Repulsive Photon-Photon Interactions mediated by Rydberg atoms.

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Realizing robust quantum phenomena in strongly interacting systems is one of the central challenges in modern physical science. Although photon−photon interactions are typically negligible in conventional optical media, hybridizing light with ensembles of strongly interacting particles has emerged as a promising route toward achieving few-photon nonlinearities. Our approach is to interface light with highly excited atomic Rydberg states by means of electromagnetically induced transparency (EIT), an approach which allows to induce strong long-range interactions between freely propagating photons in the form of polaritons.
Recently, these interactions have enabled the observation of photon blockade[3] and bound states of attractive photons[1], as well as the implementation of single-photon transistors with robust phase shifts[2]. Here, we present a new scheme to engineer repulsive interactions between photons. Photon correlation and conditional phase measurements reveal the distinct bunching and anti-bunching features associated with three-photon and two-photon repulsive interaction systems. These observations demonstrate the ability to tune and control the type of interaction among quantum many-body states of light and open a route for many-body photon crystallization.

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Polariton-assisted singlet fission in acene aggregates

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The recent developments of nanostructures that can afford a strong confinement of electromagnetic fields have opened up avenues to explore different regimes of strong light-matter interaction. Under these, photonic and material degrees of freedom mix and give rise to hybrid entities usually known as polaritons. Interestingly, in recent years there have been efforts to explore the potential applications of strong light-matter (SC) interaction on photochemistry [2, 4] and electron transfer[3], showing that fluctuations of the electrodynamic vacuum may indeed have relevance in chemical processes. In this work, we develop a simplified model to shed light on the relevance of SC on the yield of Singlet Fission (SF) in a family of acenes. SF is particularly relevant in the field of exciton harvesting since it allows to produce two low-energy excitons from a highly energetic one[1], which translates into a significant increase in the quantum yield of excitons produced per photon absorbed in the materials that feature this process. Our results show that theoretically, it is possible to enhance the SF quantum yield for some materials, by correctly tuning experimental parameters.

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Topological order in finite-temperature and driven dissipative systems

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There are many exciting topological properties of topological systems in pure states. Although mixed quantum states can be understood as a generalization of pure states their topological properties are not investigated so far. For example, quantization of charge transport in a so-called Thouless adiabatic pump is lifted at any finite temperature in topological insulators. Here we show, that many body correlations preserve the integrity of topological invariants for mixed Gaussian states in one dimension. In our approach we show that the expectation value of the many body momentum-shift operator leads to a definition of a physical observable called the "ensemble geometric phase" (EGP). It turns out that in analogy to the Zak phase of pure states this phase is a general representation of a geometric phase for mixed Gaussian quantum states in the thermodynamic limit. Additionally the EGP provides a topologically quantized observable which detects encircled spectral singularities of density matrices [1].

Acknowledgements: the work presented in this poster has been done in collaboration with C.E. Bardyn, M. Fleischhauer, A. Altland, S.Diehl

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Spin polarisation control of semimagnetic exciton-polariton condensates localised in photonic trap

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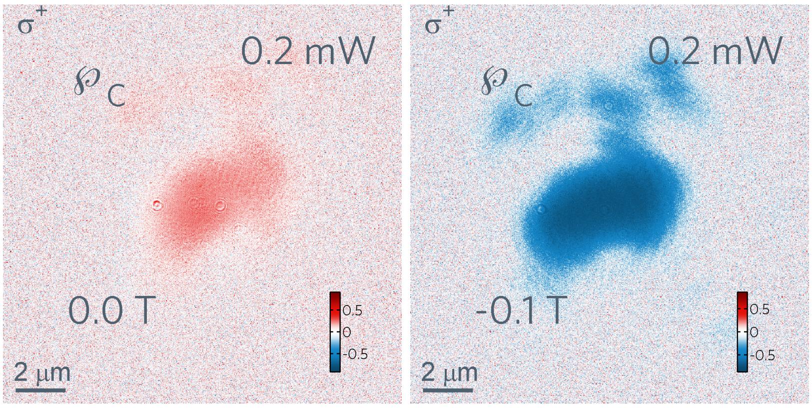
Bosonic nature of exciton-polaritons and their low effective mass allows to obtain Bose-Einstein condensation and to localise it in micrometer size traps. Such geometry can be used to investigate bosonic Josephson junctions [1] and to realize quantum simulations by using interactions of polariton condensates in lattices [2]. Our approach is to study spin properties of exciton-polariton condensates in low dimensional traps using semimagnetic semiconductors. We study microcavity with quantum wells containing 4% of manganese. The incorporation of magnetic ions results in *s,p–d* exchange interaction between localised electrons of the d^5 shell of Mn^{2+} and delocalised band electrons in the system [3].

In our work we present formation of the localised condensates with different spin polarisations depending on the photonic inhomogeneity on the sample. We observe formation of circularly polarised condensate in the absence of magnetic field which is in contrast to linearly polarised emission typically observed in nonmagnetic samples. By changing magnetic field, power, energy and polarisation of the excitation laser we are able to tune the spin polarisation of the localised condensates. For particular position on the sample it is possible to reverse the sign of circular polarisation of condensate by applying magnetic field (Figure), increasing the excitation power or changing polarisation of laser excitation. Our results demonstrate the importance of spin interactions in localised condensates for quantum manipulations.



Rysunek 1. Figure: Degree of circular polarisation of exciton–polariton condensate in real space at zero (left) and -0.1 T (right) magnetic field. Excitation power (0.2 mW) and polarisation (σ^+) of the non-resonant laser are kept constant.

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A theoretical approach for collective strong coupling of organic molecules with arbitrary photonic structures

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Strong coupling of a dense collection of organic molecules with the electromagnetic modes of nanophotonic and/or plasmonic devices holds great interest for a wide variety of applications. Currently, most theoretical models of such devices use strongly simplified models for at least one of their constituents, typically either treating the molecules as two-level systems, or describing the photonic environment through a single bosonic mode. We here implement an intermediate approach where both complex molecular dynamics as well as arbitrary photonic mode structures can be treated directly. This approach is based on the Maxwell-Bloch approximation using a multi-level description of the molecules. We first treat a simple one-dimensional model to compare and evaluate the respective strengths and weaknesses of a fully classical, a fully quantum and a Maxwell-Bloch approach. We then investigate which effects in organic polaritonics and polaritonic chemistry can be represented within the mean-field description inherent in the Maxwell-Bloch approximation.

Poster: Macrorealism in optomechanical system

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The poster will be about the search of violation of macroscopic realism in optomechanical systems. Leggett and Garg derived a set of inequalities (LGI) fulfilled by any classical system which behaves according to our intuition of macroscopic reality [1]. They rely on two postulates: (A1) macroscopic realism per se (A2) non-invasive measurement. If a system violates the inequality, either one of the two assumptions or both will fail and we can no longer interpret the evolution of the system as classical. These inequalities provides a useful tool to investigate the coherence at macroscopic level and to look for quantitative criteria to discern the classical world from the quantum world.

An optical cavity [2] in which one of the two mirror is attached to a spring is an optomechanical system in which the mechanical part and the light field are coupled through the radiation-pressure force. It is possible to create non-classical states of the mirror through a projective measurement on the cavity field[3].

Leggett-Garg inequalities have been tested with a hybrid optomechanical system, in which the cavity field is replaced by a two-level system coupled with a harmonic oscillator, which represent the mirror. We defined a total evolution map, which includes the unitary free evolution due to the Hamiltonian, plus a projective measurement on the two level system to originate non-classicality in the harmonic oscillator state. The computed Leggett-Garg function violates the boundary whithin which the system can be understood as macrorealist, then we can infer that this evolution generates totally non-classical states of the mechanical part.

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Dissipation-induced anomalous multicritical phenomena

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We explore the influence of dissipation on a paradigmatic driven-dissipative model where a collection of two level atoms interact with both quadratures of a quantum cavity mode. The closed system exhibits multiple phase transitions involving discrete and continuous symmetries breaking and all phases culminate in a multicritical point. In the open system, we show that infinitesimal dissipation erases the phase with broken continuous symmetry and radically alters the model's phase diagram. The multicritical point now becomes brittle and splits into two tricritical points where first- and second-order symmetry-breaking transitions meet. A quantum fluctuations analysis shows that, surprisingly, the tricritical points exhibit anomalous finite fluctuations, as opposed to standard tricritical points arising in $^3He - ^4He$ mixtures.

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Self-induced spatial decoherence in the Newton-Schrödinger equation

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The Newton-Schrödinger equation (NSE) is a nonlinear modification of the Schrödinger equation in the presence of a Newtonian gravitational potential. Under appropriate conditions, the nonlinear Schrödinger equation governing the propagation of an optical beam through a thermal nonlinear medium mimics the NSE. Here the nonlocal nonlinearity plays the role of the gravitational potential allowing for optical analogues of gravitational objects such as a rotating boson star [1]. One aspect of the interplay between gravity and light that we can explore through the NSE is the quantum wavefunction collapse in the presence of a nonlocal potential. In the following work we investigate the self-induced spatial decoherence of a laser beam propagating through a focusing thermal nonlinear medium, due to the generation of a heat potential simulating the gravitational potential. We use an interferometric setup (shown in Figure 1) to obtain the superposition of the transverse intensity profile of the beam and its flipped image, so that we can calculate (as in [2]) the fringe visibility, which is related to the first-order spatial coherence. We expect the spatial coherence of the beam to decrease as it propagates through the thermal focusing nonlinear medium; the self-induced decoherence in our optical analogue may suggest that the quantum wavefunction is affected by the presence of long-range interactions such as gravity.

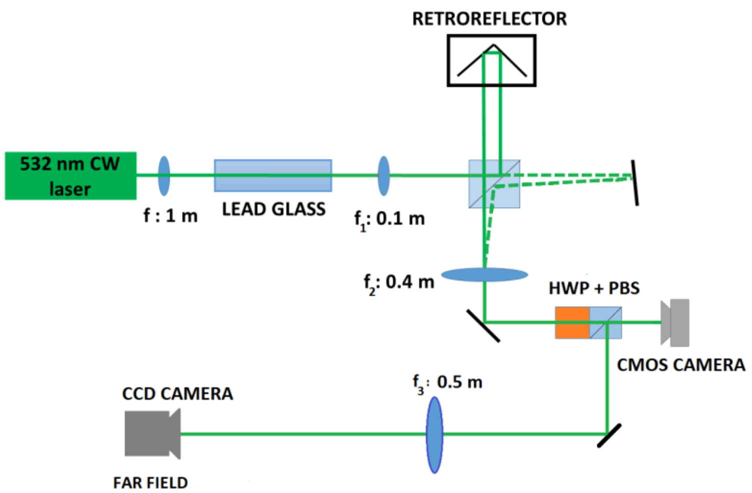

Figure 1 | Experimental setup (not in scale).

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Theory of Long-Range Energy Transfer Mediated by Collective Strong Coupling

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The phenomenon of energy transfer in organic molecules has been extensively studied in the frame of the Förster mechanism, as a result of the dipole-dipole interactions between molecules. This process can be significantly enhanced by strongly coupling the molecules to a cavity mode. Here, we shed light into the physical mechanism that allows excitation transfer from donor to acceptor molecules for an intermixed configuration [1] or for physical separations even of 100 nm or more [2]. Thanks to the appearance of polaritons in the strong coupling regime and the resulting mixing of donor and acceptor states with the cavity, non-local energy transfer can be driven by local non-radiative processes [3]. In this work [4], we study this effect by means of numerical computations based on Bloch-Redfield theory, which allows us to reproduce the effect of complex vibrational reservoirs characteristic of organic molecules. The relevance of the middle polariton in this process is revealed: it is the non-local intermediary of the transmission of the excitation from donor to acceptor molecules. We also provide analytical insight on the key magnitudes that helps to optimize the efficiency of the long-range energy transfer.

Acknowledgements: the work presented here has been done in collaboration with A. I. Fernández-Domínguez, J. Feist, and F. J. García-Vidal.

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On the nature of phase transitions in dissipative quantum spin systems

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The recent experimental advances in the field quantum technologies have enabled to control and consequently engineer interactions between various states of matter in several intriguing conditions, as for driven-dissipative systems in contact with an external environment (see, e.g., the reviews [1, 2] and references therein). One of the major questions that can be posed in this context is how quantum phase transitions in many-body systems are affected by the presence of dissipative processes. Suitable platforms to probe such physics include arrays of coupled QED or optomechanical cavities, as well as Rydberg atoms and trapped ions.

While most of the theoretical work so far has been done at the mean-field level, in the last few years it has been understood that a more careful treatment of interactions may lead to substantial changes in the emerging physical picture (see, e.g., Ref. [3]). Here we demonstrate how the coupling to a bath can drive phase transitions of different order: a thorough treatment of interactions is indeed crucial to be able to distinguish among their basic features, while a simple mean-field approach may reveal misleading.

We discuss these issues in the framework of the paradigmatic quantum Ising model, where the dissipation, modeled as simple incoherent local spin flips, can act either longitudinally or transversely with respect to the coupling direction [4–8]. Our analysis is based on a combination of numerical cluster mean-field methods, quantum trajectories, and linked cluster expansions in two and three dimensions, and clarifies how to distinguish first-order from continuous dissipative transitions, with some other intriguing features that involve correlations.

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Dissipative Phase Transitions in the Bose-Hubbard model with non-local dissipation

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The standard approach used to model an open quantum system with Markovian dynamics is to consider a phenomenological Lindblad master equation where operators acting locally in space are responsible for the system dissipation.

The spectrum of the Lindbladian together with the initial state of the system completely carachterize the system dynamics. Just like a Quantum Phase Transition may occur in the thermodynamic limit of a closed quantum system as the gap in the Hamiltonian spectrum closes when a parameter is varied, a Dissipative Phase Transition (DPT) may occur in the stationary state of an open quantum system when the gap in the Lindbladian spectrum closes [1].

We study what are the consequences of non-local Lindblad (dissipation) operators for first [2] and second order [3] DPTs expected to occur in the driven two-sites Bose-Hubbard model.

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Quantum Parametric Symmetry Breaking Transducer

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Parametrically driven quantum Kerr resonators can realize cat states which are widely used in the field of quantum information processing. These cat states are superpositions of coherent states that only differ by their phase. A near resonant external one photon drive breaks this phase symmetry. We find that there exists a special frequency at which the phase of the light field changes by π accompanied by a steep increase in the photon number. Remarkably, we can use this feature to measure the strength of the external drive from the phase of the light field. For dissipative Kerr resonators we find that this frequency depends linearly on the strength of the one photon drive. A measurement scheme for the strength of the one photon drive can be achieved using heterodyne detection. Finally we analyze the impact of the intrinsic noise in the quantum system.

Quantum Simulation of Energy Transport with Rydberg atoms

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Ultracold atoms excited to Rydberg states possessing strong electric dipole moments provide a unique platform for studying quantum dynamics with fully-programmable interactions. This would open a path to simulating key molecular and chemical processes extending far beyond atomic physics. In this poster, we will discuss a novel experimental system (sketched in figure 1) that provides control over the spatial geometry, long range interactions far beyond nearest neighbours and nontrivial system-bath interactions. This will be achieved using individual atoms in microoptical traps which are coherently coupled to two different Rydberg states possessing strong and long range Förster-type interactions. This will be combined with control over the trapping geometries using digital micromirror devices and stroboscopic interaction control and tailored environmental noise using fast acousto-optical defectors for the dressing lasers.

As a specific application, we aim to study how excitations migrate through quantum many-body systems possessing non-trivial correlations and how spatially and temporally correlated noise can enhance the robustness and efficiency of energy transport in synthetic quantum systems. Finding out which underlying properties of the system lead to the most efficient or robust transport, especially in the presence of quantum coherence and correlated noise has immediate relevance to the function of complex molecules (e.g. light harvesting complexes like LH II shown in figure 2). More broadly, the achievement of fully-programmble quantum systems based on Rydberg dressed atomic ensembles could enable breakthroughs in diverse applications of atomic physics, including quantum simulation and quantum computation, quantum matter, quantum networks and quantum chemistry.

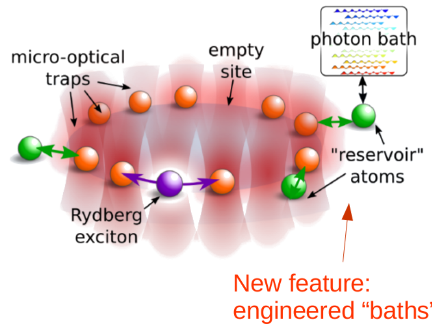

Figure 1: Artificial Atomic Model of LH II

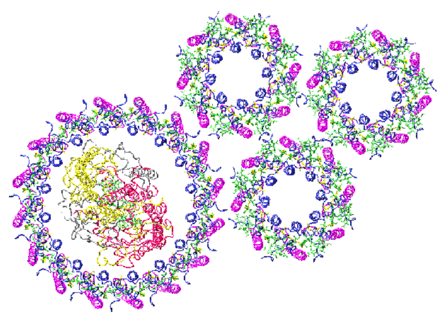

Figure 2: LH II (Light Harvesting Complex in nature)

Gaussian quantum trajectories for the variational simulation of Open Quantum Systems

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Systems of interacting photons such as *Quantum fluids of light and matter* are typically driven-dissipative and hence obey a, non-unitary, open systems version of quantum mechanics. The basic theory of such open quantum systems is well-understood by now [1]. However, the original study of these open quantum systems mainly aimed at the relatively small systems showing up in a typical quantum optics context. For larger open many-body systems such exact descriptions are practically impossible, and one must resort to approximate methods. Interestingly, variational descriptions of open quantum systems are currently still limited [2].

In general, open quantum systems can be described either on the level of the master equation for the whole ensemble or on the level of individual wavefunctions under (possibly hypothetical) continuous measurement (unraveling): quantum trajectories. Averaging over many monte carlo realizations of individual trajectories again reproduces the evolution for the whole ensemble. A widely used simulation method on the level of the master equation is the truncated wigner (TWA) method, which is, however, not always well-controlled and may predict unphysical results [3].

Here, we construct a class of variational methods for the study of open quantum systems based on Gaussian ansatzes on the level of individual quantum trajectories, partly inspired by the HFB method for closed systems. We apply these methods to a driven-dissipative Kerr cavity where we study dephasing and the stationary states throughout the bistability regime. We distinguish a Gaussian ansatz in the conjugate quadrature variables (commonly known as 'Gaussian states' [4]) from an ansatz of Gaussianity in density and phase and compare different unraveling schemes. Computational cost proves to be similar to the TWA method. Corresponding preprint: [5]

Acknowledgement: Wim Casteels.

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Edge-emitting polariton laser and amplifier based on ZnO waveguides

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Exciton-polariton (polariton) are bosonic quasiparticles resulting from the strong coupling between an excitonic resonance and a photonic mode. Thanks to their high nonlinear response, low threshold operation, and potentially high scalability, polaritons have emerged as a promising system for realizing low consumption, compact, all-optical devices. For the last 10 years, a wide variety of devices such as switches and optical transistors have been demonstrated [1][2][3]. Most of them are based on the creation of a polariton flow at cryogenic temperatures in GaAs microcavities where the slowness of the propagative modes (1-2 % of the speed of light) is balanced by the high Q factor (typically $\propto 10^5$).

To implement polariton-based switches at room temperature, microcavities based on large-bandgap semiconductors (GaN, ZnO) are required. However, as their Q-factors remain limited to a few thousands, alternative geometries have to be considered. One of them is the waveguide geometry, where guided modes confined by total internal reflection in a layer strongly couple to excitonic resonances. This geometry is very appealing because of its simple technological realization, the easier electrical injection, and the possibility it opens to design integrated polaritonic circuits with very limited radiative losses.

In this poster, we report lasing and optical amplification of guided polariton modes in two ZnO-ZnMgO waveguides grown by molecular beam epitaxy on m-plane bulk ZnO substrates [4]. The thickness of the active ZnO layer is either 50 nm or 130 nm. One sample is covered by sets of SiO2 gratings, perpendicular to the ZnO c-axis, whose period allows to extract the polariton guided mode dispersion. The two samples exhibit a series of parallel cracks which provide in-plane confinement together with the extraction of light.

First, linear properties are investigated by recording the dispersion relation provided by the gratings through a micro-photoluminescence far field Fourier imaging setup. Second, the polariton lasing effect is investigated in both samples from 5 K to room temperature. The mode dispersion below and above the lasing threshold fully demonstrate the polaritonic nature of the lasing modes. Finally, results of two-pump experiments demonstrating the amplification of guided polaritons propagating within an excitonic reservoir will be presented. This last result allows for the realistic implementation of on-chip polariton devices based on guided polaritons.

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Analog of black hole superradiance in nonlocal nonlinear optics

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Gravitational analogues have the potential to simulate unobserved gravitational effects through models realized in different physical systems such as acoustics, fluid-dynamics, nonlinear optics and Bose-Einstein condensates[1]. Their utility lies in addressing the lack of doable gravitational experiments by simulating strong gravitational fields in the laboratory.

From this perspective, one of the most interesting configurations is the black hole [2], a region of space with such an intense gravitational field that nothing can escape from it. This system exhibits characteristic and dramatic features, such as Hawking radiation and superradiance [3, 4], that make it an attractive space-time to study through the analogy. Indeed, many quantum gravity theories attempt to make contact with orthodox theory in their reproduction of these semi-classical results, making any experimental probes all the more crucial. Moreover, given that experimental tests on real black holes are beyond our current technological possibilities, analogs provide one of the only experimental windows to study its physics.

Here, we focus our attention on the phenomenon of superradiance, i.e. the amplification of excitations due to the angular velocity of the black hole. We show that nonlinear, nonlocal optics provides the framework for testing this phenomenon. Indeed, thanks to the fluids of light approach and phase-space methods, it is possible to simulate curved space-time in the proximity of a rotating black hole and hence to study its superradiant emission [5, 6]. We investigate the behavior of acoustic excitations on a vortex background in a defocusing nonlinear medium evolving through the nonlocal, nonlinear Schrödinger equation. The presence of nonlocality guarantees the stability of the optical vortex with a radial inward sink [7, 8], hence allowing experimental tests using the analogy.

These studies lead to novel perspectives on traditional superradiance through the optical realization of the analogy as well as drawing our attention to interesting new problems and phenomena from a purely nonlinear quantum physics point of view.

Acknowledgements: the work presented in this invited talk has been done in collaboration with A. Prain, C. Maitland and D. Faccio.

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Collective Frequencies
of
Trapped Photon Bose-Einstein Condensate

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In recent years the phenomenon of nonequilibrium Bose-Einstein condensation (BEC) has been studied extensively. One of the most recent and most prominent systems is a photon Bose-Einstein condensate [1]. The core of the system is a dye solution filling the microcavity in which the photons are harmonically trapped. Due to cyclic absorption and reemission processes of photons the dye leads to a thermalization of the photon gas at room temperature. Furthermore, due to a nonideal quantum efficiency, those cycles yield in addition a heating of the dye solution, which results in a change of the refractive index and, thus, in an effective photon-photon interaction [2]. In order to describe this thermooptic effect at a mean-field level, we use an open-dissipative Schrödinger equation for the condensate wave function, which is coupled to a diffusion equation for the temperature of the dye solution [3]. Elimination of the temperature as a dynamical degree of freedom leads to an effective complex Gross-Pitaevski equation for the photon wave function with spatial and temporal memory.
In our contribution we calculate analytically the lowest-lying collective frequencies and damping rates via a linear stability analysis for a harmonically trapped photon BEC. Due to the open-dissipative character of the system its energy is not conserved and, thus, it is not possible to investigate its dynamical properties within a variational approach by using an action. Instead, we work out an approximation which is based on determining the equations of motion for the lower moments under the assumption that the condensate wave function is Gaussian shaped [4]. As a result of the photon-temperature coupling the collective frequencies and damping rates turn out to depend on the diffusive properties of the dye solution. In particular, we show that the Kohn theorem [5] is not valid, i.e. the dipole-mode frequency turns out to deviate from the trap frequency due to memory effects.

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Relaxation oscillations and reservoir filling dynamics in an exciton-polariton condensate

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Exciton-polaritons enabled the creation of a novel class of bosonic condensates characterized by dissipative nonlinear dynamics. As demonstrated in recent experimental works, exciton-polariton condensates under non-resonant optical pulsed excitation can exhibit oscillatory behaviour in time [1],[2]. The manifestation of polariton condensate complex dynamics takes place when the density of incoherent exciton reservoir is rapidly depleted while increasing condensate density [3]. By analogy to the well know semi-classical nonlinear physical systems (eg. B-class semiconductor lasers), this type of dynamic behaviour is called relaxation oscillations. In this work, we performed numerical and analytical investigation of relaxation oscillations in the nonresonantly pumped polariton condensate. The presented considerations are based on the analysis of the open dissipative Gross-Pitaevskii equation with multistep free carrier-exciton-polariton relaxation process. The experimentally observed time-evolution of condensate density can be explained by studying the topology of phase space trajectory in the physical system. We used bifurcation analysis for the classification different regimes of condensate dynamics, e. g. fast stabilization, slow oscillations and ultrashort pulse emission. Next, we defined the analytical condition for the observation of relaxation oscillations. Additionally, we used the simple nonlinear oscillator model for the description of condensate time-evolution and oscillations. The analytical solution are in excellent agreement with both the results of numerical simulations and experimental observations [1],[2].

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Interactions and scattering of quantum vortices in a polariton fluid

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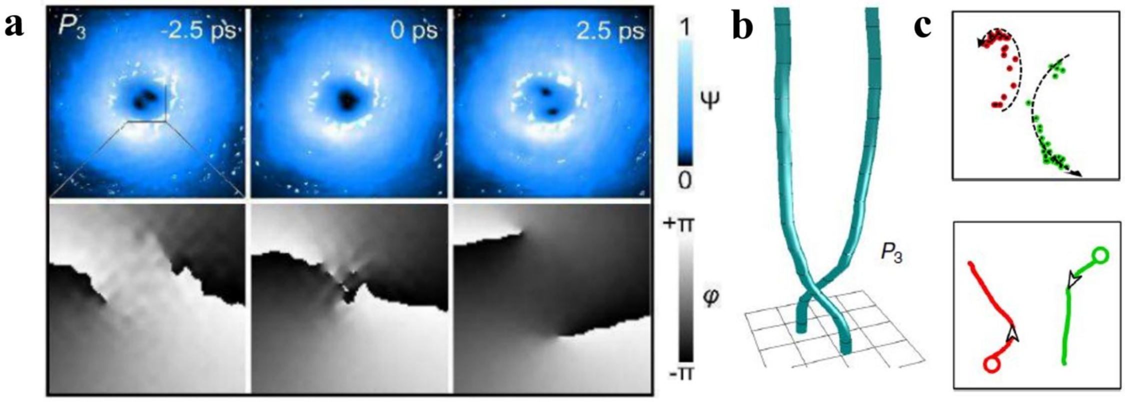
The exceptionally high coherence of microcavity polaritons confers a unique possibility to resolve both the amplitude and the phase maps of the polariton wavefunction down to the ps scale, e.g., by means of interferential Digital Holography techniques. It is indeed possible to set a precise initial condition and follow the associated system evolution, highlighting a wide tapestry of different phenomena, such as Rabi oscillations, nonlinear reshaping or even negative mass effects. Here we focus on the nonlinear dynamics of a resonant vortex pair, with adjustable initial separation, and successfully describe them in terms of effective vortex-vortex interactions.



Intervortex scattering-like event: (a) amplitude and phase maps before during and after the scattering, (b) reconstructed x,y,t vortex lines of the event, (c) experimental and numerically simulated in plane trajectory.

On the one hand, such configuration is followed by the rotational movement of the vortex cores themselves. Those results are supported by numerical GP simulations, and explained in terms of the vortex fields within the polariton fluid exerting an azimuthal dragging velocity on each other. The cowinding rotational dynamics are accelerated upon increasing the initial density, and are similar to what observed within ultracold atom systems.

On the other hand, and unexpectedly, when the vortex cores are initially placed at short distance, we observe the onset of a radial movement too, that can be described by an effective and tunable pull-push potential, ultimately leading to peculiar scattering-like events. A deeper knowledge of vortex-vortex interactions can be useful in quantum hydrodynamics and give hints in the development of vortex-based lattices, gyroscopes, and logic devices.

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Giant optical nonlinearities from Rydberg excitons

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The realization of exciton polaritons – hybrid excitations of semiconductor quantum well excitons and cavity photons – has been of great technological and scientific significance. In particular, the short-range collisional interaction between excitons has enabled explorations into a wealth of nonequilibrium and hydrodynamical effects that arise in weakly nonlinear polariton condensates. Yet, the ability to enhance optical nonlinearities would enable quantum photonics applications and open up a new realm of photonic many-body physics in a scalable and engineerable solid-state environment. Here we outline a route to such capabilities in cavity-coupled semiconductors by exploiting the giant interactions between excitons in Rydberg states [1, 2]. We demonstrate that optical nonlinearities in such systems can be vastly enhanced by several orders of magnitude and induce nonlinear processes at the level of single photons [3].

Acknowledgements: the work presented is carried out in collaboration with Thomas Pohl, Robert Johne, Manfred Bayer and Stefan Scheel.

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Advanced modeling of a resonantly excited polariton fluid

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We will report on ongoing work in the advanced modeling of the Bogoliubov dispersion for a resonantly pumped polariton fluid in a planar semiconductor microcavity. Taking inspiration from [1], a novel experimental setup is presented and supported by a variant of the driven–dissipative Gross-Pitaevskii equation [2]. We also consider the effects due to finite pump spot and disorder.

Acknowledgements: the work presented in this poster has been done in collaboration with Petr Stepanov, Maxime Richard, Anna Minguzzi (CNRS, Grenoble) and Iacopo Carusotto (CNR, Trento).

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Synchronization in asymmetrically-pumped polariton Josephson junctions

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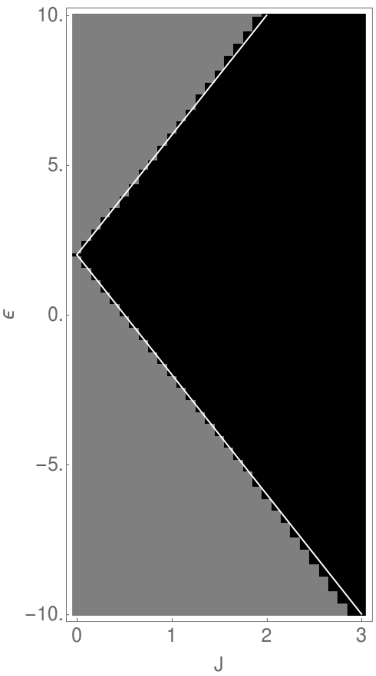
Polaritons are quantum superpositions of photons and excitons that are formed in semiconductor microcavities. Under appropriate pumping conditions they have been shown to form condensed states, characterized by macroscopic occupations of the orbitals. However, in contrast to conventional Bose-Einstein condensates such as those formed by dilute atomic gases, polariton condensates are generally out of thermal equilibrium. Typically they are steady states achieved by balancing the decay due to photons escaping the cavity with gain from optical pumping. Such nonequilibrium condensates have been described by a generalised Gross-Pitaevskii equation that incorporates gain and loss [1].

Here we consider a nonequilibrium condensate in a two-mode Josephson system, such as that formed from a spatial double well configuration with tunneling, or that formed from the two linearly polarized modes of a single spatial mode. This system has previously been shown to exhibit a phase transition from a synchronized to a desynchronized steady-state as a function of the detuning between the modes and the tunneling strength [2, 3]. We extend this work to consider the effect of asymmetric pumping on the transition. We analytically derive the phase boundary in the case of asymmetric pumping. This analysis is carried out for weak density imbalance in the Josephson regime, and we compare our results with numerical simulations. A typical phase diagram is shown in the figure. We find that imbalanced pumping is equivalent to a detuning between the two modes: thus a sufficiently large pump asymmetry can destroy the synchronization of the coupled modes. However, we show that asymmetric pumping can also compensate for detuning, establishing synchronized phases at values of coupling strength and detuning that would otherwise be desynchronized in the case of symmetric pumping.



Phase diagram of an asymmetrically pumped two-mode condensate as a function of detuning (ϵ) and tunneling strength (J). The dark region corresponds to a synchronized steady-state, and the light one a desynchronized one. The lines are analytical results for the phase boundaries. The figure is plotted in dimensionless units such that the mean amplitude-gain coefficient of the two modes is 10. Both dispersive and dissipative nonlinearities are included, in a ratio of 2:1.

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Engineering logical oscillators using two-photon blockade

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Present quantum technologies based on superconducting circuits rely on the only non-dissipative and non-linear electronic element, the Josephson junction, for manipulating quantum information[1] and engineering photon-photon interactions[2, 3]. Anharmonic Josephson circuits play a central role in implementing near term quantum computers yet suffer from limited coherence. Alternative architectures encode quantum information using microwave photons stored in superconducting resonators[4, 5] which have shown two orders of magnitude improvement in coherence[6, 7]. Since these quantum memories are harmonic, Josephson qubits are still needed for preparing and transferring quantum states[8, 9].

In this work we present a new paradigm in exploiting the Josephson non-linearity which would allow logical operations to be performed directly on the oscillator Hilbert space while still retaining improved coherence. We implement a two cavity architecture with flux-tunable inductive coupling using a superconducting quantum interference device. The coupling can be parametrically modulated to selectively activate a three wave mixing process for generating anharmonicity by strong hybridization of the two photon state. We demonstrate direct Rabi driving and measure the Wigner function of arbitrary superpositions in the single photon manifold. Measured relaxation and coherence times are limited by the resonator intrinsic losses. This architectural shift in engineering nonlinear oscillators offers potential for designing quantum networks with improved coherence.

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Vortex dynamics in exciton-polariton condensates modulated by surface acoustic waves

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Microcavity exciton-polariton condensates are low dimensional, non-equilibrium light-matter systems which support topological defects in the form of quantised vortices. The dynamics associated with these vortex defects is the paradigm for a variety of nonequilibrium phenomena, such as a topological phase transition mediated by the celebrated Berezinskii-Kosterlitz-Thouless mechanism [1]. Recent experiments [2, 3] have made it possible to periodically modulate polariton condensates via the application of surface acoustic waves across the host semiconductor microcavities. In this work we numerically study the behaviour of condensate vortices under the influence of such a periodic modulation, observing the resulting effect on spatial correlations across the condensate in relation to the geometry of surface acoustic wave.

Acknowledgements: the work presented in this poster has been done in collaboration with A. Ferrier, A. Zamora, G. Dagvadorj and M. Szymanska.

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Stabilizing zero temperature quantum phases and incompressible states of light via non-Markovian reservoir engineering

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We study the possibility of stabilizing strongly correlated quantum fluids of light in driven-dissipative devices through novel non-Markovian reservoir engineering techniques. This approach allows to compensate losses and refill selectively the photonic population so to sustain a desired steady-state. It relies in particular on the use of a frequency-dependent incoherent pump which can be implemented, e.g., via embedded two-level systems maintained at a strong inversion of population. As specific applications of these methods, we discuss the generation of a photonic Mott Insulator (MI). As a first step, we present the case of a narrowband emission spectrum and show how this allows for the stabilization of MI states under the condition that the photonic states are relatively flat in energy. As soon as the photonic bandbwidth becomes comparable to the emission linewidth, important non-equilibrium signatures and entropy generation appear, and a novel dissipative phase transition from a Mott Insulating state toward a superfluid (SF) phase is unveiled. As a second step, we present a more advanced configuration based on reservoirs with a broadband frequency distribution, and we highlight the potential of this configuration for the quantum simulation of equilibrium quantum phases at zero temperature with tunable chemical potential. As a proof of principle we establish the applicability of our scheme to the Bose-Hubbard model by confirming the presence of a perfect agreement with the ground-state predictions both in the MI and SF regions, and more generally in all parts of the parameter space.

Acknowledgements: the work presented in this invited talk has been done in collaboration with I. Carusotto, A. Biella, F. Storme, M. Wouters, D. Rossini, C. Ciuti, R. Fazio

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Towards the realization of a non-linear flat-band lattice in the microwave domain

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The aim of our work is to realize a lattice for microwave photons where one band has a flat dispersion relation and where photons interact through a Kerr term. Because the kinetic energy term vanishes for the flat band, interaction effects dominate and a large variety of many-body correlated states have been predicted in such systems [1].

Figure A shows the circuit of the lattice that we are planning to build. This is a lumped element circuit version of the Lieb lattice which is well known example of a lattice exhibiting a flat band. We envision to realize this circuit using the design shown in figure B. The sample will consist of metallic pads creating a lattice of capacitance and Josephson junctions that will realize the inductive part of the lattice. We have simulated the band structure of this design using the Sonnet software from which we extract the capacitance matrix and then calculate the complete admittance matrix. The result of the simulation is shown in figure C. We expect a flat-band with a width below 40 MHz, separated from the upper band by a gap of 210 MHz. With a non-linearity on the order of 200 MHz, we expect our system to be in the strong interacting sector.

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Figure A

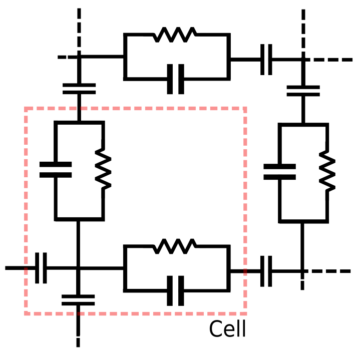


Figure C

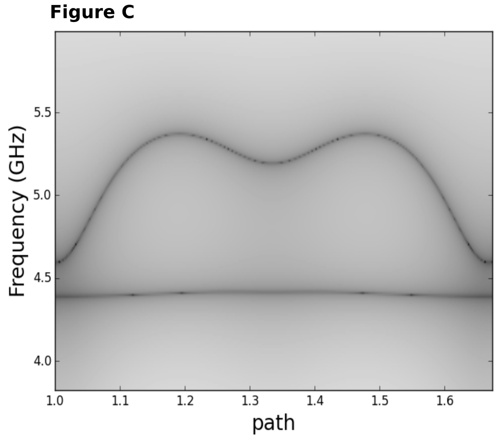
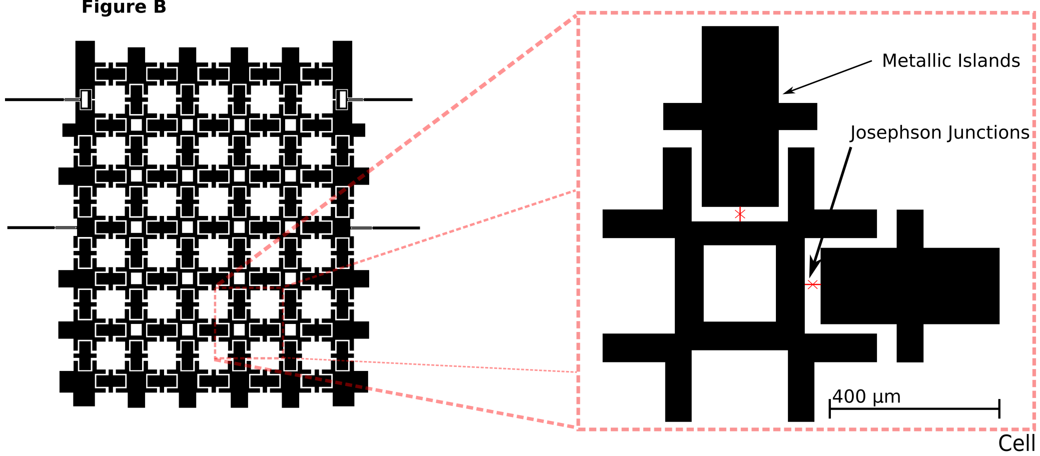


Figure B



Hydrodynamics of vortices and Ising domain walls in a resonantly pumped polariton condensate

A. Maître, G. Lerario, S. Pigeon, Q. Glorieux, E. Giacobino, A. Bramati[1]

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Almost a decade has passed since topological excitations, such as vortices and dark solitons, have been hydrodynamically generated in exciton-polariton planar microcavities.[1][2] However, the lifetime and/or the motion of these topological excitations has been limited by the experimental constraints (i.e. phase fixing when using a resonant pump and polariton lifetime in the case of transient excitation) until now.

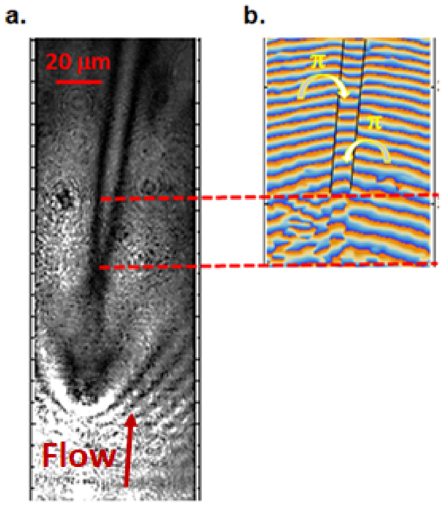

Figure a. *Space density distribution and dark soliton generation in the wake of a structural defect.* ***Figure b.*** *Phase map showing the formation of Ising walls.*

Inspired by a recent theoretical paper,[3] we experimentally engineer the spatial density distribution and in-plane velocity of resonantly-pumped polaritons. Topological excitations are generated in the wake of the structural defect when the polariton condensate is within the bistable regime. These excitations propagation is sustained by the homogeneous condensate density, therefore they can propagate for macroscopic distances, without any constraints imposed by the polariton lifetime. We observe two types of topological excitations depending on the fluid Mach number. The turbulences in the wake of the defect evolve into a pair of Ising domain walls (Figure a and b) ; or the proliferation of vortices is observed instead while decreasing the fluid velocity.

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Circuit QED : Monitoring the bath

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Understanding the way light and matter interact remains a central topic in modern physics despite decades of intensive research. At the end of the last century, the focus has been to isolate individual quantum systems (the matter) and to couple them to single electromagnetic degrees of freedom (the light), giving birth to the celebrated field of cavity quantum electrodynamics. Owing to the naturally large light-matter interaction in superconducting quantum circuit, it is now realistic to think about experiments where the actual dynamics of environments containing many degrees of freedom becomes relevant. It suggests that many-body quantum optics is within reach. Apart from quantum optics, this regime should allow us to bring new perspectives to phenomena usually observed in condensed matter physics or open quantum systems. Indeed, it is crucial for understanding these many-body systems to design experiments where the different degrees of freedom are under control, which is the case when dealing with superconducting quantum circuits. This is necessary if the different theoretical predictions are to be validated.

With this poster I will present a recent experiment [1]. The system under study consists in a single superconducting quantum bit ultra-strongly coupled to a large environment made of 4700 SQUIDs. This meta-material sustains many electro-magnetic modes. By performing microwave spectroscopy of this many-body system, we could understand in details how the qubit and its environment interact and hybridize. Thanks to a precise modelling of the system, these data can be explained by a theory without free parameters despite the fact that all the many-body ingredients are at play: non-perturbative coupling, many degrees of freedom and strong non-linearity. Finally I will also present our on-going efforts to observe many-body renormalisation in such systems and its links with dissipative quantum phase transitions.

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Vacuum-dressed vertical electron transport in a cavity-embedded heterostructure

C. Naudet-Baulieu,[1] N. Bartolo,[1] G. Orso,[1] and C. Ciuti[1]
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We present a theory for the linear electronic transport along the growth direction of an arbitrary semiconductor heterostructure coupled to a passive photonic resonator (no real photons injected).
We apply our formalism to a single cavity-embedded quantum well. The light-matter and electron-electron interactions hybridize the confined states with the continuum (delocalised) ones, leading to remarkable effects on the vertical conductance. We point out the dependance of the effects on the cavity parameters, the density of electrons per unit area and the absolute number of electrons.

Spectral theory of Liouvillians for dissipative phase transitions

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A state of an open quantum system is described by a density matrix, whose dynamics is governed by a Liouvillian superoperator. Within a general framework, we explore fundamental properties of both first-order dissipative phase transitions and second-order dissipative phase transitions associated to a symmetry breaking [1]. In the critical region, we determine the general form of the steady-state density matrix and of the Liouvillian eigenmatrix whose eigenvalue defines the Liouvillian spectral gap (see Fig. 1). We illustrate our exact results by studying the paradigmatic quantum optical models of a nonlinear Kerr resonator in the presence of coherent (one-photon) or parametric (two-photon) driving and dissipation, which are known to undergo a phase transition [2].

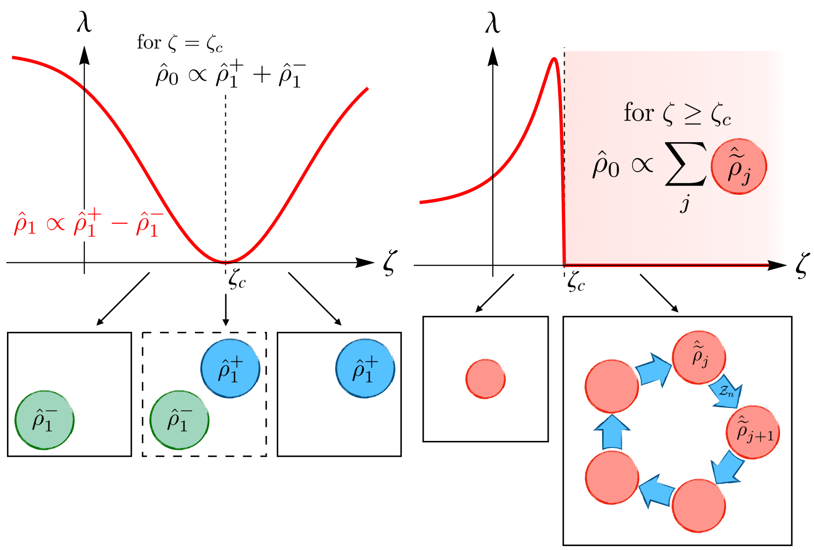

FIG. 1: Left: Sketch depicting the paradigm of a first-order dissipative phase transition. In the thermodynamic limit, the Liouvillian gap λ closes when the parameter ζ of the Liouvillian assumes the critical value ζ_c. Right before (after) the critical point, the steady-state density matrix $\hat{\rho}_{\rm ss} \simeq \hat{\rho}_1^-$ ($\hat{\rho}_{\rm ss} \simeq \hat{\rho}_1^+$), which represents one of the two different phases of the system. At the critical point $\zeta = \zeta_c$, $\hat{\rho}_{\rm ss}$ is bimodal: the steady state is a statistical mixture of $\hat{\rho}_1^+$ and $\hat{\rho}_1^-$. Right: Schematic representation of a second-order dissipative phase transition, associated to the breaking of a $\mathcal{Z}_n$ symmetry (in the sketch $n = 5$). In the thermodynamic limit, the Liouvillian gap λ closes over the whole region $\zeta \geq \zeta_c$, being ζ the critical parameter triggering the transition. When $\lambda \neq 0$ (here for $\zeta < \zeta_c$), the steady-state density matrix $\hat{\rho}_{\rm ss}$ is mono-modal. In the symmetry-broken phase ($\lambda = 0$ and $\zeta \geq \zeta_c$), $\hat{\rho}_{\rm ss}$ is an n-modal statistical mixture of density matrices $\hat{\tilde{\rho}}_j$, which are mapped one into the other under the action of $\mathcal{Z}_n$.

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Topological lasing in a 1D polariton lattice

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Recently, the exploration of topological physics in photonic structures has appeared as a promising avenue for developing novel generation of optical devices that are robust against external perturbation and fabrication defects [1]. However, due to the difficulty of implementing topological lattices in media exhibiting optical gain and/or nonlinearities, these realizations have been mostly limited so far to passive devices, such as backscattering-immune waveguides. Hence, cavity polaritons formed from the strong coupling between quantum well excitons and cavity photons are particularly appealing: their photonic part allows for engineering topological properties in lattices of coupled micropillars [2], while their excitonic part gives rise to Kerr-like nonlinearities and to lasing through coherent stimulated relaxation [3].

In this work [4], we took profit of these properties of polaritons to demonstrate the realization of a topological laser, i.e. a laser where the resonating mode is intrinsically protected against external perturbations by the underlying topology of its architecture. To do so, we used a 1-dimensional lattice of coupled micropillars where the bands formed form the coupling of the 1st excited states of each pillar (with orbital momentum $l=1$) exhibit well-defined topological properties, leading to the emergence of topological states localized at the edges of the lattice. (Fig 1 shows a SEM image of the lattice, and Fig. 2 shows a real-space image of the PL from the orbital bands where we can observe the spatial distribution of the topological mode). Then, by taking profit of the gain associated to the excitonic part of polaritons, we triggered lasing in one of these topological edge states, and demonstrated the immunity of this lasing action against optically-induced perturbations of the lattice. The most promising perspective of this work is to extend the results to 2D lattices where we envision, in systems with broken time-reversal symmetry, lasers in 1D chiral edge states allowing nonreciprocal transport of coherent light.

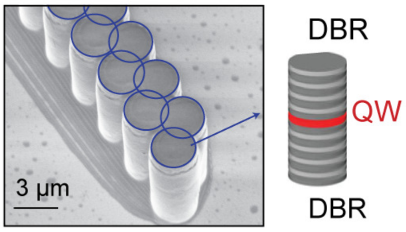

Fig. 1. (a) SEM image of the lattice corresponding to a zigzag chain of coupled micropillars. The blue circles are added for visibility. (b) Schematic representation of a pillar: several quantum well (QWs) are inserted between diffraction Bragg mirrors (DBR).

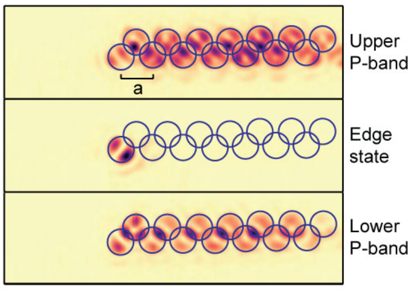

Fig. 2. Spatial image of the PL from the edge of the zigzag chain (indicated by the blue circles). The images are taken at the energies of the two p-bands (formed from bonding and anti-bonding of the 1st excited states of each pilla), and, in the middle of the orbital gap, of the topological edge state.

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Dynamical properties of critical dissipative spin lattices

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We study the dynamics of an anisotropic spin-$\frac{1}{2}$ system in presence of incoherent dissipative processes [1]. By means of stochastic quantum trajectories and matrix-product-operators simulations, we determine the time scales for the relaxation towards the nonequilibrium steady state, both in one- and two-dimensional lattices. Our results show the emergence of a critical slowing down in 2D arrays, for values of the coupling parameters where a transition from a paramagnetic to a ferromagnetic phase is expected. For 1D chains up to the thermodynamic limit, the dynamics is shown to be not critical. By tracking single stochastic quantum trajectories, we are able to get insight about the nature of the transitions and the disappearance of the ferromagnetic order in regimes of large anisotropies.

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Magneto-transport of 2DEGs ultrastrongly coupled to vacuum fields

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The second quantization of quantum field theory requires electromagnetic field excitations described as a harmonic oscillator (Photons) to be quantized. Each modes zero-point energy $E_{vac} = \frac{1}{2}\hbar\omega_{cav}$ is responsible for vacuum electric fields $E_{vac} = \sqrt{\hbar\omega/\epsilon\epsilon_0 V_{cav}}$. As such, they are responsible for the Casmir-Polder force, the Lamb shift and a non-zero spontaneous emission rate. Engineering of light-matter coupling recently gave rise to significant vacuum Rabi splittings between a matter and photon excitation. In such a regime, vacuum electric fields - despite their zero expectation value - are predicted to be observable in magneto-transport [1, 2].

Here, we present a GaAs/AlGaAs-based Hall bar inside a planar microwave cavity with a resonance at 140 GHz (see Fig. 1a). The latter couples ultra-strongly to the electrons at the Fermi energy that contribute to transport [3, 4]. We probe the changes in the longitudinal magneto-resistance $\Delta\rho_{xx}$ altered by mixed light-matter particles (polaritons) by weakly illuminating the sample with a widely tunable single frequency sub-THz source (60 GHz to 600 GHz) at temperatures of around 100 mK (see Fig. 1b). On average, the source excites only a 10 polaritons to the successive Landau level. The measurements reveal that, in contrast to the extended states at half-integer filling factors, the localised states responsible for the features of the integer quantum Hall transport only weakly couple to the vacuum field of the cavity [5], but map out polariton decay channels instead.

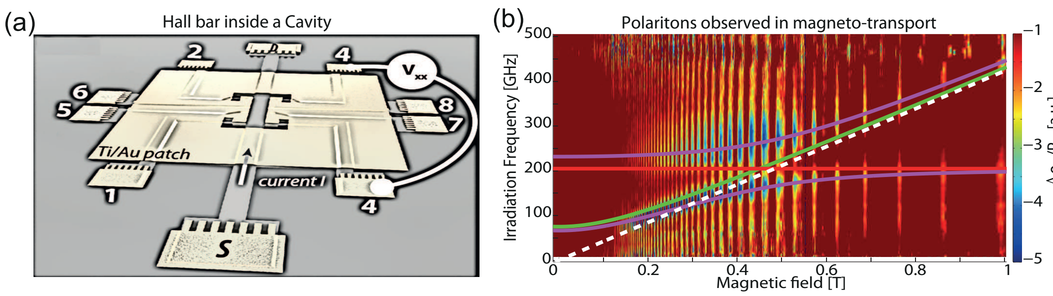

FIG. 1. a) Schematic of Hallbar inside split-ring resonator cavity whose vacuum field ultrastrongly couples the electron gas probed by magneto-transport. b) Longitudinal resistance photo response ρ_{xx}/P_{irr} to tunable single frequency sub-THz illumination reveals polariton dispersion at half-integer filling factors and polariton decay channels at integer filling factors.

As an outlook, we are currently performing experiments to manipulate the vacuum electric field in situ, in order to demonstrate the effect of vacuum electric fields on Quantum Hall transport in complete absence of a probing photons.

Acknowledgements: We thank Prof. C. Ciuti and N. Bartolo for insightful discussions and the group of Prof. K. Ensslin and Prof. T. Ihn for sharing experimental knowhow on performing magneto-transport measurements.

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Effect of Noise on Macroscopically Quantum Optomechanical Systems

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We studied an isolated optomechanical system with a macroscopic mirror [1] using a measure of macroscopic quantumness based on phase space [2]. After homodyne detection, it was found that at certain times and positions the mirror was macroscopically quantum and its state had a high value of fidelity with a Schrödinger cat state. A membrane-in-the-middle system with a quadratic interaction term was also considered [3]. We were able to find macroscopically quantum states but the fidelity with cat states was low. Our aim is now to study the effect of noise on the linear system. The evolution of the system is taken to be Markovian and to solve the master equation for the system, we will use the quantum unravelling method [4]. This involves splitting the time period into small time steps. At each time step, either the system evolves as normal with a time evolution operator or a photon is leaked into the environment. This decay occurs randomly. The solution of the master equation is found by repeating this process many times and averaging over the results.

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An orbital angular momentum microlaser with optically controlled chirality

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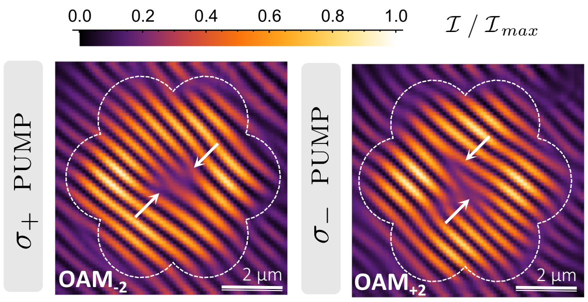
Harnessing the mechanical properties of light, e.g. its frequency, amplitude, wavevector and angular momentum, is ubiquitous in photonic technologies. Since the pioneering work of Allen et al. [1], it is well known that photons can carry an orbital angular momentum (OAM), which is an unbounded degree of freedom that appears very advantageous for applications ranging from optical manipulation [2], to sensing [3] and classical and quantum information multiplexing [4–6]. Here, we propose and demonstrate, using a fully integrated microlaser, a novel scheme based on a photonic analog of the spin-orbit interaction, to generate OAM with a chirality that can be actively controlled.

Our implementation relies on AlGaAs/InGaAs based heterostructures forming a VCSEL, subsequently dry-etched in hexagonal arrays of microresonators. In these structures, the angular momentum of photons, associated to the phase difference between the pillars, couples to their spin [7]. This spin-orbit coupling results in a photonic fine structure where modes carrying opposite OAM are now associated to orthogonal circular polarization. By spin-polarizing the gain medium, which in our system is realized (up to T = 80 K) with a circularly polarized non-resonant pump, we can selectively trigger lasing in either of these modes carrying OAM with opposite chiralities. This idea can be readily extended to other laser architectures e.g. combined with electrical spin injection, and could therefore pave the way to the realization of a wide variety of fully integrated laser sources with tunable OAM.



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Injection and manipulation of polaritons at the single particle level in microcavity-quantum well systems.

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Recently, the polaritonics field has shown to be every time more interesting with new design and realization of devices that enhance the interactions present in such kind of systems[1, 2]. These interactions could be the key to dress photons with a nonlinearity strong enough to manipulate them at the single particle level, allowing the development of a quantum Controlled NOT gate.

We have focused our efforts in the generation and manipulation of polaritons at the single particle level. We used the leading that the photonics field has in the generation, transfer and manipulation of quantum states to demonstrate that polaritons can break the classical barrier. By using a PPKTP crystal inside a Sagnac interferometer, pairs of entangled photons are generated. One of the photons is directed into a microcavity quantum well system, converted into a polaritonic excitation and detected after being re-emitted, while the other photon travels in air and is directed into the detection system. By performing quantum tomography, we prove that polaritons can be generated at a single particle level while keeping quantum correlations with the outside photon. Additionally, by putting the single excitation in presence of a bath of polaritons, we prove that the excitonic interactions taking place inside the microcavity alter the quantum properties of the entangled system[3].
The next step was to study the interactions present in the microcavity quatum well system at the two particles level. To do so, we inject pulses of polaritons that propagate along the microcavity, and post-select the cases in which only two polaritons have propagated for a certain amount of time. Excitonic interactions are expected to generate a phase shift in the full state, that is measured by mean of a quantum tomographic process.

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Vacuum-dressed cavity magnetotransport of a 2D electron gas

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Recently, a few experiments have suggested that electron transport can be modified due to the strong light-matter coupling in disordered molecular films embedded in metallic resonators [1]. A promising platform to explore cavity-embedded transport in a clear and controllable environment is offered by semiconductor 2D electron gas systems [2]. Within this scenario, we address the question of whether and how a passive cavity resonator, in which no real photon is injected nor created, can modify the electronic transport properties [3]. We present a general analytic theory showing that, for a cavity photon mode with in-plane polarization, the dc bulk magnetoresistivity of the 2D electron gas becomes anisotropic. In the regime of high filling factors of the Landau levels, the envelope of the Shubnikov-de Haas oscillations is profoundly modified. In the limit of low magnetic fields, the resistivity along the cavity-mode polarization direction is enhanced in the ultrastrong light-matter coupling regime.

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