Title: Quantum Gravity in the Sky: Interplay between theory and observations

Date: Aug 30, 2016 10:00 AM

URL: http://pirsa.org/16080096

Abstract:

Quantum Gravity in the Sky: Interplay between theory and observation

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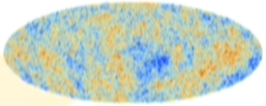


based on **arXiv:1608.04228** with
Abhay Ashtekar

Aug 30th, 2016
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

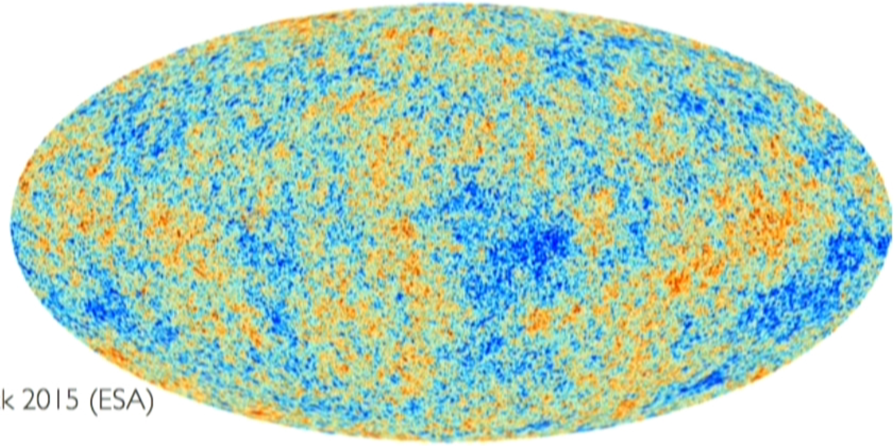
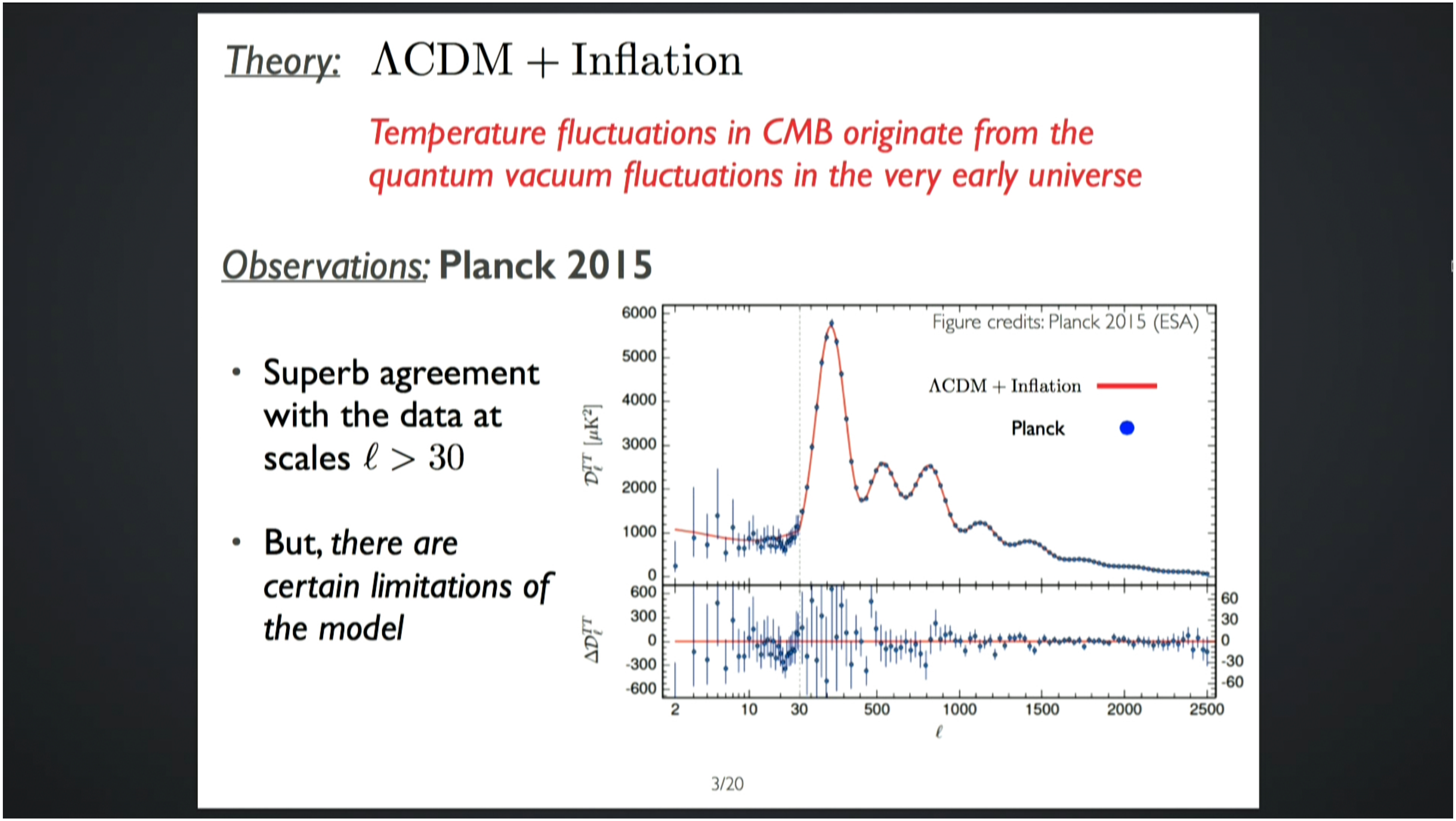


Figure credits: Planck 2015 (ESA)

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



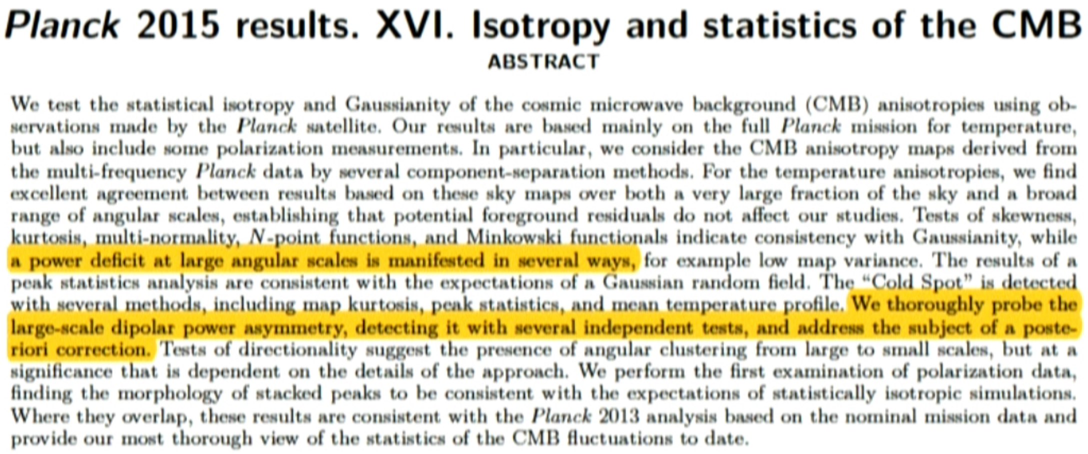
Theory: $\Lambda\text{CDM} + \text{Inflation}$

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

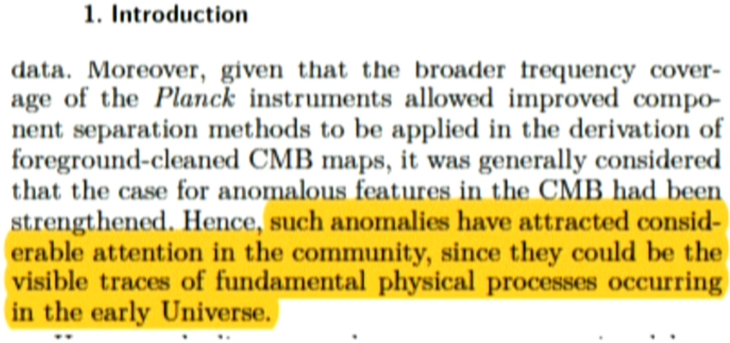


Planck 2015 results. XVI. Isotropy and statistics of the CMB

ABSTRACT

We test the statistical isotropy and Gaussianity of the cosmic microwave background (CMB) anisotropies using observations made by the *Planck* satellite. Our results are based mainly on the full *Planck* mission for temperature, but also include some polarization measurements. In particular, we consider the CMB anisotropy maps derived from the multi-frequency *Planck* data by several component-separation methods. For the temperature anisotropies, we find excellent agreement between results based on these sky maps over both a very large fraction of the sky and a broad range of angular scales, establishing that potential foreground residuals do not affect our studies. Tests of skewness, kurtosis, multi-normality, N-point functions, and Minkowski functionals indicate consistency with Gaussianity, while a power deficit at large angular scales is manifested in several ways, for example low map variance. The results of a peak statistics analysis are consistent with the expectations of a Gaussian random field. The "Cold Spot" is detected with several methods, including map kurtosis, peak statistics, and mean temperature profile. We thoroughly probe the large-scale dipolar power asymmetry, detecting it with several independent tests, and address the subject of a posteriori correction. Tests of directionality suggest the presence of angular clustering from large to small scales, but at a significance that is dependent on the details of the approach. We perform the first examination of polarization data, finding the morphology of stacked peaks to be consistent with the expectations of statistically isotropic simulations. Where they overlap, these results are consistent with the *Planck* 2013 analysis based on the nominal mission data and provide our most thorough view of the statistics of the CMB fluctuations to date.

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



1. Introduction

data. Moreover, given that the broader frequency coverage of the *Planck* instruments allowed improved component separation methods to be applied in the derivation of foreground-cleaned CMB maps, it was generally considered that the case for anomalous features in the CMB had been strengthened. Hence, such anomalies have attracted considerable attention in the community, since they could be the visible traces of fundamental physical processes occurring in the early Universe.

An opportunity for quantum gravity to connect with observations

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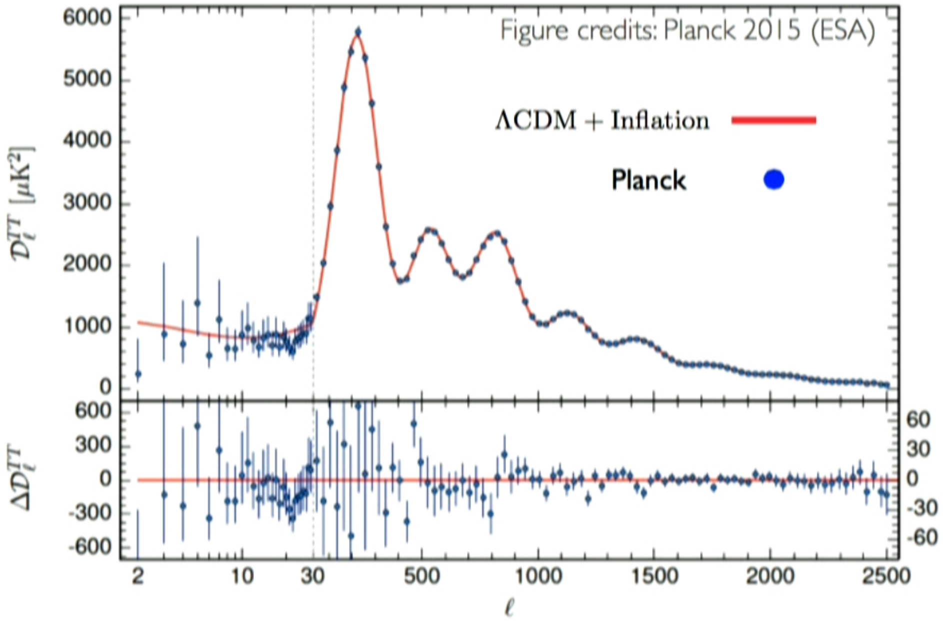

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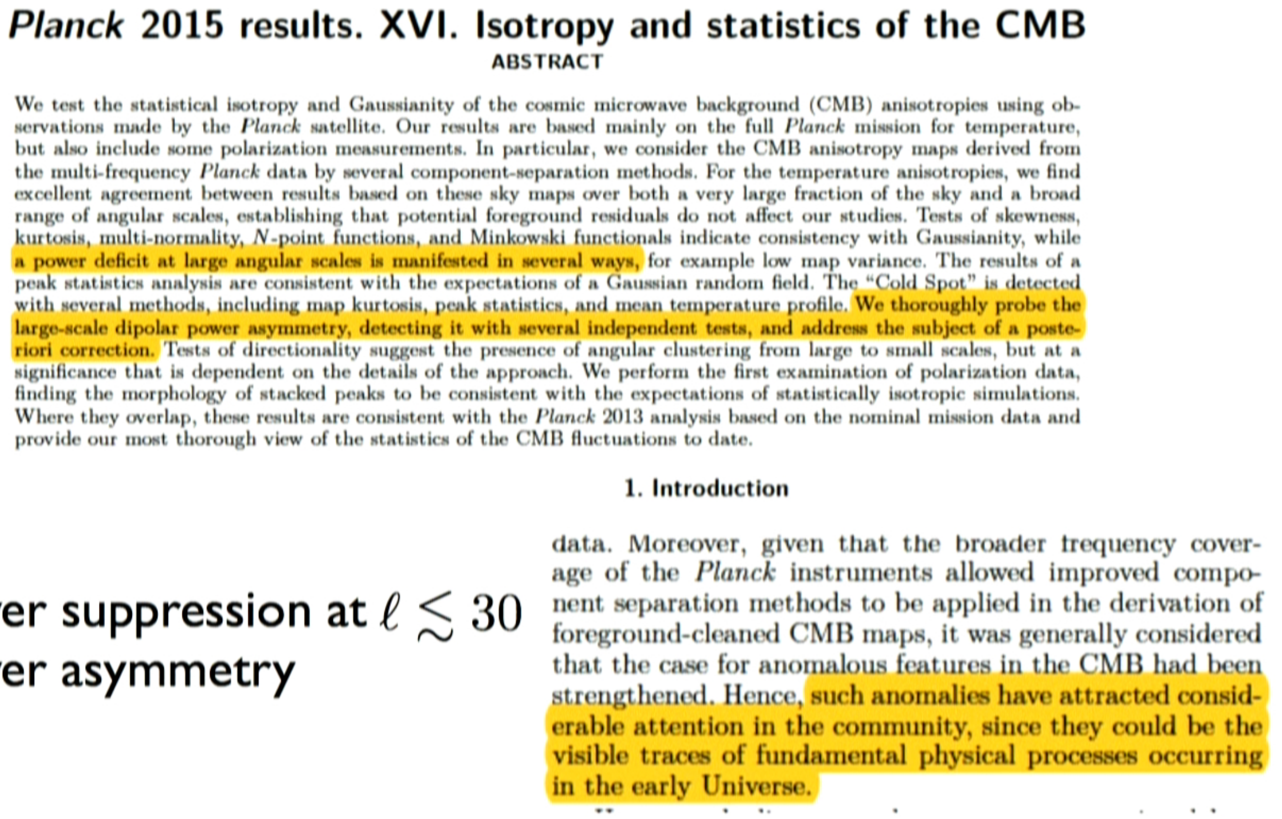
Large scale CMB anomalies



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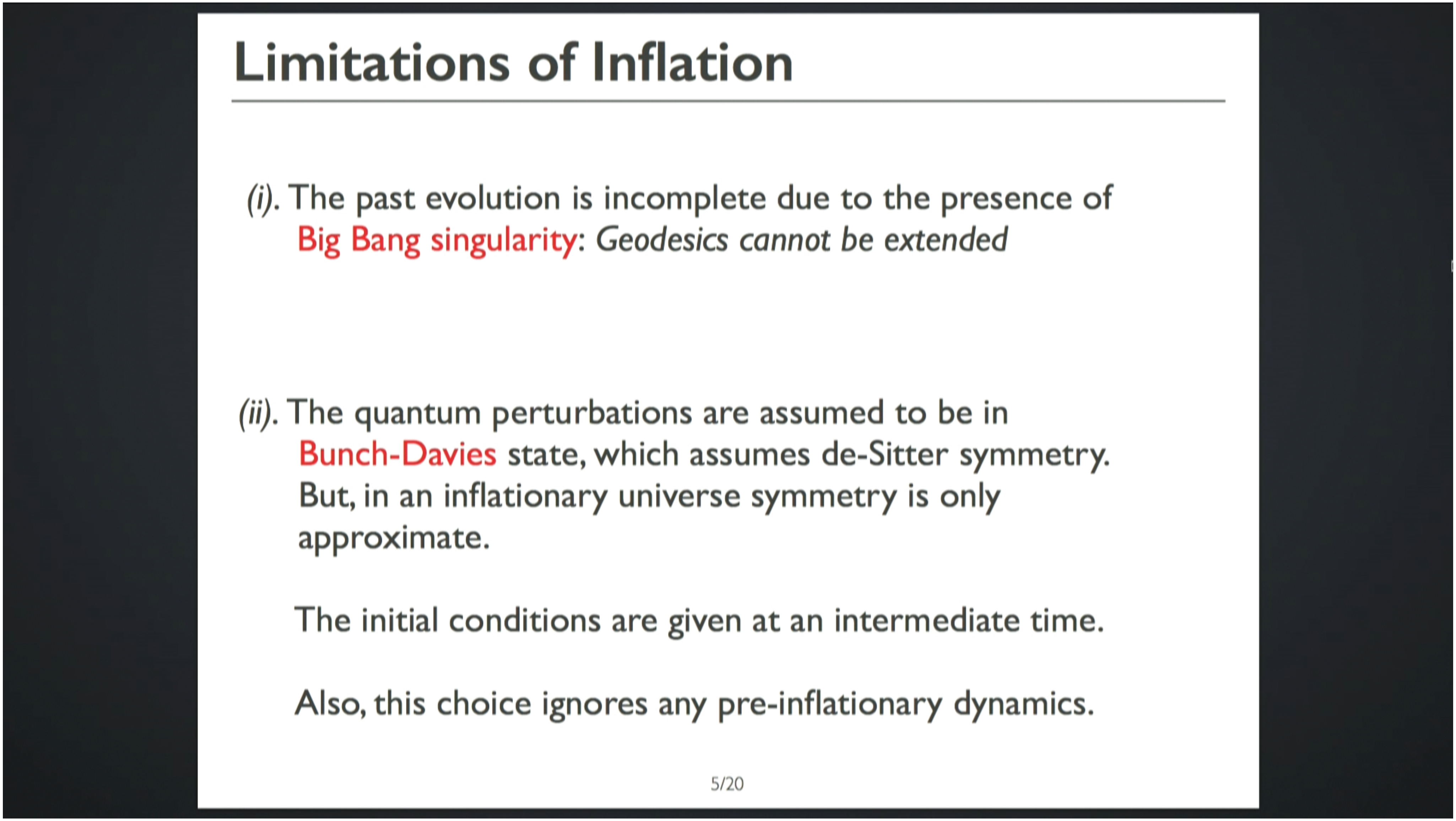
- Power asymmetry

An opportunity for quantum gravity to connect with observations



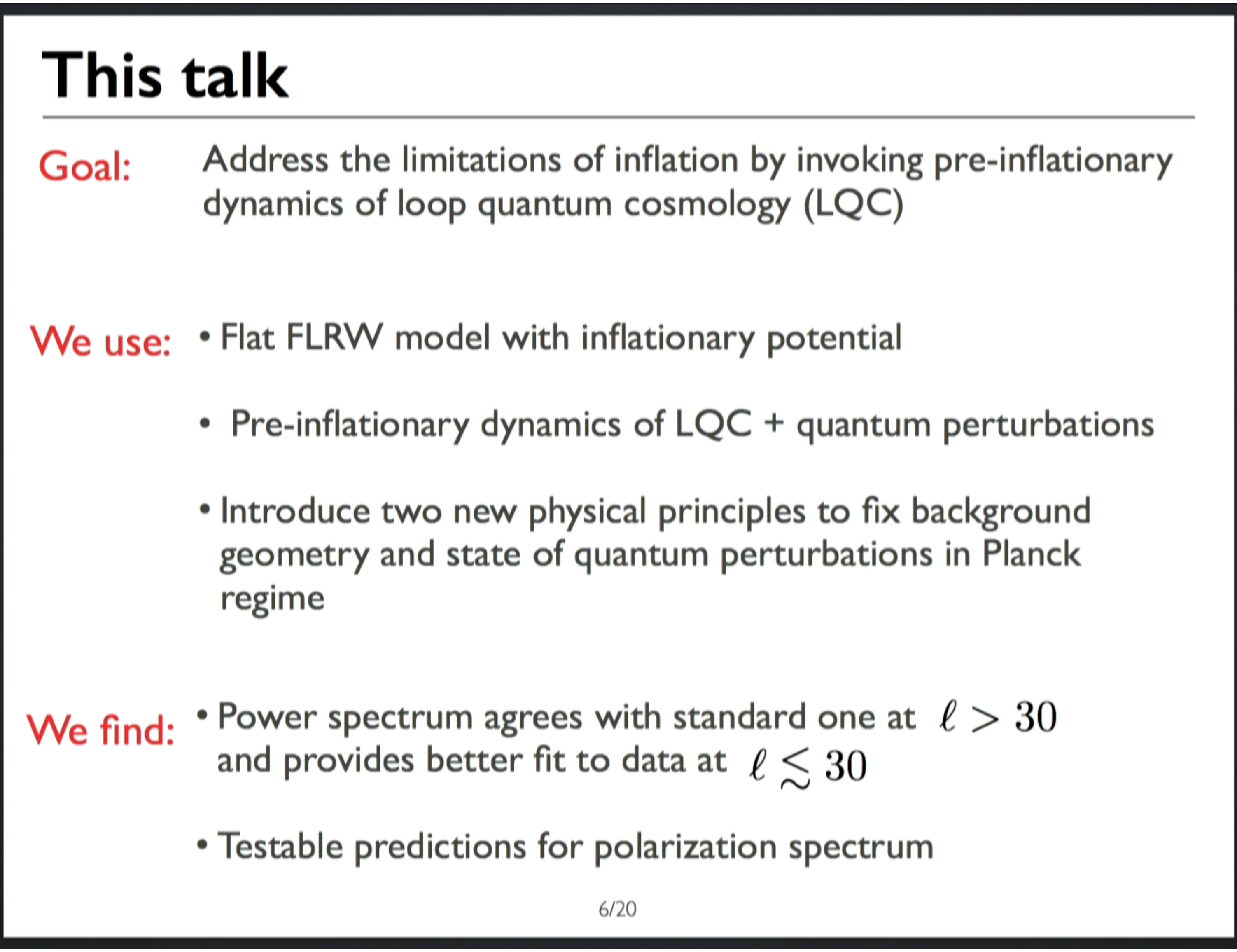
Limitations of Inflation

(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

[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…]

Background geometry Ψ_o and quantum perturbations ψ

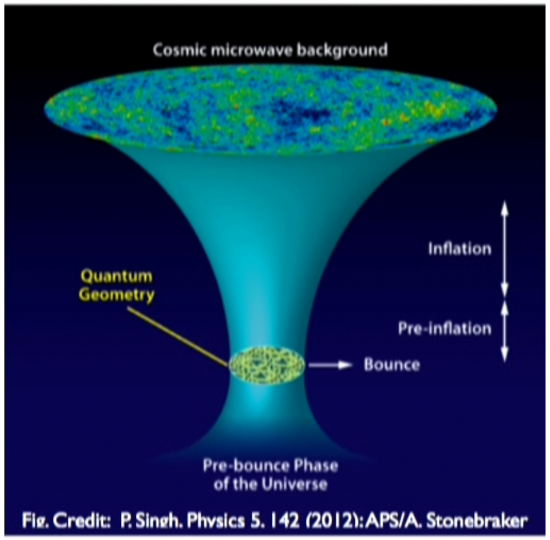


Fig. Credit: P. Singh, Physics 5, 142 (2012); APS/A. Stonebraker

★ Big bang singularity resolved (Ψ_o)

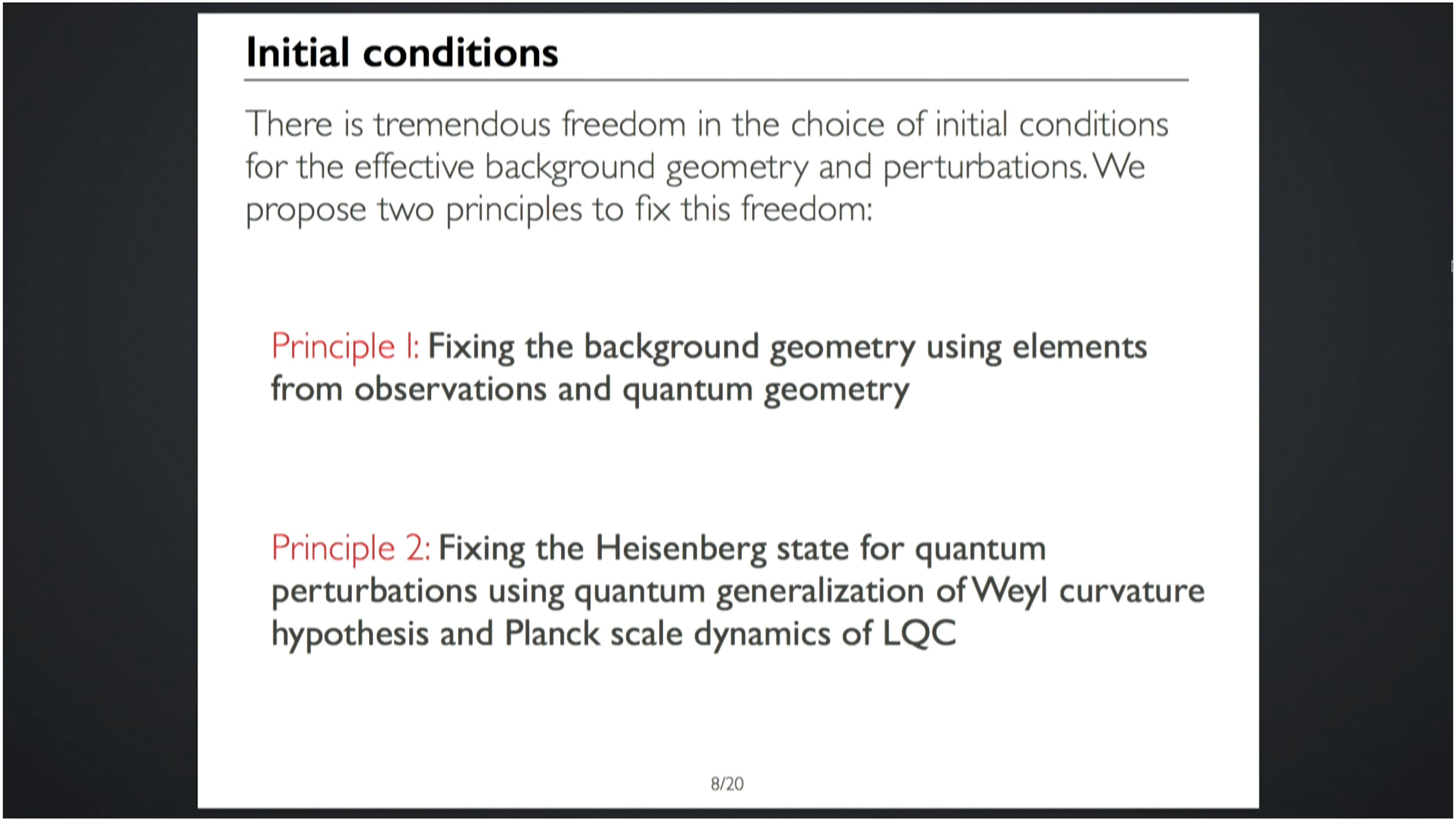
[Bojowald; Astekar-Pawlowski-Singh]

★ Given an inflationary potential Inflation occurs naturally [Ashtekar-Sloan; Corichi-Karami]

★ Quantum fields ψ on quantum geometry Ψ_o: dressed metric approach

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

We will work with sharply peaked Ψ_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:

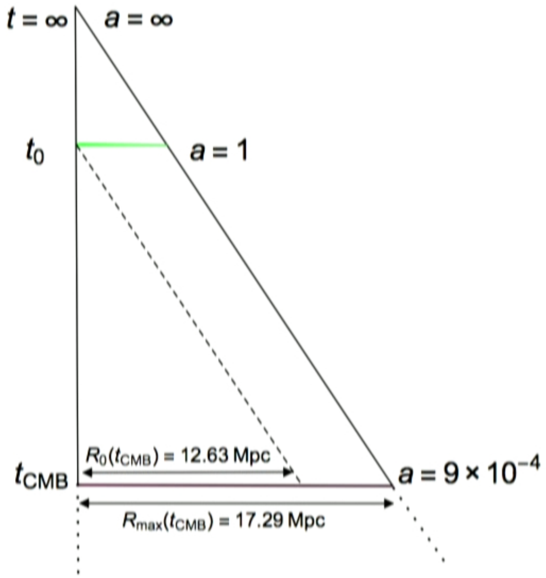
$$H_0 = 67.27 \pm\ 0.66\,\mathrm{km\ s^{-1}\,Mpc^{-1}}$$

$$\Omega_m = 0.3156 \pm 0.0091$$

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

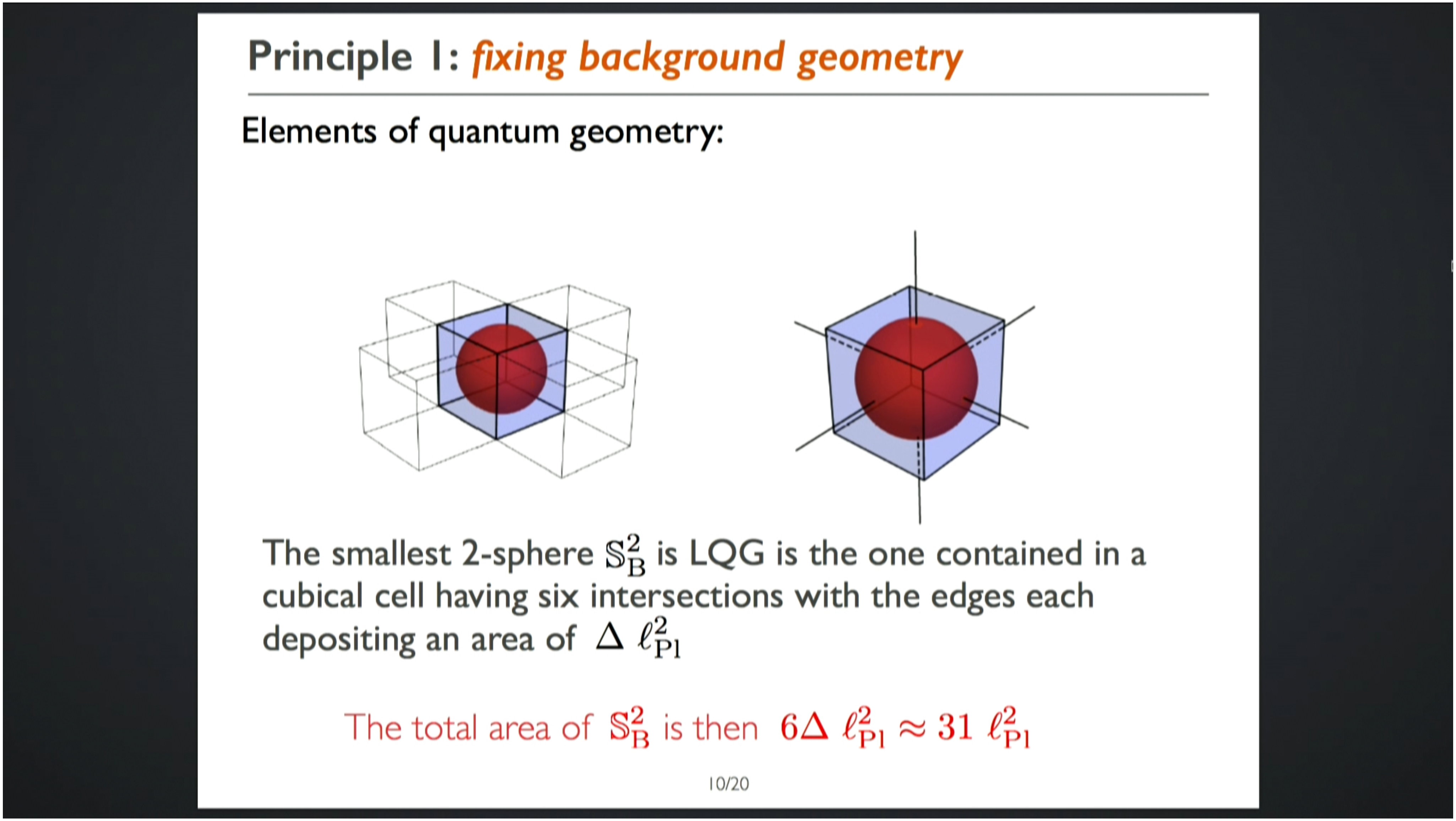
Spacetime geometry to the future of CMB is determined

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 $\mathbb{S}^2_{\rm CMB}$ of radius **17.29 MPc**

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

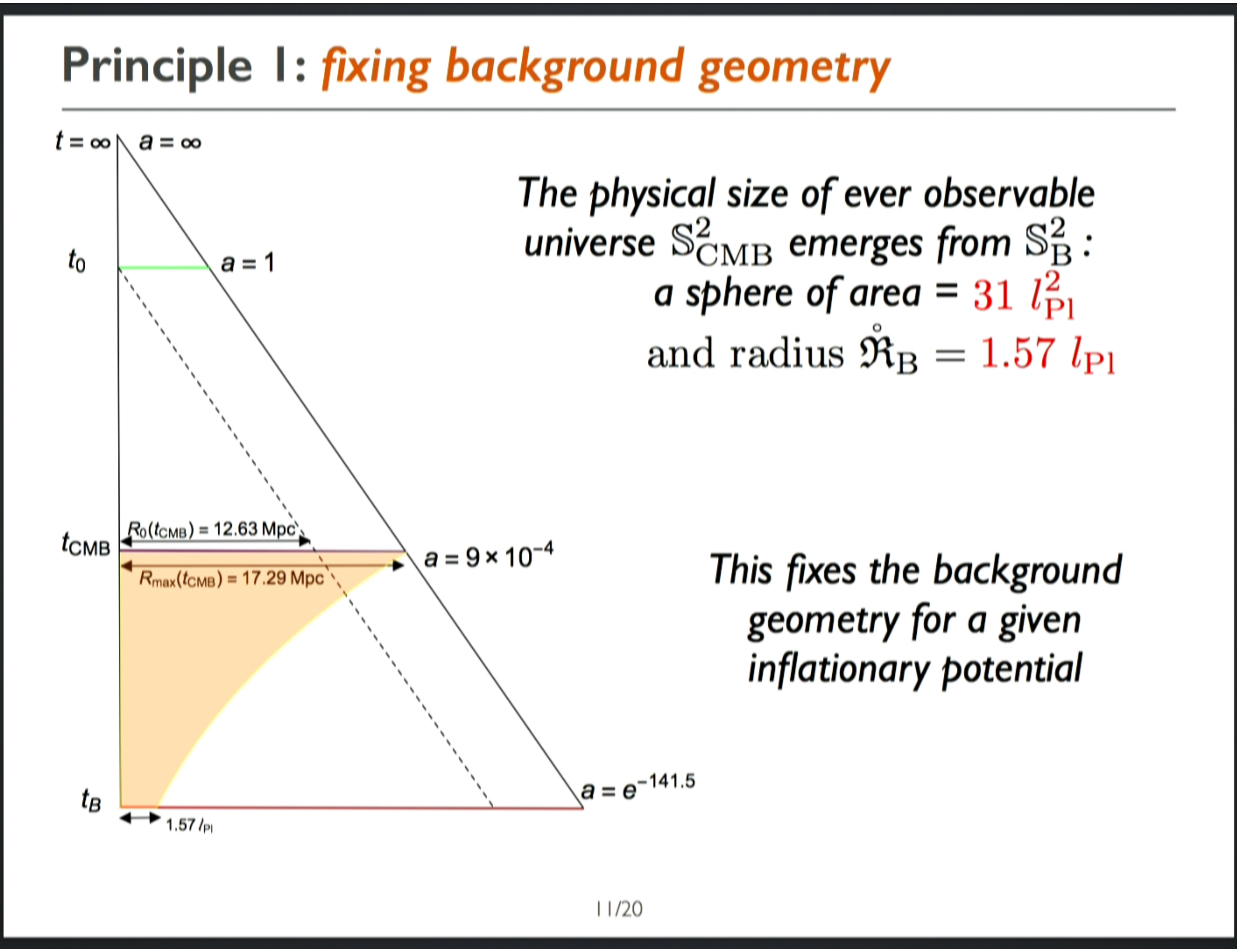


Principle 1: *fixing background geometry*

Elements of quantum geometry:

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

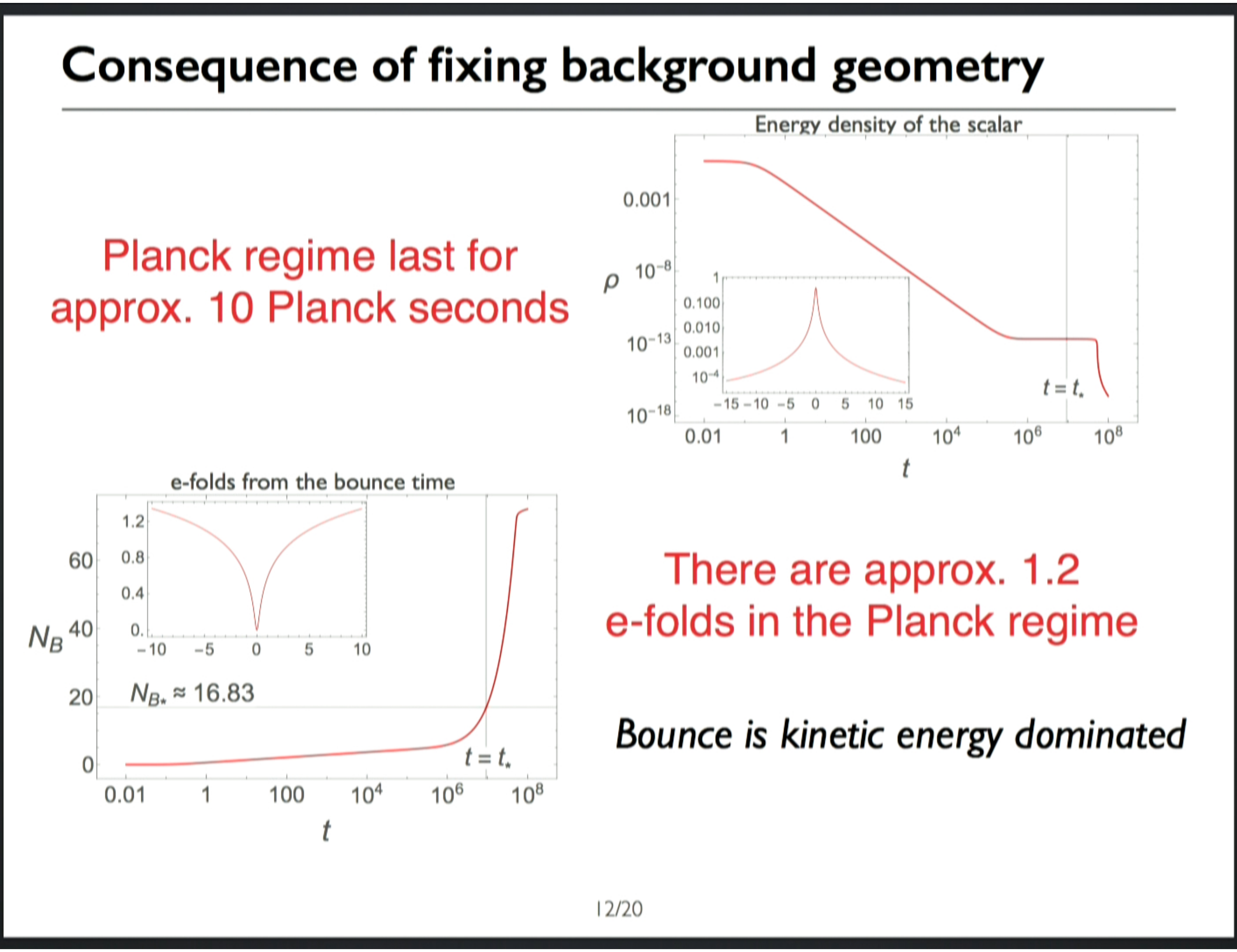
The total area of $\mathbb{S}^2_{\mathrm{B}}$ is then $6\Delta\ \ell^2_{\mathrm{Pl}} \approx 31\ \ell^2_{\mathrm{Pl}}$



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

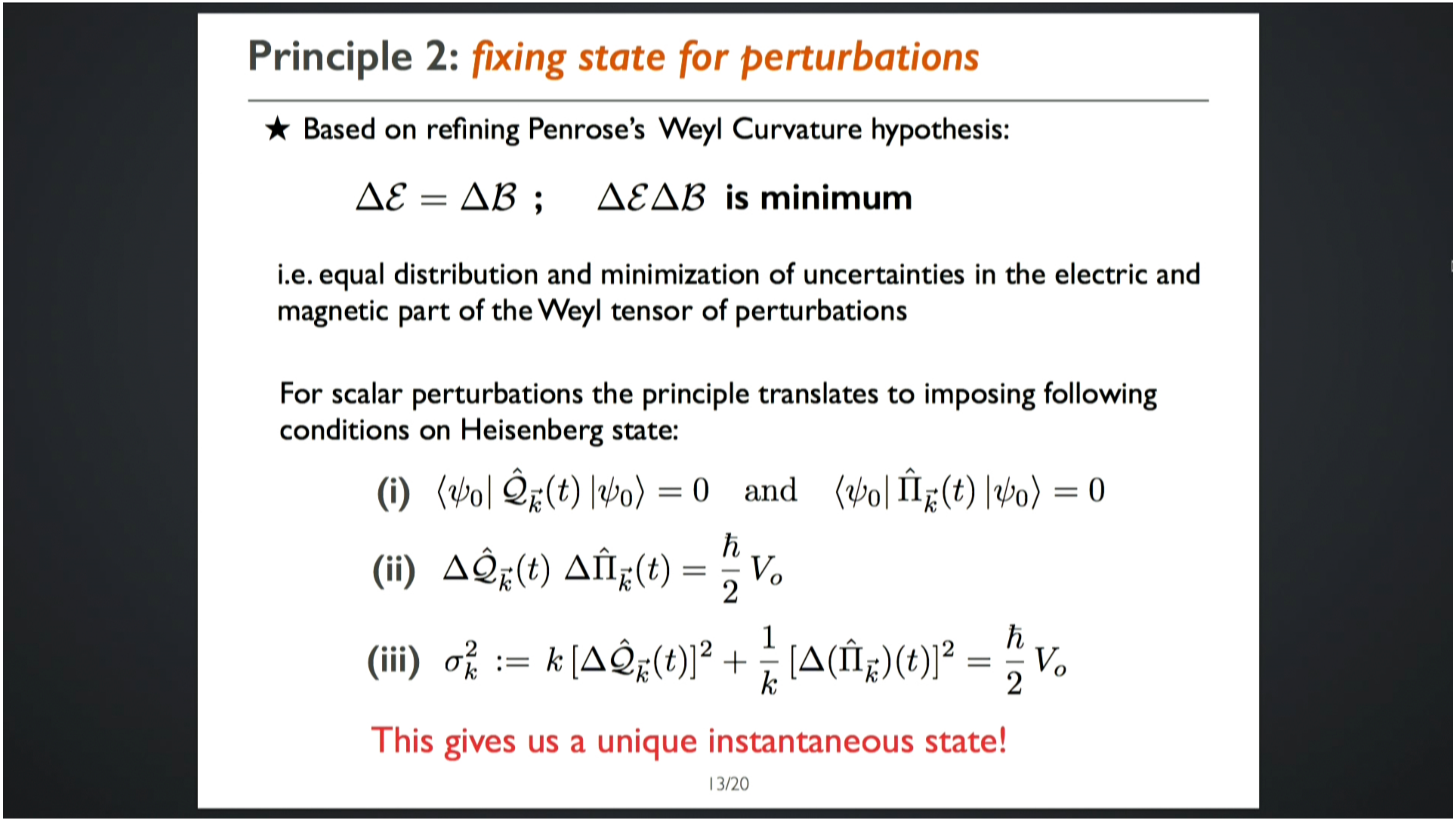


Consequence of fixing background geometry

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:

$$\Delta\mathcal{E} = \Delta\mathcal{B}\ ; \qquad \Delta\mathcal{E}\Delta\mathcal{B}\ \textbf{ is minimum}$$

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

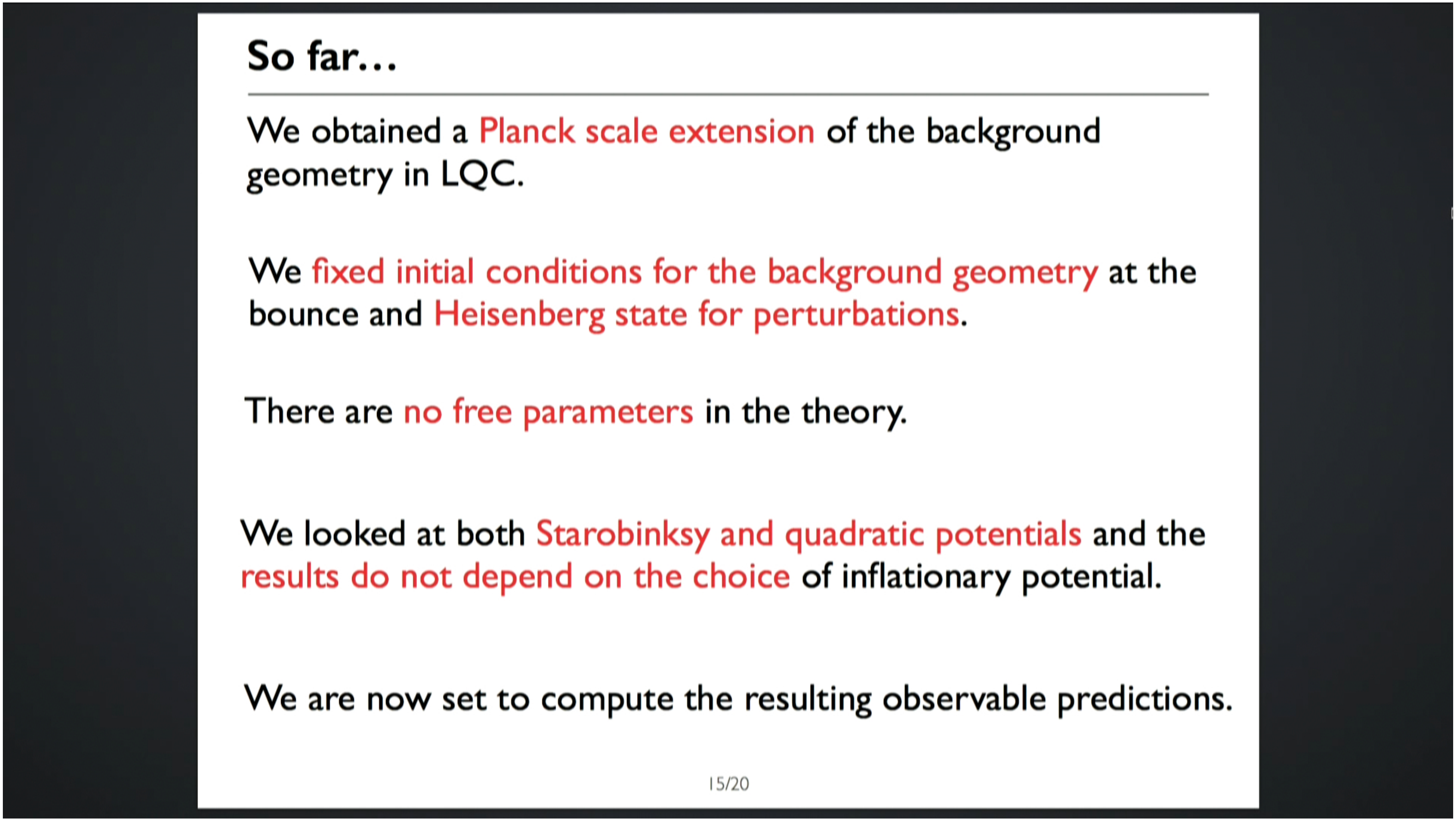
For scalar perturbations the principle translates to imposing following conditions on Heisenberg state:

(i) $\langle\psi_0|\,\hat{\mathcal{Q}}_{\vec{k}}(t)\,|\psi_0\rangle = 0 \quad \text{and} \quad \langle\psi_0|\,\hat{\Pi}_{\vec{k}}(t)\,|\psi_0\rangle = 0$

(ii) $\Delta\hat{\mathcal{Q}}_{\vec{k}}(t)\ \Delta\hat{\Pi}_{\vec{k}}(t) = \dfrac{\hbar}{2}\,V_o$

(iii) $\sigma^2_{k} := k\,[\Delta\hat{\mathcal{Q}}_{\vec{k}}(t)]^2 + \dfrac{1}{k}\,[\Delta(\hat{\Pi}_{\vec{k}})(t)]^2 = \dfrac{\hbar}{2}\,V_o$

This gives us a unique instantaneous state!



So far…

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

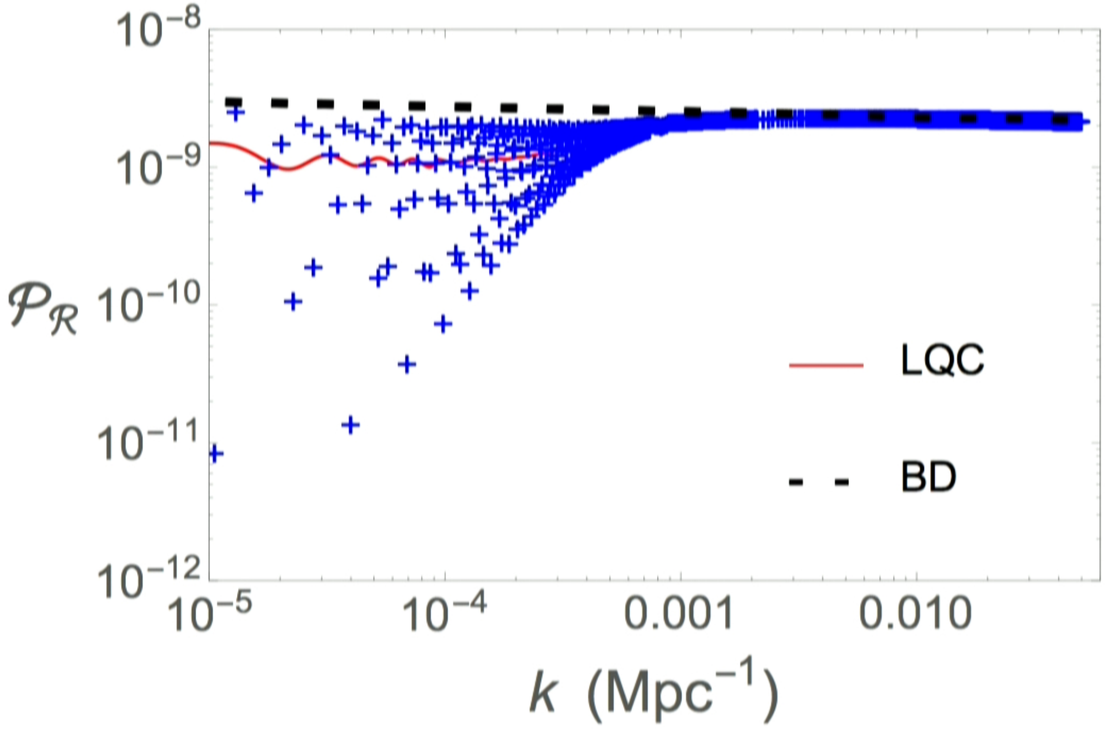
We fixed initial conditions for the background geometry at the bounce and Heisenberg state for perturbations.

There are no free parameters in the theory.

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

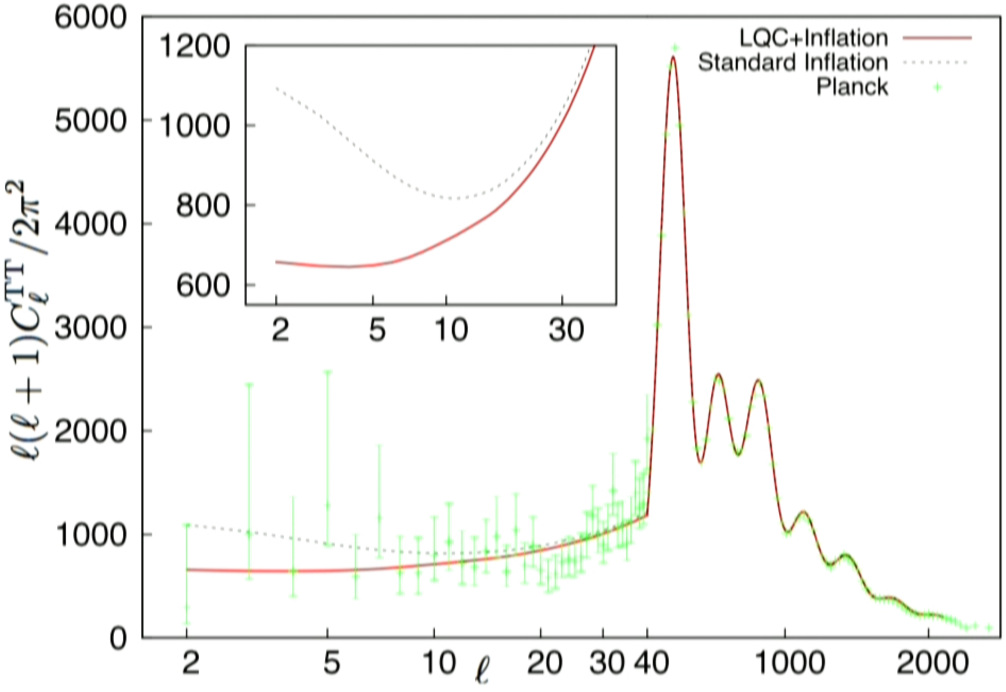
We are now set to compute the resulting observable predictions.

Scalar power spectrum



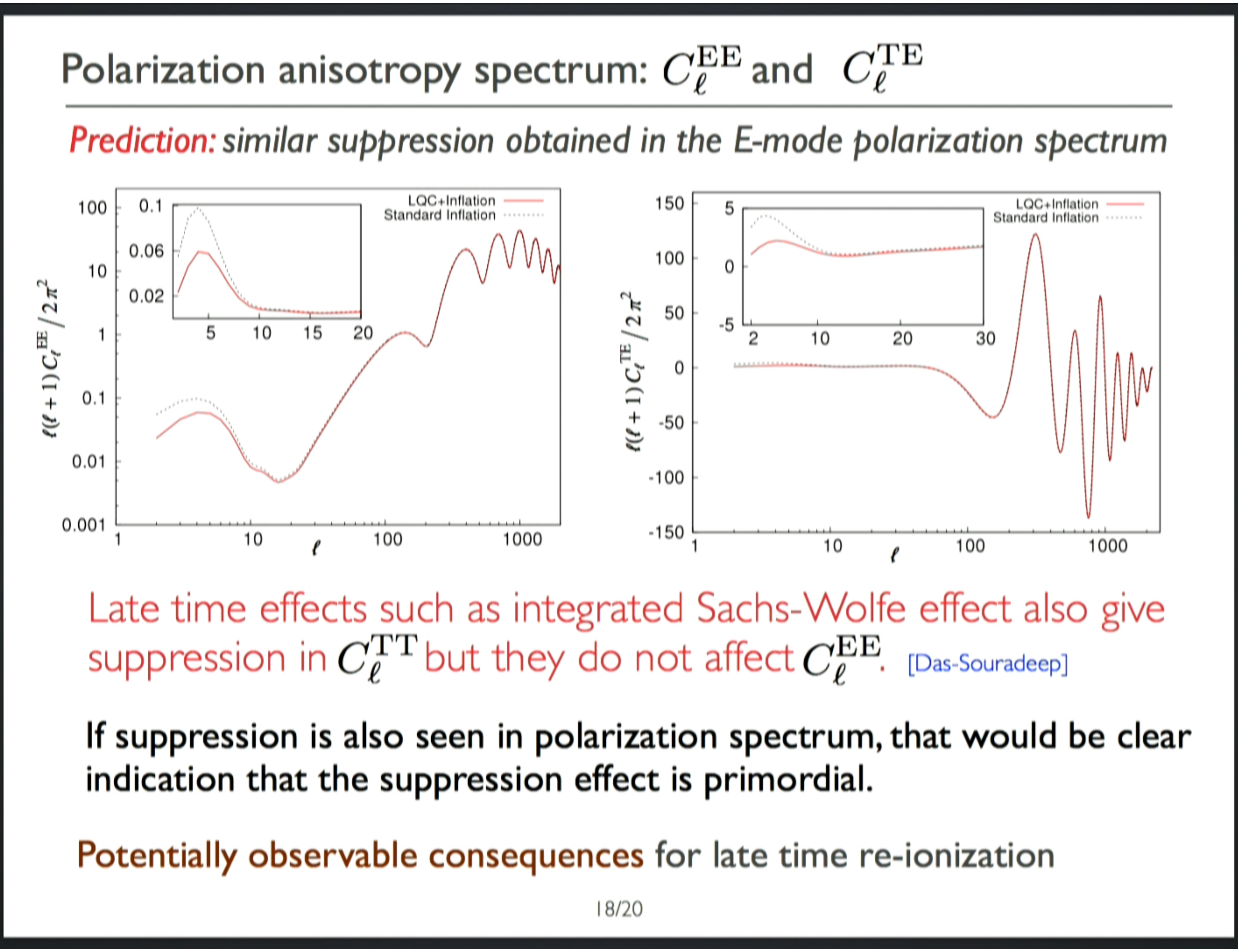
Inflationary potential: $V(\phi) = \frac{3M^2}{32\pi}\left(1 - e^{-\sqrt{\frac{16\pi G}{3}}\phi}\right)^2; \quad \phi_{\mathrm{B}} = -1.420\ m_{\mathrm{Pl}}$

Temperature anisotropy spectrum: C_ℓ^{TT}



Background geometry: $V(\phi) = \frac{3M^2}{32\pi}\left(1 - e^{-\sqrt{\frac{16\pi G}{3}}\phi}\right)^2$; $\phi_{\mathrm{B}} = -1.420\ m_{\mathrm{Pl}}$

$$\Delta\chi^2 = 3.15$$



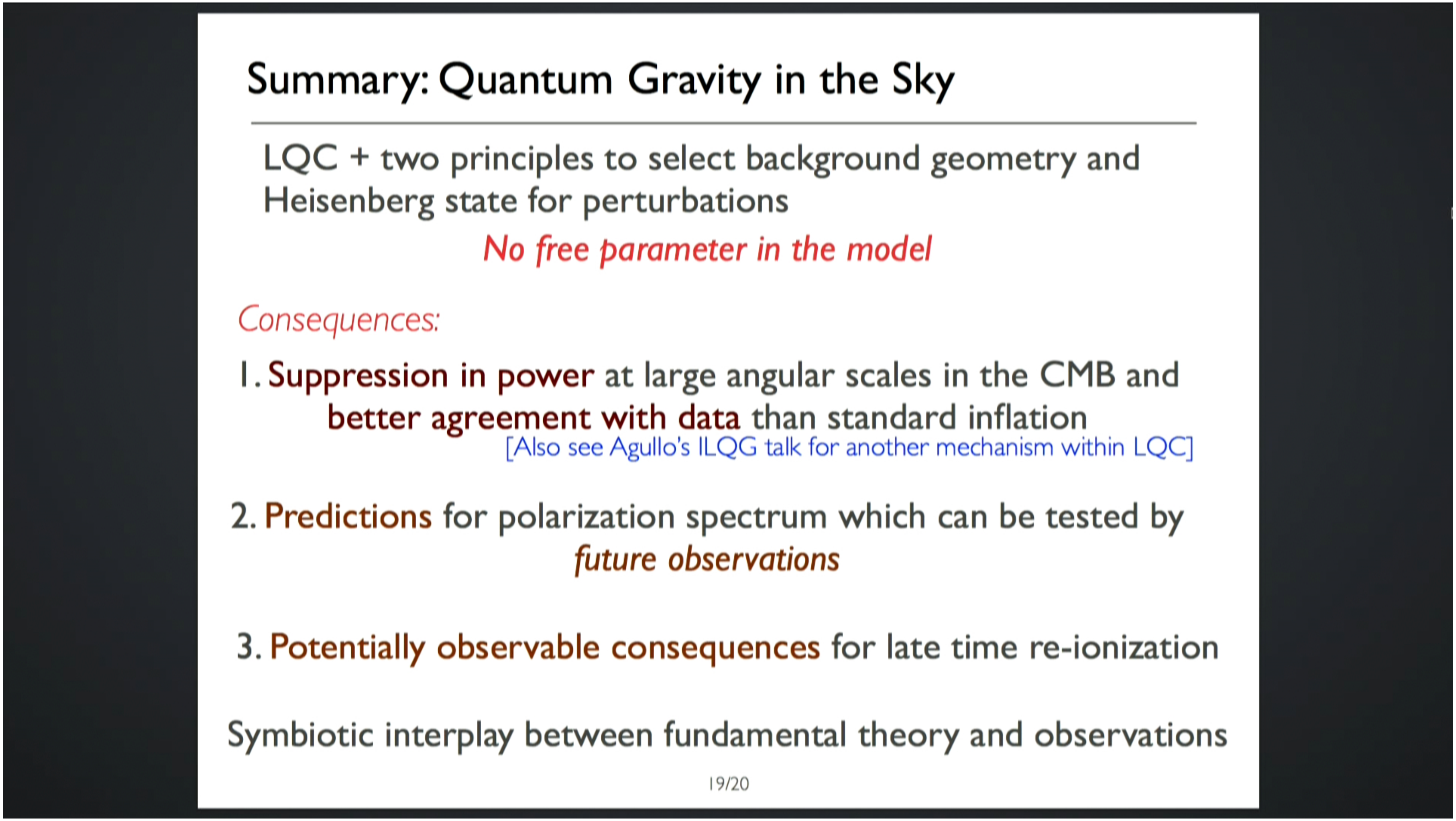
Polarization anisotropy spectrum: C_ℓ^{EE} and C_ℓ^{TE}

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

Late time effects such as integrated Sachs-Wolfe effect also give suppression in C_ℓ^{TT} but they do not affect C_ℓ^{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

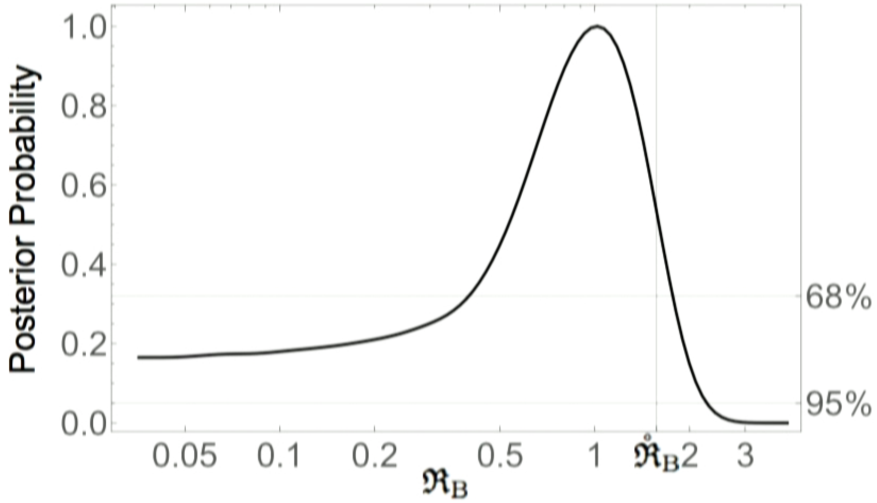
Consequences:

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

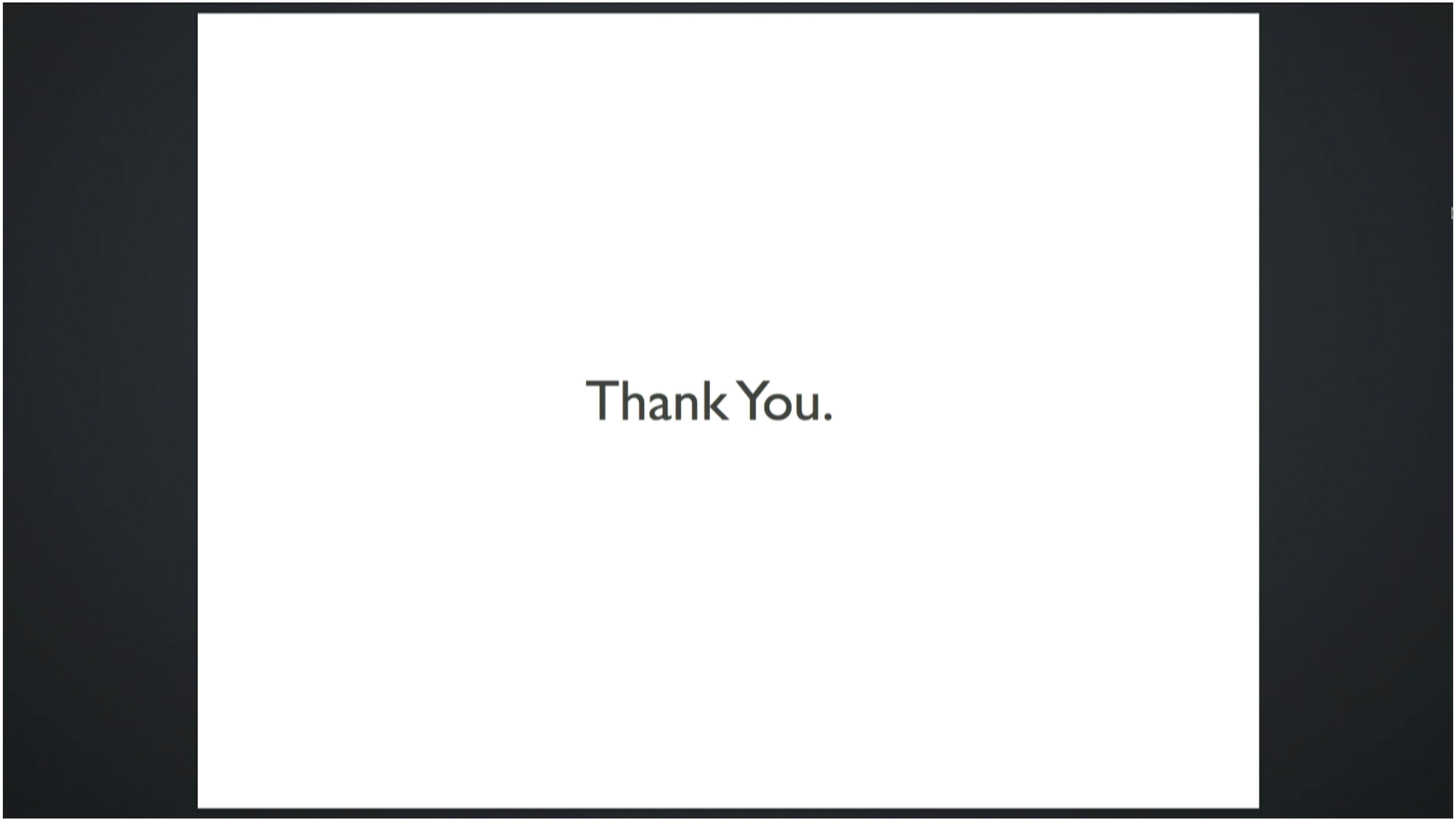
Symbiotic interplay between fundamental theory and observations

Phenomenological Robustness of Principle I

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



The value $\mathring{\mathfrak{R}}_{\rm B} = 1.57\, l_{\rm Pl}$ from Principle I is well within the 68% confidence level of the best fit value.



Thank You.