EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

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ABSTRACT BOOK

COST Joint School and Workshop in

QUANTUM SIMULATIONS AND MANY-BODY PHYSICS WITH LIGHT

— 4-11 June 2016, Chania, Crete, Greece —

COST Joint School and Workshop on Quantum Simulation and Many-Body Physics with Light

Orthodox Academy of Crete, Chania, Greece, June 4-11, 2016

Preface

Many-body physics with photons and polaritons is a highly interdisciplinary field, merging diverse areas such as nano-photonics, quantum optics, condensed matter physics, and quantum technologies. The inherent accessibility to local observables, and the ability to probe out-of-equilibrium phenomena make driven many-body photonic systems especially promising for a variety of applications in quantum simulations and quantum computing, as well as in materials science and optical circuitry. Theory proposals and preliminary experimental works cover a wide range of systems, ranging from superconducting circuits and exciton-polariton systems, to slow light set ups, all the way to integrated nano-photonic structures.

The goal of this residential joint school and workshop was to help bringing the different scientific communities together, discuss the state of the art developments and the open challenges in this field, and provide training for young researchers in diverse topics ranging from quantum many-body systems all the way to quantum-nanophotonics.

The meeting was co-organized by the COST Action MP1403 Nanoscale Quantum Optics and it was co-hosted with its annual WorkGroup 4 meeting. The COST action MP1403 on Nanoscale Quantum Optics serves as European platform to enhance networking and research collaboration in the rapidly evolving field of quantum nanooptics that has substantial overlap with the topics covered in this joint-school and workshop. Among others topics, a big part of the focus in the meeting was in photon nonlinearities, quantum coherence, cooperative effects, generation and detection of quantum states of light quantum correlations and many-body physics tailored by strongly confined optical fields

The meeting had a dual school and workshop character. In the morning sessions, top-class scientists delivered lectures on basic concepts up to the most recent developments. These were complemented by invited research seminars in the afternoon by leading experts covering a broad selection of the hottest topics. Two dedicated poster sessions were organized and posters were hang throughout the duration of the meeting.

This residential meeting was hosted in the Conference Center of the Orthodox Academy of Creta (OAC), an exceptionally beautiful location only a few meters from the Mediterranean sea, half an hour drive west of Chania. Most participants stayed together in OAC with a few in nearby hotels, and everyone took their all their meals in OAC together.

We would like to thank all that contributed to make this a success, the local organzing committee, the lecturers and speakers, as well as all the participants.

The Chair of the Organizing Committee

Dr. Dimitris G. Angelakis

Local Organizing Committee

- Dimitris G. Angelakis (chair), Technical University of Crete and Centre for Quantum Technologies, Singapore
- Jirawat Tangpatinanon, Centre for Quantum Technologies, Singapore
- Tiang Feng See, Centre for Quantum Technologies, Singapore
- Nikos Schetakis, Technical University of Crete

Scientific Advisory Committee

- Dimitris G. Angelakis, TUC Crete and CQT Singapore (Chair)
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- Cristiano Ciuti, Univ. Paris Diderot, France
- Rosario Fazio, ICTP and NEST, Italy
- Peter Rabl, TU Vienna, Austria
- Atac Imamoglu, ETH, Switzerland

Invited Lecturers

Jeremy Baumberg, University of Cambridge, UK (Many-body physics with semiconductor polaritons)
Sebastian Diehl, TU Dresden, Germany (Out of equilibrium many-body quantum systems: Phases and methods)
Dieter Jaksch, University of Oxford, UK (Numerical methods for strongly correlated quantum systems)

Jiannis Pachos, University of Leeds, UK (Topological quantum information)
Alexander Szameit, FSU Jena, Germany (Integrated photonic chips for quantum simulation)
Andreas Wallraff, ETH Zurich, Switzerland (Superconducting quantum circuits)
Peter Zoller, Innsbruck, Austria (Quantum simulations with quantum optical systems)

Invited Speakers

Alberto Bramati, Lab Kastler Brossel, France
Iacopo Carusotto, University of Trento, Italy
Eden Figueroa, University of Stony Brook, USA
Dario Gerace, University of Pavia, Italy
Mohammad Hafezi, JQI and University of Maryland, USA
Michael Hartmann, Herriot Watt, UK
Jens Koch, Northwestern University, USA
Robert Keil, University of Innsbruck, Austria
Jonathan Matthews, University of Bristol, UK
Mikhail Pletyukov, Aachen University, Germany
Helmut Ritsch, University of Inssbruck, Austria
Pedram Roushan, Google, USA
Vincenzo Savona, EPFL, Lausanne, Switzerland
Sebastian Schmidt, ETH Zurich, Switzerland
Martin Weitz, University of Bonn, Germany
Phillip Walther, University of Vienna, Austria
Vasilios Yannopappas, National Technical University of Athens, Greece

COST NQO WorkGroup 4 Annual Meeting Invited Speakers

Christophe Couteau, University of Technology of Troyes and CNRS, France
Giuseppe Calajo, Technical University of Vienna, Austria
Irene d'Amico, University of York, UK
Sile Nic Chormaic, OIST Japan
Vahid Sandoghdar, MPQ Erlangen, Germany
Emmanuel Paspalakis, University of Patras, Greece
Hashem Zoubi, University of Hannover, Germany

Contributed Talks

Wim Casteels, Laboratoire Matériaux et Phénomènes Quantiques
James Douglas, Theoretical Quantum-Nano Photonics, ICFO Barcelona
Michael Gullans, Maryland, US
Marijana Milicevic, Optics of Semiconductor nano structures, LPN Marcoussis
Hwang Myung-Joong, Institute of Theoretical Physics, ULM University
Davide Rossini, Scuola Normale Superiore
Alexandre Roulet, Centre for Quantum Technologies
Stefan Schutz, Theoretical Quantum Physics, Saarland University
Meinrad Sidler, Quantum Photonics Group, ETH Zurich
Jirawat Tangpanitanon, Centre for Quantum Technologies
Alejnadro Tudela, MPQ Munich, Germany
Giorgos Tsironis, University of Crete, Rethymno

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Program

Saturday 4th

17:00 - 20:00 Registration
19:45 - 22:30 Welcome reception 19:45 followed by dinner at OAC at 20:45

Sunday 5th

07:30 - 09:00 Breakfast
09:00 - 09:10 Welcome address by the Conference Chair and OAC Director
09:10 - 10:30 D. Jaksch**, " Numerical methods for strongly correlated quantum systems"
10:30 - 11:00 Coffee break
11:00 - 12:30 J.K Pachos**, "Topological quantum information"
12:30 - 15:35 Lunch break
15:35 - 16:10 D. Rossini, "Cluster mean-field approach to the steady-state phase diagram"
16:10 - 16:45 W. Casteels, "Power-laws in the dynamic hysteresis of quantum nonlinear photonic resonators"
16:45 - 17:30 J. Koch*, "Promises and challenges of studying dissipative phase transitions in circuit QED lattices"
17:30 - 18:00 Coffee break
18:00 - 18:45 R Keil*, "Waveguide lattices as integrated optical simulators: from gauge transformations to unphysical phenomena"
18:45 - 19:30 Yannopapas*, "Topological photonics in heavy photon bands"
19:30 - 20:15 Poster session 1
20:15 - 21:30 Dinner

Monday 6th

07:30 - 09:00 Breakfast
09:00 - 10:30 P. Zoller**, "Quantum simulation with quantum optical systems"
10:30 - 11:00 Coffee break
11:00 - 11:45 D. Jaksch**, " Numerical methods for strongly correlated quantum systems"
11:45 - 12:30 J. K Pachos**, "Topological quantum information"
12:30 - 15:35 Lunch break
15:35 - 16:10 J. Tangpanitanon, "Topological pumping of interacting photons and novel phases in driven dissipative resonator arrays"
16:10 - 16:45 J. S Douglas, "Molecular states of photons in atomic gases trapped near photonic crystal waveguides"
16:45 - 17:30 H. Ritsch*, "Spontaneous crystallisation of a BEC and light in 1D trap"
17:30 - 18:00 Coffee break
18:00 - 18:45 P. Roushan*, "Chiral ground state currents of interacting photons in a synthetic magnetic field"
18:45 - 19:30 M. Hafezi*, "Quantum transport in topological photonic structures"
19:45 - 22:30 Conference Dinner and Cretan Concert

** School Lecture * Invited talk

Tuesday 7th

07:30 - 09:00 Breakfast
09:00 - 09:45 P. Zoller**, "Quantum simulation with quantum optical systems"
09:45 - 10:30 A Wallraff**, "Exploring quantum simulations with superconducting circuits"
10:30 - 11:00 Coffee break
11:00 - 12:30 A Wallraff**, "Exploring quantum…"
12:30 - 15:35 Lunch break
15:35 - 16:10 M. J. Hwang, "Quantum phase transition of light in a finite system"
16:10 - 16:45 A Roulet, "Rabi oscillation in a quantum cavity: Markovian and non-Markovian dynamics"
16:45 - 17:30 P. Walter*, "Single photons for simulating spin interactions and investigating new computational schemes"
17:30 - 18:00 Coffee break
18:00 - 18:45 E Figueroa*, "Towards simulating the Jackiw-Rebbi model using photons and atoms"
18:45 - 19:30 S Schmidt*, "Flat bands in interacting light matter systems"
19:30 - 20:15 Poster session 2
20:15 - 21:30 Dinner

Wednesday 8th

07:30 - 09:00 Breakfast
09:00 - 10:30 S Diehl**, "Keldysh field theory for driven open quantum systems and some applications"
10:30 - 11:00 Coffee break
11:00 - 12:30 A Szameit**, "Integrated optical circuits for classical and quantum light"
12:30 - 14:00 Lunch break (*one and a half hour)
14:00 - 14:30 M. Sidler, "Fermi polaron-polaritons in $MoSe_2$"
14:30 - 15:00 S. Schutz, "Thermodynamics and relaxation in a system of photon-mediated long-range interactions"
15:00 - 15:45 I. Carusotto*, "Unitary dynamics of quantum fluids of light in propagating geometries"
15:45 - 16:15 Coffee break
16:15 - 17:00 M. Weitz*, "Bose-Einstein condensation of photons and periodic potentials for light"
17:00 - 17:45 D. Gerace*, "Digital quantum simulation of condensed matter models with hybrid qubits"
18:00 - 22:30 Excursion and free evening in Chania,

Thursday 9th

07:30 - 09:00 Breakfast
09:00 - 09:45 S Diehl**, "Keldysh field theory for driven open quantum systems and some applications"
09:45 - 10:30 A Szameit**, "Integrated optical circuits for classical and quantum light"
10:30 - 11:00 Coffee break
11:00 - 11:45 V. Savona*, "Variational approach to the non equilibrium steady state: Matrix-product-operators and beyond"
11:45 - 12:30 M. Hartmann*, "A superconducting quantum simulator for topological order and the toric code"
12:30 - 14:30 Lunch break (*two hours)
——COST WG4 Meeting——
14:30 - 15:30 Discussion on WG4 future activities (COST members only)
15:30 - 16:00 H. Zoubi, "Photon-photon interactions in nanophotonics"
16:00 - 16:30 G. Calajo, "Atom-field dressed states in slow-light waveguide QED"
16:30 - 17:-00 C. Couteau, " Coupling metamaterials and plasmons with quantum states of light "
17:00 - 17:30 Coffee break
17:30 - 18:00 V. Sandoghdar "A one-dimensional controllable polaritonic system: from order to disorder"
18:00 - 18:30 E Paspalakis, "Controlled optical absorption and resonance fluoresce from a quantum emitter near a plasmonic nanostructure"
18:30 - 19:00 S. N. Chormaic, "Atom-light interactions using ultra-thin optical fibres"
19:00 - 19:30 I. D'Amico, "DFT-inspired method to calculate work distribution and average work of a quantum many-body system"
19:30 - 20:00 R Clton-"Special event: Gender Issues in Science" 20:00 - 21:00 Dinner 21:00 - 21:30 R Clton-continue

Friday 10th

7:30 - 09:00 Breakfast
09:00 - 10:30 J. J. Baumberg**, "Microcavity polaritonics: Optically-steering interacting quantum liquids on a chip"
10:30 - 11:00 Coffee break
11:00 - 11:45 J. J. Baumberg**, "Microcavity polaritons…"
11:45 - 12:30 A Bramati*, "Lattices of quantized vortices in polariton Superfluids"
12:30 - 15:00 Lunch break
15:00 - 15:35 A G Tudela, "Atom-nanophotonics: a platform for quantum information and simulation"
15:35 - 16:10 M. J. Gullans, "Effective field theory for Rydberg polaritons"
16:10 - 16:45 G Tsironis "Electromagnetic control of qubits through quantum breathers"
16:45 - 17:15 Coffee break
17:15 - 18:00 J. C F. Matthews*, "Analogue and digital quantum simulation of quantum walks with photons"
18:00 - 18:45 M. Pletyukhov*, "Multiphoton scattering theory for waveguide QED: various applications"
18:45 - 19:15 M. Milicevic, "Orbital edge states in honeycomb lattices"
19:15 - 20:00 Closing remarks 20:00 - 21:30 Dinner

Quantum simulations and many-body physics with light

School Lectures

Microcavity Polaritonics: Optically-Steering Interacting Quantum Liquids on a Chip

J J Baumberg[1]
[1] NanoPhotonics Centre, Cavendish Laboratory, University of Cambridge, CB30HE

Constructing ultra-high finesse semiconductor microcavities produces quasiparticles called exciton polaritons which can Bose condense even up to room temperature. The resulting macroscopic quantum states are directly visible and allow superflows to be imaged. Spontaneous oscillations, self-organised vortex lattices, and geometrical phase transitions are all part of the rich phenomena observed.

While condensation of polaritons spontaneously breaks phase-symmetry, the spin is typically pinned and not spontaneously aligning in different directions. We show here the first instance of spontaneous symmetry breaking for the magnetisation of a polariton condensate. Unpolarised incoherent pumping generates randomly spin-up or spin-down magnetised condensates on each realisation, which remain stable for seconds, but can be rapidly switched. By applying an electrical field perpendicular to the quantum-well plane we precisely tune the polarisation of the condensate emission. We utilise this phenomenon to realise an electrical spin-switch, operating at record ultra-low switching energies of order attojoules and switching speeds that are only limited by the condensate dynamics. These properties give strong hope for a whole variety of practical polariton devices..

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[1] Nature Physics 8, 190 (2012); G. Tosi et al., "Sculpting oscillators with light within a nonlinear quantum fluid"

[2] Nature Communications 3, 1243 (2012); G. Tosi et. al., "Geometrically locked vortex lattices in semiconductor quantum fluids"

[3] Science 336, 704 (2012); P. Cristofolini et al., "Coupling Quantum Tunneling with Cavity Photons"

[4] Phys.Rev.Lett. (2013); P. Cristofolini et al., "Optical superfluid phase transitions and trapping of polariton condensates"

[5] Phys Rev X 5, 031002 (2015), H Ohadi et al, Spontaneous spin bifurcations and ferromagnetic phase transitions in a spinor exciton-polariton condensate

[6] Phys.Rev.Lett. 116, 106403 (2016), H Ohadi et al., Tunable Magnetic Alignment between Trapped Exciton-Polariton Condensates

Numerical methods for strongly correlated quantum systems

D. Jaksch[1]

[1] Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom

In these lectures I will introduce Tensor Network Theory (TNT) as a powerful and general method for studying strongly correlated systems. We will start by discussing the basic elements and concepts common to all TNT algorithms. I will explain what properties make low-dimensional quantum systems particularly suited to be tackled by this approach. We will then focus on using Matrix Product States and Operators for solving for the ground state and dynamical evolution of a lattice quantum many-body quantum system in one spatial dimension. The evolution of an open quantum system coupled to a thermal bath will also be discussed. I will introduce the TNT library [1] and its web-interface TNTgo [2] and use them to solve simple toy model problems. This will be followed by an investigation of how TNT methods are extended to two spatial dimensions and the challenges that this brings. Finally, I will give an overview of possible TNT applications outside of its traditional area of strongly correlated quantum systems. This will include its possible uses in Dynamical Mean Field Theory (DMFT), for solving classical stochastic systems with a focus on identifying rare events, and how to exploit TNT for solving partial differential equations.

The aim of my lectures will be to provide a solid understanding of the core concepts of TNT and to enable usage of standard TNT numerical tools in research. Furthermore I wish to encourage broader thinking about the potential future applications of these methods and the possibilities for combining them with methods in other fields of research.

[1] www.tensornetworktheory.org
[2] www.tntgo.org/

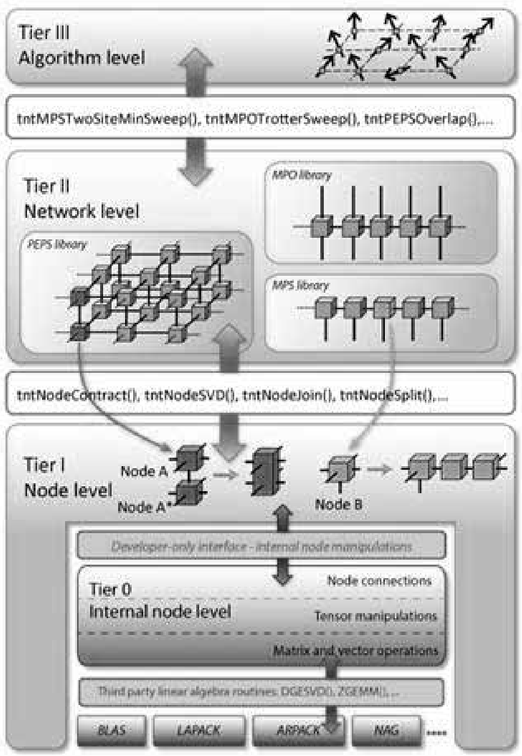

FIG. 1: Structure of the TNT library. Tiers I and II contain generic functions for manipulating tensors and network connections between them. Tier III contains ready-made standard algorithms.

Topological Quantum Information

J. K. Pachos
School of Physics and Astronomy, University of Leeds, Leeds LS2 9JT, UK

Combining physics, mathematics and computer science, topological quantum information [1] is a rapidly expanding field of research focused on the exploration of quantum evolutions that are resilient to errors. In this series of lectures I will present a variety of different topics starting from introducing anyonic models, topological phases of matter, Majorana fermions, characterising knot invariants, their quantum simulation with anyons and finally the possible realisation of anyons and topological phases in the laboratory.

[1] J. K. Pachos, Introduction to Topological Quantum Computation, Cambridge University Press, 2012.

Integrated optical circuits for classical and quantum light

Alexander Szameit[1]

[1]Institute of Applied Physics, Friedrich-Schiller-Universität Jena,
Albert-Einstein-Strasse 15, 07745 Jena, Germany

The implementation of waveguiding structures on a chip constitutes a superior possibility to specifically tailor the dynamics of light within a very small volume. Integrated optical circuits allow the realization of propagation phenomena of classical and quantum light that are not observable in free space. Such structures are in particular useful as model system for quantum mechanical processes that are inaccessible in the laboratory otherwise.

In my lecture I will present the fundamental principles of coupled optical waveguide structures and discuss several applications for emulating quantum mechanical processes, such as solid state phenomena and relativistic physics. Moreover, I will present our latest results on photonic topological insulators and integrated quantum optics, which crucially depend on the superior properties of integrated optical waveguide structures.

Exploring Quantum Simulations with Superconducting Circuits

Andreas Wallraff[1]

[1]Department of Physics, ETH Zurich, Zurich, Switzerland

The high level of control achievable over quantized degrees of freedom have turned superconducting circuits into one of the prime physical architectures for quantum computing and simulation. While conventional approaches mostly rely on unitary time evolution more recently open-system dynamics are considered for quantum information processing and simulations as well. In this presentation, I will first give an introduction to quantum simulations with superconducting circuits. Then, I will present a first set of experiments in which we simulated the physics of interacting spins using a digital approach [1] using the device shown in Fig. 1. In a second set of experiments we made use of an open cavity QED system with tunable interactions to simulate the ground state of an interacting Bose gas confined in one dimension [2–4]. These experiments rely on our ability to efficiently measure higher order photon correlations of propagating microwave fields. To facilitate these measurements we developed a quantum limited amplifier achieving phase-preserving amplification at large bandwidth and high dynamic range [5]. Our results demonstrate an alternative path towards simulating complex quantum many-body physics based on the controlled generation and detection of nonclassical radiation in open quantum systems.

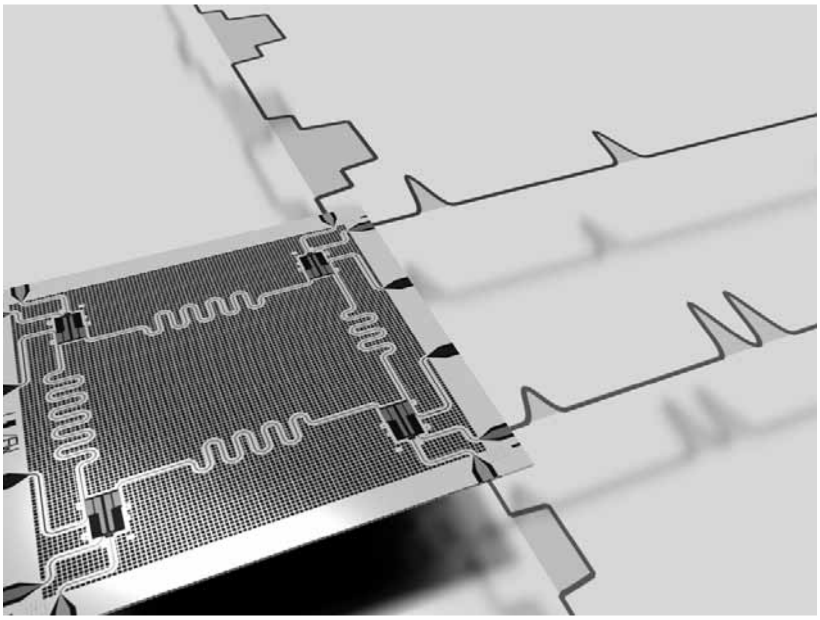

FIG. 1: The figure shows a rendering of a device with four qubits coupled to each other by four resonators. Gate lines through which microwave pulses and flux pulses are applied to the individual qubits for single-qubit state control and two-qubit interactions are also indicated with a rendering of the respective pulses. This device was used for the digital quantum simulation of interacting spins.

[1] Y. Salathé, M. Mondal, M. Oppliger, J. Heinsoo, P. Kurpiers, A. Potočnik, A. Mezzacapo, U. Las Heras, L. Lamata, E. Solano, et al., Phys. Rev. X 5, 021027 (2015), URL http://link.aps.org/doi/10.1103/PhysRevX.5.021027.

[2] S. Barrett, K. Hammerer, S. Harrison, T. E. Northup, and T. J. Osborne, Phys. Rev. Lett. 110, 090501 (2013), URL http://link.aps.org/doi/10.1103/PhysRevLett.110.090501.

[3] F. Verstraete and J. I. Cirac, Phys. Rev. Lett. 104, 190405 (2010), URL http://link.aps.org/doi/10.1103/PhysRevLett.104.190405.

[4] C. Eichler, J. Mlynek, J. Butscher, P. Kurpiers, K. Hammerer, T. J. Osborne, and A. Wallraff, Phys. Rev. X 5, 041044 (2015), URL http://link.aps.org/doi/10.1103/PhysRevX.5.041044.

[5] C. Eichler, Y. Salathe, J. Mlynek, S. Schmidt, and A. Wallraff, Phys. Rev. Lett. 113, 110502 (2014), URL http://link.aps.org/doi/10.1103/PhysRevLett.113.110502.

Quantum Simulation with Quantum Optical Systems

Peter Zoller[1]

[1]Institute for Theoretical Physics, University of Innsbruck,
and Institute for Quantum Optics and Quantum Information,
Austrian Academy of Sciences, Innsbruck, Austria

I will give a series of three lectures on quantum simulation of quantum many-body systems with atoms, ions, and photons. In the first lecture I will give a general overview and introduction to Hamiltonian quantum many-body systems including in particular Hubbard models realized with cold atoms in optical lattices, spin models with Rydberg atoms and strings of ions. The second and third lecture will be devoted to open quantum many-body systems in quantum optical setups. We will start with an introduction to open quantum systems in quantum optics, and describe techniques like the master equation. I will illustrate the ideas and concepts with our ongoing research on chiral quantum networks, where the system of interest is driven two-level atoms (qubits) with interactions mediated by photons. This provides an example, where a driven-dissipative evolution leads in steady state to the formation of pure entangled many-particle states of atoms (here in the form of quantum dimers).

Invited talks

Lattices of Quantized Vortices in Polariton Superfluids

A. Bramati
Laboratoire Kastler Brossel, UPMC-Sorbonne Universités, CNRS, ENS, Collège de France, Paris, France

Microcavity polaritons, the half-light-half-matter particles arising from the strong coupling between excitons and photons, behave like weakly interacting composite bosons. Due to their excitonic part they exhibit non-linear interaction while their photonic part allows creating and detecting them optically. In this sense the polaritons are part of a wider family of systems where an effective photon-photon interaction can be engineered, resulting in a hydrodynamical-like behavior. Such systems are labeled as quantum fluids of light [1]. These ingredients make polariton systems a unique platform to study quantum fluid effects in a semiconductor chip and to evidence properties very difficult to access in other systems.

In this talk I will focus on the description of the recent studies conducted in our group, in the quest for the observation of lattices of quantized vortices in polariton superfluids. In particular I will show how the implementation of optical traps for polaritons allows for the realization of vortex-antivortex lattices in confined geometries and how the development of flexible all-optical methods to inject a controlled orbital angular momentum (OAM) in such systems results in the observation of patterns of same sign vortices [2, 3]. These results constitute a significant step forward in our understanding of the quantum fluids of light and open the way to the study of Abrikosov-like physics and new vortex collective phenomena in these systems.

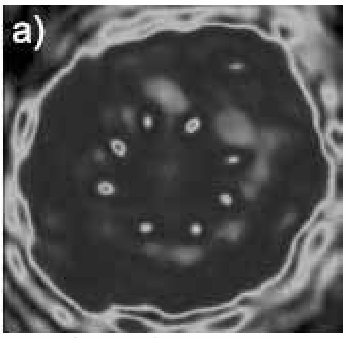

Fig.1: Chain of same sign vortices

[1] I. Carusotto and C. Ciuti, Quantum Fluids of Light, Rev. Mod. Phys. 85, 299 (2013).
[2] T. Boulier, H. Terças, D. D. Solnyshkov, Q. Glorieux, E. Giacobino, G. Malpuech and A. Bramati, Vortex chain in a resonantly pumped polariton superfluid, Scientific Reports 5, 9230 (2015).
[3] T. Boulier, E. Cancellieri, N.D. Sangouard, Q. Glorieux, A. V. Kavokin, E. Giacobino, A. Bramati, Injection of orbital angular momentum and storage of vortices in polariton superfluids, to appear , Phys. Rev. Lett. (2016).

Unitary dynamics of quantum fluids of light in propagating geometries

Iacopo Carusotto[1]
[1]INO-CNR BEC Center and Dipartimento di Fisica, Università di Trento, I-38123 Povo, Italy

In this talk I will give an overview of recent works by the Trento group on the theory of quantum fluids and condensates of light in cavity-less bulk nonlinear media, where the propagation dynamics can be recast in terms of a conservative evolution. The novel quantum effects that occur in this regime will be highlighted, as well as the promising perspectives in the direction of studies of non-equilibrium quantum statistical mechanics and quantum dynamics past quantum quenches. I will conclude with a speculative discussion of a novel concept of coherent light source based on thermalization of propagating light into a Bose-Einstein condensate.

Towards simulating the Jackiw-Rebbi model using photons and atoms.

Eden Figueroa[1]
[1]Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA

I. Introduction.

Experimental verification of relativistic field theory models requires complex accelerator experiments. A possible pathway that could faithfully reproduce the physics of such models for bosons or fermions is the use of electromagnetically induced transparency (EIT) storage techniques. The possibility of generating nonlinear Dirac type of Hamiltonians using dark state polaritons (coherent superpositions of photons in the electromagnetic field and spin wave excitations of the atoms) has recently been discussed, yet its implementation remains a considerable challenge. Three key milestones must be attained in order for such a quantum simulator based on light an atoms to come to fruition: i) the development of reliable light-matter interconnects that can deterministically receive and reproduce quantum light; ii) the realization of a quantum interface to perform engineered interactions between photons; and iii) an atomic medium in which a combination of the latter processes resembles the physical dynamics described by the theory model of choice. A good starting point is the Jackiw-Rebbi model which describes a Dirac field with a spatially dependent mass term. This model can be realized in a driven slow-light setup, where photons mimic the Dirac field and different dynamics can be implemented and tuned by adjusting optical parameters such as the light fields detunings [1]. The presentation discusses our current progress towards achieving an EIT based quantum simulator using atomic vapor quantum light-matter interfaces.

II. Room temperature low-noise quantum light matter interfaces.

In our first experiment we characterize the optimal performance of room temperature quantum light-matter interfaces and attain complete quantum memory operation for polarization qubits in a warm ^{87}Rb atomic vapour. We store 400 ns long pulses containing on average one qubit using electromagnetically induced transparency (EIT). Two independent control beams coherently prepare two volumes within a single vapour cell at 60°C, containing Kr buffer gas to serve as the storage medium for each mode of the polarization qubit. We do obtain an average fidelity of $86.6 \pm 0.6\%$, well above 83.6%, the maximum fidelity achievable considering any classical strategy exploiting the non-unitary character of the memory efficiency. This is the first time such important boundary has been crossed with a room temperature device, rendering our system suitable for true quantum operation [2, 3].

III. Room temperature single photon quantum non linearities.

In our second experiment we present the complete experimental characterization of a system designed for optically controlled phase shifts acting on single-photon level probe coherent states. The setup is based on a warm vapor of rubidium atoms under EIT conditions with its dispersion properties modified through the use of an optically triggered N-type Kerr non-linearity. We probe our system with weak coherent states and measure the phase and amplitude quadratures of the input and output via time-domain homodyne tomography. We obtain optically controlled phase shifts of $\pi/2$ radians acting on single-photon level probe pulses. Further, by collecting data for a set of weak coherent state inputs, we gain the information needed to completely characterize a rank-4 process super-operator in the Fock states basis, which can then be utilized to fully characterize the single-photon level nonlinear system. [4]

IV. Spinor of light in atomic vapor.

Lastly, we will show our progress towards building an EIT based simulator to the Jackiw-Rebbi model dynamics using highly-interacting photons strongly coupled to a room temperature atomic ensemble. In this novel approach, the Dirac particles are mimicked by polarized photons interacting in the the quantum nonlinear medium defined by room temperature spin waves. Our efforts aim for the creation of two EIT tripod systems in a spinor of light configuration in which superpositions of coherent atomic excitations and light follow tunable nonlinear dynamics equations. Here, the optically tuned interactions are a function of the strength of the control fields and the atomic detunings. Our goal is to identify suitable conditions in which the input photons dispersion relations can be tuned to mimic the Dirac regime and also investigate how to optically create the tunable interactions and mass terms of the Jackiw-Rebbi model.

[1] D. G. Angelakis, et al. Scientific Reports 4, 6110 (2014).
[2] C. Kupchak, et al. Scientific Reports 5, 7658 (2015).
[3] M. Namzi, et al. arXiv:1512.07374 (2015).
[4] C. Kupchak, et al. Scientific Reports 5, 16581 (2015).

Digital quantum simulation of condensed matter models with hybrid qubits

D. Gerace[1,*] and A. Chiesa, P. Santini, S. Carretta[2]
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[2]Dipartimento di Fisica e Scienze della Terra, Università di Parma, Italy

A quantum computation architecture is theoretically proposed, based on a hybrid definition of qubits in which spin ensembles are strongly coupled to superconducting planar resonators, allowing to perform any elementary single and two-qubit quantum gates solely by shifting the cavity resonances on nanosecond timescales [1]. Robustness of these elementary operations is tested against the main decoherence sources [2], such as photon loss and pure dephasing. An elementary unit of such an architecture is shown in Figure 1, consisting of logical resonators containing spin ensembles, and auxiliary resonators containing a superconducting transmon device, i.e. working as a strongly nonlinear element. Each logical resonator behaves as a hybrid spin-photon qubit, where the logical state $|0\rangle$ ($|1\rangle$) is encoded for zero (one) photons in the cavity mode and a single (zero) excitation of the spin ensemble, respectively. The transmon device is not used to encode information, and it is left in its ground state always except during the implementation of two-qubit gates. Consequently, short coherence times of these superconducting elements do not affect our quantum computing efficiency. The scalability of such an architecture is naturally fulfilled by realizing arrays of superconducting resonators made of the scalable platform represented in Figure.

Recently, different approaches have been proposed to realize quantum simulators of the most relevant models in condensed matter physics. We focus here on digital simulators, where the state of the target system is encoded in qubits, and its Trotter-decomposed time evolution is directly implemented by a sequence of elementary quantum gates. Digital architectures are usually able to simulate broad classes of Hamiltonians. Based on the hybrid spin-photon qubit encoding introduced above, we have devised an efficient and scalable scheme to perform digital quantum simulations of complex manybody problems, realizable with state-of-art technology. In particular, it is described a universal scheme to directly solve the time evolution of paradigmatic models, such as the transverse field Ising model, and the XY model, and the two-dimensional Fermi-Hubbard model [3, 4]. For the latter case, it is shown that our quantum computational scheme naturally allows circumventing the well known sign problem affecting the numerical simulation of interacting fermionic systems.

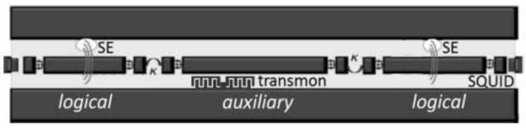

FIG. 1: Schematic representation of an elementary unit of our scalable setup to perform digital quantum simulation: logical resonators include ensembles of $s = 1$ spins placed at the magnetic field antinode of the respective superconducting resonator, where one of the spin transitions is in the strong coupling regime with the cavity mode; the auxiliary resonator contains a transmon coupled to the cavity mode electric field. The frequencies of individual resonators can be tuned by using SQUID devices.

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Quantum transport in topological photonic structures

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Following the measurement of topological invariants in silicon ring resonator systems [1], we report on the progress of investigation of non-classical light transport. In particular, we analyze the transport properties of two-photon wavefunctions in a disorders structure with protected topological edge bands, and examine the robustness of quantum transport properties [2]. Moreover, we discuss a design for photonic crystals with topological properties [3]. Both Finite-difference-time-domain simulations and tight-binding model show topological protection as controllable directional light propagation with circularly-polarized dipole excitations and backscattering-free propagation around sharp corners. Such structured be integrated with nonlinear quantum emitters such as color centers and quantum dots and could be used for robust on-chip quantum information processing and quantum simulation of fractional quantum Hall states. Finally, we discuss the effect of interacting disorder in these systems. Specifically, the possibility that topological ordered states, such as Laughlin states, may be realized in photonic systems has recently attracted a great deal of attention. These states are predicted to arise in strongly nonlinear photonic lattices with artificial gauge fields, where nonlinearities associated with the resonators mimic on-site interactions. However, these effective interaction strengths are not universal and are subject to spatial disorder. We present a detailed study of the stability of these states and what implications they have for experiments.

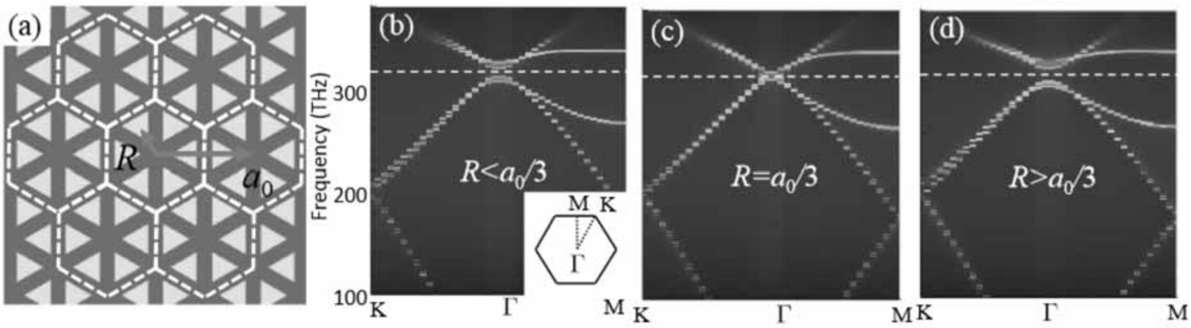

FIG. 1: Design of triangular photonic crystal with equilateral triangular holes and the corresponding TE mode band structures. (a) The lattice of triangular holes can be considered as a triangular lattice of hexagonal cells each composed of six triangles, outlined by white dotted lines. The parameters a_0 is the lattice constant of the triangular lattice and R is the distance from the center of a cell to the centroid of a triangular hole of the cell. When $R = a_0/3$, the system is exactly a honeycomb lattice with a Dirac cone. (b) Band structure when $R = 0.95 \times a_0/3$. Inset shows the Brillouin zone. (c) Band structure when $R = a_0/3$. (d) Band structure when $R = 1.05 \times a_0/3$. There is a Dirac cone in (c), but a band gap is opened for (b) and (d).

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A Superconducting Quantum Simulator for Topological Order and the Toric Code

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Topological order is now being established as a central criterion for characterising and classifying ground states of condensed matter systems and complements categorisations based on symmetries. Fractional quantum Hall systems and quantum spin liquids are receiving substantial interest because of their intriguing quantum correlations, their exotic excitations and prospects for protecting stored quantum information against errors.

In this talk I will discuss a recent approach for implementing the Hamiltonian of the central model of this class of systems, the Toric Code, in lattices of superconducting circuits. The four-body interactions, which lie at its heart, are in our concept realised via Superconducting Quantum Interference Devices (SQUIDs) driven by a suitably oscillating flux bias. All physical qubits can be individually controlled and strings of operators acting on them, including the stabilisers, can be read out via a capacitive coupling to common transmission line resonators. The architecture we propose thus provides a versatile quantum simulator for topological order.

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Waveguide lattices as integrated optical simulators - from gauge transformations to unphysical phenomena

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Many phenomena from solid state or relativistic physics are too elusive for a direct experimental investigation. Artificially engineered systems, such as cold atoms or molecules in trapping potentials or lattices of evanscently coupled optical waveguides provide a controllable environment for proof-of-principle experiments. A variety of such experiments has been successfully implemented in recent years, ranging from the simulation of Dirac's trembling motion [1, 2] to the demonstration of relativistic Landau levels in graphene [3, 4].

In this talk, I will present two new examples of such experiments, which were realised in waveguide lattices. The first relates to solids penetrated by strong inhomogeneous magnetic fields. I will show how the required topological gauge transformations can be introduced via flipping the sign of the coupling strength on individual links in a lattice [5]. On a small scale, this permits the implementation of compact Aharanov-Bohm interferometers (see Fig. 1(a)). The second example covers the optical simulation of the Majorana equation and its unphysical solutions, implemented by a decomposition of the Majorana equation into a pair of Dirac equations, which are indivually simulated in separate lattices, and subsequent interference [6, 7] (Fig. 1(b)). Both concepts rely on a precise site-resolved control of the refractive properties of the waveguide lattice, which can be achieved by femtosecond laser waveguide inscription.

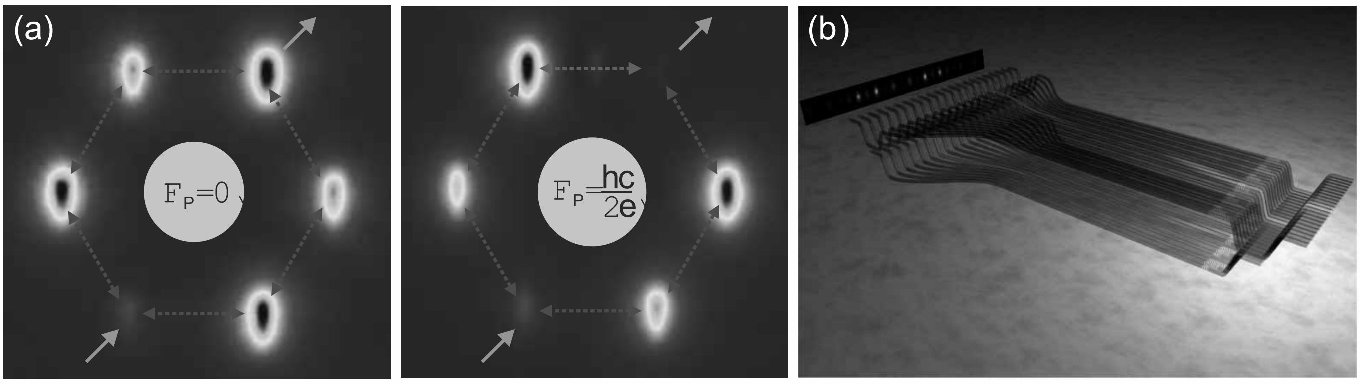

FIG. 1: (a) Aharanov-Bohm interferometry. Left: In a hexagonal configuration of positively coupled (red links) waveguides, light input to the bottom left corner leads to constructive interference in the output site (bright spot in the top right corner). This corresponds to the absence of transverse magnetic fields. Right: Turning one coupling negative (green link) corresponds to half a flux quantum penetrating the plaquette and leads to destructive interference, as visible from the dark output. (b) Optical chip for the simulation of the Majorana equation with the two parallel waveguide lattices, each simulating a Dirac equation. State preparation and read-out are performed on-chip by the directional couplers.

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Promises and challenges of studying dissipative phase transitions in circuit QED lattices

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Quantum simulations based on bosonic particles have been demonstrated beau- tifully and continue to thrive in experiments with ultracold atoms in optical lat- tices. Photons also provide an instance of bosonic particles, but crucially di↵er from bosonic atoms in their lack of chemical potential and negligible interaction at energy scales relevant to experiments. Strong photon-photon interactions can be induced, however, by light-matter interaction. Coherent light sources such as lasers or microwave generators open up the possibility to observe nonequilibrium physics of interacting photons. In this talk, I will describe how this promise is ad- dressed in the circuit-QED architecture, and report on joint theory and experimen- tal work studying a 72-site circuit QED lattice. In the dispersive regime, the ob- served bistability with very long switching times may indicate a dissipative phase transition, certain aspects of which match predictions obtained from an approxi- mate mapping to a dissipative Dicke model. [1]

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[1] In collaboration with the group of Andrew Houck at Princeton.

Analogue and digital quantum simulation of quantum walks with photons

Xiaogang Qiang,[1] Thomas Loke,[2] Ashley Montanaro,[3] Kanin Aungskunsiri,[1] Xiao-Qi Zhou,[1,4] Jeremy L. O'Brien,[1] Jingbo Wang,[2] and Jonathan C. F. Matthews[1,*]

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The random walk formalism is used across a wide range of applications, from modelling share prices to predicting population genetics. Likewise quantum walks have shown much potential as a framework for developing new quantum algorithms and for observing coherent quantum transport. In this paper, we will discuss the experimental implementation of the abstract notion of the quantum walk using photons. We will review single and multi-photon quantum walks (e.g. [1]), including for observation of fermion statistics [2] and boson "clouding" [3], and we will explore potential applications. We will also present implementation of a recently proposed scheme that uses digital quantum logic to simulate quantum walks on the circulant class of graph [4]. This will included evidence from computational complexity that the sampling that occurs efficiently from implementing this scheme with a quantum processor is unlikely to be achievable efficiently with classical resources.

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Multiphoton scattering theory for waveguide QED: various applications

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In this talk I present a diagrammatic approach to a multiphoton scattering in one-dimensional waveguides/transmission lines elaborated in [1]. It allows to compute exact N-photon scattering matrices for arbitrary quasi-local scatterers like nonlinear cavities and their arrays. In particular, modeling the latter system by a Bose-Hubbard Hamiltonian, I discuss its transmission properties as well as the second order correlation functions for a weakly coherent incident pulse. The behavior of a nonlinear correction to the transmittance in the presence of disorder is also considered.

Other applications include a case of spatially separated scatterers (e.g., two distant qubits [2]) manifesting non-Markovian effects, and models with a periodically modulated light-matter coupling which allow to realize an optical chopping of a photonic pulse at quantum level [3].

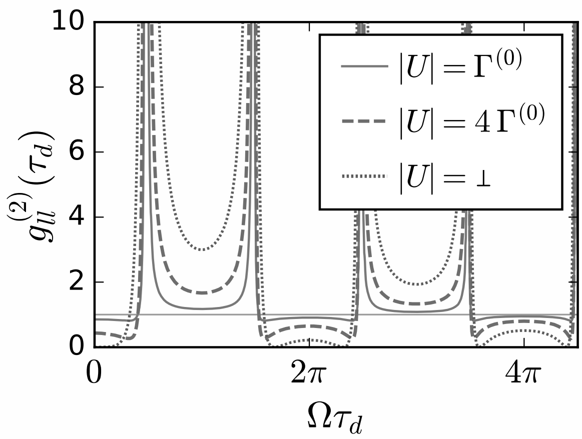

FIG. 1: Second-order correlation function in a system with a periodically modulated coupling, peculiar photon statistics – alternation of antibunching and bunching.

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Spontaneous crystallization of of a BEC and light in a 1D trap

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Coherent scattering of light from ultracold atoms involves an exchange of energy and momentum introducing a wealth of non-linear dynamical phenomena. As a prominent example particles can spontaneously form stationary periodic configurations which simultaneously maximize the light scattering and minimize the atomic potential energy in the emerging optical lattice. Such self-ordering effects resulting in periodic lattices via bimodal symmetry breaking have been experimentally observed with cold gases and Bose-Einstein condensates (BECs) inside an optical resonator. Here we study a new regime of periodic pattern formation for an atomic BEC in free space, driven by far off-resonant counterpropagating and non-interfering lasers of orthogonal polarization. In contrast to previous works, no spatial light modes are preselected by any boundary conditions and the transition from homogeneous to periodic order amounts to a crystallization of both light and ultracold atoms breaking a continuous translational symmetry. In the crystallized state the BEC acquires a phase similar to a supersolid with an emergent intrinsic length scale whereas the light-field forms an optical lattice allowing phononic excitations via collective back scattering. The studied system constitutes a novel configuration allowing the simulation of synthetic solid state systems with ultracold atoms including long-range phonon dynamics.

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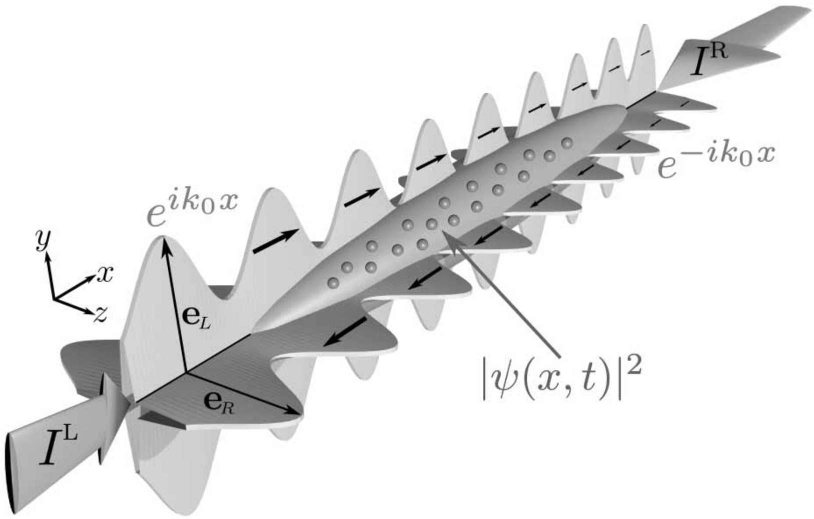

FIG. 1: Schematic representation of an elongated BEC interacting with two counterpropagating, non-interfering laser beams

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Chiral groundstate currents of interacting photons in a synthetic magnetic field

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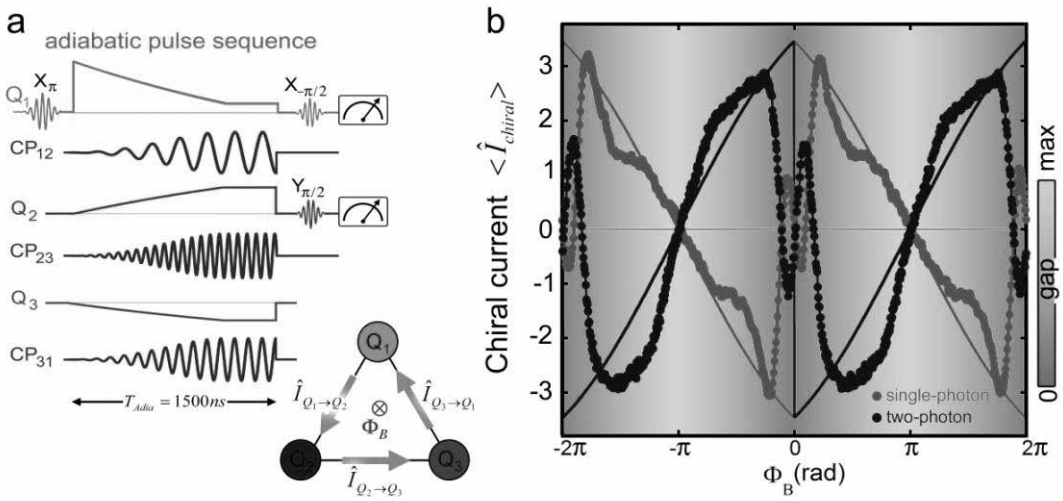
The intriguing many-body phases of quantum matter arise from the interplay of particle interactions, spatial symmetries, and external fields. However, controllably bringing all these elements together in an experimental platform is a major challenge. Here, we realize the main ingredients for creating fractional quantum Hall states using superconducting qubits. We synthesize magnetic fields by sinusoidally modulating the qubit couplings. In a closed loop formed by the three qubits, we observe the directional circulation of photons, a signature of broken time reversal symmetry. We demonstrate strong interactions via the creation of photon-vacancies, or "holes", which circulate in the opposite direction. The combination of these key elements results in chiral groundstate currents, the first direct measurement of persistent currents in low-lying eigenstates of strongly interacting bosons. These currents suggest the existence of rich phases even at small scales and highlights our capability to directly measure observables, such as entanglement and edge currents, relevant to fractional quantum Hall states. Our work introduces an experimental platform for engineering quantum phases of strongly interacting bosons and takes a major step toward realizing them.



(a) The pulse sequence for adiabatically preparing the groundstate of the three qubit Hamiltonian in the synthetic magnetic field. (b) The measured values of chiral current in the single-photon (olive-color) or two-photon manifolds (maroon-color). The solid lines are computations for infinite adiabatic ramps. The energy gap of the Hamiltonian of the system is numerically computed and is shown as the background of the data.

Variational approach to the nonequilibrium steady state: Matrix-product-operators and beyond

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Many-body open quantum systems have attracted increasing attention in recent years. From a theoretical viewpoint, these systems call for new effective methods for the simulation of the dynamics and of the nonequilibrium steady state (NESS).

The matrix-product-state (MPS) ansatz is now well established as the election method for the simulation of both the ground state and the dynamics of one-dimensional closed systems. In the case of open quantum systems, a matrix-product-operator (MPO) ansatz for the density operator allows both the simulation of the real-time dynamics, and the determination of the thermal-equilibrium state through imaginary time evolution. However, a direct variational approach to the NESS has been lacking until recently.

Here, I will introduce a variational method to determine the NESS of a linear driven-dissipative quantum chain, relying on the MPO ansatz for the system density matrix [1, 2]. The method essentially searches for the null eigenvalue of the Liouvillian super-operator by sweeping along the system while carrying out a partial diagonalization of the single-site stationary problem. Similarly to the variational MPS approach to closed systems, the numerical complexity scales as a power law with the chosen bond dimension. I will present test calculations on a driven-dissipative spin chain, and discuss the advantages of the method when compared to both time-dependent MPO and quantum jump approaches.

Finally, I will briefly present some very preliminary results on a completely different approach to the NESS, based on quantum Monte Carlo. Monte Carlo is currently used to stochastically sample the environment-induced fluctuations on quantum trajectories in the Hilbert space. Here, I will present a proof of principle of the possibility to stochastically sample also the deterministic real-time evolution of the Liouville-von-Neumann equation, in analogy to the class of projector Monte Carlo techniques traditionally applied to closed quantum systems. This method holds promise as a computationally effective tool to address open quantum system independently of their dimensionality.

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Flat bands in interacting light matter systems

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Artificially engineered light-matter systems constitute a novel, versatile architecture for the quantum simulation of driven, dissipative phase transitions and non-equilibrium quantum many-body systems. In this talk, I review recent experimental as well as theoretical works on the simulation of geometrical frustration in interacting photonic systems out of equilibrium [1]. In particular, I discuss two recent discoveries at the interface of quantum optics and condensed matter physics: (i) the experimental achievement of bosonic condensation into a flat energy band [2] and (ii) the theoretical prediction of crystalline phases of light in a frustrated qubit-cavity array. I will argue that this new line of research leads to novel and unique tools for the experimental investigation of frustrated systems and holds the potential to create new phases of light and matter with interesting spatial structure. [3].

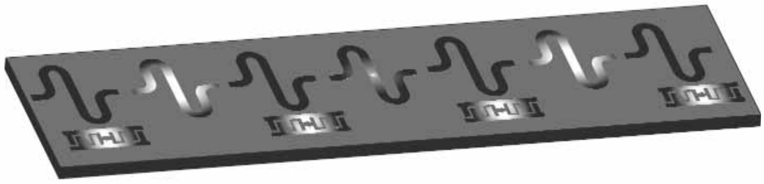

FIG. 1: Proposal for the realization of a strongly interacting Lieb lattice with a flat energy band using superconducting qubits. The qubits couple to every other resonator in a chain of transmission lines. The shading symbolizes the crystalline nature of the photonic correlations (density wave oscillations) due to the interplay between frustration and strong interactions.

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Single photons for simulating spin interactions and investigating new computational schemes

Phillip Walther[1]
[1]University of Vienna, Austria

The advantages of the photons makes optical quantum system ideally suited for fundamental quantum physics experiments and a variety of applications in quantum information processing. Here I will discuss new experimental insights into resource-e cient intermediate quantum computing utilizing the Bosonic nature of photons as well as new quantum computational concepts that superimpose the order of quantum gates and the simulation of two interacting spins. As outlook I will discuss the current status of new quantum technology for improving the scalability of photonic quantum systems by using integrated circuits, superconducting single-photon detectors and tailored light-matter interactions.

Bose-Einstein Condensation of Photons and Periodic Potentials for Light

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The advantages of the photons makes optical quantum system ideally suited for fundamental quantum physics experiments and a variety of applications in quantum information processing. Here I will discuss new experimental insights into resource-e cient intermediate quantum computing utilizing the Bosonic nature of photons as well as new quantum computational concepts that superimpose the order of quantum gates and the simulation of two interacting spins. As outlook I will discuss the current status of new quantum technology for improving the scalability of photonic quantum systems by using integrated circuits, superconducting single-photon detectors and tailored light-matter interactions.

Topological photonics with heavy-photon bands

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In topological phases of matter, properties like conductivity and optical reflectivity are not determined by the crystalline order but by the topological order of the electronic states. Such states of matter are the integer and fractional quantum Hall states [1], as well as the recently discovered topological insulators [2]. A typical example of an integer quantum Hall state is graphene under the influence of a periodic magnetic field while topological insulators are binary alloys based on Bi, e.g., $Bi_{1-x}Sb_x$. Here we propose that we can have topological states of photons in certain metamaterial structures operating as photonic analogues of the above electronic states of matter. We show in particular, that a gyrotropic (chiral) medium supporting a longitudinal-wave excitation exhibits a Dirac point in the corresponding photon dispersion lines. By breaking the time-reversal symmetry in such a medium, the dispersion relation resembles the energy dispersion of a spin-polarized two-dimensional electron gas with Rashba spin-orbit coupling. The resulting split bands of the dispersion relation correspond to nonzero Chern numbers implying the existence of nontrivial topological states of the electromagnetic field [3] in similarity to the integer quantum Hall effect. Topological photonic band structures can also emerge in two-dimensional electromagnetic lattices of metamaterial components without the application of an external magnetic field. The topological nature of the band structure manifests itself by the occurrence of exceptional points in the band structure or by the emergence of one-way guided modes. Based on an EM network with nearly flat frequency bands of nontrivial topology, we propose a coupled-cavity lattice made of superconducting transmission lines and cavity QED components which is described by the Janes-Cummings-Hubbard model and can serve as simulator of the fractional quantum Hall effect [3]. We also show that a tetragonal lattice of weakly interacting particles with uniaxial electromagnetic response is the photonic counterpart of topological crystalline insulators, a new topological phase of atomic band insulators [4, 5]. Namely, the frequency band structure stemming from the interaction of resonant modes of the individual cavities exhibits an omnidirectional band gap within which gapless surface states emerge for finite slabs of the lattice.

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Contributed talks

Power-laws in the dynamic hysteresis of quantum nonlinear photonic resonators

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We theoretically explore the dynamic hysteresis behavior of a driven-dissipative photonic resonator with a Kerr-type nonlinearity [1]. In the regime where the semiclassical mean-field approach predicts bistability, the exact steady-state density matrix is well known to be unique and a statistical mixture of two states. A direct consequence is that the full quantum treatment predicts no static hysteresis cycle of the excited population as a function of the driving intensity. We predict that in the quantum regime a dynamic hysteresis with a rich phenomenology does appear when sweeping the driving amplitude in a finite time. The hysteresis area as a function of the sweep time reveals a double power-law decay, with a behavior qualitatively different from the mean-field predictions. We show that the dynamic hysteresis can be understood as due to a non-adiabatic response region with connections to the celebrated Kibble-Zurek mechanism for dynamic phase transitions. We also consider the case of two coupled driven-dissipative nonlinear resonators, showing that dynamic hysteresis and power-law behavior occur also in presence of correlations between resonators. These theoretical predictions can be explored in a broad variety of physical systems, e.g., circuit QED superconducting resonators and semiconductor optical microcavities.

[1] W. Casteels, F. Storme, A. Le Boité and C. Ciuti, arXiv:1509.02118 (2015).

Molecular states of photons in atomic gases trapped near photonic crystal waveguides

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Recent experiments have for the first time trapped cold atoms in free space near photonic crystal waveguides [1]. This provides a unique platform for the control of atom-light coupling, where atoms may either couple to localized or propagating modes of the photonic crystal. In particular, this can lead to a novel quantum material where atomic spin degrees of freedom, atomic motion and photons strongly couple over large distances [2]. One possible application of the resulting long-range atom-atom interactions in this system is to leverage them to create tunable interactions between photons propagating in the atomic gas. In the few body limit we show that in this manner one can create molecular bound states of photon pairs [3]. We use this as a stepping stone to study the rich many-body behaviour of photons in this system.

[1] A. Goban, C.-L. Hung, J. D. Hood, S.-P. Yu, J. A. Muniz, O. Painter, and H. J. Kimble, Phys. Rev. Lett. 115, 063601 (2015), URL http://link.aps.org/doi/10.1103/PhysRevLett.115.063601.
[2] J. S. Douglas, H. Habibian, C.-L. Hung, A. V. Gorshkov, H. J. Kimble, and D. E. Chang, Nat. Photon. 9, 326 (2015), ISSN 1749-4893, URL http://dx.doi.org/10.1038/nphoton.2015.57.
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Effective Field Theory for Rydberg Polaritons

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Photons can be made to strongly interact by dressing them with atomic Rydberg states under conditions of electromagnetic induced transparency. Probing Rydberg polaritons in the few-body limit, recent experiments were able to observe non-perturbative two-body effects including: single photon switching and the formation of bound states. Although the two-body problem is amenable to exact solutions, such approaches quickly become intractable for more than two particles. To overcome this problem, we study non-perturbative effects in N-body scattering of Rydberg polaritons using effective field theory (EFT). For attractive interactions, we show how a suitably long medium can be used to prepare shallow N-body bound states in one dimension. We verify this prediction for two and three photons using full numerical simulations. We then consider conditions under which the effective interactions are repulsive and study two and three photon transmission. Finally, we show how to go beyond EFT by measuring the three-body contact force or, alternatively, scattering at high relative momenta.

Quantum phase transition of light in a finite system

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It has long been known that a single-mode cavity field coupled to thermodynamically many atoms undergo a quantum phase transition. Here, however, we demonstrate that the cavity field coupled to only a single two-level atom undergoes a quantum phase transition in the limit where the ratio of the atomic transition frequency to the cavity frequency tends to infinity [1]. We find an analytical solution which explicitly shows that there emerges a superradiant phase with a spontaneously broken-symmetry. Given that it involves only two degrees of freedom, the cavity field and the atom, this finding is rather unexpected, as the quantum phase transition typically occurs in a thermodynamic limit. Our finding shows that the quantum phase transition of light can occur even for a finite system when the cavity field is coupled to a system with a much larger characteristic frequency, regardless of its size. We further elucidate the duality between the system size and the frequency ratio through a finite-size scaling analysis which lead to the same critical exponents for both of them. Going beyond this equilibrium QPT setting, we prove that the dynamics under slow quenches in the vicinity of the critical point is universal and that the Kibble-Zurek mechanism can precisely predict the universal scaling of the dynamics.

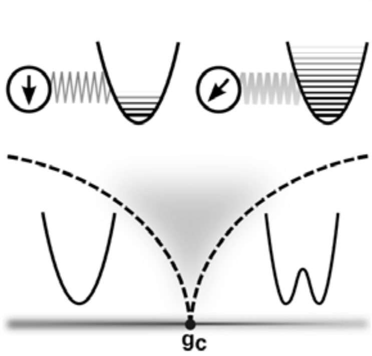

FIG. 1: Schematic phase diagram of quantum phase transition of a single-mode cavity field coupled to a two-level atom

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Orbital edge states in honeycomb lattices

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The experimental study of edge states in atomically-thin layered materials remains a challenge due to the difficult control on the geometry of the sample terminations, the stability of dangling bonds and the need to measure local properties. In the case of graphene, localised edge modes have been predicted in zig-zag and bearded edges, characterised by flat dispersions connecting the Dirac points. Due to the above mentioned difficulties, their energy-momentum distributions have not been directly measured. Polaritons in semiconductor microcavities have recently emerged as an extraordinary photonic platform to emulate 1D and 2D Hamiltonians, allowing for the direct visualisation of their dispersion and spatial wave functions in photoluminescence experiments [1]. Here we report on the observation of edge states in a honeycomb lattice of coupled micropillars. The lowest two bands of this structure arise from the coupling of the lowest energy modes of each micropillar, and emulate the π and π* bands of graphene [1] holding unidimensional quasi-flat edge states [2]. Most interestingly the first excited states of each micropillar resonator have a P-orbital geometry [1]. When coupled in the honeycomb lattice they give rise to orbital bands, inaccessible in actual graphene [3]. These bands contain novel edge states with properties different to the π and π* bands of graphene (fig 1).

Our system presents interesting perspectives in view of studying nonlinear excitations in these quasi 1D edge modes, taking advantage of the significant polariton-polariton interactions and shows the feasibility of studying topological edge state physics, as recently suggested [4, 5].

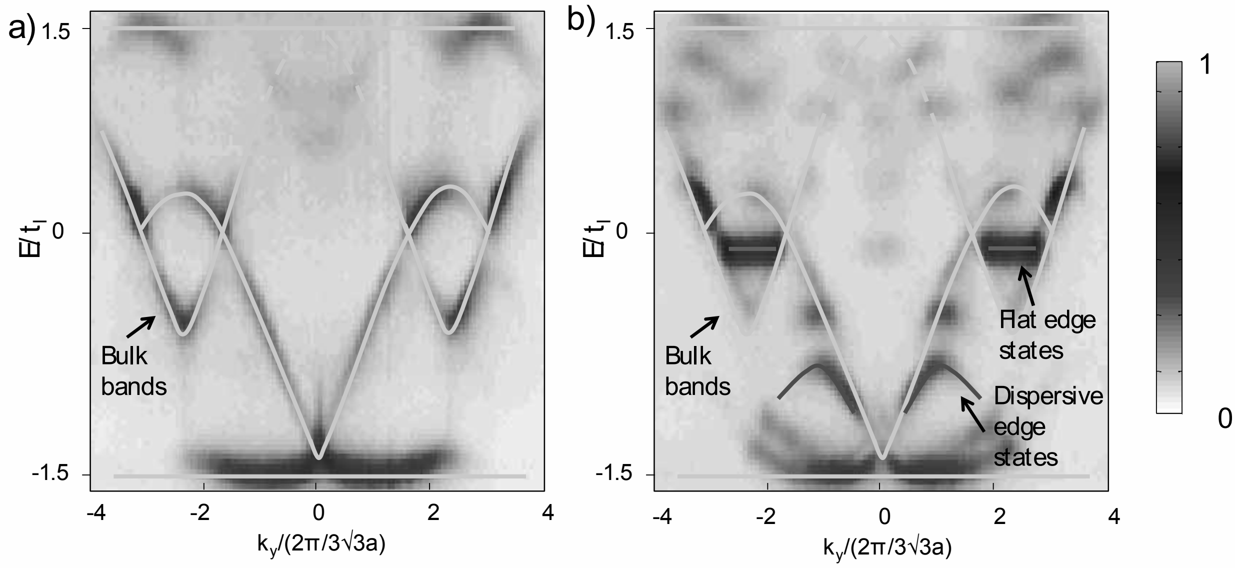

Fig.1: Measured dispersion of the orbital bands at the centre of the Brillouin zone probed in the bulk of the lattice a), and on the zig zag edge b). Flat and dispersive edge modes are marked with the red lines.

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Cluster mean-field approach to the steady-state phase diagram of dissipative spin systems

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We show that short-range correlations have a dramatic impact on the steady-state phase diagram of quantum driven-dissipative systems. This effect, never observed in equilibrium, follows from the fact that ordering in the steady state is of dynamical origin, whereas in thermodynamic equilibrium transitions it arises from the properties of the (free-)energy. To this scope we extend cluster methods, extensively used in equilibrium classical and quantum phase transitions, to the study non-equilibrium phase transitions in dissipative systems. Specifically we combine the cluster-mean field approach with quantum trajectories and with tensor-network techniques for many-body open systems. We analyse in detail a model of spins-1/2 on a lattice interacting through an XYZ Hamiltonian, each of them coupled to an independent environment which induces incoherent spin flips. The model has been already studied at the single-site mean field level [1]. In the steady-state phase diagram derived from our cluster approach, the location of the phase boundaries and even its topology can radically change, as compared to the single-site mean field where correlations are absent. Furthermore a stability analysis of the cluster mean-field indicates a susceptibility towards a possible incommensurate ordering, not present if short-range correlations are ignored [2].

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Rabi oscillation in a quantum cavity: Markovian and non-Markovian dynamics

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The interaction between a single atom and a single photon is the basic process of quantum electrodynamics. The most usual way of achieving strong interaction consists in keeping the atom in a cavity formed by two parallel highly-reflecting mirrors (Cavity Quantum ElectroDynamics). The signature of quantum behaviour is provided by Rabi oscillations, the evidence of the periodic emission and reabsorption of the photon by the atom.

While the mirrors are universally treated as classical objects, it has recently been noticed that quantum objects such as a chain of atoms trapped near a 1D waveguide can act as mirrors too (see Fig. 1). In the seminal work [1], it is assumed that the collective response time of each atomic mirror is much longer than the time it takes for the photon to travel from one mirror to the other, and as a consequence the delay due to this travel time is neglected. This approach is the Markov approximation commonly used to accurately describe the interaction of photons with many atoms in a wide range of experimental situations.

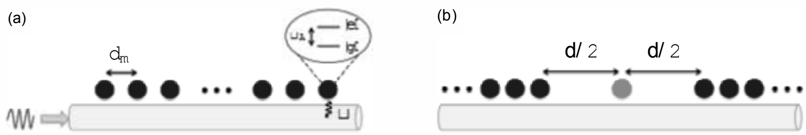

FIG. 1: Cavity QED using atomic mirrors.
(a) Scattering of an incoming photon onto an atomic Bragg mirror. (b) An initially excited atom (orange) is sitting inside a quantum cavity formed by two atomic mirrors (red).

In this work [2], we investigate the physics of Rabi oscillation of an atom placed inside such a quantum cavity. We show that in the Markovian regime the lifetime of the photon inside the cavity is not enhanced by the presence of the mirrors, and therefore sustained Rabi oscillation analogous to that observed in conventional CQED setups cannot be obtained. Thus, the delay must be taken into account and the dynamics of the problem is inherently non-Markovian. Our main result is that the vacuum Rabi oscillation of the central atom is given by

$$c_0(t) \approx e^{-\frac{\Gamma t}{2(1+N\Gamma d/v_g)^2}} \cos\left[\sqrt{\frac{2N}{1+N\Gamma d/v_g}}\,\Gamma t\right], \tag{1}$$

where d is the distance between the two atomic mirrors, Γ the single-atom decay rate into the waveguide modes and v_g the group velocity of light in the cavity. One sees from the above expression that the cavity loss rate is $\kappa = \Gamma/(1+N\Gamma d/v_g)^2$ and the Rabi frequency is $\Omega_{Rabi} = \Gamma\sqrt{2N/(1+N\Gamma d/v_g)}$. Here also appears the ratio between half the cavity round-trip time and the atomic mirrors response time $N\Gamma d/v_g$, which determines whether the dynamics of the quantum cavity is Markovian or not.

This work belongs to a series of studies where devices that are usually considered classical are replaced by quantum objects allegedly performing the same functionality. A better understanding of the physics of these quantum devices opens the door for exciting applications such as delayed-choice experiments or superposition of gates in quantum circuits.

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Thermodynamics and relaxation in a system of photon-mediated long-range interactions

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We study the steady-state properties and relaxation dynamics of atoms in the quantum field of an optical cavity and which are driven by a laser. In a semiclassical limit we show that the steady state is a thermal distribution whose temperature is solely controlled by the detuning between laser and cavity. The laser intensity, on the other hand, determines the onset of selforganized Bragg gratings. We evaluate the free energy and demonstrate that the selforganization transition is a second-order phase transition described by Landau's model: the control field is the laser intensity and the order parameter is the cavity field amplitude. We then discuss the dynamics following a sudden quench across the phase transition, and report the observation of metastable spatial patterns, whose lifetime can be several resonator lifetimes. These metastable patterns are nonthermal and result from the interplay between the dispersive and the dissipative mechanical forces of the resonator.

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Fermi polaron-polaritons in $MoSe_2$

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Transition metal dichalcogenide (TMD) monolayers are a new family of atomically thin 2D semiconductors. They feature a unique band structure giving rise to a valley pseudospin and a non-zero Berry curvature at the band minimum. Their truly 2D nature as well as their large electron mass infer strong Coulomb interactions which imply strong exciton binding energies of order 500 meV. TMDs in photoluminescence also exhibit a strongly bound trion state red-shifted from the exciton line by 30 meV. We report cavity spectroscopy of gate-tunable monolayer $MoSe_2$ exhibiting strongly bound exciton-polaron and trion resonances, as well as non-perturbative coupling to a single microcavity. Our findings constitute a first step in investigation of a new class of degenerate Bose-Fermi mixtures consisting of polaritons and electrons.

Electromagnetic control of qubits through quantum breathers

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We investigate coherence properties of qubit lattices through two specific models. The first involves an uncoupled chain of cubits that interacts with an electromagnetic wave. We show that in the strong coupling regime the non-linearity of the interaction induces traveling coherent modes in the form of breathers that propagate with a process similar to self-induced transparency. The second model involves qubit-qubit interaction of the type of the quantum Ising model. We ignore external interactions and show that a coherence wave of quantum fluctuations is induced through a sudden quench of the interactions into the ferromagnetic regime.

Topological pumping of interacting photons and novel phases in driven-dissipative resonator arrays

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In the first part of the talk, I will discuss topological pumping of photons in nonlinear resonator arrays, which is a coherent dynamics that survives in the presence of dissipation. Topological pumping allows a robust transport of quantum particles in a 1D periodic lattice. This is done by adiabatic and cyclic deformation of the Hamiltonian. In contrast to conventional 2D topological materials, the 1D material can be thought of as having (1+1) dimensions, where time acts as an extra dimension with periodic boundary conditions. Hence, the topology of the effective 2D system can be associated with the Chern number, resulting in transport properties which are robust against small perturbations. In this work, we propose a realization of such pump using photons in nonlinear coupled resonator arrays, where the frequency of the resonator is periodically modulated in space and time. In contrast to the linear regime, nonlinearities in our model enable a robust transport of a Fock state with few photons per site, rather than a group of non-interacting particles. We show that signatures of such topological pumping can be observed in a lossy array, as small as nine sites with open boundary conditions. This brings our proporsal into the realm of implementation using existing circuit QED technology.

Using the same circuit QED design, in the second part of the talk, I will briefly discuss novel observable phases that arise from an interplay between coherent drive and dissipation. This involves a bunching-antibunching transition and the antiferromagnetic phase in a driven-dissipative spin-1/2 chain.

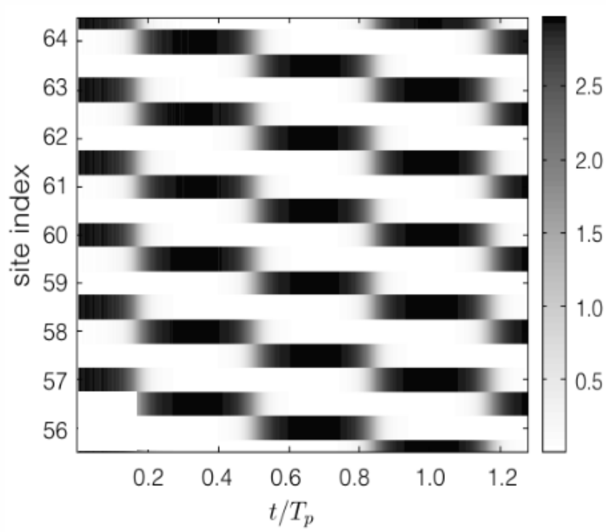

FIG. 1: Density plot of photons, showing that the Fock state $|...300300300300...\rangle$ is unidirectionally pumped to the right in a step-like manner. This transport is robust againts small disorder. The underlying Hamiltonian is the Bose-Hubbard model, whose on-site energy is modulated adiabatically and periodically in space and time.

Atom-nanophotonics: a platform for Quantum Information and Simulation

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Nanophotonics provides us with structures such as Photonic Crystals (PhCs) that allow to control and mold light at subwavelength scales [1]. This control allows not only to confine light in reduced dimensionalities (2d,1d and 0d) but also to enhance light-matter interactions. Recently, the integration of atomic systems with 1d and 0d nanophotonic structures has been experimentally achieved [2].

In this talk, we show how to exploit some characteristics of this new hybrid system (atom-nanophotonics) for two and one-dimensional systems. First, we show how to use 2d PhCs waveguides to build high-density 2d optical lattices for ultra cold atoms yielding larger energy scales for the simulation of Bose-Hubbard and spin models with long-range interactions [3]. Moreover, in one-dimensional systems we show how to use these long-range collective couplings for the preparation of many-body entangled atomic states and non-classical states of light [4].

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WG4 meeting

Atom-field dressed states in slow-light waveguide QED

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We discuss the properties of atom-photon bound states in waveguide QED systems consisting of single or multiple atoms coupled strongly to a finite-bandwidth photonic channel. Such bound states are formed by an atom and a localized photonic excitation and represent the continuum analog of the familiar dressed states in single-mode cavity QED. Here we present a detailed analysis of the linear and nonlinear spectral features associated with single- and multi-photon dressed states and show how the formation of bound states affects the waveguide-mediated dipole-dipole interactions between separated atoms. Our results provide a both qualitative and quantitative description of the essential strong-coupling processes in waveguide QED systems, which are currently being developed in the optical and the microwave regime [1–4].

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Atom-light interactions using ultrathin optical fibres

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Ultrathin optical fibres have recently come to the fore as potential tools for manipulating atoms. For a review on this topic the reader is referred to [1]. One of the primary features of these fibres that can be exploited is the fact that ultralow propagation powers generate intense evanescent fields at the waist region, thereby facilitating the study of nonlinear and quantum interference effects in atomic media. First, we will report on our work on Autler-Townes splitting [2] and a multilevel, cascaded EIT process in laser-cooled ^{87}Rb mediated via an optical nanofibre, as illustrated in Fig. 1 [3]. Using the EIT results, we have also demonstrated an all-fibred-all-optical switch which could be used for optical data processing in quantum systems. Finally, we will discuss our recent work towards the generation of Rydberg atoms, i.e. neutral atoms with very large dipole moments, in the vicinity of the optical nanofibre and the possible effect of the dielectric surface on the Rydberg blockade condition. This is a very promising system for the generation of neutral atom-based quantum logic gates.

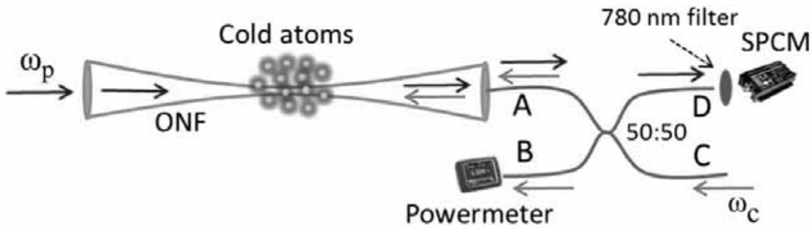

Fig.1: Experimental setup of an ultrathin optical fibre in a cloud of cold atoms. SPCM: single photon counting module; 50:50 fibre beam splitter; ONF: optical nanofibre; □p:780 nm probe beam; □c:776 nm coupling beam Taken from [3].

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Coupling metamaterials and plasmons with quantum states of light

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Metamaterials allow us to engineer materials according to a certain property required, otherwise difficult or impossible to have naturally. In the meantime, technologies of heating, photovoltaics, water photocatalysis and artificial photosynthesis depend on the absorption of light and novel approaches such as coherent absorption from a standing wave promise total dissipation of energy. In particular, it has been demonstrated that the phenomenon known as coherent perfect absorption (CPA) can be done very efficiently with metamaterials. Here, we present our latest results where we couple quantum states of light such as single photons and entangled photons to metamaterials leading to CPA and can lead the work to future photon/plasmon interaction and entanglement.

Recent studies provided unexpected but strong evidence that the quantum properties of light are conserved when photons are converted into surface plasmon polaritons, paving the way for active and ultrafast quantum plasmonic technologies. At the same time, light interaction with nanostructured materials is a rapidly growing field of research with many potential applications. Recently, Light-with-light modulation based on the coherent perfect absorption in metamaterial films of subwavelength thickness is also possible and it has now been demonstrated with a continuous wave laser [1]. In this process, two coherent beams of light interact on a layer of plasmonic metamaterial in such a way that one beam modulates the intensity of the other. Our work takes a step further by showing that this phenomenon also occurs very efficiently with at the single photon level [2] and that on top of it, entangled properties of correlated photons can be used for the metamaterial to non-locally control the quantum properties of the photons [3]. For the single photon absorption, using CPA, we show that a single photon can be converted to plasmons with almost 100% probability and with a fairly easy set-up. With the use of entangled photons and CPA, we demonstrate that photons can be entangled with plasmons also with a high probability. Figure 1 presents the set-up where we have the single photon source done by spontaneous parametric down-conversion and we have the interferometer where the CPA occurs at the place where the sample is, made of metamaterials. This work should pave the way towards future quantum devices coupling plasmons and photons together.

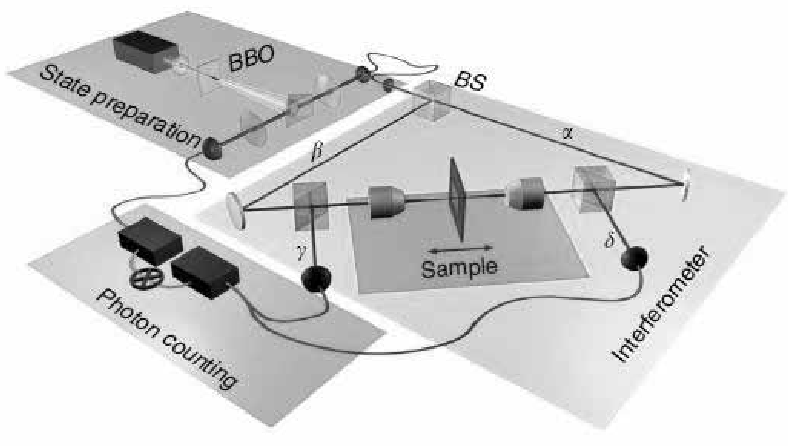

Figure 1: Single-photon experiment on perfect coherent absorption. Illumination of a type 1 beta-barium borate (BBO) crystal by a continuous wave l¼405nm laser producing correlated single photon pairs by SPDC. The correlated photon pair are separated by a knife edge prism. One photon of the correlated pair is used to herald the presence of the other photon that is launched into the interferometer. The metamaterial absorber is placed in the middle point of the interferometer and translated along the optic axis by a piezoelectrically actuated stage. The single photons are focussed onto the sample by X10 objectives. Photons are then detected in coincidence with the heralding photon at outputs d and g (from [2]).

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DFT-inspired method to calculate work distribution and average work of a quantum many-body system

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To understand how the increase of disorder in the macroscopic world follows from microscopic order we need to determine the so-called work distribution (which is related to the entropy production) for quantum systems performing suitable cyclic dynamics. This is a crucially difficult task, particularly so when interacting many-particle (or many-spin) systems are considered. Here we study the quantum fluctuations of a many-body system by proposing a new method inspired by density functional theory (DFT). Through this method, we can estimate the transition matrix elements due to the system time-dependent dynamics and obtain an approximation to the work distribution and average work of the driven quantum many-body system. We apply this DFT-inspired approach to obtain the work distribution function of a driven Hubbard dimer using an approximation based on Kohn-Sham states. This model can represent different quantum system, including excitations in coupled quantum dots driven by laser pulses. We compare this new method with the exact result and show under which conditions this approximation is effective.

Controlled optical absorption and resonance fluorescence from a quantum emitter near a plasmonic nanostructure

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Recently, there is increasing interest in the study of the interaction of quantum emitters (such as atoms, molecules and semiconductor quantum dots) with plasmonic nanostructures. Here, we present new theoretical results on the controlled optical absorption and resonance fluorescence of a four-level quantum emitter coupled to a plasmonic nanostructure, specifically a periodic two-dimensional array of metal-coated dielectric nanospheres [1-4]. The system leads to quantum interference in spontaneous emission near the plasmonic nanostructure [1]. For the study of the system's dynamics, we combine the density matrix approach for the quantum emitter with ab initio electromagnetic calculations for the plasmonic nanostructure. We present results for the absorption of a weak probe field in the presence of a pump field and the resonance fluorescence spectrum for different distances of the quantum emitter from the plasmonic nanostructure and find that the plasmonic nanostructure has a very strong influence on the both studied effects.

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A one-dimensional controllable polaritonic system: from order to disorder

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Optical studies of single quantum emitters have become routine for a number of systems ranging from atoms and ions in vacuum to molecules, ions, color centers and quantum dots in the solid state. A new agenda in experimental quantum optics is to exploit this know-how to assemble well-defined arrangements of many emitters to investigate many-body physics. This task is quite challenging because in the case of atoms in vacuum, arbitrary control of particle position remains difficult, especially when high densities are desirable. In the case of solid-state systems, the inherent spectral inhomogeneity poses a problem in addition to fabrication challenges.

Recently, we introduced a new system, where organic molecules can be arranged in a one-dimensional subwavelength waveguide based on a glass nanocapillary [1]. We showed that individual molecules could be coherently and efficiently coupled to photons traveling in the nanoguide. Our current efforts extend this configuration to an on-chip architecture, where micro-electrodes are used to tune the resonance frequencies of the molecules. This allows us to select a certain number of emitters that would interact with an incoming photon in a coherent and collective fashion, resulting in a polaritonic system. Furthermore, we have performed theoretical calculations to investigate the role of order and disorder [2]. A particularly interesting result of our calculations is the observation of normal mode splitting without the need for a cavity coupling.

In this presentation, I shall discuss our current results and plans for future experiments, where linear and nonlinear polaritonic effects can be investigated using controlled micro-ensemble of solid-state emitters, including rare earth ions [3].

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Photon-Phonon Interactions in Nanophotonics

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We develop a systematic method for deriving a quantum optical multi-mode Hamiltonian for the interaction of photons and phonons in nanophotonic dielectric materials by applying perturbation theory to the electromagnetic Hamiltonian. The Hamiltonian covers radiation pressure and electrostrictive interactions on equal footing. As a paradigmatic example, we apply our method to a cylindrical nanoscale waveguide, and derive a quantum optical Hamiltonian for Brillouin scattering. We use the resulting multi-mode Hamiltonian to derive an effective phonon-mediated interaction between photons propagating in the material. We predict strong non-linear phase shifts even among two photons, comparable to what can be achieved in nonlinear atomic media (comprising cold Rydberg atoms).

Posters

Tailoring strong photon interactions via cold atoms coupled to photonic crystal waveguides

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Realizing controllable interactions between photons in the quantum regime remains a challenging task to date. In state of the art approaches the photon number dependent nonlinearities in atom-cavity systems or Rydberg gases are exploited to achieve that goal. There is wide interest in reaching a level of control in which quantum many-body states of light can be controllably prepared and studied. However, at the moment such experiments remain technically very challenging.

We present a new system with the potential to overcome this limit: trapped atoms along photonic crystal waveguides [1]. Such systems allow for the creation of atom-atom interactions via the coupling to a common bandgap mode. Atoms excited with a frequency within the bandgap are dressed by a localized photonic cloud, whose extent over neighbouring atoms effectively leads to (long-range) atom-atom interactions. This novel type of interaction, tunable in both strength and distance, modifies the refractive index for photons propagating through the waveguide in a conditional way. That way, a rich variety of photon-photon interactions are within reach.

Here, we present some of the possible ways in which photon-photon interactions can manifest themselves, depending on the range of interaction, the atomic level configuration, and type of driving used. We also introduce a novel "spin model" formalism [2], which enables one to exactly and generally solve for the dynamics of strongly interacting photons at the few-body level in such systems.

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Measuring Topological Invariants in Disordered Discrete Time Quantum Walks

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Concepts such as topological insulators have sparked large interest in the investigation of topological material properties. Tarasinski et al. proposed a scheme for directly accessing and measuring topological invariants in a discrete-time quantum walk scattering system [1]. This protocol applies a split-step dynamic with two alternating coin operations $\hat{C}(\theta_1)$ and $\hat{C}(\theta_2)$ in a bulk region which is interfaced with a lead comprising only identity operations.

Our implementation of a photonic time-multiplexed quantum walk is well suited to realise this proposal: A fibre feedback-loop architecture is used to map the position degree of freedom into the time domain, realising the time-multiplexing. Due to interferometric stability the setup inherently provides high homogeneities with minimal needs of resources [2, 3]. Fast switching electro-optical modulators allow us to dynamically change the coin operations according to the proposed scheme [4].

Being able to read-out the position and the coin state, we measure the reflection amplitudes in the lead, which directly correspond to the topological invariants Q_0 and Q_π. We show that by tuning the coin operation, we traverse different topological sectors in the θ_1-θ_2-coin angle parameter space and thus observe different topological phases, see Fig. 1. We prove their robustness against disorder by randomly introducing a third (noise) coin. When choosing the noise coin angle from the same topological sector as the unperturbed bulk we demonstrate that the invariant remains constant. When choosing it from another topological sector, we observe a smooth transition from the original phase to the phase of the new topological sector with increasing disorder probability.

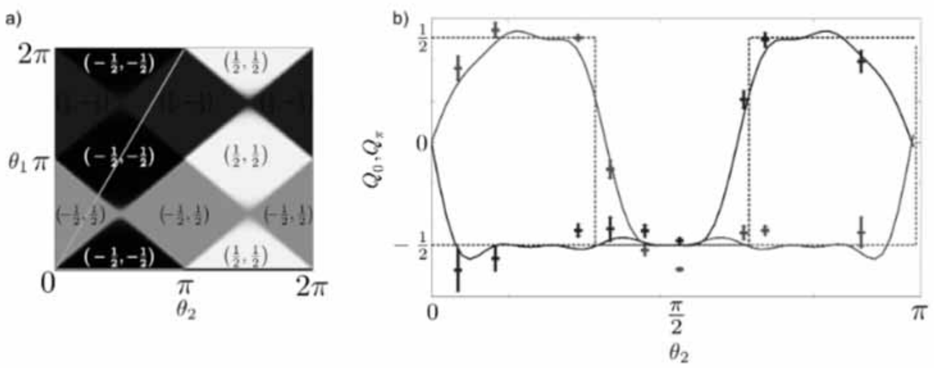

FIG. 1: a) Coin angle parameter plot of the topological invariants (Q_0, Q_π). b) Measured invariants Q_0 (red symbols) and Q_π (blue symbols) and calculated invariants for 5 full steps (solid lines) and for the asymptotics (dashed lines) for a split step quantum walk with $\hat{C}(\theta_2)$ on odd and $\hat{C}(\theta_1) = \hat{C}(2\theta_2)$ on even positions (along the green line in a).

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Exact results for Schrödinger cats in driven-dissipative systems

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We present and exploit the exact analytical solution for the steady state of a nonlinear driven-dissipative resonator subject to one-photon losses and to engineered two-photon processes [1], as sketched in Fig. 1. This kind of system, recently realized experimentally, has shown the appearance of photonic Schrödinger cat states in its transient dynamics. We demonstrate that the unique steady state is a statistical mixture of two cat-like states with opposite parity, in spite of significant one-photon losses. We investigate the transient dynamics to the steady-state, showing its dramatic dependence on the initial state and the emergence of metastable regimes. By considering individual quantum trajectories in photon counting configuration, we find that the system intermittently jumps between two cats. Hence, we propose a feedback protocol based on this behaviour and able to generate a pure cat-like steady-state.

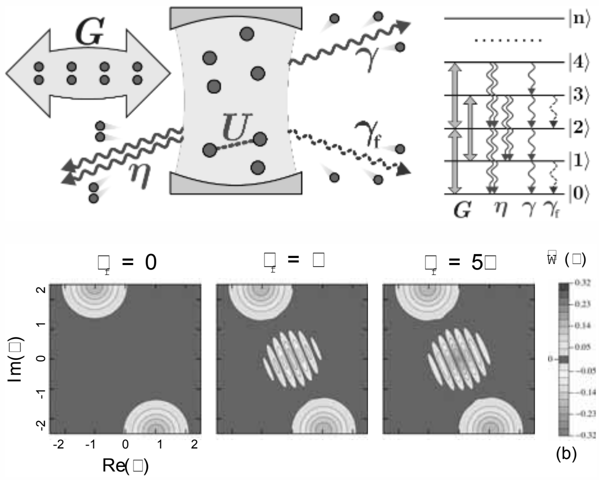

FIG. 1: Top: Sketch of the class of systems for which we present the steady-state analytical solution. Bottom: Steady-state Wigner function W (□) showing cat-like interference fringes in presence of parity-triggered dissipation.

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Semiclassical bifurcations and topological phase transitions in a one-dimensional lattice of coupled Lipkin-Meshkov-Glick models

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In this contibution we study a one-dimensional lattice of Lipkin-Meshkov-Glick models with alternating couplings between nearest-neighbors sites, which resembles the Su-Schrieffer-Heeger model [1]

$$\hat{H} = \sum_{l=1}^{N} \sum_{P \in \{A,B\}} \left[\omega_0 J^z_{Pl} - \frac{\gamma}{2j} (J^x_{Pl})^2 \right] - \frac{1}{2j} \sum_{l=1}^{N} (\kappa_1 J^+_{Al} J^-_{Bl} + \kappa_2 J^+_{Bl} J^-_{Al+1} + \text{h.c.}) . \quad (1)$$

Typical properties of these models are present in our semiclassical-topological hybrid system, allowing us to investigate an interplay between semiclassical bifurcations at mean-field level and topological phases [3]. Although the bifurcation takes place at mean-field level, there are quantum signatures of this effect in the dynamics of the system [2]. Our results show that bifurcations of the energy landscape lead to diverse ordered quantum phases. The geometry of the energy landscape determines quantum fluctuations. As a consequence, on the quantum level, the semiclassical bifurcation is accompanied by the emergence of squeezing visible in the fluctuations around the mean field. The effect of squeezing on topological properties of the system has been recently investigated [4]. The study of the quantum fluctuations about the mean field solution reveals the existence of nontrivial topological phases. These are characterized by the emergence of localized states at the edges of a chain with open boundary conditions [5].

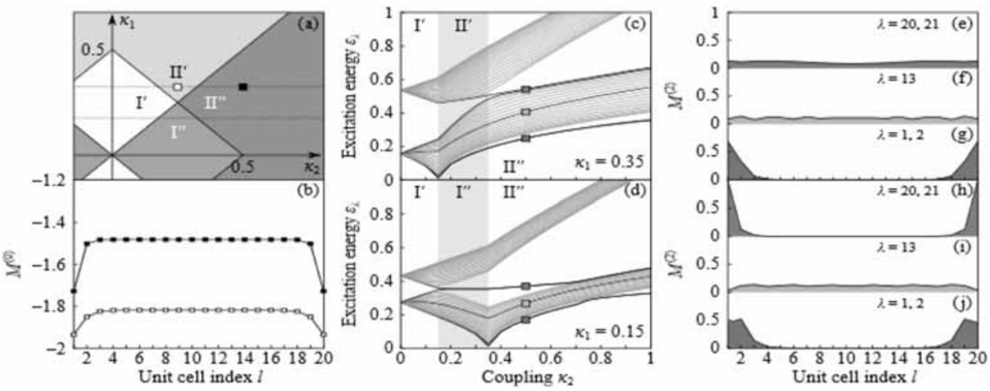

FIG. 1: Phase diagram and edge states.(a) Topological and quantum phases of the system (cf. grey box in Fig. ??a). Couplings $\kappa_{1,2}$ are assumed positive. Primed phases are topologically trivial while doubly primed phases (green-shaded) are non-trivial. (b) Macroscopic magnetization depending on position in the chain for $\gamma = 0.5$, $\kappa_1 = 0.35$, $\kappa_2 = 0.25$ (empty squares) and $\kappa_2 = 0.5$ (filled squares). (c, d) Excitation energies for the open chain with $N = 20$, $\gamma = 0.5$ and $0 \leq \kappa_2 \leq 1$ along the lines $\kappa_1 = 0.35$ and $\kappa_1 = 0.15$ respectively. (e–j) Microscopic fluctuations of the magnetization depending on the position in the chain and the number of the band. $\gamma = 0.5$, $\kappa_2 = 0.5$. For panels e–g, $\kappa_1 = 0.35$; for panels h–j, $\kappa_1 = 0.15$. Each of the plots corresponds to respectively color-coded points in panels c and d.

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Cluster mean-field approach to the steady-state phase diagram of dissipative spin systems

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We show that short-range correlations have a dramatic impact on the steady-state phase diagram of quantum driven-dissipative systems. This effect, never observed in equilibrium, follows from the fact that ordering in the steady state is of dynamical origin, whereas in thermodynamic equilibrium transitions it arises from the properties of the (free-)energy. To this scope we extend cluster methods, extensively used in equilibrium classical and quantum phase transitions, to the study non-equilibrium phase transitions in dissipative systems. Specifically we combine the cluster-mean field approach with quantum trajectories and with tensor-network techniques for many-body open systems. We analyse in detail a model of spins-1/2 on a lattice interacting through an XYZ Hamiltonian, each of them coupled to an independent environment which induces incoherent spin flips. The model has been already studied at the single-site mean field level [1]. In the steady-state phase diagram derived from our cluster approach, the location of the phase boundaries and even its topology can radically change, as compared to the single-site mean field where correlations are absent. Furthermore a stability analysis of the cluster mean-field indicates a susceptibility towards a possible incommensurate ordering, not present if short-range correlations are ignored [2].

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Incompressible polaritons in a flat band

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I will discuss the interplay of geometric frustration and interactions in a non-equilibrium photonic lattice system exhibiting a polariton flat band as described by a variant of the Jaynes-Cummings-Hubbard model. We show how to engineer strong photonic correlations in such a driven, dissipative system by quenching the kinetic energy through frustration. This produces an incompressible state of photons characterized by short-ranged crystalline order with period doubling [1]. The latter manifests itself in strong spatial correlations, i.e., on-site and nearest-neighbor anti-bunching combined with extended density-wave oscillations at larger distances. We propose a state-of-the-art circuit QED realization of our system, which is tunable in-situ.

I will also present experimental results on exciton-polaritons, where the interplay of frustration and disorder in a similar lattice of micro-pillar cavities leads to the fragmentation of the polariton condensate in real space [2].

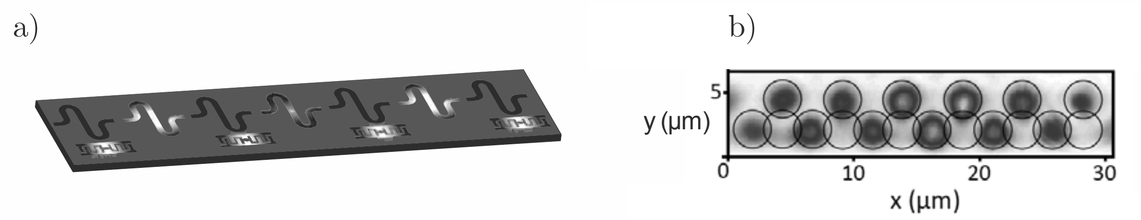

FIG. 1: Scheme of a density-wave of photons in a frustrated circuit QED lattice of alternating resonators, with qubits coupling to photons in every other resonator (a). Far field image of a polariton condensate in a lattice of micro-pillars cavities (b). The empty pillars are a signature of interference and geometric frustration.

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Quantum simulation of the spin boson system with a superconducting circuit

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We report on the experimental investigation of an analog quantum simulator of the spin-boson model based on superconducting circuits. While being a quantum mechanical model of major relevance in nature it is very hard to approach theoretically and numerical solutions are scarce. We map the spin of an atom to a superconducting concentric transmon qubit [1] while the bosonic bath is constituted by a set of harmonic resonators. The current sample design features a well controllable quantum bit with a dedicated readout device coupled to a single weakly coupled bosonic resonator mode. With this trivial bath we perform proof-of-principle measurements on the dissipative dynamics of the qubit while operating the circuit in di↵erent coupling regimes. The e↵ective coupling in the frame rotating with the drive can be tuned by applying an additional classical microwave tone [2, 3]. In the subsequent experiment, the single mode is substituted by a bath circuit previously characterized in a separate experiment. This allows for the study and emulation of the spin boson model for various spectral mode densities of the bosonic bath and to explore fundamental properties of the quantum system such as a predicted quantum phase transition and its dissipative dynamics.

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Absorbing state phase transition with competing quantum and classical fluctuations

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Stochastic processes with absorbing states feature remarkable examples of non-equilibrium universal phenomena. While a broad understanding has been progressively established in the classical regime, relatively little is known about the behavior of these non-equilibrium systems in the presence of quantum fluctuations. Here we theoretically address such a scenario in an open quantum spin model which in its classical limit undergoes a directed percolation phase transition. By mapping the problem to a non-equilibrium field theory, we show that the introduction of quantum fluctuations stemming from coherent, rather than statistical, spin-flips alters the nature of the transition such that it becomes first-order. In the intermediate regime, where classical and quantum dynamics compete on equal terms, we highlight the presence of a bicritical point with universal features different from the directed percolation class in low dimension. We determine the universal scaling behavior of the corresponding transition by renormalization group methods and propose how this physics could be explored within gases of interacting atoms excited to Rydberg states.

Simulating quantum transport by optics and bio-genetics

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Recent theoretical and experimental efforts have shown the remarkable and counterintuitive role of noise [1] in enhancing the transport efficiency of complex quantum systems. Here, we show both theoretically and experimentally three quite different simulators of such quantum phenomena, respectively based on optical fiber cavity networks, integrated photonics, and geneticaly engineered viruses.

First of all, we have realized simple, scalable, and controllable optical fiber cavity networks that allow us to analyze the performance of transport networks for different conditions of interference, dephasing, and disorder [2]. In particular, we have demonstrated that the transport efficiency reaches a maximum when varying the external dephasing noise, i.e., a bell-like shape behavior that had been predicted only theoretically – see Fig. 1.

Concerning the second one, by mapping the maze problem in an integrated waveguide array, probed by coherent light, we successfully test our theoretical result that a quantum walker can efficiently reach the output of a maze by partially suppressing the presence of interference, with an unprecedented improvement in transport efficiency [3].

These two optical platforms are very promising simulators of quantum transport phenomena and could be used, in particular, to design and test optimal topologies of artificial nano-structures for future bio-inspired solar energy and quantum communication technologies.

Finally, in this direction we have created a tunable material consisting of a connected chromophore network on an ordered biological virus template at room temperature, and, using genetic engineering, we have established a link between the inter-chromophoric distances and emerging quantum transport properties [4]. Through genetic modifications, we have obtained a significant enhancement of exciton diffusion length of about 68% in an intermediate quantum-classical regime, as observed by means of the more tunable optical simulators.

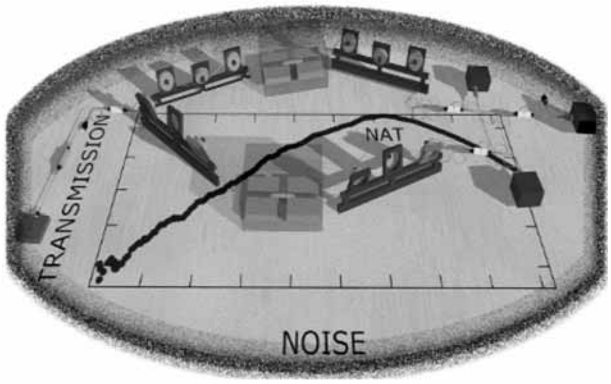

FIG. 1: Optical fiber cavity network to simulate transport phenomena in presence of disorder, interfence, and dephasing.

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Many-Body Quantum Interference on Hypercubes

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Quantum walks on hypercube (HC) graphs [1–3] attracted much attention owing to their potential applicability to quantum simulation as well as the promise of robust exponential speed-ups compared to classical random walks in search algorithms [1–3]. Beyond the regime of distinguishable particles, however, one has to take many-body quantum interferences into account, which give rise to intricate evolution scenarios. In case of HC-graphs, symmetries of the unitary scattering matrix alleviate the complexity and even allow the analytic formulation of suppression laws, which predict final states, with a probability vanishing due to total destructive interference. To date, only few such symmetric unitaries, like the discrete Fourier-transformation [4] or Sylvester matrices [5], have been investigated, leaving a general lack of knowledge about many-body evolution in higher-dimensional systems.
Here, we study many-body destructive interferences emerging in hypercubes of dimension d, generalized to have the same but arbitrary substructure on all vertices. Such graphs are described by unitaries of the form

$$\hat{\mathcal{U}} = \frac{1}{\sqrt{2^d}} \begin{pmatrix} \hat{U} & i\hat{U} \\ i\hat{U} & \hat{U} \end{pmatrix}^{\otimes d} . \tag{1}$$

Each node of the hypercube is represented by an $m \times m$ subunitary $\hat{U}$, as visualized in figure 1. We find that initial many-particle states with even particle number, being invariant under certain symmetry operations, show a large quantity of suppressed final states with the condition for suppression determined solely by the symmetry of the input state. Interestingly, we find that for particle numbers N, fulfilling mod[N, 4] = 0, fermions underlie the same suppression law as bosons, whereas for mod[N, 4] = 2, the two suppression laws are conjugate to each other.

In conclusion, our findings reveal new insights in particle statistics for ensembles of indistinguishable bosons and fermions and may be a first step towards many-particle quantum protocols in higher-dimensional structures.

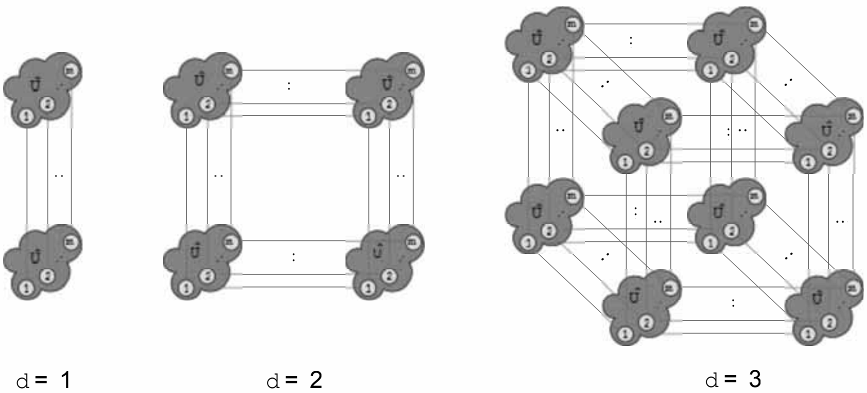

FIG. 1: Composition of graph structures under consideration. Arbitrary, but identical sub-lattices, composed of m modes and visualized by blue clouds, are arranged in a hypercube structure of arbitrary dimension d. For simplicity, only possible structures up to d = 3 are shown.

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Diagrammatic Approach to Scattering in Photonic Systems

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We study the scattering properties of an arbitrary system by coupling waveguides to it locally and sending Fock state inputs. Using techniques from input-output theory and quantum field theory, we provide a diagrammatic approach to visualise and calculate the scattering matrix. The method aims to reduce effort in finding the nonlinear response induced by the system which is the signature of photon-photon interactions. The spectra provided by the scattering matrix also directly reflect the rich many-body states of the system we are studying.

Using the results from [1], the S-matrix can be cluster decomposed into the sum of products of connected parts. Moreover, the connected n-photon S-matrix is equal to the connected 2n-point Green's function for $n > 1$ (for $n = 1$, there is an extra delta function if there is an input from that channel). Therefore, if we know all 2m-point Green's functions, for $m \leq n$, we can calculate the n-photon S-matrix. We show that the Green's functions can be represented by diagrams (Figure 1), and the expressions can be written down directly.

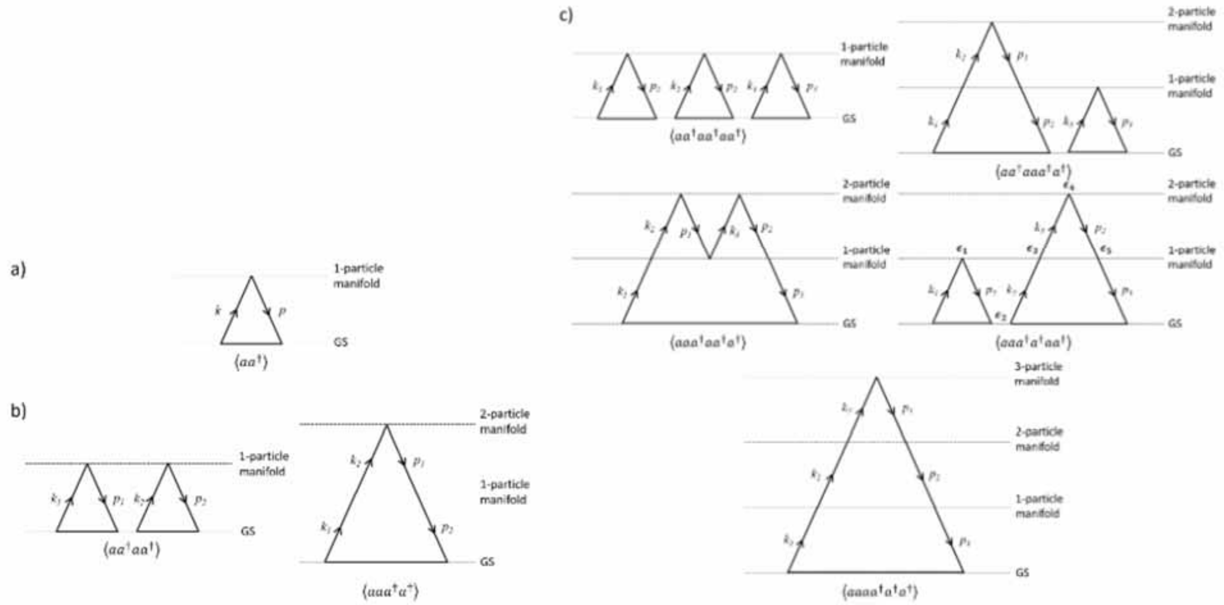

FIG. 1: Diagram for a)2-point, b)4-point and c)6-point Green's function.

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Dynamically controlled discrete time quantum walks

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Discrete time quantum walk is a proven and universal tool [1–3] and is regarded as a promising platform for building quantum simulators[4]. Quantum walks with controllable coins have been used to demonstrate effects such as localisation [5], and topological phases [6, 9]. A full fledged simulator, however, requires also the control of the underlying graph structure.

We present an optical time-multiplexed implementation of discrete time quantum walks which offers complete control over the evolution, including a temporally changing graph structure. The optical time-multiplexing technique [10] has features such as remarkable resource efficiency, excellent access to all degrees of freedom throughout the entire time evolution, and stability sustained over many consecutive measurements providing sufficient statistical ensembles. The present setup is analogous to the one used for the 2D quantum walk [11], however, the second feedback arm is now used to realize the graph operation.

Previously, we have used the setup to induce disorder to realize percolation quantum walks – a process that takes place on random graphs [12]. We present here results requiring deterministic control [13], such as quantum walks on finite graphs with reflective boundary conditions, state preparation, and a quantum walk based state transfer protocol.

Our work is a proof-of-principle experiment of quantum walks on controlled graph structures, marking a way towards complex simulation of quantum transport in random media.

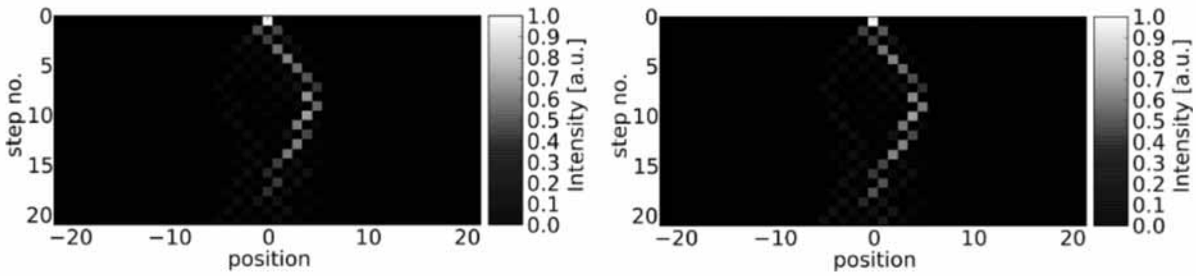

FIG. 1: Quantum walk on a finite graph with vertices {-5,...,5}, experimental data left, numerical data on the right.

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Open Quantum Magnets with Interacting Rydberg Atoms in a Cavity

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Cavity quantum electrodynamics in combination with cold atomic gases is a promising set up to realise and engineer many-body dynamics of strongly coupled light-matter systems that can lead to novel phases of matter. In this research project, I consider a set-up where a single quantized mode of the light-field interacts with an ensemble of Rydberg atoms inside a high finesse optical cavity. The atoms interact with each other and are trapped inside an optical lattice, see figure 1. I search for non-equilibrium steady-states that are realised in such driven and damped cavities, when losses of the system and the external drive balance each other. The cavity resonator mediates controllable long-range interactions between the atoms that induce collective behaviour of the many-body system of atoms and photons, for instance expressed in the superradiant transition. When the atoms additionally interact via short-ranged interactions, this opens up the possibility for phase transitions between different magnetic phases of atoms that coexist with coherent atomic radiation. As the cavity resonator is an open system, dissipative processes such as spontaneous decay of atomic excitations and photon loss through imperfect cavity mirrors can enrich the phase diagrams and lead to novel phases of matter without equilibrium counterpart. The output light of the cavity can be analysed experimentally to detect the states of matter inside the cavity. We calculate such spectra and the signatures of phase transitions.

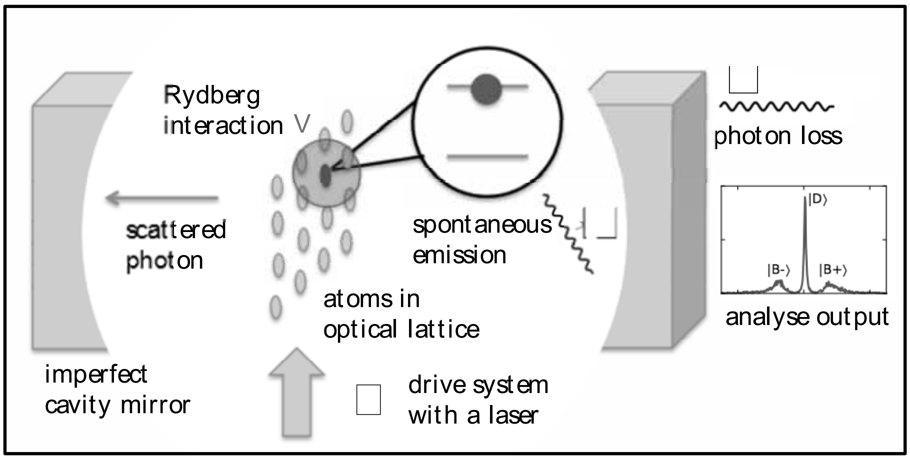

FIG. 1: Illustration of a possible experimental set-up for realising light-matter and atom-atom interactions in a cavity. Interacting Rydberg atoms are trapped in an optical lattice inside a high finesse optical cavity. The shaded ring around the atoms indicates their interaction radius. The strength of the short-range interaction is denoted by V. A transversal pump laser drives the atoms which scatter photons in the cavity. Photons can escape the cavity with a rate □ due to imperfect mirros. Atoms decay with rate □ due to spontaneous emission. The output light is analysed experimentally to investigate the spectrum.

Gaussian Boson Sampling

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Boson sampling has sparked the imagination of theorists and experimentalists since it was introduced by Aaronson and Arkhipov [1]. Here, single photon Fock states are launched into a multimode interferometer where, due to boson statistics, the probability of any output distribution of photons is related to the permanent of a matrix (derived from the interferometer transformation). This makes the output distribution of events difficult to sample from unless certain complexity classes are equivalent. There have since been several experimental realisations of Fock boson sampling [2–5].

The use of input states different from Fock states, namely Gaussian states [6], is interesting both theoretically and experimentally, as they are easier to generate. In this work we show that the output distribution of photon numbers from a Gaussian state is given by a matrix function which can be conjectured to be as difficult as the matrix permanent. We then relate the problem of the typical model of Fock boson sampling to the Gaussian model, showing the former can be seen as a special case of the latter. Finally, we look at some of the classes of Gaussian states that would be complex to simulate.

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A Quantum Electrodynamics Kondo Circuit with Orbital and Spin Entanglement

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Recent progress in nanotechnology allows to engineer hybrid mesoscopic devices comprising on chip an artificial atom or quantum dot, capacitively coupled to a microwave (superconducting) resonator and to biased metallic leads. Here, we build such a prototype system where the artificial atom is a graphene double quantum dot (DQD) to probe non-equilibrium aspects of strongly-entangled many body states between light and matter at the nanoscale (see figure). Controlling the coupling of the photon field and the charge states of the DQD, we measure the microwave reflection spectrum of the resonator. When the DQD is at the charge degeneracy points, experimental results are consistent with a Kondo impurity model entangling charge, spin and orbital degrees of freedom with the quantum fluctuations of the cavity photon [1, 2]. The light coming out from the resonator reveals the formation of the Kondo or Abrikosov-Suhl resonance at low temperatures. We also explore other routes to investigate nonlinear transport by increasing the microwave power, the bias and gate voltage.

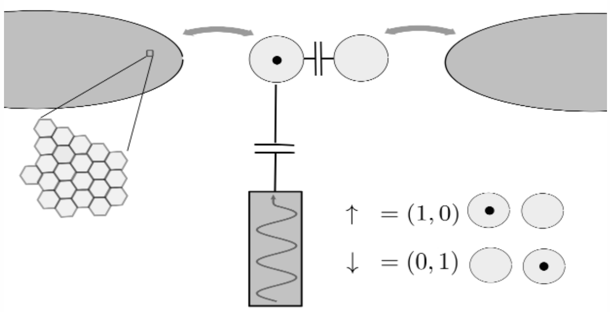

FIG. 1: Setup of the hybrid DQD device.

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Long range induction between Josephson junction arrays via microwave photon emission and absorption

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Strong induction between one-dimensional arrays of Josephson junctions separated with tens of micrometers were observed and analyzed. Arrays have a structure of superconducting quantum interference device(SQUID) connected in series, allowing one to tune Josephson coupling energy by changing the flux threading a SQUID loop. Constituent Josephson junctions were made of Al/AlOx/Al with a typical size of 100 nm, giving a charging energy of about 50 μeV. A dc current biased in one array may increase the conductance of nearby isolated arrays. Because of large inter-array distance, this mutual induction cannot be explained by capacitive coupling between two arrays.[1] It turns out that the conductance change can be understood under a picture of phase diffusion introduced by microwave excitation.[2] A detail analysis reveals that excitation microwave power is proportional to bias current in the emitter. The induction strength is largest when charging energy is dominant over Josephson coupling energy, a similar trend that an array responds to microwave excitations.[3] In short range, induction strength is inversely proportional to inter-array distance, suggesting a microwave power emission. This induction provides an application of long-range and fast signal coupler.

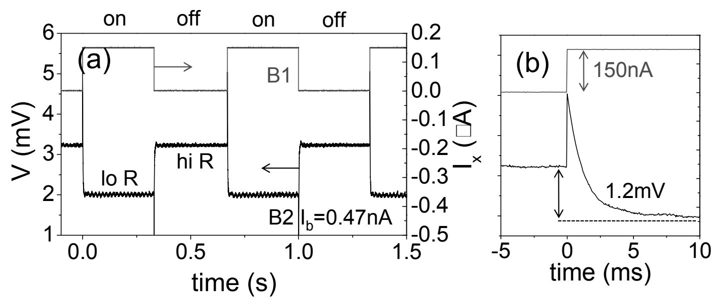

FIG. 1 Demonstration of long–range digital signal coupler (a) Time scan of the output voltage of receiving array under a bias current of 0.47 nA when the emitting array is cyclically switched on and off. When emitter current is switched on, the voltage drops due to a rapid change from high resistance(hi R) state to a low resistance state(lo R). (b) The receiving array responses with a characteristic time smaller than 5 ms, which is limited by our wiring and voltage pre-amplifier.

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Macroscopic Coherence Bounds Quantum State Disturbance via Coarse-Grained Measurement

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We demonstrate that in a coarse-grained measurement process, the degree of quantum state disturbance is bounded by the Wiger-Yanase-Dyson skew information [1]. When a measurement of observable $\hat{A}$ is performed with a limited precision σ, fidelity between pre- and post-measurement states satisfies following inequality

$$F(\rho, \tilde{\rho}) \geq e^{-\frac{I_W(\rho,\hat{A})}{2\sigma^2}}, \qquad (1)$$

where $I_W(\rho, \hat{A}) = -\frac{1}{2}\mathrm{Tr}[\sqrt{\rho}, \hat{A}]^2$ is Wiger-Yanase-Dyson skew information. Throughout two examples in the spin system and the optical field, we discuss the level of coarse graining required to perform a non-invasive measurement ($F \to 1$) when the system size increases to macroscopic limit. When measuring total spin of N-particle spin-$\frac{1}{2}$ system, degree of coarse graining $\sigma > O(N^{1/2})$ is sufficient for non-invasive measurement of product state and Dicke states with small excitation numbers ≈ 1. On the other hand, we note that GHZ-states and Dicke states with excitation numbers $\approx N/2$ require a degree of coarse graining $\sigma > O(N^1)$ in order to reach non-invasive measureability condition. Finally, we show that disturbance via coarse-grained measurement indicates an amount of macroscopic coherence [2, 3] contained in a quantum state.

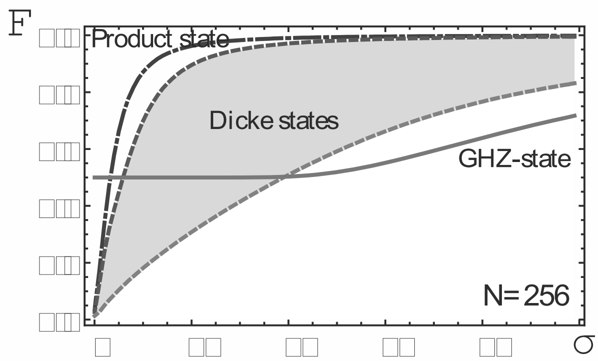

FIG. 1: Fidelity between pre- and post-measurement states via coarse-grained measurement of total spin in N-particle spin-$\frac{1}{2}$ system with coarse-graining parameter σ. Each line refers to product state(dot-dashed), Dicke state(dashed), and GHZ-state(solid), respectively. The macroscopic quantum coherence can be defined as how slowly the state becomes non-invasive when the level coarse-graining σ increases.

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Many-body dynamics through measurement and feedback

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Time-continuous homodyne measurements and feedback [1, 2] allow eﬃcient quantum control of systems such as cavity and circuit QED, atomic ensembles, and optomechanics. Here, we consider interferometric measurements on an array of such systems, and derive the corresponding feedback master equation. Since the systems only interact through feedback, they may be kept in separate locations, easing experimental realization. Moreover, there is no intrinsic limit on the range or geometry of the interaction, making the scheme quite versatile.

We show that the setup can reliably create many-particle entanglement, which may be of use to various quantum information protocols. Furthermore, we can emulate the non-equilibrium evolution of many-body systems with pairwise interaction. As an example we engineer a dissipative Ising model.

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Enhanced nonlinear interactions in quantum optomechanics via mechanical amplification

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We present an approach for exponentially enhancing the single-photon coupling strength in an optomechanical system using only additional linear resources. It allows one to reach the quantum nonlinear regime of optomechanics, where nonlinear effects are observed at the single photon level, even if the bare coupling strength is much smaller than the mechanical frequency and cavity damping rate. Our method is based on using a large amplitude, strongly detuned mechanical parametric drive to amplify mechanical zero-point fluctuations and hence enhance the radiation pressure interaction. It has the further benefit of allowing time-dependent control, enabling pulsed schemes. For a two-cavity optomechanical setup, we show that our scheme generates photon blockade for experimentally accessible parameters, and even makes the production of photonic states with negative Wigner functions possible. We discuss how our method is an example of a more general strategy for enhancing boson-mediated two-particle interactions and nonlinearities.

Weakly driven integrable models

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I will present how integrable models respond to the presence of weak integrability-breaking driving terms. The perturbations considered are either of unitary or Markovian non-unitary nature, so that the whole dynamics is governed by a Liouville operator which is for the latter case of the Lindblad form. As the test case I will consider the 1D spin-1/2 chain that is in the absence of driving described by the XXZ Heisenberg Hamiltonian. As the main result I will show how the influence of conserved charges persists in the description of the stationary state and how it enters the low orders of perturbation theory. It will be shown that a generic property of weakly-perturbed integrable models is that small perturbations can strongly affect the steady state. Furthermore I will discuss how the structure of perturbation theory, which gives the higher orders of stationary state density matrix, changes as compared to the usual equilibrium case. Besides its fundamental aspects, our approach should be relevant also for models with few conserved quantities, e.g. in ultracold atoms and photon or exciton condensates.

Microscopic description for the emergence of collective decoherence in extended systems

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Practical implementations of quantum technology arelimited by unavoidable effects of decoherence and dissipation. With achieved experimental control for individual atoms and photons, more complex platforms composed by several units can be assembled enabling distinctive forms of dissipation and decoherence, in independent heat baths or collectively into a common bath, with dramatic consequences for the preservation of quantum coherence. The cross-over between these two regimes has been widely attributed in the literature to the system units being farther apart than the baths correlation length. Starting from a microscopic model of a structured environment (a crystal) sensed by two bosonic probes, here we show the failure of such conceptual relation, and identify the exact physical mechanism underlying this cross-over, showing that it is not only a matter of system size. Peculiar scenarios in 1D environments or beyond isotropic dispersion relations are predicted, with collective dissipation possible for very large distances between probes, opening new avenues to deal with decoherence in phononic baths.

Laser from a Manybody Correlated Medium

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We consider a non-equilibrium system of interacting emitters described by the XXZ model, whose excitonic transitions are spatially and spectrally coupled to a single mode cavity. We demonstrate how the output radiation field is sensitive to an interplay between the hopping (J) and the interactions (U) of the excitons. Moderate values of the short ranged interaction are shown to induce laser with maximal output at the Heisenberg point (U = J). In the laser regime, the chain of emitters shows short range charge-density-wave order for interactions below the Heisenberg point, and long range correlations at the Heisenberg point, in remarkable contrast to the equilibrium ground state behavior of the spin chain.

1300 nm Ideal Single Photon emission of InAs QD by All-Optical Fiber Intensity Interferometry

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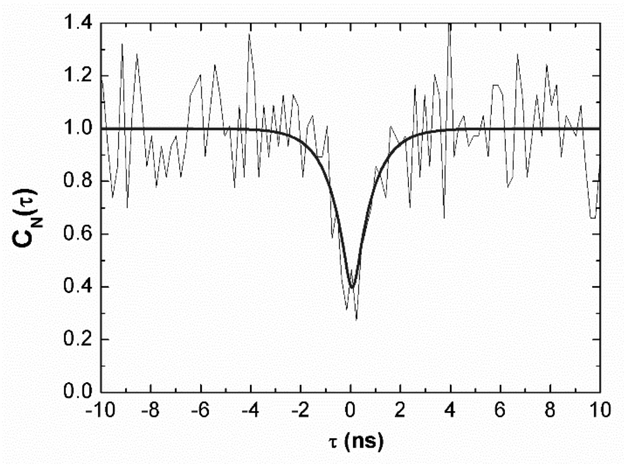
New optical fiber based spectroscopic tools open the possibility to develop more robust and efficient characterization experiments. Spectral filtering and light reflection have been used to produce compact and versatile fiber based optical cavities [1-2]. Moreover, these technologies would be also suitable to study N-photon correlations [3], where high collection efficiency and frequency tunability is desirable. We demonstrated ideal single photon emission of a single quantum dot emitting at 1300 nm after background substraction (figure 1), using a Fiber Bragg Grating for wavelength filtering and InGaAs Avalanche Photodiodes operated in Geiger mode for single photon detection. As we do not observe any fine structure splitting for neutral exciton transition, our experimental proposal could lead to a more efficient analysis of entangled photon sources at telecom wavelengths. This all-optical fiber scheme opens the door to new first and second order interferometers to study photon indistinguishability, entangled photon and photon cross correlation in the more interesting telecom wavelengths.



(FIG 1)

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Few-photon transport in many-body photonic systems: A scattering approach

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We study the quantum transport of multi-photon Fock states in one-dimensional Bose-Hubbard lattices implemented in QED cavity arrays (QCAs). We propose an optical scheme to probe the underlying many-body states of the system by analyzing the properties of the transmitted light using scattering theory. To this end, we employ the Lippmann-Schwinger formalism within which an analytical form of the scattering matrix can be found. The latter is evaluated explicitly for the two particle/photon-two site case using which we study the resonance properties of two-photon scattering, as well as the scattering probabilities and the second-order intensity correlations of the transmitted light. The results indicate that the underlying structure of the many-body states of the model in question can be directly inferred from the physical properties of the transported photons in its QCA realization. We find that a fully-resonant two-photon scattering scenario allows a faithful characterization of the underlying many-body states, unlike in the coherent driving scenario usually employed in quantum Master equation treatments. The effects of losses in the cavities, as well as the incoming photons' pulse shapes and initial correlations are studied and analyzed. Our method is general and can be applied to probe the structure of any many-body bosonic models amenable to a QCA implementation including the Jaynes-Cummings-Hubbard, the extended Bose-Hubbard as well as a whole range of spin models.

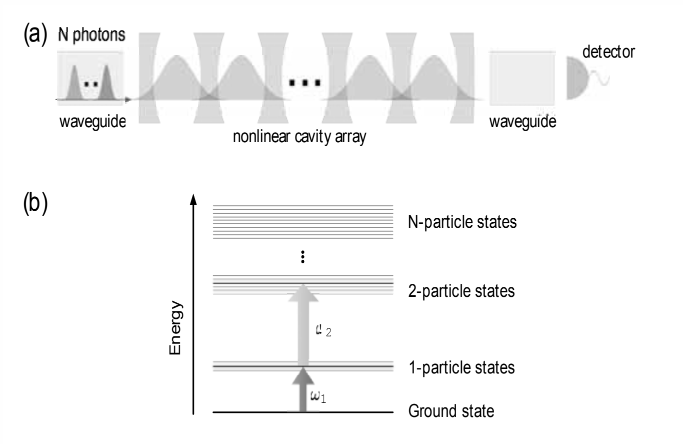

FIG. 1: (a) Proposed method to probe the structure of bosonic many-body models as implemented QCA simulators. Photons traveling in the left waveguide are injected into the array and are transported through the device to the right waveguide. In this work, the QCA is assumed to realize the Bose-Hubbard model but other models such as the Jaynes-Cummings-Hubbard, spin models, or the extended Bose-Hubbard can also be realized. The injected photons scan through the many-body eigenstates of the simulated model and if they are fully resonant to the many-body states as illustrated in (b), the full information of the relevant states is mapped out faithfully in the output spectra and correlation functions.

Frozen photons in Jaynes Cummings arrays

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We study the origin of 'frozen' states in coupled Jaynes-Cummings-Hubbard arrays in the presence of losses. For the case of half the array initially populated with photons while the other half is left empty we show the emergence of self-localized photon or 'frozen' states for specific values of the local atom-photon coupling. We analyze the dynamics in the quantum regime and discover important additional features appear not captured by a semiclassical treatment, which we analyze for different array sizes and filling fractions. We trace the origin of this interaction-induced photon 'freezing' to the suppression of excitation of propagating modes in the system at large interaction strengths. We discuss in detail the possibility to experimentally probe the relevant transition by analyzing the emitted photon correlations. We find a strong signature of the effect in the emitted photons

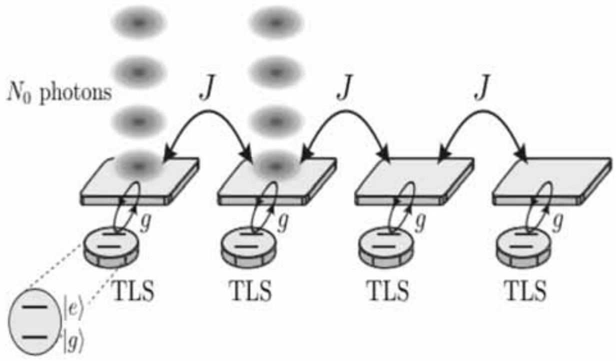

FIG. 1: Schematic of our system and the initial conditions considered. The left half of a one dimensional array with M resonators (here $M = 4$) is initialised in a Fock state of N_0 photons (in this particular schematic, $N_0 = 4$). Each resonator is coherently coupled to its two nearest neighbours with associated tunnelling rate J. Each resonator is also coherently coupled to a two-level system (TLS) with Jaynes Cummings coupling parameter g.

The absence of macroscopic quantum superpositions in a closed system

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Quantum superpositions between macroscopically distinct states are allowed in the law of quantum mechanics but we cannot see such states in everyday life. One of the most well-known scheme to explain this is decoherence which says that MQSs are very sensitive under the interaction between the system and an environment. Then, a closed system preserve MQSs under the time evolution? In this work, we show that MQSs cannot be maintained even for a closed system if a system thermalize.

We use the measure for the size of MQS for a many spin-1/2 system defined in Ref. [1, 2], which is given by the maximum variance of macroscopic observables for pure states. We first show that if the measure only scales as N where N is the number of spin, the quantum state | i cannot be detected as an MQS in coarse-grained measurement regime [3, 4].

Using this measure, we investigate the fate of macroscopic quantum superpositions in thermalization or many-body localization system. We use the disordered Heisenberg model which is in thermal for small disorder strength but enters to many-body localization phase as the disorder strength increases [5]. We show the saturated value of the measure when the initial states random Greenberger-Horne-Zeilinger (GHZ) states in random local basis. The averaged of saturated value of the measure is shown in the Figure. The results show that if a system thermalize MQSs cannot preserve their size under the time evolution. However, it is not the case when the system is in many-body localization phase.

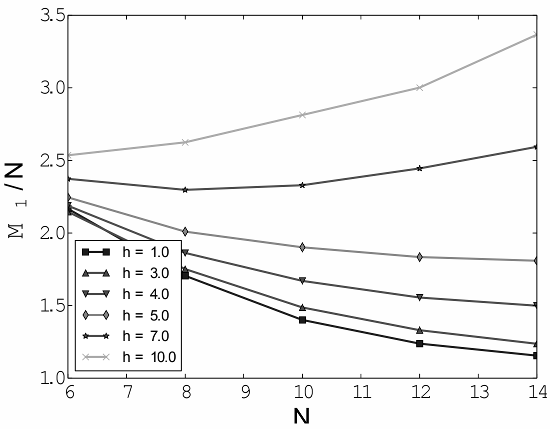

FIG. 1: When the initial states are given by GHZ states in random local basis, the average of saturated value of the measure is shown. The number of spins is given by N and the disorder strength is given by h.

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Scattering of photons on Bose-Hubbard lattices

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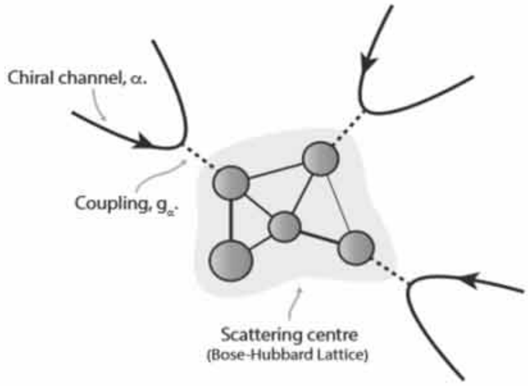
We study the photonic transport of weakly coherent light in various Bose-Hubbard lattice geometries implemented as QED cavity arrays. We use a diagrammatic scattering approach [1] to study the relation between lattice geometry, single photon transmission and the second order intensity correlation of the transmitted light. The motivation is twofold: First, a large induced correlation can be used to design circuit elements useful for photonics applications. Second, the scattering of photons on complex lattices offers a promising way to characterize quantum correlation in a range of different, exotic states of matter theorized to be present in higher-dimensional cavity arrays.



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Towards a fully guided ring-shaped matter-wave Sagnac interferometer

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Since their proposal, time-averaged adiabatic potentials (TAAPs) [1] paved the way towards the implementation of dynamical, smooth, complex potential landscapes for trapping and guiding ultra-cold neutral atoms and Bose-Einstein condensates (BECs). Of particular interest for interferometric schemes is the ring-shaped TAAP waveguide, first demonstrated by Sherlock et al. [2]; its smoothness and long lifetimes make it the perfect candidate for coherent matter-wave guiding and Sagnac-type interferometry.

Here, we report on the experimental implementation of smooth TAAPs, highly controllable, routinely loaded with cold atomic clouds. We also propose and examine in detail a Sagnac-type interferometric scheme using our ring-shaped TAAP, with state-dependent splitting and guiding of the atomic cloud. The proposal is based on splitting the |F, m_F i = |1, □1i atomic cloud, by means of microwave (mw) radiation, into the |2, ± 1i and |1, ⌥1i clock states. These clock states will form the basis of the Sagnac-type interferometry experiment. They have been shown to be ideal for the purpose, with very long coherence times [3] and easy state-dependent manipulation through the use of radio-frequency (RF) fields [4].

We corroborate the interferometric scheme by performing state-dependent matter-wave guiding of two di↵erent spin states of ^{87}Rb atoms in the aforementioned potential in separate, though identical experimental sequences.

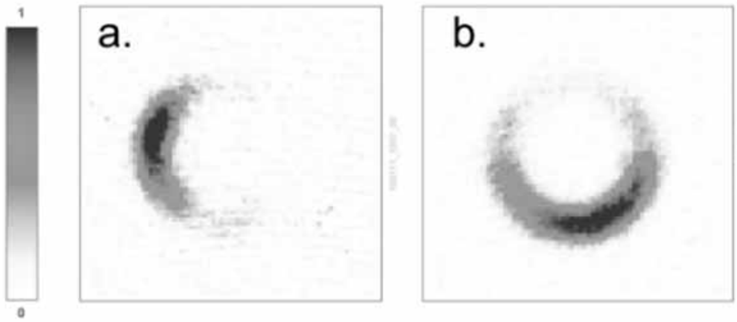

FIG. 1: Experimental realization of an arbitrary trap for the (a) |1, ⌥1i and (b) |2, ± 2i states. Note that the experimental conditions are exactly the same in both cases, but the two clouds feel di↵erent potentials.

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Temporal and spatial behaviour of density-density correlations in driven-dissipative quantum fluids

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The inherent non-equilibrium nature of driven-dissipative quantum fluids implies that, even in the stationary regime, the system is subject to statistical noise originating from the particle losses. We show that, in the regime where the noise is small compared to the mean field, Bogoliubov-de Gennes theory allows one to compute the time-dependent two-point correlators in a fully semi-analytic fashion. Henceforth, by application of Wick's theorem, any higher-order time-dependent correlation function can be obtained without resorting to cumbersome Monte-Carlo methods. Apart from the approach being exact at the considered level of approximation, it also provides a tremendous improvement in convergence time, since it merely requires the inversion of a system of linear equations.

As a first application of the method, we study the temporal and spatial density-density correlations in a homogeneous polariton fluid under quasi-resonant pumping. We will address the photon blockade effect and the appearance of an effective lightcone in both the optical limiting and bistability regime. The simulations are performed as theoretical support for experiments currently running at ETH (Zürich).

Secondly, we will discuss the method in the context of the recent acoustic black-hole experiment at LPN/CNRS (Marcoussis). Here, the density-density correlations are expected to reveal the correlations between the Hawking and particle modes across the sonic horizon in the sample. To conclude, also the quest for engineering novel observables, which may uncover the predicted entanglement between the Hawking and partner particles, will be motivated.

Non-Classicality Criteria in Multi-port Interferometry

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Driven by the increasing interest of the scientific community in experiments involving more than two photons, we study the average amount of correlations characterizing pairs of output intensities in a multi-port interferometric setup. By finding the minimum value that such functional could assume in a completely classical framework, we formulate a non-classicality criterium for the input light based on the violation of such bound. A necessary condition for beating the classical threshold is identified in the presence of sources with sub-poissonian photon-number statistics. As possible applications of our findings, we show that the amount of correlations reached by single-photon inputs could be used to infer the average degree of distinguishability between pairs of sources and to certify the impossibility of decomposing a linear optical network into independent sub-blocks.

Polariton-mediated quantum information processing

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We study the equilibrium and nonequilibrium properties of two qubits interacting through a polariton bus with an ultrastrong coupled qubit-cavity system [1], see Fig. 1. By tuning the energy gap of the qubits and maintaining the polariton within the vacuum, we demonstrate improvements of two-qubit gate operation time and excitations transfer as the ultrastrong coupling strength is increased. Our proposal might pave the way for multipurpose parity protected quantum information tasks, and enhancement of excitations transfer in disordered systems..

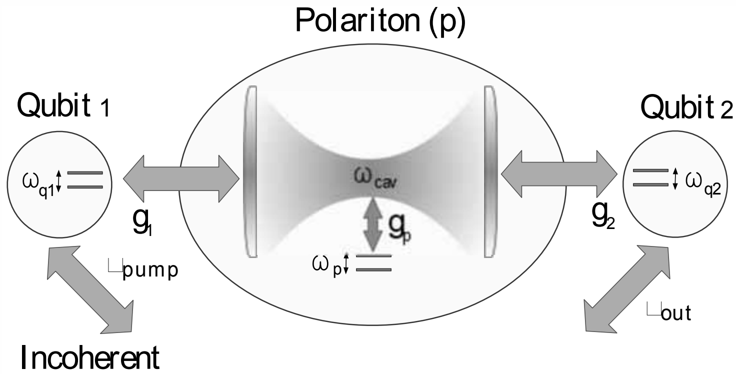

FIG. 1: Schematic representation of our model. A qubit-cavity system interacting in the ulstrastrong coupling regime constitutes the polariton. Two additional qubits interact with the polariton via the cavity mode. The qubit 1 may be driven by an incoherent pumping, while the qubit 2 experiences spontaneous decay.

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Probing photon correlations in the dark sites of geometrically frustrated cavity lattices

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We theoretically explore the driven-dissipative physics of geometrically frustrated lattices of cavity resonators with relatively weak nonlinearities, i.e. a photon-photon interaction smaller than the loss rate. In such systems, photon modes with zero probability at 'dark' sites are present at the single-particle level due to interference effects. In particular, we study the behavior of small systems with few coupled resonators as well as extended Lieb lattices in 1D and 2D. By considering an inhomogeneous pumping scheme, with the driving field not applied to the dark sites, we predict that even in presence of relatively weak photon-photon interactions the nominally dark sites achieve a finite photonic population with strong correlations. We show that this is a consequence of biphoton and multiphoton states that in the absence of frustration would not be visible in the observables [1].

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Synchronization of two ensembles of atoms via quantum and classical channels

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Ultra-cold atomic ensembles using an ultra-narrow optical transition operated in the superradiant regime can be used as active atomic clocks, promising a much lower linewidth and therefore much better precision than current optical atomic clocks. We show that in a cascaded setup of two frequency-detuned superradiant lasers, i.e. master & slave, the slave laser synchronizes to the master in a wide frequency range. Furthermore we show that this synchronization does not rely on the quantum coupling between both lasers, but can be simulated using a classical channel. Additionally we show that the synchronization in a bidirectional coupling setup, i.e. both atomic ensembles couple to the same cavity mode, can also be simulated using a classical coupling channel between both ensembles.

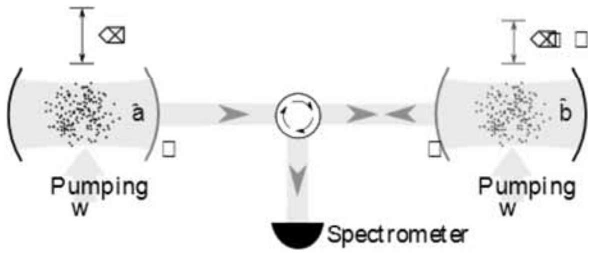

FIG. 1: Cascaded cavity setup using a Faraday rotator and analyzing the combined output of both cavities.

Magnetic field induced transparency in array of superconducting mirror flux qubits

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The coherent quantum phenomena govern the electrodynamics of superconducting quantum metamaterials, i.e artificially fabricated systems containing of an array of superconducting qubits. Thus, the electromagnetic wave (EW) propagation in a transmission line coupled to metamaterial can be varied by excitation of intrinsic coherent quantum oscillations. In a weak coupling regime the frequency f dependent transmission coefficient $S_{21}(f)$ displays a set of narrow resonant drops. Here, we experimentally and theoretically explored the propagation of EWs in superconducting quantum metamaterials in a strong coupling limit. We observed that in a broad frequency region the transmission coefficient S_{21} periodically depends on an externally applied magnetic field, and the S_{21} displays a large suppression more then 15 dB as an externally applied magnetic flux, $\Phi \simeq \Phi_0/2$ (Φ_0 is the flux quantum). Surprisingly, in this region of magnetic fields we observed also a large resonant enhancement of S_{21}. These strong variations of the metamaterial's transparency were explained by the presence of various classical and quantum metastable states trapped in complex flux qubits based metamaterials. Our theoretical analysis of S_{21} taking into account the both types of trapped metastable states is in a good accord with experimental observations, and we anticipate various applications of such magnetic induced transparency in quantum electronics and quantum information science.

Benchmarking a Polaron Master Equation and Non-Positivity in QUAPI

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The quasi-adiabatic propagator path integral (QUAPI) [1] is an established iterative numerical method used for propagating the reduced density matrix of a quantum system interacting with an environmental bath. The main approximation that makes this scheme computationally feasible is the introduction of a hard cutoff of the temporal bath correlation functions. This is generally seen as a valid approximation to make, as correlations in a continuous bath do generally drop to zero for large enough timespans.

Recently, we have been investigating a system consisting of a pair of spins immersed in a common, spatially correlated, bath using QUAPI with the goal of benchmarking the results of a polaron master equation applied to the same system [2]. We found that, for some parameter regimes, QUAPI appears to perform quite poorly and even gives unphysical, non-positive time evolution. Further comparison of QUAPI with more amenable models has led us to believe that the potential for these problems to arise is ubiquitous, regardless of the exact details of the model, and that the root of these problems lies with the finite memory approximation. Our investigation culminated in the identification of sets of parameters for which QUAPI gives trustworthy results that can reliably used to benchmark the polaron master equation.

While it possible to simply avoid the regions of parameter space where problems arise, we hope that further investigation into the performance of QUAPI (and similar numerical methods) will lead to a more rigorous diagnoses of the non-positive behaviour and also ways to deal with it.

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