CEWQO30

ERLANGEN

20–24 July 2026

The 30th Central European Workshop on Quantum Optics 2026

Book of abstracts

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Please note that this preliminary programme is still subject to changes. For an up-to-date programme, please refer to the conferences web page: `https://www.oqt.nat.fau.de/events/cewqo30/scientific-program/`.

Invited talks

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Joachim von Zanthier	Collective photon emission of correlated atoms in free space

Metasurface-Enabled Generation of Quantum Structured Light

Sergey I. Bozhevolnyi

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Manipulation of single-photon emission from quantum emitters (QEs) has attracted considerable attention in recent years due to its importance for quantum information technologies in quantum communication, computation, sensing, and metrology. In general, stand-alone QEs (i.e., QEs being placed in a homogenous environment) exhibit several shortcomings that make their use in quantum systems and networks very problematic. Based on the general theoretical framework developed for designing quantum metasurfaces, we have demonstrated that planar QE-coupled metasurfaces, consisting of arrays of subwavelength elements and supporting the propagation of surface plasmon polaritons (SPPs), possess unique capabilities to fully control free-space propagating light waves, allowing one to efficiently mold the single-photon emission from QEs [1].

Here, a general approach for designing single-photon sources of high-dimensional spin-orbital photon beams (FIG. 1) is presented with the overall goal of drastically expanding the degrees of freedom exploited for encoding photons to be used in quantum communications. The main idea is to design on-chip QE-coupled composite metasurfaces that would make full use of spatial freedom and outcouple QE-excited (nonradiative) SPPs into photon emission encoded with vectorial spin-orbital states. We further extend vectorial scattering holography [1] to separately generate the interference patterns of spin-orbital waves (i.e. signal waves) and QE-excited SPPs (i.e. reference waves), which are then superimposed as a Moiré pattern and binarized to be used to fabricate (around a QE) a nanoridge patterned metasurface. The experimentally realized generation of arbitrary vectoral spin-orbital quantum emission in high-dimensional Hilbert spaces is presented with the hybrid-order Bloch spheres (HOBSs), revealing accurate manipulation of arbitrary vectoral spin-orbital states [2].

Furthermore, we generalize this approach to enable on-chip generation of diverse skyrmionic states, which represent topologically stable field configurations that have recently emerged in classical optics as structured light for high-density data applications. Our work thereby establishes a unified framework for on-chip structured quantum light sources, offering versatile control of high-dimensional topological states, such as skyrmions, and advancing scalable quantum photonic technologies.

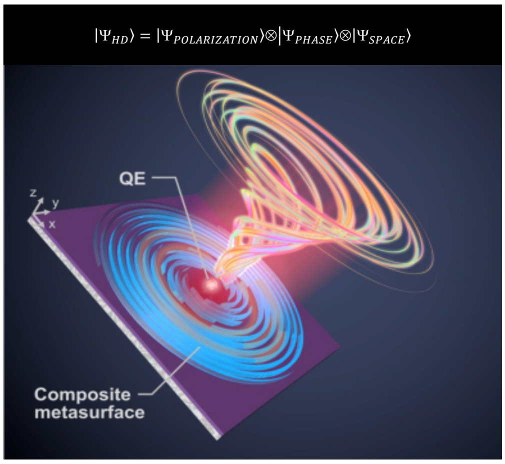

FIG. 1: Conceptual vision of generation of high-dimensional quantum structured light by using composite metasurfaces.

References

[1] Y. Kan, S. I. Bozhevolnyi, Adv. Opt. Mater. **11**, 2202759 (2023).

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The quantum harmonic oscillator on a circle – fragmentation of the algebraic method

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The harmonic oscillator is the workhorse of quantum optics. In suitable units $\omega = m = \hbar = 1$ its Hamiltonian is given by $H = \frac{1}{2}\left(p^2 + q^2\right)$ where q and p are the canonical position and momentum operators respectively. Using creation and annihilation operators $a^\dagger = (q - \mathrm{i}p)/\sqrt{2}$, $a = (q + \mathrm{i}p)/\sqrt{2}$ the Hamiltonian is equivalently written in normal and antinormal ordered form $H_N = a^\dagger a + \frac{1}{2}$, $H_A = aa^\dagger - \frac{1}{2}$. Using the algebraic ladder method, it is then easily seen that its spectrum is equidistant $\mathbb{N} + \frac{1}{2}$.

In the last decades these methods from quantum optics have made their way into superconducting electrical circuits, central to quantum technology and leading to the 2025 Nobel prize for the discovery of energy quantisation in an electric circuit. There is however an active debate if the charge and flux degrees of freedom in superconductors, which fulfill canonical commutation relations and thereby play the role of p and q respectively, are living on a full line or on a circle [**Devoret21**]. It raises the question if the algebraic method survives on the circle?

We will show [**Facchi26**] that on the circle, the algebraic method fragments: the spectra of H, H_N and H_A are no longer equal and are not equidistant ('harmonic'). In fact, H_A even has a negative eigenvalue $-\frac{1}{2}$. Some levels remain equidistant (Fig. 1).

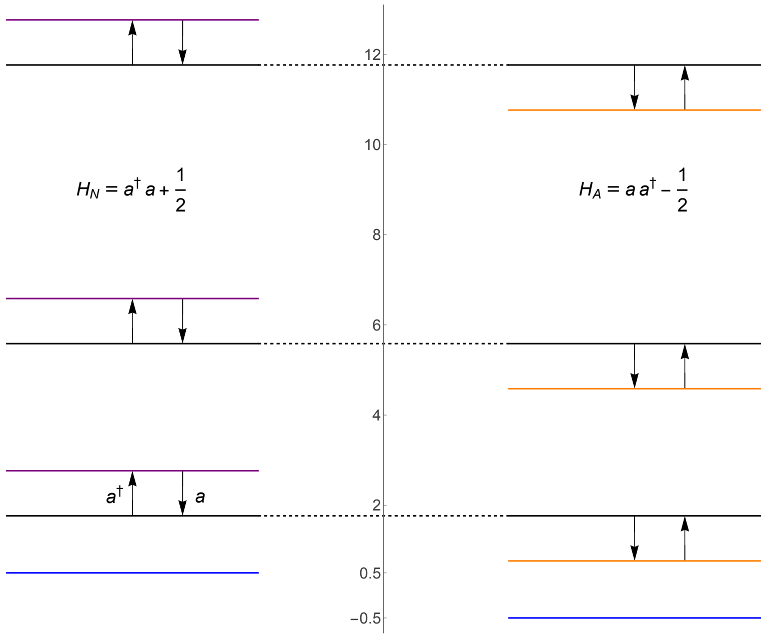

Figure 1: The lowest energy levels of H_N and H_A on a circle of circumference 4. Shown are the remnants of the usual ladder structure: starting on odd levels (black), we obtain new eigenstates of H_N (purple) by applying $a^\dagger$ and of H_A (orange) by applying a. This works only once for each odd level.

These results show that foundational algebraic tools of quantum optics can break down in compact configuration spaces, with potential consequences for oscillator-based descriptions of superconducting quantum circuits.

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Attosecond Interferometry

Nirit Dudovich

Weizmann Institute of Science

Attosecond science has undergone remarkable advances over the past three decades. One of the most important aspects of attosecond spectroscopy is its inherently coherent nature. Resolving this coherence is one of the central challenges of the field and is essential for reconstructing the underlying ultrafast dynamics. As in many areas of physics, coherence is revealed through interferometry. In this talk, I will describe advanced attosecond interferometric schemes and show how they provide direct access to a broad range of fundamental phenomena, from field-driven dynamics in atomic systems to geometrical phenomena and attosecond-scale currents in solids. Finally, I will present a new research direction in which attosecond pulses originate from quantum fluctuations, bridging the fields of quantum optics and attosecond science.

State learning from qubit pairs or trios or . . .

Berge Englert

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A source emits qubits in two pure states at random — that is, the next qubit is of either kind, and we also do not know with which frequency each kind occurs. A tomographically complete measurement on the arriving qubits will not tell us the two states or their frequencies, unless we have additional information. As shown in [1], if the qubits are paired up with partners in the same state, we can infer the states and their frequencies. I'll review this matter and explain how one can learn three states from trios, four states from quartets, and so forth.

Two ongoing experiments realize this situation, one in Beijing and the other in Toronto. I'll report on the progress of both experiments.

As a possible application of such a communication channel, I'll describe a quantum key distribution scheme inspired by the B91 protocol.

[1] P. Agarwal, N. Ali, C. Polvara, M.-I. Trappe, B.-G. Englert, and M. Hillery, *State learning from pairs of states* , Phys. Rev. A **111**, 062428 (2025); e-print arXiv:2409:11120 [quant-ph].

Heralding Probability Optimization for Nonclassical Light Generated by Photon Counting on Gaussian States

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Generation of highly non-classical quantum states of light such as Fock states, Gottesman-Kitaev-Preskill states, superpositions of coherent states, or states exhibiting nonlinear squeezing is essential for optical quantum computing, quantum error correction, quantum metrology and sensing. Arguably the most popular and fruitful approach to engineering such sophisticated quantum states of optical fields consists of conditional heralding schemes, where photon counting measurements on a part of multimode Gaussian state herald successful preparation of the state in signal mode, see Fig. 1(a). Such conditional quantum state generation schemes encompass a majority of both early and recent experiments in the field.

Recently, maximization of the heralding probability for such conditional state preparation schemes has gained significant attention [1-4]. Although generic optimization algorithms can be utilized to maximize the heralding probability, it turns out that this problem can be formulated as finding solution to a system of polynomial equations. Consequently, techniques such as Gröbner basis construction or homotopy continuation can be applied to efficiently find the optimal configuration that maximizes the heralding probability. Here we develop this approach in detail for both single and multiple heralding modes. Our approach greatly benefits from the stellar (or Bargmann) representation of quantum states of bosonic systems and the concept of core states [5].

We show that for a single heralding mode the maximization of the heralding probability p_S can be performed analytically [4] and we investigate the dependence of p_S on the number of counted photons, see Fig. 1(b). Our approach can seamlessly incorporate a bound on the available quadrature squeezing which is highly practically relevant, because the unconstrained optimization may yield squeezing levels that are not experimentally available yet. Our results provide tools for optimization of engineering sophisticated quantum states of light with complex structure in Fock basis and phase space.

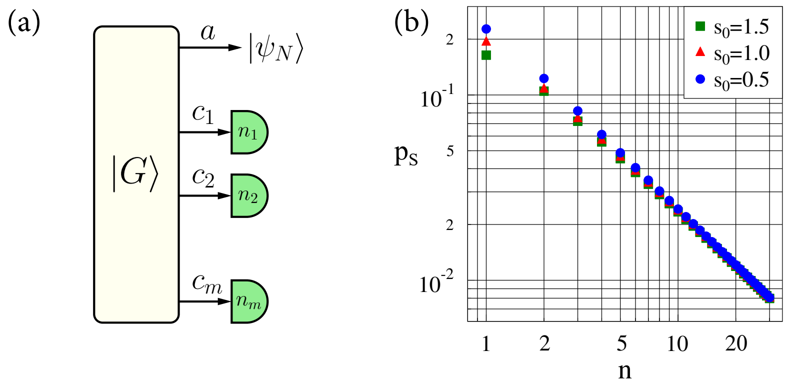

FIG. 1: (a) Conditional generation of nonclassical state $|\psi_N\rangle$ by photon counting measurements on part of multimode Gaussian state $|G\rangle$. (b) Dependence of the maximum heralding probability p_S of state $|\psi_n\rangle \propto (\hat{a}^\dagger + s_0\hat{a})^n|0\rangle$ on the number of counted photons n for single heralding mode.

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Optical Quantum Computers with Quantum Teleportation

Akira Furusawa

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We succeeded in the realization of unconditional quantum teleportation in 1998 [**Furusawa98**]. Then, we invented the scheme of teleportation-based quantum computing in 2013 [**Yokoyama13**]. In this scheme, we can multiplex quantum information in the time domain and we can build a large-scale optical quantum computer only with four squeezers, five-six beam splitters, and two optical delay lines [**Asavanant19**]. We built a real machine of optical quantum computer in Riken and put it on the cloud [**Yokoyama25**]. We will work on a neural network and Shor's algorithm with the real machine.

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Recent Progresses in quantum phase imaging

Marco Genovese

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In the last years the specific properties of quantum states (as entanglement), for long time considered as peculiarities discussed by the restricted community of physicists interested in the foundations of quantum mechanics, became a fundamental resource for the development of new technologies (as quantum communication, computation and imaging), collectively dubbed "quantum technologies".

In this talk, after a general presentation of quantum imaging [**1**] (from sub shot noise imaging to quantum illumination), I will present the most recent progress in quantum phase imaging, demonstrating as, in this case, the problem, typical of sub shot noise imaging [**2**, **3**]], related to the trade-off between resolution and noise suppression can be eliminated [**3**, **4**], paving the way to practical applications of this technique.

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[3] "Quantum enhanced non-interferometric quantitative phase imaging", G. Ortolano, A. Paniate, P. Boucher, C. Napoli, S. Soman, S. F. Pereira, I. Ruo-Berchera, M. Genovese, Light: Science & Applications 12, 171 (2023)

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QUBE-II - Quantum Key Distribution with a CubeSat

Michael Auer, Adomas Baliuka, Moritz Birkhold, Michael Steinberger, Harald Weinfurter, Lukas Knips

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Quantum Key Distribution (QKD) is a method to securely share cryptographic keys between two parties via a quantum channel and an authenticated classical channel. To enable global QKD on a scalable platform, CubeSats provide an attractive approach for fast and cost-efficient research projects.

Based on the QUBE-I mission, which served as a technology pathfinder, the QUBE-II mission [1,2] is a joint research project by the Friedrich Alexander University Erlangen-Nuremberg (FAU), the Max Planck Institute for the Science of Light (MPL), the German Aerospace Center Institute of Communications and Navigation (DLR-IKN), Zentrum für Telematik (ZfT), OHB System AG, and the Ludwig Maximilian University Munich (LMU), and aims to demonstrate QKD from satellite to ground. Using a CubeSat with a volume of about 8 liters, the satellite features amongst others a quantum random number generator (QRNG), three QKD sender payloads, a full-stack postprocessing board, as well as an laser communication terminal. The stack comprising all quantum payloads shown in Fig. 1 poses a rigid cube of only about one liter in volume. The QUBE-II satellite shown in Fig. 2 has been launched on 3rd of May 2026 with a SpaceX Falcon 9 rocket from Vandenberg Space Force Base.

In my talk, I want to highlight the major milestones and achievements towards the launch and discuss the path for the following months. I will focus on the development of both payloads from LMU and will give *lessons learnt* during development of QUBE and QUBE-II.

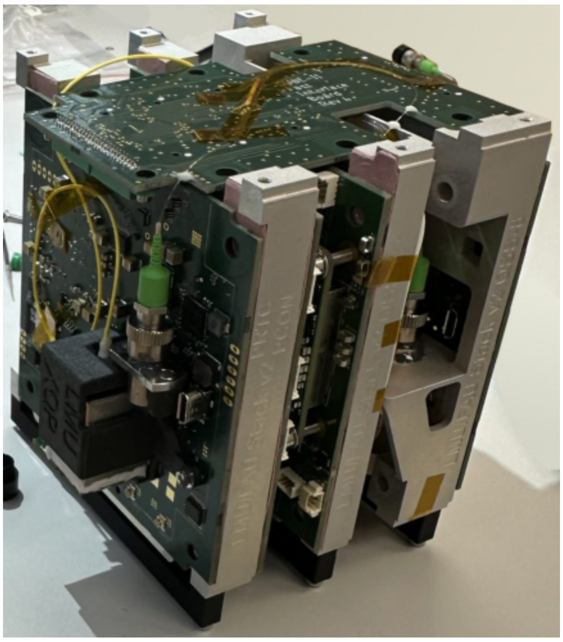

FIG. 1. The quantum payload stack of the QUBE-II mission during payload integration. A *fast interface board* at the top connects the payloads electrically.

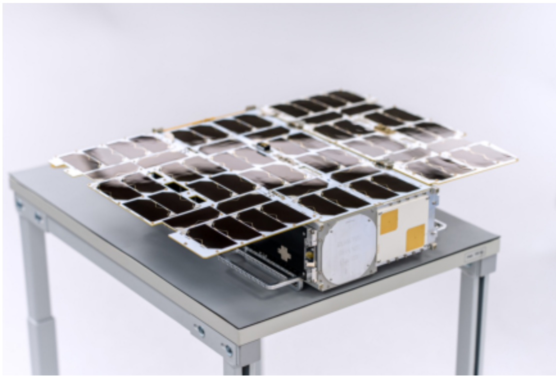

FIG. 2. The fully assembled satellite before integrating into the deployer and the rocket. On the front side, the circular shaped cover protects the 80 mm aperture of the telescope. The S-band patch antenna is placed on the right-hand side. The solar panels are unfolding after ejection from the deployer.

References

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Quantum secret sharing and microwave quantum networks

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Quantum secret sharing (QSS) is one of the key protocols for multipartite quantum networks and can provide an unconditionally secure way to share (secret) quantum states among n players. We analyze the continuous variable (CV) QSS for sharing general single-mode Gaussian quantum states, Fock states and quantum superposition states and demonstrate that quantum steering is the required resource enabling the protocol to proceed securely [1].

We then report the first demonstration of this traditionally quantum optics protocol using continuous quantum variables in microwave regime. We implement the ((2, 3)) threshold CV QSS protocol with $n = 3$ parties in a superconducting microwave quantum network [2], where a subset of at least $k = 2$ players must collaborate to faithfully reconstruct the original secret, represented by a codebook of quantum coherent states (Figure 1). The Dealer superimposes an unknown secret coherent state with one mode of a two-mode squeezing (TMS) entanglement resource and distributes the outcome to the three players, P_i. The TMS entanglement resource is generated by two Josephson Parametric Amplifiers, JPAs, that produce orthogonally squeezed states with squeezing level S. The symmetric beam splitter operations are implemented using microwave hybrid rings. We demonstrate reconstructed-state fidelities that surpass the asymptotic no-cloning threshold of $F_{\mathrm{nc}} = 2/3$ and identify a parameter regime that allows for unconditionally secure communication in the presence of an omnipotent dishonest player.

The concept of multipartite quantum networks, a rapidly developing field holding a promise for hybrid architectures for quantum internet, is a central feature in our work. We not only demonstrate for the first time the CV QSS in a tripartite superconducting network. We also experimentally show how QSS enables other fundamental quantum information processing tasks, such as quantum dense coding and elementary quantum error correction of channel erasures [2] (all the protocols can be realised either in optical or in microwave regime). Ultimately, QSS has the potential to be extended towards different quantum protocols, from conference key agreement to the blind quantum computation.

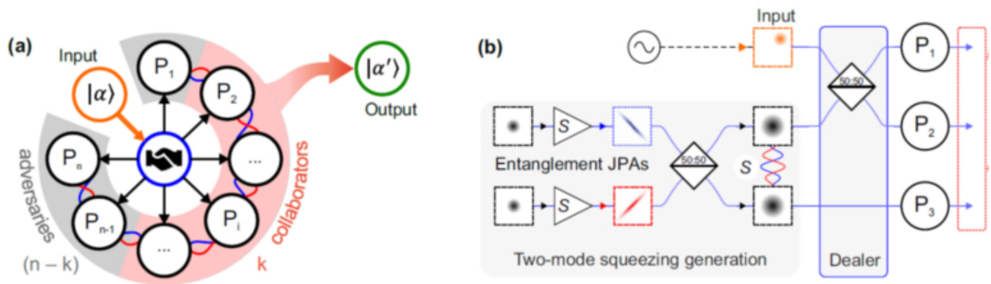

Figure 1: Schematic overview of the $((2, 3))$ threshold QSS protocol implemented in this work [2]. (a) Illustration of $((k, n))$ secret sharing among n players, where only a subset of $k > n/2$ players collaborate to securely reconstruct a secret input state $|\alpha\rangle$. (b) Experimental scheme of the Dealer part of the QSS protocol. The input and resource states are depicted by their phase-space diagrams, showing respective Gaussian-distributed quantum uncertainties.

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Entanglement Control as Quantum Information Resource

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Entanglement is a key resource for quantum technologies ranging from computing through communication to sensing. A unitary entanglement mechanism, based on giant long-range dipole-dipole interactions (DDI), has recently been demonstrated to result in single-polariton entanglement [1]. This mechanism opens the road to novel quantum thermodynamic and sensing applications [2,3]. Another major development concerns DDI-coupled spin networks whose entanglement is subject to symmetry constraints [4] and disorder [5].

Notwithstanding the promise of these trends, the generation of unitary entanglement at the few-quanta level remains challenging. A straightforward substitute is based on conditional measurements (post-selection) of multipartite states [6] but it incurs infidelity. A novel alternative we propose is based on linear stroboscopic phase control that can amplify two-mode photonic entanglement to a giant degree [7].

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7. P. Chattopadhyay et al. (preprint)

Machine-learning enhanced quantum state tomography, and its applications to gravitational wave detectors

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As a crucial diagnostic toolbox for applications with squeezed states, I will illustrate the implementation of our machine-learning (ML) enhanced quantum state tomography (QST) for continuous variables, through the experimentally measured data generated from squeezed vacuum states. Then, I will demonstrate the deployment of ML-based QST onto edge devices, specifically utilizing Field-Programmable Gate Arrays (FPGAs). This implementation was realized using the ”Vitis AI” development environment provided by AMD Inc. The FPGA-based QST offers a highly efficient and precise tool for quantum noise reduction in advanced gravitational wave detectors.

Among various upgrade options, high-frequency (kHz) sensitivity is one of the candidates for KAGRA upgrade. With the cryogenic systems, and there are almost no mysterious noises in high-frequency, the only limitation is the shot noise. As the Chief, KAGRA Squeezing Subsystem, status about vOPO (vacuum optical parametric oscillator) test in NAOJ, and our plans to install KAGRA SQZ Subsystem will also be reported.

Quantum Advantage with Continuous Variable Optical Systems

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Continuous variable (CV) optical quantum systems are achieving remarkable milestones in quantum information science and technology. Recent breakthroughs include the demonstration of quantum computation through Gaussian boson sampling and the application of squeezed states for extreme quantum sensing in gravitational wave detection. These advancements lay the groundwork for future experiments with CV systems.

In this talk, I will present my group's efforts to leverage CV optical quantum systems to achieve quantum advantage in learning and computation. Highlights include demonstrating massive quantum advantage in quantum learning and making critical progress toward quantum computational advantage. I will discuss these developments, address key challenges, and provide an outlook for the future of CV quantum information science.

The effectiveness of the Wigner functions in understanding optimized coherent state-discrimination receivers

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As E. P. Wigner once remarked, there is an "unreasonable effectiveness of mathematics in the natural sciences". Inspired by this idea, we use the Wigner function formalism to explore the physical meaning of the optimal projective measurement minimizing the error probability when distinguishing M-ary phase-shift-keying (PSK) coherent states in a quantum communication system. We start from our recent results concerning the optimization of state-discrimination receivers for continuous-variable communication systems [**1**], where the optimal measurement corresponds to the so-called pretty good measurement (PGM) [**2**]. After introducing the basic ideas of quantum state discrimination and the main results that define the optimal measurement for PSK coherent states, namely the PGM, we turn our attention to the Wigner representation to visualize and better understand the non-classical and non-Gaussian features of the PGM and its relation with the encoded states, clearly showing the connection between the indistinguishability of the encoded states and the quantum features of the PGM. Finally, we analyze how the nature of the PGM changes as both the number M of the PSK states and their energy increase, revealing how the quantum behavior approaches the "classical" limit without reaching it [**3**].

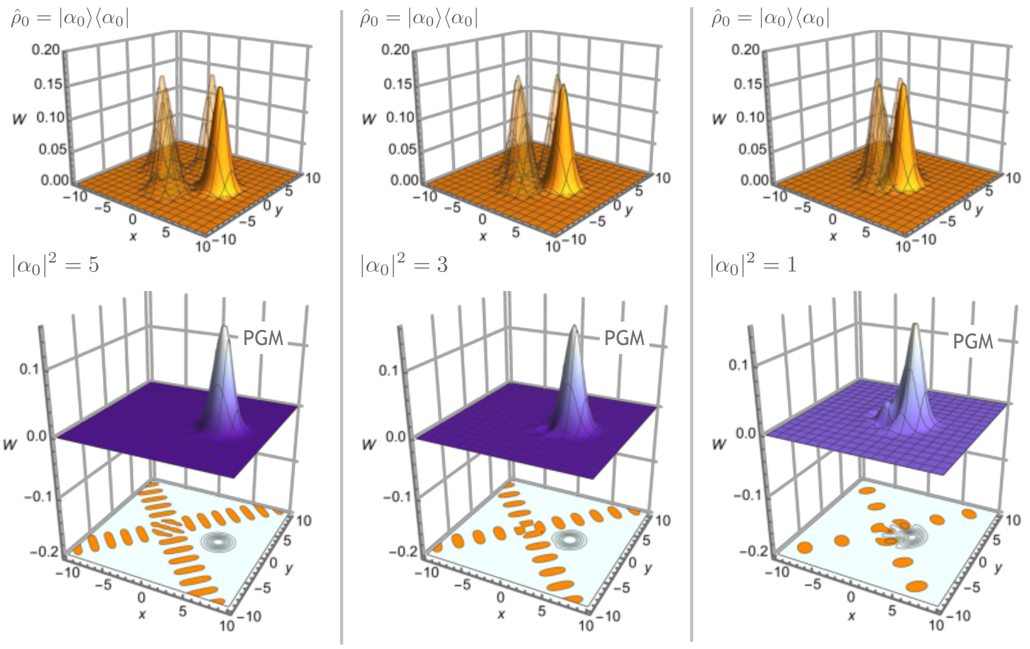

FIG. 1: Plots of the Wigner functions associated with $M = 4$ PSK coherent states for different mean photon values $\alpha_0\ ^2$ (top) and the corresponding Wingner function of the PGM (bottom, only the Wigner function associated with the first element of the PGM is plotted, the others are retrieve by applying a suitable phase shift as for the encoded coherent states).

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Protecting Collectively-Encoded Qubits From Inhomogeneous Dephasing

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In quantum technologies, qubits encoded as collective atomic or solid-state excitations present important practical advantages, such as strong directional coupling to light. Unfortunately, they are affected by inhomogeneities between the emitters, which make them decay into dark states. In most cases, this process is non-Markovian. Through a simple formalism, we unveil a regime where this decay is suppressed by a combination of driving and non-Markovianity. We experimentally demonstrate this "driving protection" using a Rydberg superatom, making its coherent Rabi oscillations last about 14 times longer than the free lifetime of the collective qubit.

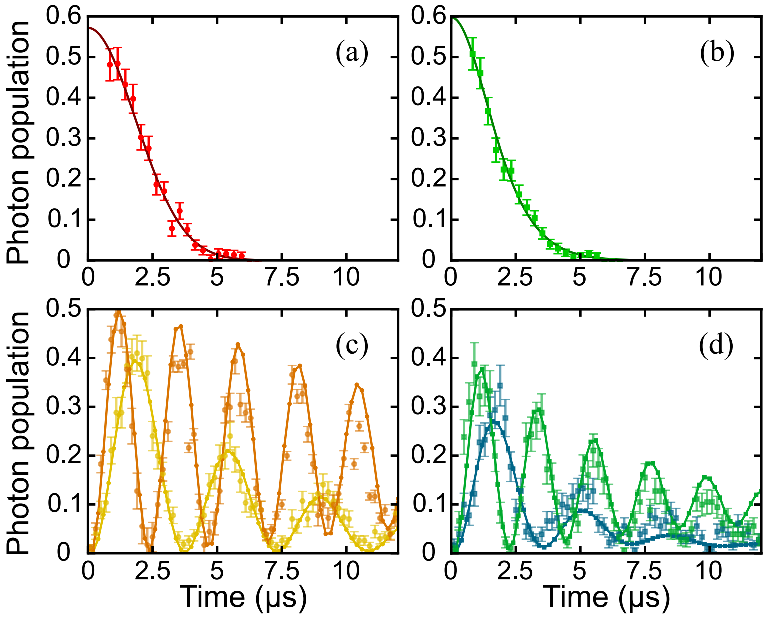

FIG. 1: Experimental illustration of driving protection. Measured population of the excited state of a qubit encoded in an ensemble of ^{87}Rb atoms, mapped to a single photon, for two inhomogeneous spectra: purely Gaussian on the left, a convolution of a Gaussian with a Gamma(3/2) distribution on the right. (a,b): Evolution of the population without Rabi flopping, with a characteristic decay time of $\tau \approx 2.6\,\mu$s. (c,d): When the collective Rabi frequency exceeds the characteristic width of the inhomogeneous spectrum, the oscillations last significantly longer than τ. As predicted by the theory, the shape of the inhomogeneous spectrum plays a central role in the process.

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Scalable Measurements of Continuous-Variable Quantum Light

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Scalability is a key requirement for bringing quantum information technology to a practical level. Continuous-variable quantum optical systems offer a promising route to scalability by allowing the deterministic generation of large-scale entangled states. In contrast to the experimental progress in quantum state generation, realizing *quantum measurements at scale* has remained challenging, where quantum homodyne detection plays essential roles for continuous-variable quantum information processing.

In this talk, I will present large-scale quadrature measurements of quantum light by introducing a camera sensor for quantum homodyne detection. Our camera-based homodyne detection operates in the shot-noise-limited regime, achieving a clearance exceeding 24 dB with negligible crosstalk among different modes. We demonstrate the compatibility of the homodyne detection with multimode quantum light [**1**, **2**] by directly observing squeezing and entanglement across 60 optical modes. This scalable quantum measurement paradigm paves the way for large-scale quantum information processing, including fault-tolerant quantum computing, quantum teleportation, quantum imaging, quantum spectroscopy, and quantum tomography.

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Discovery of the Solution to the "EPR Paradox"

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In 1935, Albert Einstein, Boris Podolsky and Nathan Rosen (EPR) published a thought experiment [**1**] that is entirely correct, has been demonstrated in real experiments, and is now the most famous in quantum physics. Their pioneering work described, for the first time, quantum correlations and can be regarded as a very early glimpse into today's 'deep' quantum technologies, by which I mean those that enhance functionality by making use of quantum correlations. However, their work also contains a paradox that Erwin Schrödinger had already recognised as such in the same year [**2**] and which has since been cemented by the Bell experiments. Here, I am now able to pinpoint the origin of the paradox within the chain of reasoning, which ultimately resolves the paradox.

The starting point – In their paper [**1**], EPR investigated the question whether quantum theory (QT) can be considered a complete theory. They proposed a thought experiment involving measurements on a position-momentum-entangled system of two free particles. The measured values and their correlations within the uncertainty intervals should indicate whether the measured values had a 'reality' prior to the measurement or whether the measurement results arise by chance, i.e., without any form of causality. EPR derived an implication from a seemingly logical line of argument which, when applied to the thought experiment, shows that quantum mechanics does not describe the whole of reality and is therefore incomplete.

This work – Here, I will show that the full line of argument put forward by EPR in their paper can be summarised by the following implication.

> If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity — but this value has no counterpart in the physical theory — then the theory is incomplete. This is because a *predictable value* cannot be the result of a *truly random process*. And it is really only the truly random process that may lie outside the scope of a complete theory. [I]

I will present an example that contradicts implication [I]. My example highlights where the reasoning in the EPR paper is flawed. I finally draw the following conclusion [**3**]:

> *The predictability of a measured value does not rule out the possibility that the value is the result of a truly random process.*

My finding is fully consistent with my recent discovery of how the original position-momentum-entangled system of two free particles in the EPR though experiment [**1**] can actually be created [**4**].

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Adaptive Boson Sampling: validation and exploitation

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Universal photon-based quantum computing fundamentally requires optical nonlinearities, which can be induced through intermediate measurements and adaptive feedback applied to linear-optical elements. A critical near-term question is whether non-linear dynamics can be accessed with limited experimental resources. While recent theoretical work establishes fundamental bounds on the photonic states accessible via linear optics alone, practical methods to quantify the emergence of non-linear behavior remain underdeveloped. This presentation addresses this gap by analyzing Adaptive Boson Sampling, a measurement-feedback architecture in which the optical transformation is progressively adapted based on real-time measurement outcomes. We develop practical nonlinearity witnesses that quantify deviations from linear-optical bounds, deriving these witnesses directly from properties of the underlying linear evolution. We experimentally validate our framework on a state-of-the-art integrated photonic platform, implementing both genuine real-time adaptive protocols and emulated adaptive schemes via post-selection for more complex configurations. Our results demonstrate experimentally that limited adaptivity can access non-linear regimes provably inaccessible to static linear optics, establishing adaptive photonic architectures as a versatile platform for exploring novel quantum dynamics with near-term resources.

Controlling Quantum Light in Integrated Photonic Systems

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Photonic quantum technologies rely on the precise generation, manipulation, and measurement of quantum states of light, with the long-term goal of realizing scalable and application-ready quantum systems. Our research addresses this challenge by developing integrated nonlinear photonic platforms that enable controlled quantum light engineering across multiple levels, from physical devices to complex quantum functionalities.

In this talk, I will present our work along three closely connected directions. First, we develop thin-film lithium niobate (TFLN) as an integrated platform for quantum photonic devices, including sources, circuits, and elementary functionalities. This includes the realization of photon-pair sources based on parametric down-conversion, quantum interference such as Hong–Ou–Mandel effects, and integrated implementations of mode-selective devices such as the quantum pulse gate.

Second, we investigate how spectral engineering can be exploited to access high-dimensional photonic systems. By tailoring parametric processes via dispersion engineering, we achieve fully controlled quantum state preparation in the spectral-temporal domain. This enables encoding in temporal modes and spectral bins, as well as mode-selective operations based on the quantum pulse gate, opening new possibilities for quantum communication, metrology, and network applications.

Third, we explore photonic quantum simulation and computation, with a focus on Gaussian boson sampling using squeezed-light resources. In this context, continuous-variable photonic states combined with photon-number-resolving detection provide a powerful non-Gaussian resource. Building on this framework, we investigate photonic model systems to develop new approaches to quantum simulation and computation, as well as benchmarking strategies and a deeper understanding of complexity in scalable photonic platforms.

Together, these efforts establish a unified approach to controlling quantum light in integrated photonic systems, linking device platforms, high-dimensional encoding, and photonic quantum computing, and paving the way toward programmable, large-scale quantum technologies.

Optoacoustic quantum signal processing

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Abstract: We use the interaction of light with acoustic vibrations, in particular stimulated Brillouin-Mandelstam scattering (SBS), to store and process optical information. We present the experimental realization of cavity-free strong coupling between groups of photons and phonons in a continuous optoacoustic system. We experimentally demonstrate efficient cooling of traveling acoustic phonons from room temperature and propose a Brillouin-mediated entanglement scheme that is particularly resilient and high-temperature-implementable. Acoustic waves can also serve as efficient memory – a concept we use to store few-photon states.

Photonics has the potential to advance modern quantum technologies and high-speed applications such as communications and the processing of large amounts of data. A new promising approach to manipulate light all-optically is to use the link of optical waves with acoustic vibrations. Our research experimentally investigates how traveling sound waves can be used to process states of light in the classical and quantum regime.

Via the nonlinear effect of stimulated Brillouin-Mandelstam scattering (SBS), acoustic waves can be created all-optically by counter-propagating optical signals. In the context of optomechanics, light has successfully been strongly coupled to discrete mechanical resonances of an optomechanical cavity [1]. In our work, we make use of anti-Stokes SBS to demonstrate cavity-less strong coupling in an optical waveguide [2]. In this process, energy from the acoustic field is transferred to the scattered blue-detuned photons. We observe mode-splitting of the system under a strong pump (Fig. 1 (a)), which is one of the signatures of the system entering into the strong coupling regime and is well confirmed by our theory (Fig. 1 (b)) [3,4]. With a novel experimental technique, we perform forced detuning measurements, which allow to measure avoided crossing points - a signature of strong coupling - in waveguides (Fig. 1 c). In order to enter the regime of quantum signal processing, cooling of traveling acoustic phonons is an essential precondition and we show experimental results of optomechanical cooling by 220K starting from room temperature [5] and from 77K [6]. This experimental work will path the way to optical-fiber-based and chip-integrated quantum optoacoustic control for application to photon-phonon entanglement [7] and quantum memory [8]. With help of acoustic waves, we also implement several building blocks for photonic neuromorphic computing [9-11], working in the frequency and spatial domain such as for orbital angular momentum modes [12-14].

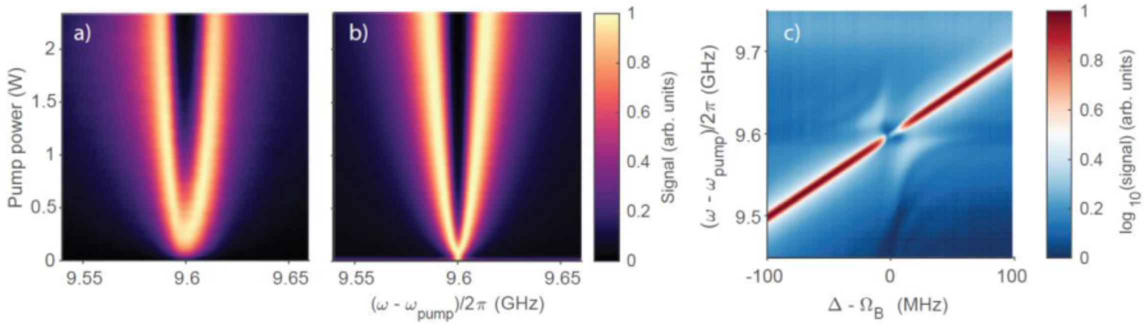

Fig. 1 a) Mode-splitting of the anti-Stokes Brillouin response at 4 K, confirming the b) theory results. c) Experimental result of the avoided crossing point at the anti-Stokes resonance.

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Estimation of multiple parameters encoded in the modal structure of light

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Quantum optical metrology aims at identifying the ultimate sensitivity bounds for the estimation of parameters encoded into an optical field. In many practical applications, such as imaging, microscopy, and remote sensing, the parameter of interest is encoded not only in the quantum state of the field but also in its spatio-temporal distribution, i.e., in its modal structure. In this context, we propose both a theoretical framework and an experimental approach to derive bounds and perform measurements that are quantum-optimal, either in the single or in the multi parameter settings.

We illustrate this with the example of two incoherent sources, in a three parameters scenario, separation, centroid and relative intensity. We perform multi-parameter estimation using a spatial mode demultiplexing technique. We determine separations well below the diffraction limit and achieve sensitive joint estimation of separation, centroid, and relative brightness over a broad range of scene configurations, in a single experimental setting. We further compare different estimators, in particular using an approach based on relative belief ratios.

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Extreme Quantum Optics: Generation of optical Schrödinger "cat" states using intense laser-matter interactions and applications in non-linear optics

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Recent theoretical and experimental investigations have shown that implementing fully quantized approaches in intense light–matter interactions opens new exciting ways for both fundamental research and applications in quantum technology and ultrafast science. These advances arise from the synergy between quantum optics, strong-field physics, and ultrafast science. Together, they have led to the development of the field of quantum optics and quantum electrodynamics in strong-field processes [1–4 and references therein], namely sometimes as *Extreme Quantum Optics*. At the core of this research field is the generation of non-classical and entangled light states from the far-infrared (IR) to the extreme–ultraviolet (XUV). This includes, coherent state superpostions (namely optical Schrödinger "cat" states) [5-7] and bright squeezed light sources [8, 9] with mean photon numbers capable to induce non-linear process in matter [10,11].

Here, after a brief introduction, I will focus my talk on our most recent studies concerning the generation of optical “cat” states and their role in nonlinear optics [12]. I will also highlight the potential of fully quantum approaches in laser-driven semiconductor crystals for developing non-classical and entangled light states [13] in the VUV spectral region with attosecond pulse durations [14]. Finally, I will briefly discuss a few additional key approaches developed more recently by other groups in this field, including our theoretical work on the propagation of bright squeezed-vacuum light states in nonlinear media [15].

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Continuous-variable quantum passive-optical networks: theory and perspectives

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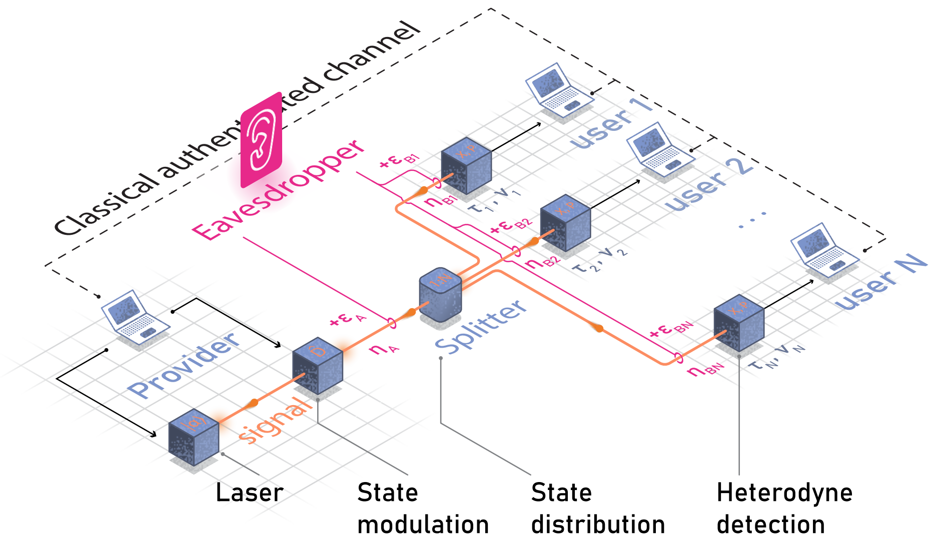
Quantum passive-optical networks (QPONs) [1] naturally extend continuous-variable (CV) quantum communication [2] to multi-user scenarios. Leveraging quadrature encoding and highly efficient coherent detection, CV QPONs enable simultaneous realization of quantum communication protocols, such as quantum key distribution, with multiple remote receivers, without the need for time sharing. Such cost-effective solution allows to upscale CV quantum communication without replicating the full set-up stacks and only extending the number of coherent detectors served by a multiport beam-splitter.



Coherent-state CV QPON architecture and operation. The provider encodes key information onto quadratures of a coherent signal state, that is broadcast to N users through untrusted quantum channels. Remote receivers employ coherent detection, decoding key information from the coherent state's quadrature values. Classical communication occurs via an authenticated channel, resulting in secret keys distributed between the provider and the remote receivers.

We will review the practical security and performance of quantum key distribution over CV QPONs upon different trust assumption levels or collaboration scenarios imposed on the receivers and extending from asymptotic to finite-size security considerations [3]. We will also discuss possibilities to further develop CV QPONs by signal state engineering, passive state preparation, and channel multiplexing, considering the role of inter-mode cross talk similarly to entanglement-based bipartite scenario [4]. Our results pave the way to efficient large-scale point-to-multipoint implementations of CV quantum communication, that can serve as a last-mile solution for future quantum networks.

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Collective photon emission of correlated atoms in free space

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Superradiance is one of the enigmatic problems in quantum optics since Dicke introduced the concept of enhanced spontaneous emission by an ensemble of identical two-level atoms, situated in collective highly entangled Dicke states [1-5]. While single excited Dicke states have been investigated since a long time, the production of Dicke states with higher number of excitations remains a challenge. In our approach, we generate these states via successive measurement of photons at particular positions starting from the fully excited system [6–10]. In this case, if the detection is unable to identify the individual photon source, the collective system cascades down the ladder of symmetric Dicke states each time a photon is recorded. We apply this scheme to demonstrate directional super- and subradiance with two trapped ions [11]. The arrangement for preparing the Dicke states and subsequently recording directional super- and subradiance corresponds to a generalized Hanbury Brown and Twiss setup. This shows that the two fundamental phenomena of quantum optics, Dicke superradiance and the Hanbury Brown and Twiss effect, are two sides of the same coin.

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Hot topic talks

Alessia Allevi	Silicon-Photomultiplier-Based Weak-Field Receiver For Quadrature Phase-Shift-Keying Communication Protocols
Beate Asenbeck	Towards a scalable ion trap architecture - Trapping 2D ion arrays in a surface penning trap
Baghdasar Baghdasaryan	Asynchronous Multiphoton Interference for Quantum Networks
Niels Böttner	Quadrature-witness readout for backscatter mitigation in gravitational-wave detectors dominated by back-action
Sourav Chatterjee	Simultaneous temperature and magnetic field sensing using a quantum diamond sensor for industrial applications
Yen-Ju Chen	Quantum teleportation between atomic and telecommunication wavelengths using independent whispering gallery resonators
Lewis A. Clark	Entering the quantum sensing regime with a diamagnetically levitated optical cavity
Attila Czirják	Electron in a quantized electromagnetic field: quantum optics in strong-field physics
Ivan Derkach	Continuous-variable quantum communication over hybrid channels
Rosario Di Bartolo	Efficient property reconstruction with classically trained model-free quantum photonic reservoir
Francesco Di Colandrea	Programmable photonic circuit for quantum simulations in free space
Behnaz Fazlpour	Polarization Structures of Quantized Light in Relativistic Frames
Zbigniew Ficek	Single-mode squeezing produced by two-mode interactions
Massimo Frigerio	Algebraic techniques for photonic states preparation and characterization
Melvee George	Indefinite Causal Order Advantage for Noisy Metrology

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Luca Innocenti	An operational explanation of the origin of singular quasiprobability distributions
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Mahmoud Kalash	Efficient detection of spectral cluster states
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Vladimir Kornienko	Wide-Field Imaging in the Mid-Infrared (6–10 μm) Range with a Nonlinear Interferometer
Michał Lipka	Spatially Split Spin-Squeezed Bose-Einstein Condensates for Multiparameter Metrology and Clock Interferometry
Gabriele Lo Monaco	The non-stabilizerness cost of quantum state estimation
Alex Maltesson	Equivalence of continuous- and discrete-variable gate-based quantum computers with finite energy
Liubov Markovich	Nonparametric Estimation of Non-Gaussian Quantum States of Continuous-Variable Systems
Michele Notarnicola	Nonlocal continuous-variable quantum nondemolition gates by optical connections
Jan Peřina Jr	Quantum Correlations in Three-Beam Symmetric Gaussian States Accessed via Photon-Number-Resolving Detection and Quantum Universal Invariants
Fabrizio Sgobba	Correlation-Enhanced Quantum Pattern Recognition via Phase-Encoded Multiphoton Interference
Petr Steindl	Wigner tomography of zero-one-photon encoded qubit generated by quantum dot in micropillar cavity
Alexander Stévins	Supermodularity and subadditivity of Rényi entropies on the majorization lattice: Applications to entanglement catalysis
Benedikt Tissot	High-Rate Remote Entanglement of Trapped Ions via Multiplexed Ensemble Memories

Nathan Walk	Certification of linear optical quantum state preparation

Silicon-Photomultiplier-Based Weak-Field Receiver For Quadrature Phase-Shift-Keying Communication Protocols

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In the contexct of quantum communication with continuous variables, encoding information in both amplitude and phase opens up interesting perspectives in terms of security, ensuring high values of mutual information and thereby improving the key generation rate. In particular, it has been theoretically proved that a hybrid detection, which combines the particle and wave properties of light, could be potentially more advantageous than the standard recceiver based on homodyne detection [1]. That is why in this work we test a weak-field homodyne detection scheme that employs a pair of Silicon photomultipliers [2] for the detection of a quaternary communication involving four coherent states with the same amplitude and different phases. In particular, we show that phase encoding requires real-time control and reduction of the phase noise affecting the optical system [3]. The obtained results are promising and foster further investigation aimed at implementing a double weak-field homodyne scheme to simultaneously modulate both the amplitude and phase of the employed coherent states.

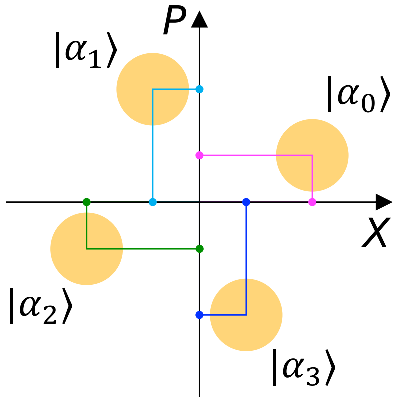

FIG. 1: Sketch of the four coherent states used to encode information.

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Towards a scalable ion trap architecture - Trapping 2D ion arrays in a surface penning trap

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Trapped ion systems are a leading platform for quantum information processing, yet scaling conventional radio frequency (RF) Paul traps remains hindered by power dissipation, driven micromotion, and the confinement of ions to motion along the RF null, typically restricting transport to a one-dimensional trajectory [1]. To address these challenges, we utilize microfabricated Penning traps, which employ static electric and magnetic fields for confinement. This architecture eliminates the need for strong radio frequency fields and specialized junctions, enabling seamless and arbitrary three-dimensional transport. This flexibility makes the architecture well suited for scalable implementations. This approach was recently validated at ETH Zurich with the experimental realization of the world's first microfabricated surface Penning trap using beryllium ions [2, 3]. This prototype demonstrated full three-dimensional control over the position of the ion, highlighted by the ability to translate and stabilize a single ion 400 μm above the trap surface to suppress the effects of electric field noise, measuring heating rates amongst the lowest of any trapped ion system [4]. Additionally, transport-induced heating was found to be negligible, which underscores the platform's potential for high-fidelity operations.

Here we present recent progress toward a new generation of surface electrode Penning traps designed for calcium ions $^{40}Ca^{+}$ with the trap enclosure visible in Fig. 1(a). The shift to calcium offers more accessible laser wavelengths, which improve compatibility with commercial laser systems and provide a richer atomic-level structure. The architecture utilizes individually controllable potential wells arranged in a two-dimensional grid, allowing for the flexible reconfiguration of ion arrays. We report on recent developments in the simultaneous transport of multiple ions, leading to 9 co-trapped ions, shown in Fig. 1(b). Finally, we describe ongoing work to achieve high-fidelity single- and two-qubit optical gates on calcium in this architecture, providing a pathway to parallelized quantum logic operations.

(a) (b)

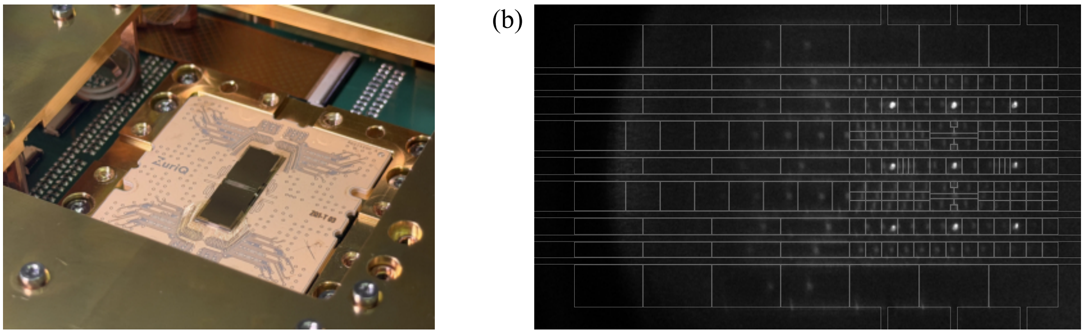

Figure 1: **(a)** Top view of the ion trap enclosure. **(b)** Nine co-trapped ions with electrode geometry overlay, with the trap structure made visible by LED illumination.

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Asynchronous Multiphoton Interference for Quantum Networks

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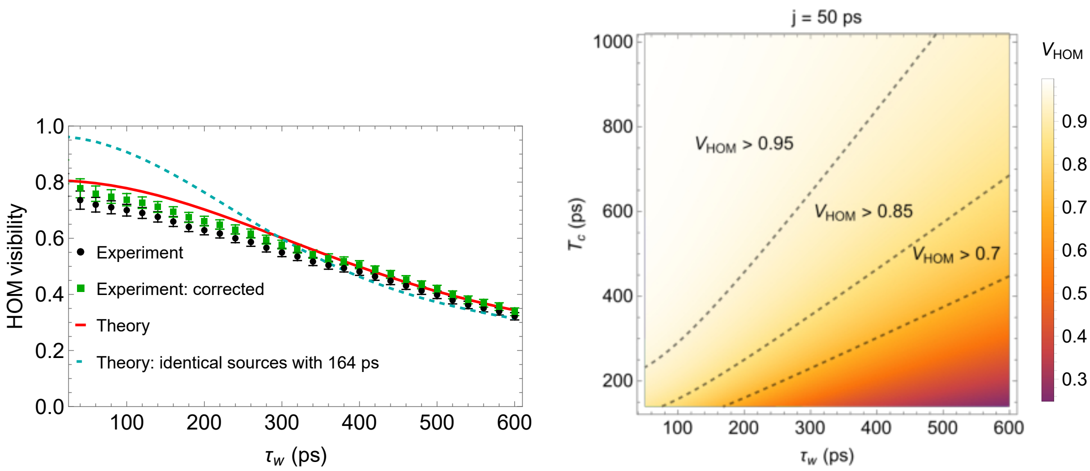
High-visibility multiphoton interference is a key resource for photonic quantum information processing and quantum networking. In long-distance implementations, however, temporal indistinguishability is difficult to maintain because path-length fluctuations directly translate into arrival-time mismatch. While pulsed sources require active synchronization, continuous-wave (CW) sources offer an attractive alternative: temporal indistinguishability can be enforced by post-selecting detection events within a coincidence window τ_w that is short compared with the photon coherence time T_c [1, 2, 3]. Despite its conceptual simplicity, the quantitative relation between relevant time scales, achievable interference visibility, and usable multi-photon rates has remained unclear. Here, we develop in detail and experimentally validate a theoretical framework that quantitatively describes time-resolved multi-photon interference in the CW regime [4]. We explicitly incorporate detector timing jitter, photon coherence time, and temporal post-selection. The model is verified using four-photon Hong-Ou-Mandel interference measurements. Based on this validated framework, we determine the coincidence window that maximizes usable four-photon rates for a target interference visibility. Finally, we compare CW and pulsed SPDC sources under equivalent indistinguishability constraints and show that CW operation can achieve comparable rates while relaxing optical synchronization requirements.



(a) (b)

Figure 1: HOM visibility is presented as a function of the coincidence window τ_w. The black circles correspond to raw data, while the green squares represent the corrected HOM visibility after subtracting the accidental counts. The dashed blue line represents the theoretical calculation for the scenario where the two sources are identical with $T_{c,1} = T_{c,2} = 165$ ps. (b) Theoretical calculation of HOM visibility presented as a function of coherence time T_c and coincidence window τ_w for fixed timing jitter $j = 50$ ps. The visibility is approximately constant for fixed ratios T_c/τ_w.

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Quadrature-witness readout for backscatter mitigation in gravitational-wave detectors dominated by back-action

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Disturbances in gravitational wave (GW) observational data are often caused by non-stationary noise in the detector itself, such as back-scattering of laser stray light into the signal field. Unlike GW signals, non-stationary noise can appear in both the GW-signal quadrature and the orthogonal quadrature, which is usually not measured. Simultaneous sensing of this orthogonal quadrature provides a witness channel that can be used to reconstruct the disturbance in the signal quadrature enabling a subtraction of non-stationary noise. Here, we present the concept of quadrature witness that is compatible with frequency-dependent squeezing, which is already used to simultaneously reduce photon shot noise and photon radiation pressure noise. We demonstrate that implementing this approach in a GW detector could reduce noise caused by loud back-scatter events, thereby improving the overall sensitivity and robustness of GW observatories.

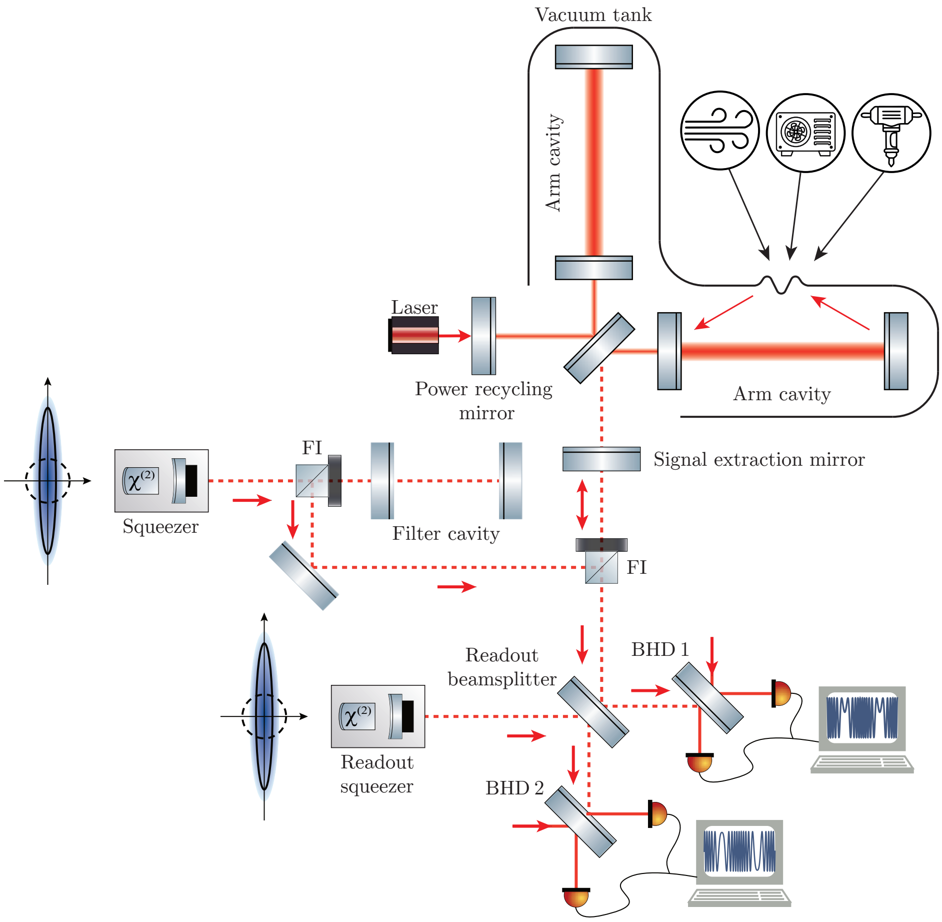

FIG. 1: Conceptual setup of our approach in a GW detector. The walls of the vacuum tanks are excited by microseims and anthropogenic sources. Dual readout is implemented by the readout beamsplitter and two balanced homodyne detectors (BHD) in the output of the interferometer. One BHD measures the signal quadrature while the other one measures the witness quadrature. A second squeezed state in injected through the open port of the readout beamsplitter. Frequency-dependent squeezing is realized by a filter cavity and injected into the detector through a Faraday isolator (FI).

Simultaneous temperature and magnetic field sensing using a quantum diamond sensor for industrial applications

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Simultaneous measurement of magnetic field and temperature is important for various industrial applications such as semiconductor chip failure analysis [1], magnetic material analysis [2, 3], and biological studies [4]. For many of these industrial applications, besides the requirement of temperature-compensated magnetic field sensing, often there is a necessity to track the temperature as well. The negatively charged nitrogen-vacancy (NV) color center in diamond has demonstrated a versatile capability of measuring magnetic field, electric field, temperature, and stress with high sensitivity under ambient condition due to its unique quantum mechanical property. NV center–based diamond magnetometers offer high magnetic field sensitivity by tracking a single resonance microwave (MW) frequency. However, the strong temperature dependence of the NV center energy levels can lead to measurement errors. This issue is mitigated by simultaneously exciting two spin sub-levels using two MW resonance frequencies, yielding two lock-in outputs containing both magnetic field and temperature variation. These signals enable simultaneous and accurate determination of magnetic field and temperature.

Our experimental setup for simultaneously measuring temperature and magnetic field is depicted in Fig. 1(a). The NV ensemble is excited by a 520 nm laser. The resulting fluorescence is collected by a compound parabolic concentrator (CPC) and collimated with a condenser lens. Thereafter the green excitation light is filtered out and focused onto a photodiode (PD). Microwave excitation is delivered using two frequency-modulated MW signals. The corresponding reference frequencies are supplied to both the MW sources and a lock-in amplifier (LIA). The PD signal is demodulated at the two reference frequencies, digitized by a data-acquisition (DAQ) card, and recorded using LabVIEW.

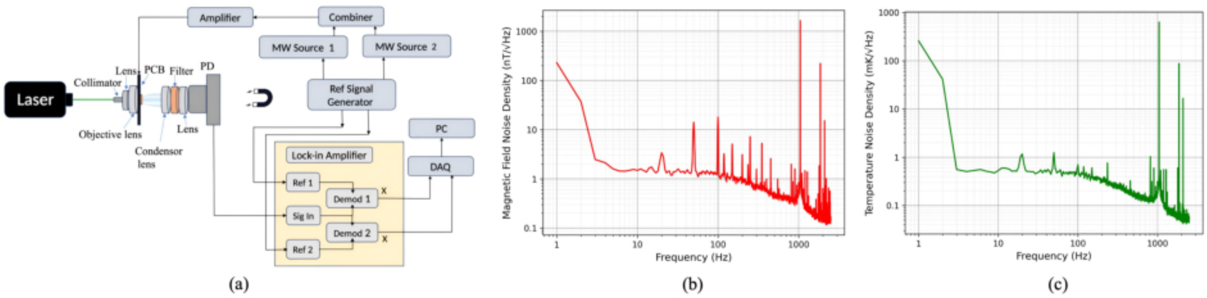

Figure 1: (a) Schematic representation of the experimental setup. Noise spectral density measurement for calibrating: (b) the magnetic field sensitivity (red trace) and (c) temperature sensitivity (green trace).

To evaluate the performance of our diamond sensor, we analyze its noise by measuring the power spectral density of the lock-in signal at resonance. As shown in Figs. 1(b) and 1(c), We have achieved a magnetic field sensitivity of $\approx 1.7\ \mathrm{nT}/\sqrt{\mathrm{Hz}}$ and a temperature sensitivity of $\approx 0.5\ \mathrm{mK}/\sqrt{\mathrm{Hz}}$, respectively. Further design modifications including improved detection schemes are expected to enable our compact magnetic and temperature sensor to meet the requirements of many practical applications.

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Quantum teleportation between atomic and telecommunication wavelengths using independent whispering gallery resonators

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Quantum teleportation lies at the heart of advanced quantum technologies, with examples ranging from quantum repeaters to distributed quantum sensing. To realize scalable quantum networks, probabilistic photonic processes must be synchronized through the integration of photonic qubits with long-lived quantum memories, such as atomic ensembles, for which narrowband photons are essential for efficient interfacing. However, photon wavelengths compatible with atomic transitions typically lie in the visible or near-infrared range, where optical fiber transmission experiences significant loss. To address this challenge, we generate narrowband, highly-nondegenerate entangled photons operating at both telecommunication and atomic wavelengths by implementing photon sources based on spontaneous parametric down-conversion in independent whispering gallery mode resonators (WGMRs).

Polarization-entangled photons are prepared using a bidirectional pumping configuration. The resulting state exhibits high-quality entanglement, with a Wootters concurrence of 0.953 ± 0.002. The generated signal wavelength (852 nm) is near the cesium D2 transition, while the idler wavelength (1360 nm) lies within the telecom O-band. To perform quantum teleportation with the telecom photons, we setup another WGMR to generate heralded single-photons. By leveraging the evanescent coupling scheme, the photon bandwidths from the two WGMRs are matched through precise control of the coupling distance between each WGMR and its prism couplers. As an example, we perform quantum teleportation using the right-circularly polarized input state $|R\rangle$. The reconstructed density matrix of the teleported photon is shown in Fig.1(c), yielding a teleportation fidelity of 0.824 ± 0.096, which exceeds the classical bound of 2/3. We further test the protocol with other input states, including $|H\rangle$ and $|D\rangle = (|H\rangle + |V\rangle)/\sqrt{2}$, all of which achieve fidelities above 0.8. These results demonstrate the high performance of quantum teleportation enabled by WGMR-based photon sources. Our work paves the way for the realization of quantum repeater and hybrid quantum communication networks.

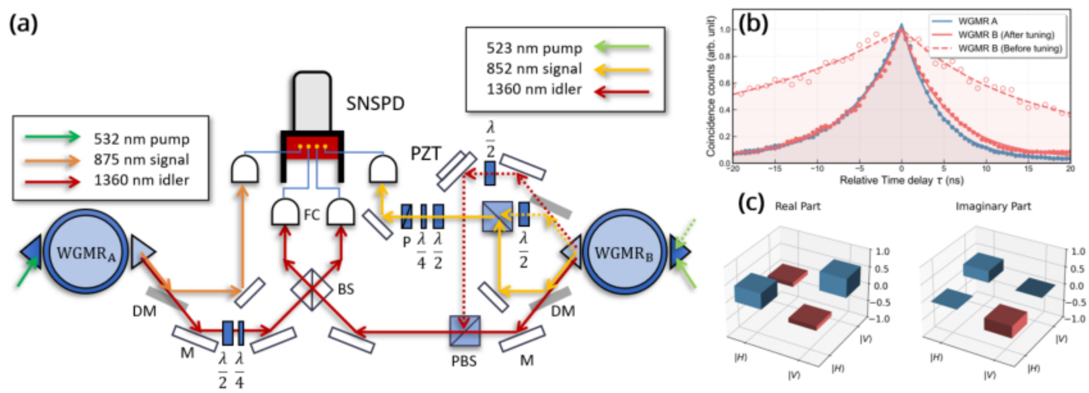

FIG. 1: (a) Schematic of the experimental setup. WGMR: whispering gallery mode resonator, M: mirror, DM: dichroic mirror, $\lambda/2$: half-wave plate, $\lambda/4$: quarter-wave plate, P: polarizer, BS: non-polarizing beam splitter, PBS: polarizing beam splitter, FC: fiber collimator, PZT: piezoelectric transducer, SNSPD: superconducting nanowire single-photon detector. The dashed lines represent the beams coupled into and out of the resonator in the clockwise directions. (b) Two-fold coincidence counts of photon pairs generated from the two WGMRs. The dashed line shows the temporal waveform before bandwidth tuning. (c) Reconstructed density matrix of teleported photons for input state $|R\rangle$.

Entering the quantum sensing regime with a diamagnetically levitated optical cavity

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Optomechanical systems, with their coherent interaction between light and mechanical motion, are highly proficient quantum sensors. Among these, levitated systems have been gaining attention due to their high sensitivity and isolation from the environment. Most levitated optomechanical platforms use optical tweezers, which are limited to microparticle sizes and involve incoherent optomechanical interaction. Passive diamagnetic levitation of a mirror offers a pathway for coherent levitated optomechanics at the milligram scale and room temperature. The coherent interaction unlocks the possibility of implementing quantum optical tools such as squeezing. Moreover, large masses are more sensitive for applications such as accelerometry, and are promising for exploring quantum effects at the macro-scale. There has been tremendous progress in diamagnetic levitation of pyrolytic graphite recently, including mechanical quality factors $> 5 \times 10^5$ at the milligram scale, comparable to superconducting systems in this mass range [1]. However, approaching the quantum regime for this mass range is highly challenging, and it is not well understood how much further we need to suppress the various inherent noise processes.

In this work, we study a sensor based on diamagnetic levitation of a mirror attached to graphite. We consider two configurations for sensing the position of the graphite: interferometry and an optical cavity. For each of these we build a comprehensive noise model, and identify which of the noise sources pose the greatest obstacle to attaining the quantum regime. We then show how the levitated mass can be used to sense weak forces, such as gravitational signals, and in what regimes quantum resources such as squeezed light can interact coherently with the levitated mass for quantum-enhanced sensing. Our work elucidates the pathway for bringing existing coherent diamagnetic levitation into the regime of quantum sensing, and provides a roadmap for the experimental improvements needed to get there.

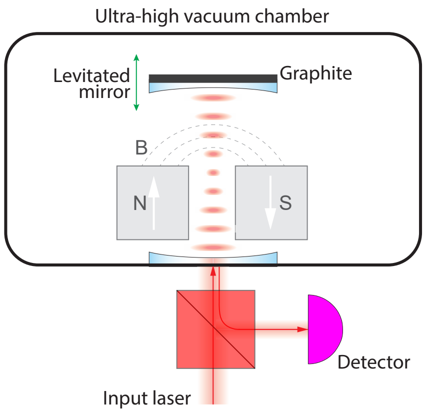

FIG. 1: Basic schematic of a diamagnetically levitated optical cavity.

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Electron in a quantized electromagnetic field: quantum optics in strong-field physics

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Motivated by strong-field physics [1, 2], we investigate the dynamics of an electron interacting with a multimode quantized electromagnetic field and present an analytic solution for the full electron+field system [3]. This framework enables the calculation of position expectation values and uncertainties for arbitrary electron wave packets and field states, allowing us to identify quantum corrections to the corresponding classical motion. While the corrections to the position expectation value are weak and largely insensitive to the quantum state of the field, the wave packet broadening exhibits a pronounced dependence on the field state. In particular, the quantum uncertainty of the radiation is directly imprinted onto the spatial uncertainty of the particle. We illustrate these effects for Gaussian wave packets interacting with coherent, Fock, and squeezed states, including bright squeezed vacuum.

As a multimode example, we present the interaction with a femtosecond near-infrared laser pulse, having a central wavelength of 1030 nm and a duration of three optical cycles. The field is modeled using 400 discrete frequency modes with a transverse Gaussian profile and a $\sin^2$ temporal envelope, corresponding to a pulse energy of 1 μJ. In Fig. 1, we plot the difference between the electron coordinate variance in an amplitude squeezed field and in the corresponding coherent field, for different values of the squeezing parameter. Negative values correspond to a reduction of the electron coordinate variance relative to the coherent state case. The red curve and its shaded background indicate the expectation value and variance of the electric field of the laser pulse.

Our results provide a transparent analytic route toward understanding how quantum fluctuations of light influence electron dynamics in strong-field scenarios.

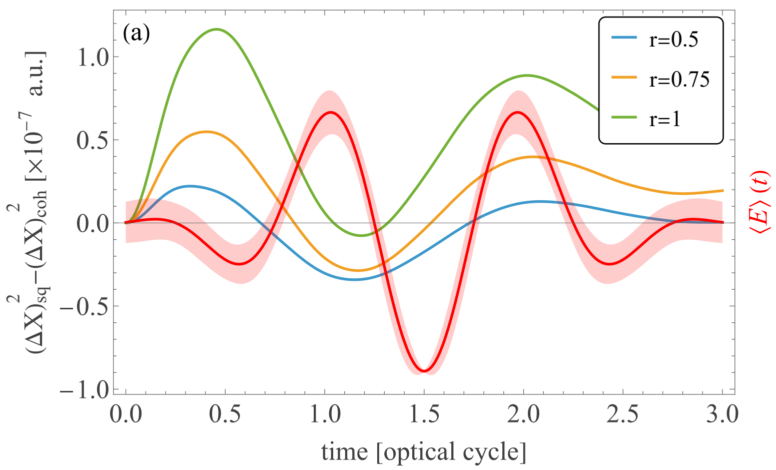

FIG. 1: Difference between the electron coordinate variance in an amplitude squeezed field and in the corresponding coherent field, for different values of the squeezing parameter r.

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Continuous-variable quantum communication over hybrid channels

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We report the continuous-variable QKD (CV-QKD) system distributing secret keys using both coherent and squeezed states over a hybrid channel composed of a 620 m free-space link followed by 2 km of optical fiber, corresponding to a total loss of 20 dB. Daylight operation is enabled by intrinsic mode filtering provided by a locally generated local oscillator, eliminating the need for complex spectral or spatial filtering. For the coherent-state protocol we employ the Gaussian-modulated no-switching scheme with heterodyne detection. The squeezed-state protocol with heterodyne detection allows for simultaneous monitoring of squeezed and anti-squeezed quadratures and enables digital phase recovery in post-processing [**1**, **2**]. To mitigate the effect of the atmospheric turbulence, we combine various post-selection strategies, taking into account the shape of the probability distribution of transmittance, identifying ranges of transmittance (bins) within which transmittance fluctuations are reduced and subsequently positive secure key rate (SKR) can be achieved (Fig. 1). Furthermore, we compare two different methods for security analysis in slow fading channels based on covariance matrix averaging [**2**] and de-fading [**3**], and choose the most suitable one for the shape of the transmittance distribution inside each bin, thus maximizing the total SKR. These results demonstrate the feasibility of CV-QKD across hybrid optical channels and highlight its potential as a plug-and-play solution for heterogeneous quantum networks integrating fiber and free-space infrastructure.

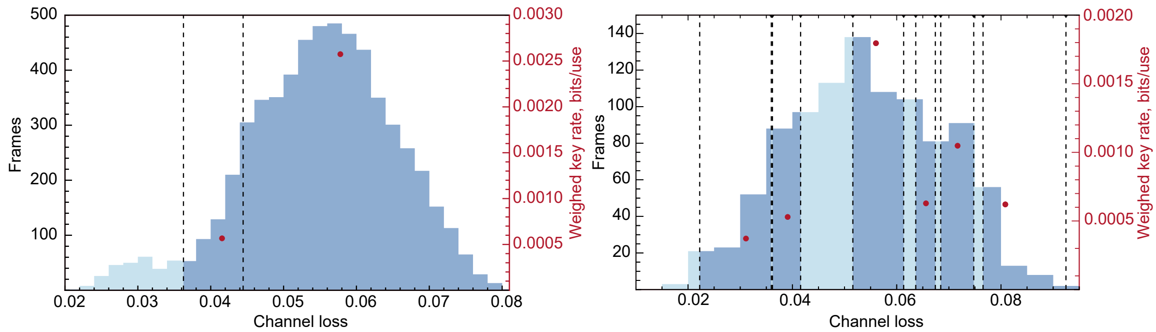

Figure 1: Security analysis of post-selected measurement results. Probability distribution of transmittance is shown in blue. Red axis and points indicate the *weighted* asymptotic secure key rate in each identified bin. **(a)** Coherent-state protocol performance. Parameters: $\beta = 95\%$, modulation variance 5.62 SNU, excess noise 1.22 mSNU, trusted electronic noise 31.1 mSNU, frame contains 1.25×10^4 symbols. Total SKR is 0.0068 bits/per channel use. (**b**) Squeezed-state protocol performance. Parameters: $\beta = 95\%$, squeezed quadrature variance 0.84 SNU, anti-squeezed quadrature noise 0.41 SNU, modulation variance 1.83 SNU, highest in-cluster excess noise 0.42 mSNU, trusted electronic noise 81.9 mSNU, frame contains 1.25×10^5 symbols. Total SKR is 0.0056 bits/per channel use.

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Efficient property reconstruction with classically trained model-free quantum photonic reservoir

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We introduce a new quantum extreme learning machine (QELM) technique for the efficient reconstruction of quantum properties of single- and two-photon states from experimental data.

The reservoir consists of a quantum walk in the spin–orbit degrees of freedom [1], while a linear readout stage trained via linear regression enables the extraction of relevant features from input states without requiring full state tomography [2, 3]. We first demonstrate generalization in QELM models across different classes of quantum states, ranging from separable states used during training to entangled states during testing. This enables the extraction of entanglement witnesses from single-setting measurements without requiring precise knowledge of the underlying dynamics, relying instead on a model-informed approach [3]. We then further stress this out-of-distribution scenario by training the learning device entirely with classical light, while performing inference on quantum states for the reconstruction of both local and nonlocal properties [4, 5]. Experimentally, we validate this capability by reconstructing Pauli observables and performing entanglement witnessing, yielding mean squared errors (MSEs) of 2.58×10^{-2} and 2.26×10^{-2} for $\langle \sigma_y \rangle$ and $\langle \mathcal{W}_{\Psi^+} \rangle$, respectively. Finally, this approach enables a gradient-based optimization procedure that does not require prior knowledge of the underlying system transformation, which would be experimentally unsuitable to access directly with single-photon states, introducing a new model-free training strategy. By further optimizing the model for specific observables, we achieve improved reconstruction accuracy, reaching MSE of 1.44×10^{-2} for $\langle \sigma_y \rangle$. More broadly, this is made possible by the fact that coherent and nonclassical states can be injected into the same linear optical reservoir without modifying the underlying transformation, identifying a concrete route toward resource-efficient transfer learning for photonic quantum learning architectures.

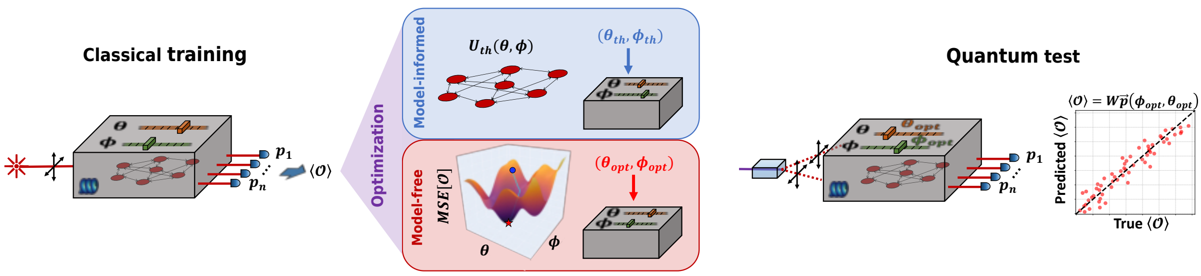

FIG. 1: Transfer learning framework. A photonic reservoir is trained with classical light using a linear readout stage and optimized measurement settings, then applied to quantum states to infer observables from single measurements.

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Programmable photonic circuit for quantum simulations in free space

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Photonic quantum simulators manipulate a set of optical modes to reproduce the behavior of complex quantum dynamics [1]. A typical example is the quantum walk, a paradigmatic model for simulating lattice Hamiltonians, quantum transport, and topological phenomena. Integrated circuits represent the dominant paradigm for simulations, driven by the demand for scalability and miniaturization. On the other hand, free-space architectures have recently emerged as attractive alternatives, offering advantages in terms of the number of addressable optical modes and reconfigurability. In the standard approach, the number of optical operations increases with the number of modes, posing significant challenges for scalability. Here, we present a compact photonic simulator that enables full control of the spatio-vectorial properties of the input field using only three patterned layers. This result is independent of the number of modes, guaranteeing stable alignment conditions and fixed optical losses. The platform consists of three spatial light modulators (SLMs) interleaved with half-wave plates [2]. The setup can be programmed in real time to simulate an arbitrary quantum walk across one-dimensional and two-dimensional lattices. The processed modes are circularly polarized beams carrying quantized transverse momentum. We also demonstrate the suitability of the platform for experiments in the single-photon regime, where space-resolved coincidence detection is enabled by an intensified camera sensor featuring nanosecond time resolution [3]. Our results surpass previous schemes that would have required hundreds of structured layers to achieve comparable mode numbers.

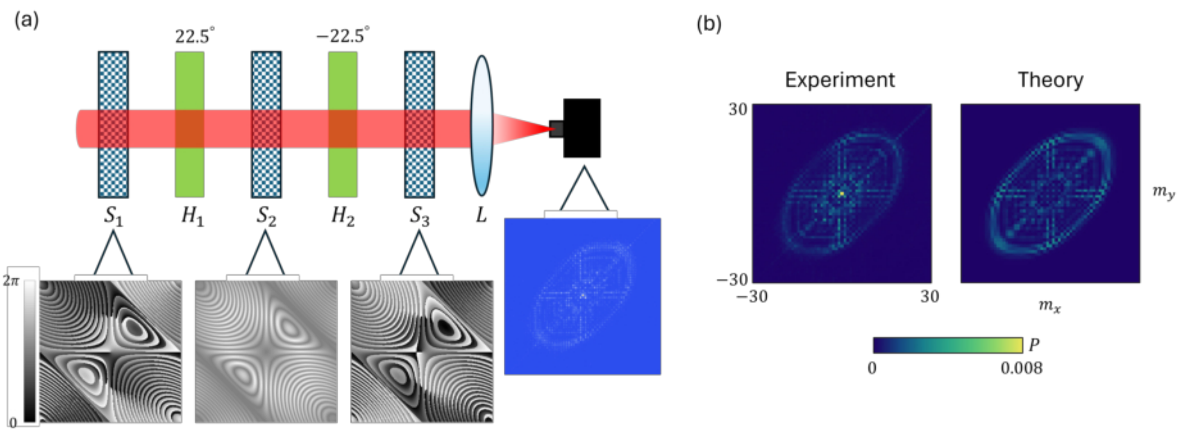

FIG. 1: (a) Experimental implementation of the reconfigurable three-SLM photonic circuit. The sequence of SLMs (S_1–S_3) and half-wave plates (H_1–H_2) implements a space-dependent polarization transformation whose output field maps into the evolved state of the target simulation. The displayed holograms correspond to a 30-step quantum walk on a two-dimensional lattice. (b) Measured output probability distribution for a 30-step two-dimensional quantum walk with a horizontally polarized input state, compared with the theoretical prediction.

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Polarization Structures of Quantized Light in Relativistic Frames

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The fundamental laws of electrodynamics, Maxwell's equations, are invariant under Lorentz transformations. However, since the electromagnetic field components generally change in such relativistic transformations, observers moving relative to each other at a constant velocity may perceive different states of polarization [**1**]. In particular, a polarization state that is two-dimensional (2D) in one frame can appear three-dimensional (3D) in the other [**2**]: in the former case the local electric field is bound to a plane, while in the latter case the electric field evolves in three orthogonal spatial directions. Moreover, any polarization state exhibits unavoidable quantum fluctuations owing to the noncommutative Stokes operators [**3**, **4**], i.e., the quantum analogs of the classical Stokes parameters. These quantum polarization fluctuations place the ultimate precision limits in polarimetry, but they also pave the way for quantum-enhanced polarimetric schemes that can surpass classical techniques.

Here we investigate the polarization characteristics of quantized light fields under Lorentz transformations [**5**]. We first consider a simple monochromatic plane wave, for which we derive general expressions for the Lorentz-transformed 3D Stokes operators [**2**, **4**] and their associated uncertainty relations. We then proceed to examine the relativistic degree of 3D polarization of blackbody radiation. The degree of 3D polarization of an arbitrary electric field is given by [**2**]

$$P = \sqrt{\frac{3}{2}\left(\frac{\mathrm{tr}\mathbf{J}^2}{\mathrm{tr}^2\mathbf{J}} - \frac{1}{3}\right)}, \tag{1}$$

where $\mathbf{J}$ is the 3×3 polarization matrix and tr denotes the trace. The upper bound $P = 1$ describes a fully polarized field and is met only if all the field components are completely correlated. The lower bound $P = 0$ represents an unpolarized field in the full 3D sense: the intensities of the three orthogonal components are the same and no correlations exist between them in any reference frame. All other values of P stands for a partially polarized field. It is well known that, in the rest frame, blackbody radiation obeys $P = 0$ [**6**] and is thus fully 3D unpolarized, consistent with what one might intuitively expect. However, in the moving frame $P = \frac{2(v/c)^2}{3+(v/c)^2}$ [**5**], where v is the relative speed and c is the speed of light. Remarkably, the degree of 3D polarization of blackbody radiation, and thus of 3D fields in general, is not preserved under Lorentz transformations. This property is in striking contrast to the Lorentz invariance of the degree of 2D polarization of transverse fields [**7**]. In the limit $v \to 0$ one obtains the rest-frame result $P \to 0$, while in the opposite limit $v \to c$ we find that $P \to 1/2$. It is interesting to note that the value $P = 1/2$ is met for an unpolarized 2D (transverse or beam-like) field [**2**]. Hence, a moving observer will experience the initially fully 3D unpolarized blackbody radiation as a partially polarized 3D field, and ultimately as an unpolarized 2D planar field when approaching the speed of light.

Our results yield new fundamental insights into the quantum-relativistic physics of truly vectorial light fields, with potential applications in high-resolution astropolarimetry in the relativistic regime.

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Single-mode squeezing produced by two-mode interactions

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An alternative way for generation of single-mode squeezed states of bosonic modes is proposed, when the modes are influenced by thermal reservoirs and are mutually coupled by two different types of two-mode interactions, the linear beam-splitter and the nonlinear parametric down conversion type interactions. This is intriguing, since it is well known that the linear beam-splitter type interaction alone cannot generate any correlations inside and between the modes. On the other hand, the nonlinear parametric down conversion type interaction alone can generate two-mode squeezing resulting in entanglement between the modes but it leaves the modes in highly fluctuating thermal states [1].

We derive equations of motion for the quadrature components of the modes and find that the presence of two couplings leads to the nonreciprocal flow of fluctuations between the modes [2], which is found to convert the initial thermal states of the modes into single-mode squeezed states [3]. The nonreciprocal flow of fluctuations results from the presence of an exceptional point at which the parameters space is divided into two regimes of $\lambda > g$ or $\lambda < g$, where λ is the strength of the linear coupling and g is the strength of the parametric coupling between the modes. The case of $g = \lambda$ corresponds to the exceptional point. We find that the exceptional point controls the conversion of thermal fluctuations of the modes into single-mode either classically or quantum squeezed fluctuations [4]. In particular, in the regime of $g > \lambda$ both modes are found to display classically squeezed fluctuations that the fluctuations are unequally redistributed between the quadratures but are not reduced below the vacuum level. However, in the regime of $\lambda > g$ fluctuations in one of the quadratures can be reduced below the vacuum level indicating that the modes can be found in quantum squeezed states. The maximum reduction of the fluctuations is obtained for g close to the exceptional point. Behaviour of the X quadratures for several values of the mean number of thermal photons n contained in the reservoirs, to which the modes are damped with rate κ is illustrated in Fig. 1(a) for $g > \lambda$, with g fixed at 0.99κ, and in Fig. 1(b) for $\lambda > g$ with λ fixed at 20κ. The vacuum level of the fluctuations is 0.5. Evidently, in the case of $\lambda > g$ the fluctuations are reduced below the vacuum level up to the value 0.25, corresponding to 50% of quantum squeezing.

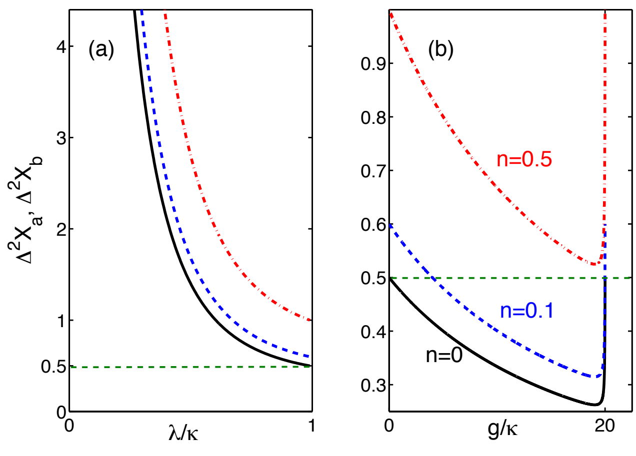

FIG. 1: Variation of the variance of the X quadratures in the regimes **(a)** $g > \lambda$ and **(b)** $\lambda > g$.

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CEWQO30 - Erlangen - July 2026

Algebraic techniques for photonic states preparation and characterization

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Multimode multiphoton states are at the center of many photonic quantum technologies, from photonic quantum computing to quantum sensing, while also describing the non-Gaussian *cores* of generic non-Gaussian states of finite stellar rank, for which they also encode the non-Gaussian quantum correlations. Despite their wide use and apparent simplicity, the vast majority of core states require ad-hoc procedures to be prepared and their entanglement properties remain poorly understood; in particular, only a measure-zero subset of them can be prepared starting from a multimode Fock state and using only interferometers to entangle the modes [1]. In the pursuit of a classification for non-Gaussian states, the very versatile tool of stellar polynomials [2, 3] was introduced to describe such states with functions on phase-space. In these works, we take full advantage of this description by showing that the algebraic properties of these multivariate polynomials are related to preparation procedures for the corresponding states and they also characterize the type of entanglement between the modes [4].

The first result consists in a full characterization of their entanglement structure through the atomic decomposition of their stellar polynomial and its associated structural graph, whose connected components determine the *mode-intrinsic entanglement* of the state and all partitions compatible with passive separability. Furthermore, we describe a new procedure [5] to generate exactly, and with a predictable number of steps, any such state by using only interferometers, photon number resolving detectors, photon additions and displacements. We achieve this goal by establishing a connection between stellar polynomials and the problem of symmetric tensor decomposition, for which we could apply known results from algebraic geometry. This unveils a mechanism of *photon catalysis*, where extra photons are injected and subsequently retrieved in measurements, to generate entanglement that cannot be obtained through Gaussian operations acting solely on the photons that we want in the target state. We also introduce another tensor decomposition that generalizes our method and allows to construct circuits yielding perfect fidelity, using the minimum number of catalysis photons.

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Indefinite Causal Order Advantage for Noisy Metrology

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Quantum physics allows for nonclassical causal structures where the order of events is indefinite. Events in such processes are said to have an indefinite causal order (ICO) [1]. ICO provide a significant advantage in quantum metrology by increasing the precision in parameter estimation protocol—even in the presence of noise [2,3]. Here we experimentally demonstrate that using indefinite causal order to probe noisy channels and a to-be-measured channel can withstand arbitrarily more noise than any quantum system with definite causal order, even if the probe is fully mixed and one of the noisy channels erases all information [3]. We investigate indefinite causal order advantages in quantum metrology by making use of polarisation and spatial degree of freedom of single photons. The experimental setup is shown in figure 1. A maximally mixed probe—the target, implemented with the transverse spatial mode of the beam—is sent through a quantum switch which is realised in a Sagnac configuration.

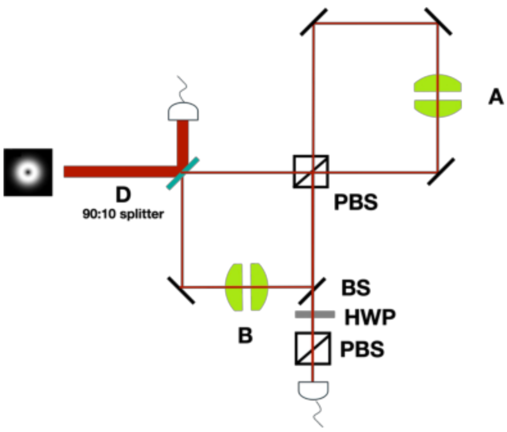

Fig. 1: ***Schematic of the experimental setup***. *The target and control state of the quantum switch is the transverse spatial mode and the polarisation of the photon respectively. A is the mixing channel implemented by continous rotation of a pair of cylindrical lenses and B is the unitary operation. HWP: Half wave plate, PBS: Polarising beam splitter, SPAD: Single photon avalanche diode.*

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Towards active superradiance clock with cold strontium atoms

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We present ongoing work towards the realization of a continuous active superradiant optical clock based on ultracold strontium atoms coupled to an optical cavity. Beyond its metrological motivation, this system provides access to a distinct regime of light–matter interaction, where collective atomic coherence directly generates the emitted field, opening new opportunities for studies in quantum optics and many-body physics.

Conventional optical atomic clocks operate in a passive configuration, where an ultra-stable laser probes an extremely narrow atomic transition. Their performance is fundamentally limited by the coherence of this interrogation laser. In contrast, an active optical clock operates in the bad-cavity regime, where the cavity decay rate exceeds the natural linewidth of the atomic transition. In this limit, the emitted light inherits its phase from the atomic ensemble rather than the cavity, enabling reduced sensitivity to cavity noise and potentially improved short-term stability [1].

Our approach builds on theoretical descriptions of superradiant emission on ultra-narrow optical transitions in strontium atoms, including realistic modeling of collective dynamics and noise properties in such systems [2,3]. These works identify parameter regimes where long-lived atomic coherence leads to steady-state superradiance and define the ultimate stability limits of active optical clocks.

Experimentally, we are under development of a versatile platform based on laser-cooled strontium atoms trapped in optical lattices at magic wavelengths and coupled to a high-finesse optical cavity [4,5]. The system will enable controlled preparation of large, nearly indistinguishable atomic ensembles and precise tuning of atom–cavity coupling. Using fermionic ^{87}Sr, we target pulsed superradiant emission on the mHz clock transition as a first step. In parallel, we explore the use of bosonic ^{88}Sr, where the clock transition can be magnetically induced, providing a unique mechanism to tune the effective spontaneous emission rate over orders of magnitude.

This tunability allows access to a rich parameter space of driven-dissipative dynamics, where collective emission, phase synchronization, and decoherence processes can be studied in a controlled manner. In particular, the system offers a platform to investigate steady-state superradiance, phase diffusion, and cavity-mediated interactions in an extreme regime of narrow linewidths and long coherence times.

The long-term goal is to achieve continuous operation via steady-state replenishment of ultracold atoms, leading to a persistent superradiant output field [6]. Such a system would not only constitute a new class of optical frequency standard, but also realize a non-equilibrium many-body quantum system with direct access to the phase of the collective atomic dipole. This opens perspectives for quantum-enhanced metrology, studies of synchronization phenomena, and exploration of open quantum systems beyond conventional laser physics.

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Protecting Heisenberg scaling in quantum metrology via engineered dressed states

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Quantum metrology promises precision beyond classical limits but environmental noise, unless properly controlled, reduces the quantum advantage to at most a constant improvement. A key challenge is therefore to design quantum control strategies that suppress noise while preserving sensitivity to the targeted signal. Here, we suggest to use dressed states generated by static fields to achieve this goal and show that success of this strategy depends on the spectral properties of the environment. For low-temperature noise, we show that Heisenberg scaling can be achieved if and only if the signal generator lies outside the linear span of the system–environment coupling operators. This implies that the proper dressed states may enable Heisenberg scaling even in cases where the well-known Hamiltonian-not-in-Lindblad-span criterion, evaluated in the absence of dressing, would forbid it. We illustrate dressed state metrology for the example of NV-center thermometry under magnetic-field fluctuations, with the framework readily applicable to other platforms.

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An operational explanation of the origin of singular quasiprobability distributions

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A well-known quirk of estimating properties of quantum-optical states from measurement data, for example with heterodyne or homodyne detection, is that unbiased estimators for many target observables do not exist as regular functions, making their estimation impossible without suitable regularization [1–3]. In the case of heterodyne detection, this issue coincides precisely with the singularity of the Glauber–Sudarshan P function. Here, we develop a general estimation framework, extending the frame-based estimation theory developed in the language of classical shadows in [4], that explains these singularities as a consequence of a feature unique to infinite-dimensional systems: a POVM may be mathematically informationally complete while still failing to support stable reconstruction of arbitrary properties when accounting for the unavoidable presence of shot noise. In particular, we show that this is the case for both heterodyne and homodyne measurements. Our results provide a unified language connecting continuous-variable tomography, measurement frames, and classical shadows.

Our starting point is the observation that many quasiprobability distributions can be understood operationally as unbiased estimators associated with specific measurement settings. From this viewpoint, their singular behavior is not just a formal feature of phase-space representations, nor should it be attributed solely to nonclassicality. Rather, it reflects a basic limitation of some infinite-dimensional measurement schemes: even if they are formally informationally complete, and thus should provide enough information to tomographically reconstruct the measured state, they may in practice not informationally complete when shot noise is accounted for. We show that a more physically meaningful notion of measurement completeness, one that takes shot noise into account, should instead be based on whether the POVM elements constitute a *measurement frame*.

Within this framework, singular distributions are traced back to a precise structural instability of the underlying measurement. When this instability is present, unbiased estimators exist only as limiting objects: one can reduce the bias arbitrarily, but only at the price of a corresponding blow up in the variance, and thus in the estimation error. This explains the singularity of the P function and, more generally, the pathologies encountered in continuous-variable quasiprobability representations. In particular, we show that heterodyne and homodyne detection both display this mechanism, thereby providing a unified operational explanation for their singular reconstruction formulas.

Beyond the theoretical interest, our approach yields practical tools for continuous-variable estimation. It provides a general recipe to construct unbiased or approximately unbiased estimators for arbitrary observables in generic measurement scenarios, clarifies when finite-variance estimation is at all possible, and connects naturally to the language of classical shadows, thereby importing performance guarantees for predicting broad classes of properties without full tomography. The framework also suggests physically motivated regularization strategies based on prior information about the measured states, enabling improved estimation accuracy without modifying the experimental measurement scheme itself.

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Programmable Generation of Large-Scale Continuous-Variable Entanglement

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Multimode continuous-variable (CV) entanglement is a key resource for quantum information processing, including quantum computing, quantum communications, and quantum metrology. A common method for generating such entanglement relies on interfering multiple squeezed states using a network of optical interferometers. However, the interferometer-based approach is typically limited in scalability because of optical loss and phase instability arising from the use of multiple interferometers. In particular, generating highly complex entangled states requires a large depth of interferometer circuits, making the conventional approach increasingly impractical.

In this work, we overcome this limitation by engineering the pump laser used for parametric down-conversion (PDC) and experimentally generate large-scale continuous-variable entangled states with programability. In multimode PDC, the generated entanglement structure is determined by the pump spectrum and the crystal phase-matching condition [1]. By engineering the pump spectrum in multimode PDC, we realize programmable generation of multimode CV entanglement without the need for optical interferometers. We tailor the pump spectrum using a pulse shaper and inject the beam into a synchronously pumped optical parametric oscillator (SPOPO)[2, 3].

In the experiment, we demonstrate programmable generation of multimode CV entanglement across 40 frequency-bin modes through pump engineering. First, we verify the proper operation of the technique using basic pump shapes. As shown in Fig. 1, experimental covariance matrices of the generated quantum states are in good agreement with the theoretical results. We further generate 1D and 2D cluster states in 12 frequency-bin modes. This result shows that our method can realize specific target entanglement structures. Finally, we obtain multimode CV entanglement from complex pump shapes. By comparing the distributions of bipartite logarithmic negativity over random bipartitions under similar first supermode squeezing and total effective photon number, we find that our scheme can generate complex multimode CV entanglement. Our method provides a promising route to the programmable generation of large-scale CV entanglement without relying on optical interferometers.

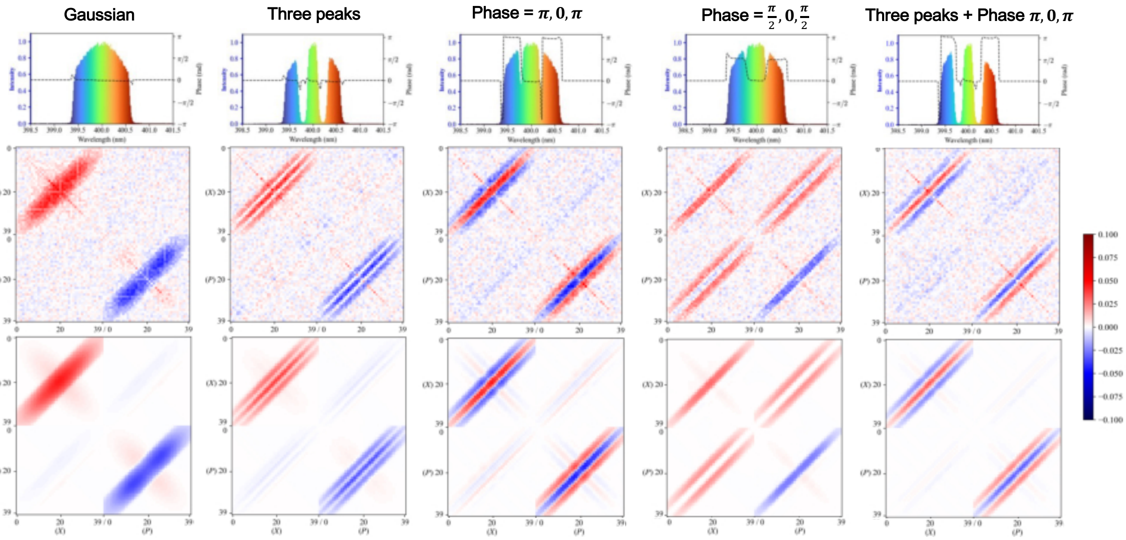

FIG. 1: Input pump shape (above), experimental (middle) and theoretical (below) covariance matrices. The identity matrix is subtracted from the covariance matrices for clarity of presentation.

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Efficient detection of spectral cluster states

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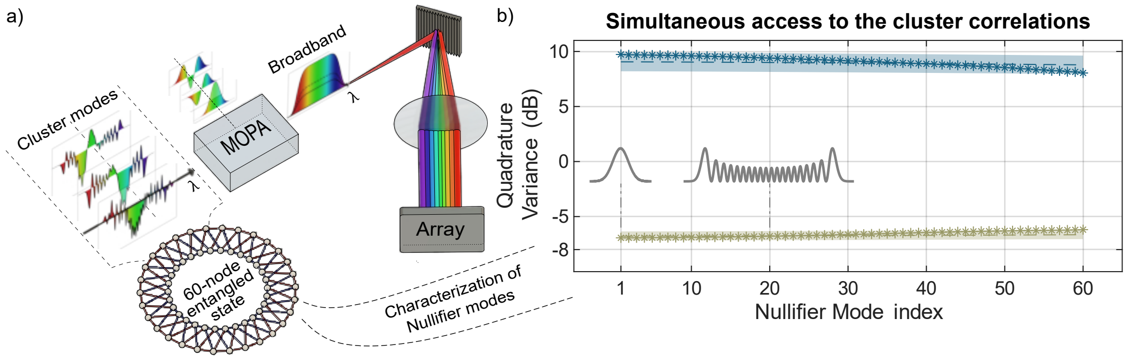
Continuous-variable (CV) multipartite entangled states of light play a central role in high-dimensional quantum information processing. In particular, CV cluster states constitute a key resource for measurement-based quantum computing. The practical use of such states relies on two essential aspects: their scalable generation and their efficient detection. While multimode squeezing—a well-established phenomenon in quantum optics—provides a deterministic and scalable route to generate CV entanglement, enabling large cluster states, their characterization remains a major challenge. This is especially relevant for spectral cluster states, where previous characterization methods have either relied on individual mode-by-mode measurements, which become impractical as the number of modes increases, or enabled simultaneous detection using dispersive elements such as gratings, which are inevitably lossy. In both cases, the reliance on homodyne detection makes the characterization highly sensitive to detection losses, a limitation that becomes particularly severe for broadband quantum states.

Here, we propose multimode optical parametric amplification (MOPA) as an efficient solution for the detection of spectral cluster states. Indeed, parametric amplifiers have proven to enhance the detection of multimode squeezed light by enabling loss-tolerant and broadband detection [1,2]. In this work, we explore the multimode capability of MOPAs to achieve the lossless simultaneous full characterization of cluster states. Figure (a) illustrates the concept. The multimode state to be detected, here a 60-node



dual-rail cluster state constructed from a picosecond-pulsed multimode squeezed vacuum state, is injected into a MOPA whose modal structure is known and can be engineered by shaping its pump field. As a result, the spectral modes of the MOPA can be tailored to match the modes of either the cluster nodes or their corresponding nullifiers. We adopt the latter scenario, with nullifier quadrature squeezing serving as the main figure of merit. After the simultaneous amplification of all nullifier modes, spectral intensity correlations are measured through employing a dispersion grating and an sCMOS camera, from which the individual modal intensity contributions of the amplified signal are extracted. These intensities directly indicate each nullifier quadrature variance [2]. Figure (b) shows the results of simultaneous characterization of all 60 nullifier quadratures, with almost constant squeezing (green) ranging between -7 and -6.5 dB. The shaded areas show the theory, whereas the grey lines present the intensity profiles of the strongest 1st and 20th nullifier spectral modes.

We believe that optical parametric amplification is of high importance to quantum technologies, particularly for integrated photonic platforms, which typically exploit spectrally high-dimensional states.

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Higher order covariance matrices

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Covariance matrices, constructed from first and second moments of quadrature operators, are a simple, powerful, and practical formalism for the description of Gaussian quantum states. Moreover, Gaussian states are fully characterized by the covariance matrix formalism, and the action of Gaussian operations can be expressed by matrix transformations. Modern quantum technologies require states with non-Gaussian distributions of quantum noise. Those generally cannot be fully characterized by their first and second moments and therefore described within the covariance matrix framework.

Some specific applications require only limited information about the non-Gaussian states, though uncovering the targeted non-Gaussian properties is often provided via witnesses that use optimized Gaussian operations and therefore require a description that enables their application. For example, a finite set of moments can be used for the evaluation of the nonlinear squeezing [1] or non-Gaussian cluster state nullifiers [2]. Here, we present a formalism that generalizes covariance matrices for the description of non-Gaussian states. It can be tailored to contain sufficient information about a non-Gaussian state for a specific application. Simultaneously, the Gaussian operations can be easily applied as matrix transformations within this formalism.

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Enhancing Stimulated Raman Scattering Using Kerr Squeezing in Fibers

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One of the most direct and promising applications of squeezed light states is to provide a way to improve signal-to-noise ratio (SNR) in various measurements where quantum uncertainty becomes a significant source of noise. With classical methods, SNR grows with the increase of optical power, but in practical applications, there is a limit to this increase. In state-of-the-art stimulated Raman scattering (SRS) experiments, particularly with biological samples, such a limit is photodamage.

In recent years, several groups demonstrated SNR improvement in SRS with the use of squeezed states of light. In each of these experiments, squeezing was generated with the use of a second-order nonlinearity in various setups [1, 2].

This work explores a different path to produce squeezing, the third-order Kerr nonlinearity, in order to improve SNR in measurements that are shot-noise limited such as SRS. We use our robust fiber-based squeezing setup [3] to produce squeezed pulses at 1.5 μm that we convert to a pair of amplitude-squeezed and correlated beams, and use one of them as the pump for the SRS in quartz. The second beam serves as a reference to further reduce the noise floor. We achieve 3.0 dB of SNR improvement, a value similar to results of other groups that use second-order nonlinearity.

The fiber geometry in our setup provides a number of advantages such as simplicity and a perfect spatial mode of the squeezed beam. The latter is particularly important for SRS because it allows replacing a coherent source with a squeezed one without deterioration in the signal strength. We believe that our method is a promising and practical approach to further improve the most sensitive SRS setups.

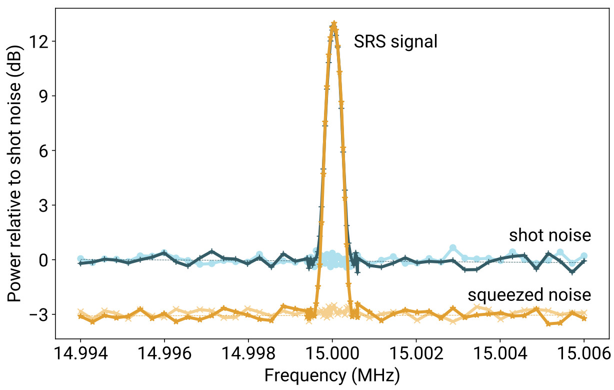

FIG. 1: SRS signal for the 464 cm^{-1} line in quartz (bright lines) and the quantum noise floor (faded lines) for a coherent and squeezed states.

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Quantum super-resolution imaging of incoherent emitters with the BLESS technique

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Abstract

The spatial resolution of a far-field imaging system is conventionally constrained by diffraction through the point spread function (PSF) of the optical setup. While fluorescence super-resolution methods such as STED and PALM/STORM overcome this limit by switching emitters in space or time, they may require demanding acquisition conditions and are not universally compatible with all classes of sources. A complementary route, motivated by quantum estimation theory, is to extract sub-diffraction information from appropriately engineered measurements on incoherent light.

It has previously been shown that PSF shaping can enable sub-diffraction resolution of two point sources, as demonstrated in the SPADE approach [1]. However, it was later established that this strategy is optimal only for balanced sources [2]. For incoherent emitters, by contrast, the brightness ratio can be inferred from photon-statistics measurements, in particular from the second-order correlation function $g^{(2)}$. In this contribution we present BLESS — Beam moduLation and Examination of Shot Statistics — for super-resolution imaging of non-interfering point emitters. By combining PSF shaping with photon-count statistics analysis, BLESS maps sub-Rayleigh spatial information onto experimentally accessible counting signals and is particularly advantageous when direct imaging becomes inefficient, especially for localization problems beyond the idealized case of balanced emitters [3].

We will discuss the application of BLESS to both single-photon and thermal sources, including experimental implementations based on NV-center single-photon emitters and on quasi-thermal light. These examples illustrate the versatility of the method across different photon-statistics regimes and its suitability for realistic localization tasks in which both source positions and brightnesses must be inferred simultaneously. Recent experimental results will be presented, demonstrating sub-diffraction localization of strongly unbalanced emitter pairs at separations on the order of one tenth of the Rayleigh limit, together with prospects for extending the method to multiple-source localization and quantum-enhanced optical metrology.

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Wide-Field Imaging in the Mid-Infrared (6–10 μm) Range with a Nonlinear Interferometer

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Infrared imaging accesses both chemical and structural composition of an object and has demonstrated potential in label-free analysis in biology, materials science, and chemical sensing. However, thermal background fluctuations impose limits on both the minimal detectable signal power and dynamic range of a detector, making spectroscopic mid-infrared imaging technically difficult and often impractically slow.

Here, we show that quantum imaging with undetected photons (QIUP) enables wide-field imaging in the 6–10 μm range using an $AgGaS_2$ crystal. Our system demonstrates over 10^4 resolvable elements within the field of view despite the unfavourable scaling of the number of imaging modes with wavelength.

Our experiment is based on the type-I spontaneous parametric down-conversion (SPDC) in a silver thiogallate ($AgGaS_2$) crystal pumped with a continuous-wave Ti:sapphire laser at 700–740 nm. We used non-collinear phase matching and an off-axis parabolic mirror for beam collection. The idler beam with 6–10 μm wavelength probed the object but was never detected directly. The signal beam (800 nm) was registered with a CMOS camera, and its interference pattern (FIG. 1a) was analyzed. Imaging wavelength was adjusted by changing the crystal orientation and pump wavelength. Resulting images in the 6–10 μm range are shown in FIG. 1b-d.

Resilience against thermal background is achieved by recording only the interference pattern in the visible beam, without directly detecting the mid-infrared light, thereby surpassing the background-limited infrared photodetection (BLIP) limit by several orders of magnitude.

Our results provide a route to virtually background-free mid-infrared spectral imaging at room temperature, with direct relevance to biomedical applications.

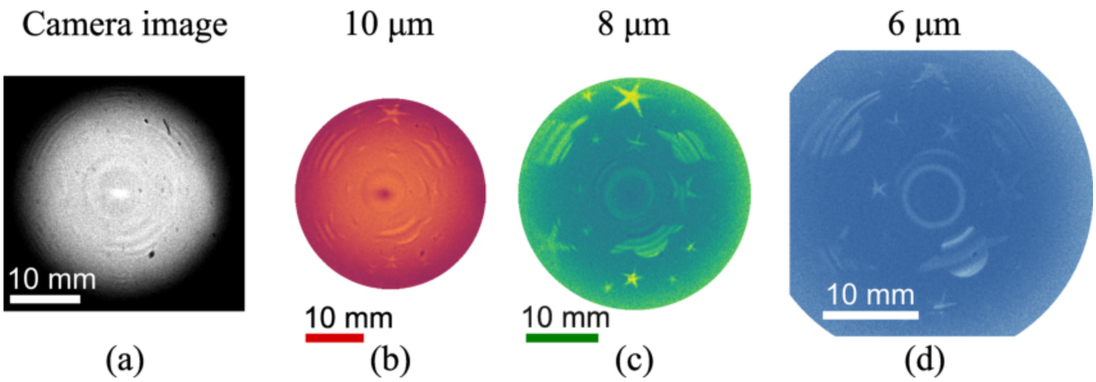

FIG. 1: **(a)** Interference pattern captured by the silicon camera – raw image. The object imaged is a shadow mask with either zero or full transmittance. Pump and signal beams travel through the central part of the mask. **(b,c,d)** Computed interference pattern visibility at idler wavelengths of 10 μm, 8 μm, and 6 μm. Scale bar shows the physical size at the imaging plane.

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Spatially Split Spin-Squeezed Bose-Einstein Condensates for Multiparameter Metrology and Clock Interferometry

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We present a versatile atom-chip platform for multiparameter quantum sensing based on a two-component ^{87}Rb Bose–Einstein condensate. Our setup enables the generation of collective spin-squeezed states via one-axis twisting dynamics, followed by the coherent spatial splitting of the condensate into multiple individually addressable clouds. This splitting process successfully preserves both the internal (intra-cloud) and distributed (inter-cloud) many-body entanglement. Recently, we utilized this capability to create an array of up to three entangled atomic sensors, each constituing several hundreds of atoms. By optimizing the measurement protocol to fully exploit the inter-sensor entanglement, we demonstrated the simultaneous estimation of multiple local parameters, achieving quantum gains of up to 3.6 dB beyond the standard quantum limit [1].

These results establish mesoscopic condensates on atom chips as a powerful experimental testbed for multiparameter quantum metrology and fundamental studies of steering and non-locality [2, 3]. Furthermore, our architecture holds great promise for proof of principle studies in quantum clock interferometry. The internal degree of freedom of each split cloud acts as a local clock measuring the phase evolution between the 2 hyperfine levels. Together with the ability to split, independently manipulate, and coherently recombine the entangled ensembles, it provides the essential tools for future studies exploring entanglement-enhanced clock interferometry, which has been proposed as a tool for measuring General Relativity effects in a laboratory setting [4, 5].

In this contribution, we will detail our recent multiparameter sensing results and outline the roadmap for future experiments in clock interferometry with our platform.

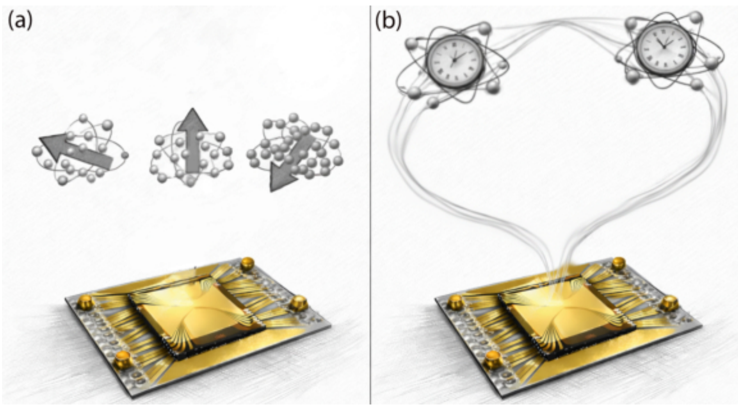

FIG. 1: (a) Idea of the multiparameter sensing with a spatial array of entangled atomic clouds on an atomic chip. The collective spin of each ensemble senses a different parameter which may correspond to a value of a field at the cloud's location and is imprinted as a spin rotation. Utilizing inter- and intra-sensor entanglement enhances the overall sensitivity beyond classical limits. (b) Idea of the clock interferometry. A squeezed or coherent state would be generated on the atomic chip platform and subsequenetly split into 2 spatially separate clouds. Each cloud maintains an internal hyperfine degree of freedom acting as a clock. The clouds can be brought back together with Stern-Gerlach type magnetic field control and interfered upon measurement.

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The non-stabilizerness cost of quantum state estimation

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Accurate estimation of quantum states and their properties is a central task in quantum information, with direct relevance to quantum learning, device characterization, calibration, and control. In this context, quantum state tomography [**1**] remains the golden standard. However, protocols based on random measurements demand extensive reconfigurability and can incur substantial overhead.

Efficient reconstruction of quantum states with a *single* fixed measurement setting [**2**] is highly desirable for near-term experiments, as it avoids the repeated reconfiguration required by randomized protocols. In this work [**3**] we study which physical resources are necessary for such single-setting schemes to become informationally complete. We consider an n-qubit input state, ancillary qubits, a fixed quantum circuit, and a final projective measurement in a fixed stabilizer basis, and ask when the resulting effective POVM allows full state reconstruction.

We show first that stabilizer resources alone are fundamentally insufficient: any protocol based only on Clifford gates, stabilizer ancillas, and fixed-basis readout is informationally equivalent to a projective measurement in a stabilizer basis and therefore cannot be informationally complete, independently of the number of ancillas employed. We then quantify the minimal amount of non-stabilizerness needed to overcome this limitation. By doping the Clifford circuits with T-gates, we demonstrate that informational completeness requires at least $2n/\log_2 3$ T gates, while explicit constructions show that $2n$ T gates are sufficient. In doing so, we clarify the role of entanglement by observing that universal reconstruction is allowed only when maximal entanglement is generated in certain auxiliary Clifford circuits.

Our results therefore single out the metrological role of non-stabilizerness in state reconstruction with fixed architectures and, more in general, connect resource theories of magic and entanglement with quantum state estimation, suggesting design principles for single-setting tomography. Following these guiding line, we also introduce a systematic algorithm to engineer minimally doped circuits that enable universal state reconstruction and can be efficiently calibrated under reasonable assumptions on device noise [**4**].

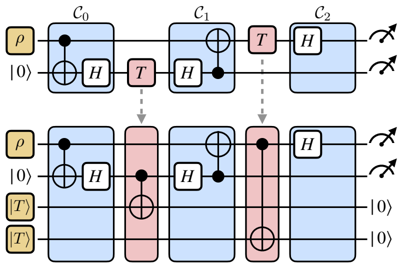

FIG. 1: Single-setting state estimation scheme. Informational completeness requires non-stabilizer resources.

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Equivalence of continuous- and discrete-variable gate-based quantum computers with finite energy

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This extended abstract is a summary of the results in arXiv:2510.08546 (2025).

The simulation of continuous systems is central to many branches of modern physics, such as high-energy physics, cosmology, condensed matter physics, quantum chemistry, and field-theories. The continuous-variable (CV) paradigm of quantum computation (QC) offers a natural host for simulating continuous systems. However, most physical quantum computing devices realized to date are based on the discrete-variable (DV) paradigm of quantum computation.

In this work, we address this fundamental discrepancy by providing a rigorous framework for translating native CV algorithms onto qubit-based quantum processors. This mapping is constructed from a gate-based model of CV quantum computers, consisting of states and operations whose total energy is polynomial in the number of modes. Gate-based CV operations refer to operations constructed from a polynomial sequence of elementary gates in a finite set, i.e., those selected from the set of Gaussian operations and cubic-phase gates. We show that the approximation is efficient and the level of precision depends on the energy scale of the CV system. This result simultaneously proves a computational equivalence of the CV model under consideration and the DV paradigm. To do this, we utilize a tool called the stabilizer subsystem decomposition (SSD) [1], which allows us to map any CV state onto a DV state. By utilizing the SSD as a map between gate-based CVQC and DVQC, we show that the action of this generating set of CV gates can be approximated by the action of a specific set of discrete gates for qudits that have sufficiently many dimensions.

To construct this mapping, we define realistic CVQC through three physically motivated assumptions. First, we restrict the circuit so that the energy of the system is bounded throughout the evolution of the circuit. Second, we assume that the majority of measurement values have a magnitude that is below a certain threshold, and all other measurement values are grouped together in an overflow bin. Third, we restrict the circuit such that measurements can only be resolved to a finite resolution. By carefully analyzing the error made by the approximation, we show that it is bounded by the energy of the CV system and the dimension of the corresponding qudit. Our method, therefore, provides a natural decomposition of the states, gates, and measurements from CV to qudits.

The titular result of this work is the construction of a framework for simulating gate-based CVQC under realistic conditions using a qudit-based quantum computer in polynomial time with arbitrarily small error. At the same time, we show that there cannot be an exponential advantage in the computational power of CV devices with finite-energy compared to devices based on the DV paradigm. Furthermore, by interpreting each qudit state as constructed from a series of qubits, we can demonstrate that qubit quantum computers are capable of simulating realistic CVQCs. A major consequence of our results is that the classical algorithms used for the simulation of DV quantum computing can be applied for the simulation of CV quantum computers. We highlight the possibility of using our framework to formulate a rigorous method to convert CV-algorithms (particularly those involving GKP-encoded states), such as finite-energy versions of Refs. [2−3], to DV-algorithms.

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†Ludvig Rodung and Alex Maltesson contributed equally to this work

Nonparametric Estimation of Non-Gaussian Quantum States of Continuous-Variable Systems

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Continuous-variable (CV) quantum states describe systems with observables taking values in continuous spectra. In quantum optics, their realizations, known as qumodes, serve as CV counterparts to qubits, as light fields naturally exhibit continuous quadrature degrees of freedom. CV platforms support a wide range of quantum information tasks, including computation, communication, and sensing. As a result, significant effort has been devoted to learning CV quantum states, with particular progress for Gaussian and mildly non-Gaussian states, establishing tight bounds on the trace distance in terms of first moments. Gaussian states are important because of their analytic tractability and efficient classical simulability, but they are not sufficient to unlock the full power of quantum technologies. In contrast, non-Gaussian states are widely recognized as the essential resource for universal CV quantum computation, quantum error correction, and quantum advantages in communication and metrology. However, efficiently learning and characterizing genuinely non-Gaussian states remains a formidable challenge. Traditional approaches reconstruct phase-space quasiprobability distribution functions (QPDFs) like Wigner function by inverting the Radon transform of quadrature distributions estimated via histograms and maximum-likelihood estimation (MLE). This process is sensitive to sampling noise and the inversion of the Radon transform can be ill-posed, necessitating the use of regularization. Detector inefficiencies blur nonclassical features such as Wigner negativity. These propagate into the reconstructed density matrix, leading to loss of nonclassicality, reduced purity, or even nonphysical states. Parametric models such as Gaussian mixtures provide stability but impose strong prior assumptions, limiting their applicability to complex states.

We introduce a *nonparametric kernel quantum state estimation (KQSE)* framework. Unlike MLE, Bayesian and machine learning approaches, which rely on parametric assumptions (e.g., truncated Fock spaces, prior state knowledge) and require high dimensional optimization, KQSE reconstructs the state directly from tomographic data using the optimal kernel density estimation [1]. KQSE achieves nearly optimal convergence: the mean squared error in estimating Wigner functions, density matrices and their trace quantities scales as $\widetilde{O}(1/T)$, where T is the number of measurements, matching parametric rates without any prior assumptions on the state. The method is fully data-driven and is robust to noise, performing equally well for Gaussian and non-Gaussian states. The experimental data analyzed in this work were obtained from the homodyne-tomographic measurements reported in [2]. While MLE improves

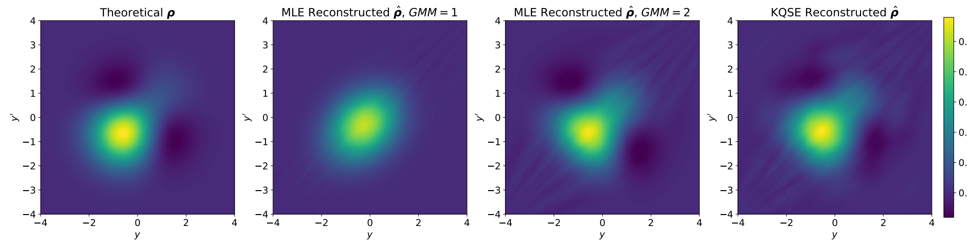

Figure 1: Heatmaps of kernel $\rho(y, y')$ of the statistical mixture of the Schrödinger kitten state and vacuum: (a) theoretical kernel; (b) and (c) MLE under Gaussian mixture model assumptions with $GMM = 1$ and $GMM = 2$, respectively; (d) KQSE

from one- to two-component Gaussian mixtures, KQSE attains the lowest error, showing robustness to model mismatch and noise. Given the central role of non-Gaussianity in enabling universal computation and quantum advantage, we expect KQSE to have broad impact across quantum optics, quantum error correction, and quantum metrology.

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Nonlocal continuous-variable quantum nondemolition gates by optical connections

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Distributed quantum computing is a crucial paradigm for the efficient scale up of quantum computers, obtained by mapping qubits to a nonlocal quantum network of smaller processing units, e.g. cluster states, connected though quantum channels to build larger quantum processors. To this aim, the realization of nonlocal quantum gates that entangle different network nodes represents a fundamental step. Those gates allow two distant users sharing a quantum channel, Alice (A) and Bob (B), to effectively implement a joint unitary operation by means of both local operations and classical communication (LOCC) and the exchange of an ancillary system through the channel to mediate the interaction, hereafter referred to as mediator (M). Experimental demonstrations have been only recently realized on discrete-variable (DV) platforms, where a nonlocal controlled-NOT (CNOT) operation has been distributed over distances of $0.6, 7, 10$ km, respectively [1-3].

The continuous-variable (CV) analog of the CNOT gate is the quantum nondemolition (QND) coupling $U_{AB} = \exp(-igx_A p_B/2)$, being advantageous for CV quantum computation due to its versatility [4]. In this work, we propose a library of feasible protocols to implement a nonlocal QND gate between two distant users sharing a quantum channel with a newly available element - single-pass waveguide optical parametric amplifiers (OPAs), allowing for both online squeezing and phase-sensitive amplification (PSA) for channel-loss compensation, and classical communication between them [5-7]. We assume QND coupling to be locally available to both the remote users and consider high-capacity optical connections between them, that are essential for transmitting large amounts of information per mode.

We design different protocols that employ mediators with different quantum resources: squeezing, entanglement, Bell measurement, and the geometric phase effect by sequential local QNDs. We characterize the resulting nonlocal entangling gates in terms of both logarithmic negativity and excess noise and optimize their performance, considering the impact of both incoupling OPA losses and, more crucially, of distributed loss inside the OPA, occurring during signal propagation through the waveguide [8]. We prove the first three schemes to be equivalent with one another, whilst the geometric phase protocol to give a factor 2 improvement over the others in both the limits of small and large losses. Further, we demonstrate application of our approach for CV cluster-state manipulation, allowing for fusion of distant cluster states into a distributed network, thus providing a first step towards development of distributed CV measurement-based quantum computation.

The suggested schemes can be naturally embedded into cluster-state technology, enabling efficient preparation of large distributed optical networks with different topologies, and also extendable to other platforms for generation of hybrid entanglement between either CV-CV or DV-CV physical systems mediated by optics. Moreover, QND interaction may conveniently replace beam splitters as universal two-mode gate for quantum computation, allowing also for efficient synthesis of nonlocal global nonlinear operations by local non-Gaussian cubic phase gates and nonlocal (Gaussian) QNDs.

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Quantum Correlations in Three-Beam Symmetric Gaussian States Accessed via Photon-Number-Resolving Detection and Quantum Universal Invariants

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Quantum correlations of symmetric 3-beam Gaussian states are analyzed using their *quantum universal invariants.* These invariants, 1-, 2-, and 3-beam purities, are expressed in terms of the beams' intensity moments up to sixth order. The 3-beam symmetric Gaussian states with varying amounts of the noise are experimentally generated using entangled photon pairs from down-conversion by the technique of compound beams [1,2], their invariants are determined [3], and their quantum correlations are quantified [4]. *The coexistence of bi- and tripartite entanglement and genuine tripartite entanglement is experimentally confirmed in these states* that resemble the noisy GHZ/W states.

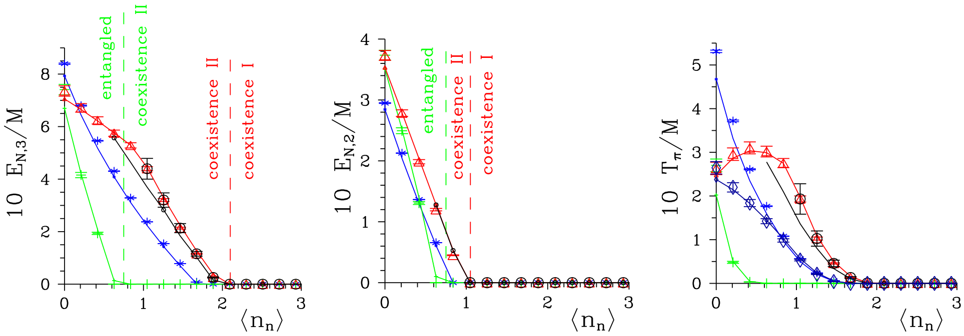

Figure 1: Tripartite (bipartite) negativity per mode $E_{N,3}/M$ ($E_{N,2}/M$) and cotangle per mode T_π/M as they depend on the mean noise photon number $\langle n_{\rm n}\rangle$ per beam. Black curves and $\circ$: exact values - sixth-order moments; green [red] curves and + [$\triangle$]: lower [upper] bounds - fourth-order moments; blue curves and $*$: second-order moments; navy blue curve and $\diamond$: noisy GHZ/W states.

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Correlation-Enhanced Quantum Pattern Recognition via Phase-Encoded Multiphoton Interference

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The large impact artificial intelligence achieved in the last decade in all aspects of science, technology and everyday life more broadly, together with its soaring energetic and computational costs, convinced the quantum sciences community to explore quantum-enhanced pattern recognition (QePR) architectures meant to replicate and even outperform traditional neural network units while reducing computational costs related to classification and training processes [1].The fundamental principle underlying QePR is that, when two or more photons interfere through the mixing of optical pathways, the visibility of the resulting interference pattern is governed by the overlap of the photons' wavefunctions, together with residual distinguishabilities in other degrees of freedom that may affect the "*welcher-Weg*" uncertainty [2, 3]. As a consequence, a direct measurement of visibility could become the preactivation function for an artificial perceptron designed to solve binary classification problems, provided that the patterns are encoded in the wavefunction of the interfering photons.
Here, we substantially extend the original architecture introduced in the first theoretical formulation of Ref.[1]. Information is encoded in the optical phase rather than in amplitude or intensity. By combining spatially resolved coincidence measurements with momentum-correlated probe states generated through spontaneous parametric down-conversion (SPDC), we realize a perceptron architecture that performs both classification and training entirely optically, enabling the full exploitation of quantum advantage.

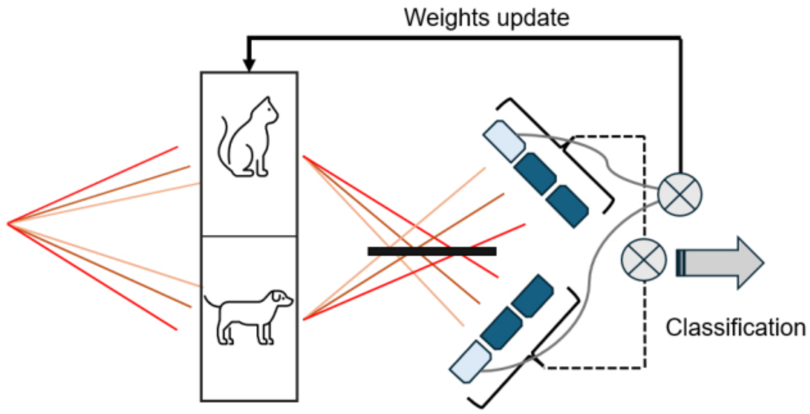

FIG. 1: Conceptual depiction of the Phase-Encoded Quantum Pattern Recognition algorithm.

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Wigner tomography of zero-one-photon encoded qubit generated by quantum dot in micropillar cavity

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The zero-one-photon encoded qubit $\alpha|0\rangle + \beta|1\rangle$ is a key resource for twin-field quantum communication [**1**], super-position state boson sampling [**2**], and reservoir quantum computing [**3**]. Until recently, the qubit has been produced only conditionally on a beamsplitter, via interference between a heralded single photon and a coherent state [**4**]. Alternatively, we generate this qubit deterministically, using a semiconductor quantum dot (QD) in a micropillar cavity [**5**]. Under coherent laser pulse excitation, the drive power sets the QD population inversion, and thus the superposition weight between vacuum and single-photon Fock states. For the first time with solid state quantum emitter, we perform Wigner tomography using direct measurement [**6**] empowered with zero-photon detection scheme [**7**] and homodyne photon correlations [**8**]. We reconstruct with close-to-unity fidelity propagation-loss-corrected Wigner functions of the zero-one-photon encoded qubit (for six different population inversions, example in Fig. 1) up to large displacements, where conventional photon-number counting fail due to limited photon-number resolution and exponentially long acquisition times required for higher-order photon correlations.

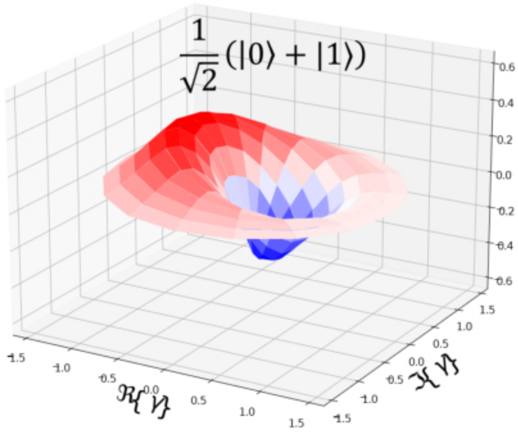

FIG. 1: Reconstructed and loss-corrected Wigner function of emitted state $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$.

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Supermodularity and subadditivity of Rényi entropies on the majorization lattice: Applications to entanglement catalysis

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Majorization theory is a rich area of mathematics which finds applications in a wide variety of fields, extending in particular to quantum information sciences. Although the link between the interconvertibility of entangled pure states and a majorization relation of their Schmidt vectors was discovered about twenty-five years ago by Nielsen [1], many interesting questions remain open today, for example regarding the extension to the so-called majorization lattice. This lattice, which is induced by the majorization preorder for a collection of quantum states, comes with the concept of majorizing infimum (called *meet*) and majorizing supremum (called *join*) for any pair of quantum states. Recently, these lattice-theoretic states have been interpreted in the context of quantum resource theories as the Optimal Common Resource (OCR) state [2] and Optimal Common Product (OCP) state [3], which gave rise to interesting ramifications. In this work, we prove a majorization relation underlying the properties of supermodularity and subadditivity on a lattice – which are well known to be linked with optimal solutions to optimization problems in the economics litterature [4] – and use it to show that the Rényi entropies of order $\alpha > 1$ are supermodular and subadditive on the majorization lattice. This generalizes a known result that the Shannon entropy is supermodular and subadditive on this lattice [5]. We also show Tsallis entropies to be both supermodular and subadditive on the majorization lattice for all values of the α parameter. Using these results, we discuss the link between entanglement catalysis and inequalities for ranges of the Rényi entropies (or ℓ_p norms) [6], and show the existence of an approximate catalysis process between the pair of OCR and OCP states and the two states generating them. Aside from its intrinsic interest for majorization theory, this finding may be relevant in the context of the interconversion of Gaussian states in quantum optics, following the lines of [7].

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High-Rate Remote Entanglement of Trapped Ions via Multiplexed Ensemble Memories

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Efficient photon-mediated entanglement between remote stationary computational qubits remains a central challenge for quantum networks. Trapped ions provide a computational toolbox and are narrowband, high-coherence quantum emitters, while ensemble-based quantum memories and spontaneous parametric down-conversion (SPDC) sources naturally operate at broadband bandwidths and support multiplexing. Combining these systems results in favorable quantum network nodes, but interfacing these systems is fundamentally limited by the severe spectral mismatch between narrowband ionic transitions and the broadband memories.

We propose to use the multimode nature of the SPDC source, that enables the multiplexing, to also overcome the bandwidth mismatch between ensemble memories and trapped ions. In this architecture, the SPDC photon pair envelop is matched in an entanglement generation step to the ion photon, a click then heralds the successful generation of entanglement between the trapped ion and a broadband photon stored in the memory (see Fig. 1). The hybrid node thus combines the multiplexing capability of SPDCs and ensemble memories with the high-fidelity processing of trapped ions.

Within this framework, we analyze single-click and double-click heralded entanglement protocols for remote ion-ion entanglement mediated by long-distance multiplexed ensemble links. The single-click protocol benefits from higher success probability but requires phase stability, whereas the double-click protocol relaxes phase requirements at the expense of additional (memory) photon loss sensitivity.

Our results show that hybrid ion-ensemble nodes can substantially increase remote entanglement rates over long distances. Furthermore, the approach to use a multi-modal photon pair for bandwidth-matching proofs to be a promising approach for combining different quantum systems.

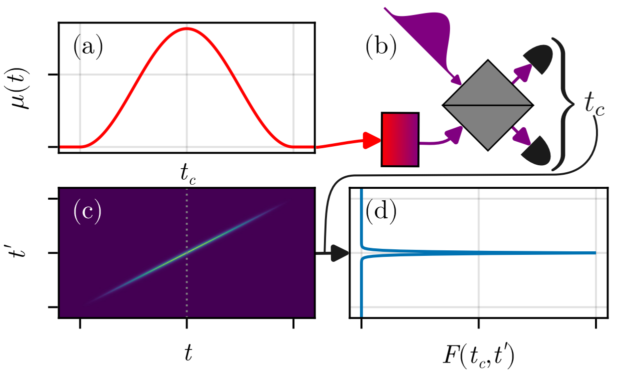

FIG. 1: Illustration of matching the envelope (a) of the SPDC photon pair two time probability distribution (b) to the ion. (c) The ion and SPDC channel are combined using a beamsplitter terminating in detectors, such that a click heralds entanglement between a temporally narrow photon (d) and the trapped ion. Figure reproduced from Ref. [1].

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Certification of linear optical quantum state preparation

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Fidelity witnessing - verifying with probability $(1-\varepsilon)$ than an experimentally prepared state has as at least some threshold fidelity with a target state - is a key quantum certification task. We study this task in the context of photonic platforms [1], where single photons are propagated through linear optical interferometers to create entangled resource states which are measured with photon counters which cannot resolve internal degrees of freedom. Here, computational power arises from the indistinguishability of the photons, i.e., their relative permutation symmetry. Thus, standard fidelity witnesses do not apply directly as they certify the closeness to some fixed target state rather than the appropriate equivalence class of permutationally invariant states. We introduce a measure of fidelity suitable for this setting and show several different ways to witness it, based on earlier proposals combining measurements of the reversibility of the interferometer and genuine multi-photon indistinguishability [2]. We consider multiple indistinguishability witnesses [2-5] and argue that the discrete Fourier transform is an optimal choice. We experimentally certify the fidelity of several multi-photon states.

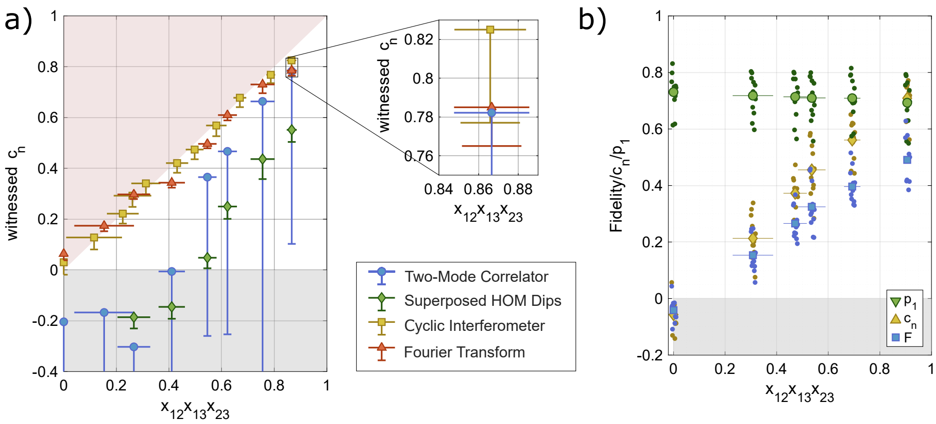

Figure 1: **Experimental results.** **(a)** Witnessed indistinguishability as a function of the product of pairwise overlaps of the internal states of 3 photons $(x_{1,2}x_{2,3}x_{1,3})$. Horizontal lines through the markers depict the standard deviation in $x_{1,2}x_{2,3}x_{1,3}$ and the horizontal lines under the markers denote $c_n(\varepsilon = 0.25)$. The area that is marked gray witnesses no indistinguishability, and the area marked red has a higher indistinguishability than is allowed according to the theory. **(b)** Gate reversibility, indistinguishability, and fidelity witnesses for 12 Haar random 6-mode interferometers with $\varepsilon = 0.1$.

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Poster presentations

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Superradiance in a strongly interacting atom-cavity system

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Even at low atomic densities, the dynamics of atoms inside an optical cavity remain a many-body problem because all atoms are coupled to the same cavity mode. We present an experimental setup(Fig. 1) for observationof the spatial self-organization of laser-driven atoms in an optical cavity. Two laser beams with opposite circular polarizations drive cold ^{87}Rb atoms inside the cavity in the transverse direction. Below the threshold value of the transverse pump intensity, the homogeneous distribution of the atomic cloud leads to a spatial destructive interference and onlz the thermal fluctuations resuls in a subradiant scattering. Above the threshold, the atoms self-organize into a checkerboard pattern, that produce a superradiant scattering into the cavity.

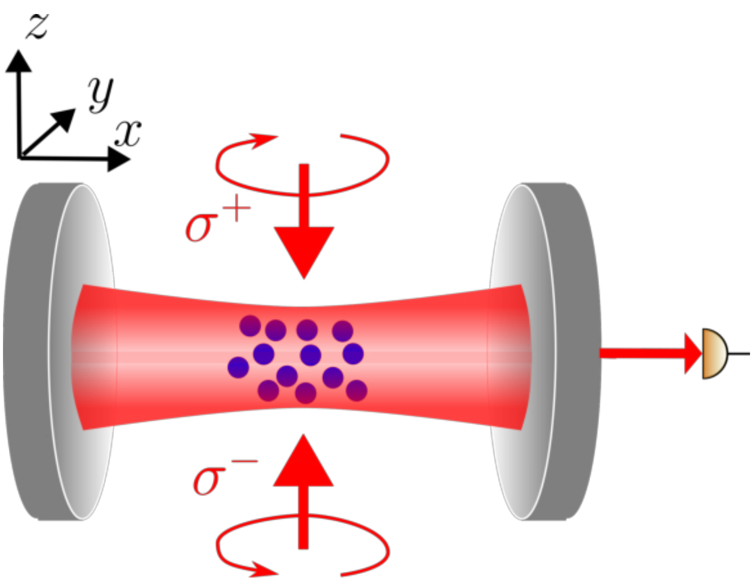

Figure 1: Schematic of the experiment. Cold atoms inside an optical cavity are transversely driven by two laser beams with opposite circular polarizations.

Experimental Realization of Quantum Analogy-to-digital Conversion

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University of Science and Technology of China

Quantum systems can be fundamentally classified into discrete-variable (DV) and continuous-variable (CV) systems. The degree of quantum advantage achieved with a quantum system is often dictated by the scalability, robustness, and operational feasibility—factors that are closely tied to the nature of the variables employed. Notably, DV and CV systems are largely complementary in these factors. Consequently, integrating DV and CV variables holds significant promise for overcoming the inherent challenges associated with relying solely on one type of variable system. In the poster, we present an experimental bidirectional quantum analog-to-digital converter (QADC/QDAC), which facilitates deterministic and reversible quantum information transfer between CV and DV systems. This QADC/QDAC is hardware-efficient, and the error decreases exponentially with the number of qubits, thereby allowing high-fidelity information transfer with a few qubits. With this photonic QADC/QDAC, we demonstrate efficient CV mode tomography leveraging DV tomography techniques and achieve deterministic generation of non-Gaussian CV mode from qubits. Our findings address a critical barrier in constructing hybrid quantum processors and open up new avenues for scientific exploration previously inaccessible to single-variable quantum systems.

An airborne resonator-enhanced parametric downconversion source for quantum communication

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Long-distance quantum communication networks rely on the ability to faithfully distribute quantum information between different network nodes. The network nodes are often considered to be based on atomic or ionic systems which exhibit narrow optical linedwidths for the transition that are used in quantum communication. However, long-distance transmission in fibers is ultimately limited by the absorption loss in optical fibers making them unsuitable for intercontinental quantum communication. It can be shown that is thus beneficial to forgo an optical fiber channel in favor of free-space channels using satellites or other moving platforms yet at the cost of additional complexity in terms of size, weight, and power constraints as well as the fluctuating channel itself. Efficient information transfer not only relies on a low-loss quantum channel but also requires sources that generate quantum states which can interact with the atom or ion in question. Whispering gallery mode resonator (WGMR) based spontaneous parametric down-conversion sources have been shown to be highly tunable sources for a variety of quantum states. Their inherent optical bandwidth in the MHz-range makes them compatible with atomic and ionic transitions.

As part of the German QuNET initiative, we are employing our WGMR-based source aboard a research aircraft of the DLR that has been outfitted with an optical communication terminal [1]. On the ground, we are receiving our quantum signals using a mobile optical ground station by Fraunhofer IOF [2]. The goal of this mission is to demonstrate the practical realization and benchmarking of quantum communication tasks, ranging from quantum key distribution to demonstrating long-distance coupling of photonic quantum states and an ion, using an aircraft as a mobile sender. As our contribution to this mission, we are investigating the overall stability of our source, as shown in Fig. 1, and the coupling of photonic quantum states to a single trapped ion under the adverse conditions from an airborne free-space link.

In our presentation, we highlight the challenges of realizing photon-atom-interaction experiments in such a demanding environment and present first results showcasing the photon-ion-interaction between a SPDC source located on an aircraft and an ion trapped on ground.

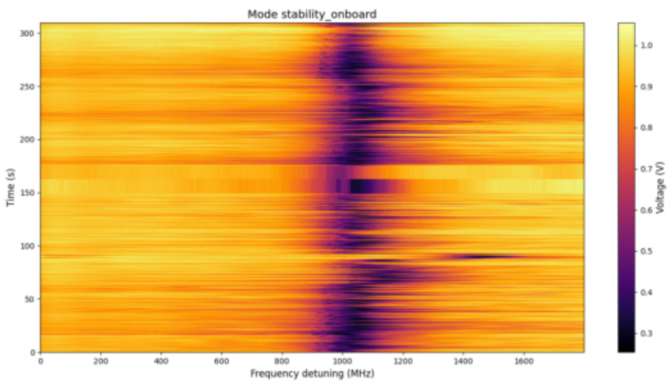

FIG. 1: Waterfall plot of the reflected pump spectrum during in-flight operation of the WGMR SPDC source above the Munich area.

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Multipartite Entanglement Dynamics in Quantum Walks

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Introduction Entanglement plays a crucial role in understanding quantum systems and is important for quantum technologies like quantum computing, quantum simulation, and quantum communication [1]. Quantum walks (QWs) offer an interesting platform for studying such systems, with various applications in quantum algorithms [2]. Discrete-time QWs are well suited for optical implementations and can be studied from a quantum optical perspective. We adopt this point of view to investigate the entanglement dynamics of QWs by constructing suitable entanglement witnesses, both for bipartite and multipartite systems [3].

Methods Similar to the classical random walk, a discrete-time QW consists of a coin space $\mathcal{H}_C$ and a position space $\mathcal{H}_P$, and the total Hilbert space is given by $\mathcal{H}_C \otimes \mathcal{H}_P$. The walk proceeds by first applying the coin-flip, which acts only on $\mathcal{H}_C$ and then the step operator, which acts on $\mathcal{H}_P$ with the coin as a control. This process is repeated the desired amount of times, before the resulting state is measured. For optical implementations, the two-dimensional coin space is usually realized via the polarization of a photon. The position space is commonly realized via spatial or time multiplexing. The QW can thus be fully realized using linear optical networks. A possible optical implementation is shown in Fig. 1.

There are many ways to study the multipartite entanglement of quantum systems. We employ the entanglement witness approach. It consists of an observable $\hat{W}$, called an entanglement witness, such that a negative expectation value $\langle \hat{W} \rangle < 0$ signals entanglement. To construct an entanglement witness for a given state $|\psi\rangle$, we utilize the geometric measure of entanglement E_g. It is given by maximizing the overlap $g = |\langle \chi|\psi\rangle|^2$ over all product states $|\chi\rangle = |\chi_1\rangle \cdots |\chi_M\rangle$ and setting $E_g = 1 - g$. By construction, $E_g \in [0, 1)$, where 0 represents no entanglement and values approaching 1 represent very high entanglement. In this work, we present an approach to efficiently compute E_g for the QWs under consideration.

Results An example for the multipartite entanglement dynamics of a quantum walk with periodic boundary conditions is shown in Fig. 2. In our work, we consider the effect of the initial condition on the entanglement, as well as different partitions. An interesting partition describes the entanglement of only the coin degrees of freedom (i.e. the polarization), where we present analytic solutions for the entanglement for arbitrary localized initial conditions. Furthermore, we demonstrate the emergence of entanglement typicality in statistical ensembles of random optical networks.

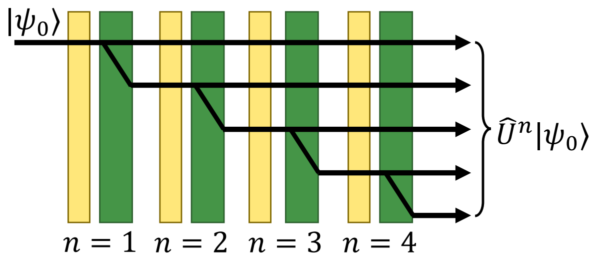

Fig. 1 Possible scheme for an optical implementation of a QW using spatial multiplexing. The yellow boxes represent half wave plates (coin-flip) and the green boxes represent polarization beam displacers (step).

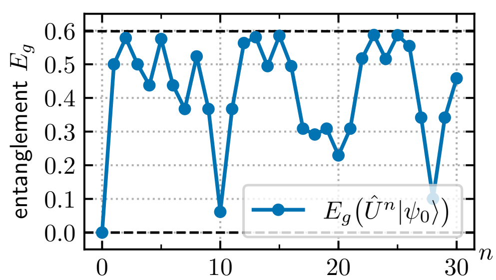

Fig. 2 Entanglement dynamics for a QW with periodic boundary conditions and a single photon starting in the initial state $|H\rangle|0\rangle$. The gray area denotes regions of unattainable E_g.

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The Paderborn Quantum Sampler - A hybrid boson sampling platform

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Gaussian boson sampling (GBS) [**1**] has emerged as a scalable photonic approach to demonstrating quantum computational advantage, employing single-mode squeezed vacuum input states, a large interferometer, and multi-channel photon-number detection. In contrast to the original boson sampling paradigm [**2**], which requires non-Gaussian single-photon inputs, GBS fully relies on non-Gaussianity in the measurement, reducing experimental complexity at the cost of reducing non-Gaussian resources - essential for outperforming any classical system. As the field moves towards practical use cases, for example simulating molecular vibronic spectra [**3**, **4**], and develops towards universal photonic quantum computing [**5**], it becomes crucial to benchmark sampling platforms that employ different (Gaussian and non-Gaussian) input states and identify the advantages that can be gained by tailoring these input states.

To address this issue, we introduce the Paderborn Quantum Sampler (PaQS) [**6**], a 12-mode hybrid boson sampling platform that can perform sampling tasks with Gaussian or non-Gaussian input states within a single experimental run. This allows direct side-by-side comparison under otherwise identical conditions. Applying a semi-device independent framework, we confirm non-classicality within our produced sampling data and show performance gains arising from utilizing non-Gaussian input states.

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Probing Casimir-type processes using radiation-pressure readout in standard optomechanical structure

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We propose a quantum state readout protocol for systems exhibiting an avoided level crossing, whose dynamics can be mapped onto an effective two-level model. The reduced dynamics is that of a two-level system coupled to one or more standard optomechanical cavities [1,2]. The optomechanical (radiation-pressure) interaction modifies the system's eigenbasis: the adiabatic eigenstates of the avoided crossing are no longer stationary, which induces Rabi-like oscillations between the original states and their superpositions. We show that this coupling enables continuous, real-time access to the system's quantum state via the cavity output field, providing a direct probe of the underlying dynamics.

An interesting feature of the proposed protocol emerges in the presence of noise, due to the emergence of a steady state. We identify a regime where the leaky cavities stabilize the internal Rabi oscillations, effectively freezing the dynamics of the two-level system, a counterintuitive effect that can be harnessed for state preservation or readout synchronization.

To highlight the persistency of the underlying quantum dynamics in the readout signal, we focus on a optomechanical two-photon hopping [3], a specific Casimir-type process. We show that, even in the presence of thermal noise, the readout signal retains clear signatures of the underlying quantum dynamics. Our results establish optomechanical platforms as effective tools for quantum state readout in generic driven two-level systems, with potential extensions to higher-order Casimir processes.

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Hanbury Brown-Twiss interference of electrons in free space

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We investigate the spatial second-order correlation function of two scattering electrons in a Hanbury Brown-Twiss like experiment. First, we consider semi-classically the effects of the Pauli exclusion principle and Coulomb repulsion on the expected correlation pattern. This is followed by a full quantum-mechanical treatment of the problem, where we separate the system into relative and center-of-mass coordinates in analogy to the Hydrogen atom ansatz. While the center-of-mass system is described as a free particle, the relative system contains the Coulomb scattering process which translates into an effective one particle problem. We expand the respective initial state of the electrons in the eigenstates of the corresponding Hamiltonian and evolve the system in time. After the scattering process, the function is then evaluated in the far field. We present the formal solution of the problem and discuss the current state of the numerical investigations.

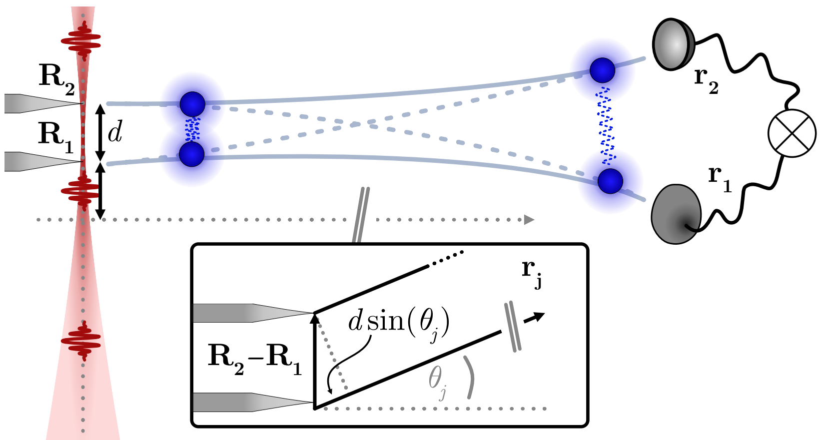

Figure 1: **Setup of the system.** Two independent needle tip sources at positions $\mathbf{R}_1$ and $\mathbf{R}_2$ with distance d are illuminated by short laser pulses to emit electrons via the photo effect. In the far field, the electrons are coincidentally detected by detectors at positions $\mathbf{r}_1$ and $\mathbf{r}_2$. The resulting correlation pattern $G^{(2)}(\mathbf{r}_1, \mathbf{r}_2)$ exhibits two-particle interference due to the interference of different two-electron quantum paths. Inset: The path difference for two electrons emitted by different sources but detected at the same detector j is given by $d\sin(\theta_j)$.

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Observation of Lie Algebraic Invariants in Quantum Linear Optics [1]

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Linear optical evolution plays a central role in photonic quantum information processing and in models such as Boson Sampling [2], where multi-photon interference in linear interferometers is used to explore regimes of computational complexity. Recent theoretical works have shown that linear optical dynamics possesses an underlying Lie algebraic structure, which implies the existence of invariant quantities that remain constant under any linear optical transformation [3].

In this work, we experimentally investigate the role of Lie algebraic invariants in quantum linear optics. Using a hybrid photonic platform based on a demultiplexed quantum dot single-photon source and a fully reconfigurable integrated interferometer, we implement linear optical evolutions of increasing size and experimentally measure invariant quantities associated with the Lie algebra of linear optical Hamiltonians, as shown schematically in Fig. 1. We show that the measured invariant quantities are preserved under arbitrary linear optical transformations, in agreement with theoretical predictions. Furthermore, we connect these invariants to quantum correlation functions and coherence properties of multi-photon states, providing a physical interpretation of the Lie algebraic formalism.

Our results demonstrate that Lie algebraic invariants can be used as a practical tool to characterize and benchmark linear optical dynamics in photonic quantum information platforms, providing new methods for the analysis and validation of photon-based quantum computing protocols.

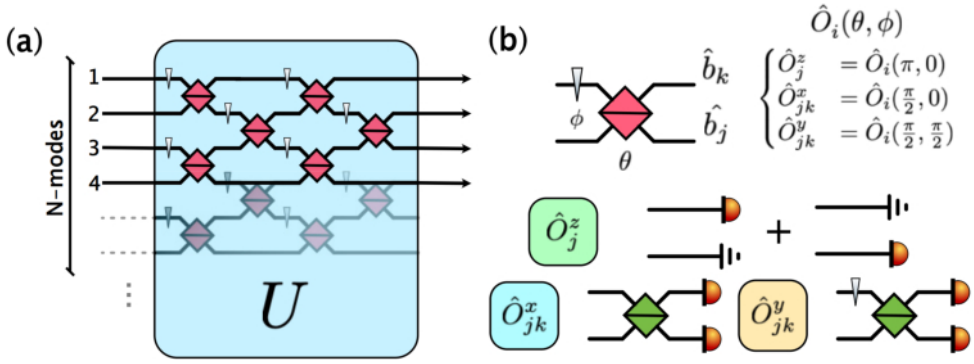

Figure 1: a) Implementation of an arbitrary linear optical transformation (U) on a multi-photon, multi-mode Fock state using an integrated photonic circuit with reconfigurable beam splitters (red squares) and phase shifters (light blue triangles). b) Measurement scheme for evaluating invariant quantities: output correlations are extracted through two-mode interference to estimate the expectation values of the relevant Lie algebraic operators. Here, green squares denote balanced beam splitters.

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A Husimi phase-space approach to a driven–dissipative quantum field at finite temperature

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Understanding the interplay between coherent driving and environmental dissipation is essential for controlling and preserving quantum features in realistic optical systems. In this work, we investigate the dynamics of a driven single-mode quantum field interacting with a finite-temperature reservoir within the framework of open quantum systems. Starting from the Lindblad master equation, which includes both resonant driving and thermal dissipation, we employ a rotating-frame transformation followed by a displacement operation to simplify the dynamics and obtain an analytical solution using superoperator techniques.

To avoid the appearance of infinite series in the density operator, we adopt a phase-space description based on the Husimi Q-function. Within this framework, we obtain a closed Gaussian form of the Husimi distribution and derive the corresponding Fokker–Planck-type equation governing its evolution. This approach enables a direct and intuitive characterization of the system in terms of physically relevant quantities, including photon-number statistics, the Mandel parameter, and entropy measures such as the Wehrl and linear entropies.

Our approach extends previous studies by incorporating the effect of external driving into the phase-space formalism, offering a complementary perspective on the competition between coherence, thermal fluctuations, and dissipation.

Hyperloss from coherent spatial-mode mixing in quantum-correlated networks

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Quantum correlated networks based on squeezed or entangled states find wide application in modern quantum technology ranging from photonic quantum computing, quantum communication to gravitational wave detection. In larger networks, loss-induced decoherence drastically reduces the strength of quantum correlations and thus quantum advantage. When designing such networks, mismatch between spatial mode is commonly treated as incoherent loss. We show that this approximations fails when the light in the higher order modes is not lost but can interfere at multiple mismatched nodes. In this case squeezed light can be converted into an effectively thermal state, effectively exceeding 100% loss. We term this effect hyperloss.

We experimentally demonstrate hyperloss in a two-node quantum network consisting of two overcoupled cavities. With a mismatch of 8% at each cavity we convert a 5.8 dB squeezed state into a state without squeezing and quantum advantage. Due to its coherent nature this effect is controllable. Part of the lost coherence can be recovered by tuning the differential spatial mode phases. We demonstrate this recovery by eleminating the hyperloss and suppressing the mode mismatch loss from 15% to 2.9%. Hyperloss will limit design for networks operating with squeezed light. Our results show how hyperloss can be avoided and how phase-aware design can reduce losses from mode mismatch, where it cannot be avoided.

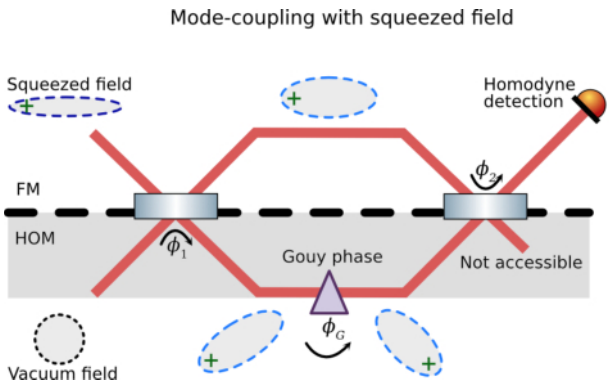

FIG. 1: Illustration of higher order mode coupling. The squeezed field in the fundamental mode (FM) mixes with vacuum in the higher order mode (HOM) due to spatial mode mismatch at the first node. The HOM now containing partly the squeezed field, copropagates and picks up a differential phase compared the the field in the FM. At the next mismatched node the HOM couples back into the fundamental mode and is detected.

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Overcoming the Technical Limitation of Weak Measurement by Incorporating Time-Momentum Correlation

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Standard Weak Measurement (SWM) amplifies signals but struggles with noises like jitter and pixelation. In this work, we propose an advanced variant of SWM that incorporates time-momentum correlation (TMC) into biased weak measurement (BWM). With theoretical analysis by Fisher Information metric and experimental validation in magnetic sensing, we demonstrate that TMC-BWM overcomes jitter and pixelation while extracting significantly higher Fisher information. This dual advantage yielded a 24.8 dB precision improvement over standard WM in our experiment, with merely classical resources utilized.

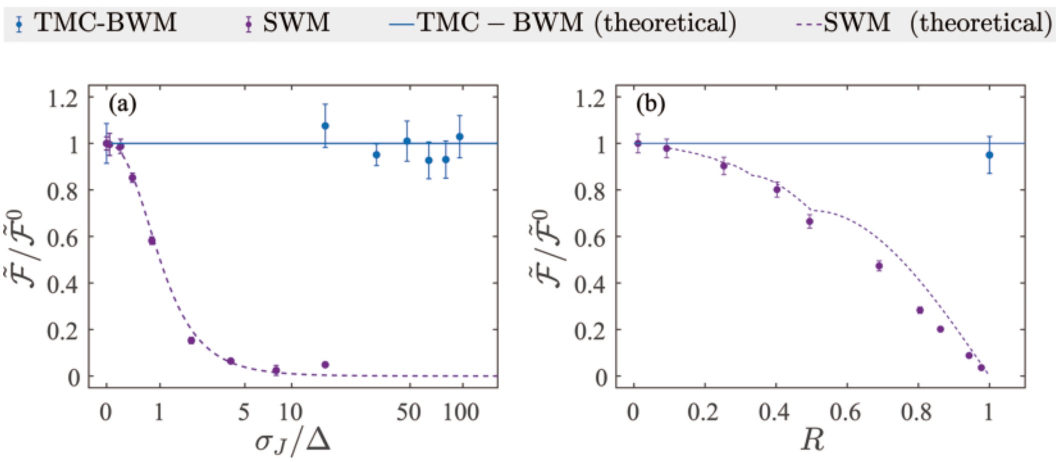

Figure 1: *The reserved rate of the CFI with varying magnitude of jitter and pixelation.* In both pictures, purple dots stand for SWM method while blue dots represent TMC-BWM method. In (a), the x-axis represents the magnitude of jitter noise. In (b), the magnitude of pixelation is characterized as R, with $1/R$ quantifying the number of pixels the light shining on the CCD, and $R = 1$ represents that the light drops into one pixel. It is obvious that when artificial jitter and pixelation noise were introduced, the precision of the SWM method plummeted, whereas TMC-BWM remained robust.

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Hong–Ou–Mandel interference between two independent narrowband thermal states

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Hong–Ou–Mandel (HOM) interference [1] is fundamental to many quantum technologies. A variety of HOM experiments have been demonstrated with different sources, including thermal sources. While traditionally studied using broadband thermal states generated via pulsed spontaneous parametric down-conversion (SPDC) [2,3], the narrowband, continuous-wave (CW) regime remains less explored. In this work, we investigate HOM interference in a distinct regime: using two independent narrowband thermal states generated from cavity-enhanced SPDC pumped by CW lasers.

Our experimental setup employs two MgO-doped lithium niobate whispering gallery mode resonators (WGMRs) as independent light sources [4]. The signal photons from each WGMR are directed into a HOM interferometer, while the idler photons are discarded. We obtain the interference pattern through two-fold coincidence counts. Unlike the standard HOM dip observed in broadband systems, our results show that the interference pattern vanishes when the two thermal states are frequency degenerate. Furthermore, the narrowband nature of our sources allows for the direct observation of an oscillatory interference pattern in the temporal correlation when the states are non-degenerate.

These results demonstrate excellent agreement with theoretical predictions. This study not only advances the fundamental understanding of thermal state correlations but also introduces a robust method for frequency matching between independent narrowband quantum sources.

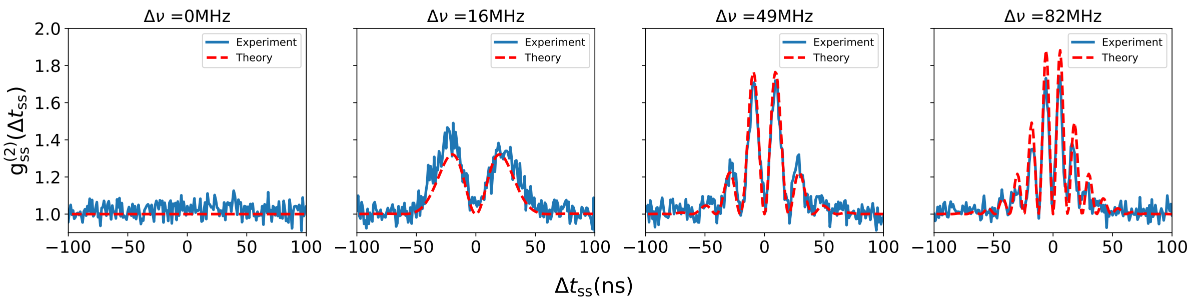

FIG. 1: HOM interference between two thermal states under different frequency detuning. Δt_{ss} repsents the time difference between two thermal states. The red lines are theoretical predictions, whereas the measured data is shown in blue.

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Quantum fundamentals with Spin-Squeezed Mesoscopic ensambles.

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Since the advent of quantum mechanics it has been a point of contention how phenomena such as entanglement and steering conflict with classical intuitions. And while microscopic experiments demonstrating paradoxical phenomena are commonplace, macroscopic experiments have proven more difficult. These experiments are critical to understanding the quantum-classical transition, and how our classical experience of the world around us comports with the quantummechanical nature of the microscopic world.

We present work done using our versatile atom-chip platform with which we can produce and manipulate spin-entangled ^{87}Rb Bose-Einstein condensates. This platform allows us to experimentally demonstrate Bell correlations[**1**], study fundamental decoherence channels[**2**], and for the first time violate the Einstein-Podolski-Rosen(EPR) paradox using spatially separated mesoscopic ensambles of massive particles[**3**]. We will also discuss how this EPR entanglement can be used to demonstrate steering, and how this steering can be used for metrological purposes.

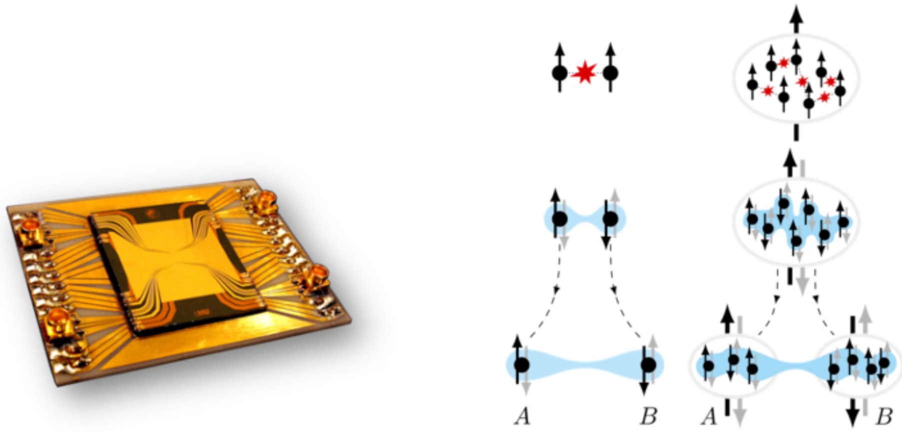

FIG. 1: Image of our atom chip and a diagram showing generation of entanglement within our ensamble, and coherent seperation into two ensambles.

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Learning to detect optical nonclassicality

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Nonclassicality, defined and understood in the quantum optical sense, acts as a resource for photon-based quantum technologies. Therefore, certifying the nonclassicality of a quantum state is crucial to gauging its potential for quantum advantage. However, traditional nonclassicality witnesses often fail in realistic scenarios involving finite-resolution photon detectors and limited statistics. Here, we propose and train a variational model using finitely many samples, measured with different detection schemes, to learn an optimal nonclassicality criterion for a given set of physically relevant states. Notably, the approach is fully-interpretable as the optimal criterion can be extracted once the model has been trained. Training the model on data simulated with the experimentally reconstructed POVM of (i) a superconducting nanowire single-photon detector and (ii) a time-bin multiplexing detection scheme demonstrates the versatility of the approach, paving the way for efficient nonclassicality detection.

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Parametric Homodyne Detection for Frequency-Multiplexed Quantum Measurement and Sensing

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Optical homodyne detection is the standard technique for accessing field quadratures, but its scalability to large numbers of modes is limited by electronic bandwidth and the requirement of mode-matched local oscillators. Parametric homodyne detection, based on broadband phase-sensitive amplification, provides an alternative measurement mechanism that directly maps optical quadratures onto amplified fields without electronic bandwidth constraints [1].

We consider parametric homodyne detection as a measurement primitive for frequency-multiplexed quantum states. In this approach, the measured quadrature is defined by the phase of the pump field driving the nonlinear interaction, enabling quadrature-selective amplification without the need for an external local oscillator. While a standard parametric interaction selects a global quadrature, dispersive propagation and pump-phase effects naturally give rise to frequency-dependent measurement bases $\theta(\Omega)$ across a broad optical spectrum. This works outlines a concrete experimental implementation based on a broadband phase-sensitive parametric amplifier, currently under development.

Applied to frequency-multiplexed squeezed states, such as squeezed frequency combs, this enables parallel and mode-selective access to many spectral modes across ultrawide optical bandwidths [3] within a single optical stage. As illustrated in Fig. 1, the sample is described by a frequency-dependent transfer function $H(\Omega) = |H(\Omega)|e^{i\phi(\Omega)}$ that encodes information across modes, while the parametric interaction defines how this information is read out through the effective measurement basis. This establishes a direct correspondence between multimode signal encoding and measurement.

Recent demonstrations of all-optical, measurement-device-free feedforward and tunable squeezing operations at bandwidths exceeding 1 THz [2] support the feasibility of ultrafast parametric processing and highlight the potential of nonlinear interactions as a platform for parallel quantum measurement. These capabilities make parametric homodyne detection a promising interface for frequency-multiplexed quantum sensing, and suggest a route towards high-rate, parallel generation and detection of non-Gaussian states.

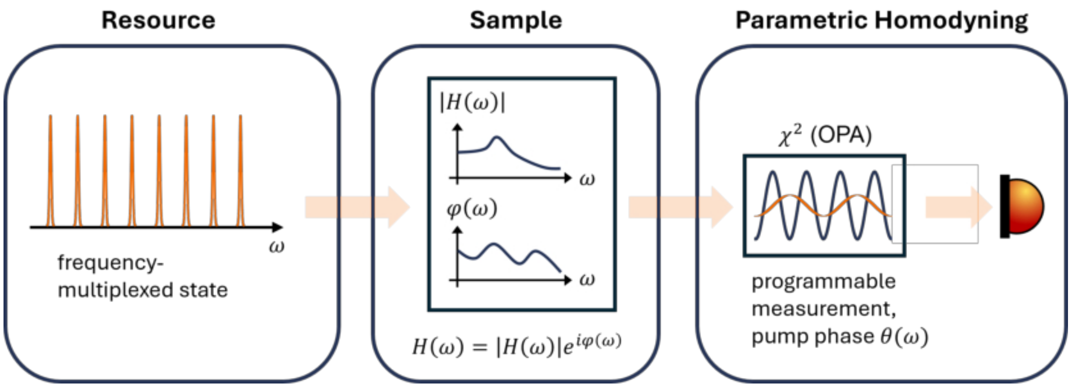

Figure 1: Frequency-multiplexed quantum measurement with parametric homodyne detection. A squeezed frequency comb probes a sample described by a frequency-dependent transfer function $H(\Omega) = |H(\Omega)|e^{i\phi(\Omega)}$, encoding information across many spectral modes. The output field is analysed using a parametric interaction, where phase-sensitive amplification selects optical quadratures without a local oscillator. Dispersive and pump-phase effects enable frequency-dependent measurement bases $\theta(\Omega)$, allowing parallel and mode-selective readout across the spectrum within a single optical stage.

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Generation of Entanglement in a Hexagonal Qubit System

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The ability of a quantum system to generate maximally or almost maximally entangled states is of fundamental importance to quantum information theory and its applications, including quantum communication, quantum cryptography, and quantum computation. Recent advances in experiments with atoms trapped in optical lattices have enabled the realisation of fermionic qubit networks and opened up new possibilities for engineering systems capable of producing and controlling quantum correlations [**1**].

In this study, we investigate a model of six interacting fermionic qubits arranged in a ring (hexagonal) geometry (see Fig. 1) and subjected to an external magnetic field. We analyse how the interplay between the system's geometry and interaction mechanisms leads to the formation of strongly entangled states [**2**].

We demonstrate that a ring of six interacting qubits, under appropriate coupling strengths and initial states, can efficiently generate maximally or almost maximally entangled states. Our analysis characterises how entanglement is produced and controlled in this system, providing quantitative benchmarks for optimizing entanglement generation in engineered quantum networks.

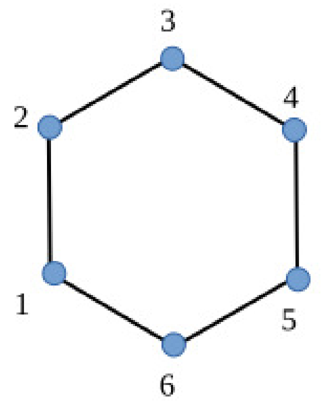

FIG. 1: Circular six-qubit system.

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A variational quantum generative adversarial network for estimating quantum umlaut information

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The quantification of quantum correlations is a cornerstone of quantum information theory. Recently, the *quantum umlaut information* has emerged as a fundamental measure with operational significance in quantum hypothesis testing and channel coding [1]. The quantum umlaut information is defined for a bipartite state ρ_{AB} as

$$U(A;B)_\rho := \min_{\sigma_B} D(\rho_A \otimes \sigma_B || \rho_{AB})$$

in terms of the Umegaki relative entropy D. However, evaluating $U(A;B)_\rho$ directly requires full state tomography, which is practically intractable for high-dimensional systems.

In this work, we propose a fully operational framework to estimate the quantum umlaut information utilizing a quantum generative adversarial network [2]. To circumvent the intractability of the Umegaki relative entropy, we introduce the *measured quantum umlaut information*, defined as

$$U^M(A;B)_\rho := \min_{\sigma_B} D_M(\rho_A \otimes \sigma_B || \rho_{AB}),$$

where D_M denotes the measured relative entropy. By applying the classical Donsker-Varadhan representation to the underlying probability distributions resulting from POVM measurements [3], we transform the measure into a min-max objective function

$$U^M(A;B)_\rho = \min_{\sigma_B} \max_{H} \left[\mathrm{Tr}((\rho_A \otimes \sigma_B) H) - \log \mathrm{Tr}(e^H \rho_{AB}) \right],$$

where H is a Hermitian observable.

This formulation naturally maps onto an adversarial learning framework suitable for near-term quantum devices. In our architecture, the Generator is trained to optimize the reference state σ_B, effectively learning the umlaut-marginal. Simultaneously, the Discriminator maximizes the measured relative entropy to find the optimal bound.

Crucially, we provide a strict mathematical guarantee for our framework. We prove that the measured quantum umlaut information serves as an ϵ-approximate of the exact quantum umlaut information, strictly bounded by the spectrum of the target state

$$U^M(A;B)_\rho \le U(A;B)_\rho \le U^M(A;B)_\rho + 2\log|\mathrm{spec}(\rho_{AB})|,$$

where $|\mathrm{spec}(\rho_{AB})|$ denotes the number of distinct eigenvalues of ρ_{AB}.

Our results demonstrate that the QGAN-based framework not only mitigates the computational bottlenecks of traditional state tomography but also provides a mathematically guaranteed estimation of complex quantum correlations, paving the way for scalable quantum information processing.

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Analysis of decoy state numbers for BB84 Satellite QKD considering realistic system parameters in the finite size regime

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Quantum Key Distribution (QKD) can provide information-secure communication even under the threat of quantum computing potentially able to break current encryption algorithms [1]. While fiber-based QKD is limited to metropolitan communication distances, satellite QKD is capable of providing long haul communication, such as intercontinental communication [2]. For practical implementations, the usage of commercially available components is desirable, especially for satellite QKD posing space engineering requirements on the payload sending unit. When designing a QKD system, one challenge is to combine the properties of such components with the security proof of a certain protocol such as the BB84 protocol [3].

Due to their technological maturity, in practical implementations, low-intensity lasers are preferable to ideal single photon sources as light source. However, according to their Poissonian photon statistics, laser sources can emit more than one photon occasionally, opening a loophole for eavesdropping that can be exploited with a Photon Number Splitting attack. One countermeasure to overcome this problem is the decoy state method, originally proposed by W.-Y. Hwang [4]. The idea is to introduce some decoy states along with the signal states, used to extract the key, by varying the intensity of the quantum states in a random manner. This method is widely used in modern QKD systems as it allows for the usage of a laser source while keeping the key distribution at a reasonable performance [5].

A QKD system should be designed considering all relevant parameters also in the design details of the security proof, such as its treatment of finite-size effects [6, 7]. A common implementation of decoy state QKD uses one signal state for key creation in combination with two decoy states. Depending on all parameters, the ideal number of decoy states might vary. Especially, in satellite QKD, the usage of one decoy state instead of two is desirable to reduce system complexity. However, in general it is not clear how much this choice affects the performance. We present a trade-off of different finite-size frameworks, decoy state numbers as well as intensity and probability choices in the view of their respective QKD performance for BB84 decoy state satellite QKD and typical satellite system parameters and technial challenges.

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Extending the Range of Continuous Variable Quantum Key Distribution with a Quantum Scissor

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Quantum key distribution (QKD) offers unconditionally secure transmission of private keys. However, quantum states are extremely vulnerable to loss, leading to a fundamental bound, known as the PLOD bound, on key rate through optical fiber [1]. In order to overcome this limitation we use a quantum scissor [3], a device that acts as a quantum repeater by non-deterministically amplifying an input state. This allows a QKD system to overcome the PLOB bound at long ranges[4].

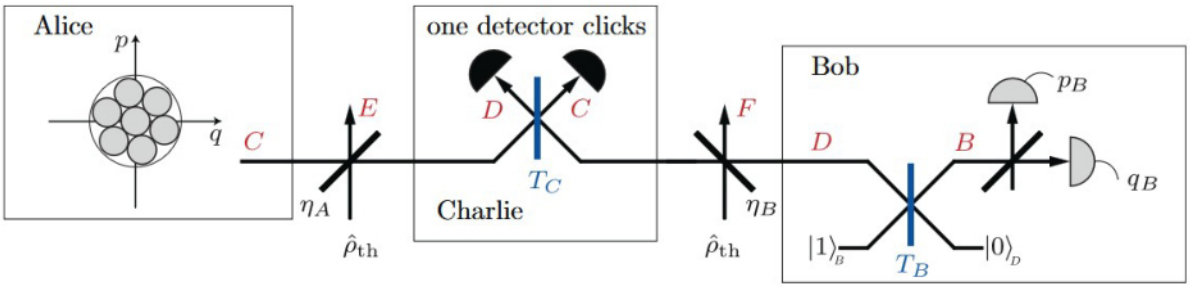

FIG. 1: Diagram of our setup from [4].

The setup involves two parties, Alice and Bob, that send a key using an untrusted intermediary, Charlie. Alice prepares a gaussian modulated series of coherent states using the attenuated output of an IQ modulator, similar to direct transmission QKD protocols [2]. She sends these states to Charlie over a lossy channel. Bob prepares heralded single photons via spontaneous parametric down-conversion. He splits his single photons on a beam-splitter to create $|0\rangle + |1\rangle$ entangled states. He sends one half of each entangled state to Charlie over a lossy channel, and performs a homodyne measurement on the other half. Charlie interferes the two states he receives on a balanced beamsplitter and performs click detection on the outputs. When Charlie's detectors click, it heralds a teleportation of the state sent from Alice to the half of Bob's entanglement he measured [3]. This allows Alice and Bob to create a key as if she transmitted her states directly to Bob, while only having to send a signal half of the way to Bob.

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Generating and Verifying Single Spectro-Temporal Mode Parametric Down-Conversion in Lossy Waveguides

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Recent progress in the fabrication of integrated photonic technologies allows for the production of compact sources of nonclassical light. One of the most promising frameworks for integrated quantum light sources is based on pulsed parametric down-conversion (PDC) in nonlinear waveguides [1, 2, 3, 4]. The PDC-based light sources provide the generation of bi-photon and squeezed states, which allows—together with quantum optical protocols— the generation of a huge variety of both Gaussian and non-Gaussian quantum states. Therefore, high-quality integrated pulsed PDC sources are in demand in modern quantum networks.

One of the challenges of the state-of-the-art quantum networks is scaling these systems to sizes where meaningful real-world applications can be found. For the sources, this requires the generation of (often bright) high-purity single spectro-temporal mode states, which is a challenging task for PDC sources. Indeed, pulsed PDC light generally contains nontrivial spectro-temporal structure, induced by nonlinear optical coupling of interacting fields. Furthermore, the realistic waveguide reveals optical losses during the PDC generation. These losses lead to the scattering and/or absorption of signal and idler fields during the PDC process, which brings significant differences between the desired ideal and the generated mixed state. It was recently shown [5] that for the PDC light, generated in lossy waveguides, the number of modes for the signal K_s and idler K_i subsystems should be introduced independently — they are not necessarily equal $K_s \neq K_i$. As a result, the correct description of realistic waveguides with lossless models (where $K_s \equiv K_i$) and the interpretation of experimental results requires a more holistic approach and expanded methods.

In the current work, we suggest a new interpretation of the joint spectral measurements for the PDC light generated in lossy waveguides, both for low- and high-gain regimes. Using the framework of Gaussian states [5, 6], we extend the definition of the joint spectral intensity (JSI) to mixed states and show that the standard technique of Schmidt mode determination from the JSI does not always give the correct value. We show how and under which conditions the JSI can still be used for the estimation of the number of modes. The results are based on the analytical derivations and demonstrated with several numerical examples. Our approach, applied to the lossless and lossy PDC states, gives us the restrictions for existing experimental methods. The presented treatment provides the necessary tools for characterizing and producing the production of high-quality PDC-based quantum sources, necessary for building large scale quantum optics networks.

This work has received funding from the German Federal Ministry of Research, Technology and Space within the PhoQuant project (Grant No. 13N16103).

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Computational resources and validation of a three-mode non-Gaussian hamiltonian

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My poster will focus on a specific three-mode non-Gaussian trilinear hamiltonian which has been recently realized in superconducting platforms [1, 2]. This hamiltonian is of great interest because, besides being non-Gaussian and therefore enabling universal quantum computation, it represents the most natural three-mode generalization of the two-mode squeezing hamiltonian, a key workhorse in quantum optics. Therefore, the poster will present a comprehensive theoretical analysis of the computational resources generated by this hamiltonian, such as Wigner negativity and entanglement, and its capability to generate non-local correlations. A strategy to efficiently detect these properties on superconducting platforms via displaced-parity measurement will be presented. Building on this resource-based characterization, a fast and reliable protocol for the experimental validation of this hamiltonian, based on the measurement of nullifiers and stabilizers, which avoids the need for full Wigner-function tomography will be introduced.

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Phase-Sensitive Nonlinear Interactions in Linear OPOs from Crystal Boundary Phases

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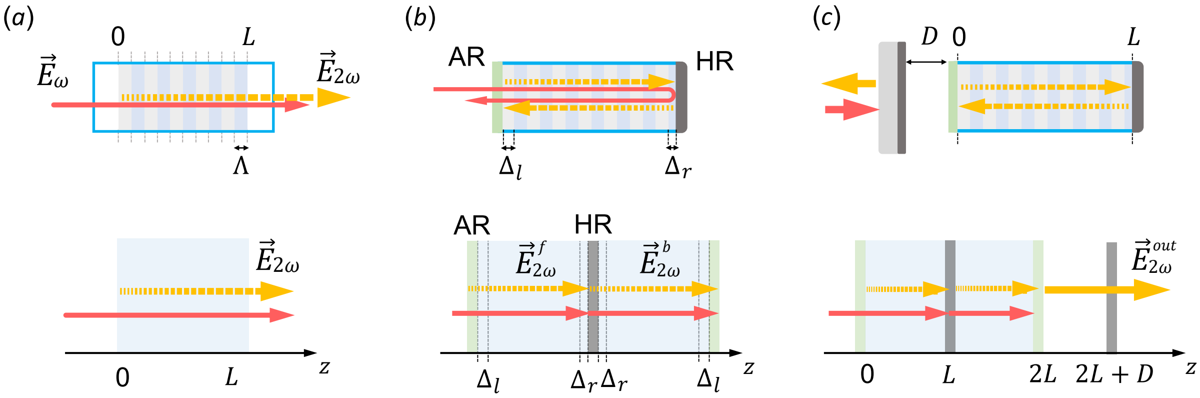
Efficient and scalable squeezed-light sources are essential for quantum information processing and precision metrology based on optical interference. Optical parametric oscillators (OPOs) provide a compact and widely used platform for generating squeezed light via cavity-enhanced nonlinear interactions [**1**]. In standing-wave linear OPO configurations, where the nonlinear crystal forms part of the cavity boundary, the interaction becomes inherently phase-sensitive due to interference between fields generated during successive cavity round trips. In particular, forward- and backward-propagating fields recombine with a relative phase set by reflective coatings and domain termination at the crystal interfaces [**2**]. While such phase contributions are well known, their quantitative impact on device performance remains unclear.

Here, we show that phase contributions from crystal boundaries and reflections can induce order-of-magnitude variations in oscillation threshold, leading to strong deviations between nominally identical OPO systems. To disentangle these effects, we characterise the phase contribution from the highly reflecting crystal facet via double-pass second-harmonic generation, and infer the remaining contributions from the opposite facet and cavity mirrors using OPO threshold measurements combined with a cavity–crystal model. These results establish a predictive framework for phase-sensitive nonlinear interactions in practical OPOs and provide design guidelines for stable and reproducible squeezed-light sources.



(a) Second-harmonic generation in a nonlinear crystal. (b) Double-pass SHG scheme for extracting boundary-induced phase contributions Δ_l and Δ_r. (c) Standing-wave linear OPO configuration showing interference between counter-propagating fields with boundary phases.

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Non-Linear Cavity Double Quantum Dot Dynamics

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Modern technologies with artificial atomic systems are advancing rapidly nowadays [1-3]. In this context, we shall present our recent theoretical results on the non-linear quantum dynamics of a compound sample, consisting from a double quantum dot (DQD) system which is coupled with a leaking single-mode micro-resonator. Initially, we focus on the resonance condition when the transition frequency of the DQD equals to the doubled resonator's frequency, respectively, and describe the resulting interplay among the involved phonon or photon decay channels. The steady-state quantum dynamics of this complex non-linear system is shown to exhibits a variety of critical behaviours in the relationship among the electrical current through the double quantum dot and the microwave field inside the resonator [4,5].

Then, we shall describe the case when a continuous microwave field is applied that modulates the DQD's frequency. The resonances occur if the difference among the qubit's and resonator's frequencies equals to the multiple frequency of the applied field, respectively. As a result, we demonstrate that the output cavity electromagnetic field is formed of a single photons flux obeying the sub-Poissonian photon statistics. This is proved via Fano's factor behaviour or by comparing the resonator's second- and third-order photon correlation functions, respectively. The phonon, cavity mode dephasing or environmental temperatures influences over the photons quantum features are also discussed [6].

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Bichromatic laser deceleration and cooling of hot positronium

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We study laser cooling and trapping of hot para-positronium bunches as produced by a Surko trap. While laser cooling via radiation pressure is a very well established technique to slow and cool down neutral atoms below mK [**1**], the fast ground state annihilation and high recoil shift poses challenging extra limitations on the required laser powers and frequencies. Some earlier work [**2**, **3**] suggests viable prospects for obtaining a cold sufficiently dense ensemble nevertheless. Our theoretical study sets out to explore new ways for these exotic atoms beyond simple Doppler-cooling on the 1^3S–2^3P transition by including an extended upper state manifold and extra transverse lasers on the 2^3P–3^3D transition. The specific objective of this study was to examine the effect of this additional excitation on the quality of positronium atoms' cooling process. This research employs semi-classical approaches of simulating light-matter interactions. We successfully found experimentally reasonable values for the lasers' parameters, whose proper application can lead to an effective slowing of positronium. With the presented scheme we were able to achieve an acceptable and fast slowing effect while the majority of atoms were not annihilated.

Future extension to collective cooling and trapping in cavities or hollow core fibres could be the basis of new discoveries in the investigation of cold Ps systems even pointing towards superradiant lasing and Bose–Einstein-condensates.

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Single- & Twin-Photon Source on a Silicon Nitride Chip

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Ring microresonators are widely adopted in quantum optics and, more recently, also in quantum communication [1]. Their use as single-photon sources is well established [2], whereas their simultaneous implementation as single as well as multi-photon sources within the same integrated architecture remains less explored. Silicon nitride (Si_3N_4) is an established platform for integrated nonlinear photonics [3, 4], offering ultralow propagation loss, CMOS compatibility and a broad transparency window. Here, we present an integrated Si_3N_4 ring microresonator as both a heralded single-photon source and a twin-photon source operating at telecommunication wavelengths [5]. To realise this, the resonator supports two pathways of spontaneous four-wave mixing (SFWM) corresponding to the respective photon-generation schemes shown in Fig. 1(a). The generated photons are coupled out of the chip, filtered, and detected using highly efficient superconducting nanowire single-photon detectors (SNSPDs).

The heralded single-photon source exhibits high purity, with an effective modal number of 1.49±0.12 in the Schmidt decomposition, a heralded $g^{(2)}(0) = 0.0042 \pm 0.0015$, and a maximum coincidence-to-accidental ratio ($\text{CAR} = g^{(2)}(0) - 1$) of 9.1. Figure 1(b) depicts the corresponding antibunching dip in the $g^{(2)}$-autocorrelation. The twin-photon source, implemented via dual-pumped SFWM, yields a maximum CAR of 5.4±0.6 between signal and idler photons of degenerate frequency, exhibiting a gradual increase of the CAR with decreasing pump-power (Fig. 1(c)). These results demonstrate the successful implementation of both a high-purity heralded single-photon source and a twin-photon source on the same ring-resonator on a Si_3N_4 chip. To the best of our knowledge, this is the first demonstration of a frequency-degenerate twin-photon source in Si_3N_4, and therefore also of both sources operating within a single integrated architecture on this platform, highlighting its potential for future integrated generation of single- and twin-photon states. These results can be applied in quantum computing, metrology and quantum information processing scenarios.

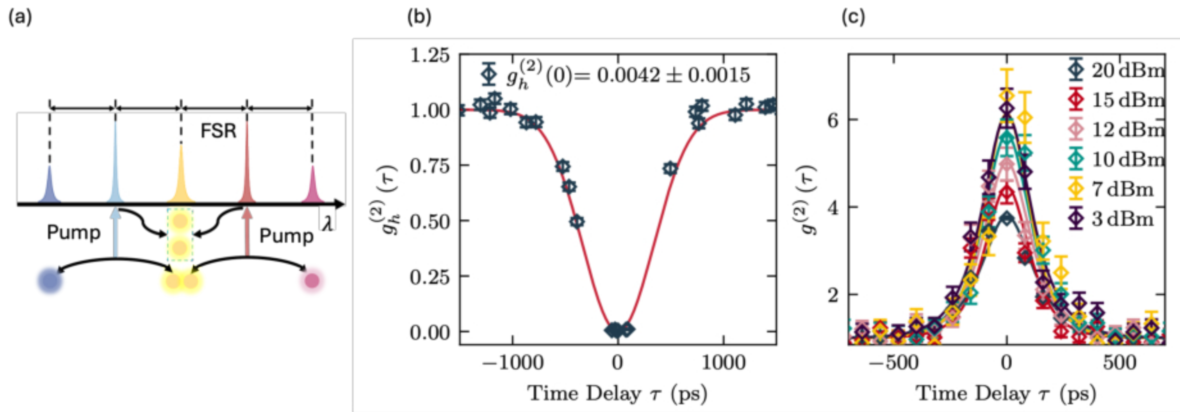

Figure 1: a) Schematic of SFWM photon-generation processes following single pumping for single photon and dual pumping for twin photon generation. b) Heralded $g^{(2)}$-autocorrelation, showing an antibunching dip. c) Dual-pumped $g^{(2)}$-autocorrelation of degenerate twin photons for different combined pump powers.

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Nonlinear Scaling Law for Squeezed-Light-Enhanced Dissipative Quantum Metrology

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Quantum-enhanced metrology with squeezed light offers a powerful route to surpass classical precision limits, particularly in nonlinear and dissipative sensing scenarios [1, 2]. In systems governed by multi-photon absorption and emission, the interplay between nonclassical fluctuations and nonlinear dynamics can lead to qualitatively different scaling behaviors. A central open question is how the structure of squeezing, whether applied independently to different modes or shared through entanglement, affects the fundamental limits of precision and the emergence of quantum advantage.

In this work, we analyze dissipative quantum metrology driven by squeezed pump and signal fields, comparing independently squeezed modes with jointly squeezed two-mode states. We derive the asymptotic scaling of sensitivities across low- and high-gain regimes and identify two distinct universality classes. Independent squeezing leads to factorized scaling, where exponential enhancements depend separately on pump and signal gains and vanish for linear processes, revealing nonlinear thresholds. In contrast, joint squeezing induces collective behavior governed by a single parameter, yielding a high-gain exponential scaling governed by the total nonlinear photon order. This collective enhancement persists even for linear processes in certain observables, highlighting the role of entanglement in sustaining quantum advantage.

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Characterizing integrated programmable photonic processors via Scattershot Boson Sampling

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Photonics has emerged as a promising platform for implementing various quantum computational and communication schemes. At the heart of many such schemes lie integrated programmable photonic processors, consisting of networks of beam splitters and phase shifters. These processors can, in principle, be used to program any arbitrary unitary transformation by precisely tuning beam splitter transmittivities and phase shifter values. In practice, however, fabrication imperfections, thermal cross-talk, and other non-ideal effects leads to deviations between the target and implemented transformations. Limited knowledge of the actual unitary transformation implemented by the processor can adversely affect benchmarking protocols and reduce the performance of quantum applications employing such processors. Accurate characterization of the implemented unitary is therefore essential.

Standard characterization techniques based on coherent light and one- or two-photon measurements become impractical as the number of modes increases, since the number of required measurements scales quadratically with processor size. This scaling makes real-time characterization increasingly difficult. To address this challenge, we develop a scalable and real-time characterization protocol that reconstructs the implemented unitary matrix using data from Scattershot Boson Sampling (SBS) experiments combined with an optimization-based algorithm. We demonstrate the reconstruction of an 8×8 unitary transformation with 97% similarity to the target matrix. The presented approach will enable scalable and practical characterization of large photonic processors without requiring changes to the experimental setup.

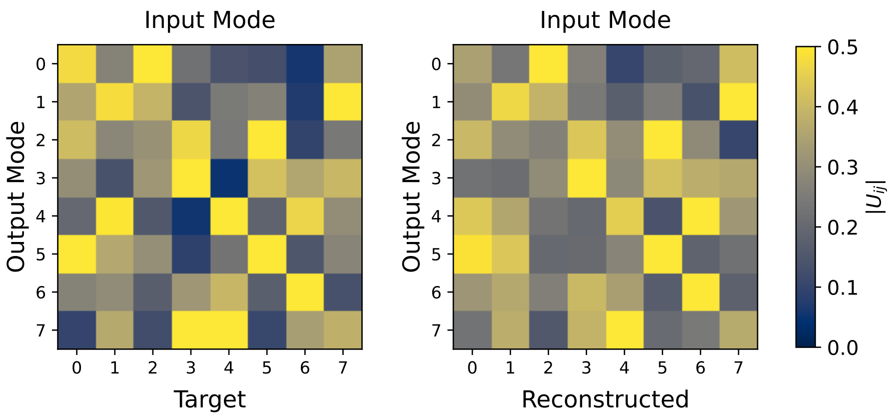

FIG. 1: Target matrix (left) and reconstructed matrix (right). The similarity between these two matrices is 97.09%.

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Phase instabilities of input states and Gaussian Boson Sampling

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Gaussian Boson Sampling [1] is a non-universal model of quantum computation based on non-classical states of light. Unlike standard boson sampling, which uses Fock states as inputs, GBS employs squeezed states, making it more experimentally accessible and scalable in photonic platforms. This model has demonstrated strong potential for exhibiting quantum advantage in optical systems and has motivated the exploration of practical applications, including dense graph problems, molecular vibronic spectra, and molecular docking. It is also an important protocol for testing the performance of photonic quantum simulators. As such, various noise sources have been investigated that degrade the operation of such devices.

We examine a situation with phase noise between different modes of the input state leading to dephasing of the system. This models the phase fluctuations which remain even when the mean phase is controlled. We investigate how this type of noise influences the system's behavior, particularly its non-classical features and its susceptibility to classical simulation. Additionally, we explore benchmarking strategies based on output probabilities and correlation functions, with the goal of developing practical tools for characterizing photonic quantum devices under realistic experimental conditions.

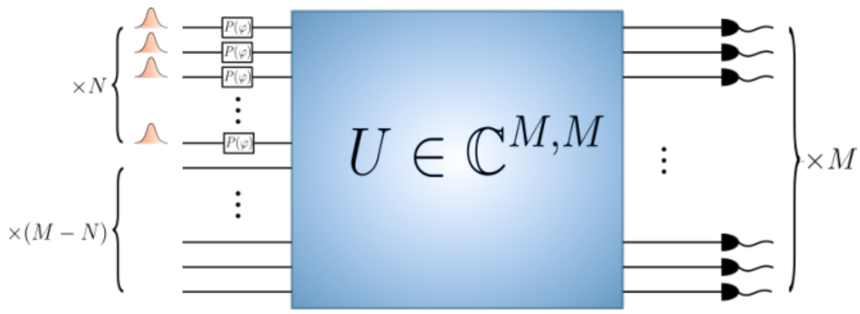

FIG. 1: Gaussian Boson Sampling set-up with N input Gaussian states entering an M-mode interferometer. The interferometer is represented by a unitary matrix U and the resulting probability distribution is measured by PND detectors at the M output modes.

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Ergodic dynamics in iterated quantum protocols

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We study measurement-induced nonlinear dynamics generated by an iterated quantum protocol combining an entangling gate, a single-qubit rotation, and post-selection. The combination of an entangling quantum gate and post-selection, applied to identical input states, leads to an essentially nonlinear protocol, providing a concrete physical realization of iterated maps and nonlinear dynamics. For pure single-qubit inputs, a particular choice of the single-qubit unitary yields globally chaotic, strongly mixing dynamics that explores the entire Bloch sphere. All initial states lead to chaotic behavior that is ergodic in the following sense: initial states from a small neighborhood of any given initial state will fully cover the state space after a critical number of iterative steps. This behavior is supported by consistent diagnostics: absence of attracting cycles, agreement of time- and ensemble-averaged statistics, rapid spreading from localized regions, and a positive Lyapunov exponent.

We extend the analysis to realistic, noisy preparation by considering mixed initial states and the induced nonlinear evolution inside the Bloch sphere. The completely mixed state is an attractive fixed point of the dynamics, and our numerical simulations suggest that a broad set of mixed states belongs to its basin of attraction. At the same time, many trajectories exhibit transient increases in purity before ultimately converging, indicating a nontrivial interplay between nonlinear dynamics and noise.

To quantify robustness against noise, we introduce a practical notion of quasi-ergodicity. In our setting, ensembles prepared in a small angular region at fixed purity rapidly spread to cover all directions, while the purity gradually decreases toward its minimal value. In this sense, small noise, which is always present in a practical realization of the protocol, does not destroy ergodicity in the experimentally relevant, finite-time sense. This behavior is supported by consistent diagnostics, including the absence of attracting cycles, agreement of time- and ensemble-averaged statistics, rapid spreading from localized regions, and exponential sensitivity to initial conditions, as quantified by a positive Lyapunov exponent. By varying the final single-qubit gate, we identify a broad family of protocols that remain ergodic-like for pure states. However, the mixed-state dynamics can change qualitatively depending on the choice of parameters. Away from the special globally mixing case, we find numerical evidence that a finite subset of noisy initial states is driven toward purification rather than complete mixing. This demonstrates the coexistence of statistical mixing and purification within a single iterated protocol. These results show that iterated quantum protocols provide a physically accessible realization of canonical complex dynamical systems, with a tunable balance between chaotic mixing on the Bloch sphere and noise-dependent purification in the Bloch ball.

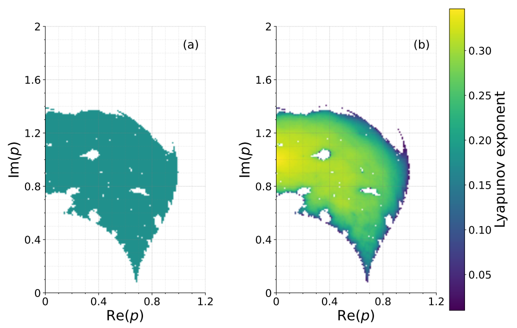

Figure 1: (a) Region of the complex parameter space where all numerical ergodicity criteria are satisfied. The criteria disagree on approximately 1.4% of points. (b) Lyapunov exponent as a function of the complex parameter, averaged over random initial states.

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Magnetic resonances in NV center ensembles and their dependence on optical and microwave power

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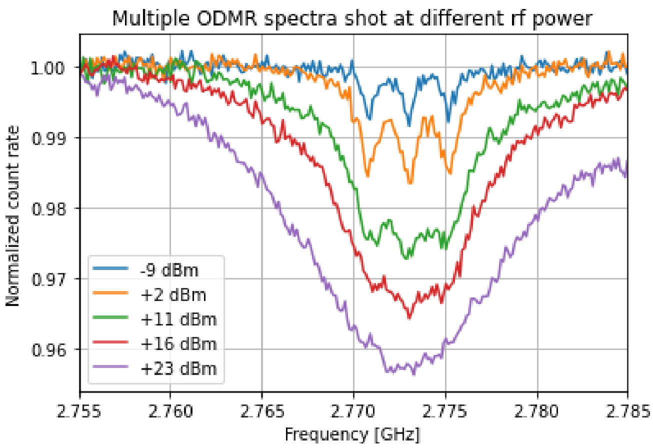
Nitrogen-vacancy (NV) centers in diamond are popular magnetic field sensors and have been investigated thoroughly as platform for quantum networking. These NV-centers have a spin transition which can be observed as a change in fluorescence in the presence of microwave radiation resonant at that transition around 2.87 GHz, a technique called Optical Detection of Microwave Resonances (ODMR). Their working principle as magnetic sensor is based on the Zeeman effect, which shifts the microwave-sensitive transitions by 28 GHz/T.

We present ODMR measurements that show why popular models of NV-based B-field sensors [1, 2] are incomplete and how they can be fixed. The left figure shows how the ODMR spectrum at $B = 4$ mT consists of three narrow lines at low microwave power, due to hyperfine coupling with the $I = 1$ nuclear nitrogen spin. Although the contrast increases at higher microwave power, broadening prevents the hyperfine structure from being resolvable. The best sensors, with the steepest slopes, should thus operate at intermediate power. A comparison with time-resolved measurements of long lived Rabi oscillations shows that the ODMR spectra observed at low microwave power are broader than expected. A comparison with a five-level model of the NV center (right figure) shows that this broadening originates from the B-field created by nearby ^{13}C nuclear spins, a field that varies on time scales $\gg \mu$s. We will also discuss the observation of: (i) dephasing/broadening induced by the optical pump power, (ii) bi-exponential dynamics of the optically-induced spin pumping, (iii) the role of spatial integration in the performance of NV sensors.



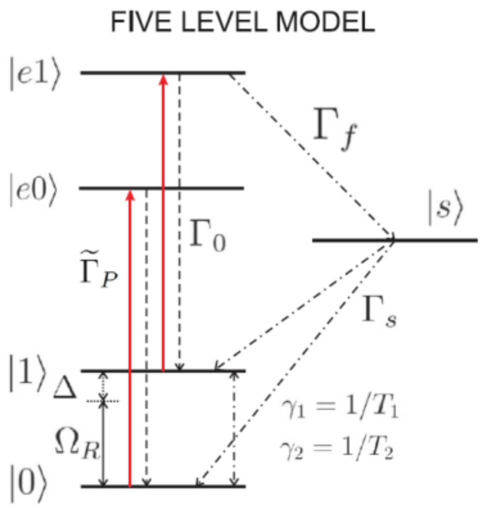


Figure 1: (left) ODMR spectra measured at different microwave powers (in dBm), (right) five-level model used to explain the observed spectra (copied from [1]), with two ground states, $|0\rangle$ and $|1\rangle$, coupled by microwave radiation Ω_R, two excited states, excited through optical pumping Γ_P, and an intermediate spin singlet state $|s\rangle$

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Optimizing SiPM-Based Detection Systems for Quantum Optics Measurements via Real-Time Digital Signal Processing

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Photon-number-resolving (PNR) detection is an emerging tool for characterizing the quantum properties of light, yet practical high-speed implementations remain limited. Silicon photomultipliers (SiPMs) offer a compelling route to PNR detection in the mesoscopic regime (spanning a dynamic range from a few photons to a hundred) making them particularly suitable for investigating nonclassical states and quantum correlations of highly populated light states.

We present the characterization of a SiPM-based PNR detection chain in which the analog output of the SiPMs is coupled to a 14-bit, 1 GS/s digital acquisition system with an FPGA-based pipeline performing real-time baseline subtraction, digital deconvolution, and charge integration. Three Hamamatsu SiPM models are systematically compared using coherent states and quantum twin-beam states, providing a controlled framework to isolate the impact of dark counts, pixel pitch, pile-up, and photon detection efficiency on the reconstructed photon-number statistics and measured quantum correlations.

Coherent state measurements (see FIG. 1) confirm a dynamic range spanning mean photon numbers from less than 1 to beyond 50 per pulse at 1 MHz (extendable to 10 MHz at lower photon flux) directly relevant to quantum communication protocols exploiting the mesoscopic regime [1]. Twin-beam measurements [2] demonstrate clear detection of nonclassical correlations and reveal their dependence on detector quantum efficiency, offering practical guidance for experiment design. Benchmarked against NIM-based chains [3], the system delivers lower noise and greater speed, opening new possibilities for high-rate quantum optical investigations.

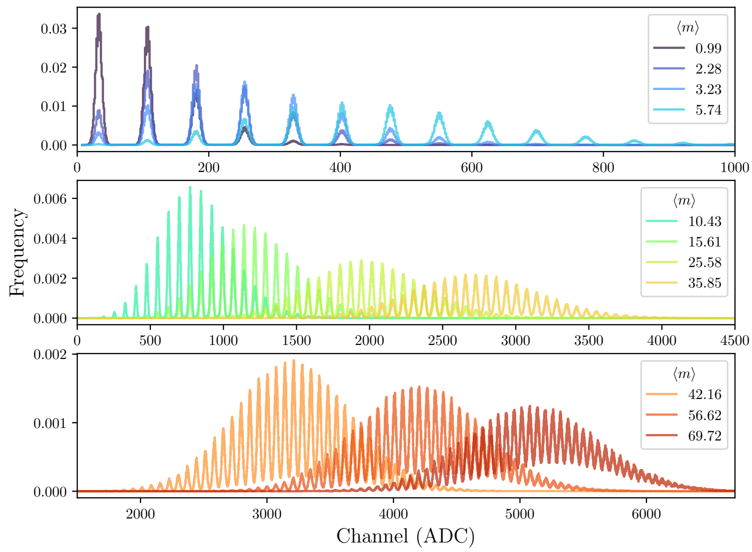

FIG. 1: Raw charge distributions measured on coherent states across a range of mean photon numbers, $\langle m \rangle$, illustrating the system's wide dynamic range. Each histogram is obtained from 10^6 consecutive laser pulses acquired at a repetition rate of 1 MHz. The peaks corresponding to individual photon-number contributions are clearly resolved in the ADC channel space across all distributions, maintaining good visibility even at high mean values.

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Phase-Space Tomography of a Macroscopic Non-Gaussian State

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Macroscopic quantum states of light are rapidly emerging as powerful tools for high-sensitivity metrology and strong-field physics [1,2]. However, the complete phase-space characterization of these ultrafast, high-photon-number states faces a fundamental barrier: standard quantum homodyne tomography fails at such extreme brightness. Consequently, the experimental phase-space structure of macroscopic quantum fields has remained largely inaccessible.

Here, we bridge this gap by demonstrating the direct phase-space tomography of a macroscopic quantum state. By adapting a single-shot f-2f interferometer, we successfully sample the Husimi Q-function of 25-fs, single-mode bright squeezed vacuum (BSV) centered at 1.6 μm (Figure 1(a)). The measurement relies on the spectral interference between the second harmonic of the BSV and a co-propagating residual pump field. This self-referencing technique allows us to extract the amplitude and phase of each single pulse [3].

We use this method to characterize BSV after nonlinear Kerr interaction. The experimentally reconstructed Husimi function reveals a clear intensity-dependent phase shift, transforming the initial Gaussian distribution into a characteristic 'S'-shaped profile (Figure 1(b)). This specific phase-space deformation serves as direct statistical evidence of a macroscopic non-Gaussian state. Our approach provides a robust, broadband framework for diagnosing and engineering ultrafast, bright quantum states in regimes where standard quantum optics detection schemes fail.

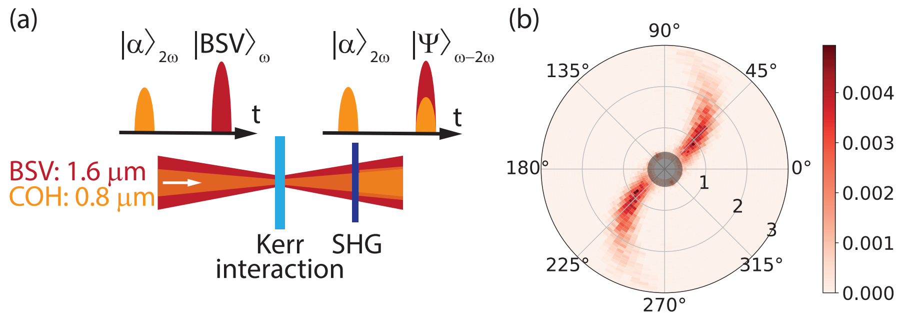

FIG. 1: (a) Sketch of the experimental setup. (b) Husimi function of the BSV after Kerr interaction.

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Beyond the rotating-wave approximation: high-frequency expansions for periodically driven light–matter systems

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Periodically driven light–matter systems in quantum optics are now entering regimes of strong and ultrastrong coupling. These regimes offer new opportunities for fast quantum gates, enhanced robustness against noise, and continuous-variable error correction. At the same time, they challenge standard approximation techniques: in particular, the rotating-wave approximation (RWA) may break down, and achieving the high fidelities required for quantum technologies calls for controlled higher-order corrections, such as the Bloch–Siegert and AC Stark shifts, that remain accurate over relevant time scales.

A central difficulty is that existing high-frequency expansion techniques, including the Floquet–Magnus expansion, provide limited quantitative control in these regimes. In particular, they do not yield reliable error bounds when the underlying Hamiltonians involve unbounded energy scales, as is typical for quantum optical systems.

Here we address this limitation by developing a new framework for constructing the Floquet–Magnus expansion based on physically relevant energy scales set by the initial state. Our approach yields systematically improvable convergence guarantees with explicit error bounds and, at the same time, provides the first systematic extension of Floquet–Magnus theory to the unbounded setting relevant for quantum optics. As an application, we use this method to derive higher-order effective Hamiltonians for the quantum Rabi model. We recover the RWA at leading order, capture the Bloch–Siegert shift, and obtain explicit higher-order corrections together with explicitly computable error bounds.

Based on joint work with D. Burgarth, R. Hillier, and D. Longiro.

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Multipartite Photon Statistics with Resource-Efficient Single- and Multi-Pixel SNSPD Readout

Gregor Sauer[1,2,3], Nayana Jalimarad Shankarappa[1,2], Dilawaiz Dilawaiz[1,2,3], Carlos Sevilla[1,2,3], Varun Kaipalath[1,2], and Fabian Steinlechner[1,2,3]

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Multipartite photon-number statistics are central to a range of quantum photonic tasks, including state characterization, photon subtraction, and Gaussian boson sampling. However, scaling photon-number-resolving (PNR) detection to many modes is often limited by the number of physical detector channels and the associated post-processing overhead. We address this challenge along two avenues: first, we develop a resource-efficient readout scheme for multi-pixel superconducting nanowire single-photon detectors (SNSPD) based on time-over-threshold discrimination; second, we demonstrate intrinsic PNR capability in a single-pixel SNSPD by applying ultra-high-resolution timing analysis to the leading and trailing edges of its electrical output pulses. The latter technique exploits photon-number-dependent waveform variations, accessible via picosecond-level time-tagging, to achieve PNR while preserving the high detection efficiency and fast recovery times of standard SNSPDs.

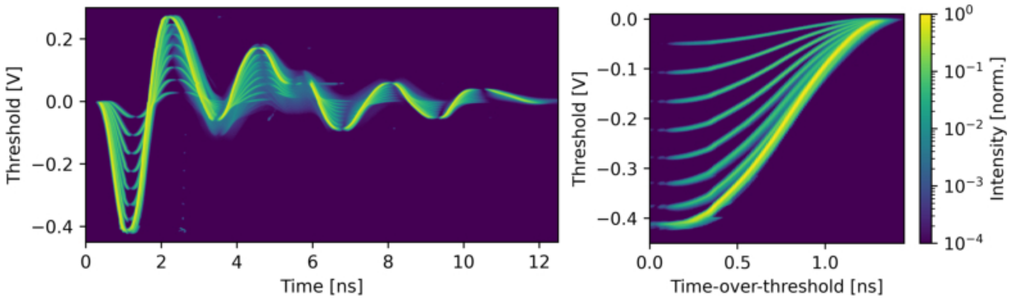

Figure 1: Waveform (left) and time-over-threshold (right) of an eight-pixel SNSPD reconstructed by recording histograms with a time-tagging unit to identify waveform characteristics for PNR readout optimization and erroneous signal detection.

We implement the readout methods with detectors in the telecom C-band and benchmark their performance by reconstructing the photon-number distributions of coherent states, demonstrating high-fidelity photon-number identification. Their applicability to quantum information processing is validated through measurements of photon-number correlations in non-classical states. Moreover, we show that our multi-pixel readout method yields improved photon-number assignment fidelity compared to previously established readout approaches.

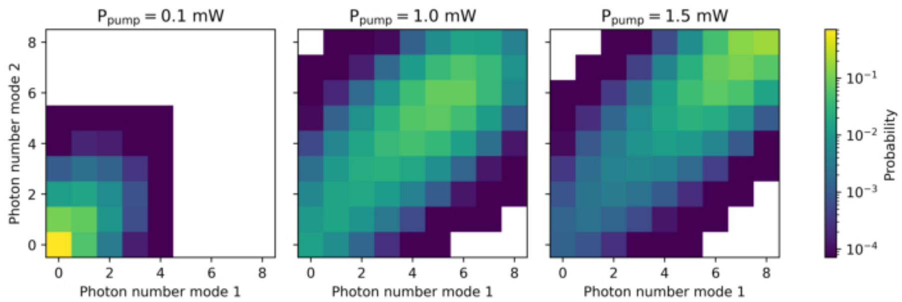

Figure 2: Joint photon statistics of a two-mode squeezed vacuum state generated at different pump powers, measured with an eight-pixel SNSPD.

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CEWQO30 Mode-Selective Nonlinear Interference for Bright, Efficient and Pure Fiber-Coupled SPDC Sources

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Spontaneous parametric down-conversion (SPDC) sources coupled to single-mode fibers are a key resource for photonic quantum technologies, where high brightness, heralding efficiency, and spectral purity are simultaneously desired. In bulk nonlinear crystals, these performance metrics can be tuned through the focusing conditions of the pump, signal, and idler beams, but are fundamentally limited by mutual trade-offs. We show that nonlinear interference in a cascaded two-crystal type-II SPDC source substantially relaxes the trade-off between brightness and heralding efficiency, yielding an improvement of more than an order of magnitude. Furthermore, we identify two approaches to obtain near-unity spectral purity while preserving high brightness and/or heralding efficiency, even with conventional periodically poled crystals, and analyze the additional benefits of Gaussian phase matching enabled by aperiodic poling. Using a spectrally resolved Laguerre–Gauss modal decomposition, we trace these enhancements to mode-selective interference in the nonlinear interferometer. The theoretical predictions are experimentally validated by stimulated-emission tomography measurements.

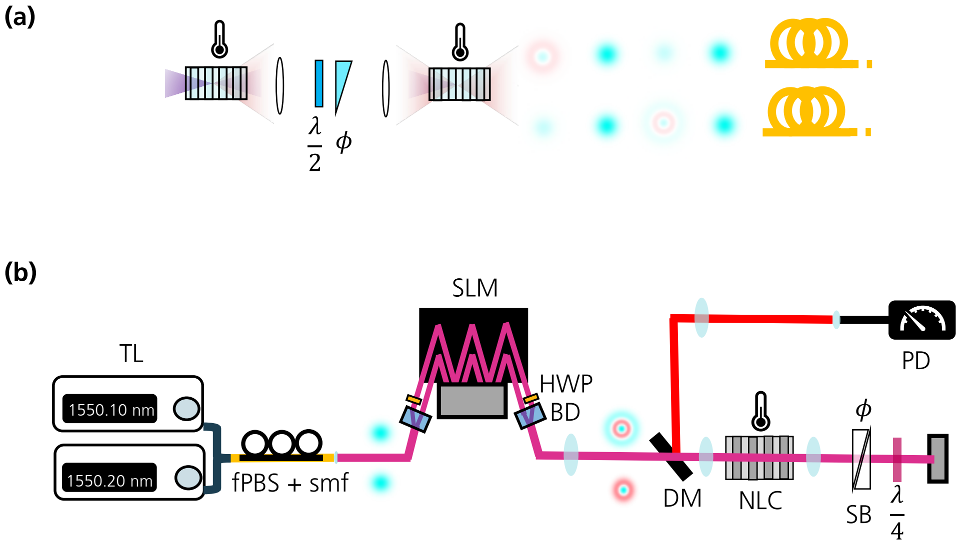

FIG. 1: (a) Sketch of the cascaded nonlinear process. The nonlinear interference enhances generation of the joint Gaussian mode over other mode combinations. (b) Experimental setup for spatial-spectral stimulated-emission tomography).

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QuaNTUM: A Modular Quantum Communication Testbed for Scalable Fiber and Satellite Integration

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Quantum communication offers security rooted in physical laws, but scaling beyond isolated laboratory demonstrations requires shared platforms in which multiple users, devices, and channel types can operate under realistic conditions. We present **QuaNTUM (the Quantum Network at the Technical University of Munich)**, a modular and extensible open-access testbed for scalable quantum communication across campus fiber networks and satellite-ground links. It supports protocol demonstrations, device benchmarking, and hybrid network integration by combining terrestrial fiber infrastructure with emerging quantum hardware and free-space channels. The terrestrial network connects research institutes via deployed single-mode fibers in a star topology, integrating multiplexing, time-synchronized analysis, dynamic routing, and active polarization control for stable quantum communication and broader quantum optics experiments.

A distinctive feature of QuaNTUM is an agile, broadband polarization-compensation scheme. This capability has been experimentally realized and verified on the platform, and preserves polarization qubits over a wide wavelength range while dynamically suppressing QBER to negligible levels. In this way, the testbed supports polarization-based experiments on deployed fiber links without requiring each user to implement dedicated compensation and monitoring hardware, thereby facilitating the use of polarization encoding in settings where it is often considered difficult to maintain over long distances.

QuaNTUM also benefits from the development of deterministic quantum emitters within our projects, and from access to a satellite platform with built-in solid state quantum emitters that is currently being deployed in space. By unifying fiber and free-space links with scalable hardware, this testbed provides a solution for future hybrid quantum networks, supporting both near-term research and the long-term vision of a global quantum internet.

FIG. 1: Geographical overview of the QuaNTUM campus network and participating sites.

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X-Ray Waveguides: From Quantum Optics To Non-Hermitian Topology

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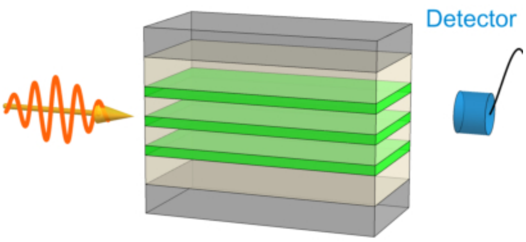
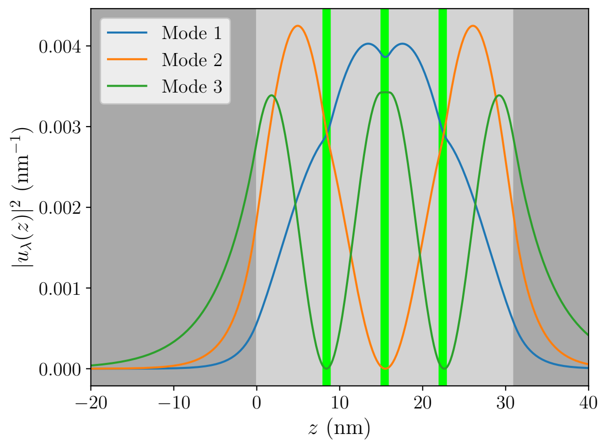
Thin-film nanostructures with multiple embedded layers of Mössbauer nuclei offer an intriguing platform for x-ray quantum optics and are well established in nuclear condensed matter physics. When probed in the so-called front coupling geometry, these structures act as x-ray waveguides, as recently demonstrated experimentally [1] in excellent agreement with the existing theoretical framework [2].

We extend this formalism to describe the mesoscopic quantum dynamics of multi-mode and multi-layer waveguides. So far, we have mainly investigated two- and three-layer waveguides supporting two or three guided modes. These modes exhibit distinct spatial field distributions, which strongly influence the in- and out-coupling of the x-ray pulses. This spatial control enables selective exposure of individual layers to different mode intensities, providing a flexible platform for designing tailored quantum optical configurations.

The resulting spatial structure of the guided modes also affects the internuclear couplings between the layers. This provides a route toward topologically robust functionalities including lasing, light trapping or protection of quantum states. In particular, the system realizes hopping models [2], allowing the investigation of more complex photonic topological settings [3].



(a) Setup of a three-layer x-ray waveguide, probed in the front-coupling geometry. The green regions depict the layer of resonant material, typically ^{57}Fe Mössbauer nuclei.



(b) Three guided modes featured by the three-layer structure. While the first and third guided mode have a symmetric pattern, the second mode is antisymmetric and couples much weaker into the waveguide.

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Quantum Exceptional, Diabolical and Hybrid Singularities in Multimode Bosonic Systems

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Quadratic Hamiltonians generate and preserve Gaussian states, whose dynamics is completely determined by the first and second moments of the canonical bosonic operators. We demonstrate that the spectrum of such Hamiltonians can be directly extracted from the Heisenberg evolution of bosonic operators, enabling a systematic analysis of eigenvalue and eigenvector degeneracies of the associated Liouvillian. In particular, spectral singularities arising in the reduced non-Hermitian dynamics manifest explicitly in the operator evolution itself [1]. Such singularities are useful for quantum sensing. Our approach provides a distinct advantage over the Schrödinger picture by yielding closed analytic expressions for higher-order exceptional degeneracies directly in the higher-order moments of bosonic operators [2,3]. This formulation allows transparent identification and classification of quantum exceptional, diabolical, and hybrid points without resorting to state-vector decomposition. We distinguish between inherited and genuine spectral singularities: the former being artifacts of the system decomposition, and the latter intrinsic to the reduced system's non-Hermitian dynamics. Finally, we analyze systems with unidirectional coupling, a strongly non-Hermitian interaction that can be realized, for example, via counter-propagating bosonic modes. While such systems enable the engineering of higher-order inherited degeneracies through concatenation, we find that the preservation of quantum consistency (e.g., operator commutation relations and physical behavior) is limited to short-time dynamics. The presented framework provides practical guidelines for engineering dynamics at and around exceptional points and nonclassical-state generation in platforms relevant to quantum communication, sensing, and information processing.

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Reversible microwave to optical conversion (Conversion of weak microwave signals to optical photons by cold atoms)

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Microwave-to-optical conversion represents a significant area of research, especially in quantum communication, where establishing a coherent interface between long-range optical signals and short-range microwave signals is essential. Rubidium (Rb) atoms are well suited for this purpose, as they exhibit simultaneous sensitivity to both microwave and optical frequencies.

In our experiments, we employ a cold atomic cloud confined in a magneto-optical trap (MOT), which is transported into a high-finesse optical resonator. Within the resonator, the atoms can be confined either in an optical dipole trap or in a purely magnetic trap [1]. The system includes near-field microwave sources positioned inside the vacuum chamber near the cavity mode. This configuration enables us to demonstrate that the atomic ensemble interacts with both the microwave radiation and the optical field.

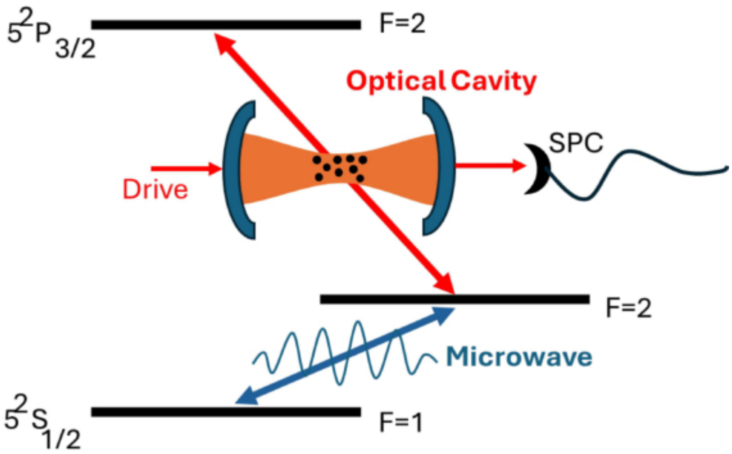

FIG. 1: Experimental configuration.

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Characterization of Doppler Shift Compensation for Coupling Light from a Fast-Moving Airborne Platform to a Single Ion

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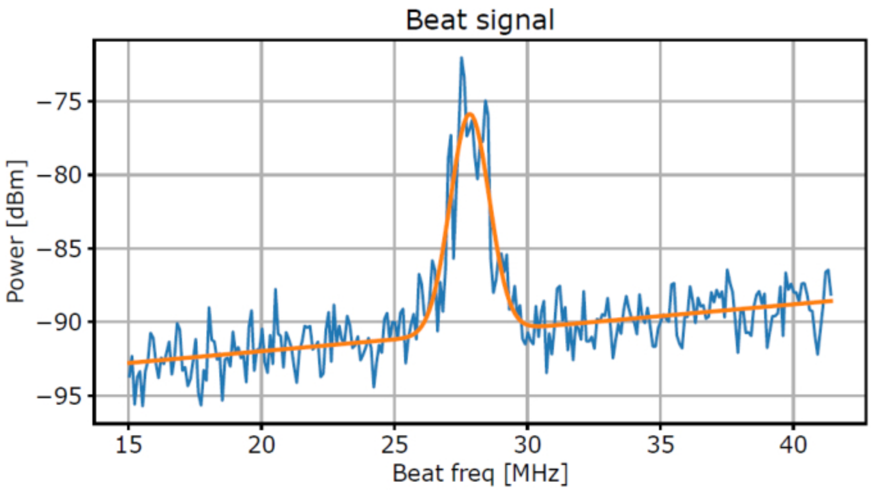
Trapped ions are promising building blocks for the realization of long-distance quantum networks due to their ability to reliably store quantum information as quantum memories. A key requirement for such networks is the efficient exchange of quantum information between remote nodes. Free-space optical links, particularly involving airborne platforms, offer a compelling approach to bridge large distances between ground stations. However, the relative motion between transmitter and receiver introduces significant Doppler shifts, which must be compensated to enable stable light–matter interaction.

To ensure spectral matching with the ion's transition, the beat signal from two acetylene-locked lasers is processed in real time using an FPGA. This system extracts instantaneous Doppler shifts on the strong laser signal to drive an acousto-optic modulator, which dynamically corrects the quantum signal. The approach was validated in a laboratory environment by emulating common-mode Doppler shifts using an acetylene-locked 1530 nm and a 935 nm laser. We demonstrate successful frequency stabilization of the 935 nm beam, confirming the feasibility of real-time compensation for airplane and satellite induced Doppler shift rates. These results represent a critical step toward robust free-space quantum networks involving mobile airborne nodes.



Measured beat note of an airborne-transmitted laser signal after fiber coupling and heterodyning with an ion-locked reference laser.

Enhanced Two-Phonon Interaction Drives Multicomponent Mechanical Cat States

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The two-phonon interaction is crucial for generating important quantum states, such as squeezed states and two-component cat states. Conventionally, it can be realized based on quadratic optomechanical coupling. However, the quadratic optomechanical coupling is several orders of magnitude weaker than the linear one, making it difficult to generate high-purity quantum states. Here, using only the linear optomechanical coupling, we obtain an enhanced two-phonon interaction in a multimode cavity optomechanical system, enabling the deterministic generation of high-purity multicomponent mechanical cat states, as illustrated in Fig. 1. We consider a multimode cavity optomechanical system consisting of three optical modes and one mechanical mode (Fig. 1(a)). When the frequencies of optical supermodes satisfy two-phonon resonance condition, a strong effective nonlinear process where photons simultaneously interact with two phonons is obtained (Fig. 1(b)). This strong two-phonon interaction drives the deterministic generation of multicomponent mechanical cat states from a mechanical coherent state (Fig. 1(c)). Moreover, even with optical and mechanical losses, the fidelity and purity of the generated cat states remain unaffected. Our work shows that adding optical modes into optomechanical system can significantly enhance mechanical nonlinearities, providing key resources for quantum state engineering and quantum computation.

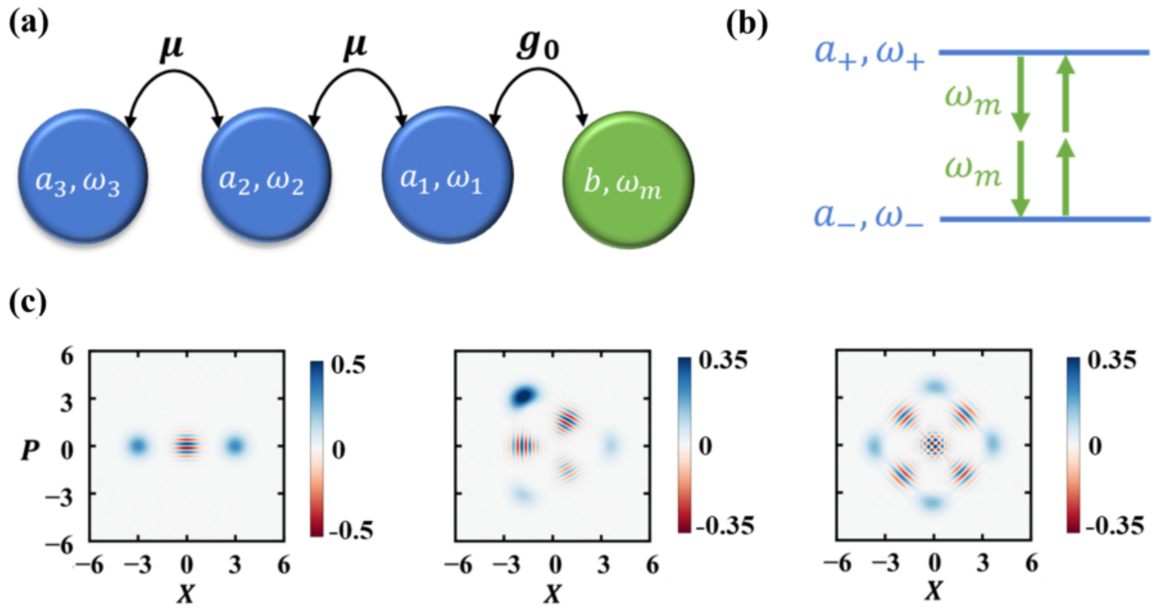

FIG. 1: Enhanced Two-Phonon Interaction Drives Multicomponent Mechanical Cat States. (a) Schematic of the multimode cavity optomechanical system. (b) Effective two-phonon interaction. (c) The generation of two-, three-. four-component mechanical cat states.

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Quantum-Enhanced Incoherent Imaging

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Accurate extraction of spatial information is central to image science from microscopy to astronomy. However, conventional direct imaging of spatially incoherent objects suffers from diffraction, which limits the ability to extract high spatial frequency information. Here we approach imaging as a quantum parameter estimation problem, parametrising an incoherent object with the Fourier components of its intensity distribution. We evaluate the physical limits of estimating these parameters in terms of Fisher information per photon and demonstrate optimised measurements that approach these limits, significantly surpassing direct imaging. Our results establish a general pathway for quantum-optimal imaging and offer new possibilities in biological fluorescence super-resolution microscopy, astronomical sub-diffraction imaging, and nanoscale surface metrology.

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Temporal modes of quantum states of light scattered by a two-level system

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Non-Gaussian quantum states of light are of paramount importance to quantum computing. Nevertheless, the fact that such states arise from non-linear dynamics makes their deterministic generation a challenging problem, both theoretically and experimentally. In this work, we aim to characterize the light stemming from one of the most fundamental quantum optics configurations, as sketched in Fig. 1: the unidirectional scattering of multi-mode and multi-photon light by a two-level system. Even though this problem reduces to the simple Jaynes-Cummings model for a single mode in a cavity, it becomes highly challenging once we consider light with a rich spectral structure.

Our results can be regarded as two complementary points of view. First, we provide an analytic and explicit description of the output state solely in terms of the input temporal modes. This formulation incorporates concepts from scattering theory [1], and allows a straightforward physical interpretation: the scattered state has contributions arising only from the sequential interaction of photons with the two-level system, and none from simultaneous interactions of multiple photons. As another advantage, our analytical approach is computationally more effective and versatile compared to numerical methods so far available in the literature [2, 3], which are mostly numerical and/or hard to scale beyond two photons. In the second part of our work, we numerically decompose the output state in terms of its temporal eigenmodes, and analyze how the associated spectral structure depends on the input modes. In spite of the output state being highly multi-mode in general, we find that, for a selection of fine-tuned input modes, it is possible for single-mode two-photon inputs to be mapped into two-mode entangled output states, i.e., two-photon NOON states, to very good approximation. Such states, in turn, are known to have more Wigner negativity compared to the associated inputs, which ultimately points towards a potential application in quantum computing. Finally, we envision combining our analytical results with the numerical techniques, and apply them for, e.g., "mode optimization" investigations — that is, to generate output states with even more Wigner negativity by carefully choosing the input modes.

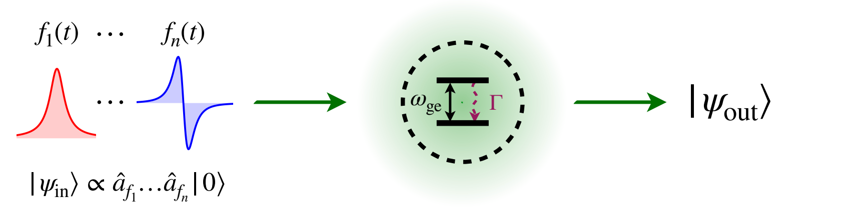

Figure 1: The setup of the considered physical system. A two-level system, with transition frequency ω_{ge} and decay rate Γ, is placed within a chiral waveguide, where the electromagnetic field propagates unidirectionally. A multi-photon incoming state of light $|\psi_{\text{in}}\rangle$, prepared in the temporal modes $f_1(t), \ldots, f_n(t)$, interacts — here indicated by the green shade — with the two-level system and evolves to the asymptotic output state $|\psi_{\text{out}}\rangle$. The horizontal dimension of the figure should be interpreted as the spatial domain.

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On-Chip Quantum Random Number Generator Using Silicon EPIC with a Flip-Chip Bonded Laser

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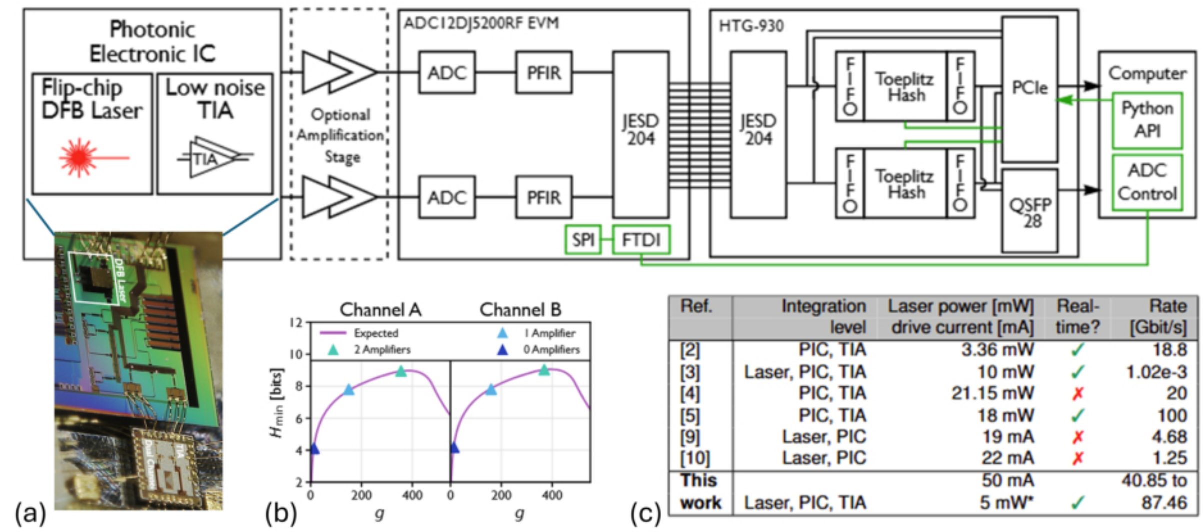
Random number generation is an essential component in modern information technologies, being used in applications ranging from games of chance to computer simulations, but most importantly cryptography and secure communication [10]. Although pseudo-random numbers are still often used due to their speed, ease of implementation, and reproducibility, their deterministic nature leaves them vulnerable in security-critical applications. Quantum random number generators (QRNG) are a subset of true random number generators that extract their randomness from physical processes believed to be truly random by quantum mechanics, making them much more suitable for these security-critical applications.

Considerable research has already been done on the development of high-speed QRNGs, particularly those based on optical noise sources such as vacuum fluctuations [1, 11, 2, 3, 5, 7] and phase noise [6, 8]. Driven by the recent advancements in photonic components and high-bandwidth detection electronics developments, these approaches have demonstrated generation rates reaching multi-Gbps regimes. However, many state-of-the-art implementations rely on discrete, off-chip components—such as external lasers, photodetectors, and transimpedance amplifiers (TIAs)—which increase system complexity, footprint size, power consumption, and cost. Furthermore, these configurations often impose limitations on scalability and robustness, hindering their deployment in compact or resource-constrained environments such as mobile and space applications. Only recently there has been an increase in effort to make these devices more compact by integrating the entire noise source into a small, low power package [8, 11, 9].

In this work, we demonstrate a compact vacuum-fluctuation-based quantum random number generator implemented on a chip-scale platform. The system integrates a flip-chip bonded laser, photonic circuitry, and high-speed electronic frontend in a small-form-factor architecture, significantly reducing the footprint and complexity compared to conventional discrete-component implementations. Quantum entropy is derived from optical vacuum fluctuations and digitized using high-speed ADCs, followed by real-time randomness extraction on an FPGA. The proposed QRNG achieves a random-bit generation rate of up to 87.46 Gb/s while successfully passing the Dieharder statistical test suite [4]. The demonstrated architecture highlights the potential of electronic-photonic integration for realizing compact, low-power, and high-performance QRNGs suitable for next-generation secure communication systems.



Ref.	Integration level	Laser power [mW] drive current [mA]	Real-time?	Rate [Gbit/s]
[2]	PIC, TIA	3.36 mW	✓	18.8
[3]	Laser, PIC, TIA	10 mW	✓	1.02e-3
[4]	PIC, TIA	21.15 mW	✗	20
[5]	PIC, TIA	18 mW	✓	100
[9]	Laser, PIC	19 mA	✗	4.68
[10]	Laser, PIC	22 mA	✗	1.25
This work	Laser, PIC, TIA	50 mA 5 mW*	✓	40.85 to 87.46

FIG. 1: (a) QRNG experiment setup with integrated quantum noise source; inset: micrograph of the silicon EPIC featuring the flip-chip bonded laser. (b) Min-entropy of the system after equalization for different levels of amplification of the output of the noise source. Measurement data points are marked with triangles. (c). State-of-the-Art comparison.

Acknowledgements

This work is partially supported by the European project Open testing and experimentation of quantum technologies (Qu-Test) (No. 101113901) and the European Quantum Flagship project Quantum Secure Networks Partnership (QSNP) (No. 101114043).

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Engineering and Measuring Multimode Entanglement in the Continuous-Variable Regime

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Developing new models of quantum computing and quantum communication protocols requires advanced technologies that are more compact, loss tolerant, and that allow us to have higher scalability to match the complexity of tasks [1]. This can be done in quantum optics with observables in the Continuous-Variable regime (CV) by encoding information on the entanglement of frequency-time modes of the electromagnetic field [2]. An example of this approach is the use of highly multimodal states, called cluster states, which can be used for one-way quantum computing protocols [3].

For our project, we aim to generate and engineer these highly multimodal states by tailoring the quantum correlations between modes of light we generate via the process of Parametric Down Conversion (PDC). We are engineering the spectral envelope of the pump that we send to a periodically poled KTP crystal (ppKTP). These correlations are fully described by the Joint Spectral Amplitude (JSA). This function is governed by the spectral envelope of the pump and the phase-matching function of the crystal (PMF). Consequently, spectral modulations of the pump will modulate the JSA and engineer correlations between multiple modes [4].

In our experimental setup, the pump of the ppKTP is a pulsed 778 nm beam generated via second harmonic generation in a periodically poled Lithium Niobate (ppLN). The measured Joint Spectral Intensity (JSI $= |\mathrm{JSA}|^2$) is presented in FIG. 1 (a) where we can see the result of the product of the gaussian spectral envelope of the pump and the *sinc* function of the PMF. This JSI is obtained by performing a stimulated parametric down conversion by seeding our crystal with a CW tunable telecom laser sent together with the pulsed pump. To inspect the modal composition of our JSI, we make a singular value decomposition (SVD), known as the Schmidt decomposition. This decomposition gives us information on the number of effective spectral modes composing the state, called the Schmidt number. For this first JSI, the Schmidt number is $K = 1.10$, which means that we just excited one spectral mode. Then, we tailored the pump spectral envelope by adding a wave shaper to the setup. The resulting tailored JSIs are presented in FIG. 1 (b) and (c). We can see how, by engineering the pump spectral envelope, the Schmidt number of the JSI gets higher, which proves the excitation of additional spectral modes. These preliminary results confirm our ability to successfully engineer multimode correlations in the spectral domain.

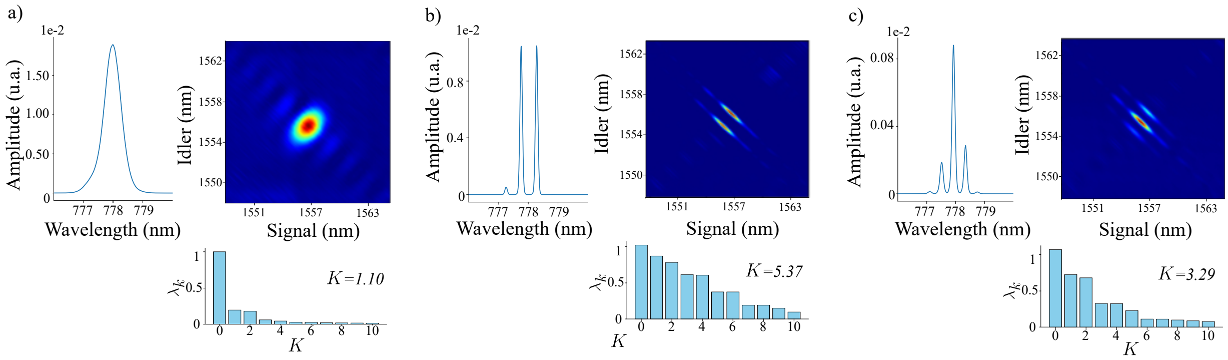

FIG. 1: Measured JSI of generated states in the ppKTP with different pump spectral envelopes. (a) Untailored pump yielding a Schmidt number of $K = 1.10$ modes composing the state. (b-c) Tailored pumps that result in higher Schmidt numbers of $K = 5.37$ and $K = 3.29$, respectively.

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Poster presentations

Session B

B38	Joan Alba	Analog Quantum Simulation of Chemical Dynamics:Hamiltonian and Realistic Dissipation Engineering
B1	David Amaro-Alcalá	Group functions in filtered randomized benchmarking for passive bosonic devices
B6	Carlos Barahona-Pascual	Non-Markovian Quantum State Transfer in Short Links
B7	Elnaz Bazzazi	Generating Squeezed Coherent State Superpositions via a Catalysis Protocol
B36	Ifra Bibi	Femtosecond Laser and Ion Implantation Based Creation of Room Temperature Single-Photon Emitters in hBN for Quantum Key Distribution
B16	Luca Giovanni Cammarata	Second-order extension of the mirror-field optomechanical Hamiltonian and renormalization of the mirror mass
B25	Riccardo Checchinato	Experimental Probing of Non-trivial Geometrical Features on the Border of the Quantum Correlation Set for the 2-2-2 Bell scenario
B2	Miguel Clavero-Rubio	Role of correlations in topological driven-dissipative bosonic chains
B20	Johanna Conrad	Alternating Squeezing Operations and Photon Subtraction for Approximating Optical Schrödinger Cat States
B23	Marc Cuenca-Larás	Langevin Theory of Quantum Non-Markovian Dynamics. Application to Coherent Feedback and the Laser's Linewidth
B32	Benoît Dubus	Bosonic and Fermionic Representation of Semi-Simple Lie Algebra Using the Jordan-Schwinger map

B31	Lukas Eisemann	An Efficient Error Correction Protocol Variant for Field Tests of Continuous-Variable Quantum Key Distribution
B21	Tommaso Fazio	Entanglement between Quantum Fields mediated by a Fluctuating Wall
B39	Felix Fischer	Limiting behaviour of higher–order squeezing operators
B37	Jonáš Fuksa	An operational continuum limit of quantum combs
B26	Suyash Gaikwad	Single Photon Storage in a Scalable Quantum Memory
B40	Adnan Hajomer	Continuous-Variable Quantum Communication over Hybrid Channels
B11	Ui-Nyung Han	Programmable Generation of Squeezed Vacuum Arrays
B35	Tim Heib	Deciding finiteness of bosonic dynamics
B24	Philip Heinzel	Exploiting higher-order correlation functions for photon-statistics-based characterization and reconstruction of arbitrary Gaussian states
B9	Hsien-Yi Hsieh	Bayesian Machine Learning for Data-Driven Quantum State Decomposition in Non-Gaussian Optical States
B46	Emanuel Hubenschmid	Time-domain field correlation measurements enable tomography of highly multimode quantum states of light
B17	Montserrat Huerta Sandoval	Unitary transformation approach to the paraxial wave equation
B8	William James Hughes	Mode Optimisation to Reach the Geometric Limits of Fabry-Pérot Optical Cavity Performance
B33	Marcin Karczewski	Monogamy of simulated particle statistics in multi-photon systems
B34	Evi Kasnetsi	Connecting Time Crystals to Many-Body Protection
B4	Konstantin Katamadze	Quantum super-resolution imaging of incoherent emitters with the BLESS technique
B3	Noah Oliver Kaufmann	Entanglement Enhanced Sensing with Qubits affected by non-Markovian Dephasing

B19	Shailesh Kumar	Metasurface Mediated Interaction and Entanglement between Quantum Emitters
B10	Kaisa Laiho	Calibrated generation of heralded one, two and three photons
B15	Jonas Lammers	Resource efficient universal photonic processor based on time-multiplexed hybrid architecture
B5	Devendra Kumar Mishra	Enhanced Phase Sensitivity in Displacement-Assisted SU(1,1) Interferometer via Photon Recycling
B41	Leonardo Novo	Native linear-optical protocol for efficient multivariate trace estimation and indistinguishability characterization
B18	Alberto Paniate	Substrate effects on photon-pair generation in metasurface
B42	Marc-Oliver Pleinert	Testing two cornerstones of quantum theory with multi-particle interference
B12	Maria Popławska	Capacity of Multimode Quantum Gaussian Channels
B27	Enrico Rebufello	Entanglement-preserving Measurement of the Bell Parameter on a Single Entangled Pair
B14	Stefan Richter	Experimental deployment of a DM-CV-QKD transmitter on a moving plane for air-to-ground quantum communication
B43	Olivia Saffer	Brillouin-based Memory for Low Photon Numbers
B44	Jan Schreck	Implementation of Unidirectional Modulation of Polarization-Squeezed States for an Experimental Free-Space Continuous-Variable Quantum Key Distribution Scheme
B28	Alexandra Simon	Cold-Atom Buoy: A Differential Magnetic Sensing Technique in Cold Quadrupole Traps
B13	Changjin Son	Spontaneous four-wave mixing in a second-order nonlinear thin film
B22	Daniel Stachanow	Dissipation Dilution in 3D Direct Laser Written Mechanical Resonators
B45	Aditya Sudharsanam	All-Optical Detection of Quadrature Entanglement
B30	Bálint Morgan Szilasi	Spatially Multiplexed Multiphoton Sources Based on Stepwise Optimized Binary-Tree Multiplexers

B29	Giovanni Zotti	Statistical properties of high-harmonic generation driven by bright squeezed vacuum

Analog Quantum Simulation of Chemical Dynamics: Hamiltonian and Realistic Dissipation Engineering

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We propose an analog quantum simulation (AQS) of chemical dynamics for standard cavity QED, circuit QED, optomechanical, and related platforms. The AQS reproduces chemical processes involving the coupling of electronic and nuclear degrees of freedom, which are naturally described by the spin-boson Hamiltonian and its multi-mode extensions, and become classically intractable as the complexity of the molecule and its environment grows. AQS platforms naturally support bosonic modes and offer a practical advantage in simulating these systems. Additionally, prior treatments of the bath have adopted the dissipation native to the quantum simulator, which may not reproduce the correct chemical dynamics. For a better match with the physical bath of the chemical system, we engineer Caldeira-Leggett dissipation in these platforms, enabling access to the overdamped regime and a faithful representation of Brownian motion. We validate the approach by reproducing the Marcus model of electron transfer and conical intersection dynamics for the multi-mode extension. We also discuss the generalization to non-Markovian reservoirs and possible approaches thereof. Our results establish a practical route to quantum simulation of realistic chemical dynamics in near-term quantum hardware.

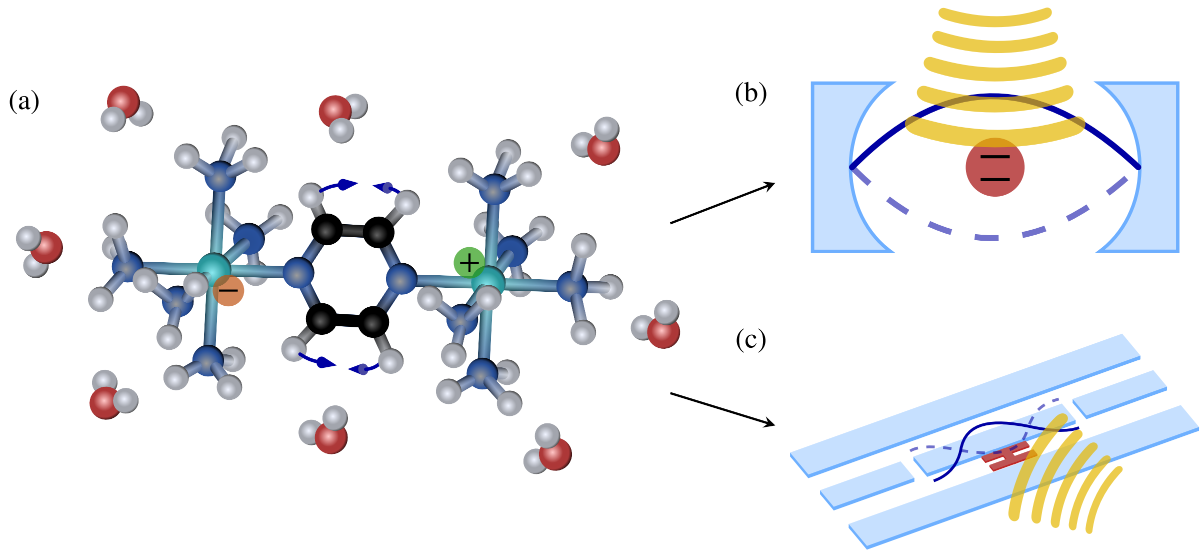

FIG. 1: Chemical dynamics for processes that have strongly coupled electronic degrees of freedom to reaction coordinates, can be reproduced in driven quantum optics platforms, even far from the ultra-strong coupling regime. Figure (a) depicts a Creutz–Taube ion, known for the electron transfer. Figure (b) represents driven cavity QED and a circuit QED setups, two possible experimental platforms where the theory from this work could be implemented.

Group functions in filtered randomized benchmarking for passive bosonic devices

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We lower the cost of the current bosonic randomized benchmarking proposal of bosonic randomized benchmarking with passive transformations [1]. We obtain our results by introducing a filter function using group functions of the unitary group; that is, entries of the irreducible representations of the unitary group. Besides, our filter then does not require computing Clebsch-Gordan coefficients [2]. We emphasize that our filter is compatible with the same data as the original scheme based on permanents, but we propose a different data-collection method that requires only a single measurement. Additionally, we argue that weak coherent states and intensity measurements are sufficient to perform the characterization. Our work could then simplify the process of characterizing platforms without a photon-number-resolving detector and streamline the necessary data analysis for characterization.

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Non-Markovian Quantum State Transfer in Short Links

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Distributed quantum computation requires robust entanglement distribution across network nodes. While often modeled in the Markovian regime, this approximation fails as networks incorporate longer distances or slow-light media, necessitating a precise understanding of non-Markovian, delayed interactions. In this work, we explore the short quantum link regime—where the photon travel time τ is comparable to the emitter lifetime $1/\gamma$—for Two-Level Systems (TLS) coupled to a waveguide.

We reveal that as retardation and multimode effects become significant, emitters spontaneously lock into self-synchronized Rabi oscillations driven by coherent photon echoes. This dynamic breaks the link's discrete time-displacement symmetry, leading to a complex spectral structure characterized by persistent quasi-dark states and vacuum Rabi splitting, even reaching the superstrong coupling regime.

Crucially, we establish photon-echo synchronization as an engineering resource for maximizing Quantum State Transfer (QST) fidelity in the presence of realistic propagation losses. By benchmarking three protocols across the $\gamma\tau$ parameter space, we demonstrate that STIRAP directly exploits this quasi-dark-state structure to achieve a quadratic infidelity floor of $\mathcal{O}((\gamma\tau)^2)$. This significantly outperforms both SWAP protocols (which exhibit a linear error of $\mathcal{O}(\gamma\tau)$) and wavepacket engineering for $\gamma\tau \lesssim 1.44$. Ultimately, these exact analytical predictions provide the physical insights necessary to design and optimize short-link quantum network experiments on current circuit-QED hardware.

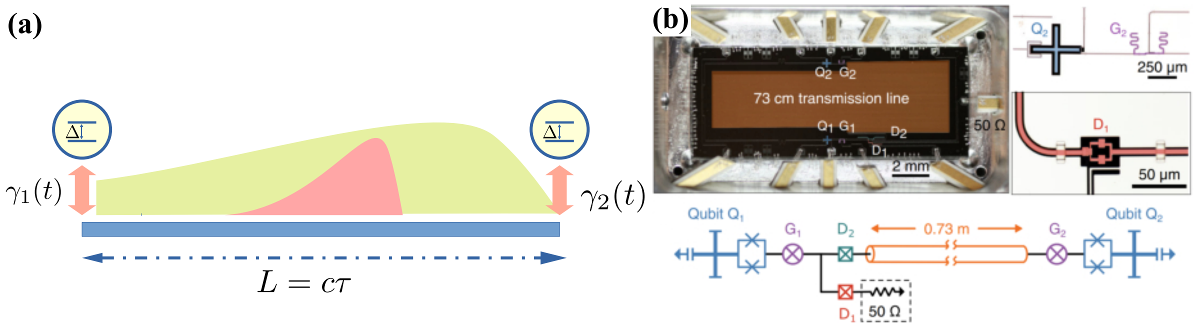

Figure 1: (a) Representation of a short quantum link (Length L) between a pair of TLS with internal transition frequency Δ. The TLSs are coupled to a waveguide with coupling strengths $\gamma_{1,2}(t)$. (b) Experimental realization of a short quantum link By Andrew Cleland's group, in the University of Chicago

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Generating Squeezed Coherent State Superpositions via a Catalysis Protocol

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Non-Gaussian states are essential resources for fault-tolerant quantum computing, enabling protection against decoherence-induced errors [1, 2]. Among them, squeezed coherent state superpositions (SCSS) are of high interest for quantum error correction [1], yet their generation remains challenging due to complex protocols and limited achievable amplitudes [3, 4].

Photon catalysis is a promising approach to breed high-fidelity SCSS with large amplitudes [5]. As shown in Fig. 1, the protocol employs a beam splitter to superimpose a squeezed vacuum state and an m-photon Fock state. Photon-number-resolving detection in one output arm of the beam splitter heralds the target state in the other output. We implement this protocol experimentally and characterize the generated states using a custom-built homodyne detector.

Squeezed vacuum states are generated by an optical parametric oscillator (OPO) with a type-0 second-order nonlinear crystal (PPKTP) inside a resonator, while heralded Fock states are generated from a second type-II PPKTP crystal. The type-0 PPKTP crystal provides a bandwidth of 2.6 THz in an OPO cavity with a free spectral range of 690 MHz corresponding to roughly 4000 longitudinal modes. Consequently, spectral filtering is essential to isolate a single mode and ensure proper spectral matching. We employ cascaded filtering to enable high single-mode purity.

We outline our experimental implementation and report recent progress, contributing to the development of quantum state engineering techniques for fault-tolerant quantum computing.

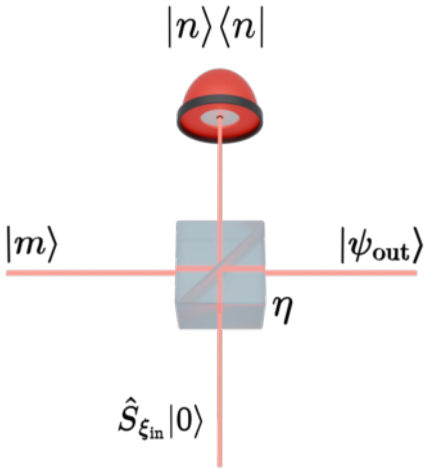

Figure 1: Optical catalysis.

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Femtosecond Laser and Ion Implantation Based Creation of Room Temperature Single-Photon Emitters in hBN for Quantum Key Distribution

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Deterministic and spatially localized single-photon sources operating at room temperature are essential for scalable quantum key distribution (QKD) technologies. Defect-based emitters in hexagonal boron nitride (hBN) provide a promising platform due to their stability and tuneable optical properties. In this work, we investigate the controlled generation of single-photon emitters using two complementary approaches: femtosecond laser irradiation and ion implantation.

The quantum optical properties of the emitters are characterized using scanning confocal photoluminescence spectroscopy, time-correlated single-photon counting, and second-order autocorrelation measurements. We observe bright, localized emission in the visible to near-infrared spectral range. Photon correlation measurements reveal pronounced antibunching with $g^{(2)}(0) < 0.5$, confirming non-classical light emission, while time-resolved measurements indicate excited-state lifetimes on the order of ~2–5 ns range.

A comparative analysis of emitters generated by the two approaches reveals distinct photon statistics and emission dynamics, reflecting differences in defect configurations and local lattice environments. In particular, variations in antibunching contrast and emission stability suggest that controlled defect formation plays a key role in determining single-photon purity and performance. These results demonstrate that combining femtosecond laser processing with ion implantation provides a versatile route for engineering quantum emitters with tailored optical properties, supporting their integration into scalable quantum photonic platforms for QKD applications.

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Second-order extension of the mirror-field optomechanical Hamiltonian and renormalization of the mirror mass

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We consider a second-order extension of the Law optomechanical Hamiltonian describing a movable reflecting mirror placed between two fixed reflecting boundaries, which divides the cavity into two sub-cavities. A massless one-dimensional scalar field is defined in each sub-cavity, while the movable wall, whose translational degree of freedom is described quantum-mechanically, is bound to its equilibrium position by an external harmonic potential. We obtain the effective Hamiltonian describing the coupled field-mirror system up to the second order in the displacement of the mirror from its equilibrium position. The resulting effective Hamiltonian contains two new singular second-order terms: one independent of the field, taking the form of an elastic-constant counterterm, and a field-dependent term. We investigate the effects of these new terms by computing energy shifts both in the wall and in the field sectors, as well as the mass renormalization of the movable mirror up to second order. In particular, the need for mass renormalization emerges from the analysis of the mirror energy shift in the absence of the harmonic potential, where a mass correction can be identified.

In the mirror sector, the static singular term cancels out the leading cubic ultraviolet divergence in the energy shift of the movable mirror, prepared in a Fock state with the field in the vacuum state. The remaining contribution yields an additional correction to the Casimir energy and a mechanical frequency shift, which becomes finite after mass renormalization is taken into account. In the field sector, we consider the energy shift of a one-photon state and show that the field-dependent singular term cancels the leading linear ultraviolet divergence of the one-photon energy shift, leaving only a weaker logarithmic divergence.

Experimental Probing of Non-trivial Geometrical Features on the Border of the Quantum Correlation Set for the 2-2-2 Bell scenario

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While the 2-2-2 scenario is the simplest Bell scenario allowing non-classical correlations, the underlying geometry of the corresponding quantum correlation set is remarkably intricate [1, 2, 3]. Most experimental efforts have focused almost exclusively on testing the maximal quantum violation of the Clauser-Horne-Shimony-Holt (CHSH) inequality [4] and its related slice [5]. Consequently, a lot of the complexity of the set remains experimentally unexplored. In this work, we move beyond the standard slicing and begin exploring other boundary points of the quantum set. We present an experimental investigation of points within a specific trajectory that links the optimal Hardy correlation [6] and the maximal violation of the CHSH inequality. We perform this analysis by closely following the boundary between the quantum and no-signaling sets. Our measurements show a good match with the predicted quantum boundaries. Moreover, an in-depth analysis of our results provides additional insights into the structure of the space of quantum correlations near geometrically non-trivial features, such as non-exposed extremal points [1].

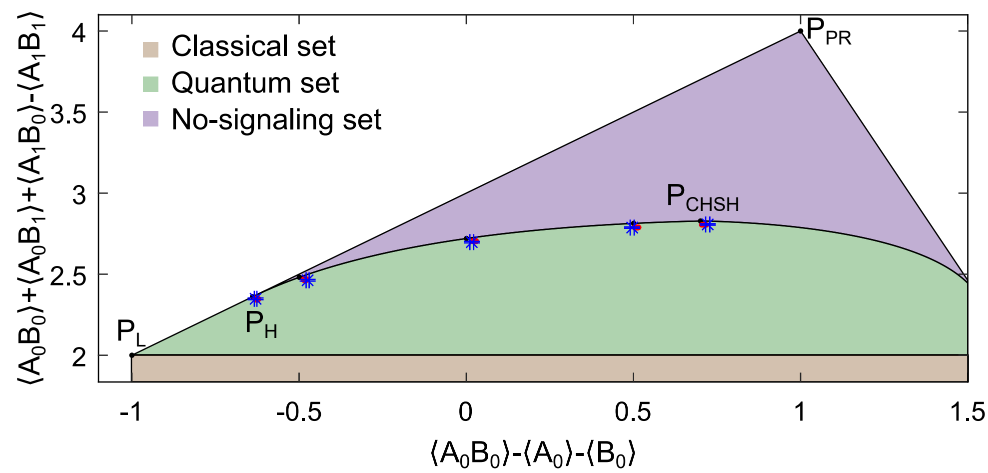

FIG. 1: Experimentally measured correlations (in blue) compared to the target correlations (in black) on the border between quantum and no-signaling sets. In red, we show the expected correlations from our state reconstruction via quantum state tomography. Here, we target the border of the quantum correlation set along the slice that contains both maximal violation of Hardy (P_H) and CHSH (P_{CHSH}) inequalities [1]. This slice also contains one of the vertices of the Popescu-Rohrlich box [7] (P_{PR}).

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Role of correlations in topological driven-dissipative bosonic chains

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Driven-dissipative quantum systems can exhibit robust transport and amplification properties when operating in topological regimes. However, the relationship between topological order and long-range correlations remains largely unexplored. In this work, we study how topological phases imprint distinct correlation patterns in one-dimensional bosonic chains with coherent parametric driving and dissipation. We demonstrate the presence of hidden long-range order (LRO) in frequency-resolved correlations within topological phases, and explore the corresponding analytical structure of time-domain correlations. To characterize the topology of the system, we introduce a novel vector-like topological invariant based on the number of singular value gap closings across frequency axis. Our results demonstrate that topological LRO is robust to disorder and persists in experimentally relevant platforms, such as trapped ions or superconducting circuits. These findings open new avenues for quantum sensing and correlation engineering in topological non-Hermitian systems.

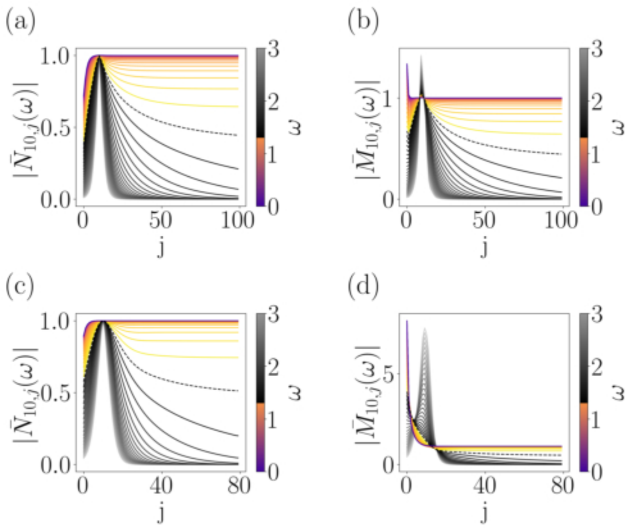

Figure 1: Normalized normal ($N_{i,j}$) and anomalous ($M_{i,j}$) correlation functions as a function of the site index j, for a fixed reference site $i = 10$, across different models. Colored curves indicate topological phases, whereas black curves correspond to trivial configurations. The black dashed line marks the critical point separating the two regimes. Model I: panels (a) and (b), with $N = 100$, $J = g_s = g_c = 1$, and $\gamma = 5$. Model II: panels (c) and (d), with $N = 80$, $J = 1$, $g_s = g_c = 0.1$, $\gamma = 3.75$, $g'_c = 3$, and $\gamma' = 30$. Unless otherwise stated, the remaining parameters are fixed to $\Delta = 0$ and $\phi = \pi/2$.

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Alternating Squeezing Operations and Photon Subtraction for Approximating Optical Schrödinger Cat States

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Schrödinger Cat States (SCS) are valuable non-Gaussian resources for quantum information processing, particularly in fault-tolerant quantum computation and quantum-enhanced phase estimation [1,2]. Although the preparation of SCS has been proposed in various schemes e.g., photon subtraction [3] and its variations [4,5], it remains experimentally challenging. When engineering SCS through photon subtraction with experimentally available resources, two main limitations persist: (I) the fidelity decreases rapidly with the size of the cat state and (II) the success probability of generating higher α cat states reduces significantly with the number of subtracted photons.

Here, we propose a scheme that alternates single-mode squeezing and photon-number subtraction operations, effectively forming a nonlinear interferometer. By conditioning on photon-number measurements in the subtraction arms, we introduce non-Gaussianity in the output state. We analytically analyze the resulting state evolution and performance metrics. The approach yields novel quantum state structures and facilitates the generation of larger and higher-fidelity SCS with enhanced success probabilities over previous techniques. We investigate the trade-offs between fidelity and experimental success probability, and analyze the sensitivity of the output states to deviations in key experimental parameters, emphasizing the scheme's tunability and practical implementation advantages.

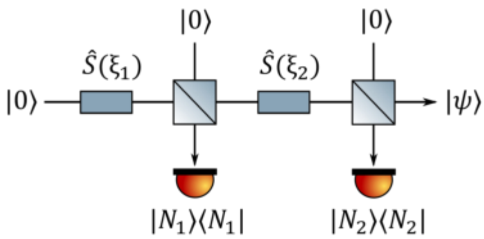

Figure 1: Setup of our proposed photon subtraction scheme. The scheme involves alternating squeezing $\hat{S}(\xi_1), \hat{S}(\xi_2)$ and photon subtraction operations implemented as a beamsplitter and photon number resolved detection of N_1 and N_2 photons. Here, we present the case of two squeezers and two photon subtraction stages.

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Langevin Theory of Quantum Non-Markovian Dynamics. Application to Coherent Feedback and the Laser's Linewidth

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Non-Markovian dynamics, where the evolution of a system S depends on its past history through interactions with the environment E, present significant challenges for efficient theoretical modeling, in stark contrast to the well-established methods for Markovian open quantum systems. Phase-space techniques are particularly effective in Markovian regimes, as they exactly map the reduced quantum dynamics of S onto Langevin equations for stochastic variables, as opposed to Heisenberg-Langevin equations for operators. Langevin equations provide analytical insights in key regimes and excel in handling strong nonlinearities and couplings, where other methods often falter. However, extending phase-space methods to non-Markovian dynamics has been a long-standing challenge. We address this gap by applying phase-space representations to the full S $\oplus$ E system. Employing normally-ordered representations, we find Langevin equations where (i) non-Markovian effects emerge exclusively in the deterministic terms via a memory kernel, and (ii) noise contributions vanish when E is initially in the vacuum state. To demonstrate the power of this framework, we investigate delayed coherent feedback characterized by a given delay T and a coupling rate f (defining $\kappa := fT$). Specifically, we consider de paradigmatic and technologically relevant case of lasers, which have seen their linewidth reduced by several orders of magnitud via feedback [1], with a scaling $(1+\kappa)^{-2}$ predicted via approximate theoretical methods. Our framework enables us to explore scennarios beyond these approximate methods, finding deviations of the linewidth reduction of the form $(1+\kappa)^{-p}$ with $1 < p < 2$ close to (and below) the laser's threshold (Figure 1).

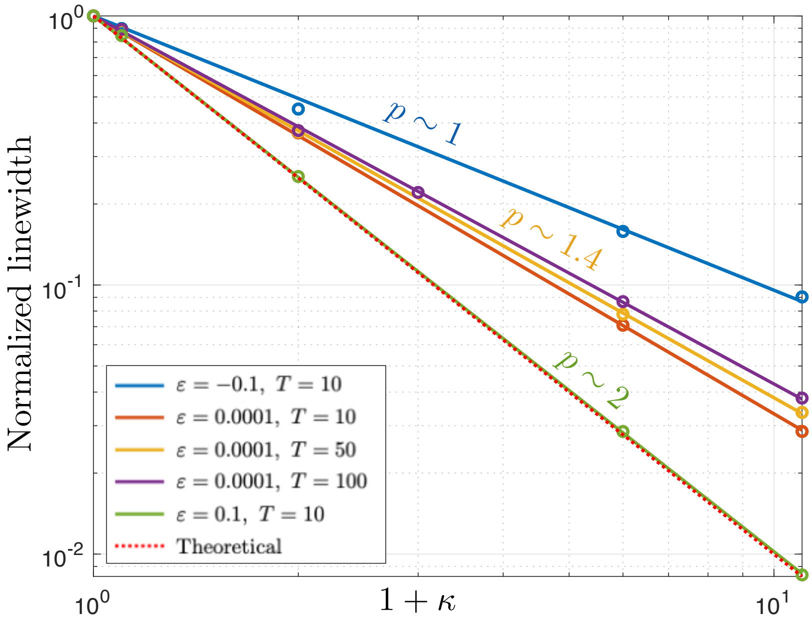

Figure 1: Normalized laser's linewidth relative to the feedbackless case as a function of $1+\kappa$ for different values of T and $\varepsilon := C - 1$, being C the normalized pump parameter (with $C = 1$ at threshold). The results are obtained from numerical simulations of the stochastic Langevin equations.

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Bosonic and Fermionic Representation of Semi-Simple Lie Algebra Using the Jordan-Schwinger map

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The Jordan-Schwinger[1,2] map is a tool widely used in quantum optics and quantum many-body physics as many models rely on the action of some semi-simple Lie algebra on either a bosonic or a fermionic Fock space. Among many other examples, $\mathfrak{su}(n)$ describes many versions of the Hubbard model[3], the collective spin in ultracold quantum gases composed out of spinful atoms[4] and has found applications in quantum optics for defining uncertainty measures[5], witnessing non-classicality[6,7] or quantum entanglement[8]. The symplectic group $SL(2, \mathbb{R})$ has many applications in linear quantum optics and quantum information theory[9] and frustrated quantum antiferromagnets[10], while $\mathfrak{su}(1,1)$ plays a role in interferometry[11].

Despite the Jordan-Schwinger map's importance for relating semi-simple Lie algebras with bosonic or fermionic creation and annihilation operators, the relation – which we refer to as the *basis relation* – between the Fock basis and the proper basis induced by the model remained incomplete. Those relations have many applications as they directly connect discrete with continuous-variable systems, thus allowing one to translate concepts and methods between two intrinsically different kinds of quantum systems. On top of that, such relations are needed when computing the complete measurement statistics of spin observables defined over multiple modes – as this requires knowing their eigenvectors[5]. Simple relations between spin and Fock states were known for $\mathfrak{su}(2)$ and two modes[2,12], and we extended this result to an arbitrary number of modes in previous work[13] by algorithmically constructing complete sets of spin states.

In this work, we generalize our construction to any finite representation of any semisimple Lie algebra by studying the weight of the representation over the Fock space. In such a way, we can create a basis were each vector is described by the total number of particles, its weight and a corresponding maximal weight plus a simple degeneracy lifting quantum number. We are able to establish closed formula if the rank of the semi-simple Lie algebra is larger than the number of modes minus one. Finally, we provide an accelerated algorithm that allows us to describe a single state without generating the full basis.

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An Efficient Error Correction Protocol Variant for Field Tests of Continuous-Variable Quantum Key Distribution

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Continuous-variable quantum key distribution (CV-QKD) relies on near-optimally efficient information reconciliation (IR) to achieve high secret key rates (SKR) and transmission distances. Here, we present a novel and improved variant of a recently introduced IR-protocol, which is based on multiple decoding attempts (MDA). We validate our method on simulated CV data sets and demonstrate significant SKR improvements over both the standard single-decoding-attempt protocol and the original MDA implementation, even at a fixed decoding complexity. Apart from average efficiency gains during the IR step, MDA-protocols offer robustness against strongly fluctuating quantum channels as well as enable a full-block parameter estimation that avoids revealing any data.

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Entanglement between Quantum Fields mediated by a Fluctuating Wall

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The Law optomechanical (multi-mode) Hamiltonian [1] is applied to the case in which a movable, perfectly reflecting mirror is placed inside a cavity delimited by two fixed ideal conducting boundaries [2] (Fig. 1). A massless scalar field is defined in each sub-cavity. The presence of the movable mirror yields an effective interaction between the mirror and the fields and between the field modes.

The system's overall ground state is calculated at second order by using perturbation theory [3] and its fields-only reduced density operator given for each sub-cavity. The bipartite field state corresponding to one mode from each sub-cavity is obtained by tracing out all other modes. The negativity [4] associated with the two-mode state is calculated analytically and a numerical analysis of the total multimode entanglement is performed, considering up to 70 modes. In both cases, the fields in the two sub-cavities are entangled, in contrast to the case in which the wall is fixed. Parameter values that maximize the entanglement are identified, both in near-resonant and non-resonant regimes. These values for the sub-cavities' resonant frequency (supposed equal for both), the overall cavity's length and for the mirror mass correspond to different pieces of hardware realizing an optomechanical system [5-7]. In the non-resonant regime, ranges of the optomechanical parameters that lead to a stronger entanglement with respect to that in the near-resonant cases are discussed. In particular, the importance of reducing the mirror mass as much as possible in order to maximize entanglement is stressed.

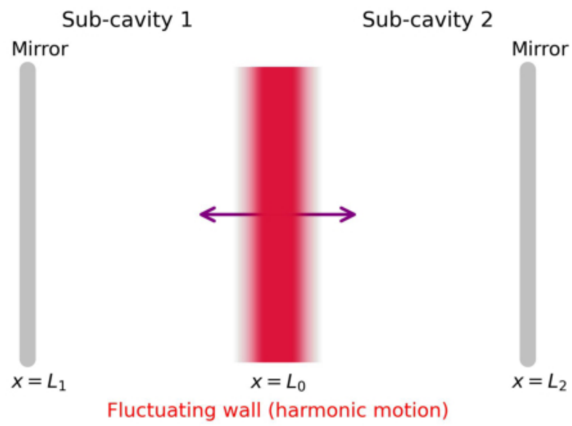

Figure 1: Pictorial representation of a cavity divided into two sub-cavities by a fluctuating wall whose equilibrium position coincides with the midpoint of the cavity.

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Limiting behaviour of higher–order squeezing operators

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Squeezing of light is one of the cornerstones of quantum optics, with applications ranging from enhancing measurement precision in gravitational wave detection to generating nonclassical states for bosonic error correction and quantum information processing. On the experimental side, squeezed states are routinely realized in optical parametric oscillators and superconducting circuits, and they constitute a key resource for pushing sensitivities beyond the standard quantum limit. While conventional (quadrature) squeezing is by now a well-established and controllable tool, there is growing interest in going beyond Gaussian operations toward genuinely nonlinear, non-Gaussian resources. Higher–order generalizations of the form $H_k = (a^\dagger)^k + a^k$, with $k \geq 3$, were popularized by Braunstein in the 80s as a natural extension of the squeezing paradigm into the multi-photon regime. Ever since then, there has been a longstanding debate on the existence and uniqueness of the dynamics generated by higher order squeezing.

In this contribution we show that additional information about the physical system in the form of boundary conditions for high photon numbers is needed in order to define unique higher–order squeezed states. These boundary conditions can, for example, be induced by additional free field contributions like Kerr terms. Such multi–photon interactions penalize high photon numbers and thus effectively cut off the system at high energies, hence implementing the aforementioned boundary conditions.

These boundary conditions strongly depend on the precise form of the free field contributions. Of particular interest is the case where these additional multi photon interactions are small, and the higher–order squeezing Hamiltonian is a good approximation of the system at hand. In this case, the boundary conditions, and therefore the higher–order squeezing dynamics are extremely sensitive against small perturbations: All possible realizations of higher–order squeezing can be achieved by arbitrarily small variations of the free field contributions. As the different realizations of higher–order squeezing, parametrized by the different boundary conditions for high photon numbers, generate quantitatively different states, this shows that these arbitrarily small additional terms cannot be neglected without a precise understanding of the system. Our analysis stresses that effective Hamiltonians and numerical simulations of multi photon interactions have to be treated with care.

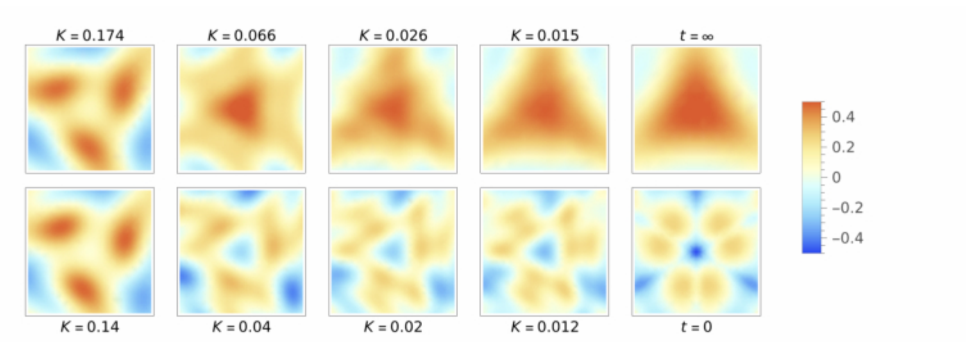

Figure 1: Different boundary conditions of 3rd order squeezing ($t = 0$ and $t = \infty$) can be induced arbitrarily small perturbations (scaled by K).

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An operational continuum limit of quantum combs

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Quantum combs are powerful conceptual tools for capturing multi-time processes in quantum information theory, constituting the most general quantum mechanical process. But, despite their causal nature, they lack a meaningful physical connection to time—and are, by and large, arguably incompatible with it without extra structure. The subclass of quantum combs which assumes an underlying process is described by the so-called process tensor framework, which has been successfully used to study and characterise non-Markovian open quantum systems [1]. Despite being motivated by an underlying dynamics, process tensors allow us to treat interactions with the system only at a discrete set of times, leading to an uncomfortable practical and conceptual gap in the description and understanding of the inherently continuous time-evolution of non-Markovian quantum systems. In this work [3], we take a decisive step toward remedying this situation.

We introduce a fully continuous process tensor (cPT) framework by showing how the discrete multipartite Choi state becomes a field-theoretic state in a multispecies bosonic Fock space on the corresponding continuous time interval. In this space, the bosonic species correspond to a complete basis of non-identity operations on the system and their finite particle number wavefunctions encode the discrete process tensor marginals of the continuous process.

CPTs allow, for the first time, for an information-theoretic treatment of multi-time correlations. We kick-start this program by proving that non-Markovianity measures based on Choi divergences vanish in the continuum and introduce a measure based on the quantum conditional mutual information appropriate for continuous time processes. Furthermore, we outline how to perform efficient simulation of open quantum systems through compression and touch on aspects of performing tomography of cPTs.

CPTs are intimately related to their continuous matrix product state (cMPS) [2] representatives, which form the basis of our framework: The cMPS formalism can be used to obtain the cPT corresponding to a specific model of the system-environment interaction, given the corresponding Hamiltonian or Lindbladian dynamics generator and the initial system-environment state. Conversely, we define positivity and causality conditions for cPTs, which constitute the physicality conditions defining the subset of Fock space vectors that correspond to a continuous process.

Similarly to the cPTs, we describe continuous instruments as dual Fock space vectors. Now, the probability density function associated with a given (continuous) experimental outcome x is computed by a generalised Born rule

$$p(x) = \langle \mathcal{I}(x) | \Upsilon \rangle, \tag{1}$$

where $\langle \mathcal{I}(x)|$ is the continuous instrument and $|\Upsilon\rangle$ is the continuous process tensor. The finite particle number wavefunctions of continuous instruments encode the (possibly correlated) generators of trace non-increasing dynamics, indexed by measurement outcomes. This shift from (correlated) CPTP maps, which define discrete-time instruments, to their generators is a crucial aspect of the framework. It paves the way to improvements in the numerical treatment of control of non-Markovian systems and allows for the implementation of energy constraints in quantum control. The framework is fully capable of describing continuous measurements, be it diffusive or jump measurements, as well as any feedback implemented based on their outcomes.

Our work closes a gap in the quantum information literature, and opens up the opportunity for the application of many-body physics insights to our understanding of quantum stochastic processes in the continuum.

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Single Photon Storage in a Scalable Quantum Memory

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Quantum networks enable long-distance entanglement distribution and the transfer of quantum information between remote nodes. Quantum memories interfaced with compatible single-photon sources form a key component of such networks. Owing to significant advances in atomic control techniques and the wafer-scale microfabrication of vapor cells, ground-state atomic vapor quantum memories have emerged as strong candidates for such applications [1]. Previously, we reported the first successful storage of 370 MHz-bandwidth single photons — generated from a heralded single-photon source based on cavity-enhanced SPDC in ppKTP — in a quantum memory implemented in warm ^{87}Rb vapor[2,3], with $g^{(2)}_{c,ret} = 0.177(23)$ confirming the non-classical character of the retrieved photons. Further technical improvements, including fast optical switching via a pulsed tapered amplifier, amplified chirped laser pulses [4], and use of a weak magnetic field led to a two-fold improvement in the end-to-end efficiency (from 1.11(2)% to 2.14(3)%), a storage lifetime of $3.4\mu s$, and a more pronounced non-classical retrieval with $g^{(2)}_{c,ret} = 0.135(17)$. Building on these results, we will implement the quantum memory in a specially engineered capillary-shaped vapor cell. Compared to bulk cells, the capillary geometry is expected to maximize the overlap between the optical field and the atomic ensemble, ensuring more uniform atom addressing and enhanced light–matter interaction. Combined with the demonstrated technical improvements, this approach represents a viable route toward scalable, room-temperature quantum network nodes.

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Continuous-Variable Quantum Communication over Hybrid Channels

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Future quantum networks require seamless integration of optical fiber and free-space links. Here, we experimentally demonstrate, to the best of our knowledge, the first continuous-variable quantum key distribution (CV-QKD) system operating over a hybrid channel composed of a 620 m free-space link followed by 2 km of optical fiber, corresponding to a total loss of 20 dB. We implement both Gaussian-modulated coherent-state and squeezed-state protocols under daylight conditions using coherent detection with a locally generated local oscillator (LO), enabling intrinsic mode filtering without additional spatial or spectral filtering.

To mitigate atmospheric transmittance fluctuations, we develop an optimized post-selection strategy combining thresholding [1, 2], binning, and clustering of channel realizations. This improves the average secure key rate (SKR) by 45%. For coherent-state CV-QKD, we achieve an SKR of 6.9×10^{-3} bits/use, while the squeezed-state protocol achieves 5.6×10^{-3} bits/use, corresponding to up to 700 kbits of secure key.

These results demonstrate the feasibility of CV-QKD across hybrid free-space–fiber channels and represent an important step toward scalable heterogeneous quantum networks.

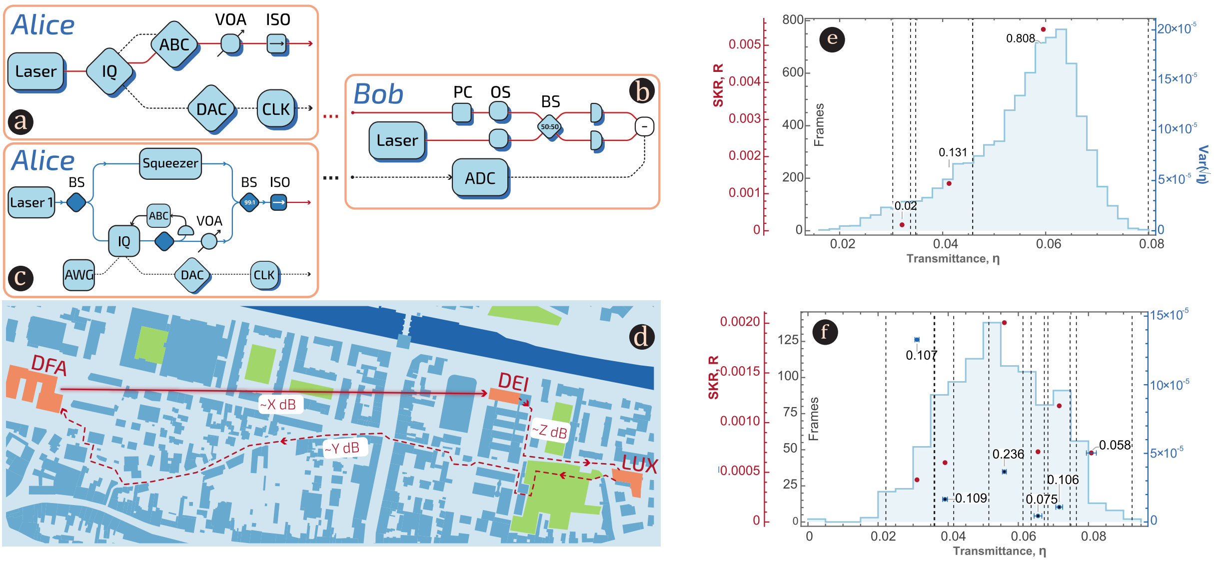

FIG. 1: Experimental demonstration of CV-QKD over hybrid free-space–fiber channels. (a–c) Coherent- and squeezed-state transmitters (Alice) and coherent receiver (Bob). (d) Hybrid link consisting of a 620 m free-space channel followed by 2 km of optical fiber (20 dB total loss). (e,f) Transmittance distribution and corresponding secret-key-rate (SKR) analysis after optimized post-selection.

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Programmable Generation of Squeezed Vacuum Arrays

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Large-scale multimode squeezed vacuum states play a crucial role to develop continuous-variable quantum technologies with scalability. A promising direction for realizing a large number of squeezed modes is to harness the supermodes from parametric down conversion processes, but this approach often suffers from limited controllability and non-uniform squeezing levels across individual modes [1,2]. Here, we present a scalable and programmable method for generating multiple squeezed vacua via array-based generation of squeezed light.

To generate squeezed vacuum arrays with tunable squeezing angles, we engineer the intensity and phase distribution of a pump laser used for parametric down conversion. We utilize a spatial light modulator (SLM) with a phase mask divided into three functional regions: shaping the pump intensity into a 2D array [3], implementing optical Fourier transform, and controlling the individual phases in the array. As illustrated in Fig. 1, an initial Gaussian intensity distribution (Fig.1 (a)) is converted into a 4×4 array (Fig.1 (b)), followed by individual phase control on each cell (Fig.1 (c)). This programmable pump array is focused into a nonlinear crystal to produce multiple squeezed vacuum in parallel. To characterize the states, a second SLM generates a similar pump array that is injected into the crystal along with the squeezed vacuum for phase-sensitive optical parametric amplification (OPA) [1]. This maps the quadrature variance of each array mode onto intensity, allowing direct squeezing detection with a camera.

Experimental results are illustrated in Fig. 2. Under a uniform phase pattern (Fig. 2(a)), all 16 modes are deamplified and amplified at the same phase, exhibiting simultaneous squeezing ($\sim 2.5\,\mathrm{dB}$) and anti-squeezing ($\sim 4\,\mathrm{dB}$). For the checkerboard pattern (Fig. 2(b)), modes with indices (1, 3, 6, 8, 9, 11, 14, 16) are amplified at the anti-squeezing phase within the red box region, while other modes are at the squeezing phase; this relationship is reversed in the blue box region. Similarly, for the vertical stripe pattern in Fig. 2(c), odd-indexed modes are amplified at the anti-squeezing phase in the red region, while even-indexed modes are squeezed, with the opposite behavior in the blue region. Overall, we demonstrated the generation of a 16-mode squeezed vacuum array with 2.5 dB of squeezing, along with individual phase control. Our approach provides a scalable and programmable platform for continuous-variable quantum information processing.

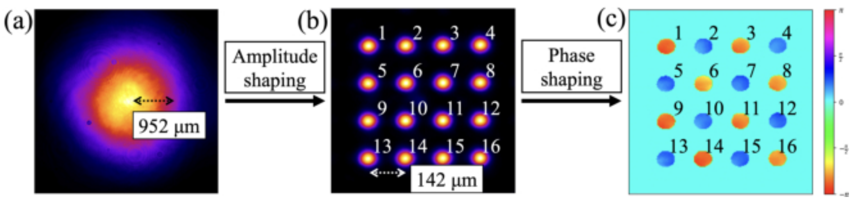

Figure 1: Experimental engineering of pump laser distributions. (a) Initial intensity distribution. (b) 4×4 array intensity distribution. (c) 4×4 array phase distribution.

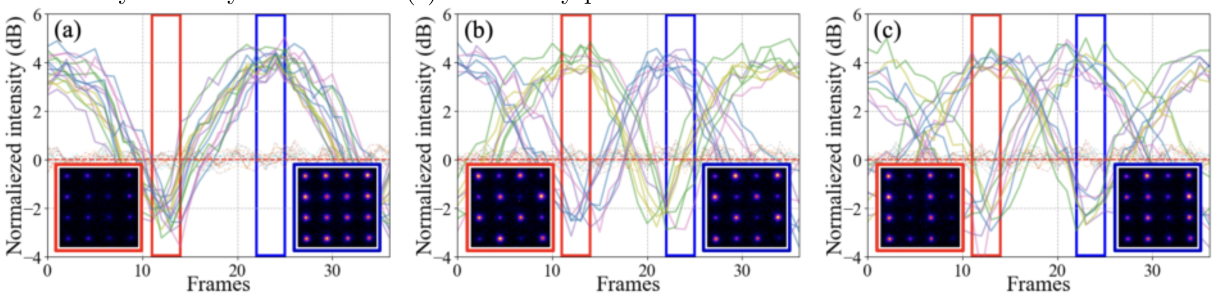

Figure 2: Programmable generation of squeezed vacuum arrays by controlling the pump phase distribution. Quadrature variances at each cell is measured while scanning the overall phase of OPA measurement. (a) Uniform pattern. (b) Checkerboard pattern. (c) Vertical stripe pattern. The insets are camera images after OPA, showing amplification or deamplification depending on the squeezing angle at each cell.

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Deciding finiteness of bosonic dynamics

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Determining the exact dynamics of a physical system is a central goal in most areas of physics, and is particularly important in quantum mechanics. A standard approach to systematically solving these dynamics is the Wei-Norman method, which factorizes the time-evolution operator into a finite product of exponentials [**W63**].

Recently, a new framework was proposed to identify classes of Hamiltonians for which this method is applicable by analyzing the dimensionality of the associated Hamiltonian Lie algebras through a suitable characterization of their generating terms [**B25**]. In our work, we extend the previous results to a broader and physically relevant class of bosonic Hamiltonians. In particular, we reduce the complexity of verifying finiteness conditions from quadratic to linear and introduce a visual algorithm that implements the corresponding procedure. Moreover, we identify a universal Lie-algebraic structure that encompasses all finite-dimensional algebras arising within this setting. These results constitute a significant step toward a comprehensive classification of Hamiltonian Lie algebras, with potential for practical applications in quantum technologies.

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Exploiting higher-order correlation functions for photon-statistics-based characterization and reconstruction of arbitrary Gaussian states

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Introduction Gaussian states are a cornerstone of quantum optics and continuous-variable quantum information, with applications ranging from quantum communication and sensing to photonic quantum computing [1,2]. While standard Gaussian-state tomography is formulated in terms of first and second moments, it typically relies on phase-sensitive measurements and does not by itself provide a direct consistency check of Gaussianity [3]. This presentation offers an alternative, photon-statistics-based perspective by analyzing the information content of second- and third-order intensity correlation functions. The key result is an explicit decomposition of arbitrary sixth-order moments of bosonic ladder operators for general Gaussian states, which enables to express third-order correlations entirely in terms of lower-order moments and thereby derive general relations between $g^{(2)}$ and $g^{(3)}$ [4].

Single-mode Gaussian states For single-mode states, these relations lead to a simple and experimentally accessible classification scheme based on correlation data alone. In particular, distinct functional dependencies between $g^{(2)}$ and $g^{(3)}$ emerge for nondisplaced and nonsqueezed Gaussian sectors, while more general displaced-squeezed states obey extended relations involving additional parameter combinations. Violations of these relations certify non-Gaussianity, whereas their fulfillment provides evidence for a Gaussian-state description and allows to distinguish between different sectors of the single-mode Gaussian state space. At the same time, the analysis shows a fundamental limitation: normalized correlation functions alone do not uniquely determine the underlying state parameters. In particular, displacement, squeezing strength, and thermal contributions cannot in general be reconstructed without additional assumptions, because the measured correlations are invariant under linear loss. This ambiguity is resolved by including a loss-sensitive observable such as the mean photon number or the vacuum overlap, which enables reconstruction of generic single-mode Gaussian states up to residual reflection symmetries [4].

Multimode Gaussian states The framework naturally extends to arbitrary multimode Gaussian states, where the structure becomes richer due to intermodal coherences and phase relations. In this case, the third-order correlations depend not only on $g^{(2)}$-type quantities, but also on first-order coherences between modes, which opens additional possibilities for hypothesis testing and state discrimination. The presentation will show how multimode Gaussian states can again be classified into nondisplaced, nonsqueezed, and displaced-squeezed sectors, and under which conditions they can be reconstructed experimentally by combining passive linear optics with intensity measurements or click statistics. Overall, the presented results establish higher-order correlation functions as a practical and loss-robust tool for Gaussian-state verification, while also clarifying the precise role of additional loss-sensitive information in achieving full state reconstruction without resorting to full homodyne tomography [4].

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Bayesian Machine Learning for Data-Driven Quantum State Decomposition in Non-Gaussian Optical States

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We present a Bayesian machine-learning framework for continuous-variable quantum state tomography of non-Gaussian optical states. Instead of reconstructing the full density matrix, we directly infer physically meaningful parameters from homodyne data using normalizing flow–based posterior estimation. By incorporating a physically motivated model of photon-added squeezed states with experimental imperfections, our approach enables data-driven state decomposition from experimental measurements. Bayesian inference provides not only parameter estimates but also uncertainty quantification and correlations, allowing us to assess how well the model explains the observed data.

Such data-driven decomposition is rarely performed directly on experimental quantum optical data, yet it offers a powerful route to link measurements with underlying physical processes. In particular, it reveals interpretable pathways of decoherence and state mixing, providing deeper insight into realistic experimental conditions beyond conventional reconstruction-based analysis.

We demonstrate the method on photon-added squeezed state data, showing that it captures key state features while offering enhanced interpretability. This highlights the potential of combining machine learning with physically informed Bayesian modeling as a practical diagnostic tool for experimental quantum optics.

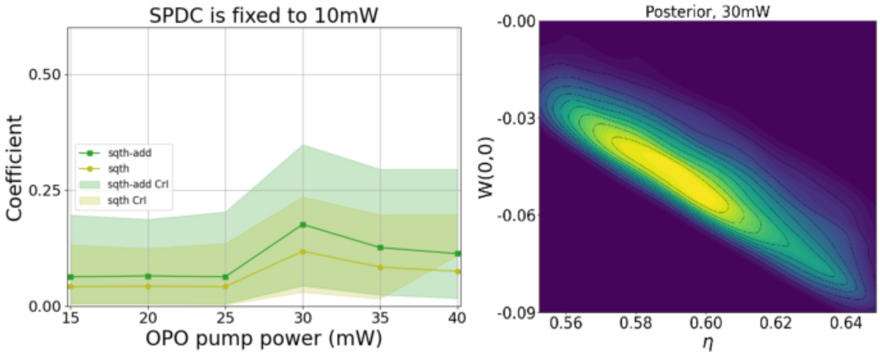

FIG. 1: Degradation and Correlation Analysis via Data-Driven State Decomposition

In Fig.1, Bayesian data-driven decomposition of a photon-added squeezed state, modeled as $\rho^{exp} \propto (1-\eta)\rho_{\mathrm{sq}}^{deg} + \eta, a^{\dagger}\rho_{\mathrm{sq}}^{deg} a$ with $\rho_{\mathrm{sq}}^{deg} = \sigma\rho_{sq}^{pure} + c\rho_{sq}^{th} + d\rho^{th}$. Left: Extracted squeezed-thermal contribution together with its photon-added component versus OPO pump power at fixed SPDC power, showing a pronounced increase around 30 mW due to degradation effects; shaded regions denote Bayesian credible intervals, enabling one-shot inference of decomposition weights directly from experimental data. Right: Joint posterior of $(\eta, W(0,0))$ exhibits broadened correlations and increased uncertainty, indicating loss-induced mixing that obscures the direct η–Wigner negativity relation. This demonstrates a model-based alternative to full state reconstruction, enabling direct, interpretable diagnosis of experimental imperfections.

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Time-domain field correlation measurements enable tomography of highly multimode quantum states of light

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Electro-optic sampling presents a powerful tool to sample the waveform of a free space mid-infrared pulse in the time domain by measuring the effect a nonlinear interaction of the sampled mid-infrared pulse has on an ultra-short near-infrared pulse. Recent experiments applied this technique to sample the electric field fluctuation of the squeezed vacuum on a subcycle scale. However, a full quantum tomography scheme in the time domain is still missing. Here we present a theoretical description of a (time local) quantum tomography scheme with subcycle resolution [1]. Furthermore, we demonstrate that some states exhibit (quantum) correlations in the time domain which limit the access to the full quantum state together with its dynamics. By extending the previously time local measurement to include temporal correlations our proposed tomography scheme is able to fully reconstruct a quantum state together with its dynamics, as long as the Wigner function of the state is Gaussian. We support our analysis by devising a notion of entanglement in the time domain based on a quantum information theoretical approach, which is experimentally verifiable by our proposed setup [2].

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Unitary transformation approach to the paraxial wave equation

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We present a framework for the paraxial wave equation based on propagation-dependent unitary transformations closely related to the Lewis-Ermakov invariant. This approach establishes a formal equivalence between free-space propagation and the dynamics in a quadratic gradient index (GRIN) medium. We show that the Gaussian modulation of physical beams induces an effective harmonic confinement, resulting in a non-removable non-commutativity between the dynamical invariant and the free-space Hamiltonian. This conceptual shift recasts free-space propagation as an intrinsic parametric oscillator problem, providing a rigorous and enabling bridge to map advanced quantum control protocols—such as Shortcuts to Adiabaticity—into spatial light engineering. Our formalism provides a unified description of mode families across various coordinate systems and enables the analytical study of complex phase dynamics and experimentally testable beam control protocols in free space.

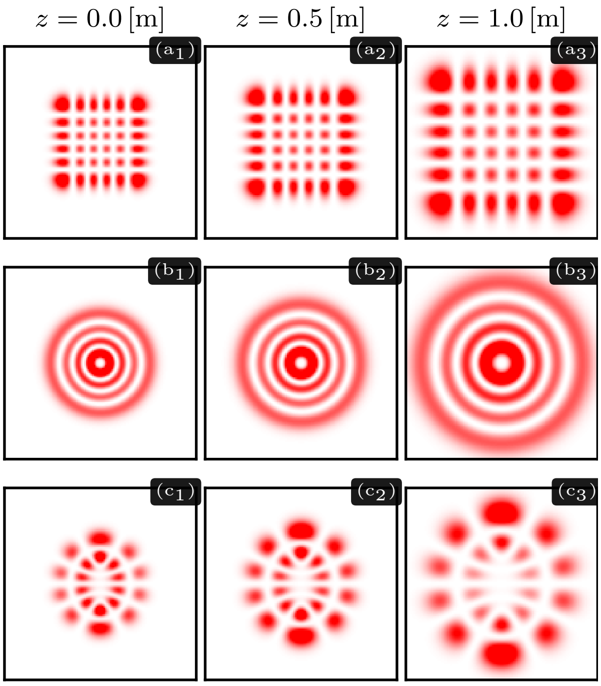

FIG. 1: Transverse intensity distributions of Hermite–Gauss, Laguerre–Gauss, and Ince–Gauss beams at different propagation distances z, computed using the operator formalism. The results reproduce the expected evolution of standard mode families for $\lambda = 633\,\mathrm{nm}$ and $W_0 \approx 200\,\mu\mathrm{m}$.

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Mode Optimisation to Reach the Geometric Limits of Fabry-Pérot Optical Cavity Performance

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Fabry-Pérot optical cavities are crucial components in many experiments and quantum technology applications as they can strongly couple quantum emitters and single photons and enhance emission into a specific directed output mode. The traditionally spherical cavity mirrors lead to Gaussian beam modes, but modern techniques can fabricate alternative mirror profiles to realise modes that transcend the limitations of Gaussian beams and reach the geometric limit of cavity performance.

We present a retroreflection-based method to find the optimum cavity mode and corresponding mirror profile in user-defined situations [1], and apply it to common experimental configurations. When coupling to a single central emitter (Fig 1 row I), e.g. for single photon extraction, the optimised mode has an unusually constant intensity on the mirror. This increases its NA compared to Gaussian beams with similar clipping loss, tightening its focus and leading to an approximately 3-fold improvement in cavity cooperativity across a range of geometries (Fig. Ib). For two emitters along the axis of the cavity (Fig 1 row II), e.g. for coherent intra-cavity interactions, the best Gaussian mode focusses once between the emitters, but the optimised mode greatly increases cooperativity by focussing separately on each emitter.

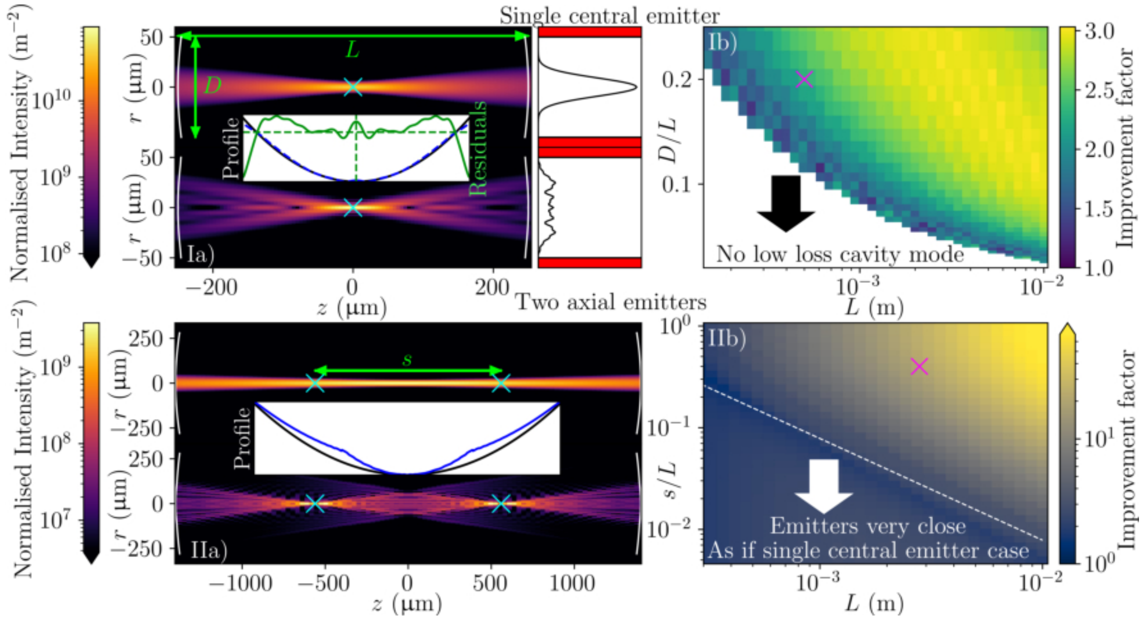

FIG. 1: Examples of cavity mode optimisation. All examples have resonant wavelength 854 nm and combined round-trip scattering and absorption losses of 20 ppm. Row I: Maximising single emitter cooperativity. a) The cavity mode, with cyan cross marking the emitter, for the best spherical mirror (top mode, black profile on inset) and optimised mirror shape (bottom mode, blue dashed profile on inset) with (right) the mode intensity on the mirror surface, where red regions represent clipping outside the mirror. b) Improvement in cooperativity due to optimisation. Row II: Maximising single-emitter cooperativity of two emitters on the cavity axis. a) Mode intensity and mirror profile. b) Improvement from using the optimised mode. For all data $D = 0.2L$. Above the white line, geometric arguments suggest the cavity can support modes that focus on both emitters separately. The purple cross in Ib (IIb) indicates the geometry in Ia (IIa).

Our optimisation approach indicates how spherical mirrors limit emitter-cavity coupling and provides optimum surface profiles as a starting point for practical designs [2]. The improvements, which for multi-focus applications exceed an order of magnitude, could significantly improve cavity performance in quantum optics experiments and quantum technology applications.

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Monogamy of simulated particle statistics in multi-photon systems

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When two identical particles interfere on a balanced beam splitter, bosons bunch while fermions antibunch. For partially distinguishable particles, this behavior can be simulated pairwise, but not independently: already for three particles, pairwise statistics obey a nontrivial monogamy relation [**1**].

We provide a complete characterization of these constraints for systems of n particles in the simplest nontrivial irreducible setting: the standard representation of the symmetric group, corresponding physically to $n-1$ identical particles and one distinguishable particle. We prove that a collection of pairwise indistinguishability parameters is physically realizable if and only if it defines a positive semidefinite Gram matrix. Equivalently, the pairwise anti-bunching probabilities can be interpreted as squared Euclidean distances in the sense of Schoenberg [**2**].

Mathematically, this yields an explicit description of the joint numerical range [**3**] of all pairwise swap operators as a spectrahedron defined by a single semidefinite constraint. This provides a simple and experimentally testable consistency condition for multi-photon interference: instead of verifying many inequalities, it suffices to check positivity of one matrix.

Our results lead to new bounds on partial indistinguishability in multi-photon systems [**4**, **5**] and enable certification of genuinely many-particle interference effects beyond few-particle tests.

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Connecting Time Crystals to Many-Body Protection

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Time crystals are phases of matter that spontaneously break the time-translational symmetry, and are characterized by time-periodic behavior that is robust against all types of fluctuations, even quantum noise [1]. They are temporal counterparts of ordinary spatial crystals, exhibiting analogous properties but in time. Since it is not yet clear if time crystals exist in equilibrium systems, attention has shifted to out-of-equilibrium situations, such as driven-dissipative systems. This has motivated the search for the so-called dissipative time crystals, where time-crystallinity emerges as a robust asymptotic state of the open-system dynamics.

Within this context, some people have proposed that small systems such as a single quantum Van der Pol oscillator can be a dissipative time crystal [2]. However, in this work, we prove that small systems like that are not robust against dephasing (a realistic source of noise in physical systems), and then we would not characterize them as time-crystalline phases of matter, but rather as mathematical analogs which nevertheless are still very interesting as toy models. In particular, we study numerically the dissipative gap, which should be zero for true time-crystalline order. In the absence of dephasing, we show in Figure 1(a) that the gap goes to zero as a power law in the number of excitations, while in its presence the gap saturates to a value close to the dephasing rate.

Following this, we then turn to extended many-body spin systems. First, we analyze a dissipative time-crystal model previously proposed in the literature consisting of collective damping and coherent driving [3, 4], complemented by local dephasing. Combining a mean-field analysis with numerical simulations, we find that, although this model exhibits oscillatory behavior in the absence of noise, the introduction of local dephasing opens a finite dissipative gap—Figure 1(b)—, indicating that the time-crystalline order is not robust. In contrast, when driving is replaced by local incoherent pumping and interactions [5], our analysis shows that the dissipative gap decreases following a power law in the system size, showing no saturation even in the presence of local dephasing—Figure 1(c)—.

Our ongoing results highlight the need to establish robustness against local noise as a defining criterion for dissipative time crystals. They further provide evidence that many-body physics is essential for stabilizing time-crystalline order.

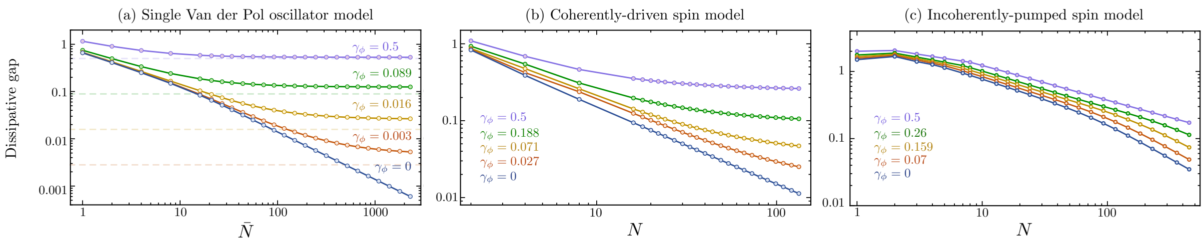

Figure 1. Dissipative gap as a function of the system size N for different dephasing rates γ_ϕ for the models considered in this work (in the first model the role of size is played by the oscillator's average number of excitations $\bar{N}$). In the absence of dephasing the gap closes for all models (blue, bottom line). The presence of dephasing causes the gap to saturate for the Van der Pol model (a) and a coherently-driven spin model (b), but not for a spin model with incoherent pumping (c), concluding that only this last model may be considered a robust dissipative time crystal.

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Quantum super-resolution imaging of incoherent emitters with the BLESS technique

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Abstract

The spatial resolution of a far-field imaging system is conventionally constrained by diffraction through the point spread function (PSF) of the optical setup. While fluorescence super-resolution methods such as STED and PALM/STORM overcome this limit by switching emitters in space or time, they may require demanding acquisition conditions and are not universally compatible with all classes of sources. A complementary route, motivated by quantum estimation theory, is to extract sub-diffraction information from appropriately engineered measurements on incoherent light.

It has previously been shown that PSF shaping can enable sub-diffraction resolution of two point sources, as demonstrated in the SPADE approach [1]. However, it was later established that this strategy is optimal only for balanced sources [2]. For incoherent emitters, by contrast, the brightness ratio can be inferred from photon-statistics measurements, in particular from the second-order correlation function $g^{(2)}$. In this contribution we present BLESS — Beam moduLation and Examination of Shot Statistics — for super-resolution imaging of non-interfering point emitters. By combining PSF shaping with photon-count statistics analysis, BLESS maps sub-Rayleigh spatial information onto experimentally accessible counting signals and is particularly advantageous when direct imaging becomes inefficient, especially for localization problems beyond the idealized case of balanced emitters [3].

We will discuss the application of BLESS to both single-photon and thermal sources, including experimental implementations based on NV-center single-photon emitters and on quasi-thermal light. These examples illustrate the versatility of the method across different photon-statistics regimes and its suitability for realistic localization tasks in which both source positions and brightnesses must be inferred simultaneously. Recent experimental results will be presented, demonstrating sub-diffraction localization of strongly unbalanced emitter pairs at separations on the order of one tenth of the Rayleigh limit, together with prospects for extending the method to multiple-source localization and quantum-enhanced optical metrology.

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Entanglement Enhanced Sensing with Qubits affected by non-Markovian Dephasing

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Entanglement has been proposed as a means to improve the sensitivity of sensing weak signals. While the degree of this quantum advantage is well understood in noiseless settings, the situation is more complex under realistic conditions, where the system is subject to decoherence. In this case, the enhancement depends on the specific noise characteristics. Previous treatments of colored noise have implicitly assumed the noise to be uncorrelated between successive experimental shots. Here, we consider the scenario in which the noise exhibits correlations across multiple shots. We derive a simple fundamental limit to the sensitivity based on the fact that the sensitivity cannot be better than the signal-to-noise ratio seen by the probe. Focusing on Ramsey spectroscopy with probes affected by pure classical dephasing, we show that, for suitable spatial and temporal noise correlations, entangled probes achieve a better scaling of the sensitivity with the number of probes than separable states. This demonstrates that entanglement can provide a substantial improvement for systems subject to realistic noise.

In the same setting, we further analyze the sensing bandwidth of entangled probes for estimating frequency components of time-dependent signals. In contrast to the sensitivity enhancement, this advantage is less dependent on the specific noise characteristics and persists even for uncorrelated noise. In particular, when the interrogation time is limited by the Nyquist frequency associated with the target bandwidth, rather than by decoherence of the system, entanglement reduces the average estimation uncertainty over a fixed bandwidth by a factor of $\sqrt{N}$ compared to separable probes.

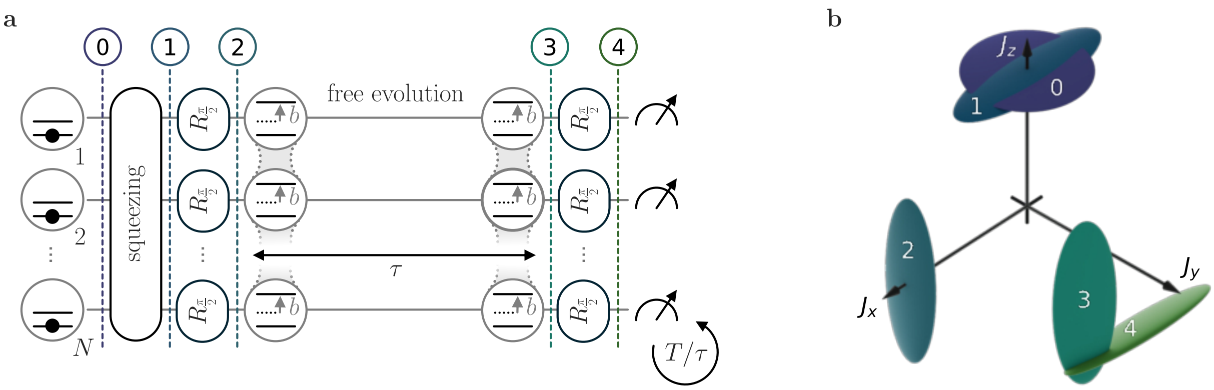

FIG. 1: (a) Ramsey spectroscopy with spin-squeezed states: an N-qubit ground state is squeezed, rotated by a $\pi/2$ pulse, evolves freely for time τ to accumulate a phase that is dependent on the static signal b, and is then rotated again and measured in the J_z basis. The sequence is repeated T/τ times, where T denotes the total interrogation time. (b) Bloch-sphere representation: squeezing reduces fluctuations along one axis. The $\pi/2$ pulses rotate the state around J_y, while free evolution induces a rotation around J_z. The uncertainty of the final measurement in the J_z basis is given by the width of ellipsoid 4 along the J_z direction. This illustrates how squeezing the initial state reduces shot noise, and thereby improves the precision of the phase estimation.

Metasurface Mediated Interaction and Entanglement between Quantum Emitters

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We present an integrated nanophotonic platform for engineering long-range interactions and entanglement between spatially separated solid-state quantum emitters (QEs) on a chip [1]. Our approach employs forward-designed dielectric metasurfaces to control the interference of surface plasmon polaritons launched by vertically oriented QEs on a metal–dielectric substrate. In particular, a phase-conjugated elliptic metasurface is designed to funnel electromagnetic energy efficiently between two QEs positioned at the two foci of an ellipse over micrometer-scale distance, thereby strongly enhancing their mutual coupling.

Using three-dimensional electromagnetic simulations combined with a Born–Markov master-equation framework, we theoretically investigate both energy transfer and quantum correlations in this architecture. We use 602nm wavelength for our calculations, corresponding to the emission wavelength of germanium vacancy centers in diamonds (GeV-NDs). The calculations predict pronounced localization of the normalized energy transfer rate at the target emitter position and show that the enhanced plasmon-mediated dissipative and coherent couplings give rise to substantial entanglement between distant emitters, as shown in FIG. 1. In the transient regime, the concurrence reaches ~ 0.45, presented in FIG. 1(c), where the theoretical maximum possible value is 0.5 for the single-excitation subspace. A steady-state entanglement of ~ 0.3 is also obtained for a range of pump powers under continuous incoherent pumping, as shown in FIG. 1(d). These results suggest that QEs coupled to metasurfaces designed with this approach is a promising route toward scalable, chip-integrated quantum photonic network. In addition to the theoretical and numerical results presented here, experimental results obtained with GeV-ND-based structures will also be presented at the workshop.

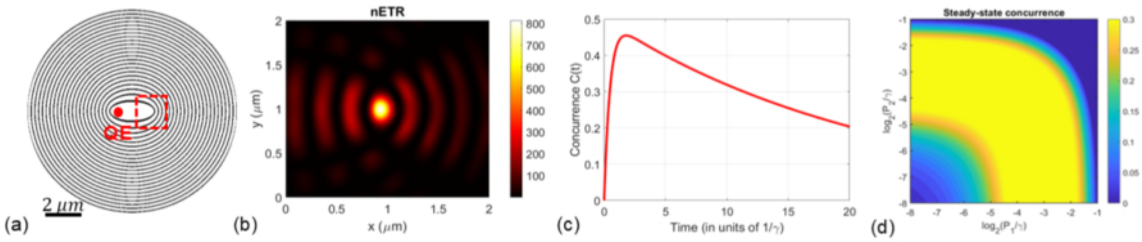

FIG. 1: **Forward-designed elliptic metasurface for plasmon-mediated coupling and entanglement between two QEs.** (a) Mask generated for the possible fabrication of elliptic ridge metasurface; the red dashed box indicates the area shown in panel (b). (b) Simulated normalized energy transfer rate (nETR) map near the target emitter position, showing strong localization of the transferred energy at the focal point. (c) Theoretically calculated transient concurrence $C(t)$ for two spatially separated emitters, exhibiting a maximum of ~ 0.45 in the single-excitation regime. (d) Steady-state concurrence under continuous incoherent pumping of both emitters, plotted as a function of the normalized pump rates P_1/γ and P_2/γ, where γ is the decay rate, assumed equal for both QEs.

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Calibrated generation of heralded one, two and three photons

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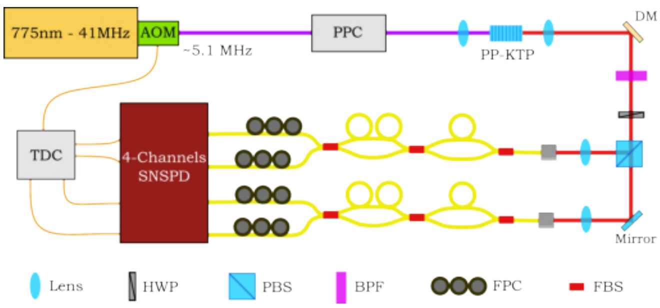
The optical number states form probably the most fundamental class of non-classical light. Until today, their generation and characterization remains challenging since the fragile quantum features easily vanish due to experimental imperfections. Nevertheless, the number states can potentially become very useful in quantum sensing applications like for example tomography of quantum objects and processes [1]. In the past, the process of parametric down-conversion (PDC), which creates twin beams denoted typically as signal and idler, has been employed in the heralded number-state generation [2]. Nevertheless, at low detection efficiencies the loss-tolerant reconstruction of the heralded states' photon statistics easily break up with the increasing photon number.

Here, we prepare optical number states up to three photons via pulsed waveguided PDC in the telecom wavelength range. Our source produces cross-polarized signal and idler beams, whose effective mode number is < 2 [3]. We start with a conventional characterization of the generated photon pairs. Via heralding on the detection of n events ($n = 1, 2, 3$) in idler we prepare heralded states in signal and extract several characteristics of the generated states just via counting singles and manifold coincidences.

Our results show that the heralded states exhibit mean photon numbers close to n. Furthermore, we extract values of their normalized correlation functions $g^{(m)}$ up to the order $m = n + 1$. Finally, we violate the criteria $g^{(m+1)} \geq g^{(m)} \geq 1$, which applies for classical states [4], to demonstrate the higher-order non-classicality of the two- and three-photon states. We emphasize that measuring the normalized factorial moments with orders higher than two is crucial for an accurate and precise classification of multiphoton states. We believe that our approach provides a fast, easy and resource saving method for quantum radiometry as well as enables a direct and loss-independent evaluation of the higher-order non-classicality.



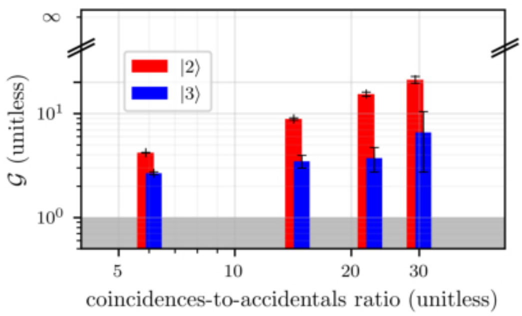


FIG. 1: (left) Experimental setup for preparing heralded states via waveguided PDC. (right) Ratio of the second- and third-order normalized moments $\mathcal{G} = g^{(2)}/g^{(3)}$ in terms of the coincidences-to-accidentals ratio of the underlying photon-pair creation process for the heralded two and three photons. Ideally, these take the values $\mathcal{G} \to \infty$ and $\mathcal{G} = 3$, respectively. The gray shaded area shows the classical region. Abbreviations: AOM = acusto-optical modulator; BPF = bandpass filter; DM = dicroic mirror; FPC= fiber-coupled polarization controller; FBS = fiber-coupled beam splitter ; HWP=half-wave plate; PBS = polarising beam splitter; PPC = power & polarization control; PP-KTP = periodically-poled $KTiOPO_4$ waveguide; SNSPD=superconducting nanowire single-photon detector; TDC = time-to-digital converter

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Resource efficient universal photonic processor based on time-multiplexed hybrid architecture

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Over the last years the field of photonic quantum information processing has taken strong leaps building on the scalability of optical systems. Experiments centered around Gaussian boson sampling (GBS) as one of the most promising platforms from the current noisy intermediate scale quantum era (NISQ) have involved record breaking numbers of photons and optical modes demonstrating quantum computational advantage [**1**]. At the heart of the GBS platform lies the photonic processor, a device capable of implementing arbitrary linear transformation matrices between a large number of optical modes. To date most universal photonic processors encode the underlying mode structure on a single degree of freedom (DoF). The most prevalent photonic processor architectures utilize the spatial DoF, demonstrating low loss and high fidelity operations, but come with a scaling problem in terms of mode numbers [**2**]. Using time-multiplexing, where the mode structure is encoded in time-bins, one can overcome this scaling problem and probe the system during its evolution. This allows for strong unitary characterization techniques as well as controlled interactions with the environment resulting in non-Hermitian dynamics. However as optical field feature a variety of different DoF, it is possible to encode the mode structure on multiple DoF resulting in a hybrid architecture. Here we put forward such a hybrid architecture that leverages both time-multiplexing and the multiple DoF of light to realize a universal photonic processor that is highly resource efficient and resilient against experimental imperfections.[**3**]

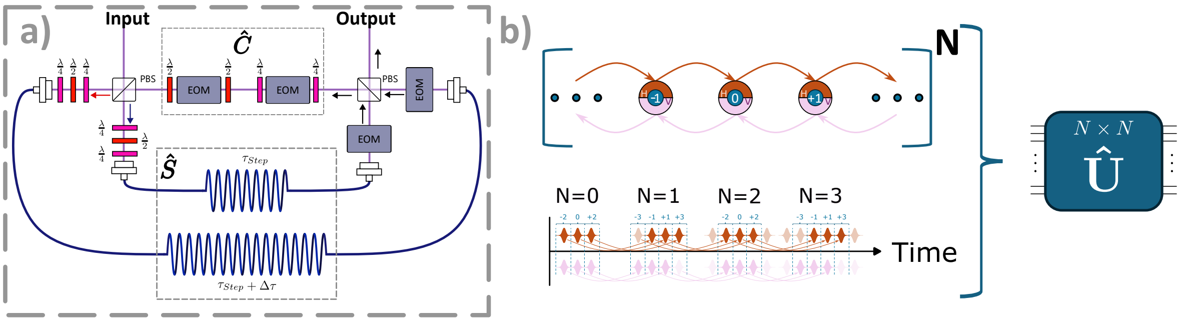

Figure 1: (a) Sketch of our hybrid architecture utilizing both the polarization and time DoF. (b) The underlying graph structure which after N repetitions represents any $N \times N$ target unitary $\hat{U}$.

Fundamentally, our hybrid architecture is based on discrete-time quantum walks (DTQW) consisting of a temporally encoded lattice (position DoF) with a polarization encoded internal DoF at each lattice point. Here we developed a protocol to translate arbitrary unitary transformations into repeating sequences of interference between the internal DoF at each lattice point and shifting between them. Based on this protocol, we provide analytical proof that our system is highly noise resilient. We further present recent experimental results characterizing the performance of our hybrid architecture implementing unitaries with up to 30 modes.

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Enhanced Phase Sensitivity in Displacement-Assisted SU(1,1) Interferometer via Photon Recycling

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We propose a novel method for enhancing phase estimation in the displacement-assisted SU(1,1) (DSU(1,1)) interferometer [1] by incorporating the photon recycling technique [2], evaluated under single-intensity detection (SID) and homodyne detection (HD) schemes. Our analysis revealed that utilizing the photon recycling technique, the photon-recycled DSU(1,1) interferometer outperforms the conventional DSU(1,1) interferometer under certain conditions. We also showed that this improvement is possible in both SID and HD schemes. In addition, to discuss the maximum sensitivity achieved by our proposed model, we have calculated the quantum Cramér-Rao bound (QCRB) within the framework and found that our proposed model approaches the QCRB. Therefore, since this modified scheme exhibits phase sensitivity and QCRB beyond the SNL, as well as beyond those in the case of a conventional DSU(1,1) interferometer, it offers a novel approach to increase phase sensitivity via photon recycling. This work is based on our recent publication [3].

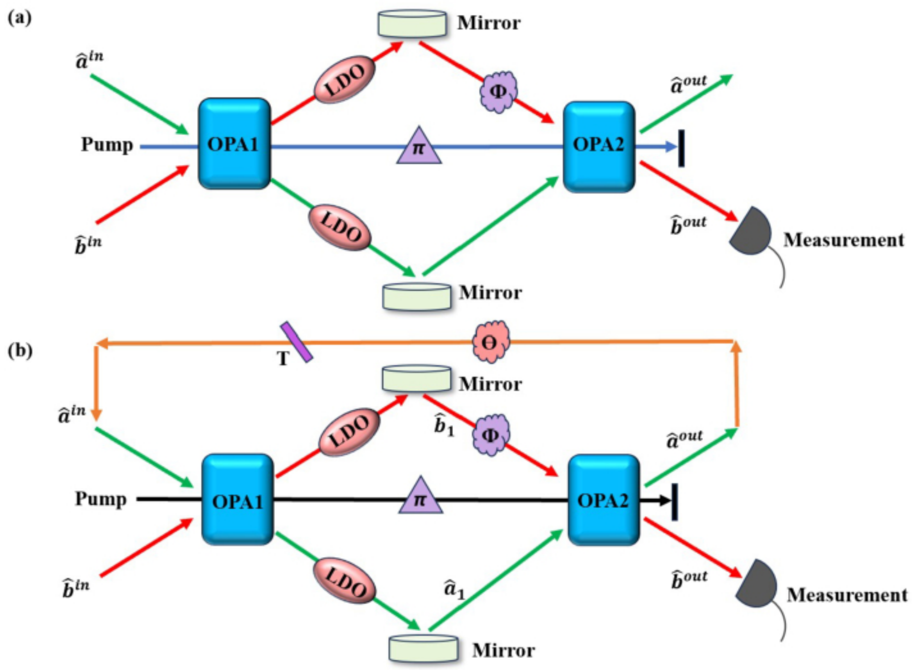

Figure 1: Scheme for phase estimation with photon recycling. (a) Conventional DSU(1,1) interferometer with output mode "a" discarded. (b) Photon-recycled DSU(1,1) interferometer where mode "a" is reinjected into the input after a phase shift θ and transmission T.

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Native linear-optical protocol for efficient multivariate trace estimation and indistinguishability characterization

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We present a native linear-optical protocol for efficiently estimating multivariate traces of quantum states of light, namely Bargmann invariants of the form $\mathrm{Tr}[\rho_1\rho_2\cdots\rho_M]$. These quantities are central in quantum mechanics because they capture basis-independent relational information among several quantum states and arise in diverse settings, including geometric phases, indistinguishability benchmarking, quantum kernel methods, and spectral estimation. While the two-state overlap can be accessed in photonics through the Hong–Ou–Mandel effect, and while the circuit-model cycle test provides an efficient method to estimate multivariate traces for qubit systems, no equally efficient and fully native linear-optical implementation had previously been available for general multimode, many-photon states. Here, we close this gap with a protocol implementable using near-term photonic hardware.

Beyond trace estimation, we derive generalized suppression laws for Fourier interferometers acting on multimode, multiphoton states. Suppression laws are a hallmark of multiparticle interference, identifying output events that are forbidden by symmetry. While such laws are well understood for indistinguishable single photons, we extend them to arbitrary bosonic states and show that violations of these suppression rules quantify deviations from cyclic symmetry of the input state. This establishes a direct connection between symmetry, interference, and relational quantum state information.

The method has several immediate applications. It provides an efficient route to quantum kernel estimation in photonic machine learning, where kernel values often reduce to state overlaps. It also enables spectral characterization of bosonic states via access to powers of the density operator, with implications for eigenvalue estimation and Rényi entropies. More broadly, the protocol enables the direct measurement of a variety of nonlinear functionals, including quantities related to geometric phase, quasiprobability distributions, weak values, and out-of-time-order correlators. Finally, it offers a practical tool for benchmarking partial indistinguishability in multiphoton experiments, including regimes relevant to boson sampling and related interference-based architectures. In particular, the protocol allows one to characterize an operationally meaningful notion of indistinguishability that extends beyond standard pairwise Hong-Ou-Mandel tests (which do not capture the full complexity of partially distinguishable multiparticle states), with resources comparable to such a scheme.

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Substrate effects on photon-pair generation in metasurface

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Most modern quantum light sources are based on spontaneous parametric down-conversion (SPDC) in bulk non-linear crystals, whose strict phase-matching requirements limit the possible two-photon states generable. Recent research has focused on generating quantum light via SPDC with metasurfaces [**1**], i.e. array of nanoresonators with sub-wavelength dimensions, that allows easier generation of complex quantum states with tailored properties. In this work the emission properties of SPDC photons generated by quantum metasurfaces are theoretically investigated, with a particular focus on the influence of substrate effects. A comprehensive simulation based on quasi-normal mode (QNM) decomposition [**2**] for metasurfaces is developed and used to analyse the directional properties, polarization and efficiency of entangled photon pair generation in various metasurface configurations, including the lithium niobate metasurface [**3**], as depicted in Fig. 1(A). The study reveals that photon generation efficiency is strongly affected by the substrate thickness L, as shown in Fig. 1(B). In particular variations in substrate thickness alter the spatial distribution of the pump field E_p, enhancing or diminishing its overlap with the resonant field E_r, changing the overall efficiency by up to 20 times.

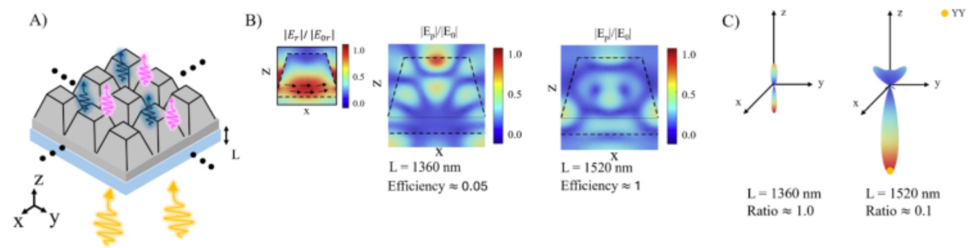

Figure 1: (A) Lithium niobate metasurface under investigation [**4**]. (B) Magnitude of the electric field for the resonant mode and pump field distribution for two different substrate thicknesses (C) Direction of the emitted photon pairs for two different substrate thickness and their polarization.

Furthermore, substrate thickness significantly influences the directionality of photon emission due to interference effects. As shown in Fig. 1 (C), the ratio of photon pairs emitted along the z-axis, either co-propagating with or opposing the pump beam, varies from 1.0 to 0.1 with changes in substrate thickness. Additionally the efficiency and the ratio change periodically as a function of the glass thickness and the ratio appears low when the efficiency is high, as shown in Fig. 1 (C). Moreover, the simulation reveals that pumping the metasurface from the substrate side enhances efficiency by up to a factor of 5 compared to pumping from the nanostructure side, in agreement with the experimental findings reported in [**3**]. This offers for the first time new insights and explanations for experimental measurements of this kind.

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Testing two cornerstones of quantum theory with multi-particle interference

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From the start, quantum mechanics has been questioned due to its counter-intuitive aspects. One example is the use of complex numbers, an essential building block of the theory, which was already criticised by Schrödinger. Another example is Born's rule, which relates detection probabilities to the modulus square of the wave function and was initially introduced only as a footnote in his seminal paper [Z. Physik 37, 863-867 (1926)].

In a double-slit experiment, quantum theory allows a single particle to interfere with itself. This quantum interference, however, is also constrained by so-called interference orders, which can be used to test the validity of quantum theory. Here, we introduce related multi-particle interference tests targeting two cornerstones of quantum mechanics:

- generalised Sorkin tests, which assess the order of interference and thus probe Born's rule [1,2] and
- generalised Peres tests probing the dimensionality of the number system of quantum mechanics [3].

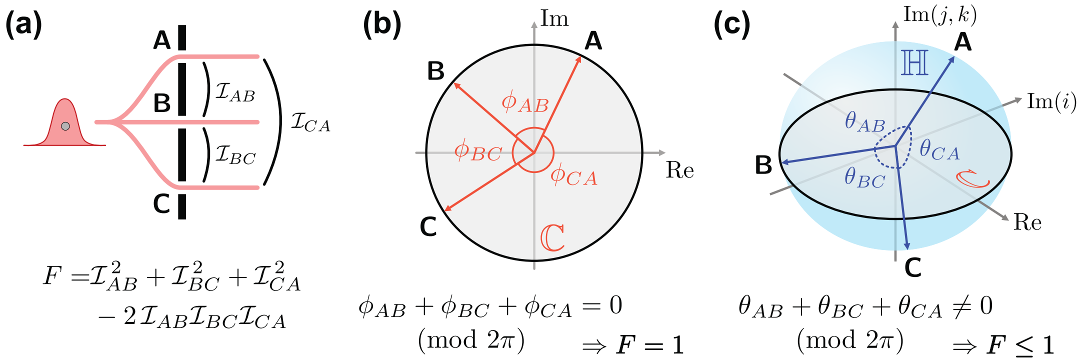

Figure 1: **Three-path interference test of complex numbers in quantum mechanics.** (a) Setup of a Peres test with three different paths A, B, and C for a single quantum object. Due to Born's rule, such a setup involves three second-order interferences $\mathcal{I}_{ij}$, which can be used to construct the Peres function F. (b) In quantum mechanics with complex numbers, the three phases associated to the three paths can be depicted in the unit circle with a closed phase relation leading to $F = 1$. (c) In quantum mechanics with quaternionic numbers, phases are three dimensional and the closed phase relation does not hold in general, leading to $F \leq 1$.

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Capacity of Multimode Quantum Gaussian Channels

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The development of multiple-input multiple-output (MIMO) systems, employing multiple transmitting and receiving antennas, has significantly increased link capacity in radio-frequency (RF) communications [1]. We translate this idea into quantum communication, where optical links are modeled as multimode Gaussian quantum channels. This is particularly relevant for modern communication systems, which exploit multiple spatial, temporal, and frequency degrees of freedom, leading to multimode channels that can be generally coupled and correlated. In contrast to the classical setting, quantum channels include environmental degrees of freedom and the symplectic structure of the global transformation, but allow for capacity improvements such as collective detection (Fig. 1(a)).

For passive optical Gaussian channels, we demonstrate a method for selecting an optimal mode basis for the input Gaussian state, which enables the decomposition of a multimode channel into a set of parallel single-mode channels [3] characterized by effective transmissivities and the corresponding additive noise. This decomposition allows us to maximize the Holevo information under an input energy constraint using a water-filling strategy analogous to that of [1], but with a modified water-filling condition reflecting quantum noise contributions [2].

Analogously to the classical RF MIMO case [1], we derive an analytical expression for the expected information capacity of a multimode Gaussian channel subject to random scattering. By representing the channel as a Bogoliubov transformation defined by a unitary matrix, we use results from random matrix theory before passing to a phase-space representation. This enables a parallel mode decomposition, where the expected capacity (Fig. 1(b)) is determined by the effective transmissivities, their density, and the input energy.

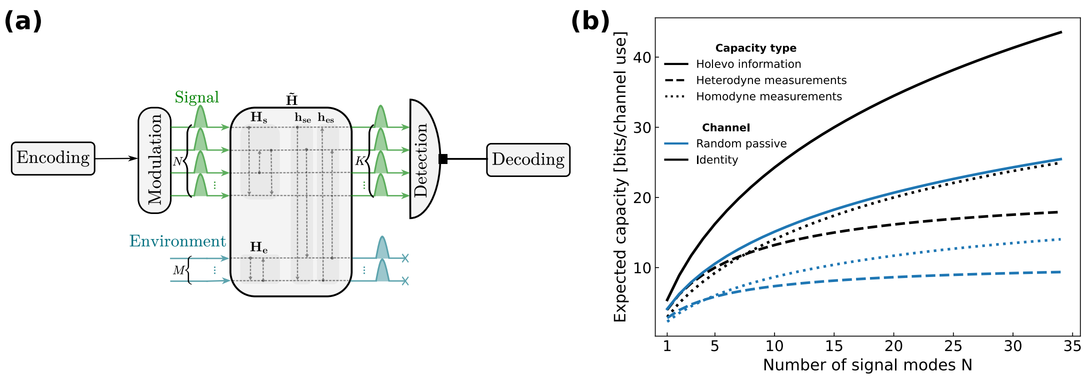

Figure 1: (a) Scheme of multimode communication. The system is decomposed into signal and environment subsystems. The symplectic transformation matrix $\tilde{H}$ is represented in block form, with off-diagonal blocks $\mathrm{h}_{\mathrm{se}}, \mathrm{h}_{\mathrm{es}}$ describing coupling between the subsystems. (b) Comparison of the expected information capacity for an ideal transmission channel (black) and a channel with random scattering (blue). The environment has the same dimension as the signal subsystem and is assumed to be in the vacuum state. In both cases, the input energy is distributed uniformly across modes.

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Entanglement-preserving Measurement of the Bell Parameter on a Single Entangled Pair

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In 1964, J. S. Bell introduced the Bell inequalities, transforming a philosophical debate into a physical experiment capable of revealing the true nature of correlations in physical systems. This development, in turn, opened several research directions, ranging from the foundations of quantum mechanics to quantum technologies. Over the past decades, the scientific community has extensively investigated Bell inequalities, ultimately achieving loophole-free tests. However, some challenges remain: for instance, the Heisenberg uncertainty principle and wavefunction collapse prevent performing all the measurements required to evaluate the full Bell parameter on the same quantum system using standard projective measurements.

To overcome these limitations, we demonstrate a method able to estimate the entire Bell parameter from each entangled pair while preserving entanglement, ensuring its availability for further applications. This method relies on weak measurements, a measurement procedure in which a tiny coupling between the observed system and the measurement device allows the estimating the observables of interest while preventing the state from collapsing. We exploit this property to measure multiple observables on the same quantum state, extracting all the correlations needed to evaluate the full Bell parameter from each pair (albeit with the large uncertainty which is the signature of weak measurements).

Our results[1] yield an average Bell parameter consistent with the Tsirelson bound and demonstrate a violation of the classical bound exceeding five standard deviations. Furthermore, we show how our procedure preserves the entanglement between the two photons, leaving it available for other purposes.

Our experiment provides new insights into understanding the foundations of quantum mechanics, such as the concept of counterfactual definiteness. Moreover, the entanglement certification leaves the quantum state nearly unaltered, making it readily usable for other quantum information protocols or foundational investigations, such as testing novel bounds that intertwine local and nonlocal correlations[2].

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Experimental deployment of a DM-CV-QKD transmitter on a moving plane for air-to-ground quantum communication

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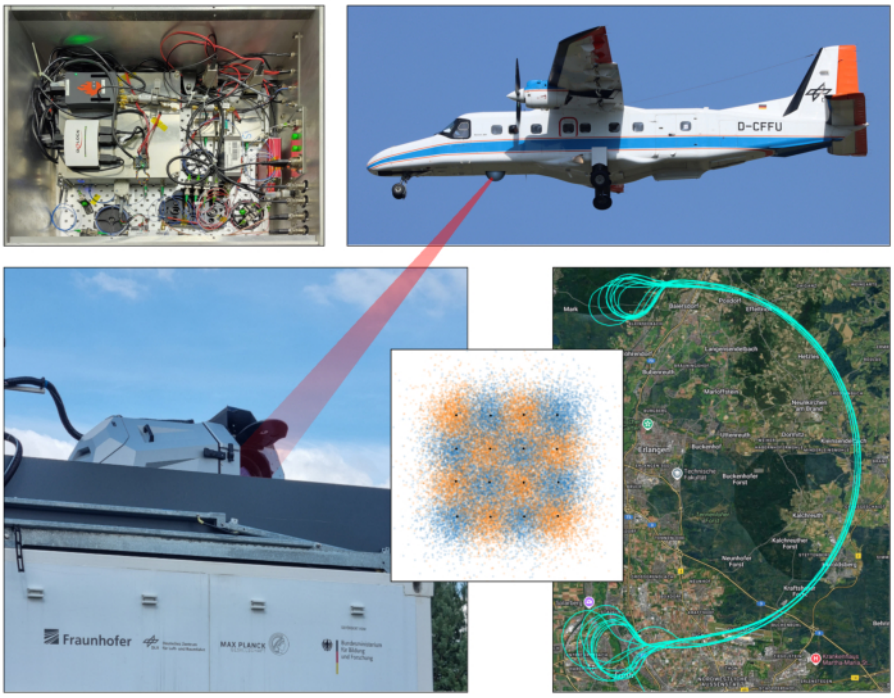
In case of natural disasters or deliberate sabotage, terrestrial communication lines may be disrupted. While challenging for all emergency communication efforts, this is particularly detrimental to secure networks relying on quantum key distribution over optical fiber links. In this scenario, mobile QKD nodes are a promising approach to quickly (re-)establish free-space connections between access nodes and mend gaps in the network topology. For the German QuNET initiative, we developed an optical QKD transmitter module and deployed it aboard a research aircraft of the German DLR. Under the restrictive conditions of a flying airplane, our transmitter is capable of producing discrete QAM modulations of coherent states suitable for continuous-variable QKD protocols. During two measurement campaigns in April and October 2025, we evaluated our systems's performance over a fluctuating air-to-ground free space link between the aircraft and an optical ground station operated by Fraunhofer IOF in Erlangen. We present experimental results from the exchange of shot-noise limited quantum states to characterize the highly dynamic channel and discuss the challenges of deploying a quantum optics experiment in such a weight- and power-constrained environment.



Impressions from the deployment of an airborne CV-QKD transmitter in Erlangen.

Brillouin-based Memory for Low Photon Numbers

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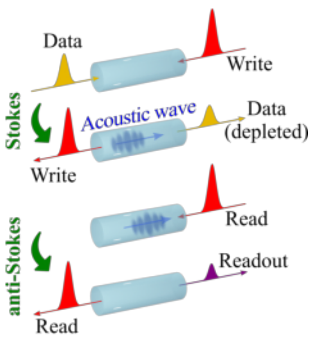
Storing optical signals is an import concept for rerouting and delaying information in communication networks. Many approaches with characteristica ranging from volatile to non-volatile, non-coherent to coherent and with varying storage times have been explored. Brillouin-based memory has already been shown to have many advantages for classical signal processing. It can store and retrieve coherent (amplitude and phase) information [2,3,5], can be operated down to 100 ps long pulses [3], operates at room and cryogenic temperatures [2,5] and allows for parallel processing since Brillouin-Mandelstam scattering is frequency, polarisation, spatial mode and orbital angular momentum selective [4,6]. We aim to bring this memory scheme to the quantum regime, storing coherent states with low photon numbers (Fig. 1b,1c) for applications in quantum signal processing and networks.

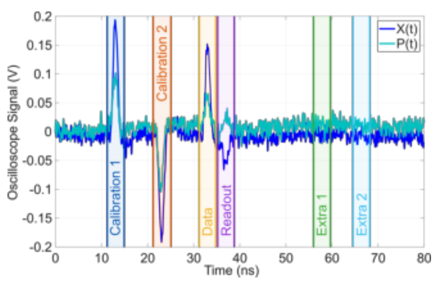
Stimulated Brillouin-Mandelstam scattering is a third order nonlinear effect between two optical waves and one acoustic wave [1]. The Brillouin-based memory scheme utilises both Stokes and anti-Stokes Brillouin-Mandelstam scattering to coherently store and retrieve optical data pulses via the slow moving acoustic wave (Fig. 1a).

Stokes scattering is used in the write process to transfer the optical data pulse into a slow moving acoustic wave. After the desired storage time, anti-Stokes scattering is used in the read process to transfer the information back into the optical domain as a readout pulse.

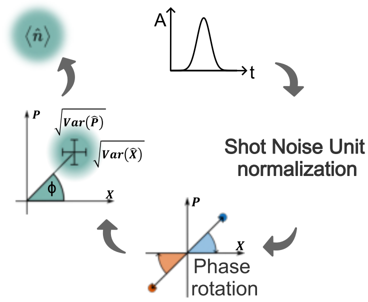
Both these processes occur in an optical fibre with a continuously tunable storage time. The maximum storage time depends on the lifetime of the acoustic wave. For highly nonlinear fibre at 4 K, the acoustic lifetime is around 40 ns and classical (high power) data pulses have been stored up to 140 ns [2,4].



(a) Brillouin-based memory scheme



(b) Raw data showing pulse window selection



(c) Post-processing scheme

Figure 1: (a) Data is stored in the slow moving sound wave during the 'write' process. After the desired storage time, the data is retrieved in the read process. (b) Signal from double homodyne detection is captured from the oscilloscope and then the relevant sections are selected. (c) The post-processing protocol takes the selected pulse windows, calibrates the phase with the calibration pulse phases, normalises to shot noise and finally calculates the photon number.

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Implementation of Unidirectional Modulation of Polarization-Squeezed States for an Experimental Free-Space Continuous-Variable Quantum Key Distribution Scheme

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Continuous-variable quantum key distribution (CV-QKD) represents a viable approach toward quantum-secure communication. The polarization degree of freedom offers an attractive platform for encoding quantum signals in free-space optical (FSO) links. In particular, the unidirectional modulation of polarization-squeezed optical states enables an experimentally accessible CV-QKD implementation with potential advantages regarding noise resilience and post-processing performance.

In this contribution, we outline our method for generating squeezed-light states serving as quantum signal sources and introduce the corresponding transmitter and receiver architectures employed for information exchange. We further present an experimental characterization of the electro-optic polarization encoding scheme, demonstrating the practical feasibility of quantum key distribution using our setup.

Cold-Atom Buoy: A Differential Magnetic Sensing Technique in Cold Quadrupole Traps

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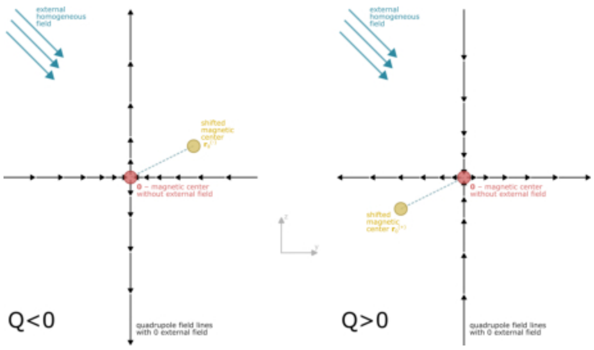
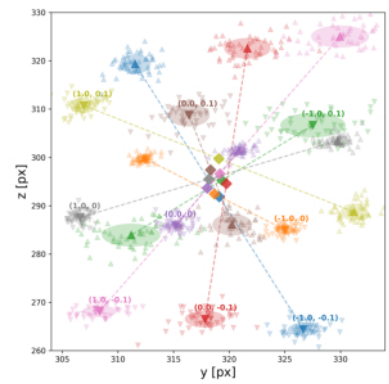
We present a novel differential technique for magnetic sensing and magnetic field compensation, which uses the symmetric displacement of a magnetically trapped ^{87}Rb atom cloud under reversed quadrupole polarities[1]. The presence of an external homogeneous magnetic field displaces the trap center by an amount proportional to the field. Using only absorption imaging, we determine the center-of-mass position of the ensemble in the magnetic trap for opposite quadrupole polarities, which invert the displacement caused by external fields. This procedure cancels common-mode effects such as gravity and weak magnetic-field inhomogeneities. Assuming micron-scale position resolution, the technique enables field resolution at the milli-Gauss level. It offers a practical tool for field compensation in magnetically sensitive experimental stages, bridging operational regimes from Earth-level fields to atomic magnetometry. Beyond this, extending to full three-dimensional sensing requires only minimal modifications to existing cold-atom infrastructure.



(a)



(b)

Figure 1: (a) Illustration of the cold-atom buoy concept, showing how an external homogeneous magnetic field induces a proportional displacement of the trap center that reverses with quadrupole polarity. (b) Demonstration of the buoy effect. Positions of a magnetically trapped atomic cloud for various applied bias-current pairs (I_y, I_z), with opposite quadrupole polarities producing symmetric displacements. The midpoint between the cloud centers identifies the zero-field magnetic center of the quadrupole trap, while the spread of positions reflects the standard deviations of the ensembles for each configuration.

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Spontaneous four-wave mixing in a second-order nonlinear thin film

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The last few years showed an increasing interest in generating photon pairs on micro- and nanoscale platforms such as thin films and metasurfaces [1]. Most of the works use spontaneous parametric down conversion (SPDC), where the second-order nonlinearity of the material is involved. An alternative way to generate photon pairs is spontaneous four-wave mixing (SFWM), mediated by third-order nonlinearity. However, works on photon pair generation through SFWM in ultrathin sources are very few [2–4] and they all use materials without second-order nonlinearity.

We demonstrate photon pair generation via SFWM in a 10 μm-thick lithium niobate (LN) crystal, a material known for its strong second-order nonlinearity. In such a source, photon pairs can be generated not only through SFWM but also via a cascaded process: second-harmonic generation (SHG) followed by SPDC. In a bulk material, with the phase-matching condition satisfied, the cascaded process typically dominates over SFWM. Due to the small thickness of our LN crystal, the phase-matching condition for SFWM is satisfied automatically over a broad spectral range. This, as we show, makes the direct process more efficient than the cascaded process, whose both stages are not phase matched in a 10 μm LN.

To detect entangled photons, we select two spectral bands on both sides of the pump wavelength (1030 nm): 10 nm around 770 nm for signal photons, and 50 nm around 1550 nm for idler photons. Fig. 1(a) shows the second-order correlation function $g^{(2)}$ measured versus the pump power P. The $g^{(2)}$ value exceeds 2 and decays with the pump power, indicating the detection of photon pairs.

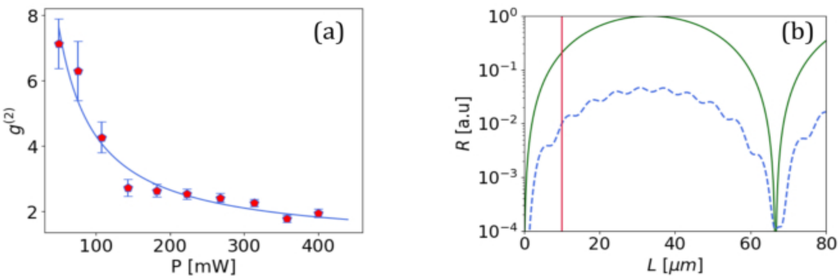

Fig. 1: (a) Second-order correlation function $g^{(2)}$ measured vs the pump power P. The solid blue line is a fit with $g^{(2)} = 1 + a/P$, giving $a = 3 \times 10^{-3}$. (b) Photon pair generation rate R for direct (solid green) and cascaded (dashed blue) processes calculated as a function of crystal length L. The vertical red line indicates our case ($L = 10$ μm).

To show that the observed pairs originate mainly from direct SFWM, we calculate the rate R of pair generation as a function of crystal length L (Fig. 1b) for both direct (green) and cascaded (dashed blue) processes. Both dependences have the same period, but their maximum values show a large difference because the nonlinear coherence length of SFWM (35 μm) is much larger than those of SHG and SPDC (about 3 μm, see the fast oscillations of R). At $L = 10$ μm (red vertical line), the contribution of photon pairs generated through the cascaded process is only 5 %. We have confirmed this result experimentally by separately measuring SHG pumped at 1030 nm and SPDC pumped at 515 nm in the same sample.

These results suggest the use of non-centrosymmetric thin films for SFWM. This will not only broaden the choice of nonlinear materials for SFWM, but also extend the toolbox of quantum state engineering at the nanoscale.

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Dissipation Dilution in 3D Direct Laser Written Mechanical Resonators

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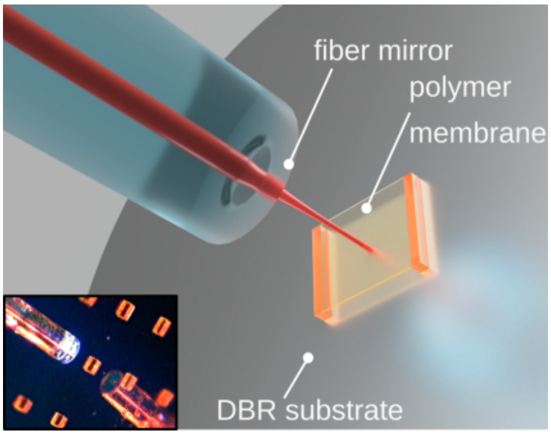
Optomechanical platforms that combine high-quality mechanical and optical resonators offer a broad range of applications from quantum-limited sensing to long-lived storage of quantum information [1]. While exceptionally high quality factors have been achieved with structures in thin layers of dielectric or semiconducting materials [2], their geometries are constrained by lithographic fabrication limitations. In contrast, recent developments in polymer-based 3D direct laser written structures provide the opportunity for manufacturing more structurally complex micromechanical designs. However, these systems are currently limited by significant mechanical dissipation [3].

This poster showcases our recent progress in implementing and improving this platform. The mechanical Q-factor of the resonator in vacuum is primarily limited by intrinsic losses within the material such as friction and thermoelastic damping. These loss channels can be substantially suppressed by introducing strain into the membrane, leading to so-called dissipation dilution. This is achieved through engineering of the resonator geometry with optimized aspect ratios, adjustment of fabrication parameters and post-processing techniques.

To quantify our results, we employ a scannable vacuum-integrated fiber cavity setup for probing mechanical resonators. We investigate the impact of shrinkage-induced strain on the mechanical Q-factor of polymeric bridge-like structures. Additionally, we report on current developments using post-fabrication oxygen-plasma treatment to further optimize the surface quality and aspect ratios.



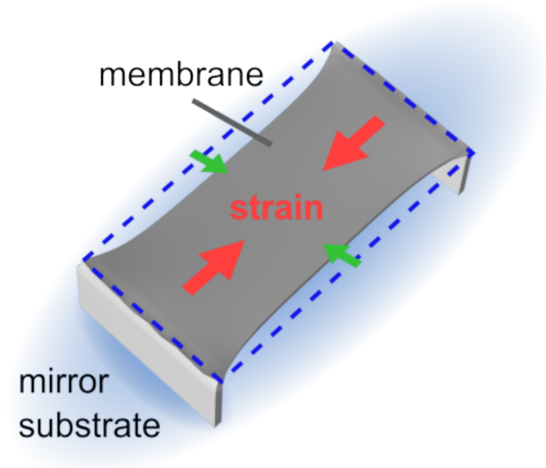


Figure 1: Schmematic of the fiber cavity probing setup with a polymer membrane in a membrane-in-the-middle configuration, with a recorded camera image shown as an inset (left). Schematic of strain in the membrane (right), where material shrinkage induces tensile strain due to the anchoring of the membrane to the mirror substrate through supporting structures.

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All-Optical Detection of Quadrature Entanglement

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Quantum technologies leverage entangled states as resources, with higher degrees of entanglement yielding greater advantages over classical systems. A non-degenerate optical parametric amplifier (NOPA) is a prominent source of such states, though their fragility makes characterisation sensitive to optical losses and detector inefficiency. This can be remedied via phase-sensitive amplification by a parametric amplifier. The process amplifies one quadrature while de-amplifying its conjugate, rendering the conjugate negligible and leaving the output intensity determined solely by the amplified quadrature [1]. After amplification, although optical losses scale the output intensity, the amplified quadrature is tolerant to losses.

In this work, we experimentally demonstrate the generation and phase-sensitive amplification of entangled Laguerre-Gaussian (LG) modes using a NOPA. Specifically, modes LG_p^{+l} and LG_p^{-l} exhibit quadrature entanglement, characterised by the Duan inseparability criterion: $D_{\pm l} \equiv \frac{1}{2}\left[Var(\hat{x}_{+l} - \hat{x}_{-l}) + Var(\hat{p}_{+l} + \hat{p}_{-l})\right] < 1$ [2]. Here, $\hat{x}_{\pm l}$ and $\hat{p}_{\pm l}$ are the position and momentum quadratures of the modes $LG_p^{\pm l}$, respectively. The p index of the LG mode is dropped for simplicity. The choice of quadrature that is amplified is controlled by the phase of amplification, such that at phase $\phi = \pi$, the NOPA amplifies the entangled quadratures. A spatial light modulator sorts the amplified modes, realising simultaneous multimode detection [3]. For each detected mode with intensity $I(\phi)$, the shot-noise level I_{SNL} is set by the intensity detected for vacuum input to the amplifier. The degree of entanglement is $D = I(\phi = \pi)/I_{SNL}$. It can be shown that, after amplification, D can be retrieved by detecting a single mode of the entangled pair. Fig. 1(a) shows $I(\phi = \pi)/I_{SNL}$ for the first-order LG modes when detecting LG_0^1 (purple), and LG_0^{-1} (yellow).

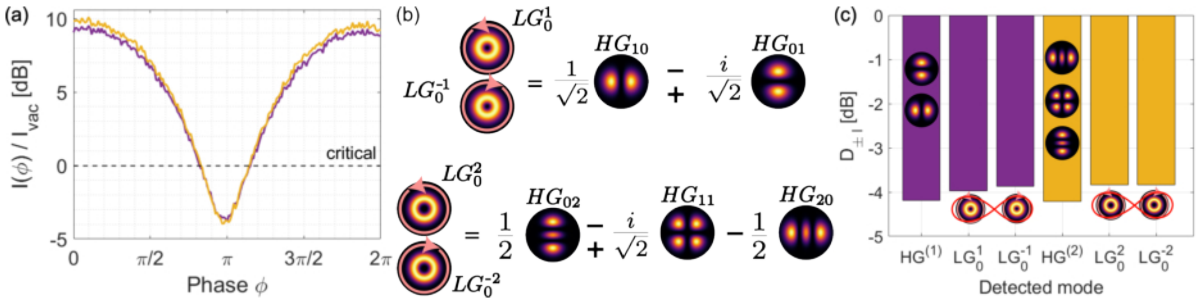

Figure 1: (a) Measurement of $I(\phi)/I_{SNL}$ for LG_0^1 (purple), and LG_0^{-1} (yellow). (b) Relation between first- and second-order LG and HG modes. (c) $D_{\pm l}$ measured for first- (purple) and second-order (yellow) modes from detection of $LG_0^{\pm 1}$ and $LG_0^{\pm 2}$ modes, and estimated from the squeezing of modes $HG_{10,01}$ (denoted $HG^{(1)}$) and of $HG_{20,11,02}$ (denoted $HG^{(2)}$).

Entanglement and squeezing are related through a basis transformation [4], therefore entanglement in LG modes implies squeezing in Hermite–Gaussian (HG) modes (Fig. 1(b)). We therefore compare the measured $D_{\pm l}$ from LG-mode detection with estimates obtained from squeezing in the corresponding HG modes. It can be shown that $D_{\pm 1} = 2\left[\mathrm{Var}(\hat{p}_{10}) + \mathrm{Var}(\hat{p}_{01})\right]$ and $D_{\pm 2} = \mathrm{Var}(\hat{p}_{20}) + 2\mathrm{Var}(\hat{p}_{11}) + \mathrm{Var}(\hat{p}_{02})$, where $\hat{p}_{mn}$ denotes the squeezed quadrature of the HG_{mn} mode. Figure 1(c) shows $D_{\pm 1} \approx -3.9 \pm 0.1$ dB and $D_{\pm 2} \approx -3.8 \pm 0.1$ dB, obtained despite detection losses exceeding 97%.

Since the NOPA amplifies multiple modes simultaneously, the scalability of this multimode detection scheme is limited only by the technique used to sort the spatial modes, enabling improvements in scenarios such as imaging and sensing with undetected photons and the characterisation of hyperentangled states.

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Spatially Multiplexed Multiphoton Sources Based on Stepwise Optimized Binary-Tree Multiplexers

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Reliable on-demand multiphoton sources are essential for many experiments in the fields of quantum information and quantum optics. There are several methods for preparing such sources, one of which involves the use of heralded photon sources. Such sources are based on nonlinear optical processes where photon pairs are generated. Detecting the expected output photon number by photon-number-resolving detectors in one of the modes heralds the presence of the same number of photons in the other mode. Unfortunately, the multiphoton probabilities that can be achieved with heralded multiphoton sources are low. Recently, it has been shown that multiplexing several heralded multiphoton sources can result in considerably higher multiphoton probabilities than those that can be achieved with a single heralded source [1]. The statistical theory developed for single-photon sources [2–6] can be used to optimize multiphoton sources, that is, to find the optimal values of the input mean photon numbers and the number of multiplexed units for which the probability of the output multiphoton state is maximal.

In this communication, we show that multiplexed multiphoton sources based on stepwise optimized binary tree multiplexers exhibit better performance for a wide range of the loss parameters of the system, that is, they give higher multiphoton probabilities than multiplexed multiphoton sources based on multiplexers implementing some rule-based building strategy. In the proposed sources the structure of the multiplexer is systematically optimized during its construction. In the course of constructing this type of multiplexer, the position of a binary photon router appended to the tree at each expansion step is determined by taking into account the current achievable multiphoton probability of the source. The method identifies the position at which this probability is maximal. We analyze the characteristics of multiplexed two-photon sources based on stepwise optimized binary-tree multiplexers in detail.

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Statistical properties of high-harmonic generation driven by bright squeezed vacuum

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Traditionally, high-harmonic generation (HHG) by non-classical fields has been considered challenging because driving the process requires high-intensity pulses of ultrashort duration [1]. However, bright squeezed vacuum (BSV) can now reach intensities sufficient for HHG [2]. The broad photon-number distribution of BSV strongly affects the statistics and power scaling of the generated harmonics. Unlike coherent driving, which inevitably risks cumulative material damage at high intensities, BSV's photon-number distribution provides a natural "sparse sampling". This drastically reduces the invasiveness of the interaction, allowing us to safely probe at intensities beyond typical classical damage thresholds.

In this work, we elevate this property into a powerful statistical sampling technique for solid-state HHG, using 25-fs BSV pulses at 1600 nm to drive a 300-nm thick lithium niobate sample. By performing simultaneous single-shot detection of the BSV pulse energy and the photon number of several emitted harmonics, we can characterize in parallel both their yields and statistical properties across the full range of driving intensities, bypassing the need for physical attenuation.

Recording the emission of harmonics with an sCMOS camera, we first reconstruct the power scaling, observing the 6th and 7th harmonics distinctly transitioning into the non-perturbative regime (Fig. 1(a)). We then evaluate the correlation characteristics, such as the normalized second-order auto-correlation functions for 4th and 5th harmonics and their cross-correlation function (Fig. 1(b)), at several energies of the pump. Crucially, we observe considerable bunching in the emitted harmonics at lower energies [3], significantly exceeding the values predicted by standard nonlinear propagation of the driving field fluctuations. Additionally, all the measured correlation functions exhibit bursts at specific pumping intensities (black dashed lines in Fig. 1(b)). These findings suggest that the harmonics' statistical properties cannot be explained solely by the nonlinear propagation of initial driving field fluctuations. Rather, additional macroscopic dynamics driven by the strong-field light - such as fluctuations arising from the formation of electron-hole pairs or Kerr nonlinearity - could govern these effects. Thus, our findings open new routes for exploring light-matter interaction in the strong-field regime and generate highly correlated photons in exotic spectral regions.

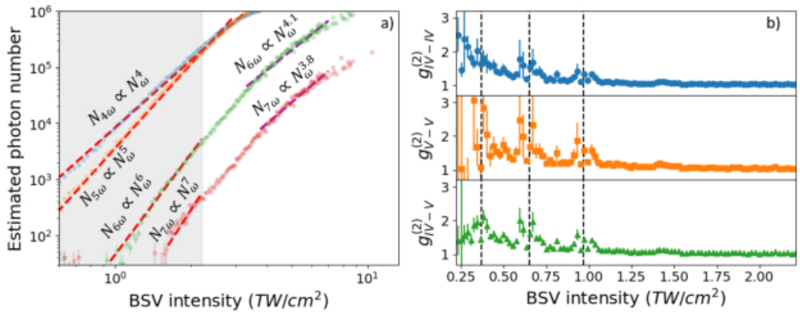

FIG. 1: (a) Power scaling of the 4th-7th harmonics emitted by a 300-nm thick lithium niobate sample. The grey shaded area corresponds to the region of interest for the statistical properties characterization; (b) Intensity dependence of the auto-correlation and cross-correlation functions between the 4th and the 5th harmonics. The black dashed lines correspond to the observed bursts at specific intensities.

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