Criticality and Continuous Measurements in Quantum Sensing: From Theory to Experiments

BOOK OF ABSTRACTS

— — — Invited Talks — — —

CAROLLO, Angelo

(Università di Palermo)

Critical sensing in non-Hermitian topological quantum phase transition

Non-Hermitian (NH) physics gives rise to unique phenomena, including exceptional points and the NH skin effect, resulting in quantum systems with distinct topological properties. We demonstrate that NH topological systems can serve as probes for bulk Hamiltonian parameters, achieving quantum-enhanced sensitivity up to Heisenberg scaling. This enhancement emerges near a spectral topological phase transition, where the entire spectrum undergoes a delocalization transition. We attribute this heightened sensitivity to the closing of the point gap, a distinctive NH energy gap with no counterpart in Hermitian systems. This establishes a direct connection between energy-gap closing and quantum enhancement in NH systems. Our findings are illustrated through several key NH topological models across different dimensions, along with potential experimental realizations.

FILIP, Radim

(Palacky University)

Quantum non-Gaussianity from genuine nonlinearity

The talk will report recent theoretical and experimental achievements that have opened the door to highly non-Gaussian quantum states at optical, microwave, and mechanical platforms from a genuine quantum nonlinearity. This territory is challenging for investigation, both theoretically and experimentally. We will present recent achievements, mainly the experimental tests of climbing the hierarchy of quantum non-Gaussian photonic and phononic states suitable for applications in sensing. Particular focus will be on new quantum non-Gaussian coherences and their experimental verification. The talk will conclude with related results and the following challenges in theory and experiments with genuine quantum nonlinear interactions with light, atoms, mechanical oscillators, and superconducting circuits to stimulate discussion and further development of this advancing and prospective field.

GATTI, Claudio

(Laboratori Nazionali di Frascati INFN)

Quantum Sensing for High Frequency Gravitational Waves and Axion Dark Matter

Microwave cavities in strong magnetic fields are among the most promising tools for detecting dark-matter axions and high-frequency gravitational waves. These searches rely on the Primakoff and Gertsenshtein effects, which predict the conversion of axions and gravitational waves, respectively, into electromagnetic radiation in the presence of a strong static magnetic field. In a microwave cavity, this interaction leads to the displacement of the vacuum state of the resonant mode, generating a coherent electromagnetic signal. Given the expected signal weakness, developing detectors with sensitivity beyond the quantum limit is crucial. In the C and X bands of the electromagnetic spectrum, superconducting qubits have demonstrated exceptional performance for this purpose. However, strong magnetic fields pose challenges, requiring either signal transport to a shielded region or the use of magnetically resilient devices. Additionally, qubit state readout errors due to noise and dephasing limit sensitivity. These challenges can be mitigated through quantum non-demolition measurements, either by repeating the measurement over time or employing multiple qubits simultaneously. During the talk, we will discuss ongoing developments at the COLD laboratory of the INFN Frascati National Laboratories, focusing on non-demolitive measurement techniques and the development of magnetically resilient qubits.

GIETKA, Karol

(University of Innsbruck)

Quantum Metrology in the Ultrastrong Coupling Regime of Light-Matter Interactions: Leveraging Virtual Excitations without Extracting Them

Virtual excitations, inherent to ultrastrongly coupled light-matter systems, induce measurable modifications in system properties, offering a novel resource for quantum technologies. In this work, we demonstrate how these virtual excitations and their correlations can be harnessed to enhance precision measurements, without the need to extract them. Building on the paradigmatic Dicke model, which describes the interaction between an ensemble of two-level atoms and a single radiation mode, we propose a method to harness hybridized light-matter modes for quantum metrology. Our results not only highlight the potential of virtual excitations to surpass classical precision limits but also extend to a broad range of ultrastrongly coupled systems.

KHANAHMADI, Maryam

(Chalmers University of Technology)

Qubit readout and quantum sensing with pulses of quantum radiation

Different hypotheses about a quantum system such as the logical state of a qubit or the value of physical interaction parameters can be investigated by the interaction with a probe field. Such fields may be prepared in particularly sensitive quantum states and we demonstrate here the use of quantum trajectories to model the stochastic measurement record and conditional evolution of the state of the quantum system subject to its interaction with a traveling pulse of radiation. Our analysis applies to different measurement strategies and to arbitrary input quantum states of the probe field pulse and it thus permits direct comparison of their metrological advantages.

KOLODYNSKI, Janek

(Institute of Physics, Polish Academy of Sciences)

Quantum sensing with photodetection: lessons from Bayesian inference and machine learning

Quantum sensing schemes based on measurements of quantum jumps present significant challenges for statistical inference. The likelihood of a specific detection pattern is often intractable, hindering the use of Bayesian methods for real-time estimation. In this talk, I will demonstrate how likelihood-free, sampling-based methods, combined with the efficient Monte Carlo wave-function approach for simulating measurement data, can circumvent this problem. Using an off-resonantly driven two-level system and an optomechanical device probed by photodetection as examples, I will show that understanding photon-click statistics is crucial for this approach to succeed and exploit quantum effects. Finally, I will compare this strategy with machine learning-based methods, demonstrating that while the latter are nominally model-free, their performance can be substantially enhanced by accounting for the underlying physics.

LESANOVSKY, Igor

(Universität Tübingen)

Continuous sensing and parameter estimation with the boundary time crystal

A boundary time-crystal is an open many-body system that features a transition between a stationary and an oscillatory phase. It can be realised within dense atomic gases or atoms held in a cavity. The fact that the system is open allows one to continuously monitor its quantum trajectories and to analyze their dependence on parameter changes. This enables the realization of a sensing device whose performance we investigate as a function of the monitoring time and system size. The best achievable sensitivity turns out to follow the standard quantum limit in time and Heisenberg scaling in the particle number. This theoretical scaling can be achieved in the oscillatory time-crystal phase and it is rooted in emergent quantum correlations. A central challenge is, however, to tap this capability in a measurement protocol that is experimentally feasible. We show that the standard quantum limit can be surpassed by cascading two time crystals, where the quantum trajectories of one time crystal are used as input for the other one.

[1] A. Cabot, F. Carollo and I. Lesanovsky, Continuous Sensing and Parameter Estimation with the Boundary Time Crystal, Phys. Rev. Lett. 132, 050801 (2024)

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MACCONE, Lorenzo

(Università di Pavia)

Mutual information vs Fisher and... quantum classifiers

I present two results: on one hand a series of inequalities that connect the local quantum metrology (based on the quantum Cramer-Rao bound) to a version of global quantum metrology (based on the mutual information between the measurement outcomes and the parameter that must be estimated). On the other hand, I show how quantum effects can be useful in complex machine learning task, such as image classification.

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PARAOANU, Gheorghe-Sorin

(Aalto University)

Josephson parametric amplifiers as photon detectors

Abstract: Josephson parametric amplifiers operated near the boundary of the first-order transition can serve as sensitive detectors of photons, magnetic fields, and frequency shifts. I will present an experiment demonstrating efficiency of the order of 73% and NEP of the order of 3.3 zW/sqrt(Hz) for the detection of microwave photons around 6 GHz. Although this detector does not have PNR (photon-number-resolving) capabilities, one can still observe signatures of the statistics of the incoming field. I will also present the theory of operation based on the method of separation of variables into slow and fast, and the resulting effective-potential theory, comparing them with the results obtained by numerical simulations of the Heisenberg-Langevin equations.

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PARIS, Matteo

(Università degli Studi di Milano)

About Some Recent Little Advances in the Field of Multiparameter Quantum Estimation

In multiparameter quantum estimation, an achievable ultimate scalar bound on the overall precision of the strategy is provided by the so-called Holevo bound, CH. Unfortunately, this bound cannot be evaluated analytically in the general case. The Holevo bound is itself bounded by the relation CS≤CH≤CS(1+R), where CS is the bound obtained from the SLD-based quantum Fisher information, and R is referred to as the asymptotic incompatibility (or simply "quantumness") of the quantum statistical model. Since 0≤R≤1, this relation is considered to mitigate the difficulties in evaluating CH. In this talk, we present some results on the evaluation of the Holevo bound for specific, yet relevant, quantum statistical models. We also discuss whether and when the quantity R is suitable for quantifying the difference between CS and CH. Finally, we explore how to assess the precision of stepwise multiparameter quantum estimation and compare it to joint estimation schemes.

PERARNAU LLOBET, Martí

(Universitat Autònoma de Barcelona)

Fundamental limits of quantum and thermal critical metrology

Abstract: "In this talk, I will discuss recent progress on our understanding of the fundamental limits of many-body metrology -and their reachability via physically relevant Hamiltonians. Focusing on a standard setting where the unknown parameter is encoded in the Hamiltonian of the many-body probe, various bounds on the Quantum Fisher Information will be presented for both dynamical and steady-state metrology, covering ground states and thermal states. The implications of these bounds for quantum critical metrology will be discussed, along with specific applications in magnetometry. If time permits, implications for the time of thermalization of many-body systems will be discussed. This talk is based on two recent works: arXiv:2402.06582 and arXiv:2412.02754."

ROUCHON, Pierre

(Mines ParisTech)

Stochastic master equations, quantum filtering and estimation: a computational perspective.

Dynamics of open quantum systems subject to decoherence and measurement back-action are governed by stochastic master equations (SME). These SME share the same structure underlying completely-positive and trace-preserving (CPTP) numerical scheme and providing an efficient way to compute the log-likelihood. Thus SME can be exploited for Bayesian inference and Maxlilke estimation. The case-study considered in https://ieeexplore.ieee.org/document/10542346 illustrates such computational perspective.

SCARLINO, Pasquale

(École polytechnique fédérale de Lausanne)

Dissipative Phase Transitions and Critical Quantum Sensing in Superconducting Two-Photon Driven Kerr Resonators

Dissipative phase transitions (DPTs) arise in open quantum systems from the interplay between coherent driving, nonlinearity, and dissipation, exhibiting rich critical behavior in the thermodynamic limit [1]. In this work, we present a comprehensive experimental and theoretical exploration of first- and second-order DPTs in superconducting two-photon (parametrically) driven Kerr resonators [2]. We first characterize the steady-state properties of the system, observing squeezing below vacuum near the second-order critical point and phase coexistence at the first-order transition. By monitoring quantum trajectories, we investigate the non-equilibrium dynamics across the critical points, witnessing hysteresis cycles and spontaneous symmetry breaking. Applying Liouvillian spectral theory, we quantify the critical slowing down of relaxation times, which span several orders of magnitude as the system approaches the thermodynamic limit.

Building upon this control of criticality, we implement a quantum metrology protocol using the same platform [3]. Operating near the finite-component second-order DPT, we demonstrate a critical quantum sensor based on a Kerr resonator terminated by a superconducting quantum interference device [4]. We show that frequency estimation precision scales quadratically with system size, enabled by the divergence of quantum fluctuations near criticality. Our results highlight how criticality can be exploited to enhance sensitivity, offering a path toward more precise and faster metrological protocols.

Together, these findings establish two-photon driven Kerr resonators as a versatile platform for engineering dissipative phase transitions and leveraging critical phenomena to achieve quantum-enhanced sensing.

[1] Minganti, F., Biella, A., Bartolo, N., & Ciuti, C. (2018). Spectral theory of Liouvillians for dissipative phase transitions. In Physical Review A (Vol. 98, Issue 4)

[2] Beaulieu, G., Minganti, F., Frasca, S. et al. Observation of first- and second-order dissipative phase transitions in a two-photon driven Kerr resonator. Nat Commun 16, 1954 (2025).

[3] Di Candia, R., Minganti, F., Petrovnin, K.V. et al. Critical parametric quantum sensing. npj Quantum Inf 9, 23 (2023).

[4] Beaulieu, G., Minganti, F., Frasca, S., Scigliuzzo, M., Felicetti, S., Di Candia, R., & Scarlino, P. (2024). Criticality-Enhanced Quantum Sensing with a Parametric Superconducting Resonator. arXiv:2409.19968

STEELE, Gary

(Kavli Institute of Nanoscience Delft)

Parametric phenomena in superconducting Kerr oscillators: Sensing, period double transitions, and transitions to chaos

In this talk, I will present work from our group exploring the physics and applications of superconducting Kerr oscillators under strong parametric driving. Starting with strong, single-tone driving of a nonlinear superconducting cavity, we observe a wide range of phenomena, including non-linear dissipation dynamics originating from quantum noise, the emergence of a negative-effective-mass Bogoliubov mode, cavity frequency stabilisation by intrinsic Kerr feedback dynamics, and squeezing-enhanced parametric interactions through Hamiltonian amplification. Including a second strong drive, we create a Kerr parametric oscillator (KPO), observing spectroscopic signatures of a few-photon parametron, squeezing, and biased switching dynamics. In the strong driving limit, we observe a transition from the period-doubling regime of the KPO into a regime of chaotic behavior, characterised by the onset of wideband background noise along with structure in quadrature phase-space observations reminiscent of quantum scars of chaotic attractors.

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YANG, Dayou

(Universität Ulm)

New Opportunities for Sensing via Continuous Measurement

The continuous monitoring of driven-dissipative quantum optical systems provides key strategies for the implementation of quantum metrology, with prominent examples ranging from the gravitational wave detectors to the emergent driven-dissipative many-body sensors. Fundamental questions about the ultimate performance of such a class of sensors remain open—for example, how to perform the optimal continuous measurement to unlock their ultimate precision; how to effectively enhance their precision scaling towards the Heisenberg limit? In this talk I will present our recent theoretical efforts towards answering these questions. In the first part I will present a universal backaction evasion strategy for retrieving the full quantum Fisher information from the nonclassical, temporally correlated fields emitted by generic open quantum sensors, thereby to achieve their fundamental precision limit. In the second part I will introduce dissipative criticality as a resource for nonclassical precision scaling for continuously monitored sensors, by establishing universal scaling laws of the quantum Fisher information in terms of critical exponents of generic dissipative critical points. Finally, if time permits, I will touch on our effects to determine the precision limit of generic continuous sensors subjected to experimental noise and imperfections.

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YOUSEFJANI, Rozhin

(Hamad Bin Khalifa University)

Exploiting Criticality in Many-Body Quantum Systems for Enhanced Sensing

Quantum criticality in many-body systems offers a promising avenue for achieving enhanced sensitivity in quantum sensing applications. This presentation will explore how various types of criticalities—such as second-order phase transitions—can be harnessed to improve measurement precision. I will discuss the role of Stark localization as a resource for weak-field sensing, demonstrating how gradient fields can suppress particle tunneling in a lattice, leading to an ultra-precise measurement in the extended phase. Additionally, I will examine the potential of discrete time crystal phases as a resource for quantum-enhanced sensing, highlighting their stability and sensitivity characteristics. A comprehensive overview of recent advancements in quantum metrology with many-body systems will be provided, emphasizing both equilibrium and non-equilibrium scenarios.

[1].X. He, R. Yousefjani, and A. Bayat, “Stark localization as a resource for weak-field sensing with super-Heisenberg precision,” Phys. Rev. Lett. 131, 010801 (2023).
[2].R. Yousefjani, X. He, and A. Bayat, “Long-range interacting Stark many-body probes with super-Heisenberg precision,” Chin. Phys. B 32, 100313 (2023).
[3].R. Yousefjani, X. He, A. Carollo, and A. Bayat, “Nonlinearity-enhanced quantum sensing in stark probes,” Phys. Rev. Appl. 23, 014019 (2025).
[4].R. Yousefjani, K. Sacha, and A. Bayat, “Discrete-time crystal phase as a resource for quantum-enhanced sensing,” arXiv:2405.00328 (2024).
[5].Montenegro, C. Mukhopadhyay, R. Yousefjani, S. Sarkar, U. Mishra, M. G. A. Paris, and A. Bayat (2024), 2408.15323.

——— Contributed Talks ———

AMOROS-BINEFA, Julia

(University of Warsaw)

Tracking time-varying signals with quantum-enhanced atomic magnetometers

Quantum entanglement, in the form of spin squeezing, is known to improve the sensitivity of atomic instruments to static or slowly-varying quantities. Sensing transient events presents a distinct challenge, requires different analysis methods, and has not been shown to benefit from entanglement in practically-important scenarios such as spin-precession magnetometry (SPM).

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 utilised by a Linear Quadratic Regulator, whose output is applied back to the system through a feedback loop.

These estimation and control techniques are applied to the experimental setting of SPM and analogous techniques. We demonstrate that real-time tracking of fluctuating fields benefits from measurement-induced spin-squeezing and that quantum limits dictated by decoherence can be reached in today’s experiments.

We illustrate this quantum advantage by single-shot tracking, within the coherence time of a spin-precession magnetometer, of a magnetocardiography signal overlain with broadband noise.

BAKEWELL-SMITH, George
(University of Nottingham)

Concentration Inequalities for First Passage Times in Continuously Measured Quantum Systems

Continuously monitored quantum systems produce count statistics as a fundamental output of their dynamics. The counting process can be viewed as a time-integrated function of the underlying quantum trajectory. A key quantity of interest is the first passage time (FPT)—the time required for the count number to reach a predetermined threshold. The thermodynamic uncertainty relations (TURs) provide lower bounds on FPT fluctuations in the large-count limit and relate the uncertainty of the FPT to dynamical quantities.

Of practical interest, particularly in experimental situations, are results for a finite count number. In previous works we derived concentration inequalities for classical Markov processes with trajectories of fixed time, where time-integrated functions are allowed to fluctuate. The concentration inequalities allow upper bounds on the uncertainty to be derived which complement the lower bounds provided by the TURs. We apply similar methods to quantum trajectories with a fixed threshold number of counts, where the FPT is instead the quantity which fluctuates, and we derive concentration inequalities for FPTs of quantum counting processes. Our results are formulated in terms of parameters of the system, hence, our bounds can be used to infer information on these parameters from the simple observations (counts) of the environment. Conversely, if the parameters are known, the FPT fluctuations can be bounded from above. Concentration inequalities can be used for parameter estimation in quantum metrology. Alternatively, bounds on the uncertainty of FPTs have application in bounding the accuracy of quantum clocks.

BANCHI, Leonardo
(University of Florence)

Complexity of Learning Quantum Features

I will present a combination of different results obtained by my group in the last few years, about quantifying the complexity of learning with quantum data, such as quantum states, quantum dynamics and quantum channels. This can be rephrased as a sensing problem, where the goal is the find the optimal measurement strategy to learn a certain “feature”, which is possibly encoded into correlated degrees of freedom of a quantum many-particle system, but where the encoding is unknown and must also be estimated/learnt. Example applications include the classification of quantum phases of matter, e.g. learning the order parameter, where “data” are ground states of quantum many-particle systems, decision problems such as learning to classify entangled vs. separable states, and sensing applications such as quantum-enhanced object/pattern recognition. I will show how to adapt bounds from statistical learning theory to assess which of these tasks are easy for a learner, in the sense of requiring few training data-points and few-measurements.

BURKHARD, Mattheus

(Université Paris Cité, MPQ)

Exploring Driven-Dissipative Phase Transitions at Fractal Dimensions in Polariton Fluids

Our study investigates the interplay between fractal geometries and driven-dissipative phase transitions, focusing on the critical dimension of the first order phase transition. Using methodologies similar to recent research, we examine a planar semiconductor microcavity in the strong light-matter coupling regime, where polaritons are excited with a quasi-resonant optical driving field. The geometry of the system is adjusted by changing the spatial profile of the incoming driving field. We can thus implement fractal patterns, such as the Sierpinsky carpet, despite distortions from the nominal fractal pattern due to constructive interference and limited detail preservation. These distorted patterns have distinct fractal dimensions, measurable through the box-counting method. By analyzing Liouvillian Gap closing and the divergence of the slope of the order parameter, we can infer the critical behaviour and its exponents for these driven-dissipative systems.

CABOT, Albert

(University of Tübingen)

Two-time measurements for parameter estimation with the boundary time crystal

A boundary time-crystal is a quantum many-body system whose dynamics is governed by the competition between coherent driving and collective dissipation. It is composed of N two-level systems and features a transition between a stationary phase and an oscillatory one. These different phases are imprinted in the properties of the emitted light. By measuring and monitoring this light, we can learn about the state of the system and estimate the value of a parameter of interest. In a recent publication, we showed that in the time-crystal phase the emitted light state displays enhanced properties for sensing, as signaled by a quantum Fisher information (QFI) that scales as TN^2, where T is the measurement time. Moreover, we provided the optimal measurement scheme, which consists on cascading the output of the sensor to a replica system that acts as a decoder. On a practical basis, monitoring the full environment state and implementing this optimal scheme is challenging. For this reason, it would be interesting if we could retrieve a significant amount of the sensitivity offered by the time crystal using a simpler protocol, that measures a smaller part of the emitted field. In a work in preparation, we have addressed this task. We first show that in the time-crystal phase the QFI of just two time modes of light already displays the enhanced N^2 scaling. Then, we provide an interferometric measurement scheme that is able to exploit this sensitivity of two-time measurements. We discuss that the proposed protocol is tailored for scenarios in which the measurement efficiency is low, and that the protocol is able to function in the presence of moderate imperfections, as local decay channels.

CLAVERO RUBIO, Miguel

(IFF- Instituto de Física Fundamental)

Vibrational parametric arrays with trapped ions: non-Hermitian topological phases and quantum sensing

We consider a linear array of trapped ions subjected to local parametric modulation of the trapping potential and continuous laser cooling. In our model, the phase of the parametric modulation varies linearly along the array, thus breaking time-reversal symmetry and inducing non-trivial topological effects. The linear response of the trapped ion chain to an external force is investigated in terms of Green's function formalism. We predict the appearance of topological amplification regimes in which the trapped ion array behaves as a directional amplifier of vibrational perturbations. The emergence of topological phases is determined by a winding number related to non-Hermitian point-gap topology. Beyond its fundamental interests as a topological driven-dissipative system, our setup can be used for quantum sensing of ultra-weak forces and electric fields. We consider a scheme in which a trapped ion at one edge of the array acts as a sensor of an ultra-weak force, and the vibrational signal gets amplified towards the last trapped ion, which acts as a detector. We consider arrays of 2–30 ions, assuming that the detector ion's displacement is measured via fluorescence with a spatial resolution of 200–500 nm, and predict sensitivities as small as 1 yN $Hz^{-1/2}$.

COPPO, Alessandro

(Institute for Complex Systems Italian - National Research Council (CNR -ISC))

Parametric Quantum Resonators: a versatile platform for collective quantum sensing and nonlinear topology

Parametric quantum resonators provide a powerful platform where quantum phase transitions arise from two-photon generation processes. These systems can be driven from a low-excitation regime into a highly populated, symmetry-broken phase, where nonlinearities, even if vanishing small, play a crucial role in determining the stable states. In this talk, we consider a one-dimensional periodic chain of parametric resonators in two distinct regimes - near and far beyond criticality - revealing two novel emergent phenomena: a collective enhancement in critical quantum sensing and the emergence of nonlinear topology. Near the critical point, we show that the chain functions as a highly responsive quantum sensor, where nearest-neighbour interactions induce a quadratic scaling of the quantum Fisher information with the system size. This collective enhancement surpasses the performance of an equivalent array of independent sensors. Beyond criticality, in the absence of quadratic couplings, we show how nonlinear nearest-neighbour cross-Kerr interactions may drive the system into a spontaneously symmetry-broken topological phase, giving rise to topological edge modes under open boundary conditions. The topology is dictated by the structure of the Kerr nonlinearity and yields a non-trivial bulk-boundary correspondence.

DI FRESCO, Giovanni

(Università degli studi di Palermo)

Monitored Quantum Many-Body Systems: From Metrological Potential to Imperfect Detection

In the last decades, out-of-equilibrium quantum many-body systems have garnered significant interest from the scientific community. Within this context, two typical scenarios have emerged: quenches in closed systems and open system dynamics, usually described by a Lindblad master equation. Here, we present new findings within a framework that lies between these two scenarios, i.e., monitored systems. The standard approach to studying these out-of-equilibrium phenomena involves the interplay between unitary dynamics, governed by a many-body Hamiltonian or random circuit, and a finite density of local projective measurements. Alternative approaches, such as weak-measurement protocols, incorporate the unraveling of Lindblad evolution, where monitoring is applied stochastically to each lattice site.
This research focuses on the entanglement properties of quantum many-body trajectories and their dependence on the interplay between unitary evolution and measurements. Across these models, measurements drive an entanglement transition, from a volume-law scaling of entanglement (or sub-volume scaling in non-interacting systems) to an area-law regime, where the quantum Zeno effect effectively freezes the system. Naturally, the question arises of whether many-body systems constrained to evolve within these monitored trajectories possess metrologically useful properties.
We demonstrate, using Quantum Fisher Information (QFI), that in certain spin/fermionic systems, these measurement-induced phases contain multi-parameter metrologically useful entanglement. Furthermore, we establish a scheme in which the QFI is directly related to the fidelity susceptibility. Our analysis reveals that, for this specific class of phase transitions, the QFI exhibits non-analytic behavior at the transition point.
Crucially, all these interesting properties are assessed at the level of quantum trajectories, which intrinsically assume the collection of all measurement outcomes using perfect detectors. We also investigate how the introduction of imperfect detection affects the entanglement properties of these systems by introducing a Liouvillian framework that allows us to assess the role of imperfect detection.

GARBE, Louis

(TU München)

Every boson is a waterfall: non-reciprocal transport and bosonic avalanches for sensing.

Non-reciprocal dynamics is a key component of signal detection, cleaning and amplification. I will present a model that implements non-reciprocity in a many-body system; namely, bosons hopping down a lattice while emitting energy in a cavity. This configuration allows us not only to achieve lasing in the cavity mode, but also a pulsing regime characterised by bursts of lasing in the cavity and “avalanches” of particles in the chain. The latter regime can even be triggered by a single particle incoming in the chain, thus offering prospects for single-photon detection and particle number discrimination. I will also present a superconducting circuit architecture that implements this model.

GIACCARI, Stefano Gregorio
(Istituto Nazionale di Ricerca Metrologica (INRiM))

Coupled atom-cavity systems for quantum-enhanced metrology: adiabatic elimination of the cavity mode beyond the leading order

Spin-squeezed states are a prototypical example of metrologically useful states where structured entanglement allows for enhanced sensing with respect to what is possible using classically correlated particles. Relevant aspects are both the efficient preparation of spin-squeezed states and the scalability of estimation precision with the number N of probes. Recently, in the context of the generation of spin-squeezed states via coupling of three-level atoms to an optical cavity and continuous quantum measurement of the transmitted cavity field, it was shown that increasing the atom-cavity coupling can be detrimental to spin-squeezing generation, an effect that is not appreciated in the standard second-order cavity removal approximation. We describe adiabatic elimination techniques to derive an effective Lindblad master equation up to third order in the collective spin operators. We then discuss two approaches to the solution of this equation: a very general one based on a systematic implementation of the truncated cumulant expansion and its numerical solution, which allows us to show that the mean field and Gaussian approximations are inadequate to predict the correct spin-squeezing scaling, and a fully analytic one leveraging on the existence of a complete set of commuting weak symmetries.

GIROTTI, Federico
(Politecnico di Milano)

Heisenberg scaling in quantum Markov dynamics

In the typical metrological scenario the unknown parameter is encoded in the state of n probes via local unitary operators; if the initial state is suitably engineered, one can estimate the parameter with a mean square error of the order of $1/n^2$ (which improves the standard scaling of 1/n corresponding to initial uncorrelated states) and this is what is known as Heisenberg scaling. However, the achievement of the Heisenberg scaling is usually hindered by the presence of noise due to the interaction between the probes and the environment. In our talk we are going to discuss whether and under which conditions the Heisenberg scaling is restored in the case where the parameter to estimate is encoded by a Markovian dissipative dynamic, distinguishing the situation in which we can perform an arbitrary measurement, or we can only measure either the system or the environment. The talk is based on ongoing joint work with Madalin Guta.

GÓRECKI, Wojciech
(INFN Sez. Pavia, via Bassi 6, I-27100 Pavia, Italy)

From precision bounds to time correlations in critical quantum metrology

In critical quantum metrology, the extreme sensitivity of a system's stationary state to minimal changes in system parameters often causes the quantum Fisher information to scale super-quadratic with the system's energy. From the Heisenberg limit, which constrains the optimal scaling of precision with resources to a quadratic dependence, it follows that the time required to reach such a stationary state must be sufficiently long. By analyzing a continuous measurement performed on the steady state of a critical system, similar conclusions can be drawn about the correlation time of the light interacting with the system. In this work, we investigate parametric Kerr resonators undergoing driven-dissipative phase transitions, demonstrating how fundamental constraints on measurement precision determine the scaling of correlation time with the average photon number. The proposed method provides a framework applicable to a wider class of problems.

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GUTA, Madalin
(University of Nottingham)

Optimal estimation of quantum Markov chains using coherent absorbers and pattern counting estimators

In this presentation I will discuss the problem of estimating dynamical parameters of a quantum Markov chain. The key tool will be the use of a coherent quantum absorber which transforms the problem into a simpler one pertaining to a system with a pure stationary state at a reference parameter value. Motivated by the proposal in [1] I will consider counting output measurements and show how the statistics of the counts can be used to compute a simple, asymptotically optimal estimator of the unknown parameter. For this, I will introduce translationally invariant modes (TIMs) of the output and show that these modes are Gaussian in the limit of large times and capture the entire quantum Fisher information of the output. Moreover, the counting measurement provides an effective joint measurement of the TIMs number operators. The unknown parameter is estimated using a two-stage estimation procedure. A rough estimator is first computed using a simple measurement, and is used to set the absorber parameter. Due to non-identifiability issues of the counting measurement the reference parameter needs to be shifted away from the initial rough estimator, as shown in the displaced-null measurements theory [2]. Finally, an optimal estimator is computed in terms of the total number of excitations of the TIMs, avoiding the need for expensive estimation procedures. Details can be found in [3].

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JULIAN, Daniel
(Palacky University)

Non Gaussian Interference in the Quantum Rabi Model with a small modulation in the qubit frequency

The Quantum Rabi Model, experimentally achievable in trapped ions and superconducting circuits, becomes a paradigmatic method for studying and verifying critical phenomena. In this work we explore the Wigner function of the stationary states of the Quantum Rabi Model when a small modulation to the qubit frequency is introduced. We use the density of states and the semiclassical approximation in order to select the specific resonant frequencies where the lowest states are affected by the modulation. Near the resonant condition, different structures and new non Gaussian interference can be observed in the Wigner functions which cannot be generated without the weak modulation. We demonstrate that the small modulation can be exploited to produce effective wells in the phase space while the coupling is not necessarily strong.

MARCHESE, Marta Maria
(Institute of Science and Technology Austria ISTA)

Cascaded Optomechanical Sensing

Coherent averaging schemes have been introduced as a method to achieve the Heisenberg limit in parameter estimation. Typically, these schemes involve multiple probes in a product state interacting with a quantum bus, with parameter estimation performed via measurements on the bus. We propose a coherent averaging scheme for force sensing applied to optomechanical detectors. A bus-laser pulse sequentially passes through several optomechanical cavities, accumulating signal-induced phase shifts, before being read out. The potential enhancement in sensitivity makes this scheme suitable for many weak sensing applications, such as the detection of the gravitational fields at the Large Hadron Collider, dark matter signatures, and effects predicted by hypothetical collapse models.

MIHAILESCU, George
(University College Dublin)

Uncertain Quantum Critical Metrology: From Single to Multi Parameter Sensing

Critical quantum metrology relies on the extreme sensitivity of a system’s eigenstates near the critical point of a quantum phase transition to Hamiltonian perturbations. This means that these eigenstates are extremely sensitive to all the parameters of the Hamiltonian. In practical settings, there always exists a degree of experimental uncertainty in the control parameters—which are approximately known quantities. Despite such uncertainties representing the most relevant source of noise in critical metrology, their impact on the attainable precision has been largely overlooked. In this work we present a general framework, interpolating between the single and multi-parameter estimation settings, allowing for the proper bookkeeping of relevant errors. We apply this framework to the paradigmatic transverse field Ising and Lipkin-Meshkov-Glick models, explicitly showing how uncertainty in control parameters impacts the sensitivity of critical sensors. For finite-size systems, we establish that there exists a trade-off between the amount of uncertainty a many-body probe can withstand while still maintaining a quantum advantage in parameter estimation.

MITCHELL, Andrew

(University College Dublin)

Metrology and work statistics in the Kibble-Zurek regime of driven boundary critical systems

When an external parameter drives a system across a quantum phase transition at a finite rate, work is performed on the system and entropy is dissipated, due to creation of excitations via the Kibble-Zurek (KZ) mechanism. Universality near the quantum critical point (QCP) controls the non-equilibrium physics along the full crossover from sudden-quench to adiabatic limits, including in this intermediate KZ regime. Here we explore the consequences of this for metrology in terms of the quantum Fisher information (QFI) for the work parameter driving the system across the QCP. For a weak perturbation applied in finite time, we exploit linear-response theory to express the QFI in terms of the dynamical susceptibility of the system. Interestingly, the quantum work statistics associated with the process depend on this same quantity, providing a link between the two. For boundary critical models describing recent experiments with nanoelectronics quantum dot devices, we use conformal field theory for the universal physics of the QCP to find exact scaling functions for the magnetometry QFI and work statistics in the KZ regime.

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O’CONNOR, Eoin

(Università degli Studi di Milano)

Bounding fidelity in feedback control protocols for quantum state engineering

In the presence of environmental decoherence, achieving unit fidelity in quantum state preparation is often impossible. Monitoring the environment can enhance the maximum achievable fidelity, yet unit fidelity remains elusive in many scenarios. We derive fundamental limits on quantum state engineering, taking inspiration from quantum speed limits, in the ideal case of perfect environmental monitoring. The work focuses on preparing Dicke states under collective damping, employing machine learning techniques to validate optimal control strategies. These strategies are then compared against the theoretical bounds, demonstrating the relevance of our bounds for estimating and benchmarking quantum control strategies.

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RADAELLI, Marco
(School of Physics, Trinity College Dublin, Ireland)

Parameter estimation for quantum jump unraveling

We consider the estimation of parameters encoded in the measurement record of a continuously monitored quantum system in the jump unraveling. This unraveling picture corresponds to a single-shot scenario, where information is continuously gathered. Here, it is generally difficult to assess the precision of the estimation procedure via the Fisher Information due to intricate temporal correlations and memory effects. In this paper we provide a full set of solutions to this problem. First, for multi-channel renewal processes we relate the Fisher Information to an underlying Markov chain and derive a easily computable expression for it. For non-renewal processes, we introduce a new algorithm that combines two methods: the monitoring operator method for metrology and the Gillespie algorithm which allows for efficient sampling of a stochastic form of the Fisher Information along individual quantum trajectories. We show that this stochastic Fisher Information satisfies useful properties related to estimation in the single-shot scenario. Finally, we consider the case where some information is lost in data compression/post-selection, and provide tools for computing the Fisher Information in this case. All scenarios are illustrated with instructive examples from quantum optics and condensed matter.

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RODA-SALICHS, Elisabet
(Universidad Autónoma de Barcelona)

Theoretical bounds and experimental viability of sequential analysis in continuously-monitored quantum systems

Quantum sensing deals with the design of quantum sources capable of outperforming any classical strategy in a huge number of technological applications. Traditional theoretical models analyse the data after the measurements are performed whilst many practical applications use sensors that operate continuously monitoring signals, whose dynamics must be determined on-line. We apply sequential methodologies to two paradigmatic primitives, namely hyothesis testing and change point detection, and give optimal performance bounds. We also analyse the protocols in real-life settings, where we tackle the problem of the presence of spurious noises – typical in laboratories – and find a way to experimentally implement these sequential techniques on a continuously monitored quantum optical magnetometer.

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SANCHEZ MUNOZ, Carlos

(CSIC)

Parameter estimation from quantum-jump data using neural networks

We present an inference method utilizing artificial neural networks for parameter estimation of a quantum probe monitored through a single continuous measurement. Unlike existing approaches focusing on the diffusive signals generated by continuous weak measurements, our method harnesses quantum correlations in discrete photon-counting data characterized by quantum jumps. We benchmark the precision of this method against Bayesian inference, which is optimal in the sense of information retrieval. By using numerical experiments on a two-level quantum system, we demonstrate that our approach can achieve a similar optimal performance as Bayesian inference, while drastically reducing computational costs. Additionally, the method exhibits robustness against the presence of imperfections in both measurement and training data. This approach offers a promising and computationally efficient tool for quantum parameter estimation with photon-counting data, relevant for applications such as quantum sensing or quantum imaging, as well as robust calibration tasks in laboratory-based settings.

TOSCA, Jacopo

(Université Paris Cité)

Emergent Equilibrium in All-Optical Single Quantum-Trajectory Ising Machines

We investigate the dynamics of multi-mode optical systems driven by two-photon processes and subject to non-local losses, incorporating quantum noise at the Gaussian level. Our findings show that the statistics retrieved from a single Gaussian quantum trajectory exhibits emergent thermal equilibrium governed by an Ising Hamiltonian, encoded in the dissipative coupling between modes. The system’s effective temperature is set by the driving strength relative to the oscillation threshold. Given the ultra-short time scales typical of all-optical devices, our study demonstrates that such multi-mode optical systems can operate as ultra-fast Boltzmann samplers, paving the way towards the realization of efficient hardware for combinatorial optimization, with promising applications in machine learning and beyond.

VITAGLIANO, Giuseppe

(TU Wien)

Characterizing resources for multiparameter estimation of SU(2) and SU(1,1) unitaries

We investigate the estimation of multiple parameters generated by a unitary evolution with non-commuting Hamiltonians that form a closed algebra. In particular, we consider the three-parameter estimation of SU(2) and SU(1,1) unitaries and analyze the ideal scaling of precision in terms of typical resources such as the total particle number, identifying novel probe states that can achieve Heisenberg scaling for all the three parameters. On top of that, we also consider a more pragmatic framework where the estimation is performed via the so-called method of moments, i.e., via measurements of signal-to-noise ratios of time-evolved observables, which we restrict to be the first two moments of the Hamiltonian generators. We consider the ideal classes of states that we have identified by maximizing the quantum Fisher information matrix, and analyze the maximal precision achievable from measuring only the first two moments of the generators. As a result, we find that in this context with limited resources accessible, the twin-Fock state emerges as the only probe state that allows the estimation of two out of the three parameters with Heisenberg precision scaling. We also analyze further states, including Gaussian states, as well as Schrödinger-cat-like states, this time restricting to measurements linear in the su(2) and su(1,1) operators. In this case, we find that while the former can indeed achieve Heisenberg scaling for one or two parameters, the latter cannot, confirming the fact that more complicated measurements would be needed.

VIVAS-VIAÑA, Alejandro

(Universidad Autónoma de Madrid (UAM - IFIMAC) and Institute of Fundamental Physics (IFF-CSIC))

Quantum metrology through spectral measurements in quantum optics

Quantum optical systems can emit light with very complex spectral properties. For instance, the emergence of dressed states from coherently driven quantum emitters, hybridized excitonic states, or hybrid light-matter states (polaritons) in cavity QED translate into rich fluorescence spectra with multiple peaks that reflect the complex structure of eigenstates. These spectra exhibit equally complex dependences with the parameters that govern the dynamics of the system, and therefore offer the opportunity to improve the inference of unknown parameters by frequency-filtering the emitted signal.
Here, we explore this idea in quantum optical systems consisting of coherently driven quantum emitters in dissipative scenarios. Specifically, in Ref. [1], we focus on the estimation of the inter-emitter distance between two nonidentical interacting quantum emitters driven by a coherent field by measuring the fluorescence spectrum. We identify, by means of the Fisher information [2], that the two-photon resonance (i.e., when the laser frequency is at half of the energy of the doubly excited state) and the onset of the two-photon saturation regime (i.e., when the two-photon dressing effects begin to be resolved in the spectrum) are the most sensitive points for distance estimation.
It is known that hybridized light-matter systems, e.g., a strongly driven two-level system [3], give complex correlations in frequency space. Following this idea, we discuss the role of quantum correlations and quantify their impact on the precision by which unknown atomic parameters can be estimated, assessing the potential of frequency-resolved correlation measurements for the task of parameter estimation in driven-dissipative quantum optical systems.

ZICARI, Giorgio

(Queen's University Belfast)

Quantum Criticality-Enhanced Probing of Spontaneous Collapse Models

Spontaneous collapse models, which are phenomenological mechanisms introduced and designed to account for dynamical wavepacket reduction, are attracting a growing interest from the community interested in the characterisation of the quantum-to-classical transition. Here, we introduce a quantum-probing approach to the quest of deriving metrological upper bounds on the free parameters of such empirical models. To illustrate our approach, we consider an extended quantum Ising chain whose elements are –either individually or collectively –affected by a mechanism responsible for spontaneous collapse. We explore configurations involving out-of-equilibrium states of the chain, which allows us to infer information about the collapse mechanism before it is completely scrambled from the state of the system. Moreover, we investigate potential amplification effects on the probing performance based on the exploitation of quantum criticality.

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BEAULIEU, Guillaume

(École Polytechnique Fédérale de Lausanne)

Criticality-Enhanced Quantum Sensing with a Parametric Superconducting Resonator

Criticality in quantum systems offers a promising approach to enhancing metrological precision by leveraging the divergence of quantum fluctuations near phase transitions. In this work, we implement a critical quantum sensor based on a superconducting parametric Kerr resonator, a non-linear system designed to undergo a finite-component second-order dissipative phase transition. By tuning system parameters, we position the resonator near its critical point, where quantum fluctuations are maximized. We then evaluate the performance of a frequency-estimation protocol at criticality, demonstrating that quadratic precision scaling with respect to system size can be achieved for finite values of the Kerr nonlinearity. Our results establish that a quantum advantage in sensing can be realized by exploiting a finite-component phase transition, bridging the gap between theoretical predictions and experimental implementation.

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BELLIARDO, Federico

(Heriot-Watt University)

Variational Bayesian Inference for Nanoscopic Magnetic Resonance

I will present theoretical and computational advances in machine learning-based signal processing for nanoscopic nuclear magnetic resonance (nano-NMR) using nitrogen-vacancy (NV) centers in diamond. NV centers represent one of the most relevant platforms for quantum sensing today. Nanoscopic magnetic resonance enables the detection of nuclei in the vicinity of the defect. In particular, the simplest nano-NMR resonance experiment involves detecting 13C nuclei within the diamond lattice. Current experiments employ dynamical decoupling techniques—specially engineered microwave pulses—to measure the hyperfine couplings between the NV center and surrounding nuclear spins. However, data acquisition for these measurements can take hours or even days. In this work, we introduce a two-stage experiment in which data from the first stage are processed to construct an approximate estimator for the unknown parameters (the hyperfine couplings). This estimator then informs the selection of measurements to be performed in the second stage. Several challenges arise in the Bayesian treatment of these data. First, the high dimensionality of the problem, e.g. estimating 20 nuclear spins corresponds to 40 parameters, makes traditional particle filter methods infeasible. Second, the number of spins and therefore parameters is a priori unknown. Third, the signal depends nonlinearly on the hyperfine couplings. Finally, the estimation process must be computationally efficient to accelerate nano-NMR experiments, ruling out Monte Carlo techniques. Stochastic variational inference applied to Bayesian estimation is the only approach that addresses all these challenges simultaneously. By applying this technique, we aim to reduce the time required for nano-NMR experiments by two orders of magnitude.

BEZERRA, Matheus Eiji Ohno

(Universidade Federal do ABC (UFABC))

Simultaneous estimation of phase and loss revisited - measurement vs. state incompatibility

The independent estimation of phase and loss encoded in an optical interferometer are well-established problems with various applications. However, simultaneously estimating both phase and loss introduces a degree of incompatibility that remains not fully understood. In this work, we analyse this incompatibility for several classes of states—including Gaussian states (displaced two- and single-mode squeezed states) and a specifically optimised two-mode non-Gaussian state with N photons—by examining the Quantum Fisher Information matrix (which sets the Cramér-Rao bound) and the Holevo-Cramér-Rao Bound. Furthermore, we investigate the nature of this incompatibility, distinguishing between probe state and measurement incompatibilities, with examples drawn from photon counting and homodyne detection.

CENEDESE, Gabriele

(Universitá degli Studi dell'Insubria)

Thermodynamics and Protection of Discrete-Time Crystals

Discrete-time crystals (DTCs) represent a fascinating frontier in the realm of quantum systems, characterized by non-equilibrium dynamics and robust periodicity. These systems exhibit a time-translation symmetry breaking, in analogy with the spatial-translation symmetry breaking of ordinary spatial crystals. 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 investigate the thermodynamic properties of these systems in the presence of a bosonic Markovian environment, proposing an approach to extend their lifespans through a repeated measurement scheme.

We investigate the dynamics of DTCs using a Lindblad master equation, and we comprehensively examine their thermodynamic properties, surpassing the existing literature. Through numerical simulations and analytical modelling, we reveal an increased lifetime of the DTC dynamics. Moreover, we introduce a novel methodology for detecting time crystal signatures exploiting measurement outcomes: by tracking the quantum evolution of the system through trajectory analysis, we identify distinct signatures associated with the presence of DTCs, providing a promising avenue for experimental verification and characterization.

Overall, our study contributes to advance the understanding of DTCs and offers a new way 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 believe that this methodology may open new possibilities for the use of DTCs in quantum technologies and fundamental physics research.

Cong, Lei

(Helmholtz Institut Mainz)

First and Second-Order Quantum Phase Transitions in the Anisotropic Quantum Rabi-Stark Model

We study the first- and second-order quantum phase transitions in the anisotropic quantum Rabi-Stark model which is an extension of the quantum Rabi model which contains an extra Stark term and where the coupling strengths of the rotating terms and counterrotating terms are different. In contrast to the second-order quantum phase transition which requires a low-frequency limit of the field, the first-order quantum phase transition boundary is found to be independent of the ratio of the frequency of the field ω and the energy splitting ω_0 of the qubit. This is found by a mathematically suitably rescaling of the coupling parameters of the system. Based on this, our result reveals that, under the rotating wave approximation, the first-order quantum phase transition has the boundary at the place where and the second-order phase quantum transition boundaries coincide happens. This works for all different for all values of γ, even for the special $\gamma=\omega$ point where the spectral collapse behavior happens. Furthermore, we propose a quantum simulation system to realize the anisotropic quantum Rabi-Stark model building depends on a trapped ion system driven by three laser beams. Our research is expected to promote further the theoretical and experimental research of quantum phase transitions in few-body quantum systems in the field of light-matter interactions.

CHESI, Giovanni

(University of Pavia)

A protocol for global multiphase estimation

In principle, global estimation strategies yield information on a phase or a set of phases without any prior knowledge about them. We devised a protocol based on Holevo’s estimation theory that straightforwardly generalizes global single-phase estimation strategies to the multiphase scenario. We exploit our protocol to investigate the performance of multiphase global estimation in terms of mutual information and show that the advantage with respect to the repeated application of a single-phase estimation protocol amounts to a constant factor, thus shedding light on the actual quantum advantage of multiphase encodings.

GRANDE DE DIEGO, Rodrigo

(CSIC)

Squeezed Lasing via Cavity-Assisted Raman Transitions

A squeezed laser is a system in which a squeezed cavity mode acquires a macroscopic photonic occupation through stimulated emission. Above the lasing threshold, the emitted light maintains both the spectral purity of a conventional laser and the quadrature-squeezing characteristics of correlated photons. Here, we propose an implementation of such a device in the optical regime by leveraging cavity-assisted Raman transitions in multi-level atoms—an approach previously suggested for simulating the Dicke model. Crucially, we demonstrate that the intricate interplay between dissipation and high-energy virtual states involved in Raman processes leads to a complex driven-dissipative phase transition, whereby a transient metastable lasing phase can emerge, which eventually breaks down in the long-time limit due to unconventional mechanisms of population of the virtual states. However, we show that careful engineering of dissipation channels can restore steady-state squeezed lasing. These findings establish this system as a compelling platform for exploring the fundamental physics of dissipative phase transitions, quantum simulation in non-equilibrium environments, and potential applications in quantum metrology.

HAMZA, Danish Ali

(University of Warsaw)

Enhancing quantum Fisher information using uncorrelated initial states

A scheme utilizing a set of double-well potentials loaded with noninteracting particles is proposed to enhance the Quantum Fisher Information (QFI). Using an uncorrelated initial state, we demonstrate that QFI can surpass the standard quantum limit even in the presence of particle number fluctuations.

HE, Jiayu

(University of Helsinki)

Scrambling for precision: optimizing multiparameter qubit estimation in the face of sloppiness and incompatibility

Abstract: Multiparameter quantum estimation theory plays a crucial role in advancing quantum metrology. Recent studies focused on fundamental challenges such as enhancing precision in the presence of incompatibility and sloppiness, yet the relationship between these features remains poorly understood. In this work, we explore the connection between sloppiness and incompatibility by introducing an adjustable scrambling operation for parameter encoding. Using a minimal yet versatile two-parameter qubit model, we examine the trade-off between sloppiness and incompatibility and discuss: (1) how information scrambling can improve estimation, and (2) how the correlations between the parameters and the incompatibility between symmetric logarithmic derivatives impose constraints on the ultimate quantum limits to precision. Through optimization of precision bounds we identify strategies to mitigate these constraints and enhance estimation efficiency. We also compare the performance of joint parameter estimation to strategies involving successive separate estimation steps, demonstrating that the ultimate precision can be achieved when sloppiness is minimized. Our results provide a unified perspective on the trade-offs inherent to multiparameter qubit statistical models, offering practical insights for optimizing experimental designs.

JASSER, Barbara

(Scuola Superiore Meridionale)

Stabilizer Entropy and entanglement complexity in the Sachdev-Ye-Kitaev model

Abstract: The Sachdev-Ye-Kitaev (SYK) model is of paramount importance for the understanding of both strange metals and a microscopic theory of two-dimensional gravity. We study the interplay between Stabilizer Rényi Entropy (SRE) and entanglement entropy in both the ground state and highly excited states of the SYK4+SYK2 model interpolating the highly chaotic four-body interactions model with the integrable two-body interactions one. The interplay between these quantities is assessed also through universal statistics of the entanglement spectrum and its anti-flatness. We find that SYK4 is indeed characterized by a complex pattern of both entanglement and non-stabilizer resources while SYK2 is non-universal and not complex. We discuss the fragility and robustness of these features depending on the interpolation parameter and temperature.

JULIAN, Daniel
(Palacky University)

The Quantum Phase Transitions of the Anisotropic Quantum Rabi Model

The Quantum Rabi Model (QRM) is a paradigmatic model for the exploration of Quantum Phase Transitions within an experimentally feasible scenario. In this work, we explore the quantum phase transitions of the Anisotropic Quantum Rabi Model (AQRM), where the symmetry of the standard QRM is broken by the carrier resonance. We pay special attention to the new concept of dynamical phase transitions, which is a particular case of quantum phase transition characterized by critical behavior of dynamical quantities. We use the protocol of quantum quenches and the complex time survival amplitude for the detection of such transitions. Then we extend the protocol to initial thermal states and find evidence that the non-analytic behavior of the survival amplitude remains robust at non-zero but low temperatures and gradually vanishes as the temperature increases.

KOZBIAL, Marcin
(Centre of New Technologies, University of Warsaw)

Spin-noise spectroscopy of alignment-based atomic magnetometers

Optically pumped magnetometers (OPMs) are revolutionising magnetic-field sensing due to their extremely high sensitivity combined with advancements in miniaturisation that have led to compact, portable devices. OPMs can be based on spin-oriented or spin-aligned atomic ensembles, which are polarised through optical pumping with circular or linear light, respectively. Characterisation of OPMs and the dynamical properties of their noise is crucial for real-time sensing applications. In our work, we experimentally perform spin noise spectroscopy of an alignment-based magnetometer. Moreover, we propose a stochastic model that predicts the noise power spectra exhibited by the device when, apart from the strong magnetic field responsible for Larmor precession, white noise is applied perpendicularly to the pumping-probing beam. By varying the noise strength and the linear-polarisation angle of the incoming light, we verify that the model accurately predicts the heights of the Larmor-induced spectral peaks and their linewidths. This work paves the way for alignment-based magnetometers to become operational in real-time sensing tasks.

LEPORI, Luca
(University of Parma)

Dephasing-tolerant quantum sensing for transverse magnetic fields with spin qudits

We propose a protocol for quantum sensing of transverse magnetic fields. This scheme exploits spin qudits, which are manipulated by longitudinal drives to generate Rabi oscillations with frequencies that vary monotonically with the transverse field. Decoherence is mitigated by leveraging the qudit's multilevel structure to embed fault-tolerant quantum-error correction within the sensing protocol. This correction procedure renders the system robust against the dominant noise sources. The overall protocol enables the detection of tiny transverse magnetic fields with remarkable sensitivity, as demonstrated by numerical simulations.

MOLENDA, Mateusz
(Institute of Physics, Polish Academy of Sciences)

Fast inference for quantum non-linear sensors: ABC vs. ML

Machine learning (ML) algorithms have become powerful tools across various scientific domains, yet their application in quantum sciences often suffers from a lack of interpretability. In particular, ML models are frequently treated as black boxes, making it difficult to extract meaningful insights about their learning process and decision-making criteria. To address this challenge, we compare a trained ML model with the Approximate Bayesian Computation (ABC) method for continuous parameter estimation in a nonlinear optomechanical system probed by photodetection. This system consists of an optical cavity strongly coupled to a mechanical mode, precluding the usage of traditional estimation techniques that rely on computing the likelihood of a particular click trajectory. While ABC provides reasonable parameter estimates, it requires significantly longer computational times. In contrast, once trained, the ML model delivers near-instantaneous predictions, making it advantageous for scenarios where rapid inference is essential. Our analysis also sheds light on how ML models extract key features from quantum measurement data, contributing to a broader understanding of their interpretability in physics-driven problems.

PIERATTELLI, Leonardo

(Scuola Normale Superiore)

ΔT noise in multiterminal hybrid systems

We focus on the study of the transport properties of hybrid multiterminal normal-superconducting systems. In the literature, focus has been devoted to the study of the electrical properties of such systems, while interest regarding their thermal and thermoelectric properties has increased only in recent years, after similar studies have been conducted for purely normal systems. Here we deeply investigate the role of stationary non-equilibrium thermal conditions in the behavior of charge current noise power. By using the Landauer-Büttiker approach, we are able to distinguish two main contributions, called background and excess noise, highlighting differences and similarities with respect to the normal case. Namely, we notice that in hybrid systems the background noise depends on a quantity strictly related to the heat conductance, the transmission function ℓ^-. This does not appear in the noise of purely normal systems, which instead depends only on the electrical conductance-related quantity ℓ^+. The excess noise instead presents, as expected, additional contributions due to the currents' partitioning into transport channels of particles of different types, this being caused by the presence of Andreev conversion processes in the system. After analyzing numerically the behavior of the various contributions of the excess noise by varying both the electrical and thermal boundary conditions, we resort to the study of noise in two specific physical configurations: we compare in both cases the behavior of the shot noise at thermal equilibrium and of the ΔT noise at electrical equilibrium, finally stressing the noticeable differences between electrically- and thermally-induced current fluctuations.

PREVIDI, Luca

(University of Bologna)

OH molecule as a quantum probe to jointly estimate electric and magnetic fields

OH molecule (OHM) in its ground state carries both electric and magnetic dipole moments and is characterised by a diatomic structure that simplifies its modelling. OHM naturally emerges as a quantum probe for precision measurements of electric and magnetic fields. In this paper, we address optimal strategies to jointly detect both fields while overcoming the additional quantum noise arising from their incompatibility. In particular, we devise a sequential control scheme to beat the limit imposed by non-commutativity in specific configurations.

RAGAZZI, Giovanni

(Università di Modena e Reggio Emilia)

Coin dimensionality as a resource in quantum metrology involving discrete-time quantum walks

In Discrete Time Quantum Walks, the quantum object (the walker) moves in a discretised position space—a motion that directly reflects the dynamics experienced in an accessory “coin” space. In this work, we unitarily encode a parameter in the evolution of the coin state and determine the optimal initial state to maximise the associated Quantum Fisher Information. We then discuss whether, and to what extent, precision enhancement can be achieved by measuring only the walker’s position. Additionally, we provide evidence that the dimensionality of the coin space is a potential resource for enhancing precision.

SHARMA, Priyanka

(Institue of Science, Banaras Hindu University)

Scrambling information in multiparameter squeezing estimation

When two successive squeezing operations are applied to a mode of the field, the output state depends solely on the sum of the two squeezing amplitudes, making it impossible to reliably estimate each individually. In this situation, the resulting quantum statistical model becomes “sloppy,” with a singular Quantum Fisher Information matrix. In our work, we investigate how an appropriate phase-shift scrambling transformation can break this sloppiness. By optimising the scrambling parameters, we aim to maximise overall estimation precision and compare the performance of joint estimation techniques against those achievable by stepwise estimation methods.