Book of Abstracts

Quasiprobability distributions in quantum mechanics, optics and information

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University of Milan

Elizabeth Agudelo (TU Wien)

Quantum Correlations in Phase Space

Quantum physics is advancing the frontiers of information science and various technological fields, yet foundational questions remain about the full potential of quantum theory and the thresholds that separate it from classical limits. In our research, we use phase space as a framework to characterize physical systems, focusing on the transition between quantum and classical mechanics. In this talk, I'll present mathematically rigorous methods for practical applications of phase space descriptions that illuminate the classical-quantum boundary and enable the characterization of quantum correlations. We'll showcase experimentally accessible phenomena that exceed classical correlations and introduce innovative techniques in quantum optics to gain insights into the dynamics of complex correlated systems.

Laura Ares (Paderborn University)

Photonic entanglement and polarization nonclassicality: two manifestations, one nature

In quantum theory, each quantum feature relates to the reference considered classically, i.e., the set of states that would never display the quantum effect under study. Thus, one state lying out of the classical references of two different quantum features may exhibit both quantum phenomena simultaneously. In addition, quantum coherence highly depends on the basis chosen to represent the states, as a direct consequence of the superposition principle. This ambiguity directly affects the perception of the nonclassicality of states, and their correspond- ing advantage to improve the performance on certain tasks. Therefore, the understanding of the fundamental differences among the distinct quantum effects is a question central to quantum theory. In particular, we will focus on the connection between entanglement between particles and the nonclassical behavior of polarization [1]. Links between these two quantum effects were previously demonstrated [2], always restricted to necessary but not sufficient conditions between their respective detection criteria. Beyond those links, we establish a strict equivalence between nonclassical polarization and the entanglement of indistinguishable photons. The equivalence is total since both classical references can be fully identified, say angular-momentum coherent states are factorizable states. We utilize a quasiprobability distribution for quantum coherence [3] to jointly characterize this dual form of quantumness. Consequently, negativities in the quasiprobability distribution serve as a necessary and sufficient criterion of nonclassical behavior for both manifestations. This criterion is complemented by a witnessing approach and the whole theoretical framework is extended to systems beyond two dimensions. Now, one should be able to experimentally verify the presence of entanglement and nonclassical polariza- tion via the same experiment. Accordingly, we report on the reconstruction of the quasiprobability distribution of an entangled pair of photons, which shows clear negativities accounting for both quantum behaviors. Finally, we analyze the dependence of the quasiprobability distribution on the polarization basis as well as on the distinguishability of the photons, showing the faithfulness of the characterization via quasiprobabilities. On a practical level, our findings imply that nonclassical polarization is equally resourceful for quantum protocols as entanglement.

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

Matthieu Arnhem (Université de Lille)

Trading off Wigner negativity and decoherence time for cubic Gaussian states

In this work, we provide a description of a cubic Gaussian state, states that are obtained when a cubic gate is applied to a Gaussian state, and we derive asymptotic upper bounds for its Wigner negativity. We study the trade-off that exist between the Wigner negativity and its decoherence time through the Quadrature Coherent Scale (QCS). We put our results in contrast to other nonclassical states such as the Fock states.

David Arvidsson Shukur (Hitachi Cambridge Laboratory)

Classical Data Can Imply Non-Classicality When Measuring KD Distributions

A popular, and rigid, notion of non-classicality is that of generalised contextuality. An experiment is non-contextual if, and only if, there exists a hidden-variable model that assigns the same probability distribution to experimentally indistinguishable procedures. In this talk, we uncover new features of contextuality. We map out a connection between contextuality and the Kirkwood-Dirac (KD) distribution. The KD distribution provides an alternative formulation of quantum theory, in which systems are described with normalised distributions whose values may lie in the complex unit disc instead of [0,1]. Within this framework, a state is deemed 'classical' or KD-positive if, and only if, the entire quasiprobability distribution lies in [0,1]. The KD distribution can be measured experimentally by performing a series of weak and projective measurements. We show that this experiment is contextual if, and only if, the underlying state is KD-nonpositive. This connection has fundamental implications when applied to mixed KD-positive states that cannot be written as convex combinations of KD-positive pure states. Our main result is the construction of scenarios in which an observer can conclude that Nature is contextual based only on non-contextual (classical) data.

Marco Barbieri (Università degli Studi Roma Tre)

Quasiprobability distributions with weak measurements

We show how quantum coherence governs the quasiprobability statistics of outcome pairs, consecutively recorded at two distinct times, using weak measurements. In doing this, we have realised weak-sequential measurement with photonic qubits, where the first measurement is carried out by a positive operator-valued measure, whereas the second one is a projective operation. We determine the quasiprobability distributions associated to this procedure, based on both the commensurate and the Margenau-Hill approach, by establishing a link between these descriptions. Our results find application to quantum monitoring aimed at implementing or stabilising task without completely loosing the initial quantum coherence.

Cameron Calcluth (Chalmers University of Technology)

Sufficient Condition for Universal Quantum Computation Using Bosonic Circuits

For qubit-based quantum computers there exist many results on quantifying the ability of certain components to achieve quantum advantage. However, for continuous-variable quantum computers much less is known. To investigate this, we first developed a method to simulate a restricted class of continuous-variable computations to understand when these types of quantum computers are unable to outperform classical computers. Using this result, we provide the first sufficient condition to achieve quantum advantage using continuous variable quantum computing.

Nicolas Cerf (Université Libre de Bruxelles)

Information and majorization theory in fermionic phase space

I will sketch a way to describe the uncertainy of the state of a fermionic mode, paving the way to extending information theory and majorization theory to fermionic phase space. The anti-commuting nature of the Grassmann variables playing the role of the (x,p) bosonic quadratures allows us to provide simple expressions for the Glauber P, Wigner W, and Husimi Q distributions of the arbitrary state of a single fermionic mode. This yields a simple proof of several fermionic uncertainty relations, including notably the fermionic analogs to the (yet unproven) phase-space majorization and Wigner entropy conjectures for a bosonic mode.The central point is that, although fermionic phase-space distributions do not have a straightforward interpretation, the corresponding uncertainty measures are expressed as Berezin integrals which take on real values, hence are physically relevant.
(Joint work with Tobias Haas.)

Ulysse Chabaud (INRIA - ENS Paris)

The stellar representation

A wide variety of quantum information processing tasks requires non-Gaussian quantum states, from entanglement distillation to universal quantum computing and quantum error-correction. Characterizing and understanding the properties of these states is therefore of major importance. In this talk, I will present the stellar representation, which is a phase-space formalism allowing to characterise non-Gaussian quantum states in bosonic quantum information processing. The main quantity of interest in this context is the so-called stellar rank, which provides a measure of the non-Gaussian character of quantum states. I will explain its operational properties, how it can be used to assess state preparation and state conversion protocols, how it can be measured experimentally and how it quantifies the computational usefulness of non-Gaussian quantum states.

Jack Davis (INRIA - ENS Paris)

Identifying quantum resources in encoded computations

Universal quantum computation relies on error-correcting codes to protect fragile logical quantum information by robustly encoding it into symmetric states of a quantum physical system. Such encodings make the task of resource identification difficult as what constitutes a resource from the logical and physical points of view can differ significantly. Here we introduce a general framework which allows us to correctly identify quantum resources in encoded computations, based on phase-space techniques. For a given quantum code, our construction provides a Wigner function that accounts for how the symmetries of the code space are contained within the transformations of the physical space, resulting in an object capable of describing the logical content of any physical state, both within and outside the code space. We illustrate our general construction with the Gottesman-Kitaev-Preskill encoding of qudits with odd dimension. The resulting Wigner function, which we call the Zak-Gross Wigner function, is shown to correctly identify quantum resources through its phase-space negativity. For instance, it is positive for encoded stabilizer states and negative for the bosonic vacuum. We further prove several properties, including that its negativity provides a measure of magic for the logical content of a state, and that its marginals are modular measurement distributions associated to conjugate Zak patches.

Stephan De Bievre (Université de Lille)

On the geometry of the Kirkwood-Dirac positive states

In this talk we present recent results on the (perhaps surprisingly) rich geometry of the convex set of quantum states that have a positive Kirkwood-Dirac (KD) distribution. We will, on the one hand, identify conditions under which this set is a minimal and simply described polytope with known vertices. On the other hand, we show that this set of KD positive states may contain extremal states that are not pure. This latter phenomenon also occurs for the Wigner function, where the equivalent identification problem remains only partially understood.

Nuno Dias (University of Lisbon)

Some topological properties of the sets of non-negative Wigner functions

The set of non-negative Wigner functions is a convex set which, in the finite dimensional case, is compact and equal to the convex hull of its extreme points. Thus, in finite dimensions, these particular (extreme) Wigner functions can be used to generate the entire set of non-negative Wigner functions. We show that the extreme Wigner functions can be identified by the properties of their null sets, and discuss the problem of constructing these states explicitly. As a by-product, we also elaborate on the properties of the interior and the boundary of the set of non-negative Wigner functions. Finally, if time permits, we will discuss the difficulties of extending some of these results to the infinite dimensional case.

Nicole Fabbri (CNR-INO and LENS)

Probe Kirkwood-Dirac quasiprobability distribution of work in a diamond spin

The Kirkwood-Dirac quasiprobability distribution emerges from the quantum correlation function of two observables measured at distinct times and is therefore relevant for fundamental physics and quantum technologies. However, its experimental reconstruction may be challenging when expectation values of incompatible observables are involved. We leverage the exquisite quantum control of the spin of a nitrogen-vacancy center in diamond, to demonstrate two different schemes to reconstruct Kirkwood-Dirac quasiprobabilities (KDQ. We measure the real part of KDQ via an ancilla-free scheme based on projective measurements in an electron spin qutrit, and the full KDQ distribution with an interferometric scheme in an electron-nuclear spin system. We observe anomalous work extraction [1], and we show the behavior of the first and second moments of work, connecting them with Robertson-Schrödinger uncertainty relation [2].
[1] Physical Review Research 6 (2), 023280 (2024)
[2] arXiv:2405.21041

Giulia Ferrini (University of Chalmers)

Magic measures and classical simulation algorithms for qudit quantum computation using the Gottesman-Kitaev-Preskill encoding

I will show that using the Gottesman-Kitaev-Preskill (GKP) encoding and computing the Wigner logarithmic negativity of the encoded states [1] allows for defining a magic measure for qubits, easier to compute than other measures [2]. I will then extend this result to qudits of arbitrary dimension, and provide an algorithm for the simulation of quantum circuits which runtime scales with the measure introduced [3].
[1] L. García-Álvarez et al, Physical Review Research 2 (4), 043322.
[2] O. Hahn et al, Phys. Rev. Lett. 128, 210502 (2022).
[3] O. Hahn et al, arXiv:2406.06418 (2024)

Radim Filip (Palacky University)

Quantum non-Gaussianity

The presentation will review the theoretical and experimental development of quantum non-Gaussian states of bosons: their generation, manipulation, detection, identification and applications for different experimental platforms.

Massimo Frigerio (Laboratoire Kastler Brossel)

Resourceful gates for photonic quantum computation

Using the framework of s-ordered quasi probability distributions, we study the conditions for non-simulability of photonic quantum circuits beyond Wigner negativity. Assuming a decomposition of the circuit in gates acting on a maximum number of modes each and exploiting the notion of nonclassicality, we derive conditions for simulability of each gate that are independent of the specific input state. We characterize in this way a universal set, containing Gaussian unitary gates and the cubic phase gate and we derive upper bounds to losses above which each element becomes simulable for any input state. Our results can be straightforwardly applied to current continuous-variables quantum computing schemes and could rule out quantum advantage in several of those notwithstanding the presence of Wigner negativity and without any restriction to linear optics in the computation.

Eva-Maria Graefe (Imperial College London)

Quantum and classical phase-space dynamics generated by non-Hermitian Hamiltonians

While traditional quantum mechanics focusses on systems conserving energy and probability, described by Hermitian Hamiltonians, in recent years there has been ever growing interest in the use of non-Hermitian Hamiltonians. These can effectively describe loss and gain in a quantum system. In particular systems with a certain balance of loss and gain, so-called PT-symmetric systems, have attracted considerable attention. The dynamics generated by non-Hermitian Hamiltonians are often less intuitive than those of conventional Hermitian systems. Even for models as simple as a complexified harmonic oscillator, the dynamics beyond coherent states shows surprising features. Here we analyse the flow of the Husimi and Wigner phase-space distributions in a semiclassical limit, leading to a first order partial differential equation, that helps illuminate the foundations of the full quantum evolution. We discuss instructive examples, demonstrating how the full quantum dynamics unfolds on top of the “classical” flow. This is based on joint work with Kathrine Holmes, Simon Mallard, and Wasim Rehman.

Majid Hassani (Leiden University)

Privacy in networks of quantum sensors

We treat privacy in a network of quantum sensors where accessible information is limited to specific functions of the network parameters, and all other information remains private. We develop an analysis of privacy in terms of a manipulation of the quantum Fisher information matrix, and find the optimal state achieving maximum privacy in the estimation of linear combination of the unknown parameters in a network of quantum sensors. We also discuss the effect of uncorrelated noise on the privacy of the network. Moreover, we illustrate our results with an example where the goal is to estimate the average value of the unknown parameters in the network. In this example, we also introduce the notion of quasi-privacy (ϵ-privacy), quantifying how close the state is to being private.

Anaelle Hertz (National Research Council of Canada)

Entanglement, loss, and quantumness: When balanced beam splitters are best

Entanglement generation by beam splitters lies at the heart of quantum optics. Yet, the conjecture that maximal entanglement for any state interfered with the vacuum is generated by beam splitters with equal reflection and transmission probabilities has remained unproven for almost two decades, despite overwhelming positive evidence [Asbóth et al. Phy. Rev. Lett. 94 (17), 173602 (2005)]. I will report on our recent proof of this conjecture. Our results yield corollaries from inequalities for quasiprobability distributions to properties of states undergoing photon loss. In particular, it proves the conjecture in [Hertz et al. Phys. Rev. A 110, 012408 (2024)] that the quadrature coherence scale always stop certifying nonclassicality at 50% loss. (Joint work with Noah Lupu-Gladstein, Khabat Heshami and Aaron Z. Goldberg)

Andrew Jordan (Rochester/Chapman)

Weak values and direct measurement methods for pseudo-distributions

The connections between weak values and pseudo-distributions will be described. I will discuss how the pseudo-distribution can be measured directly via weak measurements of the moment generating function. A possible experiment to directly measure the pseudo-distribution will be presented where only a single measurement needs to be made with a tunable parameter. This approach makes the experiment realistic, as opposed to measuring an infinite number of moments. The pseudo-distribution generating function can be considered as a fundamental object to be measured directly, with close connections to contextuality notions.

Christopher Langrenez (Université de Lille)

Identifying the set of Kirkwood-Dirac-positive states for the Discrete Fourier Transform.

The Kirkwood-Dirac (KD) distribution has emerged recently as an adaptable tool in many domains of quantum mechanics. Given two observables, one can associate to each quantum state a quasiprobability distribution called the KD distribution; and the negative values associated to this distribution have been linked to quantum advantage. In this talk, we will focus on the analogue of position and momentum in finite-dimensionnal space, given by the Discrete Fourier Transform (DFT). We will show that, for prime power dimensions, any KD-positive state can be decomposed as a convex combination of KD-positive pure states. This work improves a result already known for prime dimensions by using the framework of Fourier Transform on finite abelian groups. We also provide an example, in dimension 6, of a KD-positive state that is not in the convex hull of the set of KD-positive pure states, meaning that the result for prime power dimensions cannot be extended to every dimension.

YI LI (Peking University)

Necessary and Sufficient Condition for Randomness Certification from Incompatibility

Quantum randomness can be certified from probabilistic behaviors demonstrating Bell nonlocality or Einstein-Podolsky-Rosen steering, leveraging outcomes from uncharacterized devices. However, such nonlocal correlations are not always sufficient for this task, necessitating the identification of required minimum quantum resources. In this work, we provide the necessary and sufficient condition for nonzero certifiable randomness in terms of measurement incompatibility and develop approaches to detect them.

Darren Moore (Palacky University)

Nonlinearity and Non-Gaussianity

For quantum quasi-probability distributions, nonlinearity and non-Gaussianity are deeply linked. The strongest sign of this is the emergence of negative values in the Wigner function, requiring nonlinearity to take Gaussian states to quantum non-Gaussian states with negativities. Here we present several methods to identify nonlinear effects even without Wigner negativity, using nonlinear squeezing to identify quantum non-Gaussian states or distillable squeezing to capture the nonclassicality of phase insensitive positive non-Gaussian states. Trilinear and bilinear interactions allow entanglement growth simultaneous with the creation of the required nonclassicality. We show how to produce complex quantum non-Gaussian Wigner functions with large coherences using only incoherent states and combinations of phase insensitive, energy-conserving interactions. Finally, we complete the description of the action of universal gate sets for CV computation in phase space by showing the cubic and quartic phase gates correspond to the Airy transform of the Wigner function. This allows us to show the robustness of Wigner negativity to initial Gaussian thermal noise.

Stefano Olivares (University of Milan)

On the state-discrimination for continuous-variable quantum key distribution

We address a continuous-variable quantum key distribution protocol employing quaternary phase-shift-keying of coherent states and a non-Gaussian measurement inspired by quantum receivers minimizing the error probability in a quantum-state-discrimination scenario. We consider a pure-loss quantum wiretap channel, in which a possible eavesdropper is limited to collect the sole channel losses.

Valentina Parigi (Sorbonne Université - Laboratoire Kastler Brossel)

Gaussian and non-Gaussian multimode quantum optics in simulations

By considering quantum optics platforms with large multimode Gaussian entangled states and few non-Gaussian modes I will tackle possible emulation/simulation of physical communication and information networks, quantum thermodynamics processes, quantum walks.

João Prata (University of Lisbon)

On the zeros of the Wigner function

Wigner functions are elusive and deceptive objects. They appear to be probability densities but are only quasi-distributions. In this talk I will argue that they also share many properties with complex analytic functions, but they are not analytic. In fact, if their set of zeros is bounded, they are polyanalytic functions. This has several interesting consequences: (i) the wave function is equal to the product of a Gaussian and a polynomial (this can be regarded as an extension of Hudson's theorem); (ii) the Wigner function cannot vanish on a line segment; (iii) if the Wigner function vanishes on more than one circle, then the circles have to be concentric; (iv) if we fix the Gaussian part, then the Wigner function cannot vanish on circles of arbitrary radii; (v) if the set of zeros is contained in a ball, then the ball has a minimal radius (this is called a sign uncertainty principle); (vi) if two Wigner functions are equal on some domain, then they are equal everywhere; (vii) if the polynomial part has degree N, then the Wigner function can be determined completely from its values on N+1 concentric circles. These results apply only to pure states.

Saleh Rahimi-Keshari (Institute for Research in Fundamental Sciences)

Phase-space negativity as a resource for quantum information processing

I discuss some results about the role of negativity in the phase-space quasiprobability distributions as a nonclassical resource in quantum information processing. First, I highlight that the absence of phase-space negativity allows efficient classical simulation of quantum circuits. This has implications for the classical simulation and the verification of boson-sampling experiments. Second, I discuss a method to verify the joint-measurability of measurements using the phase-space quasiprobability distributions. This method enables us to investigate the effects of lossy and noisy channels on the incompatibility of measurements on continuous-variable systems.

Enrico Rebufello (Istituto Nazionale di Ricerca Metrologica)

Single-pair measurement of the Bell parameter and the investigation of novel nonlocality bounds

Quantum Mechanics notoriously shows counterintuitive traits. A clear example of this is represented by Bell inequalities [1], that in 1965 turned a philosophical debate into a physical experiment capable of extracting the true nature of correlations within physical systems, opening several research fields spanning from quantum mechanics foundations to quantum technologies [2]. Despite the realization of loophole-free Bell inequality tests [3-5], it was always deemed impossible to measure the entire Bell parameter on a single quantum system, because it was forbidden by the Heisenberg uncertainty principle and the measurement-induced wave-function collapse. Defying this conviction, here we present a method for estimating the entire Bell parameter from each entangled pair while preserving entanglement [6], ensuring its further availability. This is possible thanks to weak measurements, an indirect measurement paradigm capable of extracting little information about an observable without collapsing the state. This allows measuring multiple (incompatible) observables on the same quantum state, extracting all the correlations needed to evaluate the full Bell parameter from each pair (although with a large uncertainty, as it usually occurs with weak measurements). Besides providing new insights into some aspects of quantum foundations, like the concept of counterfactual definiteness [8], the fact that here the entanglement remains almost unaltered after its certification allows realizing further information protocols or quantum foundations experiments. Furthermore, our method also allows investigating novel bounds, such as the one derived from recently-introduced principle dubbed Relativistic Independence (RI) [9], showing explicitly the interplay between the nonlocal correlations connecting the two particles and the local correlations of each particle[10].

[1] J. S. Bell, Physics 1, 195 (1965).
[2] I. Georgescu, Nat. Rev. Phys. 3, 674 (2021).
[3] B. Hensen et al., Nature 526, 682 (2015).
[4] M. Giustina et al., PRL 115, 250401 (2015).
[5] L. K. Shalm et al., PRL 115, 250402 (2015).
[6] S. Virzì et al., Quantum Sci. Technol. 9, 045027 (2024).
[7] Y. Aharonov, D. Z. Albert, L. Vaidman, PRL 60, 1351 (1988).
[8] Y. Aharonov, A. Botero, S. Popescu, B. Reznik, J. Tollaksen, PLA 301, 130 (2002).
[9] A. Carmi, E. Cohen, Sci. Adv. 5, eaav8370 (2019).
[10] F. Atzori et al., manuscript under review.

Matteo Rosati (Università degli Studi Roma Tre)

Learning theories for continuous-variable and non-identical systems

We present two works on the theory of statistical learning with quantum systems. (1) MR, Quantum 8, 1433 (2024) establishes the number of experiments needed to approximate the output distribution of a bosonic circuit, for three classes of operations, including Gaussian, photo-detection and other non-Gaussian operations. We prove that the number of experiments needed to learn an approximation of the unknown circuit scales polynomially with the number of modes and suitable non-Gaussianity quantifiers. (2) M. Fanizza, Y. Quek and MR, PRX Quantum 5, 020367 (2024) establishes the possibility of learning a process with classical input and quantum output, given only random and non-identical samples of it. This framework is applicable, for example, to the study of astronomical phenomena, disordered systems and biological processes not controlled by the observer.

Flavio Salvati (University of Cambridge)

Agnostic Phase Estimation

Phase estimation is crucial to quantum-information processing. Several quantum algorithms use phase estimation as a subroutine for finding unitary operators' eigenvalues. Furthermore, phase estimation is used in quantum metrology, the field of using quantum systems to probe, measure, and estimate unknown physical parameters. I will tackle the problem of how to measure the strength of a totally unknown unitary. Imagine a unitary rotation generated by a magnetic field. If the direction of the magnetic field is unknown, no strategy with classically separable probes enables optimal measurements of the rotation angle. However, a quantum strategy, relying on entanglement, does. Our strategy leverages quantum simulations of hypothetical closed timelike curves (CTCs) to overcome limitations in phase estimation. Colleagues and I demonstrate this on a superconducting processor. I will describe how our technique can be used in tasks ranging from sensing to quantum-computer calibration. Further, I will discuss extensions and applications of our agnostic phase-estimation protocol.
[1]https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.132.260801
[2]https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.131.150202

Jonathan Thio (University of Cambridge)

The set of Kirkwood-Dirac positive states is almost always minimal

A central problem in quantum information is determining quantum-classical boundaries. A useful notion of classicality is provided by the quasiprobability formulation of quantum theory. In this framework, a state is called classical if it is represented by a quasiprobability distribution that is positive, and thus a probability distribution. In recent years, the Kirkwood-Dirac (KD) distributions have gained much interest due to their numerous applications in modern quantum-information research. A particular advantage of the KD distributions is that they can be defined with respect to arbitrary observables. Here, we show that if two observables are picked at random, the set of classical states of the resulting KD distribution is a simple polytope of minimal size. When the Hilbert space is of dimension d, this polytope is of dimension $2d-1$ and has $2d$ known vertices. Our result implies, *e.g.*, that any resource theory of almost any KD distribution has a small and simple set of free states.

Varun Upreti (INRIA - ENS Paris)

Verification of multimode continuous-variable quantum states using Gaussian witnesses

Modern quantum devices are highly susceptible to errors, making the verification of their correct operation a critical problem. Usual tomographic methods rapidly become intractable as these devices are scaled up. In our work, we present a general framework for the efficient verification of large quantum systems, with a particular focus on continuous variable quantum systems. Central to our approach is the use of phase space representations. By leveraging the two most common types of Gaussian measurements—homodyne and heterodyne detection—we develop efficient verification protocols that rely on fidelity estimation through the use of estimator functions and appropriate phase space representations as the probability distributions. These protocols are semi-device independent, designed to function with minimal assumptions about the quantum device being tested, and offer practical improvements over previous existing approaches. Overall, our work introduces efficient methods for verifying the correct preparation of complex quantum states, and has consequences for calibrating large quantum devices, supporting demonstrations of quantum computational speedups and enhancing trust in quantum computations.

Zacharie Van Herstraeten (Inria)

Wigner entropy conjecture and the interference formula in quantum phase space

Quantum Wigner-positive states have the property to be described by Wigner functions that are genuine probability distributions over phase space. For such states, the Shannon differential entropy of their Wigner function (i.e., their Wigner entropy) emerges as a fundamental information-theoretic measure of their phase-space content, and is subject to a conjectured lower bound reflecting the uncertainty principle. In this work, we prove that the conjecture holds true for a broad family of Wigner-positive states known as beam-splitter states, which are obtained by acting with a balanced beam-splitter on a separable input and discarding the environment. Our proof relies on two main ingredients: (i) bounds on the p-norms of cross Wigner functions and (ii) the ”interference formula” which relates the squared modulus of a cross Wigner function to a convolution of Wigner functions. Originally discovered in the context of signal analysis, the interference formula is to our knowledge not well-known in quantum optics, even though it unveils a powerful symmetry obeyed by pure Wigner functions. We provide here a simple proof of the formula and highlight some of its implications.

Salvatore Virzì (Istituto Nazionale di Ricerca Metrologica)

Pseudo-density operators: from modelling chronology-violating spacetime regions to recovering quantum dynamics via teleportation in the time domain

Recently, a novel quantum mechanical tool dubbed pseudo-density operator (PDO) has been introduced [1], allowing to treat spatial and temporal quantum correlations on an equal footing and resulting particularly suited for modelling, e.g., exotic spacetime scenarios.

Here we illustrate some results obtained by applying PDOs to two different frameworks. The first one involves quantum particles in chronology-violating spacetime regions, like entangled particles undergoing time travel or falling into an evaporating black hole, and quantum evolution reformulated as a series of teleportations in time. First, we consider the case of an entangled pair in which one of the qubits enters an open time-like curve (OTC), i.e. a time-travel configuration (predicted by general relativity) where the qubit does not interact with its past copy. We show that, by exploiting the PDO formalism, the causality issues typical of time travel can be solved without asking for a non-linear quantum dynamics, usually required to avoid entanglement monogamy violation. By exploiting polarization-entangled photons, we simulate an OTC and provide quantum tomographic reconstruction of its PDO, showing how entanglement monogamy violation would occur when describing such a scenario with traditional density operators [2]. The same approach is also applied to other chronology violation spacetime frameworks, e.g. the ones involving entangled particles falling into evaporating black holes [3]. Second, we illustrate how PDOs allow expressing quantum dynamical evolution as a sequence of teleportations in the temporal domain, showing how any completely positive evolution can be formally reconstructed as a teleportation based on temporally-correlated states. This stems from the strict correspondence between spatial and temporal entanglement in quantum theory, here demonstrated by a multipartite violation of generalised temporal and spatial inequalities achieved with photonic qubits [4].

[1] J. F. Fitzsimons, J. A. Jones, and V. Vedral, Sci. Rep. 5, 18281 (2015).
[2] C. Marletto, et. al., Nat. Commun. 10, 182 (2019).
[3] C. Marletto, et al., Entropy 22, 228 (2020).
[4] C. Marletto, et al., Sci. Adv. 7, eabe4742 (2021).