Alleviating the Tension in the Cosmic Microwave Background Using Planck-Scale Physics

Abhay Ashtekar,[1] Brajesh Gupt,[1] Donghui Jeong,[2] and V. Sreenath[3]
[1]Institute for Gravitation and the Cosmos & Physics Department, Penn State University, University Park, Pennsylvania 16801, USA
[2]Institute for Gravitation and the Cosmos & Department of Astronomy and Astrophysics, Penn State University, University Park, Pennsylvania 16801, USA
[3]Department of Physics, National Institute of Technology Karnataka, Surathkal 575025, India

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Certain anomalies in the CMB bring out a tension between the six-parameter flat ΛCDM model and the CMB data. We revisit the PLANCK analysis with loop quantum cosmology (LQC) predictions and show that LQC alleviates both the large-scale power anomaly and the tension in the lensing amplitude. These differences arise because, in LQC, the *primordial* power spectrum is scale dependent for small k, with a specific power suppression. We conclude with a prediction of larger optical depth and power suppression in the B-mode polarization power spectrum on large scales.

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Introduction.—The ΛCDM model selected by the PLANCK satellite data has had impressive success in explaining all major features in the temperature anisotropies and polarizations of the cosmic microwave background (CMB), using only six parameters [1]. Let us begin by recalling the procedure that is used to determine the model from the CMB data. Inspired by inflationary models, one assumes that the primordial power spectrum is nearly scale invariant with a specific form, which we will refer to as the standard ansatz (SA):

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_\star}\right)^{n_s - 1}, \tag{1}$$

where A_s is the amplitude of the scalar mode and n_s its spectral index. (Here, $k_\star = 0.05$ Mpc^{-1} is the pivot mode.) To determine a specific ΛCDM model, one requires four additional parameters: $\Omega_b h^2, \Omega_c h^2$ that refer, respectively, to baryonic and the cold matter density; and $100\theta_*$, τ that determine the observed angular scale associated with acoustic oscillations, and the optical depth that characterizes the reionization epoch [2], respectively. Given the SA and the six parameters, the Boltzmann codes [3–5] that incorporate subsequent astrophysics provides us with four power spectra $C_\ell^{TT}, C_\ell^{TE}, C_\ell^{EE}, C_\ell^{\phi\phi}$, where T, E, ϕ stand for temperature, E-mode (even-parity) polarization, and lensing potential [6,7]. One compares these theoretical predictions with the observed power spectra and finds the best-fitting values (together with uncertainties) for the six parameters. This fixes the ΛCDM model. One can then work out predictions for other observables, which can be measured independently. For example, the four-point correlation function of the CMB measures the gravitational lensing amplitude A_L [8], and the B-mode (odd-parity) polarization power spectrum C_ℓ^{BB} measures the amplitude of tensor perturbation in the early Universe [9,10].

At the same time, the CMB data exhibit some anomalies that bring out tensions between the best-fit ΛCDM model and observation. We will ignore the tension between the CMB and low-z observations, and focus instead on two anomalies in the CMB. The first is the large-scale power anomaly related to $S_{1/2} \equiv \int_{-1}^{1/2} [C(\theta)]^2 d(\cos\theta)$, obtained by integrating the two-point correlation function $C(\theta)$ of the CMB temperature anisotropies over large angular scales ($\theta > 60°$). The WMAP [11,12] and PLANCK [13,14] measured values of $S_{1/2}$ are much smaller than the expectation from the SA + ΛCDM cosmology. The second is the anomaly associated with the lensing amplitude A_L. When it is allowed to vary, A_L prefers a value larger than unity, hinting at an internal inconsistency in the ΛCDM cosmology [7,15–19] based on the SA. In particular, it was recently suggested [20] that this anomaly gives rise to a "possible crisis in cosmology" because the positive spatial curvature one can introduce to alleviate this tension makes CMB analysis inconsistent with low-z cosmological measurements.

In this Letter, we present an intriguing possibility of alleviating both anomalies within a well-motivated theoretical framework of loop quantum cosmology (LQC). First, the LQC prediction modifies the SA for the primordial power spectrum by suppressing its large-scale amplitude, which naturally leads to lower $S_{1/2}$. The scale-dependent primordial power spectrum, in turn, prefers a higher amplitude A_s that pushes lensing amplitude A_L toward unity (making it consistent with flat ΛCDM), and higher optical depth τ. Finally we show that, due to the modified primordial power spectrum and higher τ, LQC

leaves a specific signature in the B-mode (odd-parity) polarization power spectrum.

Modified primordial power spectrum.—In LQC, the big bang singularity is naturally resolved and replaced by a big bounce (see, e.g., Refs. [21,22]). Therefore, one can systematically investigate the dynamics of cosmological perturbations in the pre-inflationary epoch starting from the Planck regime (see, e.g., Refs. [23–34]). Since the quantum corrected Einstein's equations never break down, all physical quantities remain finite. In particular, while the scalar curvature R of space-time diverges at the big bang, it remains *finite* at the bounce, achieving its universal maximum value $R_{\rm max} \approx 62$ in Planck units. Now, curvature—more precisely $R/6$—provides a natural scale in the dynamics of the gauge invariant perturbations (which in de Sitter space-time coincides with $2H^2$). Fourier modes with *physical* wave numbers $k_{\rm phys} \equiv k/a(\eta) \gg (R/6)^{1/2}$ are essentially unaffected by curvature while those with $k_{\rm phys} \lesssim (R/6)^{1/2}$ get excited. Therefore the evolution during the preinflationary epoch of LQC is subject to a new scale: $k_{\rm LQC} = (R_{\rm max}/6)^{1/2} \approx 3.21$ in Planck units. Modes with $k^{\rm B}_{\rm phys} \lesssim k_{\rm LQC}$ at the bounce are excited during their preinflationary evolution. Therefore they are not in the Bunch Davies (BD) vacuum at the onset of the relevant slow roll phase of inflation—i.e., a couple of e-folds before the time at which the mode with the largest observable wavelength crosses the Hubble horizon during inflation. (For details, see Refs. [23,24]).

Now, one's first reaction may be that these excitations are observationally irrelevant because they would be simply diluted away by the end of inflation. However, this is not the case: because of stimulated emission, the number density of these excitations remains constant during inflation [22,35,36]. Therefore the primordial LQC power spectrum at the end of inflation is *different* from the standard ansatz of Eq. (1) for modes with $k^{B}_{\rm phys} < k_{\rm LQC}$.

The key question then is whether these long wavelength modes are in the observable range. The answer depends on the choice of the background metric that satisfies the quantum corrected Einstein's equations of LQC, and the Heisenberg state of the cosmological perturbations. In standard inflation, the background metric can be any solution of Einstein's equation for the given potential, and, since one cannot specify the quantum state of perturbations at the big bang, one specifies it, so to say, in the middle of the evolution by asking that they be in the BD vacuum at the start of the relevant phase of the slow roll. In LQC, geometry is regular at the bounce. Using this fact, key features of the quantum geometry in LQC, and a "quantum generalization" of Penrose's Weyl curvature hypothesis [37], a specific proposal has been put forward to make the required choices [30,31]. Quantum corrected LQC dynamics then leads to unique predictions for the primordial power spectrum for any given inflationary potential; there are no parameters to adjust. The viewpoint is to use the proposal as a working hypothesis, analyze the consequences, and use the CMB observations to test its admissibility.

The proposal constrains the background metric to be such that the ΛCDM universe has undergone $\simeq$141 e-folds since the bounce (irrespective of the choice of inflationary potential) [30]. It then follows that the mode with $k_{\rm phys} = k_{\rm LQC}$ at the bounce has comoving wave number $k_\circ \simeq 3.6 \times 10^{-4}$ Mpc^{-1}. The primordial power spectrum of LQC is nearly scale invariant for $k \gg k_\circ$ but power is suppressed for $k \lesssim 10k_\circ$:

$$\mathcal{P}^{\rm LQC}_{\mathcal{R}} = f(k) A_s \left(\frac{k}{k_\star}\right)^{n_s - 1}, \tag{2}$$

where the form of the suppression factor $f(k)$ can be seen in Fig. 1. [$f(k) \approx 1$ for $k \gg k_\circ$.] This difference from the standard ansatz can be traced back directly to the modes not being in the BD vacuum at the onset of inflation. Now, if the total energy in the scalar field is dominated by the kinetic contribution at the bounce, details of the potential do not affect the preinflationary dynamics, and the suppression factor $f(k)$ is also the same. Analysis of Ref. [38] strongly suggests that there is a large class of potentials for which our proposal to choose the background geometry will constrain the bounce to be kinetic energy dominated. This is illustrated by comparing the Starobinsky inflation [39] and the quadratic potential in Fig. 1.

Results.—All results are based on the PLANCK -2018 data [1] using the observed TT, TE, EE, and ϕ-ϕ power spectra (including the $\ell < 30$ modes for EE correlations) to which the associated likelihoods are Planck TT-TEEE + lowl + low$E$ + Lensing.

Figure 2 shows the observed TT-power spectrum together with the 1σ (68% confidence level) error bars, and the LQC and the SA predictions for the respective best-fit cosmological parameters. Clearly, LQC power is suppressed at $\ell \lesssim 30$ relative to the SA. This is also true for the

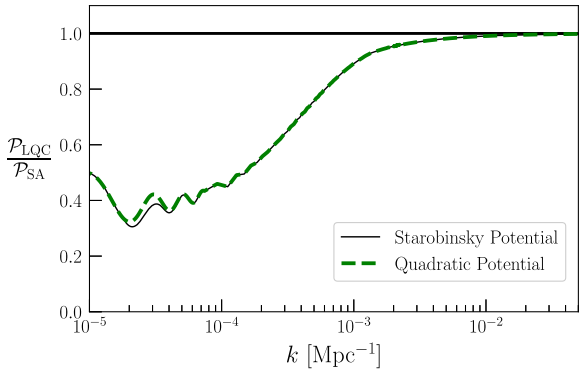

FIG. 1. Ratio of the primordial scalar-power spectrum for LQC and SA. Power is suppressed in LQC for $k \lesssim 10k_\circ \simeq 3.6 \times 10^{-3}$ Mpc^{-1}. Plots for the Starobinsky and quadratic potentials are essentially indistinguishable.

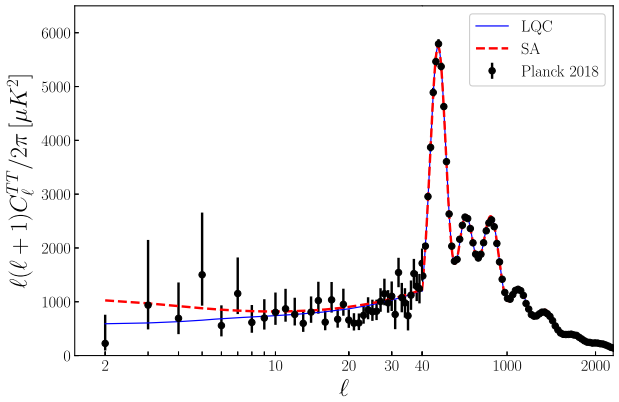

FIG. 2. TT power spectra. The 2018 PLANCK spectrum (black dots with error bars), the LQC [solid (blue) line], and the standard ansatz predictions [dashed (red) line].

EE power spectrum (as already noted in Ref. [30], using the then available PLANCK 2015 data). Note that the difference between LQC and SA best-fitting curves shown in Fig. 2 underestimates the difference in the predicted primordial spectra, for the best-fitting cosmological parameters are different. Also, had the LQC + ΛCDM model been used for their analysis, the cosmic-variance uncertainties on large scales may have been smaller than the reported values from PLANCK 2018.

Figure 3 compares the angular TT two-point correlation function $C(\theta)$ predicted by LQC with that predicted by the SA. It is clear by inspection that the LQC prediction for $C(\theta)$ is closer to the observed values for all θ. In order to quantify this difference, we computed $S_{1/2}$. As the last row of Table I shows, the $S_{1/2}$ from the best-fit LQC + ΛCDM model is about *a third* of that obtained from SA + ΛCDM, and closer to the value of $S_{1/2} = 1209.2$ given by the PLANCK Collaboration using the Commander CMB map. But since that value is obtained after masking and additional processing, a more appropriate comparison would be

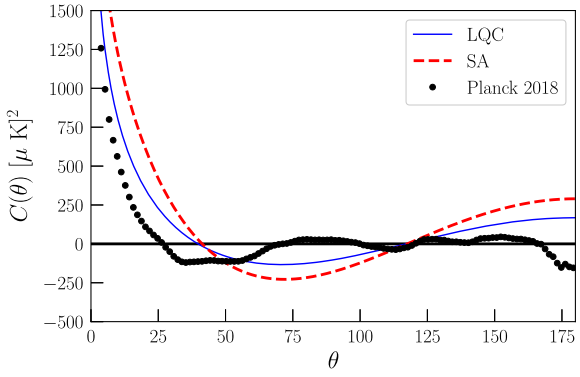

FIG. 3. The angular power spectrum $C(\theta)$. The 2018 PLANCK spectrum (thick black dots), the LQC [solid (blue) line], and the standard ansatz [dashed (red) line] predictions. Values of cosmological parameters are fixed to the mean values given in Table I.

TABLE I. Comparison between the standard ansatz and LQC. The mean values of the marginalized PDF for the six cosmological parameters, and values of $S_{1/2}$ calculated using C_ℓ^{TT}.

Parameter	SA	LQC
$\Omega_b h^2$	$0.022\,38 \pm 0.000\,14$	$0.022\,39 \pm 0.000\,15$
$\Omega_c h^2$	0.1200 ± 0.0012	0.1200 ± 0.0012
$100\theta_{MC}$	$1.040\,91 \pm 0.000\,31$	$1.040\,93 \pm 0.000\,31$
τ	0.0542 ± 0.0074	0.0595 ± 0.0079
$\ln(10^{10}A_s)$	3.044 ± 0.014	3.054 ± 0.015
n_s	0.9651 ± 0.0041	0.9643 ± 0.0042
$S_{1/2}$	42 496.5	14 308.05

with the value 6771.7 of $S_{1/2}$ obtained from the full sky map, i.e., using the PLANCK C^{TT} data for all ℓ. The difference between LQC and this PLANCK value is also significantly lower than that between SA and this PLANCK value. This is a substantial alleviation of the tension between theory and observations that has been emphasized over the years [11–14].

Table I also shows the mean values of the marginalized probability distributions of the six cosmological parameters together with their 1σ ranges. For the first three, namely, $\Omega_b h^2$, $\Omega_c h^2$, and $100\theta_{MC}$, the difference between the SA + ΛCDM and LQC + ΛCDM values is $< 0.07\sigma$ and for n_s the difference is $\sim 0.2\sigma$. However, the values of the optical depth τ and $\ln(10^{10}A_s)$ have increased in LQC by 0.72σ. As we discuss below, this significant change is a direct consequence of the scale-dependent initial power spectrum (2) of LQC, which also leads to a 0.56σ decrease in the lensing amplitude A_L from 1.072 ± 0.041 in SA + ΛCDM to 1.049 ± 0.040 in LQC + ΛCDM, when A_L is also varied. Furthermore, when A_L is included in the analysis,

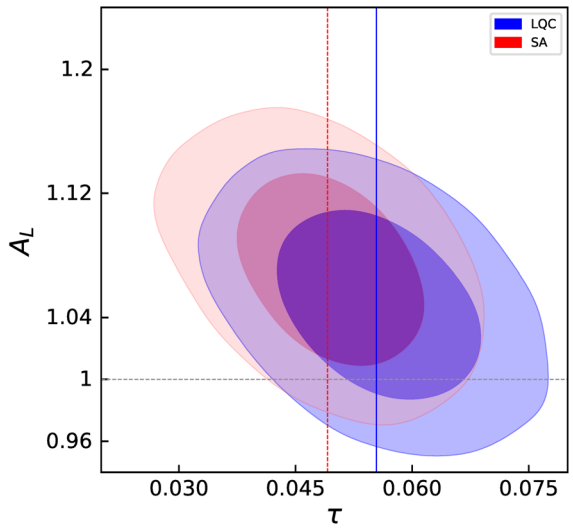

FIG. 4. 1σ and 2σ probability distributions in the $\tau - A_L$ plane. Predictions of the standard ansatz (shown in red) and LQC (shown in blue). Vertical lines represent the respective mean values of τ.

the ΛCDM parameters change by $0.59\sigma - 1.48\sigma$ in SA and $0.39\sigma - 1\sigma$ in LQC. As Fig. 4 shows, the value $A_L = 1$ lies outside of the 68% confidence level for the SA + ΛCDM model (red contours). A natural way to alleviate this tension within the SA + ΛCDM is to consider a closed universe. However, then other disagreements with observations arise that prompted the authors of Ref. [20] to raise the possibility of a "crisis in cosmology." What is the situation with the altered values of τ and A_L in LQC? We see from Fig. 4 that now the tension is naturally alleviated because the value $A_L = 1$ is within 68% confidence level (blue contours). Therefore, the primary motivation for introducing spatial curvature no longer exists in LQC.

General implications of power suppression at large angles.—In LQC, the mechanism for departure from the nearly scale invariant ansatz (1) is rooted in fundamental considerations in the Planck regime. Nonetheless, it is natural to ask if the qualitative features of some of our results will carry over if there were other mechanisms that led to the primordial spectrum of the form given in Eq. (2). We now show that this is indeed the case.

Let us then suppose that there is *some* mechanism that provides a primordial power spectrum of the form (2) for some $k_\circ$. Let us compare and contrast the resulting best fit ΛCDM model with that given by the SA of Eq. (1). As a first step, let us restrict the analysis only to smaller angular scales ($k \gg k_\circ$). Then, the primordial spectrum in both schemes is the same, whence we will obtain the same best fit values of the six cosmological parameters. Denote by $\mathring{A}_s$ the best fit value of the scalar amplitude A_s. In the second step, let us bring in the *full* range of observable modes including $k \leq k_\circ$. Now, given the *observed* large-scale suppression in the TT power spectrum, for SA + ΛCDM model the best-fit value $A_s^{(1)}$ for the entire k range will be lower than $\mathring{A}_s$. By contrast, if the primordial power spectrum is of the form of Eq. (2), $\mathring{A}_s$ will not have to be lowered as much to obtain the best fit $A_s^{(2)}$ since the initial power is already suppressed by $f(k)$. Thus, we have $\mathring{A}_s > A_s^{(2)} > A_s^{(1)}$. [For the $f(k)$ in LQC, we have $\ln(10^{10}\mathring{A}_s) = 3.089$ and $\ln(10^{10}As^{(2)}) = 3.054$ and $\ln(10^{10}As^{(1)}) = 3.044$.] The key point is the last inequality: $A_s^{(2)} > A_s^{(1)}$. Now, we know that for large k, the product $A_s e^{-2\tau}$ is fixed by observations. Hence, it follows that the best fit values of the optical depth in the two scheme must satisfy $\tau^{(2)} > \tau^{(1)}$. Finally, from the very definition of lensing amplitude, the value of A_L is anticorrelated to the value of A_s. Therefore, we will have $A_L^{(2)} < A_L^{(1)}$. Thus in any theory that has primordial spectrum of the form (2), A_s, τ, and A_L will have the same qualitative behavior as in LQC, and hence the tension with observations would be reduced. What LQC provides is a precise form of the suppression factor $f(k)$ from "first principles," and hence specific quantitative predictions. The LQC $f(k)$ also leads to other predictions—e.g., for the BB power spectrum discussed below—that need not be shared by other mechanisms.

Summary and discussion.—In LQC, curvature never diverges and reaches its maximum value at the bounce. As a result, preinflationary dynamics naturally inherits a new scale, $k_{\rm LQC}$, such that modes with $k^B_{\rm phys} \lesssim k_{\rm LQC}$ at the bounce are not in the BD vacuum at the start of the slow roll phase of inflation [23,24], whence the primordial power spectrum is no longer nearly scale invariant, but of the form (2). The LQC dynamics and initial conditions then imply [30] that there is power suppression in CMB at the largest angular scales $\ell \lesssim 30$. In contrast to other mechanisms that have been proposed, this suppression has origin in fundamental, Planck scale physics rather than in phenomenological adjustments put in by hand just before or during the slow roll. As a result of this power suppression, there is an enhancement of optical depth τ and suppression of the lensing potential A_L. The two together bring the value $A_L = 1$ within 1σ of the LQC $\tau - A_L$ probability distribution, thereby removing the primary motivation for considering closed universe and the subsequent "potential crisis" [20]. In addition, the anomaly in $C(\theta)$ at large angles [11–14] is significantly reduced; the LQC value of $S_{1/2}$ is ∼0.34 of that predicted by standard inflation. The PLANCK Collaboration had suggested [1] that "… if any of the anomalies have primordial origin, then their large scale nature would suggest an explanation rooted in fundamental physics. Thus it is worth exploring any models that might explain an anomaly (even better, multiple anomalies) naturally, or with very few parameters." In this Letter we presented a concrete realization of this idea. (For an alternate proposal within LQC see Ref. [40]).

This model also leads to other specific predictions. First, as Table I shows, the reionization optical depth τ is predicted to be ∼9.8% (i.e., 0.72σ) higher. This prediction can be tested by the future observation of global 21 cm evolution at high redshifts that can reach a percent level accuracy in the measurement of τ [41]. Second, for any given inflationary potential, the *primordial* spectra of LQC

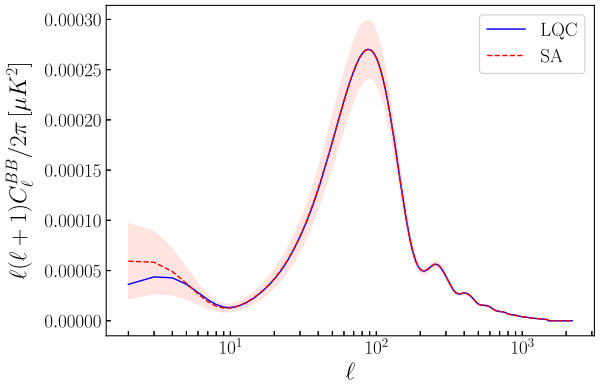

FIG. 5. Predicted power spectra for BB polarization with 1σ uncertainty. Comparison between LQC and standard inflation. The tensor to scalar ratio r has been set to 0.0041, motivated by Starobinsky inflation [39]. The shaded region indicates the cosmic variance for SA.

and SA share the same value of r—the tensor to scalar ratio—which depends on the potential. But there is a specific scale dependence in the large-scale B-mode (odd-parity) polarization power spectrum, as shown in Fig. 5. The difference is driven by the LQC suppression of the primordial tensor amplitude combined with the larger reionization contribution due to higher τ. Provided that r is sufficiently large, for example, $r \gtrsim 0.001$, we may be able to test this prediction against the data from the future B-mode missions such as LiteBIRD [42], Cosmic Origins Explorer [43], or Probe Inflation and Cosmic Origins (PICO [44]). Again, LQC modifies C_ℓ^{BB} on large scales where the cosmic variance limits its detectability. However, in light of results presented in this Letter, we hope that the LQC primordial power spectrum will be included in the future cosmological analysis.

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