Can observations determine the quantum state of the very early Universe?

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by Ivan Agullo, Abhay Ashtekar and Brajesh Gupt

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Can we hope to know even in principle what the universe was like in the beginning? This ancient metaphysical question has acquired new dimensions through recent advances in cosmology on both observational and theoretical fronts. To the past of the surface of last scattering, the universe is optically opaque. Yet, theoretical advances inform us that dynamics of the universe during earlier epochs leaves specific imprints on the cosmic microwave background (CMB). Therefore, we can hope to deduce what the state of the universe was during those epochs. In particular, success of the inflationary scenario suggests that the universe is well described by a spatially flat Friedmann, Lemaître, Robertson, Walker (FLRW) space-time, all the way back to the onset of the slow roll phase. This is an astonishingly early time when space-time curvature was some $\sim 10^{65}$ times that on the horizon of a solar mass black hole and matter density was only 11 orders of magnitude smaller than the Planck scale.
However, if one goes even further back in time, classical general relativity becomes inadequate. One has to replace the FLRW metric with an appropriate wave function, $\Psi_o$, on the space of all FLRW geometries. Therefore, one is now led to ask: Can we determine this wave function using again an appropriate combination of theory and observations? This question can be analyzed within loop quantum cosmology because it provides a well-defined evolution of $\Psi_o$, all the way back to the Planck regime. The surprising finding of our CQG paper is that constraints on $\Psi_o$ are extraordinarily weak.

In LQC, quantum geometry effects dominate pre-inflationary dynamics and replace the big bang singularity by a quantum bounce. As in standard inflation, the observed inhomogeneity in the CMB has its origin in cosmological perturbations. The scalar and tensor modes are again quantum fields, but now they propagate on the quantum geometry represented by $\Psi_o$ [1,2]. Their evolution during the Planck era near the big bounce is governed by quintessentially quantum properties of $\Psi_o$ that make space-time curvature finite. Furthermore, this evolution is also sensitive to quantum fluctuations of certain observables in this state. However, so long as the back reaction on quantum geometry of perturbations can be neglected, there is an unforeseen simplification: all these effects can be incorporated by replacing $\Psi_o$ by a smooth FLRW metric $\tilde{g}_{ab}$ called the dressed effective metric. Unlike in general relativity, components of $\tilde{g}_{ab}$ depend on Planck's constant $\hbar$, and are determined by expectation values and fluctuations of specific observables in $\Psi$. However, $\tilde{g}_{ab}$ does not have the full information encoded in $\Psi$. Consequently, dynamics of scalar and tensor modes on two very different quantum geometry states $\Psi_o$ would be identical if they define the same dressed effective metric. Furthermore, we show that the observed (T-T, T-E and E-E) power spectra themselves
do not depend on all the details of dynamics of scalar and tensor modes. Thus there are, so to say, two ‘filters’, each of which erases a part of the input information. Consequently, the observed power spectra are sensitive only to a fraction of all the rich information in $\Psi_o$. Very different choices of $\Psi_o$ can lead to the same observable quantities.

This qualitative fact is not surprising by itself. Even in the classical regime, the CMB observations provide us information captured just in the homogeneous, isotropic degrees of freedom. However, together with the theoretical paradigm in which they are interpreted, observations do suffice to determine the evolution of these degrees of freedom within the error bars. In practice this is done by finding the FLRW solution within a 6 parameter family that best fits the data. One would therefore expect that permissible wave functions $\Psi_o$ would be well constrained by observations, with only small deviations in their functional form. Surprisingly, we found that this is very far from being the case!

Specifically, for $\Psi_o$ we examined: (i) Gaussian wave functions that are sharply peaked about the dressed effective trajectory, with relative dispersions of $\sim 0.1\%$ in the Planck regime; (ii) Gaussian wave functions in which the relative dispersions are over 100\% in the Planck regime; and (iii) non-Gaussian wave functions with several unruly ‘bumps’, in which the relative dispersions are again over 100\% in the Planck regime. We found that there exist states in the three classes that lead to indistinguishable power spectra, all of which agree with observations to date.

This surprising finding has two consequences. First, for comparison with observations, in LQC we can use the simpler, sharply peaked states without loss of generality. Second, since the only probes into the nature of the very universe that we can envisage today are the cosmological perturbations, we cannot hope to determine even the qualitative features of the quantum state of the very early universe. It could have a Gaussian profile, or be extremely irregular. It could be sharply peaked on a (quantum corrected) FLRW solution, or could have wild quantum fluctuations, with relative uncertainties exceeding 100\%. Unless one finds new probes, we would never be able to tell!


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Read the full article in Classical and Quantum Gravity:
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This article is also part of a focus issue on applications of loop quantum gravity.

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