Experimental Search for Quantum Gravity

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Book of Abstracts

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Gravity in the quantum lab

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

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Moduli and a Cosmic Axion Background

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Heavy Planck-coupled scalar particles (moduli) arise generically in any higher-dimensional theory of gravity, descending from the additional modes of the graviton. In the early universe, such moduli can come to dominate the energy density of the universe before decaying. Their decays can access all gravitationally coupled hidden sectors, and can lead to a relic Cosmic Axion Background as a dark counterpart of the CMB. Such a Cosmic Axion Background may exist today at X-ray energies, and may be visible through back-conversion of axions to photons in galaxy cluster magnetic field to explain the long-standing cluster soft excess.

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Loop quantum cosmology

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I will review different approaches to loop quantum cosmology and show which results are reliable in this framework and which are still debated. I will underline that some very specific approaches to loop quantum cosmology are already excluded by the data. I will conclude by some remarks about black holes.

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Quantum gravity effects on the Higgs-Yukawa sector of the Standard Model

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After an introduction of the relevant aspects of asymptotically safe quantum gravity, I will focus on first results towards understanding its effects on the Higgs-Yukawa sector of the Standard Model. I will highlight how asymptotically safe quantum gravity can allow us to make predictions about the structure of the matter sector. For instance, exploiting the predictive power of the asymptotic-safety paradigm might allow us to explain the structure of the Higgs-Yukawa sector of the Standard Model. In particular, the asymptotic-safety paradigm could provide a mechanism that generates the difference between the fermion masses.

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A partially ordered introduction to Causal Set theory

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In causal set theory, space-time is reduced to a partially ordered set. The only remaining structure are causal curves, and discrete events. On first glance this seems to be very little structure to encode an entire universe, but on closer examination it reveals a rich structure. Recent work in the theory has given rise to proposals of Lorentz invariant non-local phenomenology.

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Welcome

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Analogue Gravity, motivations and achievements.

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We review the various motivations behind this undertaking, and their link with open questions concerning quantum gravity. We also present the relationship between analog gravity and theories of modified gravity, such as Einstein-aether and Horava gravity. We discuss some recent experiments aiming at observing the analogue version of Hawking radiation in its stimulated (classical) or spontaneous (quantum) version.

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Planck stars: Fast Radio Bursts and High Energy Cosmic rays as quantum gravity phenomena.

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A potentially observable quantum gravity phenomenon is the decay of black holes via a quantum gravitational tunneling akin to standard nuclear decay. Loop quantum gravity can be used to compute the corresponding lifetime. This could be much shorter than the Hawking radiation time, rendering the effect astrophysically relevant. Preliminary estimates indicate that centimeter-size primordial black holes should be exploding today and predict impulsive high energy as well as microwave signals tantalizing similar to the Fast Radio Bursts recently observed by the Areceibo and Parkes radio telescopes. The predicted signal has a characteristic distance/frequency relation which will allow to test the Planck star hypotheses in the near future.

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Quantum Gravity Phenomenology with Primordial Black Holes

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Quantum gravity may allow black holes to decay into white holes. If so, the lifetime of a black hole would be shorter than the one given by Hawking evaporation, avoiding the information paradox. This could open to a new window for quantum-gravity phenomenology, in connection with the existence of primordial black holes. I discuss the possibility to observe an astrophysical emission from the explosion of primordial black hole in the radio and in the gamma wavelengths. Those emissions can be discriminated from other astrophysical sources because of the peculiar way the emitted wavelength scales with the distance. In particular, the spectrum of the diffuse radiation produced by those objects presents a distortion due to this scaling. I will briefly overview the ongoing research to understand the possible consequences of such a dark matter component in cosmology.

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Status of in-vacuo-dispersion studies

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I offer my perspective on the status of studies of quantum-gravity-induced in-vacuo dispersion. For photons this has been studied for nearly 20 years and presently there is some tension between upper bounds obtained relying on apparently robust/weak assumption and a regularity exposed by the the work of Bo-Qiang Ma and collaborators. It is now possible to start doing the same studies for neutrinos, and work by my group showed that presently available IceCube data, while inconclusive, preliminarily favor in-vacuo dispersion.

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Neutrino as a probe for Quantum Gravity

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Neutrinos qualify as a perfect probe for quantum gravity as they are unique in various ways: -Neutrino masses are often understood as a consequence of the breaking of lepton number. Such global symmetries are usually expected to be broken by quantum gravity effects. -Standard Model singlets such as sterile neutrinos may probe extra dimensions of spacetime arising naturally for example in string theory. -Due to their weak interactions neutrinos maintain quantum coherence over extreme distances and energy ranges. Moreover, neutrino propagation and oscillation has been probed by experiments from the MeV to the PeV and from the meter to extra-galactic scales. This puts neutrinos in a prime position to search for unitarity or Lorentz violating effects often predicted in quantum gravity. In summary probing lepton number violation, extra dimensions, Lorentz and unitarity violations with neutrinos thus may also have important implications for the search of quantum gravity. An overview of neutrinos as probes for quantum gravity is given and the experimental status of the various frontiers is discussed.

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Theoretical Physics Implications of the Advanced LIGO Gravitational Wave Observation

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The recent gravitational-wave observations by Advanced LIGO provided the first opportunity to learn about theoretical physics mechanisms that may be present in the extreme gravity environment of coalescing binary black holes. The LIGO-Virgo collaboration verified that this observation is consistent with Einstein's theory of General Relativity and the Kerr hypothesis, constraining the presence of parametric anomalies in the signal. In this talk, I will discuss the plethora of additional inferences that can be drawn on theoretical physics mechanisms from the absence of such anomalies in the data. I will classify these inferences in those that inform us about the generation of gravitational waves, the propagation of gravitational waves and the structure of exotic compact object alternatives to black holes. I will then focus on how GW150914 constrains the generation of gravitational waves (e.g. the activation of scalar fields, black hole graviton leakage into extra dimensions, the variability of Newton's constant, the breakage of Lorentz invariance and parity invariance) as well as the propagation of gravitational waves (e.g. the speed of gravity and the existence of large extra dimensions).

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Entanglement Between Masses as a Probe of the Quantum Nature of Gravity

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Interactions between two material objects are mediated by fields. If quantum entanglement is created between two such objects due to their interaction, then it follows that the “mediating” field must have been a quantum entity. In this talk I first show that the states of two micrometer dimension test masses in adjacent matter-wave interferometers could be detectably entangled solely through their mutual gravitational interaction. I then argue that the purely gravitational mechanism for this entanglement implies that witnessing it is equivalent to certifying the quantum nature of the gravitational field that mediates the entanglement.

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Shining Light on Quantum Gravity with Pulsar-Black Hole Binaries

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Pulsars are some of the most accurate clocks found in nature, while black holes offer a unique arena for the study of quantum gravity. As such, pulsar-black hole (PSR-BH) binaries provide ideal astrophysical systems for detecting effects of quantum gravity. With the success of aLIGO and the advent of instruments like the SKA and eLISA, the prospects for discovery of such PSR-BH binaries are very promising. In this talk we will explore how PSR-BH binaries can serve as ready-made testing grounds for proposed resolutions to the black hole information paradox. I will outline a method for using timing signals from a pulsar beam passing through the region near a black hole event horizon as a probe of quantum gravitational effects. In particular the fluctuations of the geometry outside a black hole lead to an increase in the measured root-mean-square deviation of arrival times of pulsar pulses traveling near the horizon. This allows for a clear observational test of the nonviolent nonlocality proposal for black hole information escape. The prospects for carrying out such an observation will be discussed.

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Searching for Quantum Gravity through Nonlinear Field Spaces

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In recent years the idea that not only the configuration space of particles, i.e. space-time, but also the corresponding momentum space can have a nontrivial geometry has attracted significant attention, especially in the context of quantum gravity. The aim of the talk is to discuss extension of this concept to the domain of field theories, the so-called Nonlinear Field Space Theory (NFST). After presenting the motivation and general aspects of the approach we will focus on analysis of the prototype (quantum) NFST of a scalar field. The results will be presented from the perspective of possible quantum gravitational deformations of the particle physics theories. Potential applications, with the focus on early universe cosmology, will be discussed.

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Cosmological perturbations in the early universe

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I provide a simple introduction to the production of fluctuations (vacuum and thermal) in the early universe. After presenting the general formalism, I review the simplest inflationary models, moving on to more complex ones. I then review bimetric varying speed of light theories, explaining how they are somewhat related to DBI inflation algebraically but not philosophically. Finally I review the concept of dimensional reduction in the UV, showing how it can be turned into a mechanism for generation of primordial fluctuations.

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Can we Show that Cosmological Perturbations are of Quantum Mechanical Origin?

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In the early Universe, quantum vacuum fluctuations are amplified and stretched to large scales, giving rise to cosmological perturbations that seed the large scale structure of our Universe. Since this scenario relies both on Quantum Mechanics and General Relativity, it provides an

interesting playground for testing Quantum Gravity ideas. In this context, whether we can show that cosmological perturbations have a quantum mechanical origin is therefore an important question.
I will first show that the quantum discord of cosmological perturbations produced during an era of inflation is large, denoting large quantum correlations. I will then discuss the possibility to carry out Bell-type experiments on cosmological perturbations. Finally, I will show that if one wants to describe primordial perturbations with a state that contains no quantum correlations, one necessarily introduces non-Gaussianities, the non-detection of which would provide the ultimate test.

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Establishing the existence of gravitons using Gravitational Waves from Inflation

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As Dyson has described, no terrestrial experiment can detect individual gravitons. I shall describe how one might use the detection of B modes in the CMB from Inflation to demonstrate the existence of a specific quantum gravitational effect, namely an effect that vanishes in the limit hbar goes to zero. To do this, one would have to demonstrate that the source of the waves is indeed inflation, and not some causal matter or radiation background. I will discuss this issue as well.

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Entanglement in cosmology

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Current observations of the CMB, together with the inflationary paradigm, indicate that anisotropies in the sky have a quantum origin: vacuum fluctuations are stretched over cosmic distances producing a highly entangled state. In recent years, tests of the quantum origin of these fluctuations have been proposed (Campo Parentani 2005, Maldacena 2015, Martin Vennin 2016). In this talk I review these arguments and present new results on the rate of entanglement production during inflation and the pre-inflationary epoch.

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The many faces of the cosmological constant problem

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I will discuss different phenomenological aspects of the cosmological constant problem(s), including its connection to Lorentz violation, gravitational wave and pulsar timing observations.

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Lorentz violation in context

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Searching for violations of Lorentz invariance has been a major focus of quantum gravity phenomenology for over a decade. This focus is primarily due to two factors: increased observational sensitivity and a spurt of quantum gravity models that do not respect the local spacetime symmetries familiar from the standard model. As a result of this intense research focus there is now a theoretical zoo, with multiple theories that modify Lorentz symmetry in very different ways, as well as an experimental zoo, with hundreds of observations that constrain particular types of violations. I will give a student focused talk on the taxonomy of Lorentz violation studies, focusing on the motivation from the fundamental quantum gravity theories, how low energy experimentally testable frameworks relate to these theories, what experiments actually tell us, and finally where the current gaps in our knowledge are and hence where we need to go.

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Observation of quantum Hawking radiation and its entanglement in an analogue black hole

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We observe spontaneous Hawking radiation, stimulated by quantum vacuum fluctuations, emanating from an analogue black hole in an atomic Bose-Einstein condensate [1]. The Hawking radiation is observed via the correlations between the Hawking radiation exiting the black hole and the partner particles falling into the black hole. The quantum nature of the Hawking radiation is observed through entanglement, by comparing the Fourier transform of the correlations to a measurement of the population. This comparison shows that the experiment is well within the quantum regime, since the measured Hawking temperature determined from the population distribution is far below the upper limit for quantum entanglement. A broad energy spectrum of entangled Hawking pairs are observed. Maximal entanglement is observed for the high energy part of the Hawking spectrum, while the lowest energies are not entangled. Thermal behavior is seen at very low energies where the finite extent of the correlation function implies $1/\omega$ frequency dependence. Thermal behavior is also seen at high energies through the agreement of the correlation spectrum with the appropriate function of the Planck distribution. Further insight is obtained by a preliminary experiment in which the horizon is caused to oscillate at a fixed frequency, which stimulates waves travelling into and out of the black hole. The rate of particle production by the oscillating horizon is consistent with the measured Hawking temperature. Furthermore, the observed ratio of the phase velocities of the Hawking and partner particles are consistent with this preliminary experiment, as is the width of the Hawking/partner correlation feature. Additional confirmation of the results is obtained through a numerical simulation, which demonstrates that the Hawking radiation occurs in an approximately stationary background. It also confirms the width of the Hawking/partner correlation feature. The measurement reported here verifies Hawking's calculation, which is viewed as a milestone in the quest for quantum gravity. The observation of Hawking radiation and its entanglement verifies important elements in the discussion of information loss in a real black hole.
[1] Nature Physics, to be published.

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A micromechanical proof-of-principle experiment for measuring the gravitational force of milligram masses

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The experiment presented in this talk addresses a simple question: how small can one make a gravitational source mass and still detect its gravitational coupling to a nearby test mass? We present an experimental scheme based on micromechanical sensing and interferometric readout to observe gravity between milligram-scale source masses. This will improve the current smallest source mass values by at least three orders of magnitude. Further improvements will lead to alternative precision measurements of Newton's constant and a new generation of experiments at the interface between quantum physics and gravity.

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Experimental tests of (fundamentally) semi-classical gravity

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We discuss the hypothetical possibility of a theory in which only matter is quantised, but gravity is described by the classical theory of General Relativity, even at the fundamental level. From the most naive approach for such a theory, a gravity-matter coupling according to the semi-classical Einstein equations, one obtains the Schrödinger-Newton equation as a non-relativistic limit. We present possibilities of experimental tests of such an alternative to Quantum Gravity. Optomechanical tests turn out to be feasible with existing technology.

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Closing

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Minimal length theories and testable effects.

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Quantum gravity may introduce a minimal length that can be encoded effectively in a generalization of the Heisenberg uncertainty principle (GUP). In this talk, I will review this model and make some considerations about the possibility of observing these quantum gravity corrections experimentally. In particular, I will also talk about how the Casimir effect can be sensible to corrections in the minimal length parameter.