Constraining Planck scale physics with CMB and Reionization Optical Depth

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We present proof of principle for a two way interplay between physics at very early Universe and late time observations. We find a relation between primordial mechanisms responsible for large scale power suppression in the primordial power spectrum and the value of reionization optical depth \( \tau \). Such mechanisms can affect the estimation of \( \tau \). We show that using future measurements of \( \tau \), one can obtain constraints on the pre-inflationary dynamics, providing a new window on the physics of the very early Universe. Furthermore, the new, re-estimated \( \tau \) can potentially resolve moderate discrepancy between high and low-\( \ell \) measurements of \( \tau \), hence providing empirical support for the power suppression anomaly and its primordial origin.

The \( \Lambda \)CDM model of cosmology explains up to great accuracy the temperature and polarization spectrum of the cosmic microwave background (CMB) measured over the past three decades. However, the recent precise measurements by the WMAP [1] and Planck [2] missions have revealed lack of power at large angular scales corresponding to \( \ell < 30 \) at \( \sim 3 \sigma \) significance level, also known as the large scale power suppression anomaly (PSA) [3]. While its origin is still a matter of current investigation, it is envisaged that PSA could be a relic of pre-inflationary dynamics in the very early Universe [2].

In this Letter, we discuss that it is possible to use the planned observational missions to derive constraints on potential primordial mechanisms behind PSA. Any new physics in the early Universe comes with freedom in the choice initial conditions or physical parameters. We show that if PSA is indeed primordial in origin, since it affects EE polarization at low-\( \ell \) [4], it can affect the estimation of Thompson scattering optical depth \( \tau \) of late time reionization. This leads to a degeneracy between the value of \( \tau \) and the aforementioned freedom associated to primordial mechanism potentially responsible for PSA. Since the power suppression is a low-\( \ell \) phenomenon, this degeneracy can be broken via independent measurements of the optical depth using high-\( \ell \) data from future measurements. For instance, CMB S4 mission [5] and 21 cm cosmology [6] corresponding to high-\( \ell \) physics, are supposed to provide independent estimations of \( \tau \). Furthermore, we find that considering the suppressed power due to primordial mechanism can alleviate a moderate discrepancy that exists in determining mean \( \tau \) from low-\( \ell \) EE polarization in [7,8] and high-\( \ell \) in lensed temperature data in [9].

One of the most prominent estimations of \( \tau \) comes from CMB via the so called “reionization bump” in the E-mode polarization spectrum at \( \ell < 20 \), which plays a crucial role in estimating \( \tau \) [10,11]. The first constraint on \( \tau \) from CMB measurements was put by the WMAP 1-year data release to be \( \tau = 0.17\pm0.04 \) using TE-mode polarization spectrum [10] which was significantly improved by the 9-year data release to \( \tau = 0.089\pm0.014 \) [12] using the EE, TE and TT data at low-\( \ell \). In Planck 2015 data release, \( \tau \) was estimated using the lensed high-\( \ell \) TT spectrum to be \( \tau = 0.066\pm0.016 \) [13]. In recent Planck intermediate results, \( \tau \) was re-estimated as \( \tau = 0.055\pm0.009 \) using the low-\( \ell \) EE data coming from high frequency instruments [7,8]. Thus, there is a moderate discrepancy of about \( \sim 1.2\sigma \) between the mean value of \( \tau \) from high-\( \ell \) TT and low-\( \ell \) EE data by Planck. We will show that this discrepancy can be alleviated by reestimating \( \tau \) with the suppressed scalar power spectrum.

For explicit computations we will consider the large scale power suppression due to the quantum gravitational corrections of loop quantum cosmology (LQC) proposed in [13] and show that using future measurements, we can obtain constraints on the associated new physics in the pre-inflationary era [1]. For a given inflationary model with an inflaton field in presence of a suitable potential in a Friedmann, Lemaître, Robertson, Walker (FLRW) spacetime, LQC provides a consistent, non-singular extension of the inflationary scenario all the way up to the Planckian curvature scale [21,22]. Let us briefly discuss the salient features of LQC framework relevant for this paper.

**Framework:** In the standard inflationary scenario based on classical GR, the FLRW spacetime is described by a single spacetime metric \( g_{ab}(a, \phi) \), with \( a \) being the scale factor and \( \phi \) the inflaton field. We will use the Starobinsky potential to drive inflationary dynamics (see e.g. [23] for a detailed analysis). However, the final results of our analysis should hold for other choices of inflationary potential [15,23].

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1 There are also other proposals for the power suppression mechanisms [1,13,19]. The qualitative results obtained here are expected to hold true for these mechanisms as well.
In LQC, the background spacetime is given by quantum Riemannian geometry described by a quantum wavefunction $\Psi_o(a, \phi)$ which has support on several $g_{ab}$’s. The quantum wavefunction is obtained by solving the quantum Hamiltonian constraint, a difference equation with the step size given by the minimum non-zero eigenvalue of the area operator $\Delta_o$ whose value is fixed to $\Delta_o = 5.17$ via black hole entropy computations in loop quantum gravity. A direct consequence of the discrete quantum geometry is the resolution of the classical big bang singularity via a quantum bounce in the expectation value of the scale factor [20][24]. The quantum bounce defines a characteristic LQC energy scale directly related to $\Delta_o$:

$$k_{(LQC)} = 0.00024 \text{ Mpc}^{-1}. \tag{2}$$

Note that eq. (2) represents the value expected from the simplest quantum geometry in the deep quantum gravity. If this assumptions is dropped, $k_{(LQC)}$ becomes a free parameter and would need to be refined using inputs from observations.

**CMB Polarization spectrum:** $k_{(LQC)}$ defines a scale at which the pre-inflationary effects to the power spectrum become important. Modes of cosmological perturbations with $k \gg k_{(LQC)}$ remain unaffected by LQC corrections. However, the infrared modes with $k \lesssim k_{(LQC)}$ carry an imprint of the quantum gravity era and arrive at the slow-roll phase in an excited state [22]. As discussed in [13], with the appropriate choice of initial conditions for perturbations, the power spectrum of these modes is significantly different from the standard one and is suppressed at scales corresponding to multipoles $\ell < 30$. The resulting temperature-temperature spectrum then fits better with the Planck data than the one corresponding to the standard, nearly scale invariant primordial power spectrum (PPS).

For the analysis in this paper, we will restrict ourselves to the EE spectrum for $\ell = 2 - 20$, similarly to the recent analysis of the reionization history by *Planck* [7][8]. As discussed in [8], this is enough as the high-$\ell$ likelihoods in EE do not contain additional information about reionization. Fig. 1 shows the EE polarization spectrum for the standard PPS and the suppressed PPS of LQC, where the LQC characteristic scale is fixed as in eq. (2). The left panel compares the power spectra for $\tau = 0.055$, the best fit value obtained in [7], while all the other cosmological parameters are fixed to their best fit values reported in [9]. The amplitude of the reionization bump for the LQC spectrum is suppressed. The right panel compares the polarization spectra for standard PPS with $\tau = 0.055$ to the suppressed LQC PPS with $\tau = 0.072$. This implies that, the suppressed power spectrum would predict a larger value of the optical depth. Thus, there is an apparent correlation between the values of $k_{(LQC)}$ and $\tau$.

**Fisher information matrix and error bars:** To quantify the aforementioned correlation $k_{(LQC)}$ and $\tau$, we compute the Fisher information matrix [25]. Since the *Planck* data for low-$\ell$ polarization is not yet available, for this analysis we will assume that the error bars on $C_\ell^{EE}$ at low-$\ell$’s is given by the cosmic variance limit. As discussed in [24], the Fisher matrix then takes the following form:

$$\mathbf{F}_{ij} = \sum_{\ell=2}^{\ell_{\text{max}}} \frac{1}{(\Delta C_\ell^{EE})^2} \frac{\partial C_\ell^{EE}}{\partial \theta_i} \frac{\partial C_\ell^{EE}}{\partial \theta_j}, \tag{3}$$

where

$$\Delta C_\ell^{EE} = \sqrt{\frac{2}{2\ell + 1}} C_\ell^{EE}, \tag{4}$$

and $\theta = (\tau, k_{(LQC)})$, while the other cosmological parameters are fixed at their best fit value given in [9]. Recall
that effects of \( k_{(LQC)} \) are limited to very large angular scales and \( \tau \) is determined from the E-mode reionization bump which also occurs at \( \ell < 20 \). Therefore, we keep \( \ell_{\text{max}} \) in eq. (3) large enough (at least 50) to include the affected multipoles in our analysis.

Elements of the covariance matrix between \( k_{(LQC)} \) and \( \tau \) are then obtained by inverting the Fisher matrix: \( C_{ij} = (F^{-1})_{ij} \). Fig. 2 shows the error ellipse corresponding to \( C_{ij} \). The inner and outer contours correspond to the 68% and 95% confidence levels respectively. As expected from previous discussions, there is a strong degeneracy between \( k_{(LQC)} \) and \( \tau \). Note that \( C_{ij} \) only captures the information about the error bars and correlation between the two parameters. The mean values of \( \tau \) and \( k_{(LQC)} \) at which the errors ellipse is centered are given by the best fit values which we have obtained by proceeding as follows.

**Implications for future observations and Constraints on LQC:** As evident from Fig. 2, there is strong degeneracy between \( k_{(LQC)} \) and \( \tau \) measured from the low-\( \ell \) polarization data. In order to break this degeneracy we would need an independent estimation of either \( k_{(LQC)} \) or \( \tau \). The LQC scale \( k_{(LQC)} \) is a parameter of the underlying theory. On the other hand, \( \tau \) can be measured using high-\( \ell \) TT data as well as by upcoming experiments such as CMB S4 [5] and 21 cm cosmology [6] missions independent from Planck measurements. The measured value of \( \tau \) from these experiments will break the degeneracy with \( k_{(LQC)} \) and put observational constraints on \( k_{(LQC)} \).

Recall that the value of \( k_{(LQC)} \) determines \( a(t_B) \), i.e. the initial conditions of the background geometry at the bounce.\(^2\) Thus, we can learn about the properties of quantum geometry using future observational data. Moreover, as discussed before, since the suppressed power spectrum is used to determine \( \tau \) with the low-\( \ell \) EE data, the new value of \( \tau \) might increase enough and come closer to 0.066—the value obtained from high-\( \ell \) TT data [9]—hence resolving an apparent discrepancy between estimation of \( \tau \) from low-\( \ell \) EE and high-\( \ell \) TT data. Let us find out if this expectation is borne out in our analysis.

To obtain the best fit values of \( \tau \) for the suppressed PPS we perform the maximum likelihood analysis with low-\( \ell \) \( C_{EE}^{\ell} \) by varying \( \tau \), keeping \( k_{(LQC)} = 0.00024 \text{ Mpc}^{-1} \) (eq. [2]), obtained from consideration of simplest quantum geometry in the deep Planck regime [13], while fixing other cosmological parameters at their best fit values given in [9].

In order to perform this analysis, we need the EE spectrum measured from experiments at low-\( \ell \) which, however, has not been made available publicly yet. Given the lack of real data, we will work with a “simulated” EE data at low-\( \ell \) constructed in the following manner. We fix \( \tau = 0.055 \) (i.e. the mean value of \( \tau \) obtained in [7]) and compute \( C_{\ell}^{EE} \) assuming the standard almost scale invari-

\(^2\) This assumes that the state for quantum perturbations are fixed using a quantum generalization of the Weyl curvature hypothesis as discussed in [15,27]
ant power spectrum. We consider this to be the central values of $C^{EE}_\ell$ with the errors bars given by the cosmic variance at low-$\ell$. In this sense, our “simulated” data represents the best ever possible CMB measurements at low multipoles.

Fig. 3 shows the corresponding one dimensional posterior distribution of $\tau$ for the standard PPS (dashed blue curve) and the suppressed LQC PPS (solid red curve). The estimated $\tau$ with 95% error bars are:

$$\tau = 0.055 \pm 0.008 \quad \text{(Standard PPS)}$$
$$\tau = 0.062 \pm 0.008 \quad \text{(Suppressed PPS).} \quad (5)$$

Note that the width of the posterior distribution is sharper as compared to that obtained in [7], because here we have considered the “simulated” data with cosmic variance error bars which are significantly smaller. It is evident that the peak of the posterior has shifted to a higher value of $\tau$ when the suppressed power spectrum is used. Moreover, the re-estimated value is closer to the one obtained from high-$\ell$ TT data: $\tau = 0.066$. This indicates that if the large scale power suppression is indeed a primordial effect rather than a statistical fluke, it can resolve the discrepancy between the estimation of $\tau$ purely from low-$\ell$ EE polarization spectrum (estimated to be 0.055 with the standard PPS) and high-$\ell$ TT spectrum. This indicates further empirical support for the possibility that the PSA could have originated from physical processes in the very early Universe.

In this Letter we have shown that future observational data, in particular giving independent measurement of $\tau$ can be used to determine the scale at which PSA is observed in the TT spectrum, which in turn can constrain the associated pre-inflationary physics. Here we have only presented a proof of principle that there is potentially a new window on pre-inflationary physics via a symbiotic interplay between observational data and fundamental. While we performed a case study by considering the pre-inflationary dynamics of loop quantum cosmology, the overall results of the analysis can be extended to other primordial mechanisms which introduces a characteristic scale for suppression of power at large angular scales. Due to the lack of availability of observational data for polarization at low-$\ell$ we used simulated data assuming the error bars on $C^{EE}_\ell$ at low-$\ell$ to be given by the cosmic variance. The actual experimental data from Planck expected to be released in upcoming few months, will have higher error bars which is expected to only increase the width of the error ellipse while keeping the degeneracy intact. We will revisit this analysis when more data from Planck, CMB S4 and 21 cm cosmology is available, which hopefully will provide new observational insights on the physics of deep Planck regime in the very early Universe.

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3 Cosmic variance is the theoretical lower limit on the error bars at low-$\ell$ and no observational can beat it. However, see [29] for potential way of getting around cosmic variance via careful measurements of quadrupole of the galaxy clusters and CMB secondaries.

4 Of course, in the real data due to instrumental noise and systematics the real error bars would be larger which we will revisit when the low-$\ell$ polarization data from Planck is released. We performed an estimation of the effect of higher error bars on the degeneracy found here by digitizing figure 33 of [7]. We found that the degeneracy is not affected by larger error bars.

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