Review Talks

Caslav Bruckner (University of Vienna)

Quantum Reference Frames

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Esteban Castro Ruiz (University Paris-Saclay)

Quantum Causal Orders

Albert Roura (DLR Ulm)

Long-baseline quantum optics experiments in space

Talks

Mohamemd Alkhateeb (CY Cergy Paris Université)

Space-time resolved quantum field approach to Klein tunneling dynamics of fermions and bosons

We investigate Klein tunneling with space-time resolved solutions to relativistic quantum field equations with background potential barriers. We show in particular that no particle actually tunnels through a finite supercritical barrier, even in the case of resonant tunneling. The transmission is instead mediated by modulations in pair production at each edge of the barrier caused by the incoming particle which decreases (increases) the number density of anti-particles in the case of fermions (bosons). This decrease (increase) undergoes multiple reflections inside the barrier modulating pair production rate at its edges and forming the reflected and transmitted wave packets. We further examine the effect of the barrier's width on the numbers of produced pairs in the fermionic case (characterized by saturation) and in the bosonic case (characterized by exponential superradiance). We compare the results qualitatively and quantitatively to the first-quantized account of Klein tunneling.

arXiv: 2201.02038, 2110.14452 and 2002.00043

Veronika Baumann (IQOQI Vienna)

Different perspectives in (non)-causal quantum processes

The process matrix framework was developed to allow for scenarios with indefinite or quantum causal order, a phenomenon that is expected to be relevant for quantum gravity.A popular approach towards a quantum theory of gravity is the Page-Wootters formalism, which describes time-evolution of systems via correlations between a clock system and other quantum systems encoded in history states. We combined the process matrix framework with a generalization of the Page-Wootters formalism with multiple clocks. Each of these clocks can be thought of as corresponding to an agent and conditioning on a certain clock gives the respective agent's perspective inside an a priori general quantum process. We implemented scenarios where different definite causal orders are coherently controlled and explain why certain non-causal processes might not be compatible within this framework.

Phys. Rev. Research 4, 013180 (2022)

Alessio Belenchia (Eberhard-Karls-Universität Tübingen)

Testing the foundations of quantum physics with large particles in space

Quantum technologies are opening novel avenues for the exploration of the basic tenets of quantum physics and gravity. In this talk, I will focus on the possibilities offered by mesoscopic superpositions of nanoparticles in interferometric experiments in space for the investigation of the superposition principle of quantum mechanics and the quantum-to-classical transition. I will argue that, indeed, these experiments open the way for testing the foundations of quantum mechanics at an unprecedented level of detail. In order to do so, after introducing the basic concepts of near-field interferometry with large nanoparticles, I will discuss the possibilities offered by the state-of-the-art of nanoparticle physics projected in the space environment and discuss the numerous challenges and advantages that the space environment presents. In this context, I will show some ab-initio estimate of the potential of space-based interferometry for exploring nanometric superpositions of particles up to 1011 atomic mass units -- six orders of magnitude beyond current experimental achievements -- based on realistic parameters as considered in the recent ESA's CDF study report assessing the Quantum Physics Payload Platform proposal.

DOI: 10.1038/s42005-021-00656-7; DOI: 10.1103/PhysRevA.103.022214; DOI: 10.1088/2058-9565/aca3cd

Daniel Braun (University Tübingen)

Quantum metrology and the measurement of small gravitational effects

We review our recent theoretical work on possibilities of measuring small gravitational effects using quantum metrology. The first example concerns the gravitational near fields of extremely high power lasers or particle beams such as the proton beam in the linear hadron collider (LHC) at CERN. The origin of gravity is there pure electromagnetic energy or almost pure kinetic energy, respectively. We show that with state of the art opto-mechanical sensors that are further optimized, a detection of the gravitational field of the LHC beam should be possible in the near future. The second example is the question of the local measurability of the expansion of the universe, for which there has been no theory consensus for almost 80 years. Previous work on double Doppler tracking of satellites had raised the hope that one might obtain a relative frequency shift of order βH, where H is the Hubble constant and β the speed of the satellite in units of the speed of light in vacuum, which should be measurable by modern optical clocks. We show, however, that the magnitude of the effect depends very much on the observer. In particular, for a free-falling observer in a McVittie or Schwarzschild de Sitter spacetime, the effect is only quadratic in H, and this is also the case for the frequency shift of an electromagnetic cavity. Motivated by the same prediction of an effect of order βH, we also investigated the propagation of an optical soliton in a non-linear, dispersive optical fiber embedded in curved space time, where β is of order 1. We show how this situation can be described by an effective medium in flat space-time that combines the properties of space-time and the medium itself. Focusing on Schwarzschild space-time, we show that for a radially suspended fiber the modification of the speed of the soliton is dominated by photo-elasticity, i.e.~the modification of the index of reflection due to the the mechanical deformation of the fiber in the gravitational field. This might find technological application in seabed earthquake sensing with distributed optical fiber networks.

[1] Felix Spengler, Alessio Belenchia, Dennis Ratzel, and Daniel Braun, Perspectives of measuring gravitational effects of laser light and particle beams, New Journal of Physics, 24, 053021, (2022).

[2] Felix Spengler, Alessio Belenchia, Dennis Ratzel, and Daniel Braun Influence of cosmological expansion in local experiments, Classical and Quantum Gravity 39, 055005 (2022).

[3] Felix Spengler, Alessio Belenchia, Dennis Rätzel, and Daniel Braun, Optical solitons in curved spacetime, http://arxiv.org/abs/2301.04986

Cameron R. D. Bunney (University of Nottingham)

Circular motion analogue Unruh effect in a 2+1 thermal bath

The Unruh effect states that a uniformly linearly accelerated observer with proper acceleration a experiences the Minkowski vacuum as a thermal state at temperature T_U=a/(2π). An observer in uniform circular motion is known to experience a similar effective temperature, which however depends also on the orbital speed and the excitation energy. This paper addresses an observer in uniform circular motion in an ambient thermal bath. We model the observer as an Unruh-DeWitt detector, coupled to a massless scalar field in 2+1 spacetime dimensions, adopting an analogue spacetime formulation that may become experimentally testable in laboratory systems. We establish analytic results for the observer's effective temperature in several asymptotic regions of the parameter space and provide numerical results in the interpolating regions. There exist parameter regimes where the observer sees a temperature lower than the ambient temperature, experiencing a cooling Unruh effect.

arXiv: 2303.12690

Chryssomalis Chryssomalakos (Universidad Nacional Autónoma de México-UNAM)

Toponomic Quantum Computation

Holonomic quantum computation makes use of non-abelian geometric phases, associated to the evolution of a subspace of quantum states, to encode logical gates. We identify a special class of subspaces, for which a sequence of rotations results in a non-abelian holonomy of a topological nature, so that it is invariant under any $SO(3)$-perturbation. Making use of a Majorana-like stellar representation for subspaces, we give explicit examples of topological-holonomic (or \emph{toponomic}) NOT and CNOT gates.

Daniele Colosi (Universidad Nacional Autónoma de México-UNAM)

Excitation of an Unruh-DeWitt detector by quantum evanescent waves

The solution space of the Klein-Gordon equation in a neighboorhood of Minkowski hypercylinder region, namely a spacetime region bounded by a sphere in space extended over all of time, can be decomposed in propagating (E>m) and evanescent modes (E<m). We present a new quantization scheme adapted to the evanescent modes. Then, coupling the field with an Unruh-DeWitt detector (UDW) we study the possibility of absorption and emission of evanescent particles by the UDW.

Fabio M. Costa (Nordita, Stockholm University)

A de Finetti representation for quantum causal structures

What does it mean for a causal structure to be “unknown”? Can we even talk about “repetitions” of an experiment without prior knowledge of causal relations? And under what conditions can we say that a set of processes are independent and identically distributed (i.i.d.)? Similar questions for classical probabilities, quantum states, and quantum channels are beautifully answered by so-called

“de Finetti representations”, which connect a simple and easy-to-justify condition---symmetry under exchange---with a very particular multipartite structure: a mixture of identical states/channels. Practically, they provide the foundations for principle-based Bayesian methods, e.g., in tomography. Apart from the foundational relevance, de Finetti representations for general causal structures would be useful in the analysis of multi-time, non-Markovian processes, with applications to state-of-the-art quantum devices.

At face value, it appears that each causal structure or assumption on causal structure requires its own de Finetti theorems. Fortunately, I will show that each scenario can be mapped to a linear constraint on quantum states. By proving a de Finetti representation for states subject to a sufficiently large class of constraints, we can derive all the desired results for a broad class of processes.

Anne-Catherine de la Hamette (University of Vienna, IQOQI Vienna)

Quantum diffeomorphisms cannot make indefinite causal order definite

The study of indefinite causal order has seen rapid development, both theoretically and experimentally, in recent years. While classically the causal order of two timelike separated events A and B is fixed - either A before B or B before A - this is no longer true in quantum theory. There, it is possible to encounter superpositions of causal orders. In light of recent work on quantum reference frames, which reveals that the superposition of locations, momenta, and other properties can depend on the choice of reference frame or coordinate system, the question arises whether this also holds true for superpositions of causal orders. Here, we provide a negative answer to this question for quantum diffeomorphisms. First, we provide an unambiguous definition of causal order between two events in terms of worldline coincidences and the proper time of a third particle. Then, we show that superpositions of causal order defined as such cannot be rendered definite even through the most general class of coordinate transformations - quantum-controlled, independent diffeomorphisms in each branch. Finally, based on our results, we connect the information-theoretic and gravitational perspectives on indefinite causal order.

arXiv:2211.15685 [quant-ph]

Jose de Ramon Rivera (University de Burgos)

Field-particle duality and time-energy uncertainty in measurements of quantum fields

In this talk I will discuss the emergence of particle-like versus field interpretation of the detector response, in the weak versus strong coupling regime respectively. More concretely, I will present results concerning the measurement of field observables with local probes, and I will discuss in which cases the response can be interpreted in terms of the one-paticle Hilbert space of the field, or if a field description is necessary.
In the weak coupling regime, we will see how measurements of energy emerge in detector models through resonant phenomena and in which sense one can perform measurements of time. We will argue that these two measurements are complementary within the framework of particle detector models.
I will also discuss the role that perturbation theory plays in these considerations by considering the exactly solvable QBM model for a quantum harmonic oscilator coupled to the quantum field. This

model reproduces standard results for weakly as well as strongly coupled detectors, but it can also be used to explore the intermediate regime for tunable field/detector couplings.

Flavio Del Santo (University of Geneva)

The relativity of indeterminacy

A long-standing tradition, largely present in both the physical and the philosophical literature, regards the advent of (special) relativity -- with its block-universe picture -- as the failure of any indeterministic program in physics. On the other hand, quantum mechanics paved the way to an understanding of physics as manifestly indeterministic at the classical level. In my talk, I will show that upholding reasonable principles of finiteness of information hints at a picture of the physical world that should be both relativistic and indeterministic. I will thus rebut the block-universe picture by assuming that fundamental indeterminacy itself should be regarded as a relational property when considered in a relativistic scenario. I will discuss the consequence that this view may have when correlated randomness is introduced, both in the classical case and in the quantum one.

arXiv:2101.04134

Kfir S. Dolev (Stanford Institute for Theoretical Physics)

Holography as a resource for non-local quantum computation

If two parties share sufficient entanglement, they are able to implement any channel on a shared bipartite state via non-local quantum computation – a protocol consist- ing of local operations and a single simultaneous round of quantum communication. Such a protocol can occur in the AdS/CFT correspondence, with the two parties represented by regions of the CFT, and the holographic state serving as a resource to provide the necessary entanglement. This boundary non-local computation is dual to the local implementation of a channel in the bulk AdS theory. Previous work on this phenomenon was obstructed by the divergent entanglement between adjacent CFT regions, and tried to circumvent this issue by assuming that certain regions are irrelevant. However, the absence of these regions intro- duces violent phenomena that prevent the CFT from implementing the protocol. Instead, we resolve the issue of divergent entanglement by using a finite-memory quantum simulation of the CFT. We show that any finite-memory quantum system on a circular lattice yields a protocol for non-local quantum computation. In the case of a quantum simulation of a holographic CFT, we carefully show that this protocol implements the channel performed by the local bulk dynamics. Under plausible physical assumptions about quantum compu- tation in the bulk, our results imply that non-local quantum computation can be performed for any polynomially complex unitary with a polynomial amount of entanglement. Finally, we provide a concrete example of a holographic code whose bulk dynamics correspond to a Clifford gate, and use our results to show that this corresponds to a non-local quantum computation protocol for this gate.

arXiv: 2210.13500

Demosthenes Ellinas (Technical University of Crete QLab)

Superposition of topologies via indefinitely ordered composition of quantum channels

The starting idea concerns the employing of the topological states exhibited by a 1D lattice model via its dependence on two real unequal parameters a and b. The criterion of trivial (a<b) or non-trivial (a>b) topology is mathematically expressed by a contour complex integral evaluating the trace of an operator determining model's Hamiltonian. By that property random unitary quantum channels are constructed with Kraus generators provided by models' unitary evolution operator, both for trivial (a<b) and non-trivial (a>b) topologies. Those channels are combined by a 2-switch. Depending on the type of control-system density matrix, the expectation value of a simple operator at the total model-control state vector serves as a witness of model's underlying topology. Sharp topological states c.f. trivial (ball-like) or non-trivial (torus-like), or superposition of both those states are obtained as outcomes of quantum measurements performed on model's state. The obtained results are a novel manifestation of the effect of non-casual order of various state maps for some quantum systems. The same method that addresses the topological question is equivalently addresses the problem of ordering two unequal real unequal numbers a,b. Both the topological and the comparison problems are shown to be solved by constructing a comparator quantum algorithm that employs quantum switch of channels, superposition of topological states and quantum measurements.

Uwe R. Fischer (Seoul National University)

Impact of trans-Planckian excitations on black-hole radiation in dipolar condensates

We consider a quasi-one-dimensional dipolar condensate in a step-like analogue black hole setup. It is shown that the existence of roton excitations leaves significant imprints onto the Hawking radiation spectrum. The emitted radiation depends on the depth of the roton minimum, and is in general more intense. In addition, we find a novel spontaneous particle creation mechanism with no counterpart in non-dipolar condensates. Our results establish that dipolar condensates offer a richer and more versatile environment for the simulation of particle production from the quantum vacuum in the presence of horizon-interfaces than contact-interaction condensates.

arXiv:2211.01243

Joshua Foo (University of Queensland)

Quantum superpositions of Minkowski spacetime in theory and in the lab

I present a new approach to studying the phenomenological effects of spacetime in a quantum superposition of configurations. The approach capitalises on the notion of correlations in quantum field theory to construct implied superpositions of the underlying spacetime background in terms of superpositions of the coordinates that parametrize the quantum field. I apply this approach to Minkowski spacetime in a superposition of non-diffeomorphic topologies, and calculate the response of a two-level system to the quantum-controlled field. I draw a connection between the spacetime superposition considered and a cavity-QED-type scenario in which one can simulate these quantum-gravitational effects.

J. Foo, C. Arabaci, M. Zych, R.B. Mann, Phys. Rev. D 107 (2023).

Vasileios Fragkos (Stockholm University)

On the inference of quantisation from gravity induced entanglement

An almost century old question is how gravity can be reconciled with the laws of quantum mechanics. This question remains still open and part of the reason is the lack of experimental evidence. However, in recent years, the rapid progress of experimental techniques allows for quantum control and manipulation of larger and larger quantum systems. These new experimental routes have sparkled an interest in testing such fundamental questions with tabletop experiments. One particularly interesting proposal aims to test whether gravity can mediate entanglement between two spatially superposed mesoscopic masses. This proposal, in order to deduce the existence of quantized gravitational mediators, relies on a quantum- information-theoretic argument, the so-called LOCC (Local Operations and Classical Communication). In our work, we critically assess this proposal, its underlying assumptions and what teaches about quantum gravity. We conclude that the LOCC argument is not useful and by invoking it, one cannot unambiguously infer the existence of quantum mediators unless the principle of locality is elevated to a fundamental principle of nature. We support our claim by explicitly showing that well known relativistic field theories, apart from local formulations can also admit non-local ones. Therefore, the entanglement generating quantum channel can be either local or non-local.

AVS Quantum Sci. 4, 045601 (2022)

Nicholas Funai (Royal Melbourne Institute of Technology)

Covariant bandlimitation and sampling for QFT

A unifying theory of GR and QFT has many issues, one of which arises from spacetime being defined on a smooth, differentiable manifold whereas QFT can be shown to require cutoffs, resulting in minimum length scales. This issue of continuous vs discrete models is lessened when one considers the Shannon sampling theorem, which blurs this distinction by interpolating discrete points into a bandlimited smooth function. The application of the sampling theorem to QFT has led to the study of bandlimited QFT, which is expected to allow renormalised bandlimited QFTs to be defined on smooth manifolds. However, previous efforts have been hampered by the observer dependence of UV cutoffs/bandlimits. We introduce a new representation (inspired by Green's functions) of scalar field operators that allows the introduction of a covariant bandlimit (restrictions on the d'Alembertian's spectra) in canonical quantised field theory. This method agrees with the predictions of path integral quantised bandlimitation (as proposed by Pye and Kempf) and results in a combination of discrete sampling and wavelet construction as a means of compressing physical information.

Christina Giarmatzi (University of Technology Sydney)

Full characterisation of quantum non-Markovian processes

In this talk, I will present the various applications of the process matrix formalism [1,2]. It provided a way to study the most general quantum correlations in nature, without predefined causal order, to discover the causal structure of a quantum process [3], and to capture the non-Markovian noise of a multi-time quantum process [4].

Depending on the audience's preference, I will focus on either topic, but the most recent result is the characterisation of non-Markovian noise in quantum processes and its application to experiments [5,6]. More importantly, we applied our methods on superconducting qubits to perform for the first time full process tomography of a multi-time process and characterise its non-Markovian noise through tomography and witnesses. This will set the background for future works on non-Markovian noise mitigation, the main obstacle to scaling up current quantum devices.

[1] O. Oreshkov, F. Costa & Č. Brukner, Quantum correlations with no causal order, Nat Commun 3, 1092 (2012). https://doi.org/10.1038/ncomms2076.

[2] Ognyan Oreshkov and Christina Giarmatzi, Causal and causally separably processes, 2016 New J. Phys. 18 093020. https://doi.org/10.1088/1367-2630/18/9/093020

[3] C Giarmatzi and F. Costa, A quantum causal discovery algorithm. npj Quantum Inf 4, 17 (2018). https://doi.org/10.1038/s41534-018-0062-6

[4] C. Giarmatzi and F. Costa, Witnessing quantum memory in non-Markovian processes, Quantum 5, 440 (2021). https://doi.org/10.22331/q-2021-04-26-440

[5] K. Goswami, C. Giarmatzi, et al., Experimental characterisation of non-Markovian quantum process, Phys. Rev. A 104, 022432 (2021). https://link.aps.org/doi/10.1103/PhysRevA.104.022432

[6] Upcoming paper: C. Giarmatzi, T. Jones, A. Gilchrist, F. Costa, A. Fedorov, Experimental multi-time quantum process tomography.

Cisco Gooding (University of Nottingham)

Vacuum Entanglement Probes for Ultra-cold Atom Systems

I will discuss an experimental proposal to study the transfer of nonclassical correlations from an ultra-cold atom gas to a pair of identical laser beams. At sufficiently low temperature, the atoms behave as an effective vacuum field, while the lasers serve as a pair of Unruh-DeWitt detectors for phonons. Despite the absence of direct interaction between them, the pair can become entangled solely through mutual interaction with the effective vacuum - this is known as spacelike entanglement harvesting. I will report on the current status and remaining obstacles for an experimental realization of the entanglement harvesting protocol.

Hal Haggard (Bard College)

Quantum Tetrahedra and Relativistic Information

The qubit has emerged as an invaluable model for studying the foundations of quantum information and quantum computing. While much work has been done to couple qubits to relativistic fields, they are not inherently relativistic and can be tricky probes of spacetime. Is there a similarly rich and simple model for studying relativistic quantum structures? Quantum tetrahedra, or qutets, provide a model with a finite number of degrees of freedom that emerges from a gauge-theoretic approach to General Relativity. Their volume eigenstates have a nice entanglement structure connecting both to the multipartite GHZ and Werner states. The corresponding classical tetrahedra are now under intensive study and have a volume dynamics that is uncovering new facets of elliptic curves. The same structures that make ellitpic curves useful in cryptography are also useful here for classifying the set of all quantum tetrahedra, a hard diophantine problem. In sum, qutets are a compelling model for relativistic quantum information that are too little known and where much remains to be developed.

Maxime Jacquet (Sorbonne University)

Black hole experiments with polaritons

Analogue gravity experiments with quantum fluids offer the prospect of observing quantum effects of fields on curved space. In this talk, I will present a new experimental platform: microcavity polaritons, which are a driven-dissipative quantum fluid. I will explain how polaritons are created and what may be observed in this system. I will then explain how to create a 1D configuration with an acoustic horizon and present new results on the stimulation of the Hawking effect at the horizon. Based on these results and our all optical control of the geometry, I will explain how quasi-normal modes of the horizon may also be excited and how this manifests in the Hawking spectrum. Finally, I will discuss how we can progress from observing stimulated emission to spontaneous emission and, possibly, entanglement across the acoustic horizon.

Achim Kempf (University of Waterloo)

Emergence of Spacetime from Fluctuations

I report on recent work with M. Reitz and B. Soda in which we use a result of Hawking and Gilkey to define a Euclidean path integral of gravity and matter which has the property of being independent of the choice of basis in the space of fields.
This property allows the path integral to also describe physical regimes that do not admit position bases. These physical regimes are pre-geometric in the sense that they do not admit a mathematical representation of the physical degrees of freedom in terms of fields that live on a spacetime. In regimes in which a spacetime representation does emerge, its dimension and volume depend on the balance of fermionic pressure
and bosonic and gravitational pull. That balance depends, at any given energy scale, on the number of bosonic and fermionic species that contribute, which in turn depends on their masses. This yields an explicit mechanism by which the effective spacetime dimension can depend on the energy scale. We find that the effective bandwidth on the emergent spacetime is constant up to curvature corrections, generalizing the corresponding classical result by Hawking and Gilkey.

Ryszard P. Kostecki (University of Gdańsk)

Quantum Schwarzschild space-time

In this work we propose a novel approach to emergence of globally hyperbolic space-times from information geometry of manifolds of quantum states, based on Wick rotation. As an example, we derive the analytic formula for a family of quantum states, such that the Wick rotation of their Kubo--Mori--Bogolyubov riemannian metric corresponds to the Fronsdal--Kruskal--Szekeres extension of the Schwarzschild space-time. I will discuss also some new, not yet published, results along these lines.

arXiv:1110.6566

David Kubiznak (Charles University)

Quantum imprints of gravitational shockwaves

Gravitational shockwaves are simple exact solutions of Einstein equations representing the fields of ultrarelativistic sources and idealized gravitational waves (shocks). Historically studied abundantly in the context of possible black hole formation in high energy particle collisions, they are at the forefront of research even today. Representing hard modes in the bulk, shocks give rise to the gravitational memory effect at the classical level and implant supertranslation (BMS) hair onto a classical spacetime at the quantum level. The aim of this talk is to further our understanding of the 'information content' of such supertranslations. Namely, we show that (contrary to the several claims in the literature) a gravitational shockwave does leave a quantum imprint on the vacuum state of a test quantum field and that this imprint is accessible to local observers carrying Unruh-DeWitt (UDW) detectors in this spacetime.

arXiv:2105.09337

Ohkyung Kwon (University of Chicago)

Foundational Tests of Quantum Gravity with Single Photon Detection Interferometry

We have seen compelling hints in recent years that the coherence of quantum states on causal surfaces holds the key to several intractable foundational issues in quantum gravity. Craig Hogan argued that a background independent construction of holographic quantum space-time should lead to coherent quantum effects on causal diamonds in flat space-time. Kathryn Zurek and Erik Verlinde rederived a similar effect using by taking Gerald 't Hooft's algebra for black hole information and mapping its coherent states on black hole horizons (from frame dragging) to those on causal diamonds in flat space-time by use of a radially accelerated coordinate system. This effect was reproduced using entanglement entropy in a general conformal field theory of vacuum states near causal boundaries (with Tom Banks); in JT gravity; with the fluid/gravity correspondence; and from the gravitational shock waves of vacuum states quantized on light cones. Hogan further applied the same coherence to inflationary horizons and found it to be consistent with several well-known CMB anomalies. Last but not least, Ian Durham's reanalysis of Caslav Brukner's Wigner-Bell gedankenexperiment shows that accounting for horizons in flat space-time (e.g. Unruh horizons in accelerated coordinate frames) may resolve the no-go theorem for observer independent facts. If this hypothesis of quantum coherence on causal horizons is true, there exists a class of models where the holographic fluctuations on causal diamonds in flat space-time grow like random walks with Planck steps, which is observable with precision Michelson interferometers of sub-Planckian strain power spectral density measuring at frequencies exceeding the inverse light travel time of the geometry. We introduce an experiment being commissioned at Cardiff University to probe such a signature, which combines the high-power laser interferometry of LIGO and GEO600 (10^23 photons/s) with superconducting nanowire single photon detectors in a novel metrological scheme to measure space-time at sensitivities far below the quantum noise limit.

arXiv:2204.12080, https://meetings.aps.org/Meeting/MAR23/Session/F65.5

Michalis Lagouvardos (University of Patras)

Gravitational Decoherence

The ABH model for gravitational decoherence is presented, which describes the influence of small stochastic perturbations of the gravitational field upon a quantum system. We discuss its different applications and the possibility for experimental examination of the phenomenon. The applications of the model include gravitational decoherence for the scalar field and for the electromagnetic field. While the model has been used with thermal gravitational fluctuations, it can be generalized to a class of cases, including the squeezed states of relic gravitational waves from inflationary cosmology. An estimation of the decoherence rate of these squeezed state gravitons is made.

Alessio Lapponi (SSM Napoli)

Relativistic quantum communication between harmonic oscillator detectors

We propose a model of communication employing two harmonic oscillator detectors interacting through a scalar field in a background Minkowski spacetime. In this way, the scalar field plays the role of a quantum channel, namely a Bosonic Gaussian channel. The classical and quantum capacities of the communication channel are found, assuming that the detectors' spatial dimensions are negligible compared to their distance. In particular, we study the evolution in time of the classical capacity after the detectors-field interaction is switched on for various detectors' frequencies and coupling strengths with the field. As a result, we find a finite value of these parameters optimizing the communication of classical messages. Instead, a reliable communication of quantum messages turns out to be always inhibited.

Phys. Rev. D 107, 125010 (2023)

Shih-Yuin Lin (National Changhua University of Education)

Quantum coherence of relativistic wavepackets moving in electromagnetic vacuum

We have developed a linearized effective theory with quantum mechanical Gaussian wavepacket of a charged relativistic particle coupled to quantum electromagnetic fields at a scale well below the Schwinger limit. This effective theory has a similar structure to the Unruh-DeWitt detector model. Using the theory, we study the quantum decoherence of single electrons at rest or in uniform acceleration due to their interactions with electromagnetic vacuum. According to the existing data of electron interference experiments in electron microscopes, the values of the parameters in our effective theory are chosen. With these values, we find that weak decoherence by vacuum fluctuations may have blurred the interference pattern in the experiment by Tomomura et al in 1989.

Richard Lopp (Ulm University)

Dimensional Reduction in Quantum Optics

One-dimensional quantum optical models usually rest on the intuition of large scale separations associated with the different spatial dimensions, for example when studying quasi one-dimensional atomic motion, potentially resulting in the violation of 3+1 D Maxwell's theory.

Here, we provide a rigorous foundation for this approximation in quantum optics by means of the light-matter interaction. We show how the quantized electromagnetic field can be decomposed -- without approximation -- into an infinite number of one-dimensional subfields [1] when studying axially symmetric setups, such as a fiber cavity, a laser beam or a wave guide. The dimensional reduction approximation then corresponds to a truncation in the number of such subfields that in turn, when considering the interaction with for instance an atom, corresponds to an approximation to the atomic spatial profile. We explore under what conditions the standard dimensional reduction approximation of a single subfield is justified, and when corrections are necessary in order to account for the dynamics due to the neglected spatial dimensions. In particular we will examine what role vacuum fluctuations play in the validity of the approximation.

[1] Grimmer et al., Phys. Rev. A 104, 013723 (2021)

Hudson A. Loughlin (MIT)

A 40km Fiber Interferometer to Probe the Interaction of Quantum Light and Gravity

We detail a proposed scheme to measure the effects of gravity on quantum states of light, including single photons and squeezed states, using a 40km long fiber interferometer. The initial goal of this interferometer is to measure the gravitational phase shift on single photons and probe for any discrepancies with the predictions of traditional quantum field theory in an accelerated frame. The experimental implementation will employ state of the art isolation and controls technology to measure a gravitational phase shift on the order of 10^-6 radians. We also consider the potential to use this interferometer to measure the gravitational decoherence of photonic states.

Robert Mann (University of Waterloo)

Quantum Superpositions of Black Holes

If relativistic gravitation has a quantum description, it must be meaningful to consider a spacetime metric in a genuine quantum superposition. But how might such a superposition be described, and how could observers detect it? I will present a new operational framework for studying “superpositions of spacetimes” via model particle detectors. After presenting the general approach, I show how it can be applied to describe a spacetime generated that is a superposition of two expanding spacetimes. I will then move on to show how black holes in two spatial dimensions can be placed in a superposition of masses and how such detectors would respond. The response exhibits signatures of quantum-gravitational effects reminiscent of Bekenstein’s seminal conjecture concerning the quantized mass spectrum of black holes in quantum gravity. I will provide further remarks concerning the meaning of the spacetime metric, and on distinguishing spacetime superpositions that are genuinely quantum-gravitational, notably with reference to recent proposals to test gravitationally-induced entanglement.

Eduardo Martin-Martinez (University of Waterloo)

Classical vs Quantum theories: when do quantum effects matter in gravity and quantum information?

Akira Matsumura (Kyushu University)

Reduced dynamics with Poincare symmetry in an open quantum system

We consider how the reduced dynamics of an open quantum system coupled to an environment admits the Poincar\'{e} symmetry. The reduced dynamics is described by a dynamical map, which is given by tracing out the environment from the total unitary evolution without initial correlations. We investigate the dynamical map which is invariant under the Poincar\'{e} group. Based on the unitary representation theory of the Poincar\'{e} group, we develop a systematic way to give such a dynamical map. Using this way, we derive the dynamical map for a massive particle with a finite spin and a massless particle with a finite spin and a nonzero momentum. We show that the derived map gives the unitary evolution of a particle when its energy is conserved.

Andrey S. Moskalenko (KAIST)

Finite-time Unruh effect in a nonlinear-optical system: diamond temperature and transition to the Unruh-temperature regime

Unruh effect is an intriguing prediction that an accelerating observer will perceive a vacuum as a bath of thermal radiation [1]. In this contribution, we report on a theoretical exploration of the Unruh effect by studying the spectral properties of ultrabroadband squeezed vacuum state generated inside a thin nonlinear crystal (NX) with a second-order nonlinearity, which is driven by a strong ultrashort light pulse [2]. We find that in the weak squeezing regime, the temperature evaluated from the high-frequency part of the spectra corresponds to the so-called diamond temperature, which is the temperature seen by a uniformly accelerated observer having a finite lifetime span [3]. Further, with the increase in squeezing strength, we observe for the temperature evaluated from the spectra a transition towards genuine Unruh temperature.

The above findings can also be analyzed by looking at world lines of the generated squeezed light in the NX. While traveling through the NX, photon modes follow an accelerated trajectory (experience an effective curved space-time) due to a time-varying refractive index, which is controlled by the ultrashort driving pulse. This can be considered as an optical analog to the Unruh effect, where the detector is at rest and light follows an accelerated trajectory. Now since the generated light is accelerated for a finite time, determined by the duration of the driving pulse, the temperature associated with it can lead to the diamond temperature based on the thermal time hypothesis [3]. However, for a sufficiently large lifetime or acceleration, this hypothesis should lead to the Unruh

temperature. For a complete description, a generalization of the approach to non-uniform accelerations bound to short time intervals is required.
Our work can open up a possibility for a direct experimental observation of the Unruh effect, which until now has been difficult due to technological limitations, and a possibility to study the transition between the diamond and Unruh temperature regimes.

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https://doi.org/10.1103/PhysRevLett.122.053604

Sebastian Murk (Okinawa Institute of Science and Technology)

Nomen non est omen: why it is too soon to identify ultra-compact objects as black holes

Black holes play a pivotal role in the foundations of physics, but there is an alarming discrepancy between what is considered to be a black hole in observational astronomy and theoretical studies. Despite claims to the contrary, we argue that identifying the observed astrophysical black hole candidates as genuine black holes is not justified based on the currently available observational data, and elaborate on the necessary evidence required to support such a remarkable claim. In addition, we investigate whether the predictions of semiclassical gravity are equally compatible with competing theoretical models, and find that semiclassical arguments favor horizonless configurations. This has interesting physical implications for contemporary "problems" such as the apparent lack of unitarity in the infamous information loss paradox.

arXiv.2210.03750

Robert Oeckl (National Autonomous University of Mexico-UNAM)

Towards a local and compositional notion of measurement in Quantum Field Theory

It is widely acknowledged that a notion of measurement in quantum field theory satisfying space-time locality and compositionality is still lacking. We consider an approach to the problem that is based on the one hand on the positive formalism, an axiomatic framework, where it is clear from the outset that we satisfy locality and compositionality, while also having a consistent probabilistic interpretation. On the other hand, the approach is based on standard tools from quantum field theory, in particular the path integral and notably the Schwinger-Keldysh formalism. After an overview of the conceptual foundations we discuss first concrete results for point-like quadratic observables and their joint expectation values. We also show how renormalization is implemented in a way compatible with compositionality. We discuss the relation to other recent approaches in the literature.

Jonathan Oppenheim (University College London)

A covariant theory of quantum fields back-reacting on classical space-time.

We introduce path integrals for quantum fields interacting with classical fields. We show that this can be done consistently by proving that the dynamics is completely positive and norm preserving, and preserves the split of quantum and classical degrees of freedom. The path integrals generalize and combine the Feynman-Vernon path integral of open quantum systems and the stochastic path integral of classical stochastic dynamics while respecting symmetry principles. We introduce a path integral formulation of general relativity where the space-time metric is treated classically. We propose experiments to test this theory vs quantum theories of gravity, via a "decoherence vs diffusion trade-off" which we prove that all theories in which space-time is classical, must obey.

arXiv: 2203.01982; 2302.07283

Claudio F. Paganini (Universität Regensburg)

The Causal Compatibility Conjecture and its implication on time travel

In my talk I introduce the Causal Compatibility Conjecture for the Events, Trees, Histories (ETH) approach to Quantum Theory (QT) in the semi-classical setting. I then prove that under the assumptions of the conjecture, points on closed causal curves are physically indistinguishable in the context of the ETH approach to QT and thus the conjecture implies a compatibility of the causal structures even in presence of closed causal curves. As a consequence of this result there is no observation that could be made by an observer to tell any two points on a closed causal curve apart. We thus conclude that closed causal curves have no physical significance in the context of the ETH approach to QT. This is an indication that time travel will not be possible in a full quantum theory of gravity and thus forever remain a fantasy.

arXiv:2005.05748

Alessandro Pesci (INFN Bologna)

Classical vs quantum emission of gravitational radiation in the recombination of a delocalized particle

Considering a delocalized particle which goes to be (quickly) recombined, we contrast the expected gravitational emission assuming the field is classical and the same assuming instead it is quantum. In case the field is quantum we find, adding to previous results, that there is a threshold in recombination time above which no emission is allowed, and that there is a mass threshold (actually coinciding with the Planck mass) below which no emission is possible however quick the recombination is. Both these conditions, are shown to coincide with what we get (regardless of the nature of the field) if we require that the recombination produces a visible fringe pattern assuming ideal resolution on the screen of 1 Planck length.

Finally, we comment on connections between these results and collapse models of Diosi and Penrose.

arXiv:2209.10355

Nicola Pinzani (Université libre de Bruxelles)

The Topology and Geometry of Causality

Contextuality is a principle often invoked to characterise the non-classical nature of quantum systems. Abstractly, it can be phrased as the impossibility to provide a global distribution of classical deterministic behaviours that marginalise to the stochastic outcomes observed in individual measurement contexts. From this perspective, non-locality manifests itself as an obstruction to the reconstruction of a global, context-independent description of the data observed in an operational setting. Unlike other examples of contextual phenomena, however, the contexts used in non-locality scenarios are derived directly from the background causal structure, without the need to appeal to other (typically theory-dependent) assumptions.

Given the importance that Bell's intuitions held in shaping quantum foundations, it seems peculiar, to say the least, that a general theory of measurement contexts induced by arbitrary causal structures has not yet been explicitly constructed. What is there is a large body of literature that follows the breadcrumbs of causality, where several philosophical and conceptual arguments---from Wigner's friend's to macro-causality---constrain polytopes of compatible correlations by, amongst other things, making assumptions about causal structure [5,6,7]. Each of these arguments shows a specific example of interaction between contextuality, causality, and quantum: what is missing is a general description of this multifaceted interplay.

Two questions now arise: What is the structure of measurement contexts corresponding to a given set of causal assumptions? What is the space of stochastic outcomes compatible with those assumptions? We provide an answer to this question in full generality, extending a framework by Abramsky and Brandenburger [1] where contextuality---the failure of passing from empirically derived, local assignments to context-independent, global assignments---is captured by the mathematical language of sheaf theory. In doing so, we provide a definition for measurement contexts in terms of a lattice of possible loci, the "contexts", to which topological data can be associated compatibly with the underlying causal structure [2,3,4]. We show that this topological theory of measurements naturally applies to more exotic causal scenarios, where the causal structure is allowed to dynamically depend on choices performed by the agents.

In this talk, we will provide an overview of this framework: a novel theory of measurement contexts in the context of arbitrary causal order, philosophically aligned with Niels Bohr's doctrine of complementarity. We will explain how our formalism can be used to tackle questions in one of the most active topics at the intersection between quantum theory and general relativity, the verification of indefinite causal order. We will propose protocols that display a novel phenomenon of contextual causality [4], where contextual information rules out any classical hidden variable explanation for causal structure of events, and argue that this should be taken as the true theory-independent witness of indefinite causality.

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arXiv:2303.09017, arXiv:2303.07148, arXiv:2206.08911

José Polo-Gómez (University of Waterloo)

Unruh effect through machine learning

We explore the application of machine learning techniques to investigate the Unruh effect. In previous work we showed that machine learning can be used in quantum field theory to extract specific information about the field from very simple particle detector measurements. Here, we extend this approach to the experimental detection of the Unruh effect. Concretely, we analyze how assisting particle detector measurements with a neural network that processes detector data can reduce the acceleration threshold required to measure the effect, bringing direct detection experiments closer to experimental feasibility.

arXiv:1910.03637 [quant-ph]

Tales Rick Perche (University of Waterloo)

Particle detectors from quantum fields

In this talk we will show that it is possible to obtain particle detector models by considering localized quantum field theories that interact with a free field theory. We show that this analogy holds to leading order in perturbation theory, and that this is the physical origin of the causality violations and non-localities present in finite sized particle detectors. This analogy also holds in the case where more than one detector couples to the field, and we use this result to show that entanglement harvesting is a phenomenon in quantum field theory, and not a consequence of non-locality or non-relativistic effects in effective models.

Albert Roura (German Aerospace Center-DLR)

Long-baseline quantum optics experiments in space

Natália Salomé Móller (Slovak Academy of Sciences)

The quantum switch in flat, curved and quantum spacetimes

The quantum switch is the most famous task with indefinite causal order, where two agents A and B apply non-commuting quantum operations on a target qubit in an indefinite order. Most importantly is that tasks with indefinite causal order are originally supposed to testify that events happen in an indefinite order, and not just an indefinite order of operations. Many different proposals have been explored in order to implement this quantum process, but there is also much discussion about it: many authors consider different notions of what is as event, and because of this, they also diverge when considering these implementations as a genuine task with an indefinite causal order or just a simulation of it [1-3].

In this talk, we will review many different possibilities found in the literature that could be used to implement a quantum switch [4-7] and discuss how each definition of an event could lead to very different ways of interpreting such examples. Moreover, I we will present one recent result of ours that is an exact example of a quantum switch implemented in a quantum spacetime, but that is measured from an observer lying in a well-defined classical spacetime. One important aspect of this solution is that this is an example that avoids complications when defining an observer in a quantum spacetime. Another important aspect is that we show that a global superposition of light cones in a quantum spacetime does necessarily imply in a superposition of light cones from the perspective of the agent lying in the classical spacetime. This concrete example with the assertions we can make when studying it open a new understanding on what should be considered a good notion of an event in the field of indefinite causal order, and also contribute with solid arguments to the open discussion concerning the definition of this fundamental concept.

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https://doi.org/10.1103/PhysRevA.104.042414;
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Fabio Scardigli (Politecnico of Milano)

Bekenstein bound and uncertainty relations

The Bekenstein bound provides a universal limit on the entropy that can be contained in a localized quantum system of a given size and total energy. In this talk, we explore unsuspected links between the Bekenstein bound and the Heisenberg Uncertainty Principle. We also show how the Bekenstein bound is affected when the Heisenberg uncertainty relation is deformed so as to accommodate gravitational effects at Planck scale (Generalized Uncertainty Principle). Physical implications are discussed for both cases of positive and negative values of the deformation parameter.

Phys. Lett. B 824 (2022) [arXiv:2009.12530 [hep-th]]

Joseph Schindler (Universitat Autonoma de Barcelona)

Unitarity and the information problem in an explicit model of black hole evaporation

We will first describe some techniques for explicitly computing Penrose diagrams for dynamically evolving non-trivial spacetimes, and discuss what can be learned from explicit diagrams of evaporating black hole models.
This context is then used to consider the black hole information problem in an explicitly defined spacetime modelling black hole evaporation. We review basic aspects of the problem, with a particular effort to be unambiguous about subtle topics, for instance precisely what is meant by entropy in various circumstances. We then focus on questions of unitarity, and argue that commonly invoked semiclassical statements of long term, evaporation time, and Page time "unitarity" may all be violated even if physics is fundamentally unitary. We compare these conclusions to recent holographic studies, and argue that they are mutually compatible. We also comment on how the picture is modified for singular versus nonsingular and charged/rotating versus Schwarzschild models, and emphasize that resolutions of black hole unitarity issues must be stable under the inclusion of charge and rotation which qualitatively alter the causal structure.

arXiv: 2012.07973, 1907.04879, 1802.02263, 2005.05408

Fil Simovic (Macquarie University)

The Geometry of Information from Black Hole Thermodynamics

Black hole thermodynamics lies at the focal point of quantum gravity, information theory, and geometry. In this talk, I will discuss the fundamental role that black hole thermodynamics plays in relativistic quantum information theory---what quantities we can extract, how black hole entropy can be quantified, and the role of unitarity and entanglement in the black hole information paradox. I will also discuss the intimate connection between geometry and information theory, and present a geometric formulation of thermodynamics through the Ruppeiner metric. This metric is defined through the relative entropy on the space of probability distributions, and can be seen as a particular limit of the Fisher information metric. This provides an avenue for understanding thermodynamics in a covariant way, with the Ruppeiner metric representing different choices of submanifolds within the full thermodynamic phase space. Such a phase space resembles the symplectic phase space of ordinary Hamiltonian systems, but takes on the structure of a contact manifold instead. I discuss what information-theoretic quantities can be extracted from the Ruppeiner geometry and present an example from black hole thermodynamics where interesting features appear in the phase structure of asymptotically anti-de Sitter black holes.

Daniel Terno (Macquarie University)

What can the information loss problem tell us about black holes?

Bruno Torres (Perimeter Institute/University of Waterloo)

A general framework for Gaussian complexity geometry

In quantum information theory, the notion of complexity is an attempt to describe ``how hard'' it is to complete a given information-processing task, given some set amount of resource operations. This is a concept which has recently been receiving increasing levels of attention outside quantum information theory due to the powerful insights it can provide to several areas in fundamental physics, including quantum thermodynamics, many-body physics, and even quantum gravity. Assigning precise measures of complexity, however, is challenging due to the high level of ambiguity in the set of available operations and their respective cost. The problem becomes even greater in quantum field theory, where one has to deal with infinite-dimensional Hilbert spaces of systems of continuous variables. We report on work in progress on a broad class of measures of circuit complexity for Gaussian states of bosonic quantum systems. Different quantitative measures are derived from modified notions of complexity geometry on the tangent bundle to the manifold of Gaussian states, which take into account penalty costs that may depend non-trivially on the quantum state and on the direction on the space of Gaussian transformations performed at each point. This can equip us with a class of complexity measures in continuous-variable systems which is both geometrical (and thus well-adapted to optimization methods) and operationally well-motivated (as the cost functions can potentially be matched to experimental limitations of the setup at hand).

Eleftherios Tselentis (IQOQI, Vienna)

Admissible causal structures and correlations

It is well-known that if one assumes quantum theory to hold locally, then processes with indefinite causal order and cyclic causal structures become feasible. Here, we study qualitative limitations on causal structures and correlations imposed by local quantum theory. For one, we find a necessary graph theoretic criterion--the "siblings-on-cycles" property--for a causal structure to be admissible: Only such causal structures admit a realization consistent with local quantum theory. We conjecture that this property is moreover sufficient. This conjecture is motivated by an explicit construction of quantum causal models, and supported by numerical calculations. We show that these causal models, in a restricted setting, are indeed consistent. For another, we identify two sets of causal structures that, in the classical-deterministic case, give rise to causal and non-causal correlations respectively.

arXiv: 2210.12796

Vilasini Venkatesh (ETH Zurich)

Quantum information-theoretic causal structures and their compatibility with spatio-temporal causality

Marko Vojinovic (Institute of Physics Belgrade)

Operational verification of the existence of spacetime

Individual points of spacetime are not observable, due to the diffeomorphism symmetry. One is then often tempted to make a more general claim that the whole spacetime manifold is an unobservable entity. The purpose of this work is to scrutinize that claim, and demonstrate that time and space have additional properties, which are simultaneously both observable and diffeomorphism-invariant --- specifically, the dimension and topology. Thus, we argue that the observation of these properties grants time and space their objective, physical existence, despite unobservability of individual points. This stands in sharp contrast with the relational point of view that there is no spacetime and that "fields live on fields".

To that end, we propose a gedanken-experiment to operationally observe the dimension and topology of a manifold. Using that, we argue that real-world observables always display correlations reflecting an underlying structure of a 4-dimensional manifold, which we call spacetime, and that its topology is simply-connected on the scales that can be tested. Both D=4 and simply-connected topology are intrinsic properties of the observed experimental signal, since in principle we could have obtained a different set of correlations.

Given any tentative theoretical model of physics which explicitly does not assume the existence of any underlying spacetime manifold (in line with the relational point of view), the challenge for that model is to deduce from its first principles that there exist some very peculiar correlations between the observables, describing their dynamics "as if they were fields living on a manifold" with a specific dimension and topology (so-called "strong emergence" of spacetime). In particular, any viable model ought to give rise to the result D=4 purely from the interactions between the fields in the model. However, so far no such model has ever been constructed, and until one is, we can argue that time and space are notions that objectively exist in their own right, as part of our physical reality.

arXiv:2209.04783

Jinzhao Wang (Stanford University)

Some information-theoretic fine prints on the Bekenstein bound

Bekenstein bound puts a limit on the entropy associated with a spacetime region in terms of its size and energy. For a Rindler wedge, a version of Bekenstein bound has been proven by Casini using information-theoretic tools. It's natural to ask if the Bekenstein bound puts constraints on the capacity of communication and information storage in spacetime. In this work, we elaborate on the information-theoretic aspect of the Bekenstein bound with the precision offered by approximation quantum error correction and quantum Shannon theory. We revisit a mode studied by Marolf et al to resolve the species problem in Rindler spacetime. We consider the ``Unruh channel'' that describes a stationary Alice sending information encoded as distinguishable modes of a free scalar field to an accelerating Bob, who locates inside a Rindler wedge and is exposed to the noise of Unruh radiation. Constrained by the Bekenstein bound, the amount of classical/quantum information that Alice can directly send to Bob using the Unruh channel has an error that scales exponentially with the number of bits. However, given free entanglement or a noiseless side channel, Alice can send unlimited information to Bob with constant error using the zero-bit variants of the dense-coding/teleportation protocols introduced by Hayden-Penington. Zero-bits are asymptotic communication resources that can be used as the minimal resource in place for the classical/quantum bits needed for many primitive information processing protocols, such as dense coding and teleportation. Accordingly, we further show that the entanglement-assisted classical capacity and the zero-bit capacity of the Unruh channel are always finite for arbitrarily hot Unruh temperature, whereas the unassisted classical capacity drops to zero at the large temperature limit due to the Bekenstein bound. Surprisingly, unlike for bits and qubits, the Bekenstein bound doesn't constrain zero-bits in Rindler spacetime.

Carolyn Wood (The University of Queensland)

Quantum particle detector models

Results in atomic physics show that mass--energy equivalence plays a crucial role in energy and momentum conservation for atom--light interactions: absorption or emission of field quanta must also change the atom's rest mass by an equivalent energy. Though the Unruh–DeWitt (UDW) detector model of a quantum particle interacting with an external environment is powerful in its simplicity, the dominant model---which assigns the detector a classical trajectory and treats only the internal state as a quantum degree of freedom---cannot capture the above mentioned effects.

Recent models upgrading the UDW model to include more realistic quantum descriptions of the centre of mass have described the detector as either moving in superposition along classical trajectories, or dynamically evolving under a non-relativistic Hamiltonian. These have led to interesting results relating to themalisation and entanglement harvesting, but they too are unable to capture the mass-energy effects we desire.

Here I will discuss how we addressed this problem and describe a new detector model which leverages the simplicity of the UDW model while also incorporating quantisation of the detector's mass-energy to allow mass changes due to emission/absorption. I show that these relativistic effects persist even at low energies and cannot be ignored unless all centre of mass dynamics is ignored. I will also show how our new model compares to the previous models with classical CoM and quantum CoM, as well as the detector in a superposition of trajectories, and discuss particular effects that arise due to mass--energy equivalence. I will then present a further step we have taken, in which such a detector with a variable mass has ground and excited states in superposition, producing a model where the detector can be interpreted as a quantum clock weakly interacting with its environment.

Koji Yamaguchi *(University of Waterloo)*

Improving the efficiently of transmitting quantum information by utilizing correlated quantum fluctuations

Noise reduction is a key to improving the performance of information processing devices. It has been shown that correlations in noise can improve the efficiency of transmission of classical information through a quantum field [1], as well as the classification of noisy images using neural networks [2]. In the present work, we show that quantum information can be transmitted more efficiently by utilizing access to correlated noise that is due to entanglement.

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Kazuhiro Yamamoto (Kyushu University)

Two-mode theory of suspended mirror coupled cavity light: Wiener filter analysis

We investigated the quantum state of an optomechanical suspended mirror under continuous measurement and feedback control using Wiener filtering. We focus on the impact of the two-mode theory of suspended mirror on the quantum state, which is described by the pendulum and rotational modes. It is derived from the beam model coupled to the cavity light in the low-frequency regime, including the internal friction of the beam and the finite size effect of the mirror. We constructed a Wiener filter for the two-mode theory and predicted the quantum state by evaluating the conditional covariance matrix using Wiener filter analysis. The results demonstrate that multimode analysis may play an important role in generating the quantum squeezed state. We also point out the possibility that one-mode analysis can be a good approximation by choosing the range of the Fourier space in the Wiener filter analysis.

arXiv: 2303.04511

Yasaman Yazdi (Imperial College London)

Entanglement Entropy from Spacetime Two-Point Correlation Functions

Entanglement entropy of quantum fields is an essential topic in quantum gravity, quantum information, and several other areas of physics. In this talk I will review and give a status report on a formulation of entanglement entropy for Gaussian theories, in terms of the spacetime two-point correlation function. One attractive feature of this formulation is that it makes it possible to use a UV cutoff that is spacetime in nature. I will discuss applications of this formulation in settings in both continuum spacetimes and discrete causal sets, as well as extensions to non-Gaussian and interacting theories. I will also briefly mention some future directions of this work.

Adamantia Zampeli (Universidad Autonoma de Mexico-UNAM)

Composition of observables in the general boundary quantum field theory

It is well-known that the standard quantum field theoretic formalism can describe well S-matrix type measurements through transition amplitudes defined at a time interval at minus and plus infinity. The description of local as well as sequential measurements lead to problems and are not well-defined in this context. Such problems can be overpassed in the general boundary quantum field theory in which one can define local observables as well as their composition.

In this talk, I will present the composition of a quadratic observable of the Klein-Gordon theory. Specifically, I will discuss the composition of the observable map that corresponds to the energy-momentum tensor of a scalar field in the flat spacetime.

Magdalena Zych (University of Stockholm)

Relativity of quantum superpositions in the context of superpositions of gravitational sources.

It is anticipated that in a theory of quantum gravity, there exist quantum superpositions of semiclassical states of spacetime geometry. It is often discussed how such states could arise from a source mass in a spatial superposition. In this talk I will discuss such spatial superposition scenarios from the perspective of relativity of the notion of location, and thus of superposition itself. This perspective allows to show that for states in which the superposed amplitudes differ by a coordinate transformation, it is always possible to re-express the scenario in terms of dynamics on a fixed geometry albeit with adapted preparations and measurements on the involved degrees of freedom. The results unveil an ambiguity in the interpretation of such scenarios as genuinely quantum-gravitational, and motivate further research into loopholes and assumption behind such scenarios.

Posters

Jawad Allam (CY Cergy Paris Université)

From observer-dependent facts to frame-dependent measurement records in Wigner friend scenarios

In Wigner-Friend Scenarios, the description by a super-observer (Wigner) of the state evolution of a lab containing a friend which performs a quantum measurement is still controversial. Many recent works assume that the lab's state evolves unitarily after the friend measures. We present a protocol showing that this assumption, in the context of relativistic considerations, can lead to frame-dependent outcomes. Specifically, a distant agent sharing an entangled pair with the friend and performing a space-like separated measurement can steer the state of the lab, causing super-observers in different inertial frames to disagree about their observation of measurement records issued by the friend.

arXiv: 2304.09289

Luca Apadula (University of Vienna/IQOQI)

Quantum Reference Frames for Lorentz Symmetry

Since their first introduction, Quantum Reference Frame (QRF) transformations have been extensively discussed, generalising the covariance of physical laws to the quantum domain. Despite important progress, a formulation of QRF transformations for Lorentz symmetry is still lacking. The present work aims to fill this gap. We first introduce a reformulation of relativistic quantum mechanics independent of any notion of preferred temporal slicing. Based on this, we define transformations that switch between the perspectives of different relativistic QRFs. We introduce a notion of "quantum Lorentz transformations" and "superposition of Lorentz boosts", acting on the external degrees of freedom of a quantum particle. We analyse two effects, superposition of time dilations and superposition of length contractions, that arise only if the reference frames exhibit both relativistic and quantum-mechanical features. Finally, we discuss how the effects could be observed by measuring the wave-packet extensions from relativistic QRFs.

arXiv.2212.14081

Navdeep Arya (Indian Institute of Science Education and Research, Mohali)

Unruh effect via radiative atomic level shift inside a cavity

The Unruh effect states that the transition rates of a uniformly accelerated detector in the inertial vacuum have a thermal character at a temperature proportional to the detector's acceleration. Numerous observables, including atomic transition rates, radiative energy shifts, particle decay rates, and geometric phase, have been studied under varied settings for a measurable signature of the Unruh effect and ease of measurement. All these proposals still await fruition as the thermal signature in the atom's response is very feeble at the accelerations achievable in laboratory settings.

In this work, we study the radiative energy level shift in a uniformly accelerated atom coupled to a massless quantum scalar field inside a long cylindrical cavity and discuss the detectability of the

resulting noninertial contribution. The radiative energy level shift is a shift in the energy levels of an atom arising from the atomic electron's coupling to an external quantum field. The interest in the shifts in atomic spectra as an observable for detecting the Unruh effect stems from the theoretical and experimental precision that atomic spectroscopy has achieved. For instance, in H-atom the optical and microwave transitions have been measured with precision in the ranges 10^{-11} - 10^{-12} and 10^{-5} - 10^{-6}, respectively.
For an observable energy shift in a uniformly accelerated atom in free space, an acceleration of the order of 10^{21} m/s^2 is required. We show that the noninertial contribution to the energy shift can be isolated and enhanced relative to the inertial contribution by suitably modifying the density of field modes, for example, by employing an electromagnetic cavity. Specifically, a purely-noninertial energy shift orders of magnitude (~ 10^2 - 10^3) larger than the inertial energy shift can be obtained at small, experimentally achievable accelerations. The required precision in the cavity design has also been achieved in earlier experiments dealing with measurements of Lamb shift in inertial atoms. We argue that the radiative energy level shift is a promising observable for detecting the Unruh effect with current technology.

Luis C. Barbado (IQOQI Wien)

Unruh effect and Hawking radiation for detectors in quantum superposition of trajectories

Unruh effect and Hawking radiation are two of the most important predictions of Quantum Field Theory in curved space. As it is well known, these thermal radiations are perceived differently by different observers in a given spacetime. Such dependence can be analyzed by considering the excitation of a quantum particle detector coupled to the radiation field and following different trajectories. We present recent works in which we extend this sort of analysis to the case in which the detectors do not follow definite trajectories, but rather quantum superpositions thereof. More concretely, we consider a multilevel particle detector coupled to a massless real scalar field, and following a superposition of accelerated trajectories in a given Rindler wedge (for the Unruh effect), or of static trajectories outside a Schwarzschild black hole (for Hawking radiation). We find that, after the interaction with the field, the state of the detector is not in general a classical mixture of the excitations expected for each of the trajectories in superposition separately, but rather some coherences survive. These coherences are a result of the non-distinguishability of the different possible states in which the radiation field is left. Their dependence on the different excited energy levels and the different superposed trajectories can be associated physically to the characteristics of the absorbed particle of the field. The results are briefly discussed in the context of Quantum Reference Frames, and future extensions are considered.

arXiv:2003.12603

Alessio Belfiglio (University of Camerino)

Geometric inflationary entanglement

We investigate the entanglement due to geometric corrections in particle creation during inflation. To do so, we propose a single-field inflationary scenario, assuming nonminimal coupling of the inflaton field to the scalar curvature of spacetime. We require particle production to be purely geometric, setting to zero the Bogolubov coefficients and computing the S matrix associated to spacetime perturbations, which are traced back to inflaton fluctuations. The corresponding particle density leads to a nonzero entanglement entropy whose effects are investigated at primordial time of Universe evolution. The possibility of modeling our particle candidate in terms of dark matter is discussed. The classical back-reaction of inhomogeneities on the homogeneous dynamical background degrees of freedom is also studied and quantified in the slow-roll regime.

arXiv:2212.06448

Ofek Bengyat (IQOQI Vienna)

Unified Description and Local Corrections to Gravity Entanglement

Observing mediated entanglement through gravity (GME) could provide empirical evidence of quantum spacetime. Experimental protocols previously put forward fall in two categories: entanglement is due to either the parties being set in a path superposition, or, because of their intrinsic Heisenberg uncertainty, with the latter considered more experimentally feasible. An open question has been whether implications about quantum gravity from a successful realisation of either protocol are equivalent. Here, we calculate the entanglement in time for a generalised setup that encompasses both protocols using a covariant formalism that admits the interpretation of superposition of spacetimes. We also recover the two protocols as limits of a set of intermediate experiments. The general relativistic correction to entanglement in the oscillator protocol is also found, evidencing local propagation of the entanglement. We conclude that the two commonly considered protocols are conceptually equivalent physical processes that involve aspects of quantum spacetime and locally propagating quantum information.

Sara A. Butler (IQOQI Vienna)

Detection Model for Planck Mass Dark Matter Particles of Black Hole Density

A quantum description of black hole motion is required in order to complete a proper theoretical framework of our universe, thereby leaving the fate of the miniature black hole an open question [1]. Yet, we can become closer to closing this question by acknowledging that dark matter is likely formed by Planck size remnants of Black hole evaporation, that Planck size white holes are stabilised by quantum mechanics, and that Planck scale white holes can be produced at the end of the evaporation of primordial black holes, a theorized type of black hole created soon after the Big Bang that may account for all of the dark matter in the universe.
We propose a way to test this idea using an array of mechanical probes that would be able to read an impulse from a dark matter particle passing by. Using our knowledge of the difference between the density of a black hole and that of a particle of normal matter, we believe it is possible to determine whether dark matter is made up of primordial black holes.
We also introduce an alternative approach that was recently realized and that which might be a more feasible method for detecting the type of dark matter in our universe in the near future.

[1] Aharonov, Y., Casher, A., & Nussinov, S. 1987, Physics Letters B, 191, 51, doi: 10.1016/0370-2693(87)91320-7

Carlo Cepollaro (University of Vienna, IQOQI Vienna)

Quantum generalisation of Einstein's Equivalence Principle can be verified with entangled clocks as quantum reference frames

The Einstein Equivalence Principle (EEP) is one of the cornerstones of general relativity. This principle has been successfully tested in numerous experiments, from Galileo's famous experiment of dropping objects from the Leaning Tower of Pisa to the measurements of the gravitational redshift effect. The other pillar of modern physics, quantum mechanics, has also proved to be an extremely precise empirical description of the world.

However, the equivalence principle has not yet been incorporated into the framework of quantum mechanics. Exploring the interplay between the equivalence principle and quantum mechanics is necessary for a better understanding of a putative theory of quantum gravity, which is a topic under active investigation and represents a long-standing problem in physics. Even without the formulation of a complete theory of quantum gravity, an extended principle could pave the way to explain phenomena where quantum effects and strong gravitational field coexist, such as black holes or early-universe cosmological studies. Finally, it could shed light on the limits of the quantum formalism, and potentially uncover new physics beyond the standard model.

Several proposals to extend it to the quantum regime have been advanced, while some authors have argued that the EEP is incompatible with situations when either matter (i.e. the particles used to test it) or gravity acquire quantum properties. Recently, it was proposed that the EEP holds in a generalised form when the particles are in an arbitrary quantum state and the gravitational field is in a superposition of classical states [1]. Key to this generalised EEP is the possibility to transform to the reference frame associated to an arbitrary quantum system, namely a Quantum Reference Frame (QRF) in the formulation introduced in Ref. [2]. This sparked a debate over the nature of the principle and of QRFs [3].

The talk will focus on the different approaches to the role of the equivalence principle in quantum mechanics, with a particular focus on the one proposed in [3]. Furthermore, I will talk about a proposal [4] to show that this extended EEP can be verified in an interferometric setup via tests on the proper time of entangled clocks. In the paper, we find that the violation of the generalised EEP corresponds to the impossibility of defining dynamical evolution in the frame of each clock. The violation results in a modification to the probabilities of measurements calculated in the laboratory frame, and hence can be verified in an interferometric setting.

In the presence of so many different approaches to explore the relationship between the equivalence principle and quantum mechanics, it is fundamental to test these ideas, to gain a deeper insight into the interplay of the fundamental principles of quantum theory and general relativity.

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[2] F. Giacomini, E. Castro-Ruiz, and C. Brukner, Quantum mechanics and the covariance of physical laws in quantum reference frames, Nature Communications 10, 494 (2019).
[3] E. Adlam, Watching the Clocks: Interpreting the Page–Wootters Formalism and the Internal Quantum Reference Frame Programme, Foundations of Physics volume 52, 99 (2022).
[4] CC, F. Giacomini, Quantum generalisation of Einstein's Equivalence Principle can be verified with entangled clocks as quantum reference frames (2021), arXiv:2112.03303.

Huang Yu Che (National Tsing Hua University)

Quantum mechanical wavepackets of single relativistic particles

We study the time evolution of some wavepacket solutions to the Schroedinger equation for a free relativistic particle in uniform motion, and those to the Klein-Gordon equation for a relativistic charged particle accelerated in a uniform electric field. According to the behavior of these wavepacket solutions, we obtain reasonable values of the regulators for the Gaussian approximation to be applied to our effective theory of single charged particles interacting with quantum electromagnetic fields.

Kacper Dębski (University of Warsaw)

Indefinite temporal order without gravity

According to the general theory of relativity, time can flow at different rates depending on the configuration of massive objects, affecting the temporal order of events. Recent research has shown that, combined with quantum theory, this gravitational effect can result in events with an indefinite temporal order, which can be tested through the violation of Bell-type inequalities. According to Einstein, we shall assume physical equivalence of a uniform gravitational field and a corresponding acceleration of a reference system. Here we construct a non-gravitational scenario where accelerating particles interacting with optical cavities result in a violation of the temporal Bell inequalities analogous to the gravitational case. However, we find that the inequalities can also be violated by time-like events, exposing an ambiguity in their use as a theory-independent test of indefinite temporal order.

arXiv: 2205.00164

Riccardo Falcone (University of Sapienza)

Observing single particles beyond the Rindler horizon

We show that Minkowski single-particle states localized beyond the horizon modify the Unruh thermal distribution in an accelerated frame. This means that, contrary to classical predictions, accelerated observers can reveal particles emitted beyond the horizon. The method we adopt is based on deriving the explicit Wigner characteristic function for the complete description of the quantum field in the non-inertial frame and which can be generalized to general states.

10.1103/PhysRevA.107.L030203

10.1103/PhysRevD.106.045013

Joshua Foo (University of Queensland)

Relativistic Bohmian trajectories of photons via weak measurements

Bohmian mechanics is a nonlocal hidden-variable interpretation of quantum theory which predicts that particles follow deterministic trajectories in spacetime. Historically, the study of Bohmian trajectories has mainly been restricted to nonrelativistic regimes due to the widely held belief that the theory is incompatible with special relativity. Here, we present an approach for constructing the relativistic Bohmian-type velocity field of single particles. The advantage of our proposal is that it is operational in nature, grounded in weak measurements of the particle's momentum and energy. We apply our weak measurement formalism to obtain the relativistic spacetime trajectories of photons in a Michelson-Sagnac interferometer. The trajectories satisfy quantum-mechanical continuity and the relativistic velocity addition rule. We propose a modified Alcubierre metric which could give rise to these trajectories within the paradigm of general relativity. We extend our framework to a nontrivial interaction between two photons in the relativistic regime.

Nature Communications Volume 13, Article number: 4002 (2022)

Fabian Haneder (University of Regensburg)

Towards a Quantum Chaotic Dual of JT Gravity

Jackiw-Teitelboim (JT) gravity is a two-dimensional model of quantum gravity that has received a striking amount of attention in recent years as a tractable example of a holographic theory, and has been used to study many important questions in quantum gravity, such as the black hole information and factorisation problems.
Crucial for both of these programs is the non-factorisation of JT gravity partition functions with multiple boundaries. In two dimensions, this can be explained by interpreting the holographic dual of JT gravity as an ensemble of theories, rather than a single system. However, it is not clear how to generalise this notion to higher-dimensional gravity.
In this contribution, we investigate a single quantum chaotic system which, under a dynamically emergent notion of averaging, behaves as a dual to JT gravity, providing a notion of effective non-factorisation at the level of correlators of a single system, as well as a way to explain why non-self averaging quantities like the spectral form factor of JT gravity look like they belong to an ensemble of systems, rather than a single one.

Ladina Hausmann (ETH Zürich)

Measurement events in timeless quantum physics

We compare two different consistent approaches to measurements in the Page-Wootters formalism [1,2]. In the "twirled observable approach," one uses time-translation invariant observables with respect to the Hamiltonian constraint [3].
In the "purified measurement approach," one modifies the Hamiltonian to include an interaction term modeling the measurement [4]. While both approaches agree in the limit of ideal clocks, but such clocks require infinite resources. A natural generalization of the purified measurement approach to the case of finite-resource clocks, which consequently are non-ideal, yields a radically different picture. In particular, we find that, for non-ideal clocks in the purified measurement approach, there is a fundamental limitation to the operational definition of the temporal order of events, and time evolution becomes non-unitary with respect to the clock.
However, we show that the unitarity of time evolution and definite temporal order can be restored if we assume that time is discrete. Studying how the two approaches relate to one another, we shed light on the operational interpretation of measurements in timeless quantum mechanics, as well as on the question of how dynamics and measurements "look like" from the perspective of a finite-resource quantum reference frame.

[1] Don N. Page and William K. Wootters. Evolution without evolution: Dynamics described by stationary observables. Physical Review D, 27(12):2885–2892, 1983. doi: 1610.1103/physrevd.27.2885

[2] William K. Wootters. "time" replaced by quantum correlations. International Journal of Theoretical Physics, 23(8):701–711, 1984. doi:10.1007/bf02214098.

[3] Philipp A. Höhn, Alexander R. H. Smith, and Maximilian P. E. Lock. Equivalence of approaches to relational quantum dynamics in relativistic settings. Frontiers in Physics, 9, 2021. doi:10.3389/fphy.2021.587083.

[4] Vittorio Giovannetti, Seth Lloyd, and Lorenzo Maccone. Quantum time. Physical Review D, 92(4):045033, 2015. doi:10.1103/physrevd.92.045033.

Hao Jeng (Australian National University)

Photon addition using swift electrons

We wish to discuss the implementation of photon addition using swift electrons inside a transmission electron microscope. Photon addition is an especially interesting quantum operation because it can be used to generate important states of light that are otherwise difficult to obtain. Despite much research since the first experimental demonstration [1], implementations by optical means remain challenging, leaving many of its potential applications unexplored.

Remarkably, it is possible to implement photon addition using quantized interactions between swift electrons and light. Unlike contemporary quantum optics experiments which are usually carried out at low energies, electrons in the microscope move at about 70% the speed of light. It is for this reason that we are experimenting with a physical system of this kind, in the hope that we may obtain a deeper understanding of the connection between quantum information and relativity.

We first report recent studies on the applications of photon addition in quantum information [2]. Our investigations reveal: (i) Adding photons to coherent states leads to cubic phase shifts, a key but elusive component for universal quantum computation with continuous variables. (ii) Adding photons to two-mode-squeezed-vacuum states results in non-Gaussian quantum correlations, which are associated with greater secret-key generation rates, but only when the simplifying assumption of Gaussian extremality is not made. (iii) Adding photons to thermal states leads to a counter-intuitive transformation of the average number of photons, demonstrating, in a simple and direct manner, that photons do not follow the rules of classical statistics.

We next discuss the implementation of photon addition inside the transmission electron microscope, which is based on quantized absorption and emission of photons by swift electrons as it passes through the near-field of a photonic sample [3,4]. Using an event-based electron spectrometer, the change in kinetic energy of the electron can be measured precisely and the number of quanta exchanged with the optical field identified. Photon addition (or subtraction) is obtained when filtering electrons with a specific energy-change.

Our sample of choice is microresonators. These integrated photonics structures enable efficient coupling of light in and out of the interaction zone (a key requirement for quantum information processing), while also serving to enhance the strength of the interaction when the optical field is on resonance. Exchange of quanta in the hundreds have been observed when the interaction is driven by a strong laser field [5], and correlations between electron energy-loss and emission of single photons have been detected when the resonator exists initially in the vacuum state [6].

[1] DOI: 10.1126/science.1103190

[2] DOI: 10.25911/91AF-XW32

[3] DOI: 10.1038/nature08662

[4] DOI: 10.1038/nature14463

[5] DOI: 10.1038/s41586-021-04197-5

[6] DOI: 10.1126/science.abo5037

Hari K (Indian Institute of Technology, Madras, Chennai)

Unruh-DeWitt detectors in curved spacetime

The particle detector models such as Unruh-DeWitt detectors(UDD) play a significant role in understanding quantum effects in different frames of reference. The Unruh effect is a well-studied process where a linearly accelerated UDD responds as if immersed in a thermal bath of particles. Accelerated detectors are the foundation for studying quantum processes in curved spacetime. However, the interplay between acceleration and curvature in the response of the detector is often not evident in the usual perturbative analysis. Since the acceleration picks up a spacelike direction, the components of the Riemann tensor in the plane of motion may intertwine with acceleration and can affect detector response in a non-trivial and interesting manner. We uncover such a connection between them by utilizing covariant power series for the geodesic interval between points on an accelerated trajectory. The power series admit a remarkable summation of all terms involving only the component of the Riemann tensor in the plane of motion. The resultant analytic function is a combination of hyperbolic functions and depends on acceleration only through the combination $q=\sqrt{a^2-\mathcal{E}_n}$, where $\mathcal{E}_n$ corresponds to the tidal component of curvature. This gives a thermal contribution to the detector response with a modified Unruh temperature proportional to q

arXiv:2106.14496, 10.1103/PhysRevD.104.064032

Nikolaos K. Kollas (University of Patras)

Cohering and decohering power of massive scalar fields under instantaneous interactions

We employ a non-perturbative technique to investigate the ability of a quantum field to create or destroy coherence in a two level Unruh-DeWitt (UDW) detector. We observe that, above a critical value of the effective coupling constant, the maximum amount of coherence generated by a coherent field displays revival patterns with respect to the particle's radius. Extending previous perturbative results we demonstrate that even in the case of a strong coupling between detector and field, massive fields are better at shielding the detector against the decohering effects of a thermal environment. In both cases we show how it is is possible to probe the value of the field's mass by either measuring its cohering or decohering power.

Phys. Rev. A 107, 022420 (2023)

Frederic Lassiaille (FL research)

Updated relativity: long version

In General Relativity (GR), the motion of quarks is assumed to be entirely taken into account when converting their energy of motion into their corresponding macroscopic energy at rest using E=mc² equation.
This is correct locally, but this motion generates also microscopic gravitational waves which propagate their space-time deformations everywhere. Therefore globally this motion yields immediatly a retardation of the gravitational force. This is the first effect of this motion.
The other consequences of this motion should be calculated in GR, but those calculations are cumbersome. Hopefully they can be approximated using a new and discrete equation. This equation shows that another effect arises, which is that the gravitational force must be divided by the energy of the surroundings of the location where the force is exerted, after multiplication by an appropriate factor. This effect was studied in a previous work [1] and was called "surrounding".
The main result of this study is that the motion of the quarks generate a surrounding effect in gravitation which might give an explanation to the gravitational issues of today.
[1] F. Lassiaille, EPJ Web of Conf. 182 (2018) 03006.

Dominic G. Lewis (RMIT University)

Bandlimited quantum field theory and the existence of continuous symmetries in lattice systems

Bandlimited approaches to quantum field theory offer the tantalizing possibility of working with fields that are simultaneously both continuous and discrete via the Shannon Sampling Theorem from signal processing. Conflicting assumptions in general relativity (smooth spacetime) and quantum field theory (high-energy deviations from low-energy emergent smoothness) motivate the use of such an appealing analytical tool that could thread the needle to meet both requirements. Bandlimited continuous quantum fields are isomorphic to lattice theories—yet without requiring a fixed lattice. Any lattice with a required minimum spacing can be used. This is an isomorphism that avoids taking the limit of the lattice spacing going to zero. A consequence of this isomorphism is the emergence of effectively continuous symmetries from quantum lattice systems, along with their associated conserved lattice variables through Noether's theorem. We explore the ramifications of this continuous symmetry and the requirements that a quantum lattice system must meet in order to possess such symmetry.

arXiv.2303.07649

Caroline Lima (Perimeter Institute-University of Waterloo)

The limits of semiclassical gravity for quantum matter

Einstein’s equations describe the relation between the geometry of spacetime and its classical matter content. Arguably the simplest modification to them to account for quantum effects results is the semiclassical approach. This consists in replacing the classical stress-energy tensor by the expectation value of its quantum counterpart in the original equations. However, we know that the semiclassical approximation is not suitable for a number of quantum states of the matter sourcing the gravitational field. Furthermore, the well-known states for which it is valid, coherent states, closely resemble the behaviour of classical matter. To investigate how spacetime curvature is affected by the quantum properties of matter, such as entanglement, we must determine quantum states that both display quantum behaviour and are under the regime of validity of this theory. We will discuss in this talk to what extent we can apply semiclassical gravity for states of quantum fields who display quantum properties.

Venkata Rishindra Melanathuru (Imperial College London)

Coherent state and Bargmann representation in relativistic quantum mechanics

The phase space of a relativistic system can be identified with the future tube of complexified Minkowski space. A Hilbert space of square-integrable holomorphic functions can then be constructed on the relativistic phase space, upon which a quantum measurement theory of spacetime phase-space events can be formulated. This holomorphic Hilbert space can also be interpreted as the Husimi (Fushimi) representation of relativistic quantum theory. Then a Bargmann-type transform can be worked out, leading to a new formulation of relativistic quantum theory in which coherent states associated to the conformal group play an important role. (Based on joint work with Dorje Brody, Lane Hughston, and Gary Gibbons.)

Shigetora Miyashita (Keio University)

Towards digital quantum simulation of quantum field theories in curved spacetime

Quantum field theory in curved spacetime (QFTCS) is a generalization of quantum field theory that goes beyond special relativity and has made several theoretical predictions, such as Hawking radiation of black holes and particle production in expanding universes. However, these phenomena are typically too weak to be readily observable in realistic gravitational scenarios. We propose a quantum algorithm for simulating the 3+1-dimensional Dirac equation in curved spacetime. Previous approaches to the simulation of this fundamental equation relied on classical techniques. We developed a digital quantum simulator in terms of a three-dimensional quantum walk. Furthermore, we demonstrate that our results enable us to simulate QFTCS by extending it to quantum cellular automata.

Nikolija Momčilović (University Ulm)

Entanglement-Assisted Effective Models for Tests of Fundamental Physics in Atom Interferometry

Quantum resources in form of entangled atoms promise to boost the sensitivity of atom interferometers beyond the regime achievable with classical sensor devices. Future dark matter or gravitational wave detectors, tests of the equivalence principle and even simple inertial sensors based on atom interferometry in combination with entanglement are already envisioned to apply these techniques to reach their projected potential. However, a proper characterization of these devices requires a full description of the entanglement dynamics between the light and matter subsystems during typical experimental sequences combined from free propagation and the light-matter interactions. Beginning with a few-mode model of the optical field coupled to a fully quantized few-level atom, we show: how (i) effective multi-mode Rabi models with center-of-mass motion can be derived for multi-photon transitions resembling the standard Jaynes-Cummings-Paul model, (ii) a master equation describing imperfect beamsplitters can be derived and (iii) our approach and the resulting models are not limited to atom interferometry but have further possible applications in cavity optomechanics or ion traps. Lastly, we highlight how and under which classical limit the usual theory of atom interferometry arises.

Dimitris Moustos (University of Patras)

Uniformly accelerated oscillator in 2+1 dimensions: temperature-dependent frequency shift

We consider an Unruh-DeWitt detector modeled as a harmonic oscillator that is coupled to a massless quantum scalar field in the (2+1)-dimensional Minkowski spacetime. We treat the detector as an open quantum system and employ a master equation to describe its time evolution, with the field playing the role of the environment. We investigate a point-like detector moving with constant acceleration through the Minkowski vacuum and an inertial one immersed in a thermal reservoir at the Unruh temperature, exploring the implications of the well-known non-equivalence between the two cases on their dynamics. We find that both the accelerated detector's dissipation rate and the shift of its frequency caused by the coupling to the field bath depend on the acceleration temperature. This is in contrast to the case of inertial motion in a heat bath where dissipation and frequency shifts are not known to exhibit temperature dependencies. Nonetheless, we show that the fluctuating-dissipation theorem still holds for the detector-field system and in the weak-coupling limit an accelerated detector is driven at late times to a thermal equilibrium state at the Unruh temperature.

Physics Letters B 829, 137115 (2022) ; arXiv:2201.08287 [gr-qc]

Everett A. Patterson (University of Waterloo)

Unruh Phenomena for Qudit Detectors

Among the most remarkable predictions of quantum field theory in curved spacetimes are the Unruh and Hawking effects, which describe how non-inertial observers can experience thermal excitations when interacting with the vacuum state of the quantum field. These effects can be probed using localized quantum-mechanical systems, i.e., particle detectors. Most of the current literature focuses on the Unruh-DeWitt (UDW) model, where the detector is a two-level system (qubit), or use the restricted two- and three-level subspaces of the harmonic oscillator detector model. In this work, we consider the generalization of the UDW detector model to d-dimensional qudit detectors, focusing on $d=3$ for concreteness. While there is a unique qubit model, there are at least three physically relevant qutrit models, each corresponding to distinct jump operators. We will show how the Unruh effect manifests in these different models and comment on their relationships with the qubit detector models.

María R. Preciado Rivas (University of Waterloo)

Radially Infalling Detector in BTZ Spacetime: A Little More Excitement Across the Horizon

It has been shown in recent work that a local extremum is present in the transition probability of an Unruh-DeWitt (UdW) detector, coupled linearly to a massless scalar field, as it freely falls across the event horizon of a four-dimensional Schwarzschild black hole [1]. However, a deep physical explanation of this effect is yet to be formulated. Here we numerically calculate the transition rate of a detector (coupled to the Hartle-Hawking vacuum of a massless scalar field) radially infalling toward a Bañados-Teitelboim-Zanelli (BTZ) black hole, extending the work by Hodgkinson and Louko [2]. We also observe a local extremum in the transition rate for certain values of the detector's energy gap and the black hole's mass as it falls toward and crosses the horizon. Our results suggest this effect is robust for black holes, and we expect them to motivate searches for a similar effect in other spacetimes and further investigation of its physical meaning.

[1] Ng, K. K., Zhang, C., Louko, J. & Mann, R. B. A Little Excitement Across the Horizon. New J. Phys. 24, 103018 (2022). DOI: 10.1088/1367-2630/ac9547

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Sebastian Schuster (Charles University)

Relational Dynamics and Time Travel

The Hamiltonian constraint of general relativity is often described as a fundamental problem for theories of quantum gravity and our usual understanding of dynamics therein: As time does not explicitly appear, theories of quantum gravity have to face the so-called "problem of time". In recent years, older attempts of resolving this tension through relational dynamics, for example, the Page-Wootters formalism, have seen a resurgence and received a lot of attention, culminating in a more unified understanding of different approaches. Classically, time-travel is ruled out (or at the very least contra-indicated) for a long list of reasons. Nevertheless, it often rears its head when assumptions of general relativity have to be relaxed, and it can often provide for tests and new perspectives on better-behaved physics. In this project, we attempt to answer what happens when an emergent notion of time in a quantum system meets the concept of time travel. We study what this can tell us as to how to even define time travel with only relational dynamics, and what new or improved limitations can be formulated through this point of view.

Raghvendra Singh (The Institute of Mathematical Sciences Chennai India)

Decoherence due to spacetime curvature

There has been considerable interest over the past years in investigating the role of gravity in quantum phenomenon such as entanglement and decoherence. In particular, gravitational time dilation is believed to decohere superpositions of center of mass of composite quantum systems. Since true effects of gravity are encoded in the curvature of spacetime, the universality of such decoherence must be characterized through components of Riemann tensor R_{abcd}, with a clear separation from non-inertial kinematic effects. We obtain the reduced density matrix of a composite system in a

generic curved spacetime and explicitly express the decoherence time scale in terms of curvature. The decoherence in an inertial frame is caused by tidal acceleration. We also analyze the effects of self-gravity and show that the coupling of gravitational interaction with external curvature can not be captured by the replacement $m \to m + H_{\rm int}/c^2$.

arXiv:2302.09038

Charalampos Theofilis (National Technical University of Athens)

Geometry Transition in Spinfoams

The combination of General Relativity and Quantum Mechanics is the Holy Grail of Physics. One of the main approaches to the quest for a Quantum Theory of Gravity is the background-independent, non-perturbative theory of Loop Quantum Gravity (LQG), in which spacetime itself is a quantum object. This talk is about the probability amplitudes for geometry transition between spacetime configurations. The structure is as follows. At first we give a small introduction to the basics of covariant LQG covering the geist of the theory and the well-established results. Then, we show how the fixed-spin asymptotics can be used to perform the spin-sum for spin foam amplitudes defined on what is called a tree-order level approximation. We rederive a previous result on 2-complexes without boundary in a different way suitable for our purposes. We then extend this representation to 2-complexes with a boundary and derive its relation to the coherent state representation. The above then permit us to put everything together with other results in the literature and show how the spin sum can be performed analytically for the regime of interest. These results are relevant to investigations regarding the transition of a black hole to a white hole geometry and can be also used in spinfoam cosmology to investigate the possibility of a "big bounce".

arXiv: 2302.12622c

Germain Tobar (Stockholm University)

Mass-energy equivalence in gravitationally bound quantum states of the neutron

Gravitationally bound neutrons have become an important tool in the experimental searches for new physics, such as modifications to Newton's force or candidates for dark matter particles. Here we include the relativistic effects of mass-energy equivalence into the model of gravitationally bound neutrons. Specifically, we investigate a correction in a gravitationally bound neutron's Hamiltonian due to the presence of an external magnetic field. We show that the neutron's additional weight due to mass-energy equivalence will cause a small shift in the neutron's eigenenergies and eigenstates, and examine how this relativistic correction would affect experiments with trapped neutrons. We further consider the ultimate precision in estimating the relativistic correction to the precession frequency and find that, at short times, a joint measurement of both the spin and motional degrees of freedom provides a metrological enhancement as compared to a measurement of the spin alone.

10.1103/PhysRevA.106.052801

Jackson R. Yant (Dartmouth College)

Towards an Operational QFT model for Gravitational Entanglement

Detecting entanglement induced by gravity would provide novel evidence of how quantum mechanics and gravity work together. Existing models of gravitationally induced entanglement treat the particles which become entangled with nonrelativistic single particle quantum mechanics. Here I present a model for a gravitational entanglement thought experiment which lends itself to a description where the particles that become entangled are treated as excitations of a quantum scalar field and the measurements of entanglement are modeled with expectation values of field observables, thus operationalizing the model. Such a description would provide a setting to develop further insights into what we can learn about the quantum nature of gravity from gravitational entanglement. The model consists of two particles confined within one harmonic trap, each initially in a superposition of coherent states traveling along orthogonal axes and interacting through gravity. As the particles become entangled, the visibility in the fringes of the particle detection probability in the region of overlap between the coherent state components of one particle diminish. So far we have developed a model for this system using non-relativistic quantum mechanics which we plan to use as a reference for future work (arxiv: 2302.05463). A quantum field theoretic model for this system is in progress.

arXiv: 2302.05463