Quantum Origins of Cosmic Structure: From Vacuum Fluctuations to Primordial Inhomogeneities

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Lecture 4

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Outline

1. Fundamental Problem
2. Proposals to address the fundamental problem
3. Eternal Inflation
4. Our model to solve these two problems
5. Comparison with CMB data
6. Conclusions

Inflation: The Standard Picture

Well-established successes:

- An early cosmological epoch characterized by an accelerated expansion of the Universe
- *Historically:* Solves horizon, flatness.
- *Today:* Predicts nearly scale-invariant spectrum of perturbations, consistent with *Planck* 2018.

The standard story for structure:

- Inflaton field: $\phi = \phi_0(\eta) + \delta\phi(\mathrm{x}, \eta)$
- Metric: $g_{ab} = g_{ab}^{(0)} + \delta g_{ab} \rightarrow$ Prim. curv. pert. $\mathcal{R}(x, \eta)$
- Initial state: Bunch–Davies vacuum
- "Quantum fluctuations" $\rightarrow$ seeds of structure

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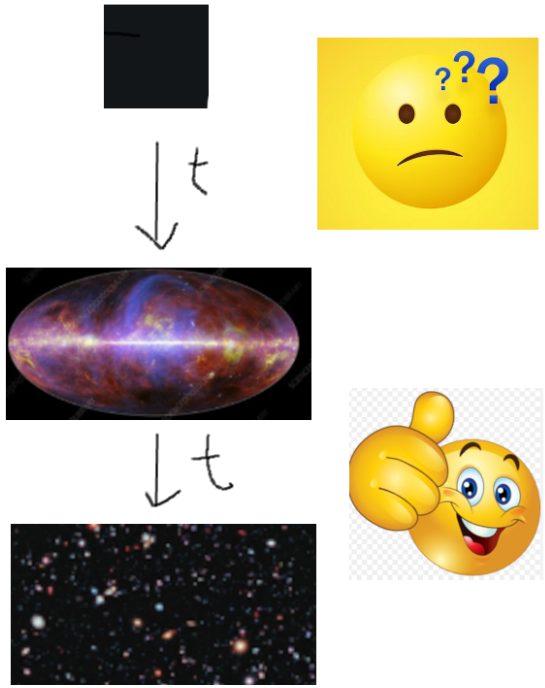
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The fundamental problem

- **Remarkable**: The universe was originally described by a **space-time which is homogeneous and isotropic**, and there is a scalar field (the inflaton) which is in a **vacuum state also homogeneous and isotropic** (there are some irrelevant deviations of this left from an imperfect inflation at the order of e^{-80}), but the universe ended up with inhomogeneities that fit the experimental data.

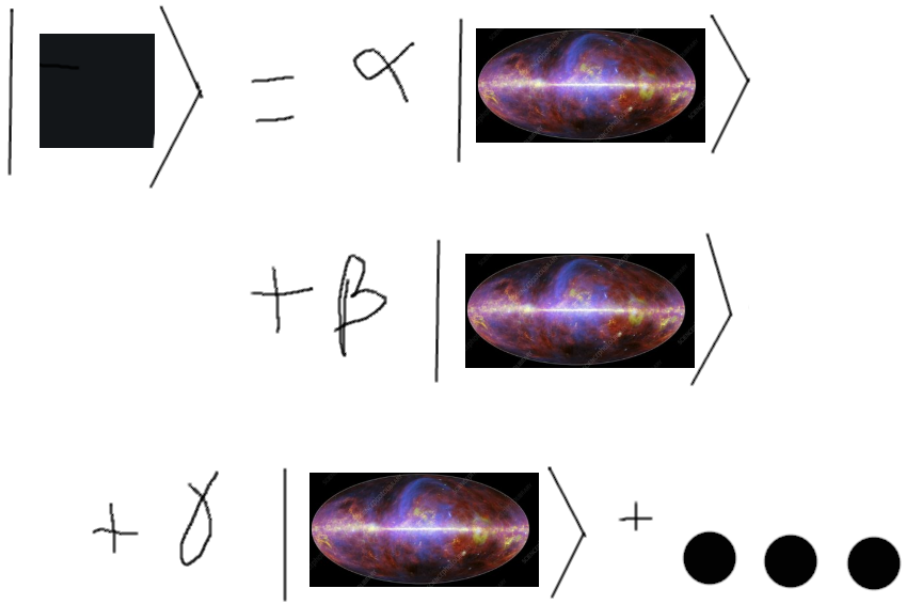


The fundamental problem

- Question: **How did it happen? (★)**

$$\underbrace{|\text{symmetric}\rangle}_{\textbf{The BD vacuum}} \underbrace{\Longrightarrow\Longrightarrow\Longrightarrow}_{\textbf{Unitary evolution}} \underbrace{|\text{non-symmetric}\rangle}_{\textbf{The quantum state characterizing our univ.}}$$

- Basically, we have



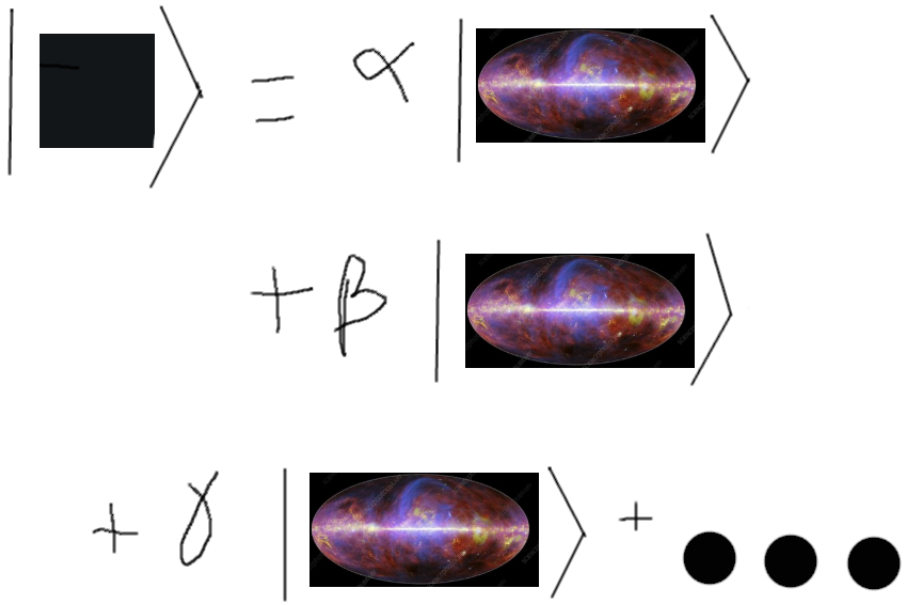
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The fundamental problem

V. Mukhanov in his book *"Physical Foundations of Cosmology"* (2005)



348 *Inflation II: origin of the primordial inhomogeneities*

no preferred position in space? Quantum mechanical unitary evolution does not destroy translational invariance and hence the answer to this question must lie in the transition from quantum fluctuations to classical inhomogeneities. Decoherence is a necessary condition for the emergence of classical inhomogeneities and can easily be justified for amplified cosmological perturbations. However, decoherence is not sufficient to explain the breaking of translational invariance. It can be shown that as a result of unitary evolution we obtain a state which is a superposition of many macroscopically different states, each corresponding to a particular realization of galaxy distribution. Most of these realizations have the same statistical properties. Such a state is a close cosmic analog of the "Schrödinger cat." Therefore, to pick an observed macroscopic state from the superposition we have to appeal either to Bohr's reduction postulate or to Everett's many-worlds interpretation of quantum mechanics. The first possibility does not look convincing in the cosmological con-

The fundamental problem

S. Weinberg in his book *"Cosmology"* (2008), page 476



When discussing $\langle 0|\hat{\mathcal{R}}(x_1)\hat{\mathcal{R}}(x_2)|0\rangle$

These are quantum averages, not averages over an ensemble of classical field configurations. We see this most clearly in Eqs. (10.1.29) and (10.1.30), which give complex results for the averages of products of real fields, and consequently also depend on the order of the fields.[9] Just as in the measurement of a spin in the laboratory, some sort of decoherence must set in; the field configurations must become locked into one of an ensemble of classical configurations, with ensemble averages given by the quantum expectation values calculated as in Eqs. (10.1.27)–(10.1.30) It is not apparent just how this happens, but it is clear that decoherence cannot occur until expectation values of products of real fields become real, which for free fields will also imply that the expectation values do not depend on the order of the fields

The fundamental problem

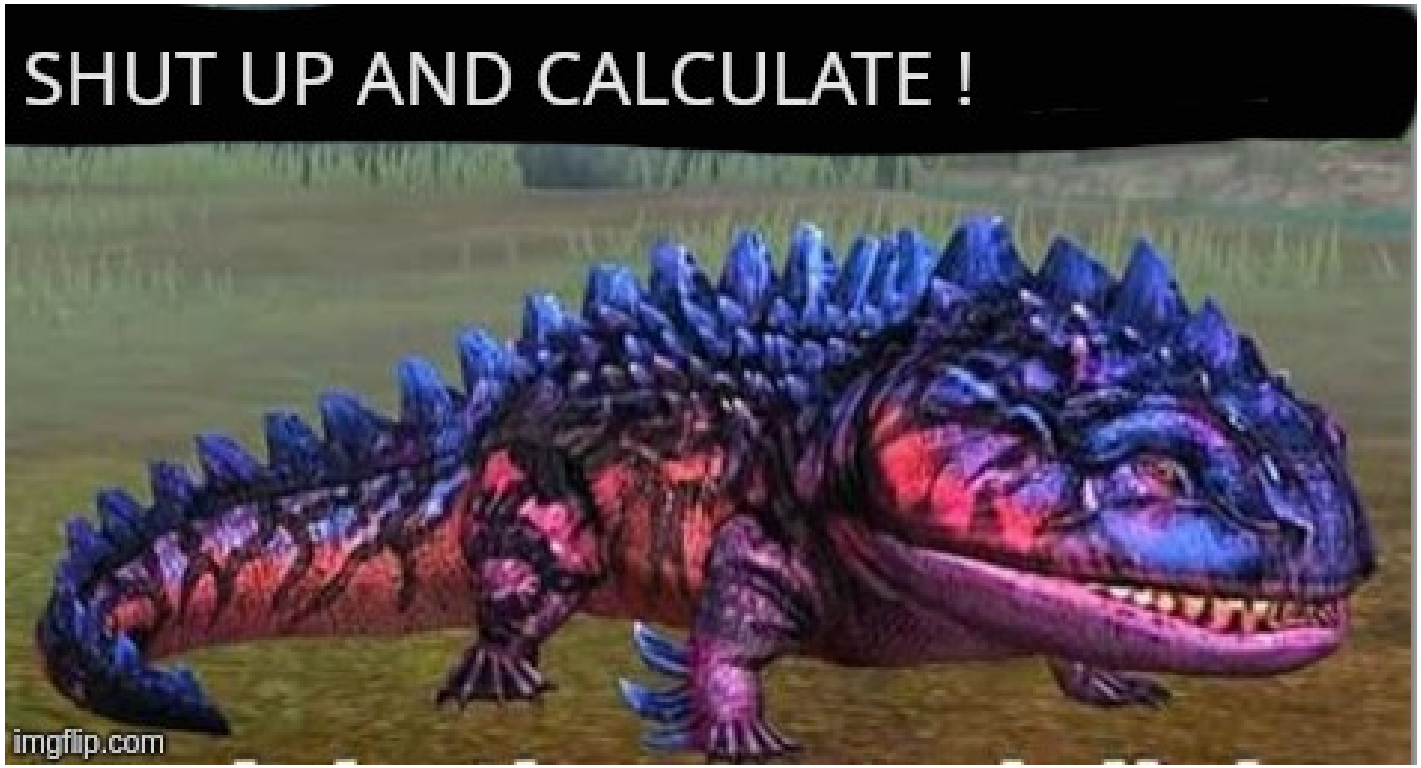
- There is an element in traditional QM, that could break the q. superposition: *The measurement performed by an observer/measurement device*
- Who is the observer in the cosmological setting?
  Perhaps it is us, *humans* measuring the CMB δT with the *Planck* satellite.

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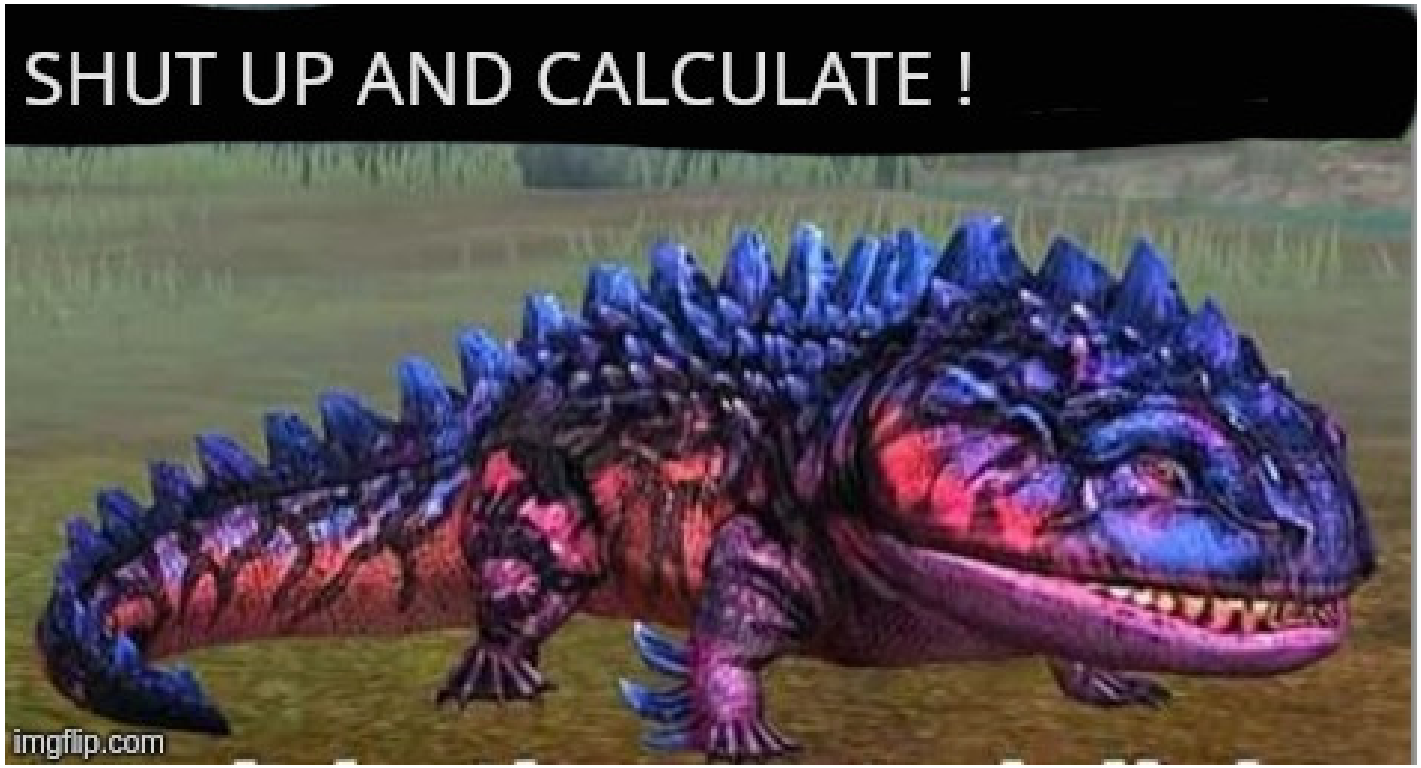
- And before humans?



- The question $(\star)$ is closely related to the quantum measurement problem–*The M-problem*, which in the cosmological context appears in an exacerbated manner.

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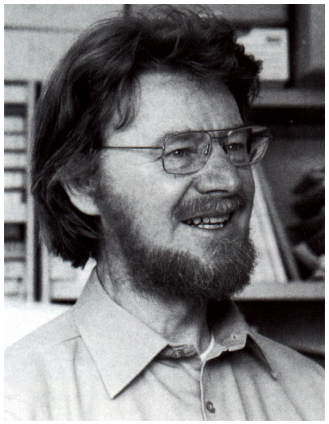
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- The question (★) is closely related to the quantum measurement problem–*The M-problem*, which in the cosmological context appears in an exacerbated manner.

- John S. Bell noticed:

  Cosmologists, even more than laboratory physicists, must find the usual interpretive rules of quantum mechanics a bit frustrating...



It would seem that the ***theory is exclusively concerned with 'results of measurement'*** *and has nothing to say about anything else.* ***When the 'system' in question is the whole world where is the 'measurer' to be found ?*** *... Was the world wave function waiting to jump for thousands of millions of years until a single–celled living creature appeared?* ***Or did it have to wait a little longer for some more highly qualified measurer – with a Ph.D.?***

"Quantum Mechanics for Cosmologists"
published in *Quantum Gravity 2*, eds. C. Isham, R. Penrose and D. Sciama (Oxford University Press, 1981), pp. 611–637

The Measurement Problem in Cosmology

The measurement problem in QM:

- Two evolution rules:
  - **Unitary** evolution $\rightarrow$ Schrödinger equation
  - **Reduction** ("collapse") postulate on measurement
- What counts as a measurement?

In the early universe, this is *worse*:

- No observers, no apparatus, no measurement
- We want to explain the very formation of the seeds that eventually make observers possible!

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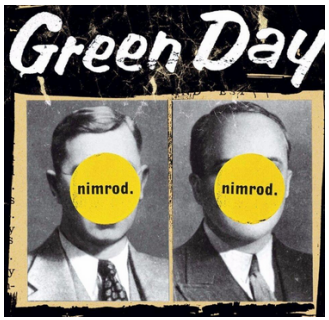
An Alternative Quantum Theory

Key insight

Decoherence & squeezing *alone* do not select a single inhomogeneous realization. **Alternative QM** is needed.

But how to modify QM ?

> *"It's something unpredictable, but in the end is right..." (Green Day, 1997)*



Non-Orthodox QM

The inflationary paradigm motivates us to study formulations in which **measurements/observers** play no fundamental role.

- **Bohmian mechanics:** the wavefunction guides an *actual configuration of particles or fields*. In cosmology, a definite primordial field configuration exists at all times. *[N. Pinto-Neto, G. Santos and W. Struyve, "Quantum-to-classical transition of primordial cosmological perturbations in de Broglie–Bohm quantum theory," Phys. Rev. D **85**, 083506 (2012)]*
- **Objective collapse models:** a *physical stochastic process modifies quantum evolution* and dynamically localizes the state, without an observer triggering the collapse. *[M. P. Piccirilli, GL, R. L. Lechuga-Solis and D. Sudarsky, "Breaking eternal inflation: Empirical viability of a spontaneous collapse scenario," Phys. Rev. D **113**, no.8, 083505 (2026)]*

Beyond QM

These alternatives provide concrete ways to address the issue that decoherence/squeezing alone leaves open.

Continuous Spontaneous Localization (CSL)

Collapse theories unify the two evolution rules of QM into a single, universal dynamics:

CSL evolution equation:

$$|\psi,t\rangle_w = \hat{\mathcal{T}}\ \exp\left\{-\int_0^t dt'\left[i\hat{H} + \frac{1}{4\lambda}\left(w(t') - 2\lambda\hat{A}\right)^2\right]\right\}|\psi,0\rangle \tag{1}$$

- $\hat{A}$: collapse-generating operator
- $w(t)$: stochastic classical noise
- λ: collapse rate parameter

Key features:

- **Amplification mechanism**: negligible for few particles, dominant for macroscopic systems
- No need to invoke "observers"
- Continuous, stochastic reduction
- Experimentally testable (bounds from X-rays, interferometry, GW detectors, XENON)

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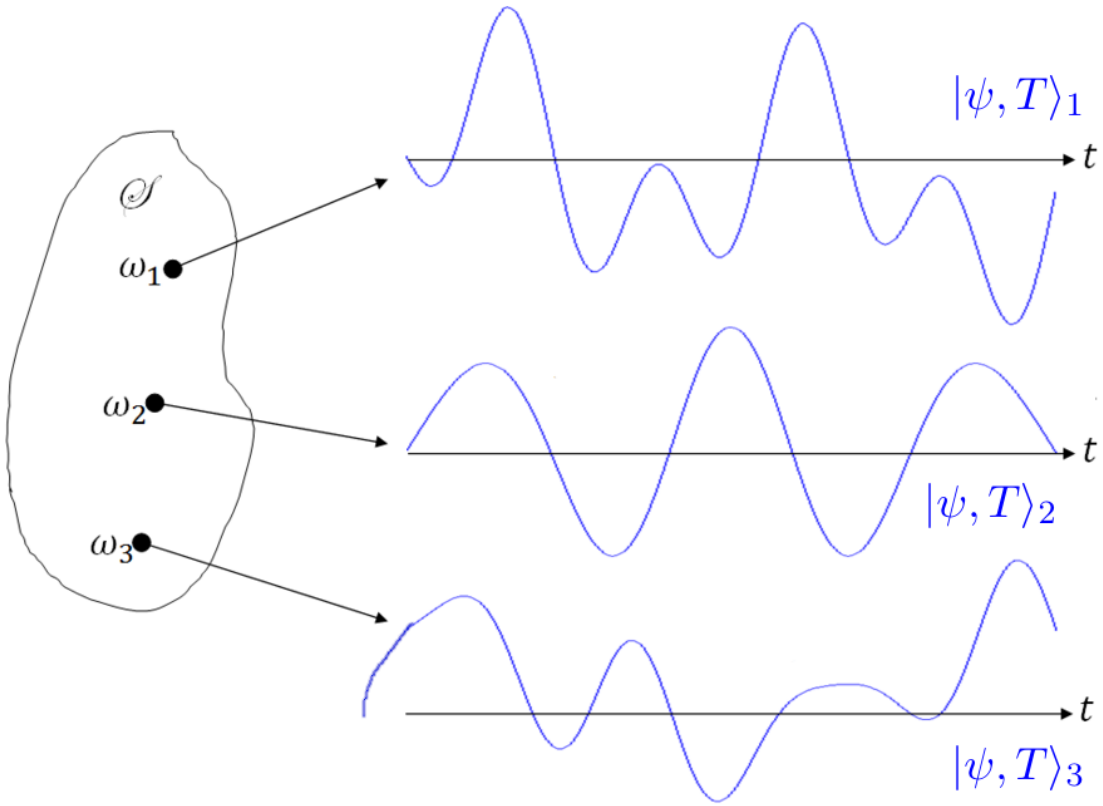
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Stochastic evolution

The most probable: the one with the largest norm ${}_i\langle\psi|\psi\rangle_i$

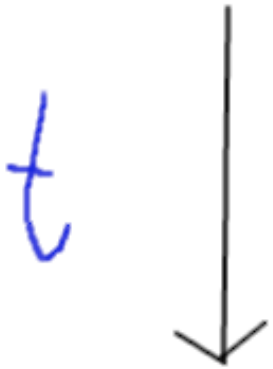
$$P(w)dw \equiv \langle\psi, t|\psi, t\rangle \prod_{t_i=0}^{t-dt} \frac{dw(x, t_i)}{\sqrt{2\pi\lambda_0/dt}}. \tag{2}$$



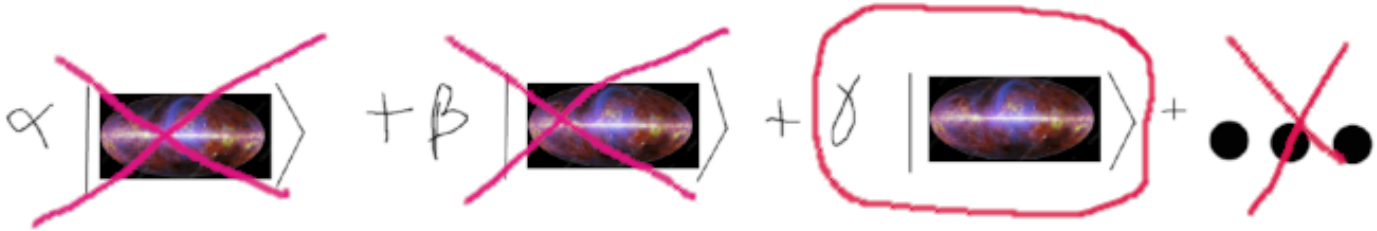
Returning to Inflation

- Our proposal is to implement the CSL theory during inflation to answer question ($\star$)





$$d|\psi\rangle = \Big\{ -iH\,dt + H_{CSL}[dW_t] \Big\} |\psi\rangle$$



Semiclassical Gravity + CSL: The Framework

Semiclassical gravity:

- Gravity: Always *classical (GR)*
- Matter: *quantum* fields
- $G_{ab} = 8\pi G \langle \hat{T}_{ab} \rangle$
- Treated as an *effective theory* (analogy: Navier–Stokes in hydrodynamics)

CSL modifies the quantum dynamics:

- Modified Schrödinger eqn $\Rightarrow$ breaks symmetry of the Bunch–Davies vacuum

Central equation

The comoving curvature perturbation becomes:

$$\mathcal{R}_k(\eta) \simeq \frac{1}{\sqrt{2\epsilon_1}\, M_P} \langle \hat{\delta\phi}_k(\eta) \rangle$$

This is **nonzero** only because of CSL. In standard QM: $\mathcal{R}_k = 0$ always!

- We choose $\hat{\delta\phi}_k$ as the collapse operator
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Bonus prediction

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Three Notions of "Fluctuations"

A crucial source of confusion in inflationary cosmology:

I. Quantum Uncertainties

Indefiniteness of a quantum quantity

E.g., width of the ground-state Gaussian in a harmonic oscillator

Not stochastic!

II. Stochastic Fluctuations

Variation across an ensemble of outcomes

E.g. the height of people here

Requires that each element has a *definite* value

III. Space-time Variations

Changes of a quantity from one point to another in an extended system

E.g. the temperature in this classroom

Physical inhomogeneity

Standard inflation treat all three equally! This confusion affects both the "explanation" of structure formation *and* the **eternal inflation problem**.

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The Eternal Inflation Problem

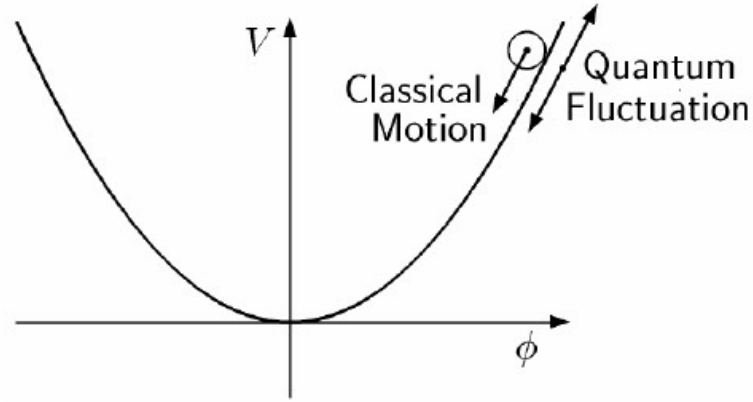
During slow-roll:

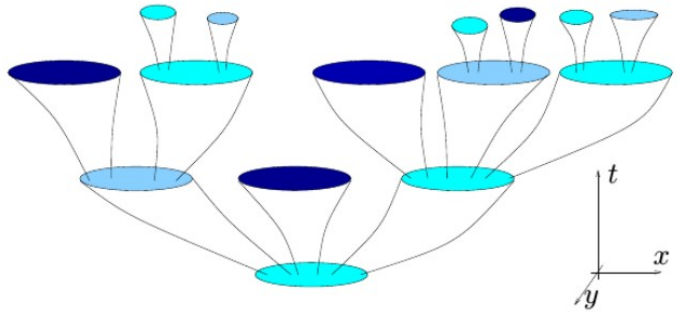
The inflaton zero mode ϕ_0 rolls toward the minimum. Over one "Hubble time", $\Delta t \sim H^{-1}$ two displacements compete:

- **Classical:** $\Delta_{\text{class}}\phi_0$ (slow-roll)
- **Stochastic:** $\Delta_{\text{sto}}\phi_0$ (from "quantum fluct.")

If $\Delta_{\text{sto}}\phi_0 > \Delta_{\text{class}}\phi_0$:

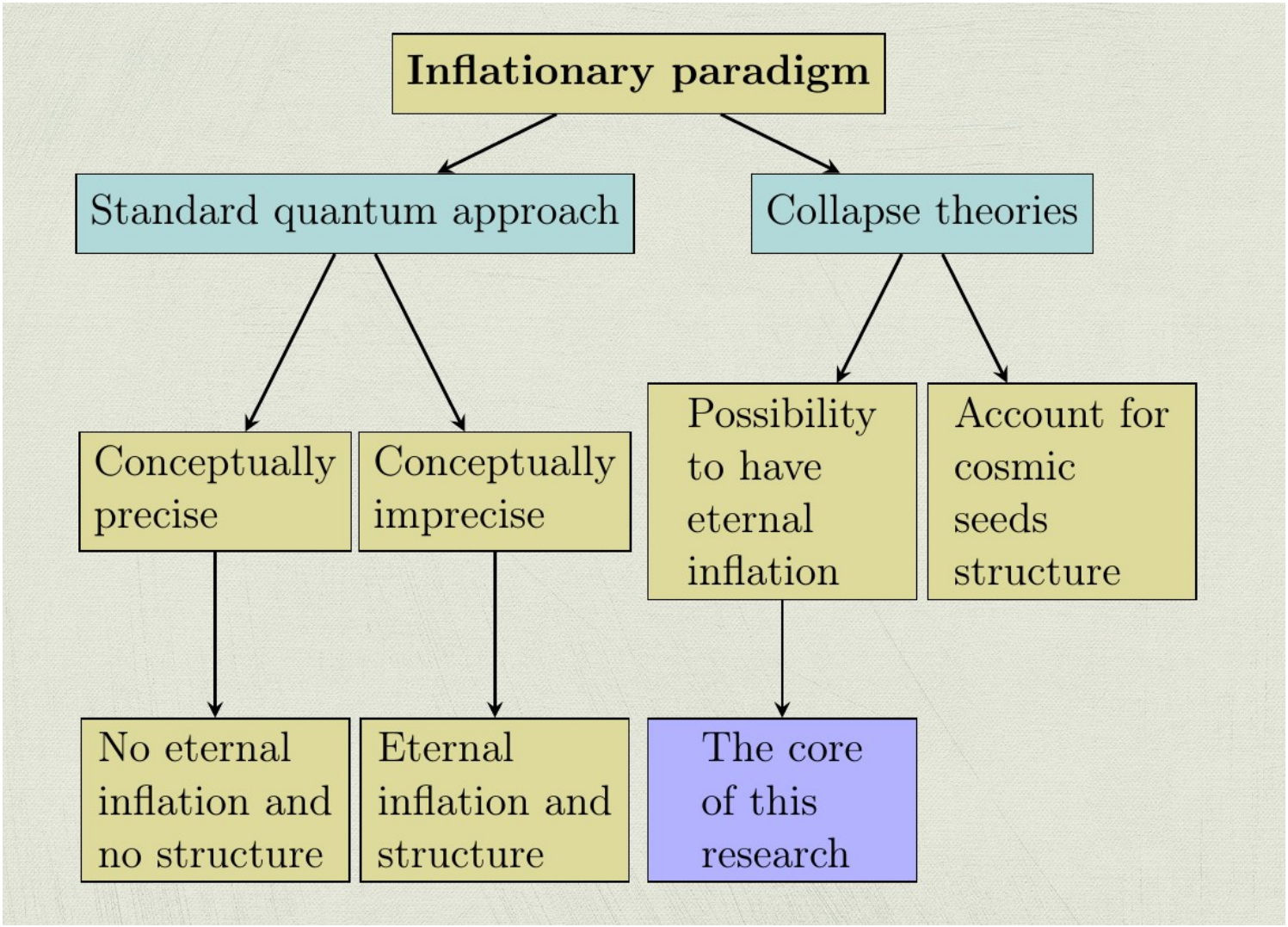
- Some regions get "kicked" up the potential
- Higher $V \Rightarrow$ faster expansion
- These regions dominate the volume. **Inflation never ends!**





Note: In standard QM (no collapse), no genuine stochastic fluctuations exist $\Rightarrow$ eternal inflation is an *illusion*. With CSL, real stochastic kicks exist and must be addressed!

The lectures so far...



The CSL Primordial Power Spectrum

After applying the CSL model for inflation, the result is:

CSL power spectrum

$$P(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1} C(k; \lambda_k)$$

- A_s, n_s: the amplitude and scalar spectral index, same predictions as in the standard model ($n_s = 1 - 2\epsilon_{1*} - \epsilon_{2*}$)
- $C(k; \lambda_k)$: **new function** encoding the CSL collapse mechanism; *depends on the collapse parameter* λ_k
- When $\lambda_k \to 0$: $C(k; \lambda_k) \to 0$ and $P(k) \to 0$
  $\Rightarrow$ **No collapse = no perturbations!** Fully consistent.

The Collapse Rate: From Structure to Eternal Inflation

Simplest choice (accounts for primordial structure): $\lambda_k = \lambda_0\, k$ with $\lambda_0 = 10^{-5}$ Mpc^{-1} ($\approx 10^{-19}$ s^{-1}). Reproduces the standard power spectrum, i.e. $C(k;\lambda_k) \to$ const.

But: modes with $k \to 0$ have $\lambda_k \to 0$, so they *do not collapse*. Long-wavelength modes can mimic the zero mode and drive eternal inflation.

Modified collapse rate:

$$\lambda_k = \lambda_0 \frac{k^{\alpha+1}}{(\beta + k)^{\alpha}}$$

- $\alpha > 0$: dimensionless, controls suppression strength; $\beta > 0$: units of k, sets transition scale
- $\beta = 0$ or $\alpha = 0$: recovers $\lambda_k = \lambda_0 k$
- $k \gg \beta$: $\lambda_k \simeq \lambda_0 k$ (standard structure) vs. $k \ll \beta$: $\lambda_k \simeq \lambda_0 k\,(k/\beta)^{\alpha}$ (suppressed)

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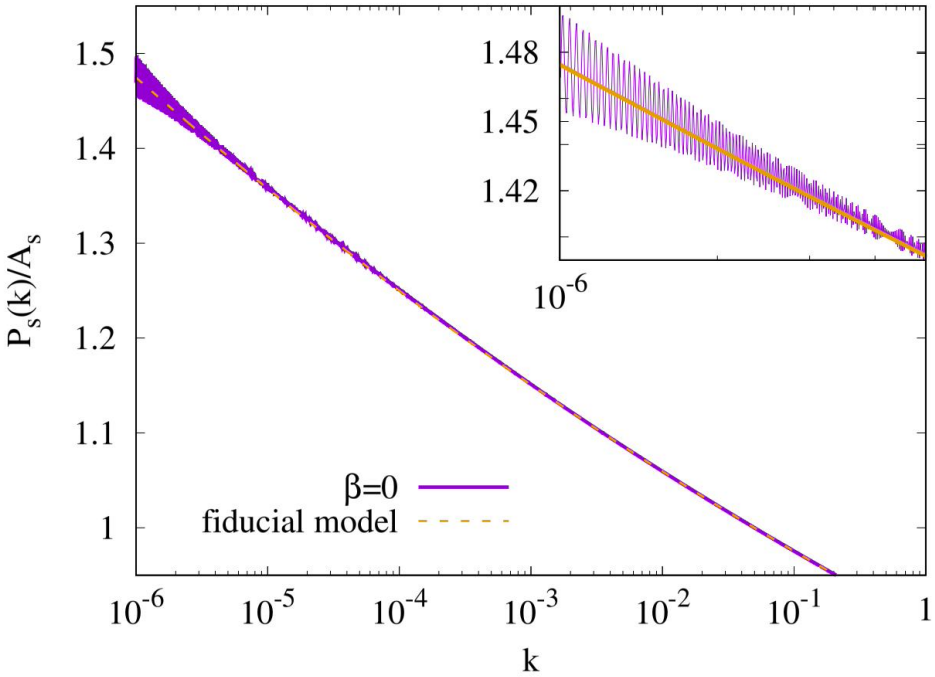
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Power Spectrum: $\beta = 0$ (Eternal Inflation Persists)



When $\beta = 0$:

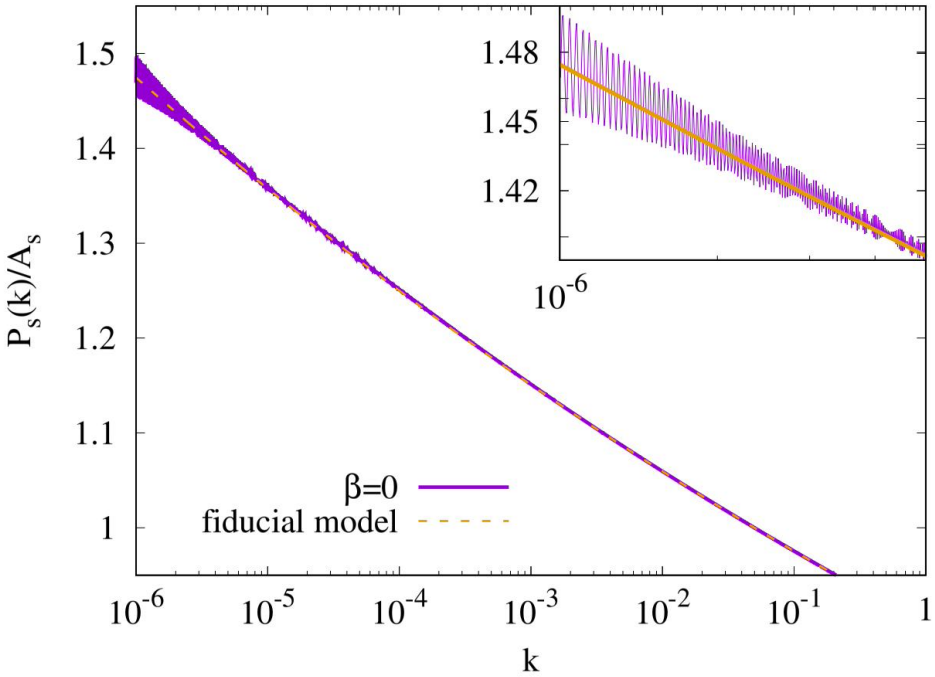
- CSL spectrum recovers the standard ΛCDM power-law shape
- Small oscillatory features at low k, amplitude $\ll 1$, these are imperceptible in the CMB.

Physical origin of oscillations:

Analogy with harmonic oscillator: collapse displaces the wavepacket; unitary evolution makes it oscillate about zero. CSL repeats this continuously.

$\Rightarrow$ **Differences from ΛCDM are purely at the conceptual level.**

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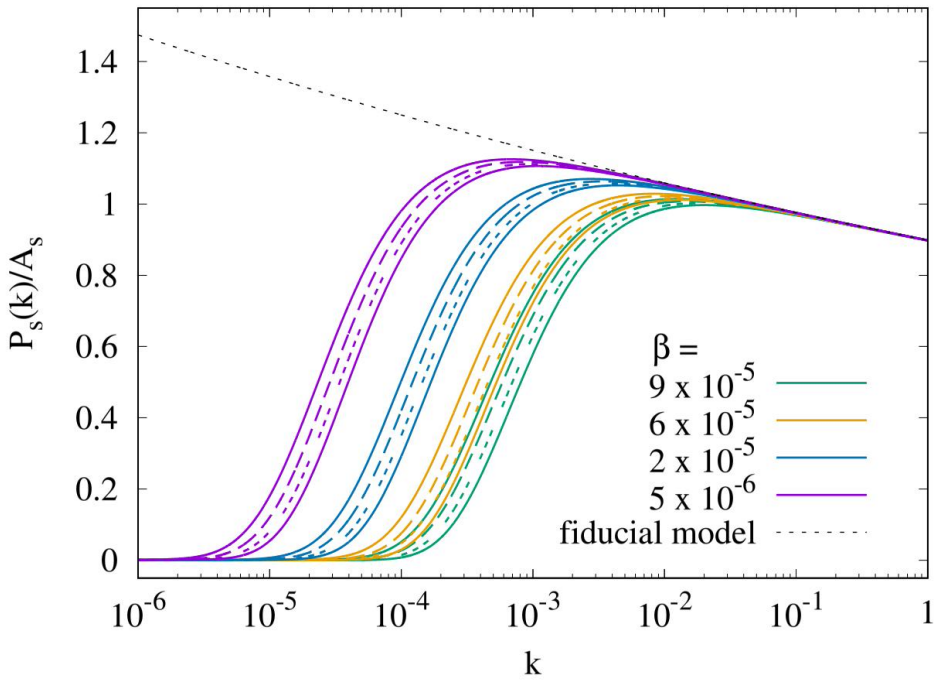
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Power Spectrum: Nonzero α and β



line types from left to right

$\alpha = 5, 6, 7, 8$

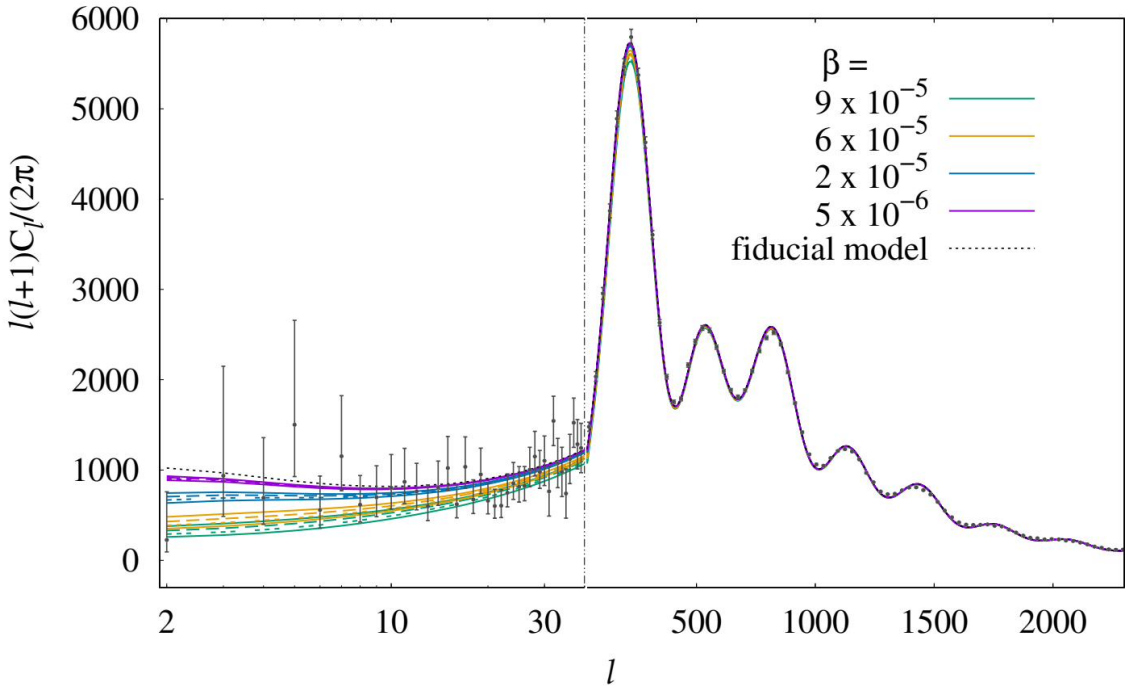
Key features:

- **Strong suppression** at low k (large angular scales)
- $k \ll \beta$: the function $C(k; \lambda_k)$ gets suppressed by a factor $\sim (k/\beta)^\alpha$, which kills the amplitude
- $k \gg \beta$: excellent agreement with ΛCDM

Physical interpretation:

Inhomogeneities progressively "switch on" as k increases past β. Modes with $k \ll \beta$ are precisely those that would drive eternal inflation $\Rightarrow$ **their amplitude is suppressed by design.**

Effect on the CMB: Angular Power Spectrum C_ℓ



- Departure from ΛCDM only at **low multipoles** $\ell \lesssim 40$; high-ℓ: identical to fiducial
- Approaches fiducial from *below* $\Rightarrow$ may help explain the **low-ℓ anomaly** (deficit observed by COBE, WMAP, *Planck*)

Condition to Avoid Eternal Inflation

Requirement: $\Delta_{\text{sto}}\phi_0 < \Delta_{\text{class}}\phi_0$ for all relevant modes $\Rightarrow$ α **and** β **are not independent parameters**.

Theoretical calculations yield:

No-eternal-inflation condition

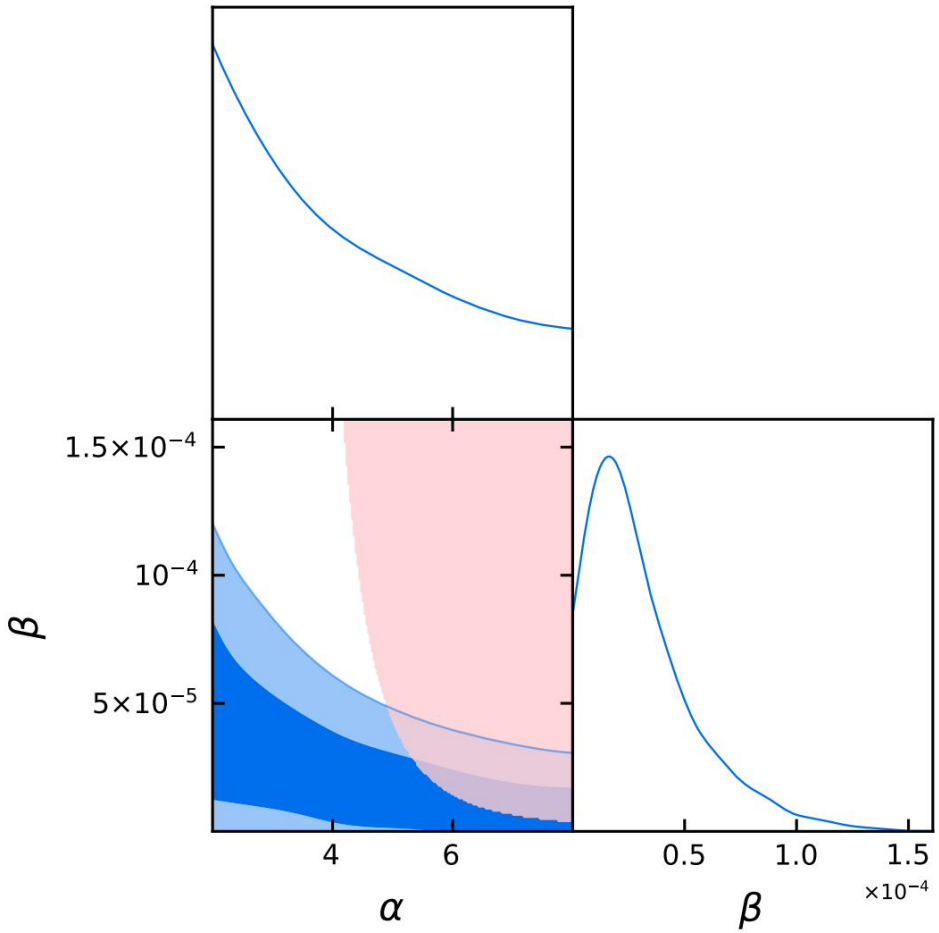
$$10^{15}\,\frac{1}{\alpha+2}\left(\frac{2\pi}{\beta\,|\tau|}\right)^{\alpha} < 1$$

Numerical inputs: $\lambda_0 \approx 10^{-19}\ \text{s}^{-1}$, τ represents the initial conformal time of inflation, so we assume inflation lasts ~ 65 e-folds, inflation energy scale $V^{1/4} \simeq 10^{-4}\,M_P$

Key question: Is this condition compatible with the CMB data?

Statistical Analysis: Unrestricted Parameters

Method: MCMC analysis using CosmoMC + *Planck* 2018 legacy likelihood
(*Planck* TT, TE, EE + lowE + lensing)

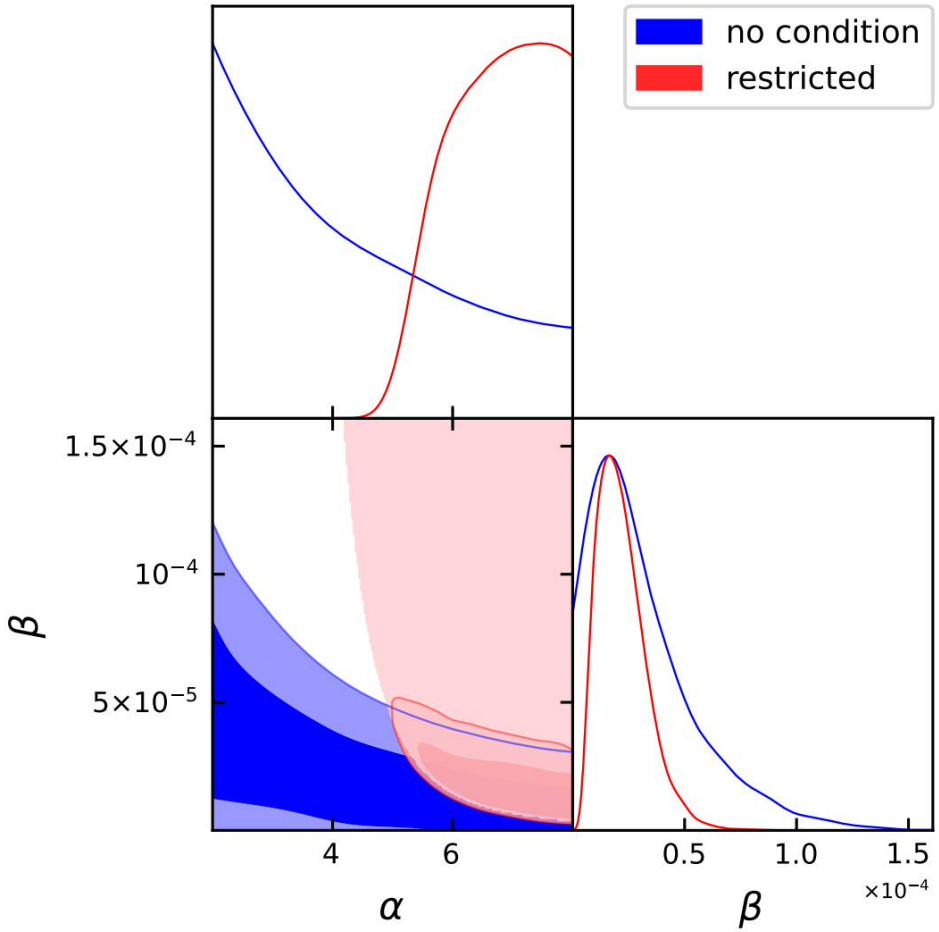


Results (no restriction):

- Data **do not favor** a specific α
- Data **do constrain** β:
  $\beta = (3.19^{+0.54}_{-3.2}) \times 10^{-5}$ Mpc^{-1} [68% CL]
  $\beta < 1.13 \times 10^{-4}$ Mpc^{-1} [99% CL]
- $\beta \leq 10^{-3}$ **Mpc^{-1} is an excellent upper bound**

The **pink shaded region** shows where the no-eternal-inflation condition is satisfied. There is clear **overlap!**

Statistical Analysis: Imposing the No-Eternal-Inflation Condition



Procedure:

Re-run CosmoMC requiring the no-eternal-inflation condition at every MCMC step.

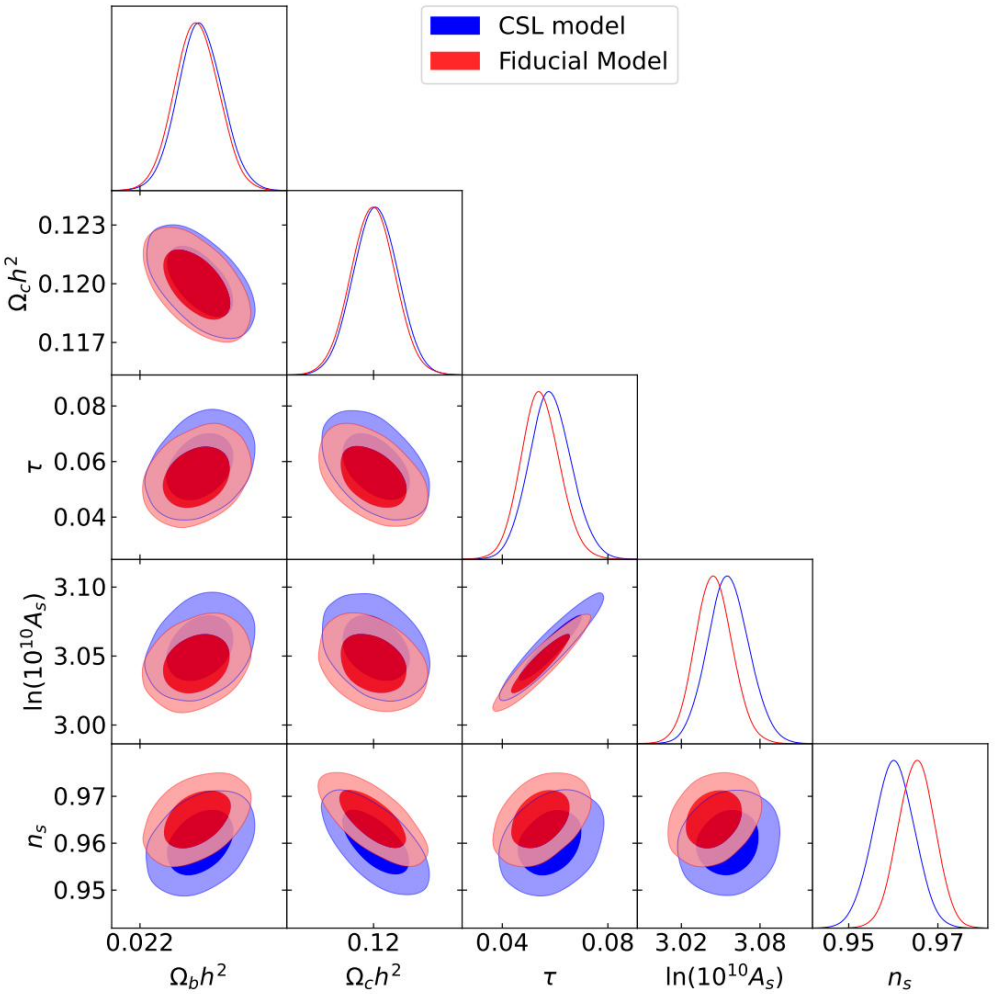
Results at 68% CL:

- $\alpha > 6.28$
- $\beta = (2.20^{+0.63}_{-1.30}) \times 10^{-5}$ Mpc^{-1}

Blue: unrestricted. **Red**: restricted.

Restricted posteriors lie within the allowed (shaded) region *and* are consistent with *Planck* data.

Impact on Standard Cosmological Parameters



CSL model (blue) vs. **ΛCDM** (red):

Param.	CSL	ΛCDM
$\Omega_b h^2$	0.02240	0.02238
$\Omega_c h^2$	0.1201	0.1200
τ_{reio}	0.058	0.054
$\ln(10^{10} A_s)$	3.056	3.045
n_s	0.9601	0.9652
H_0	67.34	67.37

- Slight shifts in τ_{reio}, A_s, n_s
- **Not statistically significant**
- $\Omega_b h^2$, $\Omega_c h^2$, H_0: unchanged

Summary of Main Results

Conceptual

- Standard inflation *cannot* explain perturbations from the symmetric vacuum alone
- CSL provides an **objective collapse** that breaks BD vacuum symmetry
- Semiclassical gravity + CSL: consistent effective framework

Observational

- CSL power spectrum: $P(k) = A_s(k/k_*)^{n_s-1}C(k;\lambda_k)$
- Modified $\lambda_k(\alpha,\beta)$ suppresses long-wavelength modes
- *Planck* 2018 data: $\alpha > 6.28$, $\beta \sim 2\times 10^{-5}$ **Mpc**$^{-1}$
- Standard cosmo. parameters: unaffected
- Low-ℓ suppression: promising for power deficit anomaly

The model simultaneously:

(1) explains emergence of cosmic structure (2) avoids eternal inflation

(3) is compatible with *Planck* CMB data (4) suppresses primordial GWs

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Conclusions 1

- Squeezing and decoherence explain important aspects of classical behavior, but do not, by themselves, explain the emergence of a particular realization of primordial inhomogeneities.
- Objective collapse theories introduce a physical, stochastic mechanism that can break the symmetries of the initial quantum state. They also provide a particular realization without invoking observers or measurements.
- In our semiclassical approach, collapse generates nonzero expectation values of matter perturbations, which source classical metric perturbations.

Conclusions 2

- These proposals have testable consequences. Depending on the gravitational framework, collapse dynamics, and background evolution, these can include suppressed primordial gravitational waves and modified CMB power at low ℓ.
- Observational constraints on inflationary potentials change within these proposals. Simple potentials, such as $V(\phi) \propto \phi^2$, therefore deserve reassessment within these frameworks.
- The early universe provides a laboratory for quantum foundations: addressing the origin of cosmic structure may reveal new physics beyond standard quantum dynamics.

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Thank you!