Quantum Gravity in the Sky?
Alleviating tensions in the CMB using Planck scale physics

Abhay Ashtekar
Institute for Gravitation and the Cosmos & Physics Department; Penn State.

Largely based on PRL 125, 051302 (2020) with Brajesh Gupt, Donghui Jeong and V. Sreenath

September 6th 2020
Fourth Zeldovich Meeting
Using \textbf{LQG} to Extend the Inflationary Paradigm

**Goal:**
Alleviate the tension between theory and observation vis-a-vis anomalies. In particular the power suppression and lensing amplitude anomalies.

**We use:**
- Flat FLRW model with inflationary potential
- Pre-inflationary dynamics of Loop Quantum Cosmology (LQC)
- Choice of the background geometry and perturbations constrained by \textit{Loop Quantum Gravity (LQG)} considerations

**We find:**
- LQC predictions provide a better fit to the observational data.
- Two anomalies are resolved.
- Testable predictions for future observations.
Universe according to Planck: **LCDM Model**

1. Nearly scale invariant primordial power spectrum.

   Standard Ansatz: \[ \mathcal{P}_R = A_s \left( \frac{k}{k_*} \right)^{n_s-1} \]
   \( A_s \): amplitude
   \( n_s \): spectral index

2. Later time astrophysics governed by:

   \( \Omega_b \): matter density
   \( \Omega_c \): CDM density
   \( 100\theta_{MC} \): BAO length
   \( \tau \): re-ionization optical depth

6 parameter model

\[
\begin{align*}
A_s & \quad n_s & \quad \Omega_b \\
\Omega_c & \quad 100\theta_{MC} & \quad \tau
\end{align*}
\]

Boltzmann equations

CAMB

Predicted observables:

\[ C^{TT} \quad C^{EE} \quad C^{TE} \quad C^{\phi\phi} \]

T: temperature, E: polarization, \( \phi \): lensing

Comparison of *predicted and measured* observables give best-fit values and error-bars of the 6 parameters. That determines a LCDM model.
All major features of the observed spectra are explained by the LCDM model selected by the Planck data:

This model further predicts lensing amplitude and B-mode polarization spectrum which can be independently tested using future observations.
Universe according to Planck: Anomalies

The observational data also exhibit some independent, low significance anomalies. However, when considered together, they become significant.

Large scale power anomaly

Observed angular correlation is suppressed compared to predicted. LCDM model predicts much higher value of $S_{1/2} = \int_{-1}^{1/2} d\cos(\theta) |C(\theta)|^2$ than Planck 2018.

$A_L = 1$ lies outside 1-sigma contour. This is incompatible with LCDM model. [Motlock, Hu, Planck 2018]

Led to a recent suggestion "A possible crisis in cosmology" [Di Valentino, Melchiorri, Silk]
1. Statistical significance of individual anomalies is low. However, when considered together, imply that we live in a very specific and highly unlikely realization predicted by the model.

2. An opportunity for quantum gravity to connect with observations. In LQC, the standard ansatz for primordial power spectrum:

\[ P_R = A_s \left( \frac{k}{k_*} \right)^{n_s - 1} \]

is modified. The LQC spectrum agrees with SA at high ‘k’, but there is a specific power suppression at low ‘k’. This results in alleviating the two anomalies.
Loop Quantum Cosmology
Loop quantum cosmology


★ Big bang singularity resolved ($\Psi_o$)

[Bojowald; AA-Pawłowski-Singh]

★ Given an inflationary potential Inflation occurs naturally

[AA-Sloan; Corichi-Karami; Barrau-Linsefors]

★ Quantum fields $\psi$ on quantum geometry $\Psi_o$:

dressed metric approach

[AA-Kaminski-Lewandowski; Agullo-Ashtekar-Nelson]

In LQC one works with sharply peaked $\Psi_o$ to avoid certain infrared issues, as discussed by [Kamiński, Kolanowski and Lewandowski].
Quantum State of the Background and of Perturbations

There is a great deal of freedom in the choice of the state $\Psi_0$ for the background geometry and the state $\psi$ of cosmological perturbations. We use the prescription introduced in [AA, B. Gupt CQG 34 (2017) 014002]

Background geometry: Fixing the background geometry using elements from observations and quantum geometry yields 141 e-folds from bounce till today.

Perturbations: Fixing the Heisenberg state for quantum perturbations using Planck scale dynamics of LQC, and maximum allowed quantum homogeneity and isotropy conditions inspired by Penrose’s Weyl curvature hypothesis.
LQC Predictions and Observations
Standard Ansatz: $P_R = A_s \left( \frac{k}{k_*} \right)^{n_s - 1}$

LQC Spectrum: $P_R = f(k) A_s \left( \frac{k}{k_*} \right)^{n_s - 1}$

- $f(k) = 1$ for large ‘$k’$
- $f(k) < 1$ for small ‘$k’$

Power suppression at small ‘$k’’!

Analytical results of [Anshuman, Copeland, Louko] suggest that these results will hold true for a larger class of inflationary potentials.

In the following slides we will stick to Starobinsky potential: $V(\phi) = \frac{3M^2}{32\pi} \left( 1 - e^{-\sqrt{\frac{18}{5\pi G}} \phi} \right)^2$
LQC spectrum is suppresses for $\ell < 30$ and agrees with SA for $\ell > 30$
TT angular correlation $C(\theta)$

$C'(\theta)$ provides a better measure of the power suppression anomaly.

[Copi, Schwarz, Spergel, Starkman; Planck 2018]

$$S_{1/2} = \int_{-1}^{1/2} d\cos(\theta) \ |C'(\theta)|^2$$

$S_{SA}^{1/2} = 42496.5$

$S_{LQC}^{1/2} = 14308.05$

Significant improvement: a 2/3 reduction!
Anomaly in $A_L - \tau$

$A_L$ : Lensing Amplitude

$\tau$ : re-ionization optical depth

In LCDM model, $A_L = 1$

For SA, $A_L = 1$ is outside $1 - \sigma$ contour.

This led [Di Valentino, Melchiorri, Silk] to introduce spatial curvature and a “possible crisis in cosmology!”

No longer an anomaly in LQC because $A_L = 1$ lies within one $\sigma$

No “Crisis”!
Universe according to ‘Planck + SA’ vs ‘Planck +LQC’

5 cosmological parameters change by less than 0.4%

Optical depth increases by 10%.

\(S_{1/2}\) decreases by a factor of 3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SA</th>
<th>LQC</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Omega_b h^2)</td>
<td>0.02238 ± 0.00014</td>
<td>0.02239 ± 0.00015</td>
</tr>
<tr>
<td>(\Omega_c h^2)</td>
<td>0.1200 ± 0.0012</td>
<td>0.1200 ± 0.0012</td>
</tr>
<tr>
<td>(100\theta_{MC})</td>
<td>1.04091 ± 0.00031</td>
<td>1.04093 ± 0.00031</td>
</tr>
<tr>
<td>(\tau)</td>
<td>0.0542 ± 0.0074</td>
<td>0.0595 ± 0.0079</td>
</tr>
<tr>
<td>(\ln(10^{10} A_s))</td>
<td>3.044 ± 0.014</td>
<td>3.054 ± 0.015</td>
</tr>
<tr>
<td>(n_s)</td>
<td>0.9651 ± 0.0041</td>
<td>0.9643 ± 0.0042</td>
</tr>
<tr>
<td>(S_{1/2})</td>
<td>42496.5</td>
<td>14308.05</td>
</tr>
</tbody>
</table>

Future observations expected to provide independent measurement of optical depth.
1. Concrete realization of the highlighted idea.

2. Suppression in power at large angular scales in the CMB and better agreement with data than standard inflation

3. Potentially observable consequences

LQC leaves observable consequences. No free parameter in the model. There are other mechanism invoking power suppression which requires additional parameters/features in the potential e.g. fast roll inflation etc.

Symbiotic interplay between fundamental theory and observations
Frequently Asked Questions
Why does LQC pre-inflationary dynamics matter?

In LQC, long wavelength observable modes interact with curvature in Planck regime and keep the memory of quantum gravity era!
Q: Can other mechanisms leading to similar power suppression result in similar consequences?

A: In any such scheme, the best fit mean value of the optical depth would be larger than in the standard scenario and that of the lensing amplitude would be lower. Therefore, the tensions in the two CMB anomalies will be reduced. This implication of primordial power suppression appears not to have been noticed before. However, the exact quantitative features and implications for future observations might be different for specific power suppression.
Q: What sets the scale for LQC corrections?

A: In LQC, the curvature scalar ‘R’ has an upper maximum at the bounce. This defines a scale $k_{\text{LQC}} = \sqrt{R_{\text{max}}/6}$ whose coming wavenumber is $4 \times 10^{-3} \text{ Mpc}^{-1}$. The modes with $k \lesssim k_{\text{LQC}}$ get excited by the Planck scale dynamics while the modes with $k >> k_{\text{LQC}}$ remain in Bunch-Davis state at the onset of inflation.