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PRIMORDIAL QUANTUM COSMOLOGY AND EFFECTIVE SPACETIMES

Abstract

In this thesis, we propose a quantization of cosmological perturbations on quantum cosmological background. For this, we introduce a new classical framework for cosmological perturbation theory. The main difference from the standard framework (not acceptable from a quantum gravity point of view, since it relies on a classical background) is that the homogeneous isotropic degrees of freedom and the (scalar and tensor) perturbations are dynamical, and their evolution is determined by a (non-vanishing) physical Hamiltonian. We apply this construction to the physically important case of a scalar field (i.e., the inflaton) minimally coupled to gravity.

The model is then quantized, based on the so-called “test field approximation”: this consists in the assumption that the “heavy” degrees of freedom representing the homogeneous quantum geometry are disentangled from the “light” degrees of freedom representing the perturbations. We show that, under this approximation, we can trace away the geometric part, and obtain a Schrodinger-like equation for the wavefunction of perturbations. The quantum Hamiltonian in this equation is a collection of non-interacting harmonic oscillators (one per every Fourier mode), whose frequencies depend on expectation values of certain time-dependent geometric operators. This realizes what we call “quantum field theory on quantum spacetime”.

This theory can then be compared with an effective one, which describes the dynamics of the same field on a classical background. We show that, if the original inflaton field has no potential, then this comparison leads to a specific effective spacetime, whose effective metric is given in terms of expectation values of geometric operators on the state of quantum geometry. We generalize this result to the massive case, and show that this leads to a mode-dependent effective spacetime: each mode of the field probes the underlying quantum geometry in a slightly different way, “interpreting” it in terms of its own effective metric. While this might seem an exotic behavior, it is exactly what happens to photons propagating in crystals: photons of different energy interact differently with the quantum structure of the medium, and consequently their path is deviated in different ways; at the effective level, we can think of such photons as moving in an energy-dependent metric, so that the path followed by each particle coincides with a geodesic in the particle’s own metric.

We then study the modification to the dispersion relation for this mode-dependent metric, and show that it is controlled by a single parameter (which can be thought of as the “refractive index” of the quantum state of geometry). This parameter is sensitive to quantum fluctuations of the geometry, and it vanishes if the state is semi-classical. While this explains why today we do not see any Lorentz-violation, it is expected that in the far past the state of the Universe was far from semiclassical: we thus investigate primordial effects and present the most recent bounds (based on Cerenkov radiation of photons into gravitons). We also estimate the parameter in Loop Quantum Cosmology and confirm agreement with observations. We finally consider another effect of this effective metric, which amounts to a correction to the CMB power spectra in the large-angle temperature correlation function, which could in principle be observed in the near future.