Inflation after Planck

Will Kinney

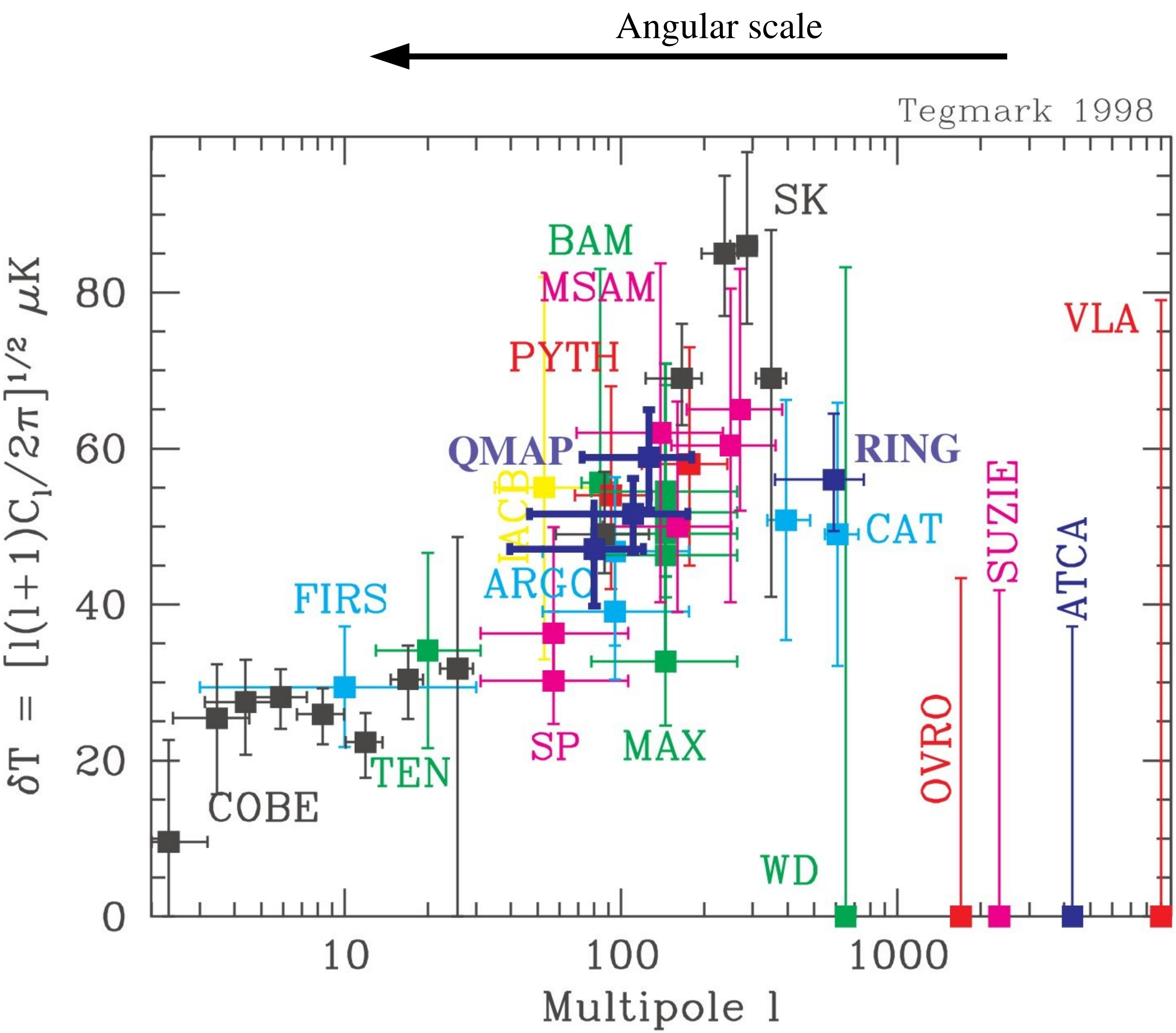
2015: The Spacetime Odyssey Continues

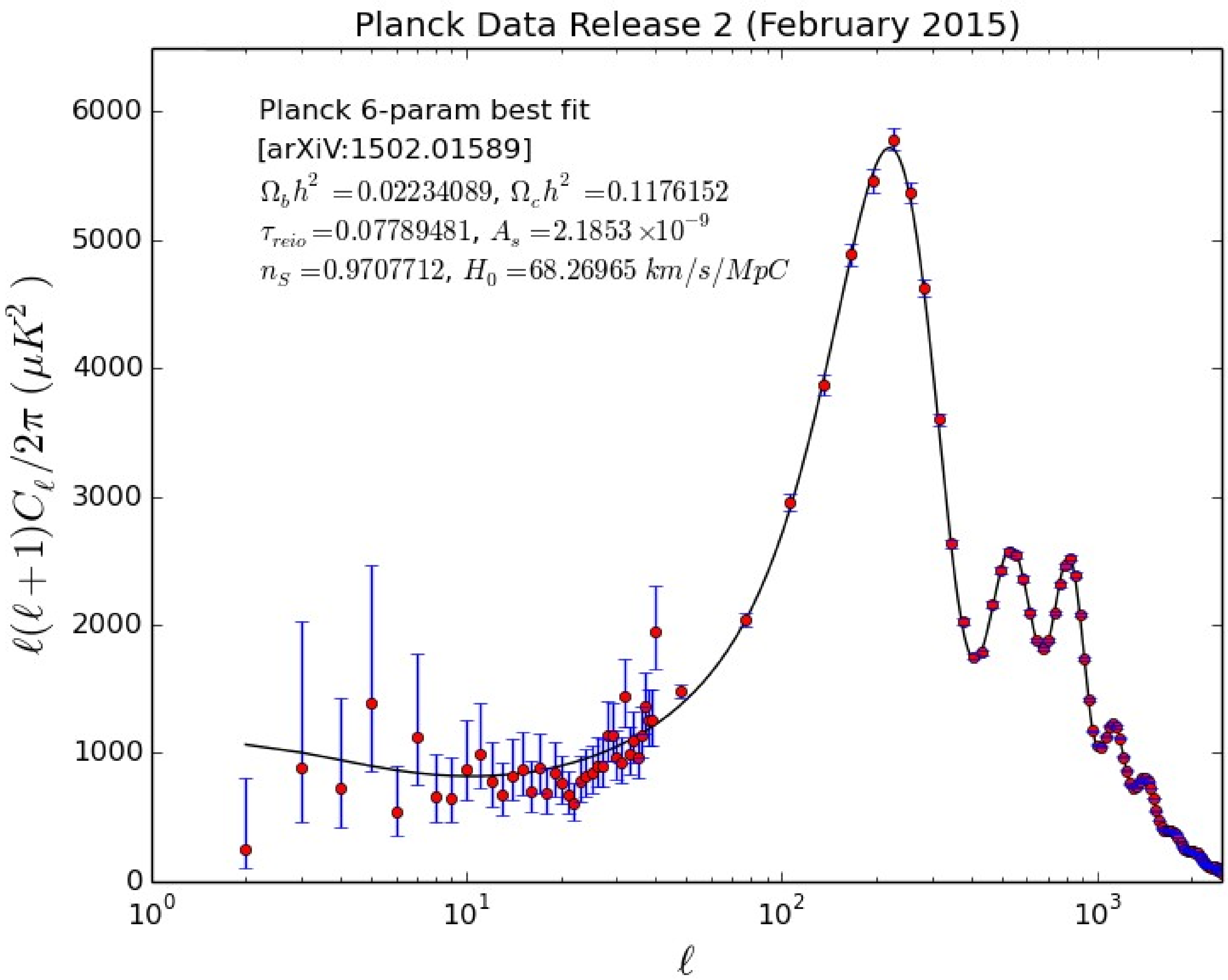
NORDITA, Stockholm, Sweden

2 June 2015

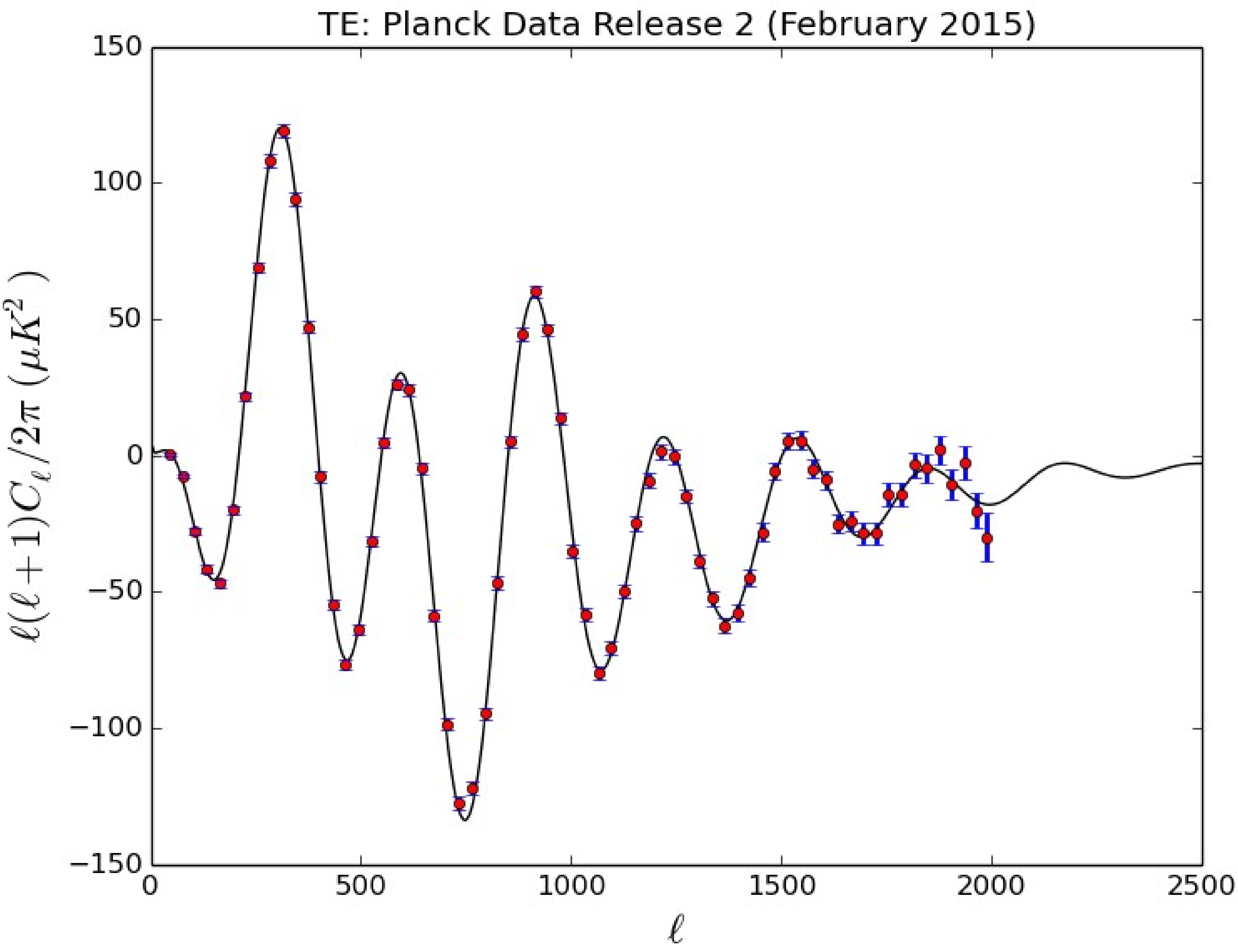
University at Buffalo *The State University of New York*

The CMB Angular Power Spectrum (1998)

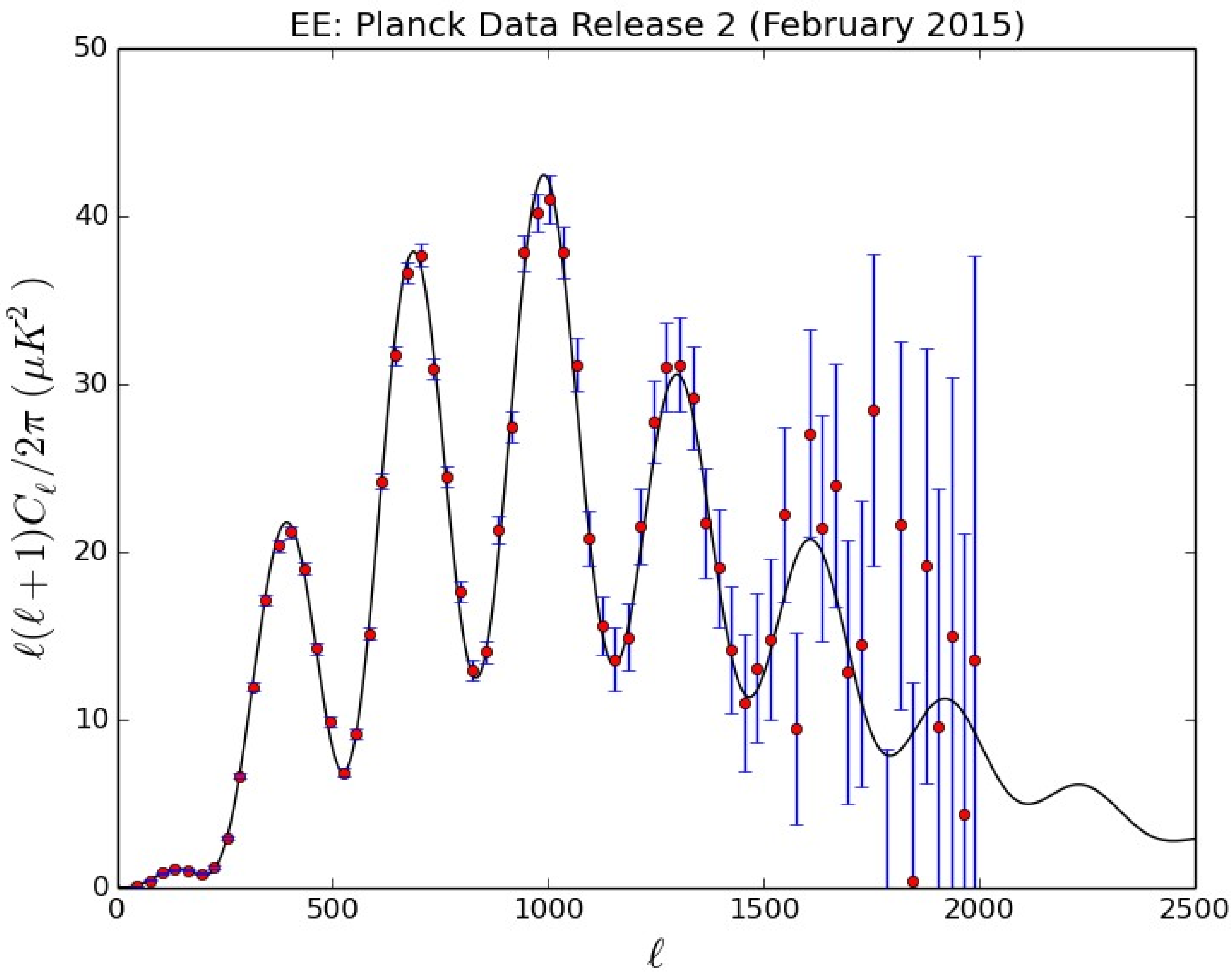




(Data: Planck Legacy Archive)



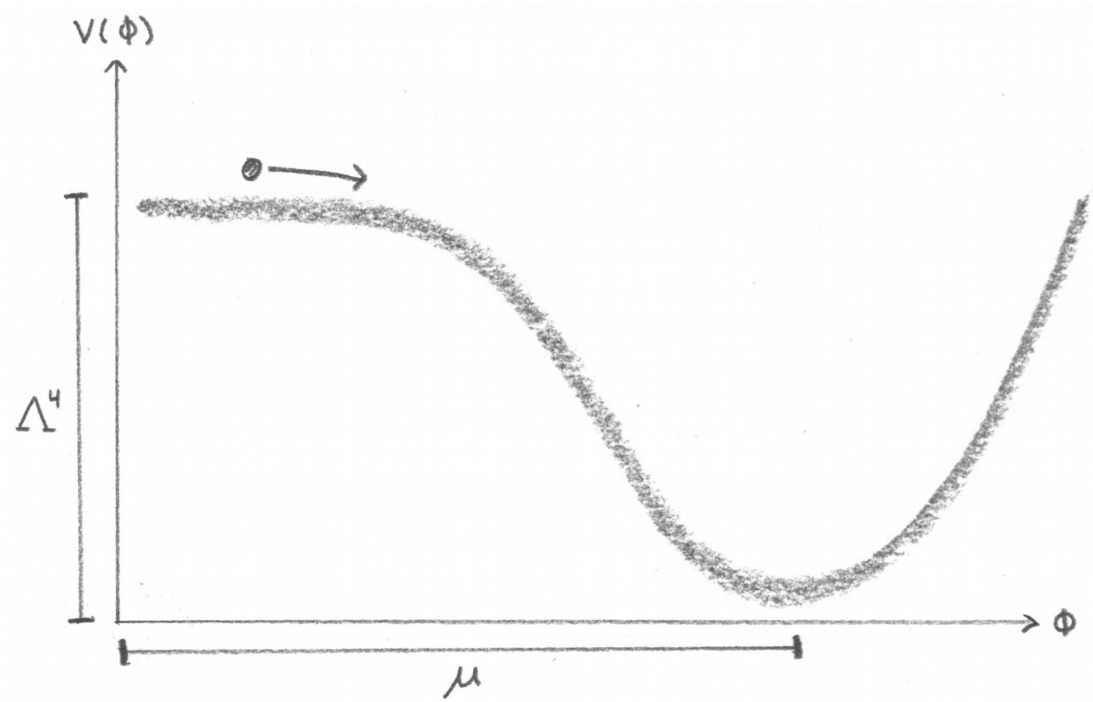
(Data: Planck Legacy Archive)



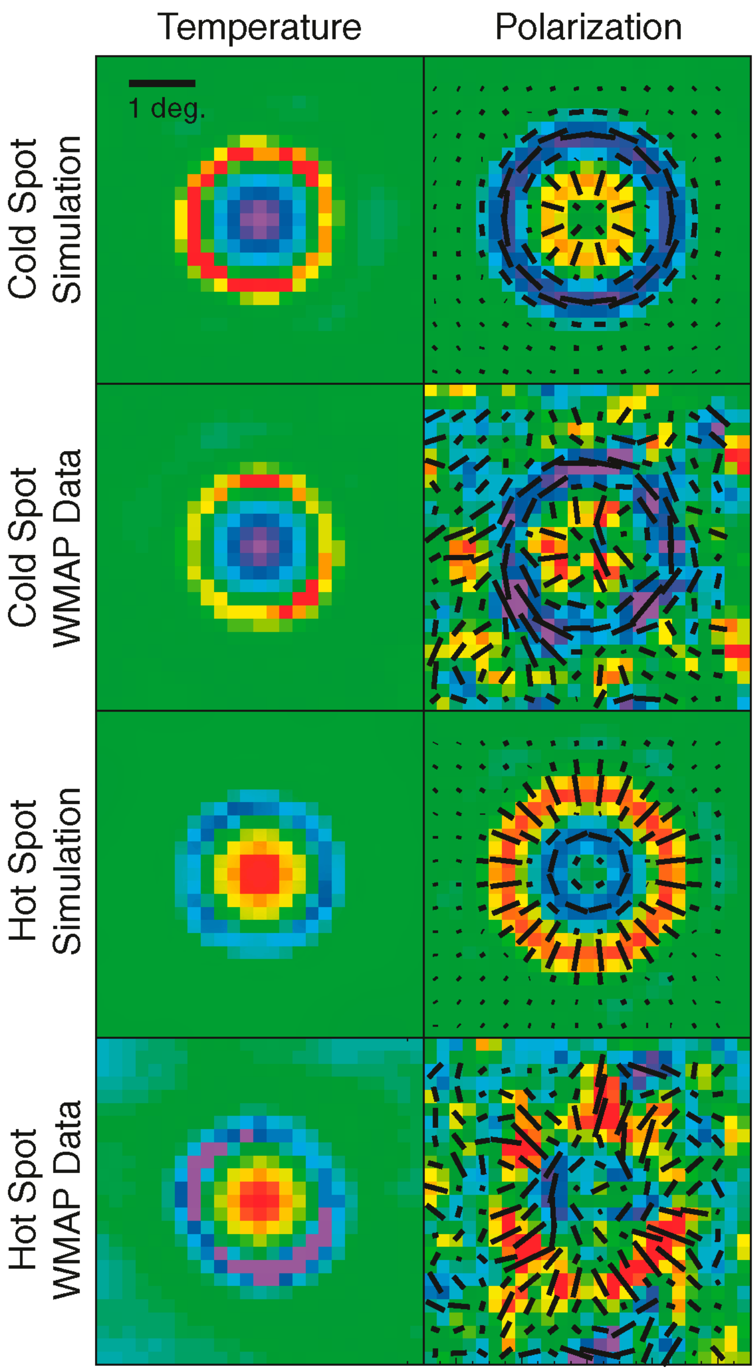
(Data: Planck Legacy Archive)

Inflation: Basic Predictions

- Adiabatic density perturbations
- Superhorizon correlations
- Gaussian statistics

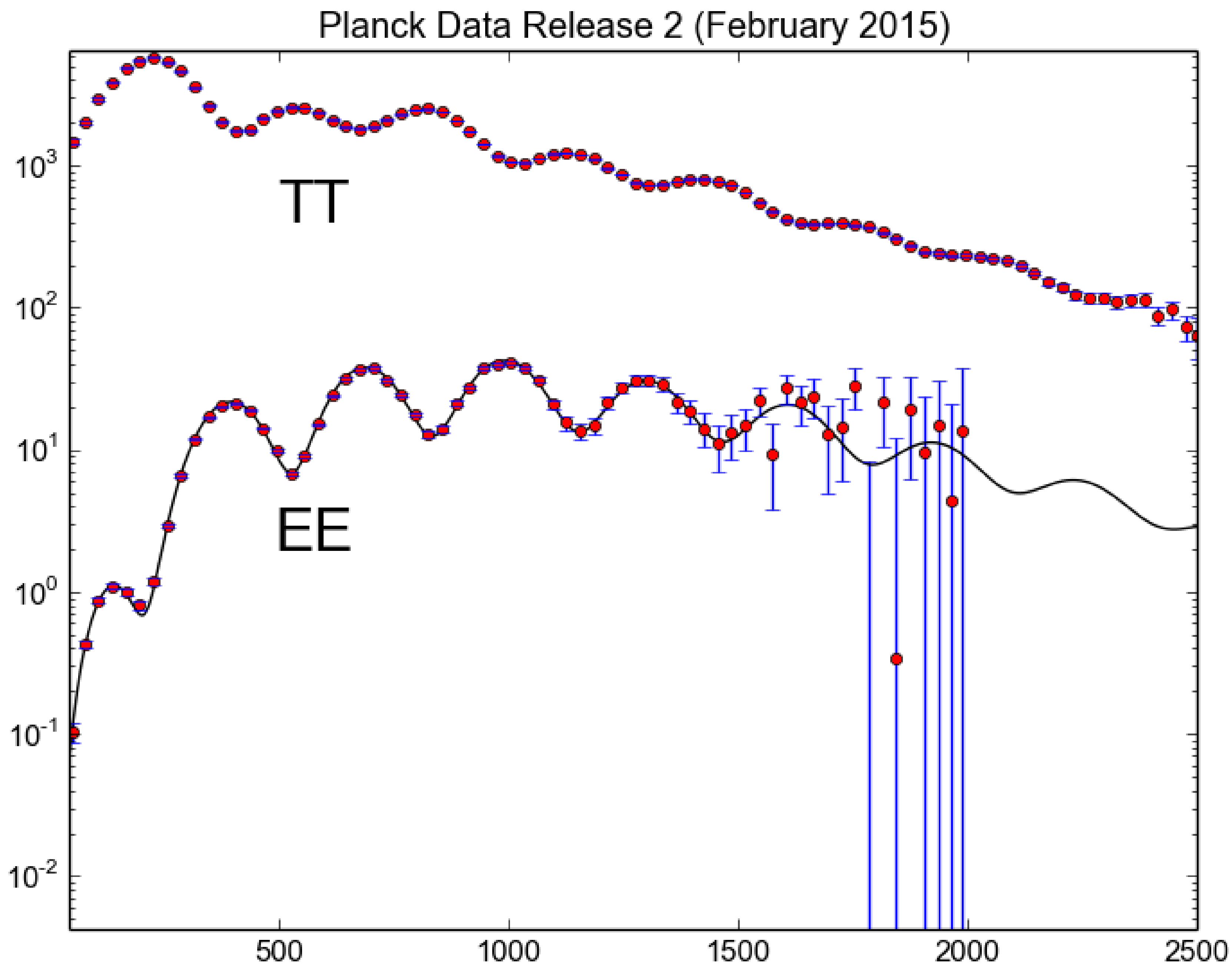


Polarization: Test of Adiabaticity

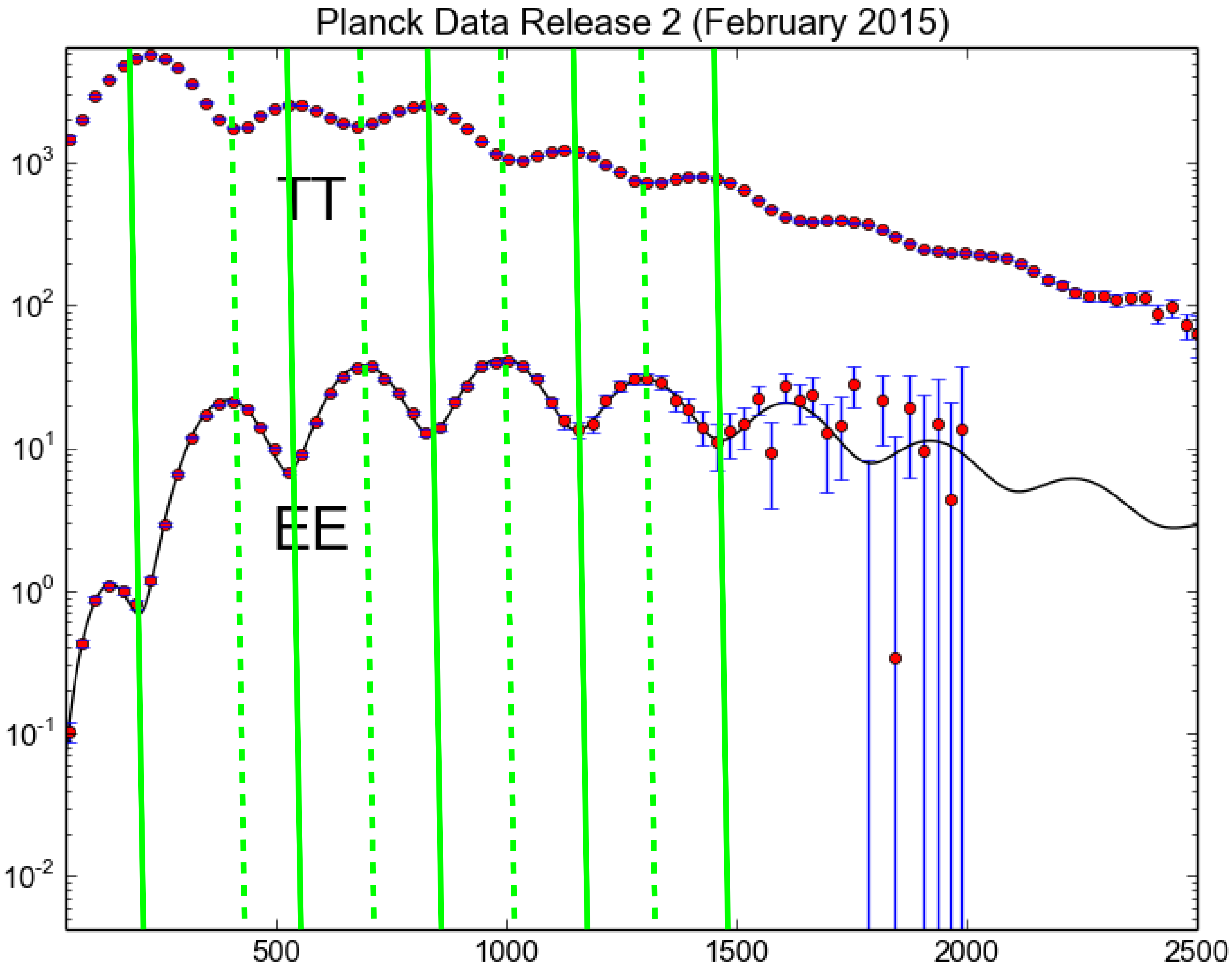


Polarization strongest along *gradients* in temperature

(Komatsu, *et al.*, arXiv:0912.0522)



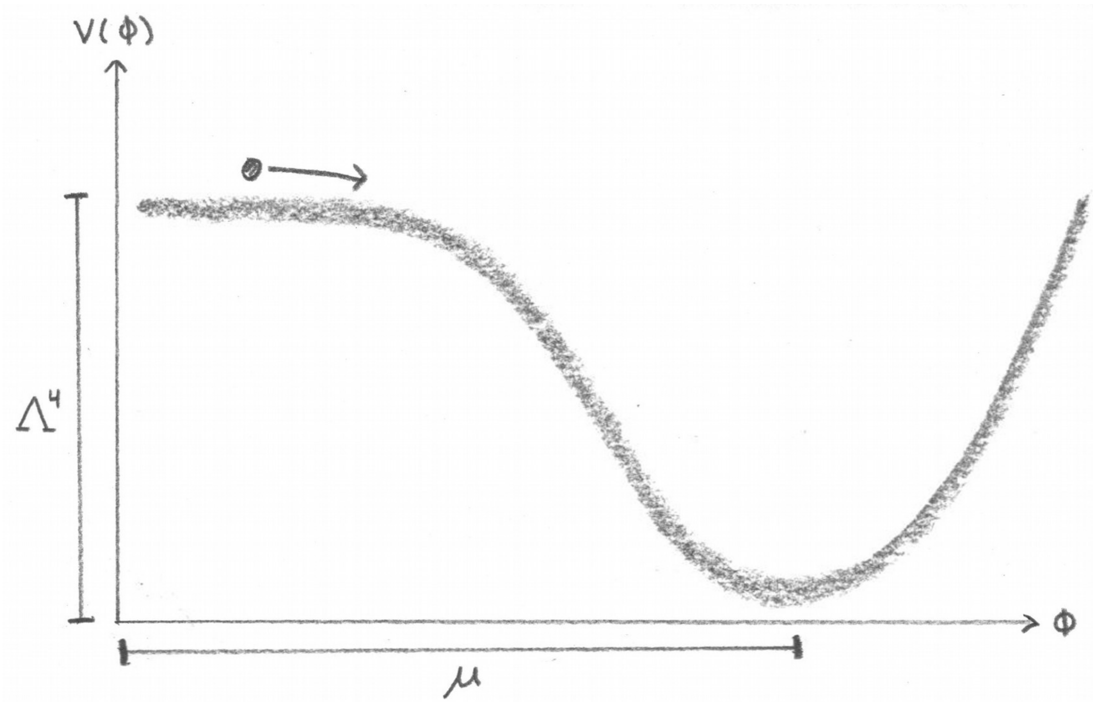
(Data: Planck Legacy Archive)



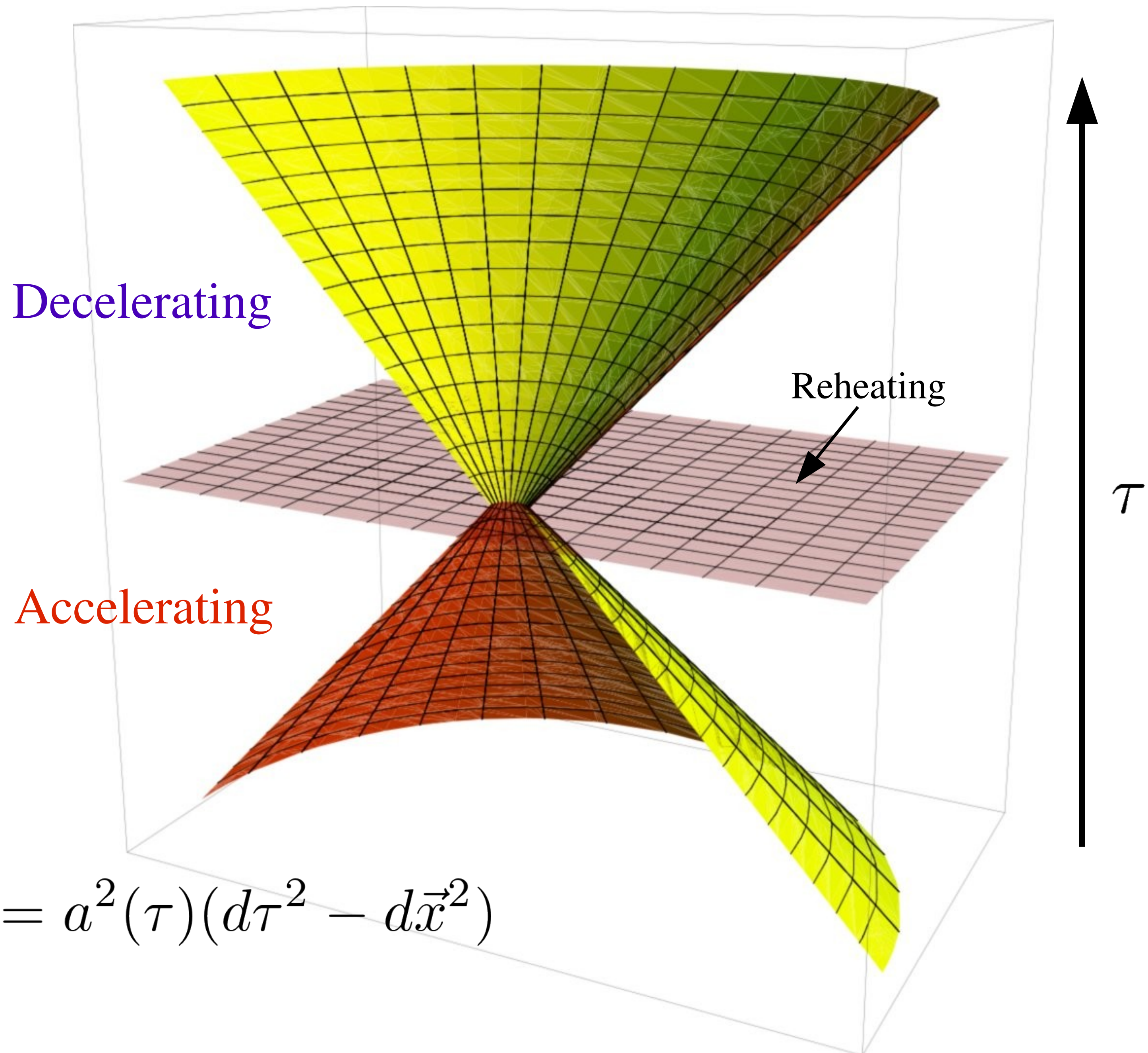
(Data: Planck Legacy Archive)

Inflation: Basic Predictions

- Adiabatic density perturbations ✓
- Superhorizon correlations
- Gaussian statistics

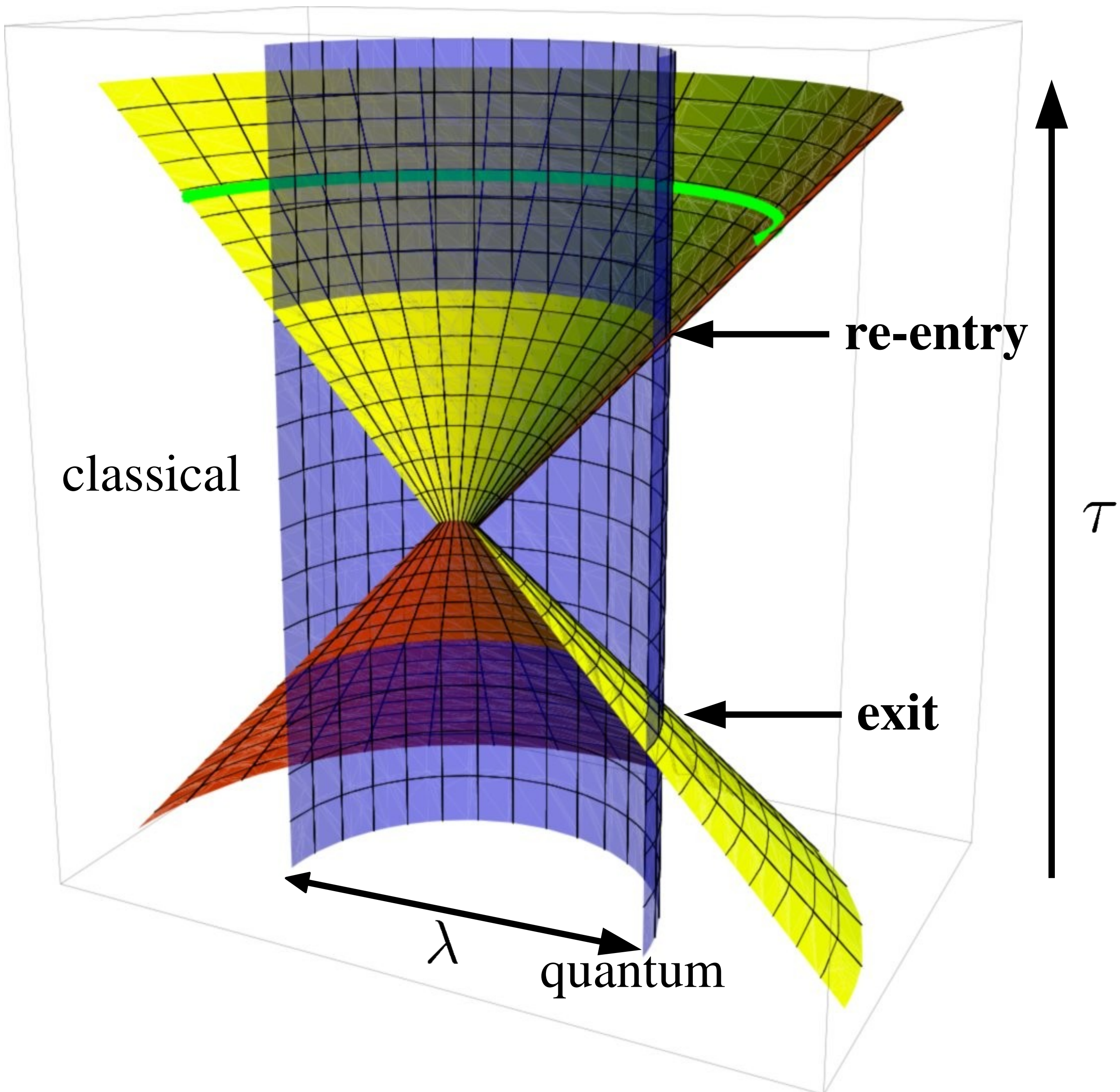


The Horizon in Inflation

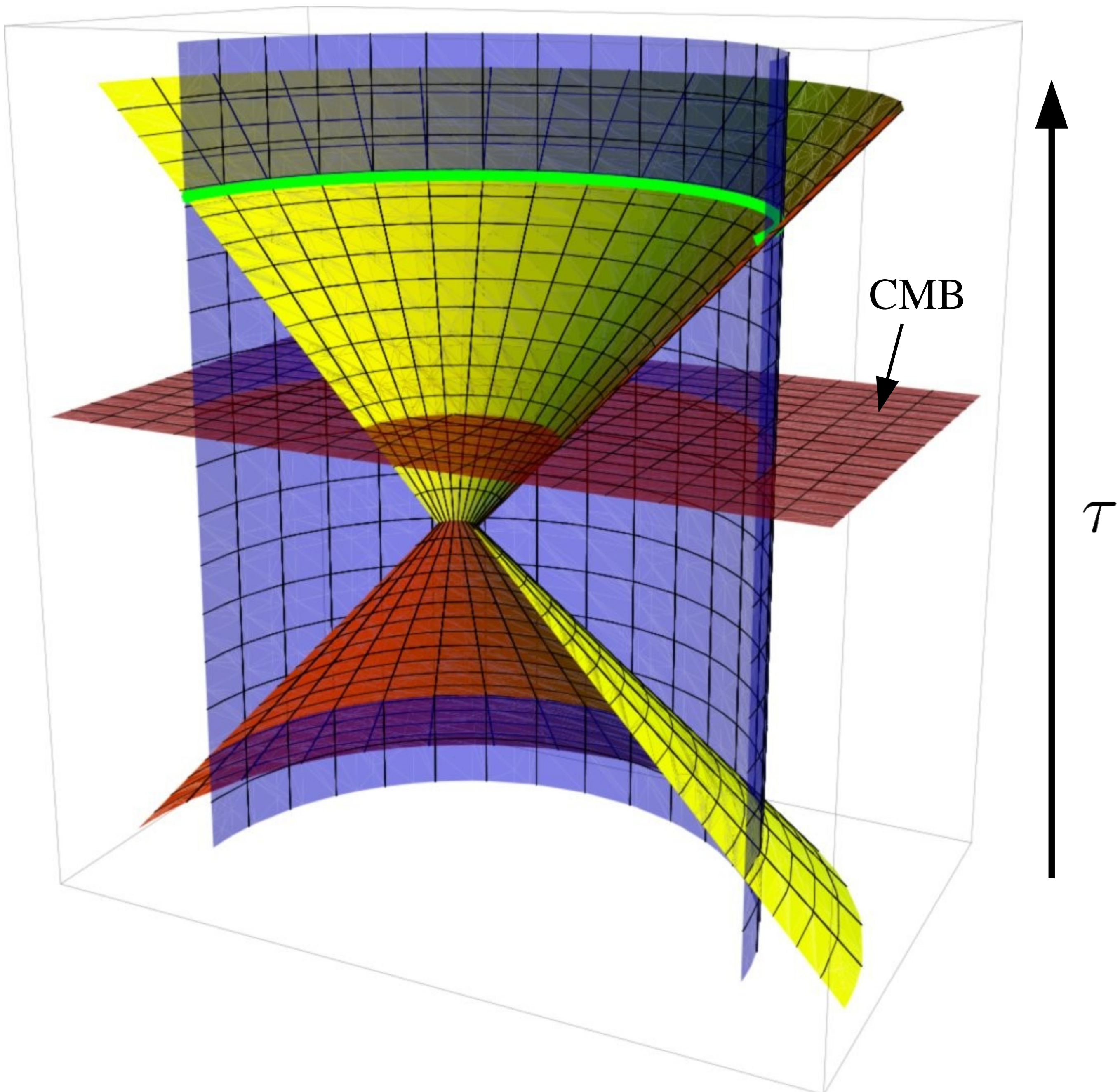


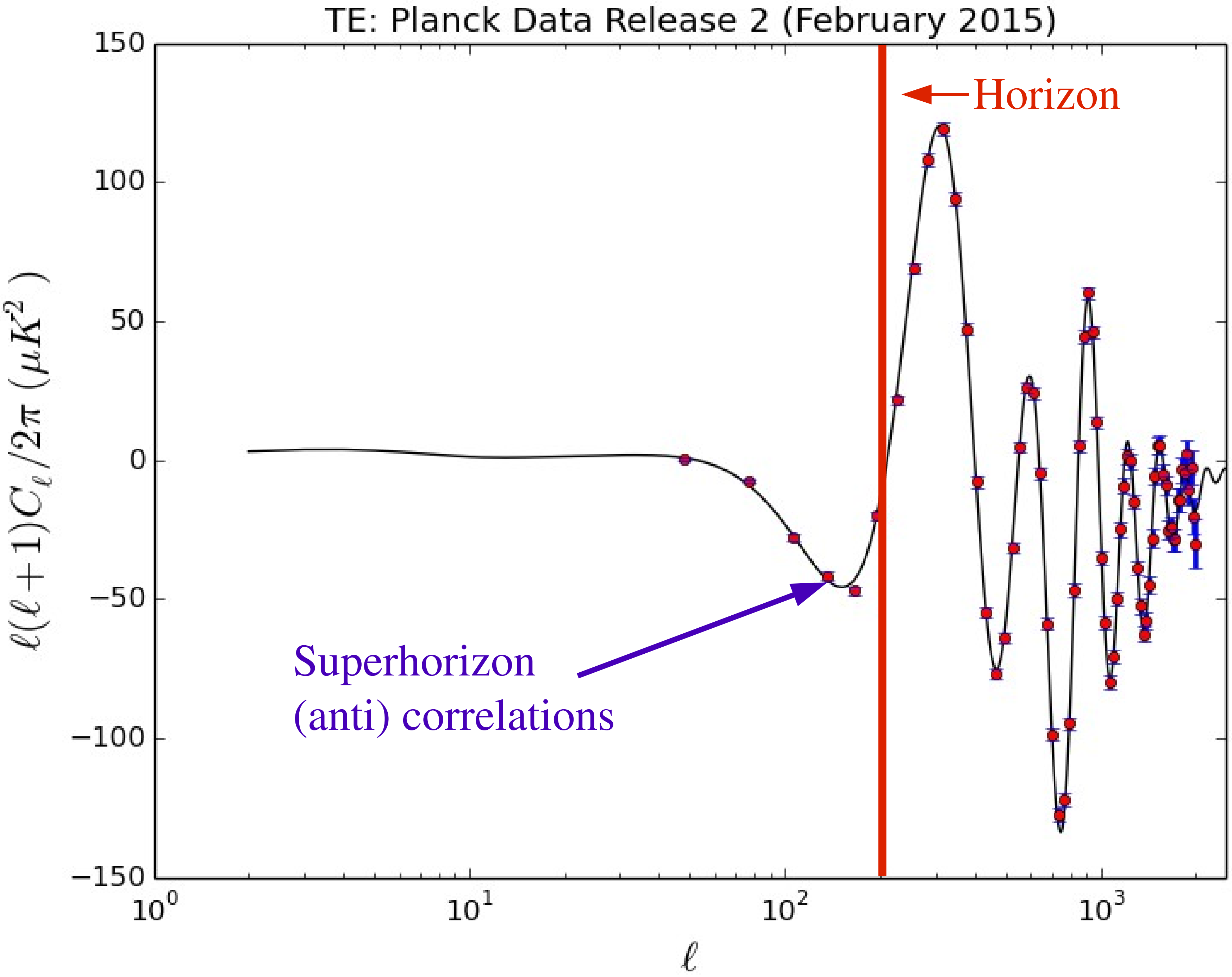
$$ds^2 = a^2(\tau)(d\tau^2 - d\vec{x}^2)$$

Mode Exit and Reentry



Superhorizon Perturbations

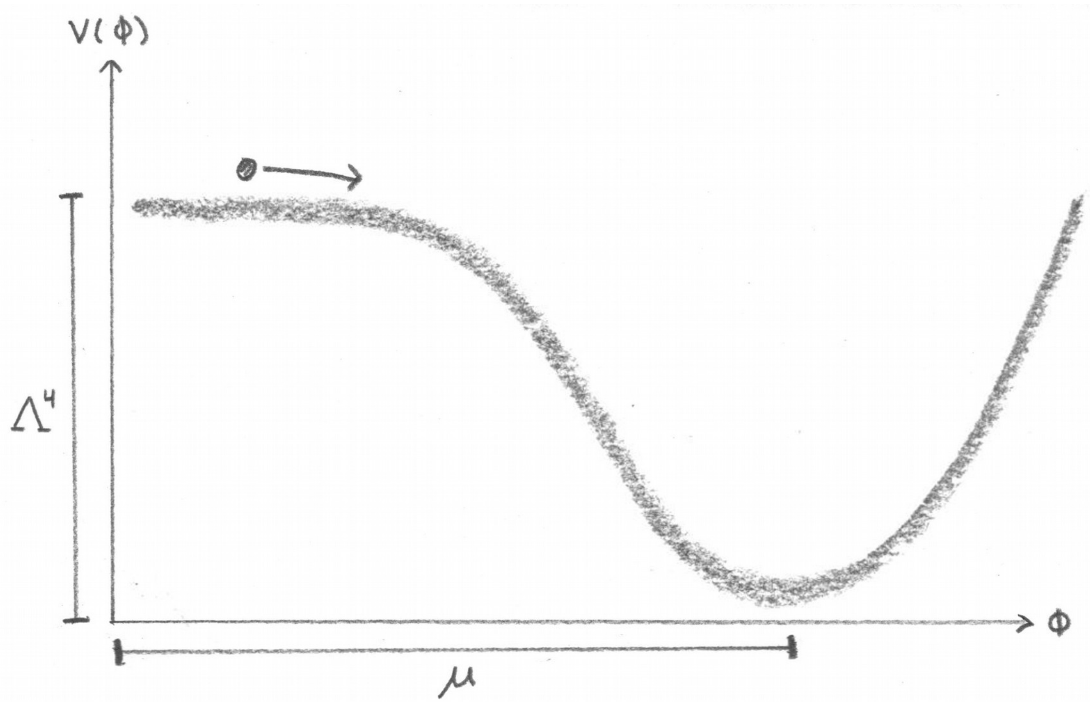




TE: Planck Data Release 2 (February 2015)
Horizon
Superhorizon
(anti) correlations
$\ell(\ell+1)C_\ell/2\pi\ (\mu K^2)$
ℓ
150
100
50
0
−50
−100
−150
10^0
10^1
10^2
10^3

Inflation: Basic Predictions

- Adiabatic density perturbations ✓
- Superhorizon correlations ✓
- Gaussian statistics



Non-Canonical Lagrangians

Lagrangian with arbitrary kinetic term:

$$\mathcal{L} = F\left(X, \phi\right) - V\left(\phi\right) \qquad X \equiv \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi$$

$$= \frac{1}{2} G^{\mu\nu}(X, \phi) \partial_\mu \phi \partial_\nu \phi - V\left(\phi\right)$$

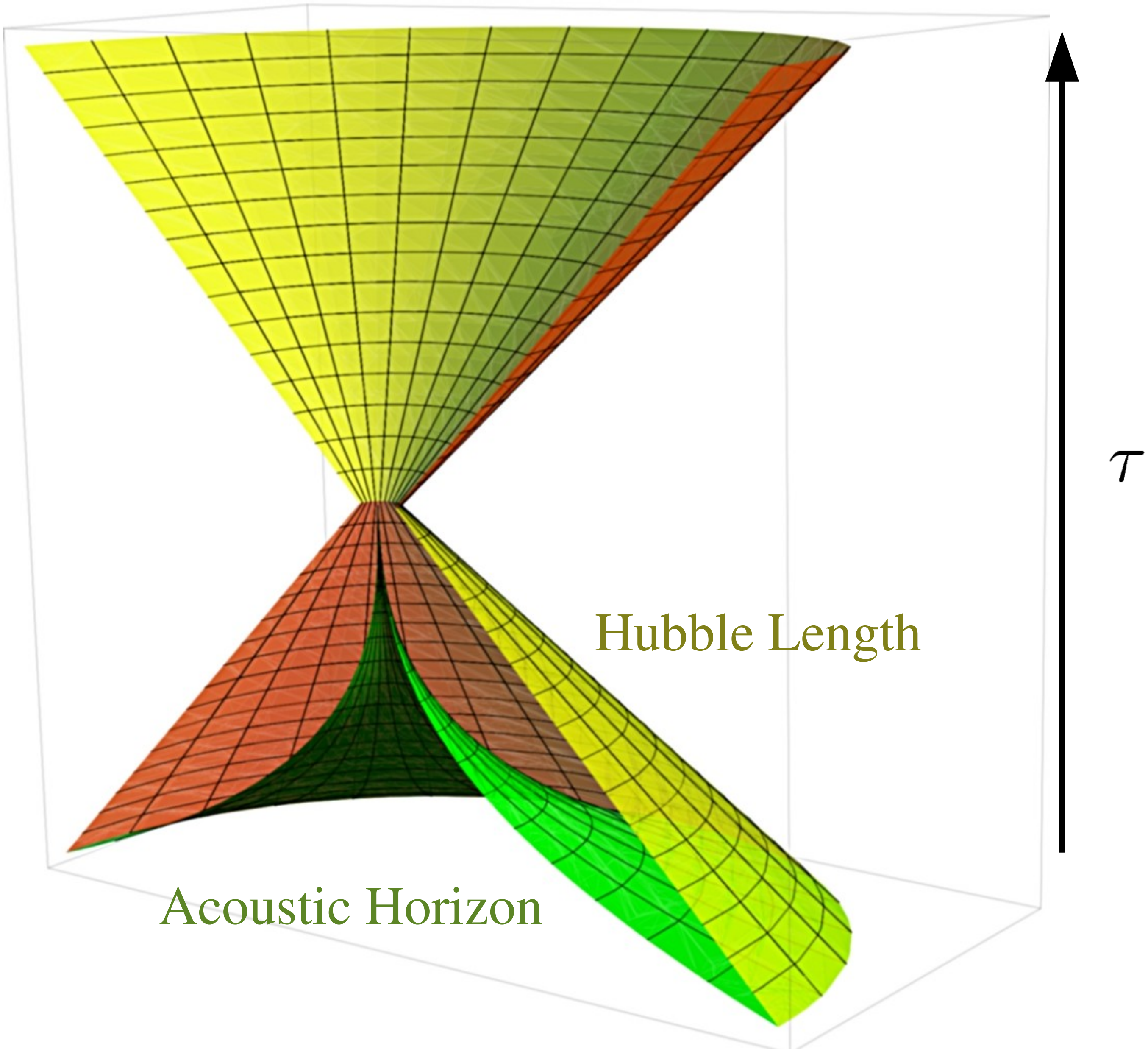
Acoustic metric

Light cone: $g^{\mu\nu} dx^\mu dx^\nu = 0$

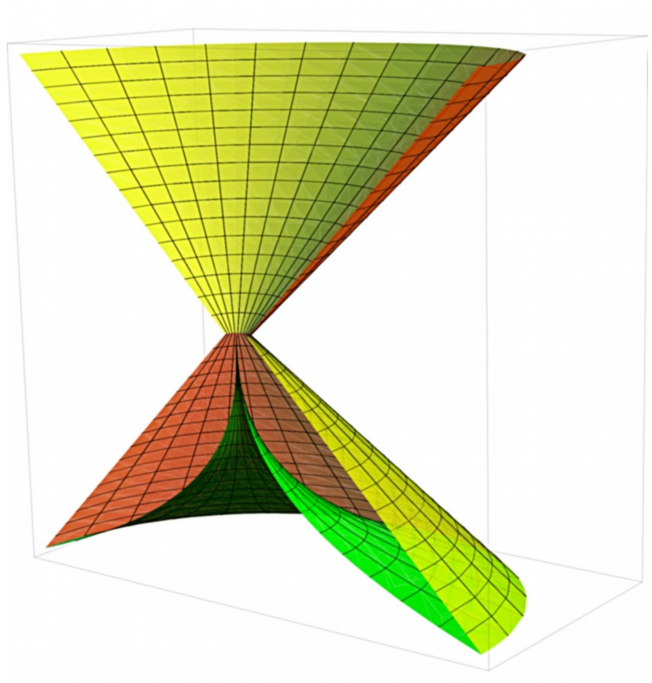
Acoustic cone: $G^{\mu\nu} dx^\mu dx^\nu = 0$

Two “light cones”!

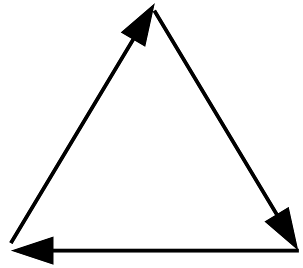
Inflation from non-Canonical Lagrangians



Inflation from non-Canonical Lagrangians

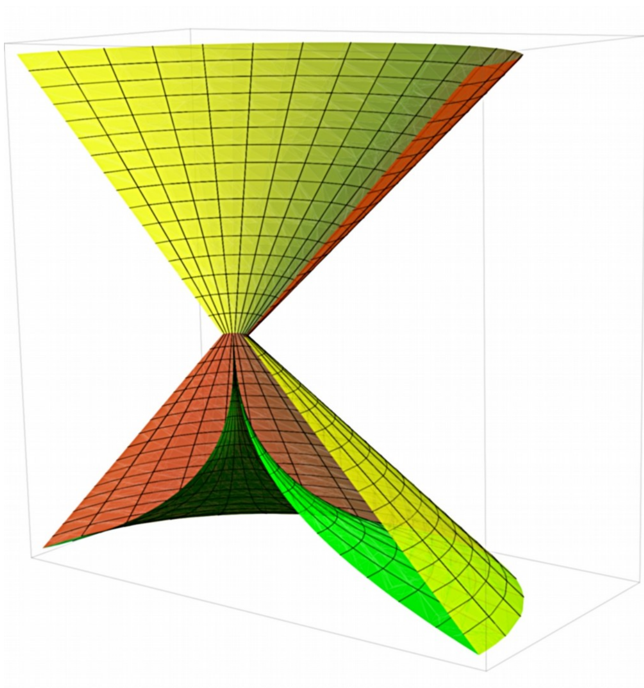


Signature: equilateral bispectrum

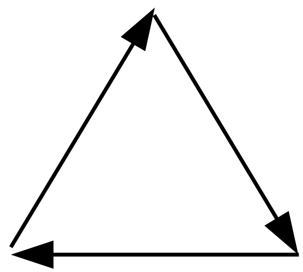


$$f_{\rm NL} \sim c_S^{-2}$$

Inflation from non-Canonical Lagrangians



Signature: equilateral bispectrum



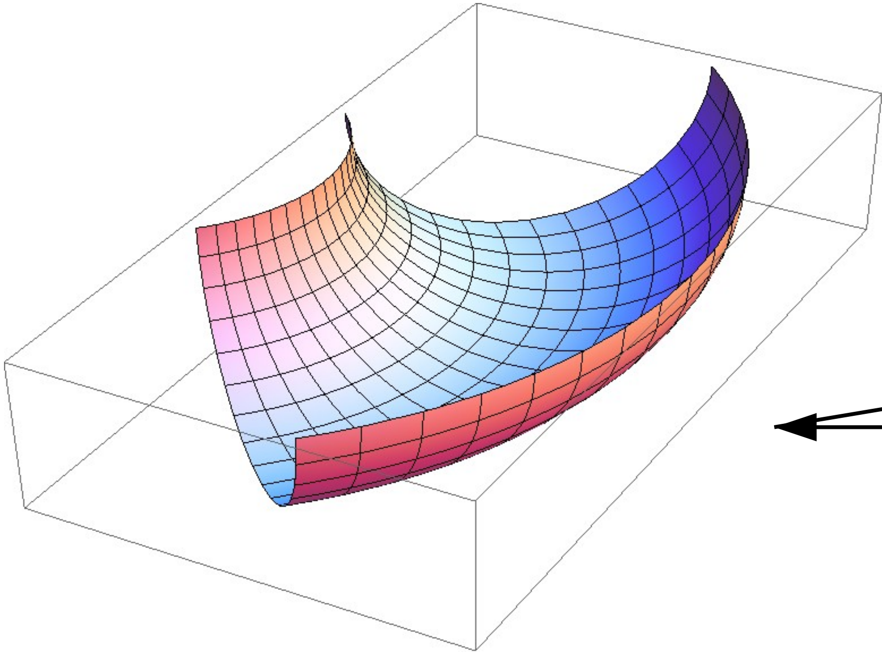
$f_{\rm NL} \sim c_S^{-2}$

Planck: $f_{NL}^{\rm equil} = 16 \pm 70$

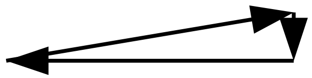
No evidence for non-canonical inflation

(Planck Collaboration arXiv:1502.01592)

Multi-Field Inflation

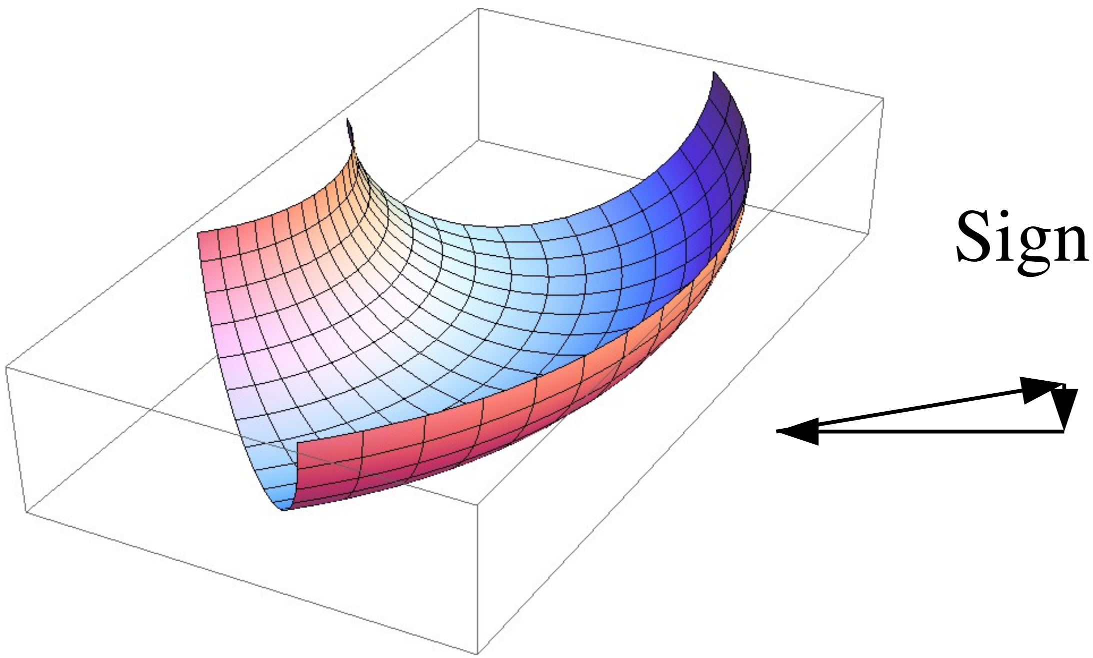


Signature: local bispectrum



$$f_{\rm NL}^{\rm local} = \frac{\delta^2 N}{\delta\phi_i \delta\phi_j} \delta\phi_i \delta\phi_j$$

Multi-Field Inflation



Signature: local bispectrum

$$f_{\rm NL}^{\rm local} = \frac{\delta^2 N}{\delta\phi_i \delta\phi_j} \delta\phi_i \delta\phi_j$$

Planck: $f_{NL}^{\rm local} = 2.5 \pm 5.7$

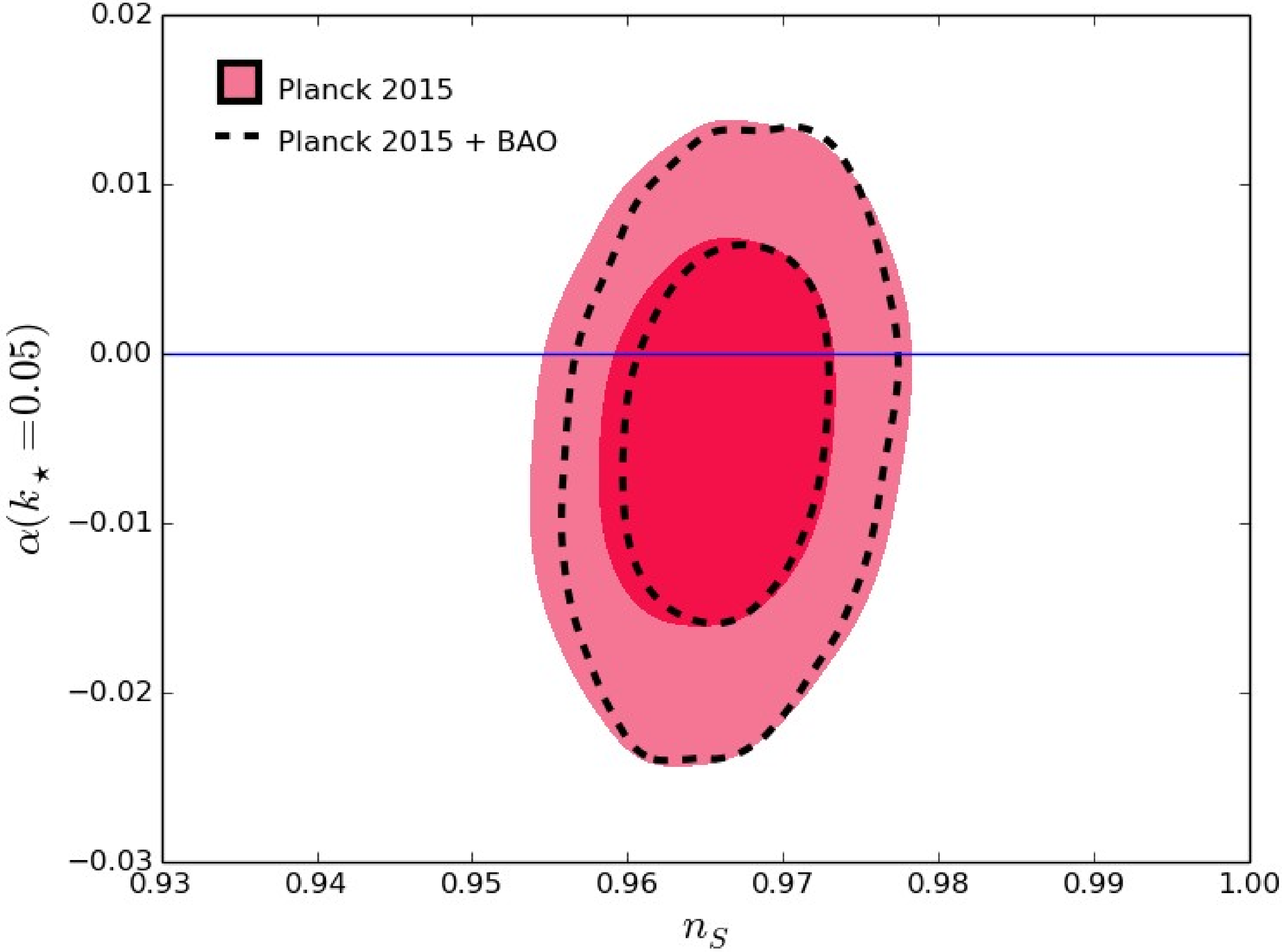
No evidence for multi-field inflation

(Planck Collaboration arXiv:1502.01592)

Inflation: Basic Predictions

- Adiabatic density perturbations ✓
- Superhorizon correlations ✓
- Gaussian statistics ✓

No Evidence of Running Spectral Index



(Data: Planck Legacy Archive)

Inflation: Basic Predictions

- Adiabatic density perturbations ✓
- Superhorizon correlations ✓
- Gaussian statistics ✓

$$\mathcal{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi)$$

Fully consistent with data.

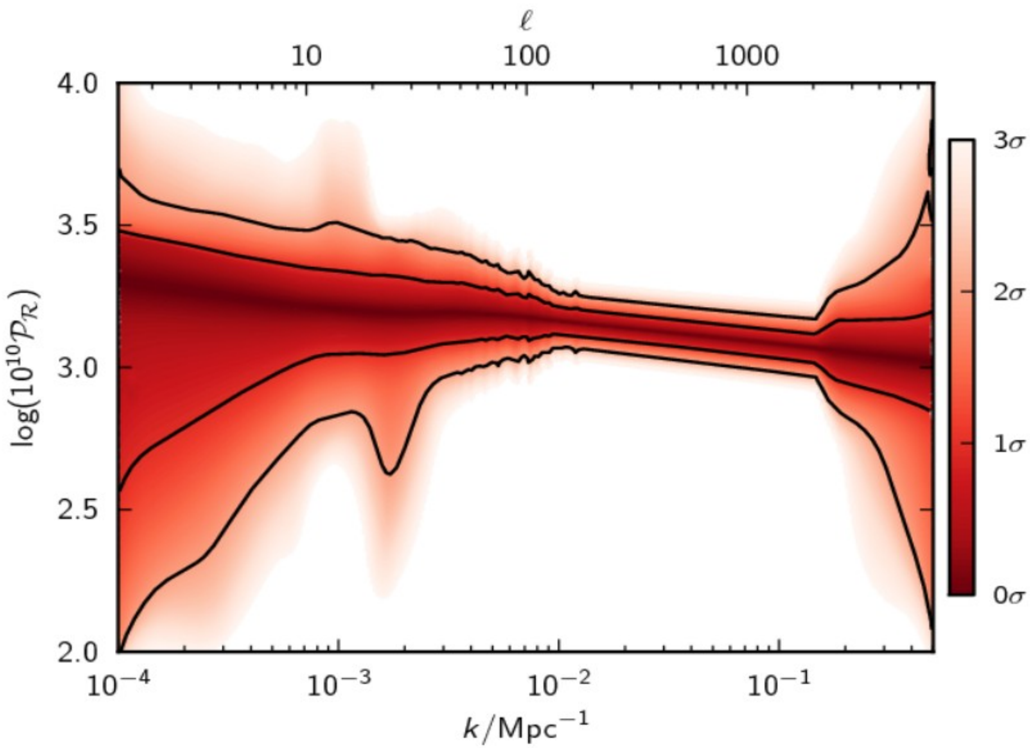
Inflation: Basic Predictions

- Adiabatic density perturbations ✓
- Superhorizon correlations ✓
- Gaussian statistics ✓

Is It

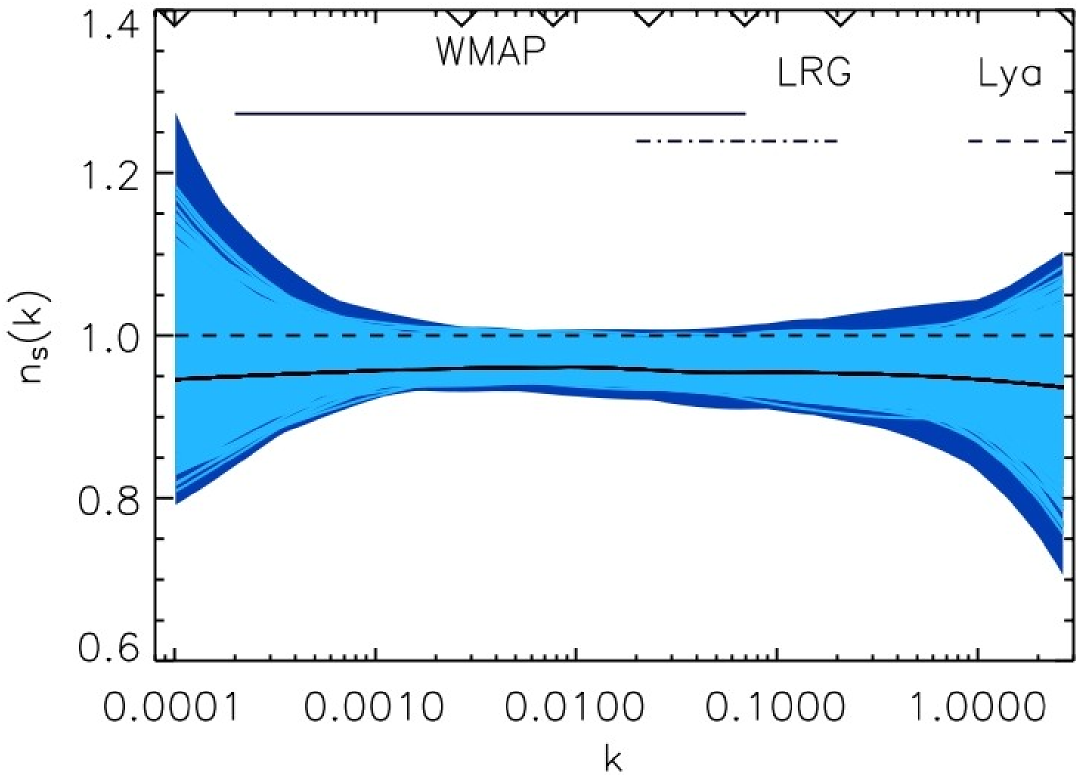
Inflation?

What We Know



Planck 2015: Ade, *et al.*, arXiv:1502:02114

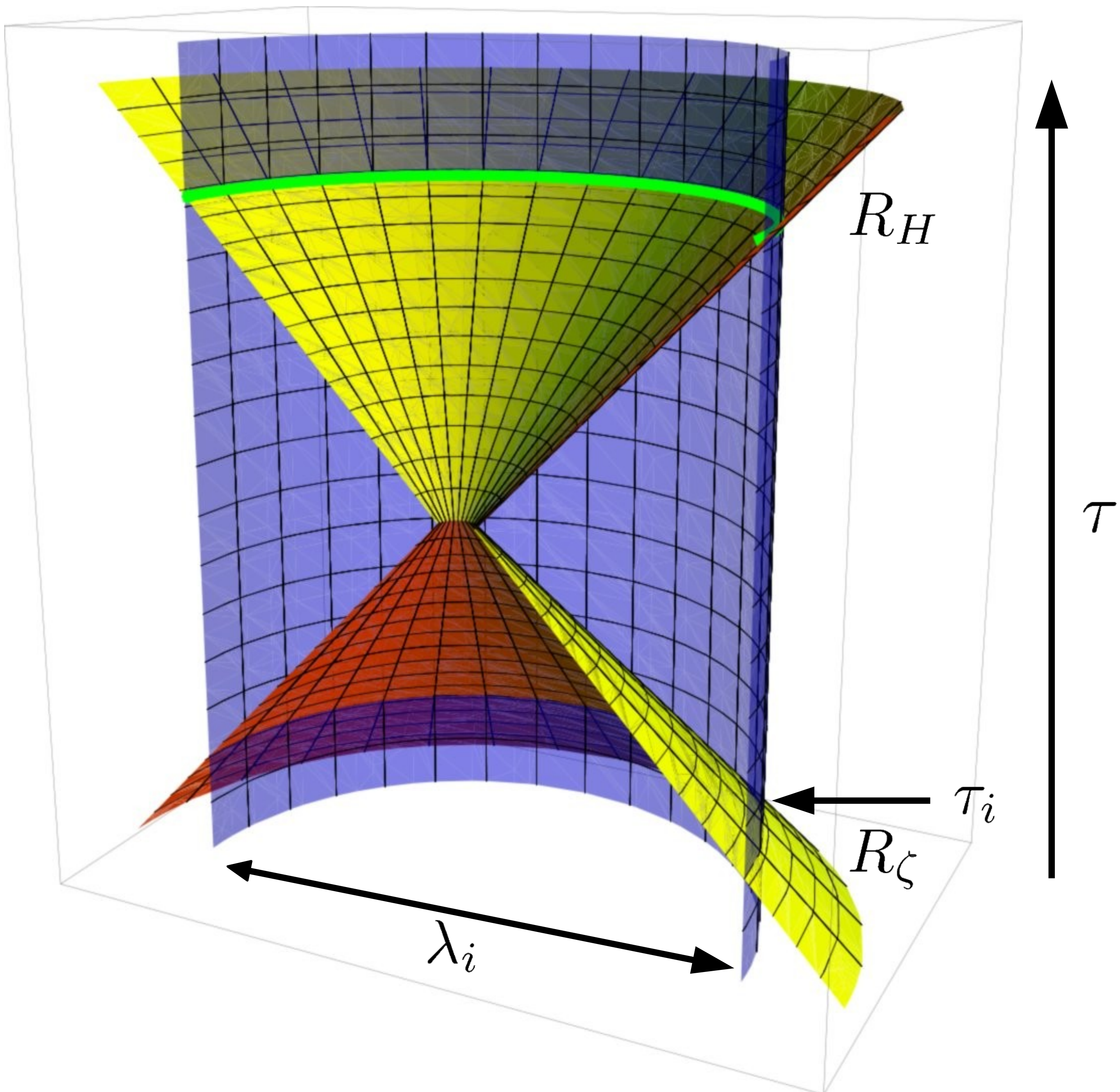
What We Know

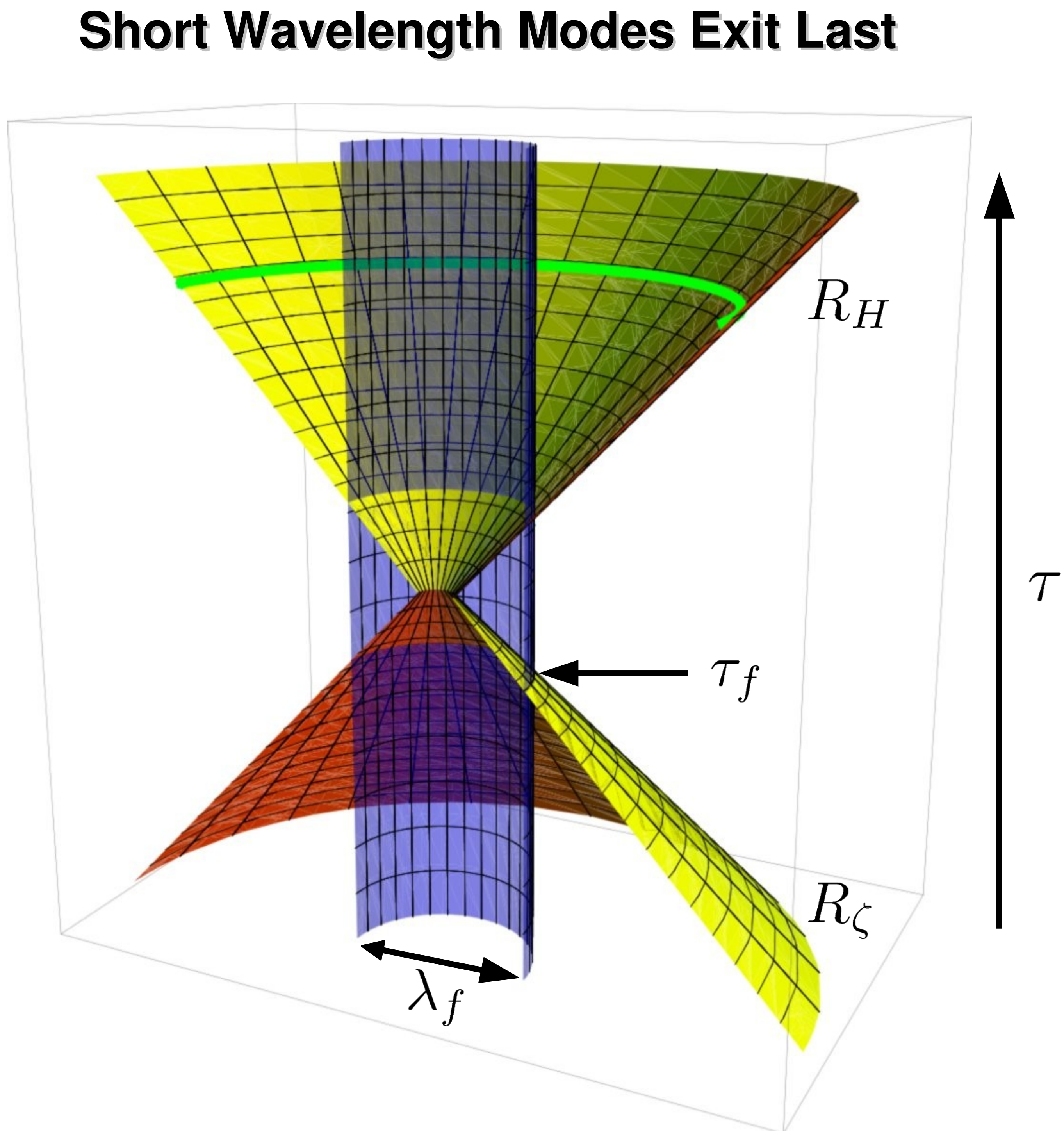


Peiris & Verde, arXiv:0912.0268

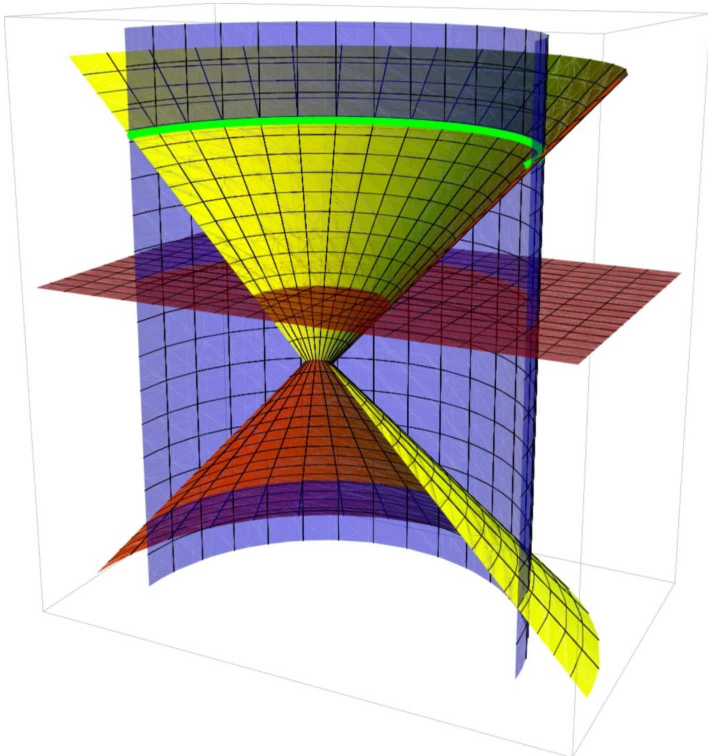
Power spectrum is approximately scale-invariant over *at least* a factor of 1000 in wavelength.

Long Wavelength Modes Exit First




Short Wavelength Modes Exit Last
R_H
τ
τ_f
R_ζ
λ_f

The "Horizon" is *Not the Hubble Length*

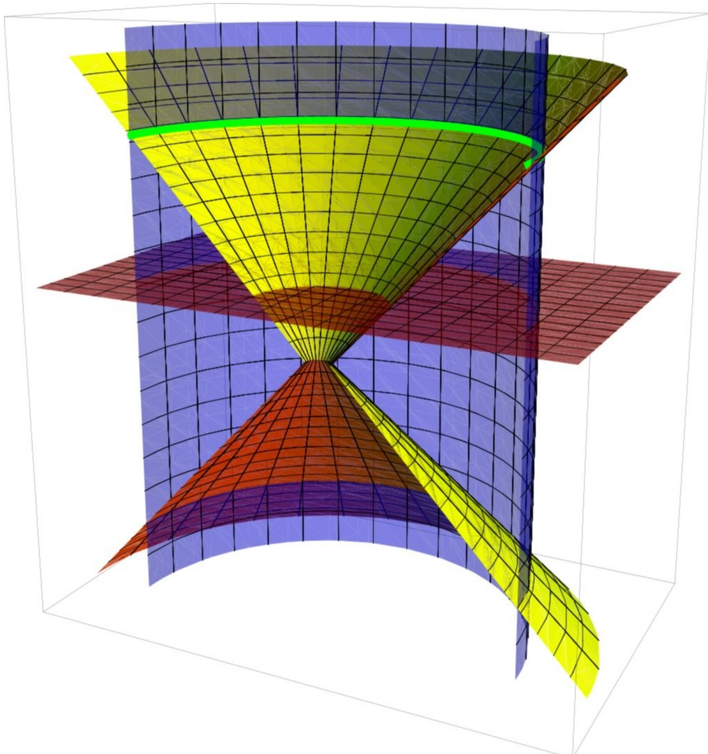


$$R_H = \frac{1}{aH} = \frac{a}{a'}$$

$$v_k'' + \left[c_S^2 k^2 + \frac{1}{R^2(\tau)}\right] v_k = 0$$

(Khoury & Miller, arXiv:1012.0846)

The “Horizon” is *Not the Hubble Length*



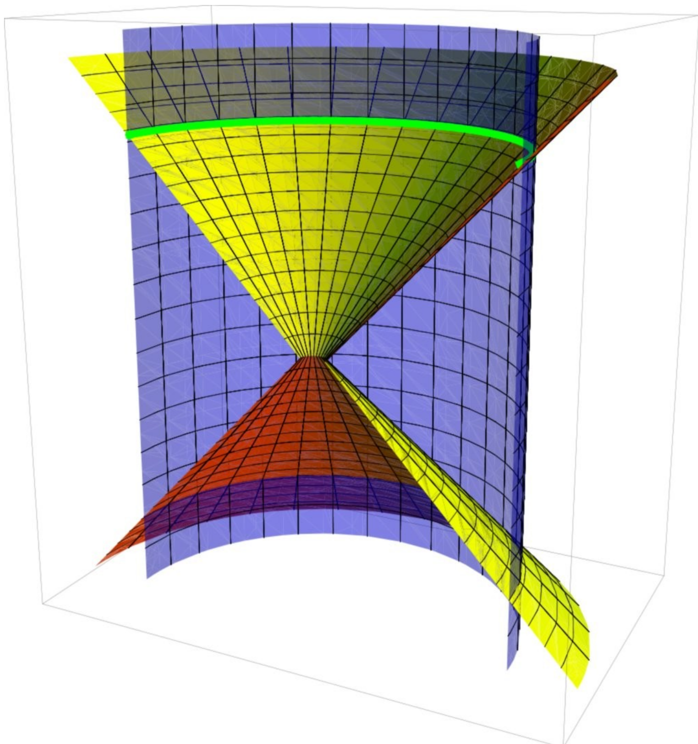
$$R_H = \frac{1}{aH} = \frac{a}{a'}$$

Scalars: $R_\zeta = \sqrt{\frac{a\sqrt{\epsilon}/c_S}{\left(a\sqrt{\epsilon}/c_S\right)''}}$

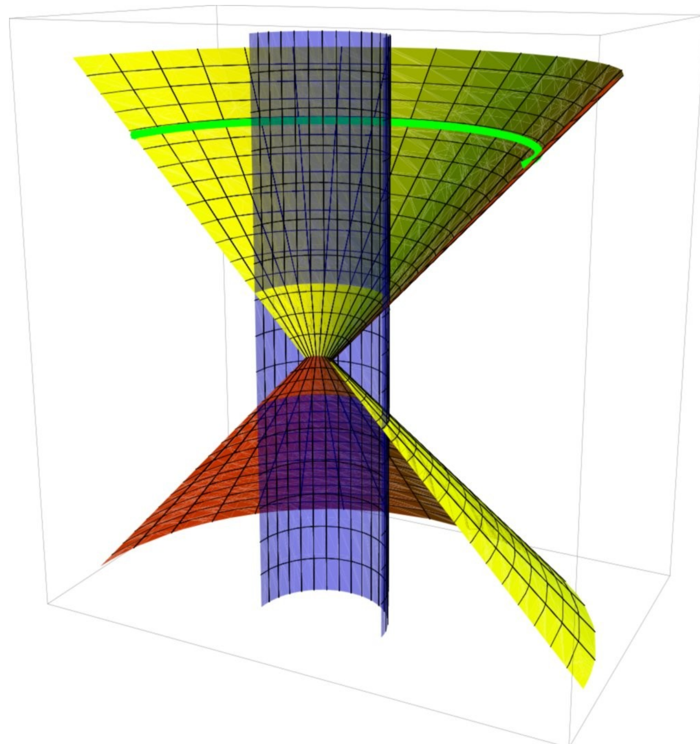
$$v_k'' + \left[c_S^2 k^2 + \frac{1}{R^2(\tau)}\right] v_k = 0$$

(Khoury & Miller, arXiv:1012.0846)

Scale Invariance and Conformal Time



$$\lambda_i \geq 1000\lambda_f$$



$$\frac{\bar{c}_S\,(\tau_f - \tau_i)}{R_H(\tau_f)} > 1000$$

Generating Superhorizon Perturbations

To generate scalar perturbations consistent with scale invariance, must have one of:

(1) Accelerated Expansion

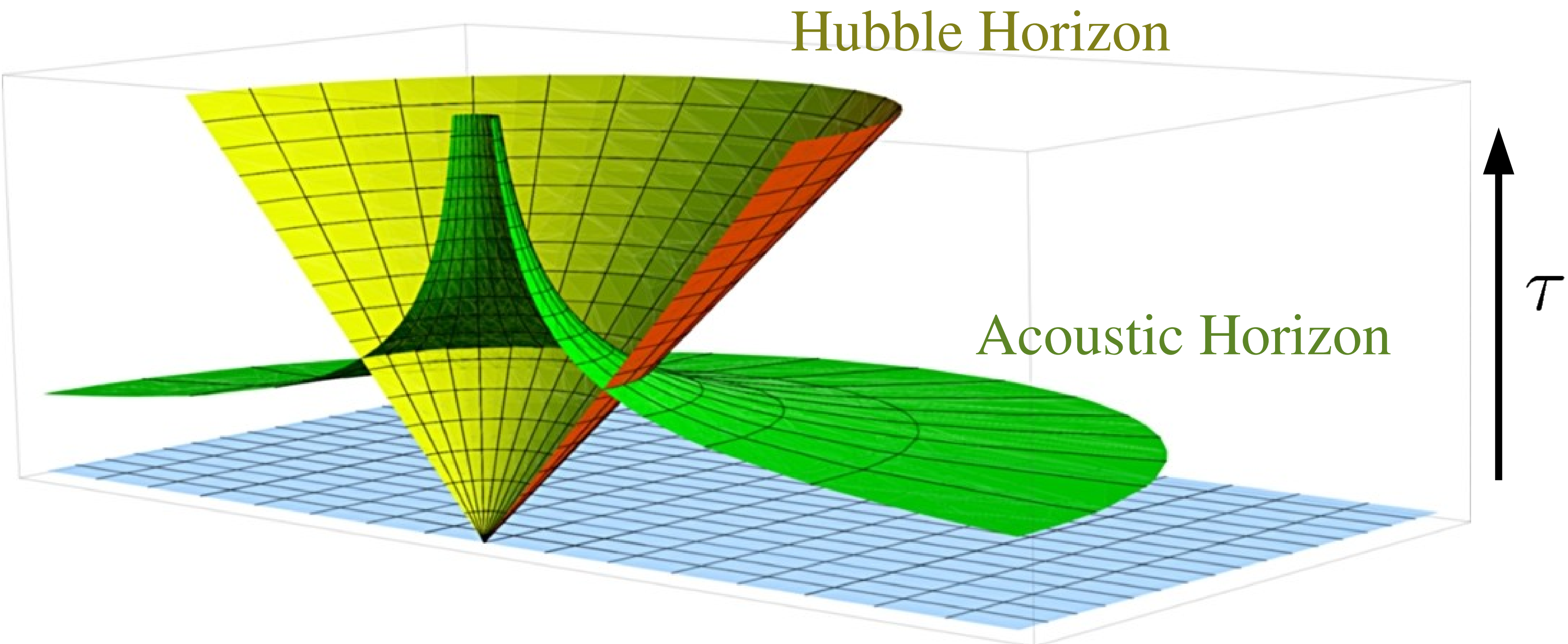
(2) Superluminal Sound Speed

(3) Violation of the Null Energy Condition

(4) Super-Planckian Energy Density

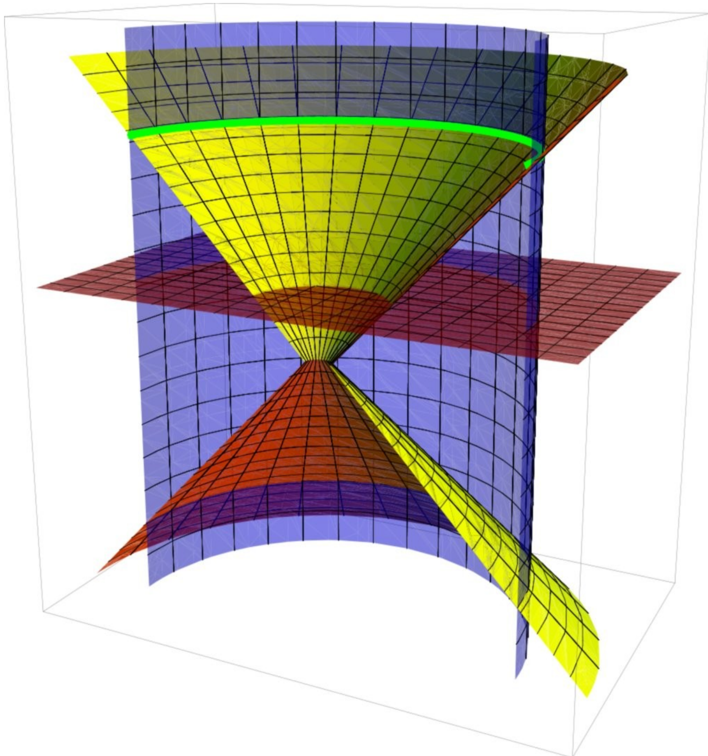
Geshnizjani, WHK, Moradinezhad Dizgah, arXiv:1107.1241
Geshnizjani, Ahmadi arXiv:1309.4782

Horizons in Tachyacoustic Cosmology



$$t \to 0, \ c_S \to \infty$$

The "Horizon" is *Not the Hubble Length*



$$R_H = \frac{1}{aH} = \frac{a}{a'}$$

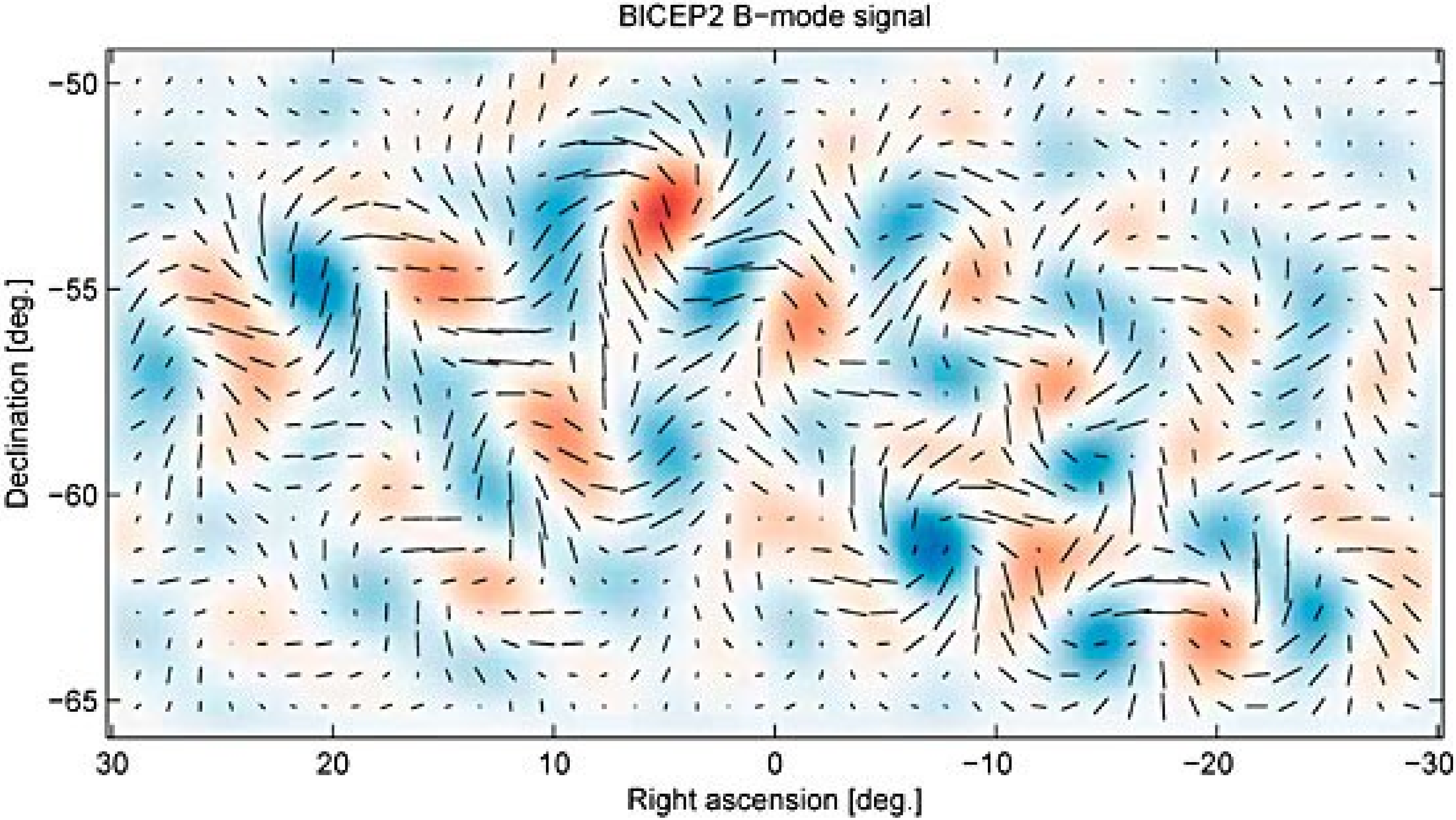
Scalars: $R_\zeta = \sqrt{\dfrac{a\sqrt{\epsilon}/c_S}{\left(a\sqrt{\epsilon}/c_S\right)''}}$

Tensors: $R_f = \sqrt{\dfrac{a}{a''}}$

$$v_k'' + \left[c_S^2 k^2 - \frac{1}{R^2(\tau)}\right] v_k = 0$$

(Khoury & Miller, arXiv:1012.0846)

Superhorizon Tensors



(Ade, *et al.*, arXiv:1403.3985)

Tensor Modes

Freezeout Horizon (tensors):

$$R_f = \sqrt{\frac{a}{a''}} = \frac{aH}{\sqrt{2-\epsilon}}$$

Freezeout length *shrinks* if:

$$\frac{1}{R_f}\frac{dR_f}{dN} = (\epsilon - 1) + \frac{1}{2(2-\epsilon)}\frac{d\epsilon}{dN} < 0$$

Tensor Modes

Freezeout Horizon (tensors):

$$R_f = \sqrt{\frac{a}{a''}} = \frac{aH}{\sqrt{2-\epsilon}}$$

Freezeout length *shrinks* if:

$$\frac{1}{R_f}\frac{dR_f}{dN} = (\epsilon - 1) + \frac{1}{2(2-\epsilon)}\frac{d\epsilon}{dN} < 0$$

$\epsilon \simeq \text{const.}$

$$\Leftrightarrow \epsilon < 1 : \text{ Inflation!}$$

Non-Inflationary Tensor Production: A Simple Example

Radiation-dominated expansion: $\epsilon = 2$

$$\frac{a''}{a} = 0 : \;\; R_f \to \infty \qquad\qquad v_k'' + k^2 v_k = 0$$

Non-Inflationary Tensor Production: A Simple Example

Radiation-dominated expansion: $\epsilon = 2$

$$\frac{a''}{a} = 0 : \ \ R_f \to \infty \qquad\qquad v_k'' + k^2 v_k = 0$$

Matter-dominated expansion: $\epsilon = 3/2$

$$\frac{a''}{a} = \frac{2}{\tau^2} : \ \ R_f = \frac{\sqrt{2}}{aH} \qquad\qquad v_k'' + \left(k^2 - \frac{2}{\tau^2}\right) v_k = 0$$

Non-Inflationary Tensor Production: A Simple Example

Radiation-dominated expansion: $\epsilon = 2$

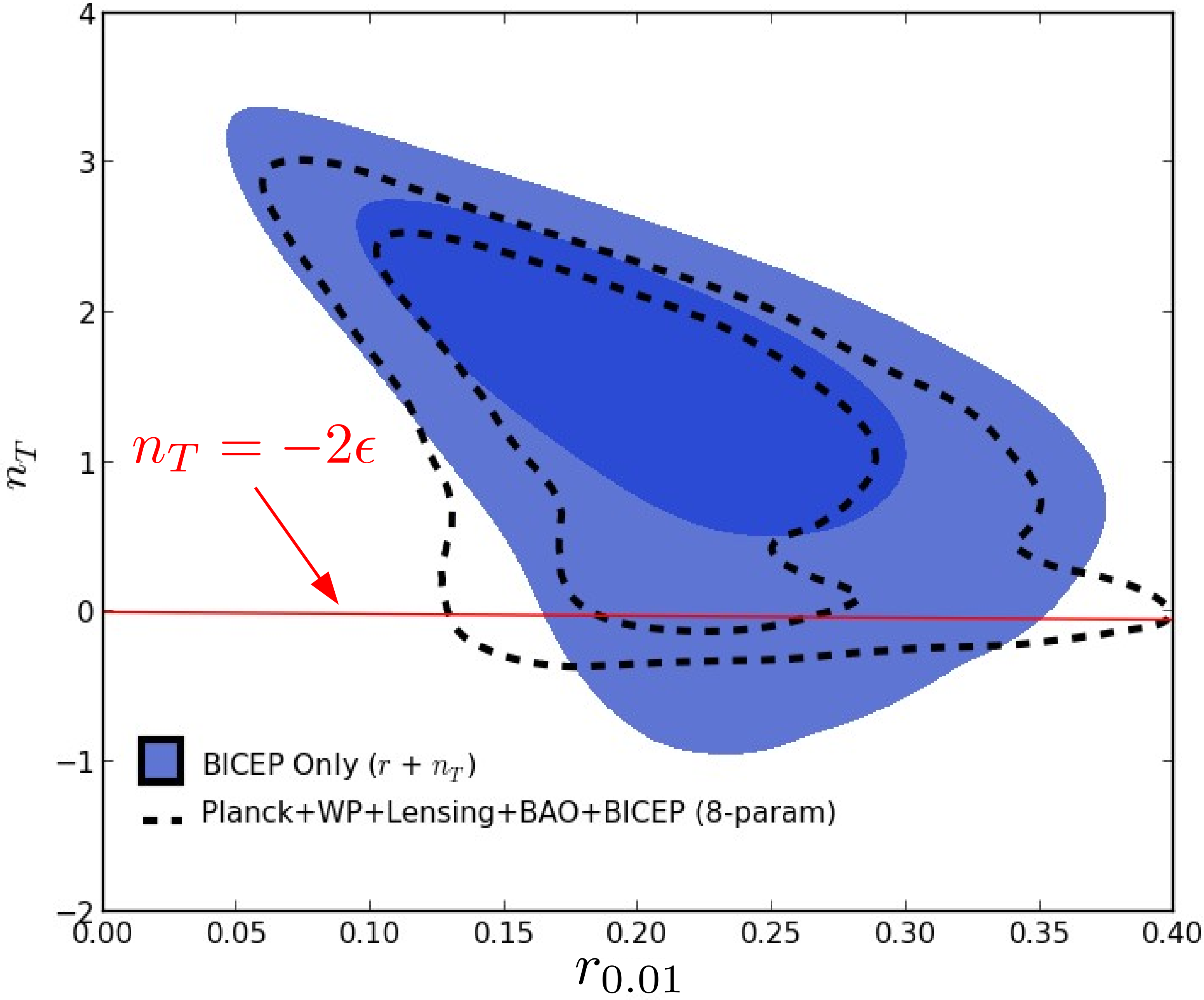
$$\frac{a''}{a} = 0 : \;\; R_f \to \infty \qquad\qquad v_k'' + k^2 v_k = 0$$

Matter-dominated expansion: $\epsilon = 3/2$

$$\frac{a''}{a} = \frac{2}{\tau^2} : \;\; R_f = \frac{\sqrt{2}}{aH} \qquad\qquad v_k'' + \left(k^2 - \frac{2}{\tau^2}\right) v_k = 0$$

$$P_T \propto \left(k/M_{\rm Pl}\right)^2$$

Tensor Spectral Index (BICEP2 Tensor Interpretation)



Generating Superhorizon *Tensor* Perturbations

To generate *observable* tensor perturbations, must have one of:

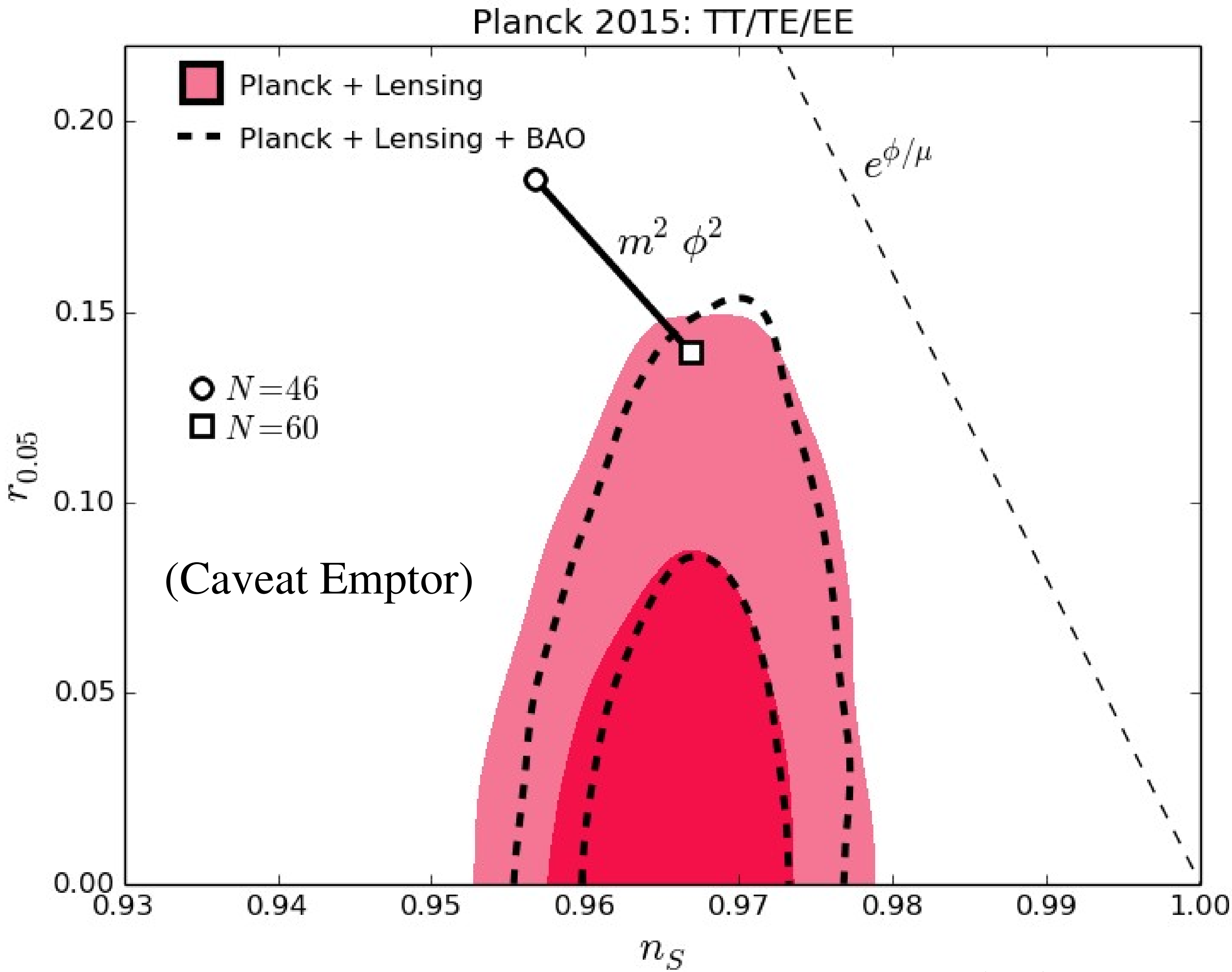
(1) Accelerated Expansion

~~(2) Superluminal Sound Speed~~

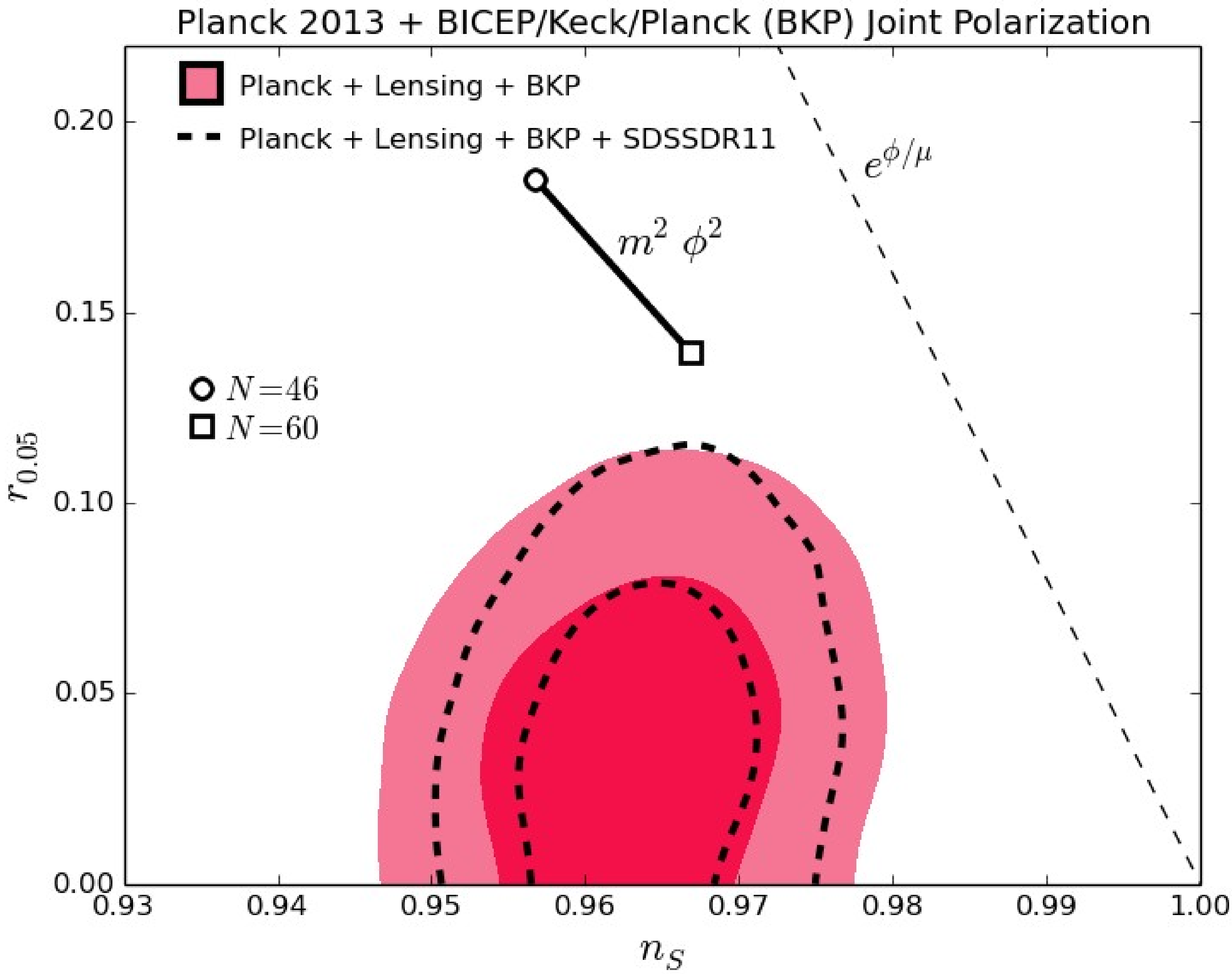
(3) Violation of the Null Energy Condition

(4) Super-Planckian Energy Density

Geshnizjani, WHK, arXiv:1410.4968

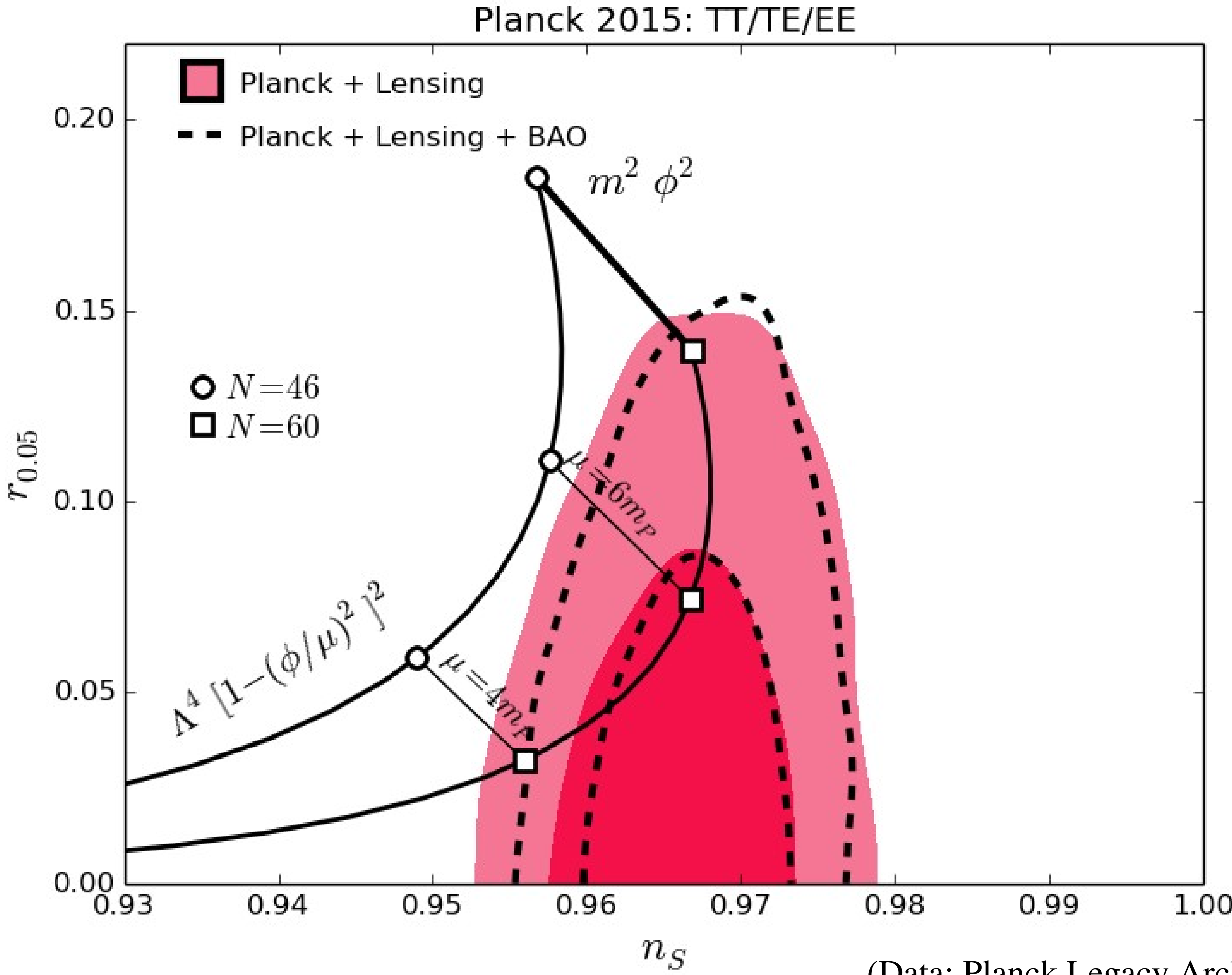


(Data: Planck Legacy Archive)



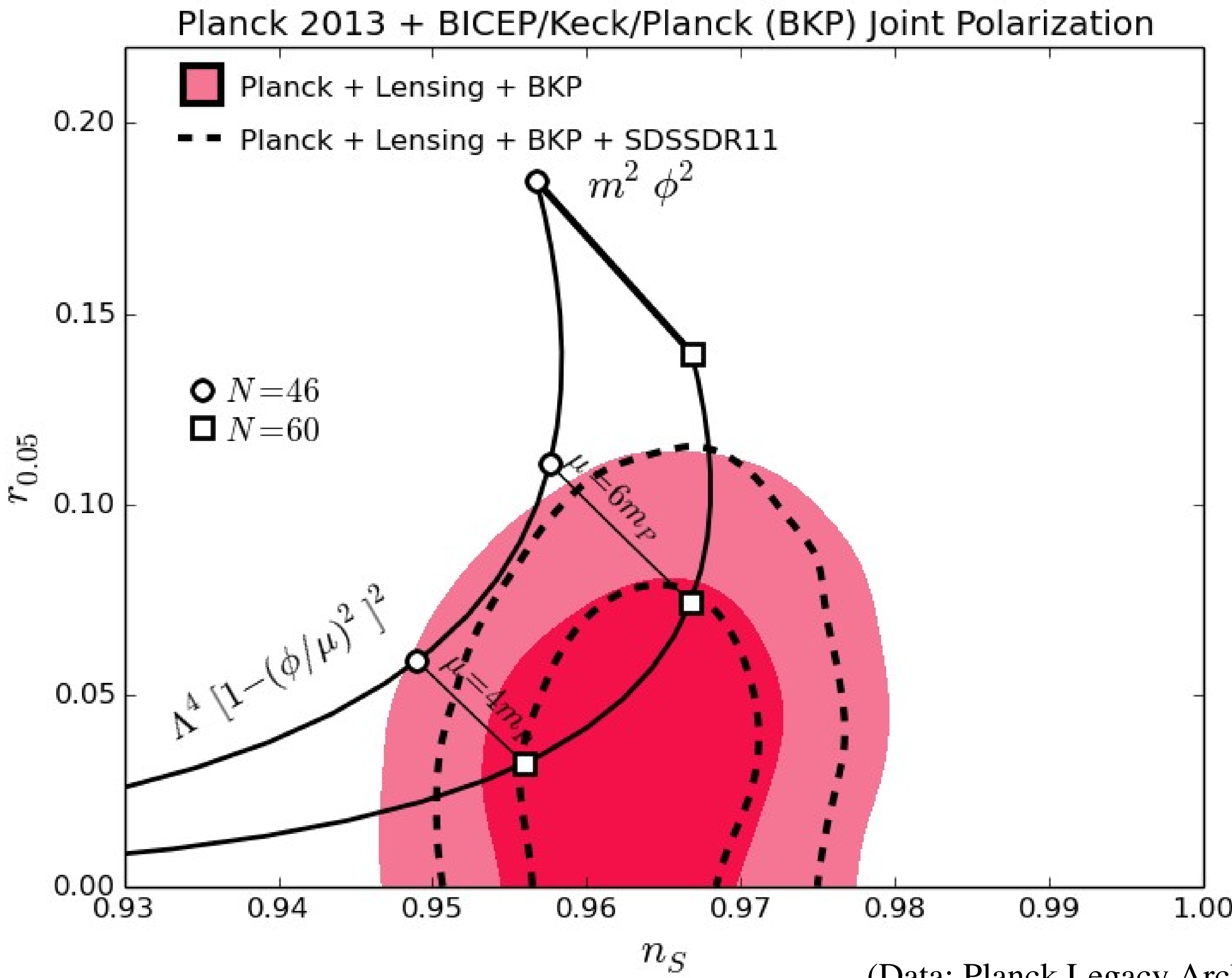
(Data: Planck Legacy Archive)

Higgs-Like Inflation



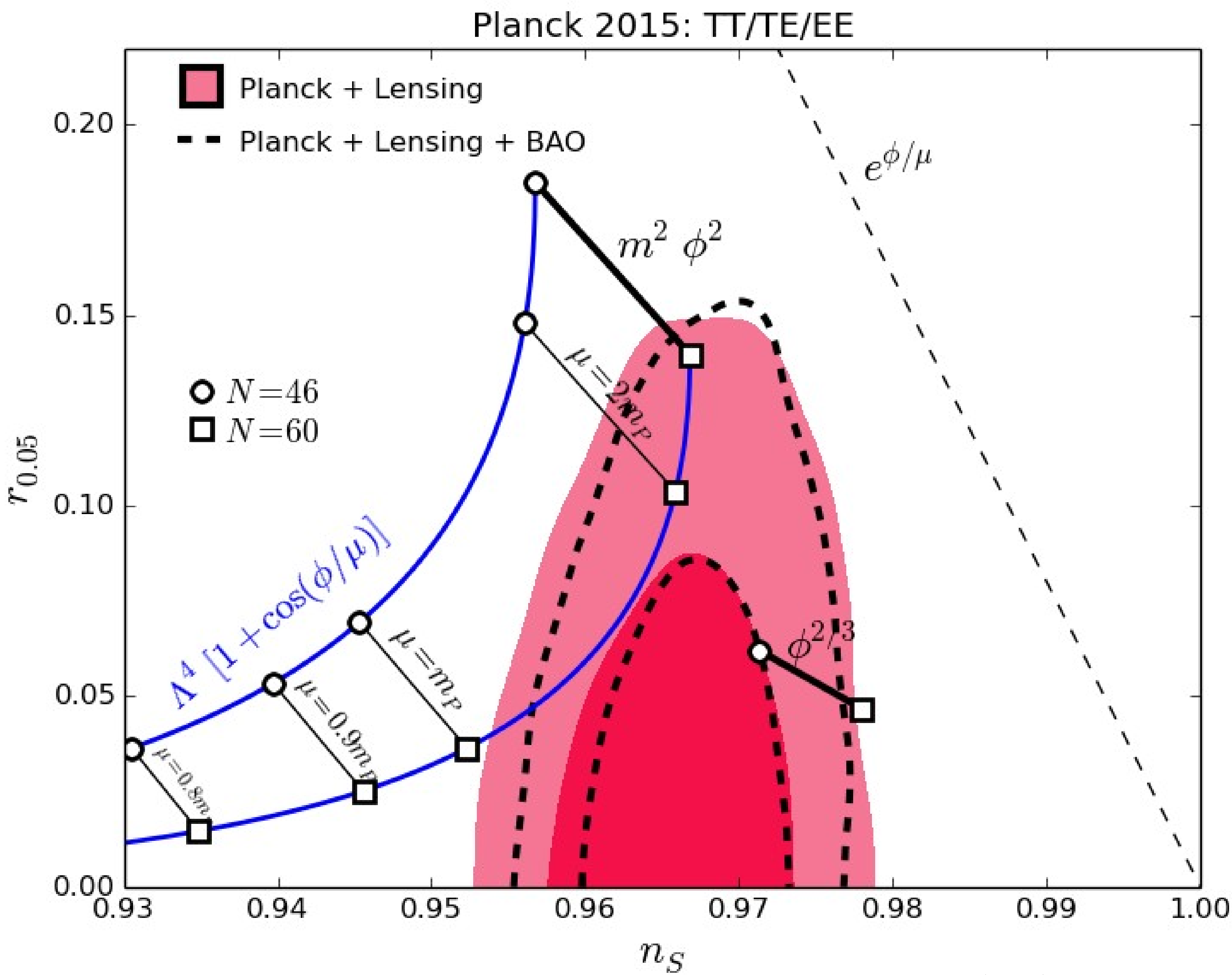
(Data: Planck Legacy Archive)

Higgs-Like Inflation



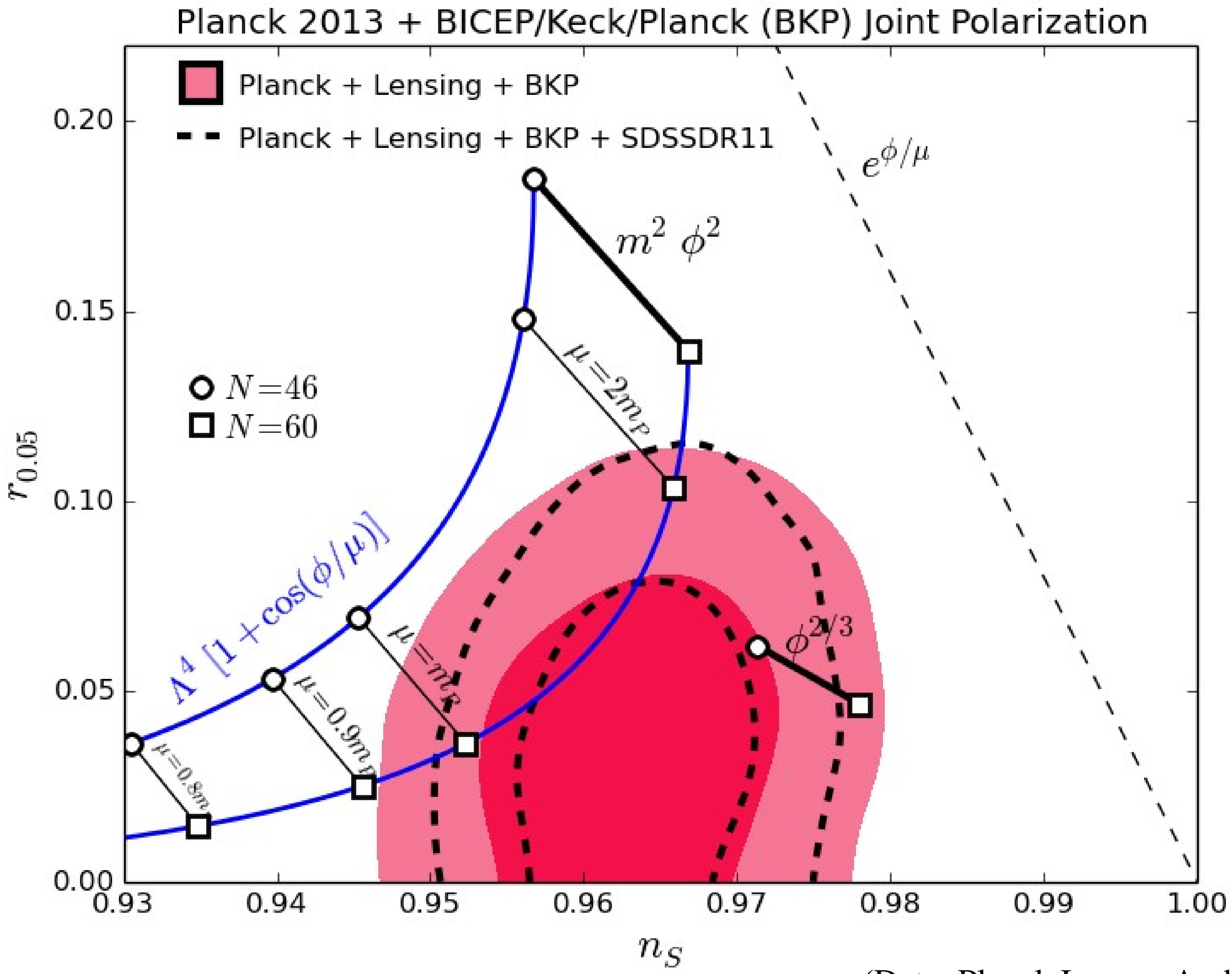
(Data: Planck Legacy Archive)

Natural Inflation



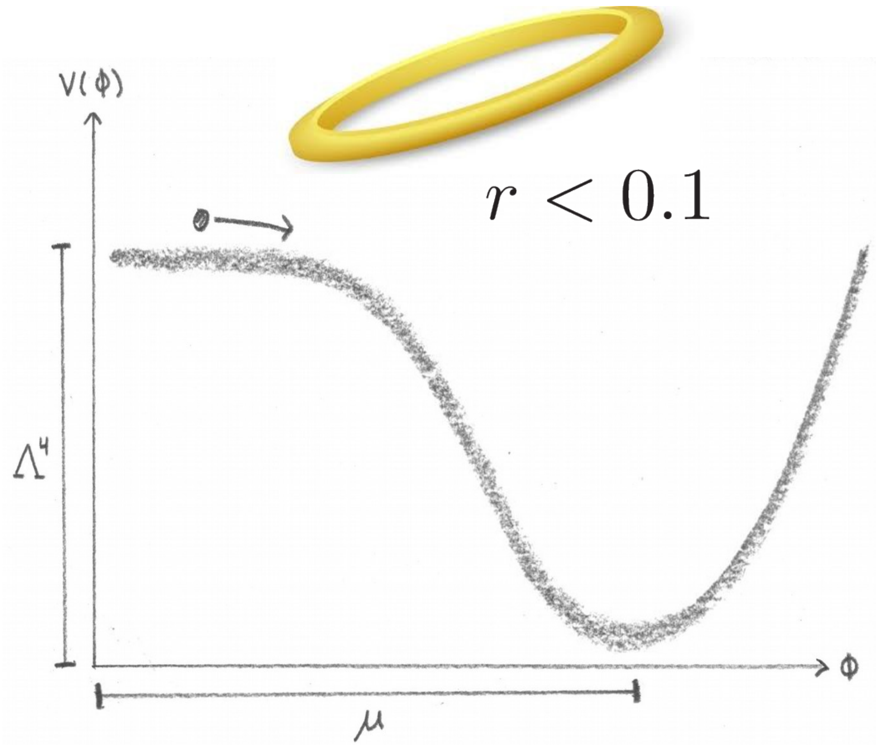
(Data: Planck Legacy Archive)

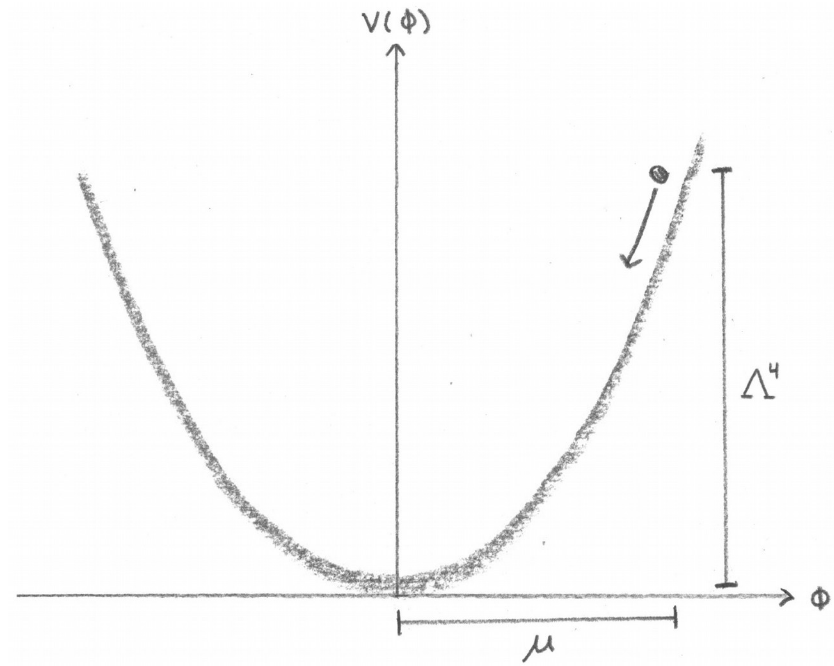
Natural Inflation



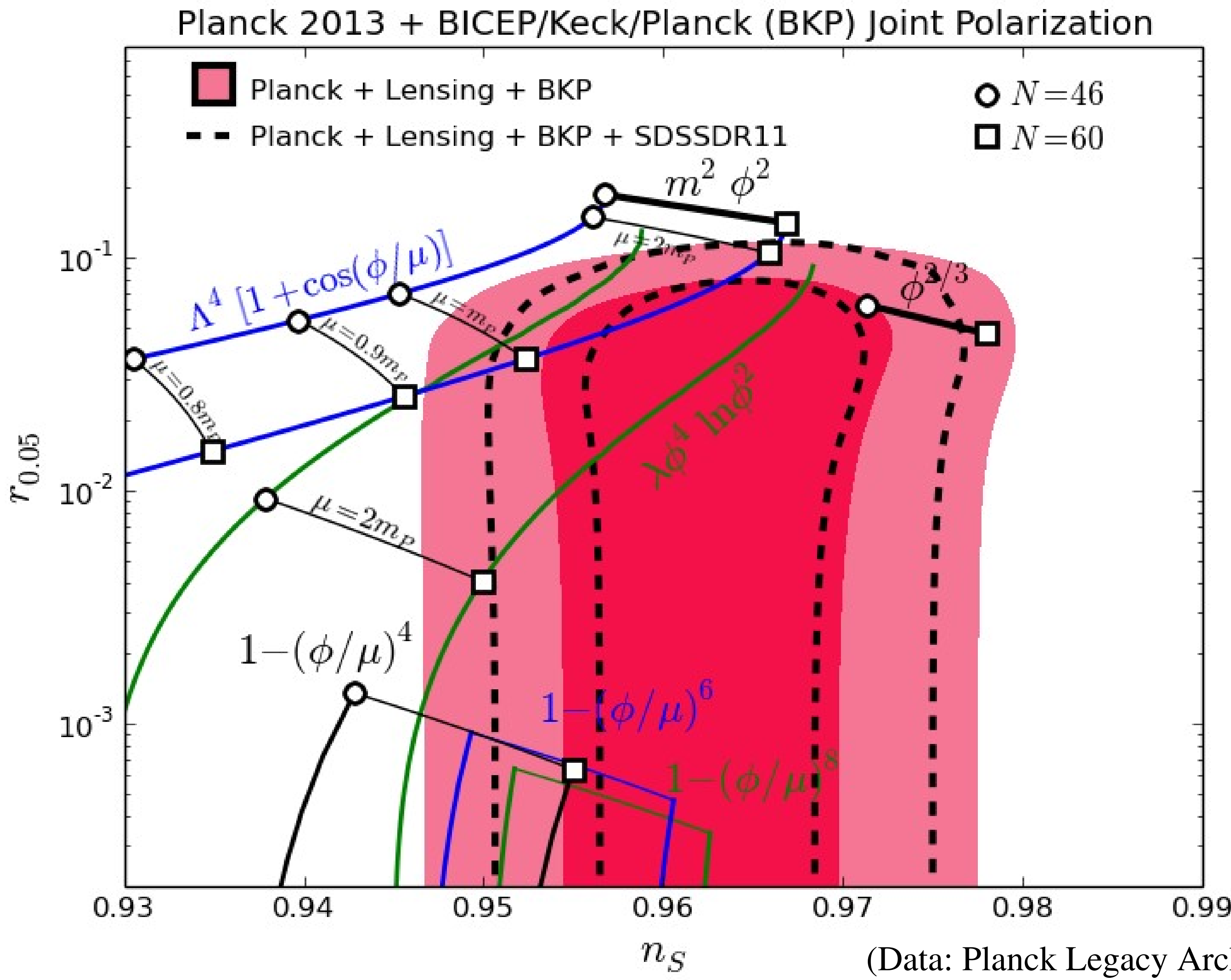
(Data: Planck Legacy Archive)

Small Field or Large Field?





Summary: Planck and Small-Field Inflation



(Data: Planck Legacy Archive)