D. Budker, P. W. Graham, M. Ledbetter, S. Rajendran, and A. O. Sushkov, Physical Review X **4**, 021030 (2014).
[4] J. Walter, O. Maliaka, Y. Zhang, J. W. Blanchard, G. Centers, A. Dogan, M. Engler, N. L. Figueroa, Y. Kim, D. F. J. Kimball, M. Lawson, D. W. Smith, A. O. Sushkov, D. Budker, H. Bekker, and A. Wickenbrock, Phys. Rev. D **112**, 052008 (2025).
[5] E. Klinger, T. Liu, M. Padniuk, M. Engler, T. Kornack, *et al.*, Phys. Rev. Appl. **19**, 044092 (2023).
[6] M. Padniuk, E. Klinger, G. Łukasiewicz, D. Gavilan-Martin, T. Liu, S. Pustelny, D. F. Jackson Kimball, D. Budker, and A. Wickenbrock, Physical Review Research **6**, 013339 (2024).
[7] D. Gavilan-Martin, G. Łukasiewicz, M. Padniuk, E. Klinger, M. Smolis, N. L. Figueroa, D. F. Jackson Kimball, A. O. Sushkov, S. Pustelny, D. Budker, and A. Wickenbrock, Nature Communications **16**, 4953 (2025), publisher: Nature Publishing Group.

Nonlinear topological photonics: from frequency combs and harmonic generation to emergent phenomena

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Microresonator frequency combs have revolutionized precision metrology, spectroscopy, and optical communication. Yet, nearly all existing platforms rely on single-ring resonators, where nonlinear dynamics are governed by a single timescale—set by one free spectral range determined by the geometry of the resonator. This inherently restricts control over optical synchronization, frequency-phase matching, and the existence of solitons. In contrast, topological photonic lattices provide a new synthetic dimension of control: multiple coupled resonators create multi-timescale interactions that reshape how nonlinear light evolves on a chip.

We overcome these challenges by combining microresonator frequency combs with topological photonics to uncover new regimes of nonlinear light generation [1], multi-timescale synchronization [2], and new mechanisms of frequency–phase matching [3]. Our ongoing work on integer quantum Hall (IQH) topological frequency combs explores waveguide-geometry-agnostic dispersion engineering and how octave-spanning microcombs can be used to probe topological physics. Moreover, our theoretical work predicts exotic solitonic states that go beyond conventional topological models. These results show that topological photonics offers advantages beyond topological protection and establishes a new design principle in nonlinear integrated photonics.

References

[1] Christopher J Flower*, Mahmoud Jalali Mehrabad*, Lida Xu*, Gregory Moille, Daniel G Suarez-Forero, Oğulcan Örsel, Gaurav Bahl, Yanne Chembo, Kartik Srinivasan, Sunil Mittal, et al. Observation of topological frequency combs. *Science*, 384(6702):1356–1361, 2024.

[2] Lida Xu*, Mahmoud Jalali Mehrabad*, Christopher J Flower*, Gregory Moille, Alessandro Restelli, Daniel G Suarez-Forero, Yanne Chembo, Sunil Mittal, Kartik Srinivasan, and Mohammad Hafezi. On-chip multi-timescale spatiotemporal optical synchronization. *Science Advances*, 11(37):eadw7696, 2025.

[3] Mahmoud Jalali Mehrabad*, Lida Xu*, Gregory Moille, Christopher J Flower, Supratik Sarkar, Apurva Padhye, Shao-Chien Ou, Daniel G Suarez-Forero, Mahdi Ghafariasl, Yanne Chembo, et al. Multi-timescale frequency-phase matching for high-yield nonlinear photonics. *arXiv preprint arXiv:2506.15016*, 2025.

Attosecond transient absorption with quantum-structured fluctuations

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Quantum fluctuations are fundamental in quantum optics, yet their impact on electronic excitations at attosecond timescales remains largely unexplored. Imprinting such fluctuations onto an electronic wavefunction requires an XUV attosecond source whose properties vary shot-to-shot while maintaining attosecond-level phase stability. Recent work has shown that when high-harmonic generation (HHG) is driven by bright squeezed vacuum (BSV), the resulting attosecond pulses inherit the statistical structure of the driving field [1–3]. BSV represents an extreme case: despite having zero average electric field, its instantaneous field exhibits strong quantum fluctuations, producing alternating periods of near-silence and intense noise bursts each optical cycle.

In my talk I will describe how we engineer quantum-structured fluctuations in an excited electronic wave packet and track its evolution using attosecond transient absorption (ATA). We first generate attosecond pulses with a quantum-origin statistical nature [3] that serve as the pump. This pump initiates stochastic coherence in the excited-state electronic wavefunction of helium, while an IR dressing field maps this coherence onto the ATA spectrum. We record the interference between the incident and generated fields versus the XUV-IR delay, on a shot to shot basis, capturing the evolution of their joint statistics. Exploiting the interferometric nature of ATA [4], we reconstruct the temporal evolution of the complex excitation with attosecond precision, revealing how quantum fluctuations propagate into and shape electronic coherence.

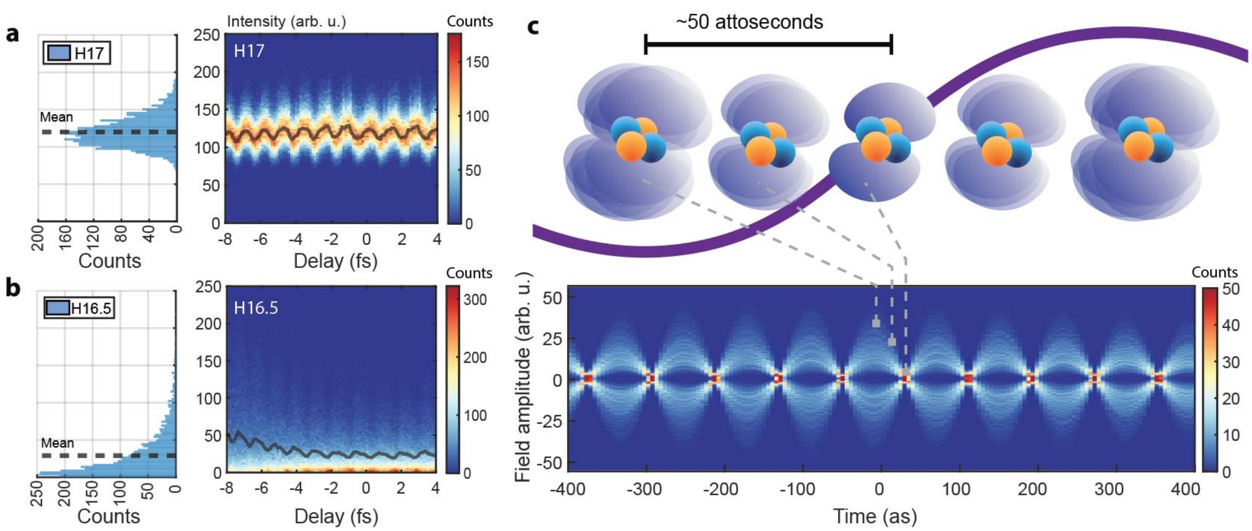

Fig 1. (**a**) Static and dynamic histograms of H17, presenting a coherent excitation. (**b**) Static and dynamic histograms of H16.5, preserving the statistical nature of BSV and demonstrating phase relation that enables ultrafast interferometry. (**c**) Reconstruction of ultrafast statistical dynamics in field-driven helium. The amplitude of the generated field switches from extreme noise to near silence within ~50 attoseconds.

[1] A. Rasputnyi et al., Nat. Phys. (2024).
[2] S. Lemieux et al., Nat. Photon. (2024).
[3] M. Even-Tzur et al., arXiv (2025).
[4] M. Wu et al., J. Phys. B (2016).

Cavity-Enabled Measurements and Interactions in Neutral Atom Quantum Processors

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Abstract:
By strongly coupling a neutral-atom array to a high-finesse optical cavity, we turn cavity photons into a versatile control knob for a quantum processor. In this setting, cavity photons act as carriers of quantum information, enabling both rapid quantum-state measurement and long-range interactions between atomic qubits. By optically selecting a single atomic qubit to emit photons into the cavity, we realize rapid mid-circuit measurements without perturbing the quantum coherence of the remaining atoms—a crucial step toward implementing quantum error correction and semiclassical quantum methods. At the same time, the collective atom–cavity coupling provides a platform for quantum simulation of many-body systems with all-to-all interactions and enables the observation of self-organization phase transitions in both motional and spin degrees of freedom. Continuous measurements of a finite-size atom array reveal key hallmarks of mesoscopic physics, including a dependence of the resulting state of matter on the measurement duration. Finally, I will discuss our progress on incorporating Rydberg excitations into cavity-coupled atom arrays.

Coherence-Enhanced Open Quantum Battery

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Quantum batteries provide a framework in which quantum coherence, correlations, and engineered dissipation can be converted into useful work. However, decoherence and energy relaxation generally reduce the active energy stored in the battery. In conventional dark-state–protected open quantum battery (OQB) protocols [1], the charger and battery interact dissipatively through a common vacuum reservoir and form the dark states, which suppresses energy loss but limits energy-utilization efficiency and charging speed especially when the charger and battery have comparable sizes.

We extend this framework by preparing the charger in a collective spin-coherent state $|\theta,\phi\rangle = e^{-i\phi J_z}e^{-i\theta J_y}|N_C/2, N_C/2\rangle$ and by coupling both domains to a squeezed reservoir with parameter $\xi = re^{i\varphi}$, as illustrated schematically in Fig. 1(a). This introduces two coherence sources for enhanced ergotropy and faster charging: the spin-coherent charger significantly enhances the steady-state ergotropy, while both the squeezed-reservoir coherence and the spin-coherent charger collaboratively accelerates the charging dynamics. The extractable work is quantified using the *ergotropy* [2] $W = \mathrm{Tr}(H_0\rho) - \min_U \mathrm{Tr}(H_0 U\rho U^\dagger)$, which we decompose into incoherent and coherent parts following ref. [3]:

$$W_B = W_B^P + W_B^C. \tag{1}$$

While earlier dark-state–protected protocols produce only incoherent ergotropy W_B^P, our scheme generates a coherent ergotropy component W_B^C through reservoir-assisted and charger-generated coherence.

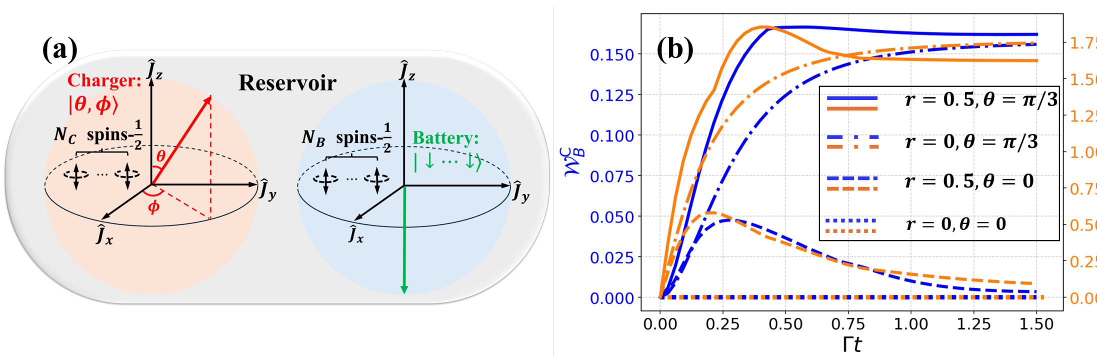

Fig. 1: (a) Schematic of the model. The quantum battery charging system consists of two spin domains as the charger and the battery, collectively coupled to a common reservoir. (b) Time evolution of the coherent ergotropy $\mathcal{W}_B^C$ (blue) and the local l_1-norm coherence $\mathcal{C}_B$ (orange) under different reservoir and initial state conditions (dotted: $r=0,\ \theta=0$; dashed: $r=0.5,\ \theta=0$; dash-dotted: $r=0,\ \theta=\pi/3$; solid: $r=0.5,\ \theta=\pi/3$) with $\delta=0$.

Previous numerical results have shown that under fixed charger-battery spin number ratio, the charging power per spin $\mathcal{P}_B^W \equiv d\mathcal{W}_B/dt$ increases proportionally with N_B, so that the total power $P_B^W = N_B\mathcal{P}_B^W$ exhibits a superradiant N_B^2 scaling behavior. The total steady state ergotropy W_B also scales proportional to N_B^2, performing a super-extensive capacity. Meanwhile, Both squeezing and initial coherence dramatically enhance $\mathcal{P}_B$, driven by the rapid buildup of $\mathcal{W}_B^C$, which closely follows the local coherence C_B as shown in Fig. 1(b). In our charging system when charger and battery have comparable sizes, W_B^C is dominant. Numerical comparisons show: (i) vacuum reservoir with all-spin-up charger yields purely incoherent ergotropy $\mathcal{W}_C^P$ and low charging power; (ii) introducing squeezing alone increases charging speed but suffers long-time coherence decay; (iii) a spin-coherent charger alone transfers coherence one-way into the battery and leads to monotonically increasing $\mathcal{W}_B^C$ with a relatively high steady state ergotropy; and (iv) the combination of spin-coherent charger initialization and reservoir squeezing yields the fastest charging while keeping high steady state ergotropy at long time.

References

1. J. Q. Quach and W. J. Munro *Phys. Rev. Appl.*, vol. 14, p. 024092, Aug. 2020.
2. A. E. Allahverdyan, R. Balian, and T. M. Nieuwenhuizen *Europhysics Letters*, vol. 67, no. 4, p. 565, 2004.
3. G. Francica, F. C. Binder, G. Guarnieri, M. T. Mitchison, J. Goold, and F. Plastina *Physical Review Letters*, vol. 125, no. 18, p. 180603, 2020.

When Light Listens: New Frontiers at the Intersection of Cavity Optomechanics and Photoacoustic Spectroscopy

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Although photoacoustic spectroscopy (PAS) has been studied extensively, modern resonator physics combined with engineered optomechanical coupling opens an unexplored regime in which acoustic waves generated through photoacoustic effects can be transduced with unprecedented sensitivity. I will begin with a brief introduction of whispering-gallery-mode (WGM) microresonators, with optical Q factors exceeding 10^6, as an excellent platform for sensing applications. Then I will discuss how the confined optical mode in a microbubble WGM is effectively decoupled from dissipative liquid environments, allowing the resonator to maintain high Q even when fully immersed in complex or highly absorbing media. This protection enables us to probe acoustic waves generated by freely flowing particles and cells without suffering the Q degradation that normally limits resonant sensors. The intracavity field serves as a highly coherent probe whose phase and frequency respond to sub-picometer boundary displacements and weak pressure waves, providing a direct and sensitive readout of photoacoustic excitation events. I will outline the optomechanical mechanisms, including radiation-pressure coupling, boundary deformations, and refractive-index modulation, and how they collectively define a new transduction pathway for PAS.

Building on this framework, I will first present an optofluidic WGM sensor capable of detecting acoustic signals generated by micro- and nanoscale particles upon pulsed optical absorption. The system captures particle-specific photoacoustic “fingerprints” that encode geometry, composition, molecular absorption features, and morphology. These measurements can be performed in strongly scattering, heterogeneous environments such as whole blood, and without surface binding or immobilization. This demonstrates that cavity-enhanced PAS can function as a label-free, immobilization-free spectroscopic method across an extended sensing volume, enabled fundamentally by resonant enhancement and mode protection. In the second part, I will describe a related implementation for monitoring microbial populations in synthetic biology. By integrating PAS with high-Q WGM detection, we obtain a compact sensor whose optomechanically transduced acoustic signatures allow real-time characterization of microbial mixtures, tracking of coculture dynamics, and early identification of population deviations or contamination.

In summary, the talk will highlight how re-examining photoacoustic spectroscopy from the perspective of high-Q cavity optomechanics can open up a new physical regime of sensitivity and selectivity. This platform shows how classical PAS can be transformed by resonant light confinement, coherent optomechanical coupling, and dissipative-protected mode engineering, offering new opportunities for fundamental studies of light-acoustic interactions, as well as transformative sensing capabilities in complex media.

Spin-squeezed clock for beyond the standard quantum limit performance at $1x10^{-18}$

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Optical atomic clocks with unrivaled precision and accuracy have advanced the frontier of precision measurement science and opened new avenues for exploring fundamental physics [1–3]. A fundamental limitation on clock precision is the Standard Quantum Limit (SQL), which stems from the uncorrelated projection noise of each atom. State-of-the-art optical lattice clocks interrogate large ensembles to minimize the SQL, but density-dependent frequency shifts pose challenges to further scaling the atom number. The SQL can be surpassed by leveraging entanglement, yet achieving a clear quantum advantage at state-of-the-art stability has remained an open problem.

In this talk, I will present a spin-squeezed optical lattice clock with performance beyond the SQL, achieving a fractional frequency precision of 1.1×10^{-18} for a single spin-squeezed clock [4]. With cavity-based quantum nondemolition (QND) measurements, we prepare two spin-squeezed ensembles of ~30,000 strontium atoms confined in a two-dimensional optical lattice. A synchronous clock comparison with an interrogation time of 61 ms achieves a metrological improvement of 2.0(2) dB beyond the SQL, after correcting for state preparation and measurement errors. These results establish the most precise entanglement-enhanced clock to date, provide a foundation for future accuracy evaluations, and offer a powerful platform for exploring the interplay of gravity and quantum entanglement. I will also discuss our recent progress and future perspectives.

References:

[1] A. D. Ludlow et al., Rev. Mod. Phys. 87, 637 (2015).
[2] T. Bothwell et al., Nature 602, 420 (2022).
[3] A. Aeppli et al., Phys. Rev. Lett. 133, 023401 (2024).
[4] Y. A. Yang et al., Phys. Rev. Lett. 135, 193202 (2025).

Quantum statistics of radiation in collective spontaneous emission

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When a quantum system is placed into an excited state, it will decay back to the ground state through a process termed spontaneous emission. Spontaneous emission occurs due to the coupling of a quantum system (for example a neutral atom) to a continuum (infinite number) of radiation modes. It was predicted by Dicke 70 years ago that the usual process of spontaneous emission could be importantly modified when there is an ensemble of emitters [1]. Specifically, the emission (decay) rate can be enhanced or reduced compared to the natural rate of a single isolated atom: effects commonly referred to as superradiance and subradiance [2, 3].

We have recently experimentally demonstrated that spatial coherence can emerge during collective spontaneous emission [4]. This type of coherence is fundamentally different from the coherence of a laser since it does not require population inversion. Because the coherence established in collective emission is distinctly different from a laser a natural question to ask is: what is the quantum statistics of the emitted light? It is well-known that the quantum statistics of the emitted photons in collective spontaneous emission is quite difficult to study theoretically [2]. The main results in this problem were derived more than 50 years ago, when Birula showed that emission from a maximally-superradiant Dicke state (i.e., half of the atoms are in their excited level while the other half is in the ground level) is in a Glauber coherent state at early times in the evolution [5]. Since this result, limited progress has been made, and most recent papers focus on either calculating the photon statistics for a low number of atoms by numerically solving the exact density matrix in the evolution, or restricting the problem to the low-intensity limit.

In this talk, I will discuss our recent theoretical results where we were able to calculate the emission statistics from ideal Dicke states with atom numbers as large as 10^4 [6]. These theoretical results show that while the system is initially in a coherent state, at later times in the evolution the emission can be truly quantum, with substantial squeezing in the photon-number basis (i.e., sub-Poissonian statistics). In particular, under certain conditions, the emitted field can approach an ideal photon-number Fock state. In addition, I will also discuss our recent experimental results where we looked at the statistics of emitted photons from a mesoscopic ensemble of laser-cooled rubidium atoms. Under certain experimental conditions, we observed signatures of photon number squeezing in the emitted light.

References

[1] R. H. Dicke, Coherence in Spontaneous Radiation Processes, Phys. Rev. **93**, 99 (1954).
[2] M. Gross and S. Haroche, Superradiance: An Essay on the Theory of Collective Spontaneous Emission, Phys. Rep. **93**, 301 (1982).
[3] M. O. Scully and A. A. Svdzinsky, The Super of Superradiance, Science **325**, 1510 (2009).
[4] D. C. Gold, P. Huft, C. Young, A. Safari, T. G. Walker, M. Saffman, and D. D. Yavuz, Spatial Coherence of Light in Collective Spontaneous Emission, PRX Quantum **3**, 010338 (2022).
[5] Z. Bialynicka-Birula, Coherence of the Radiation from the Superradiant State, Physical Review D **1**, 400 (1970).
[6] A. Yadav and D. D. Yavuz. Quantum Statistics of Single-Mode Radiation Emitted by Superradiant Dicke States, arXiv:2508.09962 [quant-ph] (2025).

Unleashing Analog Quantum Computing

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Recent advances are expanding the power and flexibility of analog quantum platforms for both quantum simulation and quantum information science. A new protocol enables access to key observables such as long-range pairing correlations relevant to high-temperature superconductivity in fermionic quantum gas microscopes using only minimal controls. In parallel, an “ansatz-free” Hamiltonian-learning method achieves Heisenberg-limited precision without assuming any prior structure, offering a powerful tool for benchmarking analog devices. Moreover, many globally controlled simulators are shown to be universal, and new optimal-control techniques make it possible to engineer complex effective interactions, including topological dynamics. Together, these results significantly broaden what can be probed and realized in large-scale quantum systems.

Generating Coherent States of Photonic Dimers

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Abstract: The bound states of light quanta were theoretically proposed in engineered nonlinear optical media [1] and have since been experimentally confirmed through spontaneous parametric down conversion (SPDC) in an optical cavity [2], as well as in ultra-cold atom systems for two-photon and three-photon cases [3], which are photonic dimers and trimers. Recent inspiration came from the proposed coherent states of photonic dimers [4], in analogy to coherent states of single photons. This talk will discuss the properties of photonic dimers and how to generate coherent states of photonic dimers in a nonlinear crystal in an optical cavity experimentally.

References:

[1] Jung-Tsung Shen and Shanhui Fan, Physical Review Letters, 98, 153003 (2007)

[2] C.-S. Chuu, G. Y. Yin, and S. E. Harris, “A miniature ultrabright source of temporally long, narrowband biphotons,” Appl. Phys. Lett., 101, 051108, (2012).

[3] Firstenberg et al. Nature 502, 71-75 (2013); Liang et al. Science 359, 783-786 (2018)

[4] Q. Liu, Y. Zhou, and J.-T. Shen, “Coherent states of photonic dimers,” Phys. Rev. A, 108, 053705, (2023)

Quantum simulation of the Hubbard model: pseudogap, charge order, and beyond

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December 4, 2025

Abstract

The Hubbard model is believed to capture many of the properties of strongly correlated electronic materials, including the cuprate superconductors. Despite the simplicity of the model, and more than four decades of concentrated study, many open questions remain. In particular, the nature of the "pseudogapped" metallic state, from which superconductivity emerges in the cuprates, is not well understood. Classical simulations in this regime are challenged by general difficulties associated with simulating quantum many body systems. Quantum simulations using ultracold atoms offer an alternative approach to answering these questions.

Leveraging recent advancements which yield a several-fold reduction in temperature, we perform quantum simulations of the Hubbard model which, for the first time, are deep in the pseudogapped regime. We develop new spectroscopic and thermodynamic measurement techniques and, using these techniques, establish an experimental phase diagram of the Hubbard pseudogap. Additional measurements already hint at a complicated interplay between nematicity, stripe order, and criticality, and could ultimately provide a resolution to long standing open questions regarding strongly correlated electronic materials.

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Terahertz wave amplification by a time-boundary-modulated Huygens' metasurface

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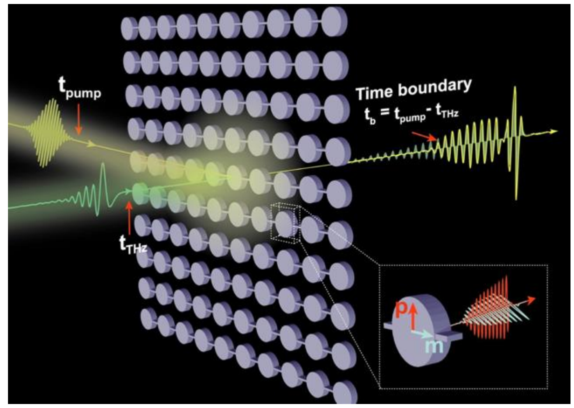

Schematic illustration of a free-space THz field (green) passing through a time-variant Huygens' metasurface and the resultant transmitted pulses without (green shade) and with (yellow line) the presence of time boundary. The time boundary is imposed by excitation from an optical pump pulse (left, yellow pulse). The close-up of individual resonator shows time-boundary-modulated local dipole moments (red, electric mode; white, magnetic mode).

Ultrafast manipulation of optical resonance can establish the time-boundary effect in time-varying media [1], leading to a new degree of freedom for coherent control of electromagnetic waves. Here, we demonstrate that a free-standing all dielectric Huygens' metasurface of degenerate electric and magnetic resonances can prompt the broadband near-unity transmission in its static state, whereas it enables wave amplification in the presence of time boundary [2][3]. The time boundary is realized by femtosecond laser excitations that transiently inject free carriers into the constituent meta-atoms for dynamic removal of a pre-established two-fold degeneracy. We observe that the transmittance in the photo-excited Huygens' metasurface can exceed unity transmittance, i.e., THz wave amplification, by a factor over 20% in intensity at frequencies tunable by varying the arrival of time boundary with respect to that of the seed terahertz pulse. By numerical simulations and analysis with time-dependent coupled mode theory, we show that the wave amplification results from the ultrafast Q-switching and shift in resonant frequencies. This work demonstrates a new approach to achieve tunable amplification in an optical microcavity by exploiting the concept of time-varying media and the unique electromagnetic properties of Huygens' metasurface. It also underscores the possibility of achieving amplification in a wider range of materials with outstanding frequency selectivity. Our observation can be considered a *single-slit diffraction* in the time domain that manifests spreading of energy in the frequency domain, which echoes the *double-slit time diffraction at optical frequencies* [4]. Parametric amplification in the presence of periodic modulation will also be discussed.

[1] E. Galiffi, R. Tirole, S. Yin, H. Li, S. Vezzoli, P. A. Huidobro, M. G. Silveirinha, R. Sapienza, A. Alù, and J. B. Pendry, Adv. Photonics 4, 014002 (2022).
[2] K. Fan, J. Zhang, X. Liu, G.F. Zhang, R. D. Averitt, W. J. Padilla, Advanced Materials, 30, 1800278 (2018).
[3] F. Deng, F. Zhu, X. Zhou, Y. Chan, J. Wu, C. Zhang, B. Jin, Jensen Li, K. Fan, J. Zhang, Advanced Optical Materials, 13(13), 2402052 (2025).
[4] R. Tirole, S. Vezzoli, E. Galiffi, I. Robertson, D. Maurice, B. Tilmann, S. A. Maier, J. B. Pendry, R. Sapienza. Nature Physics, 19 (7), 999, (2023)

Quantum-bound-guided single-molecule orientation localization microscopy

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Single-molecule (SM) imaging is ultimately limited by photon shot noise and the electromagnetic structure of emission. Quantum estimation theory formalizes this limit through the quantum Cramér-Rao bound (QCRB), an instrument-independent benchmark that bounds the best possible precision and can reveal what measurement architectures are capable of reaching that limit.

We first apply this framework to SM localization and show why the common scalar "monopole" approximation can be systematically optimistic when fluorophores are better modeled as dipole-like emitters [1]. Using a vectorial dipole emission model, we derive QCRBs for 3D localization and find that quantum limits are larger (worse) than scalar predictions; e.g., for high-NA objectives the lateral and axial bounds can increase on average by ~10% and ~3%, respectively, compared to scalar theory. This establishes a more faithful baseline for evaluating and designing practical localization microscopes.

Additionally, orientation is itself a key biophysical observable. Therefore, we derive the quantum limits for estimating the 3D orientation of rotationally fixed dipoles and propose wide-field-compatible interferometric designs that attain the quantum Fisher-information limit [2]. Crucially, we identify a necessary and sufficient condition for classical, intensity-only camera measurements to achieve the QCRB: the detected image-plane field must contain only "trivial" phase information, so that photon counting loses no information.

Finally, we show how these bounds guide new SM imaging methods and enable biology. As an example, we demonstrate radially/azimuthally polarized (raPol) microscope [3], implemented with a vortex (half) wave plate at the back focal plane and polarization splitting to sensitively report out-of-plane vs in-plane dipole emissions. With 5,000 detected photons from Nile red in supported lipid bilayers, raPol achieves 2.9 nm localization precision and 1.5° orientation precision, revealing restricted binding pockets in DPPC membranes and cholesterol-induced changes consistent with jump diffusion between nanodomains.

[1] O. Zhang and M. D. Lew, "Single-molecule orientation localization microscopy I: fundamental limits," *Journal of the Optical Society of America A*, vol. 38, no. 2, p. 277, Feb. 2021, doi: 10.1364/JOSAA.411981.
[2] O. Zhang and M. D. Lew, "Quantum limits for precisely estimating the orientation and wobble of dipole emitters," *Physical Review Research*, vol. 2, no. 3, p. 033114, July 2020, doi: 10.1103/PhysRevResearch.2.033114.
[3] O. Zhang, W. Zhou, J. Lu, T. Wu, and M. D. Lew, "Resolving the Three-Dimensional Rotational and Translational Dynamics of Single Molecules Using Radially and Azimuthally Polarized Fluorescence," *Nano Letters*, vol. 22, no. 3, pp. 1024–1031, Feb. 2022, doi: 10.1021/acs.nanolett.1c03948.

Speaker: Wenzhuo Zhang, *Texas A&M University*

Schedule: Thursday Afternoon Poster Session

Coherence-Enhanced Open Quantum Battery

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Quantum batteries provide a framework in which quantum coherence, correlations, and engineered dissipation can be converted into useful work. However, decoherence and energy relaxation generally reduce the active energy stored in the battery. In conventional dark-state–protected open quantum battery (OQB) protocols [1], the charger and battery interact dissipatively through a common vacuum reservoir and form the dark states, which suppresses energy loss but limits energy-utilization efficiency and charging speed especially when the charger and battery have comparable sizes.

We extend this framework by preparing the charger in a collective spin-coherent state $|\theta,\phi\rangle = e^{-i\phi J_z}e^{-i\theta J_y}|N_C/2, N_C/2\rangle$ and by coupling both domains to a squeezed reservoir with parameter $\xi = re^{i\varphi}$, as illustrated schematically in Fig. 1(a). This introduces two coherence sources for enhanced ergotropy and faster charging: the spin-coherent charger significantly enhances the steady-state ergotropy, while both the squeezed-reservoir coherence and the spin-coherent charger collaboratively accelerates the charging dynamics. The extractable work is quantified using the *ergotropy* [2] $W = \mathrm{Tr}(H_0\rho) - \min_U \mathrm{Tr}(H_0 U\rho U^\dagger)$, which we decompose into incoherent and coherent parts following ref. [3]:

$$W_B = W_B^P + W_B^C. \tag{1}$$

While earlier dark-state–protected protocols produce only incoherent ergotropy W_B^P, our scheme generates a coherent ergotropy component W_B^C through reservoir-assisted and charger-generated coherence.

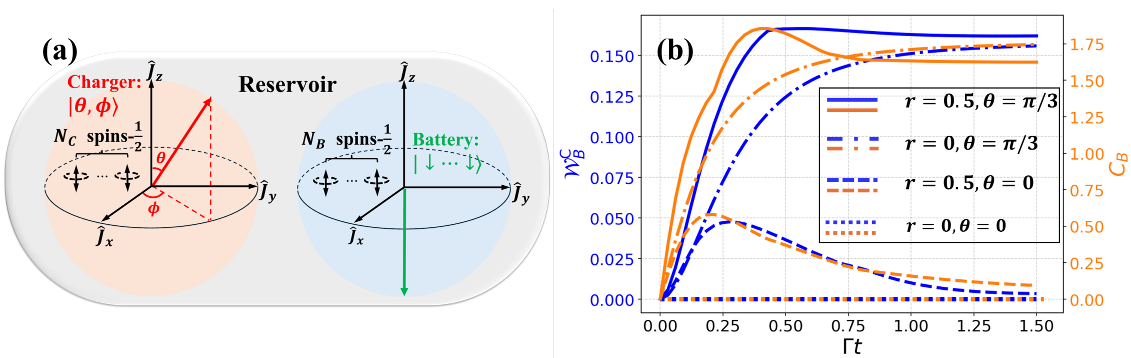

Fig. 1: (a) Schematic of the model. The quantum battery charging system consists of two spin domains as the charger and the battery, collectively coupled to a common reservoir. (b) Time evolution of the coherent ergotropy $\mathcal{W}_B^C$ (blue) and the local l_1-norm coherence $\mathcal{C}_B$ (orange) under different reservoir and initial state conditions (dotted: $r = 0,\ \theta = 0$; dashed: $r = 0.5,\ \theta = 0$; dash-dotted: $r = 0,\ \theta = \pi/3$; solid: $r = 0.5,\ \theta = \pi/3$) with $\delta = 0$.

Previous numerical results have shown that under fixed charger-battery spin number ratio, the charging power per spin $\mathcal{P}_B^W \equiv d\mathcal{W}_B/dt$ increases proportionally with N_B, so that the total power $P_B^W = N_B\mathcal{P}_B^W$ exhibits a superradiant N_B^2 scaling behavior. The total steady state ergotropy W_B also scales proportional to N_B^2, performing a super-extensive capacity. Meanwhile, Both squeezing and initial coherence dramatically enhance $\mathcal{P}_B$, driven by the rapid buildup of $\mathcal{W}_B^C$, which closely follows the local coherence C_B as shown in Fig. 1(b). In our charging system when charger and battery have comparable sizes, W_B^C is dominant. Numerical comparisons show: (i) vacuum reservoir with all-spin-up charger yields purely incoherent ergotropy $\mathcal{W}_C^P$ and low charging power; (ii) introducing squeezing alone increases charging speed but suffers long-time coherence decay; (iii) a spin-coherent charger alone transfers coherence one-way into the battery and leads to monotonically increasing $\mathcal{W}_B^C$ with a relatively high steady state ergotropy; and (iv) the combination of spin-coherent charger initialization and reservoir squeezing yields the fastest charging while keeping high steady state ergotropy at long time.

References

1. J. Q. Quach and W. J. Munro *Phys. Rev. Appl.*, vol. 14, p. 024092, Aug. 2020.
2. A. E. Allahverdyan, R. Balian, and T. M. Nieuwenhuizen *Europhysics Letters*, vol. 67, no. 4, p. 565, 2004.
3. G. Francica, F. C. Binder, G. Guarnieri, M. T. Mitchison, J. Goold, and F. Plastina *Physical Review Letters*, vol. 125, no. 18, p. 180603, 2020.

Quantum memory for hard X-ray photons with reduced mechanical complexity

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Hard X-ray–nuclear interfaces offer distinct advantages for room-temperature, solid-state quantum information processing, including high-quality resonances, potential tight photon focusing, large material densities, and low background noise. Quantum memories are key building blocks for scalable quantum computing and communication networks, yet despite major advances for optical photons, the coherent storage and on-demand retrieval of X-ray photons have remained an open challenge.

Nuclear frequency combs (NFCs)—periodic resonant absorption structures in the nuclear spectrum—enable coherent manipulation and storage of hard X-ray photons and have been experimentally demonstrated using Doppler-engineered Mössbauer absorbers [1,2]. However, on-demand retrieval remains technically constrained by the need for fast, synchronized modulations of multiple resonant absorbers. Here, we present practical NFC-based approaches that substantially relax this constraint, by either a hybrid of mechanical and magnetic NFC schemes in materials with strong hyperfine magnetic fields, such as $^{57}FeBO_3$, or a hybrid of static NFC and fast half-wavelength displacement of a stationary absorber. These strategies both enable active control of NFC echoes while significantly reducing mechanical complexity, paving the way toward feasible on-demand quantum memories for hard X-ray photons.

[1] Xiwen Zhang *et. al.*, Nuclear quantum memory and time sequencing of a single γ photon, Phys. Rev. Lett. **123**, 250504 (2019).
[2] Sven Velten *et. al.*, Nuclear quantum memory for hard x-ray photon wave packets, Sci. Adv. **10**, eadn9825 (2024).

Speaker: Yingwen Zhang, *Chapman University*
Session: Frontiers of Quantum Imaging
Schedule: Tuesday evening invited session

Light-field microscope using entangled photons

Yingwen Zhang[1,2,*], Duncan England[1], Antony Orth[1], Ebrahim Karimi[1,2] and Benjamin Sussman[1,2]
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We introduce quantum-correlation light-field microscopy (LFM), a 3D imaging technique that exploits spatially entangled photons to perform single-shot volumetric reconstruction without scanning. In our approach, one photon from each pair interacts with the sample, providing position information, while its entangled partner supplies the corresponding momentum (angular) information. These correlations enable direct reconstruction of the photon light field—and thus the volumetric information of the scene—from a single measurement.

Classical LFM performs single-shot position–momentum capture using microlens arrays, but at the cost of reduced spatial and angular resolution, which limits both image resolution and depth-of-field (DOF). Our quantum-correlation LFM overcomes this trade-off. We achieve 5 µm resolution with a 500 µm DOF, and 10 µm resolution with a DOF exceeding 1.5 mm—an order of magnitude improvement over comparable classical systems. In the extreme case of 100 µm resolution, we observe a near-infinite DOF, a regime that is practically unattainable with current classical LFM designs.

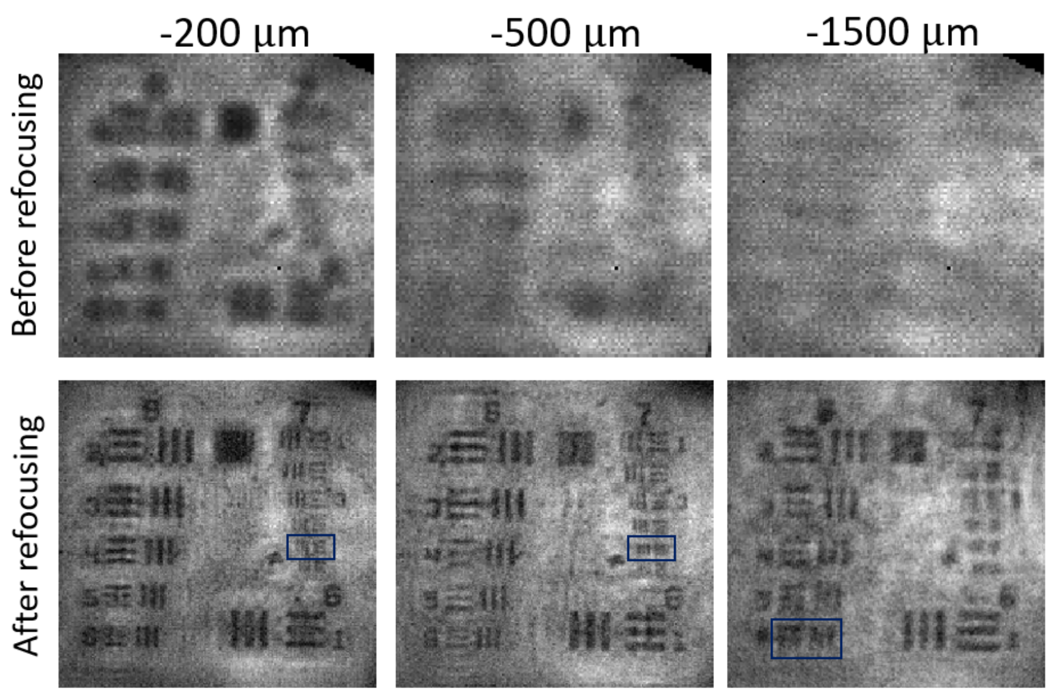


Figure: Before and after images of digitally refocusing groups 6 and 7 of a 1951 USAF resolution target placed at different distances from the objective focus with the smallest resolvable features after refocusing are boxed in blue

Speaker: Zheshen Zhang, *University of Michigan*

Quantum Sensing based on Centralized and Distributed Entanglement

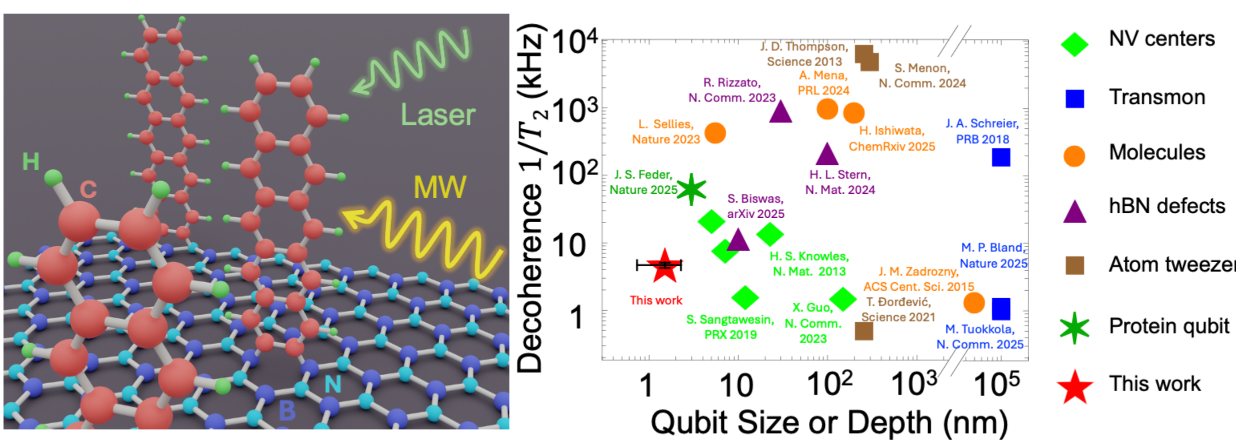
Entanglement is a quintessential quantum mechanical resource without any classical equivalent. It enables a variety of quantum computing, networking, and information processing protocols to outperform their classical counterparts. Entanglement is also an essential ingredient for precision measurements, enabling sensors to operate beyond the classical limits stemming from intrinsic quantum mechanical fluctuations. In this talk, I will introduce two different yet complementary quantum sensing regimes that harness entanglement to boost the measurement sensitivity and bandwidth. The first leverages the entanglement across different spectral lines in an optical frequency comb to reduce the integration time in dual-comb spectroscopy for gas sensing, while the second utilizes entanglement shared by multiple sensors spaced at a distance to improve the performance of networked measurement problems including distributed radiofrequency and force measurements for gradient and average amplitude estimation. We will highlight the entanglement-enabled advantages of both sensing configurations over classical, separate sensor networks. Before closing, we will discuss two primary endeavors toward future scalable quantum information technologies, including the developments of a remote-accessible quantum testbed and integrated quantum photonics platforms.

A Molecular Qubit Scaffolded on a Hexagonal Boron Nitride Surface

Tian-Xing Zheng[1], M. Iqbal Bakti Utama[2], Xingyu Gao[1], Moumita Kar[2], Xiaofei Yu[1], Sungsu Kang[1], Hanyan Cai[1], Tengyang Ruan[1], David Ovetsky[1], Uri Zvi[1], Guanming Lao[1], Yu-Xin Wang[3], Omri Raz[1], Sanskriti Chitransh[1], Grant T. Smith[1], Leah R. Weiss[1], Magdalena H. Czyz[2], Shengsong Yang[1], Alex J. Fairhall[4], Kenji Watanabe[5], Takashi Taniguchi[5], David D. Awschalom[1,6], A. Paul Alivisatos[1], Randall H. Goldsmith[4], George C. Schatz[2], Mark C. Hersam[2], and Peter C. Maurer[1,6,7]

1. The University of Chicago. 2. Northwestern University. 3. University of Maryland. 4. University of Wisconsin–Madison. 5. National Institute for Materials Science at Japan. 6. Argonne National Laboratory. 7. CZ Biohub Chicago.

Fluorescent spin qubits are central building blocks of quantum technologies. Placing these qubits at surfaces maximizes coupling to nearby spins and fields, enabling nanoscale sensing and facilitating integration with photonic and superconducting devices. However, reducing the dimensions or size of established qubit systems without sacrificing the qubit performance or degrading the coherence lifetime remains challenging. Here, we introduce a surface molecular qubit formed by pentacene molecules scaffolded on a two-dimensional (2D) material, hexagonal boron nitride (hBN). The spins exhibit stable fluorescence and optically detected magnetic resonance (ODMR) from cryogenic to ambient conditions. With fully deuterated pentacene, the Hahn-echo coherence reaches 22 μs and further extends to 214 μs under dynamical decoupling, outperforming the state-of-the-art shallow NV centers in diamond, despite being positioned directly on the surface. We map the local spin environment, resolving couplings to nearby nuclear and electron spins that can serve as auxiliary quantum resources. This platform combines surface integration, long qubit coherence, and scalable fabrication, opening routes to quantum sensing, quantum simulation, and hybrid quantum devices, and is extensible to a broader family of 2D material-supported molecular qubits.



Left: Schematic of the pentacene molecular qubit scaffolded on the surface of hBN.

Right: Decoherence rate 1/T_2 versus qubit size or depth for various qubit platforms. The longest demonstrated T_2 are plotted, regardless of measurement conditions.

Title: Transversal Architectures for Neutral Atom Logical Quantum Computation

Speaker: Hengyun Zhou, QuEra Computing (MIT starting March 2026)

Abstract: The experimental realization of early fault-tolerant quantum processors marks an exciting opportunity to rethink how we architect large-scale quantum computation. Building a scalable quantum processor requires cross-cutting advances across the entire fault-tolerance stack, spanning algorithms and compilation, quantum error correction, and hardware. In this talk, I will present recent QEC progress in designing this stack for neutral atom platforms with transversal architectures, which have demonstrated key building blocks of fault-tolerant operation and achieved substantial space–time overhead reductions compared to conventional two-dimensional approaches.

Realizing the Haldane Model in Thermal Atoms

Shiyao Zhu, Jiefei Wang, Jianhao Dai, Ruosong Mao, Xingqi Xu, Han Cai and Da-Wei Wang

School of Physics, Zhejiang University

Topological materials hold great promise for developing next-generation devices with transport properties that remain resilient in the presence of local imperfections. However, their susceptibility to thermal noise has posed a major challenge. In particular, the Haldane model, a cornerstone in topological physics, generally requires cryogenic temperatures for experimental realization, limiting both the investigation of topologically robust quantum phenomena and their practical applications. In this presentation, I will introduce a room-temperature realization of the Haldane model using atomic ensembles in momentum-space superradiance lattices, a platform intrinsically resistant to thermal noise. The topological phase transition is revealed through the superradiant emission contrast between two timed Dicke states in the lattice. Crucially, the thermal resilience of this platform allows us to access a deep modulation regime, where topological transitions to high Chern number phases emerge — going beyond the traditional Haldane model. Our results not only deepen the understanding of exotic topological phases, but also offer a robust, reconfigurable, and room-temperature-compatible platform that connects quantum simulation to real-world quantum technologies.

References:

[1] Jiefei Wang, Jianhao Dai, Ruosong Mao, Yunzhou Lu, Xiao Liu, Huizhu Hu, Shi-Yao Zhu, Xingqi Xu, Han Cai and Da-Wei Wang, “Realizing the Haldane model in thermal atoms”, arXiv:2509.08411.

Quantum Sensors in 2D Materials: Opportunities and Challenges

The recent discovery of optically addressable spin defects in two-dimensional (2D) materials, such as boron-vacancy center (VB) in hexagonal boron nitride (hBN), presents a brand-new angle to construct solid-state quantum sensors. Their atomically thin hosts allow spin qubits to be positioned within sub-nanometer distance of a target system, offering a unique platform to probe interfacial phenomena with extreme sensitivity and nanoscale spatial resolution. However, these advantages come with significant challenges: 2D spin defects typically exhibit broad spin transitions and relatively short coherence times, which can severely constrain their sensing performance. This raises a central question: under what conditions, if any, can 2D quantum sensors surpass established three-dimensional platforms such as nitrogen-vacancy (NV) centers in diamond? In this talk, I will discuss two directions in which 2D sensors may offer genuine advantages: (1) nanoscale thermometry and the study of interfacial spin–phonon coupling, and (2) the incorporation of 2D defects into diamond anvil cells to enable stress and magnetism measurements in extreme high-pressure environments.

Chong Zu
Washington University in St. Louis

Invited by Lan Yang