Book of Abstracts: Poster Session

VCQ AND TURIS SUMMER SCHOOL' 24

Interfacing Gravity and Quantum Physics
2nd-6th Sept.' 24

Poster - 01

Tim Achenbach (Uni Siegen)

Title : Connecting the notions of incompatibility and entanglement

Abstract: Quantum theory is formulated in terms of positive operators on a Hilbert space, which form a cone in the vector space of hermitian operators. The approach using the formalism of cones allows us to deduce fundamental statements about quantum theory in a general way. Here we emphasize the role of the minimal and maximal tensor product of cones of real and finite dimensional vector spaces as they correspond to the notions of separability and entanglement. This enables us to show that incompatibility corresponds to a form of entanglement in a generalized sense and we find that the CHSH inequalities are just linear isomorphisms between squares. Using these observations we are able to retrieve known results on the CHSH inequalities as witnesses of incompatible measurements in a considerably simpler manner, while shining light on the deeper underlying structures.

Poster - 02

Eduardo Amancio (IQOQI - Vienna (Guest Researcher); IFT/UNESP (PhD Student))

Title : A covariant formalism for accelerated quantum clocks with a quantized center of mass: relativistic aspects and coherent time dilation

Abstract: In the past recent years, there has been a surge of interest for the possibility of measuring quantum-gravitational effects at low energies. Theoretically, these effects have been widely explored through operational tools such as quantum clocks – incorporating the fundamental insight that a physical apparatus measuring (space)time intervals must comply with quantum mechanical laws –, which hint towards new quantum phenomena in spacetime itself, such as Quantum Time Dilation and Indefinite Causal Order. However, many of the existing results in the literature are derived solely in the context of nonrelativistic quantum mechanics, leaving open the question of whether they are robust to a first-principle relativistic treatment. In this work, we employ a fully covariant formalism to study relativistic quantum clocks with quantized center of mass dynamically accelerated through couplings with external fields and analyze how these give rise to couplings between internal clock degrees of freedom (DOFs) and external ones, as well as how such quantum-controlled DOFs give rise to coherent signatures on time dilation. As an application, we compute explicitly the time dilation for the case of charged clocks in a uniform magnetic field, whose semiclassical states remain confined in a compact spatial region and thus could be probed entirely by local measurements performed in a compact laboratory.

Poster - 03

Navdeep Arya (Stockholm University)

Title: Selective Amplification of a Gravitational Wave Signal Using an Atomic Array

Abstract: We shall discuss a novel approach for quantum sensing of gravitational waves (GWs) by exploiting the collective dynamics of a 1D array of identical atoms to selectively amplify a GW signal. The details of the radiative process sensitively depend on the interatomic spacing in the array and the mode structure of the quantum field to which the atoms are coupled. The radiative dynamics of the array receives contributions both from each atom behaving independently of the others and the collective response of the atoms. Importantly, the transition rates of each individual atom are insensitive to the GW to first order in the GW amplitude. The leading-order effect of a GW on the transition rates of an atom is quadratic in the GW amplitude. Given that the amplitude of the GWs received on Earth is minuscule, this has discouraged any thought of using radiative processes in atoms to sense GWs. In contrast, we show that the collective response of the array has both Minkowskian and GW contributions. Crucially, the collective decay of the array is sensitive to the GW at first order in the GW amplitude and, additionally, involves photon emission with well-defined directionality at shifted frequencies depending on the frequency of the incident GW. Further, the condition for the collective response of the atoms is different in the presence of the GW. The collective Minkowskian decay vanishes for interatomic spacing equal to the transition wavelength of an atom. However, this configuration of the atoms is the most suitable for sensing the GW. In such a configuration, the effective number of atoms cooperating to sense the GW scales linearly with the total number of excited atoms up to an upper limit inherent in the field correlations. Consequently, the signature of the GW in the emission rate of the array scales nearly quadratically with the number of participating atoms. We discuss the feasibility of this scheme in light of current and near-future experimental capabilities.

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Poster - 04

Matteo Bordin (Queen's University Belfast)

Title: Generation of Quantum Coherent Optomechanical States via Non-Gaussian Measurement

Abstract: The generation of quantum coherent mechanical state in optomechanical systems has recently attracted the interest from the scientific community for the possible realisation of Gravitationally Induced Entanglement detection experiments, as for the investigation of more fundamental aspects of quantum theory on a larger scale.
Different procedures are currently under investigations, as the use of dark potential or squeezing protocols. In this poster we focus on the possibility of generating them by measuring the scattered laser light onto a Non-Gaussian basis.

Poster - 05

Alexander Bott (University of Ulm)

Title: Atomic diffraction from single-photon transitions in gravity and Standard-Model extensions

Abstract: Single-photon transitions are one of the key technologies for designing and operating very-long-baseline atom interferometers tailored for terrestrial gravitational-wave and dark-matter detection. Since such setups aim at the detection of relativistic and beyond-Standard-Model physics, the analysis of interferometric phases as well as of atomic diffraction must be performed to this precision and including these effects. In contrast, most treatments focused on idealized diffraction so far. Here, we study single-photon transitions, both magnetically-induced and direct ones, in gravity and Standard-Model extensions modeling dark matter as well as Einstein-equivalence-principle violations. We take into account relativistic effects like the coupling of internal to center-of-mass degrees of freedom, induced by the mass defect, as well as the gravitational redshift of the diffracting light pulse. To this end, we also include chirping of the light pulse required by terrestrial setups, as well as its associated modified momentum transfer for single-photon transitions

Poster-06

Leonardo Castillo Veneros (Stony Brook University)

Title: Towards a Quantum Network Sandbox to Test Frontier Physics

Abstract: Long baseline quantum networks provide a flexible and modular framework to realize controllable complex and fundamental quantum systems and experiments. This work highlights the current developments and capabilities of the 158 km Quantum-Enabled Internet prototype on Long Island. We discuss the methodology and infrastructure for robust entanglement distribution and consumption between disparate light-matter interface nodes. This includes an introduction to a general network architecture to rigorously detail and design the functionality of deployed quantum networks in a scalable manner and the characterization of ancillary systems needed to enable concurrent operation of multiple quantum nodes. Finally, we discuss using this foundation to develop laboratory and long-distance experiments to probe gravitational effects along the lines of ultra-precise opto-mechanics and proper-time interferometry, providing an attractive avenue to test theories at the intersection of quantum and gravitational physics.

Poster- 07

Kai Ellers (University of California, Berkely)

Title: Towards a measurement of gravitational frame-dragging using a superfluid interference device

Abstract: Gravitational frame-dragging is a prediction of general relativity that does not exist in Newtonian gravity. Frame-dragging derives from the spacetime metric outside of a rotating mass and leads to precession of gyroscopes near such a mass. We are proposing a novel experimental test of this effect using a Superfluid Helium Quantum Interference Device (SHeQUID). Such an interferometer is a superfluid analog of a conventional Superconducting Quantum Interference Device (SQUID) and acts as a Sagnac interferometer that is sensitive to "rotation flux" through the interferometer loop. SHeQUIDs have already been used to measure the rotation of the Earth and further improvement in sensitivity could allow one to measure other phenomena such as frame-dragging. To our knowledge, this would be the first terrestrial measurement of this effect, following previous measurements using satellite laser ranging and using London moment gyroscopes on Gravity Probe B. In this work, we derive the effect of frame-dragging on a SHeQUID and analyze the requirements on a future SHeQUID to make a frame-dragging measurement possible. In particular, we consider the fundamental sensitivity limits on such a device coming from thermal noise and discuss one prospective approach to achieving the required sensitivity. We also consider how frame-dragging might be distinguished in a SHeQUID from other effects such as small variations in the Earth's rotation rate.

Poster-08

Niklas Engelhardt Önne (Uppsala University)

Title: Gravity Signatures in Atomic Clocks

Abstract: Atomic systems operate far away from a regime where quantum gravity may be expected. But the remarkable precision and control over ever-growing atomic quantum systems opens the possibility to study potential limits from quantum gravity -- and possible signatures. Here we investigate how mutual quantum gravity effects can manifest themselves in optical lattice atomic clocks, adopting previous considerations by Castro-Ruiz, Giacomini and Brukner to these systems. All effects follow directly from standard quantum theory and the mass-energy equivalence principle and do not rely on a specific speculative model of quantum gravity. We show what limitations quantum gravity provides and design protocols to enhance the quantum gravity signatures. Our work shows that even in the atomic realm, quantum gravity effects may become relevant in future experiments.

Poster- 09

Samuel Fedida (University of Cambridge)

Title: The mixture equivalence principle and post-quantum theories of gravity

Abstract: We examine the mixture equivalence principle, which states that proper and improper mixed states are experimentally indistinguishable, in gravity theories. We point out that semiclassical gravity and, more generally, nonlinear extensions of quantum mechanics violate the mixture equivalence principle. We further demonstrate that modifications of the Born rule in quantum theory also typically violate this principle. We show that such violations may lead to theoretical inconsistencies when modelling thermal baths, for example in black hole physics. We show that either semiclassical gravity is inconsistent, or standard derivations of Hawking radiation are unsound within this theory. Hence quantum field theory in curved fixed spacetime is not a limiting theory of semiclassical gravity in the context of black holes with negligible gravitational back-reactions. We argue that violations of the mixture equivalence principle implies that some post-quantum theories do not reduce to effective field theories or are simply theoretically inconsistent.

Poster- 10

Maarten Grothus (Inria Grenoble)

Title: Characterizing Signalling: Connections between Causal Inference and Space-time Geometry

Abstract: Causality is pivotal to our understanding of the world, presenting itself in different forms: information-theoretic and relativistic, the former linked to the flow of information, the latter to the structure of space-time. Leveraging a framework introduced in PRA, 106, 032204 (2022), which formally connects these two notions in general physical theories, we study their interplay.

Here, information-theoretic causality is defined through a causal modelling approach. First, we improve the characterization of information-theoretic signalling as defined through so-called affects relations. Specifically, we provide conditions for identifying redundancies in different parts of such a relation, introducing techniques for causal inference in unfaithful causal models (where the observable data does not "faithfully" reflect the causal dependences). In particular, this demonstrates the possibility of causal inference using the absence of signalling between certain nodes. Second, we define an order-theoretic property called conicality, showing that it is satisfied for light cones in Minkowski space-times with $d>1$ spatial dimensions but violated for $d=1$.

Finally, embedding our causal models in space-time and imposing no superluminal signalling (NSS), we investigate the behavior of the information-theoretic and spatio-temporal causal orders. Specifically, we find that when an information-theoretic causal model is embedded compatibly with NSS in a space-time, the two types of causal orders can behave differently and need not align. However, we prove that in conical space-times and in causal models that are faithful, a useful parallel emerges between these order relations.

This indicates a connection between informational and geometric notions of causality, and offers new insights for studying the relations between the principles of NSS and no causal loops in different space-time geometries and theories of information processing.

Poster- 11

Michael Hatzon (University of Western Australia)

Title: Advancements on the Scalar Aharanov-Bohm Effect

Abstract: The Aharonov-Bohm (AB) effect is a core outcome of quantum mechanics, it highlights the significance of potentials beyond classical theory. This comes in the form of a physical manifestation of potentials, whether they are gravitational, or electromagnetic potentials. Recent work shows that temporal electron phase variations will result in energy level splitting of degenerate modes. We apply this framework to a two level system akin to a clock, under a time varying scalar gravitational potential, and seek to extend it to formulate the theory for the scalar electric potential. Experimental validation of these tests of the scalar AB effect are conceivable with experiments under way. Notably, non-nominal orbits of two European Space Agency Galileo satellites equipped with on-board clock enable the search for modulation side-bands due to a time-varying scalar gravitational potential. Additionally, we pioneer an electric field suppression device to test the scalar electric AB effect. With the capacity to maintain a time-varying scalar electric potential without the presence of electric fields, we anticipate modulation side-bands when placing a suitable device, such as a quantum dot, under these conditions.

Poster- 12

Robert Horn (Max Planck Institute for Nuclear Physics)

Title: Towards nonlinear x-ray quantum optics with Mössbauer nuclei using periodically structured cavities

Abstract: Due to their narrow linewidth, Mössbauer nuclei, such as 57Fe, have become an important platform for studying the nature of photons in the hard x-ray regime. These nuclei not only serve as potential nuclear clocks but also emerge as promising candidates for x-ray quantum dynamics. While the linear optics regime is currently studied both theoretically and experimentally with x-ray free electron lasers [1], the nonlinear regime remains neither fully understood nor experimentally observed yet. However, recent theoretical work has explored thin-film cavities with embedded Mössbauer nuclei probed at grazing incidence by short focused pulses operating in the nonlinear regime [2], along with presenting experimental conditions for realization [3].

In this project, we propose an alternative approach that involves breaking the translational symmetry of the cavity along the wave propagation direction. The goal is to investigate the possibility of nonlinear excitations and to study photon correlations at different incident angles.

Poster- 13
Martijn Janse (Leiden University)

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Title: Characterisation of a levitated sub-mg ferromagnetic cube in an alternating current planar magnetic Paul trap

Abstract: Microscopic levitated objects are a promising platform for inertial sensing, optomechanics in the quantum regime and large-mass superpositions. However, existing levitation techniques harnessing optical and electrical fields suffer from decoherence induced by elevated internal temperatures and charge noise respectively. Magnetic Meissner-based levitation circumvents both sources of decoherence but requires cryogenic environments. Here we characterize a sub-mg ferromagnetic cube levitated in an alternating current planar magnetic Paul trap at room temperature. We show behavior in line with the Mathieu equation and Q-factors of up to 2500 for the librational modes. Besides technological sensing applications, this technique opens up MHz librational modes in the micron-sized particle limit, allowing for coupling to SQUID-based resonators and spin-based quantum systems such as NV centers.

Poster- 14

Adrian Kent (University of Cambridge)

Title: Time and distance constraints for mass and charge interferometry

Abstract: We reanalyse and extend constraints on mass and charge interferometry identified by Mari et al. (2016).
We show that their constraint on the time required for coherent interference can be extended by a factor of two. We extend their analysis to consider experiments in which one interferometer measures gravitational or electric fields generated by another.
We note that these analyses imply a maximum separation between a mass or charge interferometer and a decohering gravitational or electric field measurement that can be carried out without backreaction. We discuss the implications for testing the quantum nature of gravity. We also discuss extensions of the analyses to a full QED/perturbative quantum gravity treatment.

Poster- 15

Martin Kerschbaumer (ICFO - Institute of Photonic Sciences)

Title: Robust Bell Nonlocality in Network Configurations with High-Dimensional Quantum States

Abstract: Our study addresses a critical challenge in quantum information science: extending Bell nonlocality to network configurations, which has garnered significant attention to surpass the limitations of traditional Bell tests. A major obstacle in this endeavor is photon loss. To tackle this, we propose a novel approach using high-dimensional quantum states, specifically NOON states, with one state per source. Our configuration employs passive optical elements and non-photon-number resolving detectors, arranged in a triangle network.

The primary focus of our investigation is overcoming the vulnerability of network nonlocality to photon loss, a predominant issue in optical setups. Through analytical examination of the resulting distributions, we demonstrate that nonlocality remains robust even in the presence of photon loss, marking a critical advancement for experimental feasibility. Remarkably, this resilience is achieved with just two photons at each source, underscoring the practicality of our approach.

Furthermore, we try to introduce an experimental setup designed to implement our proposed solution. This configuration incorporates a technique that bypasses the need for global post-processing, addressing significant obstacles in achieving Bell nonlocality within networks. Our methodology not only tackles the photon loss problem but also sets the stage for future advancements in quantum communication and computation.

In summary, our work provides a substantial contribution to the field of Bell nonlocality by offering a solution to the photon loss issue in network-based experiments. By utilizing high-dimensional quantum states and innovative experimental techniques, we establish a framework for the reliable and efficient exploration of nonlocal phenomena in quantum networks. This research not only deepens our fundamental understanding of quantum mechanics but also has potential applications in quantum information processing and communication technologies.

Poster- 16

Christian Niehof (TU Darmstadt)

Title: Finite speed of light and gravitational effects in atom interferometry

Abstract: Light-pulse atomic interferometers are high-precision tools for inertial measurements and tests of fundamental physics in ground-based laboratories and in space. They are currently being used to measure rotations, gravitational accelerations, gravitational gradients and to test predictions of Einstein's equivalence principle. There are also plans to use them as detectors for dark matter, gravitational waves and further tests of Einstein's equivalence principle in regions where conventional detectors are inadequate. To achieve high enough precision, atom interferometer sequences need to cover large spacetime area, and hence there are plans for atom interferometers up to the 100m/1km scale in vertical and horizontal setups. It is necessary to take into account all relevant relativistic corrections and effects in order to obtain a description that is suitable for dealing with small relativistic effects or physics beyond the Standard Model. One of these relevant effects is due to the finite speed of light, which becomes more important for larger scale atomic

interferometers. The time delay of a diffracted light pulse between different spatially separated interferometer arms results from the finite speed of light and leads to a phase imprint on the overall interferometer phase. Another relativistic effect is the gravitational redshift of light in vertical setups. It can be compensated by a suitable chirp of the laser frequencies to the leading order. Its explicit form depends on the process used for diffraction, i.e. single-photon Raman or two-photon Bragg transitions. A theoretical framework for the description and estimation of such effects is discussed in this poster. Different diffraction techniques are proposed for existing and planned light pulse atomic interferometry.

Poster- 17

Bruno Sahdo (IQOQI Vienna)

Title: Gravitational quantum switch on a superposition of spherical shells

Abstract: Since the beginning of its study, indefinite causality has been pointed out as an expected feature in quantum gravity. The quantum information tools used to model it, like process matrices, are seen as potentially important to understand quantum spacetime and its consequences. However, only a few works have really aimed at using these mathematical constructions to represent causal structures due to quantum spacetime regions. In this work, we propose a thought experiment in a quantum gravity scenario that corresponds to a process in an operationally meaningful way: a gravitational quantum switch (GQS). In a quantum switch (QS), two agents named Alice and Bob apply local operations A and B on a system. The final state of the system derived from the switch process indicates that the order in which they are applied, A before B or B before A, is indefinite and can actually be interpreted as entangled with a control q-bit initially in a superposition. In a gravitational switch, spacetime itself acts as the control q-bit. The spacetime we propose for the protocol is composed of two massive spherical shells in a quantum superposition state of different radii. This type of spacetime is interesting because it behaves classically outside of the central region where the shells are, allowing us to better account for the description by classical external observers and apply the hypotheses of the process formalism. The setup has unique characteristics that produce indefinite order between the two events no matter which local operations or measurements agents Alice and Bob choose to make, in contrast with other proposals of QS and GQS. The universality for operations suggests that this case arises fundamentally as consequence of the spacetime quantum causal structure and that there is no straightforward way to simulate its operational properties in a non-quantum gravity scenario.

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Poster- 18

Raffaele Silvestri (University of Vienna)

Title: Experimental observation of Earth rotation with quantum entanglement

Abstract: The first measurement of Earth rotation using maximally path-entangled quantum states of light in a optical fiber Sagnac interferometer is presented. The achieved sensitivity constitutes the highest rotation resolution achieved with optical quantum interferometers. The result demonstrates the feasibility of extending the utilization of entangled quantum states to large-scale interferometers, while further improvements to the methodology will enable measurements of general-relativistic effects on entangled photons.

Poster- 19

Germain Tobar (Stockholm University)

Abstract: The quantisation of gravity is widely believed to result in gravitons -- particles of discrete energy that form gravitational waves. But their detection has so far been considered impossible. In this talk, I will discuss how signatures of single gravitons can be observed in laboratory experiments. We show that stimulated and spontaneous single-graviton processes can become relevant for gravitational wave detectors and that stimulated absorption can be feasibly resolved through optomechanical readout of phonon transitions. Our results show that single graviton signatures are within reach of laboratory experiments with modest improvements to existing technology. In analogy to the discovery of the photoelectric effect for photons, such signatures can provide the first experimental evidence of the quantisation of gravity.

Poster- 20

Chase Wallace (Stony Brook University)

Abstract: The development of scalable long-distance quantum networks is becoming an increasingly appealing route to probe gravitational effects. We describe our recent developments toward a scalable quantum internet through recent results from fundamental components of our three-node network, connected with 140 km of deployed fiber across Long Island, NY, USA. We first demonstrate photon-pair distribution at the 1324 nm rubidium transition. These pairs, produced via PPKPT, were split on a beam splitter and sent to disparate nodes, 70 km in opposing directions. The measured increase of coincidences at the time delay, corresponding to the path length difference between the fibers, indicates sufficient network phase and timing stability to support entangled pairs. Current efforts aim towards characterizing our polarization entanglement source to distribute entanglement across the 140 km network. Interfacing the entangled photon sources with our warm rubidium vapor quantum memory systems or cold atom quantum devices could yield a promising platform for many long baseline interferometric tests for gravitational effects.

Poster-21

Joseph Aziz (Royal Holloway University of London)

Title: Entanglement via Classical Gravity using a Quantum Channel

Abstract: The LOCC theorem tells us that classical channels and local operations can no generate entanglement. This fact is used in GIE experiments to deduce that witnessing entanglement implies that gravity is quantum. This work considers a process in which classical gravity is involved in entangling two states via a quantum channel. This points out that witnessing entanglement alone is not concrete proof of quantum gravity as there are processes in which entanglement is generated whilst gravity remains classical.

Poster- 22

Patrick Wong (Nordic Institute for Theoretical Physics, KTH Royal Institute of Technology & Stockholm University Department of Physics, University of Connecticut)

Title: Quantum Sensing from Gravity as Universal Dephasing Channel for Qubits

Abstract: We investigate the interaction of a transmon qubit with a classical gravitational field. Exploiting the generic phenomena of the gravitational redshift and Aharonov-Bohm phase, we show that entangled quantum states dephase with a universal rate. The gravitational phase shift is expressed in terms of a quantum computing noise channel. We give a measurement protocol based on a modified phase estimation algorithm which is linear in the phase drift, which is optimal for measuring the small phase that is acquired from the gravitation channel. Additionally, we propose qubit-based platforms as quantum sensors for precision gravitometers and mechanical strain gauges as an example of this phenomenon's utility. We estimate a sensitivity for measuring the local gravitational acceleration to be $\delta g/g \sim 10^{-7}$. This paper demonstrates that classical gravitation has a non-trivial influence on quantum computing hardware, and provides an illustration of how quantum computing hardware may be utilized for purposes other than computation. While we focus on superconducting qubits, we point the universal nature of gravitational phase effects for all quantum platforms.