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Experimenting with Loop Quantum Cosmology

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Abstract

According to loop quantum cosmology, quantum gravity effects resolve the big-bang singularity and replace it with a cosmic bounce. Furthermore, loop quantum cosmology can change the shape of primordial cosmological perturbations, such as reducing power at large scales in inflationary models or suppressing the tensor-to-scalar ratio in the matter bounce scenario; these two effects are potential observational tests for loop quantum cosmology. In this article, I discuss these and other predictions, as well as three open problems in loop quantum cosmology: its relationship to loop quantum gravity, the trans-Planckian problem, and a possible transition from a Lorentzian to a Euclidean space-time around the bounce point.

Keywords: Cosmology • Quantum • Gravity • Loop

Introduction

The boucle cosmology predicts that the effects of quantum gravity will resolve the big-bang singularity and replace it with a cosmological rebond. Furthermore, quantum physics can change the shape of fundamental cosmological perturbations, such as reducing energy at large scales in inflationary models or decreasing the tensile/scalar ratio in the matter bounce scenario; these two effects are potential observational tests for quantum physics. In this article, I review these predictions, as well as others, and briefly discuss three open problems in quantum cosmology: its relationship with quantum gravity, the trans-planckian problem, and a possible transition from a lorentzian to a euclidean space-time centred on the point of rebonding [1].

Any theory of quantum gravity is notoriously difficult to test because any effects are typically expected to become significant only near the Planck scale, which is well beyond the reach of particle accelerators or even cosmic rays. However, quantum gravity effects were likely important in the early universe when the space-time curvature was on the order of the inverse Planck length squared, R 2 Pl, and although the cosmic microwave background (CMB) formed much later, it is still possible that quantum gravity effects in the very early universe left a mark in primordial perturbations that could be observed in the CMB today. Indeed, the results of WMAP's high precision imaging of the CMB [2].

LQC quantizes symmetry-reduced space-times using the same procedures as loop quantum gravity (LQG). The big-bang and big-crunch singularities are resolved by quantum gravity effects and are replaced by a non-singular bounce, which is one of the main results of LQC. These findings will be discussed in detail in, with a focus on the spatially flat Friedmann-Lemaître-Robertson-Walker (FLRW) space-time. More recently, considerable work has been done in determining quantum gravity corrections to equations of motion for cosmological perturbations, with several complementary approaches developed, and then using these LQC-corrected equations of motion to calculate predictions that can be tested by CMB observations. Quantum gravity effects can arise directly from the presence of a non-singularity in the very early universe.

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By selecting an initial state (V,o) at some instant o of relational time and numerically evolving it using the LQC Hamiltonian constraint operator, the quantum dynamics of LQC can be studied. This was first done for initial states that sharply peaked around a classical solution to the Friedmann equations at a low enough energy density to make quantum gravity effects initially negligible. The results of numerically solving for such initial conditions are as follows: the wave function remains sharply peaked throughout the entire evolution, the wave packet follows the classical Friedmann trajectory very closely as long as the matter energy density remains small in comparison to the Planck scale, and the wave packet departs from the classical Friedmann trajectory when the matter energy density approaches the Planck scale [3].

While numerical studies initially focused on states that are sharply peaked around classical solutions, a number of recent studies have demonstrated that a large class of widely spread states that lack a nice semi-classical limit also bounce, with the same upper bound on the expectation value of the matter energy density (in fact, states with a large spread typically bounce at a lower expectation value of the energy density than sharply peaked states). Furthermore, for a given lapse and factor-ordering choices, a Hamiltonian constraint operator that is exactly soluble can be obtained, and it can be shown analytically that the bounce is generic and that the energy density of the scalar field is bounded above by.

Finally, another important point emerges from these effective equations: quantum gravity effects for sharply-peaked states in LQC become significant when the energy density (equivalently, the space-time curvature) approaches the Planck scale. When the bounce occurs, the spatial volume of space-time can (and usually will) be very large in comparison to the Planck scale. (In fact, for non-compact spaces, it will be infinite.) As a result, the radius of the space-time curvature, not the radius of the spatial volume, is the relevant length scale that determines the amplitude of LQC effects. If the spatial volume approaches Pl, quantum fluctuations become important and generate additional quantum gravity effects.

Literature Review

The three frameworks approach cosmological perturbations differently. The effective constraint approach is founded on effective equations but does not require the construction or knowledge of the underlying quantum theory. The hybrid quantization approach, on the other hand, is founded on a well-defined quantum theory, with a loop quantization for the background variables and a Fock quantization for the perturbative degrees of freedom. Finally, the separate universe approach quantifies the background and long-wavelength scalar perturbations but ignores short-wavelength perturbations. It is still necessary to extend these results to higher order in perturbation theory in order to calculate LQC effects on non-Gaussianities, as well as to investigate perturbations on a spatially curved and/or anisotropic background space-time [4].

equally accurate for cosmological perturbations. The difficulty is determining the correct effective equations without knowledge of the underlying quantum theory. The procedure used in this approach is to take the classical scalar and diffeomorphism constraints of general relativity in Ashtekar-Barbero variables (typically, the Gauss constraint is gauge-fixed, as in homogeneous LQC) for the spatially flat FLRW space-time with linear perturbations, and then apply them to the spatially flat FLRW space-time with linear perturbations. The effective constraint approach is phenomenologically motivated in large part by the high accuracy of the LQC effective Friedmann equations describing the full quantum dynamics of homogeneous space-times, even at the bounce point, for states with small quantum fluctuations. The hope is that similar effective equations will exist and be used in the future [5].

Discussion

Nonetheless, the 'correction' functions clearly have a lot of leeway in their selection. An important condition for obtaining a consistent theory, however, is that the constraints have an anomaly-free Poisson algebra. This requirement, it turns out, severely limits the form that these correction functions can take. (It should be noted that the form of the constraint algebra may change.) What matters is that the constraint algebra closes, not that it has a particular form. In fact, holonomy or inverse triad corrections are commonly used in LQC to modify the constraint algebra.This was first done for inverse triad corrections in the assumption that the corrections are small and that a perturbative expansion exists for them [6].

While this approximation may appear to be quite drastic at first glance, lessons from homogeneous LQC suggest that it is reasonable. For sharply-peaked states in homogeneous LQC, quantum gravity effects become significant only when the energy density of the matter field (or anisotropies) approaches the Planck scale (as long as the spatial volume remains much larger than 3 Pl, which it usually is, even at the bounce). As a result, if the energy density in the perturbations is always small in comparison to the Planck scale (which it is if the perturbations are linear, as explicitly checked in inflationary models), then quantum gravity effects acting directly on the perturbations may indeed be negligible [7].

Conclusion

The heuristic picture of a repulsive force simultaneously generating the bounce and smoothing out the perturbations motivates this approach, which imposes quantum vacuum initial conditions at the bounce time (as much as possible, given the quantum uncertainty relations). However, choosing a vacuum state for a quantum theory on a dynamical background is ambiguous. In the hybrid quantization framework, three possibilities have been considered thus far: I setting the vacuum state at the bounce point to be exactly the fourth-order adiabatic vacuum state at that time, requiring that oscillations in the perturbations be minimised at the initial time, and (iii) motivated by Penrose's hypothesis on the initial vanishing of the Weyl curvature, choosing the vacuum state.

Even if there were more than 80 e-folds of inflation, in which case the amplified modes are now at super-horizon scales, these modes could affect the observed power spectrum if there are strong correlations between the observable and the super-horizon modes, generated by non-linearities in the dynamics of the cosmological perturbations. There is an amplification of power at large scales for the vacuum choice I as explained above, and non-Gaussianities (during the standard inflationary era) will induce correlations between super-horizon modes and observable modes in the CMB. Non-Gaussianities are most pronounced between super-horizon modes and CMB angular multipoles.

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Conflict of Interest

There are no conflicts of interest by author.

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