WQED20

List of Attendees

Andres Agusti (IFF, Madrid)

Gian Marcello Andolina (ICFO)

Javier Argüello-Luengo (ICFO)

Ana Asenjo Garcia (Columbia University)

Kisa Barkemeyer (Technische Universität Berlin)

Jean-Baptiste Béguin (Niels Bohr Institute)

Miguel Bello (Max Planck Institute for Quantum Optics)

Ron Belyansky (University of Maryland)

Alexandre Blais (Université de Sherbrooke)

Giuseppe Calajò (ICFO)

David Castells Graells (Max Planck Institute of Quantum Optics)

Dario Cilluffo (Università di Palermo)

Daniele de Bernardis (TU Wien)

Tamara Dordevic (Harvard University)

Juan José García Ripoll (Institute of Fundamental Physics IFF-CSIC)

Simone Gasparinetti (Chalmers University of Technology)

Alejandro Gonzalez-Tudela (Instituto de Física Fundamental, CSIC)

Alexey Gorshkov (NIST/University of Maryland)

Andrés Rosario Hamann (ETH Zürich)

Sebastian Hofferberth (Universität Bonn)

Göran Johansson (Chalmers University of Technology)

Anton Frisk Kockum (Chalmers University of Technology)

Julien Laurat (Sorbonne Université)

Luca Leonforte (University of Palermo)

Davide Lonigro (University of Bari & INFN)

Maria Maffei (CNRS, Grenoble)

Sahand Mahmoodian (Leibniz University, Hannover)

Daniel Malz (Max-Planck-Institute for Quantum Optics)

Anja Metelmann (Freie Universität Berlin)

Sattwik Deb Mishra (Stanford University)

Klaus Mølmer (University of Aarhus, Denmark)

Jesper Mørk (Technical University of Denmark)

Yasunobu Nakamura (RIKEN)

Prineha Narang (Harvard University)

William D Oliver (MIT)

Saverio Pascazio (Dipartimento di Fisica, Università di Bari, Bari, Italy)

Guillermo F. Peñas (IFF-CSIC)

Francesco Piazza (Max-Planck Institute for the Physics of Complex Systems, Dresden, Germany)

Alexander N. Poddubny (Ioffe Institute, St. Petersburg)

Tomás Ramos (IFF-CSIC, Madrid)

Arno Rauschenbeutel (Humboldt-Universität zu Berlin)

Kevin Reuer (Department of Physics, ETH Zürich)

Federico Roccati (University of Palermo)

Ephraim Shahmoon (Weizmann Institute of Science)

Alexandra Sheremet (Observatoire de Paris)

Irfan Siddiqi (Lawrence Berkeley National Laboratory. Department of Physics, University of California, Berkeley)

Ariadna Soro Álvarez (Chalmers University of Technology)

Sergi Terradas Briansó (Instituto de Nanociencia y Materiales de Aragón (INMA), CSIC-Universidad de Zaragoza)

Rahul Trivedi (Max-Planck-Institute for Quantum Optics)

Hakan Tureci (Princeton University)

Carlos Vega García (IFF-CSIC)

Andreas Wallraff (ETH Zurich)

Yidan Wang (University of Maryland, Joint Quantum Institute)

Zhi-Yuan Wei (Max Planck Institute for Quantum Optics)

Christopher Wilson (University of Waterloo)

David Zueco (CSIC-Universidad de Zaragoza)

Abstracts of Talks

Ana Asenjo Garcia (Columbia University)

Atomic-waveguide QED

Tightly packed ordered arrays of atoms (or, more generally, quantum emitters) exhibit remarkable collective optical properties, as dissipation in the form of photon emission is correlated. In this talk, I will discuss quantum optics in one-dimensional arrays, and their potential to realize versatile light-matter interfaces. For small enough inter-atomic distances, atomic chains feature dark states that allow for dissipationless transport of photons, behaving as waveguides for single-photon states. Atomic waveguides can be used to mediate interactions between impurity qubits coupled to the array, and allow for the realization of multiple paradigms in waveguide QED, from bandgap physics to chiral quantum optics. Moreover, by means of an external dressing field, one can manipulate photon propagation dynamically via dispersion engineering. This enables the realization of a trap-and-release protocol where an excitation that is trapped inside an atomic chain is released at a desired and arbitrarily long time. I will finish my talk by discussing many-photon physics and the departure from the waveguide analogy.

Jean-Baptiste Béguin (Niels Bohr Institute)

Bridging gaps between cold atoms and nano-photonics

Combining cold atom research and nano-photonics holds promise for quantum matter built from atoms and photons in new parameter regimes. It offers a platform to explore and engineer tunable and strong atom-atom interactions mediated by light, with a variety of applications in quantum optics including e.g., quantum simulation, synthetic molecules of light, and atom mirrors.
I will discuss nascent work conducted at Caltech and present the early efforts of our new team at NBI towards integration of cold atoms in nanoscopic dielectric lattices.
This is a highly multidisciplinary research field and makes for a formidable challenge in the laboratory. I will put a focus on experimental difficulties and the tools to overcome them.

[1] D. E. Chang, J. S. Douglas, A. González-Tudela, C.-L. Hung, and H. J. Kimble, Rev. Mod. Phys. (2018) https://doi.org/10.1103/RevModPhys.90.031002
[2] J.-B. Béguin, J. H. Müller, J. Appel, and E. S. Polzik, PRX (2018) https://doi.org/10.1103/PhysRevX.8.031010
[3] X. Luan, J.-B. Béguin, A. P. Burgers, Z. Qin, S.-P. Yu, and H. J. Kimble, Adv. Quantum Technol. (2020) https://doi.org/10.1002/qute.202000008
[4] J.-B. Béguin, A. P. Burgers, X. Luan, Z. Qin, S. P. Yu, and H. J. Kimble, Optica (2020) https://doi.org/10.1364/OPTICA.384408
[5] J.-B. Béguin, J. Laurat, X. Luan, A. P. Burgers, Z. Qin, and H. J. Kimble, PNAS (2020) https://doi.org/10.1073/pnas.2014017117
[6]J.-B. Béguin, Z. Qin, X. Luan, and H. J. Kimble, PNAS (2020) https://doi.org/10.1073/pnas.2014851117

Alexandre Blais (Université de Sherbrooke)

A quantum metamaterial for broadband detection of single microwave photons

Detecting traveling photons is an essential primitive for many quantum information processing tasks. We propose a single-photon detector operating in the microwave domain based on a nonlinear metamaterial built from a large number of coupled Josephson junctions. By trading local nonlinearity for large spatial extent, this approach allows for a large detection bandwidth. Using numerical simulations based on many-body physics methods, we show that the single-photon detection fidelity increases with the length of the metamaterial to approaches one. The photon is not destroyed and the photon wavepacket is only minimally disturbed by the detection, in stark contrast to conventional photon detectors operating in the optical domain. The proposed detector thus offers new possibilities for quantum information processing with superconducting qubits, as well as fundamentally new experiments exploring single-photon physics and phenomenology.

Giuseppe Calajò (ICFO)

Few- and many-body photon bound states in quantum nonlinear media

The emergence of multi-photon bound states in quantum nonlinear media is an intriguing phenomenon that has attracted significant theoretical and experimental interest. Such bound states can emerge in quite different settings, such as arrays of quantum emitters coupled to photonic waveguides, to Rydberg nonlinear media. The theoretical tools to characterize the bound states are equally diverse, ranging from Bethe ansatz to effective field theories. Here, we propose a spin-model formulation of quantum atom-light interactions as a general, unified framework to study bound states, and apply this formalism to several distinct systems. We show how to obtain the bound-state dispersion relation within the two-excitation subspace, and also numerically investigate how the properties of higher multi-photon bound states manifest themselves in the propagation of large photon-number pulses. These properties can lead to spatio-temporal correlations at the output, and eventually to classical soliton-like behavior for sufficiently large photon number. Our results suggest that a quantum-to-classical transition from quantum bound states to classical solitons is a general property inherent to quantum nonlinear media.

Daniele de Bernardis (TU Wien)

Light-matter interactions in synthetic magnetic fields: Landau-photon polaritons

We study light-matter interaction in two dimensional photonic systems in the presence of a spatially homogeneous synthetic magnetic field for light. Specifically, we consider one or more two-level emitters located in the bulk region of the lattice, where for increasing magnetic field the photonic modes change from extended plane waves to circulating Landau levels. This change has a drastic effect on the resulting emitter-field dynamics, which becomes intrinsically non-Markovian and chiral,

leading to the formation of strongly coupled Landau-photon polaritons. The peculiar dynamical and spectral properties of these quasi-particles can be probed with state-of-the-art photonic lattices in the optical and the microwave domain and may find various applications for the quantum simulation of strongly interacting topological models.

Tamara Dordevic (Harvard University)

Nanophotonic quantum interface for atom arrays

The realization of an efficient quantum optical interface for multi-qubit systems is an outstanding challenge in science and engineering. We present a method for interfacing neutral atom arrays with optical photons confined in a nanofabricated photonic crystal cavity. In our approach, atomic qubits trapped in individually controlled optical tweezers are moved in and out of the cavity near-field, to which they couple with high (C = 30 - 70) cooperativity. With this platform, we demonstrate cavity-mediated interactions between two atoms [1], their full quantum control, efficient quantum non-destructive readout, and entanglement heralded by a single photon detection [2]. By encoding the qubits into long-lived states and employing dynamical decoupling, the entangled state is verified in free space after being transported away from the cavity, paving the way for nanophotonic quantum networking with neutral atom quantum processors.

[1] P. Samutpraphoot et al., Phys. Rev. Lett. 124, 063602 (2020)

[2] T. Đorđević et al., arXiv: 2105.06485

Juan José García Ripoll (Institute of Fundamental Physics IFF-CSIC)

Long distance quantum operations with propagating photons

In this talk I will discuss ongoing work on the design and optimization of quantum protocols between coupled quantum computers made of transmon qubits, cavities and a long transmission waveguide that connects both devices. I will discuss the operation of this device under realistic assumptions of finite separation, finite bandwiths, finite qubit lifetime and limited couplings. We will see the how the parameters of the device can be optimized for implementing both transfer of information as well as delocalized universal two-qubit gates, and how multiplexing can aid in increasing both the bandwidth and the effective connectivity of the device. This work has been supported by H2020 FET-Open Project SuperQuLAN (https://www.superqulan.eu)

Simone Gasparinetti (Chalmers University of Technology)

Atom-photon bound states in an array of high-impedance superconducting resonators

Engineering the electromagnetic environment of a quantum emitter gives rise to a plethora of exotic light-matter interactions. In particular, photonic lattices can seed long-lived atom-photon bound states inside photonic band gaps. We implement a novel microwave architecture consisting of an array of compact, high-impedance superconducting resonators forming a 1 GHz-wide pass band, in which we have embedded two frequency-tuneable artificial atoms. Each atom can also be individually addressed via dedicated control and readout circuitry. We study the atom-field interaction by accessing previously unexplored coupling regimes, in both the single- and double-excitation manifold. In addition, we demonstrate coherent interactions between two atom-photon bound states, in both resonant and dispersive regimes, that are suitable for the implementation of iSWAP and CZ two-qubit gates. This architecture holds potential for quantum simulation with tuneable-range interactions and quantum information processing.

Alejandro Gonzalez-Tudela (CSIC)

Topology meets quantum optics: individual and collective effects

Recent experimental advances allow one to engineer topological models in bosonic systems like photonic crystals, coupled microwave resonators, or optical lattices experiments, among other platforms [1]. In parallel, experimental progress is also being made to couple quantum emitters to such platforms in order to obtain (or simulate) light-matter Hamiltonians [2-4] with topological photons. The emergent behaviour and applications of such topological quantum optics models, however, remain mostly unexplored. In this talk, I will discuss the emergence of unconventional quantum dynamics and interactions when quantum emitters are coupled to topological 1D waveguides [5] and 3D photonic Weyl environments [6]. We will show how the photon-mediated interactions induced by these topological photons give rise to the emergence of spin models with exotic and tunable long-range interactions, that can be used for quantum simulation purposes.

[1] Rev. Mod. Phys. 91, 015006 (2019)
[2] Nature 508, 241–244 (2014), Nature Communications 5, 3808 (2014), Rev. Mod. Phys. 87, 347 (2015), Science 359, 666 (Feb 2018)
[3] Nature Physics 13 (1), 48-52 (2017), Nature Communications, 9, 3706 (2018)
[4] Nature 559, 589–592 (2018)
[5] Science Advances 5, eaaw0297 (2019)
[6] Phys. Rev. Lett. 125, 163602 (2020)

Alexey Gorshkov (NIST/University of Maryland)

Universality in one-dimensional scattering with general dispersion relations

Many synthetic quantum systems allow particles to have dispersion relations that are neither linear nor quadratic functions.
In this talk, we will explore single-particle scattering in one dimension when the dispersion relation is proportional to momentum raised to an integer power m greater than two. We will study impurity scattering problems in which a single particle in a one-dimensional waveguide scatters off of an inhomogeneous discrete set of sites locally coupled to the waveguide. For a large class of these problems, we will show that the S-matrix evaluated at zero energy converges to a universal limit that is only dependent on m. We will also give a generalization of a key index theorem in quantum scattering theory known as Levinson's theorem---which relates the scattering phases to the number of bound states---to impurity scattering for these more general dispersion relations.

[1] arXiv:2103.09830

Sebastian Hofferberth (Universität Bonn)

Waveguide QED with Rydberg superatoms

Rydberg quantum optics (RQO) allows to create strong optical nonlinearites at the level of individual photons by mapping the strong interactions between collective Rydberg excitations onto optical photons.
The strong interactions lead to a blockade effect such that an optical medium smaller than the blockaded volume 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 few-photon probe fields with directional emission into the inital probe mode.
Here we discuss how we use Ryderg superatoms to study the dynamics of single two level systems strongly coupled to quantized propagating light fields, enabling e.g. the investigation of three-photon correlations mediated by a single quantum emitter.
We also show our experimental progress towards implementing a cascaded

quantum system by interfacing multiple superatoms in a one-dimensional chain with a single probe mode and show that this system can be used as a N-photon subtractor.

Göran Johansson (Chalmers University of Technology)

An atom in front of a mirror - high-impedance transmission lines and non-markovian steady-states

First, I will discuss the dynamics of a single superconducting artificial atom capacitively coupled to a transmission line with a characteristic impedance comparable to or larger than the quantum resistance. In this regime, microwaves are reflected from the atom also at frequencies far from the atom's transition frequency. Adding a single mirror in the transmission line then creates cavity modes between the atom and the mirror. Investigating the spontaneous emission from the atom, we then find Rabi oscillations, where the energy oscillates between the atom and one of the cavity modes. Secondly, considering the part of the transmission line between the atom and the mirror as a delay line, one can investigate how this non-markovian environment influences the steady-state of the driven system. To numerically analyse this system, we apply the MPS-based method recently introduced by Pichler et al. We find that there are regimes for time-delay and drive strength where the reduced density matrix of the atom reaches steady-states which it cannot reach with a markovian environment.

[1] Emely Wiegand, Benjamin Rousseaux, Göran Johansson, Phys. Rev. Research 3, 023003 (2021)
[2] Andreas Ask, Göran Johansson, arXiv:2102.11140

Anton Frisk Kockum (Chalmers University of Technology)

Oscillating and chiral bound states in giant atoms

In quantum optics, it is common to assume that atoms can be approximated as point-like compared to the wavelength of the light they interact with. However, recent advances in experiments with artificial atoms built from superconducting circuits have shown that this assumption can be violated [1, 2, 3]. Instead, these artificial atoms can couple to an electromagnetic field at multiple points, which are spaced wavelength distances apart. Such systems are called giant atoms and have attracted increasing interest in the past few years [4]. In this talk, I will present results from two papers investigating bound states in giant atoms. In the first paper [5], we showed that a giant atom coupled to a waveguide at three or more points, with non-negligible travel time for the light between these coupling points, can support oscillating bound states, i.e., states where the energy oscillate back and forth between the atom and the waveguide modes without ever dissipating away through the waveguide. In the second paper [6], we studied giant atoms coupled to a waveguide whose impedance varies periodically. We showed that this setup supports chiral bound states, i.e., states that localise mainly to one side of the giant atom.

[1] M. V. Gustafsson et al., Science 346, 207 (2014)
[2] B. Kannan et al., Nature 583, 775 (2020)
[3] A. M. Vadiraj et al., Physical Review A 103, 023710 (2021)
[4] A. F. Kockum, in International Symposium on Mathematics, Quantum Theory, and Cryptography (Springer, 2021)
[5] L. Guo et al., Physical Review Research 2, 043014 (2020)
[6] X. Wang et al., Physical Review Letters 126, 043602 (2021)

Julien Laurat (Sorbonne Université)

Interfacing cold atoms and nanoscale waveguides

Considerable efforts have been recently devoted to combining ultracold 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. Dielectric waveguides offer a promising platform for such integration because they enable tight transverse confinement of the propagating light, strong photon–atom coupling in single-pass configurations and potentially long-range atom–atom interactions mediated by the guided photons. In this talk, I will present our ongoing efforts based on two platforms, a nanofiber and a new photonic-crystal slow-mode waveguide based on GaInP. I will also discuss specific techniques to approach atoms close to structured waveguides and present a package, Nanotrappy, enabling to calculate any evanescent dipole trap in the vicinity of nanostructures.

Peter Lodahl (University of Copenhagen)

Quantum information processing with nanophotonic waveguides

Semiconductor quantum dots embedded in nanophotonic waveguides offer a highly efficient and coherent deterministic photon-emitter interface [1]. It constitutes an on-demand single-photon source for quantum- information applications, enables single-photon nonlinear, optics and the constructing of deterministic quantum gates for photons [2]. We review recent experimental progress, and demonstrate that the current technology can be scaled up to reach quantum advantage [3] with the demonstration of near-transform-limited emitters in high-cooperativity planar nanophotonic waveguides [4]. The coherent control of a single spin in the quantum dot [5, 6] offers additional opportunities of generating advanced multi-photon entangled states [7]. We discuss potential applications of these novel deterministic photonic hardware in quantum computing and quantum communication [8], e.g., for constructing a resource efficient one-way quantum repeater [9].

[1] Lodahl et al., Rev. Mod. Phys. 87, 347 (2015).
[2] Lodahl, Quantum Science and Technology 3, 013001 (2018).
[3] Uppu et al., Science Advances 6, eabc8268 (2020).
[4] Pedersen et al., ACS Photonics (2020).
[5] Javadi et al., Nature Nanotechnology 13, 398 (2018).
[6] Appel et al., Phys. Rev. Lett. 126, 013602 (2021).
[7] Tiurev et al., Arxiv: 2007.09295.
[8] Uppu et al., Arxiv: 2103.01110.
[9] Borregaard et al., Phys. Rev. X 10, 021071 (2020).

Maria Maffei (CNRS, Grenoble)

Probing non-classical light fields with energetic witnesses in Waveguide Quantum Electro-Dynamics

We analyze energy exchanges between a qubit and a field propagating in a waveguide. The joint closed dynamics is analytically solved within a repeated interaction model [1]. This Hamiltonian approach leads to an alternative definition of work with respect to previously proposed ones based on the qubit's master equation [3, 4]. For both qubit and field, treated equally as quantum systems, we define work as the unitary, entropy-preserving, component of the local energy change. We show
that under suitable initial conditions the two work flows compensate each other, allowing us to define a unique work flow. As expected, this quantity converges to its un-ambiguous classical definition in the classical limit of the field (strong coherent field). Most importantly, in the opposite regime, when the waveguide is in the vacuum, our approach is the sole capable to capture measurable work exchanges of quantum nature along the spontaneous emission process [5]. Focusing on the charging of a qubit by a pulse of light, we evidence that the work provided by a coherent field is an upper bound for the qubit ergotropy, while this bound can be violated by non-classical fields, e.g. any coherent superposition of zero- and single-photon states. Our results provide operational, energy-based witnesses to probe the non-classical nature of a light field.

[1] F. Ciccarello, Quantum Measurements and Quantum Metrology 4, 53 (2017).
[3] F. L. S. Rodrigues, G. De Chiara, M. Paternostro, andG. T. Landi, Phys. Rev. Lett. 123, 140601 (2019).
[4] C. Elouard, D. Herrera-Mart ́ı, M. Esposito, andA. Auff`eves, New Journal of Physics 22, 103039 (2020).
[5] J. Monsel, M. Fellous-Asiani, B. Huard, and A. Auff`eves, Phys. Rev. Lett. 124, 130601 (2020).

Sahand Mahmoodian (Leibniz University, Hannover)

Dynamics of many-photon bound states in chiral waveguide QED

In this talk I will give an overview of our work looking at pulse propagation of photons in chiral waveguide QED. This system supports correlated many-photon bound states whose propagation velocity scales with the square of the number of photons in the bound state. This means that a waveguide with chirally coupled atoms causes a coherent input pulse to break up into different bound-state components that become spatially separated at the output. In the limit of few atoms and many photons, we show that a linear combination of bound states recovers the solitonic solution of self-induced transparency. Our work covers the entire spectrum from few-photon quantum propagation, to genuine quantum many-body (atom and photon) phenomena, and ultimately the quantum-to-classical transition.

Daniel Malz (Max-Planck-Institute for Quantum Optics)

Physics and applications of superradiance in waveguide QED

Dicke superradiance, in which initially fully polarized atoms decay collectively, is a useful tool to build coherent light-matter interfaces. Pure Dicke decay is only possible if the model possesses permutation invariance, which makes using this effect difficult to observe in three dimensions. However, in cavities and particularly in waveguide QED, permutation invariance can be (approximately) achieved. I present some applications such as photon detection and state generation. In a second part, I will present results on nonlinear (or "true") Dicke superradiance in the presence of disorder, free-space decay, and retardation.

Anja Metelmann (Freie Universität Berlin)

Interplay of Dissipative and Coherent Processes in Waveguide-QED

The concept of dissipation engineering has enriched the methods available for state preparation, dissipative quantum computing and quantum information processing. Combining such engineered dissipative processes with coherent dynamics allows for new effects to emerge. For example, we found that any factorisable (coherent) Hamiltonian interaction can be rendered nonreciprocal if balanced with the corresponding dissipative interaction. A concept which has been experimental realized in parametrically coupled-mode systems, and thus in systems which effectively can be considered as classical. The aspects of nonreciprocity in a true quantum system are yet to be explored in detail. Here (artificial) waveguide-QED systems realize an ideal test-bed for the interplay of coherent and dissipative processes between quantum emitters. In this talk I will discuss how waveguide-emitter systems can provide the necessary processes for nonreciprocal effects to emerge.

Klaus Mølmer (University of Aarhus, Denmark)

How do flying and stationary qubits interact in a quantum network?

How does a travelling pulse of quantum radiation interact with a local material quantum system? While a precise description of this process is crucial for numerous waveguide quantum technologies, quantum optics textbooks do not provide a formal description of this elementary interaction process. I shall introduce a new (and simple) master equation theory that describes the joint quantum state of travelling single mode wave packets of quantized radiation and local quantum systems. I shall discuss how this theory is fundamentally different from the theory of discrete modes, temporarily coupled, e.g., with qubit systems, and I shall show numerous results and applications of the theory. While the theory is developed to solve problems with few modes but arbitrary photon numbers, we shall point out some natural connections with multi-mode few-photon wave packets and quantum interactions with multiple scatterers.

Jesper Mørk (Technical University of Denmark)

Fano resonances for controlling and enhancing photon interactions and emission dynamics

In the talk I will describe how Fano resonances in photonic crystal waveguides can be used to control the transmission properties and the density of states, with application to classical and quantum switching and suppression of phonon scattering in the emission dynamics of a quantum dot.

Yasunobu Nakamura (RIKEN)

Generation and characterization of quantum states in microwave pulse modes

Superconducting quantum circuits provide a versatile platform for waveguide quantum electrodynamics. Qubits as an artificial atom and microwave transmission lines as a waveguide interact strongly with and without the help of resonators. By using them, we generate and characterize non-classical states of multiplexed microwave pulse modes such as a time-bin qubit [1] and a cluster state [2]. For constructing a fully-connected 1D quantum network, we also propose a scheme for directional emission and absorption of a microwave pulse in a waveguide [3].

[1] J. Ilves et al., npj Quantum Information 6, 34 (2020).
[2] Y. Sunada et al., APS March Meeting, A28.00006 (2021).
[3] N. Gheeraert, S. Kono, and Y. Nakamura, Phys. Rev. A 102, 053720 (2020).

Prineha Narang (Harvard University)

Creating Quantum Interfaces to Emitters at the Nanoscale

The potential impact of active quantum emitters on creating quantum information systems in the near-term is evident [1,2]. Yet, design and control of robust quantum interfaces to these emitters at the nanoscale has remained challenging. In this talk, I will present promising physical mechanisms and device architectures for coupling emitters to other qubit platforms via dipole-, phonon-, andÂ magnon-mediatedÂ interactions. I will present our latest work on coupling magnons to magnetic emitters as a natural step towards magnon-mediated efficient manipulation of spin-qubit states with applications in sensing and quantum information science. I will start with a scheme that uses magnetic nanoparticles that sustain antenna-like magnon resonances as nanomagnonic cavities for microwave magnetic fields. Here, in recent work we have shown that nanomagnonic cavities can modify the local magnetic environment of spin emitters in the microwave domain, facilitate the magnetic drive of spin transitions, and allow for strong coupling of these emitters with single magnons [3]. Next, I will discuss how the magnetic fields of nanomagnonic cavities that change spatially on the length scales of single molecular or defect emitters, coupled with descriptions of spin emitters beyond the point-dipole approximation, enables selection rule-breaking of orbital-spin transitions [4]. Such nanomagnonic cavities could pave the way towards magnon-based quantum networks and magnon-mediated quantum gates. Taking this further, I will present some of our recent work in capturing non-Markovian dynamics in open quantum systems (OQSs) built on the ensemble of Lindblad's trajectories approach [5,6]. In the outlook, I will discuss new approaches from quantum chemistry for OQSs that could guide the controllable coupling of active quantum emitters and create robust quantum interfaces to the nanoscale.

[1] Awschalom, D. et al. Development of Quantum Interconnects (QuICs) for Next-Generation Information Technologies. PRX Quantum 2, 017002 (2021).
[2] Head-Marsden, K., Flick, J., Ciccarino, C. J. & Narang, P. Quantum Information and Algorithms for Correlated Quantum Matter. Chem. Rev. (2020) doi:10.1021/acs.chemrev.0c00620.
[3] Neuman, T., Wang, D. S. & Narang, P. Nanomagnonic Cavities for Strong Spin-Magnon Coupling and Magnon-Mediated Spin-Spin Interactions. Phys. Rev. Lett. 125, 247702 (2020).
[4] Wang, D. S., Neuman, T. & Narang, P. Spin Emitters beyond the Point Dipole Approximation in Nanomagnonic Cavities. J. Phys. Chem. C 125, 6222-6228 (2021).
[5] Head-Marsden, K., Krastanov, S., Mazziotti, D. A. & Narang, P. Capturing non-Markovian dynamics on near-term quantum computers. Phys. Rev. Research 3, (2021).
[6] Krastanov, S. et al. Unboxing Quantum Black Box Models: Learning Non-Markovian Dynamics. arXiv [quant-ph] (2020).

William D Oliver (MIT)

Giant Artificial Atoms and Waveguide QED

Models of light-matter interaction with natural atoms typically invoke the dipole approximation, wherein atoms are treated as point-like objects compared with the wavelength of their resonant driving fields. 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 via resonant waveguide modes. 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

Saverio Pascazio (Dipartimento di Fisica, Università di Bari, Italy)

Bound states of artificial atoms in open and closed waveguides

An excited atom in free space decays towards its ground state through spontaneous emission. Boundary conditions and artificial dimensional reduction drastically modify this picture, enhancing or inhibiting decay, and displaying a plethora of interesting interference effects.
We consider N artificial atoms, approximated as two-level quantum emitters, coupled to a linear guided mode, in a quasi-one-dimensional configuration. We focus on the single- and double-excitation sectors, and explore the relaxation towards bound states for resonant values of the interatomic distance, the generation of entanglement, and the phenomenon of correlated emission.
We also study closed waveguides, in which photon wavenumbers and frequencies are discretized, and characterize the stable states in which one excitation is steadily shared between the field and one or two emitters.

Francesco Piazza (Max-Planck Institute Dresden, Germany)

Quantum Nonlinear Optics with a Fermi Surface

Recently it has become experimentally possible to achieve a strong light-matter coupling in quantum correlated materials. Examples include electronic Landau-levels[1], excitons forming polarons in an electron bath [2], as well as metals and even superconductors made of electrons
[3] or ultracold atoms [4]. In all these examples the fermionic nature of matter plays an important role. In the context of quantum optics it becomes then crucial to investigate the effect of the Fermi surface on single-photon nonlinearities. In this talk, I will discuss this issue in the particular case of waveguide photons coupled to a one-dimensional metal. The Fermi surface can induce very strong nonlinearities and also photon bound states. Moreover, the system can become unstable
towards the formation of a crystal of matter and light, where the photons play the role of the phonons, and which features topological soliton-polaritons as fundamental excitations [5].

[1] Paravicini-B. et al., Nat.Phys. 15 (2019)
[2] Siedler et al., Nat.Phys.13 (2016)
[3] Thomas et al., arXiv:1911.01459
[4] Roux et al., Nat. Comm. 11 (2020)
[5] Fraser and FP, Nat. Comm. Phys. 48 (2019)

Alexander N. Poddubny (Ioffe Institute, St. Petersburg)

Two-body problem in WQED: from localization to chaos

I will consider an interaction of two photons with a periodic array of two-level atoms, coupled to a waveguide. In this setup the long-ranged waveguide mediated coupling between distant atoms leads to unusual interactions and novel kinds of quantum states. Namely, due to the non-parabolic dispersion of polaritons the types of two photon quantum states in WQED are far more diverse than usual scattering, bound and fermionized states expected from interacting bosons with short-range interactions. We predict that two-photon states manifest interaction-induced localization [1], where the first photon forms a standing wave in a finite array, that creates a potential well for a

second photon and vice versa. In case when the standing wave has multiple nodes, it drives
topologically nontrivial edge states [2]. Contrary to the usual Aubry-André-Harper model, such edge states emerge solely from interactions of two photons with atoms. No external magnetic field, complex lattices or external modulations are required. Mixing between different standing waves results in highly irregular two-photon states which can be viewed
as an interaction-induced quantum chaos [3].

[1] J.Zhong et al., “Photon-Mediated Localization in Two-Level Qubit Arrays”, Phys. Rev.
Lett. 124, 093604 (2020).
[2] A.V. Poshakinskiy et al., “Quantum Hall phases emerging from atom-photon interactions”, npj Quantum Information 7, 34 (2021),
[3] A.V. Poshakinskiy, J.Zhong, A.N. Poddubny, “Quantum chaos driven by long-range waveguide-mediated interactions”, Phys. Rev. Lett. (2021, in press), arXiv:2011.11931

Thomas Pohl (Aarhus University)

Self-ordering of individual photons in 3-level waveguide-QED and Rydberg arrays

Optical nonlinearities often tend to focus light beams, which, for example, results in the formation of optical solitons or few-photon bound states, as found in optical fibres or nonlinear Kerr media of two-level atoms.
In this talk, we consider the interaction of light with three-level emitters, which leads to strikingly different collective behaviour in a chiral chain of multiple emitters. Excitation of a third level by an external control field gives rise to new two-photon scattering eigenstates, that are akin to Fano resonances in particle collisions and facilitate the generation of nonclassical light, transforming a weak classical input into a strongly correlated state of light. Remarkably, the control-field coupling also determines the form of photonic bound states and permits to remove
them altogether, which causes a sharp transition from a strong bunching to a

perfectly antibunched state of the transmitted light field.
Multi-photon simulations in the latter regime verify that this effect generates a strong repulsive interaction between propagating photons. Indeed, this effective repulsion tends to split incident single-mode pulses into trains of individual photons and builds up correlations that resemble Laughlin-type states, used to describe electrons in magnetic fields. Experimental prospects and specific schemes for realizing this system will also be discussed.

Tomás Ramos (IFF-CSIC, Madrid)

Multiphoton probing of complex quantum emitters

Controlling the interaction between single quantum emitters and single photons in nanophotonic environments is routinely achieved in many labs around the world. Nevertheless, the characterization of those interactions is typically limited to measure single-photon transmission, second order correlations, or pump-probe experiments. Developing more sophisticated two- or multi-photon probing protocols [1] can allow us, for instance, to quantify complex photon-photon interactions and correlations induced by quantum emitters [2] or to characterize the operation of nonlinear nanophotonic devices.
In this talk, I will introduce a great simplification of the original multiphoton scattering tomography method [1] so that its application now only requires weak monochromatic coherent state inputs and standard homodyne or photo-detection methods at the output. Despite the simplicity of this new approach, I will show that it can be used to characterize general two- and multi-photon interactions and to probe complex quantum emitters even in the presence of a noisy nanophotonic environment.

[1] T. Ramos, J.J. García-Ripoll, “Multiphoton Scattering Tomography with Coherent States”, Phys. Rev. Lett. 109, 153601 (2017).
[2] H. Le Jeannic, T. Ramos, S.F. Simonsen, T. Pregnolato, Z. Liu, R. Schott, A.D. Wieck, A. Ludwig, N. Rotenberg, J.J. García-Ripoll, and P. Lodahl, “Experimental reconstruction of the few-photon nonlinear scattering matrix from a single quantum dot in a nanophotonic waveguide”, Phys. Rev. Lett. 126, 023603 (2021).

Arno Rauschenbeutel (Humboldt-Universität zu Berlin)

Correlating photons using the collective nonlinear response of atoms weakly coupled to an optical mode

Typical schemes for generating correlated states of light require a highly nonlinear medium that is strongly coupled to an optical mode. However, unavoidable dissipative processes, which cause photon loss and blur nonlinear quantum effects, often impede such methods. In this talk, I will report on our recent experimental demonstration of a proposal that takes the opposite approach [1]. Using a strongly dissipative, weakly coupled medium, we generate and study strongly correlated states of light [2]. Specifically, we study the transmission of resonant light through an ensemble of non-interacting atoms that weakly couple to a guided optical mode. Dissipation removes uncorrelated photons while preferentially transmitting highly correlated photons created through collectively enhanced nonlinear interactions. As a result, the transmitted light constitutes a strongly correlated many-body state of light, revealed in the second-order correlation function. The latter exhibits strong antibunching or bunching, depending on the optical depth of the atomic ensemble. The demonstrated mechanism opens a new avenue for generating nonclassical states of light and for exploring correlations of photons in non-equilibrium systems using a mix of nonlinear and dissipative processes. Furthermore, our scheme may turn out useful in quantum information science. For example, it offers a fundamentally new approach to realizing single photon sources, which may outperform sources based on single quantum emitters with comparable coupling strength [3].

[1] S. Mahmoodian, M. Čepulkovskis, S. Das, P. Lodahl, K. Hammerer, A. S. Sørensen, Phys. Rev. Lett. 121, 143601 (2018).
[2] A. Prasad, J. Hinney, S. Mahmoodian, K. Hammerer, S. Rind, P. Schneeweiss, A. S. Sørensen, J. Volz, A. Rauschenbeutel, Nat. Photonics 14, 719 (2020)
[3]European patent pending (PCT/EP2019/075386)

Ephraim Shahmoon (Weizmann Institute of Science)

Multi-channel waveguide QED with atomic arrays in free-space

Atomic arrays are recently considered as efficient light-matter interfaces, relying on their strong collective response to light. We consider light scattering off a 2D array of atoms driven to Rydberg levels in an electromagnetically induced transparency configuration. We show that the problem can be mapped to a generalized model of waveguide QED, consisting of multiple 1D photonic channels (multiple transverse modes), each of which coupled to a corresponding dark-state surface mode of the array. In the Rydberg blockade regime, different dark-state surface excitations block each other, leading to multimode correlated photonic states. We characterize steady-state correlations of the scattered photons using an analytical theory, finding both inter- and intra-channel quantum correlations and entanglement. Our results open new possibilities for multimode many-body physics and quantum information with photons.

Alexandra Sheremet (Observatoire de Paris)

Light-matter interface based on collective and cooperative effects

Light-matter interface is a fascinating research direction, which brings a connection between fundamental nature and practical applications [1]. Thoroughly, understanding of light-matter interactions can lead to significant advancements in quantum technologies such as quantum simulations, quantum information processing, and precision measurements. Beyond these applications, the combination of complex interactions that can occur atom-light interfaces and the level of state-of-the-art experimental control makes these systems promising to investigate new types of physical phenomena and opens interesting links in quantum optics [2,3]. Recently developed techniques of cooling, trapping and localizing atoms in free space and with nanoscale structures allow artificially enhance light-atom interaction and offer a new paradigm to investigate quantum light-matter interfaces [4,5,6]. Moreover, manipulations with density and spatial organization of atoms in a system can bring fascinating results, which are interesting for quantum

information applications. For example, reducing average distance between atoms up to resonant wavelength induces dipole-dipole interaction and results in cooperative effects. These effects in spatially dense atomic ensembles can modify optical properties of the system. Moreover, spatial organization of atoms in ordered arrays and optical lattices causes a manifestation of collective effects. In such systems, long-range spatial order brings dramatic consequences for the light propagation.
In this talk, I will discuss light propagation in an atomic array with distance between atoms less than the resonant wavelength and trapped near a nanofiber surface. The light scattering in such dense atomic configuration is described in terms of microscopic approach based on the standard scattering matrix and resolvent operator formalism. We show theoretically that spatially dense atomic arrays allow obtaining effective light-matter interface and can lead to manifestation of long-lived subradiant states for a properly chosen lattice period. Moreover, we show that presence of an optical nanofiber modifies light-matter interactions and can result in effective light shift and superradiant effect.

[1] K. Hammerer et al., Quantum interface between light and atomic ensembles, Rev. Mod. Phys. 82, 1041 (2010).
[2] D.E. Chang, V. Vuletić, and M.D. Lukin, Quantum nonlinear optics – photon by photon, Nat. Photo. 8 (9), 685 (2014)
[3] A.S. Sheremet, M.I. Petrov, I.A. Iorsh, A.N. Poddubny, Waveguide quantum electrodynamics: collective radiance and photon- photon correlations, ArXiv:2103.06824 (2021).
[4] E. Vetsch et al., Optical interface created by laser-cooled atoms trapped in the evanescent field surrounding an optical nanofiber, Phys. Rev. Lett. 104, 203603 (2010).
[5] N.V. Corzo, B. Gouraud, A. Chandra, A. Goban, A.S. Sheremet, D.V. Kupriyanov, and J. Laurat, Large Bragg reflection from one-dimensional chains of trapped atoms near a nanoscale waveguide, Phys. Rev. Lett. 117, 133603 (2016);
[6] D.F. Kornovan, N.V. Corzo, J. Laurat, and A.S. Sheremet, Extremely subradiant states in a periodic one-dimensional atomic array, Phys. Rev. A 100, 063832 (2019);

Irfan Siddiqi (Lawrence Berkeley National Laboratory, Berkeley)
Quantum non-demolition detection of single itinerant microwave photons

Single photon detectors have been demonstrated at microwave frequencies, but a single detector with high quantum efficiency, non-destructive detection, a low dark count rate, and broad detection bandwidth presents a formidable design challenge. An enticing prospect involves using a traveling-wave architecture, which has been used for broadband near-quantum-limited Josephson parametric amplifiers, for the detection of discrete signals. We exploit the superradiant 'bright' and subradiant 'dark' states that are formed when superconducting transmon qubits are coupled an appropriate distance from each other on a waveguide. Detuning each transmon inhomogeneously from the operating frequency leads to coupling of the bright and dark states which allows for absorbed photons to be trapped for longer than the inverse of the absorption bandwidth. We utilize this long interaction time to achieve high-fidelity measurements of the photon number in the ensemble.

Rahul Trivedi (Max-Planck-Institute for Quantum Optics)
Simulation methods for non-Markovian quantum optics

Non-Markovian quantum optical systems are characterized by bosonic environments with a frequency dependent coupling constant to a local quantum system (such as an atom or solid-state emitter). Here, I will present several results aimed at developing and understanding methods to analytically and computationally analyze the dynamics of such systems. I will present an analytical scattering-theory based approach to understanding single and two-photon transport through (a class of) non-Markovian quantum optical systems and apply them to understanding optimal excitation of bound-states in continuum. Next, I will present a unified and rigorous convergence theory for several numerical simulation (finite difference methods, pseudo-mode theory and star-delta transformations) used in practice and provide provable error estimates and convergence guarantees for these methods.

Kanu Sinha (Princeton University)

Quantum Electrodynamics of High-impedance Transmission Lines

Recent experiments have illustrated that the system of a Josephson atom coupled to a high impedance Josephson junction array (JJA) provides a tunable platform for realizing light-matter interactions across various coupling strength regimes. We study the hybridization between the atomic and JJA modes and the radiative properties of the artificial atom in such a system. We show that there are two regimes of strong and weak hybridization that can be realized when the atom is coupled to the JJA (i) galvanically and (ii) via a coupler, respectively. Considering the atomic frequency to be tunable across the photonic band edge, we find that in the weak hybridization regime there is a distinct spatially localized atomic mode both when the atomic frequency lies within and outside of the photonic band. However, for strong atom-JJA hybridization the atomic mode is delocalized both spatially and spectrally within the band. In this regime concepts such as spontaneous emission and Lamb shift are not well-defined as this situation represents a case of non-perturbative 1+1D quantum electrodynamics. We present a theoretical framework and a conceptual basis that replaces radiative corrections in the non-perturbative regime, bridging the perturbative and the non-perturbative limits.

Andreas Wallraff (ETH Zurich)

Transferring Quantum States and Creating Entanglement Across a 30-Meter-Long Superconducting Waveguide

Superconducting circuits are a strong contender for realizing quantum computing systems. Constructing such systems with many thousands, possibly millions of superconducting qubits will likely require linking several computing nodes housed in their dedicated cryogenic systems into a larger networked cluster. Such networks could operate at optical frequencies using fiber links but would require large bandwidth and high-fidelity microwave-to-optical conversion. At ETH Zurich, in a radically different approach, we have designed, realized, and tested a first quantum microwave link which allows superconducting-circuit-based quantum processors located in different systems to directly exchange quantum information [1] over distances of up to 30 meters. This link, for a quantum computer, takes the role of a network transferring data between computing nodes located in a high-performance computing data center. However, unlike its conventional counterparts, our data link is operated at ultra-low temperatures, close to the absolute zero. This allows our quantum data link to directly connect to quantum processors operating at the same temperature [2]. Using this system, we transfer qubit states and generate entanglement on demand with high transfer and target state fidelities. The system we have constructed is a first of its kind in the world and could play an important role in both growing the power of quantum computers in the future and allowing for fundamental quantum science experiments.

[1] P. Magnard et al., Phys. Rev. Lett. 125, 260502 (2020)
[2] P. Kurpiers et al., Nature 558, 264-267 (2018)

Christopher Wilson (University of Waterloo)

Engineering the Level Structure of a Giant Artificial Atom in Waveguide QED

Engineering light-matter interactions at the quantum level has been central to the pursuit of quantum optics for decades. Traditionally, this has been done by coupling emitters, typically natural atoms and ions, to quantized electromagnetic fields in optical and microwave cavities. In these systems, the emitter is approximated as an idealized dipole, as its physical size is orders of magnitude smaller than the wavelength of light. Recently, artificial atoms made from superconducting circuits have enabled new frontiers in light-matter coupling, including the study of "giant" atoms which cannot be approximated as simple dipoles. Here, we explore a new implementation of a giant artificial atom, formed from a transmon qubit coupled to propagating microwaves at multiple points along an open transmission line. The nature of this coupling allows the qubit radiation field to interfere with itself leading to some striking giant-atom effects. For instance, we observe strong frequency-dependent couplings of the qubit energy levels to the electromagnetic modes of the transmission line. Combined with the ability to in situ tune the qubit energy levels, we show that we can modify the relative coupling rates of multiple qubit transitions by more than an order of magnitude. By doing so, we engineer a metastable excited state, allowing us to operate the giant transmon as an effective lambda system where we clearly demonstrate electromagnetically induced transparency.

David Zueco (CSIC-Universidad de Zaragoza)

Coupling magnetic molecules to waveguides

In this talk I will review both the theory and the experiments of magnetic (waveguide) QED. I.e. magnetic molecules coupled to superconducting waveguides. Several applications will be discussed: broadband spectroscopy, coupling enhancement and Fano resonances. Besides, I will discuss the competition between intrinsic magnetic interactions (e.g. dipolar, exchange...) and light mediated ones, here the suppression or enhancement of different superradiant phenomena will be explained.

Abstracts of Posters

Andres Agusti (IFF)

Genuine Entanglement in Three-Mode Spontaneous Parametric Down-conversion

Recently, our collaborators have reported the first experimental observation of three-mode spontaneous parametric downconversion (C.W. Sandbo Chang et al, Phys.Rev.X011011 (2020)). These results form the basis of an exciting new paradigm of three-photon optics in which, among other phenomena, three-mode squeezed states are generated from quantum vacuum. It has been argued that these states will not possess genuine tripartite entanglement (E.A.R. González et al. Phys.Rev.Lett. 120,043601 (2018)). However, we show that this is not the case: there is entanglement but it is revealed only when three-mode correlations are considered as witnesses. Therefore, a new notion of multipartite entanglement emerges from our results: tripartite genuine *non-gaussian* entanglement, and three-mode squeezed states are its paradigmatic representatives. This opens the door to new entanglement resources and further quantum-technological applications in the framework of three-photon quantum optics.

Gian Marcello Andolina (ICFO)

Theory of Photon Condensation in a Spatially-Varying Electromagnetic Field

The realization of equilibrium superradiant quantum phases (photon condensates) in a spatially-uniform quantum cavity field is forbidden by a "no-go" theorem stemming from gauge invariance. We here show that the no-go theorem does not apply to spatially-varying quantum cavity fields. We find a criterion for its occurrence that depends solely on the static, non-local orbital magnetic susceptibility ¥chi_orb(q), of the electronic system (ES) evaluated at a cavity photon momentum $\hbar$q. Only 3DESs satisfying the Condon inequality ¥chi_orb(q)>1/(4¥pi) can harbor photon condensation. For the experimentally relevant case of two-dimensional (2D) ESs embedded in quasi-2D cavities the criterion again involves ¥chi_orb(q) but also the vertical size of the cavity. We use these considerations to identify electronic properties that are ideal for photon condensation. Our theory is non-perturbative in the strength of electron-electron interaction and therefore applicable to strongly correlated ESs.

Javier Argüello-Luengo (ICFO)

Single-photon and single-atom optomechanical strong coupling

Single atoms coupled to a cavity offer unique opportunities as quantum optomechanical devices because of the low atomic mass and strong interaction with light. We discuss and optimize the conditions needed to achieve the single-photon strong coupling regime of optomechanics, where the scattering of single photons becomes entangled with the atomic motional wavefunction. We show that this can lead to a per-photon motional heating that is significantly larger than the single-photon recoil energy, as well as non-classical features in second-order time correlations of the emitted light. Furthermore, we show that it can be realized in current experiments. As this regime has been elusive to reach in other optomechanical platforms, our result opens the door to the realization of qualitatively different phenomena and applications based on optomechanical systems.

Kisa Barkemeyer (Technische Universität Berlin)

Boosting energy-time entanglement using coherent time-delayed feedback

Full list of authors:

K. Barkemeyer, M. Hohn, S, Reitzenstein and A. Carmele

Energy-time entangled photon pairs are well-suited carriers of quantum information in long-distance quantum networks since this type of entanglement is robust to mode dispersion when transported in fibers. The Franson interferometer allows to visualize the energy-time entanglement of two photons emitted from a three-level system in ladder configuration via an interference in the second-order coherence function [1]. We suggest to control the visibility of this interference via a coherent time-delayed feedback mechanism [2]. Modeling the non-Markovian dynamics within the matrix product state framework, we show that the visibility can be increased significantly by slowing down the decay of the upper state of the three-level system. Since we find a high visibility in parameter regimes where this is usually not the case, our method opens up the path to new sources of highly energy-time entangled photon pairs.

[1] J. D. Franson, Phys. Rev. Lett. 62, 2205 (1989).
[2] K. Barkemeyer, M. Hohn, S. Reitzenstein, and A. Carmele, arXiv:2103.02689.

Miguel Bello (Max Planck Institute for Quantum Optics)

Unconventional Quantum Optics In Topological Waveguide QED

In the past decade, quantum emitters coupled to structured photonic environments have become an exciting playground to investigate novel effects of light-matter interactions. These systems are not only interesting from a fundamental point of view, but also find application in quantum information processing and quantum simulation [1]. In parallel to these advances, the discovery of topological materials has motivated recent developments to export topological concepts into photonics to make light behave in exotic ways [2]. This novel field is just in its infancy and scientists are now starting to explore the consequences of letting quantum emitters interact with topological photons.
In our recent work [3], we predict several unconventional quantum optical phenomena that occur when quantum emitters interact with a topological

waveguide, namely, the photonic analog of the Su-Schrieffer-Heeger model. When the emitters' frequency lies within the topological bandgap, a chiral bound state emerges, which is located on just one side (right or left) of the emitter. In the presence of several emitters, this bound state mediates topological, tunable interactions between them, which can give rise to exotic many-body phases such as double Néel ordered states. Furthermore, when the emitters' optical transition is resonant with the bands, we find unconventional scattering properties and different super/subradiant states depending on the band topology. Remarkably, some of these predictions have recently been demonstrated experimentally in a setup of superconducting qubits coupled to a metamaterial waveguide [4].

[1] D. E. Chang, J. S. Douglas, A. González-Tudela, C.-L. Hung, and H. J. Kimble. Rev. Mod. Phys. 90, 031002 (2018)
[2] Tomoki Ozawa, Hannah M. Price, Alberto Amo, Nathan Goldman, Mohammad Hafezi, Ling Lu, Mikael C. Rechtsman, David Schuster, Jonathan Simon, Oded Zilberberg, and Iacopo Carusotto. Rev. Mod. Phys. 91, 015006 (2019)
[3] M. Bello, G. Platero, J. I. Cirac, and A. González-Tudela. Science Advances Vol. 5, no. 7, eaaw0297 (2019)
[4] Eunjong Kim, Xueyue Zhang, Vinicius S. Ferreira, Jash Banker, Joseph K. Iverson, Alp Sipahigil, Miguel Bello, Alejandro González-Tudela, Mohammad Mirhosseini, Oskar Painter. arXiv:2005.03802 [quant-ph]

Ron Belyansky (University of Maryland)

Frustration-induced anomalous transport and strong photon decay in waveguide QED

We study the propagation of photons in a one-dimensional environment consisting of two non-interacting species of photons frustratingly coupled to a single spin-1/2. The ultrastrong frustrated coupling leads to an extreme mixing of the light and matter degrees of freedom, resulting in the disintegration of the spin and a breakdown of the "dressed-spin", or polaron, description. Using a combination of numerical and analytical methods, we show that the elastic response becomes increasingly weak at the effective spin frequency, showing instead an increasingly strong and broadband response at higher energies. We also show that the photons can decay into multiple photons of smaller energies. The total probability of these inelastic processes can be as large as the total elastic scattering rate, or half of the total scattering rate, which is as large as it can be. The frustrated spin induces strong anisotropic photon-photon interactions that are dominated by inter-species interactions. Our results are relevant to state-of-the-art circuit and cavity quantum electrodynamics experiments.

Sina Böhling (Freie Universität Berlin)

Exceptional points in waveguide emitter systems

We investigate the appearance of degeneracies in waveguide emitter systems, so-called exceptional points (EPs), and ask what they actually mean for the physics of these setups. To this end, we focus on waveguide emitter systems which could be realized in form of qubits coupled to a transmission line. These qubits can be described as an open quantum system whose dynamics follow a Lindblad master equation. Analyzing the Liouvillian spectrum of these open quantum systems, we identify their EPs as a set of parameters where Liouvillian eigenvalues and eigenvectors coalesce. This approach is considered more general than the analysis of non-Hermitian Hamiltonians, whose EPs neglect the influence of quantum jumps. Since the connection between the appearance of EPs and the resulting physical properties remains an open question, we seek to understand their physical signature and what kind of dynamics they induce.

David Castells Graells (Max Planck Institute of Quantum Optics)

Near-coherent atom waveguide QED with atomic dimers

Optical media with tailored dispersion relations are a new paradigm of atom-light interactions. Instead of traditional solid-state nanophotonic waveguides, we consider subwavelength atomic arrays as a conceptually simple, yet rich optical medium. We find that in comparison with coupling individual impurity atoms, using the anti-symmetric state of an atomic dimer as an effective atom avoids coupling to the superradiant chain modes, while maintaining the coupling to the guided modes. This yields a high-fidelity waveguide QED setup, with collective emission from impurity atoms into the guided mode, and a coherent long-range interaction between impurity atoms mediated by the array. The finiteness of the chain and the slow group velocity at the band edge give rise to non-Markovian corrections that are difficult to observe in conventional waveguide QED systems. This paves the way toward observing and exploiting the rich phenomenology of waveguide QED in a clean, atom-based, setup.

Dario Cilluffo (Università di Palermo)

A collisional approach to WQED

Collision models (CM) provide a simple intuitive picture of open quantum dynamics in terms of sequences of two-body collisions between a system and a collection of ancillas simulating the environment. In particular, dealing with memoryless dynamics, CMs prove to be an useful tool to derive Lindblad master equation (ME) governing the evolution of the system. Here we show how this approach can be extended to describe the most generic setup in waveguide QED: a collection of emitters interacting with a guided field at many coupling points, with the focus on the negligible time delay regime. Finally, we show how CMs allow a straightforward description of the mechanism underpinning the origin of decoherence-free evolution and non-trivial decoherence-free Hamiltonians in such systems.

[1] D. Cilluffo, A. Carollo, S. Lorenzo, J. A. Gross, G. M. Palma, and F. Ciccarello, Collisional picture of quantum optics with giant emitters, Phys. Rev. Research 2, 043070 (2020).
[2] A. Carollo, D. Cilluffo, and F. Ciccarello, Mechanism of Decoherence-Free Coupling between Giant Atoms, Mechanism of decoherence-free coupling

between giant atoms Phys. Rev. Research 2, 043184 (2020).

Andrés Rosario Hamann (ETH Zürich)

Strong coupling of double quantum dots to the continuum in the microwave regime

Full list of authors:
A. R. Hamann, C. Ding, E. Al-Tavil, A. Wallraff

Strong coupling of gate defined double quantum dots to a single mode in a microwave resonator has been achieved in a number of platforms. The crucial insight in reaching this regime was increasing the characteristic impedance Z of the microwave resonator, thus leading to larger zero-point fluctuations of the electric field, and, consequently, enhancing
the electric dipole coupling by a factor proportional to ¥sqrt{Z}. However, a simple translation of this scheme to the continuum in a cryogenic microwave setup would be unfeasible, since there all components are matched to the conventional characteristic impedance of 50 Ω. Here, by making use of impedance engineering techniques, we propose a scheme to overcome this limitation, over bandwidths in the order of a GHz. A strongly coupled DQD would then allow us to explore rich physical phenomena, such as the emission of non-classical light under non-equilibrium situations, as well as correlations between multiple DQDs coupled to the same photonic environment. Furthermore, the presence of a band gap (defined by the bandwidth of the impedance-matched region) would allow us to study the interplay between evanescent modes in the waveguide and the DQD, leading to the formation of atom-photon bound states.

Luca Leonforte (University of Palermo)

Vacancy-like Dressed States in Topological Waveguide QED

We identify a class of dressed atom-photon states forming at the same energy of the atom at any coupling strength. As a hallmark, their photonic component is an eigenstate of the bare photonic bath with a vacancy in place of the atom. The picture accommodates waveguide-QED phenomena where atoms behave as perfect mirrors, connecting in particular dressed bound states (BSs) in the continuum with geometrically confined photonic modes. When applied to photonic lattices, the framework establishes a one-to-one correspondence between topologically robust dressed states and topologically robust photonic BSs seeded by a vacancy. This is used to predict new classes of dressed BSs in the photonic Creutz-ladder and Haldane models. In the latter case, states with nonzero local photon flux occur in which an atom is dressed by a photon orbiting around it.

Davide Lonigro (University of Bari & INFN)

Photon-emitter dressed states in a closed waveguide

Full list of authors:
D. Lonigro, P. Facchi, A. D. Greentree, S. Pascazio, F. V. Pepe, and D. Pomarico

One-dimensional quantum systems are attracting increasing attention in the scientific community, both from a fundamental and technological viewpoint. In particular, quantum emitters coupled to electromagnetic fields in waveguides provide a controllable and experimentally feasible testbed to observe interesting physical phenomena.
We study a system made up of one or two two-level quantum emitters, coupled to a single transverse mode of a closed waveguide, and characterize the stable states in which one excitation is steadily shared between the field and the emitters. We unearth finite-size effects in the interactions and identify a family of dressed states that represent the forerunners of bound states in the continuum in the limit of an infinite waveguide. We finally consider the potential interest of such states for applications in the field of quantum information.

Sattwik Deb Mishra (Stanford University)

Quantum control for inhomogeneous broadening compensation in single-photon transducers

A transducer of single photons between microwave and optical frequencies can be used to realize quantum communication over optical fiber links between distant superconducting quantum computers. A promising scalable approach to construct such a transducer is to use ensembles of quantum emitters interacting collectively with electromagnetic baths (waveguides) at optical and microwave frequencies. However, inhomogeneous broadening in the transition frequencies of the emitters can be detrimental to this collective interaction. We utilize a gradient-based optimization strategy to design the temporal shape of the laser field driving the transduction system to mitigate the effects of inhomogeneous broadening. We study the improvement of transduction efficiencies as a function of inhomogeneous broadening in different single-emitter cooperativity regimes and correlate it with a restoration of superradiance effects in the emitter ensembles.

Guillermo F. Peñas (IFF-CSIC)

Protocols for distributed quantum information processing based on microwave photons travelling through bidirectional waveguides

In this work we describe a distributed quantum computer implementation in which superconducting chips are connected by microwave photons sent through cryogenic waveguides. An idea that is experimentally realizable with today’s technology. Making use of this setup, we have demonstrated the feasibility of fast, highly-coherent operations and designed protocols that take advantage of its inherently distributed nature. Our approach, based on a quantum optical modelization of the setup is very versatile, allowing for the exploration of both long and short photon limits. Upon careful tuning of the physical parameters and photon pulse shaping, we are able to achieve perfect quantum state transfer, non-destructive data retrieval and two-qubit gates between distant fridges. We finally consider the application of these operations to some quantum algorithms that may benefit from a distributed architecture, specifically entanglement distribution and QRAM.

Kevin Reuer (Department of Physics, ETH Zürich)
A Universal Quantum Gate Set for Itinerant Microwave Photons

Full list of authors:
K. Reuer, J. Besse, L. Wernli, P. Magnard, P. Kurpiers, A. Wallraff, C. Eichler

Deterministic photon-photon gates enable the controlled generation of entanglement between mobile carriers of quantum information. Such gates have thus far been exclusively realized in the optical domain and by relying on post-selection. Here, we present a non-post-selected, deterministic, photon-photon gate in the microwave frequency range realized in superconducting circuits. We emit photonic qubits from a source chip and route them towards a second similar chip with which we realize a universal gate set by combining controlled absorption and re-emission with single qubit gates and qubit-photon controlled-phase gates. We measure internal quantum process fidelities for both the single and the two-qubit gates in excess of 90 %. This universal gate set has a wide range of potential applications in local area superconducting quantum networks.

Federico Roccati (University of Palermo)
Exceptional behavior of a non-Hermitian topological waveguide QED setup

Full list of authors:
F. Roccati, S. Lorenzo, G. Calajó, G.M. Palma, A. Carollo, F. Ciccarello

Since the seminal paper by Bender [1], non-Hermitian Hamiltonians turned out to be useful tools for the effective description of physical systems, especially classical optical setups [2]. A distinctive feature of non-Hermitian systems are at the so called Exceptional Points (EPs), where the Hamiltonian supports coalescence of eigenstates, on top of usual spectral degeneracies. EPs have been extensively studied at the classical level, especially in Parity-Time-symmetric (PT) systems (a special subclass of non-Hermitian systems), and one of the major quest in this field is exploring quantum effects near EPs [3]. In this talk I will present the physics of a waveguide QED setup of emitters coupled to a non-Hermitian topological waveguide [4]. At the EP, single-atom completely-chiral emission is achieved, atom-photon dressed states with vanishing localization length are formed and thus a nearest neighbor dipole-dipole interaction among emitters is mediated.

[1] Phys. Rev. Lett. 80, 5243 (1998)
[2] Nature Phys 6, 192–195 (2010)
[3] Nat Commun 11, 2454 (2020)
[4] (submitted)

Ariadna Soro Álvarez (Chalmers University of Technology)
Chiral Quantum Optics with Giant Atoms

In quantum optics, it is common to assume that atoms are point-like objects compared to the wavelength of the electromagnetic field they interact with. However, this dipole approximation is not always valid, e.g., if atoms couple toradiation at multiple discrete points. Previous work has shown that superconducting qubits coupled to a one dimensionalwaveguide can behave as such‘giant atoms’ and then can interact through the waveguide without decohering, a phenomenon that is not possible with small atoms. Here, we prove that this decoherence-free interaction is also possible when the coupling to the waveguide is chiral. Furthermore, we derive conditions under which the giant atoms in this architecture exhibit dark states. In particular, we show that unlike small atoms, giant atoms in a chiral waveguide can reach a dark state even outside the driven-dissipative regime, i.e., without being excited by a coherent drive.

Sergi Terradas Briansó (Instituto de Nanociencia y Materiales de Aragón (INMA), CSIC-Universidad de Zaragoza)
Transmission through a waveguide coupled to a molecule

In this work we analyse the role of a the vibrational spectrum of a molecule when it is coupled to the flying photons incoming from a waveguide via its first electronical transistion. The molecule has a vibrational degree of freedom coupled to their electronic level yielding two different bosonic spectra for the ground and excited states, one shifted from the other. Using an input-output like formalism, both numerically and anaytically we compute the transmission coefficient. We show that new absorption bands for energies involving the electronic transition plus a number of vibrational energies are resolved in the transmission. We discuss the inelastic channels for each of the absorption bands. Finally, we explain the transmission peaks of the inelastic channels using the Franck-Condon factors and give a first approximation for the peak's areas.

Carlos Vega García (IFF-CSIC)

Qubit-photon bound states in topological waveguides with long-range hoppings

Quantum emitters interacting with photonic band-gap materials lead to the appearance of qubit-photon bound states that mediate decoherence-free, tunable emitter-emitter interactions. Recently, it has been shown that when these band-gaps have a topological origin, these qubit-photon bound states feature chiral shapes and certain robustness to disorder. In this work, we study the light-matter interactions in an extended SSH photonic model with longer range hoppings that displays a phase diagram with large winding numbers. We first study the features of the qubit-photon bound states when the emitters couple to the bulk modes in the different phases, discern its connection with the topological invariant, and show how to further tune their shape through non-local couplings. Then, we consider the coupling of emitters to the edge modes appearing in the different topological phases. Finally, we provide a possible experimental implementation based on circuit QED systems.

Yidan Wang (University of Maryland, Joint Quantum Institute)

Universality in one-dimensional scattering with general dispersion

relations

Many synthetic quantum systems allow particles to have dispersion relations that are neither linear nor quadratic functions. Here, we explore single-particle scattering in one dimension when the dispersion relation is $¥epsilon(k)=¥pm |d|k^m$, where $m¥geq 2$ is an integer. We study impurity scattering problems in which a single-particle in a one-dimensional waveguide scatters off of an inhomogeneous, discrete set of sites locally coupled to the waveguide. For a large class of these problems, we rigorously prove that when there are no bright zero-energy eigenstates, the S-matrix evaluated at an energy $E¥to 0$ converges to a universal limit that is only dependent on m. We also give a generalization of a key result in quantum scattering theory known as Levinson's theorem---which relates the scattering phases to the number of bound states---to impurity scattering for these more general dispersion relations.

Zhi-Yuan Wei (Max Planck Institute for Quantum Optics)

Generation of isometric tensor network states and its cQED implementation

We show that arbitrary isometric tensor network states (isoTNS) [1] that contain the graph states, toric code states and string-net liquids, can be prepared with sequential quantum circuits whose depth grows linearly with the edge length L of the lattice [as Depth=O(L)] in arbitrary dimension. We then propose a protocol to deterministically prepare photonic isoTNS using an array of sequential photon sources, and provide a physical realization where each source consists of a microwave cavity dispersively coupled to a transmon qubit. Analysis shows this platform can produce a large number of strongly entangled photons with high fidelity and is capable of producing high-dimensional isoTNS.

[1] Michael P. Zaletel and Frank Pollmann, PHYSICAL REVIEW LETTERS 124, 037201 (2020)