Collective Effects and Non-Equilibrium Quantum Dynamics

724. WE-Heraeus-Seminar

28 - 30 June 2021
ONLINE

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 724. WE-Heraeus-Seminar:

Collective, non-linear dynamics and spontaneous self-organization are abundant in nature, sciences and technology. These processes are found in biology and chemistry, in non-linear optics and condensed matter physics, and across both the classical and the quantum regime. The understanding of such dynamics is important for fundamental sciences, where the non-equilibrium quantum dynamics is a major quest from a fundamental point of view, and for quantum technologies, with the demand for complex systems with robust quantum coherent dynamics.

A promising and versatile platform to study these processes in a highly controlled way is the collective interaction of light with laser-cooled cold or quantum-degenerate matter. This experimental setting explores the innovative control of matter through optomechanical effects, identifying novel quantum phases, investigating light transport in strongly scattering and disordered systems. Additionally, it is advancing our knowledge of long-range coupled systems in the presence of noise and driving fields.

This seminar focuses on collective effects and non-equilibrium quantum dynamics in systems with matter-light interaction. In addition to self-organization of matter in classical and quantized light fields, collective scattering involving coupled dipoles and finite-range interactions, via complex multi-mode light fields or via Rydberg atoms will be central topics in the workshop. The aim is to bring together the different communities working on the crucial topics of this rapidly evolving field. Each topical session is preceded by an introductory talk, followed by several invited and hot-topic talks. The poster and discussion sessions are central elements to the seminar, fostering interaction between junior and senior researchers.

Introduction

Scientific Organizers:

Dr. Tobias Donner	ETH Zurich E-mail: donner@phys.ethz.ch
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Program

Program *(CEST)*

Monday, 28 June 2021

09:45 – 10:00	Tobias Donner Thorsten Ackemann Sebastian Slama	**Welcome and Introduction (Scientific Organizers / WE Heraeus Foundation)**
Chair: Thorsten Ackemann		
10:00 – 11:00	Ehud Meron	**Classical Self-Organization: Mechanisms and Functional Aspects**
11:00 – 11:30	*MINGLING on the MeetAnyway platform*	
Chair: Tobias Donner		
11:30 – 12:10	Giovanna Morigi	**Quantum Interference in the Bose-Hubbard Model of Many-Body Cavity Quantum Electrodynamics**
12:10 – 12:35	Jean-Philippe Brantut (Hot topic talk)	**Cavity Quantum-Electrodynamics With Atoms and Pairs in a Strongly Interacting Fermi Gas**
12:35 – 14:30	*LUNCH BREAK*	
Chair: Andreas Nunnenkamp		
14:30 – 15:10	Davide Dreon	**Emerging Atom Pump in a Non-Hermitian System**
15:10 – 15:50	Oded Zilberberg	**Out-of-Equilibrium Phases: the Role of Dissipation, Noise, and Competing Drives**
15:50 – 16:15	*COFFEE TABLE DISCUSSION*	
16:15 – 17:45	*POSTER SESSION I / Coffee Table Discussion*	
17:45 – 18:00	*BREAK*	
Chair: Sebastian Slama		
18:00 – 18:40	Benjamin Lev	**An Optical Lattice with Sound**
18:40 – 19:20	Monika Schleier-Smith	**Atoms Interlinked by Light: Programmable Interactions and Emergent Geometry**

Program *(CEST)*

Tuesday, 29 June 2021

Chair: Gian-Luca Oppo, or Tobias Donner

09:00 – 09:40	Igor Lesanovsky	**Time-Crystal Phase Transition, Fluctuations, and Quantum Correlations in an Emitter-Waveguide System with Feedback**
09:40 – 10:20	Andreas Nunnenkamp	**Higher-Order and Fractional Discrete Time Crystals**
10:20 – 10:45	Hans Kessler (Hot topic talk)	**Observation of a Dissipative Time Crystal in a Driven Atom-Cavity System**
10:45 – 11:30	*COFFEE TABLE DISCUSSION*	

Chair: Sebastian Slama

11:30 – 12:10	Corinna Kollath	**Dissipative Phase Transitions of Atoms Coupled to an Optical Cavity**
12:10 – 12:35	Francesco Ferri (Hot topic talk)	**Emerging Dissipative Phases in a Superradiant Quantum Gas**
12:35 – 14:30	*LUNCH BREAK*	

Chair: Gordon Robb

14:30 – 15:10	Helmut Ritsch	**Spontaneous Self-Ordering and Crystallization Via Collective Coherent Atom–Photon Dynamics**
15:10 – 15:50	Peter Kirton	**Dissipative Phase Transitions in Collective Spin Models**
15:50 – 16:15	*COFFEE TABLE DISCUSSION*	
16:15 – 18:00	*POSTER SESSION II / Coffee Table Discussion*	

Chair: Giovanna Morigi

20:00 – 21:00	*PANEL DISCUSSION SESSION*	

Program *(CEST)*

Wednesday, 30 June 2021

Chair: Cornelia Denz

09:00 – 09:40	Nir Davidson	**Observation of Spin-Spin Fermion-Mediated Interactions and Nonlinear Spin Dynamics in a BEC**
09:40 – 10:20	Sonja Franke-Arnold	**An Atomic Compass - Detecting Magnetic Field Alignment with Vector Vortex Light**
10:20 – 10:45	Valeria Bobkova (Hot topic talk)	**Light-Driven Nonlinear Dynamics of a Colloidal Suspension in a Single Feedback System**
10:45 – 11:30	*COFFEE TABLE DISCUSSION*	

Chair: Nicola Piovella

11:30 – 12:10	Robin Kaiser	**Cooperative Effects in Atom-Light Interactions**
12:10 – 12:50	Igor Ferrier-Barbut	**Superradiance and Subradiance of Two Level Atoms on the Edge of Dicke's Regime**
12:50 – 14:30	*LUNCH BREAK*	

Chair: Peter Kirton

14:30 – 15:10	Gordon Robb	**Supersolid Formation via Diffractive Coupling**
15:10 – 15:50	Michael Drewsen	**Controlling the Normal Modes of Ion Coulomb Crystals Through Application of Optically Induced Dipole Potentials**
15:50 – 16:15	*COFFEE TABLE DISCUSSION*	

Chair: Thorsten Ackemann

16:15 – 16:40	Jamir Marino (Hot topic talk)	**Correlation Engineering Via Non-Local Dissipation**
16:40 – 17:05	Gabriel Landi (Hot topic talk)	**Quantum Phase-Space Thermodynamics in Driven-Dissipative Transitions**

Program *(CEST)*

17:05 – 17:45	Oliver Steinbock	**Non Equilibrium Pattern Formation in Biology and Materials Science**
17:45 – 18:00	*CLOSING REMARKS AND POSTER PRIZE*	

Posters

Poster Session I - 28 June - 16:15 - 17:45 h

1	Giuseppe Baio	**Structural Phase Transitions in Cold Atoms Mediated by Optical Feedback**
2	Alla Bezvershenko	**Dicke Transition in Open Many-Body Systems Determined by Fluctuation Effects**
3	Lucas Borges	**Dynamics of Matter Waves Undergoing Bloch Oscillations in a Ring Cavity**
4	Miriam Büttner	**Mott Transitions in a Cavity-BEC System: A Quantitative Comparison of Theory and Experiments**
5	Graeme Campbell	**Optomechanical Self-Structuring and Brownian-Mean-Field Phase Transitions**
6	Mark Anthony Carroll	**Collective Anti-Bunching and Laser Thresholds in Nanolasers**
7	Marco Cattaneo	**Collective Phenomena on Superconducting Qubits: Synchronization, Subradiance, and Entanglement Generation**
8	Ana Cipris	**Subradiance Beyond the Linear-Optics and the Dilute Regimes in Macroscopic Cold Atomic Clouds**
9	Tommas Comparin	**Universal Spin Squeezing from the tower of States of U(1)-Symmetric Spin Hamiltonians**
10	Adrian Costa-Boquete	**Spontaneous Atomic Crystallization via Diffractive Dephasing in Optical Cavities**
11	François Damanet	**Atom-Only Dynamics in Multimode Cavity QED**
12	Uros Delic	**Tunable Dipole-Dipole Interaction Between Optically Levitated Nanoparticles**

Poster Session I - 28 June - 16:15 - 17:45 h

13	Oriana Diessel	**Emergent Kardar-Parisi-Zhang Phase in Quadratically Driven Condensates**
14	Hodei Eneriz	**Loading and Cooling in an Optical Trap via Dark States**
15	Francesca Famà	**Towards Continuous Superradiance with a Hot Atomic Beam**
16	Catalin-Mihai Halati	**Fluctuations and Symmetry Effects in Many-Body Self-Organization in a Dissipative Cavity**
17	Grant Henderson	**Mutual Self Structuring and Novel Kerr-Like Fragmentation in Coupled Light/Matter-Wave Interactions**
18	Daniela Holzmann	**A Versatile Quantum Simulator for Coupled Oscillators Using a 1D Chain of Atoms Trapped Near an Optical Nanofiber**
19	Ole Iversen Thomas Pohl	**Correlated Light and Self-Organization of Photons in Chiral Three-Level Emitter Chains**
20	Peter Karpov	**Quantum Droplet Phases in Extended Bose-Hubbard Models with Cavity-Mediated Interactions**
21	Aleksei Konovalov	**Impact of the Atomic Multilevel Structure on Observation of Spectral Lines**
22	Mateo Kruljac	**Collective Light-Atom Interaction in Free Space and in an Optical Cavity**
23	Lukáš Lachmann	**Highly Nonlinear Quantum Optics and Mechanics**

Poster Session II - 29 June - 16:15 - 18:00 h

1	Alessio Lerose	**Influence Matrix Approach to Quantum Many-Body Dynamics**
2	Xiangliang Li	**Emergent Structures and Dynamics in a Quantum Gas Coupled to an Optical Cavity**
3	Rui Lin	**Dynamics Towards Multistable Inverted States of an Open Three-Level Dicke Model**
4	Chetan Sriram Madasu	**Homodyne Detection of a Two-Photon Resonance Assisted by Cooperative Emission**
5	Matteo Magoni	**Emergent Bloch Oscillations in a Kinetically Constrained Rydberg Spin Lattice**
6	Natalia Masalaeva	**Spin and Density Self-Ordering in Dynamic Polarization Gradients Fields**
7	Fabian Maucher	**Collective Quantum Effects in Dipolar Bose-Einstein Condensates**
8	Raphael Menu	**Adiabaticity Enhancement Via Quantum Non-Demolition Measurement**
9	John Moroney	**A Non-Equilibrium Phase Transition in Disordered Lattices of Polariton Condensates**
10	Dávid Nagy	**Quantum Noise in Cavity Bose-Hubbard Systems**
11	Laurin Ostermann	**A Nanoscale Coherent Light Source**
12	Christopher Parmee	**Signatures of Phase Transitions and Optical Bistability for Atoms in Optical Lattices**
13	Krzysztof Pomorski	**Equivalence Between Classical Epidemic Model and Non-Dissipative and Dissipative Quantum Tight-Binding Model**

Poster Session II - 29 June - 16:15 - 18:00 h

14	Fabio Revuelta	**Dynamical Localization in Non-Ideal Kicked Rotors Driven by Two Modulations**
15	Rodrigo Rosa-Medina	**Emerging Spin Currents and Dissipative Phases in a Superradiant Quantum Gas**
16	Maximilian Schemmer	**Unraveling Two-Photon Entanglement via the Squeezing Spectrum of Light Traveling Through Nanofiber-Coupled Atoms**
17	Tom Schmit	**Synchronization of Atoms with a V-Level Structure**
18	Elmer Suarez	**Detecting Atomic Dynamics in a Cavity-Rydberg System**
19	Angel Tarramera Gisbert	**Multimode Atomic Recoil Lasing in Free Space**
20	Josh Walker	**Dynamics of Optomechanical Droplets**
21	Tomasz Wasak	**Fermi Polaron Laser in Two-Dimensional Semiconductors**
22	Louise Wolswijk	**Out-of-Equilibrium Dynamics in BEC Formation**
23	Lida Zhang	**Nonlinear Behaviour of Atomic Dipole Arrays**
24	Nicolo Defenu	**Metastability and Discrete Spectrum of Long-Range Systems**

Abstracts of Lectures

(in alphabetical order)

Light-driven nonlinear dynamics of a colloidal suspension in a single feedback system

V. Bobkova[1], A. Goenner[1], G. Baio[2], and C. Denz[1]

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Spatio-temporal self-organization is a ubiquitous phenomenon that can be observed in many nonlinear optical media in a combination with various optical feedback geometries. Photorefractive crystals [1-2], atomic vapors [3], and liquid crystals [4] exhibit a variety of temporally stable transverse patterns induced by a model system based on a single mirror feedback geometry that allows identifying fundamental features of self-organized transverse pattern formation in optics. The light patterns and their dynamic evolution can be controlled by manipulation in a Fourier plane [2] within the imaging unit of the single feedback system.

In this contribution, we demonstrate the self-organized behavior of a novel artificial nonlinear media in such a model-like single feedback system. We employ a colloidal suspension of polystyrene nanoparticles in water as a saturable nonlinear optical medium. It is well-known that highly concentrated solutions of polystyrene beads with 100..200 nm diameter show nonlinear responses in a number of “classical” nonlinear optical experiments, namely self-focusing [5], four wave mixing [6], and modulation instability [7]. Being influenced by the optical gradient force, particles are dragged towards the intensity maxima. The density redistribution of the suspension in turn initiates a spatial modulation of the refractive index. Thus, within our approach, we combine modulational instability in a colloidal suspension with a single feedback configuration to achieve pattern formation by optomechanical displacement of the nanoparticles.

References

[1] T. Honda, Opt. Lett. **18**, 598-600 (1993).
[2] C. Denz et al., Springer (2003).
[3] Petrossian et al., Europhys. Lett. **18**, 689-695 (1992).
[4] M. Tamburrini et al., Opt. Lett. **18**, 855-857 (1993).
[5] A. Ashkin et al., Opt. Lett. **7(6)**, 276–278 (1982).
[6] P. W. Smith et al., Opt. Lett. **6(6)**, 284–286 (1981).
[7] P. J. Reece et al., Phys. Rev. Lett. **98(20)**, 203902 (2007).

Cavity quantum-electrodynamics with atoms and pairs in a strongly interacting Fermi gas

H. Konishi, K. Roux, V. Helson, T. Zwettler and J.P. Brantut

EPFL, Lausanne, Switzerland

The experimental realization of a quantum-degenerate, strongly interacting Fermi gas coupled to a high-finesse cavity will be presented [1,2].

In addition to the direct photon-atom coupling, manifested in the spectrum of the coupled system, this system also shows strong photon-pair coupling. The latter arises through the coupling of Fermion-pairs to light via photo-association to long-range molecular states.

The cavity transmission spectrum close to these transitions exhibits the anti-crossing characteristic of strong light-matter coupling, signaling the onset of coherent ‘pair-polaritons’. I will describe the dependence of the optical spectrum on interaction strength, and connect the optical spectrum of the cavity with Tan’s contact, a universal property of the many-body physics of the Fermi gas. This provides a new connection between quantum optics and strongly correlated matter [3].

Both the atom-photon and pair-photon strong coupling can be leveraged in the dispersive regime to perform weakly destructive, repeated measurements of an individual atomic sample, which opens perspective for the continuous measurement of currents and quantum dynamics in complex quantum systems.

References

[1] K. Roux, H. Konishi, V. Helson and J.P. Brantut, Nature Communications **11**, 1-6 (2020)

[2] K. Roux, V. Helson, H. Konishi and J.P. Brantut, New Journal of Physics **23**, 043029 (2021)

[3] H. Konishi*, K. Roux*, V. Helson and J.P. Brantut, arXiv 2103.02459 (to appear in Nature)

Observation of Spin-Spin Fermion-Mediated Interactions and Nonlinear Spin Dynamics in a BEC

Nir Davidson

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In a mixture of a condensed Bose gas (BEC) and spin polarized degenerate Fermi gas (DFG), fermions can mediate collisions between bosons, leading to an effective long-range interaction between the bosons, analogous to Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction in solids. Using Ramsey scheme spectroscopy, we measure frequency shifts of the bosons' hyperfine levels due to interactions with fermions. We isolate the frequency shift related to mediated interaction from shifts caused by direct collision of fermions and bosons. Our measurement show an increase of spin-spin interaction between bosons by a factor of 1.43 in the presence of the DFG, providing a clear evidence of spin-spin fermion mediated interaction. Fermion mediated interactions can potentially give rise to interesting new magnetic phases and extend the Bose-Hubbard model when the atoms are placed in an optical lattice. This interaction can be tuned with a boson-fermion Feshbach resonance.

We also study the evolution of a the BEC in a two-state superposition due to inter-state interactions using microwave spectroscopy. These interactions have a non-linear spin component, leading to a shearing effect on the Bloch sphere. We use a population imbalanced dynamic decoupling scheme that accumulates inter-state interactions while canceling intra-state density shifts and external noise sources. We repeat measurements on both magnetic sensitive and insensitive transitions with similar uncertainties, showing that we successfully decoupled our system from strong magnetic noises. Our scheme can be extended to other systems, such as quantum memories that are inherently imbalanced populations, and used close to a Feshbach resonance, where interactions diverge, and strong magnetic noises are ever present. Our results also allow for a better understanding of inter atomic potentials.

Emergent atom pump in a non-hermitian system

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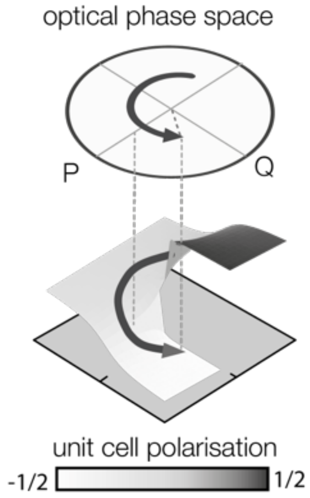
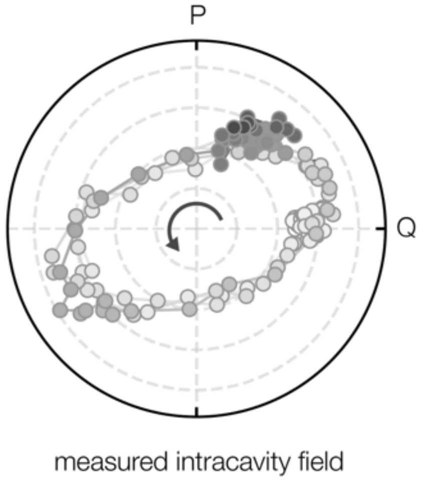
The time evolution of a quantum system can be strongly affected by dissipation. Although this mainly implies that the system relaxes to a steady state, in some cases it can bring to the appearance of new phases and trigger emergent dynamics.
In our experiment, we study a Bose-Einstein Condensate dispersively coupled to a high finesse resonator. The cavity is pumped via the atoms, such that the sum of the coupling beam(s) and the intracavity standing wave gives an optical lattice potential. When the dissipation and the coherent timescales are comparable, we find a regime of persistent oscillations where the cavity field does not reach a steady state. In this regime the atoms experience an optical lattice that periodically deforms itself, even without providing an external time dependent drive. Eventually, the dynamic lattice triggers a pumping mechanism. We will show complementary measurements of the light field dynamics and of the particle transport, proving the connection between the emergent non-stationarity and the atomic pump.





Speaker

Michael Drewsen
Center for complex Quantum systems
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Titel

Controlling the normal modes of ion Coulomb crystals through application of optically induced dipole potentials.

Abstract

Through the application of optically induced dipole potentials to ions constituting a Coulomb crystal in a linear rf trap, it is possible to pin the individual ions in the crystal with subwavelength localization with respect to the minima of such additional potential for one-, two-, and three-dimensional crystals [1]. Besides, e.g., proving the potential for the control of the global structure of ion Coulomb Crystals [2] and stronger collective coupling of the crystallized ions to a standing wave light field as a consequence of the spatial regularity of the ions position with respect to the nodes/anti-nodes of the field, tuning of the applied light intensities offer an unique opportunity of tailoring the common mode spectra and patterns of the entire Coulomb crystal with applications in a broad range of investigations of collective quantum dynamics [1].

Based on our experimental results achieved so-far on pinning of ions within Coulomb crystals, in my presentation, I will discuss future experiments and the potentials of exploiting optically induced potentials in the connection of collective quantum dynamics.

[1] T. Lauprêtre, R. B. Linnet, I. D. Leroux, A. Dantan, M. Drewsen, Phys Rev A (Rapid Communication) **99**, 031401 (2019).
[2] P. Horak, A. Dantan, and M. Drewsen, Phys. Rev. A. **86**, 043435 (2012).

Emerging dissipative phases in a superradiant quantum gas

F. Ferri[1], R. Rosa-Medina[1], F. Finger[1], N. Dogra[1], M. Soriente[2], O. Zilberberg[2], T. Donner[1], and T. Esslinger[1]
[1]Institute for Quantum Electronics, ETH Zürich, 8093 Zürich, Switzerland
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Exposing a many-body system to external drives and losses can deeply modify its phases. Beside their fundamental interest, driven-dissipative systems prompt new paradigms for material engineering. A prime example is given by hybrid systems in which tuning of the elementary excitations is obtained by coupling matter to light. In this perspective, gaining conceptual understanding on how the microscopic properties of such systems can be tuned by the coupling to the environment is of primary interest. However, it is often a challenge to find platforms combining well-defined, tunable coherent and dissipative channels and, at the same time, the access to microscopic observables of the system. We report on a synthetic many-body system offering these possibilities, based on a Bose-Einstein condensate that is strongly coupled to an optical cavity. In our experiment, both spin and momentum of the atoms are coupled to the lossy cavity mode via two independent external Raman drives [1]. Adjusting the imbalance between the drives allows to tune the competition between coherent dynamics and dissipation, with the appearance of a dissipation-stabilized phase and bistability. We characterize the properties of polariton modes and relate the observed phases to the microscopic elementary processes in the open system. Our findings provide prospects for studying squeezing in non-Hermitian systems, quantum jumps in superradiance, and dynamical spin-orbit coupling in a dissipative setting.

References

[1] F. Ferri, R. Rosa-Medina *et al.*, arXiv:2104.12782 (2021)

Superradiance and subradiance on the edge of Dicke's regime

Igor Ferrier-Barbut[1]

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Two identical two-level atoms can interact via the resonant dipole-dipole interaction: the radiation of one acts resonantly on the other, and vice-versa [3]. The description of the collective spontaneous emission of an ensemble of two-level atoms as described by Dicke in his seminal paper [1] underpins the modern understanding of collective radiation of quantum emitters. Two well-known phenomena arise in collective spontaneous emission: **superradiance**, whereby atoms radiate more efficiently than their individual decay, and reversely **subradiance** in which the atomic ensemble retains the excitation and emits it at a slower rate.

I will describe experiments in which we create the **textbook conditions of an ensemble of two-level atoms with total size a few wavelength** and interatomic distance much shorter than the wavelength [2]. While simply posed, this problem is quickly intractable as we explore the 2^N-large Hilbert space. We perform a near complete population inversion of the atoms to the excited state this create a **highly symmetric initial state**, from which we observe **Dicke superradiance** in the optical domain above a threshold for atom number. By changing the initial state and starting with an **incoherent mixture** state produces a very different decay, in which we observe a **subradiant tail**. This allows us to shed light on the structure of collective states with multiple excitations and how their construction determines their decay rate [4]. Finally, we show that the tools of atomic physics experiment allow to control the coupling between atoms, a feature we use to **release on demand** the excitations stored in subradiance.

References

[1] R. H. Dicke, *Phys. Rev.* **93**, 99 (1954).
[2] A. Glicenstein *et al., Phys Rev. Lett.* **124**, 253602 (2020).
[3] A. Glicenstein *et al., Phys Rev. A* **103**, 043301 (2021).
[4] G. Ferioli *et al., Phys. Rev. X,* in press (2021).

An Atomic Compass - Detecting Magnetic Field Alignment with Vector Vortex Light

Sonja Franke-Arnold

University of Glasgow, UK

Research on complex vector light has seen an explosion in activity over the past decades, powered by technological advances for generating such light, and driven by questions of fundamental science as well as engineering applications.Yet, when it comes to light-matter interaction we often ignore the role of polarisation. I will present the methods we use to generate and analyse vector light in our lab and discuss the interplay between vector light, external magnetic fields and atomic vapours. Specifically, I will show how we can visualising magnetic field alignment with spin aligned atoms - demonstrating an atomic compass.

Cooperative effects in atom-light interactions

Robin Kaiser

CNRS, Valbonne, France

The quest for Anderson localization of light is at the center of many experimental and theoretical activities. Cold atoms have emerged as interesting quantum system to study coherent transport properties of light. Initial experiments have established that dilute samples with large optical thickness allow studying weak localization of light, which has been well described by a mesoscopic model. Recent experiments on light scattering with cold atoms have shown that Dicke super- or subradiance occurs in the same samples, a feature not captured by the traditional mesoscopic models. The use of a long range microscopic coupled dipole model allows to capture both the mesoscopic features of light scattering and Dicke super- and subradiance in the single photon limit. I will review experimental and theoretical results on cooperative scattering of light by cold atoms and on the state of the art on the possibility of Anderson localization of light by cold atoms.

Observation of a dissipative time crystal in a driven

H. Keßler[1], P. Kongkhambut[1], C. Georges[1], L. Mathey[1,2], J. G. Cosme[3], and A. Hemmerich[1,2]

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We are experimentally exploring the light-matter interaction of a Bose-Einstein condensate (BEC) with a single light mode of an ultra-high finesse optical cavity. The key feature of our cavity is the small field decay rate ($\kappa/2\pi \approx$ 4.5 kHz), which is in the order of the recoil frequency ($\omega rec/2\pi \approx$ 3.56 kHz). This leads to a unique situation where cavity field evolves with the same timescale as the atomic distribution. If the system is pumped transversally with a steady state light field, red detuned with respect to the atomic resonance, the Hepp-Lieb superradiant phase transition of the open Dicke is realized. Starting in this self-ordered density wave phase and modulating the amplitude of the pump field, we observe a dissipative discrete time crystal, whose signature is a robust subharmonic oscillation between two symmetry-broken states [1]. For a blue-detuned pump light with respect to the atomic resonance, we propose an experimental realization of limit cycles. Since the model describing the system is time-independent, the emergence of a limit cycle phase heralds the breaking of continuous time-translation symmetry [2]. By periodically driving, the limit cycles stabilize and the system undergoes a transition from a continuous to a discrete time crystal [3].

References

[1] H. Keßler, P. Kongkhambut, C. Georges, L. Mathey, J. G. Cosme, and A. Hemmerich, Observation of a dissipative time crystal, accepted Physical Review Letters, arXiv:2012.08885 (2020)
[2] H. Keßler, J. G. Cosme, M. Hemmerling, L. Mathey, and A. Hemmerich, Emergent limit cycles and time crystal dynamics in an atom-cavity system, Physical Review A, **99**(5), 053605 (2019)
[3] H. Keßler, J. G. Cosme, C. Georges, L. Mathey, and A. Hemmerich, From a continuous to a discrete time crystal in a dissipative atom-cavity system, New Journal of Physics, **22**(8), 085002 (2020)

Dissipative Phase Transitions in Collective Spin Models

Peter Kirton

University of Strathclyde, UK

We show how a simple model of a lattice of collective spins can give rise to a rich and surprising phase diagram when subjected to an alternating pattern of pumping and decay [1]. In contrast to the equilibrium version, the model can support both paramagnetic and ferromagnetic phases as well as a highly mixed phase which appears in the thermodynamic limit. The unconventional phase transitions in this model can be understood in the context of a generalisation of the concept of parity-time-reversal (PT) symmetry to open quantum systems [2]

References

[1] Huber, Kirton and Rabl Phys. Rev. A 102, 012219 (2020)
[2] Huber, Kirton, Rotter and Rabl SciPost Phys. 9, 052 (2020)

Dissipative phase transitions of atoms coupled to an optical cavity

C. Kollath[1]
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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. We investigate the full quantum evolution of ultracold interacting bosonic atoms on a chain and coupled to an optical cavity. Extending the time-dependent matrix product state techniques and the many-body adiabatic elimination technique to capture the global coupling to the cavity mode and the open nature of the cavity, we examine the long time behavior of the system beyond the mean-field elimination of the cavity field. We show that in the self-organized phase the steady state consists in a mixture of the mean-field predicted density wave states and excited states with additional defects. In particular, for large dissipation strengths a steady state with a fully mixed atomic sector is obtained crucially different from the predicted mean-field state. Playing with the interaction between the atoms, we can further investigate the influence of symmetries in open quantum systems.

Quantum phase-space thermodynamics in driven-dissipative transitions

Driven-dissipative transitions are frequent in systems containing optical cavities, featuring a competition between losses and coherent drives. Being out-of-equilibrium, these transitions naturally encompass a finite production of entropy. It is therefore of interest to characterize their critical properties from the perspectives of the 2nd law. Many quantum optical systems, however, operate effectively at zero temperature, where the standard laws of thermodynamics are not valid. In this talk I discuss recent efforts in reformulating thermodynamics using quantum phase space, where entropy is defined in terms of the Wigner or Husimi functions. As we show, this yields a full-fledged formalism for describing the thermodynamics of driven-dissipative transitions. These results are also applied to the Kerr bistability, Dicke and Lipkin-Meshkov-Glick models.

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Time-crystal phase transition, fluctuations, and quantum correlations in an emitter-waveguide system with feedback

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We investigate the creation and control of emergent collective behaviour and quantum correlations using feedback in an emitter-waveguide system using a minimal model. Employing homodyne detection of photons emitted from a laser-driven emitter ensemble into the modes of a waveguide allows to generate intricate dynamical phases. In particular, we show the emergence of a time-crystal phase, the transition to which is controlled by the feedback strength. Feedback enables furthermore the control of many-body quantum correlations, which become manifest in spin squeezing in the emitter ensemble. Developing a theory for the dynamics of fluctuation operators we discuss how the feedback strength controls the squeezing and investigate its temporal dynamics and dependence on system size. These results allow to quantify spin squeezing and fluctuations in the limit of large number of emitters, revealing critical scaling of the squeezing close to the transition to the time-crystal.

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An optical lattice with sound

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Quantized sound waves---phonons---govern the elastic response of crystalline materials, and also play an integral part in determining their thermodynamic properties and electrical response (e.g., by binding electrons into superconducting Cooper pairs). The physics of lattice phonons and elasticity is absent in simulators of quantum solids constructed of neutral atoms in periodic light potentials: unlike real solids, traditional optical lattices are silent because they are infinitely stiff. Optical-lattice realizations of crystals therefore lack some of the central dynamical degrees of freedom that determine the low-temperature properties of real materials. We will discuss our creation of an optical lattice with phonon modes using a Bose-Einstein condensate (BEC) coupled to a confocal optical resonator [1]. Playing the role of an *active* quantum gas microscope, the multimode cavity QED system both images the phonons and induces the crystallization that supports phonons via short-range, photon-mediated atom-atom interactions. Dynamical susceptibility measurements reveal the phonon dispersion relation, showing that these collective excitations exhibit a sound speed dependent on the BEC-photon coupling strength. Our results pave the way for exploring the rich physics of elasticity in *quantum* solids, ranging from quantum melting transitions to exotic ``fractonic'' topological defects in the quantum regime.

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Spatio-temporal control of correlations via non-local dissipation

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Controlling the spread of correlations in quantum many-body systems is a key challenge at the heart of quantum science and technology. Correlations are usually destroyed by dissipation arising from coupling between a system and its environment. Here, we show that dissipation can instead be used to engineer a wide variety of spatio-temporal correlation profiles in an easily tunable manner. We describe how dissipation with any translationally-invariant spatial profile can be realized in cold atoms trapped in an optical cavity. A uniform external field and the choice of spatial profile can be used to design when and how dissipation creates or destroys correlations. We demonstrate this control by preferentially generating entanglement at a desired wavevector. We thus establish non-local dissipation as a new route towards engineering the far-from-equilibrium dynamics of quantum information, with potential applications in quantum metrology, state preparation, and transport.

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Classical self-organization: Mechanisms and functional aspects

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Self-organization in nearly periodic spatial patterns is ubiquitous in nature. Examples range from nanometer-scale corneal patterns to meter-scale vegetation patterns and more (Figure 1). Theory and experiments support the view of these regular patterns as symmetry-breaking phenomena emerging spontaneously from instabilities of spatially structureless states. Understanding these phenomena calls for the identification of small-scale positive feedback loops that amplify small random perturbations and thereby lead to large-scale state changes. A striking aspect of these patterns is their universal nature; similar patterns are observed in widely distinct systems, where the driving feedback loops are obviously different (Figure 1).

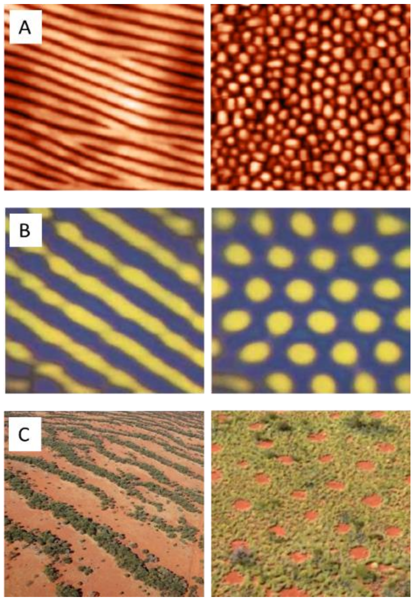

Figure 1. Stripe and spot patterns in insect cornea (A), chemical reactions (B), and dryland vegetation (C). Typical length scales range from hundreds of nm (A), to hundreds of μm (B), to tens of m (C right) and hundreds of m (C left). From Blagodatski et al. *PNAS* 2015 (A), Ouyang & Swinney *Nature* 1991 (B), and Meron *Physics Today* 2019 (C).

In this talk I will first review basic elements of pattern formation theory, including basic pattern-forming instabilities of spatially uniform and localized states and theoretical methods to study the emerging patterns, highlight the origin of universality, and present examples from fluid dynamics and chemical reactions. I will then proceed to pattern formation in animate matter, focusing on vegetation patterns in drylands as a case study. I will explain the underlying pattern-forming feedback loops, the wide variety of vegetation patterns they lead to, and their significance to ecosystem resilience. I will finally focus on fronts that form transition zones between uniform vegetation and bare soil, and discuss the possible roles of front instabilities in reversing desertification.

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Quantum interference in the Bose-Hubbard model of many-body cavity quantum electrodynamics

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Ultracold ensembles of atoms coupled to the light fields of high-finesse optical cavities are a unique platform for studying the emergence of pattern in the quantum world. The inter-atomic interactions are here mediated by multiple scattering of cavity photons and have a long-range character, which makes these systems a unique platform for shedding light into dynamics predicted in other fields of physics, ranging from nuclear physics, nonlinear dynamics, and astrophysics. In this talk we present a theoretical study of the quantum phases of bosons emerging from the interplay between an external periodic potential and the cavity long-range forces. These dynamics are described by an extended Bose-Hubbard model where the cavity long-range potential gives rise to density-density interactions and correlated tunneling. We determine the phase diagram by means of mean field and DMRG and report the emergence of exotic phases, which are due to quantum interference between single-particle hopping and cavity-mediated correlated tunneling in the lattice.

Higher-order and fractional discrete time crystals

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Discrete time crystals are periodically driven (i.e. Floquet) systems characterized by a robust response with periodicity nT, with T the period of the drive and n>1, in this sense they spontaneously break the discrete time-translation symmetry of the drive.

In the first part [1], I will show that a clean *quantum* spin-1/2 chain in the presence of long-range interactions and a transverse field can sustain a large variety of different 'higher-order' discrete time crystals with integer and, surprisingly, even fractional n>2. I will characterize these prethermal non-equilibrium phases of matter and establish their stability in the presence of competing long- and short-range interactions. Remarkably, these phases emerge in a model featuring continuous driving and time-independent interactions, convenient for ultracold atoms or trapped ions experiments.

In a second step [2], I will then show that these prethermal non-equilibrium phases of matter are not restricted to the quantum domain. Studying the Hamiltonian dynamics of a large three-dimensional lattice of *classical* spins, I will provide the first numerical proof of these prethermal phases of matter in a system with short-range interactions and in spatial dimensions larger than one.

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Spontaneous self-ordering and crystallization
via
collective coherent atom–photon dynamics

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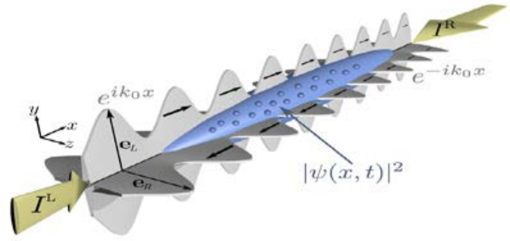

We study emerging ordered quantum phases of ultracold quantum gases in multimode optical cavities to synthesize dynamic gauge fields, spin orbit coupling, or long range spin interactions. Quantum particles coupled to field modes of optical resonators hybridize with cavity photons, which collectively couple spin and motional dynamics. By help of multiple polarization modes one is able to engineer spin-dependent dynamic optical potentials and tailored long-range density and spin-spin interactions towards a versatile analogue quantum simulator. The emerging spin-and-density-ordered complex quantum phases can often be characterized in situ via properties of the cavity output spectra. For larger interaction strength the light induced long range coupling of the particles can induce regular crystallization of the particles bound by light and the appearance of new exotic quantum phases with short and long range order as found in a supersolid or in quasicrystals.

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Supersolid formation via diffractive coupling

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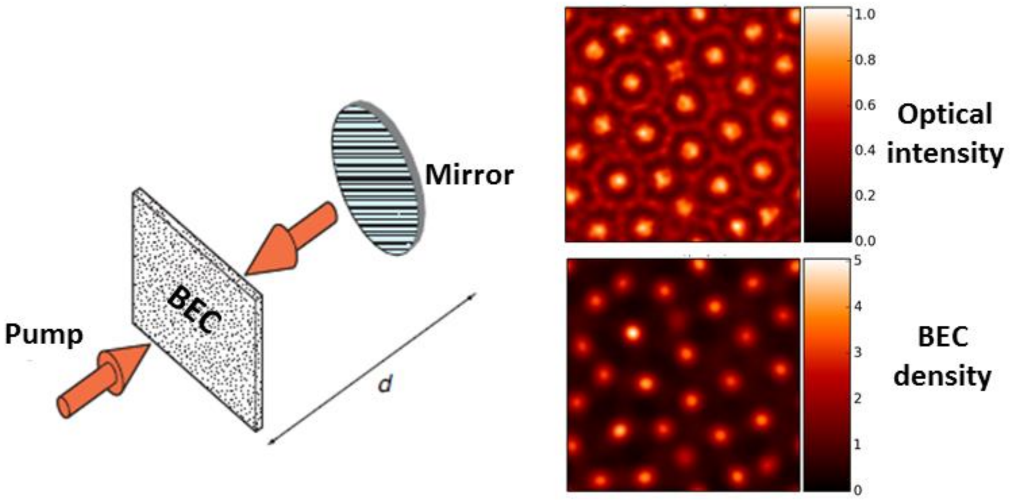
When a cold atomic gas is illuminated by an optical beam and light transmitted through the gas is retro-reflected by a feedback mirror, a process of optomechanical self-structuring can occur. This process involves the spontaneous ordering of both the atomic density and the optical intensity in the plane transverse to the beam propagation direction. It arises as a result of diffraction of light as it propagates between the atomic gas and the mirror, which produces long-range coupling between the atoms. The process has been observed experimentally in a cold, thermal Rb gas illuminated by a uniform pump field with a single feedback mirror, which demonstrated a transition from a spatially homogeneous state to a hexagonal spatially ordered state in both the atomic density and optical intensity [1].



The concept of optomechanical self-structuring was extended theoretically from the case of a thermal gas to a BEC in [2]. The non-trivial spatial order in the BEC produced by the optomechanical self-structuring instability, together with the phase coherence of the BEC constitutes formation of a supersolid, the existence of which relies on optical diffraction. Complex density structures produced via a combination of optical diffraction and atomic collisions in a BEC have also been reported [3]. The relationship between diffraction-mediated supersolid formation and the quantised Hamiltonian Mean-Field (HMF) model [4], a paradigmatic model of long-range interactions, will be discussed, including the possibility of realising a space-time crystal.

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Atoms Interlinked by Light: Programmable Interactions and Emergent Geometry

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The connectivity of interactions in a quantum system is crucial to governing the flow of information and the resulting structure of correlations. Whereas typical interactions are local — decaying with distance — a variety of applications in quantum simulation, combinatorial optimization, and quantum state engineering benefit from the ability to generate effectively non-local interactions. I will report on the realization of optically programmable non-local interactions in an array of atomic ensembles within an optical resonator [1-3], which serves as a conduit for light to convey information between distant atomic spins. We program the spin-spin couplings by tailoring the spectrum of an optical control field, harnessing this programmability to access interaction graphs conducive to frustration and to explore quantum spin dynamics in exotic geometries and topologies [3]. Illustrative examples include a Möbius ladder with sign-changing interactions and a treelike geometry [4] inspired by concepts of quantum gravity. We analyze the latter as a toy model of holographic duality, where the quantum system can be viewed as lying on the boundary of a higher-dimensional space – embodied by the tree – that emerges from measured spin correlations.

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Non Equilibrium Pattern Formation in Biology and Materials Science

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I will discuss a few classic systems that self-organize dissipative patterns in chemistry and biology. Specifically, I will explain how cellular slime molds use nonlinear wave patterns to orchestrate cell aggregation over macroscopic distances and how this cell communication eventually leads to a multicellular organism. I will also discuss very similar waves in an oscillating chemical reaction. Equipped with this background information, we will then explore how related patterns could be useful in materials science and how the resulting life-like polycrystalline assemblies complicate the search for life on other planets as well as the identification of Earth's oldest microfossils.

Out-of-equilibrium phases: the role of dissipation, noise, and competing drives

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Out-of-equilibrium phases appear as steady-states that balance constraints in a system relative to drives and dissipation originating from an environment. Commonly, the resulting steady-states are best described in a rotating picture with respect to the drives. This yields a modified effective quasienergy (phase-space) potential for the system. At the same time, the dissipation channels are also rotated, leading to an interesting competition between effective Hamiltonian potentials and engineered bath attractors, thus, modifying the phase diagram of the closed system. Subject to this complex competition while additionally being subject to noise, the dynamics of the system exhibit interesting switching between steady-states with unusual statistics. As case studies, we discuss the physics of parametrically-driven oscillators [1–7] and a ubiquitous many-body light-matter setting, where a collection of two-level systems interacts with quantum light trapped in an optical cavity [8–11].

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Abstracts of Posters

(in alphabetical order)

Structural phase transitions in cold atoms mediated by optical feedback

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Self-structuring via optomechanical forces is a prominent collective phenomenon occurring in cold atoms coupled to optical fields [1]. Experimental realizations by means of dipolar gases and optical cavities have shed light onto crystallization, supersolidity, and structural transitions in driven-dissipative atomic systems [2,3,4,5].

In this work, we address 2D structural transitions occurring in an ensemble of cold thermal atoms, with effective interactions mediated by a coherent beam retro-reflected by means of a feedback mirror. The transitions are characterized in terms of three light-atom crystalline phases, namely, hexagon (**H**+), stripe (**S**), and honeycomb (**H**−), depending on the linear susceptibility [6]. Thus, we identify phase boundaries in terms of a weakly nonlinear formalism, based on the real Ginzburg-Landau amplitude equations and corresponding Lyapunov functionals, where the minimum determines the observed phase and relative boundaries. An intriguing consequence of the structural landscape of our system, forbidden by the effective-Kerr picture, is given by the nontrivial recovery of inversion symmetry in the **S** phase, occurring without externally imposed symmetry-breaking conditions.

The universality of our approach leads to conjecture the emergence of inversion symmetric supersolid phases (stripe/square) in the quantum degenerate and dipolar cases. Moreover, it implies the existence of spatial solitons functioning as self-sustained atomic traps. Transport of such localized atomic structures is controlled by means of a phase structured input, as demonstrated recently in [7].

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Dicke transition in open many-body systems determined by fluctuation effects

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In recent years, one important experimental achievement was the strong coupling of quantum matter and quantum light. Realizations reach from ultracold atomic gases in high-finesse optical resonators to electronic systems coupled to THz cavities. The dissipative nature of the quantum light field and the global coupling to the quantum matter leads to many exciting phenomena such as the occurrence of dissipative quantum phase transition to self-organized exotic phases. Here we develop a new approach which combines a mean-field approach with a perturbative treatment of fluctuations beyond mean-field, which becomes exact in the thermodynamic limit. We argue that these fluctuations are crucial in order to determine the mixed state (finite temperature) character of the transition and to unravel universal properties of the self-organized states. We validate our results by comparing to time-dependent matrix-product-state calculations.

Dynamics of matter waves undergoing Bloch oscillations in a ring cavity

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The work developed investigate the dynamics of ultra-cold atoms trapped in a ring cavity and undergoing Bloch oscillations due to the influence of a one-dimensional vertical optical lattice and of the gravitational force. In this configuration, the atoms collectively scatter light from the pump into the co-propagating cavity mode, which then leads to a self-consistent grating of the matter: this mechanism was coined collective atomic recoil lasing (CARL).[1] Such interaction between atomic motion and cavity modes provides a possible continuous and non-destructive method to monitor the Bloch oscillations dynamics, which could be implemented in atomic gravimeters.[2] We investigate the fundamental problem of dissipation effects due to spontaneous emission of the atoms, which is responsible for a suppression of the Bloch oscillations signatures on the light modes. We also study a possible solution for this issue by including a third atomic level in the configuration to explore a probable dissipation reduction due to the phenomenon of electromagnetically induced transparency (EIT).

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Mott transition in a cavity-boson system: A quantitative comparison between theory and experiment

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The competition between short-range and cavity-mediated infinite-range interactions in a cavity-boson system leads to the existence of a superfluid phase and a Mott-insulator phase within the self-organized regime. We quantitatively compare the steady-state phase boundaries of this transition measured in experiments and simulated using the Multiconfigurational Time-Dependent Hartree Method for Indistinguishable Particles. To make the problem computationally viable, we represent the full system by the exact many-body wave function of a two-dimensional four-well potential. We argue that the validity of this representation comes from the nature of both the cavity-atomic system and the Bose-Hubbard physics, and verify that it only induces small systematic errors. The experimentally measured and theoretically predicted phase boundaries agree reasonably. We thus propose a new approach for the quantiative numerical determination of the superfluid-Mott-insulator phase boundary.

Optomechanical Self-Structuring and the Brownian Mean-Field Phase Transition

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Optomechanical self-structuring is the physical phenomenon of spontaneous spatial synchronisation in a cold atomic gas when illuminated by coherent light. Optomechanical self-structuring has been observed experimentally in a 2D cloud of Rubidium atoms illuminated by a uniform pump field with a single feedback mirror and corresponding to a transition from a homogeneous to a hexagonal pattern state [1].

Here we derive a simplified model for the position and momenta of the cold atoms with interactions mediated by the light that is reflected by the mirror. These equations reduce to the Kuramoto model in the presence of fluctuations, inertia and damping:

$$d_t\theta_i = v_i \qquad m\, d_t v_i = -\gamma v_i + Kr\sin(\psi - \theta_i) + \sqrt{\gamma}\,\eta_i(t)$$

where θ_i are the phases of N oscillators, v_i the phase velocities, m the oscillator mass, γ the damping constant, K the coupling constant, r the order parameter, ψ the average oscillator phase defined via $(r)\exp(i\psi) = N^{-1}\sum_k \exp(i\,\theta_k)$ and $\eta_i(t)$ is a stochastic noise with

$$\langle \eta_i(t)\rangle = 0 \qquad \langle \eta_i(t), \eta_k(t')\rangle = 2T\,\delta_{ik}\,\delta(t-t')$$

where T has a role similar to the temperature. This model has been studied extensively in Ref. [2] and displays a second order phase transition known as the Brownian Mean-Field (BMF) transition when reducing the temperature T [3].

By exploiting the equivalence of the simplified model that describes optomechanical self-structuring and the generalised Kuramoto equations above, we determine the conditions for a possible observation of a second-order phase transition typical of the Brownian Mean-Field approach in the self-structuring experiment.

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Collective anti-bunching and laser thresholds in nanolasers

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We consider a fully quantised model for N quantum dots (QDs) coupled to the modes of an optical cavity where we determine analytically regimes of thermal, collective anti-bunching and lasing emission that depend explicitly on the number of QDs [1]. Applying dynamical systems methods we find that the lasing regime is reached for a number of QDs above a critical number —which depends on the strength of the light-matter interaction, detuning, and the dissipation rates— via a universal transition from thermal emission to collective anti-bunching to lasing as the pump increases. The antibunching regime becomes vanishingly small in the control parameter space in the limit of large number of QDs but is still visible even for mesoscopic devices. For any system size there is a generic lasing bifurcation, and we observe the position of the laser threshold move to the inflection point of the input-output (I-O) curves as the volume of the device increases; a phase transition occurs between the incoherent and coherent emission regimes as the macroscopic limit is reached.

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Collective Phenomena on Superconducting Qubits: Synchronization, Subradiance, and Entanglement Generation

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A common environment acting on a pair of qubits gives rise to a plethora of different collective phenomena, such as the generation of qubit–qubit entanglement, quantum synchronization, and subradiance. Here, we introduce time-independent figures of merit for entanglement generation, quantum synchronization, and subradiance, and we perform an extensive analytical and numerical study of their dependence on the model parameters; we show that all these effects share a common cause, namely the action of the common bath, and yet may display opposite behaviors in certain regimes. We also address a recently proposed measure of the collectiveness of the dynamics driven by the bath, and we find that it almost perfectly witnesses the behavior of entanglement generation. Our results show that synchronization and subradiance can be employed as reliable local signatures of an entangling common bath in a broad scenario. Finally, we propose an experimental implementation of the model based on two transmon qubits capacitively coupled to a common resistor, which mimics the dynamics of several light-matter interaction systems, and provides a versatile quantum simulation platform of the open system in any collective regime [1].

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Subradiance beyond the linear-optics and the dilute regimes in macroscopic cold atomic clouds

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Subradiance is the collective spontaneous emission phenomenon of ensemble of atoms that exhibits prolonged excited state lifetimes comparing to those of individual atoms. Subradiance in macroscopic cold atomic clouds has been very well characterized in the dilute limit and in the linear-optics regime. We have extended the study of subradiance beyond those regimes.

Subradiant states are weakly coupled to environment and consequently they are difficult to populate. However, in the non-linear optics regime we have experimentally and numerically demonstrated the *super-linear* increase of the subradiant population as we increase the saturation parameter of the driving field [1]. We attributed this to a process of the optical pumping through superradiant states. On the other hand, while the subradiant population is increased, the subradiant lifetimes are not significantly affected by the strength of the driving field.

Moreover, we have studied the role of near-field dipole-dipole interactions on subradiance in macroscopic atomic clouds (in the linear-optics regime). In the dilute regime (low-density samples) the model that disregards near-field interaction terms (and the internal atomic structure) very well describes the collective temporal dynamics. However, in higher-density samples the near-field contribution cannot be omitted so we use the full *vectorial* couple-dipole model to numerically study subradiance. We have observed that the near-field interactions are detrimental for subradiance as the subradiant lifetime decrease with increasing density of the sample [2]. Furthermore we have observed that the increase of density is characterized by the strong broadening of the spectrum. Hence, we attributed this reduction of subradiant lifetimes to the inhomogeneous broadening due to the near-field contributions.

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Universal spin squeezing from the tower of states of U(1)-symmetric spin Hamiltonians

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Spin squeezing - a central resource for quantum metrology - results from the non-linear, entangling evolution of an initially factorized spin state. Here we consider a large class of S=1/2 spin Hamiltonians with axial symmetry, and we show that they induce a universal dynamics of spin squeezing at short time. This property is connected to the existence of a peculiar set of Hamiltonian eigenstates - the so-called Anderson tower of states. Such states are fundamentally related to the appearance of spontaneous symmetry breaking in quantum systems, and they are parametrically close to the eigenstates of a planar rotor (Dicke states), in that they feature an anomalously large value of the total angular momentum.

We show that, starting from a coherent spin state, a generic U(1)-symmetric Hamiltonian featuring the Anderson tower of states generates the same squeezing evolution at short times as the one governed by the paradigmatic one-axis-twisting (or planar rotor) model of squeezing dynamics. The full squeezing evolution is seemingly reproduced for interactions which decay sufficiently slowly with the distance. Our results connect quantum simulation with quantum metrology by unveiling the squeezing power of a large variety of Hamiltonian dynamics that are currently implemented by different quantum simulation platforms - including for instance experiments with Rydberg atoms.

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Self-organized spin and density ordering of thermal atoms in cavities

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In cold atoms both electronic and opto-mechanical couplings are predicted to take place as mechanisms to induce spontaneous self-organization of light and atoms in the plane transverse to the light propagation. Recent experimental results show both mechanisms at work and demonstrate that each one can be the pattern driver in specific conditions and in different time scales. Methods to distinguish both mechanisms are presented with emphasis on the opto-mechanical coupling and on the resultant modulations in the atomic density profile.

Atom-only dynamics in cavity QED

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Ultracold atoms in multimode cavity QED provide an ideal platform to study quantum many-body physics out of equilibrium, as the cavity modes mediate tunable-range interactions between atoms allowing for the exploration of a wide range of models [1]. In such systems, it is desirable to derive open quantum system descriptions of the atoms in order to significantly shrink the Hilbert space, which otherwise becomes quickly intractable. However, we will show that the most standard approximations used to derive such atom-only descriptions can lead to wrong predictions, even in the simple case of the driven-dissipative Dicke model in a single-mode cavity. In this context, we will show that a Redfield master equation for the atoms (which goes beyond the secular approximation and the large detuning limit) is needed to predict the existence of the superradiant phase transition [2]. Then, we will present how an exact non-Markovian stochastic method [3] can be used to overcome the problem of choosing the right atom-only model, allowing for an exact numerical description of the atomic dynamics in single- and multimode cavities.

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Metastability and discrete spectrum of long-range systems

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The linear dynamics of closed quantum system produces well known difficulties in the definition of quantum chaos. This leads to several issues in the theoretical justification of the equilibration and thermalisation dynamics observed in closed experimental systems. In the case of large harmonic baths these issues are partially resolved due to the continuous nature of the spectrum, which produces divergent Poincar´e recurrence times. Within this perspective, the phenomenon of long lived quasi-stationary states (QSS), which is a signature characteristic of long-range interacting quantum systems, remains unjustified. QSSs often emerge after a sudden quench of the Hamiltonian internal parameters and present a macroscopic life-time, which increases with the system size. In this work, the spectrum of systems with slow enough decaying couplings is shown to remain discrete up to the thermodynamic limit, hindering the application of several traditional results from the continuous theory of many-body quantum systems. Accordingly, the existence of QSSs is connected with the presence of finite recurrence times in the observables' dynamics and with the failure of the kinematical chaos hypothesis.

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Tunable dipole-dipole interaction between optically levitated nanoparticles

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Arrays of coupled mechanical oscillators have been proposed for exploring collective optomechanical effects, quantum many-body dynamics, topological phonon transport, (quantum) synchronization etc. So far, the experimental strategy has been to mediate interaction between two clamped oscillators via an optical cavity, thus limiting the scalability of such systems and confining the interaction toolbox to available cavity interaction techniques. Engineering a direct interaction between an array of oscillators would allow us to create macroscopic entangled states, study phonon transport and explore weak forces between two nanoscale objects even in absence of an optical cavity.

Recently we demonstrated motional ground state cooling of an optically levitated silica nanoparticle in a tweezer by implementing a novel scheme of cavity cooling by coherent scattering, which is based on the dipole radiation of the particle into an empty optical cavity [1]. Preparation of the motional ground state is a prerequisite for probing decoherence mechanisms in free-fall experiments or for creation of non-Gaussian states in anharmonic potentials. On the other hand, shaping of optical potentials enables trapping and arranging a large number of optically levitated objects in an arbitrary pattern, thus providing a fully scalable architecture to generate an optomechanical array of levitated nanoparticles in the quantum regime. Moreover, it is possible to engineer direct interactions between two mechanical states, for example via dipole radiation of trapping lasers (“optical binding”) or via Coulomb interaction, thus allowing for a much richer dynamics in an optical cavity. I will present first results on strong and tunable interaction between nanoparticles in parallel optical tweezers, a novel platform in the context of optical binding studies as well, which paves the way for studying quantum many-body physics with massive solid-state objects.

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Emergent Kardar-Parisi-Zhang phase in quadratically driven condensates

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In bosonic gases at thermal equilibrium, an external quadratic drive can induce a Bose-Einstein condensation described by the Ising transition, as a consequence of the explicitly broken U(1) phase rotation symmetry down to Z_2. However, in physical realizations such as exciton-polaritons and nonlinear photonic lattices, thermal equilibrium is lost and the state is rather determined by a balance between losses and external drive. A fundamental question is then how nonequilibrium fluctuations affect this transition. Here, we show that in a two-dimensional driven-dissipative Bose system the Ising phase is suppressed and replaced by a nonequilibrium phase featuring Kardar- Parisi-Zhang (KPZ) physics. Its emergence is rooted in a U(1)-symmetry restoration mechanism enabled by the strong fluctuations in reduced dimensionality. Moreover, we show that the presence of the quadratic drive term enhances the visibility of the KPZ scaling, compared to two-dimensional U(1)-symmetric gases, where it has remained so far elusive.

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Loading and cooling in an optical trap via dark states

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Recently self-emergence phenomena, like glassiness and crystallization, have been extensively studied using pumped condensed atomic samples, coupled to a high finesse optical resonator. So far most of these experiments have been realized in standing wave cavities, which impose the resonator geometry to the lattice being formed by the atoms and the light scattered into the cavity modes. Adopting degenerate multimode cavities opens new horizons to study order emergence effects, where compliant lattices between atoms and light can show a dynamical evolution [1].

The optical cavity we use to study self-ordering has a bow-tie geometry [2] and the intra-cavity field is in a traveling wave configuration. Therefore, there are no constraints at the cavity mirrors on the intra-cavity light, and the phase of the expected light-atom crystals results in a free parameter. As a first step, we developed a novel protocol to load cold rubidium atoms in the telecom dipole trap enhanced by the cavity: we substituted the conventional red molasses phase with a gray molasses technique utilizing hyperfine dark and bright states arising through two-photon Raman transitions [3]. In this way we obtained a seven-fold increase in the atomic loading, and the technique was crucial to obtain an all-optical BEC in microgravity [4]. Furthermore, with the same technique we could cool the atoms directly in the dipole trap, exploiting the position dependence introduced by the differential light shift caused by the light at 1560 nm. Atoms at deeper potentials need to be addressed by a further, red-detuned cooler on the D2 line, since the dipole trap creates a large differential Stark shift between ground and exited states. We could thus cool the trapped atoms by a factor of 4 in few ms, limited by the gray molasse scheme being applied on the D2 line, and notably by the presence of the F'=3 upper level. The cooling scheme could be improved by using cooling light on the D1. In general, the cooling protocol is fast, lossless, and could be applied to other atomic species.

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Towards continuous superradiance with a hot atomic beam

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Continuous superradiant lasers have been proposed as next generation optical atomic clocks for precision measurement, metrology, quantum sensing and the exploration of new physics [1].

Superradiance is a collective phenomenon resulting in an enhanced single atom emission rate [2]. A way to provide the required phase synchronization is coupling a cold cloud of atoms using a cavity mode. This technique has been used to demonstrate pulsed superradiance [3-5], however steady-state operation remains an open challenge.

Here we describe our machine aimed at validating the alternative proposal [6], a rugged superradiant laser operating on the $^1S_0$-$^3P_1$ transition of ^{88}Sr using a hot collimated atomic beam. The elegance of this approach is that a single cooling stage and a low finesse cavity appear sufficient to fulfill the requirements for continuous superradiance. Consequently, our device promises a compact, robust and simple optical frequency reference.

The nature of the superradiant phase transition offers many opportunities to study open questions in highly-correlated many body physics. For example, different regimes of superradiant emission have been predicted for an atomic beam passing a cavity with both regular and bistable steady-state superradiant phases [7]. These proposal suggests the potential of our machine as an exciting new platform with which to explore many-body phenomena.

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Fluctuations and symmetry effects in many-body self-organization in a dissipative cavity

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We investigate the full quantum evolution of ultracold interacting bosonic atoms on a chain and coupled to an optical cavity. Extending the time-dependent matrix product state techniques and the many-body adiabatic elimination techniques to capture the global coupling to the cavity mode and the open nature of the cavity, we examine the long time behavior of the system beyond the mean-field elimination of the cavity field [1-3]. We show that the fluctuations beyond the mean-field state give a mixed state character to the dissipative phase transition and self-organized steady states. In the case of ideal bosons coupled to the cavity, the open system exhibits a strong symmetry which leads to the existence of conservation laws and multiple steady states [4]. We find that the introduction of a weak breaking of the strong symmetry by a small interaction term leads to a direct transition from multiple steady states to a unique steady state.

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Mutual self-structuring and novel Kerr-like fragmentation in coupled light/matter-wave interactions

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Spatial optical solitons are self-localized wave packets arising from a balance between diffraction and self-focusing (Kerr) nonlinearity as described by the (2+1)D nonlinear Schrödinger equation:

$$\partial_z F = i\nabla_\perp^2 F + i\eta(F)F,$$

where F is the optical field, $\nabla_\perp^2$ describes diffraction and $\eta(F) = \beta|F|^2/(1+\sigma_{sat}|F|^2)$ describes a saturable self-focusing medium for $\beta > 0$. The parameter σ_{sat} describes saturation in the medium, so for a pure Kerr medium $\sigma_{sat} = 0$. When uniformly polarized light has a helical phase structure, $e^{im\varphi}$, it carries orbital angular momentum (OAM) of quantum number m ($m \neq 0$) and is characterized by an on-axis optical vortex. Such light has been shown to fragment into solitons carrying angular momentum when propagating through Kerr media, with the number of solitons formed depending on the OAM, m [1, 2]. Similar results have been observed in nonlinear colloidal suspensions [3].

Here we investigate coherent vortex beams propagating through a matter-wave i.e., a Bose-Einstein Condensate (BEC) [4]. In this case, the nonlinear term for the optical field

$$\eta(F) = \left(\frac{\mp|\psi|^2}{1+\sigma_{sat}|F|^2}\right),$$

becomes spatially dependent on the BEC wavefunction ψ, which itself evolves according to

$$\partial_z\psi = i\nabla_\perp^2\psi - i(\pm|F|^2 + \beta_{col}|\psi|^2 - iL_3|\psi|^4)\psi,$$

where β_{col} represents interatomic scattering, L_3 represents three-body loss in the BEC and the ± refers to whether the optical field is blue (+) or red (-) detuned.

We present the results of propagating vortex beams with different values of OAM in the case of a self-focusing medium and repulsive BEC interactions. We show the novel formation of coupled optical and BEC solitons, despite repulsive BEC interactions, and demonstrate that both light and BEC solitons carry angular momentum. Despite fundamental differences between our model and the pure Kerr case, the results are in remarkable qualitative agreement, and we find that the number of solitons depends on the OAM of the vortex light beam.

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A versatile quantum simulator for coupled oscillators using a 1D chain of atoms trapped near an optical nanofiber

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The transversely confined propagating light modes of a nano-photonic optical waveguide or nanofiber can mediate effectively infinite-range forces. We show that for a linear chain of particles trapped within the waveguide's evanescent field, transverse illumination with a suitable set of laser frequencies should allow the implementation of a coupled-oscillator quantum simulator with time-dependent and widely controllable all-to-all interactions. At the example of the energy spectrum of oscillators with simulated Coulomb interactions we show that different effective coupling geometries can be emulated with high precision by proper choice of laser illumination conditions. Similarly, basic quantum gates can be selectively implemented between arbitrarily chosen pairs of oscillators in the energy basis as well as in a coherent-state basis. Key properties of the system dynamics and states can be monitored continuously by analysis of the out-coupled fiber fields.

Correlated Light and Self-Organization of Photons in Chiral Three-Level Emitter Chains

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We study multiphoton transport through one-dimensional chains of three-level emitters chirally coupled to a waveguide, and we find that such chains can transform an uncorrelated two-photon state to a highly correlated output exhibiting strong antibunching [1], which is a signature of photon repulsion. By studying pulse propagation, we show that the repulsive interaction facilitates self-organization of initially uncorrelated photons [2]. This is displayed by dissociation of two-photon pulses to two spatially distinct single-photon pulses and crystallization of multiple photons.

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Quantum droplet phases in extended Bose-Hubbard models with cavity-mediated interactions

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Extended Bose-Hubbard (eBH) models have been studied for more than 30 years. We claim that we've been able to numerically discover and study a set of new phases present in generic eBH models with competing long-range attractive and local repulsive interactions [1]. These are different phases of self-bound quantum droplets. We observe a complex sequence of transitions between droplets of different sizes, and of compressible (superfluid or supersolid) as well as incompressible (Mott or density-wave insulating) nature, governed by the competition between the local repulsion and the finite-range attraction.

We propose a concrete experimental implementation scheme based on the multimode optical cavities. The analogous infinite-range model was experimentally realized by the Zürich group [2] using single-mode optical cavities. The recent progress with multimode optical cavities by the Stanford group [3] makes it possible to realize the eBH model with tunable finite-range sign-changing interactions. For the sign-changing interactions, the self-organized phases of supersolid and density-wave droplets are superradiant and can be non-destructively monitored by the cavity field.

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Impact of the atomic multilevel structure on observation of spectral lines

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We theoretically study the spectroscopic properties of an ensembles of atoms in the superradiant regime. The atoms dynamics is described by a Born-Markov master equation, which accounts for dipole-dipole interactions and includes vacuum-induced interference effects. We perform the approximation of coherent dipoles and explicitly determine the spectroscopic properties of two Rubidium atoms Rb^{87}, taking into account the full hyperfine and Zeeman structure relevant for the line D2. We find that vacuum-induced interference leads to spectral shifts which can be measured in the scattered light.

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Collective light-atom interaction in free space and in an optical cavity

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Interaction of *N* atoms with laser radiation can differ significantly from the single atom physics. While probing a sample of high density, there is a pronounced anisotropy of the light scattering pattern, with an enhanced scattering in the forward and backward direction. Consequently, reduction and broadening of the laser induced force on the atomic cloud's center of mass can be observed. If, however, the atoms are located inside a high-finesse optical cavity, the interaction can change even further compared to free space. Since all the atoms are coupled to the same cavity mode, there is a collective atom-cavity coupling proportional to the number of atoms, that can shift the cavity resonance significantly as the atoms move through the cavity potential, resulting in a complex coupled dynamics. This dynamics can be used to cool and trap the atoms in the cavity mode, relying on the photon loss out of the cavity as a dissipation mechanism, instead of the spontaneous emission as in the standard Doppler cooling techniques. This cavity cooling technique could, in theory, be used to cool any polarizable particles, regardless of their internal energy structure [1].

In free space, we experimentally investigated the signature of collective effects in a cold cloud of ^{87}Rb atoms by probing the cloud with a femtosecond pulsed laser, whose spectrum forms a frequency comb (FC). We observed reduction and broadening of the FC-induced force as the cloud's optical depth increases. We compared the measured results with two theoretical models, developed for cw interaction, and found good agreement [2]. With a horizontal high-finesse optical cavity mounted inside the vacuum chamber, we loaded the atoms in the center of the cavity and probed them longitudinally, pumping the cavity mirrors with a cw laser. Tuning the probing laser dozens of linewidths to the blue of an atomic transition, we observe trapping of the atoms along the cavity axis, as well as slowing of the cloud's free fall along the vertical axis due to gravity. This shows a collective dynamic that cannot be explained by standard free space scattering of atoms. We plan to investigate this even further, pumping the atoms transversally to the cavity axis and replacing the cw laser with a frequency comb [3] and coupling a large number of frequencies into the cavity, which creates a more complex intracavity potential.

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Abstract

The quantum non-Gaussianity recognizes nonlinearity in quantum optics that is determined by processes going beyond processes driven by Hamiltonians mostly quadratic in the annihilation and creation operator [1]. We derived criteria that certify the quantum non-Gaussianity using measurable quantities and as such they can be applied directly for realistic experimental platforms. Target states for these criteria are states approaching the Fock states [2]. Further, the approach is extended to expose the quantum non-Gaussianity of sources emitting a photon-pair [3]. We simulated the capacity of these sources to manifests the quantum non-Gaussianity with respect to those criteria by an analysis of sensitivity to realistic imperfections such as losses and noise contributions. These criteria can be satisfied even by states with positive Wigner function.

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Influence Matrix Approach to Quantum Many-Body Dynamics

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A basic and ubiquitous phenomenon in nonequilibrium dynamics of isolated quantum many-body systems is thermalization. This is commonly described as the ability of a system to act as an effective thermal bath for its local subsystems. Understanding the microscopic mechanism of quantum thermalization, and above all of its failures, is currently the subject of intensive theoretical and experimental investigations. Here, I will introduce an approach to study quantum many-body dynamics, inspired by the Feynman-Vernon influence functional theory of quantum baths. Its central object is the influence matrix (IM), which describes the effect of a Floquet many-body system on the evolution of its local subsystems. For translationally invariant one-dimensional systems, the IM obeys a self-consistency equation. For certain fine-tuned models, remarkably simple exact solutions appear, which physically represent perfect dephasers (PD), i.e., many-body systems acting as perfectly Markovian baths on their parts. Such PDs include certain solvable quantum circuits discovered and investigated in recent works. In the vicinity of PD points, the system is not perfectly Markovian, but rather acts as a quantum bath with a short memory time. In this case, we demonstrate that the self-consistency equation can be solved using matrix-product states (MPS) methods, as the IM temporal entanglement is low. The underlying “principle of efficiency” of quantum dynamics computations is complementary to that of standard methods, as it only relies on short-range temporal correlations. Using a combination of analytical insights and MPS computations, we characterize the structure of the IM in terms of an effective "statistical-mechanics" description for local quantum trajectories and illustrate its predictive power by analytically computing the relaxation rate of an impurity embedded in the system. In the last part, I will describe how to extend these ideas to study the many-body localized (MBL) phase of strongly disordered periodically kicked interacting spin chains. This approach allows to study exact disorder-averaged time evolution in the thermodynamic limit. MBL systems fail to act as efficient baths, and this property is encoded in their IM. I will discuss the structure of an MBL IM and link it to the onset of temporal long-range order.

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Emergent structures and dynamics in a quantum gas coupled to an optical cavity

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We study structural phases in an atomic Bose-Einstein condensate (BEC) of a Rubidium gas by inducing cavity-mediated long-range interactions. The BEC is placed inside an optical cavity mode and driven transversally by a repulsive pump lattice beam combining a standing wave and a running wave component. Two crystalline phases arise from the couplings to different quadratures of the cavity mode, induced by mode softening in the P-band and the S-band of the pump lattice. The two superradiant crystals are connected by a first-order structural phase transition which is related to a change of crystal polarization. We measure in real-time the transient dynamics of the order parameters across the phase transition by recording the cavity photon field, where the relaxation frequencies reveal the excitation spectrum of the self-organized crystal. In our latest experiment. A non-stationary phase is realized by inducing dissipative coupling between the two structural phases. The dissipative force drives a novel atomic transport phenomenon in the dynamical phase.

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Dynamics towards multistable inverted states of an open three-level Dicke model

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We consider a V-shaped three-level system coupled to orthogonal quadratures of a dissipative cavity field, and observe a significant multistability of states with inverted atomic population. The stability of these inverted states are closely related to properties of dark states, and is a combined result of the cavity dissipation and the underlying SU(3) symmetry of the atomic subsystem. The multistability can be probed due to three factors: the stability of the normal state is significantly suppressed; the system trajectories and final states of dynamical evolutions are highly sensitive to ramping scheme; and different inverted states have their own characteristic cavity fluctuations.

Homodyne detection of a two-photon resonance assisted by cooperative emission

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Using a transient regime approach, we explore atomic two-photon spectroscopy with self-aligned homodyne interferometry in the Λ-system. The two light sources at the origin of the interference, are the single-photon transient transmission of the probe, and the slow light of the electromagnetically induced transparency, whereas the atomic medium is characterized by a large optical depth. After an abrupt switch-off of the probe laser (flash effect), the transmission signal is reinforced by cooperativity, showing enhanced sensitivity to the two-photon frequency detuning. If the probe laser is periodically switched on and off, the amplitude of the transmission signal varies and remains large even at high modulation frequency. This technique has potential applications in sensing, such as magnetometry and velocimetry, and in coherent population trapping clock.

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Emergent Bloch Oscillations in a Kinetically Constrained Rydberg Spin Lattice

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We explore the relaxation dynamics of elementary spin clusters in a kinetically constrained spin system. Inspired by experiments with Rydberg lattice gases, we focus on the situation in which an excited spin leads to a “facilitated” excitation of a neighboring spin. We show that even weak interactions that extend beyond nearest neighbors can have a dramatic impact on the relaxation behavior: they generate a linear potential, which under certain conditions leads to the onset of Bloch oscillations of spin clusters. These hinder the expansion of a cluster and, more generally, the relaxation of many-body states toward equilibrium. This shows that nonergodic behavior in kinetically constrained systems may occur as a consequence of the interplay between reduced connectivity of many-body states and weak interparticle interactions. We furthermore show that the emergent Bloch oscillations identified here can be detected in experiment through measurements of the Rydberg atom density and discuss how spin-orbit coupling between internal and external degrees of freedom of spin clusters can be used to control their relaxation behavior.

Spin and density self-ordering in dynamic polarization gradients fields

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In our work [1] we study the zero-temperature quantum phase diagram for a two-component Bose-Einstein condensate in an optical cavity. The two atomic spin states are Raman coupled by two transverse orthogonally polarized, blue-detuned plane-wave lasers inducing a repulsive cavity potential. For a weak pump the lasers favor a state with homogeneous density and predefined uniform spin direction. When one pump laser is polarized parallel to the cavity mode polarization, the photons coherently scattered into the resonator induce a polarization gradient along the cavity axis, which mediates long-range density-density, spin-density, and spin-spin interactions. We show that the coupled atom-cavity system implements central aspects of the t-J-V-W model with a rich phase diagram. At the mean-field limit we identify at least four qualitatively distinct density- and spin-ordered phases including ferromagnetic and antiferromagnetic order along the cavity axis, which can be controlled via the pump strength and detuning. Real-time observation of amplitude and phase of the emitted fields bears strong signatures of the realized phase and allows for real-time determination of phase transition lines. Together with measurements of the population imbalance, most properties of the phase diagram can be reconstructed.

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Collective Quantum Effects in Dipolar Bose-Einstein Condensates

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This poster is devoted to symmetry-breaking phase-transitions in dipolar Bose-Einstein condensates. The possibility for the emergence of quantum states with long-ranged ordering is facilitated by the interplay between dipolar interaction and quantum fluctuations. The latter suppress can collapse [1] and with that pave the way for supersolidity in this system. We focus on the critical behaviour of the superfluid-supersolid phase-transition and find that quantum fluctuations can alter the order [2] of the phase transition from first- to second order (see Fig. 1). Furthermore, apart from the usual triangular lattice of density droplets, quantum fluctuations can give rise to a novel quantum state whose density distribution displays a honeycomb structure (see Fig 1,2). In finite, fully trapped systems [3] we also present experimentally feasible, qualitatively similar behaviour and furthermore report striped groundstates.

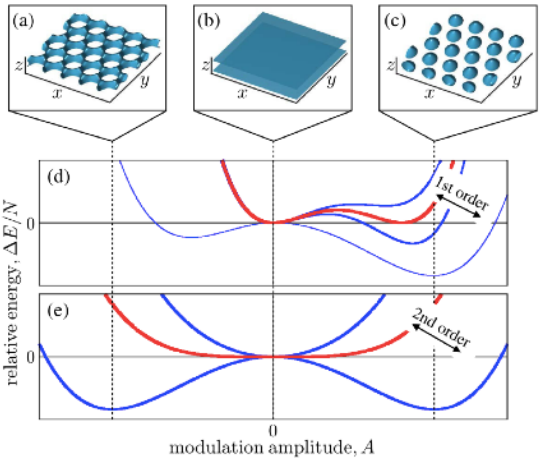

Fig 1. Quantum-fluctuations can change the phase-transition to second order (e) and give rise to honeycomb states (a).

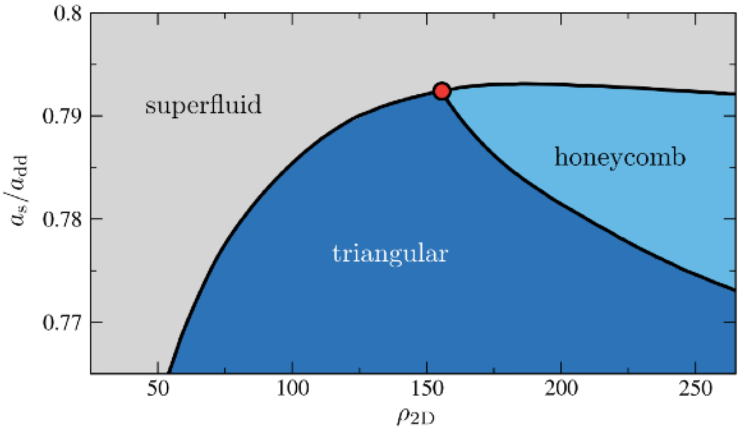

Fig 2. The phase-diagram is organised by a critical point where co-existence of phases terminates and the nature of the phase-transition becomes of second order.

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Adiabaticity enhancement via quantum non-demolition measurement

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The realization of quantum adiabatic dynamics is at the core of implementations of adiabatic quantum computers [1]. One major issue is to efficiently compromise between the long time-scales required by the adiabatic protocol and the the detrimental effects of the environment, which set an upper bound to the time scale of the operation. In this work we propose a protocol which achieves fast adiabatic dynamics by coupling the system to an external environment by means of a quantum-non-demolition (QND) Hamiltonian [2]. We analyse the infidelity of adiabatic transfer for the Landau-Zener problem [3], where the qubit couples to a meter which in turn quickly dissipates. We analyze the protocol's fidelity as a function of the strength of the QND coupling and of the relaxation time of the meter. In the limit where the ancilla's decay rate is the fastest rate of the dynamics, the QND coupling induces an effective dephasing in the adiabatic basis [4]. Optimal conditions for adiabaticity are found in the non-Markovian regime, where memory effects induce dissipative dynamics which suppress unwanted diabatic transitions.

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A non-equilibrium phase transition in disordered lattices of polariton condensates

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Polaritons are bosonic quasiparticles formed from the strong coupling of excitons and photons in semiconductor microcavities. They have been shown to form condensed states, characterised by macroscopic occupation of a single mode, leading to coherent light emission from the microcavity. The short lifetimes of polaritons mean that such condensates are generally out of thermal equilibrium and must be maintained through appropriate pumping. This gives rise to novel behaviour, distinct from that exhibited by conventional equilibrium Bose-Einstein condensates, particularly in the presence of disorder, which can result from pump noise and intrinsic disorder in the cavity. We consider lattices of spatially separated polariton condensates in one and two dimensions, with randomly distributed on-site energies. Such systems may exhibit regimes of both desynchronized and synchronized emission frequencies [1], arising from the competition between inter-well tunnelling and disorder in the on-site energies in the presence of nonlinearities.

The best-known model of synchronization is the Kuramoto model [2], in which the coupling between different oscillators is an odd function of their relative phase. Here we show that a lattice of polariton condensates is described by a generalization of that model with a non-odd coupling term. We show [3] that this leads to a true phase transition to a synchronized state, which is absent for the conventional Kuramoto model with local couplings in one and two dimensions. We derive the phase boundary for synchronization by connecting the model to a modified Kardar-Parisi-Zhang equation, and to the quantum description of localization in a random potential. Our results show that polariton condensates can establish long-range coherence that is robust against disorder, which may be important for their application in analog simulation. Furthermore, the coupling term enabling this transition will be generically present in other coupled oscillator systems, implying they too have a synchronization transition when arranged on lattices in one and two dimensions.

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Quantum noise in cavity Bose-Hubbard systems

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We investigate the quantum measurement noise effects on the dynamics of an atomic Bose lattice gas inside an optical resonator [1]. The system is described by means of a hybrid model consisting of a Bose-Hubbard Hamiltonian for the atoms and a Heisenberg-Langevin equation for the lossy cavity-field mode. We assume that the atoms are prepared initially in the ground state of the lattice Hamiltonian and then start to interact with the cavity mode. We show that the cavity-field fluctuations originating from the dissipative outcoupling of photons from the resonator lead to vastly different effects in the different possible ground-state phases, i.e., the superfluid, the supersolid, the Mott and charge-density-wave phases. In the former two phases with the presence of a superfluid wavefunction, the quantum measurement noise appears as a driving term leading to depletion of the ground state [2]. For the latter two incompressible phases, the quantum noise results in the fluctuation of the chemical potential. We derive an analytical expression for the corresponding broadening of the quasiparticle resonances.

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A Nanoscale Coherent Light Source

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A laser is composed of an optical resonator and a gain medium. When stimulated emission dominates mirror losses, the emitted light becomes coherent. We propose a new class of coherent light sources based on wavelength sized regular structures of quantum emitters whose eigenmodes form high-Q resonators. Incoherent pumping of few atoms induces light emission with spatial and temporal coherence. We show that an atomic nanoring with a single gain atom at the center behaves like a thresholdless laser, featuring a narrow linewidth. Symmetric subradiant excitations provide optimal operating conditions.

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Signatures of phase transitions and optical bistability for atoms in optical lattices

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Radiative dipole-dipole interactions lead to a rich phenomenology of phases in an optical lattice of atoms when driven by a coherent field. They can also support intrinsic optical bistability, where it is possible for two such phases to coexist. Here, we investigate the different phases that emerge in an array of atoms and how they can be identified by studying the scattered light. We find that the onset of phases predicted by mean-field theory are revealed by large jumps in coherent and incoherent signals of the transmitted light. The presence of bistability can result in a strong cooperative and weak single-atom response from the array, with hysteresis upon sweeping the incident light frequency. We discuss how the phases depend on the low light intensity collective modes, and also determine the thresholds for the optical bistability in terms of the atomic cooperativity parameter and intensity of the incident light, in many cases obtaining analytical results.

Equivalence between classical epidemic model and non-dissipative and dissipative quantum tight-binding model

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The equivalence between classical epidemic model and nondissipative and dissipative quantum tight-binding model is derived [1-2]. Classical epidemic model can reproduce the quantum entanglement emerging in the case of electrostatically coupled qubits described by von-Neumann entropy [3] both in non-dissipative and dissipative case. The obtained results shows that quantum mechanical phenomena might be almost entirely simulated by classical statistical model. It includes the quantum like entanglement and superposition of states. Therefore coupled epidemic models expressed by classical systems in terms of classical physics can be the base for possible incorporation of quantum technologies and in particular for quantum like computation and quantum like communication. The classical density matrix is derived and described by the equation of motion in terms of anticommutator. Existence of Rabi like oscillations is pointed in classical epidemic model. Furthermore the existence of Aharonov-Bohm effect in quantum systems can also be reproduced by the classical epidemic model. Every quantum system made from quantum dots and described by simplistic tight-binding model by use of position-based qubits can be effectively described by classical model with very specific structure of S matrix that has twice bigger size as it is the case of quantum matrix Hamiltonian. Obtained results partly question fundamental and unique character of quantum mechanics and are placing ontology of quantum mechanics much in the framework of classical statistical physics [4] what can bring motivation for emergence of other fundamental theories bringing suggestion that quantum mechanical is only effective and phenomenological but not fundamental picture of reality.

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Dynamical localization in non-ideal kicked rotors driven by two modulations

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Dynamical localization is the quantum suppression of classical diffusion. It is a fascinating example where the quantum dynamics of a system is dramatically different from its classical counter part [1], [2], [3]. Initially, and for a short period of time, the quantum system begins to delocalize at a rate which given by the classical diffusion constant. However, after a certain time, known as localization time, the quantum motion seems to freeze, and the delocalization process thereafter disappears. This fact can be understood as the result of the balance between classical diffusion, which acts in the sense of spreading the wave-packet, and (the more subtle) quantum interference, which acts in the sense of maintaining coherence [4].

In this communication, I will present how does dynamical localization take place in an ultracold atomic gas confined in an optical lattice simultaneously shaken by two pulsatile modulations with different periods and/or waveforms [5] (see Figure 1). A systematic study of pulse finite-size effects and modulation waveform on this phenomenon is performed. For this purpose, we compare the classical and quantum momentum. Dynamical localization is identified when the previous difference is large.

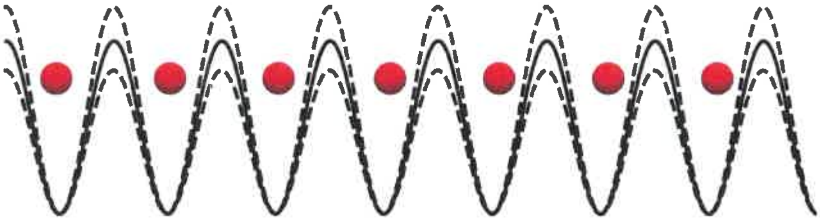

Figure 1: Sketch of an ultracold gas confined in a time-dependent optical lattice subjected to two different modulations at the same time..

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Emerging spin currents and dissipative phases in a superradiant quantum gas

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The interplay between coherent and dissipative processes is at the core of the evolution of open many-body quantum systems. Their competition can lead to new phases of matter, instabilities, and non-equilibrium transients that have no closed system counterparts. However, probing these phenomena at a microscopic level in a setting with controlled couplings and dissipative channels often proves challenging. In our experiment, we achieve such control by coupling a spinor Bose-Einstein condensate to a single mode of a lossy optical cavity. Two transverse laser fields drive cavity-assisted Raman transitions between discrete motional states of two atomic spin levels.

In a first set of experiments, we adjust the imbalance between the Raman drives in order to tune the competition between coherent dynamics and dissipation. This results in the emergence of a dissipation-stabilized phase and in a region of bistability [1]. We relate the observed phases to the underlying microscopic processes by characterizing the properties of the polariton modes. Moreover, we report on recent experimental observations of dynamical spin currents in a momentum space lattice, which are mediated by a density-dependent photon field. We identify their superradiant nature and employ frequency-resolved measurements of the leaking cavity field to gain real-time access on the system's dynamics. Our results provide prospects for the exploration of artificial magnetic fields and transport phenomena in non-Hermitian light-matter systems.

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Unravelling two-photon entanglement via the squeezing spectrum of light traveling through nanofiber-coupled atoms

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Resonance fluorescence of two-level systems has played a fundamental role in the development of quantum optics. Pioneering experiments have demonstrated that the fluorescence of single emitters exhibit many interesting features such as the Mollow triplet, photon-anti-bunching as well as squeezing. Here, we present experiments that investigate the phenomena of anti-bunching and squeezing of the light transmitted through an ensemble of weakly coupled atoms. With a series of experiments [1,2] we shine light on the two-photon interference at the origin of anti-bunching [3,4].

We use an optical nanofiber platform interacting with an ensemble of laser-cooled atoms. The atoms are weakly coupled to the nanofiber mode through the latter's evanescence field. We study the non-linear effect of atoms on the light transmitted through the nanofiber by measuring the second-order correlation function via a Hanbury-Brown-Twiss (HBT) setup, or squeezing via a balanced-homodyne detection (BHD) scheme.

The non-linearity of the atoms creates energy-time entangled photon pairs which manifest themselves as squeezing and which we detect via BHD [2]. From the measured squeezing spectrum, we gain spectral access to the phase and amplitude of the energy-time entangled part of the two-photon wavefunction. These energy-time entangled photons, can destructively interfere with the two-photon component of the incident resonant laser light and create anti-bunched light [1]. Furthermore, we show that a complex interference pattern can emerge when using an off-resonant excitation scheme. Our measurements are in good agreement with a new perturbative theoretical approach which due to its low computational complexity can be applied to arbitrarily large ensembles and provides an intuitive understanding of the underlying physics.

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Synchronization of atoms with a V-level structure

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Synchronization, the phenomenon where constituents of a system move in unison, is one example for the emergence of collective dynamics in a system due to the interaction between its constituents. Since its first experimental observation in 1665 by Christiaan Huygens, it became the subject of many studies across different fields, for instance, physics, biology, and chemistry. Recently, people started working on extending the concept of synchronization to the quantum realm. Among the various systems that show (quantum) synchronization are ensembles of incoherently driven two-level atoms in a cavity [1,2]. They are of particular interest for understanding the difference between quantum and classical synchronization as they can be mapped in a mean-field treatment to the Kuramoto model of coupled classical phase oscillators. In this work we consider an incoherently driven ensemble of atoms, whose internal states form a V-level structure. The atoms are confined in a two-mode cavity with each mode coupling to a different dipolar transition of the atoms. Focusing on the long-time limit, we first determine in a mean-field treatment the synchronized steady-states and their linear stability. Our analysis shows that by suitably tuning the incoherent drive, steady-state synchronization of the dipole's motion of one or both transitions can be achieved as well as a limit-cycle with the dipoles of one transition periodically synchronizing and desynchronizing, a behavior already observed in systems of classical oscillators [3]. The latter however does not survive in presence of quantum fluctuations, as we show by adding quantum corrections using the principle of cumulant expansion [2].

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Detecting atomic dynamics in a Cavity-Rydberg system

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Within the Jaynes-Cummings model, a single two-level atom and a single cavity mode coherently exchange one photon at a rate g_0. When a collection of N atoms is involved, this rate scales with $\sqrt{N}$ as long as the number of photons in the cavity mode is much smaller than N. In this context, the collective atom-cavity coupling $g_0\sqrt{N}$ has recently been used for measuring the time evolution of the spatial distribution of atoms in an optical lattice [1]. When $g_0\sqrt{N}$ is larger than the cavity linewidth the transmitted light's spectrum shows two peaks, instead of a single one associated with the empty cavity resonance. This effect is known as vacuum Rabi splitting and, for a cavity tuned to atomic resonance, the splitting equals $2g_0\sqrt{N}$. Determining the size of the splitting thus corresponds to a measurement of the atom number, which has been used to perform a QND measurement and prepare a conditionally spin squeezed state of a collective atomic pseudospin [2]. Overall, the collective atom-cavity coupling is a probe for the effective atom number interacting with the cavity mode.

Following this idea, we exploit the collective atom-cavity coupling for measuring the time dynamics in the excitation of ultracold Rb^{87} atoms to Rydberg states for which the cavity is "blind". We tune the empty cavity resonance to the transition frequency between the $F = 2$ and $F' = 3$ levels of the D2 transition at 780 nm. By driving the cavity with a weak field while ramping its detuning relative to atomic resonance from $-45\ MHz$ to $+45\ MHz$ we observe a vacuum Rabi splitting with peaks at $\pm 20\ MHz$, corresponding to an effective atom number of *N*~10'000. We measure variations in this atom number by fixing the driving field detuning at the outer side of any of the peaks (e.g. at $+24\ MHz$) and monitoring the transmission through the cavity with an APD. Simultaneously, the atoms are driven via a two-photon transition to the $30D_{5/2}$ Rydberg state with two counter propagating transverse beams. We observe a fast decay of the transmitted light to a constant value representing the atomic dynamics. After switching-off the transverse beams the transmitted light power goes back to its initial value.

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Title

“Multimode Atomic Recoil Lasing in Free Space”

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Abstract

Cold atomic clouds in collective atomic recoil lasing are usually confined by an optical cavity, which forces the light-scattering to befall in the mode fixed by the resonator. Here we consider the system to be in free space, which leads into a vacuum multimode collective scattering. We show that the presence of an optical cavity is not always necessary to achieve coherent collective emission by the atomic ensemble and that a preferred scattering path arises along the major axis of the atomic cloud. The model consists of a system of classical equations for the atomic motion of *N* atoms where the radiation field has been adiabatically eliminated. These equations are numerically solved by means of molecular dynamic algorithms, usually employed in other scientific fields. These simulations show the formation of an atomic density grating and collective enhancement of scattered light, both of which are sensitive to the shape and orientation of the atomic cloud and to the polarization of the incident light. The ability to use efficient molecular dynamics codes will be a useful tool for the study of the multimode interaction between light and cold gases.

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Dynamics of Optomechanical Droplets

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Optomechanical interactions between light and cold atomic gases can produce a range of interesting phenomena, including spontaneous formation of patterns in both the optical intensity and the atomic density [1,2].

The existence of quantum pressure in a Bose-Einstein Condensate (BEC) introduces an additional component to the interaction which is not present for the case of a classical, thermal gas. The repulsive nature of the pressure can increase the threshold for optomechanical pattern formation in a spatially homogeneous BEC [2], and can also result in the formation of stable "droplets" – i.e. localised structures of BEC density and optical intensity [3]. Using numerical simulations, we investigate the dynamics of these droplets within a single feedback mirror configuration. We show that the droplets can undergo uniform motion and acceleration. As the optical and BEC structures are interdependent, observation of the optical structure could provide a means of measuring the velocity and acceleration of the BEC non-destructively.

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Fermi polaron laser in two-dimensional semiconductors

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We study the relaxation dynamics of driven, two-dimensional semiconductors, where itinerant electrons dress optically pumped excitons to form two Fermi-polaron branches. Repulsive polarons excited around zero momentum quickly decay to the attractive branch at high momentum. Collisions with electrons subsequently lead to a slower relaxation of attractive polarons, which accumulate at the edge of the light-cone around zero momentum where the radiative loss dominates. The bosonic nature of exciton polarons enables stimulated scattering, which results in a lasing transition at higher pump power. The latter is characterized by a superlinear increase of light emission as well as extended spatiotemporal coherence. The many-body dressing of excitons can reduce the emission linewidth below the bare exciton linewidth set by nonradiative loss.

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Out-of-equilibrium dynamics in BEC formation

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I present recent results of experiments performed on a system of ultracold ^{23}Na atoms, confined in a magnetic trap. We investigate the dynamics occurring when the ultracold gas, initially in equilibrium at a temperature above the Bose-Einstein condensation (BEC) critical temperature T_c, is cooled down by means of linear evaporative cooling radio-frequency ramps until a final temperature below T_c.

Our aim is to achieve a deeper understanding of the out-of-equilibrium dynamics occurring near the onset of BEC, the formation of defects in the early BEC and the later relaxation towards an equilibrium condensate. We explore a vast range of quench rates, ranging from almost adiabatic very slow ramps to quasi-instantaneous quenches where the complete BEC formation dynamics occurs after the end of the ramp. We investigate, for different quench rates, the BEC formation timescales, looking for relations with the Kibble-Zurek "freeze-out time" [1]

We observe that, for increasing quench rates, the system at the end of the ramp is further away from its final equilibrium condition. In the Fourier spectrum, we notice in the newly-formed BEC the presence of high k modes, which subsequently decay: this can be related to the formation of defects, originated starting from different phase domains via the Kibble-Zurek mechanism [2][3], and their later relaxation dynamics [4].

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Photon interactions in atomic arrays

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Regular arrangments of atoms have remarkable optical properties, for example allowing to achieve virtually perfect single-mode reflection off a two-dimensional atomic array. The linear optical response of these systems has recently attracted substantial interest and a number of exciting applications have been proposed. Here, we investigate the nonlinear behaviour of such arrays that can arise from atomic interactions and explore prospects for generating and manipulating quantum states of light.

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