# CEWQO 2024

A book of abstracts

# Table of contents

A list of invited talks, contributed talks and contributed posters presented during the CEWQO 2024 conference in Olomouc.

## Invited talks


- Measurement-induced beam splitter networks
  presented by **Andersen, Ulrik L.** on page 2
- Distributed Quantum Computing between Two Ion-Trap Nodes in a Quantum Network
  presented by **Araneda, Gabriel** on page 3
- Abnormal two-photon correlations in the interference of the light emitted by many independent atoms
  presented by **Bachelard, Romain** on page 4
- Back from deep space: quantum-enhanced communication with extremely weak optical signals
  presented by **Banaszek, Konrad** on page 5
- Manipulation of qudits encoded in Rydberg blockaded arrays of single atoms
  presented by **Bienaimé, Tom** on page 6
- Sufficient condition for universal quantum computation using bosonic circuits
  presented by **Calcluth, Cameron** on page 7
- From continuous-variable entropies to majorization relations in bosonic or fermionic phase space
  presented by **Cerf, Nicolas** on page 8
- Spontaneous parametric down-conversion in a liquid crystal
  presented by **Chekhova, Maria** on page 9
- Non-Hermitian collective optomechanical effects in nanoparticle tweezer arrays
  presented by **Delic, Uros** on page 10
- Optical quantum computers with quantum teleportation
  presented by **Furusawa, Akira** on page 11
- Trapped Rydberg ions
  presented by **Hennrich, Markus** on page 12
- Realising bosonic codes with trapped ions
  presented by **Home, Jonathan** on page 13
- Spin Squeezing for Ultracold Atoms in Optical Lattices
  presented by **Juzeliūnas, Gediminas** on page 14
- With dipole-dipole interactions towards Anderson localisation
  presented by **Kaiser, Robin** on page 15
- Toward quantum advantage with trapped ions
  presented by **Kim, Kihwan** on page 16
- Quantum sensors operated in real time
  presented by **Kolodynski, Jan** on page 17
- Quantum Nonlinear Thermodynamics:Thermal Noise as Quantum Resource
  presented by **Kurizki, Gershon** on page 18
- The tripartite multiphoton Jaynes-Cummings model: bosonic entanglement, spin coherence, and Wigner nonclassicalities
  presented by **Laha, Pradip** on page 19
- Tsang's superresolution methos in application to imaging
  presented by **Lvovsky, Alexander** on page 20

- Quantum communication from space and on ground
  presented by **Marquardt, Christoph** on page 21
- Photon-mediated entanglement in a mixed-species ion trap network
  presented by **Nadlinger, David P.** on page 22
- Quantum engineering of light with intracavity Rydberg superatoms
  presented by **Ourjoumtsev, Alexei** on page 23
- Frequency estimation by frequency boost
  presented by **Paris, Matteo** on page 24
- Quantum dot sources: efficiency, entanglement, and correlations
  presented by **Predojevic, Ana** on page 25
- Correlating photons using the collective nonlinear response of atoms weakly coupled to an optical mode
  presented by **Rauschenbeutel, Arno** on page 26
- 2D trapped ion quantum information processing
  presented by **Schindler, Philip** on page 27
- Highly Charged Ion Clocks to Test Fundamental Physics
  presented by **Schmidt, Piet O.** on page 28
- Creating Ensemble Data from Measurements on another Ensemble
  presented by **Schnabel, Roman** on page 29
- Optimal parameters estimation in optics and the example of source separation
  presented by **Treps, Nicolas** on page 30
- Spin-selective coherent light scattering from ion crystals
  presented by **Verde, Maurizio** on page 31


## Contributed talks


- Experimental qualification of a homodyne-like receiver for quantum-key-distribution protocols
  presented by **Allevi, Alessia** on page 33
- Implementing a programmable symmetric-asymmetric state switch in time-modulated non-Hermitian systems
  presented by **Arkhipov, Ievgen** on page 34
- Comprehensive analysis and quantum tomography of Silicon Photomultiplier Detectors for quantum technologies
  presented by **Bondani, Maria** on page 35
- Coherent feedback and internal squeezing in cavity-enhanced detectors
  presented by **Böttner, Niels** on page 36
- The Octo-Rail lattice: a four-dimensional cluster state design
  presented by **Budinger, Niklas** on page 37
- Non-Gaussian states in levitated nanoparticles to witness gravity-induced entanglement
  presented by **Chisholm, Diana** on page 38
- Hong-Ou-Mandel interference between two photons of different colours
  presented by **Chrzanowski, Helen** on page 39
- Engineering quantum states from a spatially structured quantum eraser
  presented by **D'Ambrosio, Vincenzo** on page 40
- Experimental preparation of multiphoton-added coherent states of light
  presented by **Jiří, Fadrný** on page 41

- Non-Gaussian Correlation in the steady state of a superradiant cloud
  presented by **Ferioli, Giovanni** on page 42
- Observation of vacuum Rabi splitting of a subradiant atom-cavity system
  presented by **Gábor, Bence** on page 43
- Quantum extreme learning machines and online quantum reservoir computing via shadow tomography
  presented by **Innocenti, Luca** on page 44
- Boson-fermion complementarity in a linear interferometer
  presented by **Jabbour, Michael G.** on page 45
- Continuous-variable quantum key distribution over multispan amplified links
  presented by **Jarzyna, Marcin** on page 46
- Optical parametric amplification for the detection of quantum states
  presented by **Kalash, Mahmoud** on page 47
- On-demand generation of propagating bosonic states from Superconducting circuits
  presented by **Khanahmadi, Maryam** on page 48
- Implementation of distributed quantum phase estimation with fewer photons than number of phases
  presented by **Kim, Dong-Hyun** on page 49
- Purifying Teleportation
  presented by **Korbicz, Jarek** on page 50
- New perspectives on alignment-based atomic magnetometry
  presented by **Koźbiał, Marcin** on page 51
- Wavevector-polarization correlation in entangled photons from radiative cascades
  presented by **Laneve, Alessandro** on page 52
- Nonlinear Squeezing in Classical and Quantum Mechanics
  presented by **Moore, Darren** on page 53
- Daemonic ergotropy in continuously monitored open quantum batteries
  presented by **Morrone, Daniele** on page 54
- Photonic quantum metrology with variational quantum optical non-linearities
  presented by **Muñoz de las Heras, Alberto** on page 55
- Classical algorithm for simulating experimental Gaussian boson sampling
  presented by **Oh, Changhun** on page 56
- Beating the standard quantum limit for binary phase-shift-keying discrimination with a realistic hybrid feed-forward receiver
  presented by **Olivares, Stefano** on page 57
- Work and heat exchange in quantum nonlinear interferometers
  presented by **Opatrný, Tomáš** on page 58
- Multiple quantum exceptional, diabolical, and hybrid points in multimode bosonic systems
  presented by **Peřina, Jan** on page 59
- Experimental generation of three-dimensional cluster entangled state
  presented by **Ra, Young-Sik** on page 60
- Superradiant bursts of light from cascaded quantum emitters: Experiment on photon-photon correlations
  presented by **Schneeweiss, Philipp** on page 61
- Storage and retrieval of quantum operations – an experimental test
  presented by **Sedlák, Michal** on page 62
- Coherence and statistics of light from large trapped-ion crystals
  presented by **Slodička, Lukáš** on page 63

- A variational toolbox for analog quantum simulators
  presented by **Tabares, Cristian** on page 64
- Evidence-based certification of quantum systems with relative belief
  presented by **Teo, Yong Siah** on page 65
- Photonic quantum networks reveal the nonlocal nature of noisy entangled states
  presented by **Villegas-Aguilar, Luis** on page 66
- Advantage of multi-partite entanglement for quantum cryptography over long and short ranged networks
  presented by **Walk, Nathan** on page 67
- Generation of spatial entanglement in semiconductor nonlinear waveguide arrays
  presented by **Zecchetto, Alessandro** on page 68


## Contributed posters


- Quantum non-Gaussian Coherence via Nonlinear Absorption of Quanta
  presented by **ADHIKARY, Kingshuk** on page 70
- Noisy atomic magnetometry with Kalman filtering and measurement-based feedback
  presented by **Amoros Binefa, Julia** on page 71
- Photonic Entanglement and Polarization Nonclassicality: Two Manifestations, One Nature
  presented by **Ares, Laura** on page 72
- Scaling of multicopy interference of Gaussian states for quantum applications
  presented by **Arnhem, Matthieu** on page 73
- Quantification of Quantum Correlations in Gaussian States Using Photon-Number Measurements
  presented by **Barasiński, Artur** on page 74
- Liouvillian exceptional points of non-Hermitian systems via quantum process tomography
  presented by **Bartkiewicz, Karol** on page 75
- Optical Protocol for Generating Squeezed Coherent State Superpositions
  presented by **Bazzazi, Elnaz** on page 76
- Fantastic squeezing and where to find it.
  presented by **Bräuer, Šimon** on page 77
- Characterization of a Homodyne-Like detection scheme for quantum communication protocols.
  presented by **Cassina, Silvia** on page 78
- Enhancing Discrete Time Crystal Lifetimes via Repeated Measurement Schemes
  presented by **Cenedese, Gabriele** on page 79
- Quantum second-harmonic generation in terms of elementary processes
  presented by **Chesi, Giovanni** on page 80
- Counterintuitive improvement of two-photon blockade by a cloud of emitters trapped in an optical cavity
  presented by **Chimczak, Grzegorz** on page 81
- Lossy Teleportation of the Finite Energy GKP state
  presented by **Cho, Sungjoo** on page 82
- Understanding noise in a bulk-ppKTP quantum frequency converter
  presented by **Chrzanowski, Helen** on page 83
- Collective phenomena and correlations in atomic systems
  presented by **Cidrim, André** on page 84
- Efficient inference of quantum system parameters by Approximate Bayesian Computation
  presented by **Clark, Lewis** on page 85

- Coherent Feedback Control of a Macroscopic Mechanical Oscillator
  presented by **Couto Corrêa Pinto Filho, Luiz** on page 86
- Two-photon absorption within the Wigner-Weisskopf approximation
  presented by **Dąbrowska, Anita** on page 87
- Conditional Measurements on a semi-lossy waveguide beam splitter around Exceptional Points
  presented by **Datta, Ananga Mohan** on page 88
- Deterministic Fock states in Brillouin optomechanics
  presented by **DATTA, Shaoni** on page 89
- To be confirmed
  presented by **Deside, Serge** on page 90
- Kalman Filters applied to atomic sensors
  presented by **Dilcher, Klaudia** on page 91
- Ground-state bistability of cold atoms in a cavity
  presented by **Dombi, András** on page 92
- POLAR QUANTUM SYSTEMS IN STRONG ELECTROMAGNETIC FIELDS
  presented by **Gładysz, Piotr** on page 93
- Practical performance of entanglement-based QKD
  presented by **GUMBERIDZE, Mariia** on page 94
- Completely characterizing multimode Gaussian quantum processes
  presented by **Gwak, Geunhee** on page 95
- Four-fold Hong-Ou-Mandel Interference from a Whispering Gallery Mode Resonator
  presented by **Huang, Sheng-Hsuan** on page 96
- Optical time-domain quantum state tomography and correlations on a subcycle scale
  presented by **Hubenschmid, Emanuel** on page 97
- Quantum-enhanced joint estimation of phase and phase diffusion
  presented by **Jayakumar, Jayanth** on page 98
- Non-Gaussian state teleportation with a nonlinear feedforward
  presented by **Kala, Vojtech** on page 99
- Towards an opto-spin-mechanical interface
  presented by **Olofsson, Anna** on page 100
- Robust generation of $N$-partite $N$-level singlet states by identical particle interferometry
  presented by **Karczewski, Marcin** on page 101
- Subdiffractional localization of photon emitters based on the target mode shaping and photon number distribution analysis
  presented by **Katamadze, Konstantin** on page 102
- Squeezing extraction from mixed multimode squeezed light
  presented by **Kopylov, Denis** on page 103
- Optical quantum illumination: can the benefit of entanglement survive a beam splitter?
  presented by **Kornienko, Vladimir** on page 104
- Reconciliation Methods for Optical Key Distribution
  presented by **Kucharczyk, Mateusz** on page 105
- Non-linear interferometry based on classical light
  presented by **Labonté, Laurent** on page 106
- Certification of level dynamics in single-photon emitters
  presented by **LACHMAN, Lukáš** on page 107

- The tripartite multiphoton Jaynes-Cummings model: bosonic entanglement, spin coherence, and Wigner nonclassicalities
presented by **Laha, Pradip** on page 108
- Towards tuneable “coupling efficiency” of a single atom using a pump-probe scheme
presented by **Lamich, Tomas** on page 109
- Optimization of quantum battery charging using steady-state
presented by **Lange, Ewelina** on page 110
- Proposed optical test of continuous-variable quantum contextuality
presented by **Liu, Zhenghao** on page 111
- To be confirmed
presented by **Lo Monaco, Gabriele** on page 112
- Greedy receiver for photon-efficient optical communication
presented by **Łukanowski, Karol** on page 113
- Advantages and limitations of wavelength-division-multiplexing QKD
presented by **Maiti, Indranil** on page 114
- Signatures and control of topological phases of interacting photons in a driven-dissipative non-linear cavity array
presented by **Maity, Arkajyoti** on page 115
- Projecting quantum nonlinearity to a linear system
presented by **MANUKHOVA, Alisa** on page 116
- Ultra-fast programmable pulse pattern generator for electro-optical light control in quantum optics experiments
presented by **Mazin, Glib** on page 117
- Strategies for entanglement distribution in optical fibre networks
presented by **McAleese, Hannah** on page 118
- Quantifying Nonclassicality of sub-Poissonian Optical Beams via Artificial Neural Networks
presented by **Michálek, Václav** on page 119
- Irreversibility and entropy production in two coupled bosonic modes interacting with a thermal environment
presented by **Mihaescu, Tatiana** on page 120
- Extremal points of the quantum set in the CHSH scenario: conjectured analytical solution
presented by **Mikos-Nuszkiewicz, Antoni** on page 121
- Distinction of electromagnetically induced transparency from Autler-Townes splitting using decaying dressed state formalism
presented by **Mishra, Abhay** on page 122
- Optimal quantum Fisher information in an unbalanced interferometer
presented by **Mishra, Karunesh K.** on page 123
- Precision angular rotation measurement: assessing the benefits of a parametric amplifier in an optical interferometer
presented by **Mishra, Karunesh K.** on page 124
- Unlocking Quantum Sensing Precision Through Dynamical Singularities
presented by **Naikoo, Javid** on page 125
- Robust quantum multiple-phase estimation beating classical limit in lossy environment
presented by **Namkung, Min** on page 126
- Enhancing continuous-variable quantum key distribution by state-discrimination receivers
presented by **Notarnicola, Michele Nicola** on page 127

- Paschen – Back Effect for Plasma Diagnostics
  presented by **Oganesyan, Koryun** on page 128
- Stimulated Magneto-Optics with Different Detunings for Plasma Local Diagnostics
  presented by **Oganesyan, Koryun** on page 129
- Efficient bosonic nonlinear phase gates
  presented by **PARK, Kimin** on page 130
- Enhanced bunching of nearly indistinguishable bosons
  presented by **Pioge, Léo** on page 131
- Picosecond laser pulses for quantum dot-microcavity based single photon generation by cascaded electro-optic modulation of a narrow-linewidth laser
  presented by **Poortvliet, Mio** on page 132
- Towards time-bin entangled photon cluster states
  presented by **Qodratipour, Siavash** on page 133
- Efficient estimation of harmonic generation in unresolved sideband regime
  presented by **RÁCZ, Eva** on page 134
- Quantum Non-Gaussian states of superfluid Helium vibrations
  presented by **RAKHUBOVSKIY, Andrey** on page 135
- Nonclassicality of Quantum Hypergraph States in Continuous Variables
  presented by **RAVIKUMAR, Abhijith** on page 136
- A central limit theorem for partially distinguishable particles
  presented by **Robbio, Marco** on page 137
- An Enhanced Method for Quantum Optical Coherence Tomography Employing the Michelson Interferometer
  presented by **Romanova, Anna** on page 138
- Homodyne and heterodyne OPA tomography
  presented by **RUPPERT, László** on page 139
- Stabilization of Quantum Emission to Atomic Transitions
  presented by **Said, Hala** on page 140
- Analysis of noise impact on Bell experiment between modes of light
  presented by **Sarbicki, Gniewomir** on page 141
- Metrology based on multimode nonlinear interferometers
  presented by **Scharwald, Dennis** on page 142
- Preemptive Error Suppression in Cat Codes
  presented by **Shringarpure, Saurabh U.** on page 143
- Generation and control of quantum coherence in single atom mechanics
  presented by **Singh, Kratveer** on page 144
- Phase estimation in SU(1,1) interferofermeter with feedback
  presented by **Singh, Shivani** on page 145
- Simulation methods for generation of optical GKP states
  presented by **Solodovnikova, Olga** on page 146
- Challenging the role of superluminal observers in explaining quantum superpositions
  presented by **Stempin, Jędrzej** on page 147
- Nonlocal correlations in CV
  presented by **Sudak, Nazarii** on page 148

- Quantum Non-Gaussianity and sensing with distilled Fock states of light
  presented by **GODAVARTHI, Phani Teja** on page 149
- Measurement of quantum entanglement and Bell nonlocality in two-bit states on quantum processors
  presented by **Tulewicz, Patrycja** on page 150
- Macroscopic distant magnon modes entanglement via a squeezed reservoir
  presented by **Ullah, Kamran** on page 151
- Optimization of two-photon absorption for three-level atom
  presented by **Valipour, Masood** on page 152
- Microwave-to-Optical conversion by cold atoms
  presented by **Varga, Daniel** on page 153
- The Synthesis: high precision sensing in quantum astrometry, super-resolution microscopy and beyond
  presented by **Vintskevich, Stephen** on page 154
- Topological Invariants in Discrete Time Quantum Walks
  presented by **Wójcik, Jan** on page 155

# Invited talks

We thank the invited speakers for their presentations.

# Measurement-induced beam splitter networks

Presented by **Andersen, Ulrik L.** from
*DTU Lyngby*

Optical quantum states can be processed using circuit-based or measurement-based approaches. Large-scale circuit-based processing requires deep circuits, leading to significant losses. In contrast, the measurement-based method uses shallow circuits and measurements to achieve large-scale processing. This presentation focuses on a measurement-induced beam splitter network with 400 input and output modes, implemented through a multi-mode CV entangled cluster state followed by homodyne detection. This approach minimizes losses associated with deep circuits and enhances optical quantum information processing, offering promising directions for future research and applications.

# Distributed Quantum Computing between Two Ion-Trap Nodes in a Quantum Network

Presented by **Araneda, Gabriel** from
*University of Oxford - Department of Physics*

in collaboration with

*Ainley, Ellis and Agrawal, Ayush and Drmota, Peter and Nadlinger, David and Nichol, Bethan and Srinivas, Raghu and Lucas, David*

No quantum computing platform has outlined a definitive path toward achieving the scalability needed to surpass classical computing in practical applications, known as quantum advantage. In classical computing, the ultimate performance is found in computer clusters—complex networks of interconnected machines operating together for task execution and data processing. These individual machines, referred to as 'nodes', are seamlessly linked through a network infrastructure and are typically located in close physical proximity. It is logical to adopt a similar strategy in constructing quantum computing clusters to attain the necessary scalability toward practical quantum advantage. Towards this vision, in this talk, I will present our recent experimental results on harnessing remote entanglement between two trapped-ion-based quantum processors, separated by meters, to execute deterministic distributed quantum computation tasks, including teleported gates and simple instances of distributed quantum algorithms.

# Abnormal two-photon correlations in the interference of the light emitted by many independent atoms

Presented by **Bachelard, Romain** from
*Universidade Federal de São Carlos*

Large systems of emitters radiate light with chaotic statistics, provided there is a phase randomization mechanism - spontaneous emission and its random nature is such an example. Differently, elastic scattering produces an interference pattern, so phase randomization in this case has to come from external mechanisms, such as collisions and Doppler broadening.

In this presentation, we discuss how the combination of spontaneous emission and elastic scattering can produce extraordinary light statistics, even in large systems of independent two-level emitters. More specifically, under weak coherent drive, strong antibunching and superbunching arise in the constructive and destructive interference directions, respectively. In other words, the two-photon correlations of the radiated light are anticorrelated with the intensity. These results pave the way toward the generation of strongly correlated photons by interference from quantum emitters.

# Back from deep space: quantum-enhanced communication with extremely weak optical signals

Presented by **Banaszek, Konrad** from
*University of Warsaw*

Deep-space missions face the challenge of transferring large volumes of data collected by onboard instruments back to Earth. Changing the communication band from rf to optical holds the promise of substantially increased data rates due to broadband modulation and lower signal propagation losses. Power limitations make the quantum nature of light play a central role in achieving efficient deep-space optical communications. This talk will review state-of-the-art in this area and present some ideas how quantum-inspired approaches may help in overcoming current limitations.

# Manipulation of qudits encoded in Rydberg blockaded arrays of single atoms

Presented by **Bienaimé, Tom** from
*University of Strasbourg*

Qudits are multidimensional quantum memories which hold great promises to enhance the capabilities of qubit-based quantum technologies, including potentially more efficient quantum algorithm and enhanced information encoding capabilities [1]. I will present a protocol to realize arbitrary state synthesis and unitary operations on a qudit encoded in the dressed states of a Rydberg blockaded array of single three-level atoms [2]. This system is in isomorphism with the Jaynes–Cummings model and acts as an artificial molecule where one can precisely control the structure of the energy levels by adjusting the parameters of the laser driving the upper transition. The control of the qudit state is realized by a pulse sequence of the laser coupling the ground and intermediate state of the atoms. The infidelities of the protocol for state preparation and arbitrary unitary gates including the influence of the lifetime of the Rydberg state are compatible with the state of the art. In the second part, I will report on the realization of an arbitrary waveform generator for light using a double pass acousto-optic modulator which enables on-demand high-fidelity amplitude and phase modulations down to light pulse duration of less than 100 ns in a compact rack-mountable setup [3]. This device is relevant to generate the pulse sequence of the control laser for manipulating the qudit. In addition, it has a broader scope of applications in the context realizing perform high-fidelity quantum gates on atomic qubits.

[1] Y. Wang, Z. Hu, B. C. Sanders, and S. Kais, Qudits and high-dimensional quantum computing, Frontiers in Physics 8, 589504 (2020). [2] A. Robert, S. Whitlock, and T. Bienaimé, State synthesis and arbitrary unitaries for qudits encoded in Rydberg blockaded arrays of single atoms, in preparation. [3] S. Yang, G. Masella, A. Bellahsene, V. Moeini, C. Li, T. Bienaimé, and S. Whitlock, Compact optical waveform generator with digital feedback for phase and amplitude controlled quantum operations, in preparation.

# Sufficient condition for universal quantum computation using bosonic circuits

Presented by **Calcluth, Cameron** from
*Chalmers University of Technology*

in collaboration with

*Reichel, Nicolas and Ferraro, Alessandro and Ferrini, Giulia*

Continuous-variable bosonic systems stand as prominent candidates for implementing quantum computational tasks. While various necessary criteria have been established to assess their resourcefulness, sufficient conditions have remained elusive. We address this gap by focusing on promoting circuits that are otherwise simulatable to computational universality. The class of simulatable, albeit non-Gaussian, circuits that we consider is composed of Gottesman-Kitaev-Preskill (GKP) states, Gaussian operations, and homodyne measurements. Based on these circuits, we first introduce a general framework for mapping a continuous-variable state into a qubit state. Subsequently, we cast existing maps into this framework, including the modular and stabilizer subsystem decompositions. By combining these findings with established results for discrete-variable systems, we formulate a sufficient condition for achieving universal quantum computation. Leveraging this, we evaluate the computational resourcefulness of a variety of states, including Gaussian states, finite-squeezing GKP states, and cat states. Furthermore, our framework reveals that both the stabilizer subsystem decomposition and the modular subsystem decomposition (of position-symmetric states) can be constructed in terms of simulatable operations. This establishes a robust resource-theoretical foundation for employing these techniques to evaluate the logical content of a generic continuous-variable state, which can be of independent interest.

# From continuous-variable entropies to majorization relations in bosonic or fermionic phase space

Presented by **Cerf, Nicolas** from
*Université Libre de Bruxelles, Centre for Quantum Information & Communication*

To be determined.

# Spontaneous parametric down-conversion in a liquid crystal

Presented by **Chekhova, Maria** from
*MPI for the Science of Light*

in collaboration with

*Sultanov, Vitaliy and Kavcic, Aljaz and Kokkinakis, Emmanouil and Sebastian, Nerea and Humar, Matjaz*

Spontaneous parametric down-conversion (SPDC) is the workhorse of quantum optics and photonic quantum technologies. It is used as a source of entangled photons, single photons, and squeezed light. SPDC is a second-order nonlinear process and requires materials without centre of symmetry, like crystals. SPDC in liquids or gases has never been observed up to now.

Recently synthesized ferroelectric nematic liquid crystals change this situation drastically. They combine considerable second-order nonlinear susceptibility with the strong response to electric field, typical for usual liquid crystals, and with fluidity, typical for all liquids [1]. In my talk I will show experiments where we generate entangled photons via SPDC in a ferroelectric nematic liquid crystal, switch the process on and off with external electric field, reconfigure the molecular orientations, and tune the polarization state of the photon pairs [2]. The efficiency of photon pair generation is comparable to the one for typical nonlinear crystals of the same length. Moreover, by creating a constant twist of the molecules orientation along the sample one can implement a new type of phase matching, more efficient and more flexible than periodic poling.

[1] C. L. Folcia, J. Ortega, R. Vidal, T. Sierra, J. Etxebarria, The ferroelectric nematic phase: an optimum liquid crystal candidate for nonlinear optics. Liquid Crystals, 49(6), 899–906 (2022).

[2] V. Sultanov, A. Kavčič, M. Kokkinakis, N. Sebastián, N. Osterman, M. V. Chekhova, M. Humar, Entangled photons from liquid crystals: a new paradigm of tunable quantum light sources. arXiv:2401.07362v2 [physics.optics]; Nature 2024 (accepted).

# Non-Hermitian collective optomechanical effects in nanoparticle tweezer arrays

Presented by **Delic, Uros** from
*University of Vienna*

Optical levitation of dielectric nanoparticles is a unique optomechanical platform that combines optical control techniques from atomic physics with the detection methods and size of solid-state objects. Enabled by the realization of motional quantum ground state cooling of a single levitated nanoparticle [1], the system has shown great promise for quantum metrology, sensing, and studies of non-equilibrium physics.

Recently, we pioneered tweezer arrays of levitated particles that interact through nonreciprocal "optical binding" forces [2]. In my talk, I will show how already two particles can be used for exploring interesting non-Hermitian dynamics, such as parity-time symmetry breaking and the emergence of collective mechanical lasing [3]. Furthermore, I will discuss how we can engineer arbitrary two-mode operations between the mechanical states of two particles. When placed within a newly built ultrahigh finesse optical cavity, this will allow us to study collective quantum optomechanical effects in the presence of nonreciprocal interactions for the first time.

[1] Science 367, 892 (2020) [2] Science 377, 987 (2022) [3] arXiv:2310.02610 (2023)

# Optical quantum computers with quantum teleportation

Presented by **Furusawa, Akira** from
*The University of Tokyo*

Akira Furusawa Department of Applied Physics, School of Engineering, The University of Tokyo RIKEN Center for quantum computing

We did the first experiment of unconditional quantum teleportation at Caltech in 1998 [1]. Then we did various related experiments like quantum teleportation network [2], teleportation of Schrödinger's cat state [3], and deterministic quantum teleportation of photonic qubits [4]. We invented the scheme of teleportation-based quantum computing in 2013 [5]. 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 beam splitters, and two optical delay lines [6]. For universal quantum computing with this scheme, we need a nonlinear measurement and we invented the efficient way [7]. We recently succeeded in the realization [8]. Our present goal is to build a super quantum computer with 100GHz clock frequency and hundred cores, which can solve any problems faster than conventional computers without efficient quantum algorithms like Shor's algorithm. Toward this goal we started to combine our optical quantum computer with 5G technologies [9]. For the realization of fault-tolerance with our optical quantum computers, we use Gottesman-Kitaev-Preskill (GKP) qubits. We recently succeeded in the generation [10]. We are building a real machine of optical quantum computer and will make it on the cloud this year. Then we will launch a start-up company OptQC at that timing.

1. A. Furusawa et al., Science 282, 706 (1998). 2. H. Yonezawa et al., Nature 431, 430 (2004). 3. N. Lee et al., Science 332, 330 (2011). 4. S. Takeda et al., Nature 500, 315 (2013). 5. S. Yokoyama et al., Nature Photonics 7, 982 (2013). 6. W. Asavanant et al., Science 366, 375 (2019). 7. K. Miyata et al., Phys. Rev. A 93, 022301 (2016). 8. A. Sakaguchi et al., Nature Communications 14, 3817 (2023). 9. A. Inoue et al., Appl. Phys. Lett. 122, 104001 (2023). 10. S. Konno et al., Science 383, 6680 (2024).

# Trapped Rydberg ions

Presented by **Hennrich, Markus** from
*Department of Physics, Stockholm University*

Trapped Rydberg ions are a novel approach for quantum information processing [1,2]. This idea joins the advanced quantum computing toolbox of trapped ions with strong dipolar interaction between Rydberg atoms. For trapped ions, this method can speed up entangling interactions and enables such fast operations in larger ion crystals.

In this presentation, I will first introduce the novel experimental platform of trapped Rydberg ions [2]. I will describe the specific physics involved when exciting ions into Rydberg states, the effects on the trapping potential due to the strong polarizability of Rydberg ions, and the controllable strong interaction between ion and motion. Moreover, I will summarize methods and results in speeding up trapped ion entanglement operations via the strong dipolar Rydberg interaction [3].

References

[1] M. Müller, L. Liang, I. Lesanovsky, and P. Zoller, Trapped Rydberg Ions: From Spin Chains to Fast Quantum Gates, New J. Phys. 10, 093009 (2008).

[2] A. Mokhberi, M. Hennrich, and F. Schmidt-Kaler, Trapped Rydberg Ions: A New Platform for Quantum Information Processing, in Advances In Atomic, Molecular, and Optical Physics, Vol. 69 (Elsevier, 2020), pp. 233–306.

[3] C. Zhang, F. Pokorny, W. Li, G. Higgins, A. Pöschl, I. Lesanovsky, and M. Hennrich, Submicrosecond Entangling Gate between Trapped Ions via Rydberg Interaction, Nature 580, 345 (2020)

# Realising bosonic codes with trapped ions

Presented by **Home, Jonathan** from
*ETH Zürich*

Trapped ion mechanical oscillators provide high coherence, with control performed using laser light by coupling to the electronic internal states. I will describe experiments in which we use this control to realize single and two-qubit operations on GKP qubits, in the linear Lamb-Dicke regime of coupling between internal and motional states. In theoretical work, we have found methods for working outside the Lamb-Dicke regime, in which the non-linear ion-motion interaction induced by the parametric laser drive allows to dissipatively pump into multi-qubit cat manifolds which can be considered for bosonic error correction. This work provides new insights into the physical implementation of such codes using non-linear resources, which are applicable to multiple experimental platforms.

# Spin Squeezing for Ultracold Atoms in Optical Lattices

Presented by **Juzeliūnas, Gediminas** from
*Vilnius University*

In the initial part of the talk there will be an overview on individual and collective spins, the states of the collective spin and squeezing of these states. We will also talk on different spin squeezing mechanism including one axis twisting (OAT) and two axis countertwisting (TACT) spin squeezing models [1]. Subsequently we discuss possibilities to produce spin squeezing for spinful atomic fermions in optical lattices. It is shown that by applying laser radiation one can simulate not only OAT but also TACT spin squeezing models, the latter TACT model providing better squeezing [2,3]. The spin squeezing generated in this way is mediated by spin waves playing a role of the intermediate states facilitating the squeezing process. Finally we will mention an ongoing research on producing non-classical spin states for an ensemble of atoms characterised by a larger spin, such as spin 9/2 for $^{87}Sr$ atoms [4]. The spin squeezing can be used for increasing sensitivity of atomic clocks. References: 1. L. Pezze, A. Smerzi, M. K. Oberthaler, R. Schmied, and P. Treutlein, Rev. Mod. Phys. **90**, 035005 (2018). 2. T. Hernández Yanes, M. Płodzień, M. Mackoit Sinkevičienė, G. Žlabys, G. Juzeliūnas, E. Witkowska, One- and Two-Axis Squeezing via Laser Coupling in an Atomic Fermi-Hubbard Model, Phys. Rev. Lett. **129**, 090403 (2022). 3. T. Hernández Yanes, G. Žlabys, M. Płodzień, D. Burba, M. Mackoit Sinkevičienė, E. Witkowska, G. Juzeliūnas, Spin squeezing in open Heisenberg spin chains, Phys. Rev. B **108**, 104301 (2023). 4. D. Burba, H. Dunikowski, M. Robert-de-Saint-Vincent, E. Witkowska, G. Juzeliūnas, Effective light-induced Hamiltonian for atoms with large nuclear spin, arXiv:2404.12429 (2024).

# With dipole-dipole interactions towards Anderson localisation

Presented by **Kaiser, Robin** from
*CNRS, Institut de Physique de Nice*

The quest for Anderson localization of light is at the center of many experimental and theoretical activities. Cold atoms have emerged as interesting quantum system to study coherent transport properties of light. Initial experiments have established that dilute samples with large optical thickness allow studying weak localization of light, which has been well described by a mesoscopic model. Recent experiments on light scattering with cold atoms have shown that Dicke super- or subradiance occurs in the same samples, a feature not captured by the traditional mesoscopic models. The use of a long range microscopic coupled dipole model allows to capture both the mesoscopic features of light scattering and Dicke super- and subradiance in the single photon limit. I will review experimental and theoretical state of the art on the possibility of Anderson localization of light by cold atoms.

# Toward quantum advantage with trapped ions

Presented by **Kim, Kihwan** from
*Tsinghua University*

In this talk, I will describe our major efforts to achieve quantum advantage using trapped ions. Within the Noisy Intermediate-Scale Quantum (NISQ) realm, an important milestone is showing quantum advantage - outperforming classical computers on specific problems. So far, boson sampling with photons and random circuit sampling with superconducting qubits have achieved this. Here, I present two paths we are exploring to reach similar quantum advantages with trapped ions.

First, we construct scalable phononic networks using the vibrational modes of trapped ions. We have realized a small-scale phonon sampler and shown this is an ideal testbed, since single phonons can be prepared and measured deterministically without loss - addressing key limitations of photonic systems [1].

Second, we have developed a trap capable of holding a 2D crystal of ions, demonstrating its equivalence to the standard linear ion chain for quantum simulation. Specifically, we achieved adiabatic ground state preparation for transverse Ising models with up to 10 ions [2]. We plan to scale up the number of ions to achieve quantum advantage. We will discuss the difficulties and our strategy for overcoming challenges towards this goal.

[1] Wentao Chen, et al., Nature Physics 19, 877 (2023).

[2] Mu Qiao, et al., Nature Physics, online (2024).

# Quantum sensors operated in real time

Presented by **Kolodynski, Jan** from
*University of Warsaw*

From gravitational-wave detectors to cryogenically cooled microresonators, quantum effects have been shown to enhance capabilities of various devices in sensing external perturbations. Although this fact has led to important breakthroughs in the field of quantum metrology, one often forgets that the vast majority of real-life applications require quantum sensors to track signals that vary over time—e.g., gravitational waves generated by black holes merging, or fluctuating magnetic fields generated by the human brain.

In my talk, I will summarise recent results obtained within my group, in which we combine the description of continuously monitored quantum sensors with methods of statistical inference, so that quantum effects can still be used to boost their sensitivity in "real time".

Firstly, I will focus on an optomechanical sensor operated in the non-linear regime, in order to show how the non-classical correlations of photons being emitted may then enhance the sensitivity after resorting to Bayesian inference, which however must be tailored for it to be efficient in the quantum setting.

Secondly, I will consider the setting of optically pumped atomic magnetometers, in which case I will demonstrate that it is enough to use less demanding methods of (Extended) Kalman Filtering and measurement-based feedback in order to maintain the quantum-enhanced sensitivity or, in other words, drive the atomic ensemble into a highly entangled (spin-squeezed) state tailored to efficiently track a fluctuating magnetic field.

# Quantum Nonlinear Thermodynamics:Thermal Noise as Quantum Resource

Presented by **Kurizki, Gershon** from
*Weizmann Institute of Science*

We introduce a paradigm change in quantum thermodynamics: Instead of employing heat baths in open systems for the operation of thermal machines and sensors, as has been done since Carnot, we demonstrate the possibility of their operation via nonlinear interactions between few thermal noise channels in closed systems. Unique heat engines, quantum sensors and microscopes can be based on this principle in nonlinear interferometers that are now coming of age. A "poor man's" substitute for nonlinearity can be quantum measurements, with similar effects. References to our work T. Opatrny et al., Sci. Adv. 9, 1070 (2023) DDB Rao et al. Nat. Commun. 13, 3727 (2022) S. Virzi et al. Phys. Rev. Lett. 129, 030401 (2022) S. Virzi et al. Phys. Rev. Appl. 21,034014 (2024) T. Opatrny, A. Misra and G. Kurizki, Phys. Rev. Lett. 127,040602 (2021); Phys. Rev. E, 054131 (2022) N. Meher et al. arXiv 2308.13267 , arXiv 2310.10081

# The tripartite multiphoton Jaynes-Cummings model: bosonic entanglement, spin coherence, and Wigner nonclassicalities


Presented by **Laha, Pradip** from
*Johannes Gutenberg University Mainz*

in collaboration with

*P. A., Yasir Amin and von Loock, Peter*



Harnessing entanglement and quantum coherence plays a central role in advancing quantum technologies. In quantum optical light-atom platforms, these two fundamental resources are often associated with a Jaynes-Cummings model description describing the coherent exchange of a photon between an optical resonator mode and a two-level spin. In a generic nonlinear spin-boson system, more photons and more modes will take part in the interactions. Here we consider such a generalization, the two-mode tripartite multiphoton Jaynes-Cummings (MPJC) model. We demostrate how entanglement and quantum coherence can be optimally generated and subsequently manipulated in experimentally accessible parameter regimes. A detailed comparative analysis of this model reveals that nonlinearities within the MPJC interactions produce genuinely non-Gaussian entanglement, devoid of Gaussian contributions, from noisy resources. More specifically, strong coherent sources may be replaced by weaker, incoherent ones, significantly reducing the resource overhead, though at the expense of reduced efficiency. At the same time, increasing the multiphoton order of the MPJC interactions expedites the entanglement generation process, thus rendering the whole generation scheme again more efficient and robust. We further explore the use of additional dispersive spin-boson interactions and Kerr nonlinearities in order to create spin coherence solely from incoherent sources and to enhance the quantum correlations, respectively. As for the latter, somewhat unexpectedly, there is not necessarily an increase in quantum correlations due to the augmented nonlinearity. Towards possible applications of the MPJC model, we show how to (i) engineer arbitrary NOON states with appropriately chosen experimental parameters, and (ii) achieve perfect transfer of photon number states between the oscillators. Furthermore, besides producing substantial enhancements in the initial value for higher photon number states of the oscillators, our analysis reveals that driven solely by the initial qubit energy, with both the oscillators initialized in the vacuum state, the nonlinear MPJC interaction yields nontrivial Wigner negativities in both the oscillators.

# Tsang's superresolution methos in application to imaging

Presented by **Lvovsky, Alexander** from
*University of Oxford - Department of Physics*

Although the diffraction limit on optical imaging resolution has been known for one and a half centuries and appeared unshakeable, a recent theoretical

breakthrough revealed that it can be beaten by decomposing the field in the image plane into an orthonormal basis of spatial modes (typically, Hermite-Gaussian) and measuring the amplitude or intensity of each basis component. From these measurements, the image can be reconstructed. This method, which we call Hermite-Gaussian imaging, enables us to not only achieve sub-diffraction precision, but also, in some cases, reach the ultimate resolution limits allowed by quantum mechanics.

# Quantum communication from space and on ground

Presented by **Marquardt, Christoph** from
*Friedrich-Alexander-Universität Erlangen-Nürnberg*

In recent years the use of quantum mechanics to enhance information processing has been studied both on a fundamental and on a technical level. From a general view this contains the ability to solve complex problems with quantum computers or to enhance the sensitivity in sensing.

Crucial in most of these tasks is the transfer of quantum states. Quantum communication is challenging as quantum states tend to decay when interacting with their environment. While enabling the connection of future quantum computers, quantum communication also offers novel methods in cryptography, that in contrast to currently deployed cryptographic algorithms can offer a quantification of security at its core.

I will present conceptual and experimental progress towards quantum-safe infrastructure on ground.Quantum communication from space enables world-wide longterm secure communication by using satellite-based quantum key distribution. At the same time it enables the possibility to study the propagation of quantum states under extreme conditions. I will highlight and explain both aspects and present current ongoing activities, including the first German quantum communication satellite „QUBE" to be launched in July this year.

# Photon-mediated entanglement in a mixed-species ion trap network

Presented by **Nadlinger, David P.** from
*University of Oxford - Department of Physics*

Modular hybrid quantum systems, where stationary matter qubits are linked using photonic interconnects, hold promise across a broad gamut of applications. Trapped atomic ions are well-suited as the stationary matter qubits in such an architecture, as they combine excellent coherence and high-fidelity local operations with a native optical interface. In our elementary network of two nodes, free-space emission from $^{88}Sr^{+}$ ions coupled into single-mode fibres is used to mediate entanglement generation; we achieve state-of-the-art performance with Bell state fidelities >96% at rates  100 $s^{-1}$. We co-trap $^{43}Ca^{+}$ ions in each node which act as memory qubits well-decoupled from any network activity, demonstrating remote Bell state coherence times >10 s. In this talk, I give an overview of how these capabilities enabled recent demonstrations across different domains: in exploring non-classical correlations in the context of quantum cryptography and non-local games, in client–server (blind) quantum computing, and in entanglement-enhanced optical frequency comparisons. Finally, with a view towards fundamental limits in the photonic entanglement generation between trapped emitters, I give a coherent account of the effect of spontaneous emission recoil and propose its correction.

# Quantum engineering of light with intracavity Rydberg superatoms

Presented by **Ourjoumtsev, Alexei** from
*College de France*

in collaboration with

*Magro, Valentin and Covolo, Antoine and Vaneecloo, Julien and Garcia, Sebastien*

I will describe our efforts towards using Rydberg superatoms coupled to an optical cavity as a platform for quantum engineering of light enabling strong photon-photon interactions. Using this system, we prepared Wigner-negative free-propagating states of light by mapping the internal state of an intracavity Rydberg superatom onto an optical qubit encoded as a superposition of 0 and 1 photons. This approach allows us to reach a 60% photon generation efficiency in a well-controlled spatio-temporal mode, while maintaining a strong photon antibunching. By changing the qubit rotation angle, we observe an evolution from quadrature squeezing to Wigner negativity. I will show that, like single-atom-based setups, this system can be accurately modeled from first principles, and I will present our recent progress towards increasing the number of manipulated qubits.

# Frequency estimation by frequency boost

Presented by **Paris, Matteo** from
*Physics Department, Università degli Studi di Milano*

To be determined.

# Quantum dot sources: efficiency, entanglement, and correlations

Presented by **Predojevic, Ana** from
*Stockholm University*

Single quantum dots are established emitters of single photons and entangled photon pairs. By means of resonant excitation they efficiently generate photon pairs that feature low multi-photon contribution and are suitable for entangling schemes such as polarization and time-bin entanglement. However, the achievable degree of entanglement and the source readiness to be deployed in quantum communication protocols depend on additional functionalities, including high collection efficiency of photons. I will present engineered photonic systems that allow for entangled photon pair sources to be more efficient. Also, the cascaded generation of photon pairs intrinsically contain temporal correlations, which negatively affect the ability of such sources to perform two-photon interference, hindering applications. I will show how such correlation interplays with decoherence and temporal postselection, and under which conditions the temporal postselection could improve the two-photon interference visibility. Our study identifies crucial parameters of the source and indicates the path towards achieving optimal performance.

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

Presented by **Rauschenbeutel, Arno** from
*Humboldt-Universität zu Berlin*

Typical schemes for generating correlated states of light require a highly nonlinear medium that is strongly coupled to an optical mode. However, unavoidable dissipative processes, which cause photon loss and blur nonlinear quantum effects, often impede such methods. In this talk, I will report on our experimental implementation of the opposite approach. Using a strongly dissipative, weakly coupled medium, we generate and study strongly correlated states of light. Specifically, we study the transmission of resonant light through an ensemble of non-interacting atoms that weakly couple to a guided optical mode. Dissipation removes uncorrelated photons while preferentially transmitting highly correlated photons, created through collectively enhanced nonlinear interactions. As a result, the transmitted light constitutes a strongly correlated many-body state of light, revealed in the second-order correlation function. The latter exhibits strong antibunching or bunching, depending on the optical depth of the atomic ensemble. The demonstrated mechanism opens a new avenue for generating nonclassical states of light and for exploring correlations of photons in non-equilibrium systems using a mix of nonlinear and dissipative processes.

# 2D trapped ion quantum information processing

Presented by **Schindler, Philip** from
*University of Innsbruck, Department of Experimental Physics*

We investigate scalable ion trap architectures for quantum computing, where independent ion registers are located in individual lattice sites (or potential wells) in a 2D array of RF traps. The individual ion strings are coupled via their dipole-dipole interaction. Full 2D connectivity is achieved by tuning the distance between adjacent potential wells along two orthogonal directions: One direction (axial) is achieved controlling DC voltages, and the other (radial) controlling RF fields. In this work we demonstrate the building blocks of such an architecture using two surface ion traps. With the first, we demonstrate DC shuttling-based well-to-well coupling rates up to 40 kHz, and phonon exchange between ion strings at the quantum level. With the second, we characterize transport of ions along the radial direction, and measure well-to-well coupling rates up to 15 kHz. These results provide an important insight into the implementation of fully controllable 2D ion trap lattices, and pave the way to the realization of 2D logical encoding of qubits.

# Highly Charged Ion Clocks to Test Fundamental Physics

Presented by **Schmidt, Piet O.** from
*Physikalisch-Technische Bundesanstalt and Leibniz Universität Hannover*

The extreme electronic properties of highly charged ions (HCI) render them highly sensitive probes for testing fundamental physical theories. The same properties reduce systematic frequency shifts, making HCI excellent optical clock candidates [1, 2, 3]. The technical challenges that hindered the development of such clocks have now all been overcome, starting with their extraction from a hot plasma and sympathetic cooling in a linear Paul trap [4], readout of their internal state via quantum logic spectroscopy [5], and finally the preparation of the HCI in the ground state of motion of the trap [6]. Here, we present the first operation of an atomic clock based on an HCI ($Ar^{13+}$ in our case) and a full evaluation of systematic frequency shifts [7]. The achieved uncertainty is almost eight orders of magnitude lower than any previous frequency measurements using HCI and comparable to other optical clocks. By comparing the isotope shift between $^{36}Ar^{13+}$ and $^{40}Ar^{13+}$ the theoretically predicted QED nuclear recoil effect could be confirmed. Finally, first results on the search for a 5$^{th}$ force based on isotope shift spectroscopy of $Ca^{+}/Ca^{14+}$ isotopes will be presented. This demonstrates the suitability of HCI as references for high-accuracy optical clocks and to probe for physics beyond the standard model. References [1] Kozlov, M. G. et al., Rev. Mod. Phys. 90, 045005 (2018). [2] Safronova, M. S. et al., Rev. Mod. Phys. 90, 025008 (2018). [3] Schiller, S., Phys. Rev. Lett. 98, 180801 (2007). [4] Schmöger, L. et al., Science 347, 1233–1236 (2015). [5] Micke, P. et al., Nature 578, 60–65 (2020). [6] King, S. A. et al., Phys. Rev. X 11, 041049 (2021). [7] King, S. A. et al., Nature 611, 43-47 (2022).

# Creating Ensemble Data from Measurements on another Ensemble

Presented by **Schnabel, Roman** from
*Universität Hamburg, Institute for Quantum Physics*

in collaboration with

*Grebien, Stephan and Fiurasek, Jaromir*

Measurements on an ensemble of identical states are used to obtain a complete characterisation of the state. Here I report on two experiments, which produced ensemble measurements data by measurements on another ensemble. Required were Q-function measurement data, i.e. simultaneous measurements of non-commuting observables, combined with probabilistic postprocessing. Ensemble data from a 2.8 dB squeezed state was post-processed into ensemble data from a 3.4 dB squeezed state [1]. Ensemble data from a Schrödinger cat-like state with $|\alpha|^2 \approx 1.2$ was post-processed into ensemble data from such a state with $|\alpha|^2 \approx 6.8$. Our concept will potentially support the realisation of continuous-variable optical quantum computers.

[1] S. Grebien, J. Göttsch, B. Hage, J. Fiurášek, R. Schnabel, Multistep Two-Copy Distillation of Squeezed States via Two-Photon Subtraction, Phys. Rev. Lett. 129, 273604 (2022).

# Optimal parameters estimation in optics and the example of source separation

Presented by **Treps, Nicolas** from
*Laboratoire Kastler Brossel, Sorbonne Université*

Resolution in imaging is bounded by measurement design, detectors sensitivity, light source noise and, ultimately, the quantum nature of light. Quantum metrology provides the framework to compute the ultimate precision limit on the estimation of any parameter encoded in a beam of light. In particular, the Cramér-Rao bound indicates the minimum variance of any unbiased estimator for a given measurement setting, and its quantum counterpart its optimisation over all measurements allowed by quantum mechanics. This limit is used has a benchmark to evaluate the performances of actual measurements. As a consequence, before considering any purely quantum effects, one has to ascertain saturation of the QCRB with classical sources. This is a key point that should become a strategy when optimising or proposing new imaging systems. After introducing these general concepts we will focus on cases where 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[1]. This is of relevance for most practical applications, such as phase estimation, imaging, microscopy, and remote sensing. Then we will take the example of the quantum-metrology-inspired approach for estimating the separation between two incoherent sources. We will show experimentally how spatial mode decomposition allows for ultra-sensitive estimation [2]. We will finally study the use of optimal estimators based on the second moment of the measured data and how it can be a practical way to proceed towards multi parameter estimation[3].

[1] M. Gessner, N. Treps, C. Fabre, OPTICA 10, 996 (2023).

[2] C. Rouvière, D. Barral, A. Grateau, I. Karuseichyk, G. Sorelli, M. Walschaers, and N. Treps, OPTICA 11, 166 (2024).

[3] G. Sorelli, M. Gessner, M. Walschaers, and N. Treps, Phys. Rev. Lett. 127, 123604 (2021).

# Spin-selective coherent light scattering from ion crystals

Presented by **Verde, Maurizio** from
*Johannes Gutenberg Universität Mainz*

in collaboration with

*Schmidt-Kaler, Ferdinand and von Zanthier, Joachim and Schmiegelow, Christian T. and Schaefer, Ansgar and Zenz, Benjamin and Shehata, Zyad and Richter, Stefan.*

We study collective light scattering from linear crystals with up to twelve $^{40}Ca^{+}$ ions, acting as coherent single photon emitters. Light-scattering is induced by two-photon laser excitation, starting from the $S_{1/2}$ to $D_{5/2}$ quadrupole transition at 729 nm in combination with laser excitation of the $D_{5/2}$ to $P_{3/2}$ dipole transition at 854 nm, followed by a decay back to $S_{1/2}$ via a single photon emission near 393 nm. The scattered intensity is recorded in the far field, featuring the interference of emitted light fields of the entire crystal. We optimize the interference's visibility of coherent scattering by the chosen laser beam geometry and sub-Doppler cooling of the crystal. Furthermore, we demonstrate spin-dependent coherent scattering and unveil the time evolution of a previously encoded spin texture in a crystal employing the recorded dynamics of the spatial frequency components of the fringe pattern [1]. This might be in future of interest to read out correlation patterns of qubits as the results of a quantum computation or quantum simulation run.

[1] https://arxiv.org/abs/2404.12513

# Contributed talks

We thank the authors of contributed talks for their presentations.

There are 36 contributed talks to be presented during the conference.

# Experimental qualification of a homodyne-like receiver for quantum-key-distribution protocols

Presented by **Allevi, Alessia** from
*Department of Science and High Technology, University of Insubria, Como (Italy)*

in collaboration with

*Cassina, Silvia and Sanvito, Alberto and Lamperti, Marco and Notarnicola, Michele N. and Bondani, Maria and Olivares, Stefano*

Binary-phase-shift-keyed (BPSK) communication protocols represent one of the basic strategies to transmit information between two parties that want to share a secret key. The easiest way to implement these protocols is based on the use of two coherent states with the same energy but a $\pi$-phase difference. Indeed, such states are more robust against loss than nonclassical states. Being coherent states non orthogonal, according to quantum mechanics their perfect discrimination is not allowed. To deal with this issue, over the years different solutions to reach the minimum error probability in the discrimination process, usually called Helstrom bound, have been investigated. Most of the strategies developed so far are based on the use of single-photon detectors that allow on-off detection. Differently from these, in the continuous-variable regime, it has been demonstrated that homodyne detection approaches the Helstrom bound in the regime of large noise. Some years ago, some of us have demonstrated that a valid alternative to homodyne detection is given by a hybrid scheme, usually called homodyne-like (HL) detection [1]. As the standard homodyne detection, HL is based on an interferometric scheme, in which photon-number-resolving (PNR) detectors are used instead of the typically-employed photodiodes, and a mesoscopic local oscillator, with an energy comparable to that of the coherent states to be sent, is employed instead of a macroscopic one. We have shown that this scheme is quasi optimal in the case of BPSK communication protocols with coherent states affected by uniform phase noise. In this work, we propose a HL scheme based on the use of a commercial class of PNR detectors operated at room temperature. Indeed, we employ a pair of Silicon photomultipliers, since they are compact and characterized by a good dynamic range. In more detail, we investigate the possibility to use our scheme in communication protocols by evaluating the mutual information of our system as a function of some parameters, such as the loss affecting the employed signal states [2]. In fact, the mutual information can be used to evaluate the capacity of the transmission channel, and also to calculate the secret key rate between the sender and the receiver. At the same time, we explore the behavior of the error probability, which is complementary to that of the mutual information. Based on the results obtained in this preliminary stage, we prove that the employed HL receiver can be used in a proof-of-principle quantum-key-distribution protocol based on a binary alphabet to obtain a reliable secret key rate even in the presence of either individual or collective attacks by an eavesdropper [3]. The experimental results are compared to both numerical simulations and theoretical expectations. The good agreement among them suggests the further exploitation of the HL scheme in more complex structures.

Bibliography [1] S. Olivares et al., New J. Phys. 21, 103045 (2019). [2] A. Sanvito et al., manuscript in preparation. [3] M. Cattaneo et al., Phys. Rev. A 98, 012333 (2018).

# Implementing a programmable symmetric-asymmetric state switch in time-modulated non-Hermitian systems

Presented by **Arkhipov, Ievgen** from
*Palacký University*

in collaboration with

*Minganti, Fabrizio and Miranowicz, Adam and Özdemir, Şahin K. and Nori, Franco*

Nontrivial spectral properties of non-Hermitian systems can lead to intriguing effects with no counterparts in Hermitian systems. For instance, in a two-mode photonic system, by dynamically winding around an exceptional point (EP) a controlled asymmetric-symmetric mode switching can be realized. That is, the system can either end up in one of its eigenstates, regardless of the initial eigenmode, or it can switch between the two states on demand, by simply controlling the winding direction. However, for multimode systems with higher-order EPs or multiple low-order EPs, the situation can be more involved, and the ability to control asymmetric-symmetric mode switching can be impeded, due to the breakdown of adiabaticity. In this contribution, we demonstrate that this difficulty can be overcome if one dynamically winds around exceptional curves by additionally crossing diabolic points in multimode non-Hermitian systems [1]. Moreover, contrary to previous beliefs, we show that adiabatic state transfer can be restored in time-modulated non-Hermitian systems by properly choosing the orbiting trajectory in a system parameter space [2]. This allows to prevent the occurrence of uncontrolled non-adiabatic transitions during state evolution, thus facilitating the practical realization of a pure symmetric state flip in a system, akin to the adiabatic rapid passage in Hermitian systems. These findings hold promises to advance the field of light manipulation protocols in both classical and quantum domains.

[1] I. Arkhipov et al., Nat. Commun. 14, 2076 (2023). [2]. I. Arkhipov et al., arXiv:2402.15298 (2024)

# Comprehensive analysis and quantum tomography of Silicon Photomultiplier Detectors for quantum technologies

Presented by **Bondani, Maria** from
*National Research Council-Institute for Photonics and Nanotechnologies (CNR-IFN)*

in collaboration with

*Allevi, Alessia and Cassina, Silvia and Parola, Alberto*

In pursuing the advancement of optical implementation in quantum technologies, the development of compact and versatile light sources and detectors is a crucial goal. Silicon photomultiplier detectors (SiPM) can play a significant role in applications where photon number resolution is mandatory. SiPMs consist of an array of pixels operating in the Geiger-Müller regime and connected so that the output signal is proportional to the number of fired elements. Despite their performance as photon number detectors, SiPMs encounter difficulties due to operational non-idealities such as non-unity quantum efficiency, dark counts, optical cross-talk, afterpulses and pile-up, which complicate the direct correlation between output signals and incident photons. Recent advances have demonstrated the ability of SiPMs to characterize the statistics of light, explore entanglement phenomena and enable various quantum information applications. However, to realize their full potential, these imperfections must be addressed and mitigated. A comprehensive analysis of SiPM detectors was therefore undertaken, with the aim of elucidating their behavior through quantum tomography techniques. This approach provides a detailed description of the actual device, facilitating the identification and understanding of the underlying limitations. The analysis includes an in-depth investigation of SiPM detector performance under different operating conditions. Using quantum tomography methodologies, a detailed characterization of the detector response to incident photons was obtained, including the quantification of non-idealities such as dark counts, optical cross-talk and afterpulses. In addition, efforts were directed towards the development of strategies to mitigate the identified limitations, with a focus on reducing cross talk.

# Coherent feedback and internal squeezing in cavity-enhanced detectors

Presented by **Böttner, Niels** from
*University of Hamburg*

in collaboration with

*Bentley, Joe and Schnabel, Roman and Korobko, Mikhail*

Quantum noise is one of the main limitations of the sensitivity in quantum metrology. Over the past decades, several approaches such as improving the sensitivity with optical cavities or squeezing the quantum uncertainty of light have been invented. However, the downside of optical cavities is a reduced detection bandwidth. In some detectors, this can be a problem since it limits the access to certain frequency regimes. Here, we propose a purely optical approach that utilizes coupled optical cavities and a squeeze operation inside one of the optical cavities. The internal squeezed light compensates for the reduction of the detector bandwidth. On top of that, the coupled optical cavity structure realizes coherent feedback for the internal squeezing. The coherent feedback allows to modify the quantum state of a detector without using any additional measurements. We demonstrate the effects of the coherent feedback and internal squeezing in application to gravitational-wave detectors. We show an enhanced sensitivity that can be tailored to a specific frequency range. Our approach promises new level of flexibility in designing interferometers as well as other force sensors.

# The Octo-Rail lattice: a four-dimensional cluster state design


Presented by **Budinger, Niklas** from
*Johannes-Gutenberg Universität, Mainz*

in collaboration with

*Østergaard, Emil E.B. and Larsen, Mikkel V. and van Loock, Peter and Neergaard-Nielsen, Jonas and Andersen, Ulrik L.*



Macronode cluster states are a natural candidate to implement fault-tolerant continuous-variable quantum computation in the optical context. They achieve universality with built-in error correction by combining gate teleportation via homodyne detection with the Gottesman-Kitaev-Preskill code. Out of the different macronode designs, the two-dimensional Quad-Rail lattice was shown to exhibit favorable properties regarding flexibility and noise. However, it lacks the dimensionality to run topological error correction codes needed to achieve fault-tolerance. In this work, we use time-domain-multiplexing to generate a four-dimensional cluster state called the Octo-Rail lattice. This new macronode design combines the noise properties and flexibility of the Quad-Rail lattice with the possibility to run various topological error correction codes including surface and color codes. Besides, the presented experimental setup is easily scalable and includes only static components allowing for a straight-forward implementation. We are able to show, that a source of GKP qunaught states with a squeezing above the threshold of 10.1 dB is sufficient to render our design universal and fault-tolerant, without the need for any further resources such as non-Gaussian states or feed-forward operations. Consequently, we can conclude, that the remaining difficulty in building an optical quantum computer lies in the experimental generation of these highly non-classical states. Finally, we introduce a generalisation of our design to arbitrary dimensions, where the setup size scales linearly with the number of dimensions. We believe, that this general scheme will prove useful in applications such as state multiplexing and state injection.

# Non-Gaussian states in levitated nanoparticles to witness gravity-induced entanglement

Presented by **Chisholm, Diana** from
*Queen's University Belfast*

There is a growing interest in the design of experiments with the goal to witness gravity-induced entanglement between massive systems (e.g. levitated nanoparticles), as this would prove the fundamental quantum nature of gravity. Since gravitational interactions are extremely weak, generating a sufficiently high degree of entanglement such that it would be detectable with current experimental setups would likely require for the nanoparticles to be initially prepared in highly non-classical states, in order to increase the sensitivity of such experiments. The generation of such states for massive systems is however extremely challenging, and they result particularly fragile to the decoherence effects due to the surrounding environment. We will show that it is possible to generate non-Gaussian states by performing control protocols that involve the use of non-quadratic potentials. Simulations performed in a range of parameters compatible with current experimental setups show that such schemes are able to produce high levels of non-Gaussianity, even in the presence of detrimental environmental noise.

# Hong-Ou-Mandel interference between two photons of different colours

Presented by **Chrzanowski, Helen** from
*Humboldt-Universität zu Berlin*

in collaboration with

*Mann, Felix and Gewers, Felipe and Placke, Marlon and Ramelow, Sven*

Hong-Ou-Mandel (HOM) interference is a uniquely quantum mechanical effect that underlies quantum information processing with single photons. HOM interference, in its canonical formulation, considers two photons each entering via one of the input ports of a beam-splitter. When the photons are identical in their internal degrees of freedom, the probability amplitudes associated with the photons taking different output ports interfere destructively, and they always leave together. Here, we demonstrate an analogous effect, employing a quantum frequency converter as an active beam-splitter to realise HOM interference between two photons separated by more than an octave in frequency.

Using spontaneous parametric down-conversion in a laser-written ppSLT waveguide pumped at 455 nm, we first generate pairs of non-degenerate photons, with a red photon (637 nm) and a telecommunications photon (1587 nm). These two photons are then subsequently aligned into a quantum frequency converter which serves as a 'colour' beam-splitter. The frequency converter is implemented via bulk ppKTP crystal pumped with a strong 1064 nm field, using sum and difference frequency generation to efficiently convert photons between 637 nm and 1587 nm. The circulating pump field is chosen such that each photon has a 50% probability of either remaining at its current colour, or converting to that of its pair. Destructive interference between the probability amplitudes associated with both photons being converted and both photons remaining unconverted ensures both photons leave the converter with the same colour. The HOM interference is observed via measurement of the coincidence rate between the red and telecom photons, with a tuneable time delay in the telecom arm allowing one to tune across the coherence length of the photon pair.

We attain a HOM dip visibility of (74 ± 3)% with a measured dip width of 5.5 ± 0.3 ps. This agrees with the 5.2 ps predicted by the source and converter bandwidths of 56 and 110 GHz respectively. The measured visibility is currently limited by residual spectral mismatch and the imperfect operation of the frequency converter, which achieves a maximum conversion efficiency below unity.

These results form the first demonstration of a HOM interference between two photons of very different colours and further extends our understanding of what underlies the phenomena of quantum interference. These results also suggest a new approach to interfacing photonic qubits in heterogeneous quantum systems, in which frequency conversion and quantum interference are unified.

# Engineering quantum states from a spatially structured quantum eraser

Presented by **D'Ambrosio, Vincenzo** from
*University of Naples "Federico II"*

in collaboration with

*Schiano, Carlo and Sephton, Bereneice and Aiello, Roberto and Graffitti, Francesco and Lal, Nijil and Chiuri, Andrea and Santoro, Simone and Santamaria Amato, Luigi and Marrucci, Lorenzo and de Lisio, Corrado*

Structured photons are nowadays an important resource in classical and quantum optics due to the richness of properties they show under propagation, focusing, and in their interaction with matter. Vectorial modes of light, a type of structured light where the polarization varies across the beam profile, are a useful tool in quantum information since they provide large alphabets and enhanced resilience to noise. In quantum communication, for instance, vectorial modes enable rotational invariant protocols, therefore overcoming the requirement of a shared reference frame between users [1, 2]. Moreover, structured light can be a resource for enhanced sensing purposes as for instance in the "photonic gears" technique [3,4].

Quantum interference, on the other hand, is a central resource in many quantum-enhanced tasks, from computation to communication protocols [5]. While it usually occurs between identical input photons, quantum interference can be enabled by performing projective measurements that render the photons indistinguishable, a process known as a quantum erasing. By combining the concepts of quantum interference and structured light, we recently designed and experimentally demonstrated a simple and robust scheme that tailors quantum interference to engineer photonic states with spatially structured coalescence along the transverse profile [6]. This is done by locally tuning the distinguishability of a photon pair via spatial structuring of their polarization, creating a structured quantum eraser. By combining the potential benefits of photonic coalescence and structured light, we believe these spatially-engineered quantum states may be of significance in fields such as quantum metrology, microscopy, and quantum information.

[1] V. D'Ambrosio, et al "Complete experimental toolbox for alignment-free quantum communication", Nat. Comm. 3, 961 (2012). [2] V. Parigi, et al "Storage and retrieval of vector beams of light in a multiple-degree-of-freedom quantum memory", Nat. Comm. 6, 7706 (2015). [3] V. D'Ambrosio, et al "Photonic polarization gears for ultrasensitive angular measurements", Nat. Comm. 4, 2432 (2013). [4] R. Barboza, et al "Ultra-sensitive measurement of transverse displacements with linear photonic gears", Nat. Comm. 13, 1080 (2022). [5] F. Bouchard, et al "Two-photon interference : the Hong Ou Mandel effect", Rep. Prog. Phys. 84, 012402 (2020). [6] C. Schiano, et al "Engineering quantum states from a spatially structured quantum eraser", arXiv :2306.13821 (2023).

# Experimental preparation of multiphoton-added coherent states of light

Presented by **Jiří, Fadrný** from
*UPOL*

in collaboration with

*Neset, Michal and Bielak, Martin and Fiurášek, Jaromír and Ježek, Miroslav and Bílek, Jan*

Conditional addition of photons represents a crucial tool for optical quantum state engineering and it forms a fundamental building block of advanced quantum photonic devices. We report on experimental implementation of the conditional addition of several photons. We demonstrate the addition of one, two, and three photons to input coherent states with various amplitudes. The resulting highly nonclassical photon-added states are completely characterized with time-domain homodyne tomography, and the nonclassicality of the prepared states is witnessed by the negativity of their Wigner functions. We experimentally demonstrate that the conditional addition of photons realizes approximate noiseless quantum amplification of coherent states with sufficiently large amplitude. We also investigate certification of the stellar rank of the generated multiphoton-added coherent states, which quantifies the non-Gaussian resources required for their preparation. Our results pave the way towards the experimental realization of complex optical quantum operations based on combination of multiple photon additions and subtractions.

# Non-Gaussian Correlation in the steady state of a superradiant cloud

Presented by **Ferioli, Giovanni** from
*Università degli Studi di Firenze*

We experimentally measure the second-order coherence function of the light emitted by a laser-driven dense ensemble of atoms, dyspling strong superradiant features [1,2]. We observe a clear departure from the Siegert relation valid for Gaussian chaotic light. Measuring intensity and first-order coherence, we conclude that the violation is not due to the emergence of a coherent field. This indicates that the light obeys non-Gaussian statistics, stemming from non-Gaussian correlations in the atomic medium [3].

[1] Ferioli et al., Physical Review Letters 127 (24), 243602 (2021)

[2] Ferioli et al., Nature Physics 19 (9), 1345-1349 (2023)

[3] Ferioli et al., Physical Review Letters 132 (13), 133601 (2024)

# Observation of vacuum Rabi splitting of a subradiant atom-cavity system

Presented by **Gábor, Bence** from
*HUN-REN Wigner RCP*

in collaboration with

*Varga, D. and Sárközi, B. and Adwaith, K. V. and Nagy, D. and Dombi, A. and Clark, T. W. and Williams, F. I. B. and Vukics, A. and Domokos, P.*

We present an experimental study on collective light scattering of cold atoms into a high-finesse optical resonator. Atoms are arranged into a spatial configuration in which they cannot scatter light into a selected mode of the electromagnetic field. We found that such a sub-radiant manifold of atoms has though a strong spectral influence on the mode by the observation of vacuum Rabi splitting.

# Quantum extreme learning machines and online quantum reservoir computing via shadow tomography


Presented by **Innocenti, Luca** from
*Università degli studi di Palermo*

in collaboration with

*Lorenzo, Salvatore and Palmisano, Ivan and Albarelli, Francesco and Ferraro, Alessandro and Paternostro, Mauro and Palma, Massimo*


We introduce a new technique to implement quantum extreme learning machines (QELMs) and true online quantum reservoir computing (QRC) in the single-shot regime, leveraging ideas borrowed from the toolbox of generalised classical shadows.

QELMs and QRCs leverage uncontrolled quantum dynamics and a linear readout stage trained via linear regression to learn how to extract features from input states and time series. These techniques have attracted significant attention for their potential as easier-to-implement quantum machine learning platforms, and recently also for their potential to provide flexible quantum state estimation platforms (Innocenti et al., Communications Physics 6, 118 (2023), and Suprano et al., arXiv:2308.04543). Shadow tomography has also seen a lot of development for its potential to efficiently estimate properties of quantum states even in extremely large dimensional systems. We recently showed how to generalise shadow tomography to arbitrary measurements and pinpoint its place into the more general landscape of quantum metrology, as well as its relation with standard state tomography (Innocenti et al., PRX Quantum 4, 040328). Putting these results together, we show that there are extremely tight relations between QELMs and shadow tomography in general, and formally show that training a QELM can be seen as a particular technique to characterise the effective quantum measurement describing the whole dynamic and measurement.

Our work sheds light into the kind of information obtained by training QELMs and QRCs, the tight relations between QELMs/QRCs and shadow tomography, and finally how these connections allow to perform true online learning of time series via QRCs.

# Boson-fermion complementarity in a linear interferometer

Presented by **Jabbour, Michael G.** from
*Université libre de Bruxelles*

in collaboration with

*Cerf, Nicolas J.*

Quantum interference is responsible for some of the most counterintuitive phenomena allowed by the laws of physics. Crucially, the way identical particles interfere depends heavily on their statistics. On the one hand, the symmetrization of the bosonic many-body wavefunction favors the so-called bunching of identical bosons, as witnessed for instance by the celebrated Hong-Ou-Mandel effect or Hanbury Brown and Twiss effect. On the other hand, identical fermions have a tendency to antibunch, a consequence of the antisymmetrization of the fermionic many-body wavefunction dictated by the Pauli principle. This antibunching of fermions has more recently also been demonstrated through the Hanbury Brown and Twiss effect. In addition to its value from the point of view of fundamental physics, quantum interference is a key resource in many technologies currently rapidly gaining broad interest, such as quantum computing, quantum cryptography, and superconducting quantum interference devices. Strikingly, it turns out to be a crucial aspect of the so-called boson sampling paradigm, which investigates the computational complexity of simulating the scattering of many identical bosons through a multimode linear interferometer. Boson sampling is generally regarded as an instance of a classically hard computational problem that can be efficiently solved by a quantum computer. Interestingly, a similar conclusion has recently been reached for fermion sampling, in which fermionic linear optics circuits fed with specifically chosen entangled input states were used to demonstrate a quantum computational advantage.

In this work, we establish a fundamental relation that governs bosonic and fermionic multiparticle interferences in an arbitrary linear interferometer. The bosonic and fermionic transition probabilities appear together in the same equation which constrains their values, hence expressing a boson-fermion complementarity that is independent of the details of the interaction. To derive our main result, we exploit the powerful and elegant formalism of generating functions applied to the sequences characterized by the transition probabilities. This in turn allows us to make use of the symplectic formalism applied to the phase-space description of bosonic systems. To our knowledge, it is the first time that bosonic and fermionic transition probabilities are combined in a single unifying equation. This relation solely depends on the duality between symmetric and antisymmetric statistics and encompasses all linear interactions between the particles, that is, interactions such that the particle number is conserved. Taking inspiration from our main result, we then prove a heretofore unknown identity connecting the squared moduli of the permanent and determinant of arbitrary complex matrices. Finally, we elaborate on the physical interpretation of the aforementioned complementarity between bosons and fermions. For instance, for two particles in any interferometer, it implies that the average of the bosonic and fermionic probabilities must coincide with the probability obeyed by classical particles.

# Continuous-variable quantum key distribution over multispan amplified links

Presented by **Jarzyna, Marcin** from
*Department of Optics, Palacky University*

in collaboration with

*Michele N., Notarnicola and Cieciuch, Filip*

Transmission losses through optical fibers are one of the main obstacles preventing both long-distance quantum communications and continuous-variable quantum key distribution. In the context of classical optical communication, one can, at least partially, restore the signal by employing optical amplification. However, conventional phase-insensitive amplifiers (PIA) introduce additive noise to the communication link, which prevents their use in quantum key distribution under the most strict unconditional security scenario. On the other hand, phase-sensitive amplifiers (PSA), which in principle are noiseless devices, do not suffer from such disadvantages, while still allowing one to restore the signal in one quadrature at the cost of reducing it in the other one.

In this work [1], we address a key distribution protocol over a multi-span link employing either PIA or PSA, considering Gaussian modulation of coherent states followed by homodyne detection at the receiver's side. We perform the security analysis under both unconditional and conditional security frameworks by assuming in the latter case only a single span of the whole communication link to be untrusted, which models a less powerful but more realistic eavesdropping attack. We compare the resulting key generation rate (KGR) for both kinds of amplified links with the no-amplifier protocol, identifying the enhancement introduced by optical amplification. We prove an increase in the KGR for the PSA link in the unconditional scenario and for both PSA and PIA in the conditional security setting depending on position of the attack and the measured quadrature. Moreover, we show that in the unconditional security paradigm PSA allows one to tolerate larger excess noise when compared with the standard not-amplified link.

References: [1] M. N. Notarnicola, F. Cieciuch, M. Jarzyna, "Continuous-variable quantum key distribution over multispan links employing phase-insensitive and phase-sensitive amplifiers", arxiv:2309.08041[quant-ph].

# Optical parametric amplification for the detection of quantum states

Presented by **Kalash, Mahmoud** from
*Max Planck Institute for the Science of Light*

in collaboration with

*Chekhova, Maria*

Quantum states of light are widely used in nowadays technologies due to the non-classical features they provide. To explore these states, quantum state tomography is employed. In particular, one can retrieve full information about a quantum state through reconstructing the Wigner quasi-probability distribution. The challenge to experimentally reconstruct the Wigner distribution is the fragility of quantum states to losses, including detection inefficiency. Losses disturb quantum features such as squeezing, Wigner function negativity, and superpositions in phase space. This is the case with the most common method of tomography, based on homodyne detection of optical quadratures. Homodyne detectors need to be highly efficient over the full spectrum of an optical state, which is not the case when detecting pulsed quantum states of broad bandwidth. Another drawback of homodyne detection is the impossibility to address simultaneously different modes of multimode radiation, a property that gets increasingly important for optical quantum information.

In this work, we present another method of tomography, which is based on optical parametric amplification. While the concept of pre-amplification was already introduced for the loss-tolerant detection of quantum squeezing, we show how optical parametric amplification allows for the loss-tolerant full quantum state tomography. Since parametric amplification is broadband and multimode, the method surpasses homodyne detection in these aspects. As a proof of principle, we applied the method to the tomography of a single mode filtered from pulsed, highly broadband and multimode squeezed vacuum state, and reconstructed a −7.5 dB squeezed-vacuum state with a purity of 91%, despite more than 97% detection losses. This proves the feasibility of the method under real-life conditions. By changing the detection scheme to be multimode using mode sorting, one can characterize all modes simultaneously. The possibility to characterize all modes at once and the loss immunity make the method a perfect candidate for high-dimensional quantum information applications.

# On-demand generation of propagating bosonic states from Superconducting circuits

Presented by **Khanahmadi, Maryam** from
*Chalmers University of Technology*

in collaboration with

*Göran Johansson, Klaus Mølmer*

As quantum processors grow in size, we enter the era of distributed quantum computing, sharing information between distant quantum processors. This can be achieved by transferring photons between sending and receiving processors. The transformation protocol demands the sender to encode the quantum state into a shaped propagating wavepacket. One attractive possibility to mitigate the effects of losses is to encode the quantum information into error-correctable multiphoton quantum states, e.g., Schrödinger cat states.

The transfer protocol is performed using a tunable coupling between the processors and a photonic waveguide. In superconducting circuits, the non-linear Josephson element enabling the controlled release of microwave pulses unavoidably creates a multimode output, i.e., a combination of single-mode states with different temporal envelopes. Since the coupling between the receiver and the waveguide is controlled according to what temporal envelope to be caught, the multi-temporal modes make catching the full quantum state highly non-trivial, limiting the fidelity of state transfer protocols.

Hence, We propose a novel approach to enhance the fidelity of quantum state conversion from the stationary mode into the propagating mode. Specifically, we investigate a quantum system strongly coupled to both a waveguide and an engineered environment. We have shown that by optimizing the drive profile on the quantum system and fine-tuning its interaction with the engineered environment, one can generate improved "single-mode" propagating cat states into the waveguide. In this approach, due to the high leakage rate, the nonlinear interactions of the quantum system minimally affect the modeness of the output field. Our approach paves the way for exploring the generation of different error-correctable quantum states in the propagating mode.

# Implementation of distributed quantum phase estimation with fewer photons than number of phases

Presented by **Kim, Dong-Hyun** from
*Center for Quantum Information, Korea Institute of Science and Technology (KIST)*

in collaboration with

*Hong, Seongjin and Kim, Yong-Su and Lee, Seung-Woo and Oh, Kyunghwan and Lee, Su-Yong and Lee, Changhyoup and Lim, Hyang-Tag*

In quantum metrology, quantum mechanical effects can enhance the sensitivity of sensors to estimate unknown parameters beyond the standard quantum limit (SQL), which is a sensitivity bound that can be obtained by using classical strategies. Recently, numerous studies have been reported for the estimation of spatially distributed unknown phases, a field referred to as distributed quantum sensing. The objective of distributed quantum sensing is to estimate a linear combination of unknown parameters distributed throughout a sensor. For example, it is useful for various applications such as searching for dark matter, tracking of local beams, and world clock synchronization. Various strategies, using entanglement and squeezing, have been proposed for estimating distributed multiple unknown phases, achieving sensitivity at the Heisenberg scaling (HS).

In continuous-variable (CV) quantum sensing, an entangled CV state offers enhanced sensitivity over separable states. In discrete-variable (DV) quantum sensing, the use of mode-entangled and particle-entangled (MePe) states can theoretically achieve the HS of $1/N^2$. However, using MePe states to estimate distributed multiple phases has constraints that the number of photons should be greater than or equal to the number of phases. The scalability of distributed quantum sensing in estimating multiple unknown phases while increasing sensitivity scaling of $N$ is limited by the challenge of generating multiple photon entangled states.

In this presentation [1], we propose a scheme for distributed quantum sensing, achieving quantum-enhanced sensitivity, specifically the HS of $1/N^2$, even when the number of photons used is fewer than the number of unknown phases. Furthermore, we experimentally demonstrate quantum-enhanced estimation of the average of distributed four phases, with each phase located in distant nodes over 3 km away from the central node. This is achieved by utilizing two-photon polarization-entangled states and attaining 2.2dB quantum-enhanced sensitivity beyond the SQL.

[1] D.-H, Kim. et al, Nat. Commun. 15, 266 (2024).

# Purifying Teleportation

Presented by **Korbicz, Jarek** from
*Center for Theoretical Physics, Polish Academy of Sciences, Warsaw*

in collaboration with

*Roszak, Katarzyna*

Coupling to the environment typically suppresses quantum properties of physical systems via decoherence mechanisms. This is one of the main obstacles in practical implementations of quantum protocols. In this work we show how decoherence effects can be reversed/suppressed during quantum teleportation in a network scenario. Treating the environment quantumly, we show that under a general pure dephasing coupling, performing a second teleportation step can probabilistically reverse the decoherence effects if certain commutativity conditions hold. This effect is purely quantum and most pronounced for qubit systems, where in 25 % of instances the decoherence can be reversed completely. As an example, we show the effect in a physical model of a qubit register coupled to a bosonic bath. We also analyze general d-dimensional systems, identifying all instances of decoherence suppression. Our results are proof-of-concept but we believe will be relevant for the emerging field of quantum networks as teleportation is the key building block of network protocols.

Ref Journal: K. Roszak, JK Korbicz, Quantum 7, 923 (2023)

# New perspectives on alignment-based atomic magnetometry


Presented by **Koźbiał, Marcin** from
*Centre of New Technologies, University of Warsaw*

in collaboration with

*Elson, Lucy and Rushton, Lucas M and Akbar, Ali and Meraki, Adil and Ho, Nok and Jensen, Kasper and Kołodyński, Jan*


Optically pumped magnetometers (OPMs) allow to measure magnetic fields with sensitivities comparable to SQUID-based devices without the need for cryogenic cooling. This has been possible thanks to the rapid development of magnetometers exploiting spin-orientation that are pumped with circularly polarised light, which then facilitates their dynamical modelling, with atoms behaving effectively as an ensemble of spin-½ particles. In contrast, magnetometers that rely on spin-alignment form a novel and promising alternative to compactify even further the operation of such devices. They naturally require the same laser-beam to be used for both pumping and probing the atomic ensemble, however, the usage of linearly polarised light comes at the price of interpreting the atoms as spin-1 particles. As a consequence, thorough theoretical models of their dynamics, detected signals and intrinsic noises have been missing so far, as well as experiments verifying their correctness.

In a series of three manuscripts we show that such a theoretical model is possible not only when light-absorption measurement is considered, as done commonly in the past, but also when detecting light-polarisation rotations, which importantly may lead to much better signal-to-noise ratios. In particular, in the first experiment we characterise the sensitivity and bandwidth of the device, in order to demonstrate such a detection scheme allows to efficiently null the magnetic field in the system, opening doors for practical applications—e.g. detecting a synthetic cardiac signal we explicitly consider. In the second work, we present a more comprehensive and comparative analysis of two detection modalities, i.e., polarisation rotation and absorption measurement, while validating theoretical predictions of the resonance spectra observed as a function of various input parameters. Last but not least, in our final work we perform spin-noise spectroscopy of the alignment-based magnetometer. Crucially, we propose a stochastic model that predicts the measured noise power spectra in presence of a strong, static magnetic field responsible for the Larmor precession of the spin, and white noise in the perpendicular direction of the field. By varying the strength of the noise applied as well as the linear-polarisation angle of the incoming light, we verify the Larmor-induced spectral peaks to be correctly predicted.

We believe that the collection of our joint theoretical and experimental works paves the way for broader applications of alignment-based devices to sense magnetic fields. Moreover, as we demonstrate the characterisation of the noise they exhibit to be possible, we believe that they can be also used in the future to track fast changes of magnetic fields in real time, even at timescales beyond the magnetometer bandwidth.

# Wavevector-polarization correlation in entangled photons from radiative cascades

Presented by **Laneve, Alessandro** from
*Sapienza University of Rome*

in collaboration with

*Rota,Michele B. and Beccaceci, Mattia and Villari, Valerio and Krieger, Tobias M. and Oberleitner, Thomas and Covre da Silva, Saimon F. and Buchinger, Quirin and Stroj, Sandra and Hoefling, Sven and Basso Basset, Francesco and Huber-Loyola, Tobias and Rastelli, Armando and Trotta, Rinaldo*

Some of the most amazing advances in quantum information science have been fostered by the possibility of reliably generating entangled photon pairs. Thus, the quest for deterministic and reliable quantum plays a relevant part towards the realization of commercial quantum technologies. In this regard, quantum light sources based on radiative cascades have been drawn a great deal of attention, given their exceptional features in terms of on-demand photon generation and low multiphoton emission. These sources are generally supposed to provide with maximally polarization entangled photons; but this is not the case. Through a theoretical and experimental study, we demonstrate that this kind of emitters feature an inherent correlation between the polarization and the emission mode of the photon, namely a wavevector-polarization interplay that can affect the overall degree of entanglement of generated photons. We experimentally investigate this effect in quantum dots; these quantum emitters are usually coupled with cavities for light collection enhancement, and we analyze different kinds of structures, finding how the wavevector-polarization correlation is reshaped by the different emission modes allowed by the cavity and how the degree of entanglement of produced biphotons heavily depends on their propagation wavevector. Our results provide further understanding of the emission properties of state-of-the-art emitters both uncoupled and coupled to cavities, developing and demonstrating a general model for cascade biphoton emission accounting for wavevector-polarization correlation, and highlighting a new perspective for collection problem and cavity design.

# Nonlinear Squeezing in Classical and Quantum Mechanics

Presented by **Moore, Darren** from
*Palacky University*

For quantum continuous variables, conventional squeezing in linear combinations of the canonical variables is a fundamental sign of nonclassical behaviour. However, it cannot distinguish Gaussian states from non-Gaussian ones. Motivated by the short time effects of nonlinear potentials such as the cubic potential, we describe squeezing in a nonlinear combination of variables that can be leveraged to detect non-Gaussian states, called nonlinear squeezing [1]. The resulting thresholds are detectors of quantum non-Gaussianity, in that they also exclude incoherent mixtures of Gaussian states. The scheme relies on collecting statistics of position and momentum quadratures (homodyne detection) and is thus amenable to experiment. We present a scheme to detect this nonlinear squeezing in an optomechanical setting [2]. Additionally, we show that the concept is fruitful even in classical mechanics where, analogous to the detection of quantum non-Gaussianity, nonlinear squeezing acts as a detector of genuinely nonlinear behaviour [3]. That is, statistics below a given threshold cannot be achieved using up-to-quadratic potentials operating in environments at fixed temperature. This connects the classical and quantum pictures, as at low enough temperatures the quantum mechanical threshold must dominate. We mainly focus on the cubic potential as an exemplar, however this potential is unbounded, an unphysical situation that will not occur in any real experiment. To approach a remedy for this situation we briefly examine the effect of weakly bounding cubic potentials with a quartic potential in the short time approximation (cubic and quartic gates) and show that this bounding tends to degrade the nonlinear squeezing. In the process, we show how to calculate the effect of quartic bounded cubic phase gates on the Wigner function. This allows us to demonstrate analytically that the negativity of the Wigner function survives no matter the initial Gaussian thermal noise [4].

[1] D. W. Moore, R. Filip Commun. Phys 5, 128 (2022) [2] D. W. Moore, A. A. Rakhubovsky, R. Filip New J. Phys. 21 113050 (2019) [3] L. Ornigotti, D. W. Moore, R. Filip New J. Phys. 26 013022 (2024) [4] D. W. Moore, R. Filip (submitted to NPJ QI)

# Daemonic ergotropy in continuously monitored open quantum batteries

Presented by **Morrone, Daniele** from
*Universita degli Studi di Milano*

in collaboration with

*Genoni, Marco G. and Elyasi, Navid and Rossi, Matteo A. C.*

The amount of work that can be extracted from a quantum system can be increased by exploiting the information obtained from a measurement performed on a correlated ancillary system. The concept of daemonic ergotropy has been introduced to properly describe and quantify this work extraction enhancement in the quantum regime. We here explore the application of this idea in the context of continuously monitored open quantum systems, where information is gained by measuring the environment interacting with the energy-storing quantum device. We show that the corresponding daemonic ergotropy takes values between the ergotropy and the energy of the corresponding unconditional state. The upper bound is achieved by assuming an initial pure state and a perfectly efficient projective measurement on the environment, independently of the kind of measurement performed. On the other hand, if the measurement is inefficient or the initial state is mixed, the daemonic ergotropy is generally dependent on the measurement strategy. We first theoretically investigate this scenario via a paradigmatic example of an open quantum battery: a two-level atom driven by a classical field and whose spontaneously emitted photons are continuously monitored via either homodyne, heterodyne, or photodetection. We finally present a proof-of-principle experimental demonstration of daemonic work extraction by simulating a continuously monitored collision model on an IBM quantum computer.

# Photonic quantum metrology with variational quantum optical non-linearities

Presented by **Muñoz de las Heras, Alberto** from
*Institute of Fundamental Physics IFF-CSIC*

in collaboration with

*Tabares, Cristian and Schneider, Jan Thorben and Tagliacozzo, Luca and Porras, Diego and González-Tudela, Alejandro*

Photonic quantum metrology harnesses quantum states of light, such as NOON or Fock states, to measure unknown parameters beyond classical precision limits. Current protocols suffer from two severe limitations that preclude their scalability: the exponential decrease in fidelities (or probabilities) when generating states with large photon numbers due to gate errors [1, 2], and the increased sensitivity of such states to noise [3]. Here, we develop a deterministic protocol combining quantum optical non-linearities and variational quantum algorithms [4] that provides a substantial improvement on both fronts. The key idea of such hybrid algorithm is to use a classical optimizer to find the set of parameters of a parametrized quantum circuit implemented on the hardware such that it generates states maximizing the quantum Fisher information. In a second step of the algorithm, by maximizing the classical Fisher information, we also find optimal measurements. Our main result [5] is the generation of metrologically-relevant states with a small number of operations which does not depend on photon-number, resulting in exponential improvements in fidelities when gate errors are considered. On top of that, we show that such states offer a better robustness to noise compared to other states considered noise-resilient. Since our protocol harnesses interactions already appearing in state-of-the-art setups, such as cavity QED, we expect that it will lead to more scalable photonic quantum metrology in the near future.

References:

[1] C. Sayrin, I. Dotsenko, X. Zhou, et al., Nature 477, 73–77 (2011). [2] M. Hofheinz, H. Wang, M. Ansmann, et al., Nature 459, 546–549 (2009). [3] E. Polino, M. Valeri, N. Spagnolo, et al., AVS Quantum Sci. 2, 024703 (2020). [4] M. Cerezo, A. Arrasmith, R. Babbush, et al., Nature Reviews Physics 3, 625–644 (2021). [5] AMH, C. Tabares, J. T. Schneider, et al., arXiv:2309.09841 (2023).

# Classical algorithm for simulating experimental Gaussian boson sampling

Presented by **Oh, Changhun** from
*KAIST*

Gaussian boson sampling is a promising candidate for showing experimental quantum advantage. While there is evidence that noiseless Gaussian boson sampling is hard to efficiently simulate using a classical computer, the current Gaussian boson sampling experiments inevitably suffer from loss and other noise models. Despite a high photon loss rate and the presence of noise, they are currently claimed to be hard to classically simulate with the best-known classical algorithm. In this talk, I present a new classical algorithm that simulates Gaussian boson sampling and whose complexity can be significantly reduced when the photon loss rate is large. By exploiting a new decomposition of lossy Gaussian states, the proposed algorithm enables us to take advantage of the high-loss rate in the current experiments and simulate the largest Gaussian boson sampling experiments so far.

# Beating the standard quantum limit for binary phase-shift-keying discrimination with a realistic hybrid feed-forward receiver

Presented by **Olivares, Stefano** from

*Dipartimento di Fisica "Aldo Pontremoli", Università degli Studi di Milano and INFN Sezione di Milano, Italy*

in collaboration with

*Notarnicola, Michele N.*

There are two main detection schemes considered in optical quantum communication: one exploiting the particle-like nature of the radiation (as on/off or photon-number-resolving detection), while the other accesses its wave-light nature (as homodyne, heterodyne or intradyne detection). The two schemes are based on rather different technologies and implementing them in the same communication channel may be challenging. We propose a hybrid feed-forward receiver (HFFRE) for the discrimination of binary phase-shift-keyed coherent states based on the appropriate combination of a displacement feed-forward receiver (DFFRE) and a weak-field homodyne scheme exploiting a low-intensity local oscillator and photon-number-resolving detectors. We investigate the performance of the proposed scheme, also addressing realistic scenarios in the presence of nonunit quantum detection efficiency, dark counts, and visibility reduction. The show that the HFFRE outperforms the DFFRE in all conditions and beats the standard quantum limit in particular regimes.

[1] M. N. Notarnicola, M. G. A. Paris and S. Olivares, J. Opt. Soc. Am. B vol. 40, 705-714 (2023). [2] M. N. Notarnicola and S. Olivares, Phys. Rev. A vol. 108, 042619 (2023).

# Work and heat exchange in quantum nonlinear interferometers

Presented by **Opatrný, Tomáš** from
*Palacký University Olomouc*

in collaboration with

*Bräuer, Šimon and Kofman, Abraham and Misra, Avijit and Meher, Nilakantha and Firstenberg, Ofer and Poem, Eilon and Kurizki, Gershon*

A basic paradigm of thermodynamics assumes that heat machines are open systems dissipated by heat baths. We step beyond this paradigm by introducing closed-system heat machines that operate in a purely coherent fashion by mixing few hot and cold thermal field modes in interferometers with nonlinear intermode cross-couplers. The simplest example is a four mode interferometer with cross-Kerr couplers with two hot and two cold inputs which sends energy preferentially to a preselected output mode. One can view the model also as an automatic Maxwell demon that creates a temperature difference between the hot modes, dumping the acquired information as a waste heat into the cold modes. The model works in a coherent manner, being fully reversible. It can be scaled to an arbitrarily high number of modes.

# Multiple quantum exceptional, diabolical, and hybrid points in multimode bosonic systems

Presented by **Peřina, Jan** from

*Joint Laboratory of Optics of Palacký University and Institute of Physics CAS, Palacký University, 17. listopadu 12, 771 46 Olomouc, Czech Republic*

in collaboration with

*Thapliyal, Kishore and Chimczak, Grzegorz and Kowalewska-Kudlaszyk, Anna and Miranowicz, Adam*

The existence and degeneracies of quantum exceptional, diabolical, and hybrid (i.e., diabolically degenerated exceptional) points of simple bosonic systems composed of up to six modes with damping and amplification are analyzed. Their dynamics governed by quadratic non-Hermitian Hamiltonians, involving unidirectional mode coupling, is followed using the Heisenberg-Langevin equations. Conditions for the observation of inherited quantum hybrid points with up to sixth-order exceptional and second-order diabolical degeneracies are revealed. Exceptional and diabolical points and their degeneracies observed in the dynamics of higher-order field-operator moments are analyzed in their full complexity. Interestingly, the analysis of a system with non-conventional dynamics exhibiting an inherited quantum exceptional point only in a sub-space of the whole Liouville space is presented.

[1] J. Peřina Jr., A. Miranowicz, G. Chimczak, A. Kowalewska-Kudłaszyk: Quantum Liouvillian exceptional and diabolical points for bosonic fields with quadratic Hamiltonians: The Heisenberg-Langevin equation approach, Quantum 6, 883 (2022).

# Experimental generation of three-dimensional cluster entangled state

Presented by **Ra, Young-Sik** from
*Korea Advanced Institute of Science and Technology (KAIST)*

in collaboration with

*Chan Roh, Geunhee Gwak, Young-Do Yoon*

Measurement-based quantum computing is a promising paradigm of quantum computation, where universal computing is achieved through a sequence of local measurements. The backbone of this approach is the preparation of multipartite entanglement, known as cluster states. While a cluster state with two-dimensional (2D) connectivity is required for universality, a three-dimensional (3D) cluster state is necessary for additionally achieving fault tolerance [1,2]. However, the challenge of making 3D connectivity has limited cluster state generation up to 2D [3,4].

In this talk, I will present an experiment generation of a 3D cluster state based on the continuous-variable optical platform [5]. To realize 3D connectivity, we harness a crucial advantage of time-frequency modes of ultrafast quantum light: an arbitrary complex mode basis can be accessed directly, enabling connectivity as desired. We demonstrate the versatility of our method by generating cluster states with 1D, 2D, and 3D connectivities. For their complete characterization, we develop a quantum state tomography method for multimode Gaussian states. Moreover, we verify the cluster state generation by nullifier measurements as well as full inseparability tests. Our work paves the way toward fault-tolerant and universal measurement-based quantum computing.

[1] R. Raussendorf, J. Harrington, K. Goyal, “A fault-tolerant one-way quantum computer”, Annals of Physics 321, 2242–2270 (2006).

[2] R. Raussendorf, J. Harrington, K. Goyal, “Topological fault-tolerance in cluster state quantum computation”, New Journal of Physics 9, 199–199 (2007).

[3] M. V. Larsen, X. Guo, C. R. Breum, J. S. Neergaard-Nielsen, U. L. Andersen, “Deterministic generation of a two-dimensional cluster state”, Science 366, 369–372 (2019).

[4] W. Asavanant et al., “Generation of time-domain-multiplexed two-dimensional cluster state”, Science 366, 373–376 (2019).

[5] C. Roh, G. Gwak, Y.-D. Yoon, Y.-S. Ra, “Generation of three-dimensional cluster entangled state”, arXiv:2309.05437 (2023).

# Superradiant bursts of light from cascaded quantum emitters: Experiment on photon-photon correlations

Presented by **Schneeweiss, Philipp** from
*Humboldt University Berlin*

in collaboration with

*Bach, Constanze and Tebbenjohanns, Felix and Liedl, Christian and Rauschenbeutel, Arno*

Recently, superradiant bursts of light have been, for the first time, experimentally observed for a cascaded quantum system [1]. This was realized using an ensemble of waveguide-coupled two-level atoms that exhibit chiral, i.e., propagation direction-dependent coupling to the waveguide mode. Here, we experimentally study the collective radiative decay of a fully inverted atomic ensemble and measure the second-order quantum correlation function, $g^{(2)}(t_1, t_2)$, of the light emitted by the atoms into the waveguide. We observe $g^{(2)}(0, 0) \approx 2$ at the beginning of the decay, followed by a decrease to $g^{(2)}(t, t) \approx 1$ (where $t > 0$) within the characteristic time scale of the burst dynamics. This built-up of second-order coherence can be interpreted by assuming that, following an initially independent emission, the atoms synchronize during their decay. Interestingly, for ensembles below and above full inversion, $g^{(2)}(t, t) \approx 1$ for all times, indicating that the light is coherently scattered, even during the early dynamics of $t = 0$. In addition to these observations, we find an anti-correlation of photon detection events, i.e., $g^{(2)}(t_1, t_2) < 1$, in certain parameter regions in which $t_1 \neq t_2$, indicating a temporal sub-structure of the light emerging the ensemble. Our measurement outcomes can be well described with a model based on the truncated Wigner approximation. Our findings contribute to understanding the fundamentals of light-matter interaction and help engineering protocols for the generation of non-classical light.

[1] C. Liedl et al., PRX 14, 011020 (2024)

# Storage and retrieval of quantum operations – an experimental test

Presented by **Sedlák, Michal** from
*Institute of Physics, Slovak Academy of Sciences*

in collaboration with

*Horová, Nikola and Mičuda, Michal and Fiurášek, Jaromír and Bisio, Alessandro*

Ability to precisely capture the functioning of a state transformation is vital not only for quantum engineering. Single use of an entangled probe system can make a footprint with arbitrary precision, but the retrieval of the action of the stored transformation will either suffer from errors or will happen only with limited success probability. Thus, limits of storage and retrieval for $N$ uses of one out of two unitary transformations are a quite fundamental task. We completely solve the problem for both maximum fidelity and perfect probabilistic approach for qubits. We present results of an optical experiment for the latter approach. The storage and retrieval quality have been assessed using quantum tomography of states and processes and the results are discussed in relation to non-optimal measure-and-prepare strategy to illustrate advantages of our protocol. The retrieval part of the experiment can be also interpreted as a realization of probabilistic quantum processor operating at an optimal trade-off between overlap of program states, distinctness of the desired unitary transformations and the achievable success probability. Finally, the optimal perfect probabilistic results are generalized to $d$ dimensional case.

# Coherence and statistics of light from large trapped-ion crystals

Presented by **Slodička, Lukáš** from
*UPOL*

We present experimental realizations of free-space optical emission of light from ion Coulomb crystals in Paul traps, which result in the generation of diverse paradigmatic photon statistics, including pure single-photon emission, or the largest discrete photonic nonclassical states. We observe experimental evidence of single-modeness and coherence for light scattered from many ions, which correspond to necessary conditions for the efficient photonic generation of multi-ion entanglement, or for the directional control of light from large ion crystals. The achieved excitation and detection regimes allow for the direct demonstration of super-Poissonian quantum statistics from a finite number of indistinguishable single-photon emitters and enable the realization of substantial enhancement of collection efficiency of nonclassical light scattered from linear ion strings.

# A variational toolbox for analog quantum simulators


Presented by **Tabares, Cristian** from
*Institute of Fundamental Physics (IFF-CSIC)*

in collaboration with

*Schneider, Jan and Muñoz de las Heras, Alberto and Tagliacozzo, Luca and Porras, Diego and González-Cuadra, Daniel and González-Tudela, Alejandro*


Current experimental quantum devices do not meet the requirements for building fault-tolerant quantum computers, but they still can be used to address many-body problems as analogue quantum simulators. Different physical platforms, like superconducting circuits [1], trapped ions [2], and cold atoms [3,4], show different light-mediated interactions between their components. However, the systems simulated are constrained by the type of interactions that can be engineered in the platform, limiting the range of models that can be simulated.

Variational methods have been suggested as a way to go beyond this limitation [5]. Among the different proposals, Variational Quantum Time Evolution algorithms (VarQTE) can perform either real or imaginary time evolution within the same framework [6]. In this work, we propose to use this variational approach to fully harness the interactions present in analogue quantum simulators.

In the first part of the talk, we demonstrate how the tunable long-range interactions present in emitters coupled to waveguide-QED setups can be used to solve some of the limitations of VarQTE algorithms [5]. To do so, we show how to harness the photon-mediated interactions between the emitters. Then, in the second part, we focus on fermionic quantum simulators made with neutral atoms and show how VarQTE algorithms can be used to prepare ground states of exotic fermionic models in more efficient ways than standard methods (either because the target interactions cannot be efficiently generated or because adiabatic methods fails while variational ones do not). These results provide analog quantum simulators with a new set of tools that fully leverage their current capabilities.


References [1] X. Zhang et al., Science 379, 278-283 (2023). [2] C. Kokail et al., Nature 569, 355–360 (2019). [3] S. Ebadi et al., Nature 595, 227–232 (2021). [4] J. Argüello-Luengo et al., Nature 574, 215–218 (2019). [5] C. Tabares et al., Phys. Rev. Lett. 131, 073602 (2023). [6] X. Yuan et al., Quantum 3, 191 (2019).

# Evidence-based certification of quantum systems with relative belief

Presented by **Teo, Yong Siah** from
*Seoul National University*

in collaboration with

*Jeong, Hyunseok and Prasannan, Nidhin and Brecht, Benjamin and Silberhorn, Christine and Evans, Michael and Mogilevtsev, Dmitri and Sánchez-Soto, Luis*

The concept of the relative belief, first advocated by Michael Evans from the University of Toronto, is a powerful statistical tool that goes beyond regular hypothesis testing for ascertaining whether a hypothesis is correct or wrong based on given data at hand. It works by comparing the Bayesian posterior and prior probabilities for a hypothesis of interest and takes it to be correct when the posterior is larger than the prior; that is, when the data evidence supports the hypothesis. Although this concept has been employed in Bayesian error-region construction, it is still not widely known in the quantum-information community. Introducing this methodology into quantum information theory more generally, we propose a relative-belief-based scheme that allows us to find out the smallest effective Hilbert-space dimension that fully describes any given quantum system by solely analyzing the measurement data as evidence. No other assumptions are imposed on the quantum system. Knowing the correct minimal dimensionality of quantum systems (supported by data) is crucial for reliable and efficient quantum-information processing. Using state-of-the-art numerical format for storing extremely minuscule numbers, we apply this methodology to experimental data from spectral-temporal and polarimetry measurements, and routinely demonstrate how to correctly assign Bayesian plausible error bars for the obtained effective dimensions.

# Photonic quantum networks reveal the nonlocal nature of noisy entangled states

Presented by **Villegas-Aguilar, Luis** from
*Griffith University*

in collaboration with

*Polino, Emanuele and Ghafari, Farzad and Quintino, Marco Túlio and Laverick, Kiarn T. and Berkman, Ian R. and Rogge, Sven and Shalm, Lynden K. and Tischler, Nora and Cavalcanti, Eric G. and Slussarenko, Sergei and Pryde, Geoff J.*

Quantum entanglement and Bell nonlocality, though intimately related, are fundamentally inequivalent manifestations of quantum theory. The presence of noise degrades the quality of nonclassical correlations, as evidenced by the existence of entangled Bell-local states—mixed entangled states incapable of demonstrating any nonlocality in the standard Bell scenario [R. F. Werner, Phys. Rev. A, 1989]. Nonlocality is, however, a resource that can be activated; that is, entangled states that cannot display nonlocal correlations in standard bipartite Bell scenarios can overcome the impacts of noise and recover their nonlocality with the use of additional resources [S. Popescu, Phys. Rev. Lett, 1995]. Quantum networks with many parties provide considerably different generalizations of nonlocality with the potential to yield powerful new activation schemes. Here [L. Villegas-Aguilar et al., Nat. Communs. (in press)], we demonstrate an experimental activation of nonlocality in a photonic three-node network, requiring only one instance of a noisy entangled state per measurement round. To achieve this, we employ a quantum channel that broadcasts part of an entangled Bell-local state to two spatially separated parties, embedding the bipartite quantum state into a three-party network.

We built a source of high-quality optical isotropic states $W_\alpha = \alpha |\Phi^+\rangle\langle\Phi^+| + (1-\alpha)\mathbb{I}_4/4$, where $|\Phi^+\rangle = (|HH\rangle + |VV\rangle)/\sqrt{2}$ is a maximally entangled state encoded in polarization, with full tunability of the parameter $\alpha$. All the measured fidelities of our prepared states $\rho_{\text{exp}}$ with the nearest isotropic state were $\mathcal{F} > 0.991$.

To produce the broadcasting channel, we used an optical controlled-NOT gate with an additional ancillary photon. We measured a HOM visibility of $0.97 \pm 0.03$ between single photons from independent sources. This channel was applied to one of the original photons, broadcasting it to two spatially separated parties and forming a three-node network.

It is possible to establish a correlator inequality $\mathcal{I}_B < 0$ to establish the classical limit of the tripartite probability distribution $p(a,b,c|x,y,z)$ in this scenario [J. Bowles et al., Quantum, 2021]. A violation of this inequality certifies the presence of nonlocal correlations from the original source. For five experimental states $\rho_{\text{exp}}$ with different $\alpha$ values, we measured a value of $\mathcal{I}_B > 0$ by at least two standard deviations, representing a clear violation of the classical limit. In particular, three of these experimental states have an associated value of $\alpha \leq 0.6875$, the current known upper bound for projective local hidden variable (LHV) models for this type of two-qubit state.

To certify these results, we developed a robust and computationally efficient method to prove the existence of LHV models for general quantum states. The general idea is to use semidefinite programming to express the reconstructed density matrices $\rho_{\text{exp}}$ as a convex combination of a state with a known LHV model and a separable state. One of the three previously mentioned states was certifiably activated through our algorithm. In this way, we prepare certified Bell-local states, which, after the activating procedure, unambiguously show the emergence of nonlocality from the observed network statistics. Our results open up unexplored possibilities for quantum information processing tasks involving noisy states, an inevitable scenario for any realistic implementation of a future quantum internet.

# Advantage of multi-partite entanglement for quantum cryptography over long and short ranged networks

Presented by **Walk, Nathan** from
*Freie Universität Berlin*

in collaboration with

*Memmen, Janka and Eisert, Jens*

Whilst the use of multi-partite entanglement is known to offer an advantage in certain cryptographic contexts, the quest to find practical advantage scenarios is ongoing and substantial difficulties in generalising some bi-partite security proofs remain. We present rigorous results that address both these challenges. First, we prove the security of a variant of the GHZ state based secret sharing protocol against general attacks, including participant attacks which break the security of the original GHZ state scheme, building on similar results for a class of protocols using continuous variable Gaussian graph states [2]. We then establish security in a composable framework and identify a network topology, specifically a bottleneck network of lossy channels, and parameter regimes within the reach of present day experiments for which a multi-partite scheme outperforms the corresponding bipartite scheme in the asymptotic and finite-size setting. Finally, we show that whilst channel losses limit the advantage region to short distances and small numbers of participants ($N$) over direct transmission networks, the addition of quantum repeaters unlocks the performance advantage of multi-partite entanglement over point-to-point approaches for long distance quantum cryptography. For example, we consider a fibre-optical network equipped with memories where a single distant node 50 km away connects to a local metropolitan network with a radius of 5km though a central bottleneck network and show that the addition of quantum memories 'unlocks' a multi-partite advantage that increases linearly in player number till $N = 10$ and provides some advantage up to $N = 17$. This represents a concrete example of multi-partite entangled resources and quantum memories achieving a genuine advantage over point-to-point protocols for quantum communication and represents a rigorous, operational benchmark to assess the usefulness of such resources.

[1] Memmen, J., Eisert, J. & Walk, N., arXiv:2312.13376 (2023). [2] Walk, N. & Eisert, J, PRX Quantum, 2, 040339 (2021).

# Generation of spatial entanglement in semiconductor nonlinear waveguide arrays

Presented by **Zecchetto, Alessandro** from
*Université Paris Cité*

in collaboration with

*Raymond, Arnault and Zecchetto, Alessandro and Francesconi, Saverio and Palomo, José and Morassi, Martina and Lemaître, Aristide and Raineri, Fabrice and Amanti, Maria and Ducci, Sara and Baboux, Florent*

Harnessing high-dimensional entangled states of light presents a frontier for advancing quantum information technologies, from fundamental tests of quantum mechanics to enhanced computation and communication protocols. In this context, the spatial degree of freedom is particularly adapted for on-chip integration. While traditional demonstrations produce and manipulate path-entangled states sequentially with discrete optical elements, continuously-coupled nonlinear waveguide systems offer a promising alternative where photons can be generated and interfere along the entire propagation length, unveiling novel capabilities within a reduced footprint. Here we exploit this concept to implement a compact source of spatially entangled photon pairs based on parametric down-conversion in AlGaAs nonlinear waveguides arrays [2].

The working principle of our AlGaAs nonlinear waveguide arrays is the following. A classical pump beam (775 nm) injected into one or several waveguides generates photon pairs at telecom wavelength (1550) by spontaneous parametric down-conversion (SPDC), thanks to the strong second-order nonlinearity of the material. These photon pairs can continuously tunnel from one waveguide to the other during their propagation, implementing random quantum walks. Compared to quantum walks in passive circuits, the walkers are here generated directly inside the device and the generation can take place at any position along the propagation axis. Besides a gain of integration, this configuration allows for a significantly higher level of spatial entanglement, due to the interference between quantum walks initiated at all possible longitudinal positions [1].

We have measured the map of spatial correlations for various pump configurations. When pumping only the central waveguide, we observed that photons have an enhanced probability to exit the device either through the same waveguide (spatial bunching) or through opposite waveguides (spatial antibunching). To establish the non-classicality of the measured correlations, an entanglement witness is used, leading to an average violation of the classical limit by 10 standard deviations for several points of the correlation matrix. We then use a double-pump configuration to reconfigure the output quantum state and implement other types of spatial correlations. This control relies on a quantum interference effect between the biphoton wavefunction generated in two neighboring waveguides, which is fully accounted for by analytical calculations and numerical simulations.

In summary, we have demonstrated a compact and versatile source of spatial entanglement based on random quantum walks in AlGaAs nonlinear waveguide arrays [2], laying a promising foundation for quantum information tasks leveraging the high-dimensional spatial degree of freedom. In the future, other lattice geometries can be envisaged: e.g. alternating two coupling distances implements a nonlinear version of the SSH Hamiltonian, allowing to investigate the topological protection of photon pairs. Alternatively, disorder can be introduced deterministically in the array to study e.g. the Anderson localization of multi-particle states, making this platform appealing to simulate physical problems otherwise difficult to access in condensed matter systems.

[1] A. Solsntev et al., Phys. Rev. X 4, 031007 (2014) [2] A. Raymond et al., submitted to Phys. Rev. Lett. (2024)

# Contributed posters

We thank the authors of contributed posters for their presentations.

There are 86 contributed posters to be presented during the conference.

# Quantum non-Gaussian Coherence via Nonlinear Absorption of Quanta

Presented by **ADHIKARY, Kingshuk** from
*Palacký University in Olomouc*

A single-quantum, linear and phase-insensitive absorption by coherent interaction with a saturable system, even a single ground state qubit, is sufficient to deterministically generate nonclassicality in the oscillator, even if the oscillator is prepared in a thermal state. However, the resultant states are diagonal in the Fock state basis and do not exhibit quantum coherence. We overcome this limitation by combining nonlinear phase-insensitive absorption processes or, in the simplest case, nonlinear and linear ones. The prepared superpositions of oscillator Fock states exhibit novel nonclassical interference structures in the phase space. The method can also be extended to an unsaturated absorber. We investigate this elementary source of the emergence of quantum non-Gaussian coherence, including the alternative method of Hamiltonian switching, which is suitable for immediate experiments and further investigations.

# Noisy atomic magnetometry with Kalman filtering and measurement-based feedback

Presented by **Amoros Binefa, Julia** from
*University of Warsaw*

in collaboration with

*Kolodynski, Janek*

Tracking a magnetic field in real-time with an atomic magnetometer presents significant challenges, primarily due to sensor non-linearity, the presence of noise, and the need for one-shot estimation. To address these challenges, we propose a comprehensive approach that integrates measurement, estimation and control strategies. Specifically, this involves implementing a quantum non-demolition measurement based on continuous light-probing of the atomic ensemble. The resulting photocurrent is then directed into an Extended Kalman Filter to produce instantaneous estimates of the system's dynamical parameters. These estimates, in turn, are utilized by a Linear Quadratic Regulator, whose output is applied back to the system through a feedback loop. This procedure automatically steers the atomic ensemble into a spin-squeezed state, yielding a quantum enhancement in precision. Furthermore, thanks to the feedback proposed, the atoms exhibit entanglement even when the measurement data is discarded. To prove that our approach constitutes the optimal strategy in realistic scenarios, we derive ultimate bounds on the estimation error applicable in the presence of both local and collective decoherence, and show that these are indeed attained. Additionally, we demonstrate for large ensembles that the EKF not only reliably predicts its own estimation error in real time, but also accurately estimates spin-squeezing at short timescales.

# Photonic Entanglement and Polarization Nonclassicality: Two Manifestations, One Nature

Presented by **Ares, Laura** from
*Paderborn University, Institute for Photonic Quantum Systems (PhoQS), Theoretical Quantum Science, Warburger Straße 100, 33098 Paderborn, Germany*

in collaboration with

*Prasannan, Nidhin and Agudelo, Elizabeth and Luis, Alfredo and Brecht, Benjamin and Silberhorn, Christine and Sperling, Jan*

Most quantum features are direct consequences of the superposition principle, thus depend on the chosen representation of the states. This ambiguity in representation fuels the investigation of the differences and similarities among the distinct quantum effects, a question that lies at the heart of quantum mechanics. Moreover, unifying apparently dissimilar phenomena makes them equally valuable for applications in quantum technologies.

Entanglement is a prime illustrator for how composite quantum systems and their interference challenge the classical understanding of nature, and it is a key resource for quantum communication protocols [1]. On the other hand, polarization is one of the most commonly used attributes for encoding quantum information in photonics, and the corresponding nonclassical effects, such as polarization squeezing and hidden polarization, are valued resources for quantum metrology [2]. In this work, we establish a strict equivalence between nonclassical polarization and the entanglement of indistinguishable photons, going beyond softer connections previously demonstrated.

To jointly characterize this double-sided form of quantumness, we use a quasiprobability distribution for quantum coherence [3]. Negativities in the quasiprobability distribution arise as a necessary and sufficient criterion for nonclassical behavior for both manifestations. The equivalence relies on correspondence between the classical references, say factorizable and angular-momentum coherent states. This common framework allows us to experimentally verify the presence of entanglement and nonclassical polarization within the same experiment. Specifically, we reconstruct the quasiprobability distribution of an entangled pair of photons produced by parametric down-conversion. Then, we analyze the dependence of this distribution on the polarization basis as well as on the distinguishability of the photons. This framework is extended to entanglement in higher dimensional systems and complemented by a witnessing approach. Our findings show how nonclassical polarization turns out to be equally resourceful for quantum protocols as entanglement, emphasizing its importance in practical applications.

References: [1] B. Morris, B. Yadin, M. Fadel, T. Zibold, P. Treutlein, and G. Adesso, Entanglement between Identical Particles Is a Useful and Consistent Resource, Phys. Rev. X 10, 041012 (2020).

[2] A. Z. Goldberg, P. de la Hoz, G. Björk, A. B. Klimov, M. Grassl, G. Leuchs, and L. L. Sánchez-Soto, Quantum concepts in optical polarization, Adv. Opt. Photon. 13, 1 (2021).

[3] J. Sperling and I. A. Walmsley, Quasiprobability representation of quantum coherence, Phys. Rev. A 97, 062327 (2018).

# Scaling of multicopy interference of Gaussian states for quantum applications

Presented by **Arnhem, Matthieu** from
*Université de Lille*

in collaboration with

*Filipe, Radim*

Quantum technology advances crucially depend on the scaling up of essential quantum resources. Their ideal multiplexing offers more significant gains in applications; however, the scaling of the nonidentical resources is neither theoretically nor experimentally known. For bosonic systems, multimode interference is an essential tool already exploited to build distributed Gaussian quantum sensing and communication, but also Gaussian cluster states and boson sampling architectures for quantum computing. Here, we analyze, predict and compare essential scaling laws for multiplexed nonclassical Gaussian states carrying information by displacement with weakly fluctuating squeezing in different multimode interference architectures. We introduce a *bona fide* figure of merit, called *instability ratio* to numerically estimate the effect of such fluctuations in a large scale interferometer. This analysis opens steps for extensive theoretical investigation of other bosonic resources and follow-up feasible experimental verification necessary for further development of these platforms.

# Quantification of Quantum Correlations in Gaussian States Using Photon-Number Measurements

Presented by **Barasiński, Artur** from
*Institute of Theoretical Physics, Uniwersity of Wroclaw, Plac Maxa Borna 9, 50-204 Wrocław, Poland*

in collaboration with

*Peřina Jr., Jan and Černoch, Antonín*

Identification, and subsequent quantification of quantum correlations, is critical for understanding, controlling, and engineering quantum devices and processes. We derive and implement a general method to quantify various forms of quantum correlations using solely the experimental intensity moments up to the fourth order. This is possible as these moments allow for an exact etermination of the global and marginal impurities of two-beam Gaussian fields. This leads to the determination of steering, tight lower and upper bounds for the negativity, and the Kullback-Leibler divergence used as a quantifier of state nonseparability. The principal squeezing variances are determined as well using the intensity moments. The approach is demonstrated on the experimental twin beams with increasing intensity and the squeezed super-Gaussian beams composed of photon pairs. Our method is readily applicable to multibeam Gaussian fields to characterize their quantum correlations.

# Liouvillian exceptional points of non-Hermitian systems via quantum process tomography

Presented by **Bartkiewicz, Karol** from
*Institute of Spintronics and Quantum Information Faculty of Physics Adam Mickiewicz Univeristy in Poznań*

in collaboration with

*Abo, Shilan and Tulewicz, Patrycja and Bartkiewicz, Karol and Özdemir, Şahin K. and Miranowicz, Adam*

Hamiltonian exceptional points (HEPs) are degeneracies of non-Hermitian Hamiltonians for classical and semiclassical systems, which usually exhibit both dissipation and amplification. However, this definition ignores the effect of quantum jumps on the evolution of quantum systems. Quantum Liouvillian exceptional points (LEPs), defined as degeneracies of quantum Liouvillians, are natural generalizations of the standard semiclassical HEPs by including the effect of quantum jumps [Minganti et al., Phys. Rev. A 100, 062131 (2019)]. Here we explicitly describe how standard quantum process tomography, which is a popular method to reveal the dynamics of a quantum system (a black box), can be readily applied for revealing and characterizing LEPs of non-Hermitian systems. We analyze a prototype model of a single qubit decaying through three competing channels to show how to tune their system parameters to observe LEPs, although the model does not exhibit HEPs. Specifically, we tomographically reconstructed the corresponding experimental Liouvillian and its LEPs by applying single- and two-qubit operations on an IBM quantum processor.

Acknowledgements: This work was supported by the Polish National Science Centre (NCN) under the Maestro Grant No. DEC-2019/34/A/ST2/00081.

# Optical Protocol for Generating Squeezed Coherent State Superpositions

Presented by **Bazzazi, Elnaz** from
*Humboldt University of Berlin*

in collaboration with

*Kögler, Roger Alfredo and Reichgardt, Leon and and Schmidt, Marco and Benson, Oliver*

Non-Gaussian states play a crucial role in fault-tolerant quantum computing, where the manipulation of quantum states is susceptible to errors [1]. Certain classes of non-Gaussian states, notably coherent state superpositions known as cat states, pose challenges in generation due to complexity of breeding protocols and limitations in their output state [2,3]. In this study, we explore an extension of the protocol proposed in ref [4] that makes use of squeezed states and photon number-resolving detectors as resources, demonstrating potential in generating high-amplitude squeezed cat states. Simulation results validate the efficacy of this protocol, and we suggest an experimental setup for its practical realization. This research contributes to advances in fault-tolerant quantum information processing through the generation of non-Gaussian states. [1] Phys. Rev. A 106, 022431 (2022). [2] Phys. Rev. A 103, 013710 (2021). [3] Opt. Express 31, 12865-12879 (2023). [4] Phys. Scr. 97 115002 (2022).

# Fantastic squeezing and where to find it.

Presented by **Bräuer, Šimon** from
*Palacký University Olomouc*

Squeezed states can be found in many areas of quantum physics, and they are advantageously utilized in many areas, starting with quantum metrology, quantum communication, and quantum computation. We generalize the concept of squeezing into nonlinear squeezing and discuss its uses to describe quantum resources. We explicitly demonstrate it in the case of cubic squeezing in the systems of collective spins.

# Characterization of a Homodyne-Like detection scheme for quantum communication protocols.

Presented by **Cassina, Silvia** from
*Insubria University*

in collaboration with

*Sanvito, Alberto and Notarnicola, Michele and Lamperti, Marco and Olivares, Stefano and Allevi, Alessia*

Among the techniques exploited to perform state-reconstruction or continuous-variable quantum-key- distribution protocols, homodyne detection plays a fundamental role. This scheme is based on the interference of the optical state of interest and a very intense coherent state. At variance of the phase difference between the two fields, the outputs of the mixing beam splitter are then detected by two low-noise photodiodes and analogically subtracted. The difference of the photocurrents is acquired and post processed. It has been demonstrated [1], both theoretically and experimentally, that a comparable result can be achieved by exploiting photon-number resolving detectors. In this case we talk about Homodyne-Like (HL) scheme. The change of detectors implies some modification of the acquisition scheme, such as the intensity of the local oscillator, that must be reduced because of the detection working range, and the signal processing. In fact, the signal is acquired directly at the output of each detector and the subtraction is performed during data post processing. In this work we want to characterize this acquisition scheme in order to make it suitable for quantum communication protocols. In particular, we focus on a binary phase-shift protocol, where the bit of information is encoded in a coherent state $|\alpha\rangle$ that can be turned into $|-\alpha\rangle$ by applying a phase shift of $\pi$ [2]. The core of this presentation is the evaluation of some critical parameters, more precisely the optimal phase shift, the local oscillator intensity, and the a-priori state probability in terms of mutual information and error probability. All the experimentally obtained results are compared with theoretical expectations and numerical simulations in the case of HL scheme. Moreover, a comparison with simulated homodyne detection with the same parameters has been performed. The results are in agreement with the expectations and suggest the further exploitation of the scheme. Indeed, this work is meant to be a preliminary investigation about the experimental suitability of this detection system to be implemented in more complex detection schemes, such as the Hybrid Near Optimum detection scheme (HYNORE), which is a promising state-discrimination strategy to approach the Helstrom bound.

Bibliography [1] S. Olivares et al., New J. Phys. 21, 103045 (2019). [2] M. Bina et al., Opt. Express 25, 10685 (2017). [3] M. N. Notarnicola et al., J. Opt. Soc. Am. B 40, 705 (2023).

# Enhancing Discrete Time Crystal Lifetimes via Repeated Measurement Schemes

Presented by **Cenedese, Gabriele** from
*Università degli Studi dell'Insubria*

Discrete time crystals (DTCs) represent a fascinating frontier in the realm of quantum systems, characterized by non-equilibrium dynamics and robust periodicity. Despite their potential applications in various fields such as quantum computing and precision sensing, the inherent challenge lies in their susceptibility to decoherence and short lifetimes. In this study, we delve into the thermodynamic properties of these open quantum systems, proposing an approach to extend their lifespans through repeated measurement schemes. We investigate the dynamics of DTCs under the influence of environmental coupling using the Lindblad master equation. Through numerical simulations and analytical modeling, we reveal an increased lifetime of the DTC dynamics due to the quantum Zeno effect. Our results showcase the emergence of robust features characterized by non-trivial spin dynamics, indicative of the underlying symmetry-breaking phenomena. Overall, our study contributes to advancing the understanding of DTCs and offers a promising avenue for mitigating decoherence effects in such quantum systems. The proposed methodology not only extends the lifetimes of DTCs but also unveils intriguing connections between quantum thermodynamics and non-equilibrium dynamics. Through further exploration and experiments, we envision unlocking new avenues for harnessing DTCs in quantum technologies and fundamental physics research.

# Quantum second-harmonic generation in terms of elementary processes

Presented by **Chesi, Giovanni** from
*Università degli Studi di Pavia*

We address the quantum dynamics of second harmonic generation with a perturbative approach. By inspecting the Taylor expansion of the unitary evolution, we identify the subsequent application of annihilation and creation operators as elementary processes and find out how the expansion of the second-harmonic photon-number probability distribution can be expressed in terms of the interplay of these processes. We show that overlaps between the output states of different elementary processes contribute to the expansion of the probability distribution and provide a diagrammatic technique to analytically retrieve terms of the distribution expansion at any order.

# Counterintuitive improvement of two-photon blockade by a cloud of emitters trapped in an optical cavity


Presented by **Chimczak, Grzegorz** from
*Institute of Spintronics and Quantum Information, Faculty of Physics, Adam Mickiewicz University, Poznań, Poland*

in collaboration with

*Kowalewska-Kudłaszyk, Anna and Abo, Shilan and May, Julia and Miranowicz, Adam*


Single-photon blockade (1PB) is a phenomenon that can be used to produce sources of single photons. The criterion that allows us to determine the occurrence of this phenomenon is the condition that the second-order correlation function has to be less than unity $g^{(2)}(0) < 1$. Single-PB has been generalized to two-photon blockade(2PB), and quite recently the phenomenon of 2PB was experimentally observed by Hamsen et al. [1] in a system composed of an optical cavity and a single atom trapped inside the cavity. The criterion for 2PB takes the form $g^{(3)}(0) < 1 \leq g^{(2)}(0)$. The smaller the third-order correlation function, the better 2PB [2].

Here, we significantly improve 2PB of Ref. [1] in a counterintuitive way, i.e., we add to their system a cloud of two-level emitters. Despite the common belief that it is impossible to observe good PB in many atom systems, this cloud of atoms decreases $g^{(3)}(0)$ by two orders of magnitude [3]. We show that the reason for this improvement is destructive interference, which can take place after trapping the cloud of atoms in the cavity. The improved scheme exhibits an almost perfect 2PB for experimentally feasible parameters.


[1] C. Hamsen, K. N. Tolazzi, T. Wilk, G. Rempe, "Two-photon blockade in an atom-driven cavity QED system", Phys. Rev. Lett. 118 (2017) 133604.

[2] A. Kowalewska-Kudłaszyk, S. I. Abo, G. Chimczak, J. Peřina Jr., F. Nori, A. Miranowicz, "Two-photon blockade and photon-induced tunneling generated by squeezing", Phys. Rev. A 100 (2019) 053857.

[3] G. Chimczak et al., to be published.

# Lossy Teleportation of the Finite Energy GKP state

Presented by **Cho, Sungjoo** from
*Seoul National University*

in collaboration with

*Jeong, Hyunseok*

Gottesman-Kitaev-Preskill (GKP) code is considered as a promising candidate for realization of fault tolerant quantum computing using continuous variable (CV) systems. Previously proposed methods such as the twirling approximation, pre-amplification and the subsystem decomposition have effectively described performance of lossy error correction. However, the aforementioned methods require high(>20dB) squeezing and ideal error correction that may be too demanding for current optical technology. In this work, we analyze the complete dynamics of teleportation-type GKP error correction including photon loss, non-ideal squeezing of 10-15dB and finite resolution of homodyne measurements. We model GKP state as a finite superposition of gaussian state, which is equivalent to well known representation using ideal GKP state and damping operator. Gaussian decomposition of approximate GKP states enables efficient simulation of its noisy evolution.

# Understanding noise in a bulk-ppKTP quantum frequency converter

Presented by **Chrzanowski, Helen** from
*Humboldt-Universität zu Berlin*

in collaboration with

*Mann, Felix and Gewers, Felipe and Placke, Marlon and Ramelow, Sven*

Quantum frequency conversion (QFC) will be an indispensable component of future quantum networks. It enables the coherent transfer of quantum information between disparate energies, allowing quantum nodes to harness the low-loss capabilities of telecommunications infrastructure when sharing quantum information. The performance of existing QFC devices - typically realised in periodically poled nonlinear crystals - is often severely limited by parasitic noise that arises when the pump wavelength lies between the two interconnected wavelengths. Understanding the physical origins of this pump-induced noise is crucial for progress in the future development of QFC devices. Here we investigate the near-infrared noise spectrum of a QFC based on bulk-ppKTP pumped by a CW 1064 nm laser, designed to interconnect photons between diamond NV centres (637 nm) and the telecommunications band (1587 nm).

The wideband measurements of the noise spectra of the QFC were measured from 1140 nm to 1650 nm using a single-photon capable InGaAs grating spectrometer. Complementary to these measurements, high-resolution measurements were taken over a reduced spectral window of 1320 nm to 1620 nm using a combination of a tuneable filter and a single photon detector. By combining polarisation resolution, alongside temperature and frequency tuning of the crystal and pump respectively, these measurements enabled the identification of the different noise processes, including Raman noise and parasitic spontaneous parametric downconversion (SPDC), and their respective regions where they are the dominant noise source.

Most notably, we also identified a heretofore unobserved effect of higher-order counter-propagating SPDC, apparent as a succession of nearly equidistant, very narrow-band peaks contaminating the spectrum. These peaks arise when the design poling period coincides with an integer multiple of the ideal poling period for a counter-propagating process, for instance, where the pump and signal photons co-propagate and the lower energy idler photon travels backwards, and are an unavoidable consequence of quasi-phase matching.

This analysis provides a comprehensive overview of the noise sources that currently limit QCF, highlighting both fundamental limitations and also strategies for potential improvement. The insights obtained will facilitate the further development of QFC for future quantum networks and also quasi-phase-matched devices for quantum technology applications in general.

# Collective phenomena and correlations in atomic systems

Presented by **Cidrim, André** from
*Federal University of São Carlos (UFSCar), Brazil*

Detecting entanglement in large quantum systems remains an overwhelming challenge, both theoretically and experimentally. Inspired by optimal spin squeezing inequalities, we introduce analogous electric-field-based witnesses to detect the entanglement of quantum emitters. Our generalized inequalities rely on quadratures of the radiated electric field, which allows tuning the phase terms of collective spin operators due to the optical path from the emitters. We show that these phases allow us to detect new classes of entangled states. In particular, we demonstrate the generation of entanglement using our inequalities in the dynamics of dipole-dipole interacting ensembles of neutral atoms.

# Efficient inference of quantum system parameters by Approximate Bayesian Computation

Presented by **Clark, Lewis** from
*Palacky University Olomouc*

in collaboration with

*Kolodynski, Jan*

Conducting inference in quantum systems is both an important and difficult task. Recently, there has been a strong growth in interest in using continuously monitored quantum systems for sensing tasks. For all but the simplest of systems, solutions to the dynamics require intense numerical modelling, in order for inference to be performed. This limits the potential applicability of such technology, as the theoretical analysis of the collected data is the bottleneck in the process. To address this issue, we present an algorithmic approach to inference that can be utilised for complex quantum systems, providing a vital speed-up to the processing time for obtaining posterior distributions. As an example of the applicability of our method, we demonstrate how inference can be performed in a non-linear optomechanical system subject to continuous photon-counting. Now with workable computational times, we investigate the power of adaptive sensing methods in non-linear optomechanical systems, which with previous methods would have been computationally exhaustive. Using the results presented here, we demonstrate novel techniques that will enable researchers to apply quantum inference to a wider range of models.

# Coherent Feedback Control of a Macroscopic Mechanical Oscillator

Presented by **Couto Corrêa Pinto Filho, Luiz** from
*Center for Macroscopic Quantum States (bigQ), Technical University of Denmark*

in collaboration with

*Isaksen, Frederik and Requena, Daniel and Høj, Dennis and Hoff, Ulrich and Andersen, Ulrik*

The cooling of nano- and micromechanical systems to their ground states is a critical requirement for quantum sensing, quantum information processing, and the study of fundamental physics of macroscopic systems. Traditional techniques, such as dynamical backaction cooling and measurement-based feedback control, have been employed to achieve such cooling.

This work presents a distinct method for cooling a mechanical oscillator using a coherent feedback approach. Unlike conventional measurement-based feedback cooling, which relies on projective measurements, our method preserves the full coherence of the system. The same optical mode is used first for transducing the oscillator and later for actuating it. This is achieved using the mechanical displacement information acquired by the phase of the optical mode in the first pass of the cavity. Subsequently, the light field undergoes two critical unitary transformations before reinjection: a delay corresponding to a quarter of a mechanical period, and a conversion of the phase quadrature information into amplitude. We propose using a displacement operation for the latter, which involves the interference between the signal beam and an auxiliary displacement beam in a beam splitter. Our work, diverging from the work of Ernzer et al. (2023), exclusively focuses on implementing on-resonance coherent feedback cooling. We aim to examine the impact solely from this cooling method, rendering dynamical sideband cooling inactive.

This technique has been experimentally tested using a cavity optomechanical system comprising a high-Q micro-mechanical membrane (Høj et al., 2024), which was cooled from room temperature to millikelvin temperatures. Our findings suggest that by improving the quality of the mechanical resonator, it is possible to cool the oscillator into its ground state without using cryogenics. This coherent feedback control approach offers a promising alternative for efficient cooling in quantum systems.

References: 1. Ernzer, M., Aguilera, M. B., Brunelli, M., Schmid, G., Karg, T. M., Bruder, C., Potts, P. P., Treutlein, P. (2023). Optical Coherent Feedback Control of a Mechanical Oscillator. Phys. Rev. X 13 021023. 2. Høj, D., Hoff, U. B., Andersen, U. L. (2024). Ultracoherent Nanomechanical Resonators Based on Density Phononic Crystal Engineering. Phys. Rev. X, vol. 14, no. 1, pp. 011039.

# Two-photon absorption within the Wigner-Weisskopf approximation

Presented by **Dąbrowska, Anita** from
*University of Gdańsk*

We consider the interaction of a quantum system with a continuous-mode electromagnetic field prepared in a two-photon state [1]. We describe the interaction between the open system and the environment within the Wigner-Weisskopf approximation. It means that we assume that the coupling constants become independent of frequency, make the rotating wave approximation, and extend the lower limit of integration over frequency to minus infinity [2,3,4]. In this model, the bandwidth of the light pulses is much smaller than their central frequencies. If there is no correlation between the photons, the reduced evolution of the open system is given then by the set of hierarchical master equations [5,6].

Using the collision model, we determine analytical formulas for the quantum trajectories associated with the photon counting process [7]. The quantum trajectories allow us to derive both the conditional and unconditional evolution of an open system and to obtain the whole statistics of photon counting for the output field.

We use the quantum trajectories to determine the analytical formula for the probability of two-photon absorption for a three-level atom of a ladder configuration. We consider two situations: the atom interacting with unidirectional and bidirectional fields. We determine the formulas for the probability of the two-photon absorption for an arbitrary two-photon state of light both for uncorrelated and correlated photons. Finally, we present a recipe for the two-photon state providing the optimal condition of two-photon absorption at a given moment.

References: [1] R. Loudon, The Quantum Theory of Light, third edition, (Oxford University Press, Oxford, 2000). [2] C. W. Gardiner, P. Zoller, Quantum noise, Springer-Verlag, Berlin-Heidelberg (2010) [3] H. M. Wiseman, G. J. Milburn, Quantum measurement and control, University Press, Cambridge (2010) [4] M. O. Scully, M. S. Zubairy, Quantum Optics, Cambridge University Press, Cambridge (1997) [5] B. Q. Baragiola, R. L. Cook, A. M. Brańczyk, and J. Combes, Phys. Rev. A, 86, 013811 (2012). [6] A. Dąbrowska, G. Sarbicki, D. Chruściński, Phys. A: Math. Theor. 52, 105303-1–105303-22 (2019). [7] A. Dąbrowska, paper in preparation

# Conditional Measurements on a semi-lossy waveguide beam splitter around Exceptional Points

Presented by **Datta, Ananga Mohan** from
*Institut für Physik, Humboldt-Universität zu Berlin*

in collaboration with

*Perez-Leija, Armando and Busch, Kurt*

Exceptional points (EPs) are branch point singularities found within non-Hermitian systems[1], giving rise to a myriad of intriguing characteristics in the behavior of light[2]. These EPs hold potential for various applications, including the development of photonic sensors[3]. Previous studies primarily focused on sensitivity around EPs under the assumption of classical light. In this study, we investigate the behavior of nonclassical light generated through conditional measurement techniques[4] over a semi-lossy waveguide beam-splitter in the vicinity of EPs. Furthermore, we investigate the feasibility of utilizing our findings to design quantum sensors.

1. C. M. Bender, Am. J. Phys. **71**, 10951102(2003).
2. C. E. Rüter *et al*., Nature Phys **6**, 192195(2010).
3. J. Wiersig, Phys. Rev. Lett. **112**, 203901(2014).
4. M. Dakna *et al*., Eur. Phys. J. D **3**, 295308(1998).

# Deterministic Fock states in Brillouin optomechanics

Presented by **DATTA, Shaoni** from
*Palacký University in Olomouc*

in collaboration with

*Rakhubovsky, A. and Filip, Radim*

Brillouin devices have emerged recently as a novel perspective platform for optomechanics, including applications like sensing, transducers and memories. Combining high mechanical quality with high mechanical oscillations frequency (and consequently very low equilibrium thermal occupation) they hold promise to be used as quantum memories and for fundamental studies of quantum mechanics at the macroscopic scale. Simultaneous optomechanical and piezoelectric control of mechanical motion can potentially enable microwave-to-optical conversion at the quantum level. For such applications, reaching quantum non-Gaussian mechanical states deterministically is crucial but has been challenging. Here, inspired by the recent experimental progress of Brillouin optomechanics, we consider the pulsed deterministic optomechanical conversion of optical single- and two-photon Fock states to the quantum states of mechanical oscillations. We investigate the conditions necessary to achieve the mechanical Wigner function negativity and the mechanical-state quantum non-Gaussianity. As a practical recipe, we provide concrete thresholds for relevant parameters of the optomechanical interaction required to reach quantum non-Gaussian mechanical states and address applications in quantum sensing, transducers and memories.

# To be confirmed

Presented by **Deside, Serge** from
*Université Libre de Bruxelles*

Entanglement is among the most fundamental—and at the same time puzzling—properties of quantum physics. Its modern description relies on a resource-theoretical approach, which treats entangled systems as a means to enable or accelerate certain informational tasks. Hence, it is crucial to determine whether—and how—different entangled states can be converted into each other under free operations (those that do not create entanglement from nothing). Here, we show that the majorization lattice provides an efficient framework to characterize the allowed transformations of pure entangled states under local operations and classical communication. The underlying notions of meet $\wedge$ and join $\vee$ in the majorization lattice lead us to define, respectively, the optimal common resource and optimal common product states. Based on these two states, we introduce two optimal probabilistic protocols for the (single-copy) conversion of incomparable bipartite pure states, which we name greedy and thrifty. Both protocols reduce to Vidal's protocol [G. Vidal, Phys. Rev. Lett. 83, 1046 (1999)] if the initial and final states are comparable, but otherwise the thrifty protocol can be shown to be superior to the greedy protocol as it yields a more entangled residual state when it fails (they both yield the same entangled state with the same optimal probability when they succeed). Finally, we consider the generalization of these protocols to entanglement transformations involving multiple initial or final states.

# Kalman Filters applied to atomic sensors

Presented by **Dilcher, Klaudia** from
*University of Warsaw*

in collaboration with

*Kolodynski, Jan*

Information inference from noisy systems is a focus of interest of various research and engineering disciplines. In 1960, Rudolf E. Kalman published a paper on an optimal filtering technique for systems described by linear dynamics and measurement models whose noise statistics is Gaussian [1]. In particular, this so-called Kalman Filter constitutes a way to construct an estimator that allows one to optimally extract the signal encoded in the system dynamics by minimizing the average mean-squared-error, despite the dynamics and measurement all undergoing uncontrolled independent stochastic fluctuations. In contrast to previously known algorithms, Kalman Filters do not require a full history of all previous computational steps, and so this technique is suitable for real-time data analysis and has proven to be very successful in many applications, including navigation systems, robotics, image processing and many more.

In this work, we applied Kalman Filters for magnetic field inference from an atomic sensor with optical read-out. Such sensors are widely used in magnetometry both within and beyond the classical limit, achieving precision comparable to cryogenic methods. The Linear Kalman Filter has been applied to such systems before [2, 3], however the usability of this technique is very limited though, as the magnetic field obeys highly non-linear dynamics in most regimes. This suggests that using the Extended Kalman Filter can greatly improve the estimator beyond the linear regime. In this work, we simulate, for relevant experimental parameters, an output of such a sensor and show that in fact the magnetic field can be successfully estimated in real-time with the Extended Kalman Filter. We benchmark the results with the theoretically attainable precision limits.

[1] R. E. Kalman, A New Approach to Linear Filtering and Prediction Problems, Journal of Basic Engineering, vol.81, 1960.

[2] Ricardo Jiménez-Martínez et. all Signal Tracking Beyond the Time Resolution of an Atomic Sensor by Kalman Filtering, PRL, vol. 120, 2018

[3] Jia Kong et. all Measurement-induced, spatially-extended entanglement in a hot, strongly-interacting atomic system, Nature Communications vol. 11, Article number: 2415, 2020.

# Ground-state bistability of cold atoms in a cavity

Presented by **Dombi, András** from
*HUN-REN Wigner Research Centre for Physics*

in collaboration with

*Gábor, Bence and Nagy, Dávid and Clark, Thomas and Williams, Francis and Adwaith, Varooli and Vukics, András and Domokos, Peter*

We experimentally demonstrate an optical bistability between two hyperfine ground states of trapped, cold atoms, using a single mode of an optical resonator in the collective strong coupling regime. Whereas in the familiar case, the bistable region is created through atomic saturation, we report an effect between states of high quantum purity, which is essential for future information storage. The source of nonlinearity is a cavity-assisted pumping between ground states of the atoms and the stability depends on the intensity of two driving lasers. We interpret the phenomenon in terms of the recent paradigm of first-order, driven-dissipative phase transitions, where the transmitted and driving fields are understood as the order and control parameters, respectively [1]. A semiclassical mean-field theory is invoked to describe the nontrivial two-dimensional phase diagram arising from the competition of the two drive. The saturation-induced bistability is recovered for infinite drive in one of the controls. The order of the transition is confirmed experimentally by hysteresis in the order parameter when either of the two control parameters is swept repeatedly across the bistability region.

[1] B. Gábor, D. Nagy, A. Dombi, T. W. Clark, F. I. B. Williams, K. V. Adwaith, A. Vukics, and P. Domokos; Phys. Rev. A 107, 023713

# POLAR QUANTUM SYSTEMS IN STRONG ELECTROMAGNETIC FIELDS

Presented by **Gładysz, Piotr** from
*Nicolaus Copernicus University in Toruń*

in collaboration with

*Petkova, Niya and Słowik, Karolina*

In this study, we explore a widely used model that approximates the quantum system with two energy levels. The optical characteristics of this model are determined by spatial symmetries, characterized by multipolar transition moments. When subjected to a resonant plane wave, the system undergoes cyclic population transfers between its levels, commonly referred to as Rabi oscillations. In the simplest scenario, the frequency of these oscillations scales linearly with the amplitude of the driving field and the transition dipole moment of the quantum system.

We extend this elementary analysis by incorporating polarity into the model. This means that the system exhibits distinct permanent dipole moments in its ground and excited states. These moments introduce an extra oscillating dipole during population transitions, significantly altering the system's response to the driving field. The implications include the emission of low-frequency radiation [1] and nonlinear corrections to the Rabi frequency scaling with the driving field amplitude. Surprisingly, these aspects have not been extensively explored in existing literature.

The analysis of such models is generally complex, typically relying on numerical solutions. However, we propose a series of unitary transformations to simplify the equations. Ultimately, we present a time-independent effective Hamiltonian of the Jaynes-Cummings form, significantly reducing the complexity and computational time required, simultaneously maintaining good agreement with the full numerical solution. To achieve this, we build upon works addressing the issue of polarity in Bloch equations [2] and providing corrections to the rotating- wave approximation [3] crucial for strong driving fields.

The described approach allows us to analyze the response of the system in a broad range of parameters and determine the regimes for which polarity and strong field corrections are important. As the main application, we demonstrate that the nonlinearity of the Rabi frequency can improve the coherence of the collective response of multiple systems driven in a strongly space-varying field, e.g. in the vicinity of plasmonic nanoparticles.

[1] Gładysz, Piotr, Piotr Wcisło, and Karolina Słowik. "Propagation of optically tunable coherent radiation in a gas of polar molecules." Scientific Reports 10.1 (2020): 17615.

[2] Kibis, O. V., et al. "Matter coupling to strong electromagnetic fields in two-level quantum systems with broken inversion symmetry." Physical review letters 102.2 (2009): 023601.

[3] Yan, Yiying, Zhiguo Lü, and Hang Zheng. "Effects of counter-rotating-wave terms of the driving field on the spectrum of resonance fluorescence." Physical Review A 88.5 (2013): 053821.

# Practical performance of entanglement-based QKD

Presented by **GUMBERIDZE, Mariia** from
*Palacký University in Olomouc*

We theoretically analyze the performance of entanglement-based quantum key distribution (QKD) protocols, considering both SPDC and quantum dot sources. We account for multi-photon emission in SPDC sources and fine structure splitting in quantum dots. Additionally, we incorporate imperfect detection, including dark counts and limited efficiency. For SPDC sources, the presence of vacuum and multi-photon events renders them unsuitable for secure device-independent (DI) QKD implementations. Conversely, with quantum dot sources, accounting for the effects of fine structure splitting results in reduced secret key rates compared to ideal conditions. Our findings are crucial for the practical implementation of entanglement-based QKD protocols using realistic sources and detectors.

# Completely characterizing multimode Gaussian quantum processes

Presented by **Gwak, Geunhee** from
*Department of Physics,Korea Advanced Institute of Science and Technology (KAIST),Daejeon*

in collaboration with

*Gwak,Geunhee and Roh,Chan and Yoon,Young-Do and Ra,Young-Sik*

Gaussian operation is widely used in many quantum protocols, including quantum communication, quantum metrology, and quantum information processing. As demand for scalable quantum systems increases, research using Gaussian operation has expanded toward multimode regimes [1,2]. To completely exploit the controllable multimode Gaussian operation in a larger and more complex quantum system, implementing and characterizing multimode Gaussian operations becomes essential. However, the existing works have been mostly limited to investigating linear operations. This is because multimode entanglement generating operation gives more complexity to be explored than linear operation. Here, we experimentally characterized complete information about multimode Gaussian operation, including multimode squeezing operation and multipartite entangling operation.

Any multimode Gaussian processes can be described with the amplification matrix A and noise matrix N [3]. A represents the (de)amplification gain during the process, and the N shows the added noise. We have developed a technique to obtain both A and N as fulfilling the physical condition for a quantum operation. To characterize A, we prepared the coherent state probe and measured the output coherent state after a multimode process. Using input and output field relations, we obtained the complete information on A. With physical condition on N and A, we reconstruct N by maximum likelihood estimation(MLE) using quadrature data from homodyne detection.

In our experiment, we characterized the multimode entangling process in frequency modes. Multimode spontaneous parametric down conversion(SPDC) process creates a correlation between multiple frequency bands simultaneously. We obtained the A matrix and N matrix for 16 frequency spectral modes. The A matrix clearly shows EPR entanglement for frequency pairs, and the diagonal element in N matrix indicates the obtained noise during the process. For further analysis of A, we identified eigenchannels of A and measured associated amplification or deamplification ratios for each eigenchannel. To showcase the broad applicability of our method, we also characterize a cluster-state generation process, a mode-dependent loss channel, and a quantum noise channel. We expect this work to apply to versatile quantum protocols, including four-wave mixing process, multimode nonlinear interferometry, and characterization of lossy quantum channels.

[1] C. Roh, G. Gwak, Y.-D. Yoon, and Y.-S. Ra, "Generation of three-dimensional cluster entangled state", arXiv:2309.05437 (2023). [2] Arrazola, J.M., et al., "Quantum circuits with many photons on a programmable nanophotonic chip", Nature 591, 54–60 (2021). [3] Weedbrook, C., et al., "Gaussian quantum information", Reviews of Modern Physics 84, 621 (2012).

# Four-fold Hong-Ou-Mandel Interference from a Whispering Gallery Mode Resonator

Presented by **Huang, Sheng-Hsuan** from
*Chair of Optical Quantum Technologies, Friedrich-Alexander-Universität Erlangen-Nürnberg*

in collaboration with

*Dirmeier, Thomas and Shafiee, Golnoush and Laiho, Kaisa and Strekalov, Dmitry and Leuchs, Gerd and Marquardt, Christoph*

Four-fold Hong-Ou-Mandel Interference from a Whispering Gallery Mode Resonator Sheng-Hsuan Huang1,2, Thomas Dirmeier1,2, Golnoush Shafiee1,2, Kaisa Laiho3 Dmitry V. Strekalov1, Gerd Leuchs1,2, and Christoph Marquardt2,1 1 Max Planck Institute for the Science of Light, Staudtstrasse 2, 91058 Erlangen, Germany 2 Department of Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, Staudtstrasse 7/B2, 91058 Erlangen, Germany 3 German Aerospace Center (DLR e.V.), Institute of Quantum Technologies, Wihelm-Runge-Str. 10, 89081 Ulm, Germany Crystalline Whispering Gallery Mode Resonators (WGMRs) which are made from $^2$ nonlinear dielectric materials have been shown to be efficient sources of quantum states such as squeezed states [1], heralded single photons [2], or polarization entanglement [3]. Also, due to their high Q factor and the variable coupling rate, photons generated from WGMRs can efficiently interact with atomic systems [4]. These features make WGMRs a potential platform for implementing building blocks for quantum information processing. Here, we further investigate this type of source and demonstrate the Hong-Ou-Mandel (HOM) effect between heralded photons that are produced in two independent photon-pair creation processes within a single WGMR. The ability to generate indistinguishable photonic quantum states is a key requirement when realizing many applications in quantum information processing such as entanglement swapping and linear optical quantum computing. In this work, we use a WGMR made of a z-cut lithium niobate wafer to generate heralded photons via spontaneous parametric down-conversion. To observe the four-fold HOM effect, generating two pairs of photons which are indistinguishable is essential. In our case, we achieve this by coupling the pump beam from the clockwise (CW) and counterclockwise (CCW) directions into the same whispering gallery mode. Since these two propagating beams share the same crystal and resonator mode, they should follow the same phase-matching condition, which makes the two signal respectively the two idler photons emitted from the CW and CCW beams indistinguishable and travel in opposite directions. Later, we combine the signal photons generated from the two beams on a beam splitter and couple the light from the two output ports into two detectors. Similarly, the idler photons from the two beams are coupled into another two detectors separately. The four-fold HOM can be observed when the four detectors have clicked within the photon coherence time. In our experiment, we achieve four-fold HOM visibilities greater than 70%. This is, to the best of our knowledge, the first time that the four-fold HOM interference is generated from a WGMR. Acknowledgments: This research was conducted within the scope of the project QuNET, funded by the German Federal Ministry of Education and Research (BMBF) in the context of the federal government's research framework in IT-security "Digital. Secure. Sovereign" Reference: [1] M. Förtsch, et al., Nature communications 4.1 (2013) [2] A. Otterpohl, et al., Optica 6.11 (2019) [3] S-H. Huang, et al., arXiv:2310.16589 (2023). [4] G. Schunk, et al., Optica 2.9 (2015)

# Optical time-domain quantum state tomography and correlations on a subcycle scale

Presented by **Hubenschmid, Emanuel** from
*University of Konstanz*

in collaboration with

*Guedes, Thiago and Burkard, Guido*

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 possible (time local) quantum tomography scheme with subcycle resolution [https://doi.org/10.48550/arXiv.2307.13090]. 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.

# Quantum-enhanced joint estimation of phase and phase diffusion

Presented by **Jayakumar, Jayanth** from
*University of Warsaw*

in collaboration with

*Mycroft, Monika and Barbieri, Marco and Stobińska, Magdalena*

Accurate phase estimation in the presence of unknown phase diffusive noise is a crucial yet challenging task in noisy quantum metrology. This is particularly interesting due to the detrimental impact of the associated noise. In our work, we numerically investigate the problem of enhancing precision in joint estimation of phase and phase diffusion using generalized Holland-Burnett (gHB) states, known for their experimental accessibility. These states are also known to provide performance close to the optimal state in single-parameter phase estimation, even in the presence of photon losses. Thus, they exhibit high phase sensitivity and robustness to losses.

Despite the issue of measurement incompatibility in our problem, we demonstrate that utilizing gHB states in tandem with an experimentally implementable separable measurement, yields high levels of sensitivity for jointly estimating the parameters. Our approach contrasts with the use of a collective measurement on numerous copies of probe states, which allows for achieving the best possible sensitivities in general joint estimation schemes. However, implementing the latter is experimentally challenging, albeit ideal.

Specifically, we adopt a twofold approach by analyzing the joint information extraction through the double homodyne measurement and the joint information availability across all gHB probe states. Through our analysis, we find that the highest sensitivities are obtained by using states created by directing all input photons into one port of a balanced beam splitter. Furthermore, for such states, we infer that good levels of sensitivity persist even in the presence of moderate photon losses, demonstrating their metrological resourcefulness and experimental feasibility.

# Non-Gaussian state teleportation with a nonlinear feedforward

Presented by **Kala, Vojtech** from
*Palacky University*

in collaboration with

*Walschaers, Mattia and Filip, Radim and Marek, Petr*

Quantum advantage with continuous variable quantum computing requires a complex interplay between large entangled cluster states and non-Gaussianity. Both pieces of the puzzle were succesfully experimentaly demonstrated, yet separately and their joint implementation still remains challenging.

The basic mechanism of propagating a quantum state through the cluster state is the canonical teleportation protocol. We analyzed a propagation of a state with nonlinear squeezing through the cluster state. Nonlinear squeezing is a property that can be found in specific non-Gaussian states and it is a resource for quantum computing.

We compared the performance of the canonical teleportation protocol to a teleportation equipped with recently experimentally demonstrated nonlinear feedforward [1]. Our analysis showed that the nonlinear feedforward allows to transmit more nonlinear squeezing compared to the canonical teleportation scheme.

Such an improvement in propagation of non-Gaussian states increases the potential to chain the steps of their processing within a cluster state.

[1] A. Sakaguchi, S. Konno, F. Hanamura, W. Asavanant, K. Takase, H. Ogawa, P. Marek, R. Filip, J.-i. Yoshikawa, E. Huntington, H. Yonezawa, and A. Furusawa, Nonlinear feedforward enabling quantum computation, Nature Communications 14, 3817 (2023).

# Towards an opto-spin-mechanical interface

Presented by **Olofsson, Anna** from
*Technical University of Denmark*

in collaboration with

*Kara, Dhiren and Andersen, Ulrik and Huck, Alexander.*

Mechanical resonators from the nano- to cm-scale are interesting for a range of applications including force sensing, intertial navigation, to searches for quantum gravity and dark matter. With improved fabrication techniques and understanding of mechanical losses over the past decade the Q-factor, which is the ratio of mechanical frequency, $f_{\mathrm{m}}$, to mechanical damping rate, $\gamma_{\mathrm{m}}$, of some resonator devices now surpass the billions. This has opened up the potential of using functionalised resonators for the transduction of information in quantum computing architectures and also scanning-probe based quantum sensing.

To date opto-mechanical interactions, such as radiation pressure, have typically been used for investigating these systems, and have proved extremely successful, for example leading to demonstrations of cooling to the ground-state, mechnical squeezing, entanglement of distant phonon-modes, and conversion between optical and microwave photons. We are exploring interfacing micro-scale resonators with the electronic spin state of nitrogen-vacancy centres in diamond, via magnetic gradients. Coupling resonators to what is effectively a two-level system, would enable the creation of non-gaussian mechanical states, including phonon-superpositions to allow the study of phonon quantum-coherence, quantum enhanced gyroscopes, and the possibility of interconnecting superconducting qubit processors with optical quantum networks.

I will present recent work characterising shallow (within 10 nm of the surface) NVs in diamond and our progress toward using them to sense the motion of a nearby magnetic force microscopy probe with high spectral resolution by implementing a quantum heterodyne technique. I will finish with our initial results of functionalising high-Q trampoline resonators with nanoscale magnetic structures.

# Robust generation of $N$-partite $N$-level singlet states by identical particle interferometry

Presented by **Karczewski, Marcin** from
*Adam Mickiewicz University*

in collaboration with

*Piccolini, Matteo and Winter, Andreas and Lo Franco, Rosario*

In the recent manuscript arXiv:2312.17184, we propose an interferometric scheme for generating the totally anti-symmetric state of $N$ identical bosons with $N$ internal levels (generalized singlet). This state is a resource for tasks ranging from quantum metrology to simulation of particle statistics, offering dramatic quantum advantage. The procedure uses a sequence of Fourier multi-ports, combined with coincidence measurements filtering the results. Due to the suppression laws linking symmetries with destructive multipartite interference, successful preparation of the generalized singlet is confirmed when the $N$ particles of the input state stay separate (anti-bunch) on each multiport. The scheme is robust to local lossless noise and works even with a totally mixed input state. We will discuss its potential implementation for generating the tripartite generalized singlet state with the existing photonic chip platforms.

# Subdiffractional localization of photon emitters based on the target mode shaping and photon number distribution analysis

Presented by **Katamadze, Konstantin** from
*Techology Innovation Institute, Abu Dhabi, UAE*

in collaboration with

*Bantysh, Boris and Vintskevich, Stephan and Romanova, Anna*

We present a groundbreaking imaging technique, BLESS (Beam moduLation and Examination of Shot Statistics) [1], designed for subdiffractional localization of photon emitters. BLESS combines target mode shaping and photon number distribution analysis to achieve unprecedented precision in emitter localization.

From a fundamental standpoint, BLESS effectively breaks Rayleigh's Curse, enabling precise distance estimation between two sources irrespective of the distance value. In contrast with other techniques like SPADE or SLIVER [2-4] it doesn't require a prior knowledge about sources' centroid and brightness ratio.

Thereby, from a practical perspective, BLESS offers remarkable applicability to real-world imaging scenarios, such as the localization of quantum dots, NV centers or die molecules in biological samples, with an impressive accuracy of about 10 nm. Importantly, this accuracy can be achieved under realistic experimental conditions, including background noise and non-ideal beam shaping, demonstrating the robustness of the technique.

One of the key advantages of BLESS is its versatility, as it can accommodate photon sources with diverse photon statistics, ranging from single-photon to thermal sources. This flexibility expands the scope of potential applications and ensures the technique's relevance across various experimental setups.

The efficacy of BLESS is supported by rigorous theoretical analyses, including classical and quantum Crammer-Rao bound calculations. Additionally, numerical simulations and real experimental results provide empirical validation of the technique's performance and reliability.

In summary, our presentation introduces BLESS as a revolutionary imaging technique capable of achieving subdiffractional localization of photon emitters with unprecedented precision. Through a combination of innovative methodologies and robust experimental validation, BLESS offers a powerful tool for advancing research in quantum optics and related fields.

1. K. Katamadze, B. Bantysh, A. Chernyavskiy, Yu. Bogdanov, and S. Kulik, "Breaking Rayleigh's curse for two unbalanced single-photon emitters using bless technique," ArXiv , 2112.13244 (2023).

2. M. Tsang, R. Nair, and X.-M. Lu, "Quantum theory of superresolution for two incoherent optical point sources," Phys. Rev. X 6, 031033575 (2016).

3. R. Nair and M. Tsang, "Interferometric superlocalization of two incoherent optical point sources," Opt. Express 24, 3684 (2016).

4. R. Nair and M. Tsang, "Far-field superresolution of thermal electromagnetic sources at the quantum limit," Phys. Rev. Lett. 117, 190801 (2016).

# Squeezing extraction from mixed multimode squeezed light

Presented by **Kopylov, Denis** from
*Paderborn University*

in collaboration with

*Meier, Torsten and Sharapova, Polina*

Nowadays, one of the most relevant challenges of quantum technologies is the development of high-quality squeezed light sources, which are the basis for a huge amount of protocols in quantum optics and quantum information science [Weedbrook et al., Rev. Mod. Phys. 84, 621 (2012)]. There are two main experimental challenges which concern the multimodness of squeezed light and the presence of optical losses. The first one originates from the limitations imposed by the physical properties of parametric down conversion or four-wave-mixing processes. The parametric amplification of electromagnetic vacuum fluctuations in single-pass schemes provides multimode light, which imposes constraints on the detection system, e.g., there are strict requirements on the spectral shape of local oscillators in homodyne measurement setups. The second difficulty comes from optical losses, which are present in essentially all experiments. Losses destroy the purity of squeezed light and can corrupt the mode-structure of the resulting squeezed light. Consequently the squeezing properties of such mixed states can significantly differ from ideal pure states. For a proper development of high-quality quantum optical schemes not only the squeezed light source itself, but also the detection system has to be included. In turn, there is a high demand for descriptions of experiments with multimode squeezed light.

In this work, we theoretically investigate the mode structure of lossy broadband multimode squeezed light and show how the maximal possible squeezing can be extracted and measured. We demonstrate that in opposite to an ideal multimode squeezed states, where the unique basis of Schmidt modes can be found via Bloch-Messiah reduction of Bogoliubov transformation [Raymer and Walmsley, Phys. Scripta 95, 064002 (2020)], the broadband basis of Schmidt modes for lossy squeezed states cannot be uniquely defined. In order to construct different broadband bases, the Mercer expansion and the Williamson decomposition were considered and we show that these bases do not allow one to realize the best squeezing hidden in the system. Therefore, we introduce a new type of broadband basis for lossy systems in which the squeezing is maximized, i.e., the upper bound for squeezing is reached, and show how these modes can be constructed. As an example we illustrate properties of different broadband bases (Mercer, Williamson and basis of maximally squeezed modes) for a pulsed parametric down conversion process in a lossy medium with frequency-dependent losses [Kopylov, Meier and Sharapova, arXiv:2403.05259 (2024)].

This work is supported by the "Photonic Quantum Computing" (PhoQC) project which is funded by the Ministry for Culture and Science of the State of North-Rhine Westphalia.

# Optical quantum illumination: can the benefit of entanglement survive a beam splitter?

Presented by **Kornienko, Vladimir** from
*Department of Electronics and Nanoengineering, Aalto University, Helsinki, Finland*

in collaboration with

*Raasakka, Matti and Tittonen, Ilkka*

Electromagnetic radiation can be used in detecting and locating objects of various kinds, as demonstrated by modern radars. Quantum illumination (QI) is a class of target detection protocols where two beams sharing an entangled state are used to suppress the uncorrelated noise. Storing one of the beams and sending the other one to a remote target, QI benefits from correlations in frequency, phase, and arrival time between the beams. This facilitates the detection of a weakly reflecting target against a strong background in the low photon flux regime.

Following our recent article [1], we demonstrate how admixing a fraction of the transmitted signal to the target return affects the QI. As opposed to the uncorrelated background noise, placing a beam splitter between the transmitter and the target results in a jamming signal which is correlated with the stored beam. We show that the jammer object with the reflectance $\zeta$ deteriorates the performance of QI by a factor of $\zeta/bd$, where $b$ is the mean number of thermal photons per radiation mode, and $d$ is the number of radiation modes used in the protocol. We analyze the means to mitigate this noise and introduce an indistinguishability parameter $0 \leq \mu \leq 1$ showing how efficiently the jammer can be distinguished from the target. We use quantum Chernoff bound and the density matrix orthogonalization procedure to separate the contributions from the target, the background, and the jammer.

Our findings are illustrated with a simple experiment with optical entangled photon pairs. We use the spontaneous parametric down-conversion (SPDC) from a 0.25 mm type-I BiBO crystal pumped with a 403 nm continuous-wave laser. We only consider the correlations between the photocounts instead of a full quantum illumination protocol. The discussion is also provided on applying our results to the case of twin beam microscopy.

[1] V.V. Kornienko, C. Vidal, A. Pönni, M. Raasakka, I. Tittonen, "Partially Reflecting Jamming Objects in Correlation-Enhanced Target Detection with Entangled Photons" // APL Quantum 1, 016107 (2024).

# Reconciliation Methods for Optical Key Distribution

Presented by **Kucharczyk, Mateusz** from
*Centre for Quantum Optical Technologies, University of Warsaw*

in collaboration with

*Jachura, Michał and Jarzyna, Marcin and Banaszek, Konrad*

Data security in the digital realm primarily relies on software solutions. At the moment, a whole spectrum of solutions is being studied to safeguard the physical layer of communication between two parties. One of them is the optical key distribution (OKD) [1], which ensures security against passive eavesdropping with relatively small hardware requirements. The recently proposed [2] and demonstrated proof-of-concept setting [3] intensity modulation/direct detection (IM/DD) integrates data transmission with OKD, allowing for cost-effective generation of random cryptographic key between two legitimate users, namely Alice and Bob. The concept involves using two types of modulation for the optical signal: coarse modulation for encoding data bits and fine modulation for generating random bits, which are essential for key generation. After demodulation of the optical signal, Alice and Bob communicate over an authenticated public channel which events were rejected, and perform a key reconciliation protocol in order to produce the secret key from the raw key. The errors in the raw key arise from the discrimination thresholds employed in the demodulation process, where Gaussian statistics of intensity measurements overlap with each other. In the error correction phase, tailored low-density parity-check (LDPC) codes are designed and used, indicating the high efficiency of the reconciliation. The numerical methods in privacy amplification remove any knowledge about the key from the unauthorized eavesdropper using the hashing function SHA-3 commonly used in cryptography.

We introduce numerical methods for simulating the reconciliation protocol, with a specific focus on the efficiency of LDPC error correction codes. Additionally, we analyze the effectiveness of these techniques across various eavesdropper advantage parameters.

References: [1] T. Ikuta and K. Inoue, "Intensity modulation and direct detection quantum key distribution based on quantum noise", New J. Phys. 18, 013018 (2016). [2] K. Banaszek, M. Jachura, P. Kolenderski, and M. Lasota, "Optimization of intensity-modulation/direct-detection optical key distribution under passive eavesdropping", Opt. Express 29, 43091–43103 (2021). [3] M. Jachura, J. Szlachetka, M. Kucharczyk, M. Jarzyna, P. Kolenderski, J. P. Turkiewicz, K. Banaszek, "Simultaneous IM/DD Data Transmission and High-Rate Secret Key Distribution Over a Single C-Band Channel", Optical Fiber Communication Conference, W1H.6 (2024).

# Non-linear interferometry based on classical light

Presented by **Labonté, Laurent** from
*University of Côte d'Azur, Institute of physics of Nice (France), CNRS*

in collaboration with

*Dalidet, Romain and Martin, Anthony and Sauder, Gregory and Tanzilli, Sebastien*

This work delves into the intersection of quantum interferometry and classical methods, presenting a groundbreaking approach to achieve super-resolved single-photon interferometry. The conventional technique of generating entangled photon pairs through spontaneous parametric down-conversion has proven effective but is hampered by limitations such as a constrained rate and diminished signal-to-noise ratio when compared to classical methods. In response to these challenges, our study introduces an innovative classical method, employing coherent states of light in a single-photon detection scheme to unlock the potential of super-resolution in quantum interferometry. The work introduces the concept of maximally photonic entangled N00N states, including collective phase and super-resolution. A pivotal aspect of our approach lies in demonstrating that classical correlations can emulate quantum outcomes without the need for non-classical light generators and detectors. The discussion also underscores the induced coherence in non-linear interferometers, showcasing its applicability in mid-infrared spectroscopy. In the experimental implementation section, we elucidate the practical aspects of our proposed classical setup. Overcoming challenges related to frequency anti-correlation, energy conservation, and the role of nonlinear crystals is discussed. The work introduces a proof-of-concept experiment aimed at measuring chromatic dispersion using super-resolved single-photon interferometry. Results from our experiment are presented, showcasing an interferogram acquired during a wavelength scan. We obtain a statistical error of $2.10^2$ ‰, which falls within the manufacturer's specifications. This result is among the most precise reported to date in the literature, both in the classical and the quantum regime. The precision of our approach is bounded by the shot-noise limit, which can be surpassed through the utilization of non-classical probes. Recent studies have harnessed the advantages of quantum nonlinear interferometry, leading to a significant enhancement of measurement sensitivity beyond the shot-noise limit. However, these quantum resources are susceptible to losses. There are several scenarios in which our classical approach could offer advantages over the quantum case, particularly in domains where significant losses are systematically introduced, such as spectroscopy and imaging with undetected photons or absorption measurements. Moreover, the capability to discern optical phase at a wavelength different from the one being measured is particularly valuable in these fields, notably in the mid-IR. We have chosen to measure CD through a spectral method as a proof of principle, requiring a static measurement where the phase term within the interferometer remains constant over time. However, it is crucial to emphasize our capability to perform dynamic measurements, which represents a current challenge for quantum sensors relying on entangled photon pairs due to their moderate coincidence counting rates, limiting signal acquisition to the kHz range. In our case, detecting photons using a photodiode removes this constraint, allowing us to exploit the photodiode's bandwidth, which can extend up to several 10 GHz In conclusion, our research successfully introduces and validates a classical super-resolved single-photon interferometry approach. The proposed methodology offers an alternative to traditional quantum methods, demonstrating its potential applications in spectroscopy and imaging.

# Certification of level dynamics in single-photon emitters

Presented by **LACHMAN, Lukáš** from
*Palacký University in Olomouc*

in collaboration with

*Radko, I. P. and Bergamin, M. and Andersen, U.L and Huck, A. and Filip, Radim*

Emitters of photonic states relying on transitions among discrete energy levels in a solid state correspond to a promising platform for the prospective applications of the quantum technologies due to their easy integration. However, the further development of these emitters requires an understanding of the dynamics between an emitter and its environment. We typically assume that the environment affects the emitted light by non-radiative transition occurring through a shelving state in a solid state [1]. We propose a methodology that certifies the expected dynamics based on rejection of photonic states that mimic the impacts of the shelving state on the radiated light. This rejection is achieved by surpassing a relevant threshold established in terms of quantities measurable in the Hanbury Brown and Twiss detection scheme. In contrast to fitting [2] correlation function , this evaluation enables conclusive rejection that is analogous to tests of the nonclassicality and the quantum non-Gaussianity employed in the quantum optics [3].

[1] M. W. Doherty, N. B. Manson, P. Delaney, F. Jelezko, J. Wrachtrup, and L. C. Hollenberg, The nitrogen-vacancy colour centre in diamond, Phys. Rep. 528, 1 (2013)

[2] M. K. Boll, I. P. Radko, A. Huck, and Ulrik L. Andersen, Opt. Express 5, 28 pp. 7475-7487 (2020)

[3] L. Lachman and R. Filip, Progress in Quantum Electronics 83, 100395 (2022)

# The tripartite multiphoton Jaynes-Cummings model: bosonic entanglement, spin coherence, and Wigner nonclassicalities

Presented by **Laha, Pradip** from
*Johannes Gutenberg Universität Mainz*

in collaboration with

*Ameen Yasir, P. A. and van Loock, Peter*

Harnessing entanglement and quantum coherence plays a central role in advancing quantum technologies. In quantum optical light-atom platforms, these two fundamental resources are often associated with a Jaynes-Cummings model description describing the coherent exchange of a photon between an optical resonator mode and a two-level spin. In a generic nonlinear spin-boson system, more photons and more modes will take part in the interactions. Here we consider such a generalization, the two-mode tripartite multiphoton Jaynes-Cummings (MPJC) model. We demostrate how entanglement and quantum coherence can be optimally generated and subsequently manipulated in experimentally accessible parameter regimes. A detailed comparative analysis of this model reveals that nonlinearities within the MPJC interactions produce genuinely non-Gaussian entanglement, devoid of Gaussian contributions, from noisy resources. More specifically, strong coherent sources may be replaced by weaker, incoherent ones, significantly reducing the resource overhead, though at the expense of reduced efficiency. At the same time, increasing the multiphoton order of the MPJC interactions expedites the entanglement generation process, thus rendering the whole generation scheme again more efficient and robust. We further explore the use of additional dispersive spin-boson interactions and Kerr nonlinearities in order to create spin coherence solely from incoherent sources and to enhance the quantum correlations, respectively. As for the latter, somewhat unexpectedly, there is not necessarily an increase in quantum correlations due to the augmented nonlinearity. Towards possible applications of the MPJC model, we show how to (i) engineer arbitrary NOON states with appropriately chosen experimental parameters, and (ii) achieve perfect transfer of photon number states between the oscillators. Furthermore, besides producing substantial enhancements in the initial value for higher photon number states of the oscillators, our analysis reveals that driven solely by the initial qubit energy, with both the oscillators initialized in the vacuum state, the nonlinear MPJC interaction yields nontrivial Wigner negativities in both the oscillators.

# Towards tuneable “coupling efficiency” of a single atom using a pump-probe scheme

Presented by **Lamich, Tomas** from
*ICFO*

in collaboration with

*Zarraoa Sardon, Laura and Veyron, Romain and Mitchell, Morgan W.*

We propose an experimental implementation of a scheme proposed by Goncalves et al. [1], to produce unusual and tunable photon correlations by interfering resonance fluorescence from a single atom with probe light from a weak laser beam. A number of interesting and potentially useful features are predicted by Goncalves et al., including (under different conditions of pump-probe relative phase and power) the complete extinction of the probe, amplification of the probe, and generation of extremes of anti-bunching and bunching, i.e., $g^{(2)}$ approaching zero or infinity. Interestingly, the expressions for the transmitted power and $g^{(2)}$ can be given in terms of a single parameter, an effective interaction efficiency, suggesting that interference can be used to make up for geometrical and technical limitations on the coupling to single atoms.

We will present the current state of the experimental implementation, using a single atom far-of-resonance trap in a ”Maltese cross” geometry system of four high numerical aperture lenses [2] and recent experimental results, as well as the technical considerations we made in order to implement it, including: choice of beam geometry, to minimise the the effects of atomic motion, pump and probe polarisation, optical pumping and coherent population trapping induced by the pump and probe beams, atom heating and methods to mitigate it.

References [1] D. Goncalves, M. W. Mitchell, et al. “Unconventional quantum correlations of light emitted by a single atom in free space”. In: Phys. Rev. A 104 (1 2021), p. 013724. doi:10.1103/PhysRevA.104.013724. [2] L. C. Bianchet, N. Alves, et al. “Manipulating and measuring single atoms in the Maltese cross geometry”. In: Open Research Europe 1.102 (2022). doi: 10.12688/openreseurope. 13972.2.

# Optimization of quantum battery charging using steady-state

Presented by **Lange, Ewelina** from
*Institute of Spintronics and Quantum Information, Faculty of Physics, Adam Mickiewicz University, Poznan, Poland*

in collaboration with

*Chimczak, Grzegorz and Kowalewska-Kudłaszyk, Anna*

The development of quantum energy storage devices, known as quantum batteries (QBs), is a growing area of interest in current quantum thermodynamic research [1, 2]. QBs are formally described as d-dimensional quantum systems with non-degenerate energy levels from which work may be reversibly extracted - and energy can be reversibly deposited - using cyclic unitary operations [3]. One of the most important issues is to optimize the charging of such a battery. In the quantum scale, dissipation might be a positive phenomenon that can lead to an increase in the QB charging rate, however its negative effects must also be considered.

We present a technique of charging QB in a steady-state. We show the relationship between the maximum level to which the QB can charge and the steady-state value. This method is applicable to many QBs described by non-Hermitian Hamiltonians.

[1] J. Q. Quach et al., Sci. Adv. 8, eabk3160 (2022) [2] R. Alicki and M. Fannes, Phys. Rev. E 87, 042123 (2013) [3] F. Impens et al., Phys. Rev. A 104, 052620 (2021)

# Proposed optical test of continuous-variable quantum contextuality

Presented by **Liu, Zhenghao** from
*Danish Technical University*

Contextuality is a distinctive feature of quantum theory and has been observed in various discrete-variable systems, but a contextuality experiment using observables with continuous spectra remains elusive. Here we show how a continuous-variable test of contextuality can be achieved in an optical platform with the spatial mode degree of freedom. As an example, we give a recipe for testing a state-independent noncontextuality inequality where the compatibility of observables resembles that in the Peres–Mermin square proof of contextuality. Our approach could help to observe the nonclassicality in continuous-variable quantum systems from a hidden-variable point of view.

# To be confirmed

Presented by **Lo Monaco, Gabriele** from
*University of Palermo*

Among the proposed paradigms of supervised quantum machine learning, quantum extreme learning machine (QELM) is emerging as one of the most promising routes. In the QELM paradigm, classical data are encoded in some input qubits and are processed by a quantum circuit whose unique role is to embed the data in a higher-dimensional space and it does not contain any parameter to be optimized. The input qubits are then measured and the outcomes of the measurement are then post-processed on a classical computer in order to fit the output data. This routine allows to minimize the quantum resources needed during the training.

In this poster, I present the application of QELM to quantum chemistry and biological tasks. On quantum chemistry side, we employed QELM to learn the map between the geometry of a given molecular species and its energy, The QELM outperforms other quantum routines such as VQE and there are evidences that it may also outperform classical algorithms. We also implemented the algorithm on a IBM Quantum device, showing encouraging results for near term use.

On the biological side, we utilized QELM as a support vector machine in classification tasks for proteins with medical relevance. Also il this case, we observe that QELM may outperform classical methods using few qubits, making the algorithm suitable for immediate application on NISQ devices. Moreover, in the case of classification tasks, QELM results to be quite robust against error due to finite statistics and decoherence.

# Greedy receiver for photon-efficient optical communication

Presented by **Łukanowski, Karol** from
*University of Warsaw*

In optical communication information is encoded into a set of light states defined by the modulation format tailored to specific channel conditions. In severely power-limited scenarios, such as deep-space optical communication, pulse position modulation is the common choice due to its high photon information efficiency near the quantum-optimal Holevo limit. An $M$-PPM transmitter encodes data into the temporal position of a pulse within a frame divided into $M$ slots, whereas the goal of the output receiver is to identify the slot containing the pulse in the received frame.

Various receiver architectures have been designed to improve the demodulation performance. Two strategies are the most prevalent for PPM reception. The basic approach is to perform direct detection (DD) in each slot of the frame and output the one with the highest number of photocounts. A more sophisticated quantum-inspired approach put forward by Kennedy and Dolinar makes use of phase-space displacement of the incoming signals before direct detection. This can modify the photodetection statistics in a way beneficial for the final error probability of the receiver. The algorithm governing displacements can be prescribed, like in Dolinar's original conditional pulse nulling (CPN) scheme, as well as numerically optimized based on observed noise statistics, albeit only for low modulation orders $M$ due to exponentially increasing complexity of the decision algorithm.

In this work I introduce a new displacement receiver scheme for coherent state discrimination and apply it to PPM. The underlying displacement strategy belongs to a class of algorithms called "greedy". It displaces each slot in a locally optimal way that maximizes the probability of a correct output estimate only after the next slot is measured. The receiver reduces the error probabilities of previously proposed strategies across all signal strength regimes and achieves results comparable with those obtained by numerical optimization of the detection process. In contrast, however, it is conceptually simple and can be therefore scaled to arbitrarily high modulation orders for which numerical methods become intractable. In the photon-starved regime, the greedy receiver approaches the quantum-optimal Helstrom bound on state discrimination error probability. In the regime of few-photon pulses, the error reduction offered over the other methods grows up to an order of magnitude.

To gauge the possible advantage of greedy reception in real-life communication scenarios, I apply it to two practical use-cases of high-order PPM. For the recently launched NASA PSYCHE mission, operating in the photon-starved regime, the use of CPN or DD leaves a gap of approx. 0.30 dB to the Helstrom bound. The greedy receiver would allow to cut this in half, improving the error probability by approx. 0.15 dB over DD&CPN and approaching the bound within 0.15 dB as well. For the theorized Deep Space Optical Transceiver concept coupled with the Large Binocular Telescope, greedy reception allows to reduce the error level by a factor of three when compared with DD and CPN.

# Advantages and limitations of wavelength-division-multiplexing QKD

Presented by **Maiti, Indranil** from
*Nicolaus Copernicus University*

in collaboration with

*Lasota, Mikolaj*

In theory quantum key distribution (QKD) provides a great promise for basing the security of communication on the fundamental laws of quantum physics instead of some unjustifiable assumptions on the computational power available for the potential eavesdropper. However, practical QKD suffers from many setup imperfections leading to strong limitations on the achievable key generation rate and maximal security distance, decreasing its potential for future commercial use.

Wavelength-division-multiplexing (WDM) is one of the basic technologies utilized in classical communication to increase the bandwidth of a communication system by sending many independent signals in parallel through the same fiber. In the context of QKD it has been studied for almost 30 years, mainly as a mean to introduce quantum communication to the already existing communication networks [Electron. Lett. 33 188–190 (1997)]. However, this technology can be also used to increase the overall key generation rate produced by a QKD system alone. It can be done by spectrally splitting the signals produced by the source of correlated photon pairs in order to generate many separate keys in parallel, as suggested and experimentally demonstrated in Ref. [Quantum Sci. Technol. 6 035013 (2021)]

In this work, we theoretically investigate the proposed key rate increasing technique for the realization of the entanglement-based version of the BB84 protocol with the use of a pulsed spontaneous parametric down-conversion (SPDC) source. We estimate the possible improvement of the key generation rate provided by such a system as a function of multiple setup parameters, including the duration of the pumping pulse, the width of the effective phase-matching function describing the nonlinear crystal and the power of the source. We study multiple setup configurations by changing the length of the fibers, the types of detectors used by the receiver and the WDM channel grid. We show that with proper optimization of the setup, the combined key rate can be significantly increased in comparison with the traditional QKD setup configuration and find the constraints for this improvement in the limit of infinitely many WDM channel pairs used for the QKD process.

# Signatures and control of topological phases of interacting photons in a driven-dissipative non-linear cavity array

Presented by **Maity, Arkajyoti** from
*Max Planck Institute for the Physics of Complex Systems, Dresden, DE*

in collaboration with

*Deb, Bimalendu*

We investigate topological phases and symmetry-protected edge states by probing the optical response of a Su-Schrieffer-Heeger lattice of strongly non-linear optical microcavities. The absorption spectrum and intensity correlations of the non-equilibrium steady state of the interacting photons, show clear signatures of fermionized topological phases due to a correlation-induced Bose-Fermi mapping. We perform a detailed analysis to investigate the onset of these phases and show how one can selectively excite edge modes, bulk modes or both via fine-tuning experimentally accessible parameters.

# Projecting quantum nonlinearity to a linear system

Presented by **MANUKHOVA, Alisa** from
*Palacký University in Olomouc*

Linear oscillators contribute to most branches of the contemporary quantum science. They have already successfully served as quantum sensors and quantum memories, found applications in quantum communication, and hold promise for cluster-state-based quantum computing. To master universal quantum processing with linear oscillators, an unconditional nonlinear operation is required.

We propose such an operation using light-mediated interaction with another system that possesses a highly nonlinear potential. Such a potential grants access to a nonlinear operation that can be broadcast to the target linear system like [1]. The nonlinear character of the operation can be verified by observing negative values of the target system's Wigner function and the squeezing of the variance of a certain nonlinear combination of the quadratures below the thresholds attainable by Gaussian states.

We consider two systems, a nonlinear source one and a linear target one. The source system has access to a non-linear evolution beyond the quadratic one. We assume that the nonlinear evolution can be accessed on-demand and can be implemented as a unitary gate. The two systems can be coupled (directly or using a mediator) via a linear quantum non-demolition (QND) coupling in a pulsed manner.

We explicitly evaluate feasible optically levitating optomechanics for a proof-of-principle demonstration of the nonlinearity broadcasting to linear macroscopic atomic spin ensembles using non-Gaussianity criteria [2] and Wigner function negativity approach.

[1] A. D. Manukhova, A. A. Rakhubovsky, and R. Filip, npj Quantum Information 6, 4 (2020).

[2] D. W. Moore and R. Filip, Communications Physics 5,1 (2022).

# Ultra-fast programmable pulse pattern generator for electro-optical light control in quantum optics experiments

Presented by **Mazin, Glib** from
*Palacký University*

in collaboration with

*Švarc, Vojtěch and Dudka, Michal and Ježek, Miroslav*

Electro-optical light control plays a significant role in the advent of emerging quantum technology. Since light is a potent candidate for enabling the quan- tum technology, developing the photonic platforms become more and more relevant. Numerous fields where fast optical switching is exploited e.g., fundamental tests of physics, quantum information, photon number resolving. To achieve precise and robust operation in the mentioned areas, time of electro-optical switching is as important as low-losses. In this work, we present ultra-fast programmable pulse generator incorporated in general-purpose field-programmable gate array(FPGA) board. We demonstrate its direct application to control the split- ting ratio of a photonic coupler realized in free-space Mach-Zehnder interferometer scheme. We present its balanced time-multiplexing functionality along with active preparation of a temporal photonic state with up to 16 time bins.

# Strategies for entanglement distribution in optical fibre networks

Presented by **McAleese, Hannah** from
*Queen's University Belfast*

in collaboration with

*Vasan, Vivek and Campbell, Conall and Hawkins, Adam and Agrawal, Anuj and Kilper, Dan and Paternostro, Mauro and Ruffini, Marco*

Optical fibres play a key role in the development of large-scale quantum networks. However, distributing entanglement over long distances remains a challenge due to its fragility when exposed to environmental effects. In this work, we explore the use of various entanglement distribution protocols to examine how they could be carried out in a realistic noisy fibre network.

We study two types of protocol. The first kind is direct entanglement distribution (DED) where a maximally entangled Bell state is generated in one node and distributed to the required node pair in the network. In this case, we use zero-added-loss-multiplexing architecture [1] for the entangled photon source. The second type is entanglement distribution using separable states (EDSS) [2] where we send a carrier photon from one node of the network to another, establishing entanglement through interactions between photons at the nodes. This carrier is separable with all other systems at every point of the protocol, but instead shares quantum discord [3] with the photons with which it interacts. EDSS requires only single photon sources and we consider parametric down-conversion. We adapt two different EDSS protocols to our fibre network [2,4].

We consider a six-node network with optical fibre links of lengths ranging from 5km to 15km. We build a robust model of photon loss based on the channel and the different components required inside the nodes in the various protocols. Encoding our entangled states in photon polarisation, we analyse the effect of depolarising noise on the photonic states as the carrier passes through the fibres. This noise causes the entanglement to decrease and eventually vanish. We evaluate the amount of remaining entanglement we can distribute between each pair of nodes as the strength of the noise grows.

Since maximally entangled Bell states are highly sought-after for many quantum communication tasks, we also evaluate a range of entanglement distillation protocols to see which is the most effective in each case. This allows us to calculate how many ebits we can generate between each node pair every second.

[1] K. C. Chen, P. Dhara, M. Heuck, Y. Lee, W. Dai, S. Guha and D. Englund, Phys. Rev. Applied 19, 054029 (2023)

[2] T. S. Cubitt, F. Verstraete, W. Dür and J. I. Cirac, Phys. Rev. Lett. 91, 037902 (2003)

[3] H. Ollivier and W. H. Zurek, Phys. Rev. Lett. 88, 017901 (2001)

[4] A. Fedrizzi, M. Zuppardo, G. G. Gillett, M. A. Broome, M. P. Almeida, M. Paternostro, A. G. White and T. Paterek, Phys. Rev. Lett. 111, 230504 (2013)

# Quantifying Nonclassicality of sub-Poissonian Optical Beams via Artificial Neural Networks

Presented by **Michálek, Václav** from
*Institute of Physics of AS CR*

in collaboration with

*Peřina, Jan, Jr and Michálek, Václav and León-Montiel, Roberto, de J. and Haderka, Ondřej*

Identification of nonclassical nature of multiphoton quantum states represents a task of utmost importance in the development of the most of quantum photonic technologies. Under realistic experimental conditions, a photonic quantum state gets affected by its interaction with several non-ideal opto-electronic devices, including those used to guide, detect or characterize it. The result of such noisy interaction is that the nonclassical features of the original quantum state get considerably reduced or are completely absent in the detected, final state. The self-learning features of artificial neural networks are exploited to experimentally show using sub-Poissonian states generated by photon-number-resolved post-selection from twin beams that the nonclassicality of multiphoton quantum states can be assessed and fully characterized. This holds even in the cases in which the nonclassical features are concealed by the measuring device. The work paves the way toward artificial-intelligence-assisted experimental-setup characterization, as well as smart quantum-state nonclassicality identification.

# Irreversibility and entropy production in two coupled bosonic modes interacting with a thermal environment

Presented by **Mihaescu, Tatiana** from
*Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering*

in collaboration with

*Isar, Aurelian*

We investigate the Markovian time evolution of the entropy production rate as a measure of irreversibility created in a quantum system consisting of two coupled bosonic modes interacting with a common thermal environment. We consider a general bilinear interaction between the modes, which accounts for the excitation exchange coupling and the two-mode squeezing coupling. The dynamics of the system is described in the framework of the theory of open quantum systems based on completely positive quantum dynamical semigroups. We provide an analytical and numerical investigation of this model for initial two-mode squeezed thermal states and show that the entropy production rate strongly depends on the two considered types of coupling between the modes.

# Extremal points of the quantum set in the CHSH scenario: conjectured analytical solution

Presented by **Mikos-Nuszkiewicz, Antoni** from
*Department of Optics, Palacký University Olomouc*

in collaboration with

*Kaniewski, Jędrzej*

The security of device-independent protocols in quantum cryptography can be proven under fewer assumptions than conventional schemes. They rely on using devices producing non-local statistics, which ideally, correspond to an extremal point of the quantum set in the probability space. Observing these statistics in an experiment may ensure that the entanglement shared by parties cannot leak to an eavesdropper, securing the secret information. Optimisation of security and information processing within the device-independent paradigm is in general a cumbersome task, which could be simplified by existence of an analytical criterion for extremal points of the quantum set. However, even in the simplest non-trivial Bell scenario called Clauser-Horn-Shimony-Holt, one does not have a complete description of the extremal quantum points. In fact, only a couple of analytic families of such points are known. For example, a well-known Tsirelson-Landau-Masanes criterion only applies to points with uniform marginal probabilities. In this work, we develop its generalisation based on the sequence of papers by Satoshi Ishizaka. We propose a new set of conditions determining if a given point is an extremal point of the quantum set. The conjectured conditions have an elegant mathematical form and an intuitive geometrical interpretation. As a justification, we provide a comparison of our conditions with analytically known families of quantum extremal points and we perform numerical validations finding a full coincidence. Finally, we discuss the specific class of quantum extremal points that are not exposed points of the quantum set, such as Hardy's point, and show how they behave in terms of our conjecture.

# Distinction of electromagnetically induced transparency from Autler-Townes splitting using decaying dressed state formalism

Presented by **Mishra, Abhay** from
*QuantumDiamonds GmbH*

In this work, we form a biorthogonal basis consisting of 'left' and 'right' eigenvectors of the effective non-Hermitian Hamiltonian of a three-level $\Lambda$-type system driven by a bi-chromatic field, and resolve the probe absorption spectrum into components corresponding to the decaying dressed states of the system. It is observed that the spectrum primarily consists of three components and two of them undergo dramatic changes when the control field Rabi frequency is changed from the low to high field regime. Based on the symmetry properties of a combination of these components, a parameter internal to the dynamics of the system is defined and is used to distinguish between electromagnetically induced transparency (EIT) and Autler–Townes (AT) splitting, and the threshold for transition between them in an objective manner. The formulation is further extended to the resonance fluorescence spectrum on the probe transition in the EIT and AT regimes.

# Optimal quantum Fisher information in an unbalanced interferometer

Presented by **Mishra, Karunesh K.** from
*Extreme Light Infrastructure - Nuclear Physics (ELI-NP)*

in collaboration with

*Ataman, Stefan*

Quantum Fisher information (QFI) [1] is a tool of paramount importance in quantum metrology [2], due to its connection to the so-called quantum Cramér-Rao bound (QCRB) [3]. Indeed, this bound is the optimum one over all possible detection schemes.

In this work we address the problem of quantum Fisher information (QFI) maximization in an unbalanced lossy interferometer. Two scenarios are discussed, namely the single- ($\mathcal{F}^{(i)}$) and two-parameter ($\mathcal{F}^{(2p)}$) QFI cases [4].

The lossless case was analytically considered in [5]. The paper concluded that when no external phase reference is not available (i. e. $\mathcal{F}^{(2p)}$ applies), then the balanced case is almost always optimal. An opposite conclusion was drawn regarding $\mathcal{F}^{(i)}$.

For the lossy interferometer scenario we implemented the scheme put forward in reference [4]. For simplicity we assume losses in one arm only (modelled via the loss coefficient $\eta_2$, $\eta_2 = 1$ for the lossless case and $\eta_2 = 0$ for total losses). We obtain compact expressions for the optimized lossy QFI in each scenario, namely $\mathcal{G}^{(i)}$ ($\mathcal{G}^{(2p)}$) for the single (two-) parameter case. Their expression are $\mathcal{G}^{(i)} = \frac{\eta_2}{\frac{\eta_2}{\mathcal{F}^{(i)}} + \frac{1-\eta_2}{4\langle\hat{n}_3\rangle}}$ and $\mathcal{G}^{(2p)} = \frac{\eta_2}{\frac{\eta_2}{\mathcal{F}^{(2p)}} + \frac{1-\eta_2}{4\langle\hat{n}_3\rangle}}$ where $\langle\hat{n}_3\rangle$ denoted the average number of photons in the interferometer arm containing the phase shift. Mirroring the lossless case [5], by optimizing the transmission coefficient of the first beam splitter, we maximize each QFI in question. We consider this problem for both single- and two-parameter QFI, i. e., for the scenarios with or without access to an external phase reference. Contrary to the lossless case, calculations are much more involved, however we are able to put forward a large number of results in closed form. In order to evaluate the advantage of unbalancing an interferometer, we introduce the concept of balanced penalty, defined as the ratio of the optimized and force-balanced QCRBs, $\mathcal{P}(\eta_2) = \frac{\Delta\varphi_{QCRB}|_{\vartheta=\frac{\pi}{2}}}{\Delta\varphi_{QCRB}|_{\vartheta=\vartheta_{opt}}}$ where $\vartheta = 2\arccos T$ models the transmission coefficient of the beam splitter. Another considered metric is the QFI loss rate, $\mathfrak{L}^{(2p)}(\eta_2) = \frac{\max_{\vartheta}\{\mathcal{G}^{(2p)}(\eta_2)\}}{\mathcal{F}^{(2p)}_{max}}$. Finally, we thoroughly discuss our results through a number of examples, including both Gaussian and non-Gaussian input states. We conclude that in a lossy scenario, for both the single- and two-parameter QFI scenarios, unbalancing the interferometer brings an advantage in terms of QFI.

References [1] M. G. A. Paris, Int. J. Quantum Inf. 07, 125 (2009). [2] V. Giovannetti, S. Lloyd, and L. Maccone, Phys. Rev. Lett. 96, 010401 (2006). [3] S. L. Braunstein and C. M. Caves, Phys. Rev. Lett. 72, 3439 (1994). [4] M. Jarzyna and R. Demkowicz-Dobrzański, Phys. Rev. A 85, 011801(R) (2012). [5] S. Ataman, Phys. Rev. A 105, 012604 (2022). [6] B. Escher, et al., Nature Physics 7, 406 (2011).

# Precision angular rotation measurement: assessing the benefits of a parametric amplifier in an optical interferometer

Presented by **Mishra, Karunesh K.** from
*Extreme Light Infrastructure - Nuclear Physics (ELI-NP)*

in collaboration with

*Ataman, Stefan*

The significance of precision measurements extends beyond the validation of a specific physical theory, encompassing potential practical implementations [1-2] of the asserted theory. Nowadays, the interferometric generation and measurement of orbital angular rotation (OAM) has attracted a lot of attention. Moreover, the estimation protocols for angular displacement rotation on OAM have been successfully implemented in both SU(1,1), SU(2) as well as hybrid interferometers [3-5]. In this work, we theoretically explore the advantages presented by implementing a parametric amplifier (PA) in angular rotation estimation. We employ a Mach-Zehnder interferometer (MZI) and balanced homodyne detection scheme, with one input being a coherent state and the other being a vacuum state. We discuss both the symmetric ($\varphi/2$ in one arm and $-\varphi/2$ in the second one) as well as the asymmetric ($\varphi$ in a single arm) angular rotations. We implement two setups with a modified MZI namely: (a) No Parametric amplifier is used (b) Two Parametric amplifiers have been used in the arms of the MZI, these being characterized by gain factors ($G_1$, $g_1$) and, respectively, ($G_2$, $g_2$).

In the first case when PA is not available, we get the angular rotation sensitivity $1/4\left|\ell\alpha\cos\left(2\ell\varphi-\theta_\alpha\right)\sqrt{\tau_1}\sqrt{1-\tau_2}\right|$ for asymmetric rotations and $\frac{1}{2\left|\alpha\ell\left(\cos(\ell\varphi+\theta_\alpha)\sqrt{\tau_1}\sqrt{1-\tau_2}-\cos(\ell\varphi-\theta_\alpha)\sqrt{1-\tau_1}\sqrt{\tau_2}\right)\right|}$ in the symmetric case. Here the parameter used $\ell$ is the topological charge, $\alpha$ denotes the magnitude of the coherent beam, $\theta_\alpha$ is the phase space angle, $\varphi$ is the angular rotation of the beam, and $\tau_1, \tau_2$ are the transmissivities of the MZI. In the scenario when the PA is accessible and both PA are assumed identical i. e., ($G_1 = G_2 = G$) and ($g_1 = g_2 = g$), the angular rotation sensitivity can be evaluated to $\frac{\sqrt{g^2+2gG(\tau_2-1)\sin(4\ell\varphi)+G^2}}{4\left|\ell\alpha(G\cos(2\ell\varphi-\theta_\alpha)+g\sin(2\ell\varphi+\theta_\alpha))\sqrt{\tau_1}\sqrt{1-\tau_2}\right|}$, for an asymmetric homodyne scheme and in a similar manner we can obtain $\frac{\sqrt{g^2+2gG\sin(2\ell\varphi)+G^2}}{2\left|\alpha\ell\left((G\cos(\ell\varphi+\theta_\alpha)-g\sin(\ell\varphi-\theta_\alpha))\sqrt{\tau_1}\sqrt{1-\tau_2}+(g\sin(\ell\varphi+\theta_\alpha)-G\cos(\ell\varphi-\theta_\alpha))\sqrt{1-\tau_1}\sqrt{\tau_2}\right)\right|}$ in the symmetric case. Furthermore, in order to quantity the effectiveness of the PAs, we introduce the performance metric called effective phase sensitivity, defined as $\Delta\varphi_{\text{eff.}} = \frac{\Delta\varphi_{\text{with}_{\text{PA}}}}{\Delta\varphi_{\text{Without}_{\text{PA}}}}$. Here $\Delta\varphi_{\text{with}_{\text{PA}}}$ and ($\Delta\varphi_{\text{Without}_{\text{PA}}}$) denotes the angular rotation sensitivity with PA (without PA), respectively. The analysis of the angular rotation sensitivity reveals that parametric amplifier plays a crucial role in amplifying the quantum properties of the propagating states under suitable choices of squeezing parameters. By exploiting the non-linear interaction in the amplifiers, we achieve improved angular displacement sensitivity. Further, our analysis also allows us to ascertain the optimal parameter of the optical interferometer in order to achieve the optimal working point.

References: [1] I. Kim, et al., Nature nanotechnology 16, 508 (2021) [2] M. A. Taylor, et al., Nature Photonics 7, 229 (2013). [3] A. K. Jha, G. S. Agarwal, and R. W. Boyd, Phys. Rev. A 83, 053829 (2011). [4] J. Liu, et al., Photon. Res. 5, 617 (2017). [5] K. K. Mishra,et al., Women in Optics and Photonics in India 2022, Vol. 12638 (SPIE, 2023) pp. 72–75.

# Unlocking Quantum Sensing Precision Through Dynamical Singularities

Presented by **Naikoo, Javid** from
*Adam Mickiewicz University, Poznań, Poland*

in collaboration with

*Chhajlany , Ravindra W. and Kołodyn´ski, Jan*

Evolution of quantum systems via non-Hermitian generators offers a fresh approach to exploring their dynamic properties, such as exceptional point operation, preservation of parity-time symmetry, and exploitation of singular dynamics. Our focus lies in achieving unbounded sensitivity in sensing linear perturbations away from singular points within this framework. By integrating multiparameter estimation theory of Gaussian quantum systems with that of singular-matrix perturbations, we introduce tools necessary for probing the ultimate limits of precision in these singularity-tuned sensors. We identify conditions and rates at which sensitivity can diverge, underscoring the importance of including nuisance parameters in the analysis, as their presence may alter the error scaling with the estimated parameter.

# Robust quantum multiple-phase estimation beating classical limit in lossy environment

Presented by **Namkung, Min** from
*Center for Quantum Information, Korea Institute of Science and Technology (KIST)*

in collaboration with

*Kim, Dong-Hyun and Hong, Seongjin and Kim, Yong-Su and Lee, Changhyoup and Lim, Hyang-Tag*

Quantum state is a resource for quantum-enhancing precision in simultaneously estimating multiple phases, which could not be benchmarked by classical approaches. For example, it was shown that a multiple-phase estimation scheme with multi-mode NOON states can achieve the Heisenberg limit, which is known to be a precision limit allowed by quantum metrology, as well as can outperform classical schemes. However, in the real world, a quantum state easily decoheres due to the presence of photon loss, and the quantum-enhancement exhibited by the quantum state is also easily degraded. For this reason, it is utmost importance to investigate quantum states that optimize the precision in multiple-phase estimation, such that they exhibit the quantum-enhancement even when they are exposed to the lossy environment.

We provide optimal quantum states employed for the robust multiple-phase estimation scheme. To consider the experimental feasibility with the Sagnac interferometer setup, we focus on multiple-phase estimation schemes using discrete variable quantum states. We use the quantum Cramer-Rao bound (QCRB) to quantify the precision in simultaneously estimating multiple phases. We then demonstrate the quantum-enhancement by showing that the QCRB of the optimal quantum states can surpass the standard quantum limit (SQL), which is the QCRB limit allowed by the classical schemes, in presence of photon loss. Particularly, the optimal quantum states are different from what was proposed by Humphreys' et al. in [Phys. Rev. Lett. 111, 070403 (2013)], which is known to be optimal in the lossless case.

For experimental relevance, we further consider a multiple-phase estimation scheme where a phase-encoded quantum state is measured by a measurement consisting of a multi-mode beam-splitter followed by photon-number-resolving detectors. Here, we use the Cramer-Rao bound (CRB) to quantify the precision in estimating phases with the proposed scheme. To evaluate the optimal precision in view of the CRB, we first theoretically model the multi-mode beam-splitter via multiple two-mode beam-splitters together with phase shifters on the basis of Clements' configuration proposed in [Optica 3, pp. 1460-1465 (2016)]. Note that this configuration is known to have better experimental feasibility compared to a well-known configuration introduced in [Phys. Rev. Lett. 73, 58 (1994)]. We optimize the CRB over all possible parameters included in the multi-mode beam-splitter, as well as that over all quantum states. We show that, although it is sub-optimal compared to the QCRB, the CRB of the proposed optimal scheme can surpass the SQL. Interestingly, a quantum state optimizing precision quantified by the QCRB does not always guarantee the optimal precision by the CRB. It gives us the reason why the CRB needs to be considered for the experimental metrology.

We believe that our results are fruitful regarding the development of quantum sensing and imaging technologies which are usable in the noisy real world. The detailed information is presented in arXiv:2401.09734.

# Enhancing continuous-variable quantum key distribution by state-discrimination receivers

Presented by **Notarnicola, Michele Nicola** from
*Università degli Studi di Milano*

in collaboration with

*Jarzyna, Marcin and Olivares, Stefano and Banaszek, Konrad*

Continuous-variable quantum key distribution (CV-QKD) is the art of sharing a secret key between a sender and a receiver communicating via an untrusted channel. Several protocols have been proposed in literature employing either continuous [1,2] or discrete modulation [3,4] of coherent states. However, most of them always consider a Gaussian measurement, namely quadrature detection, at the receiver's side. This is due for many reasons. From a practical point of view, quadrature measurements are the conventional detection schemes employed in optical communications. On the other hand, from a theoretical perspective, unconditional security proofs are established in the presence of Gaussian measurements.

Nevertheless, in many other frameworks non-Gaussian measurements often outperform Gaussian ones, and this makes it interesting to investigate their role also for CV-QKD. A relevant example is provided by quantum state discrimination theory, in which Alice encodes information onto non-orthogonal states and the task is to design an efficient receiver minimizing the error probability of Bob's decision [5].

We propose a CV-QKD protocol employing quadrature phase-shift-keying (QPSK) of coherent states and a non-Gaussian measurement inspired by quantum receivers minimizing the error probability in a quantum-state-discrimination scenario. We investigate physical layer security over a pure-loss quantum wiretap channel, and design the optimized receiver maximizing the asymptotic secure key rate (SKR), namely the key-rate optimized receiver (KOR), comparing its performance with respect to the conventional heterodyne-based protocol [6]. We show that the KOR increases the SKR for metropolitan-network distances.

References:

[1] F. Grosshans and P. Grangier, Phys. Rev. Lett. 88, 057902 (2002).

[2] F. Laudenbach et al., Adv. Quantum Technol. 1, 1800011 (2018).

[3] A. Leverrier and P. Grangier, Phys. Rev. Lett. 102, 180504 (2009).

[4] M. N. Notarnicola, S. Olivares, E. orestieri, E. Parente, L. Potì and M. Secondini, IEEE Trans. Commun. 72, 375-386 (2024).

[5] G. Cariolaro, Quantum Communications (Springer, 2015).

[6] M. N. Notarnicola, M. Jarzyna, S. Olivares and K. Banaszek, New J. Phys. 25 103014 (2023).

# Paschen – Back Effect for Plasma Diagnostics

Presented by **Oganesyan, Koryun** from
*Institute of Experimental Physics SAS, Kosice, Slovakia*

in collaboration with

*Kopcansky, Peter*

The determination of the magnitude of magnetic field occupies an important place in the diagnostics of higher temperature hydrogen plasmas in external magnetic fields. The use of spectroscopic methods in hydrogen plasmas is extremely difficult because of the large Doppler and Stark broadening of spectral lines [1]. The measurement of the magnetic field by observation of the Faraday rotation of the polarization plane of light by the conduction electrons is applicable only for fairly dense plasmas in high magnetic fields [2].

Here we theoretically examine the possibility of determining the magnitude of the magnetic field in a hydrogen plasma based on the resonant Faraday rotation of the polarization plane of light by residual natural atoms in the plasma (or by specially introduced impurity atoms). We note that this method can also be used to determine the density of neutral component in a plasma when the magnetic field is known. In our earlier studies [3,4] the average and local magnetic field and neutral atom density were found in plasma.

The Faraday effect is closely coupled to the splitting and shifting of the energy levels of hydrogen atoms in a magnetic field (the Zeeman and Pashen-Back effects). Usually the hydrogen plasma is in a magnetic field $H \geq 10^3\ Oe$. For such fields the magnetic splitting parameter $\mu_0 H$ in hydrogen becomes comparable to the fine structure interval ($\delta E \approx 10^{-1}$ cm$^{-1}$) so that the Pashen-Back effect appears.

References

[1] D. Budker, W. Gawlik, D.F. Kimball, et al., Resonant nonlinear magneto-optical effects in atoms, Reviews of Modern Physics, 74, 1153 2002

[2] S.E. Segre, A review of plasma polarimetry - theory and methods, 1999 Plasma Phys. Control. Fusion 41 R57, DOI 10.1088/0741-3335/41/2/001

[3] K.B. Oganesyan, K. Dzerdziega, P. Kopcansky,et al., Polarimetric method of plasma diagnostics, Laser Phys. Lett, 2022, 19(9) 096001, DOI 10.1088/1612-202X/ac3eeb

[4] K.B Oganesyan, K. Dzier˙ze¸ga, A.H. Gevorgyan, et al. , Plasma local diagnostics by polarimetric method Laser Phys. Lett. 20 (2023) 056002, DOI 10.1088/1612-202X/accdd4

Acknowledgements:

This research is supported by the EU NextGenerationEU through the Recovery and Resilience plan for Slovakia under the project No. 09103-03-V01-00052, the Slovak Research and Development Agency under project APVV-22-0060 MAMOTEX and the Slovak Academy of Sciences, in the framework of project VEGA 2/0061/24.

# Stimulated Magneto-Optics with Different Detunings for Plasma Local Diagnostics

Presented by **Oganesyan, Koryun** from
*Institute of Experimental Physics SAS, Kosice, Slovakia*

in collaboration with

*Kopcansky, Peter*

The polarization plane stimulated rotation angle of a probe signal in an intense laser field in plasma is calculated for arbitrary detunings of intense and weak laser waves in comparison with the resonant transition frequency of the medium. Estimates of the residual gas local density in a cesium plasma based on the effects of Faraday, Cotton-Mouton and stimulated rotation of the probe signal in an intense laser have been found. It is shown, that the rotation in the medium has a complex structure consisting of the sum of only the influence of the magnetic field, only the influence of the intense laser field and the interfering part of the magnetic and intense laser fields.

It is interesting to study the anisotropic properties of resonant gases (plasma) placed simultaneously in a constant magnetic and intense light fields. The nonlinear rotation of the polarization plane that occurs in such a situation can be used to determine the magnitude of the magnetic field. The nonlinear resonant rotation of the plane of polarization is directly related to the rearrangement of atomic energy levels in an intense light pole. In our previous study [1,2] the average and local magnetic field and neutral atom density were found in plasma.

In this study, we theoretically investigated the change in the polarization of a probing light signal propagating through a resonant two-level medium in the presence of constant magnetic and intense light fields. This consideration is carried out within the framework of the adiabatic passage of a light pulse, that is, neglecting the relaxation and the spectral linewidths. We will limit ourselves to considering the resonant transition $S_{1/2} \rightarrow P_{1/2}$.

References

1. K.B. Oganesyan, K. Dzerdziega, P. Kopcansky,et al., Polarimetric method of plasma diagnostics, Laser Phys. Lett, 2022, 19(9) 096001, DOI 10.1088/1612-202X/ac3eeb

2. K.B Oganesyan, K. Dzier˙ze˛ga, A.H. Gevorgyan, et al. , Plasma local diagnostics by polarimetric method Laser Phys. Lett. 20 (2023) 056002, DOI 10.1088/1612-202X/accdd4

Acknowledgements:

This research is supported by the EU NextGenerationEU through the Recovery and Resilience plan for Slovakia under the project No. 09103-03-V01-00052, the Slovak Research and Development Agency under project APVV-22-0060 MAMOTEX and the Slovak Academy of Sciences, in the framework of project VEGA 2/0061/24.

# Efficient bosonic nonlinear phase gates

Presented by **PARK, Kimin** from
*Palacký University in Olomouc*

Continuous-variable (CV) quantum information processing harnesses versatile experimental tools that leverage the power of infinite-dimensional oscillators controlled by a single qubit. Increasingly available elementary Rabi gates have been proposed as a resource for implementing universal CV gates, but the requirement of many weak, non-commuting gates is a bottleneck in scaling up such an approach. In [1], we proposed a resource-efficient technique using Fourier expansion to implement arbitrary non-linear phase gates in a single oscillator. This method reduces the number of sequentially required gates exponentially. These gates represented by cubic, quartic, and other arbitrary nonlinear potentials have applications in CV quantum information processing with infinite-dimensional oscillators controlled by a single qubit. Our method outperforms previous approaches and enables the experimental realization of a wide range of applications, including the development of bosonic quantum sensors, simulations, and computation using trapped ions and superconducting circuits.

[1] Park, K., Filip, R. Efficient bosonic nonlinear phase gates. npj Quantum Inf 10, 25 (2024).

# Enhanced bunching of nearly indistinguishable bosons

Presented by **Pioge, Léo** from
*Université libre de Bruxelles (ULB)*

in collaboration with

*Pioge, Léo and Benoit, Seron and Novo, Leonardo and Cerf, Nicolas*

The indistinguishability of bosons is at the origin of remarkable quantum interference phenomena, such as the celebrated Hong-Ou-Mandel (HOM) effect, which arises from the impossibility of distinguishing the situation in which two identical photons have crossed a 50:50 beam splitter from the trajectory in which they have both been reflected. Destructive interference leads to the bunching of the two photons in the same output mode, an effect that becomes less pronounced as soon as the photons become partially distinguishable. Larger scale experiments involving many bosons provide a testbed for the fundamental study of more general boson bunching phenomena. The latter have been suggested as an efficient way to test the correct functioning of experiments which are difficult to simulate classically, relevant not only in photonics but also in atomic physics.

A natural way to quantify bunching is to measure the multimode bunching probabilities, $i.e.$, the probability that all photons coalesce in some chosen subset of output modes. In most practical cases, they decrease as the particles become more distinguishable. However, the behavior of multimode bunching probabilities with particle distinguishability is subtle. While numerical explorations and physical intuition strongly suggest that indistinguishable bosons should always maximize such bunching probabilities, it was recently demonstrated that this is not always the case. There exist some specific optical set-ups, with 7 or more photons, in which partially distinguishable photons prepared in a specific polarization state can exhibit higher multimode bunching probabilities than perfectly indistinguishable photons.

However, an important open question remained about the behavior of multimode bunching probabilities for input states in the vicinity of the state of perfectly indistinguishable photons. In fact, all states found to lead to anomalous bunching happened to be located $far from$ the perfectly indistinghuishable state. Moreover, any perturbation to this perfectly indistinguishable state was shown to leave multimode bunching probabilities invariant (to the first order), suggesting that it could be a local maximum.

In this presentation, we investigate the behavior of multimode bunching probabilities for *nearly* indistinguishable bosons, revealing several counterintuitive phenomena and, in particular, contradicting the above assumption about a local maximum. First, we connect the question of whether boson bunching can only decrease after a small perturbation to the state of indistinguishable bosons to a conjecture on matrix permanents introduced by Bapat and Sunder in 1986, whose physical meaning had not yet been understood. Furthermore, we convert a recent mathematical counterexample to this conjecture into a linear optical circuit, implying that multimode bunching can be actually be *enhanced* by applying a suitable perturbation to the photons' internal states. The found set-up requires 8 photons passing through a 10-mode interferometer and the perturbation requires only the ability to manipulate a two-dimensional internal degree of freedom such as polarization.

Reference: L. Pioge, B. Seron, L. Novo and N. J. Cerf. Enhanced bunching of nearly indistinguishable bosons. arXiv:2308.12226, 2023

# Picosecond laser pulses for quantum dot-microcavity based single photon generation by cascaded electro-optic modulation of a narrow-linewidth laser

Presented by **Poortvliet, Mio** from
*Leiden University*

in collaboration with

*van Amersfoort, A.C.J. and Visser, H. and Löffler, W.*

A high quality, on-demand, high-rate single photon source is crucial for photonic quantum information applications, and III-V quantum dots (QDs) in optical microcavities are a prominent candidate: this system can produce highly pure and indistinguishable single photons at GHz rates, thanks to Purcell enhancement [1]. To avoid re-excitation, we require excitation pulses much shorter than the QD lifetime, and the pulses must be bandwidth limited for efficient excitation. Such picosecond pulses are usually produced by pulse shaping of mode-locked Ti:Sa lasers with a fixed repetition rate around 80 MHz. However, modern quantum optics experiments, including GHz rate single photon generation and coherent spin manipulation, require flexible pulses that are rather hard to produce with Ti:Sa lasers. For systems with a longer lifetime such as trapped atoms or color centers, it is common to produce pulses from continuous wave lasers using an electro-optic modulator (EOM). Recent developments in integrated optics have made it possible to modulate light with several tens of GHz bandwidth. In parallel, advances in high frequency electronics allow the generation of picosecond-scale electronic pulses to drive such EOMs [2].

We show here a custom-made electronic pulse compressor to drive commercial waveguide lithium niobate EOMs, and transform continuous-wave narrow-linewidth external cavity diode laser light into high-quality optical pulses with pulse lengths down to 24 ps. By cascading two such EOMs, we show pulses down to 17 ps. Our custom-built electronics allow us to change the pulse length electronically with picosecond resolution. First, we show a novel cross-correlation technique to characterize the pulses with high resolution, and secondly, we use the pulses to coherently drive a QD-cavity system at GHz rates. We change the pulse length to investigate the transition between pulsed and continuous-wave dynamics of the cavity-QED system, including pulse length dependent Rabi oscillations and multi-photon bundles [3].

[1] Snijders, H. J. et al. Extended polarized semiclassical model for quantum-dot cavity QED and its application to single-photon sources. Phys. Rev. A 101, 053811 (2020).

[2] Dada, A. C. et al. Indistinguishable single photons with flexible electronic triggering. Optica, OPTICA 3, 493–498 (2016).

[3] Muñoz, C. S. et al. Emitters of N-photon bundles. Nature Photon 8, 550–555 (2014).

# Towards time-bin entangled photon cluster states

Presented by **Qodratipour, Siavash** from
*Humboldt university of Berlin*

in collaboration with

*Häffner, Thomas and Benson, Oliver*

Single photons are ideal carriers of quantum information due to the lack of interaction with each other. However, manipulating and controlling them for quantum computing becomes a difficult task. One-way quantum computation [1] overcomes this challenge by avoiding non-linear two-qubit interaction and instead uses highly entangled states called "cluster states". Together with single qubit measurements and feedforward a scalable universal quantum computer can be implemented [2]. The aim of our research is to realize a cluster state by fusion of few photon qubits which are time-bin encoded (early and late time-bins) in optical fibres. In this presentation, we will report on the generation of time-bin entangled photon pairs at 1560 nm and the subsequent characterization of the energy-time and time-bin entanglement by two photon interference [3]. We will also outline how we implement interferometric phase stability and arbitrary phase point control which are necessary to achieve a reproducible and deterministic interference. Scalability of our approach will be discussed as well. References: [1] Raussendorf, R. et al. Phys. Rev. Lett. 86, 5188-5191. (2001). [2] Lu, CY. et al. Nature Phys 3, 91-95 (2007). [3] Tanzilli, S. et al. Eur.Phys. J. D 18, 155-160 (2002).

# Efficient estimation of harmonic generation in unresolved sideband regime

Presented by **RÁCZ, Eva** from
*Palacký University in Olomouc*

in collaboration with

*Ruppert, László and Filip, Radim*

Harmonic generation (HG) is a well-known non-linear process in quantum optics. Usually, the different harmonics are defined well by the frequency of the respective modes. However, in some cases, it is not clear what the exponent of an HG (or HG-like) process is, so we investigate the case of efficient estimation of this unknown exponent.

The standard method uses the mean of the photon number of input and output beams. Then, assuming a power-law relation of the HG process, plotting the logarithm of the output means, the exponent could be estimated simply by the slope of the fitted line. This works reasonably well if the input is concentrated around its mean (e.g., for coherent input), but in the case of a highly fluctuating, noisy source (like a thermal or bright-squeezed vacuum source), the method does not perform as well.

We introduced an improved method, which fundamentally changes the order of taking the mean and the logarithm and discards the low-intensity, noisy observations. We show that this improved method increases estimation efficiency by an order of magnitude, providing good performance even in the case of highly fluctuating sources. We also investigated the case of an input consisting of a mixture of two harmonics. We show that the standard method produces a large bias, as the higher harmonics will dominate the lower one if only the means are investigated. With our method, we can linearize the change of the mean, providing a good estimate for the distribution of the mixed inputs. The presence of an additive noise will cause a bias also in our improved estimate, but we can minimize this effect by discarding the low value outcomes, which are most affected by this noise. Finally, we also provide an estimation method that does not use different mean values for input. That is, the exponent could be estimated even for a single input.

# Quantum Non-Gaussian states of superfluid Helium vibrations

Presented by **RAKHUBOVSKIY, Andrey** from
*Palacký University in Olomouc*

in collaboration with

*FILIP, Radim*

Quantum non-Gaussian states of phononic systems interacting with light are crucial for both fundamental research on single-phonon macroscopic quantum mechanics and practical applications in quantum technology. While non-classical mechanical states have already been demonstrated, the more challenging aspect of achieving verifiable quantum non-Gaussianity in these states remains limited. We propose a method for generating quantum non-Gaussian states with few phonons in low-temperature vibrating superfluid Helium based on photon counting detection in an optomechanical setup. Our predictions include the quantum non-Gaussian depth of these phononic states and their resilience to the relevant mechanical heating. Given the high quality of these phononic states, we confirm their ability to bunch multiple single phonons together, which will be useful for classifying them in future mechanical experiments. Furthermore, we predict that the capability of such non-Gaussian states for force sensing and thermometry will increase as the number of heralded phonons increases

# Nonclassicality of Quantum Hypergraph States in Continuous Variables

Presented by **RAVIKUMAR, Abhijith** from
*Palacký University in Olomouc*

Quantum hypergraph states form a generalisation of the graph state formalism that goes beyond the pairwise (dyadic) interactions imposed by remaining inside the Gaussian approximation. Networks of such states can achieve universality for continuous variable measurement-based quantum computation even with only Gaussian measurements. For normalised states, the hypergraph states are formed from $k$-adic interactions acting on a collection of $k$ harmonic oscillator ground states. Here, we show the criteria for hypergraph nonclassicality based on simultaneous squeezing in the nullifiers of hypergraph states, analyse quantum non-Gaussian aspects and present several basic proof-of-principle options for experiments to discover hypergraph nonclassicality for the first time.

# A central limit theorem for partially distinguishable particles

Presented by **Robbio, Marco** from
*Université libre de Bruxelles*

in collaboration with

*Robbio, Marco and Cerf, Nicolas and Novo, Leonardo and Jabbour, Michael*

The exploration of quantum interference holds significant implications both from a foundational point of view and in terms of its technological applications. Understanding the scattering behavior of multiple photons within linear networks is intricately linked to addressing key challenges in quantum information processing, metrology, and quantum state engineering. However, the phenomenon of interference between particles becomes more nuanced when considering the potential for distinguishing them, whether completely or partially, through additional characteristics such as polarization, time, or frequency. This distinction leads to the concept of partially distinguishable particles, which plays a crucial role in many quantum phenomena. In our work, we study how partial distinguishability affects equilibration phenomena after a linear interference experiment with many photons. We focus on the simplest version of the bosonic quantum central limit theorem derived by Hudson and Cushen. This theorem predicts that, after an unbiased interference experiment between many identical bosonic quantum states, the density matrix of any single output mode is well approximated by a Gaussian state. This seminal work provides the basic tools for an understanding of one of the most fundamental questions in quantum statistical physics, that is how subsystems of large bosonic quantum systems evolving unitarily reach equilibrium. However, the theorem does not take into account that different bosons may have different internal degrees of freedom, making them partially distinguishable. We derive a quantum central limit theorem taking explicitly into account partial distinguishability. This allows us to encompass in the same formalism the case of ideal bosons described by the Hudson and Cushen as well as distinguishable particles, described by classical statistics. In particular, our results allow us to predict equilibrium properties of single-mode photon number distributions, showing that they are significantly influenced by the degree of photon distinguishability. These properties in turn serve as essential quantifiers of indistinguishability in multi-photon experiments. We formalize this idea by defining a partial ordering for distinguishability matrices based on majorization, which ensures a monotonic increase of measurable quantities such as the photon number variance or the entropy of the photon number distribution. These results may be of independent interest and lead a better understanding of how indistinguishability can be seen as a resource in photonic quantum technologies.

# An Enhanced Method for Quantum Optical Coherence Tomography Employing the Michelson Interferometer

Presented by **Romanova, Anna** from
*Technology Innovation Institute*

in collaboration with

*Katamadze, Konstantin and Rodimin, Vadim*

Quantum Optical Coherence Tomography (QOCT) emerged as a promising extension of classical Optical Coherence Tomography (OCT) in the early 2000s [1]. Traditional OCT utilized a Michelson interferometer (MI) using one arm as a reference for scanning and another one for holding a test sample. Despite further advancements, there is a challenge in achieving adequate scanning depth and resolution for highly dispersive samples.

QOCT uses entangled photon pairs (biphotons) and exploits the Hong-Ou-Mandel (HOM) effect to achieve superior resolution. This method demonstrates resistance to dispersion in the sample and offers double the resolution, reaching unprecedented levels [2]. Initially, a hurdle was the requirement for a bright broadband biphoton source, typically produced by non-collinear or type-II SPDC. However, subsequent studies uncovered that QOCT could also be implemented using a brighter, broader, and easily adjustable collinear type-I SPDC source, coupled with an MI [3], where the output signal of the interferometer is divided, and then the coincidence count rate is measured. This approach not only tackles the initial challenge but also presents the same benefits as standard QOCT.

However, a new challenge arises as the signal after the MI contains both HOM interference and components from classical Michelson interference [4]. Filtering out these components, crucial for extracting desired information, becomes intricate, particularly when using ultra-broadband sources that make unwanted overlapping between these components and HOM-dip.

To address this challenge, we propose a novel scheme: measuring photon coincidence rates between two MI outputs, in contrast to the previous approach focusing on single-output signals. This modification eliminates broadband terms related to single-photon interference, simplifying data analysis. Theoretical insights and experimental findings will be discussed, examining scenarios with both interferometer arms comprising mirrors and with dispersive media in the sample arm, demonstrating dispersion cancellation.

In conclusion, our introduced MI-based scheme for QOCT enables the use of broadband collinear type-I biphoton sources and simplifies separation of HOM-dip from unwanted components. This progress not only simplifies the process of measurements and data analysis but also creates new possibilities for the practical implementation of QOCT. Our findings lay the groundwork for a more accessible and effective QOCT, moving us closer to unlocking its full potential in real-world scenarios.

[1] Abouraddy, Ayman F., Magued B. Nasr, Bahaa E. A. Saleh, Alexander V. Sergienko, and Malvin C. Teich. 2002. “Quantum-Optical Coherence Tomography with Dispersion Cancellation.” Physical Review A 65 (5): 053817. [2] Okano, Masayuki, Hwan Hong Lim, Ryo Okamoto, Norihiko Nishizawa, Sunao Kurimura, and Shigeki Takeuchi. 2015. “0.54 Mm Resolution Two-Photon Interference with Dispersion Cancellation for Quantum Optical Coherence Tomography.” Scientific Reports 5 (1): 18042. [3] Lopez-Mago, Dorilian, and Lukas Novotny. 2012. “Quantum-Optical Coherence Tomography with Collinear Entangled Photons.” Optics Letters 37 (19): 4077. [4] K. Katamadze, A. Romanova, D. Chupakhin, A. Pashchenko, and S. Kulik, “Broadband biphoton source for quantum optical coherence tomography based on a Michelson interferometer.” 2024. arXiv:2401.17836.

# Homodyne and heterodyne OPA tomography

Presented by **RUPPERT, László** from
*Palacký University in Olomouc*

in collaboration with

*Rácz, Éva and Filip, Radim*

Current advances in nonlinear optics have made it possible to perform a homodyne-like tomography of an unknown state without highly efficient detectors or a strong local oscillator. Thereby, a new experimental direction has been opened into multimode and large-bandwidth quantum optics. An optical parametric amplifier (OPA) allows us to reconstruct the quadrature distribution of an unknown state directly from the measured intensity distribution with high precision.

We propose adding a controllable displacement to the standard scheme, thus obtaining a method applicable even to asymmetric and non-Gaussian states while significantly increasing estimation accuracy and lowering the OPA amplification requirement. We investigate in more detail the case of realistic single photon detection. We obtained a model of single-photon generation that included the most relevant losses and noises in practice. In this case, the reconstruction of the state gets more difficult, so we analyzed different estimation strategies for numerically generated data to determine which performs best.

We extend the method to heterodyning; that is, we split the input mode with a beam splitter to two arms and perform a parametric homodyne measurement in the two orthogonally squeezed states. We show that in the case of estimating the full covariance matrix of the signal state, the heterodyne OPA estimation performs better than the standard homodyning. Finally, we show a potential application to perform conditional squeezing with a modified heterodyne setup.

# Stabilization of Quantum Emission to Atomic Transitions

Presented by **Said, Hala** from
*Humboldt-Universität zu Berlin*

in collaboration with

*Gomez-Lopez, Esteban and Benson, Oliver*

Single photon sources (SPS) based on quantum dots provide bright, high purity single photon on demand, making them ideal for distributing quantum information in networks, e.g., for quantum communication [1,2]. Embedding quantum dots into micropillar cavities significantly improves their efficiency and coherence [3]. Recently storage of photons from quantum dots in a quantum memory was shown [4]. The goal of our study is to stabilize the quantum dot emission to atomic (Cs) transition lines with precision of less than 100 MHz in a closed cycle cryostat (Attocube). After frequency conversion we plan to connect the quantum dot node to a distant atomic EIT memory [5]. We report on recent progress in this direction.

[1] Senellart, P., Solomon, G., White, A. (2017). High-performance semiconductor quantum-dot single-photon sources. Nature nanotechnology, 12(11), 1026-1039.

[2] Vajner, D. A.; Rickert, L.; Gao, T.; Kaymazlar, K.; Heindel, T. Quantum communication using semiconductor quantum dots. Adv.Quantum Technol. 2022, 5, 2100116.

[3] Y.-M. He, et al., Deterministic implementation of a bright, on-demand single- photon source with near-unity indistinguishability via quantum dot imaging, Optica 4, 802 (2017).

[4] S. E. Thomas, et al., Deterministic storage and retrieval of telecom light from a quantum dot single-photon source interfaced with an atomic quantum memory, Sci. Adv., eadi7346 (2024).

[5] F. Davidson-Marquis, et al., Coherent interaction of atoms with a beam of light confined in a light cage, Light: Sci. and Appl. 10:114 (2021).

# Analysis of noise impact on Bell experiment between modes of light


Presented by **Sarbicki, Gniewomir** from
*Nicolaus Copernicus University*

in collaboration with

*Ghosh Dastidar, Madhura and Bhallamudi, Praveen Vidya*


We analyse a two-mode light, where each mode is measured in one of two spatially separated laboratories using a photodetector preceded by Mach-Zender interferometers fed by coherent states in their controlling inputs. It is shown that by using two appropriate settings of MZ interferometers on both sides, one can obtain the maximal violation of the CHSH inequality.

On the poster, we will analyse the effect of noises in the optical fibre resulting from interaction with thermal EM, from the non-unitary action of MZ interferometer for finite power of the coherent state on the controlled output, and from the photodetector noise. We will discuss how these noises affect the ability of the setting to detect non-locality.

# Metrology based on multimode nonlinear interferometers

Presented by **Scharwald, Dennis** from
*Paderborn University*

in collaboration with

*Barakat, Ismail and Kalash, Mahmoud and Lindlein, Norbert and Chekhova, Maria and Sharapova, Polina*

Currently, multimode quantum light is of great interest due to the possibility of multiplexing its components, which leads to parallelization of information processing and miniaturization of devices. Such quantum light can be generated in the parametric down-conversion (PDC) process and has a great potential in metrology for multi-parameter estimation with the use of nonlinear interferometers.

Compared to classical interferometers operating with coherent light, nonlinear SU(1,1) interferometers may surpass the shot noise limit (SNL) and reach the Heisenberg scaling. However, the multimodedness of light completely destroys this important property. In our recent work [1], we present a rigorous approach for describing high-gain multimode nonlinear interferometers and demonstrate that even for strongly multimode light, it is possible to reach the Heisenberg limit at high intensities using the so-called compensated SU(1,1) interferometers (wide-field SU(1,1) interferometers). These interferometers consist of a single crystal and a focussing element to reflect the generated signal and idler radiation back through the same crystal. We show how the spatial overlap of the output Schmidt modes of the first PDC section and the input Schmidt modes of the second PDC section of such an interferometer influences the phase sensitivity.

Furthermore, we expand our approach and demonstrate how compensated multimode nonlinear interferometers can serve to simultaneously measure squeezing in different Schmidt modes [2]. In such a scheme, the second crystal can be considered as a multimode analyzer. Since in general the gain of the analyzer does not coincide with the gain of the generated PDC light, imperfect mode overlap even in a case of compensated SU(1,1) interferometer takes place. To overcome this obstacle, we construct a processing method for obtaining information about the squeezing in each output mode of the first PDC section by measuring the output intensity of light of the full nonlinear interferometer.

[1] D. Scharwald et al., Phys. Rev. Res. 5, 043158 (2023) [2] I. Barakat et al., arXiv:2402.15786v1 [quant-ph] (2024)

# Preemptive Error Suppression in Cat Codes

Presented by **Shringarpure, Saurabh U.** from
*Seoul National University*

in collaboration with

*Teo, Yong Siah and Jeong, Hyunseok*

Noiseless attenuation before a lossy channel, followed by noiseless amplification, is effective in suppressing decoherence due to photon loss. We propose the combined use of multiphoton subtraction and teleamplification on qubits encoded on the four-component cat states which is effective in suppressing errors on the encoded qubit under detection and channel losses. Bosonic codes are multiphoton superposition states with a significant contribution of the higher Fock states. For example, a large coherent-state amplitude is essential for quantum computation using the cat encodings. We exploit a key feature of the cat states that they remain cat states under any number of photon annihilations, to ensure recoverability of the original qubit with teleamplification post a nonunitary distortion due to the back-action from multiphoton subtraction. Error correction can be used subsequently to correct for the suppressed errors that were accumulated during its passage through the loss channel. We show that with a realistic, noisy scheme based on multiphoton subtraction and teleamplification, followed by numerically optimized error-correcting maps, one can get a worst-case fidelity (over all encoded pure states) of over 93.5% (82% without photon subtraction) with a success probability of about 3.42% under a 10% environmental-loss rate with 95% efficient detectors for heralding and a sufficiently large cat states with coherent-state amplitude 2. The high success probability is obtained by adapting the error-correcting maps to a greater number of outcomes during the physical realization of noiseless attenuation with multiphoton subtraction and noiseless amplification with a generalized teleamplification. Potential applications of these results may lie in quantum optical memories and direct communication for continuous-variable encoded qubits of the NISQ era wherein passive losses on the optical platform pose a challenge.

# Generation and control of quantum coherence in single atom mechanics

Presented by **Singh, Kratveer** from
*Palacký University in Olomouc*

in collaboration with

*Kovalenko, A. and Lachamn, Lukáš and Pham, T. and Číp, O. and Slodička, Lukáš and Filip, Radim*

Quantum coherence between energy eigenstates of mechanical oscillators is crucial for various applications including quantum sensing and bosonic quantum error correction protocols. A single atomic ion confined in a Paul trap and laser-cooled provides the ability to experimentally create and measure coherent superpositions of the ion's motional energy levels through the application of a sequence of laser pulses that act on both the ion's electronic states and motional states together. This allows deterministic generation and characterization of motional coherences with high fidelity. A motional Ramsey-type interferometer then allows for the precise measurement of the off-diagonal elements of the density matrix to quantify the quantum coherence. We experimentally demonstrate climbing up a hierarchy of criteria excluding the convex closure of Gaussian states of the linear oscillations by analysis of their corresponding observable coherence on a single trapped $^{40}Ca^{+}$ ion-motional oscillator. We evaluate how robust these motional coherences are against the main decoherence mechanisms in mechanical systems corresponding to the interaction with thermal amplitude and phase reservoirs.

# Phase estimation in SU(1,1) interferofermeter with feedback

Presented by **Singh, Shivani** from
*The Czech Technical University in Prague*

The phase sensitivity of SU(1,1)-interferometer with feedback is investigated. We show that the phase estimation can be improved significantly in SU(1,1)-interferometer using either sequential scheme or adaptive scheme of feedback. In the sequential scheme, both the arms of the SU(1,1)-interferometer are in the loop while in the adaptive scheme only one arm of the interferometer is fedback in the loop, respectively. Our analysis shows that the quantum Fisher information in both the schemes increases with the pump-amplitude but the enhancement rate in the adaptive scheme is higher than the sequential scheme which can be attributed to the entanglement in the system.

# Simulation methods for generation of optical GKP states

Presented by **Solodovnikova, Olga** from
*Technical University of Denmark*

in collaboration with

*Niklas, Buddinger and Andersen, Ulrik L. and Neergaard-Nielsen, Jonas S.*

In this project, we develop numerical methods to simulate continuous-variable circuits that incorporate both Gaussian and non-Gaussian elements under experimental conditions with the ultimate application of simulating realistic Gottesmann-Kitaev-Preskill state generation.

The realisation of fault-tolerant optical quantum computing relies on the ability to continuously produce high quality GKP states, a feat almost unattainable with current technology as we have yet to produce a single fault-tolerant GKP state. Unfortunately in optics, the most accessible source of Wigner negativity is provided by the photon counter; non-Gaussian states must be heralded by photocounting subsystems of an entangled multimode Gaussian state. The theoretical success probability for fault-tolerant GKP states from Gaussian Boson Samplers (GBS) is therefore very low. In a recent proposal by Takase et al., the generation probability can be increased to as high as 10%. In the proposal, many small GBS devices produce resource states that can be bred together using homodyne detection. When adaptive Gaussian operations are performed on the GBS output, more photon number events are accepted, increasing the success probability. The protocol demands high squeezing (18 dB) levels and a photon resolution capability of up to 20 photons, and does not yet consider loss. Experimental imperfections will undoubtably affect the feasibility of such an experimental setup, and it will therefore be crucial to have the ability to optimise the setup with the experimental limitations.

The numerical tools developed in this project build upon the framework from Strawberryfield's bosonicbackend by Bourassa et al. in which Gaussian states, operations and measurements can be efficiently simulated with the Gaussian Wigner function. Symplectic transforms, generaldyne measurements and Gaussian noise models can be implemented as a simple transformation of the covariance matrix and displacement vector. In the bosonicbackend, non-Gaussian states and measurements are approximated as linear combinations of Gaussians, which allows one to use the simple Gaussian transformations at the expense of growing the number of Gaussians exponentially. The bosonicbackend is therefore an alternative to using the Fock basis for simulations of CV systems.

In this project (which is a work in progress) we have solved certain limitations of the bosonicbackend by utilising a different approximation of Fock states and their superpositions and have performed numerical optimisation of GKP generation schemes using various GKP quality measures.

Takase, K. et al. Generation of Flying Logical Qubits using Generalized Photon Subtraction with Adaptive Gaussian Operations. Preprint at http://arxiv.org/abs/2401.07287 (2024). Bourassa, J. E. et al. Fast Simulation of Bosonic Qubits via Gaussian Functions in Phase Space. PRX Quantum 2, 040315 (2021).

# Challenging the role of superluminal observers in explaining quantum superpositions

Presented by **Stempin, Jędrzej** from
*Faculty of Physics, Adam Mickiewicz University*

in collaboration with

*Grudka, Andrzej and Wójcik, Antoni and Wójcik, Jan*

The dichotomy between classical and quantum descriptions of reality poses profound challenges, demanding a detailed understanding at its core. Recent investigations by Dragan and Ekert (New J. Phys. 22 (2020) 033038) have proposed a novel approach, urging for the consideration of "superluminal observers" to explain the counterintuitive results of quantum theory. Their conjecture relies on the idea that the expansive mathematical framework of the generalized Lorentz transformation may contain valuable insights into the emergence of multiple quantum mechanical trajectories. Contrary to this proposition, our study offers a divergent interpretation. We present compelling evidence that, under careful study, the generalized Lorentz transformation fails to establish a coherent link between the classical notion of a definite path and the multiplicity of paths inherent in quantum mechanics.

# Nonlocal correlations in CV

Presented by **Sudak, Nazarii** from
*University of Wroclaw*

in collaboration with

*Barasiński, Artur and Peřina, Jr., Jan*

Investigation of nonlocal realism violations using entangled continuous- and hybrid-variable states with dichotomic observables. Specifically, examination of cases with pseudospin operators and Wigner representations in phase space, parity measurement, and displacement operations. Addressing a proposed measure of nonlocality, we demonstrate its utility and limitations in detecting nonlocal correlations efficiently with random measurements, achieving up to 100% detection efficiency and reducing experimental requirements significantly.

# Quantum Non-Gaussianity and sensing with distilled Fock states of light

Presented by **GODAVARTHI, Phani Teja** from
*Palacký University in Olomouc*

New fundamental tests involving nonclassical photons and their applications demand highly quantum non-Gaussian resources. Fock states of light serve as crucial components, directly applicable to quantum sensing and communication. However, generating high Fock states with verifiable quantum non-Gaussian features remains a significant challenge, despite employing conditional methods to distill approximate states from Gaussian ones. Here, we conclusively estimate and analyze the power of the distillation approach and discuss the principal requirements based on the use of a hierarchy of quantum non-Gaussian criteria, the robustness of such features, the bunching capability of realistic Fock states, and the sensing capability to estimate the magnitude of unknown force and noise.

# Measurement of quantum entanglement and Bell nonlocality in two-bit states on quantum processors

Presented by **Tulewicz, Patrycja** from
*Institute of Spintronics and Quantum Information, Adam Mickiewicz University Poznań, Poland*

in collaboration with

*Bartkiewicz, Karol*

Measuring complex aspects of quantum systems, like entanglement and Bell inequality violations can be a challenge. The usual way involves analyzing the full density matrix of the system, which demands detailed knowledge of the quantum system, under study, while we propose an alternative method using non-classical correlations that are invariant to local unitary operations.

To reduce the amount of system information needed, we can use multiple copies of the system under study and take common measurements. Although this approach was once considered impractical due to the complexity of preparing and controlling quantum correlated systems, we show that despite challenges including nonlinear amplification of experimental noise, it has become workable.

In our research, we successfully measured two-qubit quantum systems for Horodecki and Werner states, using this multicopy approach outlined in [1,2]. We tested on both, noiseless simulations and real quantum processors from IBMQ [3] to determine negativity and nonlocality values. We compared our approach with the conventional tomography-based method.

To deal with noise problems, we employed a maximum likelihood method that considers physical constraints on jointly observed multicopy data. Additionally, using SHAP analysis [4], we pinpointed the impact of specific singlet projections on entanglement witnesses. Based on that results, we demonstrated the possibility of training a neural network to quantify nonlocality and negativity in quantum systems base on the singlet projections with the greatest impact.

Acknowledgments This work was supported by the Polish National Science Centre from funds awarded through the Maestro Grant No. DEC-2019/34/A/ST2/00081.

References: [1] K. Bartkiewicz, G. Chimczak, and K.Lemr, Phys. Rev. A 95, 022331 (2017). [2] K. Bartkiewicz and G. Chimczak, Phys.Rev. A 97, 012107 (2018). [3] IBM Quantum, https://quantum-computing.ibm.com/, (2021). [4] S. M. Lundberg and S.-I. Lee, Advances in Neural Information Processing Systems 30, Curran Associates, Inc., pp. 4765–4774 (2017).

# Macroscopic distant magnon modes entanglement via a squeezed reservoir

Presented by **Ullah, Kamran** from
*Koc University*

in collaboration with

*Naseem, Tahir and Mustecaplıoglu, Ozgur.*

The generation of robust entanglement in quantum system arrays is a crucial aspect of the realization of efficient quantum information processing. Recently, the field of quantum magnonics has garnered significant attention as a promising platform for advancing in this direction. In our proposed scheme, we utilize a one-dimensional array of coupled cavities, with each cavity housing a single yttrium iron garnet (YIG) sphere coupled to the cavity mode through magnetic dipole interaction. To induce entanglement between YIGs, we employ a local squeezed reservoir, which provides the necessary nonlinearity for entanglement generation. Our results demonstrate the successful generation of bipartite and tripartite entanglement between distant magnon modes, all achieved through a single quantum reservoir. Furthermore, the steady-state entanglement between magnon modes is robust against magnon dissipation rates and environment temperature. Our results may lead to applications of cavity-magnon arrays in quantum information processing and quantum communication systems.

# Optimization of two-photon absorption for three-level atom

Presented by **Valipour, Masood** from
*Nicolaus Copernicus University in Torun*

in collaboration with

*Sarbicki, Gniewomir and Słowik, Karolina and Dąbrowska, Anita.*

We consider an interaction of a three-level atom of a ladder configuration with a propagating light prepared in a continuous-mode two-photon state [1]. We study the probability of two-photon absorption by the atom using the result obtained within the input-output formalism [2, 3] in the framework of standard assumptions made in quantum optics. Namely, a flat coupling constant, rotating wave approximation, and the extension of the lower limit of integration over frequency to minus infinity [2, 4]. Thus, we assume that the bandwidth of the light pulses is much smaller than their central frequencies. In this approach, the evolution of the atom interacting with a wave packet of a definite number of photons is given by a set of hierarchical equations [5, 6]. This set can be solved analytically [7]. The starting point in our consideration is the analytical formula for the probability of two-photon absorption for the three-level atom. We study the time-dependent probability of the excitation of the system. Our principal goal is to optimize the pulse shape to achieve the highest probability of two-photon absorption. We show how the field drives the atom and how the effectiveness of this process depends on the state of light and the parameters of the atom such as the lifetime of the excited states. We present the solution to this problem for different states of light. We study and compare different scenarios including entangled and unentangled photon pairs. We show that field correlations can significantly enhance the two-photon absorption probability for short-lived middle states. The excitation probability is considerable even in the virtual-state regime for correlated two-photon inputs, while it goes to zero for uncorrelated photon pairs.

[1] R. Loudon, The Quantum Theory of Light, third edition, (Oxford University Press, Oxford, 2000). [2] C. W. Gardiner, P. Zoller, Quantum noise, Springer-Verlag, Berlin-Heidelberg (2010) [3] H. M. Wiseman, G. J. Milburn, Quantum measurement and control, University Press, Cambridge (2010) [4] M. O. Scully, M. S. Zubairy, Quantum Optics, Cambridge University Press, Cambridge (1997) [5] B. Q. Baragiola, R. L. Cook, A. M. Brańczyk, and J. Combes, Phys. Rev. A, 86, 013811 (2012). [6] A. Dąbrowska, G. Sarbicki, D. Chruściński, Phys. A: Math. Theor. 52, 105303-1–105303-22 (2019). [7] A. Dąbrowska, paper in preparation

# Microwave-to-Optical conversion by cold atoms

Presented by **Varga, Daniel** from
*Wigner Research Centre for Physics*

Microwave-to-Optical conversion is an important research area, especially in quantum communication, where we must connect the long-range optical and short-range microwave signals. Rb atoms have the interesting property that they are sensitive both to microwaves and optical frequencies at same time. In our measurements we use a cold atomic cloud trapped in a MOT, which than is transported into a high finesse optical resonator. There the atoms can be kept either in an optical dipole trap or a purely magnetic trap. We can aim a high-powered microwave antenna towards the atoms from outside the vacuum chamber. In this way we demonstrated that the atomic cloud interacts both with the microwave radiation and the optical field. Currently we are developing a new system where we integrate a nearfield microwave antenna into the optical resonator itself, such that both can be used at same time to manipulate the Rb atoms.

# The Synthesis: high precision sensing in quantum astrometry, super-resolution microscopy and beyond


Presented by **Vintskevich, Stephen** from
*Technology Innovation Institute*

in collaboration with

*Katamadze, Konstantin and Stankus, Paul and Nomerotski, Andrei and Slosar, Anze*


Developing advanced optical imaging techniques and processing information from optical measurements is crucial for super-resolution microscopy[1] and high-precision astrometry[2,3]. One seeks to break Rayleigh's curse for sources that generally could have different statistics (e.g., single-photon or/and thermal sources). Recently, various techniques (SPADE, SLIVER (see [4] and reference within), BLESS [5], etc.) were proposed for harnessing the quantum features of light, combining quantum and classical optical information to achieve high-speed super-resolution computational imaging[6]. However, it is still challenging to synthesize all the pros and cons of all these approaches together. The goal is to gain intuition about how one can harness the quantum features of light to achieve the best precision when the number of sources grows (e.g., hundreds of sources that we need to resolve), what is an optimal and feasible measurement protocol for sources with different types of statistics or when sources have mixed statistics, etc. In the present work, we propose a very compact, practical ansatz describing the state of the field in the observation plane produced by an ensemble of statistically independent sources. Within our ansatz density operator has the following form:

$\hat{\varrho} = \int \prod_{s=1}^{Ns} P(\alpha_s) \left( |\{\sum_s^{Ns} \alpha_s f_s(\vec{k})\}\rangle\langle\{\sum_s^{Ns} \alpha_s f_s(\vec{k})\}| \right) \left( \prod_s^{Ns} d^{(2)}\alpha_s \right)$, where value is the total number of sources. We use Glauber - Sudarshan representation for a density operator describing the ensemble of sources.

The main advantage of this ansatz is the ability to perform a relatively straightforward analysis to estimate the scalability of the Cramer - Rao bound (as a precision measure) concerning the growth of the number of sources. We use the Gaussian Continuous Variable Quantum Information Processing framework to derive and analyze Quantum Fisher Information. However, we can also consider the case of an ensemble of single-photon sources by slightly modifying its form. Note that the proposed ansatz perfectly fits both astrometry and microscopy.

While the Cramer - Rao bound provides an upper limit for precision estimation, its practical achievability can be a challenge. In addition, our research focuses on developing suboptimal protocols and algorithms that can enhance overall precision. Our approach is based on a thorough analysis of symmetric logarithmic derivative operators' algebraic ("geometric") structure, combined with insights from compress sensing/sampling. We expect that these ideas will pave the way for the development of practical, feasible techniques and high-speed algorithms for high-precision super-resolution microscopy and astrometry with multiple sources.


[1] Mankei Tsang, Ranjith Nair, and Xiao-Ming Lu, Phys. Rev. X 6, (2016)

[2] P. Stankus, A. Nomerotski, A. Slosar, and S. Vintskevich, The Open J. Astrophysics (2022).

[3] Z. Chen, A. Nomerotski, A. c. v. Slosar, P. Stankus, and S. Vintskevich, Phys. Rev. D 107, 023015 (2023).

[4] Shan Zheng Ang, Ranjith Nair, and Mankei Tsang, Phys. Rev. A 95, 063847 (2017)

[5] K. Katamadze, B. Bantysh, A. Chernyavskiy, Y. Bogdanov, and S. Kulik, ArXiv p. 2112.13244 (2023).

[6] Randy A. Bartels, Gabe Murray, Jeff Field, Jeff Squier, Intell Comput. 2022:0003.

# Topological Invariants in Discrete Time Quantum Walks

Presented by **Wójcik, Jan** from
*Adam Mickiewicz University*

in collaboration with

*Grudka, Andrzej and Karczewski, Marcin and Kurzyński, Paweł and Wójcik, Antoni*

We focus our presentation on discrete-time quantum walks and their topological properties. Quantum walks are periodically driven (Floquet) systems. Their discrete model due to its simplicity may be a very powerful tool while studying complex systems. They've been studied both theoretically and experimentally [1]. As was previously shown even the most basic model of the quantum walk may have some interesting topological properties. Quantum walks can help study topological phenomena as was shown in [2-3]

The dynamic of a quantum walk consists of two parts, the step of the walker and the coin toss. We can distinguish the topological properties of the quantum walk based on the coin toss operator.

We define topological properties for translational invariant walks. Due to this symmetry, we define a unique map from the first Brillouin zone to the Bloch sphere. We want to infer the topological properties of discrete-time quantum walks only by studying this map.

Until now the most popular way to approach the distinction of topological phases in quantum walks is the usage of a winding number.

In a recent paper [5] we show possible issues regarding inferring the topological properties of a quantum walk only from studying the winding number. We propose a new approach. Using relative homotopy we propose a new topological invariant. We show that it agrees with previous models and more generalized ones. Our invariant indicates the number of edge states at the interface between two topological phases. We identify those states for arbitrary coin toss operators. Those states we found to be protected by PHS. We manage to find the exact form of topological edge states in the sharp edge model.

[1] J. Wu, W.-W. Zhang, and B. C. Sanders, Frontiers of Physics 14, 61301 (2019). [2] F. Harper, R. Roy, M. S. Rudner, and S. L. Sondhi, Annual Review of Condensed Matter Physics 11, 345 (2020). [3] T. Kitagawa, Quantum Information Processing 11, 1107 (2012). [4] T. Kitagawa, M. S. Rudner, E. Berg, and E. Demler, Physical Review A 82, 033429 (2010). [5] A. Grudka, M. Karczewski, P. Kurzyński, J. Wójcik and A. Wójcik, Phys. Rev. A 107 (2023) 032201.