Abstracts

Invited Talks (Alphabetical order)

Gerardo Adesso (University of Nottingham, UK)
Relativistic Quantum Metrology

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David Bruschi (University of Leeds, UK)
Relativistic Quantum gates

One of the central questions in our field is whether relativistic effects can be exploited in quantum information tasks. In our work, we show that the relativistic motion of a quantum system can be used to generate quantum gates. In particular, the non-uniform acceleration of a cavity is used to implement bipartite and multipartite quantum gates. Observable amounts of entanglement between the cavity modes are produced through resonances, which are obtained by repeating periodically any trajectory. The applications of these cavity setups are far reaching, ranging from relativistic quantum metrology to quantum information processing in superconducting circuits.

Iacopo Carusotto (Università di Trento, Italy)
Entanglement features in analogue Hawking radiation

After a general review of analogue Hawking radiation in different condensed matter and optical contexts and of the main difficulties encountered in its experimental characterization, I will present our recent results on how entanglement between the Hawking partners can be exploited to characterize the quantum origin of analogue Hawking radiation.

Giacomo D'Ariano (Università di Pavia, Italy)
Deriving the Dirac equation without using relativity from Quantum Cellular Automata

I will show how the Dirac equation in three space-dimensions emerges from the large-scale dynamics of the quantum automaton derived from a principle of minimum algorithmic complexity (minimum field dimension, unitarity, locality, homogeneity, discrete isotropy). The derivation can be considered as the prototype of a Planck-scale extension of quantum field theory. Differently from the lattice-gas approach, where quantum field theory is recovered in the continuum limit, here the theory is recovered in the large-scale limit for small momentum and small inertial mass, with Lorentz covariance holding as an approximate symmetry in such a relativistic limit, whereas in the ultra-relativistic regime it is distorted a la Amelino-Camelia/Smolin-Magueijo. The resulting theory thus describes all scales ranging from Planck to Fermi in a unified way, and is an ideal framework for quantum gravity, with a list of good features lacking from other conventional approaches: it is fully quantum ab-initio, computable, with no divergences, no problem arising from the continuum, and no localization and causality issues, relativistic covariance is emergent and not assumed a priori. A simple asymptotic approach allows us to derive a general dispersive Schrödinger equation that holds in all regimes for the narrow-band states typical of quantum field theory. Such equation allows us to make predictions for possible experimental evidences or falsifications. During the seminar I will also project animated computer simulations for the 2d Dirac automaton.

Per Delsing (Chalmers University of Technology, Göteborg, Sweden)
Experiments on the dynamical Casimir effect in superconducting circuits
(coll. with C. M.Wilson, I.-M. Svensson, G. Johansson, A. Pourkabirian, M. Simoen, M. Pierre, J. R. Johansson, T. Duty, and F. Nori)

The Dynamical Casimir Effect (DCE) was recently observed in a superconducting circuit consisting of a coplanar transmission line with a tunable electrical length [1]. The rate of change of the electrical length can be made very fast (a substantial fraction of the speed of light) by modulating the inductance of a superconducting quantum interference device at high frequencies ($\sim$ 10 GHz). Broadband generation of photons is observed and in addition, we detect two-mode squeezing in the emitted radiation, which is a signature of the quantum character of the generation process. A new related experiment, with a doubly tunable cavity is also discussed. The cavity is terminated by one SQUID in each end, so that the cavity can be parametrically pumped in different ways. In particular the difference between the breathing mode and the translational mode of the cavity is discussed [2].

[1] C. M. Wilson, G. Johansson, A. Pourkabirian, M. Simoen, J. R. Johansson, T. Duty, F. Nori, and P. Delsing, *Observation of the dynamical Casimir effect in a superconducting circuit*, Nature **479**, 376 (2011).
[2] I.-M. Svensson, *Photon generation in a doubly tunable resonator*, MSc. thesis, Chalmers University of Technology, 2012.

Hal Haggard (Centre de Physique Théorique, Marseille, France)
General boundary field theory, thermality, and entanglement

In its usual formulation quantum field theory considers evolution between two spacelike planes where the initial/final states of the field are specified. In the general covariant setting of gravity it is more natural to consider a compact spacetime region. I will discuss how to formulate field theory for such general boundaries. In particular I will show that the Unruh effect becomes manifest in this setting and is deeply connected to the Lorentz invariance of the Minkowski vacuum: its thermality is a consequence of entanglement between initial and final Rindler time slices.

Beatrix C. Hiesmayr (University of Vienna)
Entanglement Features at Relativistic Speeds and at High Energies

Entanglement is with no doubt one of the most puzzling features of the quantum theory. It can be found in many distinct physical systems. In this talk I want to discuss entanglement features of massive systems. Firstly, I focus on how bipartite and multipartite entanglement features change for boosted observers [1] and what we learn from that for the understanding of proper classifications of entanglement [2]. Secondly, I focus on massive particle-antiparticle systems entangled in the quantum number flavour [3]. I emphasize that these systems copiously produced at accelerator facilities reveal different features of entanglement than systems of ordinary matter and light. In particular, I want to point out a puzzling relation to the violation of the Charge-Conjugation-Parity symmetry that relates to the cosmological question: why we live in a matter dominated universe. Last but not least I want to show that these massive systems produced at different relativistic speeds are unique systems to look for tiny deviations from standard theories such as, e.g., a possible violation of the Lorentz symmetry [4].

[1] N. Friis, R. A. Bertlmann, M. Huber, and B.C. Hiesmayr, *Relativistic entanglement of two massive particles,* Phys. Rev. A **81**, 042114 (2010).
[2] M. Huber, N. Friis, A. Gabriel, C. Spengler, and B. C. Hiesmayr, *Lorentz invariance of entanglement classes in multipartite systems*, Europhys. Lett. **95**, 20002 (2011).
[3] B. C. Hiesmayr, A. Di Domenico, C. Curceanu, A. Gabriel, M. Huber, J.-Å. Larsson, and P. Moskal, *Revealing Bell's Nonlocality for Unstable Systems in High Energy Physics*, Eur. Phys. J. C **72**, 1856 (2012).
[4] G. Amelino-Camelia et al., *Physics with the KLOE-2 experiment at the upgraded DAPHNE,* Eur. Phys. J. C **68**, 619 (2010).

Bei Lok Hu (University of Maryland, USA)
Foundational Issues in Gravitational Decoherence

Will quantum matter be decohered by the gravitational field at low energy (in contrast to Planck energy quantum gravity) [1], and if so, to what degree and how? How different is this from decoherence by a non-gravitational environment such as a matter field or via intrinsic decoherence [2]? Here we derive from first principles a master equation for a nonrelativistic particle interacting with a weak gravitational field based on bona fide quantum field theory and general relativity. From it we show the particularities and special features of gravitational decoherence. With this we point out the ambiguities and inconsistencies of alternative quantum theories based on stochastic Schrödinger equations with a phenomenological noise term added in an ad hoc manner, their good physical motivations notwithstanding. This talk is based on [3].

[1] C. Anastopoulos and B. L. Hu, *Decoherence in Quantum Gravity: Issues and Critiques*, J. Phys. Conf. Ser. **67**, 012012 (2007).
[2] C. Anastopoulos and B. L. Hu, *Intrinsic and Fundamental Decoherence: Issues and Problems*, Class. Quant. Grav. **25**, 154003 (2008).
[3] C. Anastopoulos and B. L. Hu, *Gravitational Decoherence: Inconsistencies and Ambiguities*, in preparation.

Thomas Jennewein (ICQ & University of Waterloo, Ontario, Canada)
The Quantum Space Race, and how it can help Exploring new Physics

Quantum information, and its use in quantum communication and other novel protocols, has its origins in the very fundamental and philosophical questions on quantum superposition and quantum entanglement. Today, we know that these new protocols will enable communication task which are not possible with classical systems. One very important example is the secure key exchange based on the exchange of quantum communication, with a global quantum entanglement network the long term vision. At the same time, it is fascinating how such a global scale quantum entanglement network will enable tests of quantum mechanics at distances and velocities not possible on the ground. I will discuss recent advances in the experimental implementation of quantum entanglement cover global distances using satellites, and outline some of the fundamental tests than may be possible using the first generation of quantum satellites.

Göran Johansson (Chalmers University of Technology, Göteborg, Sweden)
Simulating relativistic motion in superconducting circuits

In this presentation, I will start by briefly describing circuit quantization, i.e. the basic method to describe the quantum dynamics of the electromagnetic field confined to superconducting circuits. I'll also the key non-linear element, i.e. the Josephson junction (JJ). The JJ can be regarded as a nonlinear dissipationless inductance. Two JJs in a loop function as a tunable inductance, which can then be used for ultrafast modulation of the circuit parameters, i.e. the boundary conditions for the electromagnetic field. This setup can be used to study the dynamical Casimir effect [1,2]. Finally, I will discuss a recent proposal by the Nottingham group to study the effects of relativistic motion on quantum teleportation in superconducting circuits [3]. Computing the bounds on the optimal fidelity of teleportation when one of the observers undergoes nonuniform motion for a finite time, the upper bound to the optimal fidelity is degraded due to the observer's motion. These effects are observable for experimental parameters that are within reach in superconducting circuits.

[1] J. R. Johansson, G. Johansson, C. M. Wilson, F. Nori, Phys. Rev. Lett. 103, 147003 (2009).
[2] J. R. Johansson, G. Johansson, C. M. Wilson, and Franco Nori, Phys. Rev. A 82, 052509 (2010).
[3] Nicolai Friis, Antony R. Lee, Kevin Truong, Carlos Sabín, Enrique Solano, Göran Johansson, Ivette Fuentes, Phys. Rev. Lett. 110, 113602 (2013).

Jose Ignacio Latorre (Universitat de Barcelona, Spain)
Quantum Simulation of external conditions

The simulation of dynamical degrees of freedom of sophisticated theories is a highly non-obvious experimental task. Instead, the study of the modification of external conditions for well controlled systems is within experimental reach. We here focus on the essential ingredients to simulate quantum systems on non-trivial geometries.

Robert Mann (ICQ & University of Waterloo, Ontario, Canada)
Universality and Thermalization of Accelerated Detectors

I discuss the effects of different boundary conditions and coupling schemes in the response of a constantly accelerated particle detector in optical cavities. Thermalization properties of the accelerated detector are analyzed via non-perturbative calculations. If the switching process is smooth enough, then I show non-perturbatively that (to an excellent approximation) the detector thermalizes to the Unruh temperature regardless of the boundary conditions and the form of the coupling considered.

Carlo Rovelli (Centre de Physique Théorique de Luminy, Marseille, France)
General relativistic quantum statistical mechanics and information

I describe the attempts and the problems in formulating classical and quantum statistical mechanics in a fully general realistic way. I illustrate the notion that information plays in this context, both for quantum mechanics and for the definition of statistical equilibrium.

Terry Rudolph (Imperial College, London, UK)
Does relativistic/field-theoretic QI theory allow for information processing provably impossible in non-relativistic settings?

For computation, quantum mechanics does not change the class of things computable, only the efficiency with which they can be computed. For communication, however, things are different - quantum theory allows for the completion of tasks provably impossible in classical settings. However there are limitations to the magic, and certain cryptographic protocols are known to be impossible to do securely, at least within non-relativistic QI theory. In this talk I will outline several directions I think could lead to classes of secure cryptographic protocols in relativistic QI that are provably impossible in its non-relativistic counterpart.

Ralf Schützhold (Universität Duisburg-Essen, Germany)
Hawking radiation with dispersion versus breakdown of WKB

Inspired by the condensed matter analogues of black holes (a.k.a. dumb holes), we study Hawking radiation in the presence of a modified dispersion relation which becomes super-luminal at large wave-numbers. In the usual stationary coordinates (t,x), one can describe the asymptotic evolution of the wave-packets in WKB, but this WKB approximation breaks down in the vicinity of the horizon, thereby allowing for a mixing between initial and final creation and annihilation operators. Thus, one might be tempted to identify this point where WKB breaks down with the moment of particle creation. However, using different coordinates, we find that one can evolve the waves so that WKB in these coordinates is valid throughout this transition region -- which contradicts the above identification of the breakdown of WKB as the cause of the radiation. Instead, our analysis suggests that the tearing apart of the waves into two different asymptotic regions (inside and outside the horizon) is the major ingredient of Hawking radiation. These findings could be relevant for the black-hole information "paradox" because some of the proposed resolutions suggest that the information leaks out of the black hole via Hawking radiation and is imprinted on the emitted photons at the horizon.

Michael Skotiniotis (University of Innsbruck, Austria)
Quantum frameness for charge-parity-time inversion symmetry

Due to Lorentz invariance and linearity, physical laws are invariant under simultaneous charge-parity-time (CPT) inversion making this symmetry one of the most fundamental ones in the universe. We consider the superselection rule that arises from CPT symmetry, and develop a theory of CPT frameness resources. We show that even for this fundamental symmetry, superselection can be circumvented using appropriate resources, which we construct and quantify for the case of spin-0, -1/2, -1, and Majorana particles. In addition, we show that quantum information processing is possible even in the presence of a CPT superselection rule. We treat CPT inversion unitarily by considering the aggregate action of CPT rather than the composition of C, P and T, which results in an anti-unitary representation of CPT. This work is a joint collaboration with Borzu Toloui, Ian Durham and Barry C. Sanders.

William G. Unruh (University of British Columbia, Vancouver, Canada)
Radiation from an accelerated sponge

A sponge is a device for absorbing garbage, and no better definition of garbage exists than a thermal state-- the maximum entropy for a given energy. What happens when a sponge absorbs the radiation that an accelerated observer sees?

Vlatko Vedral (University of Oxford, UK)
Operational treatment of the spin in (special) relativistic quantum information

I will show that the exact form we need to use to describe the spin of a relativistic particle depends on the details of how the spin is to be measured. Hence, I will conclude that in order to have the Lorentz invariance of the probabilities of the outcomes of any measurement, the spin must transform (under Lorentz transformations) in the same way as the physical quantity that couples to it via the measuring apparatus. As a consequence, it will be transparent that it is impossible to measure the spin state of a particle in a way independent from its momentum. The results can be put into a firm quantum field-theoretic language, and I will contrast the present approach with other existing approaches to define the relativistic spin operator using conservation of angular momentum.

Contributed Talks

Valentina Baccetti (Victoria University of Wellington, New Zealand)
The effects of gravity and motion on quantum entanglement in space-based experiments

We devise an experiment to test the effect of gravitational fields and acceleration on quantum entanglement in space-based setups. We show that the entanglement between transverse excitations of two Bose-Einstein Condensates is degraded after one of them undergoes a period of accelerated motion. This prediction can be tested if the condensates are initially entangled in two separate satellites while being in the same orbit and after that one moves to a different orbit. We show that the effect is observable in a typical orbital manoeuvre of microsatellites like CanX4 and CanX5.

Eric Brown (University of Waterloo, Ontario, Canada)
Harvesting correlations from the vacuum and thermal amplification

I will speak on some recent results regarding the harvesting of correlations from a quantum field by two harmonic particle detectors. In the case of stationary detectors the system evolution can be solved exactly (analytically) and non-perturbatively. Rather than focusing on entanglement I will instead shed light on the harvesting of total correlations, quantified by the mutual information, and correlations regarded as being of a quantum nature, here quantified by the quantum discord. As will be seen, the harvesting of such correlations is generally very different than that of entanglement, and in fact displays some very surprising and counter-intuitive properties. In attempting to explain such properties I will examine the structure of harvested correlations from an alternative perspective. I will go on to argue that this perspective may provide considerable explanatory power more generally.

Xavier Busch (Université Paris Sud, France)
How dissipation affects the entanglement due to DCE

We study the consequences of dissipation in homogeneous media when the system is subject to a sudden change, thereby producing pairs of correlated quasi-particles with opposite momenta. We compute both the modifications of the spectrum, and those of the correlations. In particular, we compute the final coherence level, and identify the regimes where the state is non-separable.

Marek Czachor (Politechnika Gdanska, Poland)
Subtleties of relativistic qubits

I would like to discuss certain less known aspects of relativistic qubits: the role of principal null directions for error correction, null tetrads of a twistor type and their possible roles for electromagnetic qubits, invariance vs. covariance of vacuum in various representations of the Poincare group and harmonic oscillator Lie algebras, and their consequences for non-uniform motion...

Andrea Di Falco (University of St. Andrews, UK)
Synthetic Optical Materials for Photonics Applications

The current advances in photonics have given us ways to control and manipulate light virtually at will. We have learnt how to bend it, slow it down and even stop it, confine it in dimensions smaller that its wavelength and ultimately determine its path. This progress has been generated by enabling technologies, like that of photonic crystals and metamaterials, which allow the design of the properties of matter at the nanoscale. In this talk I will present the portfolio of techniques developed at the University of St Andrews to fabricate synthetic optical materials, like chaotic broadband resonators and flexible metamaterials, and discuss their potential applications.

Stefano Finazzi (Università di Trento, Italy)
Quantum entanglement of phonons in Bose-Einstein condensates with a sonic horizon

Correlations between pairs of phonons have been proposed as a signature of the Hawking mechanism in analogue black-hole geometries in Bose-Einstein condensates. Unfortunately, the detection of these correlations is not sufficient to prove the quantum nature of the emission. An incontrovertible proof of the quantumness of this phenomenon would be provided by the detection of entangled phonons. We have analysed the results of numerical simulations of flowing Bose-Einstein condensates with analogue horizons using a Peres-Horodecki-like criterion. We have found that the emitted phonons are entangled if the temperature of the condensate is sufficiently low. I shall present these results and briefly discuss issues related to a possible experimental implementation of this technique.

Nicolai Friis (University of Nottingham, UK)
On the robustness of entanglement in analogue gravity systems

Following [1], we investigate the possibility to generate quantum-correlated quasi-particles utilizing analogue gravity systems. The quantumness of these correlations is a key aspect of analogue gravity effects and their presence allows for a clear separation between classical and quantum analogue gravity effects. However, experiments in analogue systems, such as Bose-Einstein condensates, and shallow water waves, are always conducted at non-ideal conditions; in particular, one is dealing with dispersive media at nonzero temperatures. We analyse the influence of the initial temperature on the entanglement generation in analogue gravity phenomena. We lay out all the necessary steps to calculate the entanglement generated between quasi-particle modes and we analytically derive an upper bound on the maximal temperature at which given modes can still be entangled. We further investigate a mechanism to enhance the quantum correlations. As a particular example we analyse the robustness of the entanglement creation against thermal noise in a sudden quench of an ideally homogeneous Bose-Einstein condensate, taking into account the super-sonic dispersion relations.

[1] D. E. Bruschi, N. Friis, I. Fuentes, and S. Weinfurtner, e-print arXiv:1305.3867 [quant-ph] (2013).

Margaret Hawton (Lakehead University, Canada)
Counting Unruh photons

A photon's number density on a spacelike hypersurface is the absolute square of the projection of its incident state vector onto a basis of exactly localized states [1,2]. The probability for a photon counting detector to absorb a photon is the integral of this probability density over the surface area of the device and measurement time. I will compare photon counting and Unruh-deWitt detectors and discuss the paradoxical properties of localized states that have hindered their application to the counting of photons. Orthonormal exactly localized Rindler states will be defined on a rigid spacelike hypersurface that have a common proper time and define a POVM for position measurements. This POVM will be used to calculate the probability for accelerated detectors to absorb Unruh photons from the Minkowski vacuum. I will show that the spacetime coordinates of the photons absorbed by a pair of counteraccelerating detectors in causally disconnected Rindler wedges are correlated. If a photon is absorbed by a single accelerated detector the Minkowski vacuum collapses to a state containing at least one photon and that photon can be absorbed by an inertial detector.

[1] M. Hawton, *Photon position measure*, Phys. Rev. A **82**, 012117 (2010).
[2] M. Hawton, *Photon location in spacetime*, Phys. Scr. **T147**, 014014 (2012).

Jen-Tsung Hsiang (National Dong-Hwa University, Taiwan)
Quantum Entanglement in N Moving Detectors via the Influence Functional

Being an exclusive feature of quantumness entanglement should be a useful criterion for or measure to detect macroscopic quantum phenomena (MQP). We study the nonequilibrium evolution of a system of N interacting oscillators coupled with a common thermal bath via the influence functional formalism [1]. We derive the covariance matrix of this open quantum systemand show how to obtain its entanglement dynamics [2]. We provide exact solutions for N=3 with strong interaction [3]. We use the case of disparite coupling to illustrate how entanglement at inter- and infra- levels of structure [4] differ which should play an important role in discerning MQP.

[1] A. Raval, B. L. Hu, and J. Anglin, *Stochastic theory of accelerated detectors in a quantum field*, Phys. Rev. D **53**, 7003 (1996).
[2] J. T. Hsiang, B. L. Hu, and S. Y. Lin, *Quantum Entanglement in N Moving Detectors via the Influence Functional*, in preparation.
[3] J. T. Hsiang, R. Zhou, and B. L. Hu, *Entanglement Structure of an Open System of N Quantum Oscillators II. Direct Strong and Disparate Coupling N=3*, in preparation.
[4] B. L. Hu and Y. Subasi, *Pathways toward understanding Macroscopic Quantum Phenomena*, e-print arXiv:1304.7839 [quant-ph], to appear in J. Phys. Conf. Ser. (2013); C. H. Chou, B. L. Hu, and Y. Subasi, *Macroscopic Quantum Phenomena from the Entanglement Perspective*, in preparation.

Petr Jizba (Czech Technical University, Prague, Czech Republic)
Special Relativity induced by Granular Space
(work in collaboration with H. Kleinert and Dr. F.Scardigli)

We show that the special relativistic dynamics when combined with quantum mechanics and the concept of superstatistics can be interpreted as arising from two interlocked non-relativistic stochastic processes that operate at different energy scales. This interpretation leads to Feynman amplitudes that are in the Euclidean regime identical to transition probability of a Brownian particle propagating through a granular space. For illustration we consider the dynamics and the propagator of a Klein-Gordon particle. Implications for, doubly special relativity, quantum field theory and quantum gravity are discussed. The related papers are:

[1] P. Jizba and H. Kleinert, *Superstatistics approach to path integral for a relativistic particle*, Phys. Rev. D **82**, 085016 (2010).
[2] P. Jizba and H. Kleinert, *Superpositions of probability distributions*, Phys. Rev. E **78**, 031122 (2008)
[3] P. Jizba and F. Scardigli, *Emergence of special and doubly special relativity*, Phys. Rev. D **86**, 025029 (2012); P. Jizba and F. Scardigli, *Superstatistics Approach to Doubly Special Relativity*, Int. J. Mod. Phys. B **26**, 1241003 (2012).
[4] P. Jizba and F. Scardigli, *Special Relativity induced by Granular Space*, e-print arXiv:1301.4091 [hep-th].

Benito Alberto Juárez Aubry (University of Nottingham, UK)
Onset of Hawking radiation in 1+1 dimensions

We analyse the Hawking and Unruh effects in strongly time-dependent situations in 1+1 spacetime dimensions, using a derivative-coupling Unruh-DeWitt detector that is insensitive to the infrared ambiguity of massless Green's functions. Examples include the onset of thermality in the radiation emitted by an accelerating mirror in Minkowski spacetime, and the loss of thermality seen by an observer who falls from infinity into a radiating black hole.

Friedrich König (University of St Andrews, UK)
Negative frequency light from fibres
(work in collaboration with J. McLenaghan)

Light waves contain positive and negative frequencies as seen in Fourier analysis. Using an analogue horizon in an optical fibre, we experimentally demonstrate coupling between positive and negative frequencies. Quantum particles oscillate with positive frequencies only. The positive (negative) frequency part of a quantum field is the amplitude of the annihilation (creation) operator. If positive and negative frequencies couple particles are created. In our experiment, fibre solitons, subject to higher order dispersion, excite dispersive waves sharing the frequency in the moving frame with the soliton (Resonant- or Cherenkov radiation). The fibre dispersion allows for two of these excitations, of positive frequency (resonant radiation (RR)) and negative frequency (NRR). We coupled a nJ, 7-fs pulse into a few mm-long microstructured fibre. It compresses to a wide spectrum and excites RR and NRR modes [Rubino, PRL, 108, 253901, (2012)]. We studied a few fibres and how the excitation depends on pulse compression and the associated spectral support in the ultraviolet. The NRR requires the dispersion to pass through zero frequency in the moving frame, the condition for a phase velocity horizon. Thus, the generation of NRR is a first step towards astrophysical particle creation in optical analogues.

Shih-Yuin Lin (National Changhua University of Education, Taiwan)
Projective Measurement in Relativistic Systems

I will talk about the problems in adapting the von Neumann projective measurement to relativistic systems. The failure of the nonlocal projective quantum non-demolition state-verification in relativistic systems will be discussed in details. A few issues about causality, covariance, entanglement, and local/nonlocal measurements will also be addressed.

Nicolas C. Menicucci (University of Sydney, Australia)
Detectors for probing relativistic quantum physics beyond perturbation theory

Success of the (qubit-based) Unruh-DeWitt model of particle detectors stems from its use in analysing the observer dependence of relativistic quantum phenomena, but its reliance on perturbation theory still limits its potential. By replacing the qubit with a harmonic oscillator, we can model the evolution nonperturbatively as a readily solvable set of first-order, linear differential equations. The formalism applies unchanged to the analysis of a wide variety of physical setups and physical phenomena. This talk will describe our analytic methods and report on numerical analyses of the following physical effects: (i) universality of the Unruh effect for detectors accelerating through cavities; (ii)minimum number of cavity modes required to ensure causal behaviour in the model; (iii) entanglement harvesting by spacelike separated detectors; (iv) backreaction in the detector due to the switching function. Clearly an idea whose time has come, this work [1] was independently completed and released simultaneously with that of another group working along similar lines [2].

[1] E. G. Brown, E. Martín-Martínez, N. C. Menicucci, and R. B. Mann, *Detectors for probing relativistic quantum physics beyond perturbation theory*, Phys. Rev. D **87**, 084062 (2013).
[2] D. E. Bruschi, A. R. Lee, and I. Fuentes, *Time evolution techniques for detectors in relativistic quantum information*, J. Phys. A: Math. Theor. **46**, 165303 (2013).

Sorin Paraoanu (Aalto University, Finland)
Casimir effect in a Josephson metamaterial

The picture about vacuum that emerges from modern quantum field theory is very different from that offered by classical physics. In classical field theory, the vacuum is the zero-energy state of the field, defined by the absence of any excitation. In quantum field theory, the vacuum state has a finite zero-point energy associated with it, and the uncertainty principle indicates that fluctuations exist even in this state. Due to existence of fluctuations, under certain perturbations the quantum vacuum can become unstable, and the energy of the perturbation is converted into creation of real particles. For example, in the Schwinger effect a static intense electric field can create pairs of electrons and positrons. In very strong gravitational fields, at the event horizon of black holes, the vacuum becomes unstable and energy is radiated away (Hawking effect). By the equivalence principle, an accelerated observer in the Minkowski vacuum will detect a finite-temperature field (Unruh effect). Finally, the energy and the fluctuations of the electromagnetic vacuum confined in a cavity have real, measurable effects: they produce an attractive force between the walls of the cavity (static Casimir effect), and, if the boundary conditions [1] or the index of refraction [2] are changed, photons are created apparently out of nothing (dynamic Casimir effect). In this talk I report on the observation of the dynamical Casimir effect using a flux-biased Josephson metamaterial (an array of SQUIDs) embedded in a microwave cavity at 5.4 GHz [2]. A non-adiabatic change in the index of refraction of the cavity (or in the electrical length) is realized by modulating the flux at values close to double the resonant frequency of the cavity. We measure the frequency-correlated photons thus generated from the cavity at T = 50mK, and we obtain a power spectrum displaying a bimodal, sparrow-tail distribution. The experimental results are in excellent agreement with the theoretical predictions. We also demonstrate squeezing below the vacuum level and we verify that the photons generated by the dynamical Casimir effect are in a non-separable (EPR) state. The experiment demonstrates the potential of superconducting quantum circuits to serve as a platform for simulating effects from cosmology and quantum field theory. I will also briefly describe a few directions in which this type of experiments could be further developed.

[1] C. M. Wilson, G. Johansson, A. Pourkabirian, M. Simoen, J. R. Johansson, T. Duty, F. Nori, and P. Delsing, *Observation of the dynamical Casimir effect in a superconducting circuit*, Nature **479**, 376 (2011).
[2] Pasi Lähteenmäki, G.S. Paraoanu, J. Hassel, and Pertti J. Hakonen, *Dynamical Casimir effect in a Josephson metamaterial*, Proc. Natl. Acad. Sci. U.S.A. **110**, 4234 (2013).

Igor Pikovski (University of Vienna, Austria)
Universal Decoherence Due to Gravitational Time Dilation
(work in collaboration with M. Zych, F. Costa, and Č. Brukner)

The fact that quantum effects are not observed on macroscopic scales is usually attributed to decoherence – the suppression of quantum superpositions due to the interaction with an environment. The precise working of this mechanism, however, crucially depends on the type of interaction and results are typically derived by assuming specific, often ad-hoc, models. Here it is shown that gravitational time-dilation provides a universal decoherence mechanism for any complex system. The effect takes place even for isolated particles that do not interact with any external environment. In particular, curved space-time causes decoherence in the position basis of the centre of mass of the system. Remarkably, the Earth's gravitational field is sufficient to decohere gram-scale objects and complex molecules. Therefore, the decoherence due to gravitational time dilation may play a major role in the transition to classicality. Possible experimental verifications of the effect will be briefly discussed.

Fabio Scardigli (Politecnico of Milano, Italy)
Polycrystalline space-time: roots of Special and Doubly Special Relativity

A polycrystalline structure of spacetime can originate a statistical emergence of (doubly) Special Relativity. The smearing distributions describing the polycrystalline medium represent links between spacetime microstructures and different emergent relativistic symmetries. A small departure from their standard shapes brings from Lorentz Symmetry to DSR symmetry. Some kind of spacetime granularity could be held responsible for the emergence at larger scales of various symmetries. Consequences for relativity and cosmology are discussed.

[1] P. Jizba and F. Scardigli, *Emergence of special and doubly special relativity*, Phys. Rev. D **86**, 025029 (2012).

Michaël Simoen (Chalmers University of Technology, Göteborg, Sweden)
Experimental investigations of the dynamical Casimir effect
(work in collaboration with A. Pourkabirian, I.-M. Svensson, C. Wilson, G. Johansson, and P. Delsing)

Modern quantum theory predicts the existence of vacuum fluctuations, which have measurable consequences. It was already discussed from early on if these fluctuations could be measured directly. Around forty years ago it was suggested by G. Moore [1] that a mirror undergoing relativistic motion could interact with these vacuum fluctuations and produce directly measurable radiation. This phenomena was coined the dynamical Casimir effect and was first observed experimentally in a superconducting circuit [2] closely resembling the single mirror setup proposed by Fulling and Davies [3]. Both the creation of photons and the two-mode squeezing in the emitted radiation have been measured. We are presenting a modified experiment and measurement setup to observe the broadband nature of the generated radiation more easily and how to use its nonclassical nature [4] as a possible resource for (relativistic) quantum information.

[1] G. T. Moore, *Quantum Theory of the Electromagnetic Field in a Variable-Length One-Dimensional Cavity*, J. Math. Phys. **11**, 2679 (1970).
[2] C. M. Wilson, G. Johansson, A. Pourkabirian, M. Simoen, J. R. Johansson, T. Duty, F. Nori, and P. Delsing, *Observation of the dynamical Casimir effect in a superconducting circuit*, Nature **479**, 376 (2011).
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Christoph Westbrook (Laboratoire Charles Fabry de l'Institut d'Optique, Palaiseau, France)
Analogs to the dynamical Casimir effect in Bose Condensates
(in collaboration with D. Boiron, J. Ruaudel, R. Lopes, M. Cheneau)

It is a remarkable prediction of quantum field theory that the vacuum can generate real particles when boundary conditions are suddenly changed. Thus the 'dynamical Casimir effect' results in the spontaneous generation of photon pairs in an empty cavity with non-uniformly accelerating boundaries. Recent advances have permitted the realization of this effect, or analogues to it in a variety of systems, some of which will be discussed at this workshop. Bose Einstein condensates are attractive candidates in which to study acoustic analogues to such phenomena, because their low temperatures promise to reveal quantum effects. I will discuss a recent experiment in our group to realize an acoustic analogue to the dynamical Casimir effect by modulating the confinement of a Bose-Einstein condensate. We observe correlated pairs of Bogoliubov quanta, both phonon-like and particle-like, are excited by this modulation in a process that formally resembles parametric down conversion. I will discuss our current ideas on how to observe and quantify the degree of entanglement in the excitations we observe.

Angela C. White (Newcastle University, UK)
Ultra-cold thermometry: Setting the framework for RQI measurements in emergent space-times
(work in collaboration with Carlos Sabín, Lucia Hackemüller, and Ivette Fuentes)

Analogue models of gravity are built around the observation that the propagation of sound waves in an ideal fluid are equivalent to the propagation of massless minimally coupled scalar fields in curved space-time. This analogy provides a basis for exploring and testing kinematical effects of quantum field theory in curved space-times in experimentally accessible systems that can be easily manipulated, such as Bose-Einstein condensates (BECs). In particular, in addition to measuring effects such as Hawking and Unruh radiation, emergent space-times in BECs promise the first verification of entanglement in curved space-times, an exciting prospect for the field of RQI. Such measurements require a precise knowledge of the condensate at temperatures near absolute zero, in the sub-nK regime. Calculating the Fisher Information, we show that state of the art in ultra-cold thermometry can be improved upon by measurement, through a Ramsey Interferometry scheme, of the temperature-dependent dynamical phase acquired by an array of impurity atoms immersed in an ultra-cold BEC. Furthermore, the Heisenberg limit can be reached through the preparation of initially entangled impurity atoms. An additional advantage of our technique is its minimally destructive nature, promising precise temperature estimation can be coupled with RQI experiments in emergent space-times.

Erez Zohar (Tel Aviv University, Israel)
Simulation of dynamic abelian and non abelian gauge theories with ultracold atoms
(work in collaboration with Benni Reznik and Ignacio Cirac)

We use several methods of ultracold atoms trapped in optical lattices in order to simulate 1+1 and 2+1 dimensional dynamic gauge theories and probe confinement - flux tubes and flux loops. The simulating methods are different and use various implementations - either BECs or single atoms, and include the possibility to simulate the dynamics and observe confinement, as well as measure Wilson Loops, in abelian (U(1) - compact QED) or nonabelian (SU(N)) lattice gauge theories.

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Magdalena Zych (University of Vienna, Austria)
Quantum Schiff's Conjecture

The quantitative version of the Schiff's conjecture derived by Nordtvedt is considered an important guideline for analyzing experimental tests of general relativity. It is a relation between possible violations of the universality of free fall and deviations from general relativistic time dilation. I will show, however, that this result is based on counterfactual reasoning and does not necessarily extend to quantum mechanics. It is in fact consistent with a whole set of semiclassical theories that do violate Schiff's conjecture. I will derive a quantum version of Nordtvedt's relation and show how the result crucially depends on the extension of the mass-energy equivalence principle into quantum mechanics. A fully quantum extension of the principle yields the expected special and general relativistic time dilation effects, whereas various semiclassical extensions correspond to theories violating Schiff's conjecture.

Posters/Short Talks

Luis Cortés Barbado (Instituto de Astrofísica de Andalucía, CSIC, Granada)
Unruh radiation: When does it appear?

There is now little doubt about the existence of the Unruh effect, that is, the fact that an accelerated detector, coupled to a field on its Minkowski vacuum state, would get excited as if immersed in a thermal bath of the field with temperature proportional to the acceleration. On the contrary, there is still some controversy on whether the detector would also emit particles of the field with the same thermal spectrum as a result of the acceleration, or at least on when this emission would happen. This effect is what is called Unruh radiation. Some authors claim that this kind of radiation would only appear during transient non-constant acceleration periods, or during the thermalization of the detector; but that, once reached a stationary equilibrium situation, this radiation would vanish. Other authors claim that considering a perfectly stationary (constant acceleration) trajectory is an idealization, and that, due to the back-reaction of the emission to the trajectory of the detector, the emission itself will be spread all over the now nearly-constant acceleration period. In this talk, I will review the main arguments on this topic, and introduce an heuristic way of understanding the phenomenon, that supports the second view.

Lucas Chibebe Céleri (Federal University of Goiás, Brazil)
The uncertainty principle in the presence of a quantum memory and the Unruh effect

Fabio Costa (University of Vienna, Austria)
Quantum Protocols with Indefinite Causal Order

In a classical, causal spacetime the causal relations between events are determined by the underlying metric. Extending the notion of quantum superposition to spacetime degrees of freedom makes it necessary to consider superpositions of different metrics, and thus of different causal relations. The consequences of such a possibility for quantum information processing will be analysed, showing that the notion of quantum circuit has to be necessarily extended to include superpositions of causal relations. A possible implementation for table-top experiments will be proposed, and the difference between such implementations and genuine “superpositions of spacetimes” will be discussed.

Emile Raymond Ferreira Taillebois (Universidade Federal de Goiás, Brazil)
A new view on spin reduced density matrix for relativistic particles

In this work we apply a new method to construct effective reduced density matrices of secondary variables for relativistic systems that is capable to reproduce the usual result obtained through the partial trace of momentum degrees of freedom and, beyond that, is able to reproduce results that were not explained using the original reduced states. The proposal is based on identifying the complementary set associated to the operator used as spin observable. The system that will be analyzed is a recent model were the violation of CHSH inequality was investigated using Stern-Gerlach measurements. We show that, using our proposal, correct reduced density matrices can be used to describe this system.

Mohamed Farouk Ghiti (University of Constantine 1, Algeria)
Pure states entanglement in non-commutative Bianchi universe

A new approach using Seiberg-Witten non-commutative geometry is applied for a Bianchi I universe. The entanglement of pure states quantified by the von--‐Neumann entropy and generated by the fermionic as well as bosonic modes is studied. The effect of the space-time non-commutativity is also discussed.

Lee Hodgkinson (University of Nottingham, UK)
Unruh-DeWitt detectors on the Schwarzschild black hole

We examine Unruh-DeWitt particle detector models on the Schwarzschild black hole in 3+1 dimensions. Unruh-DeWitt particle detectors are first introduced with a particular emphasis on the necessity of smoothly switching on (off) the detector coupling. On the Schwarzschild spacetime the detector is coupled to a massless scalar field and we examine how the response depends on the vacuum (Hartle-Hawking, Boulware, Unruh). The static, circular-geodesic and radial infall trajectories are considered in turn.

Dominic Hosler (University of Sheffield, UK)
Parameter estimation using NOON states over a relativistic quantum channel

We study the effect of communication with an accelerated observer on the parameter estimation of a quantum state. An inertial observer, Alice, prepares a parameterized state which she then sends to an accelerated observer, Rob, using Unruh modes of a quantum field. We calculate the Fisher information of the state Rob receives to find the amount of information he can extract about the parameter. We find the counter-intuitive result that the single rail encoding outperforms the dual rail. Using NOON states, there is an optimal N for maximum information extractable by Rob, contradicting the standard notion that a higher N performs better. This optimal N decreases with increasing noise.

Robert Johnson (University of Waterloo, Ontario, Canada)
Signalling between UdW-detectors: a) How amplitude modulation can be improved upon and b) why not too many cavity modes are needed to obtain causality effectively

We study signalling between Unruh-DeWitt detectors and report on two findings concerning the states Alice should choose to encode a message, and on causality violations from UV cutoffs. Firstly, we show that although the energy eigenstates (|e>,|g>) appear to be a natural choice for Alice to encode a message, they are actually the worst choice: For all other states the effect on Bob's final measurements are of second order in the coupling constant. The energy eigenstates are the only pure states, such that this effect is only of fourth order. Hence Alice should always use superposition states, like (|+>,|->), for encoding. Secondly, we address the question of causality violations arising from UV cutoffs in cavity QFT. We demonstrate that a UV cutoff leads to superluminal signalling. However, with increasing cutoffs these acausal effects are suppressed following a power law. Hence effective models considering only a finite, but sufficiently large number of field modes are always able to approximate causal behaviour within a given resolution.

Joel Lindkvist (Chalmers University of Technology, Göteborg, Sweden)
The twin paradox on-chip

We discuss a demonstration of the twin paradox using superconducting circuits. By using SQUIDs to modify the boundary conditions in a coplanar waveguide resonator, a relativistically moving cavity can be simulated. The idea is to prepare two cavities in identical ”clock states”. One of them is then taken on a ”twin paradox trajectory” while the other one stays inertial. Finally, the proper times elapsed in the two cavities are compared.

Matteo Lostaglio (Imperial College London, UK)
Scale Anomaly as the Origin of Time
(work in collaboration with Julian Barbour and Flavio Mercati)

We explore the problem of time in quantum gravity in a point-particle analogue model of scale-invariant gravity. If quantized after reduction to true degrees of freedom, it leads to a time-independent Schrodinger equation. As with the Wheeler--DeWitt equation, time disappears, and a frozen formalism that gives a static wavefunction on the space of possible shapes of the system is obtained. However, if one follows the Dirac procedure and quantizes by imposing constraints, the potential that ensures scale invariance gives rise to a conformal anomaly, and the scale invariance is broken. A behaviour closely analogous to renormalization-group (RG) flow results. The wavefunction acquires a dependence on the scale parameter of the RG flow. We interpret this as time evolution and obtain a novel solution of the problem of time in quantum gravity. We apply the general procedure to the three-body problem, showing how to fix a natural initial value condition, introducing the notion of complexity. We recover a time-dependent Schrodinger equation with a repulsive cosmological force in the `late-time' physics and we analyse the role of the scale invariant Planck constant. We suggest that several mechanisms presented in this model could be exploited in more general contexts.

Eduardo Martin-Martinez (University of Waterloo, Canada)
Experimental quantum gravity via RQI

Relativistic Quantum Information has managed to seize tools from quantum optics and information theory and use them to make quantum theory in general relativistic regimes experimentally accessible. For the first time we are able to propose experiments probing regimes that can only be described with general relativity and quantum theory. I will present several new results regarding how quantum optics and quantum information techniques lead to experimental implementations of gravitational quantum effects. From giving a feasible test of falsifiability to quantum gravity theories to being able to experimentally probe the structure of spacetime via the entanglement structure of the quantum vacuum, all without the need of going into space.

Gibran David Valdés Ramírez (Universidad Nacional Autónoma de México)
Numerical approach for quantum Lorentz transformations for massive particles of spin ½

We develop software capable of applying Lorentz transformations to spin ½ massive particles, in an arbitrary quantum momentum superposition. This facilitates and opens the way to study new cases outside the analytical so far, and thus widen the perspective on the field. We present a couple of paradigmatic, but simple, examples.

Veiko Palge (University of Leeds, UK)
Relativistic entanglement of Werner states

We will study the structure of maps that Lorentz boosts induce on the spin degree of freedom of spin-1/2 massive two particle systems. We assume that momenta are discrete and can be viewed as qubits while the spin state is described by the Werner state. Transformations on the spin state are then systematically investigated in various boost scenarios by calculating spin orbits and concurrence for different classes of product and entangled momenta. We find that the behavior of the spin state falls into seven classes. Visualisation of the evolution of the spin state explains the pattern of concurrence in all but one case. Also, this idealised model provides a basis of explanation to understand the phenomena in systems involving continuous momenta.

Igor Pikovski (University of Vienna, Austria)
Probing Planck-Scale Physics with Quantum Optics

One of the main challenges in physics today is to merge quantum theory and the theory of general relativity into a unified framework. Researchers are developing various approaches towards such a theory of quantum gravity, but a major hindrance is the lack of experimental evidence of quantum gravitational effects. Yet, the quantization of spacetime itself can have experimental implications: the existence of a minimal length scale is widely expected to result in a modification of the Heisenberg uncertainty relation. Here we introduce a scheme to experimentally test this conjecture by probing directly the canonical commutation relation of the centre-of-mass mode of a mechanical oscillator with a mass close to the Planck mass. Our protocol uses quantum optical control and readout of the mechanical system to probe possible deviations from the quantum commutation relation even at the Planck scale. We show that the scheme is within reach of current technology. It thus opens a feasible route for table-top experiments to explore possible quantum gravitational phenomena.

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Ida-Maria Svensson (Chalmers University of Technology, Göteborg, Sweden)
Photon Generation in a Doubly Tunable Resonator
(in collaboration with M. Pierre, M. Simoen, C. Wilson, G. Johansson, and P. Delsing)

By moving a perfectly reflecting mirror in vacuum with a speed comparable to the speed of light and a non-uniform acceleration, photons can be generated as excitations of vacuum fluctuations [1]. In a superconducting microwave circuit this moving mirror can be implemented as a variable boundary condition for the electromagnetic _field at the end of a transmission line. With superconducting technologies this can be done with a SQUID, superconducting quantum interference device [2, 3]. Here we investigate the relativistic motion of a superconducting cavity with one SQUID in each end, i.e. a doubly tunable resonator. Theoretically when the mirrors oscillate with different frequencies, the photon generation is simply the sum of the photon generation from the two individual mirrors. However when the mirrors move with the same frequency interference occur [4]. We have designed and fabricated a circuit where we can address the two boundary conditions individually. If the two mirrors are assigned the same oscillation frequency but with a phase difference we can create both a breathing mode, where the length of the cavity is modulated, and a translational mode, where the cavity is translated in space. Our measurements show that an interference pattern can be obtained in agreement with theory. This setup is interesting as a base for on-earth-experiments on relativistic effects.

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Ardiley Torres Avelar (Universidade Federal de Goiás, Brazil)
Influence of the complementary set on the violation of CHSH inequality

We present a new interpretation for reduced density matrices of secondary variables in relativistic systems via an analysis of Wigner's method to construct the irreducible unitary representations of the Poincaré group. We argue that the usual partial trace method used to obtain spin reduced matrices is not fully rigorous, however, employing our interpretation, similar effective reduced density matrices can be constructed. In addition, we show that our proposal is more useful than the usual one since we are not restricted only to the reduced density matrices that could be obtained by the ordinary partial trace method.

Sonali Warriar (University of Nottingham, UK)
Towards an Ultracold Bose-Fermi Mixture of Cesium and Lithium

Ultracold mixtures hold the promise of understanding new phases of matter at very low energies. These systems are well suited to study impurities, transport and inter-species collisional properties. In this talk, I will present the current status of a Bose-Fermi mixture experiment at the University of Nottingham with Cesium-133 and Lithium-6. I will focus on the cooling schemes for the two atom species and include the recent development of implementing an optical dipole trap. We will show that a system of a Cesium BEC with Lithium impurities is well suited to test predictions in the RQI regime. The favourable interaction properties of these two species make it possible to switch interspecies interactions on and off quickly while leaving the intra-species interactions constant. I will discuss future experiments where this feature will be exploited, using Li impurities as temperature sensors or creating entanglement between far distant impurities.