Alleviating tensions in the CMB using LQC

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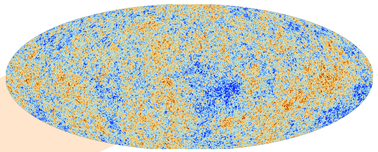


based on **arXiv:2001.11689** with
Abhay Ashtekar, Donghui Jeong and V. Sreenath

Feb 18th, 2020
ILQGS

Universe according to Planck: LCDM Model

1 Nearly scale invariant primordial power spectrum.

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

A_s : amplitude

n_s : spectral index

2 Later time astrophysics governed by: Ω_b : matter density Ω_c : CDM density

$100\theta_{\rm MC}$: BAO length τ : re-ionization optical depth

6 parameter model

$A_s \;\; n_s \;\; \Omega_b$

$\Omega_c \;\; 100\theta_{\rm MC} \;\; \tau$

Boltzmann equations

CAMB

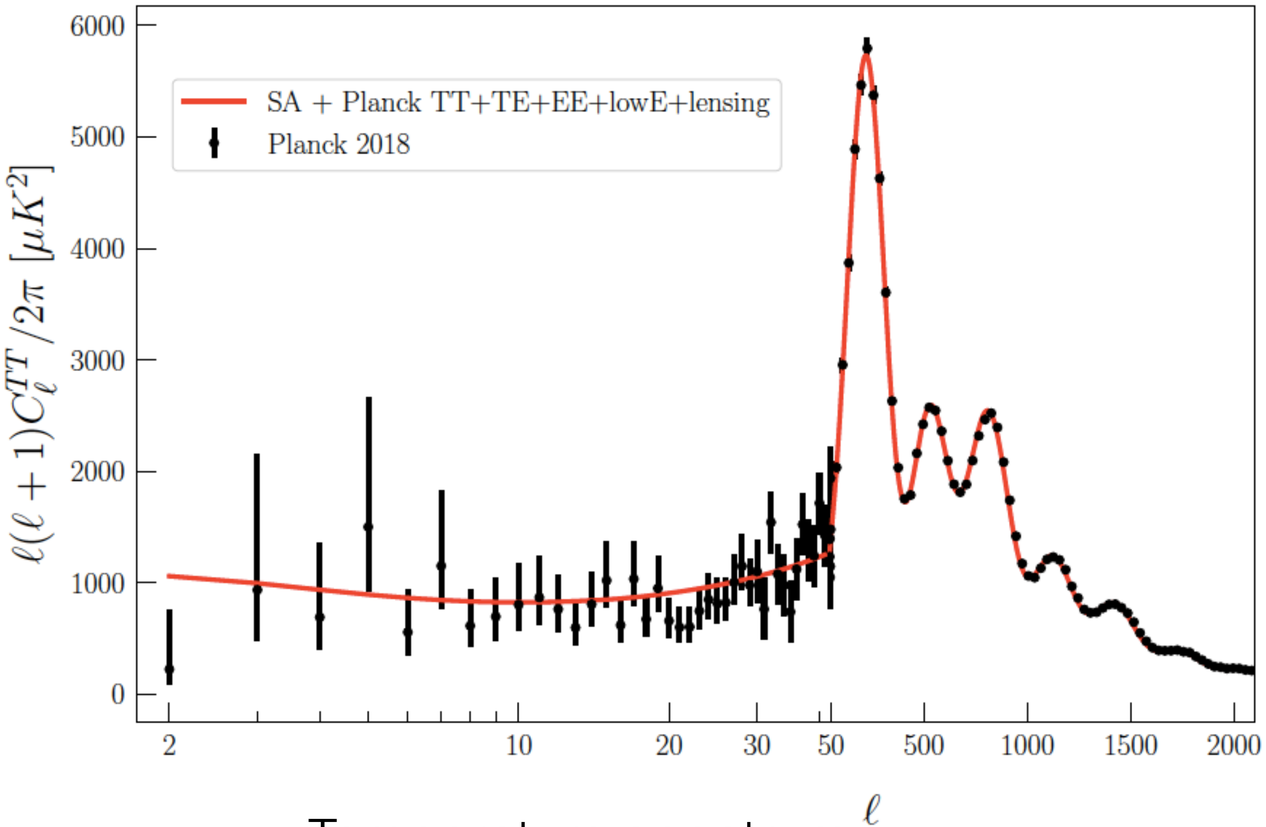
Predicted observables:

$C_\ell^{TT} \;\; C_\ell^{EE} \;\; C_\ell^{TE} \;\; C_\ell^{\phi\phi}$

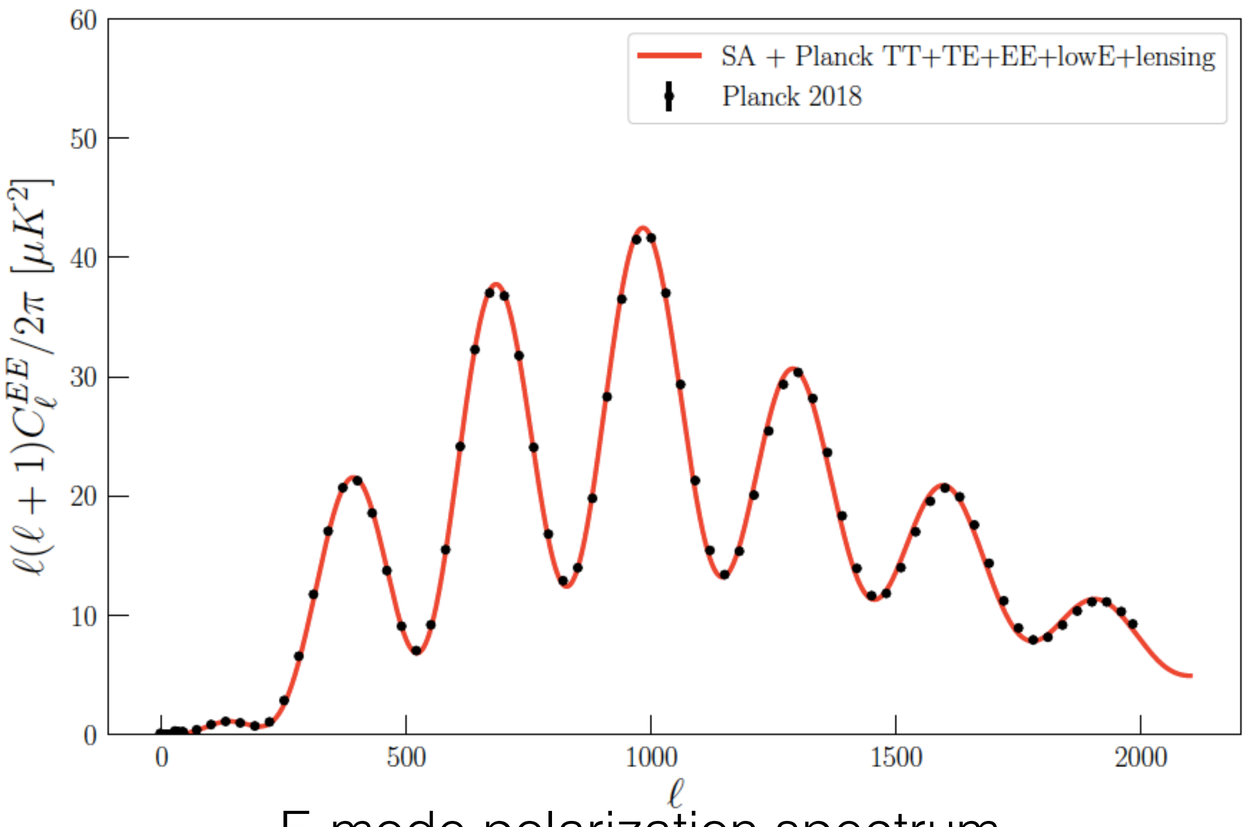
T: temperature, E: polarization, ϕ: lensing

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:



Temperature spectrum



E-mode polarization spectrum

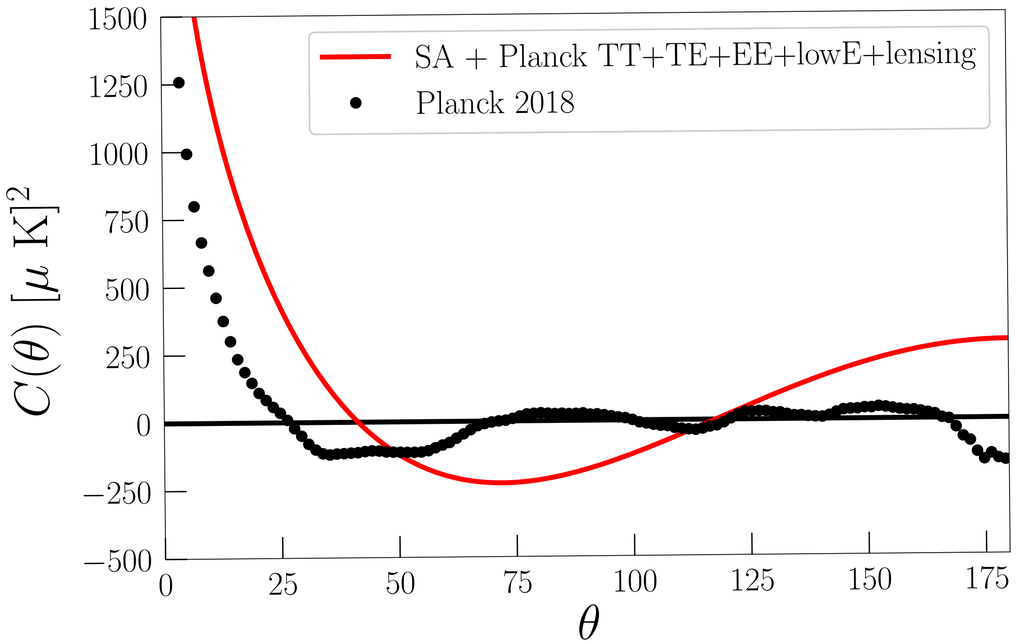
This model further predicts lensing amplitude and B-mode polarization spectrum which can be independently tested using future observations.

Universe according to Planck: Anomalies

The observational data also exhibit some independent, low significance anomalies.

However, when considered together, they become significant.

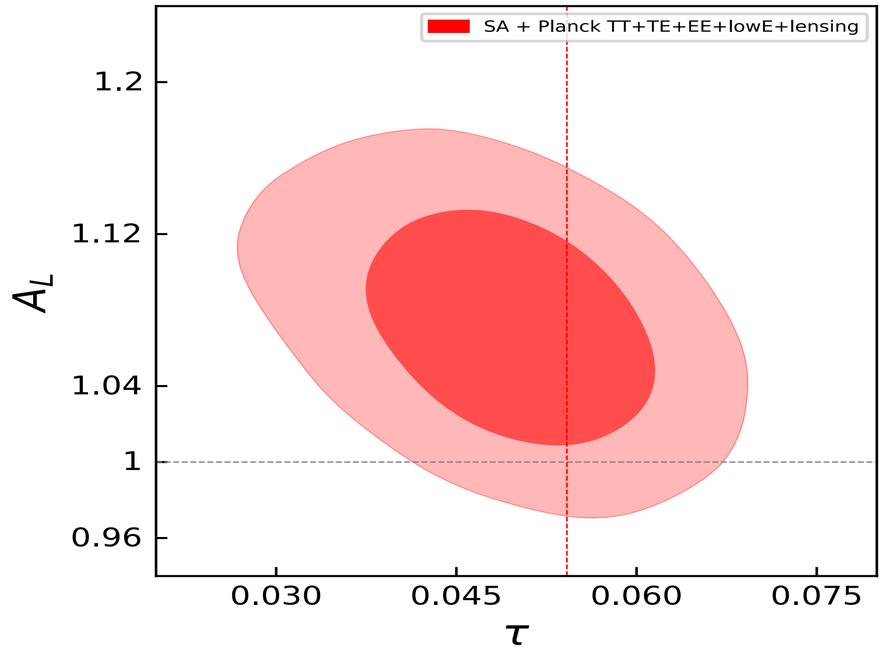
Large scale power anomaly



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.

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

Lensing amplitude anomaly



$A_L = 1$ 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]**

Why are the anomalies interesting?

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.

***Planck* 2018 results. I.**
Overview and the cosmological legacy of *Planck*

similar tests. It would nevertheless be premature to completely dismiss all the CMB anomalies as simple fluctuations of a pure ΛCDM cosmology, since if any of the anomalies have a 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 (or even better, multiple anomalies) naturally, or with very few free parameters. Given a theoretical prediction, new probes of independent modes on similar scales (obtained through more sensitive polarization measurements, lensing, Ly α, or 21-cm studies for example) would increase the significance of existing anomalies

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

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

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.

This talk

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 LQC + quantum perturbations
- Suitable initial conditions for the background geometry and perturbations

We find:

- LQC predictions provide better fit to the observational data.
- Two anomalies are resolved.
- Testable predictions for future observations.

Loop Quantum Cosmology

Loop quantum cosmology

[Agullo, Ashtekar, Barrau, Bojowald, Brizuela, Campiglia, Cailleteau, Corichi, Diener, Fernandez-Mendez, Garray,Grain, Henderson, Karami, Linsefors, Martin-Benito, Martin De Blas, Megevand, Mena-Marugan, Mielczarek, Montoya, Lewandowski, Olmedo, Pawlowski, Singh, Sloan, Taveras, Vandersloot, Wilson-Ewing…]

★ Big bang singularity resolved (Ψ_o)

[Bojowald; Astekar-Pawlowski-Singh]

★ Given an inflationary potential Inflation occurs naturally

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

★Quantum fields ψ on quantum geometry Ψ_o :

dressed metric approach

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

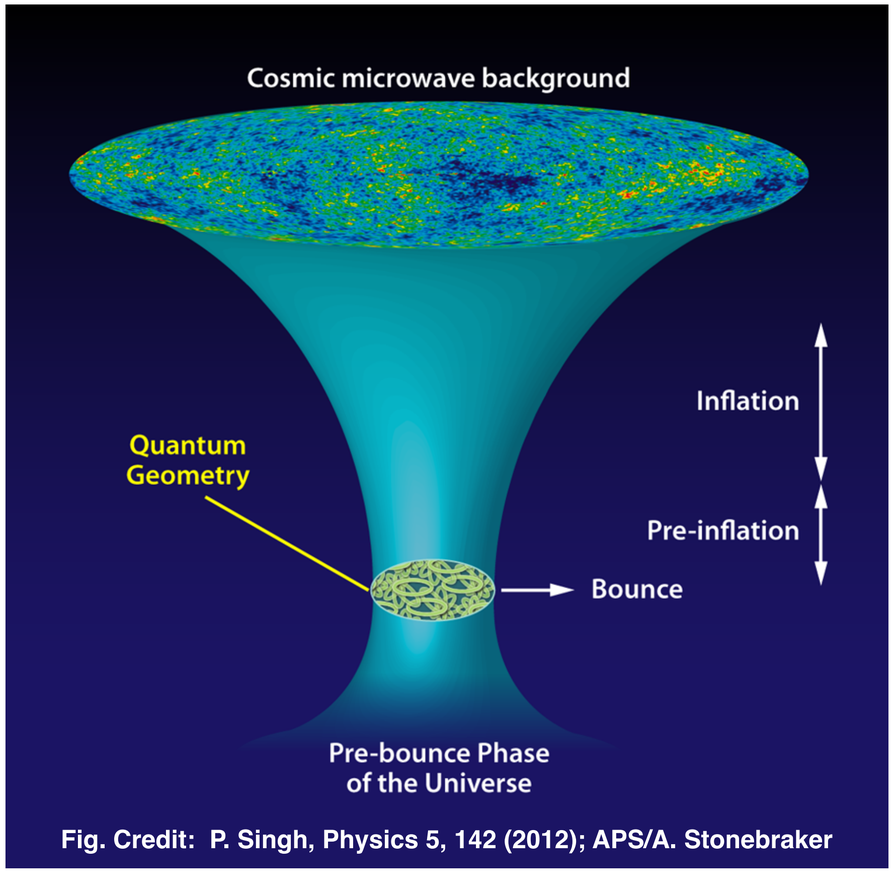


Fig. Credit: P. Singh, Physics 5, 142 (2012); APS/A. Stonebraker

As usual, we will work with sharply peaked Ψ_o. For which, as discussed recently by [Kamiński, Kolanowski and Lewandowski], the dressed metric approach is free their infrared complications.

Initial conditions

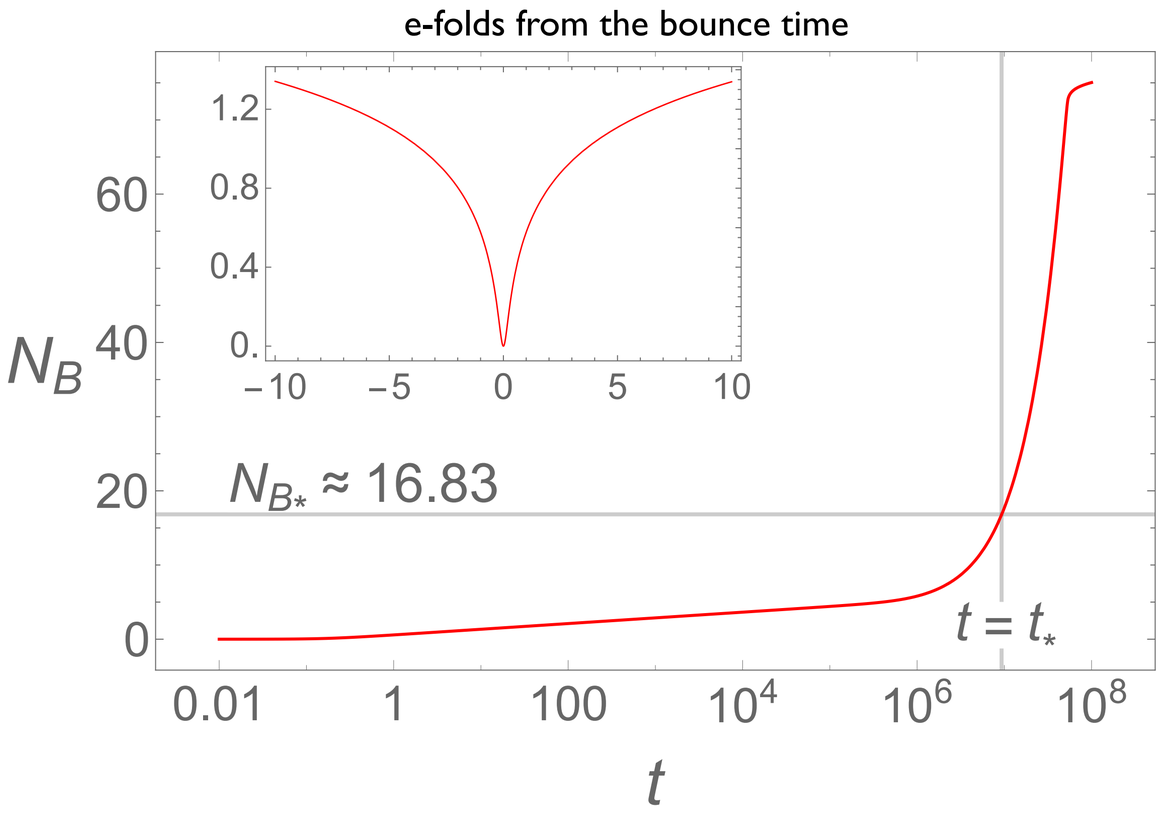
There is tremendous freedom in the choice of initial conditions for the effective background geometry and perturbations. We use prescription introduced in [Ashtekar, BG, CQG 34 (2017) 014002]

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

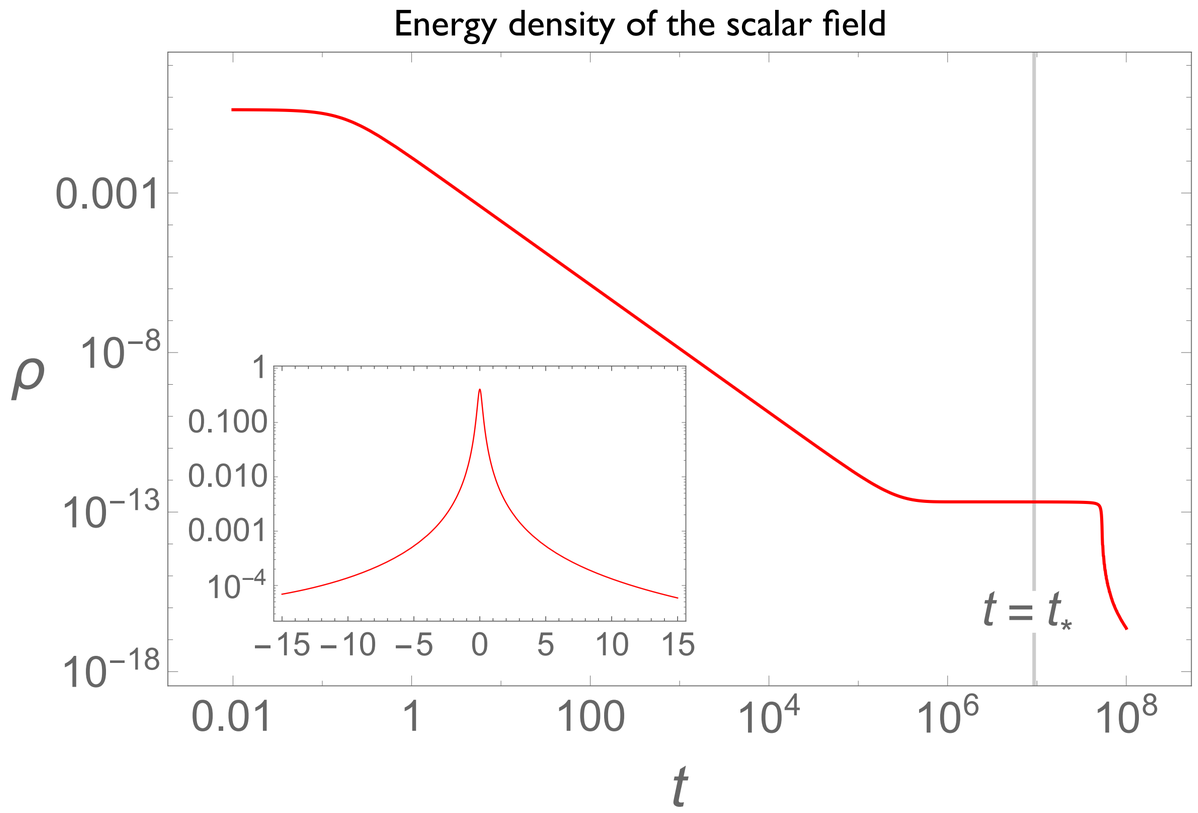
Perturbations: **Fixing the Heisenberg state for quantum perturbations using Planck scale dynamics of LQC and maximum allowed quantum homogeneity and isotropy conditions inspired by Penrose's Weyl curvature hypothesis.**

For more details see ILQGS talk by BG on Aug 30th, 2016.

Background geometry



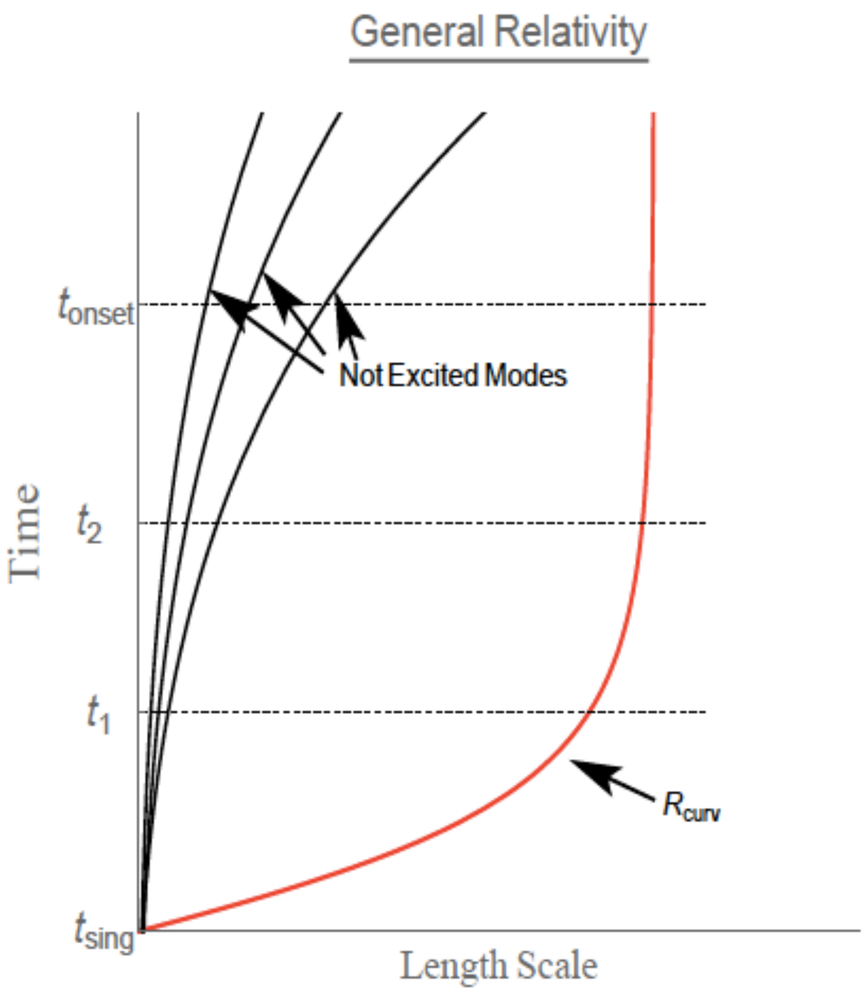
There are approx. 1.2 e-folds in the Planck regime

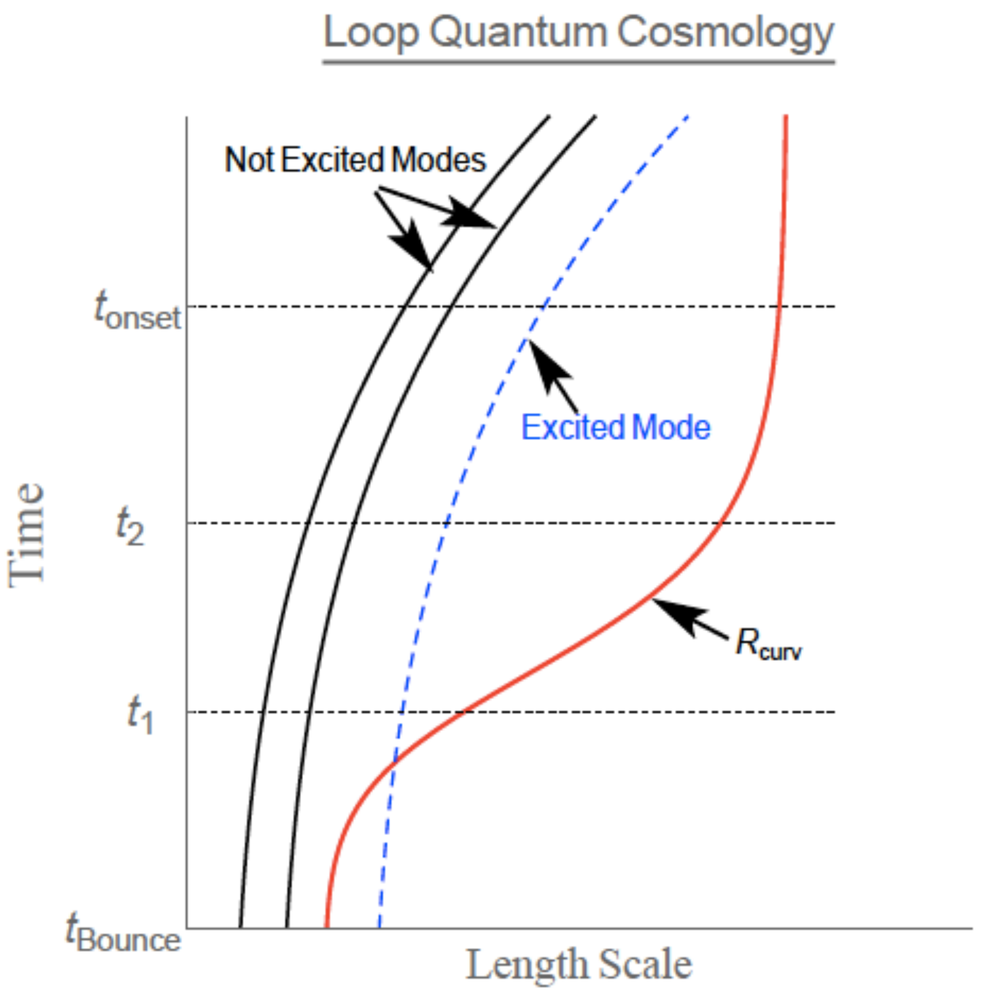


Planck regime last for approx. 10 Planck seconds

Inflationary potential is taken to be the Starobinsky potential: $V(\phi) = \frac{3M^2}{32\pi}\left(1 - e^{-\sqrt{\frac{16\pi G}{3}}\phi}\right)^2$

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!

LQC Predictions and Observations

Primordial spectrum of scalar perturbations

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

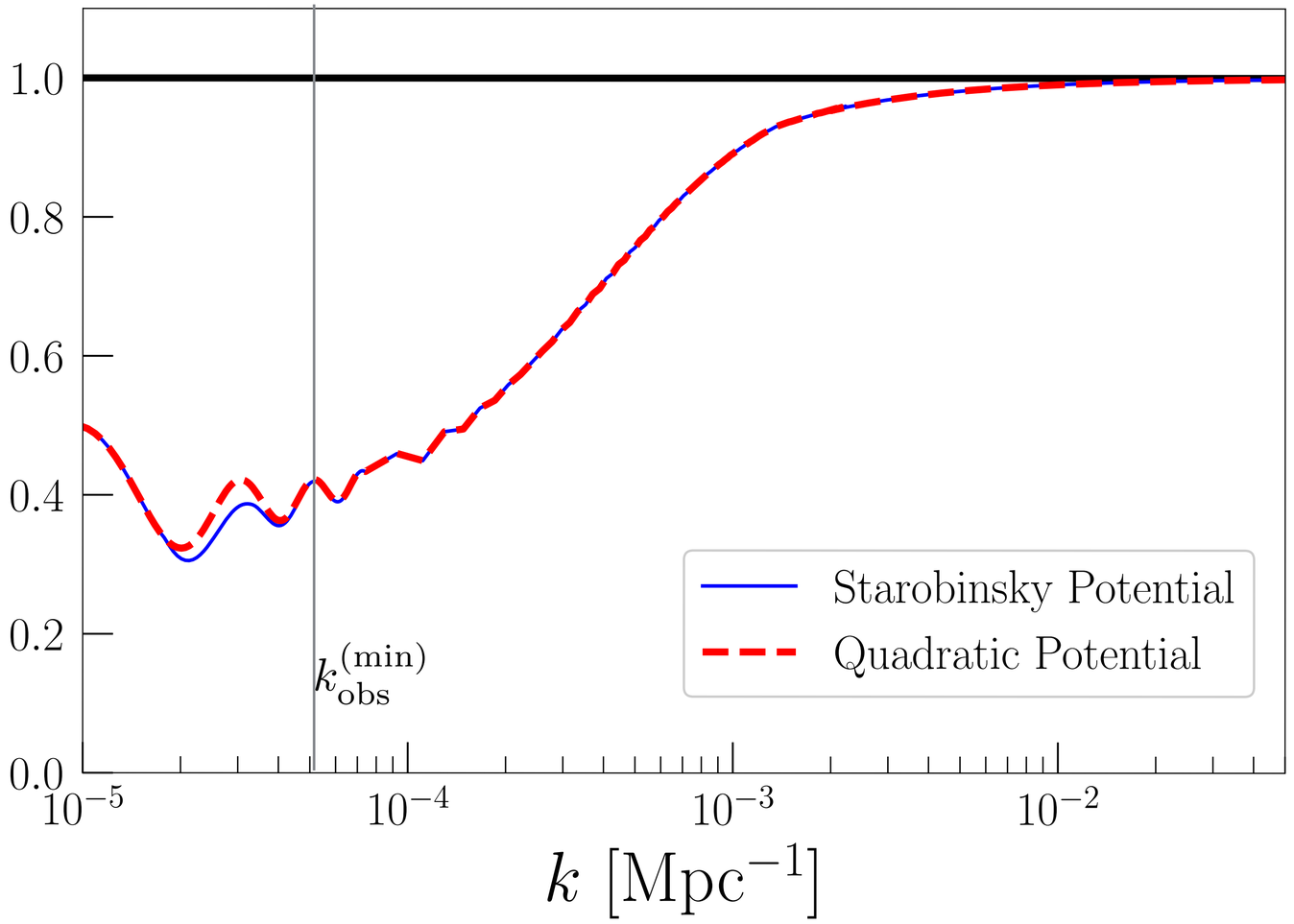
LQC Spectrum: $\mathcal{P}_{\mathcal{R}} = f(k) A_s \left(\frac{k}{k_\star}\right)^{n_s - 1}$

$f(k) = 1$ for large ‘k’

$f(k) < 1$ for small ‘k’

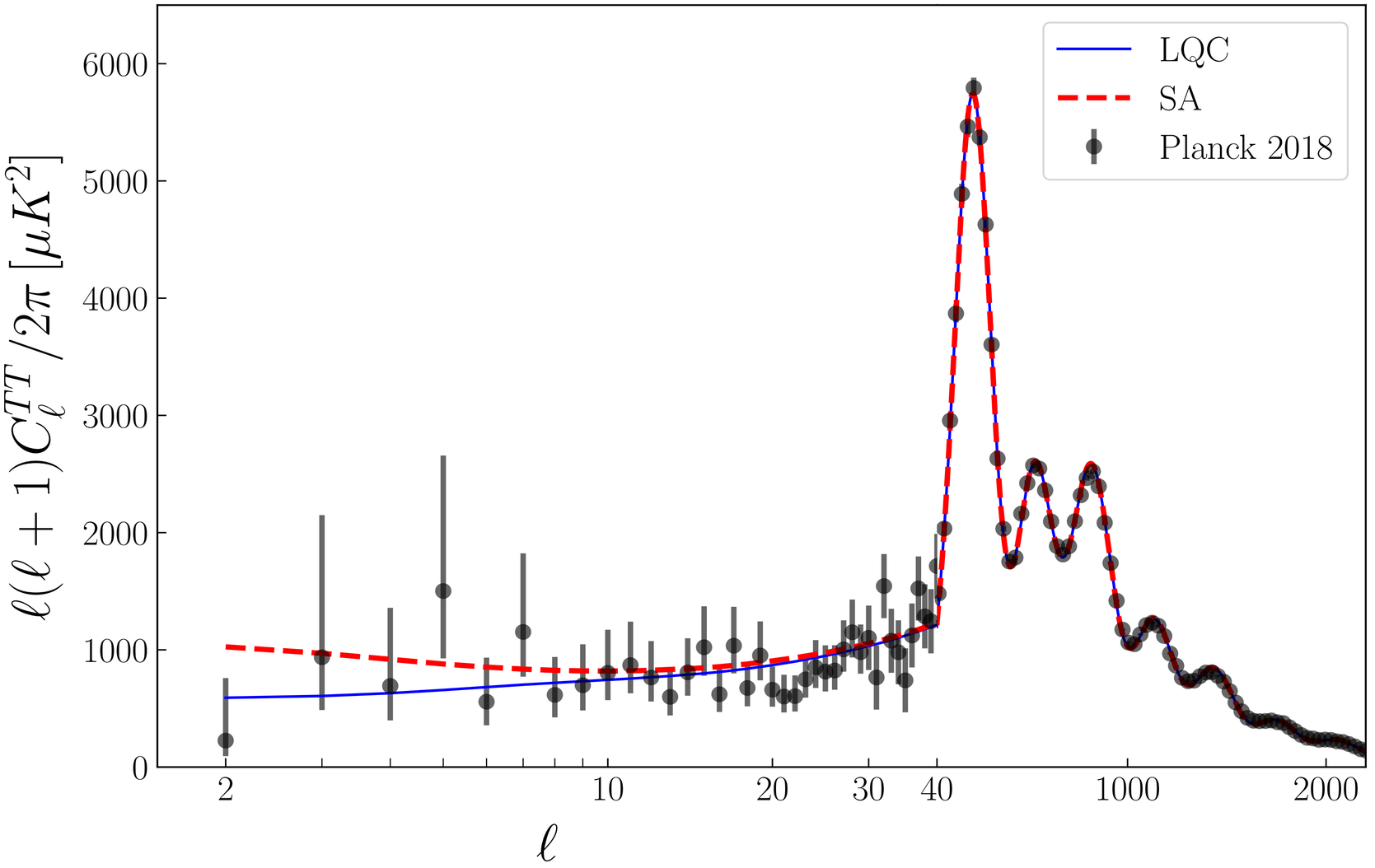
Power suppression at small ‘k’!

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: $V(\phi) = \frac{3M^2}{32\pi}\left(1 - e^{-\sqrt{\frac{16\pi G}{3}}\phi}\right)^2$

The TT power spectrum



LQC spectrum is suppressed for $\ell < 30$ and agrees with SA for $\ell > 30$

TT angular correlation $C(\theta)$

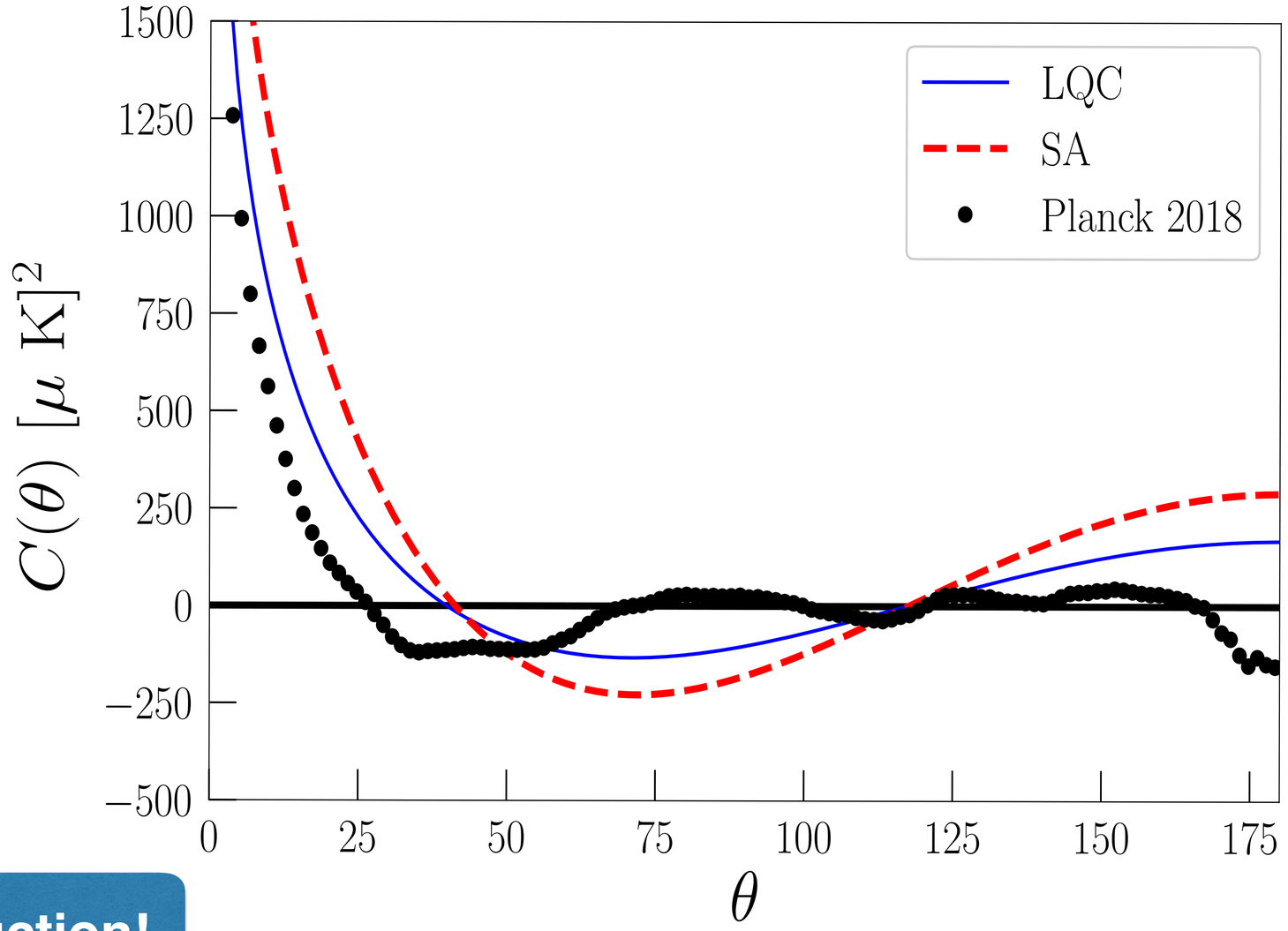
$C(\theta)$ provides a better measure of the power suppression anomaly.

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

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

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

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



Significant improvement: a 2/3 reduction!

Anomaly in $A_L - \tau$

A_L : Lensing Amplitude

τ : re-ionization optical depth

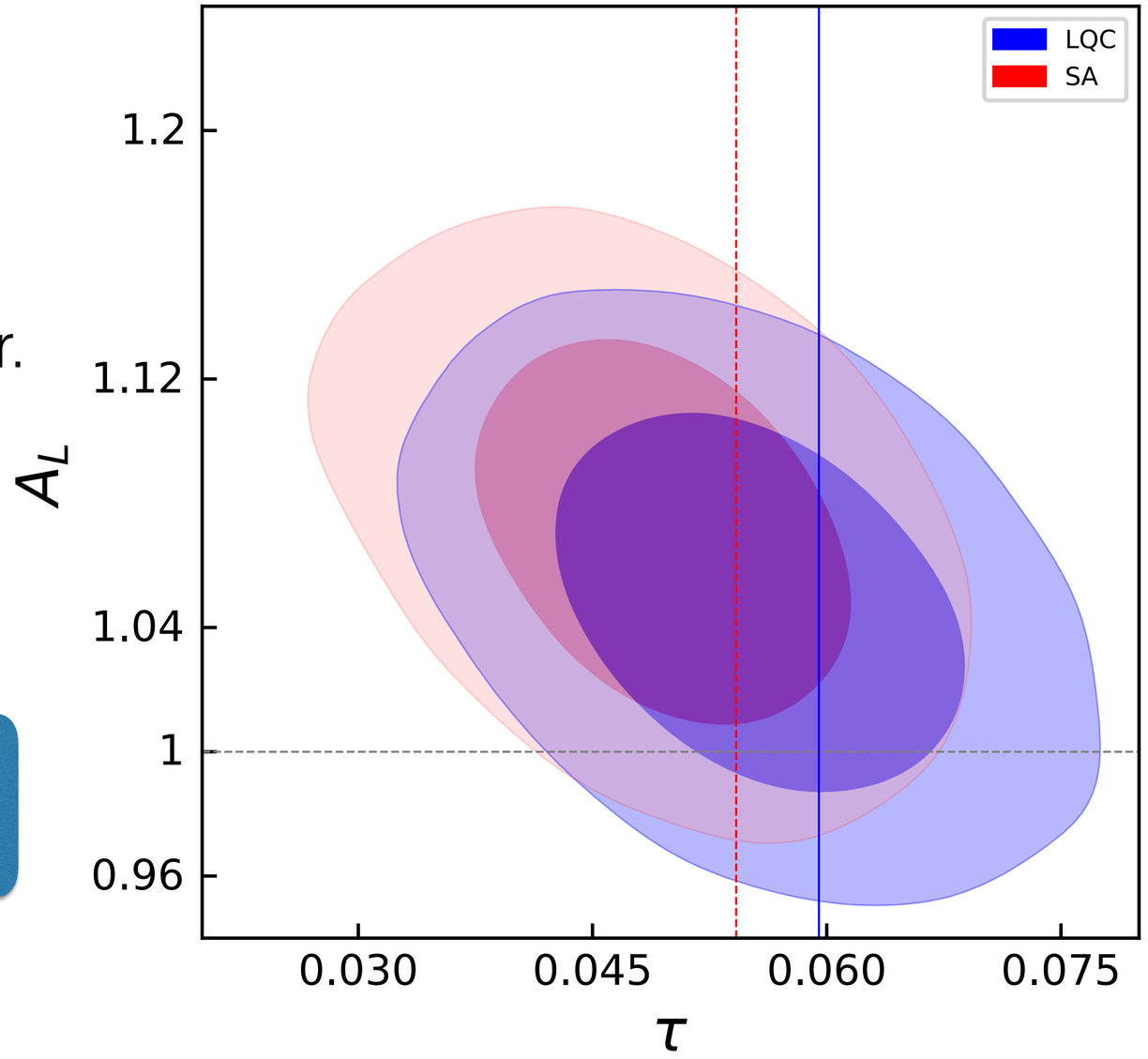
In LCDM model, $A_L = 1$

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!"

Anomaly resolved in LQC, by restoring $A_L = 1$ in $1 - \sigma$ contour.

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.

Parameter	SA	LQC
$\Omega_b h^2$	0.02238 ± 0.00014	0.02239 ± 0.00015
$\Omega_c h^2$	0.1200 ± 0.0012	0.1200 ± 0.0012
$100\theta_{MC}$	1.04091 ± 0.00031	1.04093 ± 0.00031
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
$S_{1/2}$	42496.5	14308.05

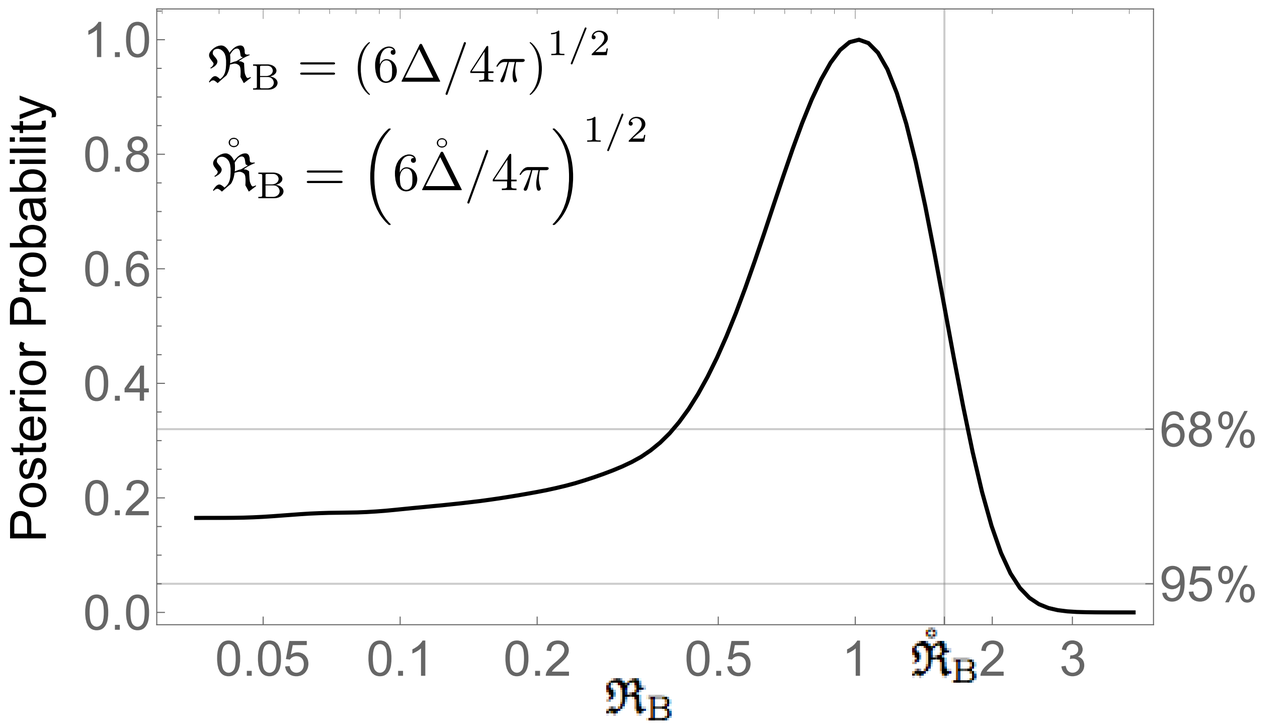
Future observations expected to provide independent measurement of optical depth.

From Observations to Fundamental theory

So far, we fixed the area gap to the value obtained from blackhole entropy computation in LQG: $\Delta = \mathring{\Delta} \approx 5.17\ell_{\mathrm{Pl}}^2$

We can treat Δ as a free parameter and estimate it's best fit value from Planck data.

$\mathring{\mathfrak{K}}_{\mathrm{B}}$ is well within 68% confidence level!



Constraints show that:

- a 10 times increase in area gap is ruled out at 95% confidence level.
- a 10 times decrease in area gap is ruled out at 68% confidence level.

Summary: Quantum Gravity in the Sky

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

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similar tests. It would nevertheless be premature to completely dismiss all the CMB anomalies as simple fluctuations of a pure ΛCDM cosmology, since if any of the anomalies have a 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 (or even better, multiple anomalies) naturally, or with very few free parameters. Given a theoretical prediction, new probes of independent modes on similar scales (obtained through more sensitive polarization measurements, lensing, Ly α, or 21-cm studies for example) would increase the significance of existing anomalies

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

Q: Can other mechanisms leading to similar power suppression result to 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 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 $k_{\rm LQC} = \sqrt{R_{\rm max}/6}$ whose comoving wavenumber is $4 \times 10^{-3}\ {\rm Mpc}^{-1}$. The modes with $k \lesssim k_{\rm LQC}$ get excited by the Planck scale dynamics while the modes with $k >> k_{\rm LQC}$ remain in Bunch-Davis state at the onset of inflation.

Thank You.

Supplementary material

ΛCDM + Inflation

Using inflation evolution of the universe can be extended to very early for a given potential

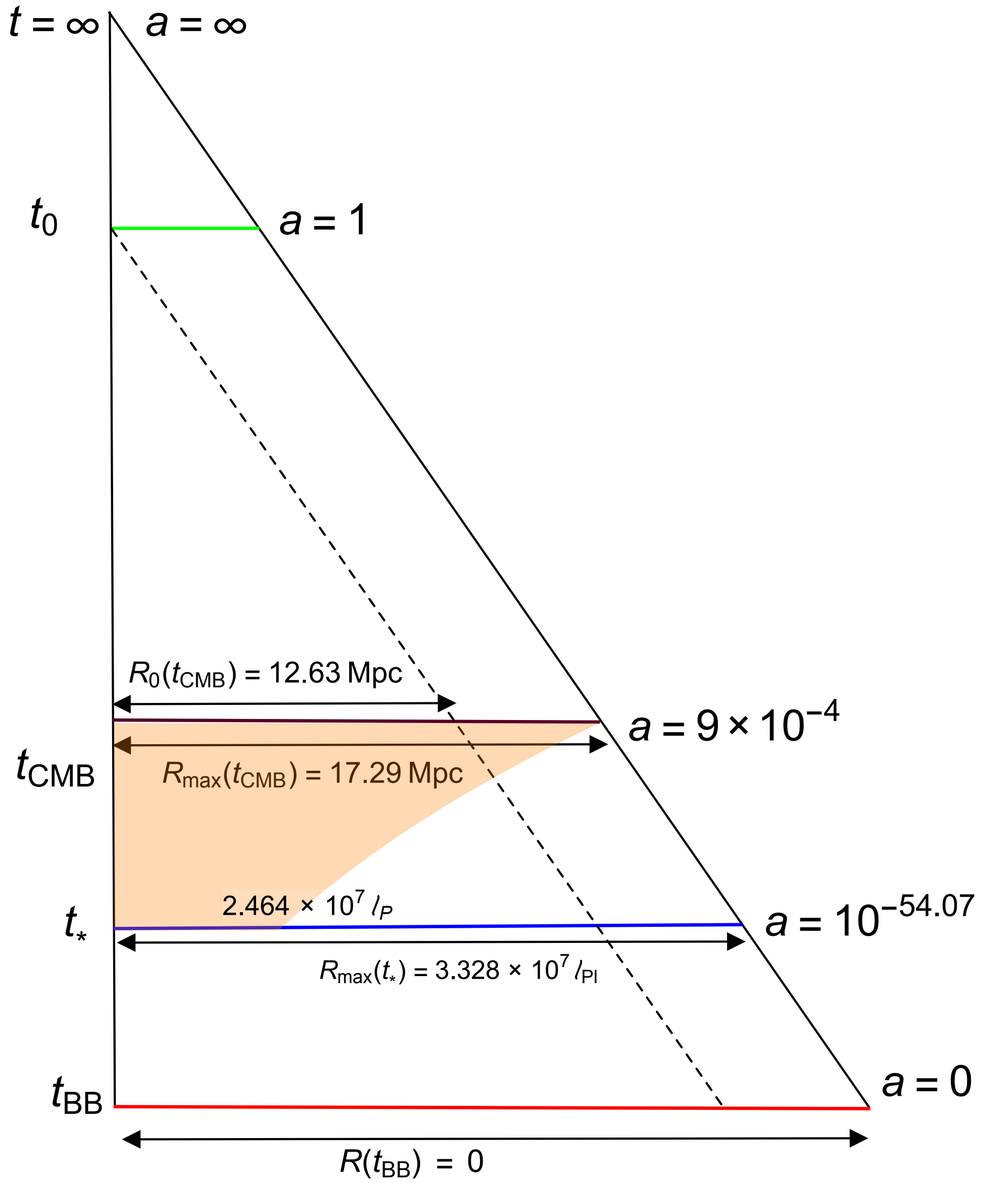
From PLANCK data:

$$A_s \text{ and } n_s$$

$$\downarrow$$

$$\phi_\star, \; H_\star, \; \epsilon_\star$$

$$k_\star = 0.002 \text{ Mpc}^{-1}$$



Constraints on Inflation from PLANCK

$$A_s(k_\star) = \frac{G\hbar\, H_\star^2}{\pi\epsilon_\star} \simeq \left(\frac{G\hbar\, H_\star^2}{\pi\epsilon_V}\right)\Big|_{\phi=\phi_\star} \quad \text{and}$$

$$n_s(k_\star) \simeq (1 - 6\,\epsilon_V + 2\,\delta_V)\Big|_{\phi=\phi_\star}.$$

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

$$H_\star = 1.321 \times 10^{-6} m_{\rm pl},$$
$$\phi_\star = 1.064\; m_{\rm Pl},$$
$$\epsilon_\star = 2.244 \times 10^{-4}$$

Einstein's eq. →

$$m = 2.676 \times 10^{-6}\; m_{\rm pl}$$

LQC Modified Friedmann equations

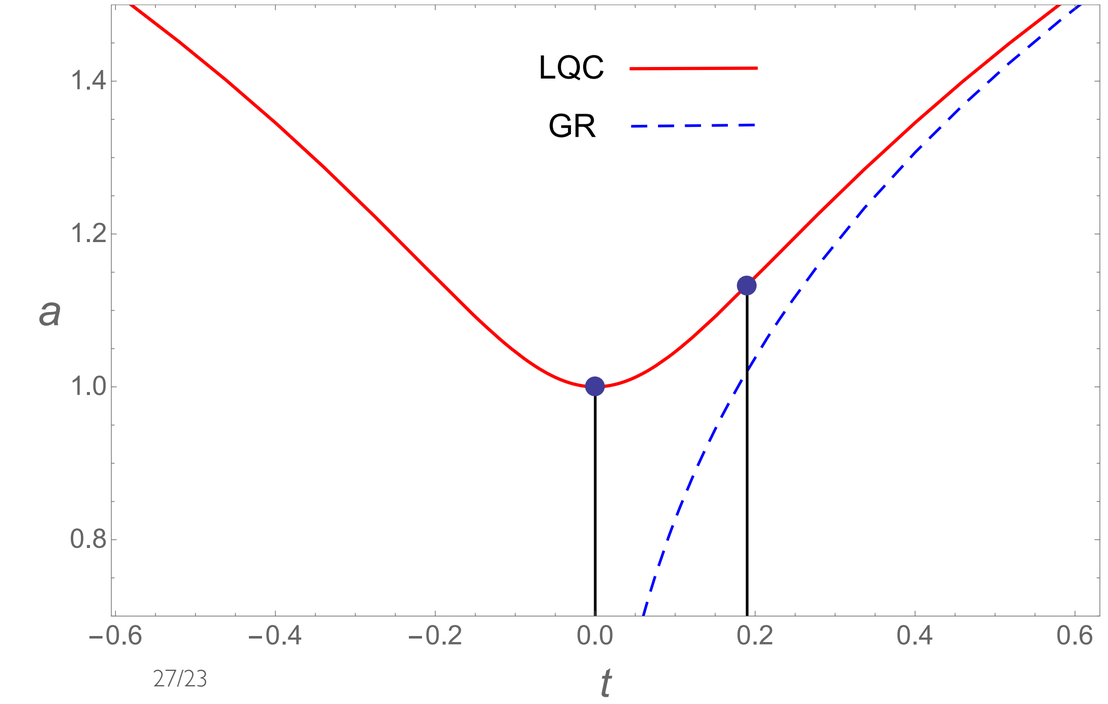
$$H^2 = \frac{8\pi G}{3}\rho\left(1 - \frac{\rho}{\rho_{\rm sup}}\right)$$

$$\dot{H} = -4\pi G\,(\rho + P)\left(1 - 2\frac{\rho}{\rho_{\rm sup}}\right)$$

★ Bounce at: $\rho = \rho_{\rm sup}$

★ No exotic matter needed

★ Purely quantum geometric



Principle 1: *fixing background geometry*

Elements of observations:

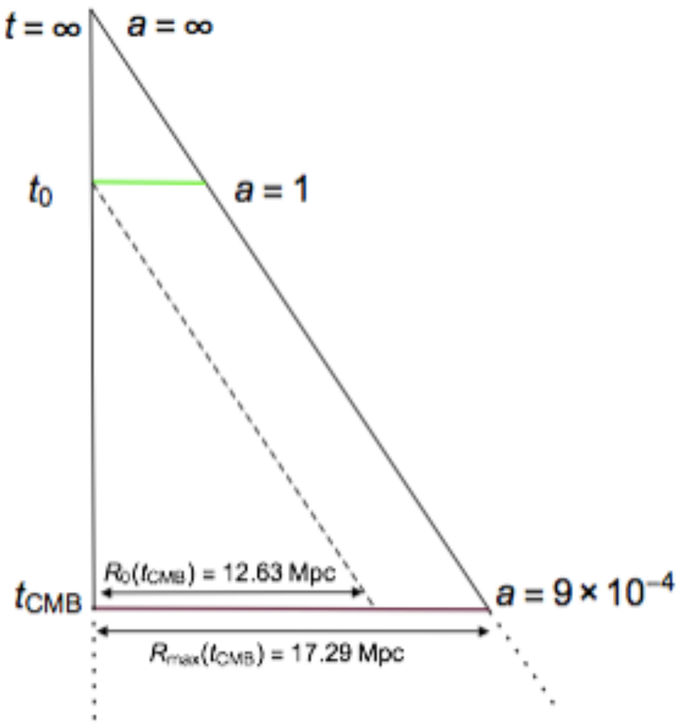
$$H_0 = 67.27 \pm 0.66\,\mathrm{km\ s^{-1}\,Mpc^{-1}}$$

$$\Omega_m = 0.3156 \pm 0.0091$$

$$\Omega_\Lambda = 1 - \Omega_m = 0.6844$$

Spacetime geometry to the future of CMB is determined

Due to positive Ω_Λ, *every eternal observer* has a past horizon.

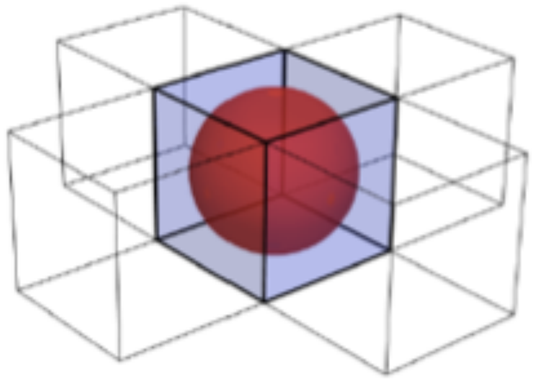


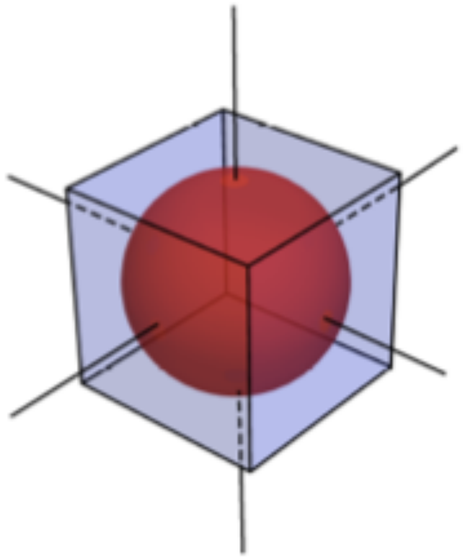
The entire past horizon of an eternal observer is contained in a 2-sphere $\mathbb{S}^2_{\mathrm{CMB}}$ of radius 17.29 MPc

Task: *Extend this geometry all the way to the Planck scale*

Principle 1: *fixing background geometry*

Elements of quantum geometry:

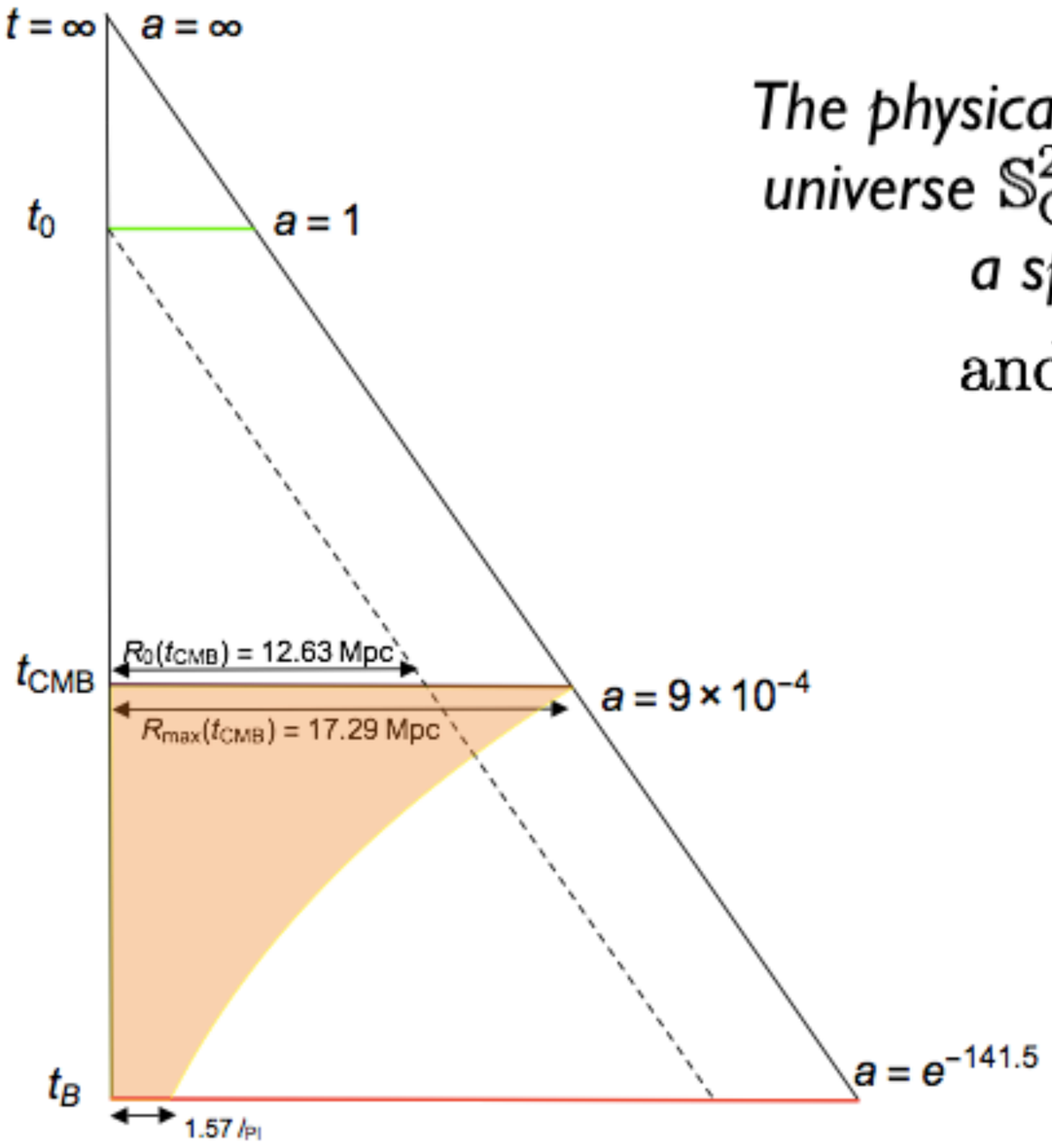




The smallest 2-sphere $\mathbb{S}^2_{\rm B}$ is LQG is the one contained in a cubical cell having six intersections with the edges each depositing an area of $\Delta\ \ell^2_{\rm Pl}$

The total area of $\mathbb{S}^2_{\rm B}$ is then $6\Delta\ \ell^2_{\rm Pl} \approx 31\ \ell^2_{\rm Pl}$

Principle 1: *fixing background geometry*



The physical size of ever observable universe $\mathbb{S}^2_{\rm CMB}$ *emerges from* $\mathbb{S}^2_{\rm B}$ *:*
a sphere of area = $31\ l^2_{\rm Pl}$
and radius $\mathring{\mathfrak{R}}_{\rm B} = 1.57\ l_{\rm Pl}$

This fixes the background geometry for a given inflationary potential