WQED23

3rd WORKSHOP ON WAVEGUIDE QED

May 8-13, 2023, Erice, Italy

BOOK OF ABSTRACTS

UNIVERSITÀ DEGLI STUDI DI PALERMO

Duke UNIVERSITY

Technische Universität München

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About WQED23

Scope

The emerging field of Waveguide Quantum ElectroDynamics (WQED) investigates the coherent coupling between quantum emitters and photonic waveguides or other engineered photonic environments. The WQED workshop series aims to bring together leading experts in this field. WQED23 is the 3rd edition of the series, the previous two editions were held in 2018 in Mazara del Vallo (see `https://wqed18.weebly.com`) and in 2021 (online, see `https://wqed20.weebly.com`).

WQED23 will be hosted by the Ettore Majorana Foundation and Centre for Scientific Culture in Erice, Italy, and in particular within the "School of Non-equilibrium Phenomena" having as scientific directors Alessandra Lanzara (Berkeley), Massimo Palma (University of Palermo) and Bernardo Spagnolo (University of Palermo).

Erice

Erice is a charming town located on a mountain top in western Sicily, providing a stunning backdrop for anyone looking to engage in cutting-edge research or explore the town's rich history and unique character. The town's winding cobblestone streets, ancient stone buildings, and breathtaking panoramic views of the sea and surrounding hills attract tourists from around the world.

One of Erice's most famous landmarks is the Norman-era Castle of Venus, which dates back to the 12th century and offers stunning views of the surrounding countryside. The town is also home to several beautiful churches, including the Chiesa Madre, a stunning Gothic church built in the 14th century. Visitors can stroll through the town's picturesque alleyways, admire the traditional architecture, and soak up the town's relaxed atmosphere. Erice's reputation as a hub of scientific activity, as well as its rich history and unique character, make it a must-see destination for anyone visiting Sicily.

Scientific organizing committee

Francesco Ciccarello	NEST Istituto Nanoscienze-CNR & University of Palermo, Italy
Harold U. Baranger	Duke University, USA
Peter Rabl	TU Munich / Walther-Meißner-Institute, Germany
Darrick Chang	ICFO, Spain

Local Organizer: Marcel Pinto, University of Palermo, Italy

Program

WQED23

Program

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11.20	Oliver Giant Artificial Atoms and Waveguide QED	11.50	Florens Quantum simulators in Josephson waveguides	11.40	Poddubny Multiple-excited subradiant states	11.40	Jordan Quantum information and energy exchange in cQED
11.50	Ustinov Slowing down microwave photons with superconducting qubits	12.20	Zueco Waveguide QED in the dipole gauge	12.10	Alaeian From Dipolar to Rydberg Photonics	12.10	Calajò Interacting photons in 2D waveguide QED
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15:30	Wallraff Loophole-free Bell Inequality Violation with Superconducting Circuits			16.20	Coffee Break	16.20	60th birthday of Massimo Palma
16.00	Felicetti Waveguide QED with Quadratic Light-Matter Interactions			16.50	Gonzalez-Tudela Opportunities in waveguide QED simulators	16.50	Closing remarks
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Abstracts of Talks

CT Contributed Talk, IT Invited Talk.

Hadiseh Alaeian, Purdue University IT

From Dipolar to Rydberg Photonics

Strong light-induced interactions between atoms lead to nonlinearities at a few-photon level which is crucial for applications in quantum information processing. Such interactions give rise to density shifts and broadenings, and when confined to less than a wavelength size, they lead to collective blockade phenomena, mostly studied in the context of strongly interacting Rydberg states. Here we combine the high densities achievable in atomic vapors with an efficient coupling to a slot waveguide. In contrast to free-space interactions, atoms aligned within the slot exhibit repulsive interactions that are enhanced by the Purcell effect. The corresponding blueshift of atoms arranged in this 1D geometry vanishes above the saturation, providing a controllable nonlinearity at the few-photon level. Later, I will introduce our novel platform in thin-film cuprous oxide, which allows us to realize strongly interacting Rydberg excitons in solid states. The results of these studies pave the way towards a robust scalable platform for quantum nonlinear chiral optics and all-optical quantum information processing in an integrable and scalable platform, and potentially at elevated temperatures.

Aamir Ali, Chalmers University of Technology CT

Waveguide quantum thermodynamics

Quantum thermodynamics should become more useful. The field has yielded fundamental insights, but realistic demonstrators are lacking, which hinders applications. I will introduce a comprehensive platform for experiments in quantum thermodynamics with superconducting circuits, combining the established capabilities of circuit quantum electrodynamics with the use of thermally populated microwave waveguides as heat baths. As an example, I will present an experiment in which a superconducting quantum bit (qubit) is autonomously reset by a quantum absorption refrigerator. The refrigerator is integrated on the same chip as the qubit and connected to a hot and to a cold waveguide. The reset mechanism is activated by the temperature of the hot waveguide, which effectively controls the lifetime of the qubit. We demonstrate that this scheme outperforms passive thermalization to either the cold waveguide or the qubit's own bath. We believe that this is just the first example of a practical application of quantum thermodynamics.

Francesco Andreoli, ICFO

CT

The maximum refractive index of an atomic crystal

All known materials have an index of refraction of order unity. Despite the implications that an ultrahigh index material could have for optical technologies, little research has been done on why the index is universally small. Here, we describe insights in this direction, by posing a slightly different problem - what is the largest refractive index that one can expect from an ordered arrangement of atoms. We shown that, as long as the inter-atomic interactions are only mediated by multiple scattering, the system exhibits a lossless, single-mode response, which builds up a very large and purely real refractive index. To address the limits to this picture, we extend our analysis to higher densities, where the electronic orbitals on neighboring nuclei begin to overlap. We develop a minimal model to include the onset of this quantum-chemistry regime into our non-perturbative analysis of multiple light scattering, arguing that this effectively suppresses the single-mode response, decreasing the index back to unity. Nonetheless, right before the onset of chemistry, our theory predicts that an ultra-high index n 30 and low-loss material could in principle be allowed by nature.

Iñigo Arrazola, TU Wien

CT

High-fidelity phonon-mediated spin-spin interactions with SiV centers

We propose and analyse the implementation of high-fidelity, phonon-meditated gate operations and quantum simulation schemes for spin qubits associated with silicon vacancy centers in diamond. Specifically, we show how the application of continuous dynamical decoupling techniques can substantially boost the coherence of the qubit states while increasing at the same time the variety of effective spin models that can be implemented in this way. Our detailed analytical and numerical simulations show that this technique can be used to suppress gate errors by more than two orders of magnitude and to reach gate infidelities of 10-4 for experimentally relevant noise parameters.

Ana Asenjo-Garcia, Columbia University

IT

Many-body decay in waveguide QED

The many-body decay of extended collections of two-level systems remains an open problem. Here, I will discuss the conditions for an array of qubits coupled to a one-dimensional bath to undergo Dicke superradiance, a process whereby a completely inverted system self-organizes as it decays, generating correlations between qubits via dissipation. This leads to the release of all the energy in the form of a rapid photon burst. Many-body superradiance occurs because the initial fluctuation that triggers the emission is amplified through the decay process. I will show that this avalanche-like behavior leads to a dynamical spontaneous symmetry breaking, where most photons are emitted into either the left- or the right-propagating optical modes, giving rise to an emergent chirality. Superradiant bursts may be a smoking gun for the generation of correlated photon states of exotic quantum statistics. This physics can be explored in diverse setups, ranging from atoms close to nanofibers to superconducting qubits coupled to transmission lines.

Matteo Brunelli, University of Basel

CT

Dissipative generation of multi-mode Schrödinger cat states in circuit QED

Schrödinger cat states are a fundamental resource for quantum communication, quantum computation and quantum metrology. The potential for applications of Schrödinger cat states arguably increases when considering extensions to multiple modes. However, the preparation of cat states beyond single mode remains challenging. In this contribution I will illustrate how to dissipatively generate multi-mode cat states in a scalable fashion in driven-dissipative cavity arrays, in the form of a decoherence-free subspace spanned by multi-mode Schrödinger cat states. These states are multi-photon and multi-mode quantum superpositions of coherent states in a single normal mode, i.e., delocalized over an arbitrary number of cavities. The main idea consists in upgrading dissipation engineering from a single mode to a collective mode (normal mode) of dissipatively coupled arrays of nonlinear resonators. I will present two closely related models that are readily realizable with superconducting circuits, involving resonators that are parametrically driven and feature an on-site nonlinearity, which is either a Kerr-type nonlinearity or an engineered two-photon loss.

P. Zapletal, A. Nunnenkamp, and M. Brunelli PRX Quantum 3, 010301 (2022).

Amir Burshtein, Tel Aviv University

CT

Inelastic decay from integrability

Recent experiments in circuit QED setups have demonstrated the high probability splitting of single-photons, a phenomenon rarely observed in nature. This exotic effect is enabled by a high-impedance Josephson transmission line which increases the effective coupling of the microwave photons to an artificial atom, and provides a useful tool to probe fundamental phenomena in many-body systems. I will a discuss a collaboration with the Manucharyan group, in which we utilized single-photon splitting to observe the Schmid-Bulgadaev quantum phase transition, whose lack of clear evidence has sparked a recent debate. The experimental system realizes the boundary sine-Gordon model, which is known to be integrable and is characterized by purely elastic scattering of elementary excitations, that seems at odds with photon splitting. I will show that a nonlinear relation between these excitations and the photons not only allows for inelastic decay of the latter, but also that integrability provides powerful analytical tools yielding exact results for the total inelastic decay rate and the spectrum of the resulting photons. These results compare nicely with measurements by the Manucharyan group.

Giuseppe Calajò, INFN-Padova IT

Interacting photons in 2D waveguide QED

One dimensional confinement in waveguide QED plays a crucial role to enhance light-matter interactions and to induce strong quantum nonlinear optical effects. In higher dimensions such response is reduced by the fact that photons emitted into random directions prevents efficient interactions between emitters. Indeed, unlike the infinite range photon-mediated interactions between the emitters in 1D, in the 2D case the interactions decay as the square root of the distance between the atoms. In this talk we show that, by considering an ordered array of atoms coupled to a two dimensional waveguide, strong photon-photon interactions can be observed. In particular, by employing a minimal model assuming isotropic emission and Markov approximation, we demonstrate the existence of two-photon bound states as a paradigmatic signature of the presence of photon interactions in the system.

Aashish Clerk, University of Chicago IT

Many-qubit entanglement and dissipative spin chain physics using waveguide QED

There are by now many proposals for how to use the collective dissipation generated by a waveguide to prepare and stabilize entangled states of two distant qubits. I'll discuss recent work showing how these ideas can be extended to a many-body setting, where two distant chains of qubits interact via a single common waveguide. Despite only using local Rabi drives on two qubits (and no squeezed light), pure N-qubit entangled states can be stabilized over a wide range of parameters. Even though the system does not have integrable dynamics, we are able to derive an exact description of its dissipative steady state. This state has a number of remarkable many-body features, including emergent pairing correlations somewhat reminiscent of eta-pairing in fermionic Hubbard models. The system we describe is compatible with a number of experimental platforms, including superconducting qubits.

Daniele De Bernardis, Pitaevskii BEC Center, CNR-INO and Dipartimento di Fisica, Università di Trento IT

Chiral quantum optics in the bulk a photonic quantum Hall system

We study light-matter interactions in the bulk of a two-dimensional photonic lattice system where photons are subject to the combined effect of a synthetic magnetic field and an orthogonal synthetic electric field. In this configuration, chiral waveguide modes appear in the bulk region of the lattice, in direct analogy to transverse Hall currents in electronic systems. By evaluating the non-Markovian dynamics of emitters that are coupled to those modes, we identify critical coupling conditions under which the shape of the emitted photons becomes almost fully symmetric. Combined with the directionality, this property enables a complete reabsorption of the photon by another distant emitter, without any time-dependent control. We show that this mechanism can be generalized to arbitrary in-plane synthetic potentials, thereby enabling flexible realizations of re-configurable networks of quantum emitters with arbitrary interconnectivity.

Simone Felicetti, Istituto dei Sistemi Complessi CNR-ISC CT

Waveguide QED with Quadratic Light-Matter Interactions

Quadratic light-matter interactions are nonlinear couplings such that quantum emitters interact with photonic or phononic modes exclusively via the exchange of excitation pairs. Implementable with atomic and solid-state systems, these couplings lead to a plethora of novel phenomena that have recently been characterized in the context of cavity QED, where quantum emitters interact with localized bosonic modes. Here, we explore for the first time quadratic light-matter interactions in a waveguide QED setting. We present a general scattering theory under the Markov approximation and discuss paradigmatic examples. Our analytical and semi-analytical results unveil fundamental differences with respect to conventional waveguide QED systems. This novel phenomenology unlocks new opportunities in quantum information processing with propagating photons. As a striking example, we show that a single quadratically-coupled emitter can implement a two-photon logic gate with unit fidelity, circumventing a no-go theorem derived for conventional waveguide-QED interactions.

Igor Ferrier-Barbut, Institut d'Optique CNRS IT

Laser-driven superradiant atomic ensembles

We study collective spontaneous emission in dense ensembles of two-level atoms, that are indistinguishably coupled to a mode of the electromagnetic field, akin to cavity or waveguide QED systems but here in free space. I will discuss our studies of the systems behaviour when continuously driven by a resonant laser that leads to a competition between laser driving and collective spontaneous emission. In a configuration that realizes a textbook model of a driven-dissipative many-body system, we observed that this competition induces a transition to a steady-state superradiant phase. Beyond measuring the field intensity, we measure photon-photon correlations. This precious tool of quantum optics allows us to question wether atomic correlations can impart non-trivial photonic correlations. I will show that indeed photonic correlations emerge, and despite the system's simplicity, their description poses a challenge to many-body theories.

Serge Florens, NEEL Institute - CNRS IT

Quantum simulators in Josephson waveguides

Superconducting Josephson waveguides are seen as a promising platform for engineering quantum many-body states.We investigate both experimentally and theoretically the possibility to realize dissipative models in the ultra-strong coupling regimes of quantum electrodynamics, equivalent to boosting the fine structure constant close to unity. As a result, we evidence several interaction-driven effects that represent two sides of the same coin: i) a giant renormalization of the frequency of a superconducting qubit by vacuum fluctuations of the quantum fields in the waveguide; ii) a broadband inelastic scattering of the external photons by the internal non-linear dynamics of the qubit. We discuss also critically the advantages and limitations of superconducting circuits for the exploration of many-body phenomena.

Juan José García-Ripoll, IFF-CSIC

IT

Waveguide-QED as quantum links between quantum computers

In this talk I will review our work on the engineering and realistic modelization of state transfer protocols for quantum computers that are linked by photonic (microwave) waveguides. I will present the motivation, basic quantum optical models, and tools to engineer single-qubit state transfer, including new controls that correct for incoherent imperfections in the waveguide, beyond standard input-output theory. I will also discuss the multiplexing of state-transfer, frequency and mode-based, and our effort towards analyzing the information capacity of these channels.

Eva María González-Ruiz, Niels Bohr Institute, University of Copenhagen

CT

Entanglement properties of a quantum-dot biexciton cascade in a chiral nanophotonic waveguide

We analyse the entanglement properties of deterministic path-entangled photonic states generated by coupling the emission of a quantum-dot biexciton cascade to a chiral nanophotonic waveguide, as implemented by Østfeldt et al. [PRX Quantum 3, 020363 (2022)]. We model the degree of entanglement through the concurrence of the two-photon entangled state in the presence of realistic experimental imperfections. The model accounts for imperfect chiral emitter-photon interactions in the waveguide and the asymmetric coupling of the exciton levels introduced by fine-structure splitting along with time-jitter in the detection of photons. The analysis shows that the approach offers a promising platform for deterministically generating entanglement in integrated nanophotonic systems in the presence of realistic experimental imperfections.

Alejandro Gonzalez-Tudela, Instituto de Física Fundamental-CSIC

IT

Opportunities in waveguide QED simulators

Recent experimental advances integrating natural and artificial emitters with waveguides made by microwave metamaterials [1], dielectric photonic crystals [2], or matter-waves [3] has made waveguide QED an experimental platform ripe for developing novel quantum technologies. Among other potentialities, these setups can be used to engineer tunable-range emitter interactions when interacting with photonic band-gap materials. In this talk, we will overview how these waveguide QED simulators can be used to engineer unconventional photon-mediated interactions using giant atoms [4], to probe topological many-body phases [5], or to improve the performance of certain variational quantum algorithms [6].

[1] Phys. Rev. X 12, 031036 (2022); [2] Science, 379, 6630, pp. 389-393 (2023); Phys. Rev. X 11, 031021 (2021); . Phys. Rev. Lett. 124, 063602 (2020) [3] Nature 559, 589–592 (2018). [4] Phys. Rev. Lett. 122, 203603 (2019) [5] Science advances 5 (7), eaaw0297 (2019); PRX Quantum 3, 010336 (2022) [6] arXiv:2302.01922

Alexey Gorshkov, NIST and University of Maryland IT

Quantum optics with photonic and atomic crystals

First, we will discuss ultrastrong coupling between a fluxonium qubit and a one-dimensional photonic crystal. In particular, we will show, both theoretically and experimentally, that the transport of a single photon in this regime is strongly modified by the presence of multi-photon bound states. Second, we will discuss an interplay between collective behavior of ordered atomic arrays and optical nonlinearities of Rydberg systems. In particular, we will propose a protocol for quantum non-demolition photon counting in a 2D Rydberg atom array.

Mohammad Hafezi, Joint Quantum Institute, University of Maryland IT

Optical manipulation of topological and correlated states of electrons

I will discuss recent theoretical and experimental developments in our group in optical probing and manipulating correlated states of electrons in two-dimensional systems. (a) investigation of fermionic and excitonic Mott insulators in moire lattices, (b) beyond dipole approximation physics and its implications in quantum Hall and superconducting systems.

Chen-Lung Hung, Purdue University IT

Coupling single atoms to a nanophotonic whispering-gallery-mode resonator

Integration of cold neutral atoms with nanoscale photonics has become a new paradigm as a light-matter interface in the settings of cavity and waveguide QED. New opportunities are enabled by advances in nanophotonic engineering, as well as cooling and trapping single to an array of atoms near nanoscale dielectrics to realize scalable and efficient atom-light interactions. In this talk, I will discuss our successful realization of large cooperative coupling of single atoms to a nanophotonic whispering-gallery-mode resonator using optical guiding and conveyor-belt transport methods, with which we observed efficient chiral atom-photon coupling to a whispering gallery mode and nonclassical on-chip photons routed by single atoms. I will discuss prospects of using cavity cooling with an evanescence pump field to directly capture single atoms in a nearfield optical microtrap, and possible extensions to atom array trapping. Our realization paves a way towards new applications utilizing trapped atoms on a nanophotonic circuit for quantum optics and many-body physics.

Andrew Jordan, Chapman University IT

Quantum information and energy exchange in cQED

I will present how the use of quantum, coherent, and classical thermal states of light in a circuit quantum electrodynamics setup impacts the performance of quantum measurements, by comparing their respective measurement backaction and measurement signal to noise ratio per photon. When investigating the energy change of the measurement apparatus when a qubit is measured in bases that do not commute with energy, I will demonstrate that the drive's energy change associated with the measurement backaction can exceed by far the energy that can be extracted by the qubit. Supporting experimental data will be shown.

Alicia Kollár, University of Maryland and JQI IT

Engineering Qubit-Qubit Interactions in Circuit QED Lattices

The inherent strong coupling between microwave resonators and superconducting qubits available in the circuit QED architecture makes it possible to use the spectrum of multimode photonic environments to engineer qubit-qubit interactions. Previously, one-dimensional cavity arrays and modulated waveguides have been used to induce exponentially-localized interactions. Lattices of coplanar waveguide resonators realize artificial photonic materials that provide a tailored environment for with versatile control. Qubits in these lattices experience a photon-mediated flip-flop interaction, which takes on different forms depending on the structure of the lattice, giving rise to a direct hardware-level implementation of a graph-like spin model with connections determined by the microwave resonator network. Here we present results towards realizing a larger variety interactions, such as frustrated interactions, in which different terms compete and favor different configurations, allowing a spin model to exhibit memory, and hyperbolic interactions, which lead to rapid growth of connectivity and efficient connections.

Alfonso Lanuza, Stony Brook University, NY, USA CT

Analysis of matter-wave decay into an optically structured vacuum

Ultracold atoms in state-selective optical lattices constitute an unconventional platform to study waveguide QED [1,2], characterized by full tunability (including adiabatic control), slow dynamics, momentum-state measurability of both emitters and radiation, and infinite Purcell factor. In this talk we give an analytical description of such systems [3] that addresses important questions such as the retardation between emitters, the interplay between emitter size and the wavelength of the emitted radiation, and their precise positioning.

Work supported by NSF PHY-1912546/2208050

[1] L. Krinner, et al., Nature 559, 589 (2018). [2] M. Stewart, J. Kwon, A. Lanuza, D. Schneble, Phys. Rev. Research 2, 043307 (2020). [3] A. Lanuza, J. Kwon, Y. Kim, D. Schneble, Phys. Rev. A 105, 023703 (2022).

Julien Laurat, Sorbonne Université IT

Quantum optics with cold atoms trapped along nanowaveguides

Considerable efforts have been recently devoted to combining cold atoms and nanophotonic devices to obtain not only better scalability and figures of merit than in free-space implementations, but also new paradigms for atom-photon interactions. In the talk, I will present our efforts in this neutral-atom waveguide-QED field of research. Using nanofiber trapped atoms, we demonstrated the capability to herald, store and read out a single collective excitation that is preferentially coupled to the guided mode. In this nanofiber setting, using a dynamically-controlled Bragg configuration, we also recently pushed the non-linearity down to the few-photon level. I will then describe our works towards stronger coupling in single pass by using photonic-crystal slow-mode waveguides with engineered dispersion. Localizing and trapping atoms in the proximity is a strong challenge and I will describe how novel structures and optical techniques can be used.

Peter Lodahl, Niels Bohr Institute, University of Copenhagen IT

Waveguide QED with quantum dots

We review recent progress on waveguide QED with solid-state quantum dots embedded in nanophotonic waveguides. The high quantum cooperativity of a waveguide photon-emitter interface enables a range of new opportunities in quantum optics. We discuss the realization of deterministic single-photon sources, multi-photon entanglement sources based on spin-photon entanglement, and the observation of collective super- and sub-radiance of multiple quantum dots. Finally we discuss possible applications of this novel hardware for photonic quantum computing and quantum communication.

Klaus Moelmer, Niels Bohr Institute IT

Flying and stationary qubits – an open systems approach

With the scaling of quantum technologies to many separate material quantum components, we may have recourse to couple these systems by quantum radiation of light, microwaves or phonons. In future optical quantum processors, we may, conversely, need to manipulate the quantum states of radiation pulses by their interaction with non-linear stationary quantum components. Several physical processes have been proposed and already demonstrated for these tasks. There are, however, rather fundamental obstacles to, e.g., merely interchange flying and stationary qubits in circuits for quantum computing. These obstacles include the general multimode character of propagating fields and the duration and spatial extent of useful light and microwave pulses. The talk will review recent developments of a cascaded master equation approach to deal theoretically with these obstacles, and it will present examples of new, unforeseen, possibilities for preparation and manipulation "on the fly" of quantum states of light and matter.

Yasunobu Nakamura, RIKEN Center for Quantum Computing IT

Intrinsic Purcell filters and their applications in cavity and waveguide QED

Superconducting quantum circuits provide a versatile platform for cavity and waveguide quantum electrodynamics. To maintain the coherence of a qubit while allowing strong dispersive/parametric interaction with a cavity and a waveguide connected to the cavity, we implement a notch-type Purcell filter based on the multi-mode nature of the cavity [1]. By using the setup, we demonstrate fast, high-fidelity readout and reset of a qubit using the so-called f0g1 drive. We also use the device for the deterministic generation of single microwave photons with tunable frequency and temporal modes in the waveguide. Generation and characterization of entangled photonic states in the waveguide are also demonstrated.

[1] Y. Sunada et al., Physical Review Applied 17, 044016 (2022).

Sile Nic Chormaic, OIST Graduate University IT

Optical nanofibres and nanofibre-based cavities

The use of optical nanofibres, that is silica optical fibres with subwavelength diameter, in quantum systems is already well-demonstrated with a large number of theoretical and experimental studies reported during the last two decades. Optical nanofibres can provide very high intensity electric fields with a very steep field gradient at their surface. Such an electric field can be used to study spin-selection rules in single-frequency, two-photon excitation via non-paraxial light or electric quadrupole excitations in atomic systems. It is possible to further engineer the optical nanofibre in order to fabricate nanofibre-based cavities. We will discuss several designs of cavities which can be viewed as external or internal to the optical nanofibre. We will present recent work on a Fabry-Perot type cavity containing a higher-order mode optical nanofibre and how the optical field seems to support polarisation singularities.

William Oliver, MIT IT

Giant Artificial Atoms with Waveguide QED

In this talk, we present a demonstration of "giant artificial atoms" realized with superconducting qubits in a waveguide QED architecture. The superconducting qubits couple to the waveguide at multiple, well-separated locations. In this configuration, the dipole approximation no longer holds, and the giant atom may quantum mechanically self-interfere. This system enables tunable qubit-waveguide couplings with large on-off ratios and a coupling spectrum that can be engineered by design. Multiple, interleaved qubits in this architecture can be switched between protected and emissive configurations, while retaining qubit-qubit interactions mediated by the waveguide. Using this architecture, we generate a Bell state with 94% fidelity, despite both qubits being strongly coupled to the waveguide. We furthermore use an artificial molecule comprising two qubits to demonstrate directional photon emission with 97% fidelity (a chiral waveguide). Such waveguide QED technologies are applicable to quantum interconnects and support architectural modularity.

Saverio Pascazio, Physics Department, University of Bari IT

Finite-size effects and multimerization in an array of emitters coupled to a waveguide

We consider a system of two-level quantum emitters coupled to a closed waveguide, in different geometries. Photon wavenumbers and frequencies are discretized, and we look at states in which one excitation is shared between the field and the emitters. We focus on the relaxation towards bound states, entanglement generation, correlated emissions, and multimerized bound states for multi-emitter arrays.

Alexander Poddubny, Weizmann Institute of Science IT

Multiple-excited subradiant states

Emergence of waveguide quantum electrodynamics has stimulated interest to the classical problem of quantum optics: enhancement and suppression of spontaneous emission via constructive and destructive interference of photons from different emitters. Subradiant states, that form because of such destructive interference, promise applications for quantum information processing and also provide important insights into the physics of collective light-matter interactions. In this talk I will try to review recent theoretical and experimental progress in the studies of subradiant states in the waveguide setup. I will start with the basic concepts of wave interference, that enable explanation of formation of subradiant states in periodic one-dimensional atomic arrays in the single-photon regime. Next, I will discuss multiple-excited subradiant states and subradiant states in the strongly driven systems. I will demonstrate that the dependence of the lifetime of the correlations on the driving strength and the array period can be strongly nonmonotonous and is very sensitive to the details of many-body interactions in the array.

Diego Porras, Instituto de Física Fundamental, CSIC IT

Topological amplification in quantum driven-dissipative chains

Quantum non-reciprocal lattices can exhibit topological phases in which they behave as directional amplifiers [1]. The connection between non-reciprocal systems and topological insulators can be formalized by studying the singular values of the non-Hermitian Hamiltonian, which turn out to reveal non-trivial topological phases by the appearance of zero-singular value modes. The latter are the dissipative counterpart of zero-energy edge states in condensed matter systems. We have shown that topological amplification can be observed in parametrically coupled chains of oscillators, which can be implemented in the quantum regime with superconducting circuits, trapped ions and optomechanical systems [2]. We have applied our ideas to the design of a quantum limited broadband amplifier with superconducting circuits, where topological amplification is induced by cross-Kerr interactions [3].

[1] T. Ramos et al., Phys. Rev. A 103, 033513 (2021) [2] A. Gómez-Leon et al, arXiv:2207.13715 [3] T. Ramos et al., arXiv:2207.13728

Kazi Rafsanjani Amin, Chalmers University of Technology CT

Quasiparticles in Superconductor, real-time detection using transmon coupled to a Waveguide

Quasiparticles (QP) have been routinely observed to be present in superconducting islands at temperatures well below the superconducting transition temperature, with a density several orders of magnitude larger than expected thermal distribution. This puzzle has been an active topic of research since last decade. QP tunnel through Josephson-junctions, a major component of superconducting quantum processing units, resulting in decoherence, and dephasing of quantum states in such devices, degrading their performance. Hence study of QP tunneling and their dynamics is of extreme importance. In this work, in a waveguide quantum electrodynamics (QED) setup, we strongly couple a charge-sensitive superconducting qubit to a waveguide and observe QP tunneling events in real-time. A second charge-insensitive qubit, strongly coupled to the waveguide, is used to measure the field temperature in the waveguide. Combining these two, we study timescale of thermalization of radiation field and equilibration of QP tunneling, immediately after using a cryogenic mechanical switch to toggle measurement lines inside our cryostat. We also observe pump induced enhancement of QP tunneling rates.

Arno Rauschenbeutel, HU Berlin IT

Observation of superradiant bursts in waveguide quantum electrodynamics

Dicke superradiance describes the collective decay dynamics of a fully inverted ensemble of two-level atoms. There, the atoms emit light in the form of a short, intense burst due to a spontaneous synchronization of the atomic dipoles. Here, here we experimentally observe superradiant burst dynamics with a one-dimensional ensemble of atoms where the interatomic distance exceeds the emission wavelength. This is enabled by coupling the atoms to a nanophotonic waveguide, which mediates long-range dipole-dipole interactions between the emitters. We excite the atoms by a resonant, fiber-guided probe pulse that is much shorter than the excited state lifetime. We realize strong inversion and study the subsequent radiative decay into the guided modes. The burst occurs above a threshold atom number, and its peak power scales faster with the number of atoms than in the case of standard Dicke superradiance. Moreover, we study the coherence properties of the burst and observe a sharp transition between two regimes: in the first, the phase coherence between the atoms is seeded by the excitation laser. In the second, it is seeded by vacuum fluctuations.

Sylvain Ravets, Université Paris-Saclay, CNRS, Centre de Nanosciences et de Nanotechnologies (C2N), 91120, Palaiseau, France

IT

Kardar-Parisi-Zhang universality in a one-dimensional polariton condensate

Cavity polaritons are exciton-photon quasi-particles emerging from the strong coupling between cavity photons and quantum well excitons. From the photon part, they inherit a small effective mass and can be confined in micron-sized lattices. The excitonic part provides inter-particle (Kerr non linearity). Cavity polaritons exhibit fascinating properties such as Bose Einstein condensation at elevated temperature, superfluidity, multistability. Importantly, the system is driven-dissipative: the driving field maintains an out-of-equilibrium steady-state by compensating photon losses. Remarkably, the phase dynamics of out-of-equilibrium condensates obeys the Kardar Parisi Zhang (KPZ) equation. In this talk, I will present our recent experimental observation of universal KPZ scaling laws in the first order coherence of a 1D polariton condensate. I will first explain how we generated highly elongated polariton condensates in a 1D polariton lattice. I will then report on our measurements of the condensate coherence. Finally, I will show that data points lying within a well-defined spatio-temporal window collapse onto a single scaling function, characteristic of the KPZ universality class.

Federico Roccati, University of Luxembourg

CT

Hermitian and Non-Hermitian Topology from Photon-Mediated Interactions

Light can mediate second-order effective interactions between atoms or emitters. In this context, a long-term endeavour is to find general criteria to tailor a photonic environment that mediates a desired effective atomic Hamiltonian. Among these criteria, topological properties are of utmost importance since an effective atomic Hamiltonian endowed with a non-trivial topology can be protected against disorder and imperfections. I will present general results ruling the topological properties (if any) of photon-mediated Hamiltonians in terms of both Hermitian and non-Hermitian topological invariants. For a photonic lattice where each mode is coupled to a single quantum emitter, we link the topology of the atoms to that of that of the photonic bath: we unveil the phenomena of topological preservation and reversal. For example, the bulk-edge correspondence implies the existence of atomic boundary modes with group velocity opposite to the photonic ones in a 2D Hermitian topological system. When there are fewer emitters than photonic modes, the atomic system is less constrained and no general photon-atom topological correspondence can be found.

Nicolas Roch, Institut Néel, CNRS

IT

Josephson waveguides: a new platform for quantum optics

Josephson waveguides have recently emerged as very promising platform for superconducting quantum science and technologies. Their distinguishing potential resides in ability to engineer them at sub-wavelength scales, which allows complete control over wave dispersion and nonlinear interaction. In this talk I will discuss a Josephson waveguide with strong third order nonlinearity, which can be tuned from positive to negative values, and suppressed second order non-linearity. As first implementation of this versatile meta-material, we operate it to demonstrate a novel reversed Kerr phase-matching mechanism in traveling wave parametric amplification. In a second part, I will report on our observation of broadband vacuum two-mode squeezing in these Josephson waveguides. Besides such advances in amplification performance and the generation of broadband squeezing, Josephson meta-materials open up exciting experimental possibilities in the general framework of microwave quantum optics, single-photon detection and quantum limited amplification.

Rocío Sáez-Blázquez, TU Wien

CT

Non-perturbative vacuum shifts in cavity QED

We address the fundamental question whether or not it is possible to achieve conditions under which the coupling of a single dipole to a strongly confined electromagnetic vacuum can result in non-perturbative corrections to the dipole's ground state. To do so we consider two simplified, but otherwise rather generic cavity QED setups, a lumped-element LC-resonator and a plasmonic nanocavity, which allow us to derive analytic expressions for the total ground state energy and to distinguish explicitly between purely electrostatic and genuine vacuum-induced contributions. Importantly, this derivation takes the full electromagnetic spectrum into account while avoiding any ambiguities arising from an ad-hoc mode truncation. Our findings show that while the effect of confinement per se is not enough to result in substantial vacuum-induced corrections, the presence of high-impedance modes, such as plasmons or engineered LC-resonances, can drastically increase these effects. Therefore, we conclude that with appropriately designed experiments it is at least in principle possible to access a regime where light-matter interactions become non-perturbative.

Dominik Schneble, Dept. of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, USA.

IT

Waveguide QED with matter waves

Understanding and harnessing light-matter interactions is central to the development of the field of waveguide QED. Recent experiments have observed phenomena such as modified spontaneous emission, bound-state mediated interactions, and collective radiative behavior, but full access to and control of some of them can be challenging. Using ultracold atoms in an optical lattice as a platform to mimic these systems [1], we have implemented artificial quantum emitters (QEs) that spontaneously radiate atomic matter waves, rather than photons, into the analogue of a photonic crystal waveguide [2]. Our platform offers independent and full control of the QEs' vacuum coupling and excitation energy around the band edge, while unwanted decay into non-waveguide modes is absent, leading to a diverging Purcell factor. After introducing the experimental platform, I will describe some recent and current work on radiative interactions in novel regimes and scenarios, including the effects of 'atom-photon' bound states on fractional decay in a single band [3], the formation of matter-wave polaritons [4], and the emergence of super- and subradiant states [5].

Work supported by NSF Grants No. PHY-1607633 and PHY-1912546

[1] I. de Vega, D. Porras, J. I. Cirac, PRL 101, 260404 (2008) [2] L. Krinner, et al., Nature 559, 598 (2018) [3] M. Stewart, et al., Phys. Rev. Research 2, 043307 (2020); A. Lanuza, et al., PRA 105, 023703 (2022) [4] J. Kwon, Y. Kim, A. Lanuza, DS, Nat. Phys. 18, 657 (2022) [5] Y. Kim; A. Lanuza, DS (in prep.)

Alexey Ustinov, Karlsruhe Institute of Technology

IT

Slowing down microwave photons with superconducting qubits

Progress in quantum information processing leads to a rising demand for devices to control the propagation of electromagnetic wave pulses and to ultimately realize a universal and efficient quantum memory. While in recent years significant progress has been made to realize slow light and quantum memories with atoms at optical frequencies, superconducting circuits in the microwave domain still lack such devices. I will present an overview of our recent experiments with arrays of eight frequency-tunable transmon qubits coupled to a one-dimensional waveguide. By consecutively bringing the qubits to a common resonance frequency we observe the formation of super- and subradiant states, as well as the emergence of a bandgap. We also experimentally demonstrate slowing down electromagnetic waves in this qubit array. Time-resolved experiments show electromagnetic wave group velocities reduced by a factor of about 1500 in the single-photon regime. Our findings demonstrate high flexibility of superconducting circuits to realize custom band structures and open the door to microwave dispersion engineering in the quantum regime.

Cornelis Van Diepen, Niels Bohr Institute

CT

Super- and subradiance with coupled solid-state optical quantum emitters

Light-matter interaction is of central interest for quantum information technology. The interaction of light with an emitter can be tailored by engineering the photonic environment. In addition, an engineered environment can extend the spatial range of radiative interaction between multiple emitters. In this work [1], we demonstrate radiative interaction between solid-state optical emitters embedded in a nanophotonic waveguide. The emitters, self-assembled quantum dots, are separated by multiple wavelengths and are tuned into and out of resonance with an out-of-plane magnetic field. On resonance, enhanced and suppressed decay rates are observed, commonly referred to as super- and subradiance, which are a direct consequence of the coupling mediated by the waveguide. In addition, we study in detail the multiemitter dynamics as a function of detuning and demonstrate the preparation of a collective state by driving both emitters. This work forms a foundational step for multiemitter applications, including the generation of highly entangled photon states.

[1] A. Tiranov*, V. Angelopoulou*, C.J. van Diepen*, et al., Science 379, 389-393 (2023)

Andreas Wallraff, ETH Zurich

IT

Loophole-free Bell Inequality Violation with Superconducting Circuits

Superposition, entanglement, and non-locality constitute fundamental features of quantum physics. Remarkably, the fact that quantum physics does not follow the principle of locality can be experimentally demonstrated in Bell tests performed on pairs of spatially separated, entangled quantum systems. While Bell tests were explored over the past 50 years, only relatively recently experiments free of so-called loopholes succeeded. Here, we demonstrate a loophole-free violation of Bell's inequality with superconducting circuits. To evaluate a CHSH-type Bell inequality, we deterministically entangle a pair of qubits and perform fast, and high-fidelity measurements along randomly chosen bases on the qubits connected through a cryogenic link spanning 30 meters. Evaluating more than one million experimental trials, we find an average S-value of 2.0747 ± 0.0033, violating Bell's inequality by more than 22 standard deviations. Our work demonstrates that non-locality is a viable new resource in quantum information technology realized with superconducting circuits with applications in quantum communication, quantum computing and fundamental physics.

Bennet Windt, Max Planck Institute of Quantum Optics

CT

Fermionic matter-wave quantum optics with cold atoms in optical lattices

The quintessential quantum optical system is composed of one or multiple quantum emitters coupled to a bath of (electromagnetic) modes. This coupling leads to individual and collective spontaneous emission, as well as bath-mediated emitter interactions. Engineering non-trivial bath dispersion relations can lead to exotic phenomena, such as population trapping in bound states, sub- and superradiant collective emission, purely coherent bath-mediated interactions, and more. It has been recently suggested and experimentally confirmed that such features can be observed using cold atoms in state-dependent optical lattices rather than traditional optical setups (e.g. photonic crystal waveguides). I propose an extension of the cold-atom setup to fermionic atoms, which unlocks a new paradigm of non-Markovian quantum optics with fermionic matter waves. I discuss how the theoretical formulation of single-excitation dynamics in atom-photon systems can be extended to multi-excitation dynamics in fermionic impurity models. Within this new framework, I present signatures of non-Markovian individual and collective fermionic matter-wave dynamics, as well as some exotic ground-state features.

Johannes Zeiher, Max-Planck-Institute of Quantum Optics IT

Controlling light using ordered atomic arrays

Ordered arrays of emitters with subwavelength spacing have emerged as a novel platform to realize efficient light-matter interfaces. In such arrays, strong cooperative coupling down to the level of single photons emerges due to the dipolar interactions between the atoms. In our experiments, we realize ordered atomic arrays by preparing near-unity filled Mott insulators in an optical lattice at subwavelength distances. We confirm the cooperative nature of the array by probing the subradiant optical response both in reflection and transmission of a weak laser beam. Employing strong Rydberg interactions, we subsequently controllably switch the optical properties of the array with a locally addressed single ancilla atom. Driving coherent Rabi oscillations on the ancilla, we find evidence that the mirror can be brought in a superposition between transmission and reflection before probing. Furthermore, we observe indications for dipolar hopping as a potential limit to the performance of the switch, and use spatial shape control to overcome this problem. Our results pave the way towards the realization of novel quantum metasurfaces and the creation of controlled atom-photon entanglement.

David Zueco, CSIC-Universidad de Zaragoza IT

Waveguide QED in the dipole gauge

In this talk, we address the nuances of the gauge choice in the ultrastrong coupling between light and matter in the context of waveguide QED. We present a fully gauge-invariant description of a quantum dipole coupled to a 1D cavity array using a both numerical and analytical techniques. Our results show that for mantaining gague invariance matter truncation is a good approximation in the dipole gauge. As a consequence gauge invariance leads to an asymmetric dispersion relation in the corresponding spin-boson model, with implications for spontaneous emission, frequency renormalization and single photon scattering. Specifically, we use numerical MPS simulations and Polaron to compute these quantities, and we demonstrate that the consequences of truncating in a manner consistent with the gauge principle can be detected experimentally. In particular, we show that this asymmetry for the dispersion relation can be measured via the spontaneous emission by choosing the atomic frequency at different points in the photonic band. In addition, we discuss the consequences of gauge invariance for the Lamb shift , Fano resonances resonances and inelastic scattering regions.

Abstracts of Posters

Joan Agustí Bruzón, Walther-Meißner-Institut

Programmable distribution of multi-qubit entanglement in dual-rail waveguide QED

We investigate the autonomous generation of multi-partite entangled states between two sets of qubits that are arranged along two separate waveguides. The waveguides are driven by the output of a nondegenerate parametric amplifier, which effectively acts as a two-mode squeezed reservoir. We show that in this configuration the qubits are driven into a pure steady state, which exhibits a controllable amount of entanglement between the qubits. Specifically, we show that by simply changing the detunings of the qubits, different patterns of two-partite and multipartite entanglement can be generated without any fine-tuned pulse control.

Lukas Ahlheit, Institute for Applied Physics, University of Bonn

Rydberg superatoms for waveguide QED

The field of waveguide QED investigates how light in a single mode propagates through a system of localized quantum emitters. In the case of strong coupling between individual photons and individual emitters, the photons mediate an effective interaction between the distant emitters. The cascaded interaction between photons and saturable emitters can be interpreted as a photon-photon interaction. We realize effective two-level emitters by exploiting the Rydberg blockade effect of atomic ensembles. By confining N 10.000 Rb87 atoms to a single blockaded volume, the ensemble only supports a single excitation creating a so-called Rydberg superatom. Due to the collective nature of the excitation, the superatom effectively represents a single emitter coupling strongly to single photons. The directional emission of the superatom into the inital probe mode realizes a waveguide-like system in free-space. We employ a double magic-wavelength optical lattice to pin atoms during optical experiments using Rydberg states and thus reduce motional dephasing of the collective excitation.

Aamir Ali, Chalmers University of Technology

Engineering symmetry-selective couplings of a superconducting artificial molecule to microwave waveguides

Tailoring the decay rate of quantum emitters opens new avenues for quantum optics, collective phenomena, and quantum communications. Here we demonstrate a novel coupling scheme between an artificial molecule comprising two coupled transmon qubits, and two microwave waveguides. The coupling is engineered so that transitions between states of the same (opposite) symmetry, with respect to the permutation operator, are predominantly coupled to one (the other) waveguide. The symmetry-based coupling selectivity, quantified by the ratio of the coupling strengths, exceeds a factor of 30 for each waveguide. In addition, we implement a Raman process activated by simultaneously driving both waveguides, and show that it can be used to coherently couple states of different symmetry in the single-excitation manifold of the molecule. Thereby, we implement frequency conversion across the waveguides, mediated by the molecule, with efficiency of about 95%. Finally, we show that this coupling arrangement makes it possible to generate spatially-separated Bell states propagating across the waveguides. We envisage further applications to quantum thermodynamics and microwave photodetection.

Uesli Alushi, Aalto University

Waveguide QED with Quadratically-Coupled Emitters

Quadratic light-matter interactions are nonlinear couplings such that quantum emitters interact with photonic or phononic modes exclusively via the exchange of excitation pairs. These couplings lead to a plethora of phenomena that have been characterized in the context of cavity QED, where quantum emitters interact with localized bosonic modes. We explore quadratic interactions in a waveguide QED setting, where quantum emitters interact with propagating fields confined in a one-dimensional environment. We develop a general scattering theory under the Markov approximation and discuss paradigmatic examples for spontaneous emission and scattering of biphoton states. Our results unveil fundamental differences with respect to conventional waveguide QED systems such as the generation of correlated biphoton states via spontaneous emission or the emitter full transparency to single-photon inputs. This unlocks new opportunities in quantum information processing with propagating photons. For instance, we show that a single quadratically-coupled emitter can implement a biphoton logic gate with unit fidelity, circumventing a no-go theorem derived for conventional waveguide-QED interactions

Miguel Bello, Max Planck Institute of Quantum Optics

Topological Effects in 2D Quantum Emitter Systems

In this work we show how novel topological effects appear when considering arrangements of increasing complexity of quantum emitters coupled to two-dimensional bosonic topological insulators. For a single emitter coupled to the Haldane model, we find a “fragile” quasibound state that makes the emitter dynamics very sensitive to the model’s parameters, and gives rise to effective long-range interactions that break time-reversal symmetry. We then discuss one-dimensional arrangements of emitters, emitter line defects, and how the topology of the bath affects the effective polariton models that appear in the weak-coupling regime when the emitters are spectrally tuned to a bandgap. In the Harper-Hofstadter model we link the non-monotonic character of the effective interactions to the Chern numbers of the surrounding energy bands, while in the Haldane model we show that the effective models are either gapless or not depending on the topology of the bath. Last, we discuss how the presence of emitters forming an ordered array, an emitter superlattice, can produce polariton models with non-trivial Chern numbers, and also modify the topology of the photonic states in the bath.

Adrien Bouscal, Laboratoire Kastler Brossel, Sorbonne Université

A robust half-W1 photonic crystal waveguide platform for interfacing trapped cold atoms with slow light

Novel platforms interfacing trapped cold atoms and guided light in nanoscale waveguides are a promising route to achieve a regime of strong coupling between light and atoms in single pass, with applications to quantum non-linear optics and quantum simulation. Implementing these platforms is challenging as they should combine facilitated optical access for atom transport and trapping via guided modes. In this endeavor, we propose to interface Rubidium atoms with a photonic crystal waveguide based on a large-index GaInP slab. With a specifically tailored half-W1 design, with a strong emphasis on robustness to nanofabrication imperfections, we show that a large coupling to the waveguide can be obtained and that guided modes can be used to form two-color dipole traps for atoms at about 100 nm from the edge of the structure. This very realistic optimized device should greatly improve the level of experimental control and facilitate the atom integration. We might benefit from the optical tweezer toolbox to get the atoms in the trap. As such, Laguerre-Gauss tweezers are promising as they could allow for tighter traps and reduce reflections on the waveguide surface.

Giuseppe Calajò, INFN-Padova

Cavity-QED approach to waveguide QED in the regime of non-negligible delay times

Recently, waveguide-QED setups in the regime of non-negligible retardation times received considerable attention also spurred by the recent possibility to experimentally access such regime through surface acoustic waves or slow-light coupled-cavity resonators. Such processes are intrinsically non-Markovian, hence their description is generally demanding. Here, we present a novel theoretical framework relying on a spatial decomposition of the waveguide into communicating blocks. The block where emitters lie is treated as an effective, intrinsically-open, multi-mode cavity coupled to the rest of the waveguide. The joint dynamics (atom+field) is well-approximated by retaining only a finite number of modes of the block (open cavity) containing the emitter so that the longer the delay the more modes need to be considered. This picture provides a sort of perturbative expansion of the full dynamics in terms of the delay time. Moreover, it conceptually and explicitly connects delayed waveguide QED with multimode cavity-QED.

Claudia Castillo Moreno, Chalmers University of Technology

Dynamical control of excitation in atom-photon bound states in microwave photonic photonic crystal

The control and manipulation of light and its interaction with matter are of tremendous importance in many fields, including spectroscopy, sensing, and quantum information processing. Dispersion-engineered photonic bandgap metamaterials have emerged as an efficient platform for study photon-photon interactions, making them suitable for studying light-matter interactions emerging there-in. Our system comprises of a slow microwave-light photonic crystal waveguide fabricated with linear array of 21 compact, high-impedance superconducting microwave resonators with nearest-neighbor coupling, and two frequency-tunable superconducting transmon qubits inducing non-linearity in the medium. Atom-photon bound states emerge in this dispersion-engineered photonic crystal when the qubit couples to the band-edge. By utilizing precise control of qubit frequency, we can dynamically control formation of atom-photon bound state, and interaction mediated by them. We investigate timescales associated with excitation transfer to these bound state from the qubit, and to propagating mode in the waveguide.

Alberto Del Ángel Medina, Chalmers University of Technology

Effects of environment correlations on the onset of collective decay in waveguide QED

We analyze the dynamics of one and two two-level atoms interacting with the electromagnetic field in the vicinity of an optical nanofiber without making either the Born or the Markov approximations. We model the dielectric response of the nanofiber with a constant dielectric function and the Drude-Lorentz model, observing deviations from the standard super- and sub-radiant decays. We discuss the validity of approximating the speed of the atom-atom communication to the group velocity of the guided field in the presence of non-trivial environment correlations. Our work presents a deeper understanding of the validity of commonly used approximations in recent waveguide QED platforms.

Enrico Di Benedetto, Università degli Studi di Palermo

Quantum Optics near a Photonic Flat Band

Flat bands (FBs) are dispersionless energy bands arising from destructive interference between neighbouring atomic orbitals in a solid. A few years ago, FBs drew lot of attention due to the discovery of a topological phase transition in a twisted bilayer of graphene, a system that exhibits isolated FBs. A non-singular FB can be spanned by a set of so-called compact states (CLSs), each being localized only on neighbouring sites. Remarkably, CLSs can have width larger than the lattice unit cell, meaning that they can form a non-orthogonal FB basis. In this poster, I will present some fresh results about the coupling of a quantum emitter to an engineered photonic lattice featuring a FB in the case study of a 1D sawtooth lattice, showing the effects of a non-orthogonal set of CLSs on the bound state and the dynamics in the single-excitation sector. We observe the formation of a strictly localized atom-photon bound state whose shape depends only on the detuning from the dispersive band. Such counterintuitive property is an effect of destructive interference. In the case of a local coupling, the dynamics can be reduced to a lossy Jaynes-Cumming model.

Daniel Goncalves, ICFO

Local dissipation effects in the driven-dissipative Dicke phase transition

The driven Dicke model, wherein an ensemble of atoms is driven by an external field and undergoes collective spontaneous emission due to coupling to a leaky cavity mode, is a paradigmatic model that exhibits a driven dissipative phase transition as a function of driving power. Recently, a highly analogous phase transition was experimentally observed, not in a cavity setting, but rather in a free-space atomic ensemble. Motivated by this, we present our ongoing efforts to better characterize the free-space problem, and understand possible differences compared to the cavity version. We specifically discuss a cavity QED model with weak local dissipation as a minimal model for the free space. We find that the presence of local dissipation dramatically changes the properties of the phase transition. In particular, we present preliminary arguments that suggest that the free-space case might exhibit a smooth crossover rather than a true phase transition in the thermodynamic (large atom number) limit.

Alonso Hernández Antón, ETH Zürich

Deterministic generation of 2D tensor-network states of itinerant microwave photons

Multidimensional tensor-network states, such as cluster states, are a key resource for quantum communication and measurement-based quantum computing. Recently, cluster states have been generated both in the microwave and optical regime but the generation of large-scale 2D cluster states in discrete-variable systems remains challenging. Here, we present a superconducting device to enable the generation of two-dimensional tensor-network states of itinerant microwave photons. The device contains two long-lived storage qubits and two emitter qubits which rapidly decay into a waveguide. Two-qubit gates and deterministic photon emission are realized by parametric operations on tunable couplers. We demonstrate the emission of a time- and frequency-multiplexed four-photon 2D cluster state with over 50% fidelity. States like this could be used as a resource for measurement-based quantum computation and for quantum communication in the microwave domain.

Tsung-Sheng Huang, Joint Quantum Institute, University of Maryland

Excitons in Mott insulators

Excitons from correlated-insulating materials have attracted great interest as they could serve as probes to the many-body physics. This motivates the understanding of the interplay between these optical excitations and strong correlations. In this presentation, we focus on two kinds of excitons from Mott insulators — Intraband exciton with both charges from a single band Hubbard model, and interband exciton with only one charge in the Hubbard band. We discuss the role of spin physics in their properties and compare them with excitons from band insulators.

Teresa Karanikolaou, ICFO

Effect of an optical dipole trap on resonant atom-light interactions

The optical properties of a fixed atom are well-known and investigated: The atom can respond extraordinarily strong to a resonant photon, as characterized by a resonant elastic scattering cross section given by the wavelength of the transition itself. The case of a tightly trapped ion, where the ground and excited states are equally trapped, is also well-known: The elastic cross section is reduced by a fraction corresponding to the square of the “Lamb-Dicke parameter”, while this same parameter also dictates the probability of inelastic scattering that gives rise to motional heating. In contrast, there are many emerging quantum optics setups involving neutral atoms in tight optical dipole traps, where the goal is to utilize efficient atom-light interactions on resonance. Often, while the ground state is trapped, the excited state may in fact be untrapped or even anti-trapped. Here, we systematically analyze the consequences that this unequal trapping has on reducing the elastic scattering cross section and increasing the motional heating rate. This analysis may be useful to optimize the performance of quantum optics platforms where equal trapping cannot be readily realized.

Therese Karmstrand, Chalmers university of technology

Unconventional saturation effects with few emitters within the driven-dissipative Tavis–Cummings model

The loss rates in highly dissipative cavity-emitter systems render the realization of many desirable nonlinear effects, such as saturation and photon blockade, problematic. Here, we present another effect occurring within the Tavis-Cummings model: a nonlinear response of the cavity for resonant external driving of intermediate strength, which makes use of large cavity dissipation rates. In this regime, (N+1)-photon processes dominate when the cavity couples to N emitters. We provide a picture of how the effect occurs due to destructive interference between the emitter ensemble and the external drive. We also find an analytical expression for the critical drive at which the effect appears. Our results have potential for quantum state engineering and could be used for the characterization of cavity-emitter systems with unknown emitter number. In particular, our results open the way for investigations of unique quantum-optics applications in a variety of platforms that neither require high-quality cavities nor individual strong coupling.

Karmstrand et al., arXiv:2110.00595 (2021)

Maryam Khanahmadi, Chalmers University of Technology

Release and Catch of Multi-Mode Quantum States in Superconducting Quantum Circuits

Distributed quantum computing requires to share of information between distant stationary quantum systems which can be implemented by transferring photons from a sender to a receiver. Optimal transformation demands encoding the quantum state into a propagating mode which is performed by employing tunable coupling between the quantum system and the quantum channel. Superconducting circuits, with low loss rates, are promising platforms to efficiently prepare and transfer complex quantum states. In our work, we store a quantum state in a cavity and by coupling to a flux tunable transmon, we optimally transfer the quantum state into a waveguide. However, the state transformation regardless of the quantum state and the photon number needs to be encoded in a desired shaped photonics wave packet, we show that due to the nonlinear behavior of the coupler, the output mode would be a state-dependent multimode with different shapes which restricts the efficiency of the transformation of quantum states with a high number of photons. In addition, we investigate the fidelity of catching multimode-quantum states which depends on the sender parameters and the total number of photons.

Youngshin Kim, Stony Brook University, NY, USA

Polaritons and excitons in waveguide QED with matter waves

Ultracold atoms in state-selective optical lattices allow for studies of quantum optical phenomena in which the roles of atoms and light as quantum emitters and radiation are interchanged [1]. We review our group's recent experimental and theoretical studies [2,3] on the formation of matter-wave polaritons, and report new work on coherent matter-wave emission from such radiatively coupled quantum matter. We study interesting regimes of collective dynamics in a loss-free environment, including directional matter-wave emission, super- and subradiance with propagation delays, and spontaneous coherence formation in the strongly-interacting regime.

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Luca Leonforte, Università di Salerno

Bound states of Giant atoms in quantum optical lattices

Giant atoms are an emerging paradigm of quantum optics, which can exhibit unprecedented effects thanks to their multiple, non-local coupling to a photonic waveguide/ lattice. Here, their behavior is studied within a general theory. This comprehensive framework effects predicts effects such as decoherence-free Hamiltonians in a waveguide and emergence of atom-photon bound states (BSs) in structured lattices, both inside the bandgap and the bands. The number of couplings and the structure of the lattice determines all the properties of the effective Hamiltonian and of the BS. As a relevant application, we study two specific, but conceptually important, paradigmatic situations where it is known what happens for normal atom BSs: linear dispersion (deep inside a band) and parabolic dispersion (close to a band edge). Moreover, we predict that in the photonic SSH model, in contrast to normal atoms (local coupling), occurrence of zero-mode bound states is generally not guaranteed.

Zhengze Li, LKB Sorbonne University

Single photon routor using a waveguide coupled atomic array

On our experiment, we use a two-color dipole trap scheme to interface cold Cesium atoms with the evanescent field of a tapered optical nanofiber. We demonstrated up to 80% Bragg reflection with as low as 2000 atoms when carefully tuning the interatomic distance. More recently, we heralded the creation of a single collective excitation in the atomic chain, which was subsequently stored and retrieved as a single photon in the guided mode of the nanofiber. Here, we report on guided optical switching and routing of single-photon level coherent fields using an atomic Bragg mirror controlled by very low energy fields. Focusing first on the regular three-level setup, we switch the reflection and the transmission paths of a Bragg mirror using EIT. We demonstrate routing, or controlled directionality of the probe photon by destroying the reflection by the atomic array and simultaneously opening up an EIT window. In order to push this number even lower, we employ a four-level scheme consisting of the previous scheme to which we add an additional level coupled with the metastable state by a switch field.

Luke Masters, Humboldt-Universität zu Berlin

Will a single two-level atom simultaneously scatter two photons?

The interaction of light with a single two-level emitter is the most fundamental process in quantum optics, and is key to many quantum applications. As a distinctive feature, two photons are never detected simultaneously in the light scattered by the emitter. This is commonly interpreted by saying that a single two-level quantum emitter can only absorb and emit single photons. However, it has been theoretically proposed that the photon anti-correlations can be thought to arise from quantum interference between two possible two-photon scattering amplitudes, which one refers to as coherent and incoherent. This picture is in stark contrast to the aforementioned one, in that it assumes that the atom even has two different mechanisms at its disposal to scatter two photons at the same time. Here, we validate the interference picture by experimentally verifying the 40-year-old conjecture that, by spectrally rejecting only the coherent component of the fluorescence light of a single two-level atom, the remaining light consists of photon pairs that have been simultaneously scattered by the atom.

Alberto Muñoz De Las Heras, Institute of Fundamental Physics IFF-CSIC
Variational Waveguide QED Simulators

Current quantum devices are limited by their connectivity and noise tolerance. To make the best out of existing quantum hardware, variational quantum algorithms have been proposed. These make use of classical optimizers to train parametrized quantum circuits to solve a given task. However, the performance of such algorithms is restricted by the type of interactions appearing in state-of-the-art devices. On the other hand, waveguide QED simulators, i.e., setups where quantum emitters interact with one-dimensional photonic modes can be used to engineer tunable-range interactions between the emitters. In this talk, I will show how this tunability can be used as a resource for developing more efficient quantum algorithms. Our main results show that, when applied to certain problems, ansatzë featuring parametrized tunable-range interactions outperform state-of-the-art ones. In particular, waveguide QED ansatzë capture the ground state of the studied critical spin models with the largest precision, while exhibiting a lower sensitivity to noise. Our results establish waveguide-QED simulators as a promising candidate for noisy intermediate-scale quantum computing.

Tojosoa Nantenaina Raveloarijaona, University of Grenoble Alpes - Insitut Néel
Effect of a single quasiparticle on multi-photon states in a superconducting waveguide

Superconducting quantum circuits are interesting controllable devices that display quantum behavior at a non-atomic scale. For the purpose of quantum information processing, various losses mechanisms have been evidenced. We focus here on applications of superconducting circuits in non-linear quantum optics, and investigate the effect of the presence of Bogoliubov quasiparticles. The studied device consists in a single superconducting qubit coupled to a finite Josephson waveguide, behaving globally as a large island where quasiparticles can be trapped. We show theoretically that photonic states of the waveguide inherit the non-linearity of the qubit, so that their multi-photon spectrum depends on the presence of an extra quasiparticle, in agreement with recent experimental measurements.

Ariadna Soro Alvarez, Chalmers University of Technology
Interaction between giant atoms in a structured waveguide

Giant atoms–quantum emitters that couple to light at multiple discrete points–are emerging as a new paradigm in quantum optics thanks to their many promising properties, such as decoherence-free interaction. While most previous work has considered giant atoms coupled to continuous waveguides or a single giant atom coupled to a structured bath, here we study the interaction between two giant atoms mediated by a structured waveguide, e.g., a photonic crystal waveguide. This environment is characterized by a finite energy band and a band gap, which affect atomic dynamics beyond the Markovian regime. Here we show that, inside the band, decoherence-free interaction is possible for different atom-cavity detunings, but is degraded from the continuous-waveguide case by time delay and other non-Markovian effects. Outside the band, where atoms interact through the overlap of bound states, we find that giant atoms can interact more strongly and over longer distances than small atoms for some parameters–for instance, when restricting the maximum coupling strength achievable per coupling point. The results presented may find applications in quantum simulation and quantum gate implementation.

Cristian Tabares, Institute of Fundamental Physics (IFF-CSIC)
Tunable photon-mediated interactions between spin-1 atoms

Quantum simulators are highly controllable devices that exploit quantum effects to answer questions about another system. When built using atoms (or other emitters) coupled to waveguide-QED setups, they can be tailored to generate exotic photon-mediated interactions between atoms [1], opening the door for the exploration of a wide range of physical models. However, these atoms are typically considered as two-level systems, which limits the type of models that can be explored [2,3]. Our work [4] considers the full hyperfine structure of the atoms to go beyond this and study effective spin-1 interactions between the quantum emitters, where Raman-assisted transitions allow a mapping to well-known models such as the Ising or the XX spin-1 interactions. These results could be interesting both in quantum simulation (to study spin chains or even simulating some lattice gauge theories) and quantum computation (to obtain quantum gates between qutrits).

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Matija Tečer, University of Padova
Photon interactions in 2D waveguide

The physics of the quantum emitters coupled to 1D waveguide modes have been extensively studied in the last decade. However, order arrays emitters coupled to 2D waveguides has received less attention in the quantum optic community. Unlike the infinite range photon-mediated interactions between the emitters in 1D, in the 2D case the interactions decay as the square root of the distance between the emitters. This long-range interaction in 2D opens the door for interesting physical phenomena to be studied. In this poster, we present our study of the photon-emitter coupling in 2D waveguides in the low excitation regime. After analyzing the single excitation spectrum we study the double excitation spectrum in which we investigate the existence of two-photon bound states as a paradigmatic signature of the presence of photon interactions in the system.

Benedikt Tissot, Universität Konstanz
Efficient High-Fidelity Flying Qubit Shaping

Matter qubit to travelling photonic qubit conversion is the cornerstone of numerous quantum technologies such as distributed quantum computing, as well as several quantum internet and networking protocols. We find the upper limit for the photonic pulse emission efficiency of arbitrary matter qubit states for imperfect emitters and show a path forward to optimize the fidelity. We formulate a theory for stimulated Raman emission which is applicable to a wide range of physical systems including quantum dots, solid state defects, and trapped ions, as well as various parameter regimes, including arbitrary pulse durations. Furthermore, the mathematical idea to use input-output theory for pulses to absorb the dominant emission process into the coherent dynamics, followed by a quantum trajectory approach has great potential to study other physical systems.

Kseniia Vodenkova, University of Innsbruck

Solving the problem of delayed coherent quantum feedback

We develop methods to obtain (numerically) exact solutions for the dynamics and steady states of a system with time delayed feedback in all parameter regimes, including those not accessible by previous methods. This includes in particular solutions of the dynamics up to arbitrary long times, for arbitrary large time delays, and arbitrary values of driving field strength. Using our approach we not only are able to obtain numerical solutions, but interestingly, these solutions also suggest simple analytical approximations in many cases: they provide a justification for mean-field type solutions, which allow us to gain semi-analytic insights in the properties of the systems.

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