# Relativistic Quantum Information Workshop

# RQI-N 2011

Instituto de Física Fundamental
Consejo Superior de Investigaciones Científicas
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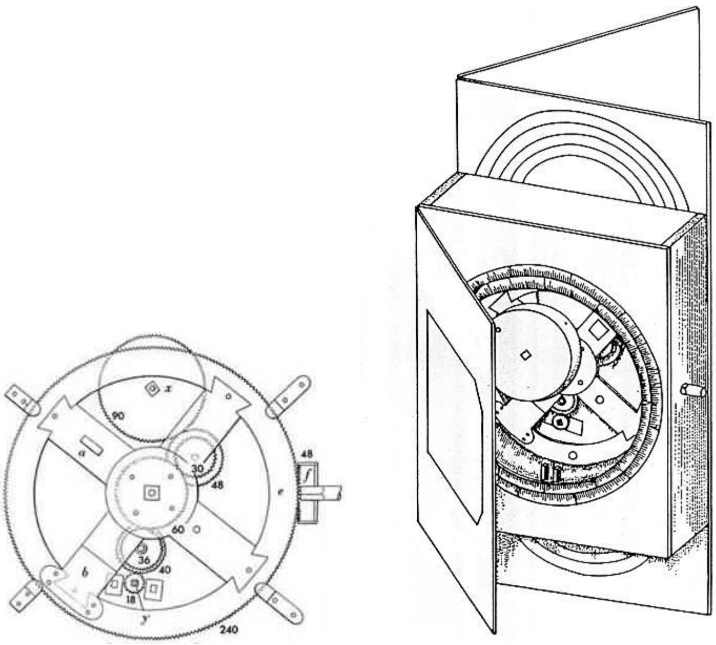
## Book of abstracts



## Spacetime could be simultaneously continuous and discrete, in the same way that information can be simultaneously continuous and discrete.

## (Invited talk)

**Achim Kempf**

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Information theory on curved space ultimately depends on the physics of the Planck scale since at that scale a kind of overall bandlimitation can be expected to set in. This talk addresses the possibility that, because of this bandlimitation, spacetime is simultaneously both continuous and discrete, in the same mathematical way that information can be simultaneously continuous and discrete. The underlying mathematical structure is that of Shannon sampling theory and we discuss how, in the quantum context, the sampling of signals could be replaced by Unruh-DeWitt detector measurements of fields. To handle curvature, new methods of spectral geometry ("Can one hear the shape of a drum?") are developed.

## Entanglement amplification via the Unruh and Hawking effects

**Miguel Montero** and **Eduardo Martín-Martínez**

*Instituto de Física Fundamental, Consejo Superior de Investigaciones Científicas. Madrid, Spain*

Previous works in relativistic quantum information found that starting with a bipartite entangled field state from an inertial perspective, we end up with a less entangled state when one of the parties is non-inertial. This talk will show that going beyond the single mode approximation there are some states whose degree of entanglement increases with acceleration. We will show examples of these states for fields of spin 0, 1/2, and 1. We will also discuss the connection of these results with experimental or analog settings trying to probe or simulate quantum effects due to gravity.

## The importance of being fermion

**Eduardo Martín-Martínez**

*Instituto de Física Fundamental, Consejo Superior de Investigaciones Científicas. Madrid, Spain*

In the field of Relativistic Quantum Information and in the last 8 years, huge differences between bosonic and fermionic entanglement in non-inertial frames and in curved spacetimes have been found. This striking differences extend from entanglement behaviour from accelerated frames to the expansion of the Universe and stellar collapse. Fermions behave in a most non-intuitive way. I will present some results regarding these differences, their posible origin and the way in which one can take advantage of them to extract information about the underlying spacetime.

# Residual entanglement of of accelerated fermions is not nonlocal

**Nicolai Friis**[1], **Philipp Köhler**[2], **Eduardo Martín-Martínez**[3], **Reinhold A. Bertlmann**[2]

[1] *School of Mathematical Sciences, University of Nottingham, University Park, Nottingham NG7 2RD, United Kingdom*
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We analyze the operational meaning of the residual entanglement in non-inertial fermionic systems in terms of the achievable violation of the CHSH inequality. We demonstrate that the quantum correlations of fermions, which were previously found to survive in the infinite acceleration limit, cannot be considered to be non-local. The entanglement shared by an inertial and an accelerated observer cannot be utilized for the violation of the CHSH inequality independently of the strength of the acceleration for most of the states. Our results are shown to extend beyond the single mode approximation commonly used in the literature.

# Voyage to Alpha Centauri: Entanglement degradation of cavity modes due to motion

**David Edward Bruschi, Ivette Fuentes and Jorma Louko**

*School of Mathematical Sciences, University of Nottingham, University Park, Nottingham NG7 2RD, United Kingdom*

We investigate the behavior of entanglement, contained in a maximally entangled state of uncharged scalar fields confined in Dirichlet boxes in 1+1 D, shared by inertial Alice and "arbitrarily" moving Rob. We provide the techniques to compute the negativity. We show that the entanglement is always periodic as a function of any of the times Rob spends accelerating or inertially coasting in his trip thorough the Cosmos. In the case of a trip to Alpha Centauri, one can finetune the dffierent times of acceleration, coast and brake such that in the leading order in acceleration there is NO degradation of entanglement during the whole journey. We discuss these results and applications for space based experiments.

# Optics in non-stationary media: from Hawking radiation to the dynamical Casimir effect

## (Invited talk)

**Daniele Faccio**

*School of Engineering and Physical Sciences, SUPA, Heriot-Watt University, Edinburgh EH14 4AS, United Kingdom*

Recent developments in laser pulse synthesis have opened the possibility to study how light behaves and is transformed in the presence of non-stationary media. Of particular interest is the possibility to observe light amplification. The aim of the talk is to give an overview of these processes and to describe recent experimental and numerical results. We will consider two specific cases in which non-stationarity and amplification can be obtained by means of an intense laser pulse that couples to the medium through the nonlinear Kerr effect and thus creates a variation in the refractive index. In the first example, we generate a travelling refractive index perturbation that moves within a dielectric medium. If the perturbation moves at speeds close to the speed of light, then the analogue of a black or white hole horizon is formed and various fascinating effects may be observed such as the generation of negative frequencies or even the excitation of photons from the vacuum state in a process analogous to Hawking emission. Both experimental and numerical results will be described. In the second example we discuss the effect of a periodic modulation of the medium contained within an optical cavity. Photons are excited out of the vacuum state and an initial seed pulse may be strongly amplified or frequency converted in a process that bears a strong resemblance to the dynamical Casimir effect. Numerical results will be described and planned experiments will be analysed.

# Generating entanglement between massive Bosonic cavity modes in non-inertial frames

**Antony Lee, Andrzej Dragan and Ivette Fuentes**

*School of Mathematical Sciences, University of Nottingham, University Park, Nottingham NG7 2RD, United Kingdom*

We show how to generate entanglement between massive Bosonic cavity modes when one cavity is inertial and the other is in uniform acceleration. We find that both the acceleration of the cavity and the mass of the field decrease our ability of generating entanglement. A method of adjusting the set up such that it is always possible to create maximally entangled states will be discussed.

## From Zeno to Fermi: probing QFT with circuit QED

**Carlos Sabín, Marco del Rey, Juan José García-Ripoll, Juan León.**

*Instituto de Física Fundamental, Consejo Superior de Investigaciones Científicas. Madrid, Spain*

In this talk we will address mainly the so-called Fermi problem [1], which presents an ideal configuration with two separate atoms in free space and was originally proposed by Fermi in order to check causality in quantum fields. However, if proper analysis is carried on, fundamental quantum theory questions arise due to the interplay between causal signaling and quantum non-local phenomena. Indeed, we will show that a correct understanding of non- locality [4] and ground state self-excitations [5] is required. These issues led to a controversial debate, whose conclusions were never put to experimental test. We propose a possible circuit QED setup [2], as a 1-D feasible version of the gedanken experiment using two superconducting qubits. We also complete former descriptions of the problem by providing a general non-perturbative proof of strict causality, showing that the probability of excitation of a two-level artificial atom with a dipolar coupling to a quantum field is completely independent of the other qubit until signals from it may arrive. By treating causality and non-local correlations at the same level in the formalism, we show our analysis is in perfect agreement with previous results [3] which were used to claim apparent causality problems for the Fermi two-atom system.

[1] E. Fermi, Rev. Mod. Phys. 4, 87 (1932)
[2] C. Sabín, M. del Rey, J.J. García-Ripoll, J. León, arXiv: 1103.4129 [quant-ph]
[3] G. C. Hegerfeldt, Phys. Rev. Lett . 72, 596 (1994)
[4] C. Sabín, J. J. García-Ripoll, E. Solano and J. León, Phys. Rev. B 81,184501 (2010)
[5] C. Sabín, J. León, J. J. García-Ripoll, Phys. Rev. B 84, 024516 (2011)

# Entanglement in (Loop) Quantum Gravity's Black Hole Models.

## (Invited talk)

**Etera Livine** [1,2]

[1] *Laboratoire de Physique, ENS Lyon, CNRS-UMR 5672, 46 Allée d'Italie, Lyon 69007, France*

[2] *Perimeter Institute, 31 Caroline St N, Waterloo ON, Canada N2L 2Y5*

In a completely-background independent framework for quantum gravity, one must necessarly use the notion of correlations and entanglement to localize events and quantum information becomes essential in reconstructing the space-time geometry. I will discuss this point from the perspective of loop quantum gravity and spinfoam histories and illustrate it by formulating in quantum information terms the entropy and evaporation of quantum black hole in some simple models. This shows how tools developed in quantum information and quantum computing become highly relevant and useful in the context of quantum gravity.

## Spin operator for a relativistic Stern-Gerlach measurement

**Matthew Palmer, Maki Takahashi and Hans Westman**

*School of Physics, The University of Sydney, Sydney NSW 2006, Australia*

We present a model of a spin measurement for a relativistic fermion passing through a Stern- Gerlach device. Our starting point will be the Dirac equation minimally coupled to the electromagnetic field. Analyzing this in the WKB limit, we derive the spin-operator for a Stern- Gerlach measurement. This operator depends not only on the direction of the Stern-Gerlach device but also on the velocity of the fermion relative to the Stern-Gerlach device. We find that in the relativistic domain the direction of spin measured does not in general correspond to the direction of the Stern-Gerlach device. We compare this result to the existing proposals of a relativistic spin operator.

# Timelike teleportation

**Andrzej Dragan**, **Gerardo Adesso**, **Ivette Fuentes**

*School of Mathematical Sciences, University of Nottingham, University Park, Nottingham NG7 2RD, United Kingdom*

The vacuum state of a quantum field is entangled. It has previously been shown that two point-like detectors moving in flat spacetime can extract time-like and space-like vacuum entanglement when coupled to the field. In this talk we show how timelike entanglement can be used as a resource to transmit information between a detector in the past an another in the future.

## Quantum holonomy in spacetime

**Jason Doukas**

*Yukawa Institute for Theoretical Physics, Kyoto University Kyoto, 606-8502, Japan*

In this talk I will survey some recent attempts to understand spacetime effects of the quantum spin of single particle states in the context of EPR type experiments and show how these attempts are related to notions of spacetime phase-holonomy.

# Relativity, Quantum Theory, Information and Cryptography.

## (Invited talk)

**Adrian Kent** [1,2]

[1] *Centre for Mathematical Sciences, University of Cambridge, Wilberforce Road, Cambridge, U.K.*
[2] *Perimeter Institute for Theoretical Physics, Waterloo, Canada*

Special relativity and quantum theory both provide strong constraints on information communication and processing. This allows us to find interesting information processing tasks that essentially distinguish relativistic quantum theory from either non-relativistic quantum theory or relativistic classical theories. In particular, relativistic quantum cryptography is now clearly established as a distinct field from standard (non-relativistic) quantum cryptography: we have a respectable and growing list of intriguing and practical cryptographic applications that rely essentially on the properties of relativistic quantum theory. In this talk I review these developments, focussing in particular on the no-summoning theorem – a relativistic quantum analogue of the no-cloning theorem – and its application to the cryptographic task of bit commitment.

## Optimal Quantum Estimation of the Space-Time Metric

**T.G.Downes**[1] and **G.J.Milburn**[2]

[1] *School of Maths and Physics, The University of Queensland, Australia*
[2] *Department of Physics The University of Queensland, Australia*

We write down for the first time the optimal quantum Cramer-Rao lower bound for any parameter describing a metric for space-time. Four key examples are demonstrated covering a broad range of relativistic phenomena. We describe quantum-limited estimation of the mass of a black hole, the acceleration of a uniformly accelerating observer, the amplitude of a gravitational wave and the expansion parameter in a cosmological model. The standard time-energy uncertainty relation and the Heisenberg uncertainty relation are special cases of our space-time uncertainty relation. In agreement with earlier work by Unruh, our uncertainty relation takes a particularly simple and revealing form, when the measurement region is made sufficiently small. We use the locally covariant formulation of quantum field theory in curved space-time, which allows for a manifestly covariant derivation. The result is an uncertainty relation applicable to all causal space-time manifolds.

## Probing the canonical commutator of massive mechanical oscillators

**Igor Pikovski**[1], **Michael Vanner**[2], **Markus Aspelmeyer**[1], **Myungshik Kim**[2], **Caslav Brukner**[1]

[1] *Faculty of Physics, University of Vienna, Austria*
[2] *Faculty of Science, Imperial College, London, UK*

While the canonical commutation relation is one of the main cornerstones of quantum mechanics,in many theories of quantum gravity the commutator acquires a small modification. Such modifications remain outside the reach of quantum experiments as of yet. Here we show how the commutation relation of a massive mechanical oscillator can be probed using pulsed opto-mechanical systems. With the mass of the oscillator being close to the Planck mass, we show that certain theories of quantum gravity that predict a deformation of the commutation relation can be tested. The proposed setup thus allows to distinguish between the classical, quantum and even quantum gravitational regimes.

## Unruh effect without entanglement

**Carlo Rovelli and Matteo Smerlak**

*Centre de Physique Théorique, Luminy, France*

We estimate the transition rates of a uniformly accelerated Unruh-DeWitt detector coupled to a quantum field with reflecting conditions on a boundary plane (a mirror). We find that these are essentially indistinguishable from the usual Unruh rates, viz. that the Unruh effect persists in the presence of the mirror. This shows that the Unruh effect is not merely a consequence of the entanglement between left and right Rindler quanta in the Minkowski vacuum. Since in this setup the state of the field in the Rindler wedge is pure, we argue furthermore that the relevant entropy in the Unruh effect cannot be the von Neumann entanglement entropy. We suggest, in alternative, that it is the Shannon entropy associated with Heisenberg uncertainty.

# Photon location in spacetime

**Margaret Hawton**

*Physics Department, Lakehead University, Thunder Bay, Canada*

The NewtonWigner basis of orthonormal localized states is generalized to a family of localized photon bases on all hyperplanes in spacetime. This covariant formalism is applied to a hypothetical spacelike probability density measurement using a 3D pixel array throughout space and a timelike measurement using a 2D photon counting array detector with good time resolution. A moving observer will see the spacelike and timelike experiments as rotated in spacetime but the spacelike and timelike experiments remain distinct.

# Quantum Theory in Space of Probabilistic Theories (Invited talk)

**Caslav Brukner**

*Faculty of Physics, University of Vienna, Austria*

Quantum theory makes the most accurate empirical predictions and yet it lacks simple, comprehensible physical principles from which the theory can be uniquely derived. Attempts at principle-based reconstructions of quantum theory are motivated by our wish (1) to extract the meaning of the theory, along with extracting the formalism, in the course of a derivation of the theory from some deeper physical principles, (2) to see quantum theory as an instance of generalized probabilistic theories that arise when one or more principles are relaxed, and then to contrast the alternatives in experiments , (3) to find formulation of quantum theory, which is more conductive for merging it with general relativity. I will first show that quantum theory can be reconstructed from three reasonable axioms: (1) (Information capacity) All systems with information carrying capacity of one bit are equivalent. (2) (Locality) The state of a composite system is completely determined by measurements on its subsystems. (3) (Reversibility) Between any two pure states there exists a continuous reversible transformation. Then I will discuss the reconstruction in the view of points (1-3).

## Quantum interferometric visibility as a witness of general relativistic proper time

Magdalena Zych, Fabio Costa, Igor Pikovski, Caslav Brukner

*Faculty of Physics, University of Vienna, Austria*

Current attempts to probe general relativistic effects in quantum mechanics focus on precision measurements of phase shifts in matter-wave interferometry. Yet, phase shifts can always be explained by an Aharonov-Bohm effect, where a particle in a flat space-time is subject to an effective potential. We propose a novel quantum effect that cannot be explained without the general relativistic notion of proper time. We consider interference of a "clock" - a particle with evolving internal degrees of freedom - that will not only display a phase shift, but also reduce the visibility of the interference pattern to the extent to which the path information becomes available from reading out the proper time from the "clock". Such a gravitationally induced decoherence would provide the first test of a genuine general relativistic effect in quantum mechanics.

# Quantum Correlations with no Causal Order

**Ognyan Oreshkov**[1], **Fabio Costa**[2], **Caslav Brukner**[2]

[1] *Ecole Polytechnique, Université Libre de Bruxelles, Belgium*
[2] *Faculty of Physics, University of Vienna, Austria*

Much of the recent progress in understanding quantum theory has been achieved within an operational approach. Within this context quantum mechanics is viewed as a theory for making probabilistic predictions for measurement outcomes following specified preparations. However, thus far essential elements of the theory — space, time and causal structure — elude this operational formulation and are assumed to be fixed. Is it possible to extend the operational approach to quantum mechanics such that the notions of an underlying space-time or causal structure are not assumed? What new phenomenology can follow from such an approach? We develop a framework for multipartite quantum correlations that does not presume these notions, but simply that experimenters in their local laboratories can perform arbitrary quantum operations. All known situations that respect definite causal order, including signalling and no-signalling correlations between time-like and space-like separated experiments respectively, as well as probabilistic mixtures of these, can be expressed in this framework. Remarkably, we find situation where two experiments are neither causally ordered nor in a probabilistic mixture of definite causal orders. These correlations are shown to violate a causal inequality, enabling a communication task that is impossible if the operations are ordered according to a fixed background time. However, we show that classical correlations are always causally ordered, which suggests a deep connection between definite causal structures and classicality.

# Time in relativistic quantum information (Invited talk)

Timothy C. Ralph[1], S. Jay Olson[1], Casey Myers[1], and Jacques Pienaar[2,3]

[1] *Paculty of Science, University of Queensland, Brisbane, Australia*
[2] *Centre for Mathematical Sciences, University of Cambridge, Cambridge, U.K.*
[3]*Perimeter Institute for Theoretical Physics, Waterloo, Canada.*

The role of time in relativistic quantum information science is attracting increasing interest. I will discuss two new results: entanglement between the future and the past; and progress towards a consistent quantum field theory for closed timelike curves.

It is known that the quantum vacuum of flat space is entangled between spacelike separated regions. This is the basis of the Unruh effect [1] in which accelerated observers see thermalization of the vacuum due to this entanglement. We have recently shown that vacuum entanglement also exists between timelike regions of space time, i.e. between the past and the future [2]. We will describe how this entanglement can be efficiently extracted via stationary detectors with scaled energy levels [3] and discuss applications.

Closed timelike curves, i.e. time machine to the past, are allowed by exotic solutions of general relativity but are incompatible with quantum field theory. A consistent treatment of qubits interacting with CTC??s exists [4], but it is not a field theory. We describe a non-standard quantum field theory [5] and prove that it reduces to ref. [4] in the limit of point like 2-level systems [6]. We investigate the behaviour of this theory for different field states and simple CTC interactions.

[1] W.G. Unruh, Phys. Rev. D 14, 870 (1976)
[2] S.J. Olson and T.C. Ralph, Phys. Rev. Lett. 106, 110404 (2011)
[3] S.J. Olson, T.C. Ralph, arXiv:1101.2565 (2011)
[4] D. Deutsch, Phys. Rev. D 44, 3197 (1991)
[5] T.C. Ralph, G.J. Milburn, and T. Downes, Phys. Rev. A 79, 022121 (2009)
[6] T.C. Ralph and C.R. Myers, Phys. Rev. A 82, 062330 (2010)

# Beamsplitter interaction of a photon with its future self

**Jacques Pienaar**[1,2], **Casey Myers**[3], **Timothy C. Ralph**[3]

[1] *Centre for Mathematical Sciences, University of Cambridge, Cambridge, U.K.*
[2] *Perimeter Institute for Theoretical Physics, Waterloo, Canada*
[3] *Faculty of Science, University of Queensland, Brisbane, Australia*

Time travel in physics has a long history, culminating in a 1991 paper by Deutsch revealing a consistent and paradox-free model of quantum evolution for a single qubit on a closed time-like curve (CTC). We extend Deutsch??s model to quantum fields and calculate what happens in theory when a photon travels back in time to interact with itself on a beamsplitter.

# Short-time quantum detection: probing quantum fluctuations

**Marco del Rey, Carlos Sabín, and Juan León**

*Instituto de Física Fundamental, Consejo Superior de Investigaciones Científicas. Madrid, Spain*

In the framework of Quantum Field Theory, detector models preserving causality include interaction terms in the Hamiltonian which account for self-excitations of the detector when at rest in the vacuum. This spontaneous absorption associated with the vacuum field is claimed by many to be unphysical, although it is restricted to very short times and it has never been within reach of experimental physics. In this work we present a possible setup in the framework of circuit QED where such effects could, in principle, be measured. In particular we focus on the information provided by a detector regarding a possible de-excitation of a source in terms of conditional probabilities evolving with time. We find that no practical information can be extracted for very short times.

# Relativity, Quantum Theory, Information and Cryptography.

# (Invited talk)

**Péter Lévay**

*Department of Theoretical Physics, Budapest University of Technology and Economics. Budapest, Hungary*

Recently striking multiple relationships have been established between two seemingly unrelated fields, the physics of extremal black holes in string theory and the physics of simple entangled systems. The main correspondence is between the black hole entropy formulas obtained within the framework of string theory and certain multipartite entanglement measures well-known in quantum information theory. In this talk after reviewing the basic results, by using IIB string theory we trace back the origin of this black hole-qubit correspondence to the geometric properties of the extra dimensions that are compactified.

# Dynamics of entanglement between an inertial and a non-uniformly accelerated detector

**David C. M. Ostapchuk**[1], **Shih-Yuin Lin**[2], **Robert B. Mann**[1], **Bei-LokHu**[3]

[1] *Department of Physics and Astronomy, University of Waterloo, Canada*
[2] *National Changhua University of Education, Taiwan*
[3] *University of Maryland, Maryland, USA*

In the framework of Quantum Field Theory, detector models preserving causality include interaction terms in the Hamiltonian which account for self-excitations of the detector when at rest in the vacuum. This spontaneous absorption associated with the vacuum field is claimed by many to be unphysical, although it is restricted to very short times and it has never been within reach of experimental physics. In this work we present a possible setup in the framework of circuit QED where such effects could, in principle, be measured. In particular we focus on the information provided by a detector regarding a possible de-excitation of a source in terms of conditional probabilities evolving with time. We find that no practical information can be extracted for very short times.

## Quantum Key Distribution with an Accelerating Partner

**T. G. Downes, N. Walk and T. C. Ralph**

*Faculty of Science, University of Queensland, Brisbane, Australia*

We present a method for analyzing quantum information processes between localized accelerating observers, which does not rely on approximation methods, such as Unruh modes or perturbation theory. The explicit localization of all our operators allows for the analysis of a larger range of physics, including time-dependent effects. This also represents a significant step forward in the realism of the quantum information protocols under analysis. We apply this technique to quantify a continuous variable quantum key distribution protocol between the two observers. Finally we highlight some differences between the detection used here (homodyne detection) and the commonly encountered Unruh-DeWitt detector.

## Hawking radiation as perceived by different observers

**Luis J. Garay**[1]

[1] *Faculty of Physics, Universidad Complutense de Madrid, Madrid, Spain*

We analyse Hawking radiation in a Schwarzschild black hole as perceived by different observers in the system.The method we use is based on the introduction of an effective temperature function that varies with time. First we introduce a non-stationary vacuum state for a quantum scalar field, which interpolates between the Boulware vacuum state at early times and the Unruh vacuum state at late times. In this way we mimic the process of switching on Hawking radiation in realistic collapse scenarios. Then, we analyse this vacuum state from the perspective of static observers at different radial positions, observers undergoing a free-fall trajectory from infinity and observers standing at rest at a radial distance and then released to fall freely towards the horizon. The physical image that emerges from these analyses is rather rich and compelling. Among many other results, we find that generic freely-falling observers do not perceive vacuum when crossing the horizon, but an effective temperature a few times larger than the one that they perceived when it started to free-fall. We explain this phenomenon as due to a diverging Doppler effect at horizon crossing.

## Localized qubits in curved spacetime from the WKB limit

**Matthew C. Palmer, Maki Takahashi and Hans F. Westman**

*School of Physics, The University of Sydney, Sydney NSW 2006, Australia*

I present a way to obtain spatially localised qubits from the Dirac or Maxwell field equations in curved spacetime (CST) via the WKB approximation. This yields a simple manifestation of qubits from field theory in CST. Transport of the fermion or photon qubits along trajectories in CST can be computed, revealing a gravitationally induced evolution of the quantum state. We obtain spin and polarization transport equations which can be used to compute corresponding Wigner rotations. However, a benefit of the presented approach is that the spin, polarization, and transport equations are Lorentz covariant, allowing for straightforward manipulation and interpretation of qubits in CSTs.

# Probing a quantum field by a non-stationary detector (Invited talk)

**Jorma Louko**

*School of Physics, University of Nottingham, Nottingham, United Kingdom*

The concept of a particle in Minkowski space quantum field theory is tied mathematically to Poincare invariance and physically to inertial observers. The concept becomes more subtle with more general observer motions or more general spacetimes: a celebrated consequence is black hole evaporation. This talk discusses pointlike particle detectors as a tool of extracting information about the quantum field in such situations. We shall in particular discuss how nonstationarity due to the detector trajectory or to the quantum state can be isolated from transient switch-on and switch-off effects.

## Polarized photon qubits in curved space-time

**Aharon Brodutch** and **Daniel Terno**

*Department of Physics and Astronomy, Macquarie University, Sydney, Australia*

The polarization degree of freedom is frequently used to encode qubits. Polarization rotation is operationally meaningful only with respect to local measurement bases. Gravitational field may cause photon polarization to rotate. These rotations which are sometimes called the gravimagnetic effect usually depend on the trajectories. For a stationary spacetime we construct local, path independent, physically motivated reference frames which can be used to set up the measurement apparatus. Using these frames one can isolate the gravimagnetic effects (such as those caused by Kerr's black hole spin) by gauging out the geodetic terms (those that are caused by the mass). From a different perspective, the net polarization rotation results from a combination of Machian and geometric terms that lead to a gauge-independent phase for closed trajectories. We find polarization rotation to be more significant than is usually believed, indicating that it may serve as the basis for future gravity probes.

## Quantum optical analogs of accelerated emitters

**M. del Rey**[1], **E. Martn-Martinez**[1], **D. Porras**[2]

[1] *Instituto de Física Fundamental, Consejo Superior de Investigaciones Científicas. Madrid, Spain*
[2] *Faculty of Physics, Universidad Complutense de Madrid, Madrid, Spain*

Quantum optical analogs of the Unruh effect and the physics of accelerated emitters in general relativity may appear quite naturally in experimental systems subjected to time-dependent drivings. In this work, we present how to implement those ideas with trapped ions and artificial atoms coupled to cavities in circuit QED. In particular, by studying ensembles of emitters, experiments could enter the regime of quantum many-body physics.

Whereas most previous proposals have focused on the modulation of quantum field frequencies

to implement analogies with general relativity, we consider only the interaction of emitters with time-dependent forces. As a result, the effective couplings between emitters and quantum fields induce the quantum dynamics of a set of accelerated particles. Our work has an exciting outlook, since it provides us with a toolbox to implement analogs of collective effects, dissipation and back- action in the framework of General Relativity.

In the case of trapped ions, the physical implementations that we propose rely on using an electronic transition to simulate the two-level system, and a vibrational mode to implement a quantum field. Analogs in solid-state setups, such as circuit QED would imply using different flux states of a superconducting artificial atom, and a microwave cavity to host the quantum field. Our analogy also reveals the relation of the physics of accelerated emitters with Landau-Zener dynamics, and non-equilibrium related phenomena in Condensed-Matter physics.

## How to send quantum messages across spacetime (Invited talk)

**Gerardo Adesso**

*School of Physics, University of Nottingham, Nottingham, United Kingdom*

The toolbox of quantum optics and continuous variable quantum information is proving to be extremely fruitful for applications in relativistic contexts. The striking analogy between the Unruh and Hawking effects and the action of an optical amplification channel, for instance, enables one to exploit a number of techniques from entanglement theory and the description of Gaussian quantum channels to achieve a better grasp, and possibly to develop optimised detection schemes, for those fundamental quantum field theory effects. In this talk, after providing an overview of these techniques and a guided tour of some seminal applications in the relatistic quantum information context, I will focus on quantum communication. Protocols to transmit quantum states between spacelike and/or timelike distant observers, as mediated by a quantum field in the vacuum, will be investigated. Beyond conventional quantum teleportation, which is indeed implementable in spacetime, a novel scheme to beam quantum states perfectly and virtually anywhen in the future, without the need for any feedforward of classical stored data, is introduced and discussed.

## The causal and the quantum

**Bob Coecke** and **Raymond Lal**

*University of Oxford, Department of Computer Science, Quantum Group, Oxford, United Kingdom*

First we expose an inconsistency between (1) the symmetries of relativistic causal structure, and (2) agents interacting via probabilistic devices: for (1), time-reversal does not introduce the ability to signal for spacelike separated agents, while for (2) it may create a perfect channel. This leads to a new arrow of time, and shows that the traditional conception of causal structure as partial orders (e.g. Penrose-Kronheimer, Zeeman, Malament) cannot be retained. The remainder of the talk will consist of efforts to unveil the bare structural bones of a universe consisting of relativistically interacting quantum processes, drawing from our own work in categorical quantum mechanics and other recent work in quantum foundations (e.g. Hardy, D'Ariano-Chiribella- Perinotti).

## The Unruh effect for non-uniform acceleration

**Paul M. Alsing**

*Information Directorate, Air Force Research Laboratory, Rome, New York, USA*

In its simplest form, the Unruh effect states that the power spectrum for a scalar plane wave mode in an inertial (Minkowski) spacetime is thermal at negative frequencies when observed from the frame of a uniformly accelerated observer. In this talk I present a 2-parameter class of coordinates which smoothly transforms between inertial and uniform accelerated trajectories in Minkowski spacetime, and (i) compute the Bogolyubov coefficients (BC) for these non-uniformly accelerated motions and (ii) discuss the non-Planckian aspects of the negative frequency BCs for these trajectories.