BOOK OF ABSTRACTS FOR **QUANTUM2CLASSICAL**

INVITED CONTRIBUTIONS

Angelo Bassi
Wave function collapse, gravity and cosmology

To make quantum theory consistent, models of spontaneous wave function collapse (collapse models) propose to modify the Schrödinger equation by including nonlinear and stochastic terms, which describe the collapse of the wave function in space. These spontaneous collapses are "rare" for microscopic systems, hence their quantum properties are left almost unaltered. At the same time, since the collapses add coherently in composite systems, macroscopic spatial superpositions of macro-objects are rapidly suppressed. I will review the main features of collapse models, and will present an update of the most promising ways of testing them in interferometric and non-interferometric experiments, showing the current lower and upper bounds on their parameters. Next, I will discuss ideas to connect the collapse of the wave function to gravity: The Diosi-Penrose model, Adler's model and the Schroedinger-Newton equation. I will also show how collapse models can possibly shed a light on some cosmological problems.

Robin Blume-Kohout
What "Semiclassical Computation" might mean

Near-future quantum processors will be too noisy to run known digital algorithms. One potential route to quantum utility is to temporarily set aside the digital computation paradigm and focus on analog quantum simulators (AQS), in which a direct analogy between the processor and a system of interest ensures that the processor will imitate the system. If the analogy is strong enough, noise need not be catastrophic — but it will cause heating. This can be counteracted by active logical cooling, but the simulator will still suffer decoherence on medium timescales. In this talk, I'll explore the consequences of this unmitigated noise, and suggest a plausible argument why the resulting "semiclassical computing" might still provide advantage over purely classical methods.

Ivette Fuentes
Gravity in the quantum lab

Quantum experiments are reaching relativistic regimes. Quantum communication protocols have been demonstrated at long lenghts scales and experiments are underway to distribute entanglement between Earth and Satellite-based links. At these regimes the Global Positioning System requieres relativistic corrections. Therefore, it is necessary to understand how does motion and gravity will affect long-range quantum experiments. Interestingly, relativistic effects can also be observed at small lengths scales. Some effects have been demonstrated in superconducting circuits involving boundary conditions moving at relativistic speeds and quantum clocks have been used to measure time dilation in table-top experiments. In this talk I will present a formalism for the study of gravitational effects on quantum technologies. This formalism is also applicable in the development of new quantum technologies that can be used to deepen our understanding of physics in the overlap of quantum theory and relativity. Examples include accelerometers, gravitational wave detectors and spacetime probes underpinned by quantum field theory in curved spacetime.

Rainer Kaltenbaek

Towards a space platform for fundamental tests of quantum physics

Tremendous progress in space and quantum technology over the last decades has rendered space an attractive platform for fundamental tests of quantum physics, and promises applications of quantum technology in space in the near future. Heritage in laser and optical technologies from LISA Pathfinder comprises core technologies required for quantum optical experiments. Low-noise micro-thruster technology from GAIA and LISA Pathfinder allows achieving impressive microgravity levels, and passive as well as low-vibration active cryogenic cooling has been or will be harnessed in missions ranging from Planck to the James Webb Space Telescope and Athena. Developments like these have rendered space an increasingly attractive environment for quantum-enhanced sensing and for fundamental tests of physics using quantum technology. In particular, there have already been significant efforts towards realizing atom interferometry and atomic clocks in space as well as efforts to harness space as an environment for fundamental tests of physics using quantum optomechanics and high-mass matter-wave interferometry. Here, we will present recent efforts in mission, payload and spacecraft design as well as technology development towards realizing a space-based platform for testing quantum physics and the transition to classical physics. The talk will focus on the mission proposal MAQRO and the on-going QPPF (Quantum physics platform) study at the European Space Agency's (ESA) Concurrent Design Facility following ESA's recent call for New Science Ideas.

Thao Le

Strong quantum Darwinism

Quantum Darwinism [1] and spectrum broadcasting [2] are two different frameworks providing insight into how the objective world might emerge from the underlying quantum world. However, recent works show these two frameworks are unequal and can lead to conflicting conclusions on the (non-)objectivity of a state [2–4]. By upgrading quantum Darwinism to “strong quantum Darwinism”, we prove that strong quantum Darwinism, when combined with strong independence of the subenvironments, is equivalent to spectrum broadcasting [5]. Along the way, we also find that strong quantum Darwinism alone is equivalent to bipartite spectrum broadcast structure and argue that objectivity of the state does not necessarily require strong independence of the subenvironments. We now have two complementary approaches to perceiving objectivity: the entropic and information-theoretic picture described in strong quantum Darwinism and the state structure and geometric picture painted by spectrum broadcasting.

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Florian Mintert
Anderson localisation and decoherence

Since Anderson localisation is the result of the interference of many path amplitudes, it is destroyed in the presence of decoherence. We show that for many decoherence models the transition from Anderson localised quantum states to decohered classical states involves the appearance and disappearance of transient interference features. A semi-analytic theory predicts the dynamics of these interference features that are most pronounced for a finite decoherence rate.

Mauro Paternostro
Revealing quantumness without looking

Your prankster friend gave you a box into which, he says, there is a quantum system. He asks you to hold the box for him, and not to ruin the fragile quantum system that is inside. But you do not trust him and want to find out if he is telling the truth or not. How would you ascertain that the system within your friend's box is indeed genuinely quantum?

As preposterous as this situation might sound, it is not far from conditions routinely found in quantum labs: the direct revelation of the non-classical properties of a system is often either too disruptive for the system itself (if you measure it, you ruin it!), or simply technically difficult to realise (the system might be difficult to access, just like the one in your friend's box).

In this talk I will illustrate a scheme based on quantum communication and the theory of quantum correlations, that allows you to "certify" the quantum nature of an inaccessible system. I will show how, besides its fundamental interest, the scheme is prone to verification in a number of experimental settings, including quantum optomechanics. Finally, I will conjecture that it can be used as a trojan horse to investigate the possible quantum nature of gravity and describe a recent proposal for an experiment based on matter-wave interferometry.

The work presented in this talk is based on the following papers:

- T. Krisnanda, M. Zuppardo, M. Paternostro, and T. Paterek, Phys. Rev. Lett. 119, 120402 (2017)
- S. Bose et al., Phys. Rev. Lett. 119, 240401 (2017) [see also Synopsis in Physics: https://physics.aps.org/synopsis-for/10.1103/PhysRevLett.119.240402]

Matteo Rossi
Quantum walks on graphs affected by classical noise

Continuous-time quantum walks (CTQWs) describe the free evolution of quantum particles on N-vertex graphs. They have been subject of intense studies, both theoretical and experimental, as they have proven useful for several applications, ranging from universal quantum computation, to search algorithms (e.g. Grover), quantum transport and state or energy transfer. Given their relevance in technological application, a realistic description of the dynamics of quantum walkers should take into account those sources of noise and imperfections that might affect its propagation and destroy its quantum properties. Here we address the effects of classical random telegraph noise (a typical source of noise in solid state quantum devices) affecting the nearest-neighbor hopping amplitudes on CTQWs on different graph topologies, and we study the transition from quantum to classical propagation and its effect on applications, such as search algorithms.

CONTRIBUTED TALKS

Optimal feedback cooling of levitated nanoparticles

Luca Ferialdi
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Experimental tests of the limits of Quantum Mechanics are at the forefront of research these days. These limits are not far from being tested with present day technology, but a last step forward needs to be taken. Cooling and control of quantum systems plays a crucial role in performing high sensitivity experiments. We consider the experimental setup for trapped nanoparticles, where feedback cooling is so far provided through an approximated scheme. We find the optimal control that minimizes the trapped particle energy by exploiting Pontryagin's minimum principle. We show numerically that the control is suitable for cooling the particle, and we make the case for real time implementation on the experimental setup.

Signatures of temporal signalling in quantum systems strongly coupled to an environment

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Judging the existence of non-classical phenomena is a long-standing open challenge in physics. Recent experimental tests have witnessed the existence of discrete-variable quantum coherence in well-isolated systems such as superconducting qubits [1] and photons [2]. While this is of no surprise, applying similar witnesses in biological or macroscopic systems could have a profound impact on our understanding of nature and of quantum theory.

We consider three generalisations of the No-Signalling-In-Time experimental protocol in the case where the system of interest is strongly coupled to an environment – a prerequisite step for designing experimental tests on bio-molecular systems such as light harvesting complexes [3]. Depending on the way the protocol is generalised, the resulting witness either reports on system coherence alone, or a combination of system coherence and either non-Markovianity or system-environment correlations. We make the link to resource theories of coherence [4].

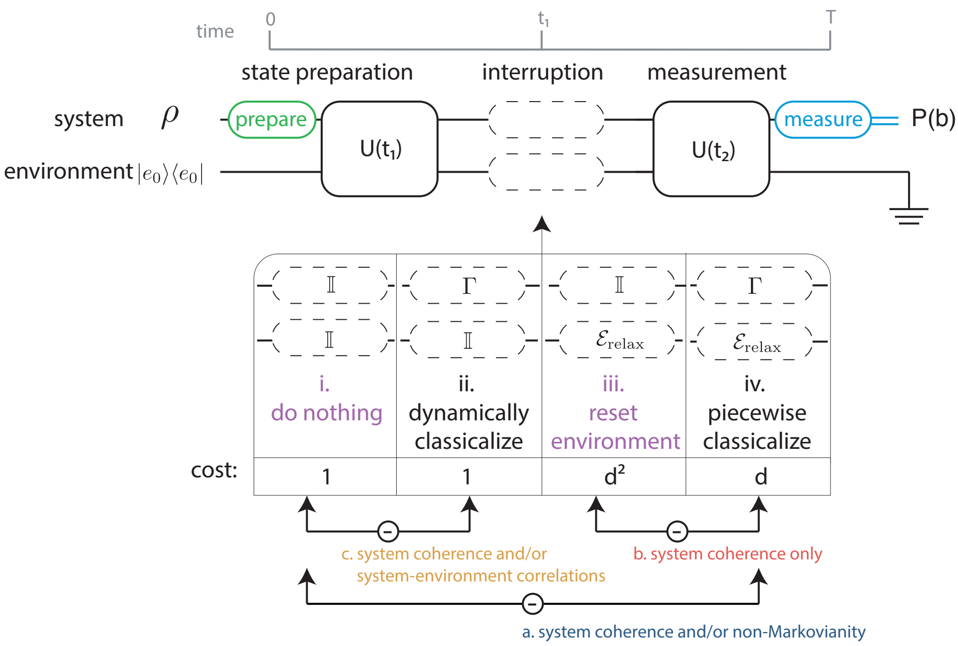

FIG. 1. Procedure for testing coherence witnesses. Γ is the completely dephasing map.

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Classicality and objectivity in general probabilistic theories

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The experience of our everyday world is classical and objective, and different observers agree on what they see. This contrasts with the quantum world, where observations cause an irreducible disturbance on physical states. Being the fundamental theory of Nature, quantum theory must explain the origin of the classical behaviour out of the very different quantum one. This has always been one of the central issues since the very inception of quantum mechanics.

The theory of decoherence [1] made the first steps towards a satisfactory explanation, subsequently improved by the methods of quantum Darwinism [2–4]. Later two of the authors derived from first principles that all objective states in quantum theory must have a specific form, called spectrum broadcast structure (SBS) [5], which arises in many concrete dynamical examples [5, 6].

In this work, for the first time we push the analysis of objectivity outside the boundaries of quantum theory, using one of the most successful tools in quantum foundations: general probabilistic theories [7, 8], which describe generic physical theories admitting probabilistic processes. In this way we gain a better understanding of which quantum mechanisms are responsible for the emergence of objectivity by contrasting them with conceivable post-quantum scenarios. At the same time this enables us to study the behaviour of potential extensions of quantum theory, which may be necessary for a future theory of quantum gravity.

Specifically, we study the form of objective states in all physical theories satisfying the axiom of Causality [8], stipulating that information propagates from the past to the future. Very surprisingly, we show that the SBS structure is *not at all* specific to quantum theory, instead is the general form of objective states in *all* causal theories admitting classical states.

In this work we also study operationally how classical states emerge from a generic theory, showing that the measurement process provides a canonical way to decohere a generic system and make it classical, as it happens in quantum theory. We also show that some holistic phenomena can take place when composite systems are decohered, unless the theory satisfies two axioms, which express a sort of "locality condition" in the emergence of classicality.

All these results suggest that the scope of quantum Darwinism might go beyond quantum theory.

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Does there exist a macro-scale?

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Quantum theory provides one of the most successful descriptions of physical phenomena. However, its mathematical structure allows for counterintuitive properties, such as superposition of states and, subsequently, entanglement. On one hand, at a microscopic scale, these properties are now observed on a regular basis with experiments. On the other hand, the question of whether quantum mechanics is a *universal* theory, in the sense that macroscopic systems are also subject to its laws, remains unresolved. If quantum theory is universal, we expect to be able to observe quantum effects on "macro-scale" as characterized by the well-known Schrödinger's cat gedankenexperiment. However, this has remained far from reach, despite decades of significant effort [1–10]. This challenge is typically referred to as *the macroscopicity problem*.

The above mentioned inability to observe quantum features of macroscopic systems is commonly attributed to decoherence dynamics and the size of physical systems [11, 12]. Loosely speaking, the larger the system is (according to some appropriate notion of macroscopicity [13–19]), the harder it is to perfectly isolate it from interactions with its environment. Such interactions, in turn, destroy the coherence of the system, hence, no quantum property of a *sufficiently large* system can be observed unless via extremely high-precision measurements [13, 16]. In other words, it is assumed that there exists a so-called "macro-scale" beyond which physical systems can be analysed without any reference to the quantum formalism.

In this paper, we challenge this view using a fully information-theoretic analysis and showing that, with the assistance of a second system, a macroscopic system can be proved to be entangled even after *arbitrary* decoherence [20]. We show this by introducing a modified Wigner's friend gedankenexperiment where the observer is not assumed to preserve quantum coherence; see Fig. 1. In our variant, Wigner's friend is in possession of two particles, labelled $\mathbf{a}$ and $\mathbf{t}$, which are *nonentangled*, while she undergoes decoherence. Starting from a GHZ state, Wigner's final evaluation of the quantum state for the system $\mathbf{a}$-$\mathbf{t}$-Alice, in the presence of decoherence and regardless of its dynamics, has the form

$$\begin{aligned}\hat{\varrho}^{(\mathbf{W})}_{\mathbf{atA}} = {} & p|\Psi_+\rangle_{\mathbf{at}}\langle\Psi_+|\otimes\hat{\tau}_{\mathbf{A};\mathrm{ud}} \\ & + (1-p)|\Psi_-\rangle_{\mathbf{at}}\langle\Psi_-|\otimes\hat{\upsilon}_{\mathbf{A};\mathrm{ud}}.\end{aligned} \tag{1}$$

We then show that the joint subsystem of Wigner's friend and particle $\mathbf{t}$ exhibits entanglement with particle $\mathbf{a}$. Consequently, as long as the informational content of Wigner's friend is concerned, she constitutes a quantum system in assistance with particle $\mathbf{t}$ regardless of her size. More specifically, Wigner has to use the quantum formalism to describe the entanglement in this particular partition, independent of his choice of interpretation of quantum theory. Hence, there seems to be no escape from the conclusion that Wigner's friend, despite being a macroscopic observer by any sensible definition, is an *informationally indispensable* part of the quantum system. We provide a link between such a quantum property of macroscopic observers and the security of quantum key distribution (QKD) protocols in terms of the distinguishability of the friend's macroscopic states and argue that a semi-classical analysis of this situation is suboptimal, thus reflecting the necessity of both *presence* and *a quantum treatment* of Wigner's friend.

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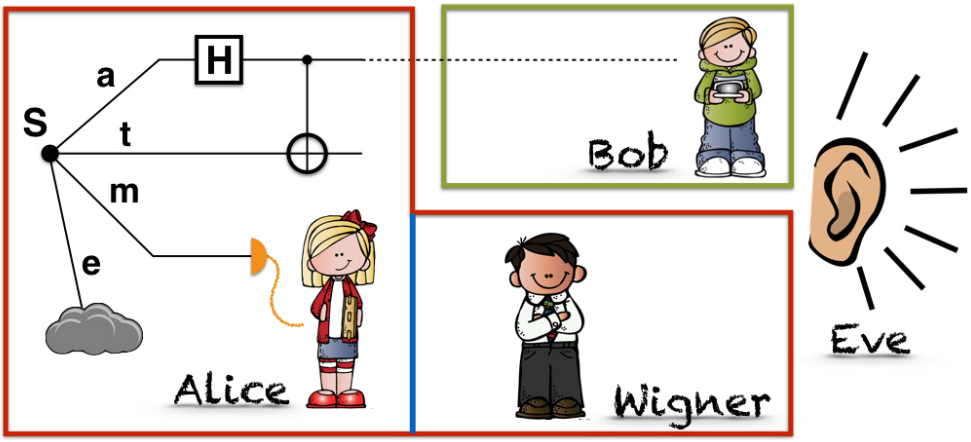

FIG. 1. The schematic of our protocol. A source $\mathbf{S}$ produces a four-mode GHZ state. The ancilla $\mathbf{a}$ goes through a Hadamard gate. A CNOT operation is then performed on the ancilla and the target mode $\mathbf{t}$. The qubit in mode $\mathbf{m}$ goes to Alice, while the mode $\mathbf{e}$ is "lost" within the closed environment of Alice's lab. Alice, as a macroscopic observer, also undergoes decoherence. Wigner, who is outside Alice's laboratory, concludes that Alice and any of the two qubits $\mathbf{a}$ or $\mathbf{t}$ are jointly entangled with the other qubit, while there is no entanglement between $\mathbf{a}$ and $\mathbf{t}$ qubits alone. Wigner may send the ancilla qubit to Bob to distribute a secure quantum key. The security of the key against Eve is directly measured by the distinguishability of Alice's macroscopic states.

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CONTRIBUTED POSTERS

Quantum logic and non-classicality

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The often surprising and non-intuitive consequences of quantum mechanics owe precisely to the fact that it is a new probability theory, not fitting within the framework of the Kolmogorov formulation [1]. The essence of quantum probability lies in its mooring in quantum logic which is quintessentially non-Boolean [2]. It is, therefore, highly desirable to formulate nonclassicality directly in the language of quantum logic. We accomplish this by introducing what we call pseudo-projection operators, and show that they allow us to characterise non-classicality of states comprehensively. This task brings out the facets and layers of quantumness in a more transparent and a structured manner.

We are motivated by a query, posed by Fine [3, 4]: are there circumstances under which a given quantum state permits assignments of joint probabilities for the outcomes of a given set of observables? It is always possible for a classical system, where the joint probability is given by the overlap of the classical state with the corresponding indicator function. An indicator function is a binary function defined over a support on the classical phase space. The quantum representative of the indicator function, for outcomes of individual observables, is a projection operator. For joint outcomes of a set of observables, however, we find the representative to be a pseudo-projector ($\mathbf{\Pi}$), which is nothing but the symmetrised product of the corresponding projection operators. Pseudo-projections are hermitian, but not positive, unless all projection operators commute, in which case they become genuine projections. Pseudo-projections generate pseudo-probabilities ($\mathcal{P} = Tr[\rho\mathbf{\Pi}]$). They can take negative values.

Assignment of joint probabilities for a set of observables is possible, for a quantum state, iff the complete set of pseudo-probabilities corresponding to all possible outcomes of the set of observables is positive. *A state that allows this, is defined to be classical with respect to these observables.* Otherwise the state is non-classical. This definition of non-classicality as expressed via the negativity of pseudo-probabilities had it's roots in the non-Boolean nature of quantum logic. For example, the absurd statement $\mathcal{L}\wedge\neg\mathcal{L} = \perp$, where $\mathcal{L}$ is a classical Boolean proposition, may not find a corresponding expression in quantum logic. In other words, the corresponding pseudo-projection (which represents the joint occurrence of two mutually exclusive events) does not go to zero.

Non-classicality, specially for coupled systems, is much richer in connotation. There has been a veritable explosion in the number of criteria, often driven by physical considerations, and at times by violation of the rules of classical probability. Non-locality and entanglement are particularly important. They too find their natural expression in terms of pseudo-projectors. This requires a modified definition of classicality, which involves imposing the classical Boolean logic on the quantum representative of indicator functions aka. pseudo-projections. This combined with the requirement of positivity on pseudo-probabilities, applied to carefully chosen disjunction of propositions, naturally leads to the Bell-CHSH and other entanglement inequalities.

A preprint of a part of this work is available at [5]

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Open quantum generalization of Hopfield neural networks

Eliana Fiorelli

Neural networks (NNs) are artificial networks inspired by the interconnected structure of neurons in animal brains. They are now capable of computational tasks where most ordinary algorithms would fail, such as speech and pattern recognition, with a wide range of applicability both within and outside academia. Hopfield NNs constitute a simple, but rich, example of how an associative memory can work; they have the ability to retrieve, from a set of stored patterns, the one which is closest to the input. In the last decades, many models have been proposed in order to combine the properties of NNs with quantum mechanics, aiming at understanding if NNs computing can take advantage of quantum effects.

In this work we consider a generalization of classical stochastic Markov processes in terms of quantum spin systems in a way that permits to construct a purely dissipative – yet quantum – dynamics whose stationary state yields the same expectations of its classical counterpart for any classical observable. We explore the question as to whether quantum effects can yield a speed up of the non-equilibrium evolution of spin systems towards such an effective thermal state. We exploit that the corresponding quantum jump operators are defined up to a unitary transformation u, that affects the dynamics but leaves the stationary state invariant. Firstly, we study the approach to stationarity in the fully-connected Ising model, showing that the freedom in choosing u allows to interpolate between a regime in which the order parameter evolves like under a simple Glauber dynamics, to a quantum regime that displays a speed up in the early stages of the dynamics. Secondly, we highlight, under some approximations, similar results in the dynamics of the Hopfield NN, leading to a speedup of pattern retrieval.

Generic emergence of objectivity of observables in infinite dimensions

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Quantum Darwinism posits that information becomes objective whenever multiple observers indirectly probe a quantum system by each measuring a fraction of the environment. It was recently shown that objectivity of observables emerges generically from the mathematical structure of quantum mechanics, whenever the system of interest has finite dimensions and the number of environment fragments is large [F. G. S. L. Brandão, M. Piani, and P. Horodecki, Nature Commun. 6, 7908 (2015)]. Despite the importance of this result, it necessarily excludes many practical systems of interest that are infinite-dimensional, including harmonic oscillators. Extending the study of Quantum Darwinism to infinite dimensions is a nontrivial task: we tackle it here by using a modified diamond norm, suitable to quantify the distinguishability of channels in infinite dimensions. We prove two theorems that bound the emergence of objectivity, first for finite energy systems, and then for systems that can only be prepared in states with an exponential energy cut-off. We show that the latter class of states includes any bounded-energy subset of single-mode Gaussian states.

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Inadequacy of modal logic in quantum settings

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We explore the extent to which the principles of classical modal logic can be applied to fully quantum settings. Modal logic models our reasoning in multi-agent problems, and allows us to solve puzzles like the muddy children paradox. The Frauchiger-Renner thought experiment [1] highlighted fundamental problems in applying classical reasoning when quantum agents are involved; we take it as a guiding example to test the axioms of classical modal logic. In doing so, we find a problem in the original formulation of the Frauchiger-Renner theorem: a missing assumption about unitarity of evolution is necessary to derive a contradiction and prove the theorem. Adding this assumption clarifies how different interpretations of quantum theory fit in, i.e., which properties they violate. Finally, we show that most of the axioms of classical modal logic break down in quantum settings, and make suggestions to generalize them.

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Finding the Quantum-Classical Transition with Poor Measurements

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Recent experimental progress in the control and measurement of quantum systems has enabled the continuous measurement of individual quantum systems, and the calculation of quantum trajectories and state estimates [1]. One of the difficulties in such experiments is the efficiency of the measurement process. In an ideal measurement, the noise will be purely quantum in origin and the measurement efficiency, η, defined to be the fraction of the noise power due to the quantum measurement as opposed to extraneous classical noise from other sources, will be 100%. Unfortunately, practical measurement systems are often far from ideal, and even the best experiments have efficiencies well below 100%. For example, the experimental efficiencies reported in [1] are around 35%. Here, we remove a major obstacle to exploring the quantum-classical transition in continuously measured systems by showing that one characteristic of classicality, the transition to a positive Lyapunov exponent, can be resolved clearly from observed trajectories even with measurement efficiencies as low as 20% [2].

The system that we consider is a standard example from classical chaos which has been widely studied in the classical-quantum regime: the Duffing oscillator. This system has been studied for pure states and efficient measurements and it has been shown to make a transition from non-chaotic to chaotic motion as the action is increased relative to $\hbar$, normally via the introduction of a scaling parameter β. We show that the positive Lyapunov exponent is robust to highly mixed, low purity states and to variations in the parameters of the system [2]; and we show that the system is one that can be realised in the type of experimental superconducting systems currently being used to study continuous quantum measurements and the reconstruction quantum trajectories [1].

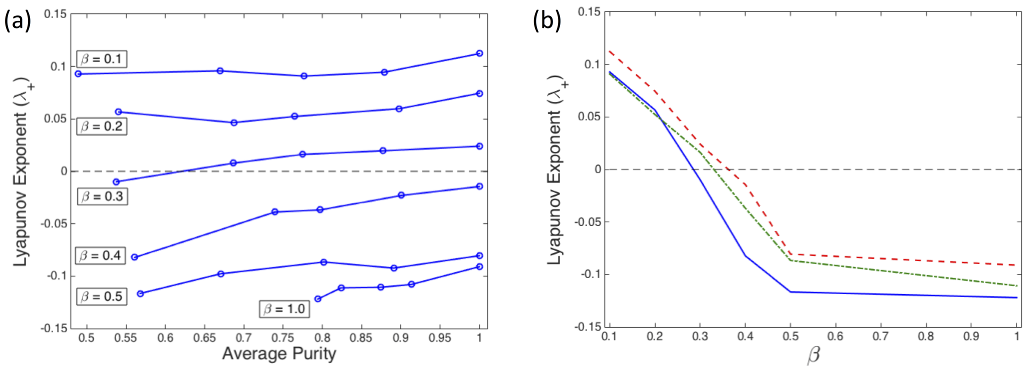

FIG. 1: (a) The largest non-zero Lyapunov exponent (λ_+) calculated for $\beta = 1.0$ (quantum) to $\beta = 0.1$ (near classical) as a function of the average purity of the estimated state, the points marked correspond to measurement efficiencies of $\eta = 1.0$, 0.8, 0.6, 0.4 and 0.2 (right to left); (b) λ_+ for $\beta = 1.0 - 0.1$ and measurement efficiencies of $\eta = 1.0$ (red-dashed line), 0.6 (dot-dashed-green line) and 0.2 (blue-solid line).

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Quantifying identical particle entanglement

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Inter-particle entanglement in systems of identical bosons and fermions is still not entirely understood, unlike *mode* entanglement, yet it yields potential applications in quantum-enhanced metrology and cold atom systems. Identical Particle Entanglement (IPE) affects the quantum system's Fisher information and may enhance sensitivity beyond classical bounds. Furthermore, IPE may be in principle extracted from states of cold atom lattices leading to better insight in these many-body systems.

The identity of particles is a highly non-classical feature of quantum particles. The spin-statistics and wavefunction (anti)symmetrization are a fundamental property of elementary particles which nonetheless apply to composite systems of very large numbers of components, such as may be observed in the bunching and anti-bunching properties of interacting ultracold atoms. In our work we explore the connection between the consequences of the spin-statistics theorem and the entanglement properties of systems of identical particles.

We identify the symmetrization requirement for bosonic and fermionic states to be crucial in the difficulties arising in quantifying entanglement of identical particles and propose an entanglement measure based on standard entanglement negativity. Given a target (anti)symmetrized state, we evaluate its inter-particle entanglement as the minimum distinguishable-particle entanglement associated with an unsymmetrized state which upon projection on the (anti)symmetric subspace yields the target state, up to a normalization constant. Our definition is implementable by means of convex optimization packages, such as Matlab package *cvx*, by formulating the problem as a Semi-Definite Program (SDP) and the distinguishable-particle entanglement measure we adopt is negativity, which may also be evaluated by means of an SDP.

We explore the bipartite and tripartite case and pave the way for the study of multipartite identical particle entanglement in many-body systems.

Quantum feedback and control of levitated microscopic systems

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Over the past few years, considerable developments have been made in controlling quantum systems through a combination of measurement and feedback. Measurements in general will naturally disturb the system through direct interaction with it. However, if we can characterise the resulting disturbance and appropriately interpret the measurement information, then we can determine how to perform feedback in such a way as to drive the system into low-temperature and potentially highly non-classical states [1].

We have been interested specifically in using feedback to prepare and manipulate quantum states of motion of levitated nano-particles. Recently there has been experimental development in nanomechanical systems, in which magnetic traps are capable of creating sufficiently large trapping potentials for levitated nanospheres and nanodiamonds about a micron in diameter [2]. We have been theoretically exploring this parameter regime, which differs from previous work with trapped ions or nanomechanical resonators in high-frequency trap systems. In particular, we typically need to control these large systems on a timescale faster than the trap frequency, to avoid adverse effects of heating and coupling to the environment. We have explored several possible measurement and feedback schemes that can be useful for cooling these particles. By considering a combination of measurements, we further develop ideas for creating non-classical states in a new generation of quantum control technologies immediately appropriate for implementation in these experiments.

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