QFC2024- Quantum gases, fundamental interactions and cosmology

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Sala riunioni ”Galilei”

Book of Abstracts

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Field theory description of surface and vorticity waves incident on an analogue black hole

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Analogue Gravity [1] enables the replication and investigation of phenomena normally associated with (Quantum) Field Theory in Curved Spacetime through meticulously controlled tabletop experiments. In the particular system of a classical open channel flow, gravity waves on the surface of an inviscid, incompressible and irrotational fluid serve as a means to simulate phenomena akin to those observed around black holes within laboratory settings [2]. The flow, if transcritical, plays the role of an effective spacetime featuring a horizon. This approach provides a pathway to experimentally investigate various classical instabilities associated with black (and white) holes [3-7].
While the assumption of an irrotational flow is necessary to construct the analogy, it is in practice a strong assumption. Friction on the bottom of the channel tends to induce a boundary layer where the flow velocity drops rapidly to zero [6], while flow recirculation tends to occur in the downstream wake of an obstacle [7]. It is thus an experimentally relevant question to determine how the wave propagation is altered by a non-trivial depth-dependence of the flow.
In this presentation, we propose a novel approach to construct an analog model incorporating gravity waves while considering the effects of vorticity. Our model involves an incompressible and inviscid fluid flowing in two layers: one characterised by constant vorticity at the bottom and another with vanishing vorticity at the top, with perturbations applied to the interface between the layers and on the free surface. Using this method, we derive new equations of motion for both the scalar field associated with the potential velocity and a new scalar field linked to the variation of vorticity. We develop a new Lagrangian, define a novel scalar product, and deduce WKB-like solutions [8] for the fields. Finally, we compute the scattering coefficients associated with modes falling into an analogue black hole [6].

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Dephasing-tolerant quantum sensing for transverse magnetic fields with spin qudits

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We propose a dephasing-tolerant protocol for quantum sensing of transverse magnetic fields which exploits spin qudit sensors with embedded fault-tolerant quantum error correction. By exploiting longitudinal drives, the transverse field induces logical Rabi oscillations between encoded states, whose frequency is linear in the transverse field to be probed. Numerical simulations show that the present fault-tolerant protocol enables the detection of very small fields, orders of magnitudes below the limit imposed by the coherence time.

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Gravitational Waves and Black Hole perturbations in Acoustic Analogues

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In 1981 Bill Unruh established an analogy between hydrodynamic flow with a supersonic region and a black hole, initiating the research field of analogue gravity. One possibility to exploit this hydrodynamics/gravity analogy is to create analogue black holes within Bose-Einstein condensates. At sufficiently low temperatures, phonons, which are low-energy collective excitations of the condensate, propagate as a massless scalar field on an emergent acoustic metric tensor. This metric tensor, in turn, is determined by the characteristics of the condensate. Specifically, an acoustic black hole is created by a transonic fluid, and concepts like the event horizon are applicable. At this acoustic horizon, quantum fluctuations result in a thermal radiation of phonons, which is the acoustic equivalent of Hawking radiation. Remarkably, this emission near the acoustic horizon has been simulated numerically and verified experimentally with atomic Bose-Einstein condensates.

This talk builds upon the above field of research in analogue gravity: the goal is to design a system where an acoustic horizon is excited by a gravitational wave-like perturbation. As a first step, I will present a way to reproduce a gravitational wave perturbation on a flat background acoustic metric emergent from a Bose-Einstein condensate. Secondly, I will demonstrate how to realize an impinging gravitational wave-like perturbation to an acoustic horizon. Then, I will show how the horizon of the above system is perturbed by such an analogue gravitational wave. Finally, possible implications and perspectives stemming from this work are discussed, including the study of reflectivity, quasi-normal modes, shear viscosity and entropy density of a perturbed acoustic horizon. Notably, all these interesting research directions could be probed in a real experiment performed, for example, in ultra-cold quantum gas platforms.

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High Precision Quantum Tests of the Equivalence Principle to Distinguish Between Equivalent Gravities

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Recent theoretical advancements in gravitational physics, particularly within the framework of the Geometric Trinity of Gravity, challenge the traditional assumptions on spacetime underlying General Relativity (GR). The Geometric Trinity comprises GR, grounded in the curvature of spacetime; the Teleparallel Equivalent of GR (TEGR), formulated in terms of torsion; and the Symmetric Teleparallel Equivalent of GR (STEGR), built up on nonmetricity. Recent results show that GR, TEGR and STEGR are dynamically equivalent in many different aspects but not exactly in everything. In particular, the Equivalence Principle (EP) can be recovered in TEGR and STEGR, but it is not at the foundation of them as in GR. Therefore, the central argument of this work shows that, given the equivalence between GR, TEGR and STEGR in non-trivial multiple predictions, and given the fact that the EP is not necessary for TEGR and STEGR in order to have the same predictive power, the EP should not be considered as fundamental, but emergent. Moreover, many open conceptual difficulties which are consequences of the EP can be addressed in the framework of the Geometric Trinity. In conclusion, this argument shows that current precision levels of EP tests should not discourage further research, especially at quantum level. Therefore, the incoming experiments of free falling with ultra-cold atoms could be the quintessential method to explore the very foundations of our understanding of gravity and spacetime. In Florence in particular, we are designing a very high precision test of the EP with a gradiometer with squeezed Strontium atoms.

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Signatures of quantum chaos in the Yukawa-SYK model

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The Sachdev-Ye-Kitaev (SYK) model describes a strongly-correlated quantum many-body system consisting of N Majorana fermions with random all-to-all q-body interactions, exhibiting several intriguing properties. Notably, the SYK model displays maximal scrambling of mutual information and maximal quantum chaos. Additionally, the model is of significant interest in the context of the AdS/CFT correspondence, being holographically dual to Jackiw-Teitelboim gravity and sharing much of its interesting features with two-dimensional black holes.

Recently, a proposal has been put forward for the analog quantum simulation of the SYK model in a cavity QED experiment consisting of a cloud of fermionic atoms interacting with the eigenmodes of an optical cavity [1]. The cavity realizes long-range all-to-all fermion-fermion interactions, mediated by the exchange of virtual cavity photons. Furthermore, the interactions are randomized using an optical speckle pattern, approaching the SYK physics. This shows that the SYK model is within the reach of cQED-based experiments and a significant step forward in the search of holographic quantum matter. With this experimental proposal in mind, we investigate a generalization of the SYK model called the Yukawa-SYK model [2], incorporating a boson represented by the cavity photons in the experimental setup. We analyze the chaotic nature of the model by numerically computing the spectral form factor, a typical marker for the spectral statistics and diagnostic tool for quantum chaos.

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Programmable potentials to study synthetic horizons

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Ultracold atoms in optical lattices have become a crucial tool for exploring quantum many-body quantum problems. Enhanced control over atomic interactions and optical potentials has enabled the study of increasingly complex phenomena. Recently, several proposals suggested to simulate Hamiltonians, which occur in cosmological systems with curved metrics, using ultracold quantum gases[3,4]. In my presentation, I will discuss approaches to generate such synthetic horizons using tunnel-coupled tweezer arrays in our quantum gas microscope experiments.

Quantum gas microscopes enable us to visualize individual atoms within a single layer of a three-dimensional lattice. In recent years, we have also developed the ability to manipulate atoms at the scale of single lattice sites using a programmable Digital Micromirror Device. Utilizing this technology, we were able to dynamically adjust the number of lattice sites in one-dimensional systems with a given atom number. This allowed us to study the properties of a quantum gas as the number of lattice sites became commensurate and incommensurate with the atom number [1].

We used repulse light potentials in that study to generate barriers around the atoms. With the same method one can also program attractive potentials to make tweezer traps which capture individual atoms. Recently, it has been demonstrated that tweezers can be combined to form custom one-dimensional lattices [2]. By precisely controlling the positions of the tweezers and the inter-site barriers, we can create a slowly increasing tunnelling rate along a 1D array. In such a lattice, it becomes gradually more difficult for atoms to tunnel, analogous to falling into a black hole. With the dynamic control provided by the DMD potentials, we can also quench between different lattice configurations. For instance, we can switch from a system with uniform tunnelling (flat metric) to one with gradually increasing barriers (curved metric) [4].

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Correlation functions in inhomogeneous superfluids

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We investigate the two-point correlation functions that characterize the low-energy properties of inhomogeneous superfluids. Employing a covariant formalism and an appropriate perturbative expansion we determine the correlation functions in an arbitrary inhomogeneous background. Our result apply to standard non-relativistic superfluids, realizable in laboratory, as well as to relativistic superfluids, relevant for compact stellar objects.

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False Vacuum decay and Hawking radiation in Coherently Coupled Bose Gases

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In the present talk, I present some recent theoretical and experimental results on the physics of **coherently coupled Bose-Einstein condensates** (BECs). The Ising-like ferromagnetic transition and the elementary excitations of the system are reviewed in order to introduce the phenomenon of bubble formation due to the metastability in the presence of the ferromagnetic critical point. The bubble formation in the coherent BEC field is very much related to the phenomenon of ***false vacuum decay***. Numerical and experimental results are therefore compared with an instanton theory for our platform.

Eventually I present the results for possible detection of ***massive and massless Hawking-like radiation*** using a typical sonic hole configuration for coherently coupled BECs.

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Detector-based measurements in AQFT

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I present a method to introduce a measurement postulate in Quantum Field Theory (QFT) in Minkowski spacetime using Unruh-DeWitt detectors and algebraic tools. Beginning with a review of the detector-based measurements for QFT presented by J. Polo-Gomez, J. J. Garay, and E. Martin-Martinez (Phys. Rev. D 105, 2022), I demonstrate how this scheme can be extended to induce localised Kraus operators and selective measurements within the framework of Haag-Kastler's QFT axioms. This extension leads to a robust measurement postulate for (A)QFT in flat spacetime. Additionally, I will discuss the implications of the detector-based measurement scheme for entanglement entropy and the feasibility of defining measurements in more general spacetimes.

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Improvement of accuracy and precision in quantum-enhanced differential measurements in presence of correlated noise

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Atom interferometers can be used to measure accelerations with a wide spectrum of possible applications[1-3]. In this kind of set-up, absolute measurements can be significantly limited by vibration noise. Conversely, acceleration gradients can be measured in a differential configuration by two interferometers that share a common reference frame. Vibration noise, affecting the two phase shifts equally, can thus be efficiently rejected[4-5]. It has also been demonstrated that very large phase fluctuations can be tamed by applying ellipse-fitting techniques to coupled fringe data[6]. Ellipse fitting's immunity to correlated phase noise and its lack of requirement for a detailed noise model are two highly crucial advantages. On the other hand, one disadvantage of the method concerns its precision, which is currently limited by classical shot noise. Entangled states, which are typically linked to sub shot-noise sensitivities, operate best around some phase optimal working point; therefore, their compatibility with fitting techniques and noisy environments is doubtful and has up to now been matter of discussion[7]. Moreover, conic fitting has the drawback of producing biased estimates[8-9], an effect that is hardly eliminated by increasing the number of measurement repetitions. Here, we show that entangled input states created by a spin-squeezing dynamics can be combined with data-fitting techniques in presence of arbitrary large, correlated phase noise leading to an improvement in both accuracy and precision. By simulating state evolution and data acquisitions numerically and supported by analytical calculations, we prove that different fitting procedures all lead to bias and uncertainty reduction around a specific optimal value of the squeezing strength. Interestingly, we find that the squeezing strength required is moderate and smaller than those commonly considered as optimal for other estimation protocols[10]. For what concerns improvement in precision, we find a gain over the shot noise limit which follows the scaling $\sim N^{1/6}$, with N the atomic population in each interferometer. For what concerns bias reduction, we single out two fitting procedures which, combined with an optimal squeezing strength, can remove the bias completely. We interpret this last result, which cannot be reproduced by simply increasing the atom number in a classical state, in terms of the unique statistics of the state obtained from a spin-squeezing dynamics. Our work has reconciled the use of entangled states, needed for high-sensitivity measurements, with a technique that is uniquely robust against phase noise, thus paving the way for the full exploitation of entanglement in precision measurements in a strong noise scenario.

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Nonlinearities in black hole ringdown

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We study the quadratic quasi-normal modes of a Schwarzschild black hole, which are perturbations originating from the coupling of two linear quasi-normal modes. As recent studies suggest, nonlinear effects in black hole perturbation theory may be crucial for accurately describing a black hole ringdown. We present a new class of "quadratic" quasi-normal modes at second order in perturbation theory, where both the frequency and amplitude are entirely determined by the linear modes. Assuming the amplitude of the two linear modes is known, we compute the amplitude of the resulting quadratic mode across a wide range of possible angular momenta using Leaver's algorithm. Finally, we reconstruct the waveform in the radiation gauge. These quadratic modes could enhance black hole ringdown models by incorporating nonlinear features without adding extra free parameters for data analysis, or serve as a tool to test General Relativity in the nonlinear regime.

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Shear to entropy ratio of superfluids

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We discuss the shear viscosity to entropy ratio in superfluids. We focus on transonic superfluids, showing that the presence of an horizon may lead to the saturation of the so-called KSS bound.

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Particle and entanglement production in an analogue preheating experiment

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In the leading paradigm of cosmology, most particles are created during a reheating period following inflation. Part of this creation proceeds via parametric resonance 1, a process referred to as preheating. Since inflation dilutes any pre-existing particles, the relevant fields are initially in their vacuum state and particle production is seeded by vacuum fluctuations, a phenomenon of purely quantum origin similar to the dynamical Casimir effect (DCE).

While the predicted quantum origin seems hard to test in the cosmological context, experiments involving genuine quantum fields evolving under similar dynamics have been realised. Ref. 2 reports on such an experiment in an elongated cigar-shaped Bose-Einstein condensate (BEC). The BEC is modulated in time and acts as a strong classical field exciting its own quantum perturbations, created in pairs of opposite momenta ±k. Entanglement of the generated pairs is known to be a signature of pair production seeded by vacuum fluctuations [3] but is also fragile. Indeed, in 2 the observed pair correlations were much weaker than expected and far from the regime indicating entanglement.

In a series of publications, the theoretical description behind the experiment was re-analysed in increasing detail to account for the absence of entanglement. First, in [3], weak dissipation of the excitations was phenomenologically introduced and shown to be able to prevent the generation of entanglement. Fully nonlinear numerical studies of the modulated gas based on the Truncated Wigner Approximation (TWA) were then conducted [4,5]. These confirmed that phonon-phonon interactions can induce an effective dissipation acting against the parametric resonance and degrading or indeed destroying the induced entanglement. In [6], the dominant interaction channel for small occupation numbers in 1D quasi-BEC was identified as Beliaev-Landau scattering between the resonant mode and the thermal population. The associated dissipation rate was analytically derived and checked against TWA simulations. Most recently [7], it has been shown that the phenomenological model of [3], when supplemented by the rate derived in [6], accurately reproduces the dynamics seen in TWA simulations akin to those of [5].

In this talk, I will recount the above history and describe the dynamics at play, emphasising the subtle interplay between growth and dissipation that leads to distinct regimes of particle and entanglement production. Implications for experimental optimisation will also be discussed.

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[7] A. Micheli and S. Robertson, to be published

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Proper time path integrals for gravitational waves: an improved wave optics framework

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When gravitational waves travel from their source to an observer, they interact with matter structures along their path, causing distinct deformations in their waveforms.
In this study we introduce a novel theoretical framework for wave optics effects in gravitational lensing, addressing the limitations of existing approaches. We achieve this by incorporating the proper time technique, typically used in field theory studies, into gravitational lensing.
This approach allows us to extend the standard formalism beyond the eikonal and paraxial approximations, which are traditionally assumed, and to account for polarization effects, which are typically neglected in the literature. We demonstrate that our method provides a robust generalization of conventional approaches, including them as special cases. Our findings enhance our understanding of gravitational wave propagation, which is crucial for accurately interpreting gravitational wave observations and extracting unbiased information about the lenses from the gravitational wave waveforms.

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Quantum Signatures and Decoherence during Inflation

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In order to shed light on the quantum to classical transition of the primordial perturbations during inflation, we investigated the decoherence of a system of scalar curvature perturbations induced by an unobservable environment of deep subhorizon tensorial modes. We computed the associated corrections to the cosmological correlation functions, looking for distinguishable signatures which could, in future observations, prove the quantum origin of primordial perturbations. In doing this, we commented on proposed techniques to deal with non-Markovianity (i.e. memory effects in the environment, which drastically complicates calculations), which seems to be ubiquitous in an inflationary framework.

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The effect of quantum decoherence on inflationary gravitational waves

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The theory of inflation provides a mechanism to explain the structures we observe today in the Universe, like, e.g., the Cosmic Microwave Background (CMB) anisotropies, starting from quantum-mechanically generated fluctuations. However, this leaves us with the unanswered question: how did the quantum-to-classical transition, which leads to such structures, occur? During inflation, tensor perturbations interact (at least gravitationally) with other fields, meaning that we need to view these perturbations as an open system that interacts with an environment. In this paper, the evolution of the system is described using a Lindblad equation, leading to the quantum decoherence of the system, which is a possible mechanism to explain the quantum-to-classical transition. We show that this quantum decoherence leads to a scale-dependent increase of the gravitational wave power spectrum, depending on the strength and time dependence of the interaction between the system and the environment. By using current upper bounds on the gravitational wave power spectrum from inflation, obtained from CMB and the LIGO-Virgo-KAGRA constraints, we find an upper bound on the interaction strength. Furthermore, we compute the decoherence criterion, which indicates the minimal interaction strength needed for a specific scale to have successfully decohered by the end of inflation, therefore looking at which scales relic quantum signatures (beyond decoherence) might have survived. Assuming that the CMB modes have completely decohered, this gives a lower bound on the interaction strength. In addition, we look at which scales might not have fully decohered and could still show some quantum signatures. Lastly, we use sensitivity forecasts to study how future gravitational-wave detectors, such as LISA and ET, could constrain the parameter space. Due to the scale-dependence of the power spectrum, LISA could only have a very small impact. However, ET will be able to significantly improve our current constraints for specific scenarios.

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Quantum field theory of scalar dark matter: a simple model

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We build up a simple Lorentz invariant model of dark matter consisting of a massive, real, scalar field coupled to its massless, real scalar mediator field. From a mathematical point of view the model belongs to the Klein-Gordon-Wave family of models. The dynamics is ruled by a single parameter, containing the mass of the dark particles and their initial number. It is shown that if the latter number is set to one, then the stationary states of the model exist only for values of the particle mass that are quantized, the minimum possible value being at the Planck scale, whereas no upper bound exists. Such states can be tentatively interpreted, within all the limits of the theory, as primordial black holes. On the other hand, allowing for a very large number of particles and plugging into the model a value of the dark particle mass of the order of $10^{-24}eV$, we get, by a perturbative procedure, the Schroedinger-Wave model. The spherically symmetric, stationary states of the latter model are those first interpreted by Sin (1994) as "cold" BEC clumps of galactic size. Thus, the simple model considered here allows for two components of dark matter (primordial black holes and ultralight scalars) whose mass ranges are completely far apart. The important issue concerning the stability of the two families of stationary states is also discussed.

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Welcome: Dario Pisignano/Chiara Roda (Director Physics Department - University of Pisa) and Paolo Spagnolo (Director INFN - Pisa)

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Open Quantum Systems for Interdisciplinary Science

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Artificial intelligence and quantum many-body problems

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What can we learn from testing the gravitational field of a quantum source

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Observations in Quantum Cosmology

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Closure Remarks

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Welcome speech: Benedetta Mennucci Delegate of the Rector for research promotion (University of Pisa) - Dario Pisignano/Chiara Roda (Director Physics Department - University of Pisa) and Paolo Spagnolo (Director INFN - Pisa)