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A CAVITY AS A GIANT IMPURITY: INDUCING SPIN LOCALIZATION THROUGH BOUND POLARITONS

Using cavity quantum electrodynamical effects, specifically vacuum electromagnetic fields, to modify material properties has garnered significant attention over the past decade. Broadly, this field is referred to as cavity QED materials. A common example is strong light-matter coupling, achieved when the interaction of material excitations with confined light modes overcomes dissipation and hybridizes to form mixed light-matter eigenstates, known as polaritons. These polaritons inherit properties from both light and matter and exhibit fundamentally new phenomena. A more challenging regime arises when light-matter interactions reach the so-called ultrastrong coupling regime, where, in principle, phases of matter can be modified through light-mediated novel matter-matter interactions.

In this work, we introduce cavity QED materials and present a field-theoretical approach that enables analytical insights in the limit $N \to \infty$ where N represents the number of matter degrees of freedom coupled to light. Following this, we discuss how cavity quantum electrodynamics can alter the magnetism of quantum materials. Finally, we show that the vacuum field can localize spin excitations, leading to the formation of bound polaritons, where the cavity binds spin-wave pairs into localized states.

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A CHIRAL LIGHT-MATTER INTERFACE FOR SUPER-CONDUCTING QUBITS

Improving connectivity and controlling the flow of light within complex networks remains a challenge for solid-state qubit platforms. In this talk, I will discuss our recent work on realizing nonreciprocal light-matter interactions in the microwave domain using a transmon qubit strongly coupled to a 1D waveguide. By modulating the atom-waveguide coupling using magnetic fields, we gain control over the direction of photon emission from the qubit, with the ratio of forward-to-backward coupling rates exceeding 100. I will discuss applications of this platform, including photon-mediated gates between distant qubits and the preparation of many-body dark states in chiral atom arrays.
Work based on: Phys. Rev. X 13, 021039 (2023).

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BOUND STATES AND DYNAMICS IN GIANT ATOM WAVEGUIDE QED SYSTEM

In this talk, we will talk about the bound state in the single and a pair of giant atoms which couple to a coupled resonator waveguide. For the single giant atom system, we will demonstrate how to use the coupling phase to modulate the bound states and the beat phenomenon in the dynamics. For the two giant atom setup, we further illustrate the Rabi oscillation and Fractional population dynamics, which is induced by the bound states in the continuum.

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COMPACT HIGH IMPEDANCE CAVITY ARRAY COLLECTIVELY COUPLED TO A QUBIT

In waveguide quantum electrodynamics, traditional studies often assume that emitters couple to waveguides with linear dispersion, where photon group velocity is independent of the wave vector. However, recent advances in technology have enabled the creation of discrete site waveguides using microwave photonic crystals or superconducting coupled cavity arrays (CCA), which exhibit a quasi-continuous band structure with a cosine dispersion relation.

We introduce a versatile platform based on a low-disorder CCA, composed of ultracompact, high-impedance superconducting resonators made from high kinetic inductance Niobium Nitride (NbN) thin films. An essential aspect of our platform is its low disorder, achieved by minimizing fabrication imperfections that could randomize the frequencies and couplings within the array.

We have implemented and characterized one-dimensional metamaterials with up to 100 resonators, demonstrating various engineered band structures. Additionally, we analyze the platform's resilience to fabrication-induced disorder and its impact on the topological properties of Su-Schrieffer-Heeger (SSH) edge states in short arrays. This analysis, conducted in both frequency and time domains, serves as a metric for assessing metamaterial quality.

Furthermore, we coupled the CCA to a ‘giant’ artificial atom at multiple points, exploring interference effects both spectroscopically and in the time domain. We demonstrated superstrong coupling between the artificial atom and the CCA, highlighting the platform's potential for multimode strong and ultrastrong coupling with quantum emitters.

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CONTINUOUS COHERENT QUANTUM FEEDBACK WITH TIME DELAYS: TENSOR NETWORK APPROACH

Coherent quantum feedback refers to the situation when both the system and its controller are quantum in nature. An exciting scientific frontier in this field is the exploration of phenomena that emerge in a regime when the controller can store and process the quantum state of multiple degrees of freedom. This is the case when time delay in the feedback loop is large, i.e., when the time required for excitations to propagate through the feedback loop is large compared to the time required to emit an excitation. We developed a novel method to solve problems involving quantum optical systems coupled to coherent quantum feedback loops featuring time delays. Our method is based on exact mappings of such non-Markovian problems to equivalent Markovian driven dissipative quantum many-body problems. We show that the resulting Markovian quantum many-body problems can be solved (numerically) exactly and efficiently using tensor network methods. In particular, we show that our method allows solving problems in so far inaccessible regimes, including problems with arbitrary long time delays and arbitrary numbers of excitations in the delay lines. We obtain solutions for the full real-time dynamics as well as the steady state in all these regimes. Finally, motivated by our results, we develop a novel mean-field approach, which allows us to find the solution semi-analytically, and we identify parameter regimes where this approximation is in excellent agreement with our tensor network results.

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CONTROLLING MARKOVIANITY WITH CHIRAL GIANT ATOMS

A hallmark of giant-atom physics is their non-Markovian character in the form of self-coherent feedback, leading, e.g., to nonexponential atomic decay. The timescale of their non-Markovianity is essentially given by the time delay proportional to the distance between the various coupling points. In parallel to this, with the state-of-the-art experimental setups, it is possible to engineer complex phases in the atom-light couplings. Such phases simulate an artificial magnetic field, yielding a chiral behavior of the atom-light system. In my talk I will report a surprising connection between these two seemingly unrelated features of giant atoms, showing that the chirality of a giant atom controls its Markovianity. In particular, by adjusting the couplings' phases, a giant atom can, counterintuitively, enter an exact Markovian regime, irrespectively of any inherent time delay. I will illustrate this mechanism as an interference process and via a collision model picture.

Ref: F. Roccati and D. Cilluffo. Phys. Rev. Lett. 133, 063603 (2024)

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COUPLING QUANTUM SYSTEMS WITH A LASER LOOP

Many of the breakthroughs in quantum science and technology rely on engineering strong Hamiltonian interactions between quantum systems. Typically, strong coupling relies on short-range forces or on placing the systems in high-quality electromagnetic resonators, which restricts the range of the coupling to short distances. In this talk I will show how a loop of laser light can generate Hamiltonian coupling over a distance [1] and report experiments using this approach to strongly couple a nanomechanical membrane oscillator and an ultracold atomic spin ensemble across one meter through a room-temperature environment [2]. We observe spin-membrane normal mode splitting, coherent energy exchange oscillations, two-mode thermal noise squeezing, and dissipative coupling with exceptional points [2]. We furthermore realize an optical coherent feedback loop and use it for cooling of the membrane vibrations [3,4]. Our experiments demonstrate the versatility and flexibility of light-mediated interactions, a powerful tool for quantum science that offers many further possibilities and is readily applicable to a variety of different systems.

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[4] M. Ernzer, M. Bosch Aguilera, M. Brunelli, G.-L. Schmid, T. M. Karg, C. Bruder, P. P. Potts, and P. Treutlein, Optical coherent feedback control of a mechanical oscillator, Phys. Rev. X 13, 021023 (2023)."

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DETERMINISTIC REMOTE ENTANGLEMENT USING A CHIRAL QUANTUM INTERCONNECT

Quantum interconnects facilitate entanglement distribution between non-local computational nodes. For superconducting processors, microwave photons are a natural means to mediate this distribution. However, many existing architectures limit node connectivity and directionality. In this work, we construct a chiral quantum interconnect between two nominally identical modules in separate microwave packages. We leverage quantum interference to emit and absorb microwave photons on demand and in a chosen direction between these modules. We optimize the protocol using model-free reinforcement learning to maximize absorption efficiency. By halting the emission process halfway through its duration, we generate remote entanglement between modules in the form of a four-qubit W state with 62.4±1.6% (leftward photon propagation) and 62.1±1.2% (rightward) fidelity, limited mainly by propagation loss. This quantum network architecture enables all-to-all connectivity between non-local processors for modular and extensible quantum computation.

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DIRECTIONAL EMISSION IN A GIANT ATOM SUPERSTRONGLY COUPLED TO A HIGH-IMPEDANCE CAVITY ARRAY.

In waveguide quantum electrodynamics, traditional studies often assume that emitters couple at a single point to waveguides with linear dispersion, where photon group velocity is independent of the wave vector. However, recent technological advancements have enabled the creation of discrete site waveguides using microwave photonic crystals or superconducting coupled cavity arrays (CCA), which exhibit a quasi-continuous band structure with a cosine dispersion relation. In addition, artificial atoms can be coupled at multiple points of a mode's wavelength beyond the standard dipolar approximation, forming giant atoms [1]. In this work, we experimentally study a transmon qubit coupled to multiple cavities of a CCA, made with a high-kinetic inductance metamaterial [2]. The system's geometry allows us to reach the superstrong coupling regime, where the coupling between the CCA modes and the qubit far exceeds the free spectral range of the CCA ($g/\Delta\omega > 11$). We measure the atomic ratio in the eigenmodes of the system with a precision down to 10^(-2) and find, as expected from theory, a low qubit participation in the eigenmodes where $g/\Delta\omega > 1$. Additionally, reflection measurements of the CCA reveal tunable directional behavior in the superstrong coupling regime.

[1] Kockum, A. Frisk. Quantum optics with giant atoms—the first five years, International Symposium on Mathematics, Quantum Theory, and Cryptography. Vol. 33. Singapore: Springer, 2021.

[2] Jouanny, Vincent, et al. Band engineering and study of disorder using topology in compact high kinetic inductance cavity arrays. arXiv preprint arXiv:2403.18150 (2024).

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DYNAMICAL EXCITATION CONTROL AND MULTIMODE EMISSION OF AN ATOM-PHOTON BOUND STATE

Atom-photon bound states arise from the coupling of quantum emitters to the band-edge of dispersion-engineered waveguides. Thanks to their tunable-range interactions, they are promising building blocks for quantum simulators. Here, we study the dynamics of an atom-photon bound state emerging from coupling a frequency-tunable quantum emitter -- a transmon-type superconducting circuit -- to the band-edge of a microwave metamaterial. Employing precise temporal control over the frequency detuning of the emitter from the band-edge, we examine the transition from adiabatic to non-adiabatic behavior in the formation of the bound state and its melting into the propagating modes of the metamaterial. Moreover, we experimentally observe multi-mode emission from the bound state, triggered by a fast change of the emitter's frequency. Our study offers insight into the dynamic preparation of APBS and provides a method to characterize their photonic content, with implications in quantum optics and quantum simulation.

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ENGINEERING GIANT ATOMS WITH SUPERCONDUCTING CIRCUITS

TBD

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GIANT ATOM WITH DISORDER

Most studies of giant atom assume the coupling legs are equally spaced and the coupling strengths are constant. Such regular setting of system parameters facilitates analytical predictions of unique and novel phenomena for giant atom, i.e., decoherence-free interaction (DFI) and bound states in continuum (BIC). However, in the realistic experiments to implement giant atom, there is always some level of disorder both in distances and strengths of coupling legs. We investigate the effects of disorder on the giant atom related phenomena. We find that the phenomena of DFI and BIC are suppressed by the disorders of coupling distance and strength suppress basically in a similar manner in Markovian regime but are more sensitive to distance disorder in non-Markovian regime. I will also discuss the impact of the nonuniform distances and coupling strengths on the chiral emission, and the possibility to manipulate travelling single photon with non-Markovinan giant atom.

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GIANT EMITTERS MEET THE NON-HERMITIAN SKIN EFFECT

Giant emitters derive their name from nonlocal field-emitter interactions and feature diverse self-interference effects. Most studies on giant emitters have focused on Hermitian waveguides or photonic lattices. In this talk, I will introduce a series of peculiar behaviors of giant emitters coupled to a non-Hermitian bath, specifically the Hatano-Nelson (HN) model, which features the non-Hermitian skin effect due to the asymmetric tunneling rates. I will show that the behaviors of the giant emitters are closely related to the stability of the bath. In particular, giant emitters can exhibit an exclusive amplification mechanism, which we find enables decoherence-free dynamics even in the presence of additional dissipation in the system. The protection from dissipation arises from the cooperation of the non-Hermiticity and the self-interference effect and is therefore lacking for normal emitters. These findings not only provide a deeper insight into the interplay of non-Hermiticity and various interference effects, but also have potential applications in engineering exotic spin Hamiltonians and quantum networks.

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GIANT SPIN ENSEMBLES IN WAVEGUIDE MAGNONICS

The dipole approximation is usually employed to describe light-matter interactions under ordinary conditions. With the development of artificial atomic systems, 'giant atom' physics provokes much interest, where the scale of atoms is comparable to or even greater than the wavelength of the light they interact with, and the dipole approximation is no longer valid. It reveals interesting physics impossible in small atoms and may offer useful applications. Here we experimentally demonstrate the giant spin ensemble (GSE), where a ferromagnetic spin ensemble interacts twice with the meandering waveguide, and the coupling strength between them can be continuously tuned from finite (coupled) to zero (decoupled) by varying the frequency. In the nested configuration, we investigate the collective behavior of two GSEs and find extraordinary phenomena that cannot be observed in conventional systems. Our experiment offers a new platform for 'giant atom' physics.

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GIANT ATOMS WITH TUNABLE CHIRAL BOUND STATES AND REALIZING QUANTUM OPTICS IN STRUCTURED ENVIRONMENTS WITH GIANT ATOMS

We propose [1] tunable chiral bound states in a system composed of superconducting giant atoms and a Josephson photonic-crystal waveguide (PCW), with no analog in other quantum setups. The chiral bound states arise due to interference in the nonlocal coupling of a giant atom to multiple points of the waveguide. The chirality can be tuned by changing either the atom-waveguide coupling or the external bias of the PCW. Furthermore, the chiral bound states can induce directional dipole-dipole interactions between multiple giant atoms coupling to the same waveguide. Our proposal is ready to be implemented in experiments with superconducting circuits, where it can be used as a tunable toolbox to realize topological phase transitions and quantum simulations.

We propose [2] to realize structured light-matter interactions by engineering multiple coupling points of hybrid giant atom–conventional environments without any periodic structure. We present a general optimization method to obtain the real-space coupling sequence for multiple coupling points. We report a broadband chiral emission for frequency-tunable giant emitters, with no analog in other quantum setups. Moreover, we show that the QED phenomena in the band-gap environment, such as fractional atomic decay and dipole-dipole interactions mediated by a bound state, can be observed in our setup. Numerical results indicate that our proposal is robust against fabrication disorders of the coupling sequence. Our work opens up a route for realizing unconventional light-matter interactions.

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[2] X. Wang, Huai-Bing Zhu, T. Liu, and F. Nori, Realizing quantum optics in structured environments with giant atoms, Phys. Rev. Research, 6, 013279 (2024). https://doi.org/10.1103/PhysRevResearch.6.013279

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NONLINEAR WAVEGUIDE QED WITH GIANT ATOMS

Multi-photon QED phenomena have attracted a lot of interests due to strong interactions between individual photons. The nonlinear quantum optics with photon-by-photon interactions, is totally different from its single-photon counterpart. In the first part of this talk, we consider the emitters of giant atom form. Given that there are phase differences between legs of giant atoms, quasi-EM particles with strongly correlated photons, named as doublons, will be unidirectionally emitted. We reveal the chirality is led by the combined contributions of different interference paths. In the second part of this talk, we will briefly discuss the many-body interactions between giant atoms with nonlinear waveguide hosting traveling-wave parametric gain. Application examples will also be discussed for both two parts.

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PRODUCTION OF SCHRÖDINGER CAT AND PAIR-CAT STATE QUANTUM WAVE PACKETS BY RESERVOIR ENGINEERING

We present a hardware-efficient approach for generating propagating non-Gaussian bosonic states on superconducting circuit platforms. This method enables secure quantum communication between distant quantum memories by deterministically preparing microwave-traveling wave packets. Rather than producing the non-Gaussian states in the eigenmode of a cavity by a high-order nonlinear Hamiltonian and subsequently releasing it to a waveguide, we propose and analyze a scheme that applies coherent excitation and a combination of linear and non-linear losses to form and emit Schrödinger cat states directly into cavity output pulses. By leveraging the effective anti-Hermitian Hamiltonian induced by losses—which achieves high-order nonlinearities more easily than its Hermitian counterpart—the technique enables efficient, deterministic creation of complex propagating quantum states, including two- and four-component cat states, grid states, and pair cat states.

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QUANTUM OPTICS NEAR PHOTONIC FLAT BANDS

Flat bands (FBs) are energy bands with zero group velocity, which in electronic systems were shown to favor strongly correlated phenomena. Although photons are intrinsically non-interacting particles, it is still possible to witness (even in this simple case) signatures of light-matter interaction in a FB, that can be harnessed for quantum technologies and metrology. In this seminar, we will focus on a system in which emitters are coupled to the photonic analogue of a FB, a setup within reach in state-of the-art experimental platforms, e.g. superconducting circuits. For instance, we will discuss the emergent dipole-dipole interactions between emitters in the dispersive regime, whose strength decays exponentially with distance with a characteristic localization length which, unlike typical behaviors with standard bands, saturates to a finite value as the emitter's energy approaches the FB. Remarkably, we find that the localization length grows according to an analytically derived universal scaling law valid for a large class of FBs both in 1D and 2D. Furthermore, we will discuss the transport properties of light around the FB frequency showing how, due to the dispersionless nature of a FB, transport happens through bound states-assisted tunneling. This phenomenon can be harnessed in principle to develop an on-demand Notch filter for light.

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QUANTUM OPTICS WITH GIANT ATOMS IN A STRUCTURED PHOTONIC BATH

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 for the first time settled within a general theory based on the Green's function. This encompasses, within a comprehensive framework, effects such as decoherence-free Hamiltonians (DFHs) in a waveguide and emergence of atom-photon bound states (BSs) in structured lattices. As a major application, we provide for the first time a general criterion to predict/engineer DFHs of giant atoms, which can be applied both in and out of the photonic continuum and regardless of the structure or dimensionality of the photonic bath. This is used to show novel DFHs in 2D baths such as a square lattice, photonic graphene and an extended photonic Lieb lattice.

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RYDBERG GIANT ATOMS IN THE OPTICAL REGIME

We propose a synthetic giant-atom platform operating in the optical regime, composed of two interacting Rydberg atoms coupled to a photonic crystal waveguide and driven by a coherent field. In this setup, giant-atom effects, such as phase-dependent decay and tunable effective chirality, emerge as distinct features. Specifically, the double Rydberg excitation decays in a phase-dependent manner in the short-time regime, while the onset of atomic entanglement becomes prominent in the long-time regime, influenced by Rydberg intrinsic decay toward non-guided modes. By geometrically adjusting the incident direction of the driving field, controllable chirality can be achieved, enabling on-demand switching of nonreciprocal photon scattering direction and offering a novel approach to realizing effective chiral couplings. Moreover, with multiple driving fields, the platform can function as a frequency converter with asymmetric efficiency, significantly enhanced by effective chiral couplings. These findings advance the understanding of giant-atom physics and offer promising applications in tunable frequency conversion, chiral quantum optics, and quantum information processing in the optical domain.

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SCATTERING FROM ONE AND MORE ATOMS IN WAVEGUIDE QED

In this talk, I'll review some earlier results on measuring the field scattered from one and more atoms in a one-dimensional waveguide. Then I will discuss some new analytical and numerical results on the statistical properties of coherent light scattered on one, two and more atoms in the waveguide as well as the relation to unconventional saturation [1].

[1] Unconventional saturation effects at intermediate drive in a lossy cavity coupled to few emitters, T Karmstrand, B Rousseaux, AF Kockum, T Shegai, G Johansson Physical Review A 108 (5), 053706

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TWO-PHOTON PHYSICS AND QUANTUM GATES WITH TWO-LEVEL EMITTERS

The search for deterministic conditional gates between photons remains as a major objective within the quantum optics and waveguide QED community. Many proposals have emerged using different quantum non-linear media such as Rydberg atoms, Kerr non-linearities or V-type emitters. We wanted to answer the question: can the simplest form of quantum non-linearity—a two-level emitter—be harnessed to construct an effective conditional gate? The use of two-level emitters has posed challenges, as strong photon correlations usually come at the price of significant distortions in the wavepacket spectrum. In this presentation, I will discuss our approach to overcoming these limitations through a novel architecture. This design can be realized within a two-mode chiral waveguide QED framework, such as the one resulting from employing a two-level emitter coupled to a topological waveguide or connected to two optical fibers.

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EMISSION OF (GIANT) ATOMS UNDER AN ELECTRIC FIELD

Giant atoms allow for two major effects: engineered coupling to field modes and time-delayed non-Markovian dynamics. Here, we discuss two novel paradigms for these phenomena, both arising in a photonic lattice (implemented through a 1D or 2D coupled-cavity array) with an applied synthetic electric field.

We first consider a 2D lattice implementing photonic graphene with an open gap. We propose that, by relying on giant atoms, one can combine ideas from valleytronics [1] with quantum optics to produce chiral light orthogonal to the electric field direction, without the need to break time-reversal symmetry of the lattice [2].

We then consider a simple 1D array with an applied electric field, where Bloch oscillations are known to occur. We show that an atom emitting into such a lattice generally undergoes non-Markovian dynamics. In a suitable regime, this resembles the dynamics of an atom in a long, multi-mode, perfect cavity (despite no true mirrors being present), with the photon time delay embodied by the Bloch oscillations period [3].

[1] J. R. Schaibley et al., *Valleytronics in 2D materials*, Nature Reviews Materials 1, 1 (2016).
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WAVEGUIDE QUANTUM THERMODYNAMICS WITH SUPERCONDUCTING CIRCUITS

Experiments in quantum thermodynamics require dual capabilities: the ability to coherently manipulate a quantum system, and the ability to couple it to heat baths and perform measurements of heat currents and their fluctuations. These needs can be met by augmenting the established toolbox of circuit quantum electrodynamics with the use of thermally populated microwave waveguides as heat baths - a combination which I refer to as waveguide quantum thermodynamics. I will present our recent experiments in which we leverage this combination for fundamental studies in the thermodynamics of heat engines, refrigerators, and precision. These experiments take advantage of symmetry-selective couplings between a superconducting artificial molecule and microwave waveguides, a concept akin to that of giant atoms. I will also present preliminary measurements of a microwave photodetector based on the same concept. Altogether, these experiments demonstrate a comprehensive platform for studies in quantum thermodynamics.