Quantum Gravity in the Sky: Interplay between theory and observation

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ILQGS
Modern Cosmology

Remarkably precise measurements of the Cosmic Microwave Background (CMB) by *Planck* and WMAP have put strong constraints on cosmological parameters and paradigms of early universe such as inflation.

Many next generation CMB observations have been planned to measure E and B mode polarization and non-Gaussianity at cosmological scale more precisely which will teach us more about the early universe.

*Cosmology offers the best chance of testing direct quantum gravity effects in the foreseeable future.*
**Theory:** $\Lambda$CDM + Inflation

*Temperature fluctuations in CMB originate from the quantum vacuum fluctuations in the very early universe*

**Observations:** Planck 2015

- Superb agreement with the data at scales $\ell > 30$
- But, *there are certain limitations of the model*
Large scale CMB anomalies

• Power suppression at $\ell \lesssim 30$
• Power asymmetry

An opportunity for quantum gravity to connect with observations
Limitations of Inflation

(i). The past evolution is incomplete due to the presence of Big Bang singularity: Geodesics cannot be extended

(ii). The quantum perturbations are assumed to be in Bunch-Davies state, which assumes de-Sitter symmetry. But, in an inflationary universe symmetry is only approximate.

The initial conditions are given at an intermediate time.

Also, this choice ignores any pre-inflationary dynamics.
This talk

Goal: Address the limitations of inflation by invoking pre-inflationary dynamics of loop quantum cosmology (LQC)

We use:

• Flat FLRW model with inflationary potential

• Pre-inflationary dynamics of LQC + quantum perturbations

• Introduce two new physical principles to fix background geometry and state of quantum perturbations in Planck regime

We find:

• Power spectrum agrees with standard one at $\ell > 30$ and provides better fit to data at $\ell \lesssim 30$

• Testable predictions for polarization spectrum
Loop quantum cosmology


Background geometry $\Psi_o$ and quantum perturbations $\psi$

- Big bang singularity resolved ($\Psi_o$)
  [Bojowald; Astekar-Pawlowski-Singh]
- Given an inflationary potential Inflation occurs naturally [Ashtekar-Sloan; Corichi-Karami]
- Quantum fields $\psi$ on quantum geometry $\Psi_o$: dressed metric approach
  [Agullo-Ashtekar-Nelson; Ashtekar-Kaminski-Lewandowski]

We will work with sharply peaked $\Psi_o$ for which the dynamics of the dressed metric can be very well approximated by the effective dynamics
Initial conditions

There is tremendous freedom in the choice of initial conditions for the effective background geometry and perturbations. We propose two principles to fix this freedom:

**Principle 1:** Fixing the background geometry using elements from observations and quantum geometry

**Principle 2:** Fixing the Heisenberg state for quantum perturbations using quantum generalization of Weyl curvature hypothesis and Planck scale dynamics of LQC
Principle 1: *fixing background geometry*

Elements of observations:

\[ H_0 = 67.27 \pm 0.66 \text{ km s}^{-1} \text{ Mpc}^{-1} \]
\[ \Omega_m = 0.3156 \pm 0.0091 \]
\[ \Omega_\Lambda = 1 - \Omega_m = 0.6844 \]

Spacetime geometry to the future of CMB is determined

Due to positive \( \Omega_\Lambda \), every eternal observer has a past horizon.

The entire past horizon of an eternal observer is contained in a 2-sphere \( S^2_{\text{CMB}} \) of radius 17.29 MPc

**Task:** *Extend this geometry all the way to the Planck scale*
Principle 1: *fixing background geometry*

Elements of quantum geometry:

The smallest 2-sphere $S_B^2$ is LQG is the one contained in a cubical cell having six intersections with the edges each depositing an area of $\Delta \ell_P^2$

The total area of $S_B^2$ is then $6\Delta \ell_P^2 \approx 31 \ell_P^2$
Principle 1: **fixing background geometry**

The physical size of ever observable universe $S_{\text{CMB}}^2$ emerges from $S_B^2$:

- a sphere of area $= 31 \ell_{\text{Pl}}^2$
- and radius $\mathcal{R}_B = 1.57 \ell_{\text{Pl}}$

This fixes the background geometry for a given inflationary potential.
Consequence of fixing background geometry

Planck regime last for approx. 10 Planck seconds

There are approx. 1.2 e-folds in the Planck regime

Bounce is kinetic energy dominated
Principle 2: *fixing state for perturbations*

★ Based on refining Penrose’s Weyl Curvature hypothesis:

\[
\Delta \mathcal{E} = \Delta \mathcal{B} ; \quad \Delta \mathcal{E} \Delta \mathcal{B} \text{ is minimum}
\]

i.e. equal distribution and minimization of uncertainties in the electric and magnetic part of the Weyl tensor of perturbations

For scalar perturbations the principle translates to imposing following conditions on Heisenberg state:

(i) \( \langle \psi_0 \mid \hat{Q}_{\vec{k}}(t) \mid \psi_0 \rangle = 0 \) and \( \langle \psi_0 \mid \hat{\Pi}_{\vec{k}}(t) \mid \psi_0 \rangle = 0 \)

(ii) \( \Delta \hat{Q}_{\vec{k}}(t) \Delta \hat{\Pi}_{\vec{k}}(t) = \frac{\hbar}{2} V_o \)

(iii) \( \sigma_k^2 := k \left[ \Delta \hat{Q}_{\vec{k}}(t) \right]^2 + \frac{1}{k} \left[ \Delta \hat{\Pi}_{\vec{k}}(t) \right]^2 = \frac{\hbar}{2} V_o \)

This gives us a unique instantaneous state!
Principle 2: *fixing state for perturbations*

Since the background geometry is dynamical $\sigma_k^2$ is time dependent.

In the Planck regime, we get a ball of states characterized by:

$$\sigma_k^2 \leq \sup(\sigma_k^2)$$

The Heisenberg state of the scalar mode $\hat{Q}_k^-$ is the one that minimizes the uncertainty in $\hat{Q}_k^-$, at the end of inflation, within the ball selected by the Planck regime and the quantum version Weyl curvature hypothesis.
So far...

We obtained a Planck scale extension of the background geometry in LQC.

We fixed initial conditions for the background geometry at the bounce and Heisenberg state for perturbations.

There are no free parameters in the theory.

We looked at both Starobinsky and quadratic potentials and the results do not depend on the choice of inflationary potential.

We are now set to compute the resulting observable predictions.
Inflationary potential: \[ V(\phi) = \frac{3M^2}{32\pi} \left(1 - e^{-\sqrt{\frac{10\pi G}{3}} \phi}\right)^2; \quad \phi_B = -1.420 \, m_{Pl} \]
Temperature anisotropy spectrum: $C_{\ell}^{TT}$

Background geometry:

\[ V(\phi) = \frac{3M^2}{32\pi} \left( 1 - e^{-\sqrt{\frac{16\pi G}{3}} \phi} \right)^2 ; \quad \phi_B = -1.420 \ m_{Pl} \]

\[ \Delta \chi^2 = 3.15 \]
Polarization anisotropy spectrum: $C_{\ell}^{EE}$ and $C_{\ell}^{TE}$

**Prediction:** similar suppression obtained in the E-mode polarization spectrum

Late time effects such as integrated Sachs-Wolfe effect also give suppression in $C_{\ell}^{TT}$ but they do not affect $C_{\ell}^{EE}$. [Das-Souradeep]

If suppression is also seen in polarization spectrum, that would be clear indication that the suppression effect is primordial.

Potentially observable consequences for late time re-ionization
Summary: Quantum Gravity in the Sky

LQC + two principles to select background geometry and Heisenberg state for perturbations

*No free parameter in the model*

Consequences:

1. **Suppression in power** at large angular scales in the CMB and better agreement with data than standard inflation
   
   [Also see Agullo’s ILQG talk for another mechanism within LQC]

2. **Predictions** for polarization spectrum which can be tested by future observations

3. **Potentially observable consequences** for late time re-ionization

Symbiotic interplay between fundamental theory and observations
Phenomenological Robustness of Principle I

What do observations tell us about the radius of the observable 2-sphere at the bounce?

The value $\hat{R}_B = 1.57 \ l_{Pl}$ from Principle I is well within the 68% confidence level of the best fit value.
Thank You.
**$\Lambda$CDM + Inflation**

Using inflation evolution of the universe can be extended to very early for a given potential $V(\phi)$.

From PLANCK data:

- $A_s$ and $n_s$
- $\phi_\star$, $H_\star$, $\epsilon_\star$
- $k_\star = 0.002 \text{ Mpc}^{-1}$

\[ R_0(t_{\text{CMB}}) = 12.63 \text{ Mpc} \]
\[ R_{\text{max}}(t_{\text{CMB}}) = 17.29 \text{ Mpc} \]
\[ R_{\text{max}}(t_*) = 3.328 \times 10^7 / \ell_P \]
\[ R(t_{\text{BB}}) = 0 \]
Constraints on Inflation from PLANCK

\[
A_s(k_\star) = \frac{G \hbar H_\star^2}{\pi \epsilon_\star} \simeq \left( \frac{G \hbar H_\star^2}{\pi \epsilon_V} \right) \bigg|_{\phi=\phi_\star} \quad \text{and} \quad n_s(k_\star) \simeq (1 - 6 \epsilon_V + 2 \delta_V) \bigg|_{\phi=\phi_\star}.
\]

For Starobinksy potential: \( V(\phi) = \frac{3m^2}{32\pi} \left( 1 - e^{\sqrt{\frac{16\pi G}{3}} \phi} \right)^2 \)

\[
H_\star = 1.321 \times 10^{-6} m_{\text{Pl}}, \quad \phi_\star = 1.064 m_{\text{Pl}}, \quad \epsilon_\star = 2.244 \times 10^{-4}
\]

\[
\text{Einstein's eq.} \quad m = 2.676 \times 10^{-6} m_{\text{Pl}}
\]
Interplay between UV and IR

Longest wavelength observable modes interact with curvature in Planck regime and keep the memory of the bounce!
LQC Modified Friedmann equations

\[
H^2 = \frac{8\pi G}{3} \rho \left( 1 - \frac{\rho}{\rho_{\text{sup}}} \right)
\]

\[
\dot{H} = -4\pi G (\rho + P) \left( 1 - 2\frac{\rho}{\rho_{\text{sup}}} \right)
\]

- ★ Bounce at: $\rho = \rho_{\text{sup}}$
- ★ No exotic matter needed
- ★ Purely quantum geometric
Conditions at the Bounce

\[ H = 0 \]

\[ \frac{\dot{\phi_B}^2}{2} + V(\phi_B) = \rho_{\text{sup}} \equiv 0.4092 \, \rho_{\text{pl}} \]

One parameter freedom, parameterized by: \( \phi_B \)

Essentially the same freedom as number of e-folds between bounce and CMB

Can we fix this freedom using quantum geometry?