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Cosmology analogues in optical systems

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Abstract. We discuss the possibility of exploiting polariton-exciton physics as an analogue experimental tool to study challenging ideas and existing problems arising in the context of gravity theory and theoretical cosmology. We search for cosmology analogues with specific focus on simulating non-equilibrium dynamics across cosmological phase transitions in laboratory as well as employing optical analogue horizons in Bose-Einstein condensates (BECs) and signatures of white hole radiation to study gravitational and cosmological processes. Our analysis aims to uncover conceptual similarities between condensed matter systems and various phenomena in the Early Universe such as the symmetry breaking of the vacuum energy, spontaneous production of particles, false vacuum and cosmic inflation together with a number of unsolved cosmological problems.

1 Introduction

Latest theoretical and experimental advances in the physics of strong light-matter coupling, both in the classical and the quantum regimes and more recent, in the exciton-polariton research makes possible a range of new interdisciplinary forefront research topics with fundamental purposes in cosmology, gravitation and astrophysics. Analogue models of gravity [1] were inspired by various concepts from general relativity, and especially by the equivalence of optical media and space–time geometries. Such models have already being realized in recent laboratory experiments around the world. However, the simulation of cosmological scenarios and non-gravitational analogue models of large-scale cosmic processes were given much less attention in laboratories
Several cosmological phenomena may be simulated in the laboratory [2], such as cosmological particle creation, caused by the expansion or contraction of the Universe, dynamical quantum phase transitions, soliton and topological defect formation (vortices, textures, domain walls or cosmic strings) that may have affected the dynamics of the Early Universe, or the presence of Hawking radiation arising from artificial event horizons, Bogoliubov-Cerenkov emission of soundwaves in bulk dilute superfluids, vacuum instability Penrose process (superradiant scattering), Unruh effect, Eardley instability, Gibbons-Hawking effect, dynamical Casimir emission and Schwinger mechanism. The standard model of cosmology describes the Early Universe as nearly homogeneous, with most inhomogeneities, including the seeds of large-scale structures as originating from the quantum vacuum fluctuations of the inflaton scalar field. The analogy between phonons in expanding BECs and quantum fields in a universe undergoing an accelerated expansion introduces an effective tool to study effects such as freezing of modes after horizon crossing and the amplification of quantum fluctuations. Such amplification mechanism was predicted to be responsible for the formation of the initial inhomogeneities as the first seeds for the formation of cosmic structures such as galaxies. A number of recent results in quantum fluids and exciton-polariton physics can be used as a test-bed capable of simulating a variety of cosmological toy models, with possibilities for recreating fundamental effects relevant for cosmological phase transitions, cosmic inflation, black holes and other gravitational scenarios in the laboratory.

2 Cosmology analogues

Quantum collective dynamics in light-matter systems and quantum fluids of light [3] such as exciton-polariton condensates are novel convenient tools to investigate phase transitions, find new universality classes for bosonic and fermionic fields, simulate solitons and topological structures occurring in the symmetry breaking phase transitions equivalent to cosmological strings or other defects in the Early Universe. Kibble-Zurek (K-Z) theory describes the breakdown of the adiabatic dynamics across a critical point, providing an insight for the preparation of ground-state phases of matter in the laboratory. Discovered in a cosmological setting, the theory was extended to quantum phase transitions such as vortices in superfluids [4] and domain walls in spin systems. While the theory described only second-order phase transitions, recent work reports the observation of a generalized K-Z mechanism across a first-order quantum phase transition in a spinor condensate. The intuitive connections between K-Z theory of topological defect production in second order phase transitions and the dynamics of the Landau-Zener transition is a centre piece

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in understanding the cosmological phase transitions in the Early Universe. Non-equilibrium Landau-Zener tunneling in exciton-polariton condensates is a framework that may be extended to investigate dissipative cosmological dynamics occurring at the beginning of the Universe and open a new perspective toward understanding inflationary cosmology.

Exciton-polariton BECs are hybrid light-matter bosonic quantum fluids formed in a semiconductor microcavity, with the advantage of direct optical access, measurement and control of their condensate order parameters. Due to their light-matter nature, they display similar properties to normal fluids, when confined in an optical cavity, due to the effective mass of the photon and the effective photon-photon coupling. Such systems are capable of manifesting macroscopic quantum phenomena with intrinsic open-dissipative nature, enabling the investigation of universal dynamics with topologically non-trivial configurations that may describe cosmic structures. Polariton condensates embed diverse properties of lasers, atomic BECs and semiconductor physics, providing a variety of nonlinear physical phenomena, such as solitons, vortex lines in superflluids, universal scaling laws or spontaneous spin bifurcations and possible connections to cosmology, while maintaining a simple theoretical description. These features enable the simulation of different Hamiltonians with the advantage of studying effective curved spacetimes determined by the flow properties. We suggest employing characteristic phenomenological signatures in exciton-polariton BECs dynamics that may lead to observational constraints for cosmology, such as the simulation of the critical transition between cosmic inflation and the Big Bang. Such models may instigate pioneering insights into fundamental ideas and problems in standard cosmology, traditionally solved by inflation: the horizon problem, refering to the uniform temperature of causally disconnected patches of space-time, the flatness problem, refering to the extremely small spatial curvature of our universe and the monopole problem refering to the absence of Grand Unified Theory (GUT) monopoles after GUT phase transition. The spontaneous occurrence of spin vortices in polariton condensates and the associated spatial polarization patterns or spin textures are good examples of second-order phase transitions, accompanied by spontaneous symmetry breaking. Topological excitations in spinor quantum fluids, where the additional spin degree of freedom allows for mixed spin-phase topologies and the occurrence of spin vortices and hedgehogs (magnetic monopoles-like excitations) or spontaneous chiral symmetry breaking are valuable connections to large-scale non-equilibrium dynamics of cosmic structures. Cosmology toy models in exciton fluids can be made easily available as the vector order parameter can be accessed by optical means. We aim at validating such toy models and posible connections between the distribution of topological defects, determined by the scaling theory of phase transitions and signatures of universality beyond K-Z theory in the Early Universe. By combining coherence and spin properties, exciton-polariton fluids are a promising experimental platform for observing stimulated and spontaneous amplification by Hawking, Penrose, Zeldovich and superradiance effects via formation of event horizons for waves in media and rotating geometries with horizons and ergoregions. It has already been shown that the event horizon of black holes and white holes can be realized in the context of analogue gravity [5]. The dynamical equation of BECs with a sink or a vortex have the same wave equation as light in a strong curved-space. Experimental realization of black holes [6] and white holes in a nonlinear optical medium has been reported, as an analog example of spontaneous particle creation from vacuum fluctuations. Observational signatures from artificial white holes in flowing BECs may offer new predictions and open the door for further exploring the trans-plankian problem associated with Hawking radiation, gravitational backreaction and superradiance of black holes. In cosmology, the only possible white hole which by definition would radiate light, is the Big Bang. Quantum fluid analogues of white hole horizons may provide new perspectives on quantum field theory effects behind Big Bang theory. The study of signatures from sonic horizons in a moving fluid with superluminal (Bogoliubov) dispersion leading to the amplification of particle production and black hole lasing [7], may help with the understanding of spontaneous particle creation from vacuum fluctuations in quantum field theory in curved spacetime or simulating exotic forms of matter driving the cosmic inflation such as inflatons.

3 Conclusion

Properties and dynamics of quantum fluids of light, such as exciton-polariton condensates may be empoyed as a tool to simulate different cosmology and high-energy scenarios with the aim of answering existing fundamental questions and possible experimental investigation of exotic quantum effects in the Early Universe.

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