Cavity Control: From Condensed Matter to Ultracold Atoms

846. WE-Heraeus-Seminar

14 - 18 December 2025

at the Physikzentrum Bad Honnef, Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

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Aims and scope of the 846. WE-Heraeus-Seminar:

Confining electromagnetic fields in cavities has emerged as an important new tool to create and control complex quantum systems. The first experimental realizations were based on ultracold atoms and on semiconductor heterostructures with the generation of polaritonic quantum fluids of light. Since then, efforts on applications in quantum technologies are ongoing, where extremely well controlled atomic or ionic building blocks are assembled to generate highly entangled states of matter. Besides the promising advancements for quantum simulation and computing, the recent achievements in cavity-enabled control of molecular reactions and the manipulation of electronic properties in strongly correlated electronic materials have opened two new and rapidly evolving research directions.

This interdisciplinary workshop brings together leading experts and early-career researchers working on different aspects of cavity control, and provides an environment to share ideas, find synergies and establish new collaborations. Topics will include cavity field fluctuations, cavity polaritonics, cavity control of phase transitions in ultracold atoms and in materials, entanglement for quantum networks, as well as applications in quantum sensing, quantum computing, and quantum simulation.

Introduction

Scientific Organizers:

Dr. Hans Keßler	Physikalisches Institut Universität Bonn, Germany
Dr. Andrea Bergschneider	Physikalisches Institut Universität Bonn, Germany
Dr. Frank Schlawin	Fakultät für Mathematik, Informatik und Naturwissenschaften Hamburg Centre for Ultrafast Imaging, Germany

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Introduction

Venue:

Physikzentrum
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Registration:

Nadine Mock (WE Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (17:00 h – 21:00 h) and Monday morning

Program

Program

Sunday, 14 December 2025

17:00 - 21:00	Registration
18:30 - 20:00	*BUFFET SUPPER and informal get-together*

Program

Monday, 15 December 2025

07:30 - 09:00	*BREAKFAST*	
09:00 - 9:40	Richard Warburton	**A quantum dot in an open microcavity**
9:40 - 10:20	Tracy Northup	**t.b.a**
10:20 - 10:30	CONFERENCE PHOTO (in front of the main entrance)	
10:30 - 10:50	*COFFEE BREAK*	
10:50 - 11:30	Francesco Piazza	**Non-equilibrium as a resource: Non-thermal steady-states of cavity-quantum-materials**
11:30 - 12:10	Olivier Morin	**Single atoms in a cavity: A platform for graph states generation**
12:10 - 12:40	Francois Damanet	**Controlling Matter Phases beyond Markov**
12:40 - 14:00	*LUNCH*	
14:00 - 14:40	Ana Maria Rey	**New frontiers in quantum simulation and sensing via cavity mediated interactions**
14:40 - 15:10	Mikolaj Schmidt	**Molecular optomechanics: cavity control of molecular vibrations**
15:10 - 15:40	*COFFEE BREAK*	
15:40 - 16:20	Parvinder Solanki	**Universal relaxation speedup in open quantum systems through transient conditional and unconditional resetting**

Program

Monday, 15 December 2025

16:20 - 17:30	**Poster flash**
17:30 - 18:30	**Poster Session 1**
18:30 - 20:00	*HERAEUS-DINNER*
20:00 - 21:00	**Poster Session 1**

Program

Tuesday, 16 December 2025

07:30 - 09:00	*BREAKFAST*	
09:00 - 9:40	Sylvain Ravets	**Exploring Multiband Topology in Exciton-Polariton Lattices**
9:40 - 10:20	Cristiano Ciuti	**Recent theoretical advances on cavity-controlled quantum materials and circuits**
10:20 - 10:50	*COFFEE BREAK*	
10:50 - 11:30	Cristina Benea-Chelmus	**On-chip measurements of cavity-confined fields**
11:30 - 12:10	Frieder Lindel	**Cavity control in multimode nanophotonic resonators**
12:10 - 12:40	Michael Spencer	**Electro-Optic Cavities for THz Cavity Electrodynamics**
12:40 - 14:00	*LUNCH*	
14:00 - 18:30	**Christmas Market**	
18:30 - 20:00	*DINNER*	
20:00 - 20:15	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
20:15 - 21:00	Dan Stamper-Kurn	**Cavity control and measurement of mesoscopic atomic systems**

Program

Wednesday, 17 December 2025

07:30 - 09:00	*BREAKFAST*	
09:00 - 09:40	Jean Philippe Brantut	**Fermi gases with cavity-mediated interactions**
09:40 - 10:20	Corinna Kollath	**Dynamics of interacting atoms in an optical cavity**
10:20 - 10:50	*COFFEE BREAK*	
10:50 - 11:30	Jonathan Simon	**Quantum Science in Cavity Arrays**
11:30 - 12:00	Ameneh Sheikhan	**Fluctuation-Induced Bistability of Fermionic Atoms Coupled to a Dissipative Cavity**
12:00 - 12:30	Maximilian Pruefer	**A continuous-wave cavity microscope**
12:30 - 14:00	*LUNCH*	
14:00 - 14:30	Hamid Pashaei Adl	**Exploring Strong Light–Matter Coupling and Polariton Condensation in Quasi-2D Perovskites at Room Temperature**
14:30 - 15:00	Tomasz Wasak	**Engineering interactions by collective coupling of atom pairs to cavity photons for entanglement generation**
15:00 - 15:30	*COFFEE BREAK*	
15:30 - 16:00	Gian-Marco Schnüriger	**Quantum correlations of exciton polaritons**
16:00 - 16:30	Olivier Bleu	**Resonantly enhanced polariton-mediated superconductivity in a monolayer semiconductor**

Program

Wednesday, 17 December 2025

16:30 - 17:30	**Discussion Time**
17:30 – 18:30	**Poster Session 2**
18:30 - 20:00	*DINNER*
20:00 - 21:00	**Poster Session 2**

Program

Thursday, 18 December 2025

07:30 - 09:00	*BREAKFAST*	
09:00 - 09:40	Angela Montanaro	**Cavity electrodynamics of quantum materials in terahertz Fabry-Pérot resonators**
09:40 - 10:20	Michael Sentef	**Towards cavity control of superconductivity**
10:20 – 10:50	*COFFEE BREAK*	
10:50 - 11:30	Tobia Nova	**Cavity-Driven Attractive Interactions in Two-Dimensional Quantum Materials**
11:30 - 12:00	Olesia Dmytruk	**Probing fermion parity switching points in the Kitaev chain with cavity embedding**
12:00 - 12:30	Peter Kirton	**PT Symmetry Breaking in an LMG Dimer**
12:30 - 12:40	**Poster prize and closing remarks**	
12:40 - 14:00	*LUNCH*	

End of the seminar and departure

Posters

Posters

Pritwish Agarwal	**Coupling Single Strontium Atoms to Photonic Crystal Defect Cavities**
Seyma Esra Atalay	**Cavity polaritons in a hybrid van-der-Waals superconductor-seminconductor structure**
Pierre Barral	**A scalable photonic platform for interconnecting ion-based quantum computers**
Paul Bodewei	**Influence of Cavity-Induced Polariton Formation on Superconductivity**
Kenneth Burch	**New Quasiparticles Revealed by Quantum Interference and Light Scattering**
Nils Johan Engelsen	**Room-temperature quantum optomechanics using an ultralow noise cavity**
Paul Fadler	**Polaritonic near-field effects on the metal-to-insulator transition of the Hubbard model**
Jiecheng Feng	**Color Centers as Quantum Sources of Hyperbolic Phonon Polaritons in Hexagonal Boron Nitride**
Catalin Mihai Halati	**Tuning the dynamics of complex quantum correlations with optical cavities**
Olav Irgens Henanger	**Path-integral approach to spin liquids in cavities**
Tsung Sheng Huang	**Optical manipulation and detection of moirè magnetism**
Md Mursalin Islam	**Cavity-induced Eliashberg effect: superconductivity vs charge-density-wave**
Nils Jacobsen	**Probing topological Floquet states in graphene with ultrafast THz STM**

Posters

Simon Balthasar Jäger	**Effective Lindblad master equations for atoms coupled to dissipative bosonic modes**
Roy Jr Jara	**Kibble-Zurek mechanism in open systems: From superradiance to discrete time crystals**
Marcel Kern	**Laser-machined cavities for cavity-enabled quantum simulations**
Klemen Kovac	**Interplay of Static and Photon-Mediated Interactions in Rydberg Lattices Inside an Optical Cavity**
Jan Kumlin	**Repulsive bound states and strong photon interactions from dipolar moiré excitons**
Nicolino Lo Gullo	**Narrow-band enhanced excitonic order**
Julian Mayr	**Phase diagram and dynamical phases of self organization of a Bose-Einstein condensate in a transversely pumped red-detuned cavity**
Fabio Pablo Miguel Mendez Cordoba	**Control and Detection of Topological Features in a Majorana Chain Coupled to a Cavity**
Raphael Menu	**Towards the observation of dark-state semi-localization in dissipative systems**
Leon Mixa	**Engineering quantum droplets with cavity-mediated interactions**
Ipsika Mohanty	**THz probe for topological magnon edge mode detection**
Siddharth Mukherjee	**Building a Confocal Cavity for a Degenerate cQED Apparatus**
David Nagy	**Demonstration of strong coupling of a subradiant atom array to a cavity vacuum**
David C. Nak	**(Quasi-)Continuous Wave Superradiant Lasers**

Posters

Omidreza Nourmofidi	**Cavity-enhanced superconductivity: Linking critical temperature and electron localization**
Alexei Ourjoumtsev	**Cavity QED with Rydberg superatoms**
Axel Pelster	**From Lasers to Photon Bose--Einstein Condensates: A Unified Description via an Open-Dissipative Bose--Einstein Distribution**
Claudio Pessoa	**Light-Matter Collective Phenomena and Quantum Sensing with Ultracold Atoms in Optical Cavitie**
Loïc Philoxene	**Collective modes of lattice fermions with short and long range interactions**
Michele Pini	**Non-thermal pairing glue of electrons in the steady state**
Vadim Plastovets	**Cavity-control of the Ginzburg-Landau stiffness in superconductors**
Mio Poortvliet	**Pulsed to continuous wave microcavity-quantum dot dynamics**
Jonah Post	**Mode-shaping effects in Fabry–Pérot Optical Microcavities**
Clement Raphin	**Background-free atom array imaging in an optical microcavity**
Julian Rapp	**Towards Cavity Control of the spin-Peierls transition in $CuGeO_3$**
Anna Ritz Zwilling	**Topological invariants for the SSH model coupled to a single mode cavity**
Saptarshi Saha	**Correlations in cascaded quantum optical systems : A cumulant based approach**

Posters

Andreas Schellenberger	**To infinity and back – 1/N graph expansion of light-matter systems**
Lena Schumacher	**Towards Cavity Enhanced Rydberg Superatoms as Deterministic Quantum Network Nodes**
Reka Schwengelbeck	**Non-classical features in vibrational states under electronic strong coupling**
Christopher Gerard Sevilla	**Comparing dynamics of bosons in an optical lattice inside a cavity between Wannier and position bases**
Palina Shaban	**Non-Hermitian Floquet Engineering with Cavity-QED Tweezer Arrays**
Anju Kumar Singh	**Purcell-enhanced quantum yield of spin defects using open resonators**
Vineesha Srivastava	**Entanglement-enhanced quantum sensing via optimal global control with neutral atoms in cavity**
Paul Steinmann	**Quantum dot - photon interface based on an open-tunable fiber cavity**
Marti Struve	**Room-temperature polariton condensate in a quasi- 2D dimensional hybrid perovskite**
Benedikt Tissot	**High-Rate Remote Entanglement Generation using Hybrid Single-Ion Atomic-Ensemble Nodes**
Huimin Wang	**Ultrafast manipulation of topological transport properties in Td-MoTe2 via coherent phonon excitation**
Raghuveer Singh Yadav	**Towards minimally destructive detection of cold molecules using optical cavity**
Jeremy Young	**Engineering One Axis Twisting via a Dissipative Berry Phase Using Strong Symmetries**

Abstracts of Talks

(in alphabetical order)

On-chip measurements of cavity-confined fields

Aleksei Gaier[1], Jiawen Liu[1], Xuhui Cao[1], Yazan Lampert[1], and Cristina Benea-Chelmus[2]

[1]Hybrid Photonics Laboratory, EPFL, Switzerland
[2] Quantum Science Center, EPFL, Switzerland

Cavity confined electromagnetic fields have long been a useful tool to establish correlations between otherwise uncorrelated two-level systems through their coupling to the vacuum cavity field. Since in-situ observation of the electromagnetic field and its correlation has long been very challenging, the effect has been rather quantified by read-out of the state of the matter part. The terahertz range is particularly interesting for studying light-matter coupling since it hosts a variety of matter excitations such as Landau level transitions, interband transitions in various single-layer and bulk semiconductors, or roto-vibrational modes of extended molecules. In this context, long-range correlations are predicted theoretically to play an important role in electron transport, optical decay rates, and even in the nature of the ground state of a system.
Only recently, integrated photonic circuits have enabled for the first time sampling of electromagnetic waves on at-will controlled sub-cycle spatio-temporal scales in the terahertz frequency range by means routing of optical probes along well-defined waveguides (with well-defined linear and non-linear properties) into highly confining terahertz elements [1-3].
In this presentation, I will highlight recent advances in the field of terahertz metrology using integrated photonic circuits realized on thin film lithium niobate.

References

[1] Y. Lampert, A. Shams-Ansari, A. Gaier, A. Tomasino, S. Rajabali, L. Magalhaes, M. Loncar, I.-C. Benea-Chelmus, Photonics-integrated terahertz transmission lines, *Nature Communications* 16, 1 (2025)

[2] A. Gaier, K. Mamian, S. Rajabali, Y. Lampert, J. Liu, L. Magalhaes, A. Shams-Ansari, M. Loncar, I.-C. Benea-Chelmus, Wireless millimeterwave electro-optics on thin film lithium niobate, *arxiv:2505.04585* (2025)

[3] J. Liu, T. Zhang, G. Dhaoui, Y. Lampert, A. Gaier, and I.-C. Benea-Chelmus, Monolithic millimeter wave generation and detection from resonant lithium niobate circuits," *CLEO/Europe 2025*, paper cd_1_2 (2025)

Resonantly enhanced polariton-mediated superconductivity in a monolayer semiconductor

K. Choo[1], O. Bleu[2], J. Levinsen[1], M. M. Parish[1]

[1] *School of Physics and Astronomy, Monash University, Victoria 3800, Australia*
[2] *Institute für Theoretische Physik, Universität Heidelberg, 69120 Heidelberg, Germany*

In this presentation, I plan to discuss a recent work in which we propose a scheme for controlling the superconducting transition in a doped monolayer semiconductor embedded in an optical microcavity.
Specifically, we consider the scenario of polariton-induced superconductivity. Microcavity exciton-polaritons are neutral quasiparticles, hybrid between matter and light, that arise from the strong coupling between semiconductor excitons and cavity photons. Their ability to form coherent condensates is now firmly established experimentally.
It was proposed in 2010 that a polariton condensate could mediate attractive electron-electron interactions and give rise to superconductivity [2]. While the emergence of two-dimensional semiconductors hosting tightly bound excitons [3] has led to a resurgence of theoretical works exploring scenarios to realize exciton or polariton-mediated superconductivity [4-8], there is no experimental evidence to date of this phenomenon.
In our work, we present a way to tune the strength of polariton-electron scattering by controlling the exciton-photon detuning and exploiting Feshbach resonances. We demonstrate that this has a direct impact on the electron-electron effective attraction and can significantly enhance the superconducting transition temperature --- offering a possible pathway toward the experimental realization of polariton-induced superconductivity.

References

[1] K. Choo *et al*., arXiv:2508.09619 (2025)
[2] F. Laussy *et al*., Phys. Rev. Lett. 104, 106402 (2010)
[3] G. Wang *et al*., Rev. Mod. Phys. 90, 021001 (2018)
[4] A Julku *et al*., Phys. Rev. B 106, 134510 (2022)
[5] A. S. Plyashechnik *et al*., Phys. Rev. B 108, 024513 (2023)
[6] J. von Milczewski *et al*., Phys. Rev. Lett. 133, 226903 (2024)
[7] C. Zerba *et al.,* Phys. Rev. Lett. 133, 056902 (2024)
[8] G. Bighin *et al*., Phys. Rev. Res. 7, L022070 (2025)

Fermi gases with cavity-mediated interactions

<u>J.P. Brantut</u>

EPFL, Lausanne, Switzerland

In this talk, I will describe experiments where an ultracold Fermi gas is strongly coupled to light in optical resonators. In such a system, virtual photon exchanges between atoms yield a long-range, all-to-all interaction leading to a number of emergent phenomena. I will describe how it induces charge-density wave ordering, and the observation of this transition in real time and with high spatial resolution. I will also discuss extensions of this physics to photon-pair interactions in a superfluid, and show first evidences for pair-density wave ordering in this case.

Controlling Matter Phases beyond Markov

B. Debecker, L. Pausch, J. Louvet, T. Bastin, J. Martin and F. Damanet

Institut de Physique Nucléaire, Atomique et de Spectroscopie, CESAM,

Université de Liège, 4000 Liège, Belgium

Controlling phase transitions in quantum systems via coupling to reservoirs has been mostly studied for idealized memory-less environments under the so-called Markov approximation. Yet, most quantum materials and experiments in the solid state, atomic, molecular and optical physics are coupled to reservoirs with finite memory times. Here, by using the spectral theory of non-Markovian dissipative phase transitions [1], we show that memory effects can be leveraged to reshape matter phase boundaries, but also reveal the existence of dissipative phase transitions genuinely triggered by non-Markovian effects [2]. In a Lipkin-Meshkov-Glick model [3], we demonstrate that non-Markovian dissipation can be leveraged to engineer tricriticality via the fusion of 2^{nd} order and 1^{st} order critical points. Also, we identify phases that arise from different ways of breaking the single weak symmetry of our model, which led us to introduce the concept of directional spontaneous symmetry breaking} (DSSB) as a general framework to understand this phenomenon. We show that signatures of DSSB can be seen in the emergence of spin squeezing along different directions, and that the latter is controllable via non-Markovian effects, opening up possibilities for applications in quantum metrology. Finally, we propose an experimental implementation of our non-Markovian model in cavity QED. Our work features non-Markovianity as a resource for controlling phase transitions in general systems, and highlights shortcomings of the Markovian limit in this context.

[1] B. Debecker, J. Martin and F. Damanet, Phys. Rev. A **110**, 042201 (2024).

[2] B. Debecker, J. Martin and F. Damanet, Phys. Rev. Lett. **133**, 140403 (2024).

[3] B. Debecker, L. Pausch, J. Louvet, T. Bastin, J. Martin and F. Damanet, Phys. Rev. A **112** 012210 (2025). *Editor's suggestion.*

Probing fermion parity switching points in the Kitaev chain with cavity embedding

Olesia Dmytruk[1]

[1]CPHT, CNRS, École polytechnique, Institut Polytechnique de Paris, 91120 Palaiseau, France

Embedding quantum materials into photonic cavities provides a platform for the investigation of new phenomena induced by light-matter coupling. Topological superconductors in one dimension, characterized by a superconducting gap in the bulk and localized Majorana bound states at the edges, might also benefit from the coupling to light. Models such as the Kitaev chain and other one-dimensional models of topological superconductors have been coupled to cavity photons to reveal Majorana polaritons, control of topological phases with quantum light and the implementation of Majorana parity-based qubits [1,2]. Moreover, experiments have realized two and three-sites Kitaev chain Hamiltonian in the platforms based on quantum dots connected to superconductors making it a promising setup for studying Majorana bound states.

In [3], we study a finite-length Kitaev chain coupled to a single mode photonic cavity. Topological phase of the finite-length Kitaev chain is characterized by the presence of the fermion parity switching points that correspond to the degeneracy between even and odd parity ground states. Using exact diagonalization, we compute the many-body energy spectrum of the electron-photon Hamiltonian and we find that the ground state in the topological phase of the Kitaev chain is only weakly affected by the cavity coupling. This is in contrast with higher excited states showing strong dependence on the cavity coupling. We find that the photon number and the photonic field quadratures peak at values of the chemical potential corresponding to parity switching points revealing a property of the finite-length Kitaev chain in the topological phase. This later finding suggests that quantum optics experiments could be used to detect topological features of the Kitaev chain embedded into a photonic cavity.

References

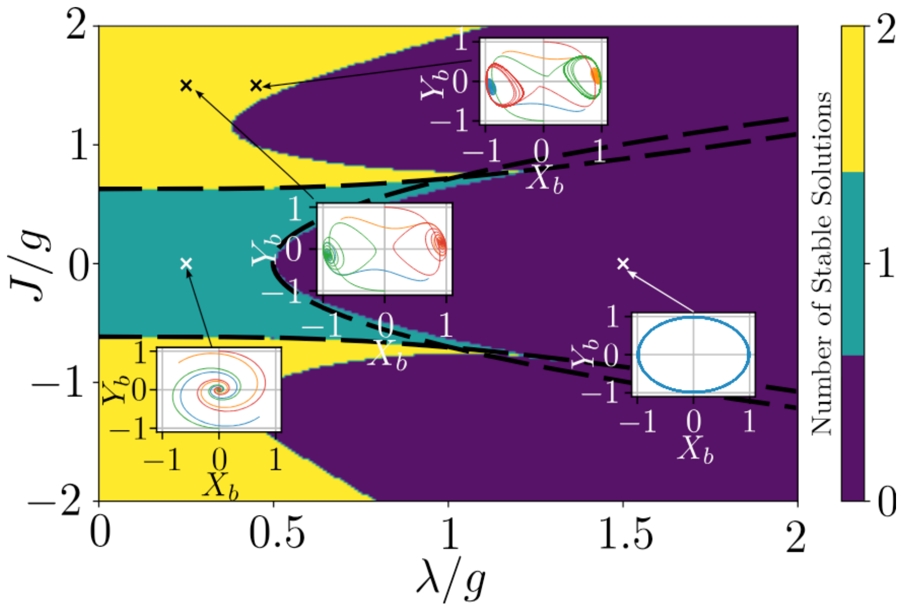
[1] O. Dmytruk and M. Schirò, Physical Review B **110** (7), 075416 (2024).
[2] Á. Gómez-León, M. Schirò, O. Dmytruk, Physical Review B **111** (15), 155410 (2025).
[3] V. Fernandez Becerra and O. Dmytruk, arXiv:2506.06237.

PT Symmetry Breaking in an LMG Dimer

S. Kothe, C. Oliver and P. Kirton

University of Strathclyde, Glasgow, UK

The open Lipkin-Meshkov-Glick (LMG) model [1] provides a prototype of a dissipative phase transition which can be realized in cavity QED experiments. By combining the physics of this model with those of a quantum analogue of a parity-time reversal symmetry breaking transition [2] we analyze the steady states phase diagram of a pair of coupled LMG models. The interplay of these two distinct physical effects leads to a complex phase diagram with multiple different types of steady state including fixed points, limit cycles and chaotic regimes [3]. We show that the effects predicted from mean-field theory survive in the full quantum model.



References

[1] S. Morrison and A. S. Parkins, Phys. Rev. Lett. **100**, 040403 (2008)
[2] J, Huber, P. Kirton, S. Rotter, P. Rabl, SciPost Phys. **9**, 052 (2020)
[3] S. Kothe, P. Kirton, arXiv:2504.18426 (2025)

Dynamics of interacting atoms in an optical cavity

C. Kollath

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Quantum gases in optical cavities have shown many exciting phenomena as the self-organization into superradiant phases. Additionally many complex phases have been predicted to be realizable in these systems reaching from topologically interesting phases to glass like phases. The theoretical treatment of these systems is very difficult due to the presence of the long range coupling of the cavity to the atoms and fluctuations need to be critically taken into account. We investigate bosonic and fermionic atoms on a lattice and coupled to an optical cavity using many-body adiabatic elimination technique and exact matrix product state methods to capture the global coupling to the cavity mode and the open nature of the cavity. We simulate the spreading of correlations and discover a new type of bistabilities which are caused by the excited states in the system.

References

[1] L. Tolle, A. Sheikhan, T. Giamarchi, C. Kollath, and C.M Halati, arXiv:2509.07469 (2025)

[2] L. Tolle, A. Sheikhan, T. Giamarchi, C. Kollath, and C.M Halati, Phys. Rev. Lett. 134, 133602 (2025)

[3] C.M Halati, A. Sheikhan, G. Morigi, C. Kollath, and S. Jäger, accepted in Phys. Rev. Lett., arXiv:2503.13306

Cavity control in multimode nanophotonic resonators

Frieder Lindel[1,2]

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[2]Quantum Center, ETH Zurich, 8093 Zürich, Switzerland

Controlling correlated electronic phases by strongly coupling them to tailored vacuum field fluctuations of cavities is a novel approach to the optical control of emergent phenomena. Most theoretical approaches are based on simplified quantum optics models that are applicable to low-loss, single-mode cavities. However, nanophotonic platforms such as plasmonic resonators and metasurfaces offer richer design possibilities through their geometry and material properties.

In this talk, we will discuss new perspectives for cavity quantum materials that fully embrace the multimode and dissipative nature of nanophotonic resonators. Topics will include the possibility of Casimir-mediated control of electronic nematic order [1], especially quantum Hall stripes [2], limitations of simplified quantum optics models [3], and a general framework for constructing coupled few-mode descriptions of strong light-matter coupling in nanophotonic environments [4,5].

References:

[1] O. Carlsson, S. Chattopadhyay, J. B. Curtis, F. Lindel, L. Graziotto, J. Faist, E. Demler, *Casimir Stabilization of Fluctuating Electronic Nematic Order,* preprint at *arXiv:2510.05088.*

[2] L. Graziotto et al., *Cavity QED Control of Quantum Hall Stripes*, preprint at *arXiv:2502.15490*.

[3] C. J. S. Martínez, F. Lindel, F. J. Garcia-Vidal, J. Feist, J. Chem. Phys. 161, 194303 (2024).

[4] F. Lindel, C. J. S. Martínez, J. Feist, F. J. Garcia-Vidal, *Close encounters between periodic arrays of quantum emitters and periodic light,* preprint at *arXiv:2508.00797.*

[5] M. Lednev, D. F. de la Pradilla, F. Lindel, E. Moreno, F. J. Garcia-Vidal, J. Feist, *Spatially resolved photon statistics in general nanophotonic systems,* PRX Quantum 6, 020361 (2025).

Cavity electrodynamics of quantum materials in terahertz Fabry-Pérot resonators

A. Montanaro[1], N. Khatiwada[1], G. Jarc[1], S.Y. Mathengattil[2,3], E.M. Rigoni[1], F. Fassioli[1], M. Eckstein[4] and D. Fausti[1,2,3]

1. Department of Physics, University of Erlangen-Nürnberg, Erlangen, Germany
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3. Elettra Sincrotrone Trieste, Trieste, Italy
4. Institute of Theoretical Physics, University of Hamburg, Hamburg, Germany

Cavity electrodynamics is emerging as a powerful route to control macroscopic properties of quantum materials, in both weak and strong coupling regimes. A number of theoretical works have shown that embedding solids in tailored electromagnetic environments can induce long-range interactions and modify dissipation, effectively adding a new control parameter to their phase diagrams [1].

In the first part of the talk, I will discuss our pioneering demonstration that the metal–insulator transition in the charge-density-wave compound 1T-TaS_2 can be controlled inside a terahertz Fabry–Pérot resonator [2-5]. Using terahertz time-domain spectroscopy, we showed that the response of 1T-TaS_2 can be reversibly tuned between insulating and metallic by adjusting the cavity length and mirror alignment. The associated shift of the transition temperature demonstrates that a correlated phase transition can be manipulated reversibly via cavity electrodynamics.

I will then present our ongoing work on cavity control of the superconducting transition in cuprate superconductors. Preliminary data suggest that the cavity provides a feedback mechanism that can affect and eventually support superconducting pairing, hinting at a route to stabilize or enhance superconducting fluctuations by engineering the electromagnetic environment.

[1] *Appl. Phys. Rev.* **9**, 011312 (2022)

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[3] *Rev. Sci. Instrum.* **93**, 033102 (2022)

[4] *J. Chem. Phys.* **161**, 154711 (2024)

[5] *Phys. Rev. B* **111**, 165425 (2025)

Single atoms in a cavity: A platform for graph states generation

P. Thomas, L. Ruscio, O. Morin and G. Rempe

Max-Planck-Institut für Quantenoptik, Garching, Germany

Graph states constitute a particular class of multipartite entangled states. Since the seminal proposal by Briegel and Raussendorf [1], they have been used in a plethora of protocol proposals for quantum information. The most prominent examples are measurement-based quantum computing and the one-way quantum repeater. Over the last two decades, significant experimental efforts have focused on generating graph states, particularly with photons. Most realizations were based on spontaneous parametric down-conversion. However, this approach is inherently probabilistic and therefore not scalable.

An obvious alternative is the use of deterministic photon sources. In this endeavor, single atoms coupled to an optical cavity offer a promising route. Indeed, we have shown the efficient generation of large GHZ and linear cluster states [2]. More recently we have shown the implementation of cavity-assisted fusion, a feature that enables the generation of more complex topologies such as tree and ring states [3]. These milestones bring the field closer to leveraging the full potential of graph states for practical quantum information processing.

References

[1] R. Raussendorf and H. J. Briegel, Phys. Rev. Lett. **86**, 5188 (2001)
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Cavity-Driven Attractive Interactions in Two-Dimensional Quantum Materials

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Controlling many-body interactions in quantum materials via cavity-mediated vacuum fluctuations is a frontier in condensed matter physics, offering opportunities to engineer novel hybrid phases. Here, we show that terahertz cavity photons can induce attractive electron-hole interactions in gate-tunable van der Waals heterostructures, transforming a broad interband continuum into a discrete exciton-like state. To realize this, we developed a broadband, sub-wavelength terahertz time-domain microscope that integrates exfoliated, dual-gated bilayer graphene (BLG) into a metallic bow-tie cavity. Our platform enables the first direct measurement of BLG's field-tunable bandgap at terahertz frequencies, while achieving ultrastrong light-matter coupling with a vacuum Rabi splitting exceeding $\Omega_{Rabi}/\omega \approx 40\%$. Crucially, we identify a novel cavity-induced resonance that resembles a Coulomb-bound exciton and remains stable across a broad temperature range. These results pave the way for cavity-engineered correlated phases in gate-tunable two-dimensional quantum materials.

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Exploring Strong Light–Matter Coupling and Polariton Condensation in Quasi-2D Perovskites at Room Temperature

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Layered halide perovskites are organic and inorganic 2D or quasi-2D layers [1], which self-assemble in solution realizations of quantum well stacks with giant exciton oscillator strengths, tunable emission spectra and very large exciton binding energies. In this contribution, we discuss widely tunable room-temperature cavity exciton polaritons at the cross-over from the strong coupling to the very strong coupling regime [2,3], utilizing mechanically exfoliated quasi-2D Ruddlesden-Popper iodide perovskite $(BA)_2(MA)_2Pb_3I_{10}$ integrated into an open microcavity [4]. The observed Rabi splitting exhibits a systematic reduction with increasing cavity length; however, the scaling behavior deviates from the square root dependence typically observed in the strong coupling regime. Moreover, under strong non-resonant optical excitation, polariton condensation can be observed, and interferometric measurements reveal the emergence of spatial coherence throughout the condensate. Our findings provide a foundation for future on-chip applications involving tunable polaritonic and nonlinear optical devices based on strongly coupled perovskite systems.

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Non-equilibrium as a resource: Non-thermal steady-states of cavity-quantum-materials

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Coupling a system to two different baths can lead to novel phenomena escaping the constraints of thermal equilibrium. In quantum materials inside optical cavities, this feature can be exploited as electrons and cavity-photons are easily pulled away from their mutual equilibrium, even in the steady state. This offers new routes for a non-invasive control of material properties and functionalities. Motivated by recent experimental puzzles arising with transition-metal-dichalcogenides inside Fabry-Perot cavities, we show how the absence of thermal equilibrium between electrons and photons leads to qualitative modifications of the material's properties in two different ways: 1) the electron distribution shows enhanced fluctuations near the Fermi surface due to the breaking of detailed balance; 2) the scattering between electrons in the steady state acquires a genuinely non-thermal component which can for instance enhance the tendency to pair and become superconducting.

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A continuous-wave cavity microscope

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Atoms coupled to optical cavities provide a powerful platform for quantum simulation. Until now, most experiments have relied on single-mode cavities. We introduce a self-imaging 4f cavity setup [1] that supports multimode operation, enabling local control of the cavity field. This opens new possibilities for manipulating atomic samples and performing in-cavity microscopy for high-resolution readout. Using our proof-of-concept cavity, we have demonstrated cavity-enhanced microscopy, and I will outline future directions for exploring atom–cavity interactions in the multimode regime.

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Exploring Multiband Topology in Exciton-Polariton Lattices

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Exciton-polaritons, hybrid quasiparticles arising from the strong coupling between quantum well excitons and cavity photons, offer a versatile platform to study topological physics [1,2]. Their unique light-matter nature allows for engineering topological bands, topological lasers, topological solitons... [3-7] In this presentation, I will report on recent progress in the experimental investigation of multiband topology in exciton-polariton lattices.

Building upon earlier studies of two-band systems, we have developed and implemented a generalized tomography technique that reconstructs the full Bloch eigenstate structure across the Brillouin zone for lattices with an arbitrary number of bands. This method relies on *k*-space interferometric measurements combined with controlled phase modulations between sub-orbitals, enabling us to extract the full Stokes vector for each Bloch mode. Applied to polariton honeycomb lattices incorporating multiple orbitals and/or polarization-dependent effects, our approach allows the measurement of the Berry curvature and quantum geometric tensor of each band. We demonstrate this technique on a honeycomb lattices featuring up to six bands, and reveal clear signatures of topology beyond the two-band paradigm.

Our work highlights the potential of exciton-polariton lattices as a testbed for exploring multiband topological effects in a highly tunable photonic platform, and paves the way for accessing more exotic phenomena, such as non-Abelian topology in driven photonic systems [8].

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New frontiers in quantum simulation and sensing via cavity mediated interactions

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Atoms and photons are the fundamental building blocks of our universe. Their interactions rule the behavior of our physical world but at the same time can be extremely complex, especially in the context of many-body quantum systems. Understanding and harnessing them is one of the major challenges of modern quantum science. In recent years, ultracold atomic systems have emerged as a pristine platform for the exploration of atom-light interactions. In this talk, I will discuss the potential of atomic systems loaded in optical cavities as a resource to enhance the energy scales needed to observe complex many-body behaviors by harnessing infinity range interactions mediated by photons that can couple a large set of internal levels. I will show how cavity systems can help us not only to shed light on behaviors of iconic Hamiltonians describing real materials but also to engineer broader classes of Hamiltonians with multi-body interactions too complex to emerge naturally. Furthermore, I will explain how they can facilitate the generation of quantum entanglement and overcome physical constraints currently limiting the performance of state-of-the-art atomic clocks and interferometers.

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Molecular optomechanics: cavity control of molecular vibrations

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Molecular optomechanics provides a unifying framework that recasts Raman scattering on molecular vibrations as an optomechanical interaction—one that controls optical rather than acoustic phonons [1,2]. This mapping enables direct analogies to canonical cavity-optomechanical effects such as dynamical backaction, optical spring shifts, and parametric instabilities [2–4], while operating in an extreme regime of ultrafast optical dissipation (tens of THz) and single-phonon coupling arising from deeply subwavelength field confinement (~100 GHz) [5,6]. The framework also captures phenomena unique to molecular systems, including collective vibrational responses [7] and strong intrinsic anharmonicities [8].

Despite its potential, demonstrations of quantum advantage in Raman microscopy remain scarce and mostly limited to shot noise suppression using nonclassical light [9]. In our work, we extend this perspective by employing concepts from quantum information theory to quantify the ultimate sensitivity of different Raman measurement protocols [10]. This framework allows us to identify where genuine quantum resources, such as squeezing of molecular vibrations or correlated Stokes–anti-Stokes photon pairs, can enhance estimation precision beyond classical limits.

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Quantum correlations of exciton polaritons

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Cavity exciton-polaritons are quasiparticles that form when quantum well excitons hybridize with a cavity mode (Fig.1a) [1]. In our experiment we carry out photon correlation measurements under continuous wave resonant laser excitation to demonstrate quantum correlations between cavity–polaritons (Fig.1b). Our experiments reveal an unexpectedly strong dependence of polariton interactions on cavity-exciton detuning (Fig.1c). When the polaritons are predominantly exciton-like, we observe a transition from photon antibunching to bunching as the laser is tuned across the polariton resonance, in agreement with a simple Kerr-nonlinearity model [2]. When the lower-branch polariton energy is tuned to resonance with the biexciton mode, the degree of polariton antibunching becomes independent of the laser detuning: we explain our finding by invoking a dissipative blockade mechanism arising from large biexciton broadening. Our experiments demonstrate that the strong polariton blockade regime could be achieved by reducing the polariton decay rate by a factor of 10.

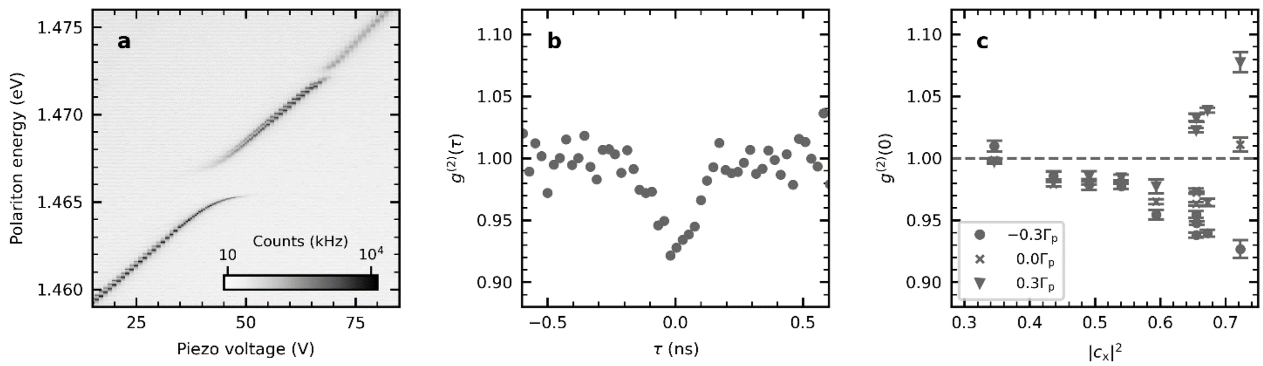

Fig 1 a Cavity transmission spectrum showing the normal mode splitting characteristic of the hybridized light-matter states. **b** Second order correlation function of a polariton with an excitonic content of 72% measured with negative laser detuning reveals the non-classical nature. **c** g2(0) as function of the exciton content for three different laser detunings, shows an unexpectedly strong dependence on the exciton content.

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Towards cavity control of superconductivity

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In recent years, light-driven quantum materials science has undergone a fundamental transformation. What was once a theoretical vision—the ability to control and manipulate emergent properties of materials on ultrafast timescales—has now become a reality [1]. This progress has been enabled by rapid advancements in shaping laser pulses, probing nonequilibrium dynamics with femtosecond resolution, and developing sophisticated theoretical approaches to describe light-driven many-body systems [2]. As a result, we are now entering an era in which quantum materials can be actively “designed” and controlled using tailored light fields.

A cornerstone of this approach is Floquet engineering, which exploits periodic driving to coherently modify electronic states and induce novel phases of matter. I will briefly review key developments in realizing Floquet states in quantum materials and discuss their implications for controlling competing orders. However, despite its promise, Floquet engineering also faces intrinsic limitations, particularly due to heating effects and decoherence, which can constrain its applicability as a general tuning mechanism.

Moving beyond conventional Floquet approaches, a new frontier is emerging: cavity quantum materials [3]. By embedding materials in tailored quantum-electrodynamical environments, such as optical cavities, it is possible to enhance light-matter interactions and create hybrid light-matter states with fundamentally new properties. Unlike classical laser-driven schemes, cavity-mediated interactions can modify quantum fluctuations and collective excitations even in thermal equilibrium, offering a novel route to control material properties without direct external driving. I will highlight recent advances in this field, both from theoretical [4] and experimental [5,6] perspectives, and specifically discuss how strong correlations in cavity quantum materials provide new opportunities for engineering competing electronic orders through light-matter hybridization. Importantly, this relies on a generalization of the “cavity paradigm” beyond optical resonators into the realm of “polaritonic quantum matter” in order to structure fluctuations in cavity quantum materials [7]. This may open pathways toward controlling superconductivity, charge density waves, and other ordered phases in a fundamentally new way.

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Fluctuation-Induced Bistability of Fermionic Atoms Coupled to a Dissipative Cavity[1]

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We investigate the steady state phase diagram of fermionic atoms subjected to an optical lattice and coupled to a high finesse optical cavity with photon losses. The coupling between the atoms and the cavity field is induced by a transverse pump beam. Taking fluctuations around the mean-field solutions into account, we find that a transition to a self-organized phase takes place at a critical value of the pump strength. In the self-organized phase the cavity field takes a finite expectation value and the atoms show a modulation in the density. Surprisingly, at even larger pump strengths two self-organized stable solutions of the cavity field and the atoms occur, signaling the presence of a bistability. We show that the bistable behavior is induced by the atom-cavity fluctuations and is not captured by the mean-field approach.

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Quantum Science in Cavity Arrays

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In this talk I will discuss ongoing efforts in the Simon-Schuster collaboration at Stanford that leverage arrays of optical and microwave resonators for quantum science. On the microwave side, I will describe our Bose-Hubbard circuit platform and share experimental work assembling and studying liquids and solids of photons, culminating in our demonstration of many-body Ramsey spectroscopy as a probe of chemical potential and pressure in photon fluids. On the optical side, I will introduce our recently developed cavity array microscope as a tool for rapidly reading out atom arrays, and discuss prospects for networking, computing and many-body physics.

Universal relaxation speedup in open quantum systems through transient conditional and unconditional resetting

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Abstract: Speeding up the relaxation dynamics of many-body quantum systems is important in a variety of contexts, including quantum computation and state preparation. In this study, we demonstrate that such acceleration can be universally achieved via transient stochastic resetting. This means that during an initial time interval of finite duration, the dynamics is interrupted by resets that take the system to a designated state at randomly selected times. We illustrate this idea for few-body open systems and also for the extreme case of many-body open systems, which exhibit first-order phase transitions, associated with a divergence of relaxation time. In all scenarios, a significant and sometimes even exponential acceleration in reaching the stationary state is observed, similar to the Mpemba effect. The universal nature of this speedup lies in the fact that the design of the reset protocol only requires knowledge of a few macroscopic properties of the target state, such as the order parameter of the phase transition, while it does not necessitate any fine-tuned manipulation of the initial state.

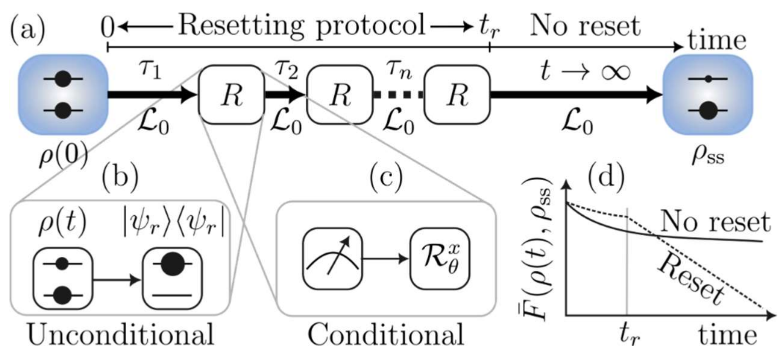

Fig. Illustration of stochastic resetting protocols and relaxation speedup. (a) For simplicity, we showcase a single qubit system, initialized in the state $\rho(0)$ and evolving under a reset-free Liouvillian $\mathcal{L}_0$. Times τ_j elapsing between consecutive reset projections, sketched with R boxes, are random. Stochastic resets take place up to an initial transient time t_r: $0 < t < t_r$. After this time, $t > t_r$, the system relaxes to the steady state ρ_{ss} of $\mathcal{L}_0$. We consider two resetting protocols: (b) unconditional, where the system resets to a fixed state $|\psi_r\rangle$ regardless of the instantaneous state $\rho(t)$, and (c) conditional, where a state-specific operation (a rotation $\mathcal{R}_\theta^x$ gate in the qubit case) is applied based on measurement outcomes (measurement symbol). (d) Both protocols lead to universal acceleration of relaxation to the stationary state. This is quantified by the faster decay in time of the distance measure $\bar{F}(\rho(t), \rho_{ss})$ to zero.

Electro-Optic Cavities for THz Cavity Electrodynamics

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Cavity control over material excitations and order parameters represents a major driving force for the rising field of THz cavity electrodynamics. A significant limitation in the work so far is an over-reliance on conventional techniques of measuring light-matter interactions – i.e. measurement of transmitted or reflected fields (i.e. ex-situ) rather than in-situ measurement of cavity fields themselves. This shortcoming is readily addressed by performing electro-optic sampling inside of the electromagnetic cavity, here using alpha quartz, thereby creating what we call an electro-optic cavity (EOC), which allows measurement of cavity electromagnetic fields.

As a first example of local light-matter interaction measured in the electro-optic cavities, we demonstrate strong coupling of a cavity photon to a phonon within the EOC. This discovery of bulk electro-optic phonon polaritons serves as a promising example of the novel opportunities for fundamental research in light-matter interactions in the THz range. More specifically, the identification of strong light-matter interactions in these electro-optic cavities opens an important new testing ground for measurement of potential light-matter entanglement, created due to the strong interaction. Furthermore, our choice of quartz is an ideal electro-optic medium for measuring tailored and textured light fields, thus setting the stage for measurement of tailored light pulses within engineered electro-optic cavities.

Cavity control and measurement of mesoscopic atomic systems

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We have recently gained the ability to prepare precisely ordered arrays of single neutral atoms, suspended in vacuum using optical tweezer traps. Integrating such atom arrays into high finesse optical cavities and the physics of cavity quantum electrodynamics presents new opportunities ranging from controlling the quantum-optical response of atomic metamaterials, to studying many-body quantum phenomena with digital control over their constituent atom numbers, to quantum information processors coupled strongly to light. I will present experimental results touching on all three of these points.

A quantum dot in an open microcavity

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A semiconductor quantum dot can mimic a real atom, in particular a coherent two-level system. Coherence is by no means guaranteed in a complex solid-state host. For a quantum dot in GaAs, a weakly polar material, phonon scattering of the upper level (the "exciton") is relatively weak. Furthermore, in state-of-the-art devices, fluctuations in the emitter frequency (spectral wandering) are almost entirely suppressed. The consequence is that in the best case (high-quality material, best-practice heterostructure design, resonant excitation at low temperature), the optical linewidths are very close to the transform limit. To mimic a lambda system, an electron or hole can be added to the quantum dot and a magnetic field applied. The spin's coherence is degraded by the magnetic noise created by the host nuclei. This noise can be suppressed by laser-cooling the nuclear spins in which case the spin coherence time (specifically, T_2^*) takes on values several hundred times the radiative lifetime [1]. Furthermore, a fast Raman process can be used to rotate the spin.

These developments in creating a coherent few-level "atom" inside a semiconductor point to the interest in pursuing cavity-QED with this platform. The cavity can be created in a number of ways, for instance with a micropillar [2], a photonic crystal [3], or an open microcavity [4]. Here, progress with the open microcavity platform is reported. The "bottom" cavity mirror is part of the semiconductor heterostructure. The "top" mirror is a micro-fabricated curved mirror positioned just above the semiconductor chip.

With a high-reflectivity top mirror, the quantum dot-cavity system enters the regime of strong coupling [5]. A cooperativity of 300 is achieved. With a lower-reflectivity top mirror, the system operates as a single-photon source with high end-to-end efficiency (57%) and good coherence metrics (two-photon interference visibility >95%) [6]. Moreover, the system mimics the canonical one-dimensional atom: the transmission on resonance drops to just 0.8%, close to the ideal (0%) limit [7]. Recent work adds the spin degree of freedom. Single-shot spin readout is achieved within 3 ns with an optical pulse: one spin state results in the detection of a single photon, the other spin state does not [8]. Furthermore, full spin control has recently been developed inside the cavity [9].

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Engineering interactions by collective coupling of atom pairs to cavity photons for entanglement generation

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Engineering atom-atom interactions is essential both for controlling novel phases of matter and for efficient preparation of many-body entangled states. In our approach [1], we propose a scheme to tailor these interactions by coupling driven atom pairs to optical cavity photons via a molecular state in the dispersive regime, resulting in an effective cavity-induced quantum potential.

As an illustrative example, we investigate two-mode ultracold bosons in a double-well potential, and by analyzing the quantum Fisher information, we show that the photon-induced interactions can dynamically generate robust many-body entanglement, similarly to the One-Axis Twisting protocol. By tuning these photon-induced interactions through the cavity drive, we identify conditions for preparing highly entangled states on timescales that mitigate decoherence due to photon loss. We find the entanglement formation rate scales strongly with both photon and atom number, dramatically reducing the timescale compared to bare atomic interactions. Moreover, the strong atomic entanglement persists on time scales long after the photons have decayed from the cavity due to losses. Also, for this driven dissipative system, we identify a single optimal measurement for exploiting the metrological potential of the atomic state in an interferometric protocol with significant photon losses, saturating the quantum Cramer-Rao lower bound. Finally, we show,despite these losses, the atomic state exhibits strong nonlocal many-body Bell correlations.

Our results provide insights on cavity-induced atom-atom interactions and open paths to study novel phases of light and matter in hybrid atom-photon systems, as well as for tailoring complex quantum states for new quantum technology protocols and fundamental tests of quantum mechanics.

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Abstracts of Posters

(in alphabetical order)

Coupling Single Strontium Atoms to Photonic Crystal Defect Cavities

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Strong interactions between atoms and photons enable quantum control over both photonic and atomic systems. This interaction is significantly enhanced when the atom is placed inside an optical cavity as has been realized with Fabry-Pérot cavities. Nanophotonic cavities have high quality factors and extremely small mode volumes, enabling new capabilities for cavity control of atoms.. We make such cavities by introducing localised defects in a photonic crystal. Such defect cavities achieve low mode volumes, high field localisation and quality factor on the order of a million. We will fabricate suspended silicon nitride defect cavities for interfacing light and single Strontium-88 atoms.

By capturing a single Strontium atom in a tightly focused optical tweezer, we will couple them to defect cavities. Strontium-88 atoms are a powerful tool for metrology and quantum technology due to their optical transitions with linewidths ranging from kilohertz to millihertz. We will use this system as a tool to measure Van der waals forces, create an optical quantum memory and entangled states of atoms. The creation of an on-chip atom-light interface will pave the way towards using the nonlinearity of the atom to create macroscopic quantum states of motion of silicon nitride mechanical resonators.

In this poster, I describe the progress towards this system, our planned apparatus, simulations of the parameter regime we can reach and proposed experiments.

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Cavity polaritons in a hybrid van-der-Waals superconductor-seminconductor structure

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Monolayers of transition metal dichalcogenides (TMDs) offer new possibilities to study superconductivity. In this project, we investigate hybrid heterostructures of $NbSe_2/MoSe_2$ van der Waals layers, in the framework of cavity experiments. $NbSe_2$ and $MoSe_2$ are TMDs; superconductivity occurs in $NbSe_2$ [1], and the monolayer $MoSe_2$ is a direct band gap semiconductor that hosts excitons with high oscillator strength. By embedding the $NbSe_2/MoSe_2$ heterostructure in an open cavity [2] sketched in Fig. 1, we achieve strong coupling between the $MoSe_2$ excitons and the cavity photons, forming exciton-polaritons, as evidenced by the pronounced Rabi-gap seen in subsequent longitudinal and transversal cavity modes in Fig. 2 where we tuned the open cavity length. This implementation of a hybrid superconductor-semiconductor monolayer polariton cavity forms the foundation of experiments to gain insight into how exciton–polariton coupling can influence the superconductive phase of $NbSe_2$ and allow us to further investigate optically tunable superconducting hybrid systems.

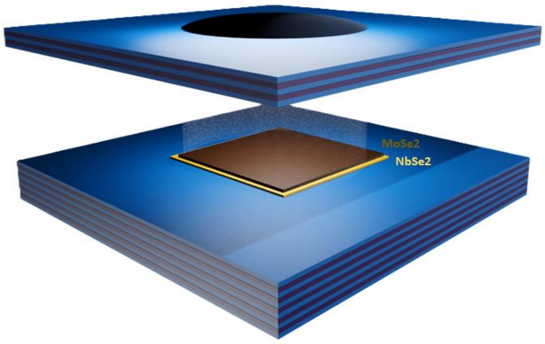

Figure 1: Open cavity with two dielectric DBRs embedding a $NbSe_2/MoSe_2$ heterostructure

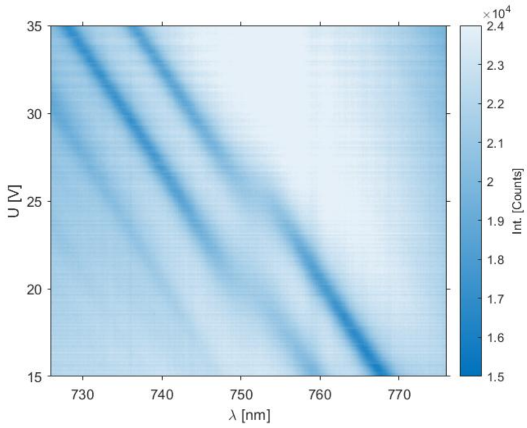

Figure 2: Reflectivity spectrum of the structure in Figure 1, Cavity is tuned over a range of ~1µm via piezo voltage

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A scalable photonic platform for interconnecting ion-based quantum computers

Pierre Barral

Quantum computers based on ions or atoms offer promising scalability. However, running fault-tolerant algorithms will require millions of physical qubits. A modular architecture with optically mediated entanglement between smaller computing nodes can achieve that scale.
IonQ aims to use color centers (SiV) in diamond cavities to speed up optical entanglement between modular ion quantum computers. I will introduce our vision and our progress towards building a prototype quantum networking system interconnecting ions and SiV in diamond.

Ref: Riedel, Daniel, et al. "A scalable photonic quantum interconnect platform." arXiv preprint arXiv:2508.06675 (2025).

Influence of Cavity-Induced Polariton Formation on Superconductivity

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A very exciting direction in modern condensed matter physics is the manipulation of quantum materials using light. In particular, laser-driven control of superconductivity has attracted significant research interest in recent years [1, 2]. However, for greater controllability, cavity systems offer a powerful way to access and manipulate equilibrium quantum properties without the drawbacks of transient optical methods, such as detrimental heating. By tuning parameters such as geometry, light frequency, and coupling strength, one can steer fluctuations to stabilize or even generate entirely new quantum phases, including novel superconducting states. Notably, it has been demonstrated that cavity-induced phonon polaritons can enhance electron-phonon interactions [3], although the potential modification of superconductivity remains an open research question. Recent experiments on charge-transfer κ-salts report a dramatic suppression of the superfluid density when those are coupled to a cavity [4]. The prevailing hypothesis for this suppression arises from a resonant coupling between the cavity modes and infrared-active molecular phonon modes in the κ-salt. However, the microscopic mechanism by which such cavity-induced phonon/polariton coupling alters superconductivity remains unknown. To gain further understanding on this, we focus on charge-transfer κ-salts with strong electronic correlations, which are well captured by a Hubbard model [2, 5]. Building on that, our goal is to understand how the emergence of cavity-mediated phonon polaritons modifies the effective interactions (e.g. spin fluctuations or mediated electron pairing), and thereby to examine how and why the superconducting state is suppressed.

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New Quasiparticles Revealed by Quantum Interference and Light Scattering

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In materials, new quasi-particles can emerge as collective excitations of ordered states. Detecting these modes and their associated properties is an essential step to understanding these new phases. Here, I will discuss the utility of Raman Spectroscopy in detecting the various excitations that emerge in quantum materials. I will focus on our discovery of an Axial Higgs mode emerging from a Charge Density Wave (CDW) in the 2D Material family RTe3. For decades, the CDW in RTe3 was thought to be conventional. However, using quantum interference and various optical techniques, we have proved that a hidden Ferroaxial order emerges from a combined orbital and charge order.

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Room-temperature quantum optomechanics using an ultralow noise cavity

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At room temperature, mechanical motion driven by the quantum backaction of light has been observed only in pioneering experiments in which an optical restoring force controls the oscillator stiffness. For solid-state mechanical resonators in which oscillations are controlled by the material rigidity, the observation of backaction-dominated motion has been hindered by low mechanical quality factors, optical cavity frequency fluctuations, thermal intermodulation noise and photothermal instabilities. However, during the last decade, the phenomenon 'dissipation dilution' has been exploited to increase the quality factors of nanomechanical resonators by three orders of magnitude[1].

On this poster, I will show how dissipation dilution can be greatly enhanced by engineering the resonator geometry. I will then show how we reach the quantum-backaction dominated regime of optomechanics at room temperature with a phononic-engineered membrane-in-the-middle system[2]. By using phononic-crystal-patterned cavity mirrors, we reduce the cavity frequency noise by more than 700-fold. In this ultralow noise cavity, we insert a membrane resonator with high thermal conductance and a quality factor (Q) of 180 million. These advances enable the operation of the system within a factor of 2.5 of the Heisenberg limit for displacement sensing, leading to the squeezing of the probe laser by 1.09(1) dB below the vacuum fluctuations. Moreover, the long thermal decoherence time of the membrane oscillator (30 vibrational periods) enables us to prepare conditional displaced thermal states of motion with an occupation of 0.97(2) phonons using a multimode Kalman filter. We then perform sideband asymmetry thermometry to show an unconditional phonon occupancy of 9.5 phonons[3].

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Polaritonic near-field effects on the metal-to-insulator transition of the Hubbard model

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The influence of the dielectric environment on material properties has been studied theoretically mostly within two different contexts: Within Coulomb engineering electrostatic screening of the longitudinal electromagnetic field, which renormalizes interactions [1]. In contrast, within cavity material engineering one tries to shape the transverse electromagnetic field to produce desired material properties [2]. For certain settings, such as in the near-field of materials hosting phonon- or plasmon-polaritons, this separation is no longer possible as the longitudinal and transverse components of the electromagnetic field mix. We investigate the resulting effect on the metal-to-insulator phase transition of a 2-D Hubbard model suspended above a polariton-hosting material using DMFT + GW treating the longitudinal and transverse fields consistently. Lastly, we consider the gauge dependence introduced by our scheme for the Coulomb [3] and Weyl gauge [4].

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Color Centers as Quantum Sources of Hyperbolic Phonon Polaritons in Hexagonal Boron Nitride

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Hyperbolic phonon polaritons (HPPs) in hexagonal boron nitride (hBN) confine mid-infrared (mid-IR) light to deeply subwavelength scales and have become a powerful platform for studying light–matter interactions. Yet their generation and control are typically accessed through classical near-field probes, which constrain quantum-level experiments. A complementary frontier in hBN research focuses on color centers—bright, stable, atomically localized emitters that now form a rapidly maturing platform for solid-state quantum optics. Here we establish a key connection between these two directions of research by developing a cavity quantum electrodynamics (cavity QED) framework in which a single hBN color center acts as a quantum source of HPPs. We quantify the emitter–HPP interaction and analyze two generation schemes: spontaneous emission into the phonon sideband, which produces single-HPP events with a thickness-dependent, Purcell-like enhancement; and a stimulated Raman process that offers frequency selectivity, tunable conversion rate, and narrowband excitation. The latter launches directional, ray-like HPPs that propagate over micrometer distances. We further outline a two-emitter correlation measurement to directly test the single-polaritonic character of the emission. By connecting color-center quantum optics with hyperbolic polaritonics, our approach provides reciprocal benefits: quantum emitters supply on-chip, intrinsically quantum sources and control of HPPs, while HPPs provide long-range channels to mediate interactions between spatially separated emitters. Together, these capabilities point to a new direction for mid-IR light–matter experiments that unite strong coupling, spectral selectivity, and spatial reach within a single material system.

Tuning the dynamics of complex quantum correlations with optical cavities

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We analyze the non-equilibrium dynamics in an open system composed by a quantum gas of bosons in a lattice interacting via both contact and cavity-induced global interactions. We discuss several dynamical features stemming from the quantum nature of the cavity field and the fluctuations in the atoms-cavity coupling, using numerically exact simulations based on novel matrix product states implementations [1,2,3]. Firstly, we characterize the interplay of light-cone dynamics and of the non-causal propagation of the globally interacting dynamics, reporting a crossover between the light-cone behavior and the supersonic spreading of correlations, where correlations can spread across the system almost simultaneously, independent of the distance [2]. We identify the key ingredients necessary for the supersonic propagation and to pinpoint fluctuations of the global coupling which act as the carriers of the long-range correlations. Furthermore, we investigate the mechanisms necessary for the stabilization of current-current correlations by exploring dissipative couplings to nonreciprocal reservoirs [3]. We analyze the role of locality in the coupling to the environment of the quantum system of interest, as we consider either local couplings throughout the system, or a single global coupling to a cavity mode.

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Path-integral approach to spin liquids in cavities

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Quantum spin liquids are a highly entangled phase of matter. A recent article proposed that by introducing a long-ranged interaction between spins via an electromagnetic cavity, it is possible to engineer spin liquid states in an antiferromagnetic material [1]. We will consider higher order contributions of this interaction by utilizing the Matsubara path integral formalism, which we have previously shown to reveal the possibility of strong cavity coupling to antiferromagnets [2]. We will present an effective theory of electrons in two low-energy bands of an antiferromagnetic insulator with long-ranged spin interactions mediated by polarized cavity photons and an external laser. The theory is obtained by considering a third energy band of higher energy, and eliminating this band along with the cavity photons for an effective theory of the low-energy electrons.

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Optical manipulation and detection of moiré magnetism

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Moiré transition metal dichalcogenide bilayers provide a versatile platform for exploring the interplay between optical control and correlated electronic phenomena. In this work, we show that magnetism in these systems can be engineered with light. Polarization-dependent Raman drives introduce anisotropic spin interactions that stabilize magnetic states absent in undriven bilayers. We further establish a direct link between spin correlations and optical signals, offering a powerful and accessible method for probing magnetic order. These results open new opportunities for using light to engineer and detect quantum phases in moiré materials.

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Cavity-induced Eliashberg effect: superconductivity vs charge-density-wave

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Recent experiments have shown that non-equilibrium effects can play a key role in cavity-based control of material phases, notably in systems with charge-density-wave order. Motivated by this, we extend the theory of the Eliashberg effect, originally developed for superconducting phases, to charge-density-wave phases. Starting from a minimal electronic model where superconductivity and charge-density-wave order are equivalent at equilibrium, we introduce coupling to cavity photons, which are in turn coupled to an environment at a temperature different from the one of the electronic environment. This drives the system into a non-thermal steady state, which breaks the equivalence between superconductivity and charge-density-wave order. In the superconducting case, we recover the known behavior: a shift from continuous to discontinuous phase transitions with bistability. In contrast, the charge-density-wave case displays richer behavior: tuning the cavity frequency induces both continuous and discontinuous transitions, two distinct ordered phases, and a bistable regime ending at a critical point. These findings demonstrate that the scope of cavity-based non-thermal control of quantum materials is broader than at thermal equilibrium, and strongly depends on the targeted phases.

Preprint: **arXiv:2509.07865**

Probing topological Floquet states in graphene with ultrafast THz STM

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Floquet band engineering enables control of solid-state systems via periodic laser driving. The light-induced anomalous Hall effect in graphene under circularly polarized light [1] has been observed in ultrafast transport measurements [2], and more recently, Floquet replica bands induced by linearly polarized light have been reported using time-resolved photoemission spectroscopy [3]. Here, we propose probing topological Floquet states in graphene using ultrafast scanning tunneling microscopy (THz STM) as a complementary experimental technique [4].

Specifically, we present Keldysh Green's function simulations of the THz STM signal for Floquet-driven graphene. We analyze signatures of light-induced gap openings and the formation of topological edge states, focusing on their imprints in the THz STM response. We further investigate how these signatures depend on key experimental tuning parameters—namely, the pump frequency (ranging from near-infrared to optical) and light polarization (linear vs. circular). Finally, we explore the potential of imaging the topological nature of Floquet states by analyzing their quasiparticle interference (Floquet-QPI) patterns. Our findings highlight ultrafast STM as a versatile and promising tool for probing light-induced topological states in quantum materials.

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Effective Lindblad master equations for atoms coupled to dissipative bosonic modes

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We develop atom-only Lindblad master equations for the description of atoms that couple with and via dissipative bosonic modes. We employ a Schrieffer-Wolff transformation to decouple the bosonic from the atomic degrees of freedom in the parameter regime where the decay of the bosonic degrees is much faster than the typical relaxation time of the atoms. In this regime we derive the transformation which includes the most relevant retardation effects between the bosonic and the atomic degrees of freedom. After the application of this transformation, the effective Lindblad master equation is obtained by tracing over the bosonic degrees of freedom and captures the atomic interactions and dissipation mediated by the bosons. We use this approach to derive Lindblad master equations which can describe the phase transitions, steady states, and dynamics in the dissipative Dicke model. In addition, we show that such master equations can be used in presence of resonant periodic driving and predict the formation and stabilization of dissipative Dicke time crystals. We also discuss how to extend the theory to describe systems with very strong light-matter interactions.

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Kibble-Zurek mechanism in open systems: From superradiance to discrete time crystals

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The Kibble-Zurek mechanism (KZM) is a well-celebrated theory that predicts a universal power-law scaling of the defect number and delay of phase transition with the timescale at which the system is quenched from a disordered phase to an ordered phase. In this work, we theoretically demonstrate the validity of the KZM in systems forming dissipative discrete time crystals (DTCs). We do this by first establishing its validity in open spin-cavity systems in the absence of periodic driving. We observe that dissipation can obscure the transition of the system from a normal to a superradiant phase, resulting in an apparent delay in the manifestation of the KZM in open systems in the thermodynamic limit. This behavior vanishes in the finite-size limit of the spin-cavity systems due to the quantum noise, motivating the study of the KZM for DTCs in the presence of either classical or quantum fluctuations. We test the validity of the KZM in two DTC-forming systems: the Sine-Gordon model connected to a thermal bath, which is a paradigmatic model for emulating classical DTCs; and the open Dicke lattice model, which is a lattice of spin-cavity systems subject to quantum noise due to dissipation. For both systems, the defect number and the transition delay follow a power-law scaling with the quench time regardless of the spatiotemporal order. Using the adiabatic-impulse approximation, we argue that the KZM is a universal feature of periodically driven systems that can be mapped onto a dissipative linear parametric oscillator. These predictions are experimentally tested in an atom-cavity system, in which the scaling of the transition delay from a superradiant phase to a DTC is observed.

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Laser-machined cavities for cavity-enabled quantum simulations

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The exploration of multi-atom entangled states and their applications represents a rapidly growing field with many different experimental techniques to study these systems. A powerful example is arrays of single atoms in optical tweezers. To go beyond Rydberg interaction, the array can be placed inside an optical cavity. This effectively extends the interaction range to infinity, and in combination with the high degree of parametrization, leads to a new generation of cavity quantum electrodynamics experiments.

In our group, laser-machined, high-finesse fiber Fabry-Perot cavities provide a small mode cross-section and thus, strong light-matter coupling for a single emitter. To create symmetric entangled states such as spin-squeezed states, all atoms must be uniformly coupled to the cavity. Our approach uses an array of individually movable, optical tweezers in combination with a commensurate trapping lattice to precisely control their positions in the cavity mode. To overcome the position-dependent coupling of standing-wave cavities and, at the same time, keep the advantages of our miniaturized open cavity, we have demonstrated the shortest open ring cavity to date. Besides a standing wave, this cavity geometry can also house a traveling wave, adding the advantage of position-independent, uniform coupling. We present the mode mapping of our linear cavity with a single atom, as well as the characterization of our ring cavity.

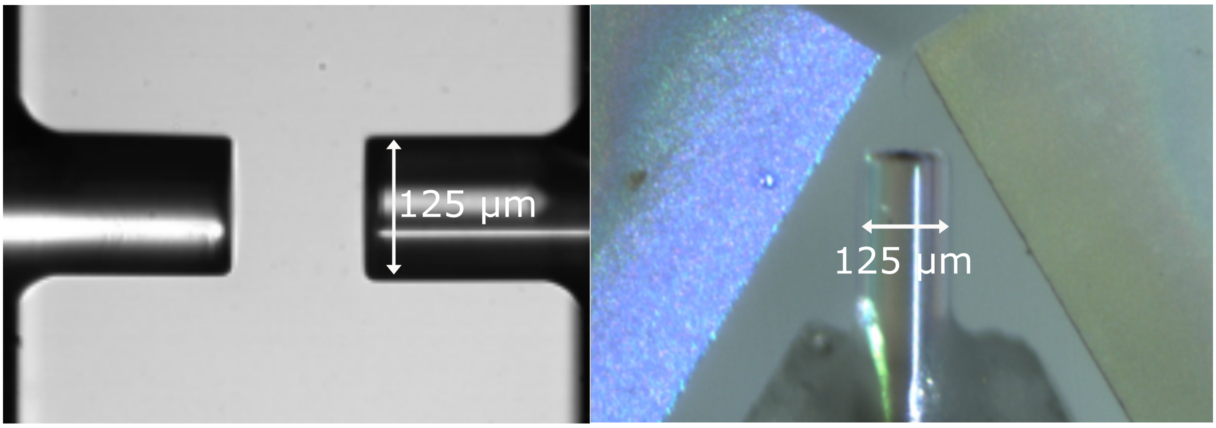

FIG. 1: Microscope image of a fiber Fabry-Perot cavity (left) and a miniature ring cavity (right).

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Interplay of Static and Photon-Mediated Interactions in Rydberg Lattices Inside an Optical Cavity

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Arrays of Rydberg atoms provide a platform for exploring many-body quantum physics with controllable long-range interactions. When such an array is placed inside a high-finesse optical cavity, the Rydberg spins couple collectively to quantized electromagnetic modes, giving rise to photon-mediated interactions that are intrinsically retarded in time. The coexistence of static van der Waals couplings and dynamically generated, frequency-dependent interactions opens a rich landscape of correlated light–matter phases.

Using an extended dynamical mean-field theory (EDMFT) framework, we study the steady-state properties of a two-dimensional lattice of Rydberg atoms coupled to the multimode cavity field. Our analysis captures on equal footing the instantaneous Ising-type interactions and the retarded exchange mediated by vacuum fluctuations of the photons. We identify competing regimes characterized by antiferromagnetic ordering, superradiant-like phases with collective photon coherence, and magnetically polarized states controlled by the effective longitudinal field. The resulting phase diagram reveals how cavity confinement and retardation qualitatively modify the nature of magnetic and superradiant transitions.

Our results demonstrate that cavity-embedded Rydberg arrays constitute a versatile platform where static and dynamic long-range couplings can be engineered and tuned, providing a route toward designing quantum phases of light and matter in and out of equilibrium.

Repulsive bound states and strong photon interactions from dipolar moiré excitons

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Achieving strong optical nonlinearities at the few-photon level is a key challenge in quantum photonics, essential for advancing quantum information processing and optical logic. Two-dimensional transition metal dichalcogenide (TMD) heterostructures offer unique opportunities due to their strong excitonic effects and tunable moiré potentials.

In our work, we investigate cavity-coupled twisted TMD bilayers, focusing on how moiré-induced hybridization between interlayer and intralayer exciton can enhance photon-photon interactions. We show that dipole-dipole interactions lead to the formation of repulsively bound exciton pairs, which profoundly modify the polariton spectrum under resonance conditions.

Our results demonstrate that tuning the upper polariton spectrum into resonance with a two-exciton bound state yields a nonlinear spectral splitting and strong few-photon nonlinearity, analogous to a Feshbach resonance in atomic systems.

These findings establish moiré TMD heterostructures as a promising platform for tunable quantum nonlinear optics.

Narrow-band enhanced excitonic order

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Flatband materials have attracted a lot of interest for their peculiar properties. In recent years there has been a focus on how to exploit their peculiar properties for practical applications. I will present the study of the formation of excitons in a simple one-dimensional model, which has been inspired by the recent realization of wuch model in a Cu/Te sample. I will first show the phase diagram of the system as a function of the bandwidth and the electron-electron interaction followed by a study of the dynamical properties of such systems. To study the dynamics we use the non-equilibrium Green function approach, and specifically a master equation based on the Generalized-Kadanoff-Baym Ansatz. The main result of our study is that narrow bands favor the formation of excitons and that they are also stable under time evolution.

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Phase Diagram and dynamical phases of self organization of a Bose–Einstein condensate in a transversely pumped red-detuned cavity

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We study a transversely pumped atomic Bose–Einstein Condensate coupled to a single-mode optical cavity, where effective atom–atom interactions are mediated by pump and cavity photons. A number of experiments and theoretical works have shown the formation of a superradiant state in this setup, where interference of pump and cavity light leads to an optical lattice in which atoms self-consistently organize.

This self-organization has been extensively studied using the approximate Dicke model (truncating to two momentum states), as well as through numerical Gross–Pitaevskii simulations in one and two dimensions.

Here, we perform a full mean-field analysis of the system, including all relevant atomic momentum states and the cavity field.

We map out the steady-state phase diagram vs pump strength and cavity detuning, and provide an in-depth understanding of the instabilities that are linked to the emergence of spatio-temporal patterns.

We find and describe parameter regimes where mean-field predicts bistability, regimes where the dynamics form chaotic trajectories, instabilities caused by resonances between normal mode excitations, and states with atomic dynamics but vanishing cavity field.

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Control and Detection of Topological Features in a Majorana Chain Coupled to a Cavity

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We explore phenomena emerging from the global or local coupling of QED cavities with topological matter. We demonstrate that globally embedding a topological chain in the cavity field stabilizes topological order. Moreover, ground state light-matter entanglement facilitates the identification of the topological phase through measurements of experimentally accessible photon observables, such as the Fano factor and cavity quadrature fluctuations. Thus, this method provides an indirect approach to detecting chain order [1]. Depending on the coupling geometry, considering spatially selective coupling to the cavity offers a means to manipulate localization or even create new topological qubits. Consequently, this provides a method for obtaining the building blocks required for braiding processes [2].

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Towards the observation of dark-state semi-localization in dissipative systems

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Since their discovery, hybrid states of light and matter have sparked bustling interest across diverse fields, ranging from condensed matter physics and atomic physics to chemistry. While "bright" states are largely unaffected by disorder, it has been demonstrated that strong light-matter coupling gives rise to unconventional localization behavior in "dark" light-matter states [1,2]. This phenomenon, coined as semi-localization, has been theoretically evidenced in ensembles of quantum emitters with randomly distributed transition frequencies coupled to a single-mode cavity. However, for meaningful comparison with experimental realizations, a proper description of semi-localization must account for cavity losses and spontaneous emission. In this work, we assess the feasibility of observing semi-localization as a transient phenomenon under experimental conditions [3]. We explore the robustness of this phenomenon in dissipative systems using experimentally accessible figures of merit, and investigate the relation between subradiance and localization phenomena.

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Engineering quantum droplets with cavity-mediated interactions

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Quantum droplets are an exotic state of matter which emerges from zero-point energy corrections to the ground state, resulting in a self-bound many-body system. We present a theoretical framework for a new type of quantum droplet. In the simplest case, the correction is provided by a single collective mode of the finite-size system. This situation can be engineered by coupling a dilute Bose-Einstein condensate to an optical cavity in a transverse pumping scheme. The vacuum fluctuations of the cavity mediate an effective long-range atom-atom interaction. Using the Bogoliubov formalism, we demonstrate that this interaction leads to the formation of a distinct roton mode. The zero-point energy of the roton mode scales favorably with the atomic volume and thus competes with the repulsive s-wave contact interaction, facilitating the formation of the droplet. The quantum energy correction and its crucial scaling are determined by the modes of the light field. We investigate how changing the characteristics of the light field and the coupling parameters affect the droplet. We present temperature effects, including a critical temperature for the droplet. Our results provide analytical expressions for the droplet characteristics and classify the regimes in which self-bound states emerge.

THz probe for topological magnon edge mode detection

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Topological magnon insulators, characterized by non-trivial spin wave excitations with symmetry-protected edge modes, have emerged as promising candidates for low-dissipation information storage and transport. Despite several theoretical proposals and indirect experimental evidence supporting their existence, the direct detection of magnon edge modes remains a significant challenge due to their weak coupling to conventional probes. In this work, we develop a theoretical framework to probe and amplify edge magnons in ferromagnetic topological insulators on a honeycomb lattice, with magnonic band gaps in the terahertz (THz) regime. We explore symmetry-allowed mechanisms for spin-induced polarization, identifying pathways for electric field coupling via dynamical magnetoelectric effects. Our study reveals that resonant electromagnetic driving can lead to parametric amplification and steady-state edge magnon populations through magnon-magnon interactions. Furthermore, we propose a cavity-mediated enhancement scheme using THz cavities to probe topological edge states via strong magnon-photon coupling. This approach extends previous works by systematically analyzing all symmetry-permitted polarizations and demonstrating the role of electromagnetic cavities in accessing and amplifying topological magnon edge modes.

<u>Building a Confocal Cavity for a Degenerate cQED Apparatus</u>

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Cavity QED (cQED) with ultracold atoms has made great strides in recent years, with atomic tweezer arrays and quantum gas microscopy experiments now frequently implementing single-mode cavities to increase the tunability and lifetime of atom-light interactions. To further build on this, multimode cQED is an appealing prospect, as being able to control the number of cavity modes participating in atom-light interactions adds the ability to engineer more complex coupling than the all-to-all interactions seen in single mode cavities. Previous experiments have already used multimode cavities to induce phonon-like effects for ultracold atoms within optical lattices [1], as well explore unique spin glass phases for ultracold bosons [2].

We will describe the design of our current confocal cavity, which will serve as the core of a future multimode cQED experiment involving ^{6}Li. We will describe plans for the construction and spectroscopy of our high finesse cavity, as well as how we plan to integrate this cavity into our UHV system.

We will also highlight our future plans for the fermionic multimode cQED experiments this cavity will be used for. In particular, we will discuss our plans for the analog quantum simulation of holographic models such as the SYK model, which will leverage the degeneracy of our cavity modes, a randomly disordered optical potential, and strong atom-light interactions between fermions to generate quantum chaotic dynamics and fast quantum information scrambling [3].

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Demonstration of strong coupling of a subradiant atom array to a cavity vacuum

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Cold atoms trapped in the volume of a high-finesse optical resonator [1] form a hybrid quantum system that can serve as an interface between photonic and atomic qubits. Quantum information transmitted by photons can be stored in the atomic hyperfine ground states. Bistability between these states [2] is useful for quantum sensing applications, while hybridized states of light and matter will be exploited in future quantum technology applications.

The cavity-mediated interaction induces a new class of phase transitions, which can be interpreted in an open-system framework. The key point in this is to quantify and understand fluctuations in the vicinity of the critical point. A unique feature of cavity systems is that the cavity field and its fluctuations can be monitored real time [3], that helps us to reveal the very nature of cavity controlled phase transitions. Arranging atoms in an incommensurate lattice, with respect to the resonator mode, the scattering is suppressed by destructive interference: resulting in a subradiant atomic array. We show, that strong collective coupling leads to a drastic modification of the excitation spectrum, as evidenced by well-resolved vacuum Rabi splitting in the intensity of the fluctuations [4].

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(Quasi-)Continuous-Wave Superradiant Lasers

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Superradiant Lasers are promising candidates for next-generation light sources with ultralow bandwidth, suitable as read-out tools for passive optical atomic clocks or active frequency standards themselves [1,2]. Their main advantages are the possible utilization of ultranarrow transitions for lasing and a strongly suppressed dependence on an eigenfrequency of the laser cavity [4]. However, achieving the full potential of sub-natural linewidths requires continuous-wave operation, as pulsed emission is Fourier-limited.

We report the successful operation of a quasi-continuously emitting superradiant laser using cold bosonic calcium-40 atoms as the gain medium. These atoms are cooled in a bichromatic magneto-optical trap and loaded into a magic-wavelength one-dimensional optical lattice prepared inside a cavity. After incoherent population of the upper laser state, pulsed superradiant emission on the 370 Hz intercombination line was realized [4]. We extended this scheme to continuously pump the decayed atoms back into the upper laser state, prolonging the lasing by up to three orders of magnitude until too many atoms are lost due to heating. We could observe a Fourier-limited but sub-natural emission linewidth of less than 100 Hz and confirmed suppressed cavity influence with a cavity pulling factor of only 0.5 %.

Furthermore, we present our current progress toward a truly continuously operating superradiant laser using cold fermionic strontium-87 atoms inside a ring cavity. This laser will operate on a mHz-linewidth clock transition and continuously load laser-cooled atoms into the cavity to maintain a stable atomic population during lasing [5].

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Cavity-enhanced superconductivity: Linking critical temperature and electron localization

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Predicting superconducting properties from first principles—especially in non-equilibrium conditions—is computationally intensive. Here, we propose a more efficient approach by using the electron localization function (ELF) as a proxy for estimating the superconducting critical temperature T_C. Through first-principles calculations, we investigate how coupling conventional superconductors to an optical cavity—without external driving—modifies their phonon properties and electron–phonon interactions via vacuum fluctuations alone. We focus on three representative materials: lead (Pb), niobium (Nb), and magnesium diboride (MgB_2). Our methodology combines Density Functional Theory (DFT), Density Functional Perturbation Theory (DFPT), Quantum Electrodynamical Density Functional Theory (QEDFT), and Wannier-based electron–phonon coupling to solve the Eliashberg equations for T_C. Our results demonstrate that ELF can effectively capture trends in superconducting behaviour under light–matter coupling, offering a promising, low-cost descriptor for screening or designing superconductors in both equilibrium and cavity-modified regimes.

CAVITY QED WITH RYDBERG SUPERATOMS

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In optical cavity QED, strong atom-photon coupling is generally reached by confining the photons in a small volume. A relatively new paradigm consists, instead, in enhancing the scattering cross-section of the atom by replacing it with a “superatom” made of an interacting atomic ensemble. This approach allows one to use larger cavities with complex geometries, good optical access, and high photon extraction efficiencies, enabling, among other applications [1], the deterministic generation of Wigner-negative light pulses [2]. I will show that the additional complexity of these superatoms can be efficiently modeled, and experimentally tamed. In particular, we have recently demonstrated that inhomogeneous dephasing, which limits their coherence time, can be efficiently suppressed by a combination of driving and intrinsic non-Markovianity, in a process akin to cavity protection [3].

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From Lasers to Photon Bose-Einstein Condensates: A Unified Description via an Open-Dissipative Bose-Einstein Distribution

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Photon condensation was first experimentally realized in 2010 within a dye-filled microcavity at room temperature. Since then, interest in the field has increased significantly, as a photon Bose-Einstein condensate (BEC) represents a prototypical driven-dissipative system. Here, we investigate how its inherent open nature influences the condensation process both quantitatively and qualitatively. To this end, we consider a mean-field model, which can be derived microscopically from a Lindblad master equation. The underlying rate equations depend on various external parameters such as emission and absorption rates of the dye molecules as well as the cavity photon loss rate. In steady state, we obtain an open-dissipative Bose-Einstein distribution for the mode occupations. The chemical potential of this distribution depends on the occupations of the dye molecules in both their ground and excited state and must therefore be determined self-consistently. We find that the resulting photon distribution is strongly influenced by the driven-dissipative parameters. Based on this result, we identify the main differences between a photonic BEC, an atomic BEC, and a laser.

Light-Matter Collective Phenomena and Quantum Sensing with Ultracold Atoms in Optical Cavities

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We present two complementary experiments exploring light–matter interaction in optical cavities with ultracold atomic ensembles. In the first, we report a Z_2 symmetry-breaking phase transition in a system of multilevel ^{87}Rb atoms strongly coupled to a weakly driven two-mode optical cavity[1]. In the symmetry-broken phase, non-ergodic dynamics manifests in the emergence of multiple stationary states with disjoint basins of attraction. This feature enables the amplification of a small atomic population imbalance into a characteristic macroscopic cavity transmission signal. Our experiment does not only showcase strongly dissipative atom-cavity systems as platforms for probing nontrivial collective many-body phenomena, but also highlights their potential for hosting technological applications in the context of sensing, density classification, and pattern retrieval dynamics within associative memories.

In the second work, we investigate quantum bi-stability and study cavity-assisted sensing using ultracold ^{88}Sr atoms trapped in a ring cavity[2]. Normal Mode Splitting reveals strong atom–cavity coupling and the emergence of bistable behavior. Through simulations, we design a sensitivity matter-wave interferometer based on Ramsey–Bordé sequences, aiming toward precision measurements in gravimetry and inertial sensing with Bloch Oscillations. Furthermore, we will pursue studies and experiments on non-linear effects as spin-squeezing.

Together, these studies highlight how optical cavities provide versatile platforms for probing collective quantum phenomena and implementing quantum-enhanced sensing protocols.

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Collective modes of lattice fermions with short and long range interactions

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Two-component fermions in a static optical lattice can be described by a Hubbard model, in which they can tunnel between neighboring lattice sites and interact locally via an SU(2)-symmetric interaction that can be tuned by means of a Feshbach resonance. On the other hand, ultracold atoms dispersively coupled to a transversely driven optical cavity experience long range density-density interactions with a coupling strength depending, in particular, on the frequency detuning between the cavity and pump lasers. Combining both of these aspects may therefore lead to systems in which one can engineer competing short and long range interactions over a broad range of coupling range. As a first approximation to the cavity-mediated infinite range interaction, one may consider more familiar instances of non local interactions like, e.g., a Coulomb interaction potential decaying as the inverse of the intersite distance. Here, we analyze the influence of the competition between the local Hubbard interaction and the non-local Coulomb interaction on the dynamical properties of the paramagnetic phase spin-1/2 lattice fermions, in three dimensions and for interaction strengths ranging from weak to strong coupling. By means of a comparison with standard Random Phase Approximation and a non-perturbative slave boson treatment of the interaction terms, we highlight the strong correlation features of the density response spectrum of the system, focusing in particular on the plasmon mode and its fate as the system is tuned towards the Mott transition at half-filling.

Non-thermal pairing glue of electrons in the steady state

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The study of mechanisms for enhancing superconductivity has been a central topic in condensed matter physics due to the combination of fundamental and technological interests. One promising route is to exploit non-equilibrium effects in the steady state. Efforts in this direction have so far focused on enhancing the pairing mechanism known from thermal equilibrium through modified distributions for the electrons or the bosons mediating the electron-electron interaction.

In this work, we identify an additional pairing mechanism that is active only outside thermal equilibrium. By generalizing Eliashberg theory to non-equilibrium steady states using the Keldysh formalism, we derive a set of Eliashberg equations that capture the effect of this genuinely non-thermal pairing glue even in the weak-coupling regime.

We discuss two examples where this mechanism has a major impact. First, in a temperature-bias setup, we find that superconductivity is enhanced when the boson mediator is colder than the electrons. Second, we find that an incoherent drive of the boson mediator at energies much greater than the temperature pushes the system far from thermal equilibrium but leaves the critical coupling essentially unchanged, owing to a competition between electron heating and the enhancement of pairing by the non-equilibrium glue.

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Cavity-control of the Ginzburg-Landau stiffness in superconductors

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Confining light around solids via cavities enhances the coupling between the electromagnetic fluctuations and the matter [1]. We predict that in superconductors, this cavity-enhanced coupling enables control of the order-parameter stiffness, which governs key length scales such as the coherence length of Cooper pairs and the magnetic penetration depth. Using the action formalism we systematically derive the Ginzburg-Landau equation close to the transition temperature and show that the effect originates from a renormalization of the Cooper-pair kinetic mass caused by photon-mediated (Amperean) repulsive interactions between the electrons building the pair. This mechanism, generic to Bardeen-Cooper-Schriffer superconductors, modifies the Ginzburg-Landau stiffness at fixed temperature and gap, allowing non-invasive control of superconducting properties through cavity geometry. By tuning the longitudinal size of a Fabry-Pérot cavity, one can drive the material deeper into the type-II regime, enhancing the upper critical field H_{c2} and confining spatial variations of the order parameter, potentially improving scalability in superconducting microelectronic circuits. We estimate the strength of this effect to be sizable for cavities in the infrared range. Importantly, this mechanism relies solely on the dependence of the Cooper-pair kinetic energy on cavity size, without requiring modification of the phonon-mediated pairing interaction [2,3] or any resonant coupling to phonon modes, making it broadly applicable to conventional superconducting compounds.

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Pulsed to continuous wave microcavity-quantum dot dynamics

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Quantum dots (QDs) are a promising source of quantum states of such as single-, bunched or entangled photons and are well studied in two regimes of resonant excitation. On one hand, in the coherent regime the dynamics are localized in time and pulsed excitation gives rise to Rabi oscillations, a crucial application of coherent control for quantum light because it allows deterministic population inversion. On the other hand, in the steady state regime the dynamics are localized in frequency where continuous wave excitation gives rise to Mollow triplets. In the intermediate regime of excitation with long pulses the time-bandwidth uncertainty relation limits the resolution of both the time domain and frequency domain. Excitation with pulses of length comparable to the lifetime probes the dynamics where coherent control is no longer coherent and the steady state solution has not yet been reached.

Epitaxially grown quantum dots in a microcavity are an ideal platform to study this regime because of the cavity-enhanced lifetime of around 100 ps. The incoherent dynamics happen in the regime where the time-bandwidth product delocalizes in both the frequency and time domains. Using a picosecond pulsed laser with flexible pulse length between 17 ps and a nanosecond we experimentally explore the transition from coherent to steady-state cavity-QD dynamics. We study a QD intermediately coupled to a cavity. By simultaneously measuring the second-order correlation function we find a single-photon subtracted coherent state when the QD is detuned away from both the excitation and collection cavity modes. We develop a simple theory which describes the role of the cavity modes through Purcell enhancement and the generalized Rabi frequency. This breaks down in the intermediately coupled regime, but using a full quantum master model we still get good agreement with our data. A surprising feature of our data in the intermediate coupling regime is incoherent-like scattering of resonant excitation light in the coherent regime.

Mode-shaping effects in Fabry–Pérot Optical Microcavities

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Open-access optical microcavities are essential devices for cavity-QED experiments, such as the study of single emitters. The paraxial description predicts that the eigenmodes of such cavities are Hermite-Gaussian or Laguerre-Gaussian modes that are characterized by a longitudinal quantum number q and a transverse order N and that modes with the same (q,N) labels are frequency degenerate in a rotation-symmetric cavity. But optical cavities with mirror radii and cavity lengths of only a few wavelengths don't operate in the paraxial limit. We will show that the eigen modes of such cavities are effected by non-paraxial and mode-shaping effects. These effects explain fine-structure in higher order modes, as well as mirror-shape induced polarization splitting of the fundamental modes.
The observation of these effects via the (fine structure in the) resonance spectrum and the polarization-resolved higher-order modes is relatively straightforward [1], but their interpretation is more challenging [2]. We provide guidelines for experimentalists to characterize the dominant mode-shaping effects in their cavities, using resonance spectra and mode profiles [3].
Our semi-analytic theory describes how the mode-shaping effects arise from mirror-shape and non-paraxial effects. Mirror-shape effects include spherical aberrations, astigmatism and gaussian shaped mirrors. The non-paraxial effects include a vector correction due to optical spin-orbit coupling.
Our measurements demonstrate the competition between the various effects. Spin-orbit coupling, which is one of the nonparaxial effects, is prominently visible in the intriguing polarization patterns of the resonant modes. Polarization tomography yields the shape-induced birefringence and associated polarization splitting of the two fundamental modes , even when these modes overlap spectrally.

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Background-free atom array imaging in an optical microcavity

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FIG. 1: Superimposed image of the scattering fiber cavity [left and right] illuminated by fluorescence beams, and a mean background-free image of the atom array [center].

Resonant cavity probing allows for fast, non-destructive, high-fidelity detection of a single atom strongly coupled to an optical cavity [1], but doesn't scale easily to larger number of atoms. On the other hand, traditional fluorescence, widely performed in free-space cold atoms experiments, typically fails near photonic devices such as waveguides or fiber microcavities [2]. Scattering of excitation light drastically increases background light level and prevents single-atom-resolved detection.

In this work, we report high fidelity detection of an array of single atoms of ^{87}Rb within a high-Finesse, fiber optical microcavity. Atoms are trapped in optical tweezers generated by a high-N.A. lens perpendicular to the cavity. We simultaneously drive two ladder transitions in ^{87}Rb - including the D2 line - and exploit a decay channel producing D1-line photons that are collected through the tweezers lens and spectrally filtered from excitation light. We measure detection fidelity and retention probability dependence on experimental parameters. A comparison of current imaging sensor technologies, including qCMOS and EMCCD, was motivated by the low number of collected photons.

This platform opens the way to experimental study of excitation transport in disordered spin chains with long-range interactions. In the disordered Tavis–Cummings model, dark states are thought to become weakly coupled ("gray") and semi-localized [3], enabling them to play a central role in mediating spin-flip transport.

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Towards Cavity Control of the spin-Peierls transition in $CuGeO_3$

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The 1D Mott insulator CuGeO3 undergoes a structural phase transition below its critical temperature of 14 K, which is characterized by a dimerization of the Cu chains. The transition is driven by the interplay of spin waves with lattice modes that show the corresponding symmetry of the distortion. Modern cavities, which allow for frequency tuning from mid-infrared to THz regimes, provide a platform capable of nonlinear coupling to both phononic and magnonic excitations in the material. This gives access to a wide range of interactions, and we hypothesize that it could enable optical control of the transition. We derive a minimal coupling model of spin, lattice and cavity degrees of freedom, discuss driving protocols for the phase transition and present early results.

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Topological invariants for the SSH model coupled to a single mode cavity

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Coupling electronic systems to cavity photons offers a promising route to probe and control material properties through light-matter interactions. In particular, recent studies have shown that coupling to light can enable manipulation of topological phases of matter, which have gained significant attention following the theoretical prediction of topological insulators and superconductors due to their potential applications in quantum technologies and quantum computing.

While the topological classification of non-interacting fermionic systems is well established within the tenfold way, much less is understood about how to identify and characterize topological protection when photonic operators are involved.

In this work, we investigate the Su–Schrieffer–Heeger (SSH) model, a paradigmatic one-dimensional topological insulator. In its topological phase, the SSH model exhibits a quantized Zak phase in the bulk and zero-energy edge states protected by chiral symmetry. When the system is coupled to a cavity, however, it remains unclear whether chiral symmetry, and thus topological protection, survives.

To address this question, we employ a recently developed high-frequency expansion of the light–matter Hamiltonian, which allows us to trace out the photonic degrees of freedom and obtain an effective fermionic model. In this picture, light-matter coupling manifests as additional interaction terms, enabling us to employ existing results for interacting topological insulators and compute observables such as the electronic polarization, which may serve as a topological invariant. We further analyze the fate of edge states in the open SSH chain coupled to a cavity and discuss open questions regarding the definition of chiral symmetry and topological invariants in coupled electron–photon systems.

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Correlations in cascaded quantum optical systems : a cumulant based approach

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Recent advances in the cumulant expansion scheme have been proven beneficial for studying the dynamics of many-body open quantum systems. In this presentation, we introduce a generalized framework for calculating unequal-time correlation functions within the cumulant expansion approach. As a part of the formalism, we propose an ansatz that enables the implementation of the quantum regression theorem. To validate our method, we apply it to cascaded optical systems and compute many-body correlations, comparing our results against exact simulations. We discuss the domains of validity of our approach and the factors that constrain its performance. Overall, our approach provides an effective tool for exploring correlated dynamics in complex quantum systems.

To infinity and back – $1/N$ graph expansion of light-matter systems

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We present a method for performing a full graph expansion for light-matter systems, utilizing the linked-cluster theorem. This enables us to explore $1/N$ corrections to the thermodynamic limit $N \to \infty$, giving us access to the mesoscopic regime.
Yet largely unexplored, this regime hosts intriguing features, such as the entanglement between light and matter, which vanishes in the thermodynamic limit [1–3].

We calculate ground-state properties, like energy and entanglement entropy, of generalized Dicke models by accompanying the graph expansion by both exact diagonalization (NLCE [4]) and perturbation theory (pcst^{++} [5]), benchmarking our approach against other techniques for the limiting cases of microscopic and macroscopic systems [6].

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Towards Cavity Enhanced Rydberg Superatoms as Deterministic Quantum Network Nodes

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The Rydberg blockade effect, a result of the strong dipolar interactions between Rydberg states, can make a small atomic ensemble behave as a single two-level quantum system while preserving its collective nature, creating what is known as a Rydberg superatom [1]. Coupling such a superatom to an optical cavity provides a system with a strong light-matter interface and a highly nonlinear optical response, making it an ideal candidate for scalable deterministic quantum networks and quantum information processing.

We present the design and current status of a new state-of-the-art experimental setup that we will use to exploit cavity-enhanced Rydberg superatoms for applications in quantum communication. In our setup, a new vacuum system with ultralow reflection coatings will allow to effectively enhance the clouds optical depth by placing it inside of an external triangular cavity with Finesse of 140, boosting the efficiency of the single photon generation significantly. We will also discuss how to deterministically generate time-bin entanglement between a collective Rydberg excitation in the ensemble and a single photon, using what is known as a cyclical retrieving and patching protocol [2]. Inspired by a theoretical proposal, we will also share our ideas on how to encode a qubit register inside the atomic ensemble and conduct deterministic two-qubit gates based on Rydberg interactions [3]. This project will establish atomic Rydberg ensembles as deterministic ’stand-alone’ quantum network and processing nodes and advance the field of quantum communication.

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Non-classical features in vibrational states under electronic strong coupling

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We analyze the nature of vibrational states in a toy-model setup for polaritonic chemistry [1] under collective electronic strong coupling. We employ a disordered Holstein-Tavis-Cummings model, incoherently excited by a photon [2-3]. On the single-trajectory level, after both vibrational and cavity excitation, we demonstrate that vibrational Wigner functions cannot be properly described by Ehrenfest or truncated Wigner approximations. Also, approximations in terms of thermal states fail to describe the vibrational features properly. This implies that capturing full quantum effects is crucial to understanding modified nuclear dynamics in polaritonic chemistry.

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Comparing dynamics of bosons in an optical lattice inside a cavity between Wannier and position bases

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We study the dynamics of a Bose-Einstein condensate (BEC) inside an optical cavity with transverse pumping and an additional intracavity optical lattice along the cavity axis. Specifically, we investigate the theoretical predictions obtained from expanding the atomic field operators of the second-quantized Hamiltonian using the position basis, and single-band Wannier basis. Both bases agree on the existence of most types of static and dynamical phases. However, the large sea of irregular dynamical phase, captured within the position basis, is absent in the Wannier basis. Moreover, we show that they predict different types of limit cycles due to the inherent limitation of the single-band Wannier expansion. Using truncated Wigner approximation, we also investigate the fragmentation dynamics of the BEC. We demonstrate that both position and Wannier bases qualitatively agree on the photon-mediated fragmentation dynamics of the BEC in the density-wave phase, despite the absence of interatomic interactions. The presence of interatomic interaction leads to further fragmentation, which can only be observed in larger system sizes. Finally, we predict a sudden increase in fragmentation behavior for larger pump intensities.

Non-Hermitian Floquet Engineering with Cavity-QED Tweezer Arrays

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We propose a theoretical framework for engineering non-Hermitian many-body states through Floquet modulation of cavity-QED tweezer arrays. In this setup, individually trapped atoms in optical tweezers couple collectively to a single cavity mode with position-dependent phases. The intrinsic dissipation from cavity decay and spontaneous emission is captured by a time-periodic Lindblad master equation. In the fast-driving regime, we derive an effective time-independent Lindbladian, which under weak pumping conditions or post-selection reduces to a non-Hermitian effective Hamiltonian. Preliminary matrix product state simulations suggest that this driven-dissipative dynamics generates graph states with complex-valued entanglement structures and state-dependent decoherence rates. The controlled non-Hermitian evolution opens prospects for topological quantum computing where engineered dissipation could actively suppress errors while preserving topological degrees of freedom. Our predictions are developed in close collaboration with ongoing experiments where current tweezer technology already enables the necessary control for implementing these protocols.

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Purcell-enhanced quantum yield of spin defects using open resonators

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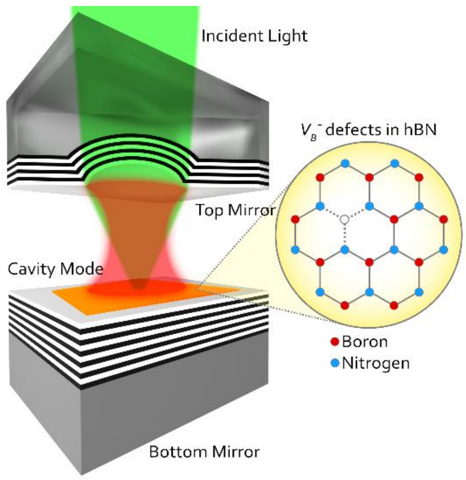
Two-dimensional materials are the emerging materials for quantum photonic applications. Hexagonal boron nitride (hBN) has attracted significant interest due to the defect states, which provide emission across the ultraviolet to near-infrared range at room temperature. While many of the defects act as single photon emitters, the negatively charged boron vacancy (V_B^-) in the hBN exhibits spin-dependent optical response[1]. Spin qubits from these V_B^- defects are promising for quantum sensing applications, similar to the nitrogen vacancy centres in diamond. The two-dimensional nature of hBN and the ability to create defects at its surface make it a favourable platform for integration with photonic chips compared to NV centres in diamond or other bulk systems. Despite these advances, V_B^- defects suffer from low quantum efficiency due to the faster intersystem crossings being non-radiative and faster by many orders of magnitude than radiative decay. One approach to solve this problem is to make radiative decay faster using Purcell enhancement. Here, we use open micro resonators, concentrating the electric field by enhancing the light-matter interaction[2]. When the number of states available to emitters in the cavity is reduced and the radiation is directed into specific modes, the emitter's properties are enhanced through the Purcell effect[3]. Recent advances in Focused Ion Beam (FIB) fabrication now let researchers create concave features with minimal radii of curvature[4]. This enables ultra-small mode volumes at the scale of the wavelength. This facilitates a sizable Purcell effect even in the bad emitter regime, where the homogeneous linewidth of the emitter is larger than the linewidth of the cavity mode. We assume that this method not only opens up a new tunable approach for enhancing the quantum yield of the V_B^- defects but also enriches the field of quantum sensing.



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Entanglement-enhanced quantum sensing via optimal global control with neutral atoms in cavity

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We present a deterministic protocol for the preparation of entangled states in the symmetric Dicke subspace of medium sized spin systems N up to 100, coupled to a common cavity mode that prepares entangled states useful for quantum sensing, achieving a precision significantly better than the standard quantum limit in the presence of photon cavity loss, spontaneous emission and dephasing [1]. The protocol combines a new *cavity driven geometric phase gate* [2] which can be utilized for exact unitary synthesis on the Dicke subspace, an analytic solution of the noisy quantum channel dynamics and optimal control methods to shape the laser pulses -- i.e. the classical photon field driving the cavity mode and a global laser driving spin rotations. Our noise-informed protocol, which requires only a few global cavity-drive pulses and rotations, predicts promising performance for atom–cavity cooperativities of C = 25, a regime already demonstrated experimentally [3].

This work provides a simple experimental route to entanglement-enhanced sensing with cold trapped atoms in cavities and can be extended to other spin systems coupled to a bosonic mode.

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Quantum dot - photon interface based on an open-tunable fiber cavity

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Advances in quantum communication rely on robust and efficient single-photon (SP) sources. Indium arsenide quantum dots (QDs) are a well-established platform for SP generation, offering high purity, indistinguishability, and brightness. Embedded in high-refractive-index GaAs, only a small fraction of the emitted photons can be extracted from the host material, hindering direct integration into optical fibers for practical applications.
To address this limitation, we present an open, tunable fiber microcavity that allows precise spatial and spectral control (cf. Fig. 1a). Such cavities offer Purcell-enhanced (F_P) emission rates, selective coupling to individual QDs, and inherently high collection efficiency through direct fiber coupling [1-3].
Integrated into a cryogenic setup and engineered for high passive mechanical stability (~10^1 pm RMS, Fig. 1b), the system allows stable operation and controlled coupling to near-infrared InAs QDs (Fig. 1c). This platform enables scalable, fiber-integrated single-photon sources for quantum communication networks.

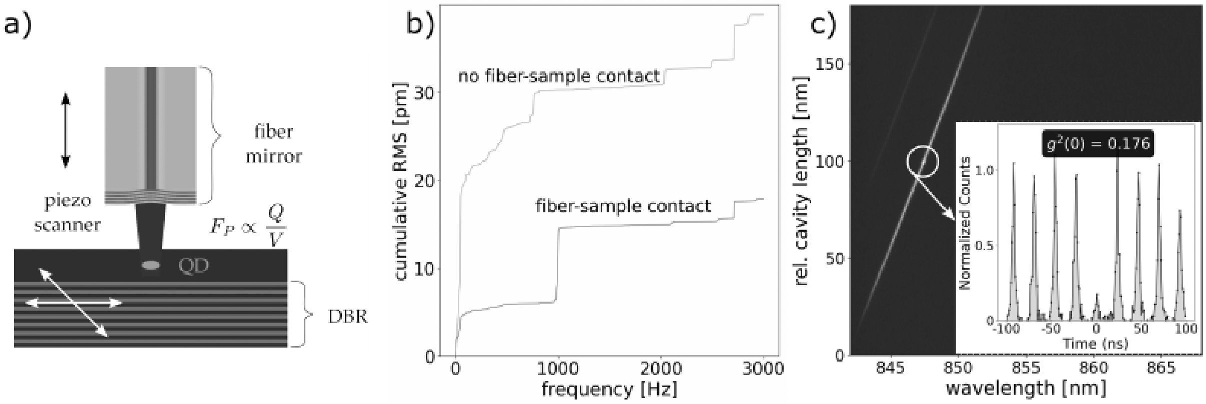

Figure 1: *(a) Schematic of the fiber-based QD microcavity. (b) Cumulative RMS cavity displacement with and without fiber–sample contact. (c) PL map during cavity-length scan showing coupling to a QD; inset: $g^{(2)}(0)=0.176$ confirms SP-emission.*

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Room-temperature polariton condensate in a quasi-2D dimensional hybrid perovskite

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Quasi-2D halide perovskites are chemically synthesized realizations of quantum well stacks with giant exciton oscillator strengths, tunable emission spectra and very large exciton binding energies. While these features render quasi-2D halide perovskites a promising platform for roomtemperature polaritonics, bosonic condensation and polariton lasing in quasi-2D perovskites have so far remained elusive at ambient conditions. Here, we demonstrate room-temperature cavity exciton-polariton condensation in mechanically exfoliated crystals of the quasi-2D Ruddlesden-Popper iodide perovskite $(BA)_2(MA)_2Pb_3I_{10}$ in an open optical microcavity [1]. We observe a polariton condensation threshold of P_{th}= 0.41 µJ cm^{-2} per pulse and detect a strong non-linear response. Interferometric measurements confirm the spontaneous emergence of spatial coherence across the condensate with an associated first-order autocorrelation reaching $g^{(1)} \approx 0.6$ with 1 ps coherence time and an effective de Broglie wavelength of 13 µm. Our results lay the foundation for a new class of room-temperature polariton lasers based on quasi-2D halide perovskites with great potential for hetero-integration with other van-der-Waals materials and combination with photonic crystals or waveguides.

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High-Rate Remote Entanglement Generation using Hybrid Single-Ion Atomic-Ensemble Nodes

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Different quantum systems possess favorable qualities for different tasks. Ensemble-based quantum memories are suited for fast multiplexed long-range entanglement generation, while single-atomic systems have advanced (local) gates available. Both provide distinct advantages for high-rate entanglement generation within quantum networks. Thus, we develop a hybrid architecture that takes advantage of these properties by combining trapped-ions in cavities, spontaneous parametric down conversion photon pair sources, and absorptive memories of rare-earth ion ensembles. We solve the central challenge of matching the different bandwidths of photons emitted by those systems in an initial entanglement-generation step. Furthermore, we compare a double-click and single-click scheme within the ion nodes. We show that our approach enables fast ion-ion entanglement generation over hundreds of kilometers.

Ultrafast manipulation of topological transport properties in Td-MoTe2 via coherent phonon excitation

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The ultrafast manipulation of topological properties in quantum materials has recently attracted significant attention due to its potential applications in dissipationless and fast-responding optoelectronic devices. In particular, the selective photoexcitation of coherent phonons in type-II Weyl semimetals, such as Td-$MoTe_2$ and related compounds, has been proposed as an efficient non-thermal pathway to induce topological phase transitions by modifying lattice symmetry. However, the microscopic mechanisms that drive the excitation of interlayer shear modes under varying laser parameters remain elusive. Both electron–phonon coupling (EPC) and strong phonon anharmonicity appear to play critical roles. Here, by combining real-time time-dependent density functional theory (rt-TDDFT) with non-adiabatic molecular dynamics (NAMD) simulations, we explore the excitation pathways of this key mode under different photon energies, polarizations, and field amplitudes. We identify the cooperative contributions of EPC and phonon–phonon scattering processes, enabling control over the phase and amplitude of the coherent phonon. Furthermore, we predict shifts in the Weyl node positions and associated photocurrent responses, offering insight into experimental observations of ultrafast nonlinear Hall transport.

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Towards minimally destructive detection of cold molecules using optical cavity

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The interaction of atoms with cavities has largely centered around the coupling of an atomic, two-level, closed system coupled to the cavity mode. When the number of atoms coupled to the cavity increases and/or the finesse decreases, the regime of collective strong coupling is accessed. In such a system, when N two level systems are coupled to the cavity mode, the measured vacuum Rabi splitting (VRS) is a factor of $\sqrt{N}$ W.r.t the single atom-cavity coupling g_0.This leads to collective effects.

In our experiments with Rb atoms in an MOT collectivelly coupled to a cavity, multiple-atom cavity phenomena are exhibited, including a-Damped oscillations in the g^2 of cavity emission from the driven atom-cavity system, at two different frequencies [1], b-"Gain, amplification, and lasing in a driven atom-cavity system," [2]. In addition to driven MOT atoms coupled to the cavity, we have investigated the nearly non-destructive detection of multi-level atoms using cavity-based collective strong coupling [3]. This is motivated by the possibility of cold molecule detection using cavity QED techniques. The challenge is that for multi-level systems, the atom/molecule can decay to dark states, and therefore be lost to cavity detection. Building on the theoretical proposal of Sawant et al [4], we demonstrate that the VRS based detection of an open atomic system is possible, and this is a critical step towards the detection of the strongly coupled molecules.

In this recent study [3], we have developed a cavity detection scheme of a multi-level system; for that, we have used an ^{85}Rb MOT that is coupled to the cavity mode. This VRS measurement gives us the advantage to investigate the same ensamble of atoms for long duration of time. To extend this further our goal is to study the interaction between different species (Molecules, Atoms, ions) with the minimal destruction by probe of the ensemble.

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Engineering One Axis Twisting via a Dissipative Berry Phase Using Strong Symmetries

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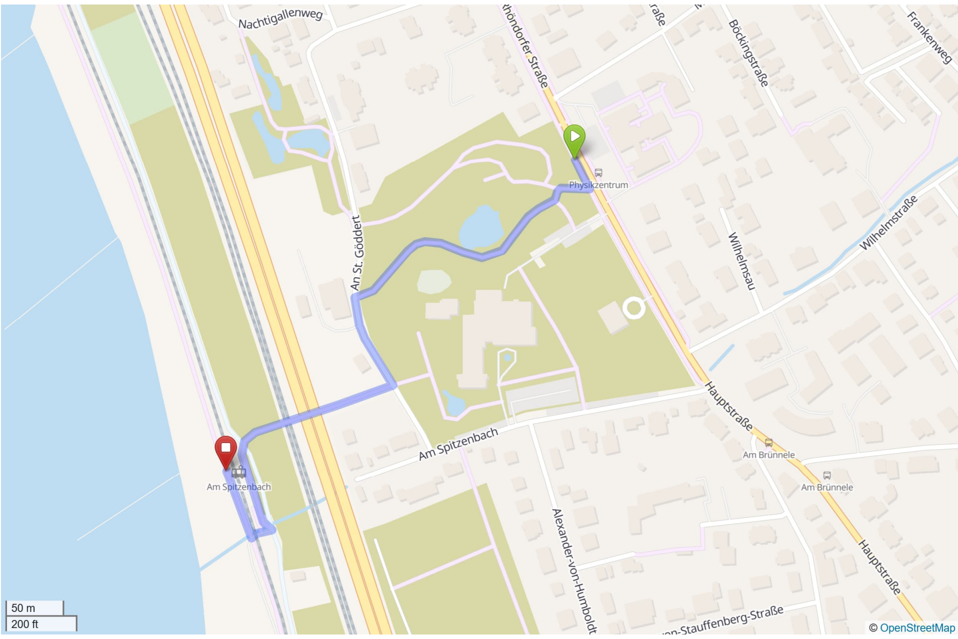
In many-body quantum systems, the environment tends to destroy quantum entanglement via dissipation. However, it is also possible to instead harness the effect of the environment as a resource to prepare useful quantum entanglement. In this poster, we theoretically show how a driven-dissipative cavity coupled to a collective ensemble of multilevel atoms can dynamically generate metrologically useful spin-squeezed states [1]. In contrast to other dissipative approaches, we do not rely on complex engineered dissipation or input states, nor do we require tuning the system to a critical point. Instead, we utilize a strong symmetry, a special type of symmetry that can occur in open quantum systems and emerges naturally in systems with collective dissipation, such as superradiance. We demonstrate how this symmetry allows for the generation of spin-squeezed states via emergent one-axis twisting dynamics that arise from an atom-number dependent Berry phase and discuss how our approach provides advantages over comparable dissipative and coherent approaches for implementation in state-of-the-art optical clocks.

References

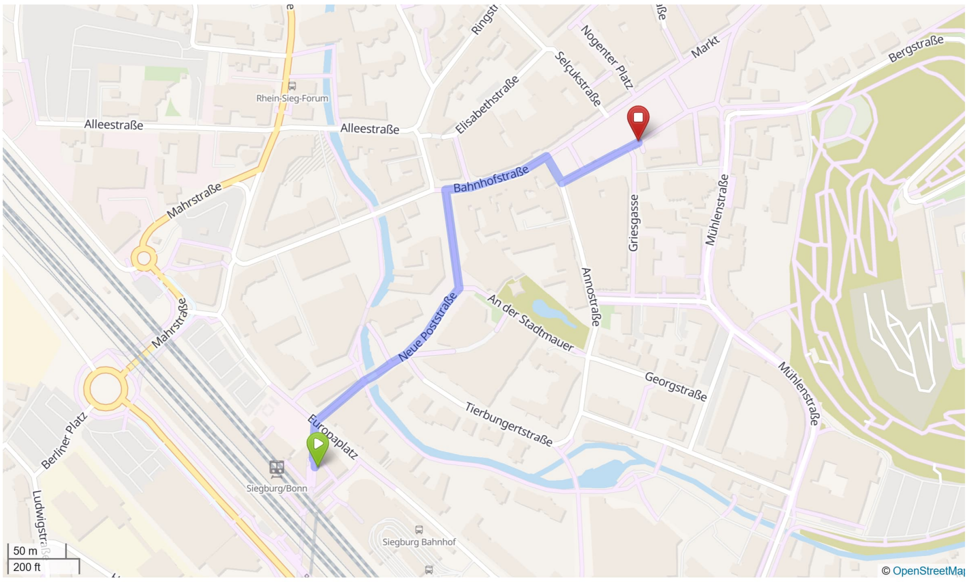
[1] J.T. Young, E. Chaparro, A. Piñeiro Orioli, J.K. Thompson, and A.M. Rey Physical Review Letters **134**, 040801 (2025)

Excursion to the Medieval Christmas Market in Siegburg

To get to the Christmas market, take the tram line 66 from Bad Honnef, Am Spitzenbach to Siegburg, Bahnhof. One trip takes about 60 minutes. The tram runs every 20 minutes in each direction. We will purchase tickets (Preisstufe 4) in advance.
In Bad Honnef: the closest tram stop of the line 66 is at "Am Spitzenbach".



In Siegburg: the Christmas market is located at the *Markt* in Siegburg



To go back from Siegburg, please, take the line 66 to "Bad Honnef Stadtbahn", not to Königswinter. The tram back to Bad Honnef goes every 20min.