Recent Developments in Primordial Cosmology

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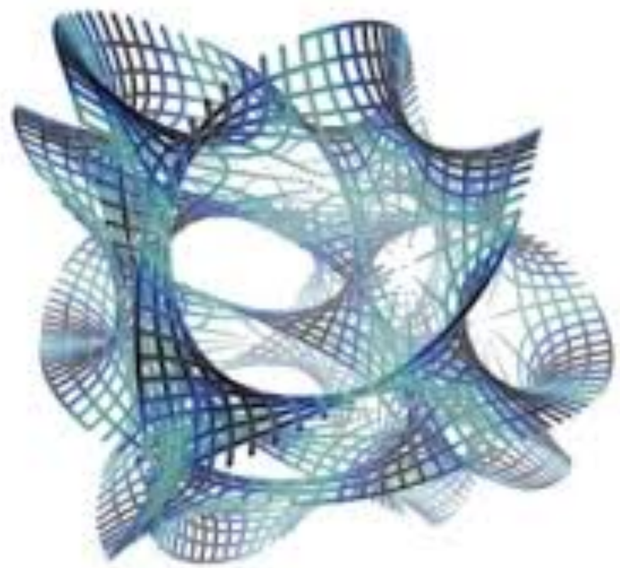
Bad Honnef, March 2015

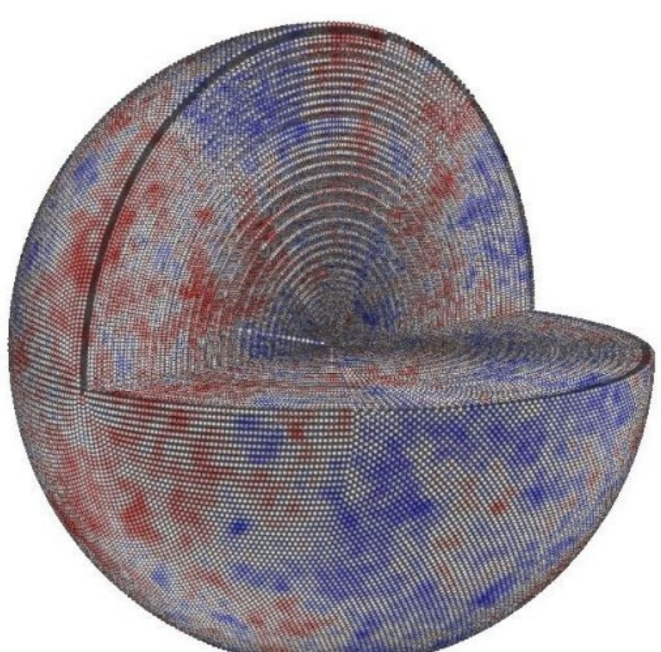
Outline

1. Recent Results from Planck
2. Inflation from the Bottom Up
3. Inflation from the Top Down
4. Conceptual Problems of Inflation

ultraviolet completion

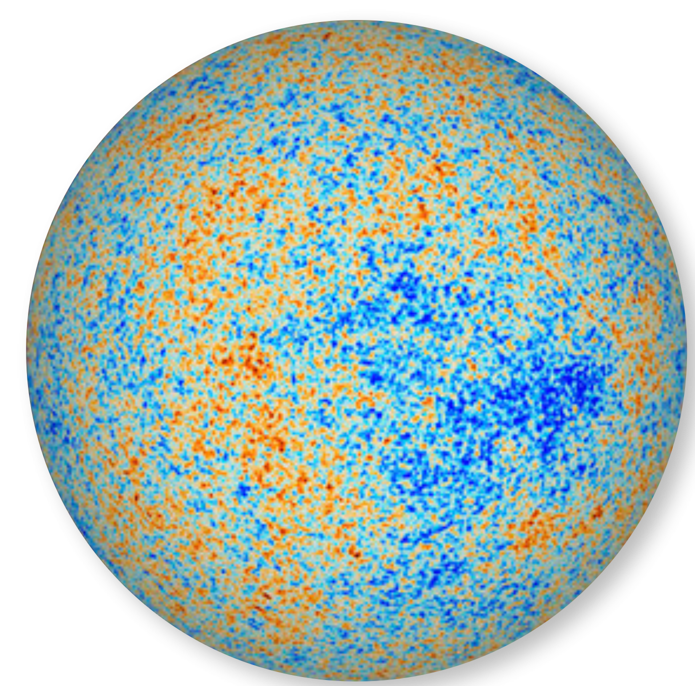


3. 2.



primordial perturbations

1.



CMB anisotropies

References

DB and McAllister, *Inflation and String Theory,* Cambridge University Press, 2015.

Planck 2015. XX. Constraints on Inflation, [arXiv:1502.02114]

Planck 2015. XVII. Constraints on Primordial Non-Gaussianity, [arXiv:1502.01592]

Ade et al, A Joint Analysis of BICEP2/Keck Array and Planck Data, [arXiv:1502.00612]

DB, Green, and Porto, *B-modes and the Nature of Inflation,* [arXiv:1407.2621]

DB, Green, Lee, and Porto, *Signs of Analyticity in Single-Field Inflation,* [arXiv:1502.07304]

DB and Green, *Signatures of Supersymmetry from the Early Universe,* [arXiv:1109.0292]

Assassi, DB, Green, and McAllister, *Planck-Suppressed Operators,* [arXiv:1304.5226]

Arkani-Hamed and Maldacena, *Cosmological Collider Physics,* [to appear]

Please ask questions

1.

Recent Results from Planck

Planck 2015. XX. Constraints on Inflation, [arXiv:1502.02114]

Planck 2015. XVII. Constraints on Primordial Non-Gaussianity, [arXiv:1502.01592]

Preliminaries

*The temperature anisotropies (and polarization) of the cosmic microwave background measure **distortions of space**:*

ζ

scalar mode

$$d\ell^2 = a^2(t)\left[1 + 2\zeta(t, \boldsymbol{x})\right]\delta_{ij}\,dx^i dx^j$$

curvature perturbation

expansion of space

isotropic stretching

h_{ij}

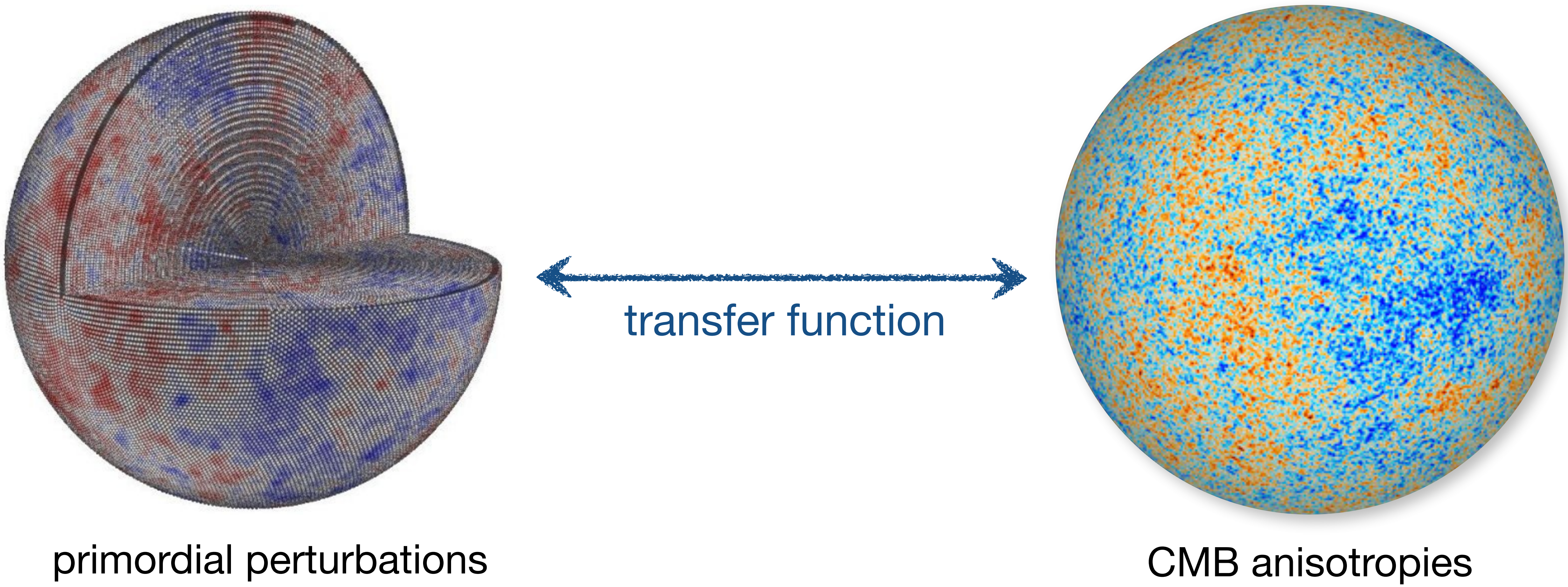
tensor mode

$$d\ell^2 = a^2(t)\left[\delta_{ij} + h_{ij}(t, \boldsymbol{x})\right]dx^i dx^j$$

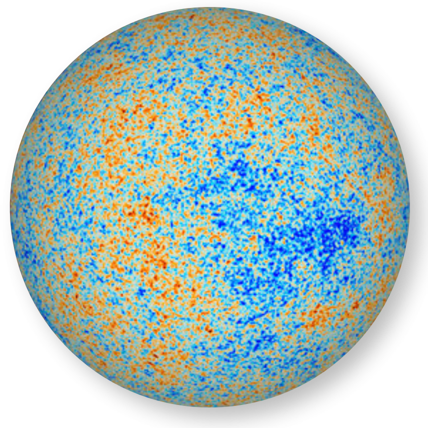
gravitational waves

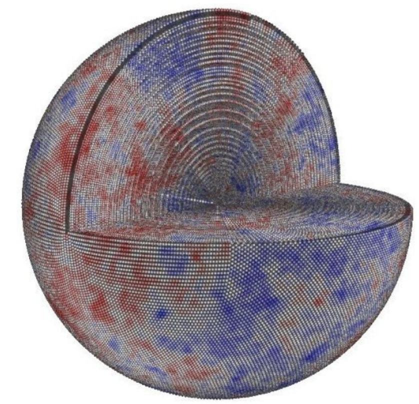
anisotropic stretching

These metric perturbations are small and can be traced back to their cosmic origin in perturbation theory:



All cosmological observables are (computable) remappings of the primordial perturbations.



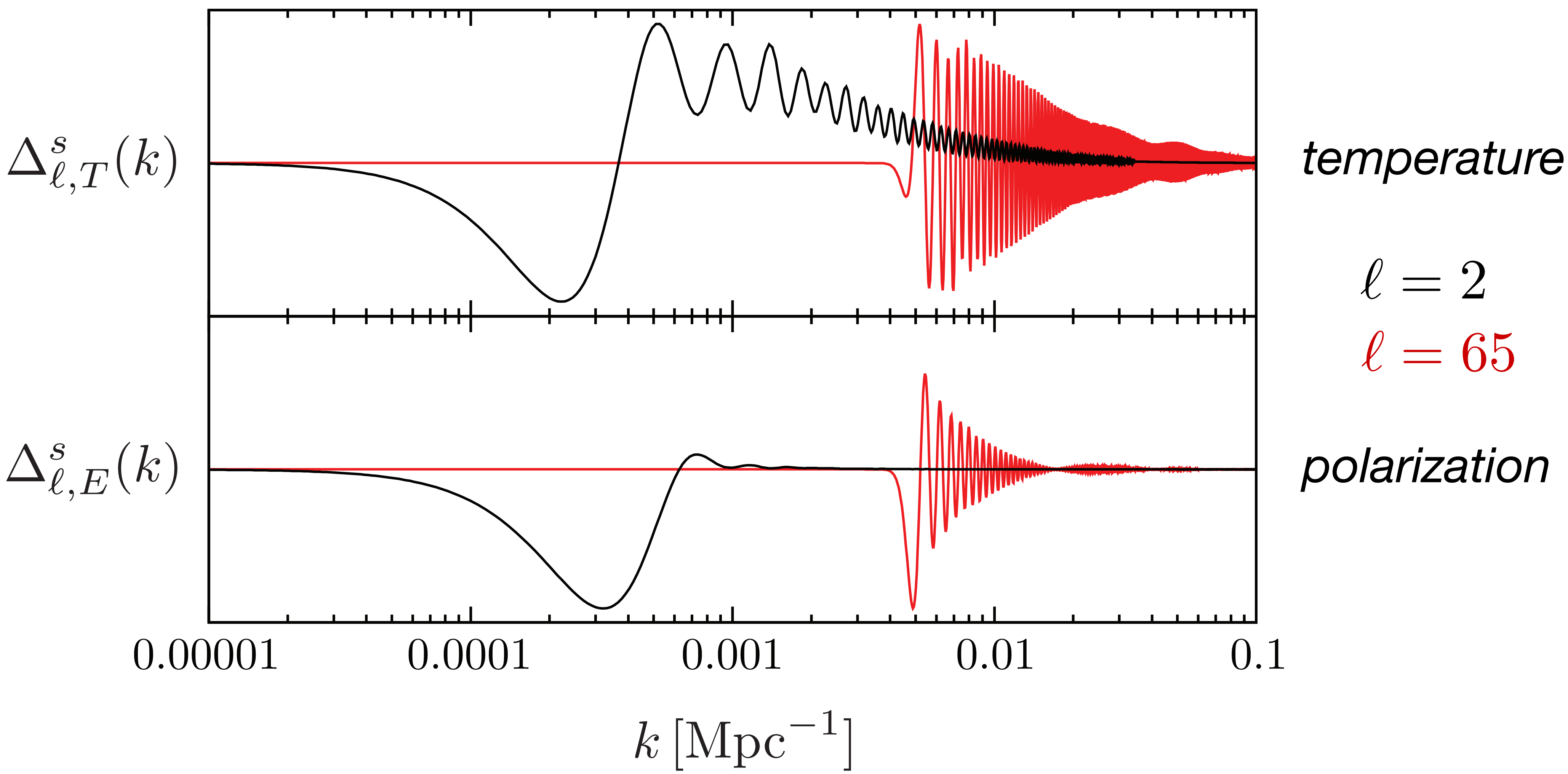


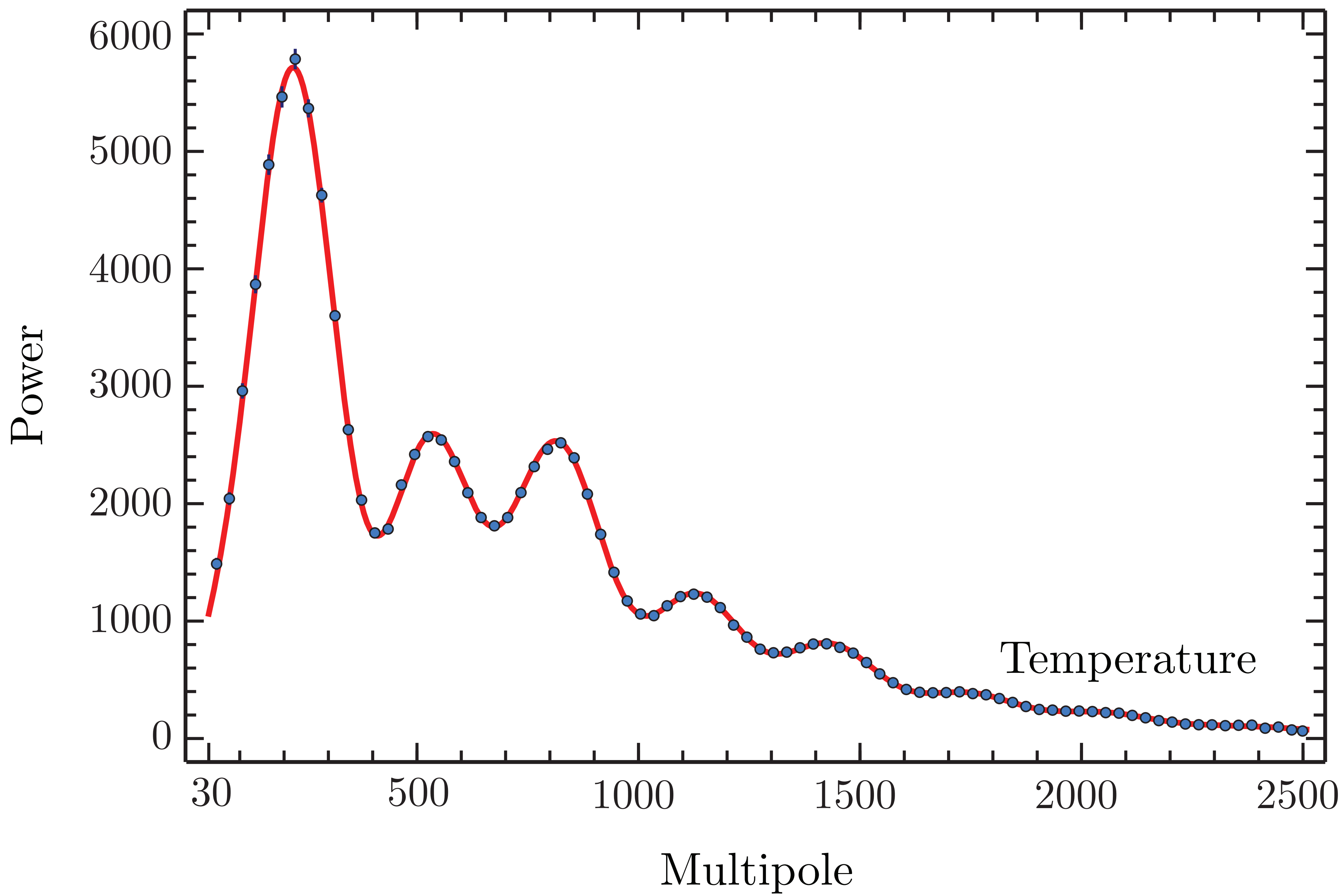
$$C_\ell = \int \frac{\mathrm{d}k}{k}\, \Delta_\ell^2(k)\, P(k)$$

transfer function
= evolution × projection

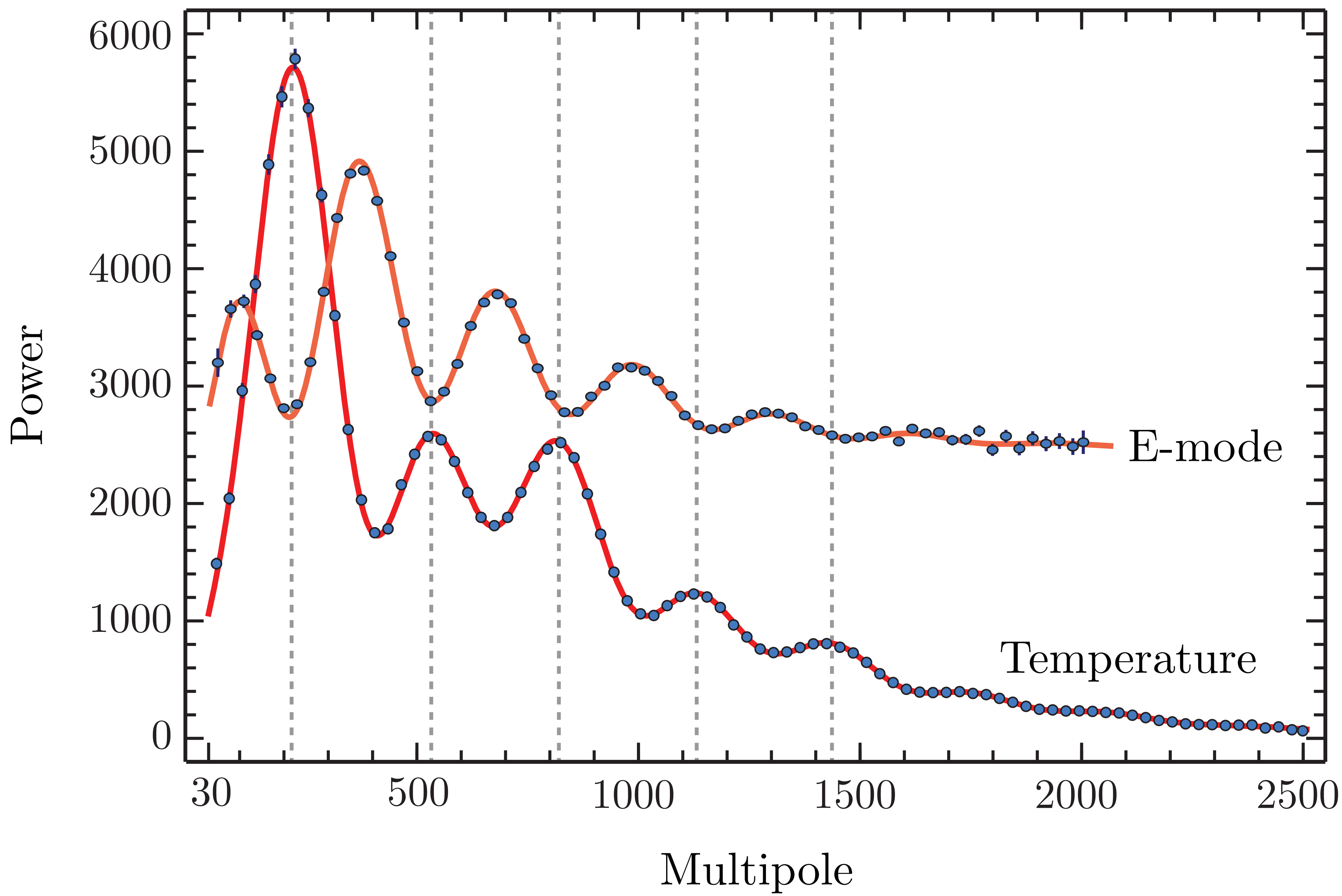
curvature perturbations

$$C_\ell^{XY} = \int \frac{\mathrm{d}k}{k}\, \Delta^s_{\ell,X}(k)\Delta^s_{\ell,Y}(k)\, P_{\mathcal{R}}(k)$$





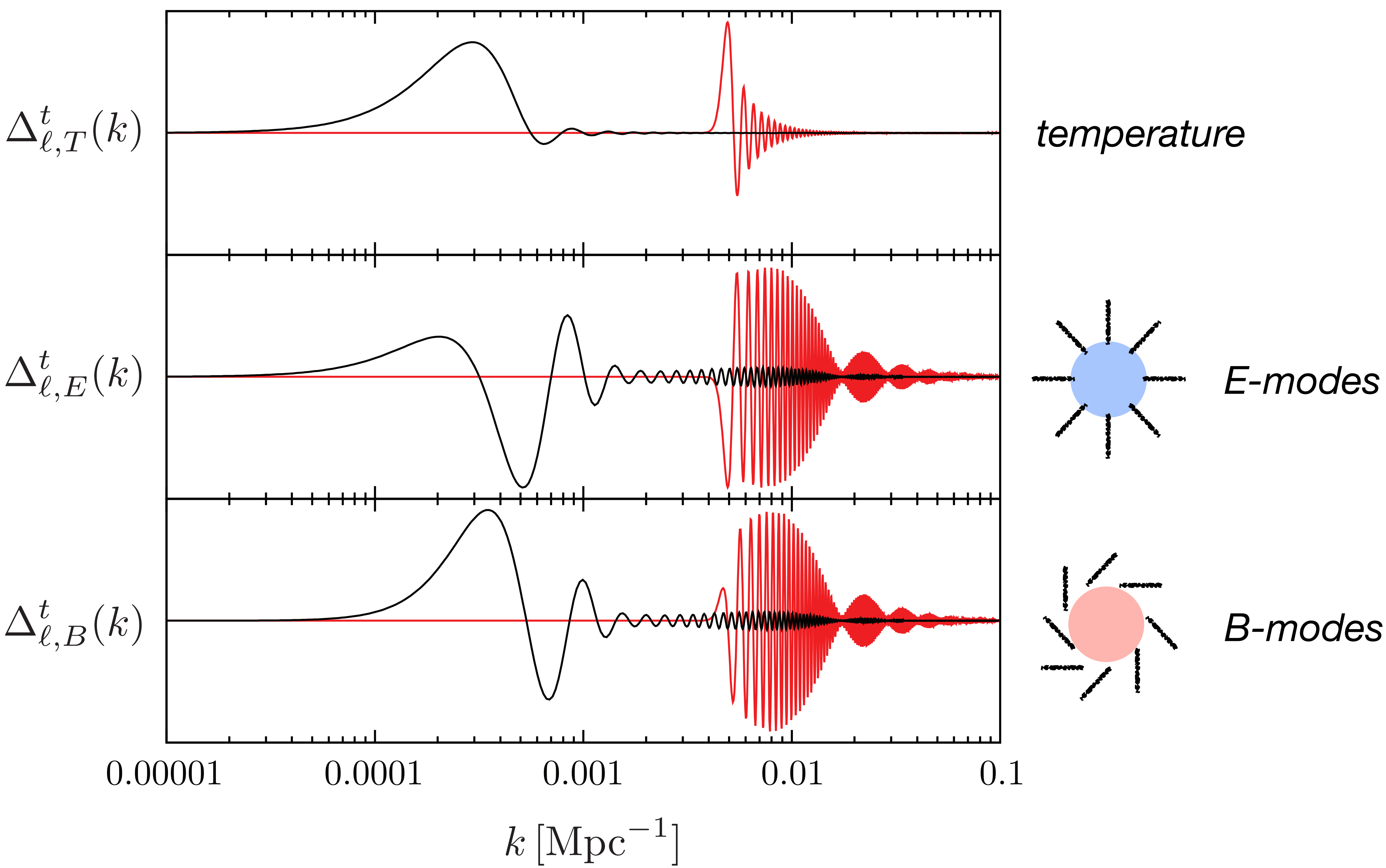
Power
6000
5000
4000
3000
2000
1000
0
30
500
1000
1500
2000
2500
Multipole
Temperature

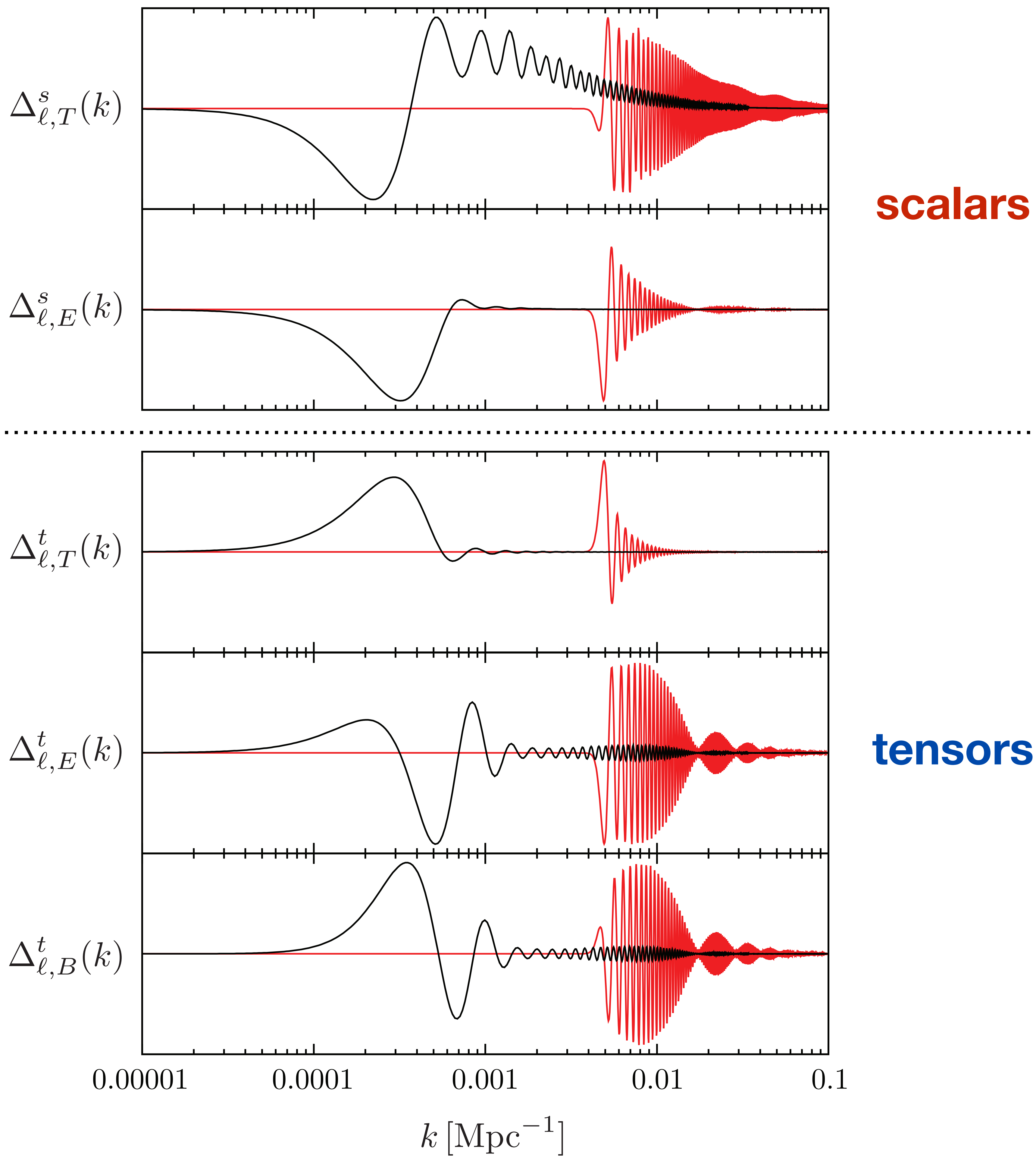


Power
Multipole
E-mode
Temperature
6000
5000
4000
3000
2000
1000
0
30
500
1000
1500
2000
2500

$$C_\ell^{XY} = \int \frac{\mathrm{d}k}{k}\, \Delta^s_{\ell,X}(k)\Delta^s_{\ell,Y}(k)\, P_t(k)$$

gravitational waves



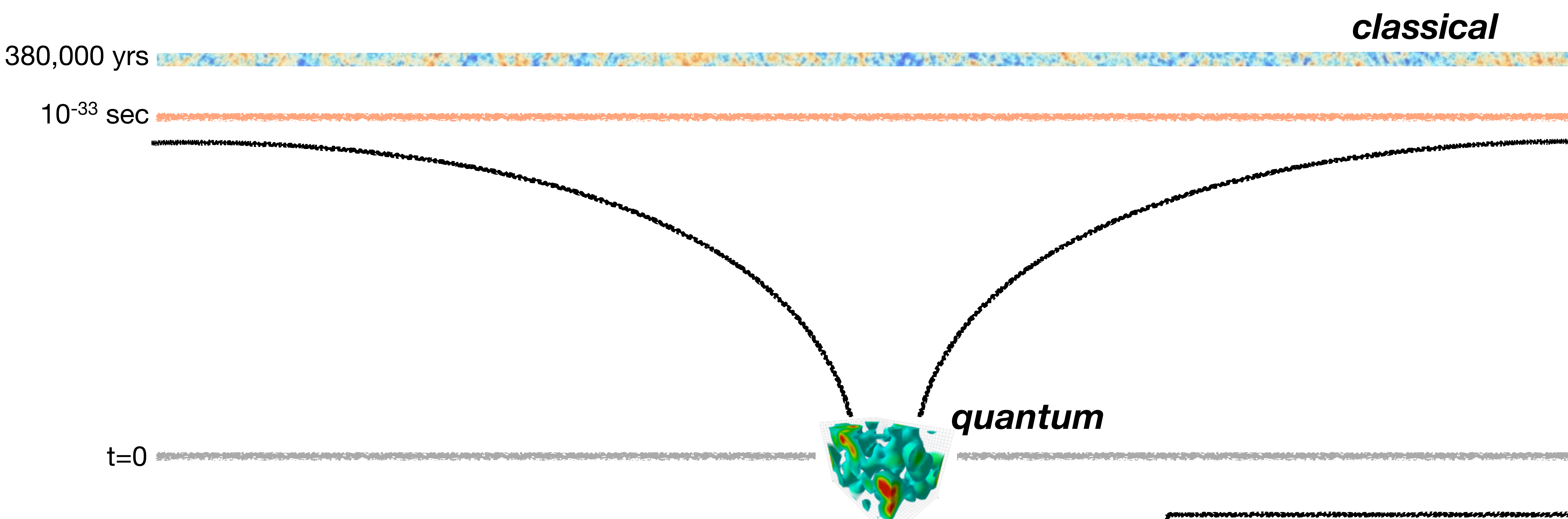

$\Delta^s_{\ell,T}(k)$
$\Delta^s_{\ell,E}(k)$
scalars
$\Delta^t_{\ell,T}(k)$
$\Delta^t_{\ell,E}(k)$
$\Delta^t_{\ell,B}(k)$
tensors
0.00001
0.0001
0.001
0.01
0.1
k [Mpc^{-1}]

Given that we understand the evolution so well, we can use the observations to probe the initial conditions.

Constraints on Initial Conditions

Hypothesis

The primordial perturbations originated from quantum fluctuations in a quasi-de Sitter background



$$\mathrm{d}s^2 = \mathrm{d}t^2 - e^{2Ht}\mathrm{d}\boldsymbol{x}^2$$

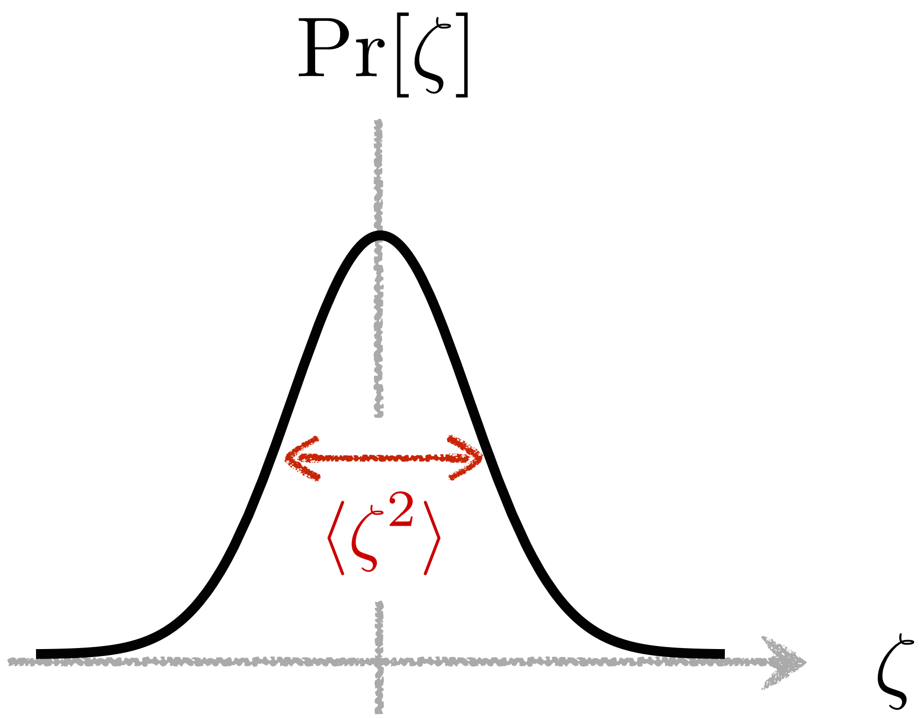
exponential expansion

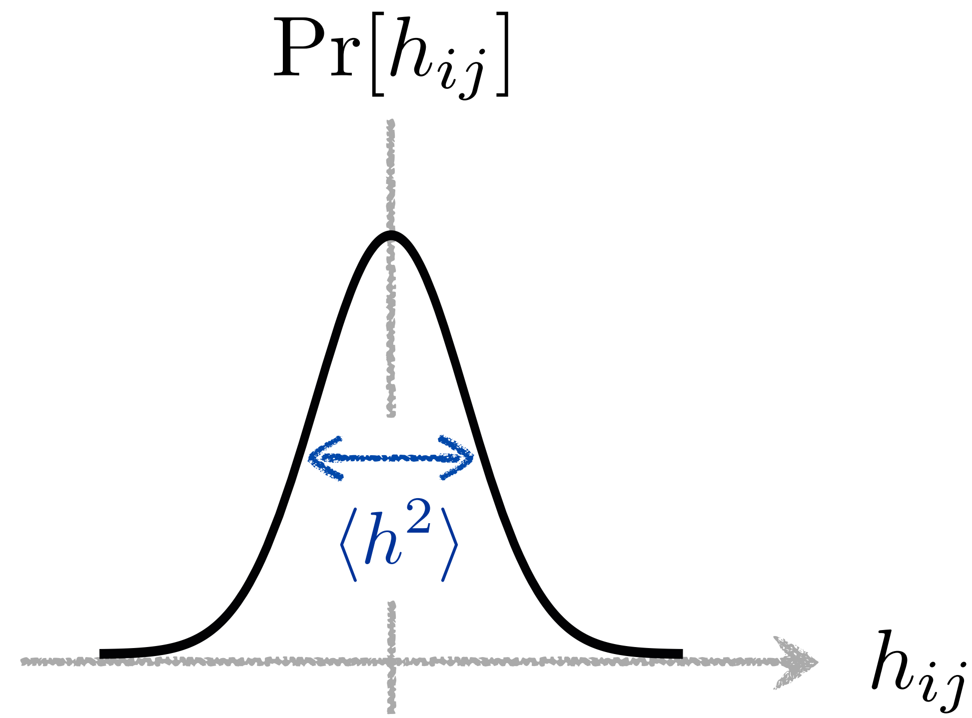
constant expansion rate

$$\epsilon_1 \equiv -\frac{\dot{H}}{H^2} \ll 1$$

Predictions

- ζ and h_{ij} are draw from nearly **Gaussian** distributions



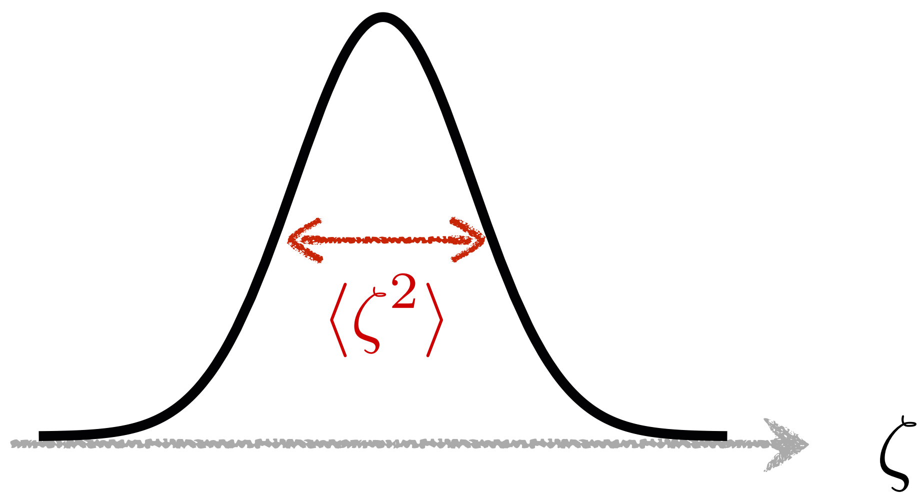


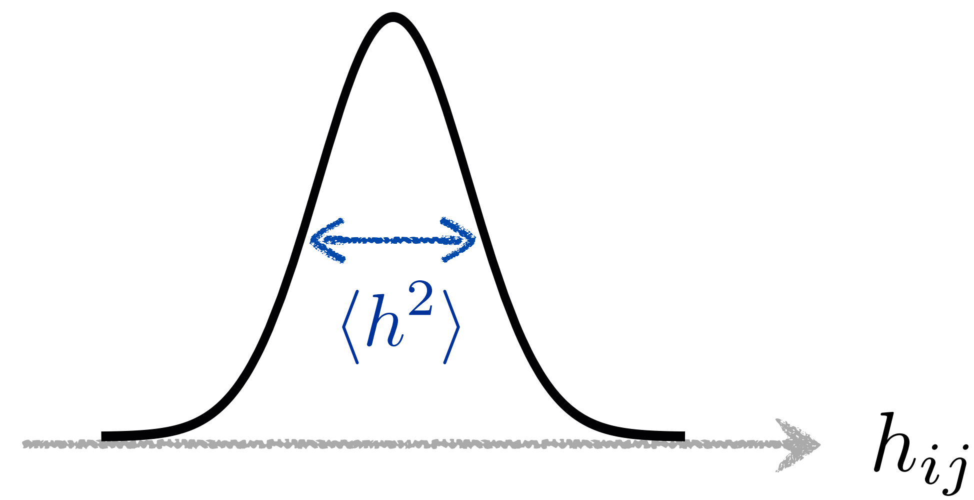
$$P_\zeta(k) \equiv \frac{k^3}{2\pi^2}\langle\zeta^2\rangle$$

$$P_t(k) \equiv \frac{k^3}{2\pi^2}\langle h^2\rangle$$

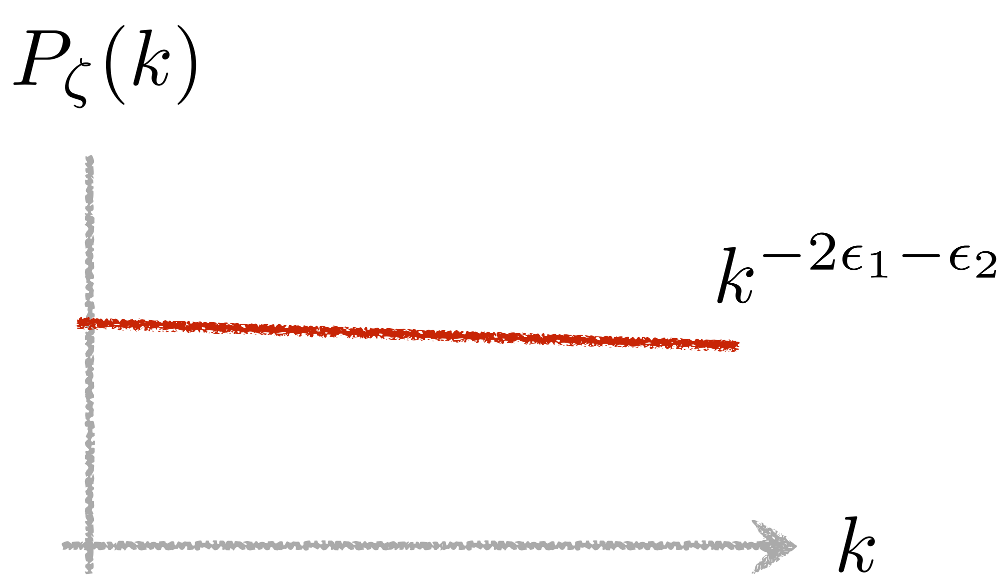
Predictions

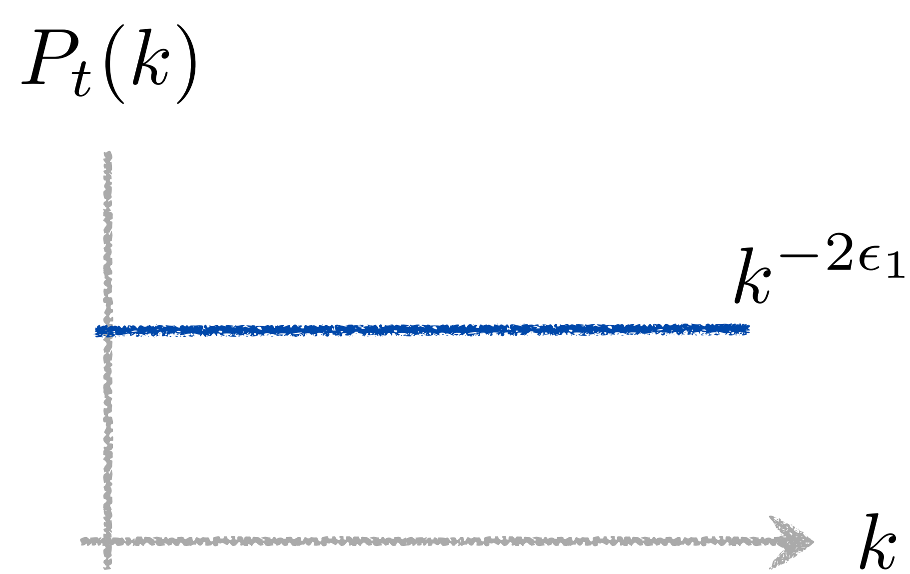
- ζ and h_{ij} are draw from nearly **Gaussian** distributions.





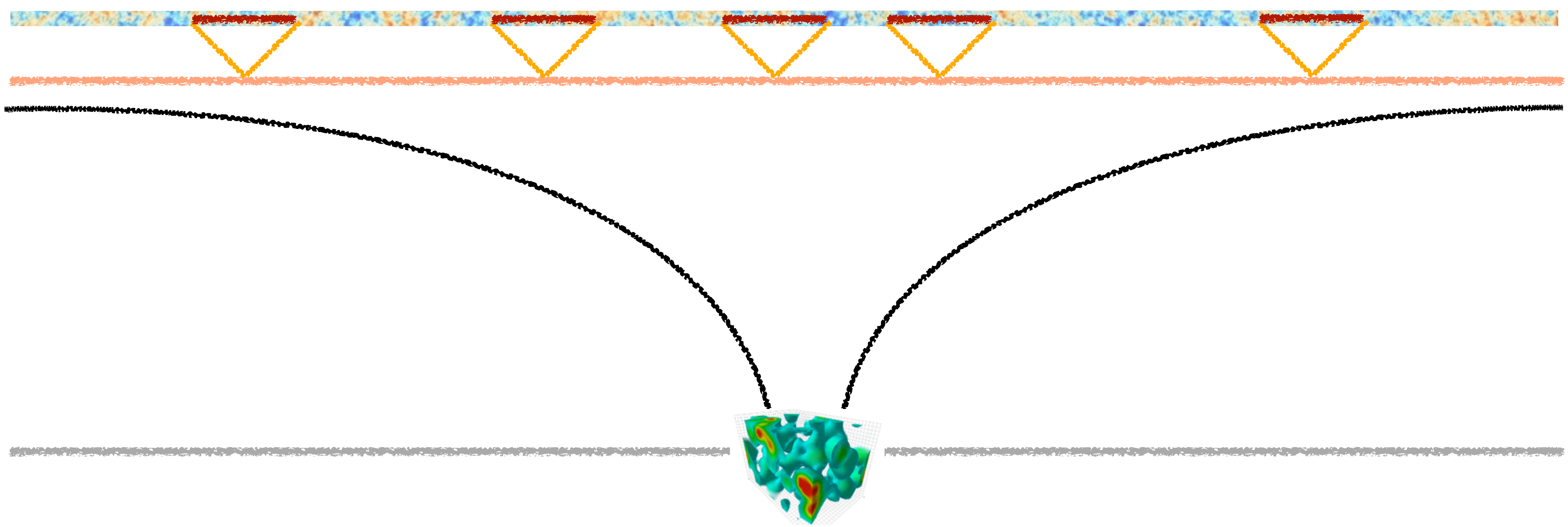
- The spectrum of fluctuations is nearly **scale-invariant**





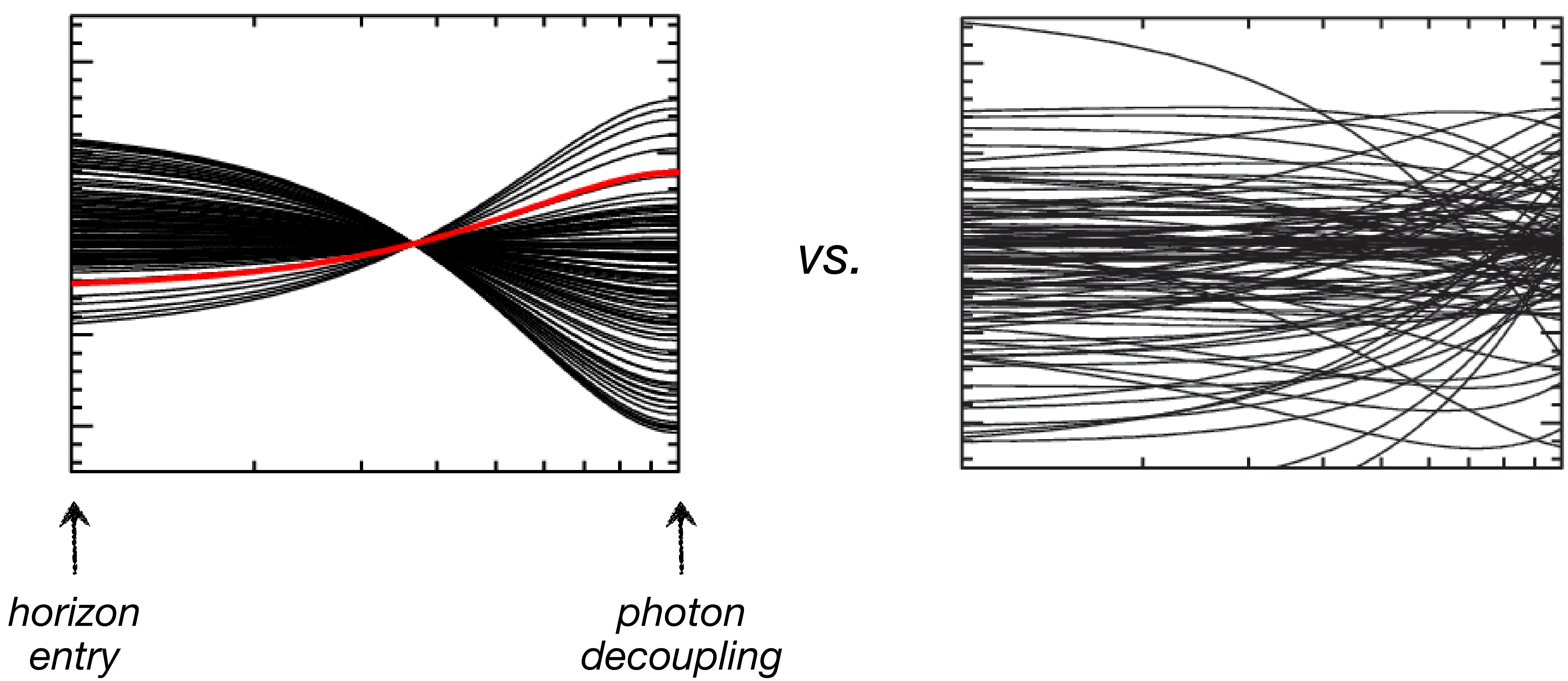
Predictions

- ζ and h_{ij} are draw from nearly **Gaussian** distributions.
- The spectrum of fluctuations is nearly **scale-invariant**.
- They span **superhorizon** scales at recombination



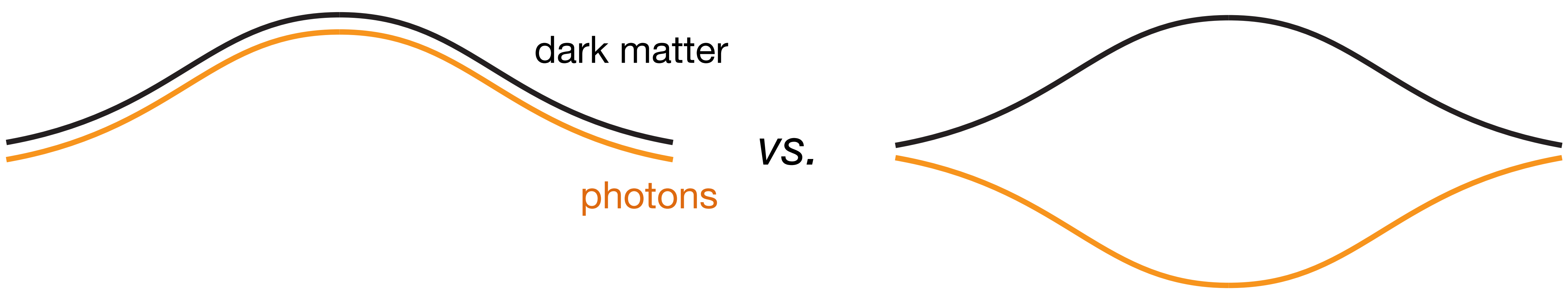
Predictions

- ζ and h_{ij} are draw from nearly **Gaussian** distributions.
- The spectrum of fluctuations is nearly **scale-invariant**.
- They span **superhorizon** scales at recombination.
- They have **coherent phases**



Predictions

- ζ and h_{ij} are draw from nearly **Gaussian** distributions.
- The spectrum of fluctuations is nearly **scale-invariant**.
- They span **superhorizon** scales at recombination.
- They have **coherent phases**.
- They are **adiabatic**



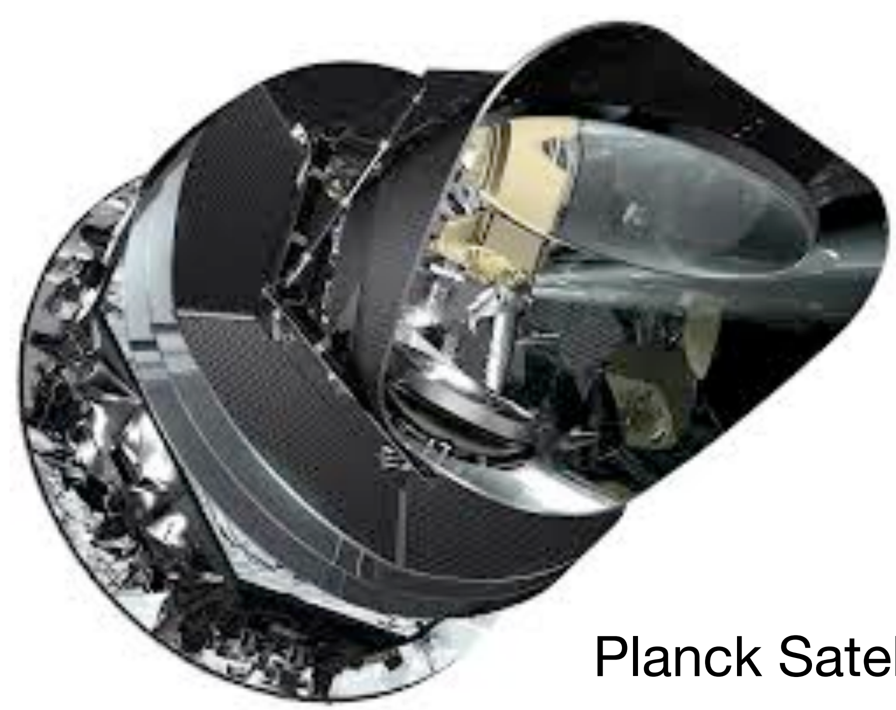
No fluctuations in composition

Predictions

The primordial perturbations are:

- **Gaussian**
- **scale-invariant**
- **superhorizon**
- **coherent phases**
- **adiabatic**

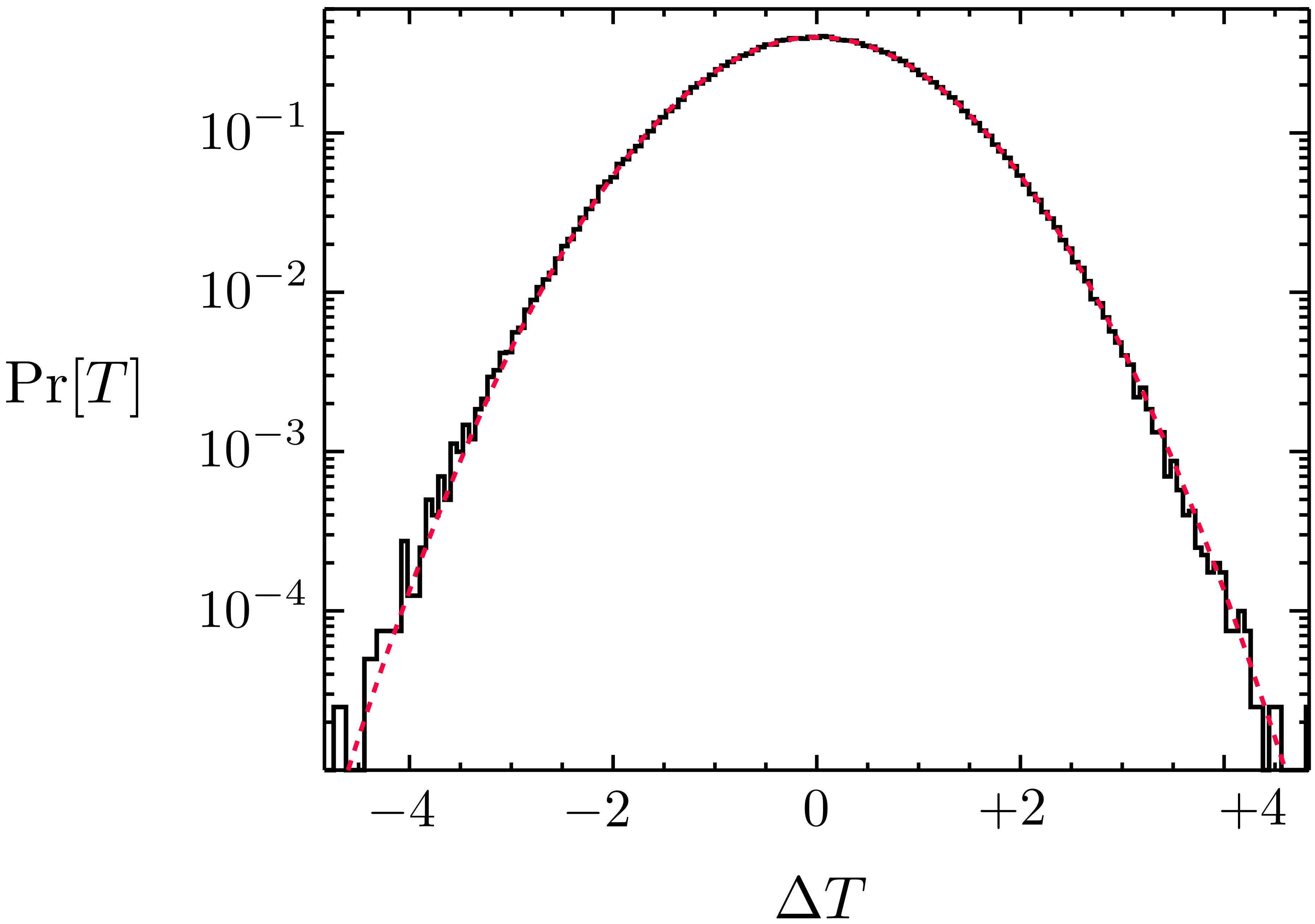
Let's check.



Planck Satellite

Gaussian?

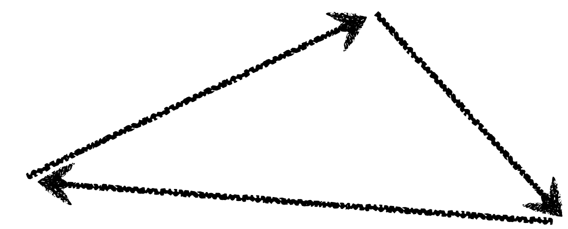
The one-point PDF doesn't show any deviations from Gaussianity:



WMAP3

Gaussian?

To tease out small levels of non-Gaussianity, we need a template:

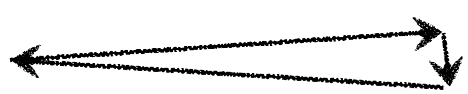


amplitude **shape**

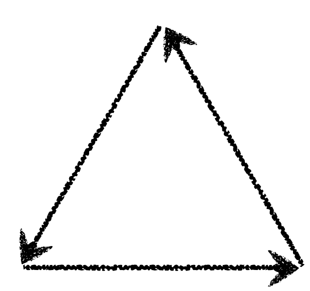
$$\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \rangle = f_{\mathrm{NL}} \, B_\zeta(k_1, k_2, k_3) \, \delta(\vec{k}_1 + \vec{k}_2 + \vec{k}_3)$$

bispectrum

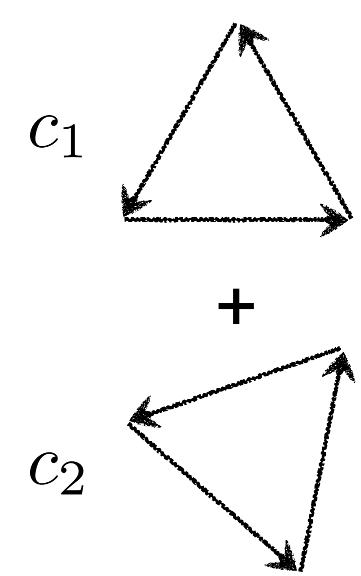
local



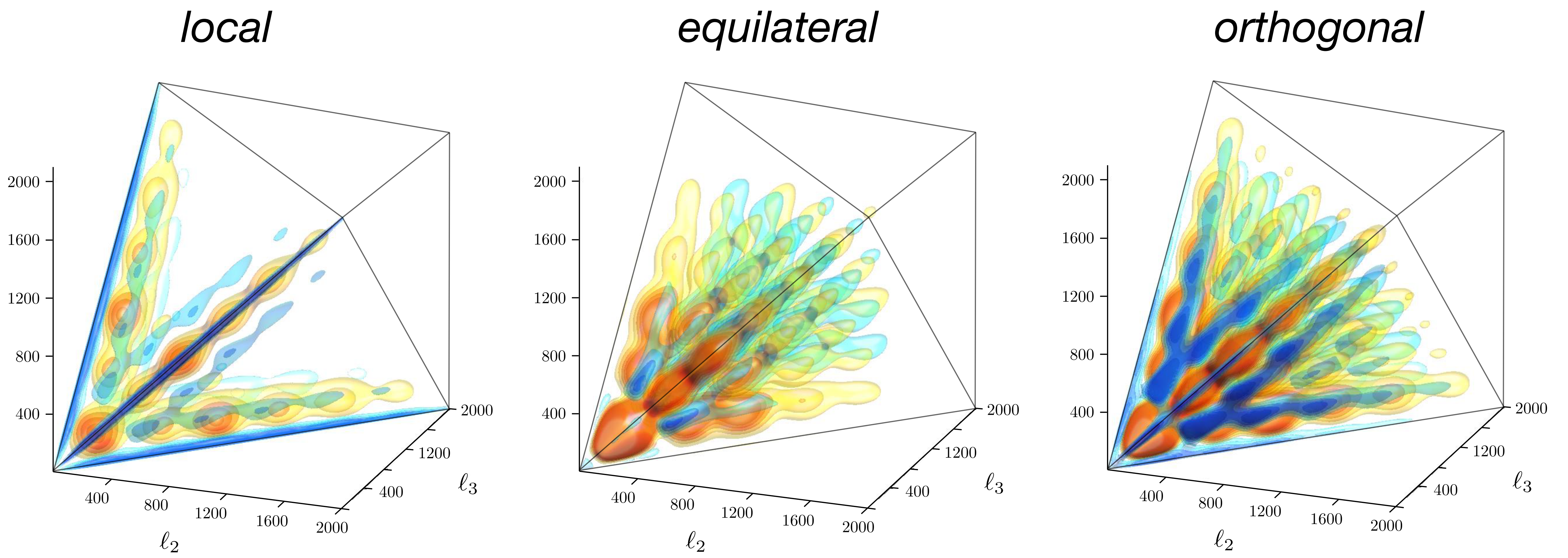
equilateral



orthogonal



Gaussian?



Temperature only:

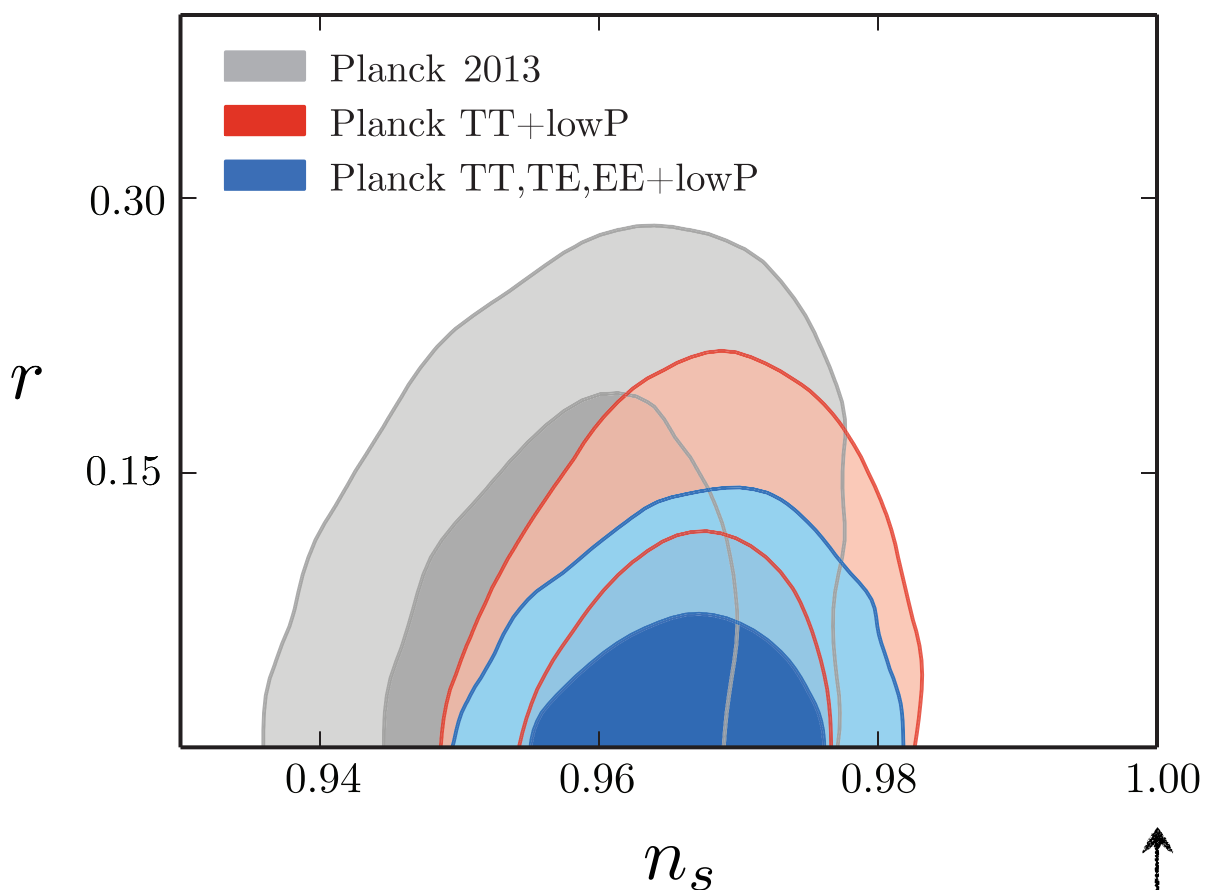
$$f_{\rm NL}^{\rm local} = 1.8 \pm 5.6 \qquad f_{\rm NL}^{\rm equil} = -9.2 \pm 69 \qquad f_{\rm NL}^{\rm ortho} = -20 \pm 33$$

With polarization:

$$f_{\rm NL}^{\rm local} = 0.7 \pm 5.1 \qquad f_{\rm NL}^{\rm equil} = -9.5 \pm 44 \qquad f_{\rm NL}^{\rm ortho} = -25 \pm 22$$

Scale-Invariant?

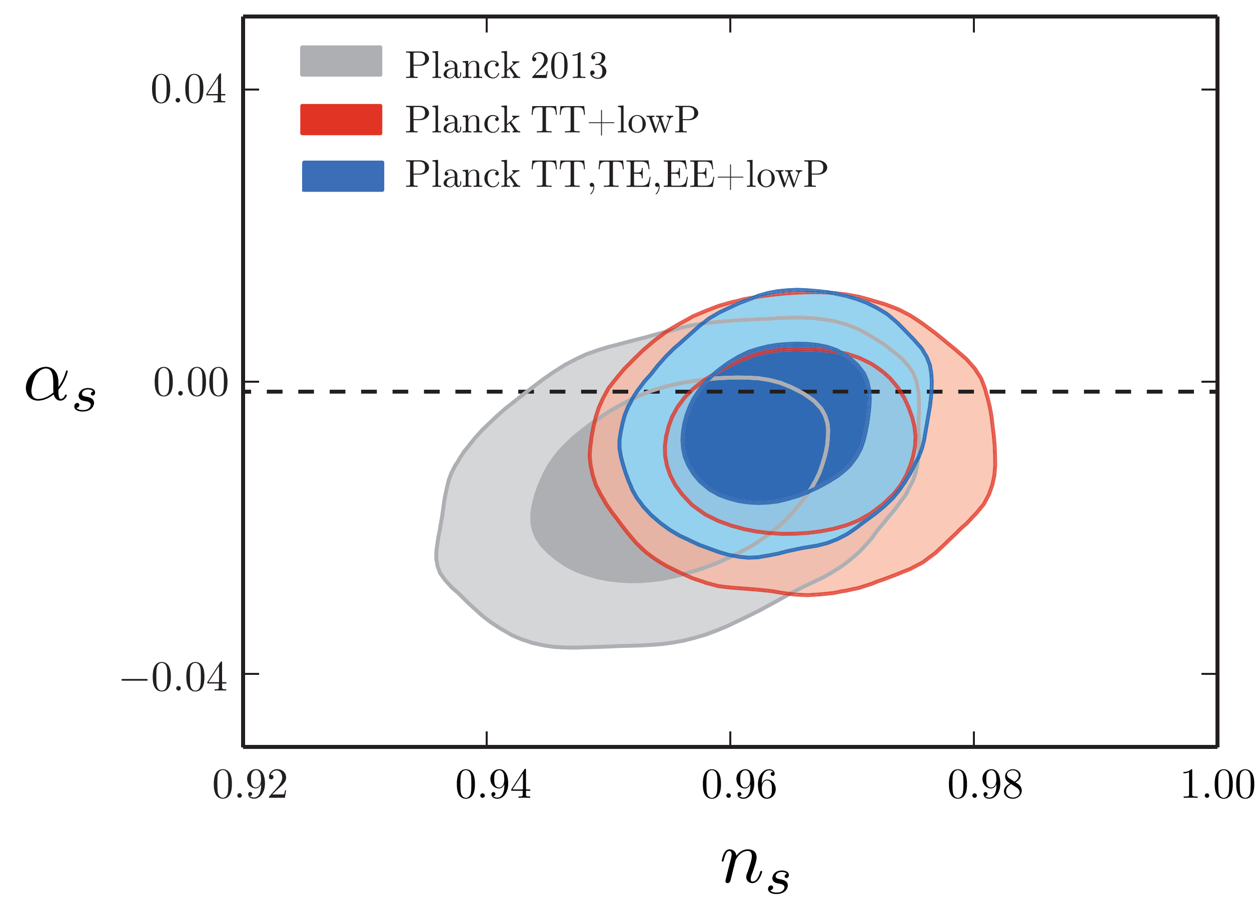
$$n_s \equiv 1 + \frac{d \ln P_\zeta}{d \ln k} = 0.968 \pm 0.006$$



scale-invariant

no running

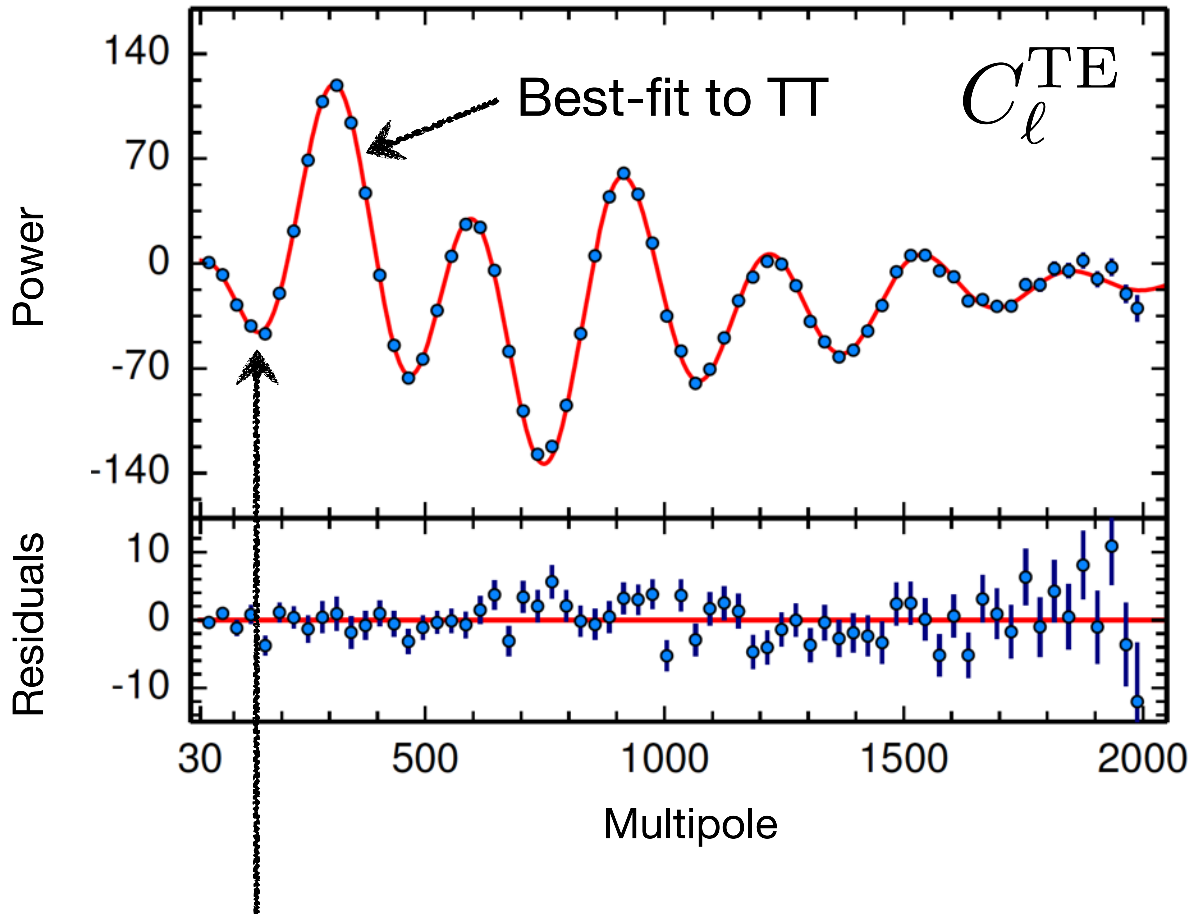
$$\alpha_s \equiv \frac{dn_s}{d \ln k} = -0.003 \pm 0.007$$

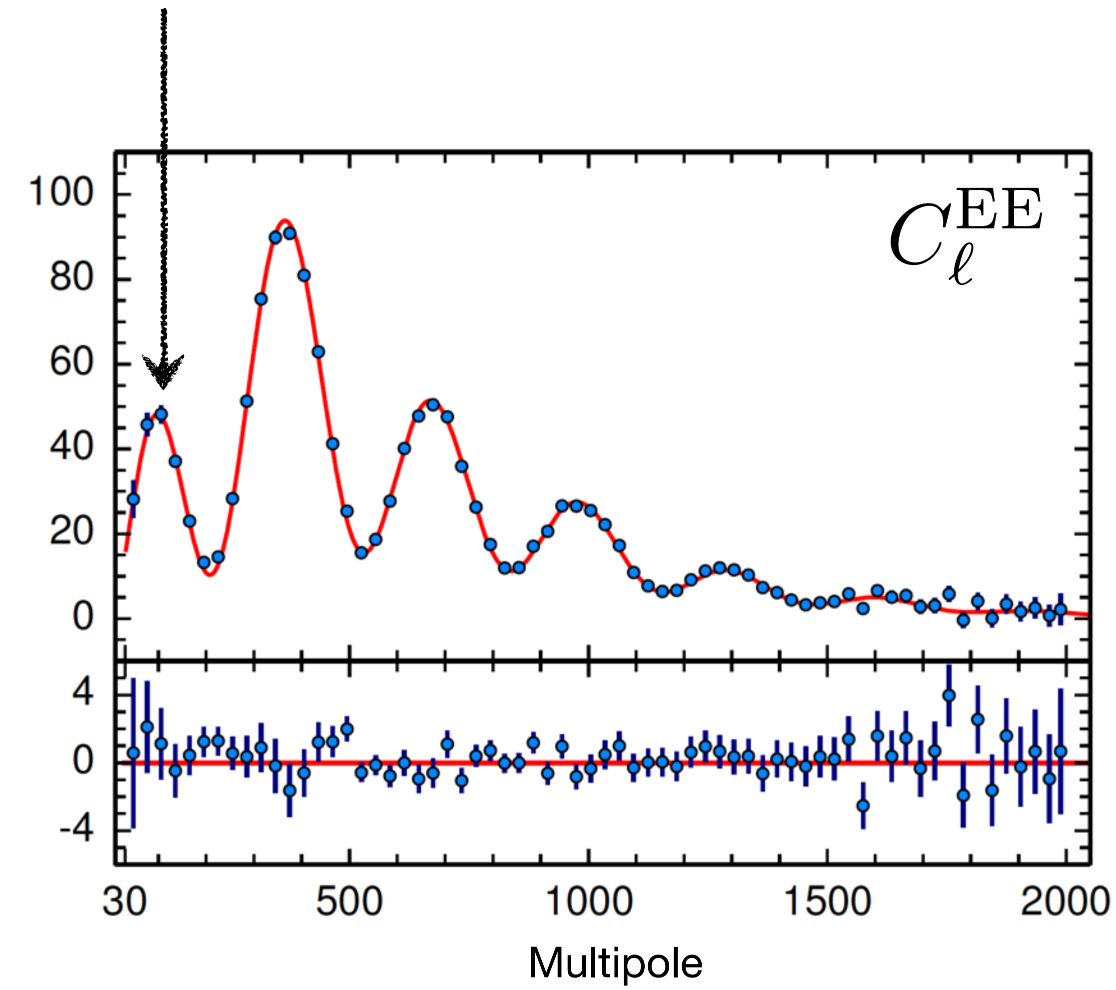


✔ expected percent-level deviation

Superhorizon and Coherent Phases?

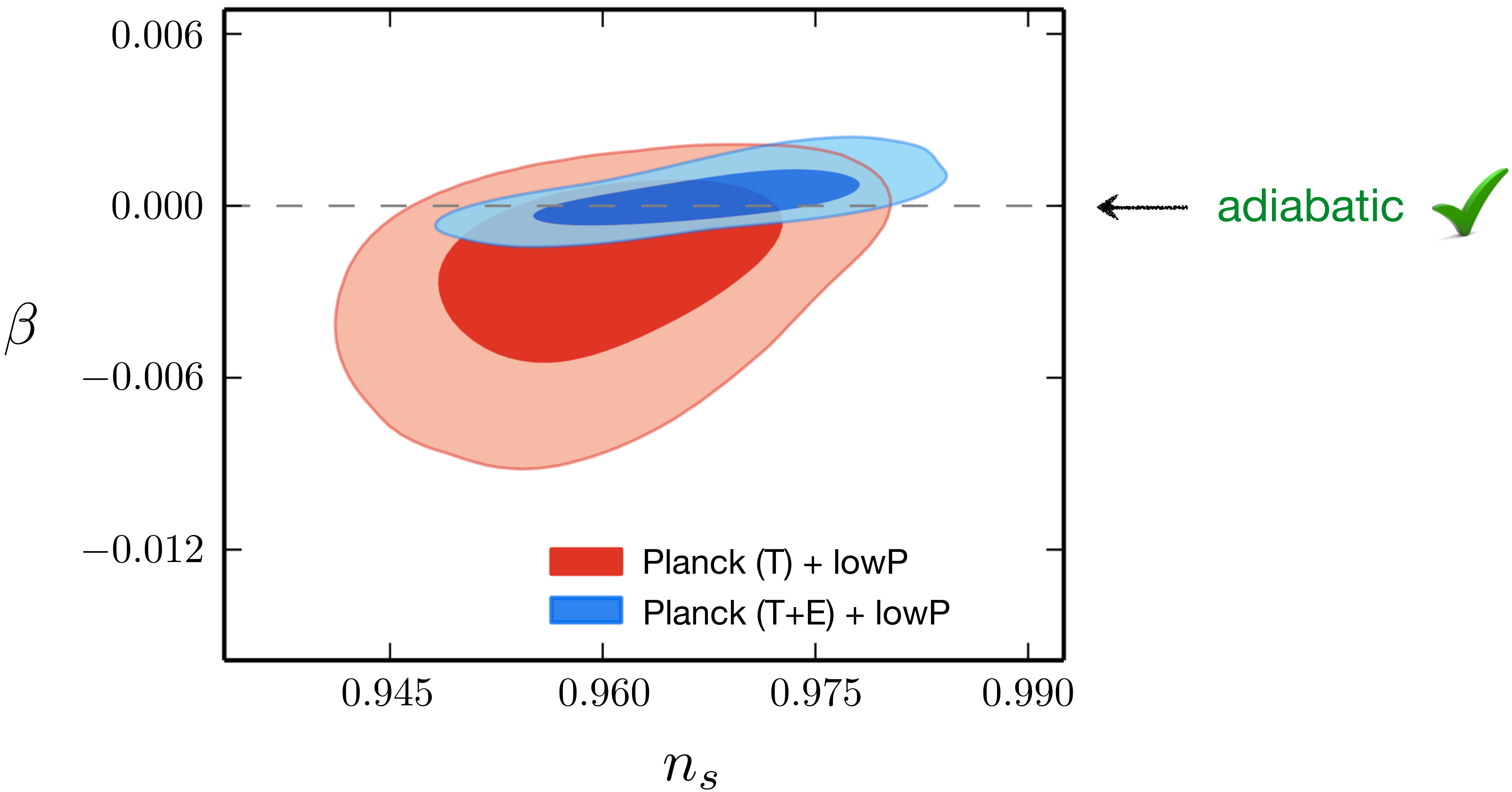
✓ coherence



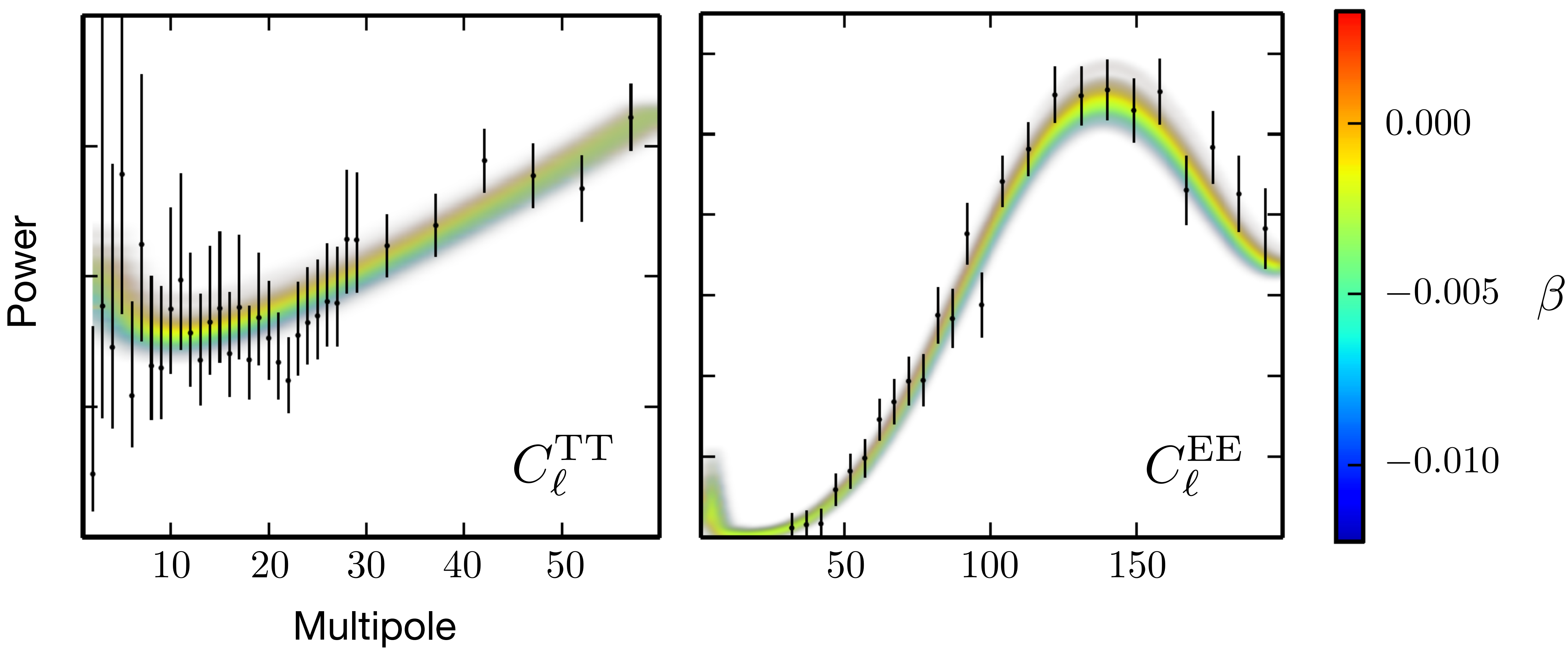


✓ superhorizon

Adiabatic?


0.006
0.000
−0.006
−0.012
β
0.945
0.960
0.975
0.990
n_s
Planck (T) + lowP
Planck (T+E) + lowP
adiabatic

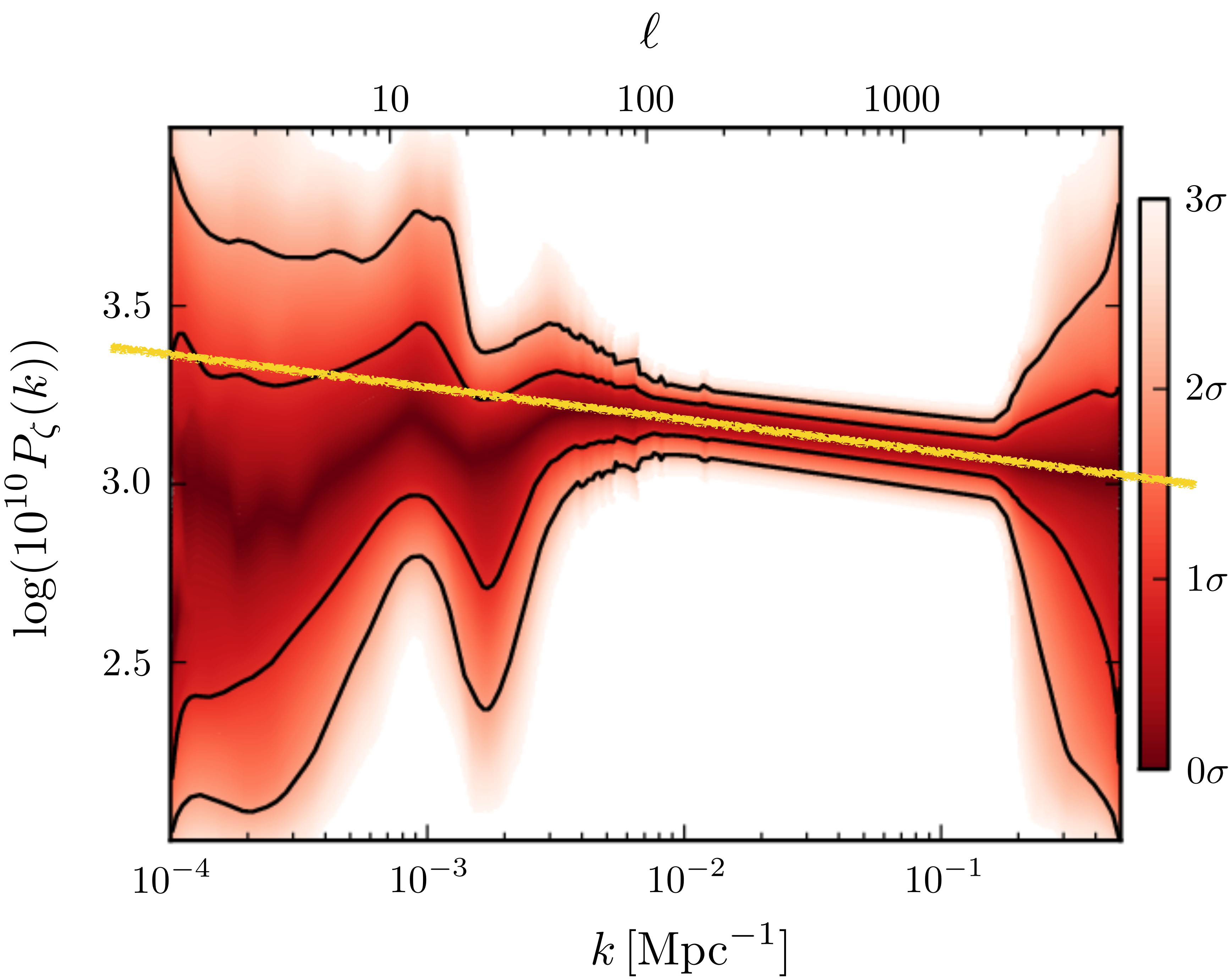
Adiabatic?



Preference for anti-correlated isocurvature from low-ell TT, disfavoured around the first peak of EE.

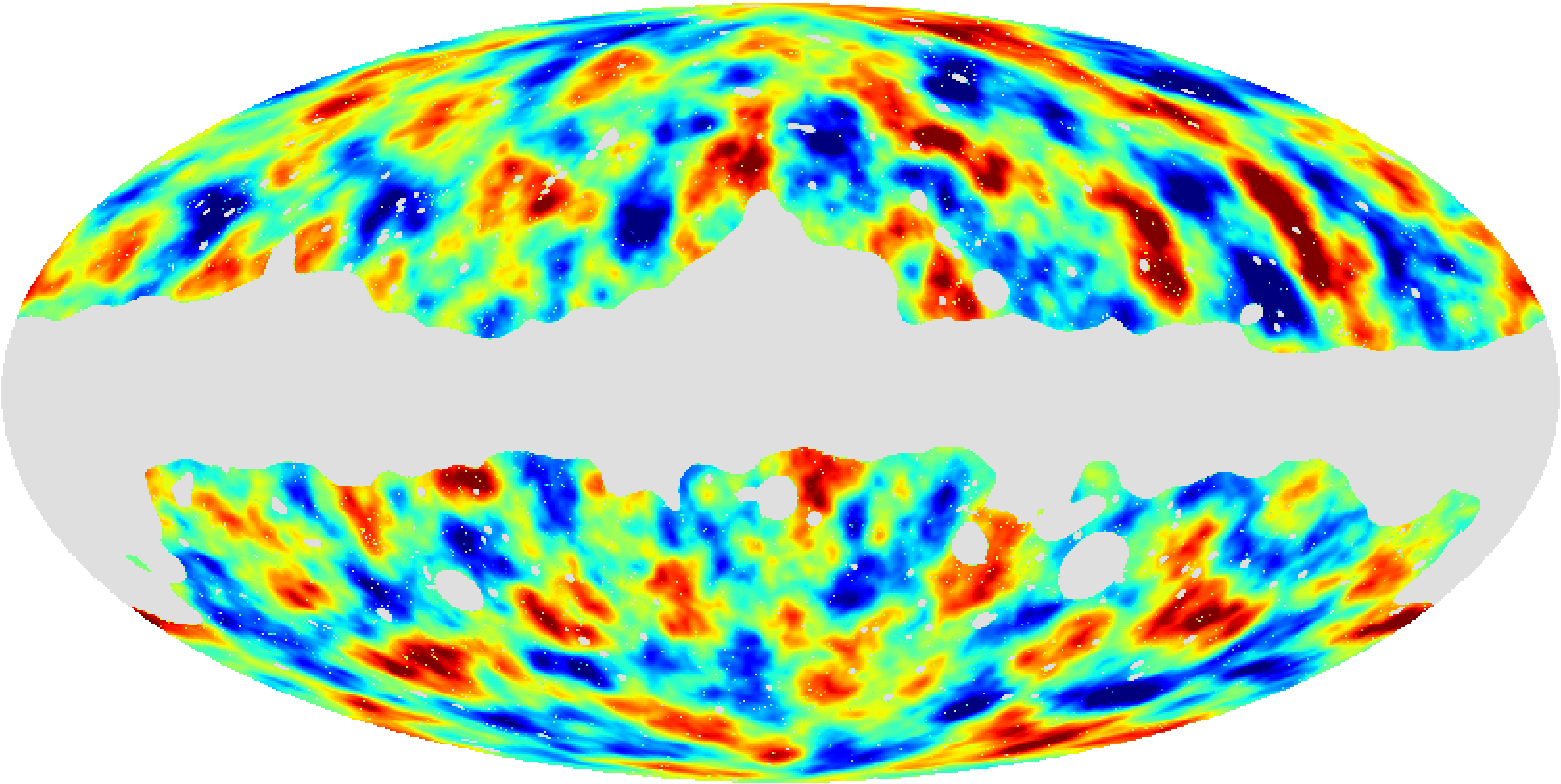
2-sigma deviations in search of a theory

Lack of Large-Scale Power?



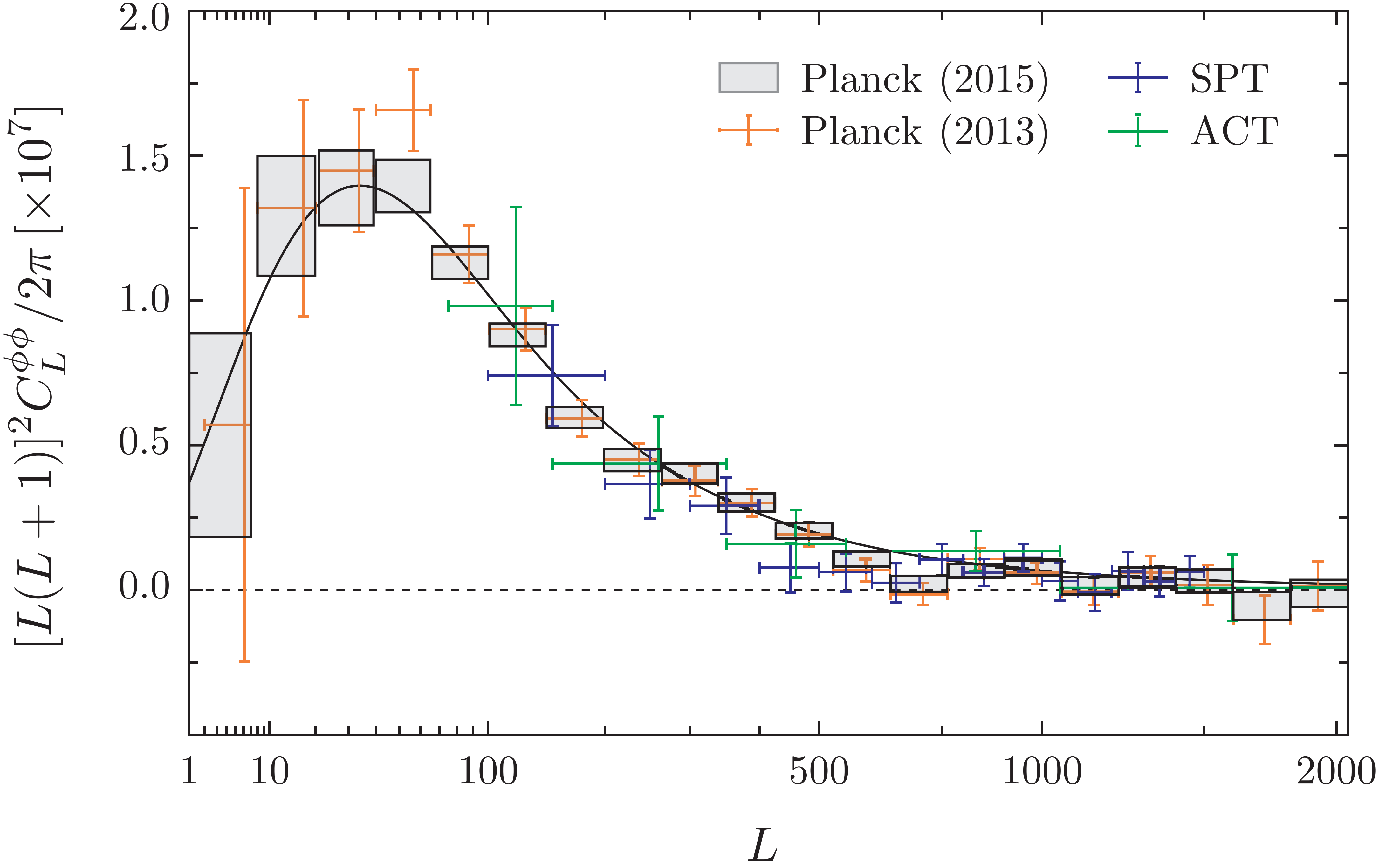
The significance of the lack of power at low-ell is hard to evaluate in the absence of a theory.

Lensing Anomaly?

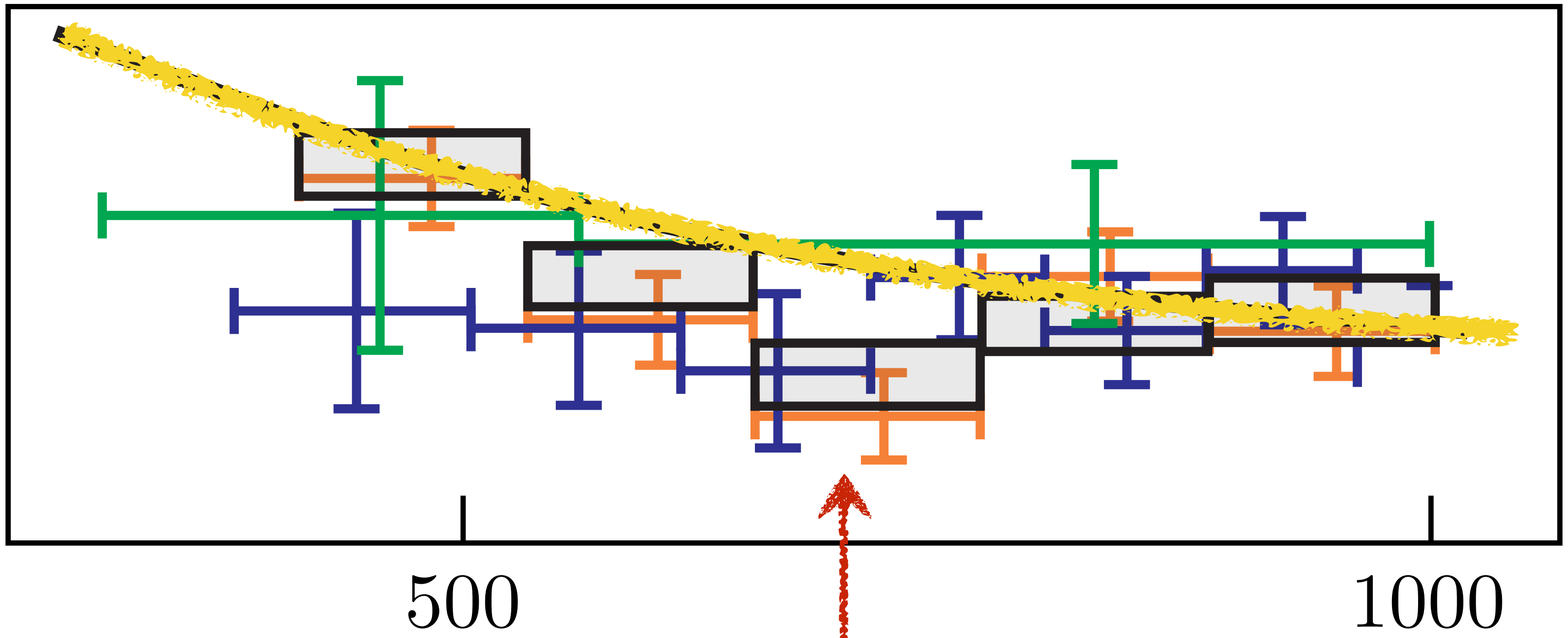


Planck detected gravitational lensing at a stupendous 50-sigma.

Lensing Anomaly?



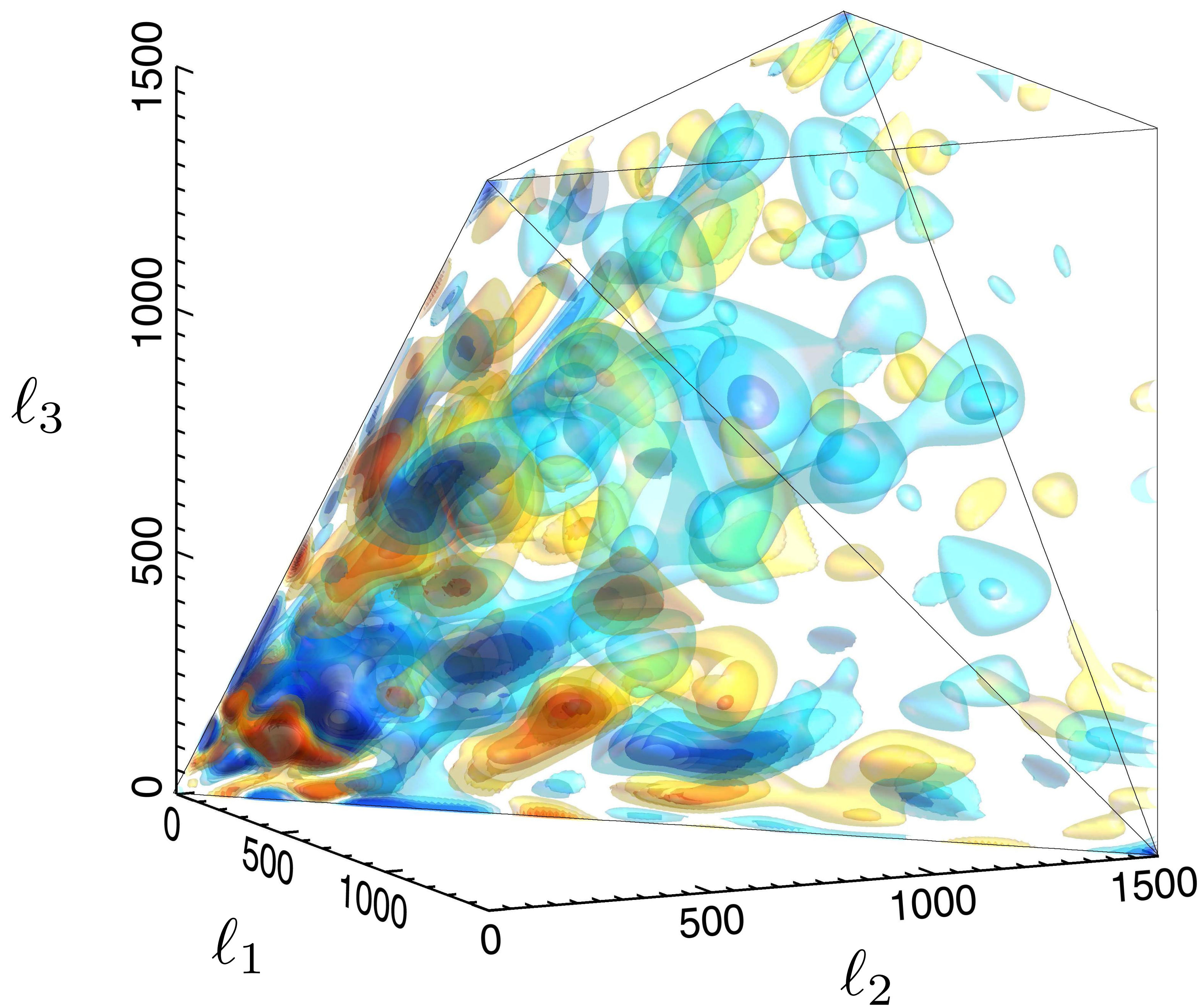
Lensing Anomaly?



more than 3-sigma off

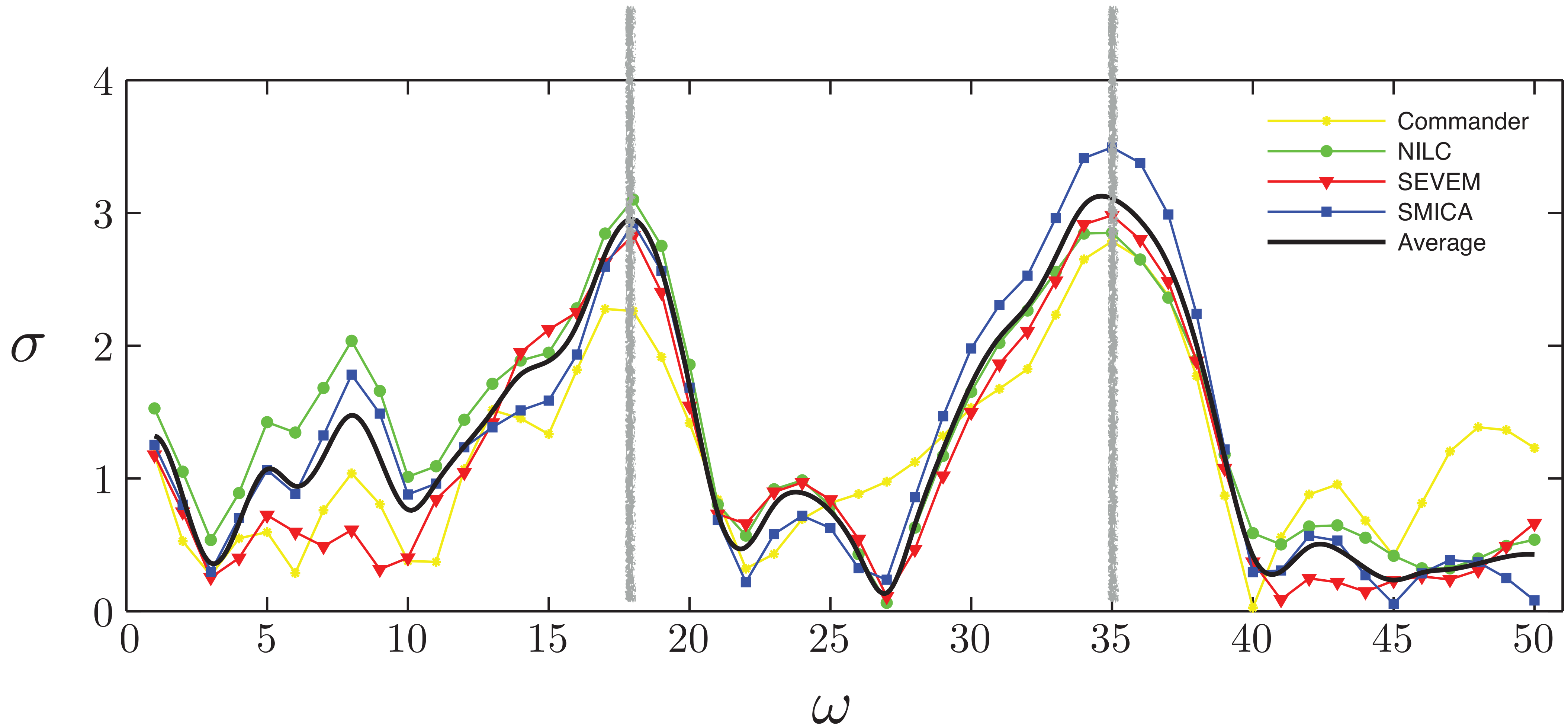
(systematic or primordial four-point function?)

Non-Gaussian Features?



The reconstructed bispectrum has strong features.

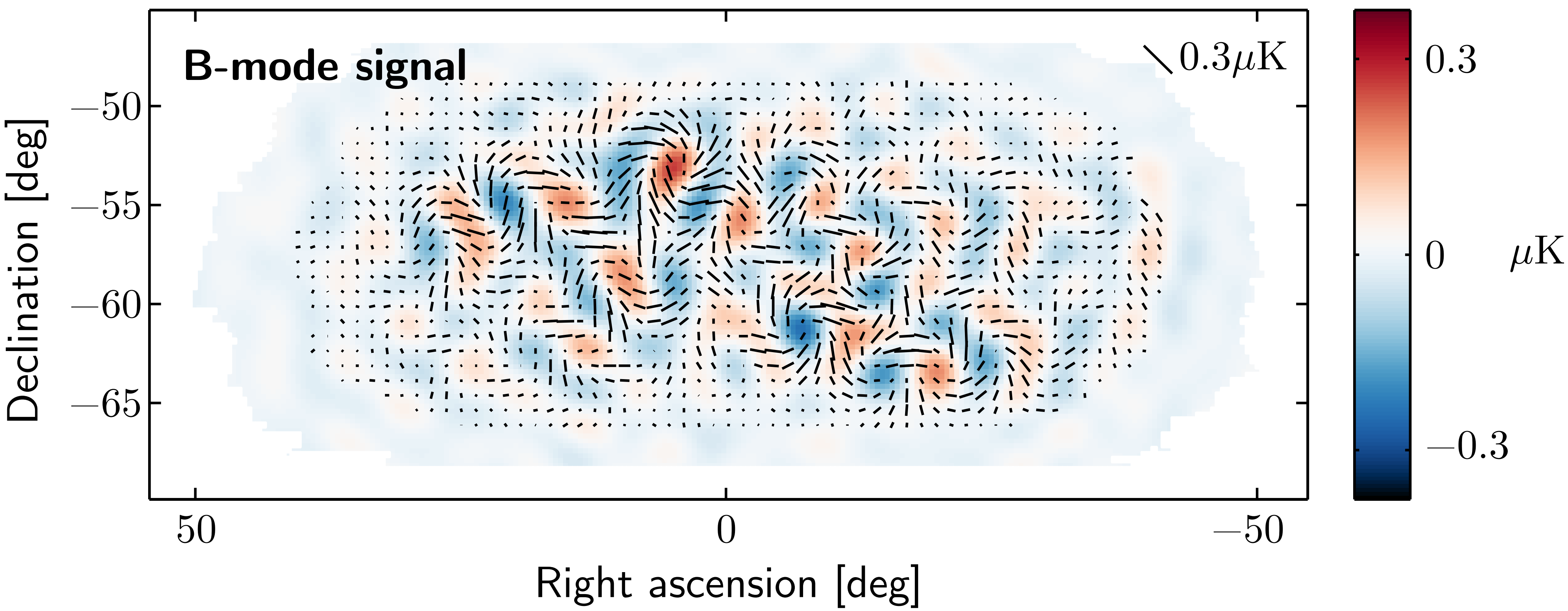
Non-Gaussian Features?



Oscillatory equilateral bispectra are observed at more than 3-sigma (after look-elsewhere).

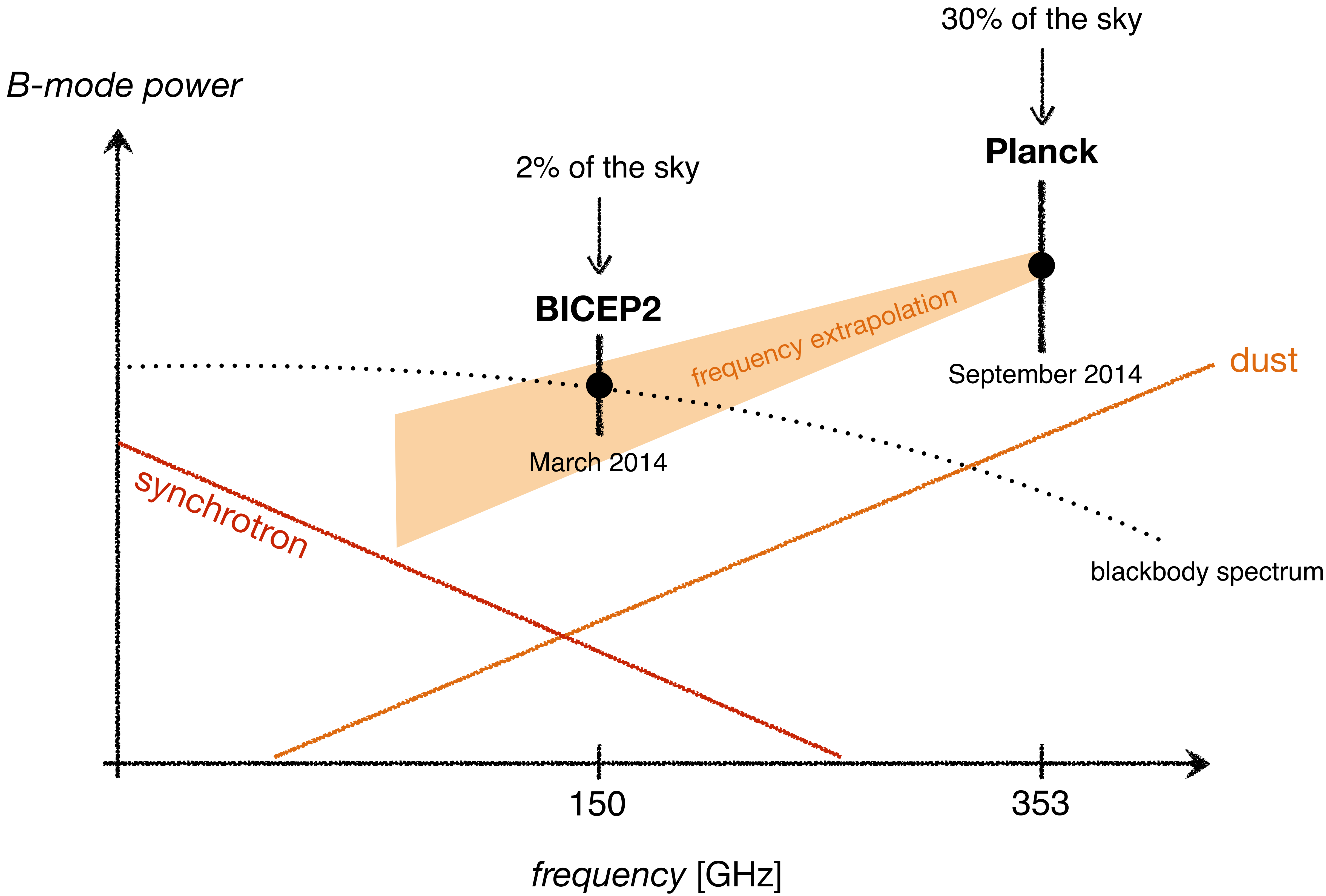
B-modes and BICEP

There is no question that the BICEP team has performed a heroic measurement of B-mode polarization:

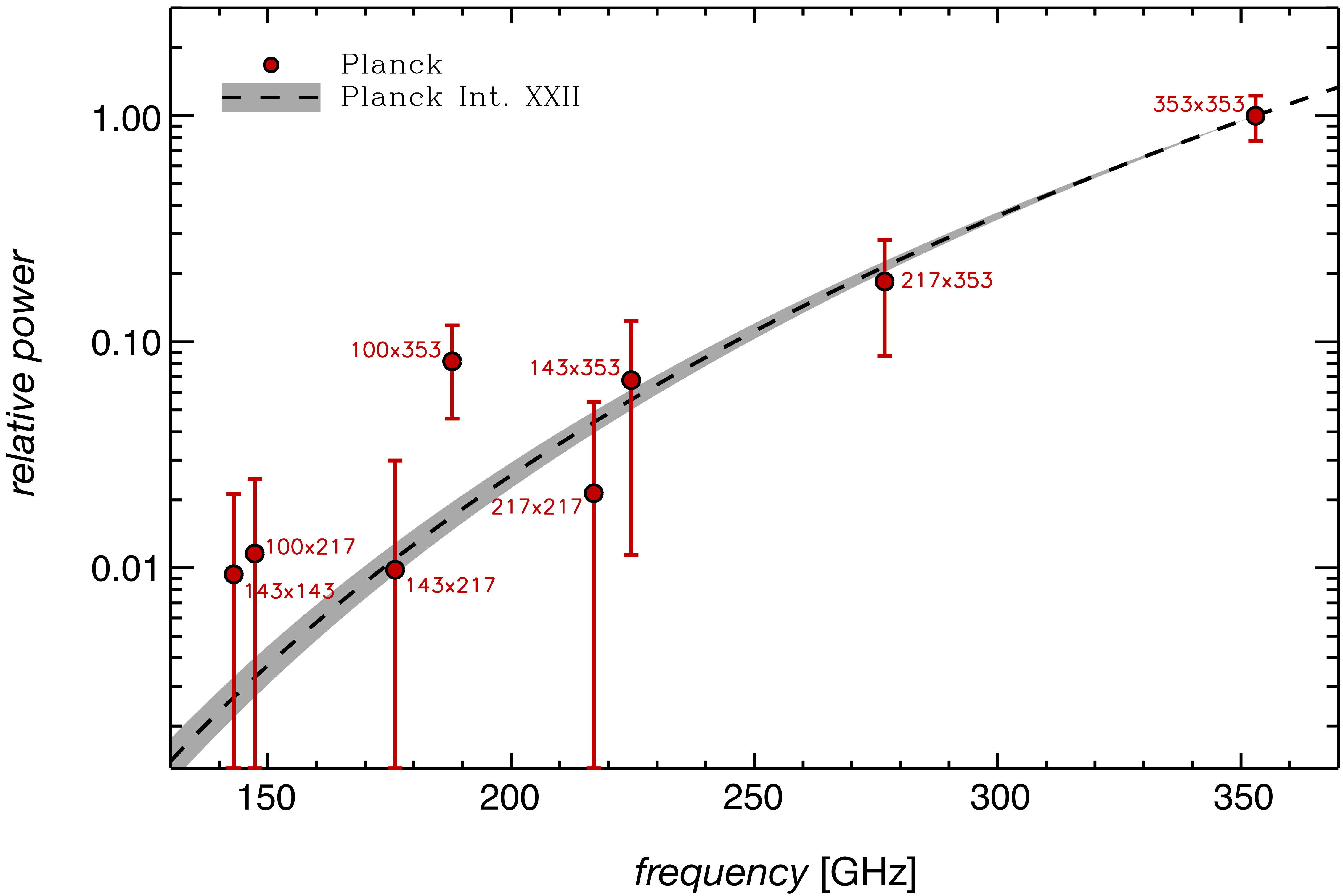


We are only arguing about the interpretation of the result.

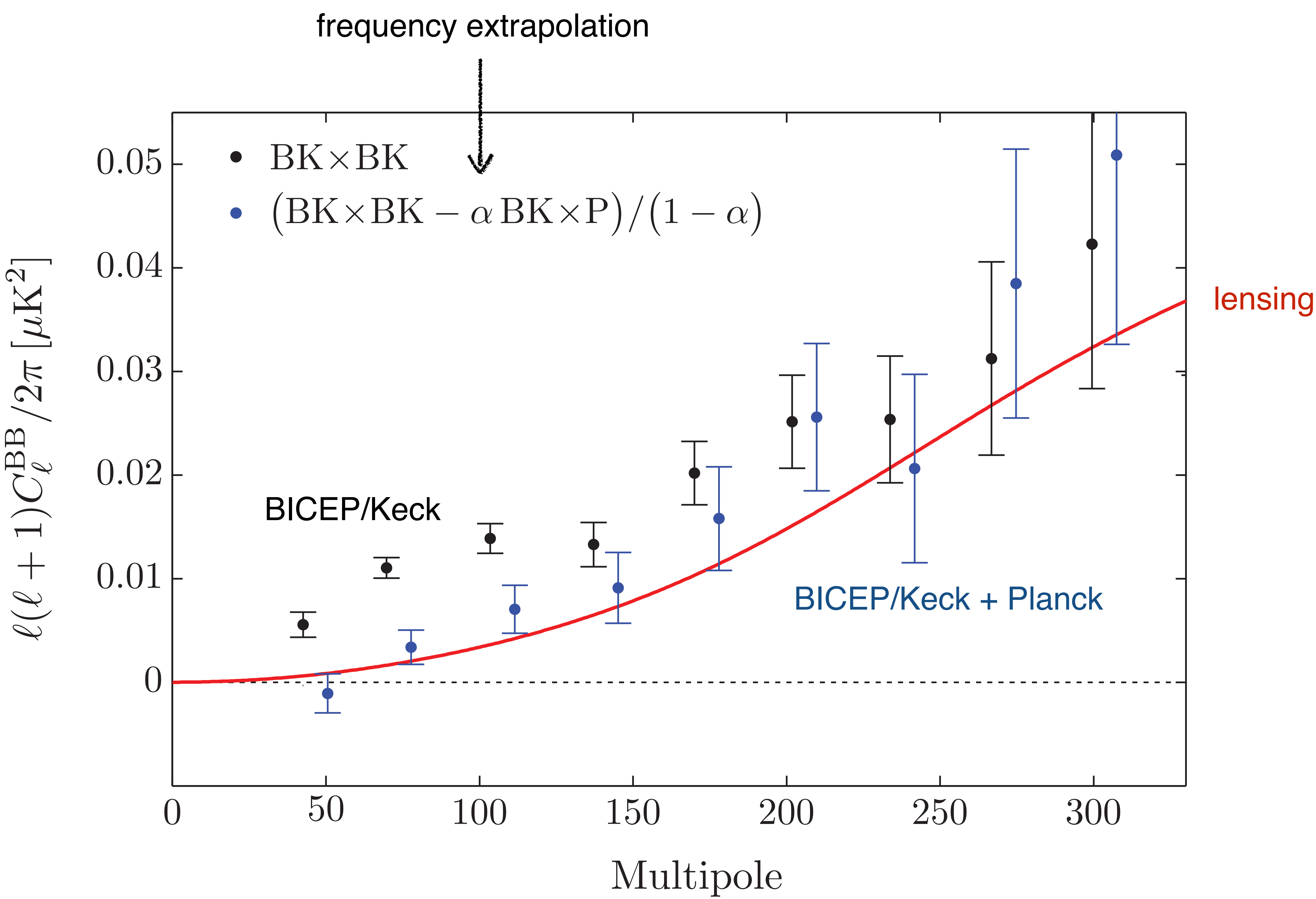
Let's discuss where we stand today.



30% of the sky
B-mode power
Planck
2% of the sky
BICEP2
frequency extrapolation
dust
September 2014
March 2014
synchrotron
blackbody spectrum
150
353
frequency [GHz]

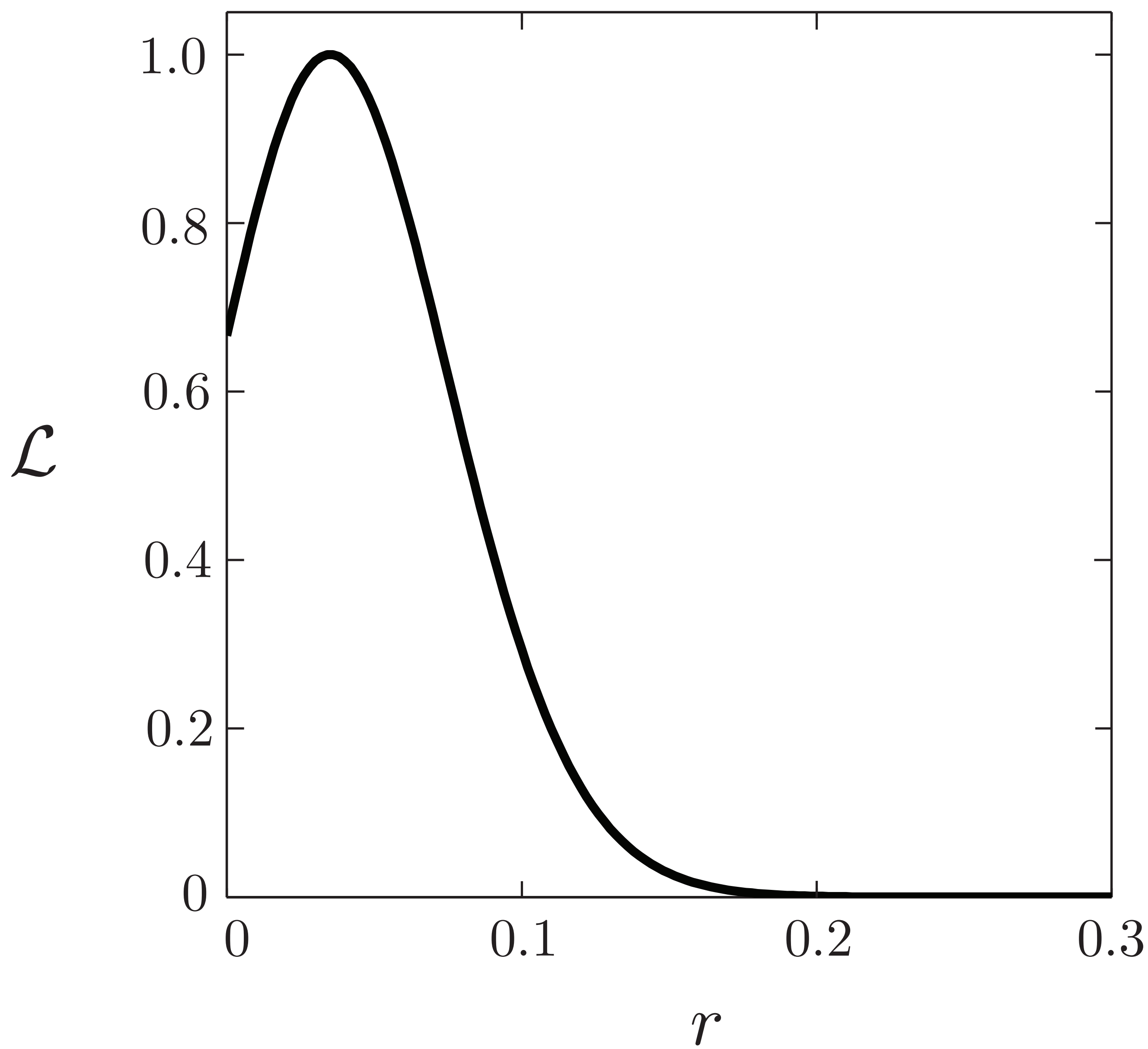


Planck
Planck Int. XXII
353x353
217x353
100x353
143x353
217x217
100x217
143x143
143x217
1.00
0.10
0.01
150
200
250
300
350
relative power
frequency [GHz]



frequency extrapolation
BK×BK
(BK×BK − α BK×P)/(1 − α)
lensing
BICEP/Keck
BICEP/Keck + Planck
$\ell(\ell+1)C_\ell^{\rm BB}/2\pi\ [\mu{\rm K}^2]$
0.05
0.04
0.03
0.02
0.01
0
0
50
100
150
200
250
300
Multipole

The final likelihood is somewhat sensitive to the priors assumed in the frequency extrapolation.



$$r < 0.12 \quad (95\%)$$

The situation will be clarified later this year with the release of the 100 GHz data of the Keck Array.

2.

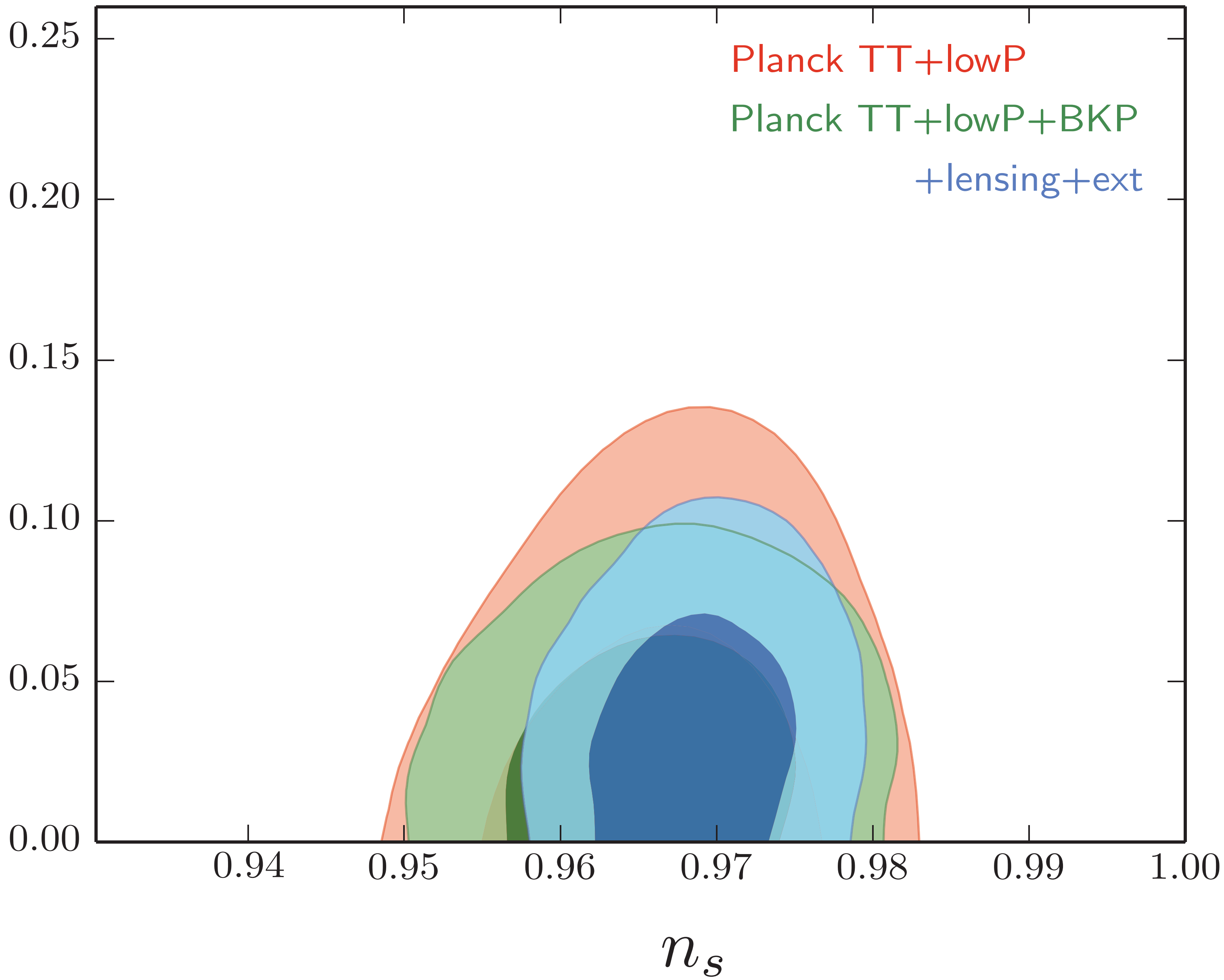
Inflation from the Bottom Up

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - V(\phi) + \sum_i c_i \frac{\mathcal{O}_i[\phi]}{M^{\Delta_i - 4}}$$

slow-roll inflation *UV corrections*

Constraint on Slow-Roll Inflation

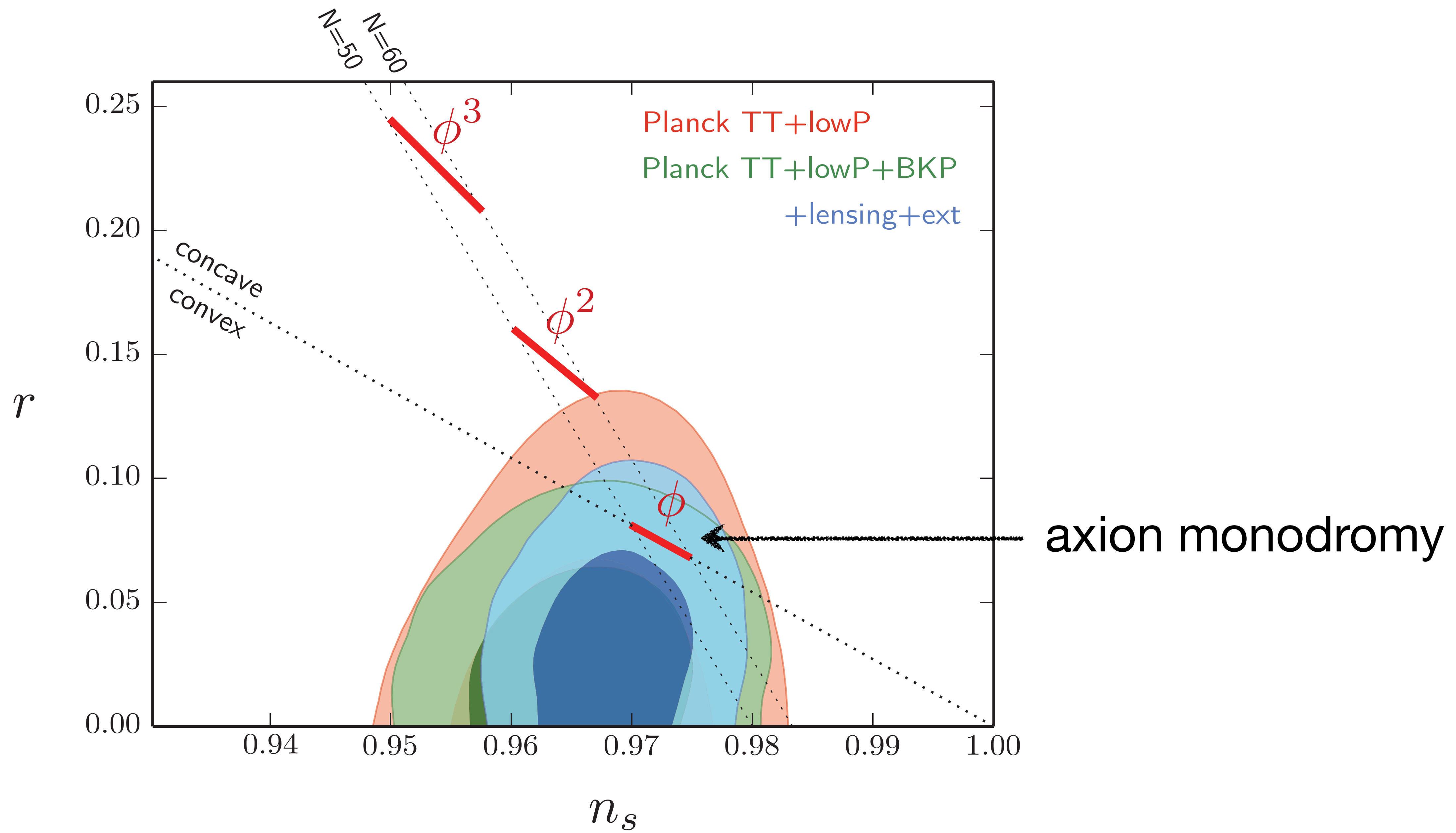
$$8M_{\rm pl}^2\left(\frac{V'}{V}\right)^2 = r$$



$$= 1 - 3M_{\rm pl}^2\left(\frac{V'}{V}\right)^2 + 2M_{\rm pl}^2\frac{V''}{V}$$

Chaotic Inflation

$$V(\phi) = \lambda M_{\rm pl}^4 \left(\frac{\phi}{M_{\rm pl}}\right)^n$$

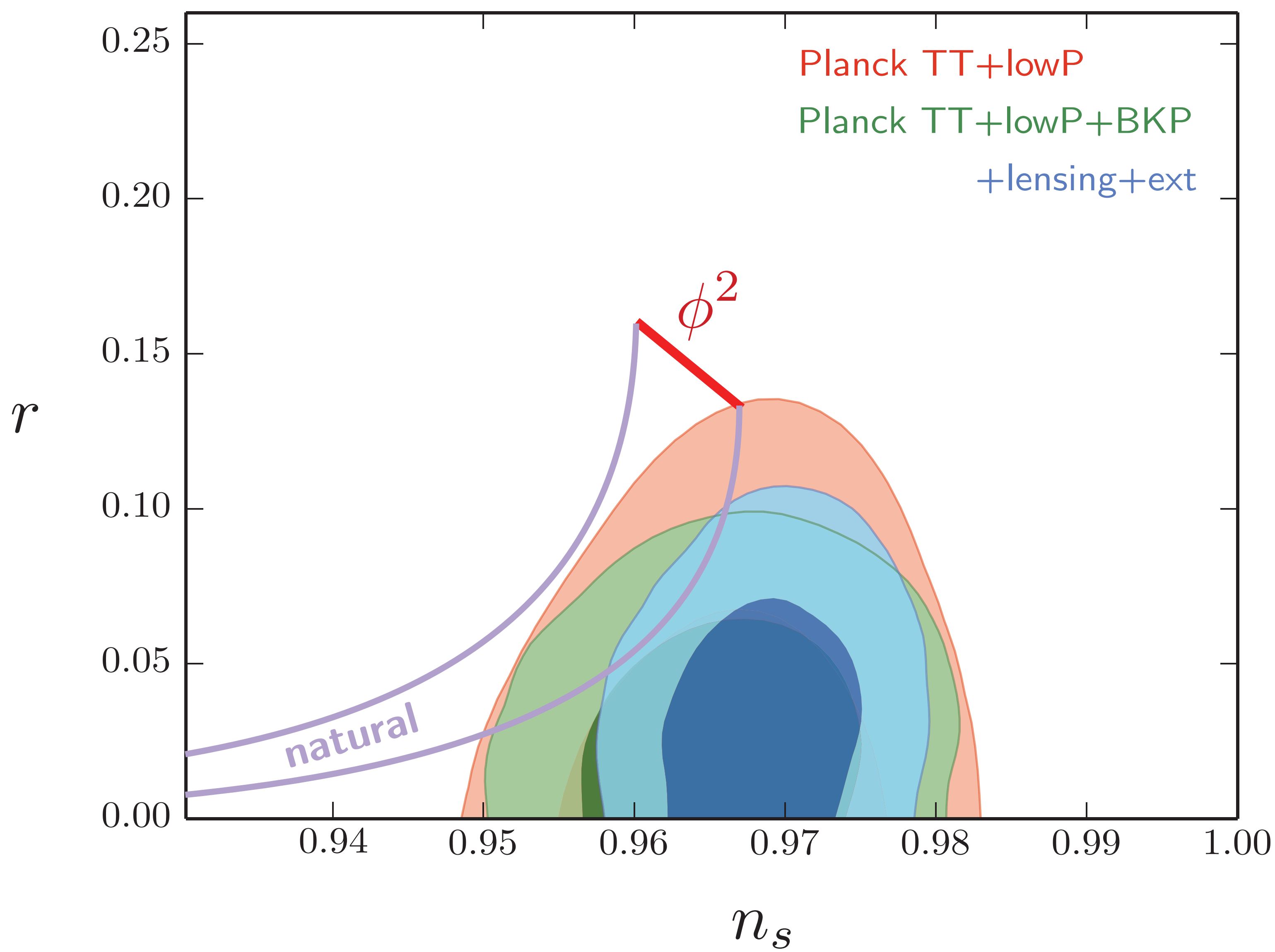


Does coupling to heavy fields really flatten the potential?

Dong et al.

Natural Inflation

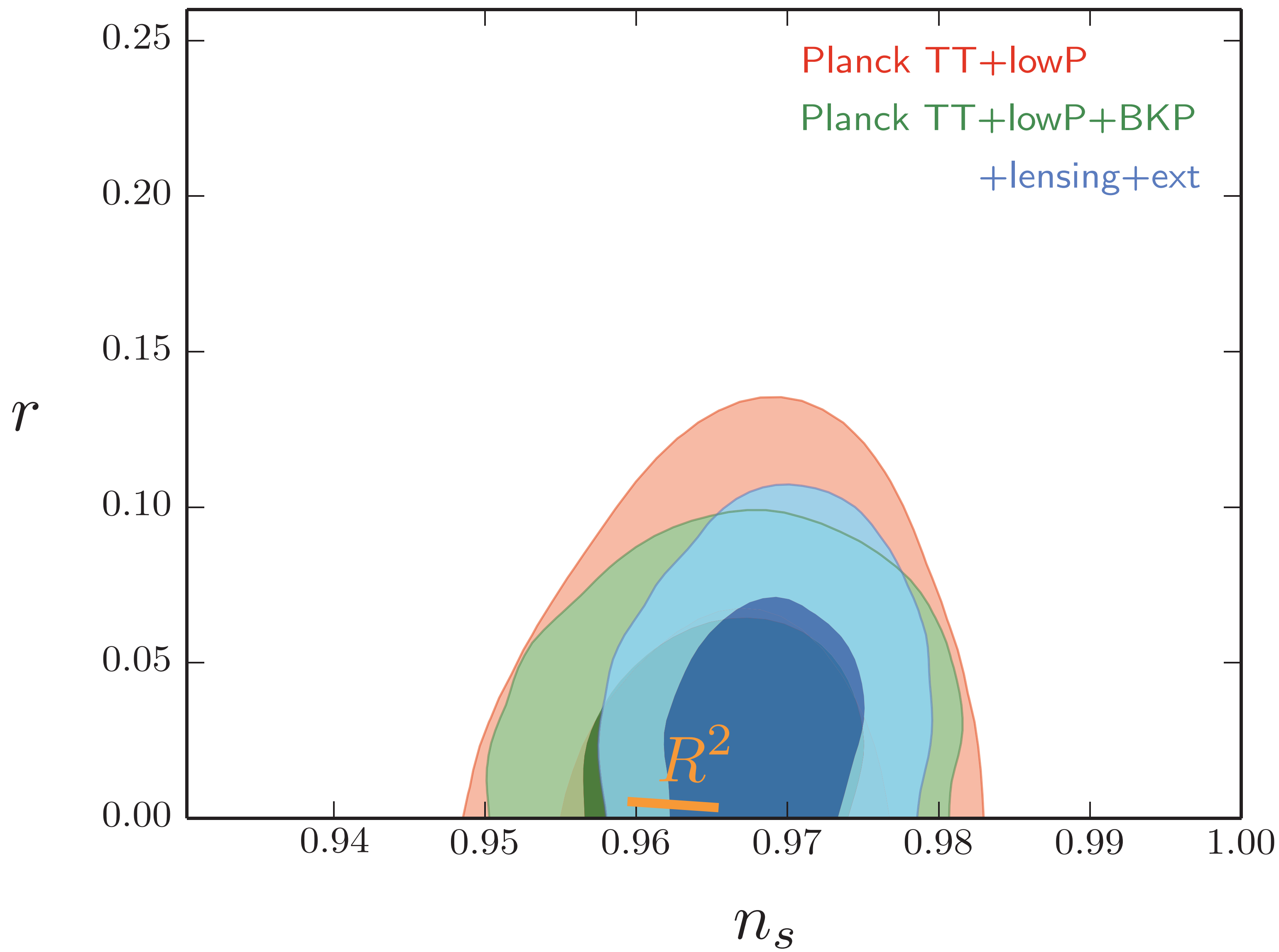
$$V(\phi) = \Lambda^4 \left[1 + \cos\left(\frac{\phi}{f}\right)\right] \qquad f > 6.9\, M_{\rm pl}$$



Is a super-Planckian axion possible?

Starobinsky Inflation

$$S = \int \mathrm{d}^4x\sqrt{-g}\,\frac{M_{\rm pl}^2}{2}\left(R + \frac{R^2}{M^2}\right) \longrightarrow V(\phi) = \Lambda^4\left(1 - e^{-\sqrt{2/3}\,\phi/M_{\rm pl}}\right)^2$$

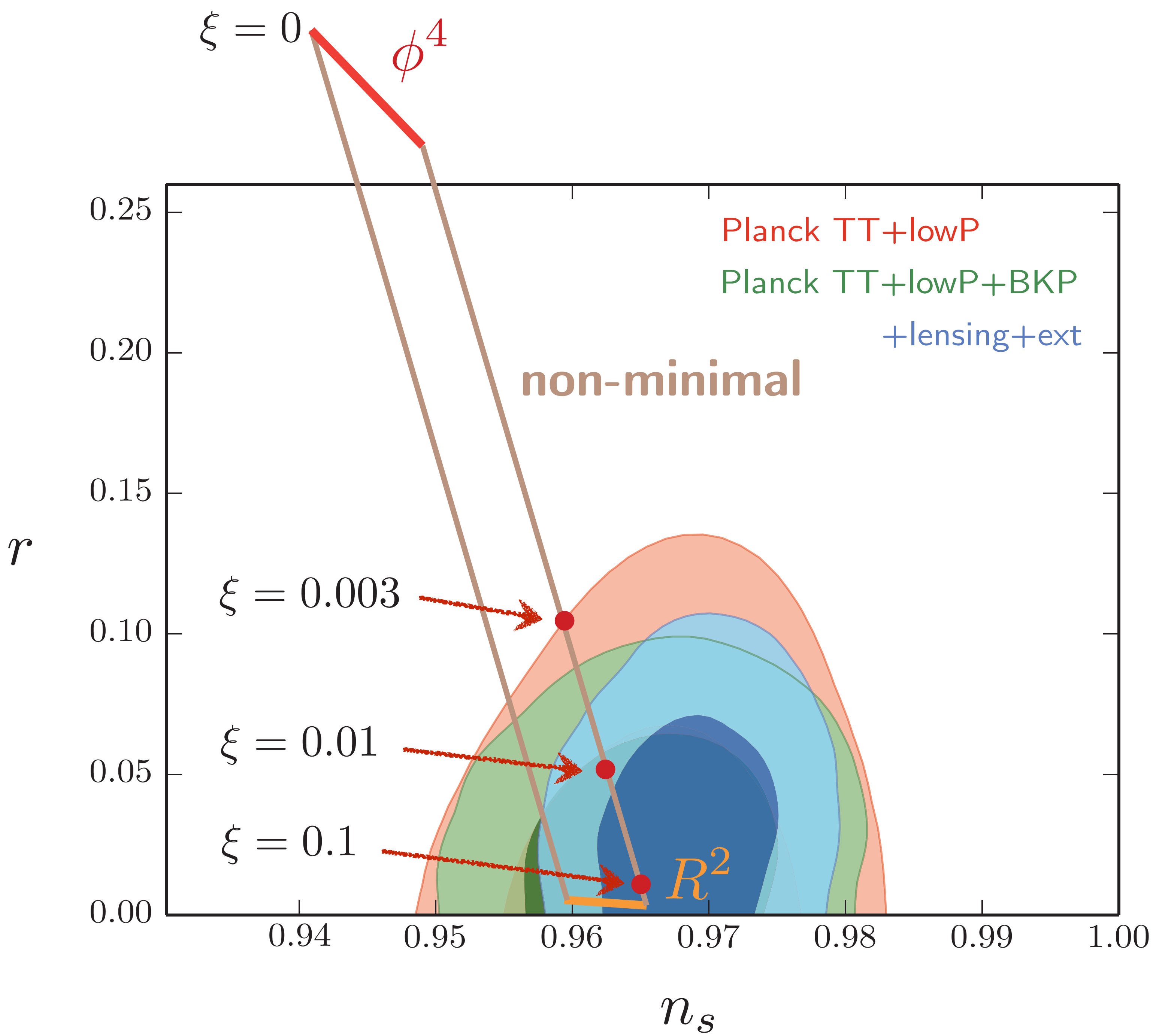


Where does Starobinsky come from?

see Ralph's talk?

Non-Minimally Coupled Inflation

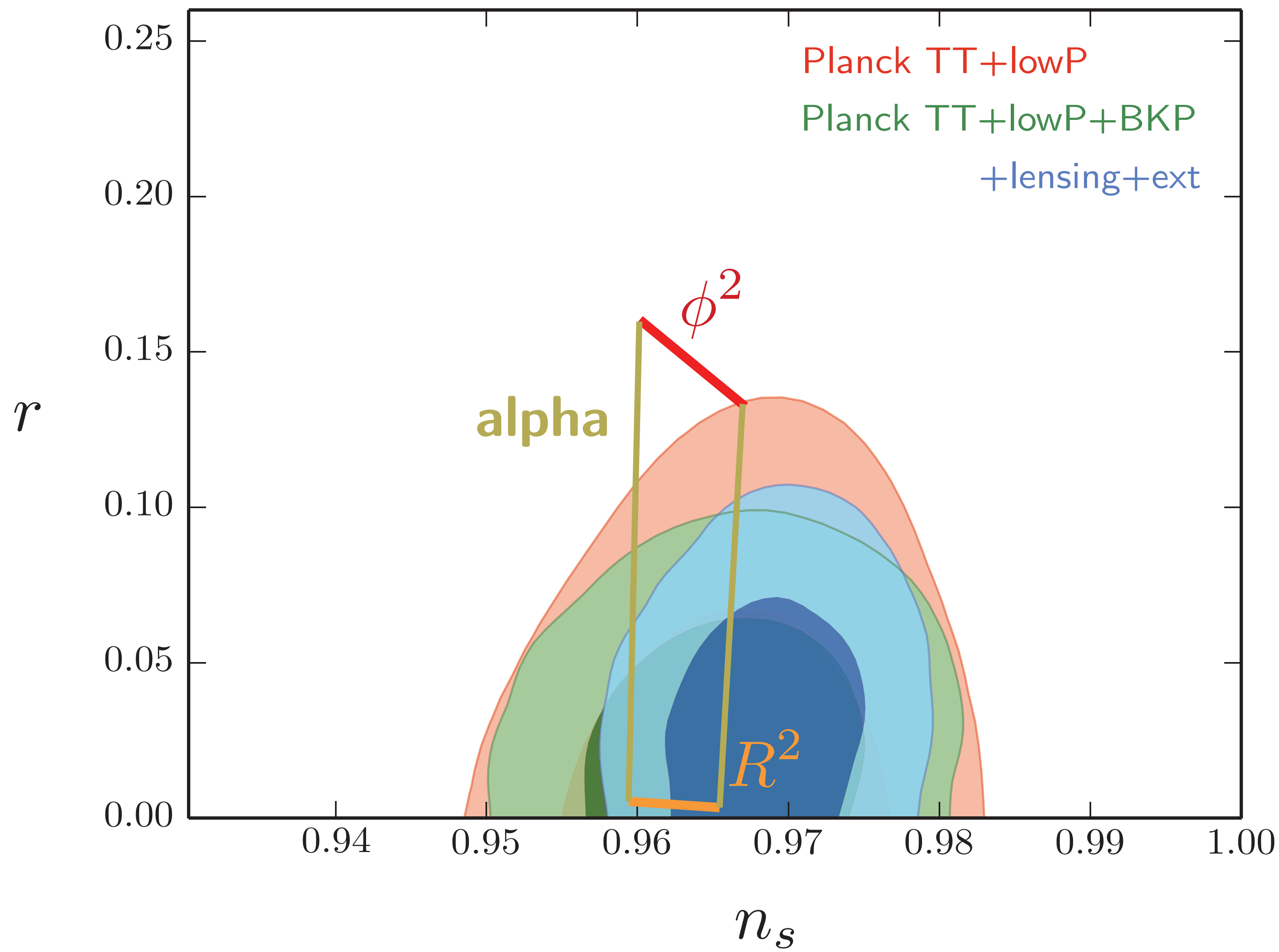
$$V(\phi) = \frac{\lambda}{4}\phi^4 - \frac{\xi}{2}\phi^2 R$$



Alpha-Attractors

$$V(\phi) = \Lambda^4 \left(1 - e^{-\sqrt{2/(3\alpha)}\phi/M_{\rm pl}}\right)^2$$

Kallosh and Linde



Is the bias towards slow-roll models justified by observations?

Just because theorists have an easier time working with weakly coupled scalars, doesn't mean that the same holds for Nature …

Speed of Sound

Broken Lorentz allows for a non-trivial sound speed for the perturbations:

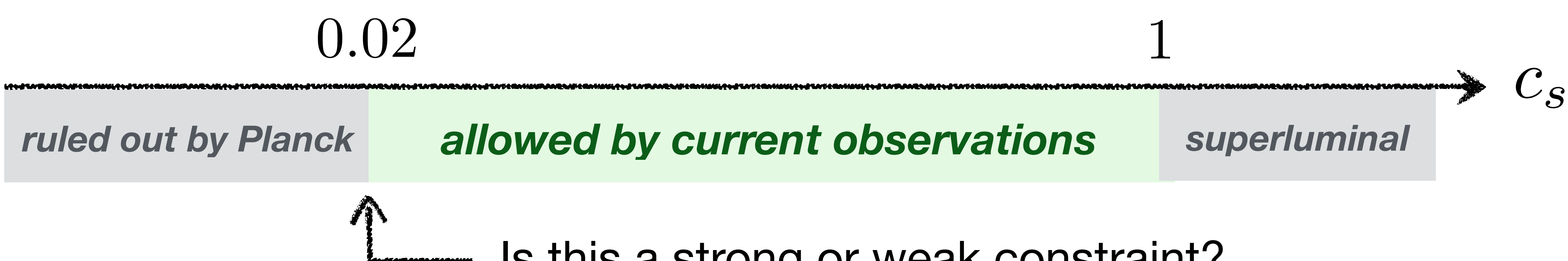
modified dispersion *non-Gaussianity*

$$\mathcal{L} = \frac{M_{\rm pl}^2 |\dot{H}|}{c_s^2} \Big[\left(\dot{\pi}^2 - c_s^2 (\partial_i \pi)^2\right) - (1 - c_s^2)\, \dot{\pi} (\partial_\mu \pi)^2 + \cdots \Big]$$

non-linearly realized symmetry

where $\pi \equiv \dfrac{\delta\phi}{\dot{\bar{\phi}}}$ is the Goldstone boson of broken time-translations. Cheung et al.

The Planck constraint on the sound speed is:



Is this a strong or weak constraint?

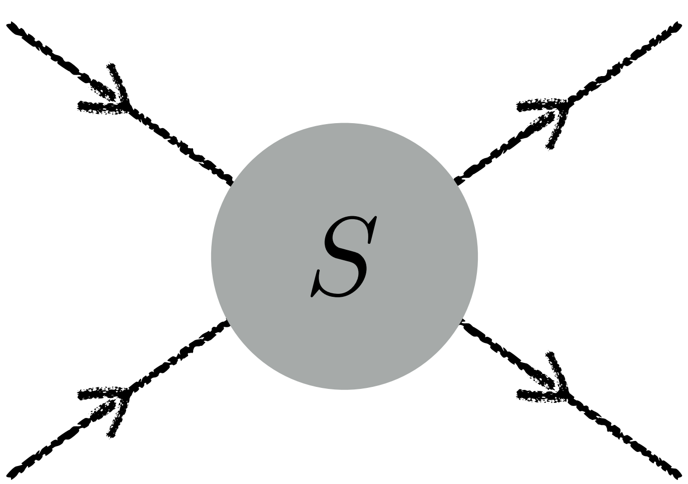
Perturbative Unitarity

Writing $\tilde{x}^i = c_s x^i$ and $\pi_c \equiv (2M_{\rm pl}^2|\dot{H}|c_s)^{1/2}\pi \equiv f_\pi^2 \pi$, we get

$$\mathcal{L} = \frac{1}{2}(\tilde{\partial}_\mu \pi_c)^2 - \frac{\dot{\pi}_c(\tilde{\partial}_\mu \pi_c)^2}{\Lambda^2} + \cdots$$

where $\Lambda^2 \equiv f_\pi^2 \frac{c_s^2}{1-c_s^2}$ is the **strong coupling scale**.

We use this to compute the 2-2 scattering of the Goldstone bosons:



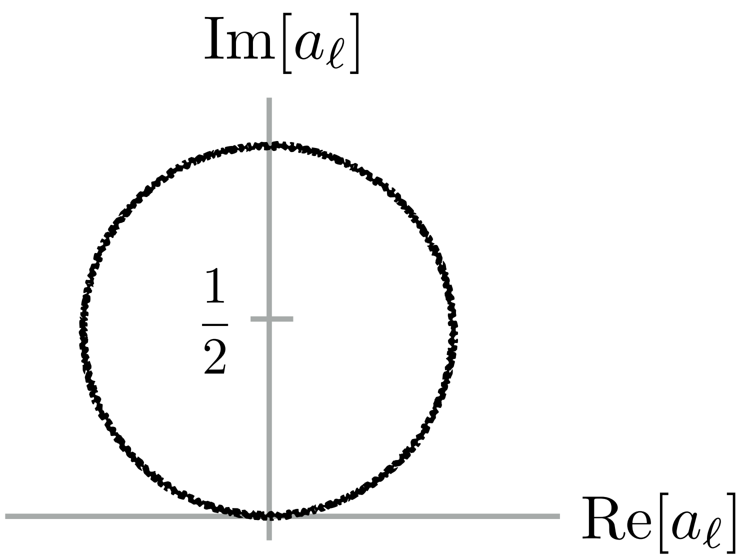
$$= 16\pi \sum_\ell (2\ell+1) a_\ell(\omega) P_\ell(\cos\theta)$$

partial wave amplitude

Perturbative Unitarity

Unitarity requires

$$\mathrm{Im}[a_\ell] = |a_\ell|^2 \quad \longleftrightarrow \quad |\mathrm{Re}[a_\ell]| < \frac{1}{2}$$



Only the sound speed interaction contributes to the d-wave amplitude:

$$|\mathrm{Re}[a_2]| = \frac{1}{60\pi}\frac{1-c_s^2}{c_s^4}\frac{\omega^4}{f_\pi^4} < \frac{1}{2}$$

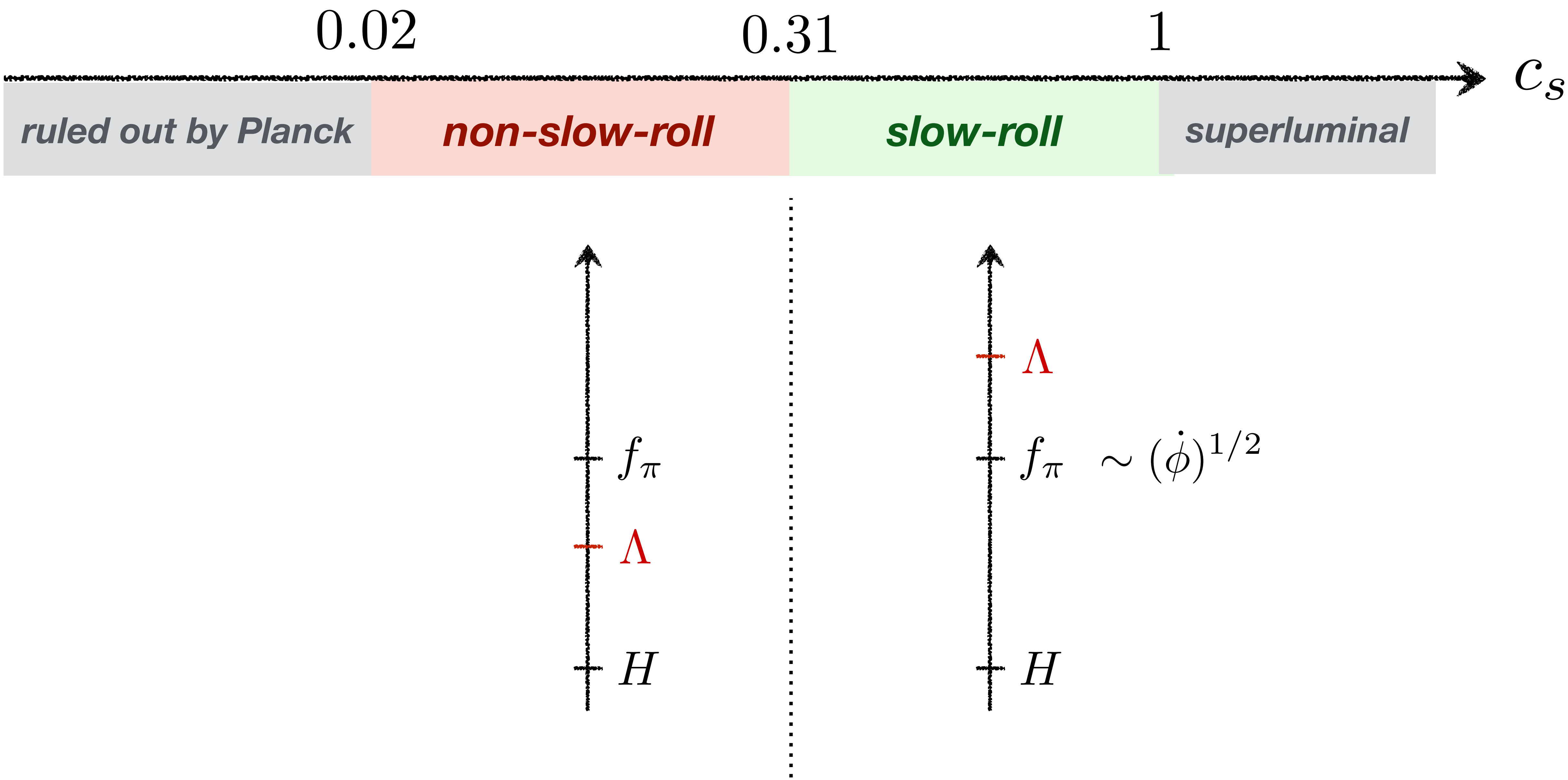
symmetry breaking scale:

$$f_\pi^4 \equiv 2M_{\mathrm{pl}}^2|\dot{H}|c_s$$

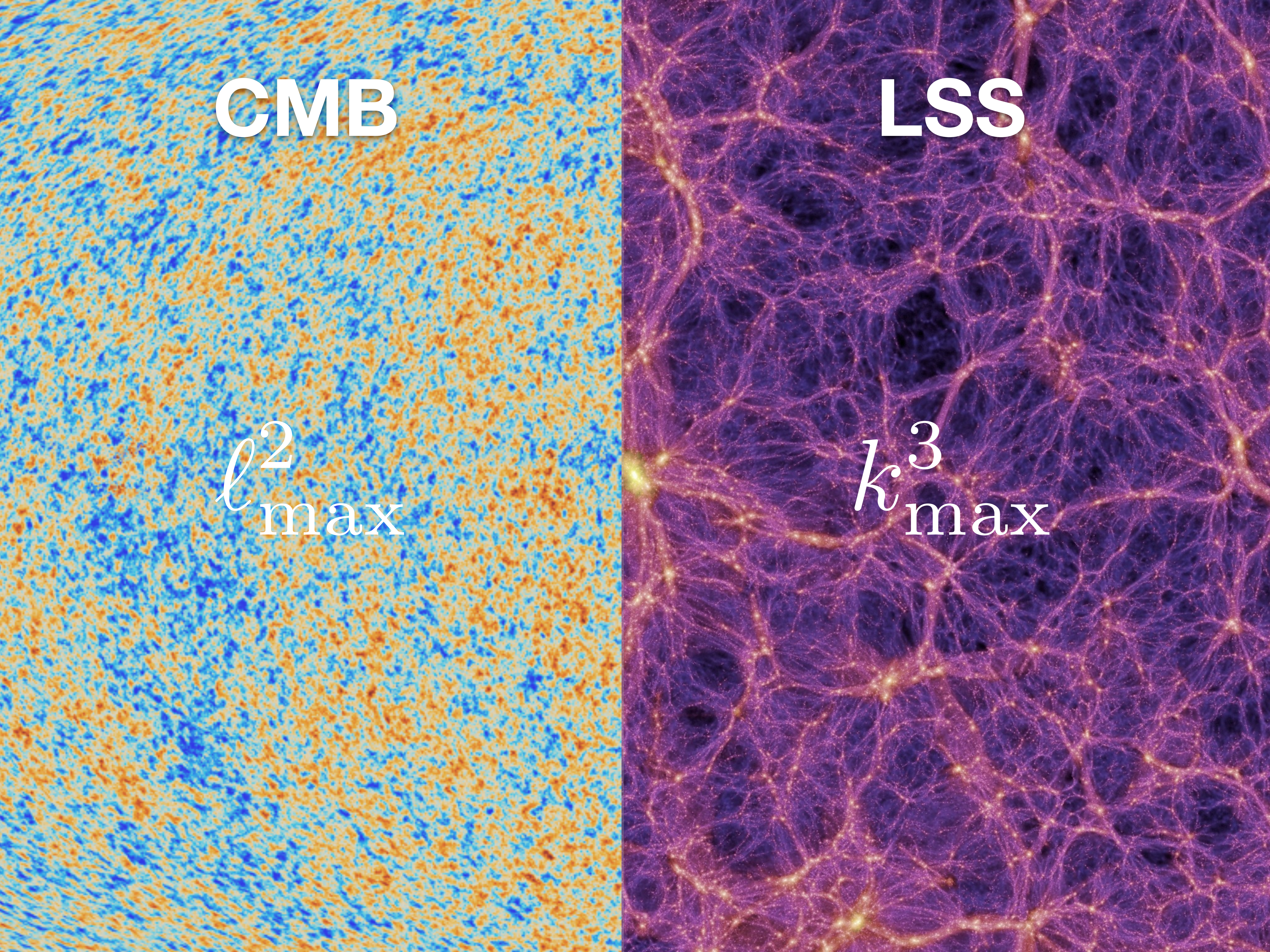
A Critical Sound Speed

Asking for the theory to be weakly coupled up to the symmetry breaking scale implies a critical value for the sound speed:

$$(c_s)_\star = 0.31$$



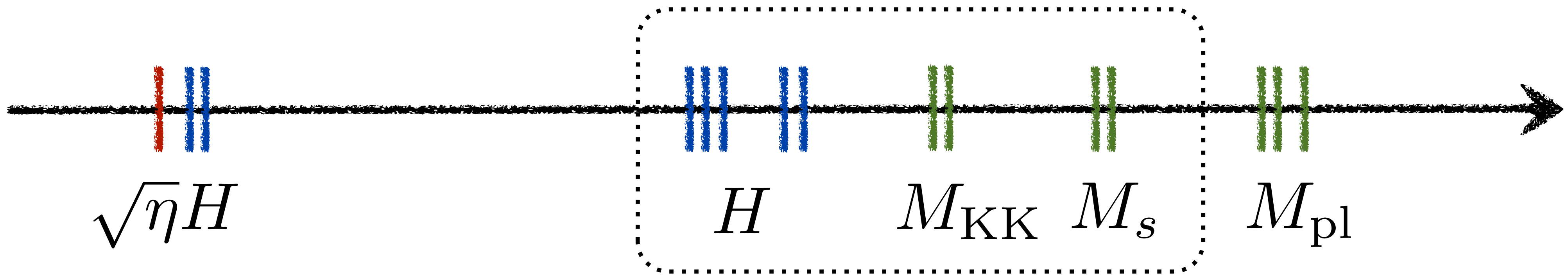
We are still one order of magnitude away from ruling out a strongly coupled inflationary background.


CMB
LSS
ℓ_{max}^2
k_{max}^3

3.

Inflation from the Top Down

String compactifications are **complex**



What is the phenomenology of inflation if we take this seriously?

1. *How does the simplicity of the data emerge from the complexity of the UV-completion?*

2. *Can we see imprints of stringy UV effects?*

Challenge 1: Many Extra Fields

Amin and DB, *in progress.*

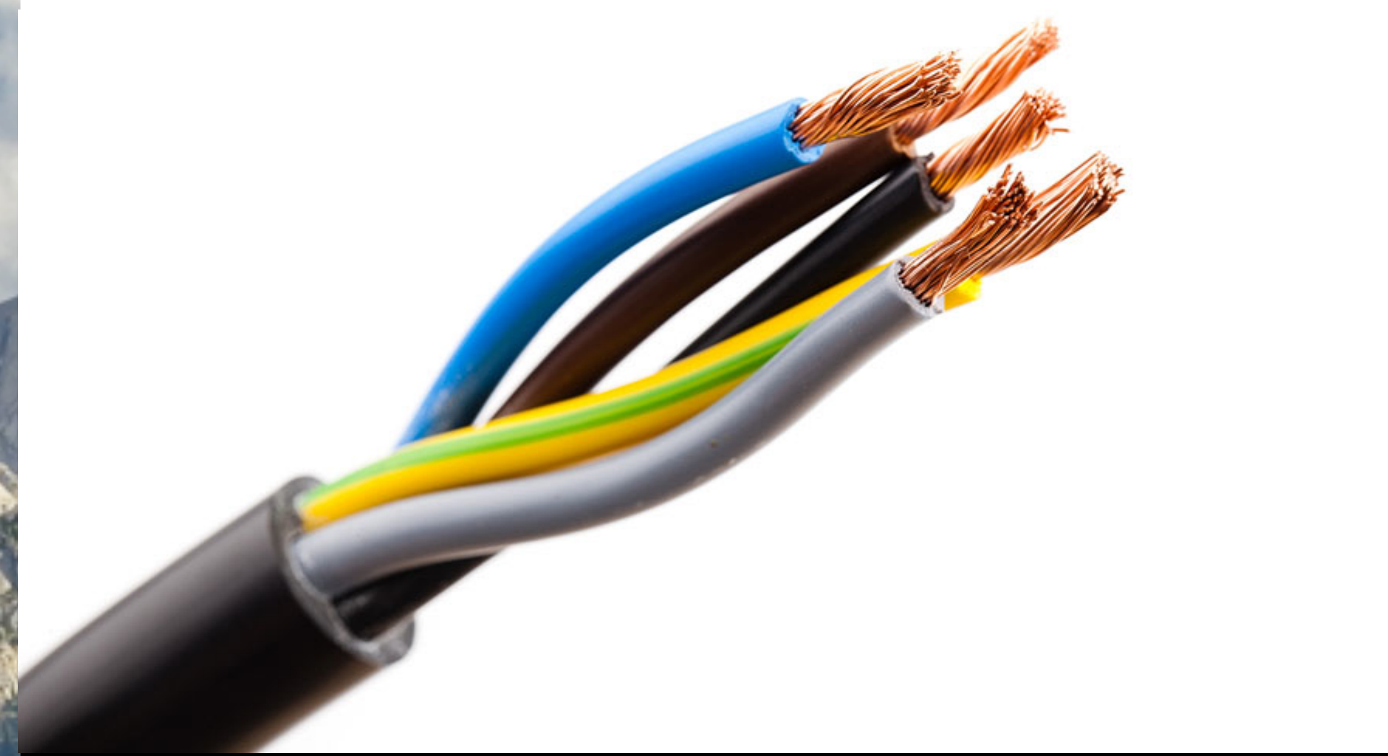

Fine-tuning
ϕ

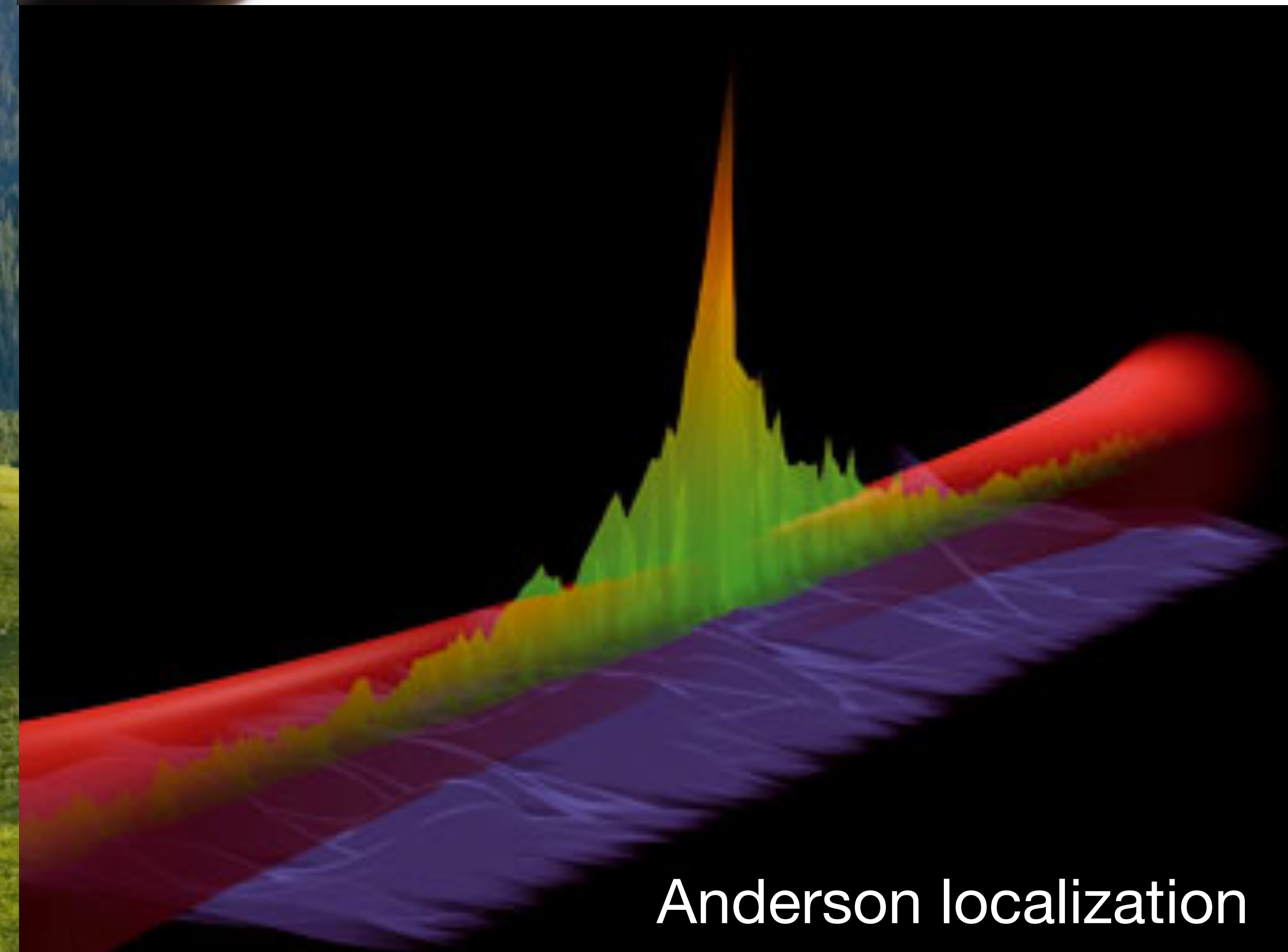

ϕ
Symmetry

Fine-tuning

How do we compute observables?

Impurities in Wires





Disorder in Inflation

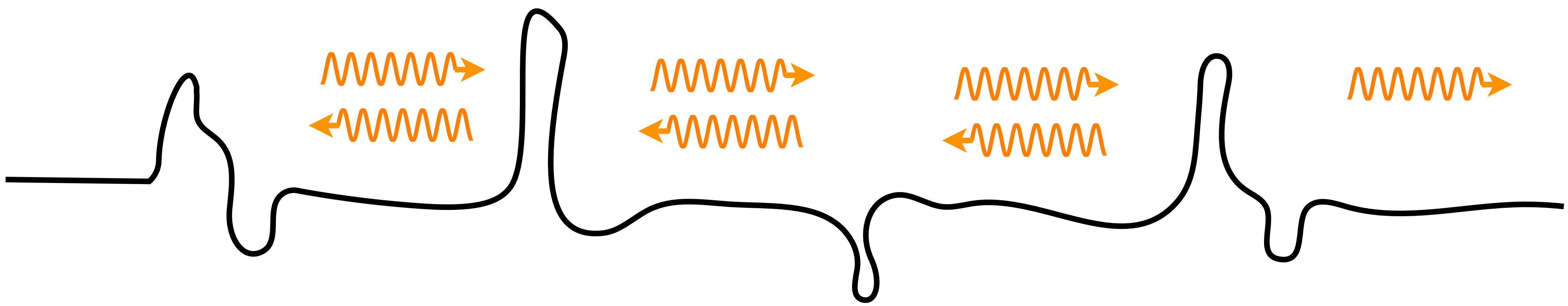
Time-dependent Klein-Gordon

$$\frac{d^2\varphi_k}{d\tau^2} + \left(k^2 + m^2(\tau)\right)\varphi_k = 0$$

Impurities in Wires

Time-independent Schrödinger

$$\frac{d^2\psi}{dx^2} + \left(E - V(x)\right)\psi = 0$$



particle production

$$\langle n \rangle = e^{\mu T} - 1$$

Anderson localization

$$\langle \rho \rangle = e^{L/l}$$

Fokker-Planck equation

$$P(n, T)$$

Fokker-Planck equation

$$P(\rho, L)$$

multiple fields

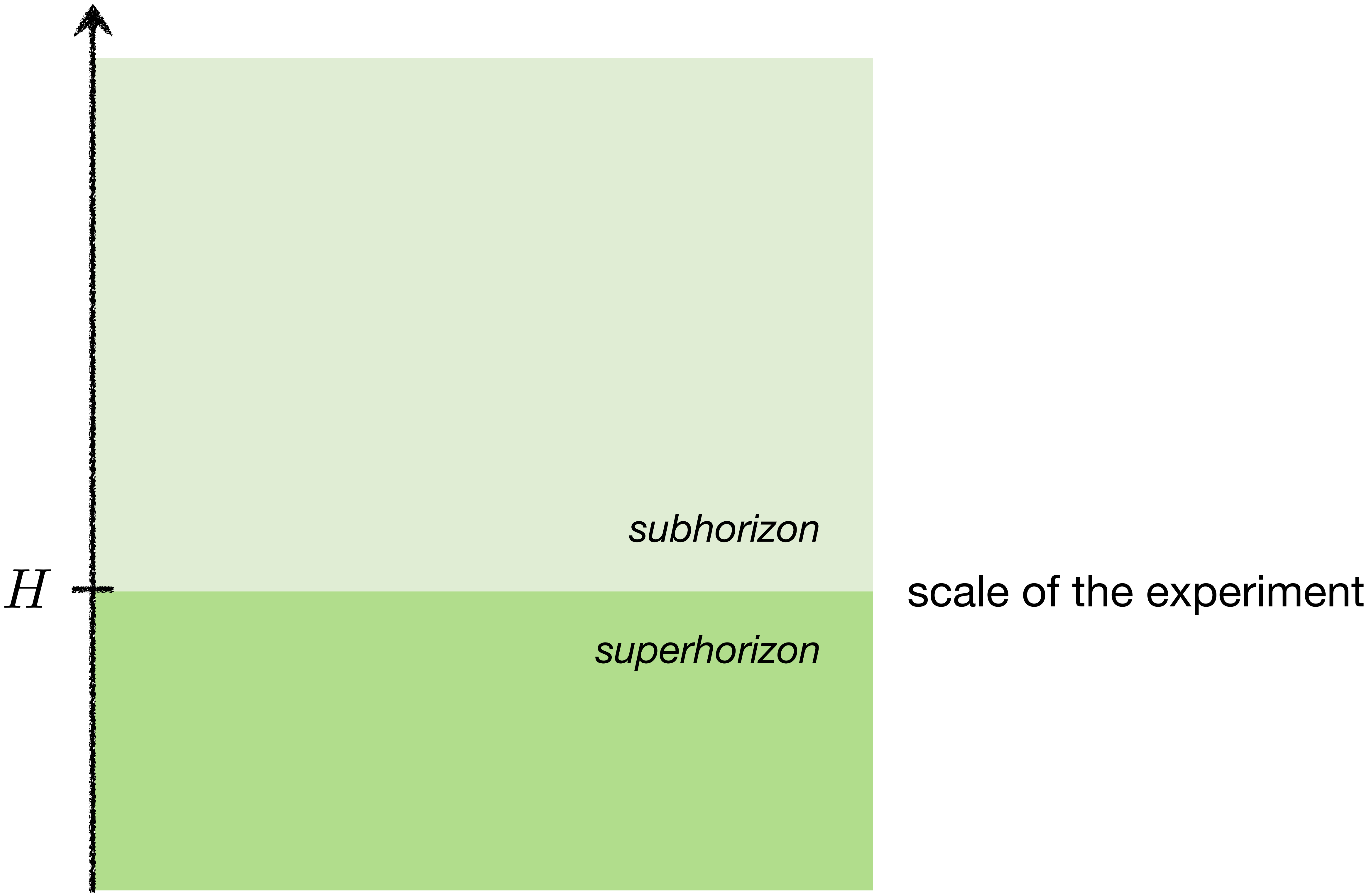
multiple channels

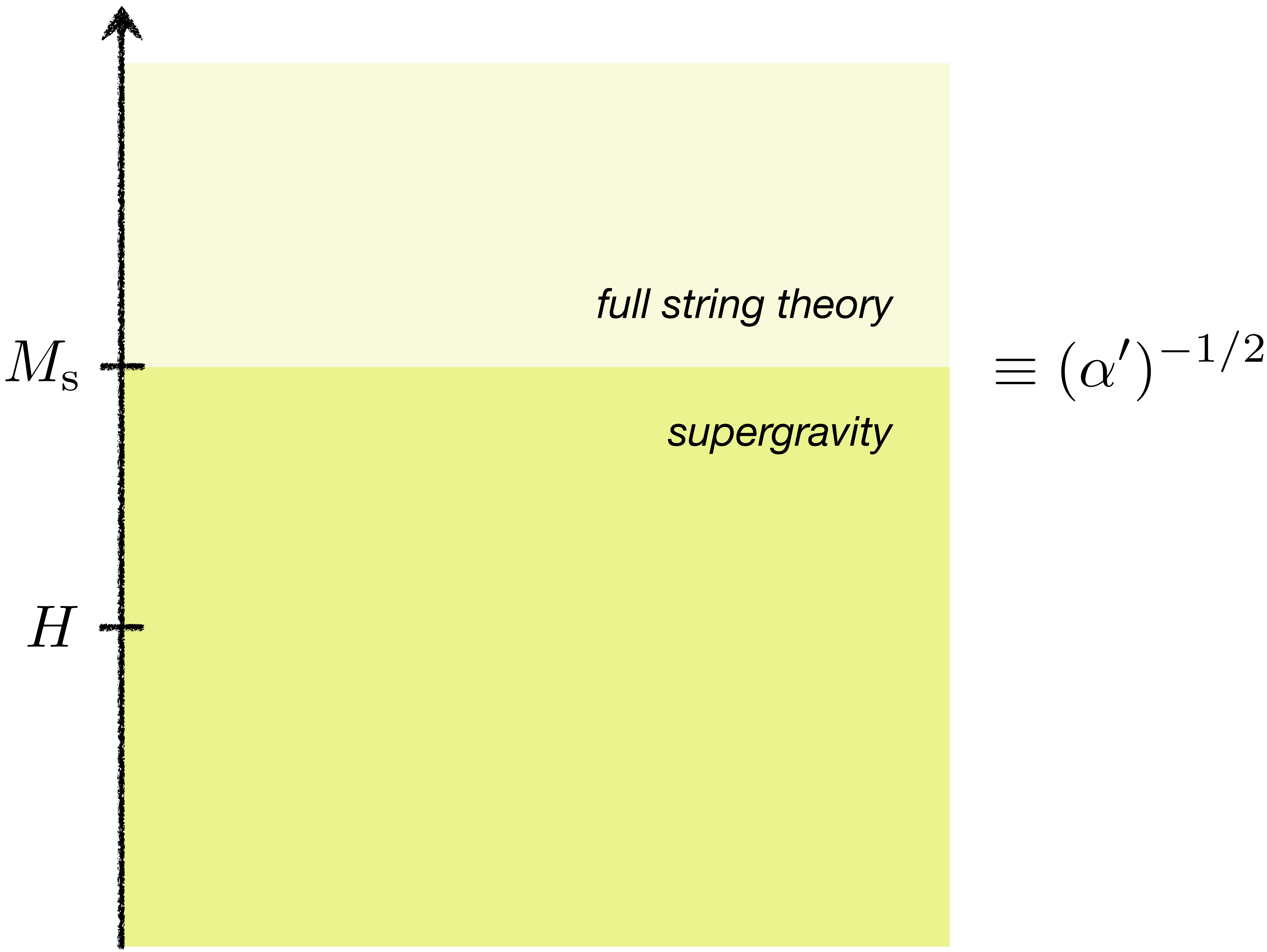
etc.

Amin and DB, *in progress.*

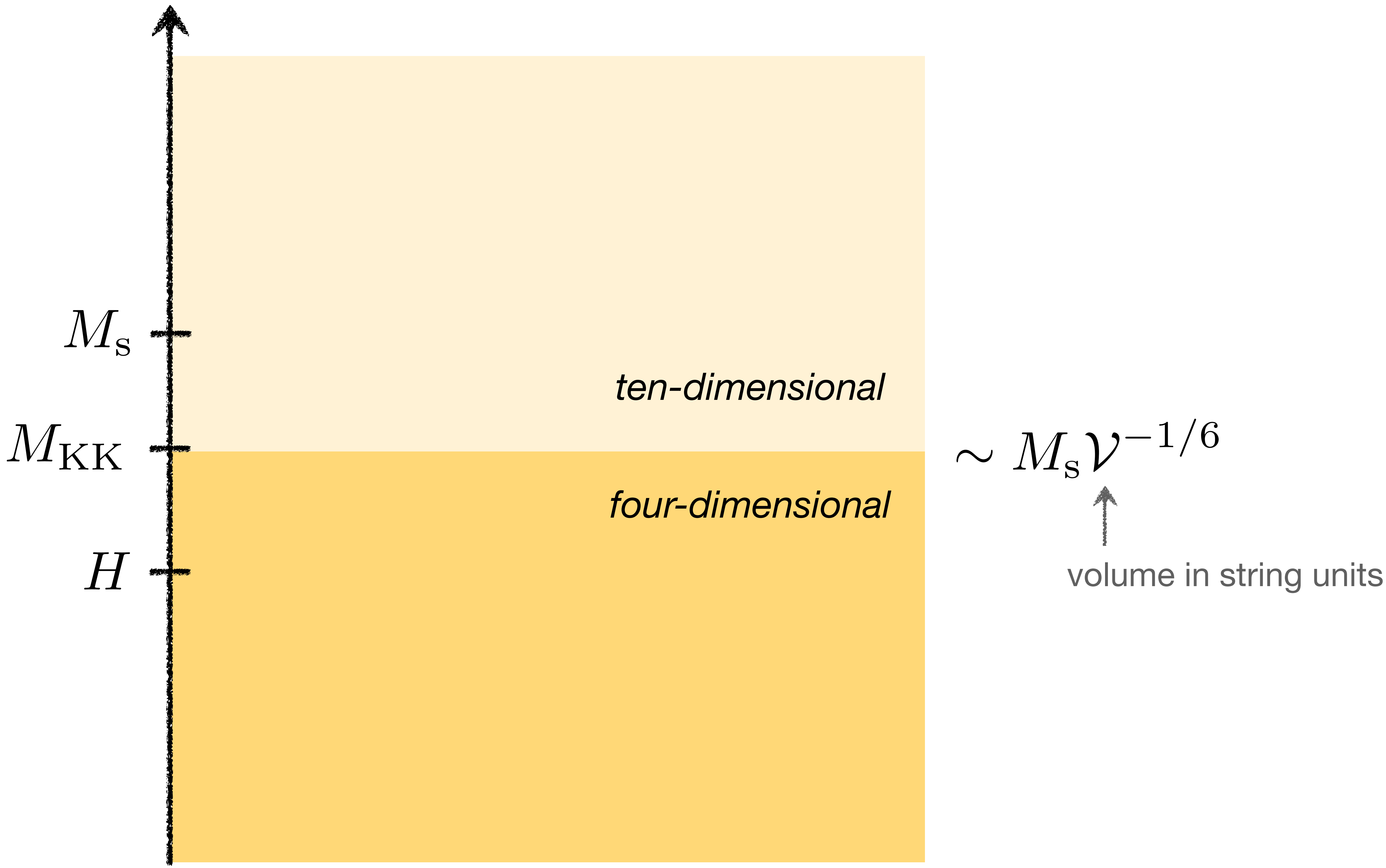
Challenge 2: Many Extra Scales

DB and Green, *Signatures of Supersymmetry from the Early Universe,* [arXiv:1109.0292]
Assassi, DB, Green, and McAllister, *Planck-Suppressed Operators,* [arXiv:1304.5226]
Arkani-Hamed and Maldacena, *Cosmological Collider Physics,* [to appear]

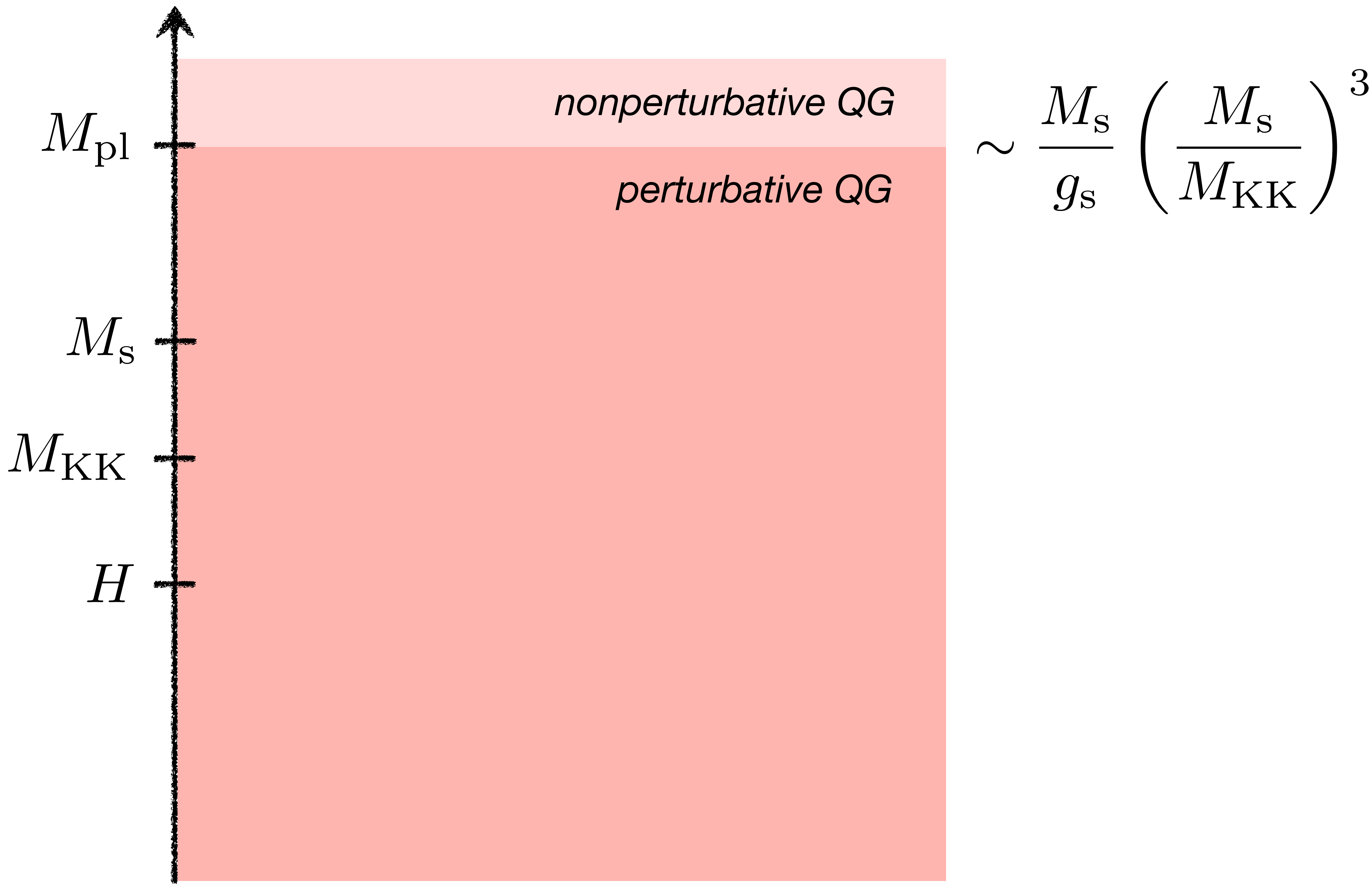

subhorizon
H
scale of the experiment
superhorizon



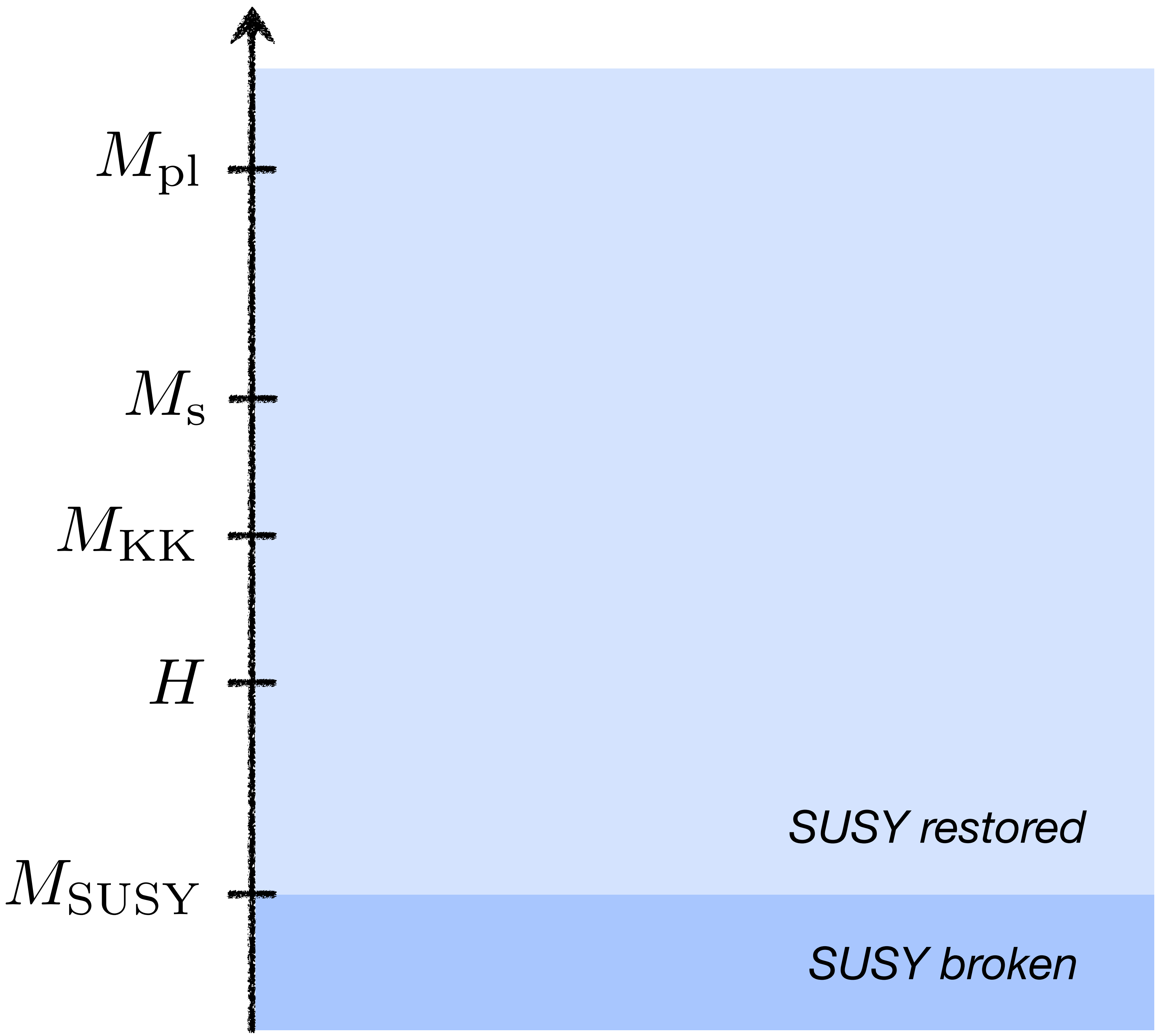
full string theory
supergravity
$M_{\rm s}$
H
$\equiv (\alpha')^{-1/2}$

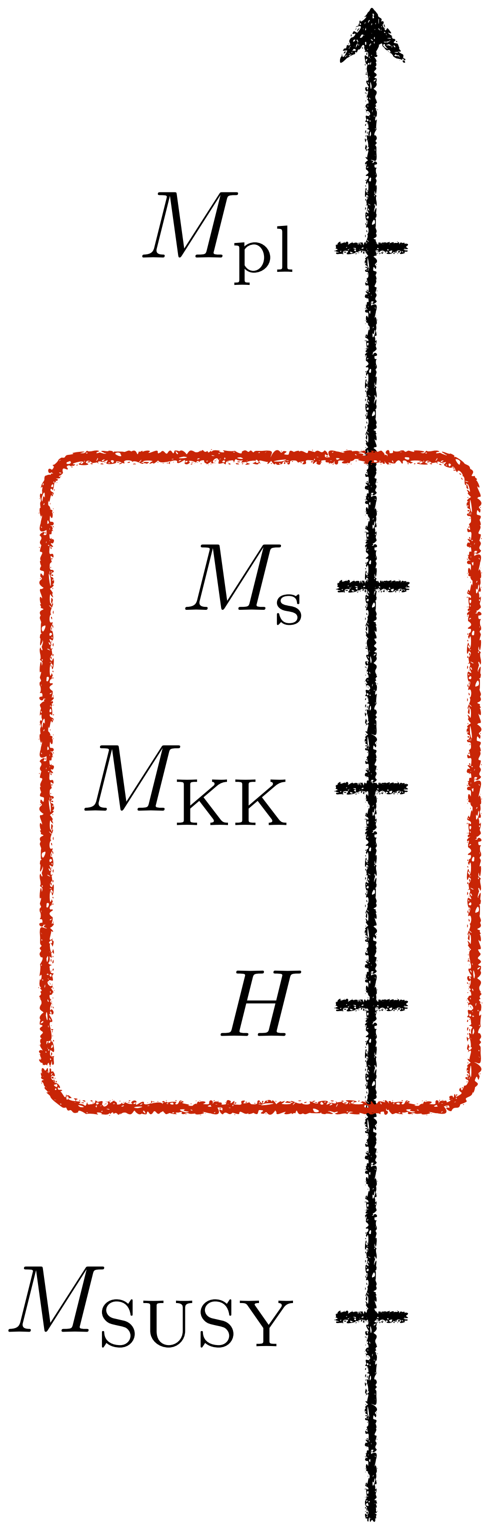


$M_{\rm s}$
ten-dimensional
$M_{\rm KK}$
$\sim M_{\rm s}\mathcal{V}^{-1/6}$
four-dimensional
H
volume in string units



nonperturbative QG
perturbative QG
$M_{\rm pl}$
$M_{\rm s}$
$M_{\rm KK}$
H
$\sim \frac{M_{\rm s}}{g_{\rm s}} \left(\frac{M_{\rm s}}{M_{\rm KK}}\right)^3$


$M_{\rm pl}$
$M_{\rm s}$
$M_{\rm KK}$
H
SUSY restored
$M_{\rm SUSY}$
SUSY broken



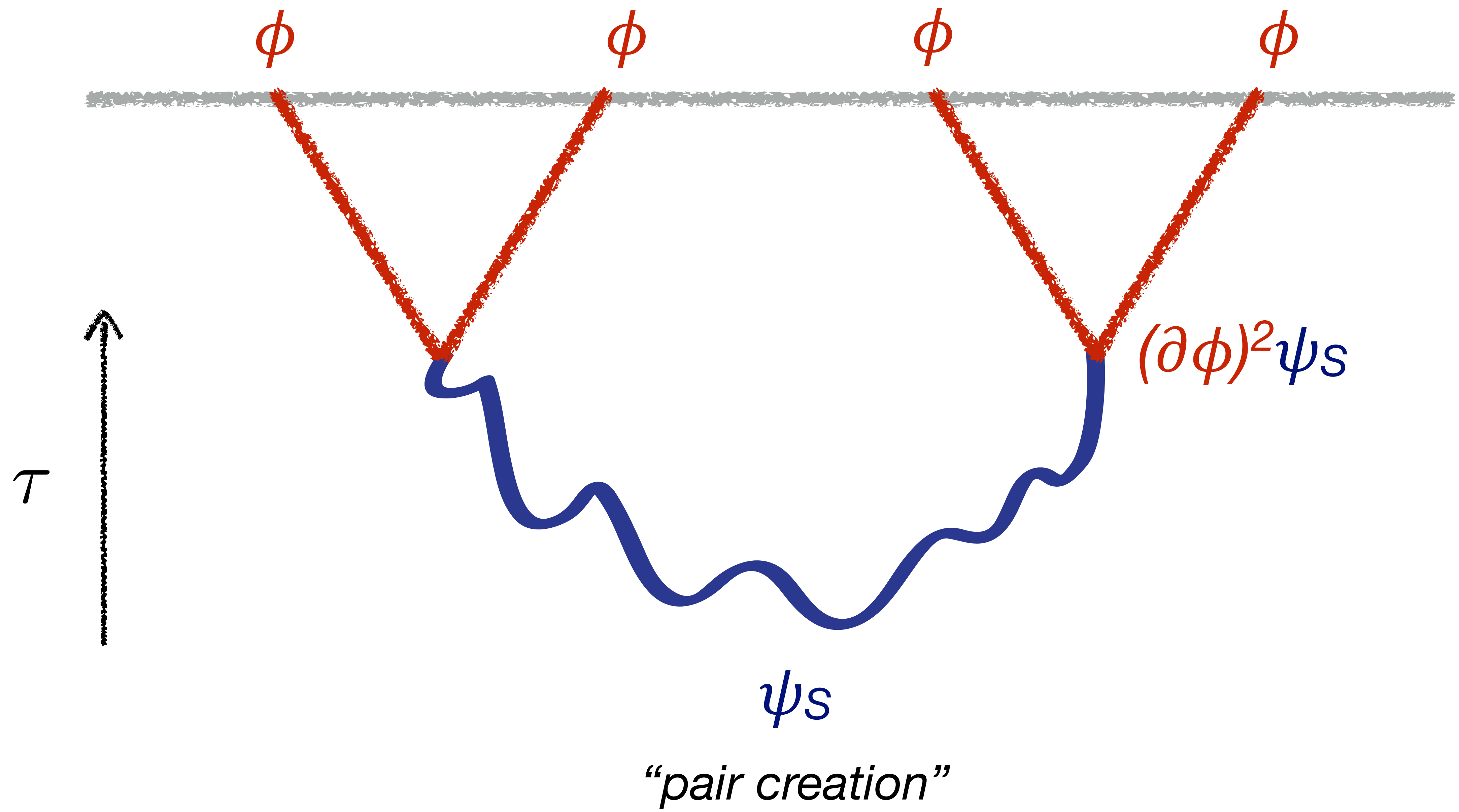
Especially, in high-scale inflation we struggle to decouple all UV effects from physics at the Hubble scale.

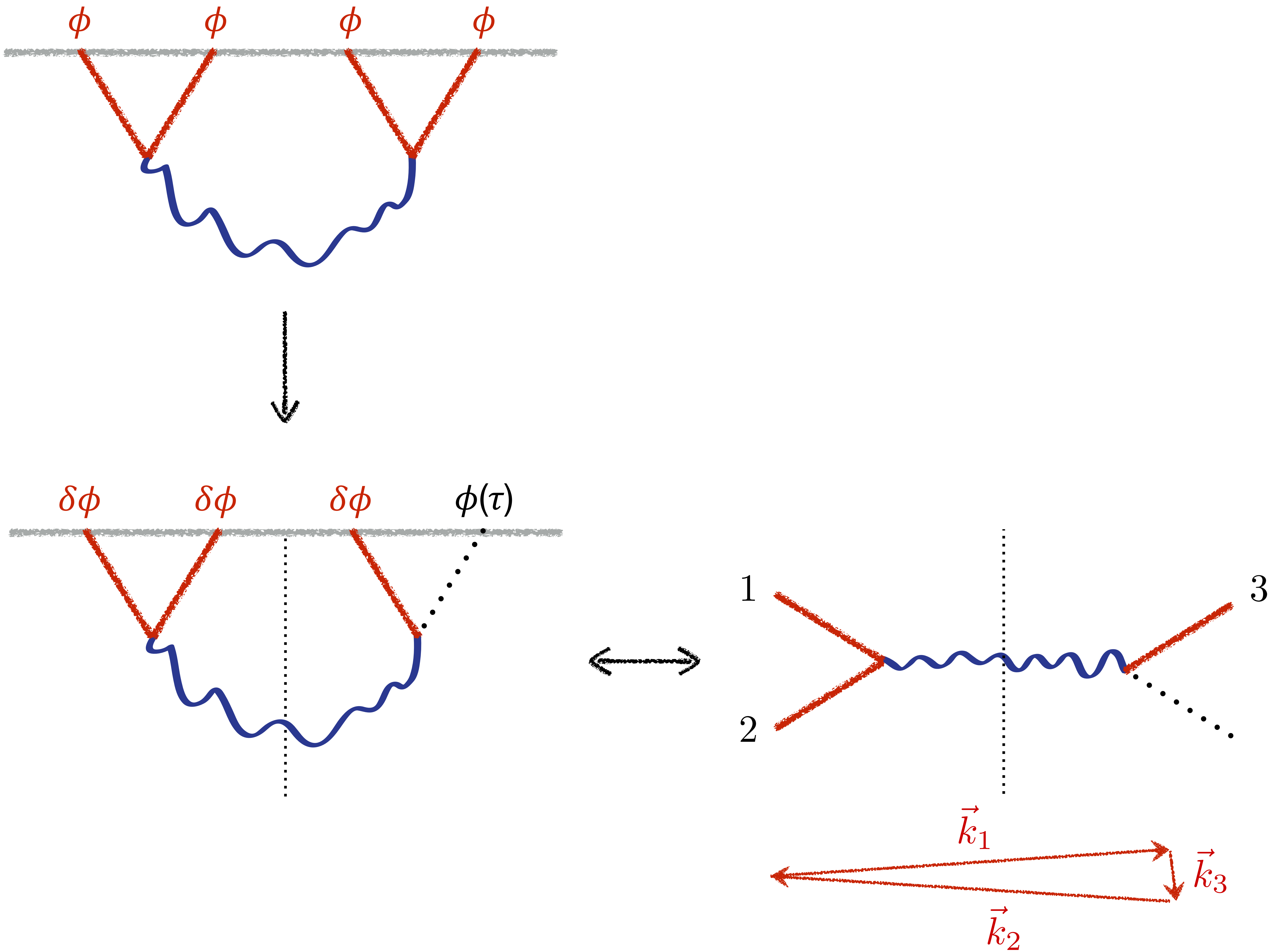
SUSY naturally leads to extra fields near the Hubble scale.

Let's not fight it, but embrace it.

Let the inflaton ϕ couple to particles ψ_S with mass M and spin S.

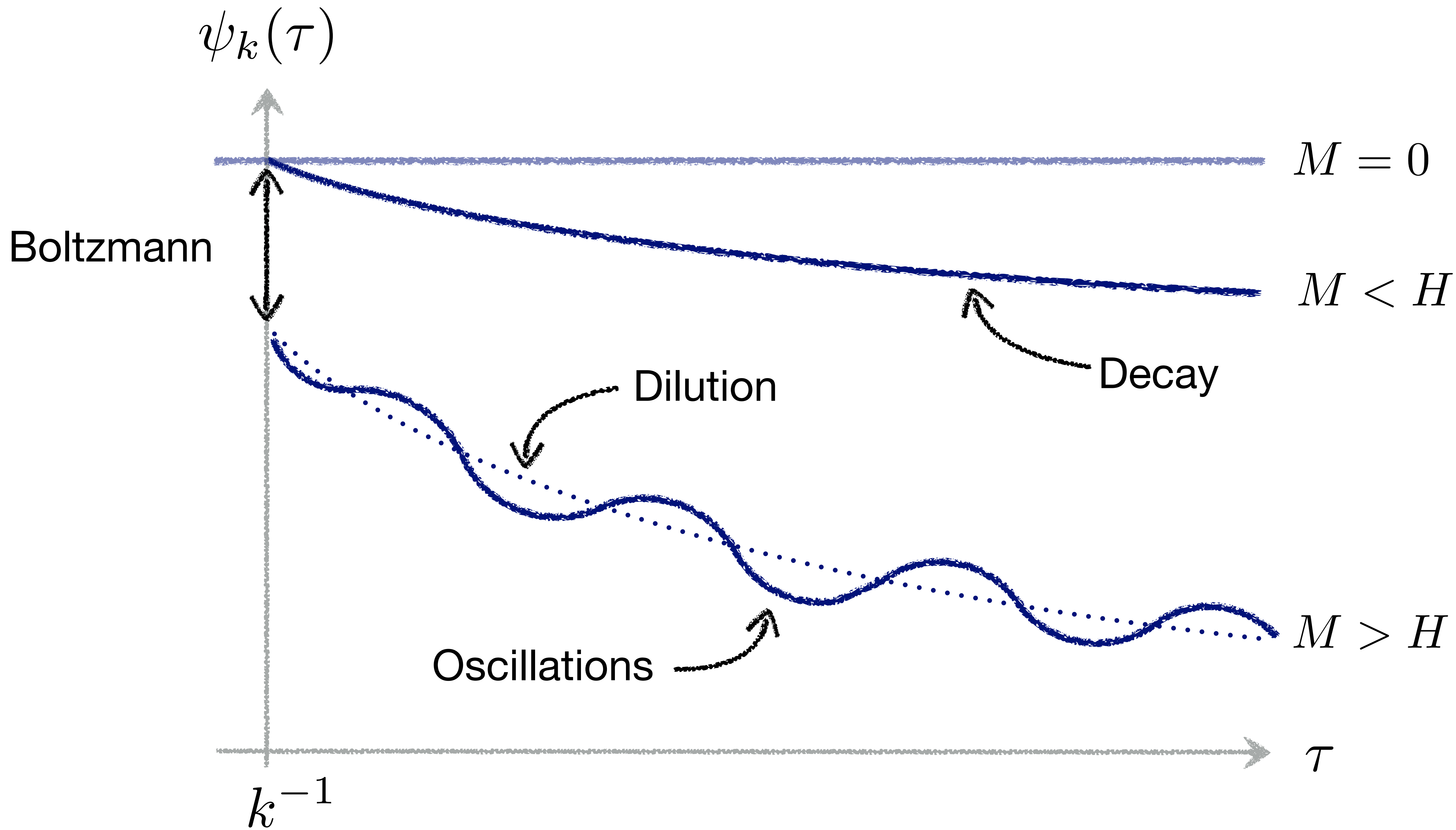
Pair creation of ψ_S-particles leads to non-Gaussian correlations of ϕ-particles:





ϕ
ϕ
ϕ
ϕ
$\delta\phi$
$\delta\phi$
$\delta\phi$
$\phi(\tau)$
1
2
3
$\vec{k}_1$
$\vec{k}_3$
$\vec{k}_2$

Massive Fields in de Sitter Space



Non-Gaussianity as a Particle Detector

Chen and Wang
DB and Green
Arkani-Hamed and Maldacena

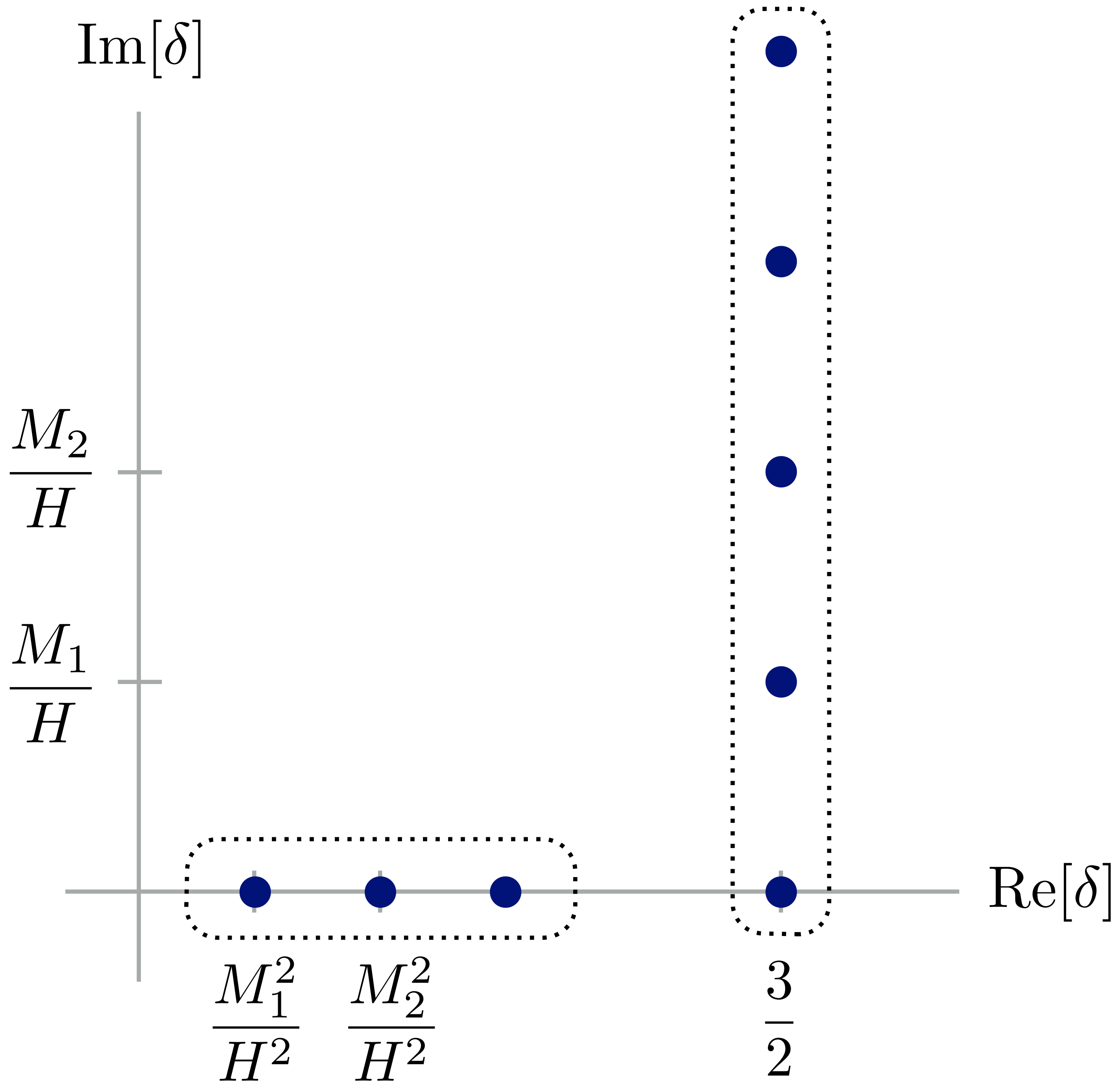
The superhorizon evolution of the massive field gets imprinted in the squeezed limit of the bispectrum:

$$\lim_{k_3 \to 0} k_3^3 B(k_1, k_2, k_3) = \begin{cases} \left(\dfrac{k_3}{k_1 + k_2} \right)^{3/2-\nu} & M < H \\ \left(\dfrac{k_3}{k_1 + k_2} \right)^{3/2} \cos(2i\nu \ln(k_3)) & M > H \end{cases}$$

where $\nu \equiv \sqrt{\dfrac{9}{4} - \dfrac{M^2}{H^2}}$.

Regge Spectrum in Mellin Space

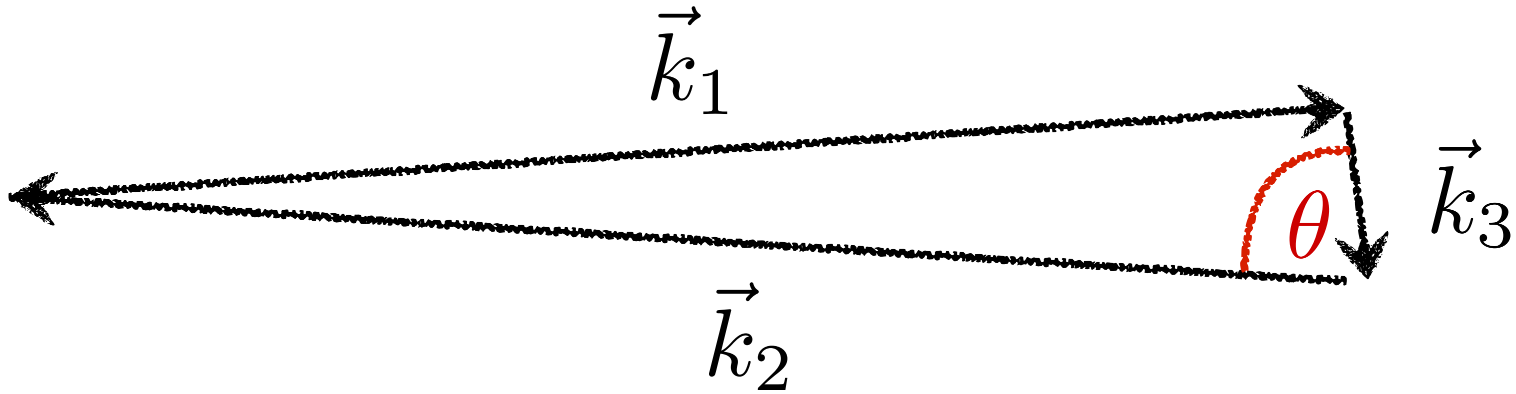
$$\tilde{B}(\delta) \equiv \int \frac{\mathrm{d}k_3}{k_3} \left(\frac{k_3}{k_1 + k_2} \right)^{-\delta} B(k_1, k_2, k_3)$$



Spin

induces a unique signature in the bispectrum:

Arkani-Hamed and Maldacena



$$\sim \; P_S(\cos\theta)$$

Finding S > 2 would be very interesting.

Weinberg
Green, Schwarz, and Witten

Finding a correlation of the poles in Mellin space with the expected spins would be stupendous …

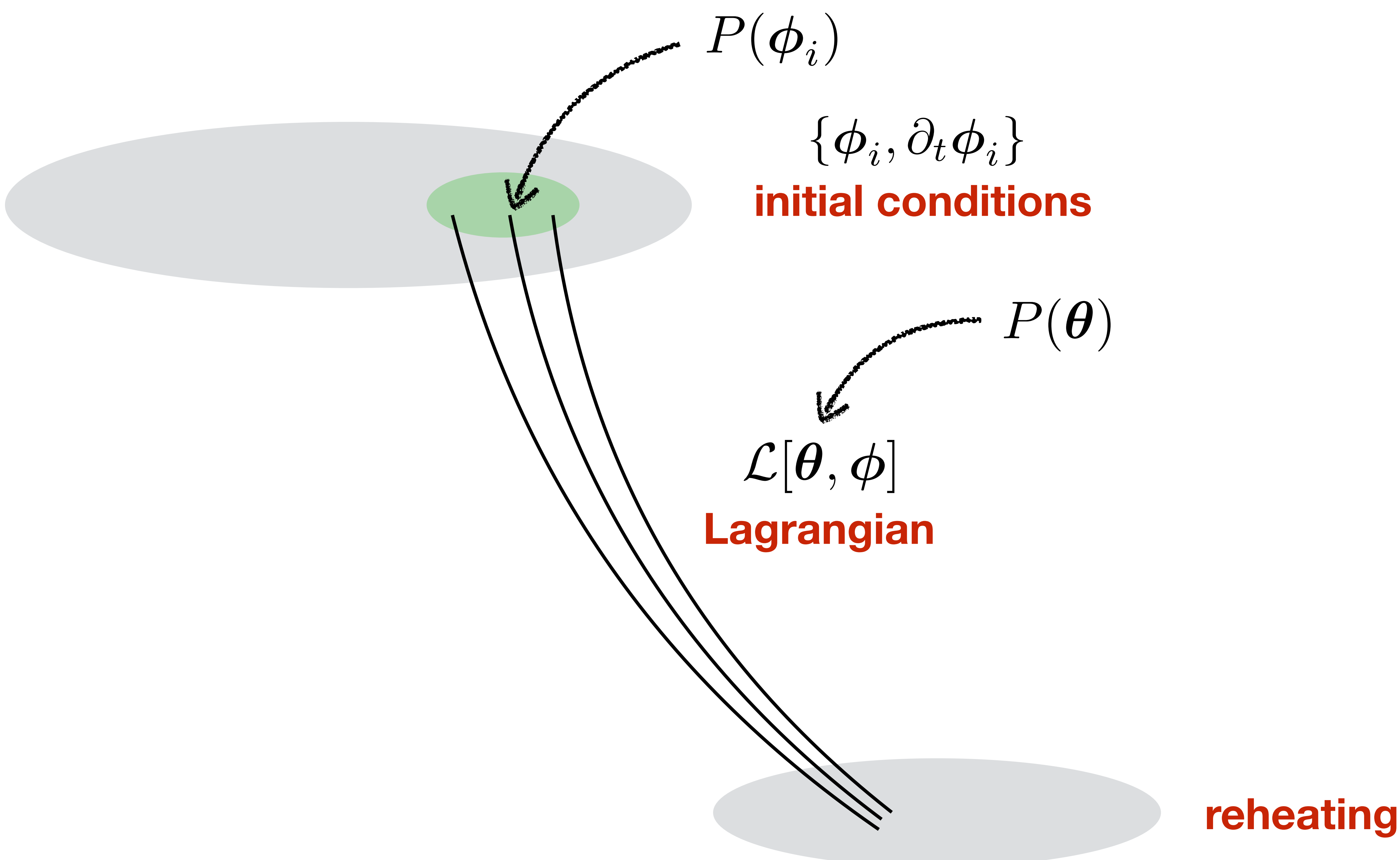

Vielen Dank für Ihre Aufmerksamkeit

4.

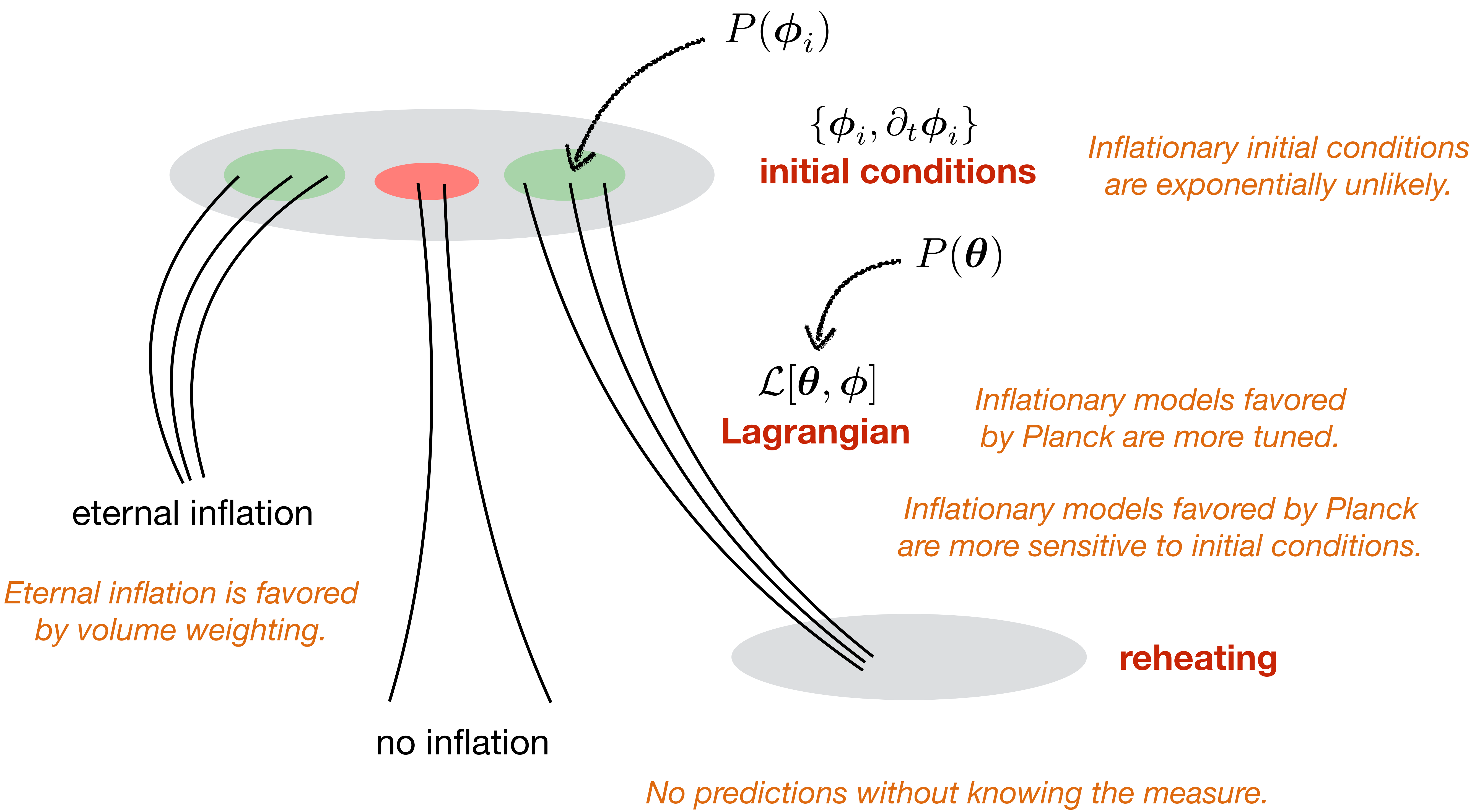
Conceptual Problems of Inflation

Ijjas, Steinhardt and Loeb VS Linde
Guth, Kaiser, and Nomura

Making Predictions in Inflationary Cosmology

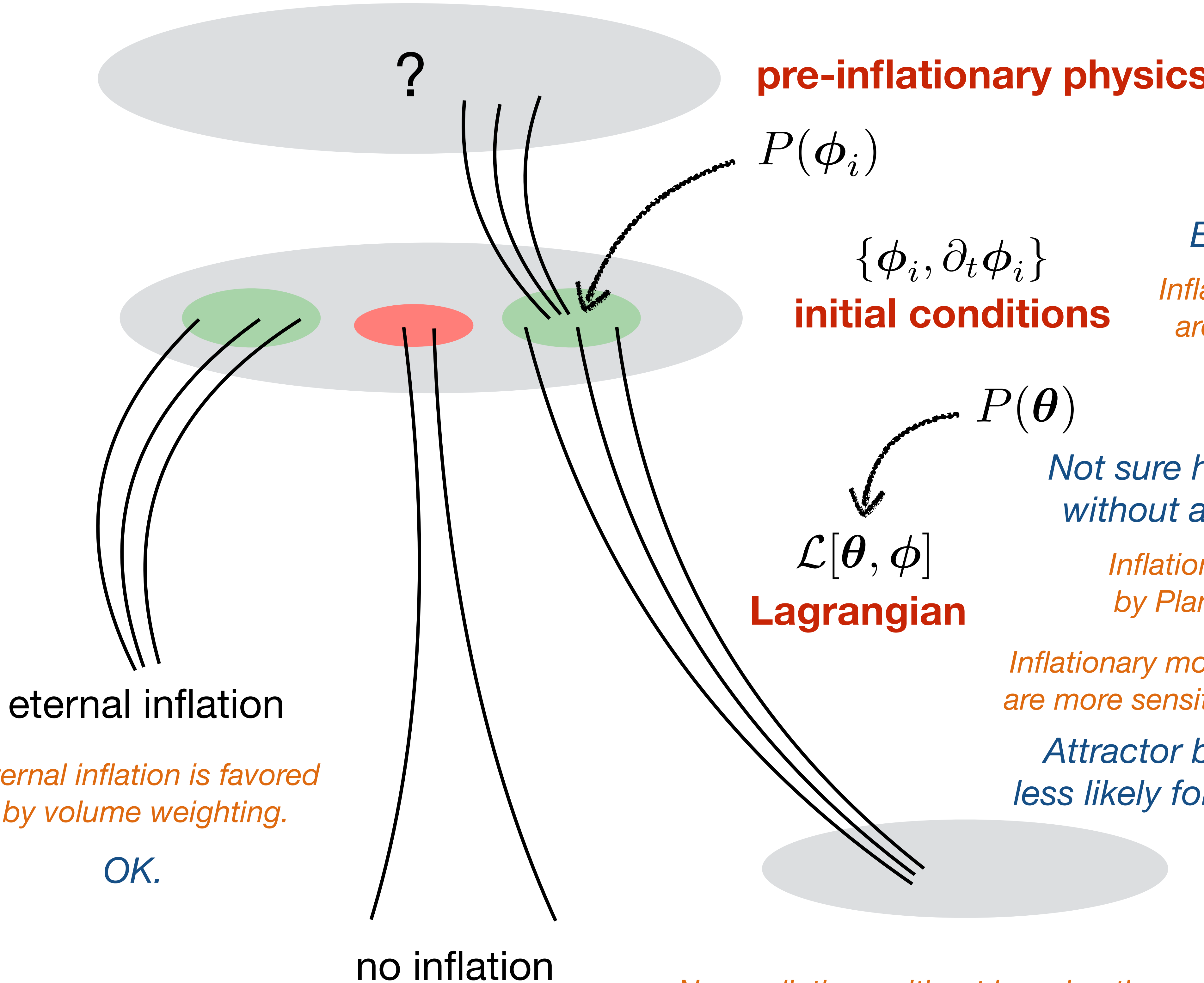


Critique of Steinhardt et al.



Discussion

Inflation is an incomplete theory.



Entropy measure?

Inflationary initial conditions are exponentially unlikely.

Not sure how to quantify tuning without a fundamental theory.

Inflationary models favored by Planck are more tuned.

Inflationary models favored by Planck are more sensitive to initial conditions.

Attractor behavior is indeed less likely for low-scale models.

Eternal inflation is favored by volume weighting.

OK.

No predictions without knowing the measure.

Why do we require anything other than relative (and conditional) probabilities?