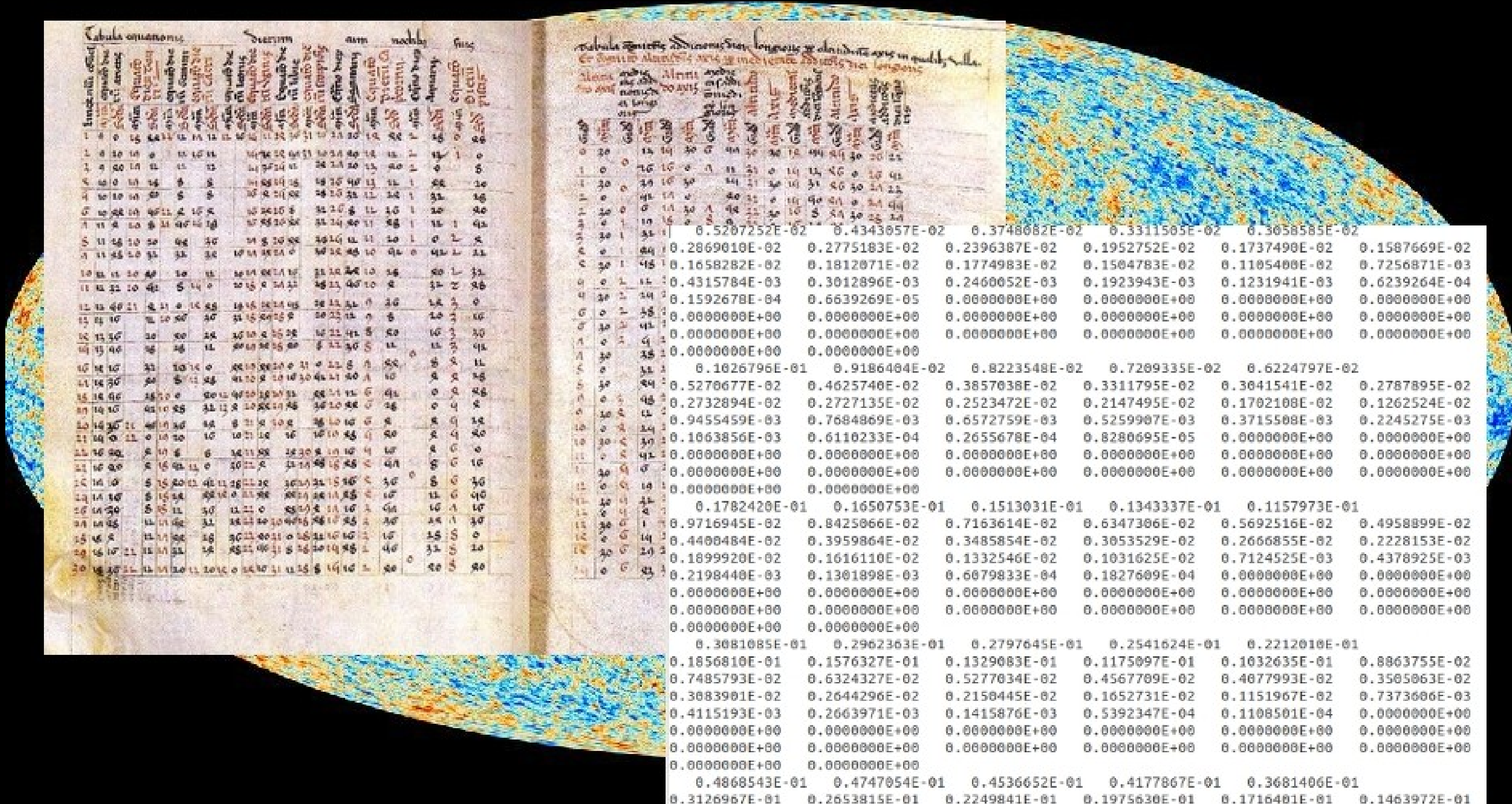
Inflation in 2013

Will Kinney

University at Buffalo *The State University of New York*

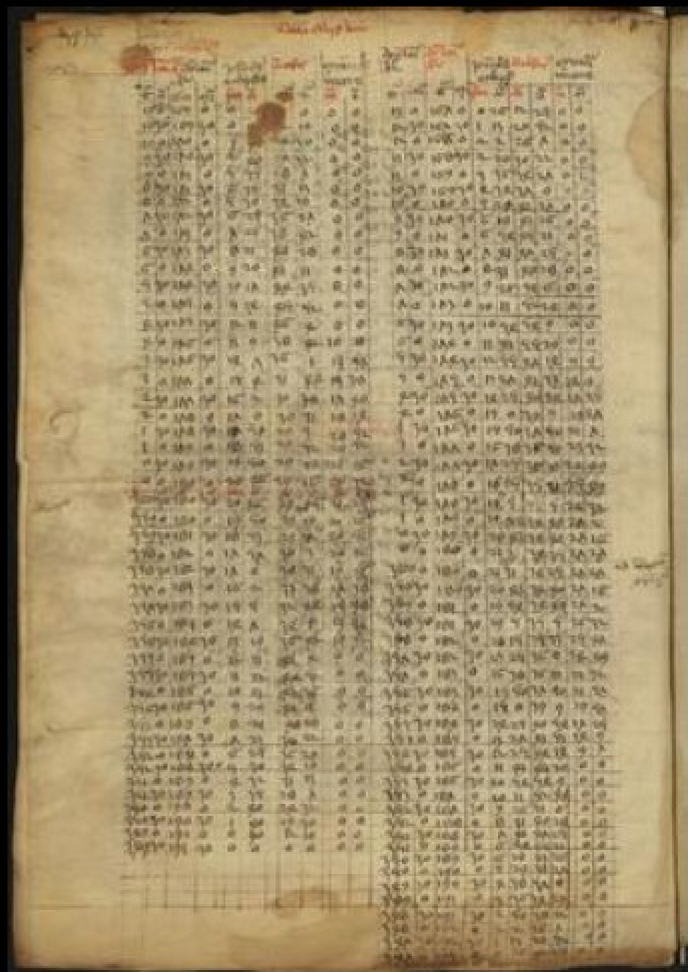


EPI2013 Exploring the Physics of Inflation

Santander, España

26 June 2013

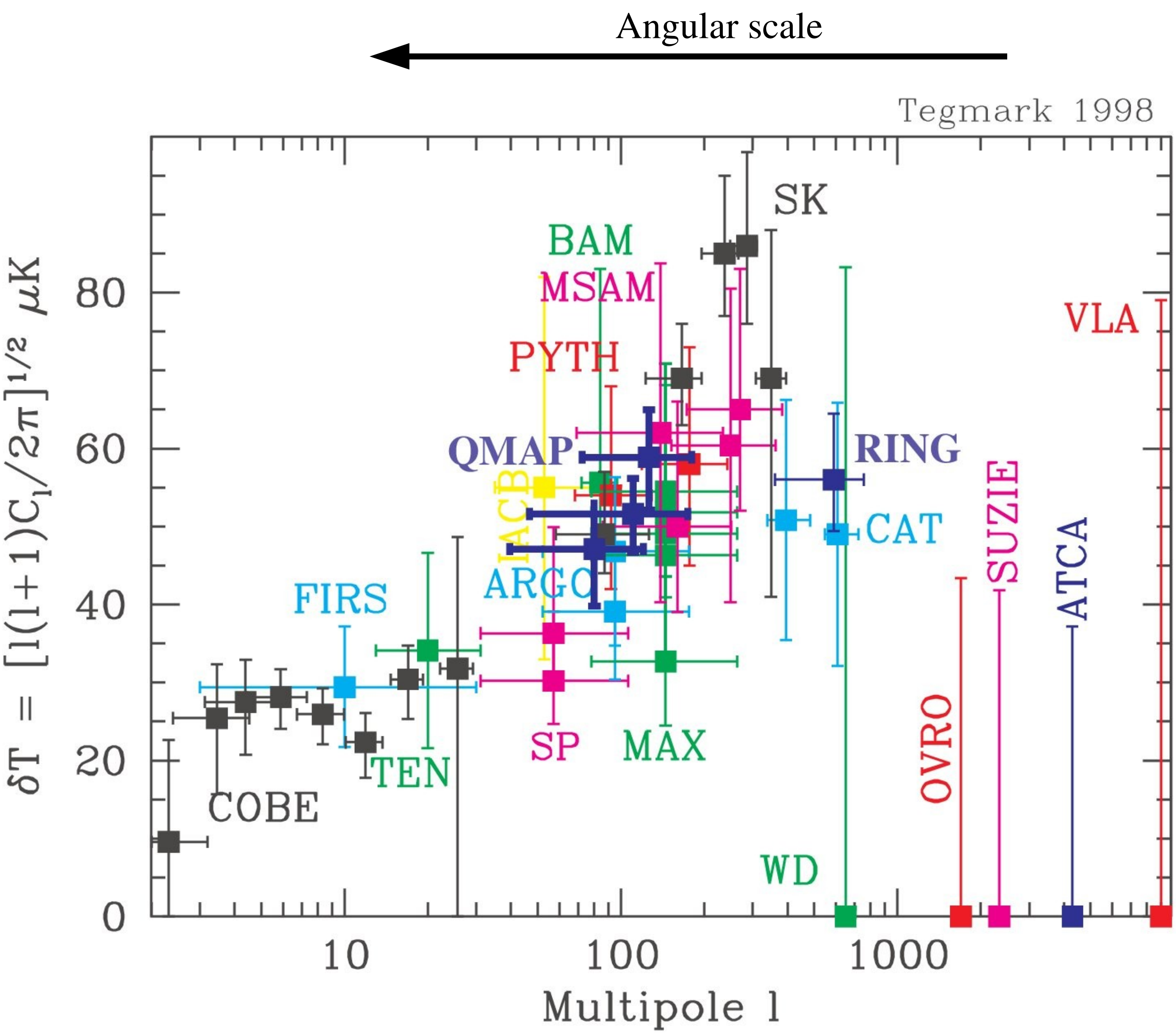
Alfonsine Tables:
Compiled in Toledo ca. 1252, financed by Alfonso X.
50 astronomer collaboration, led by Isaac ibn Sid.
First printed edition 1483.

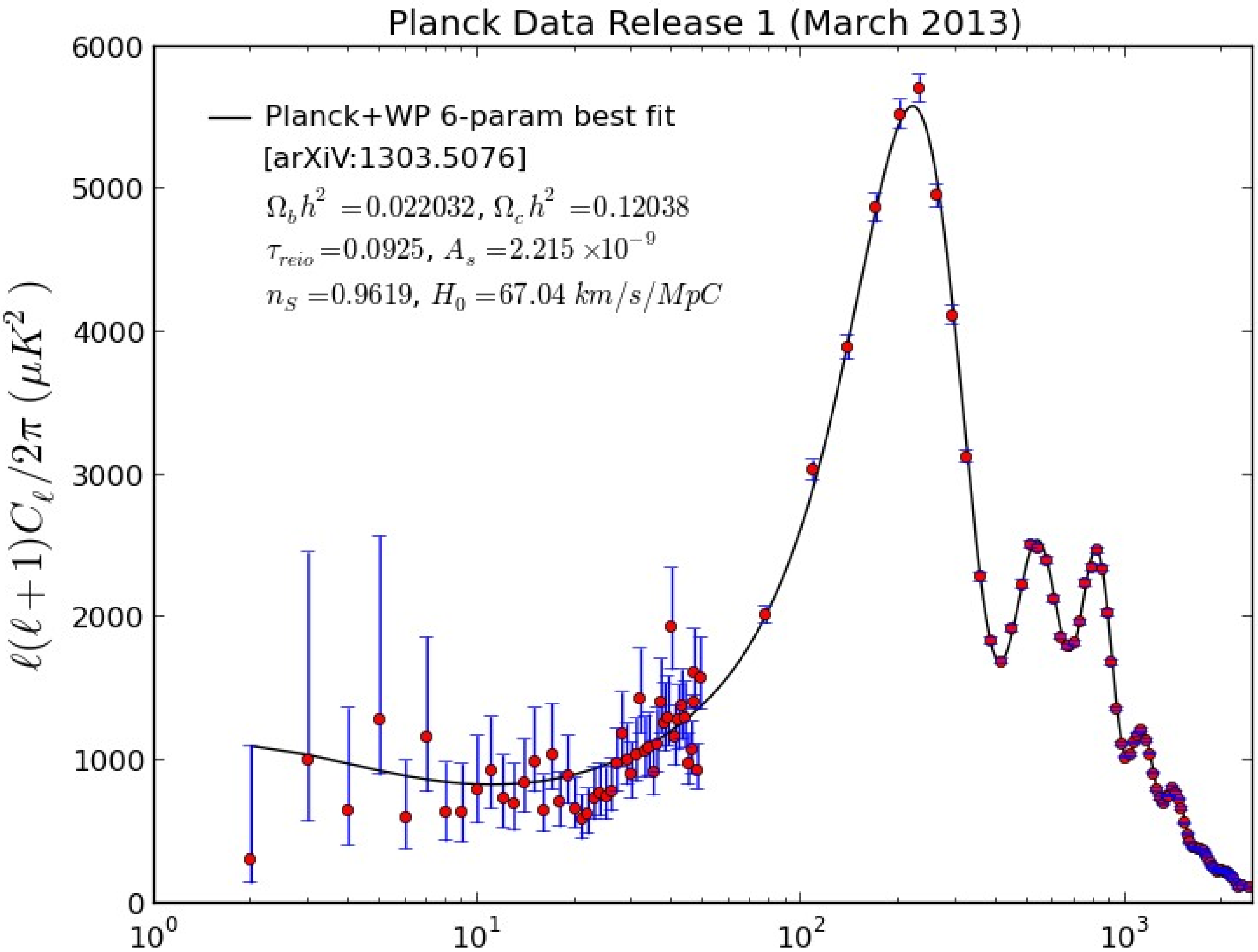


"If the Lord Almighty had consulted me before embarking on creation thus, I should have recommended something simpler."

Alfonso X of Castile (r. 1252–84) on the Ptolemaic system

The CMB Angular Power Spectrum (1998)



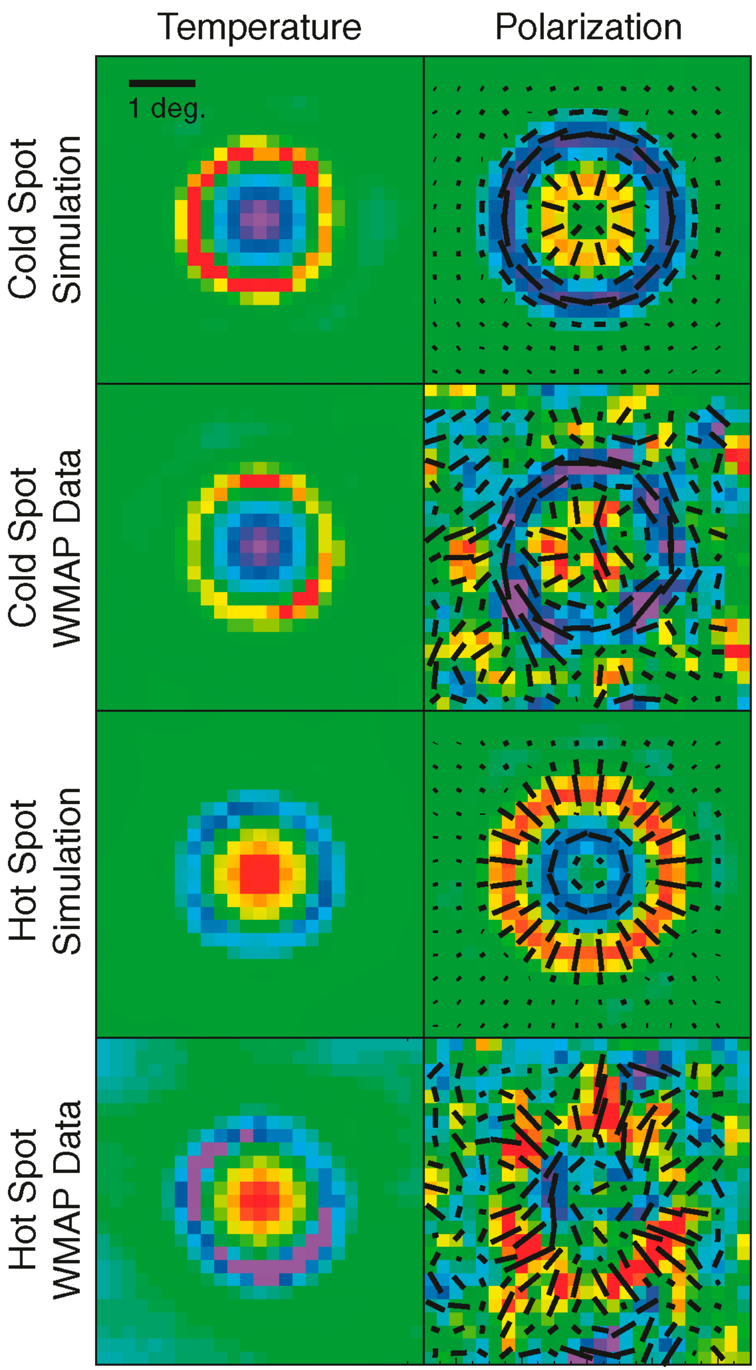


(Data: Planck Legacy Archive)

Inflation: Basic Predictions

- Adiabatic density perturbations
- Superhorizon correlations
- Gaussian statistics

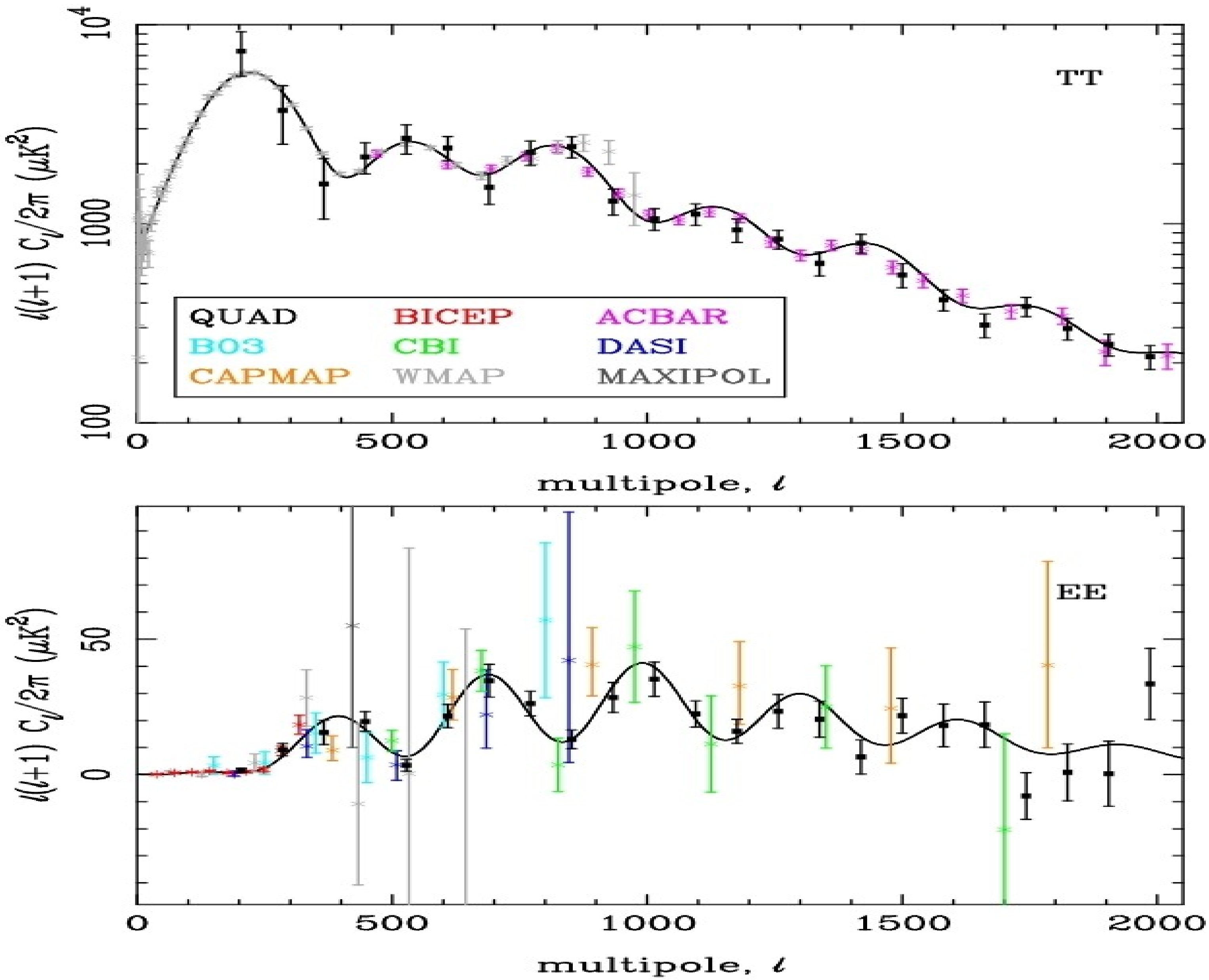
Polarization: Test of Adiabaticity



Polarization strongest along *gradients* in temperature

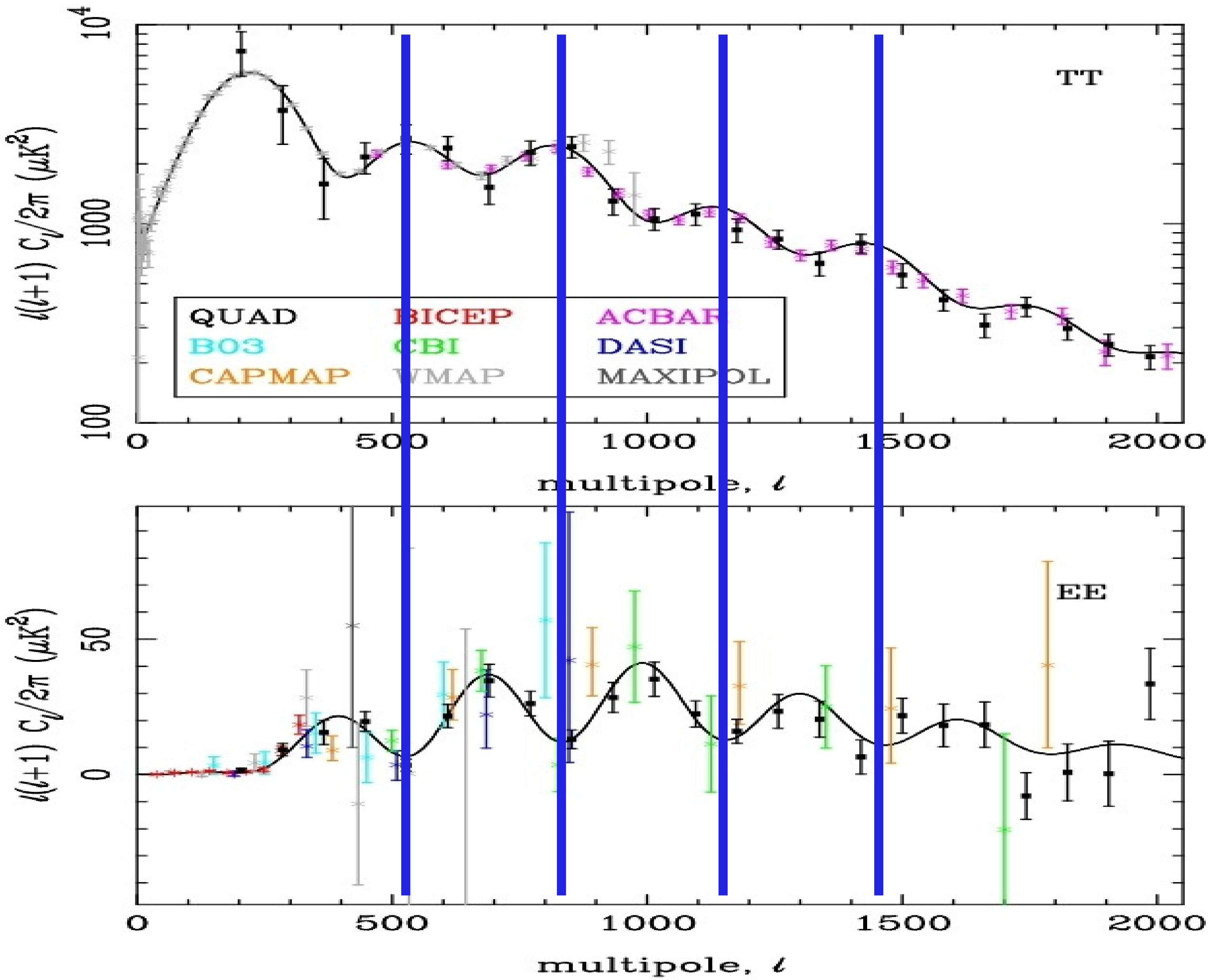
(Komatsu, *et al.*, arXiv:0912.0522)

Adiabatic Perturbations:
Temperature and Polarization Spectra Anticorrelated



(QuaD Collaboration, arXiv:0906.1003)

Adiabatic Perturbations:
Temperature and Polarization Spectra Anticorrelated



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Inflation: Basic Predictions

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- Superhorizon correlations
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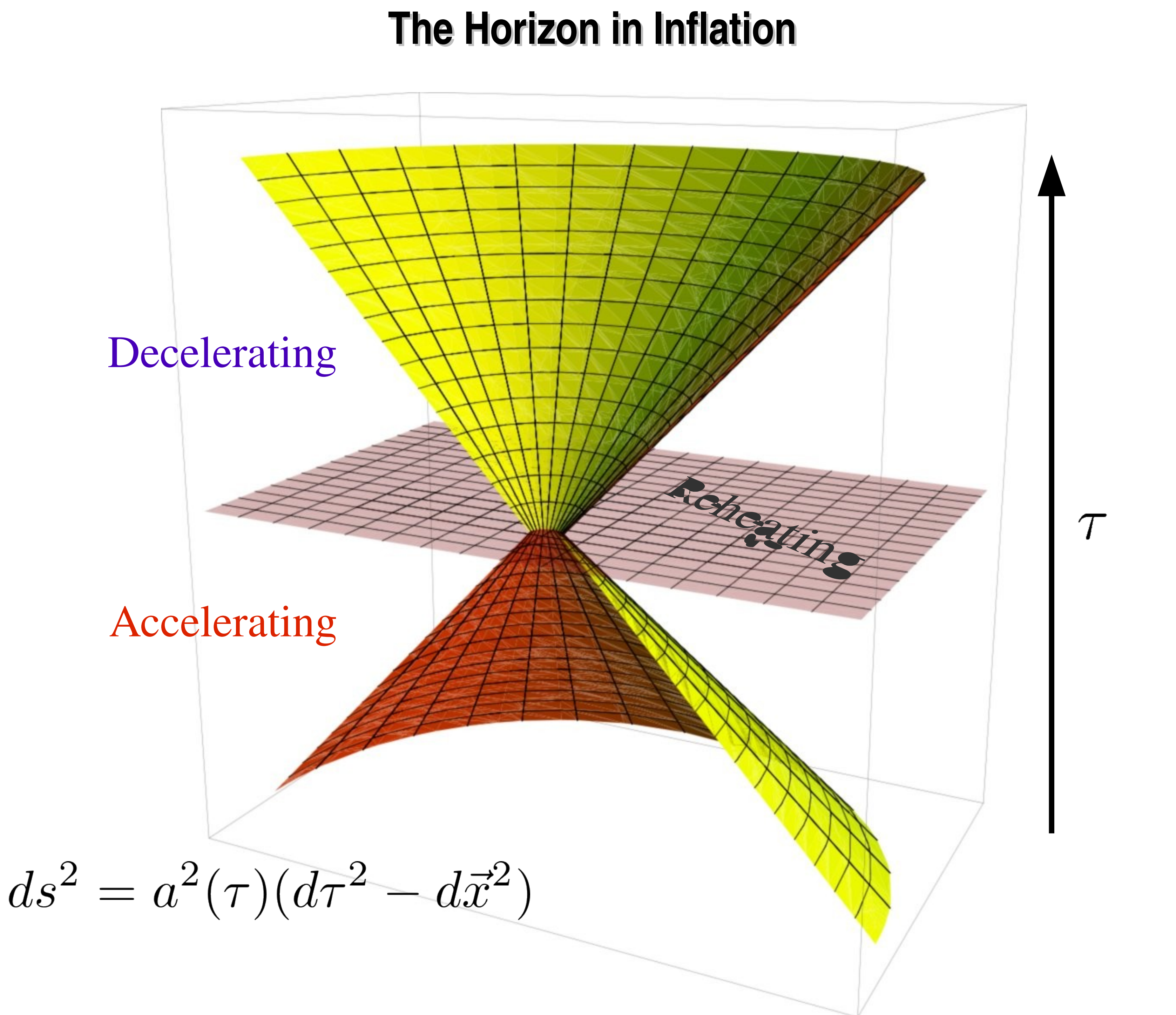
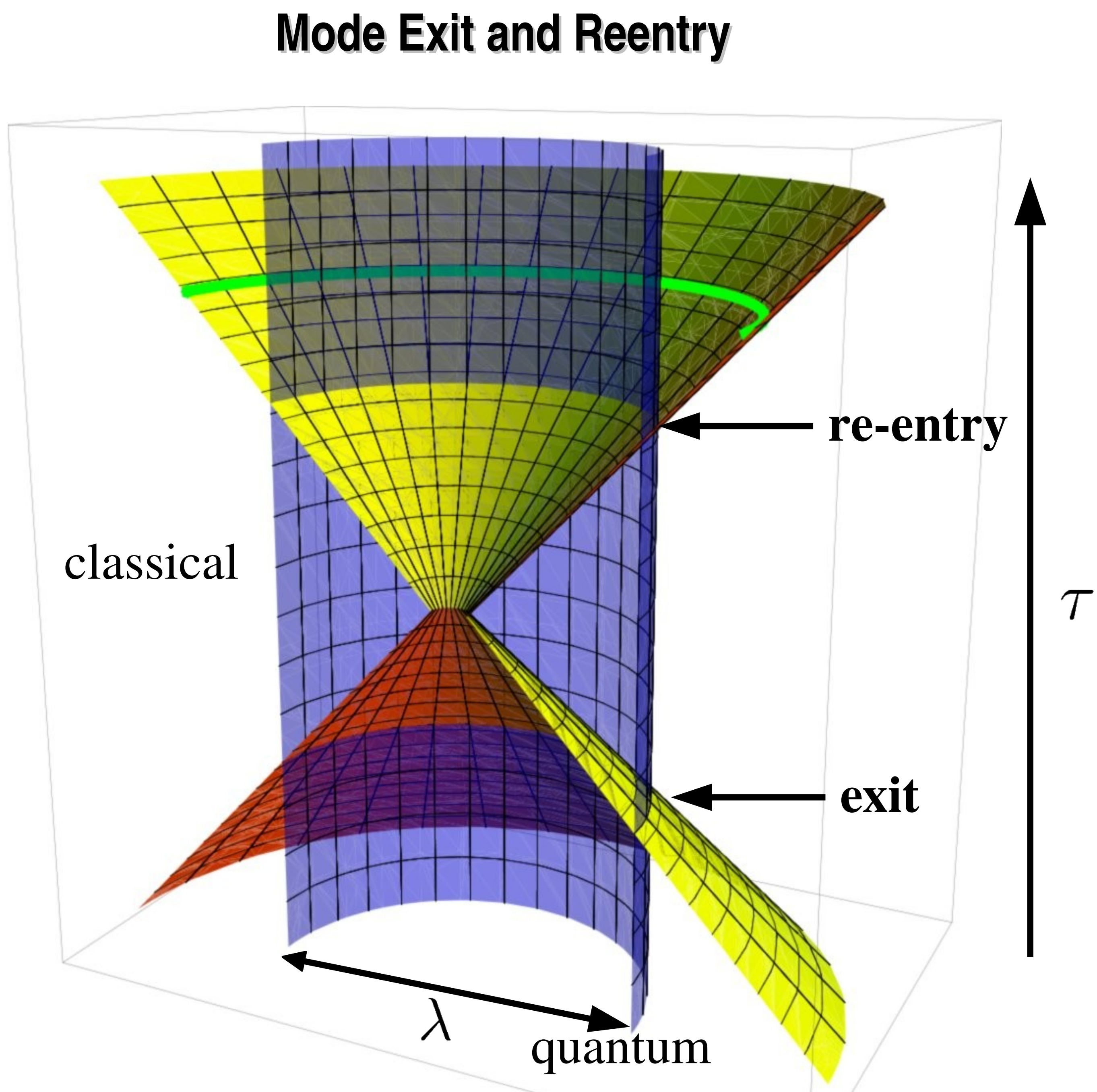
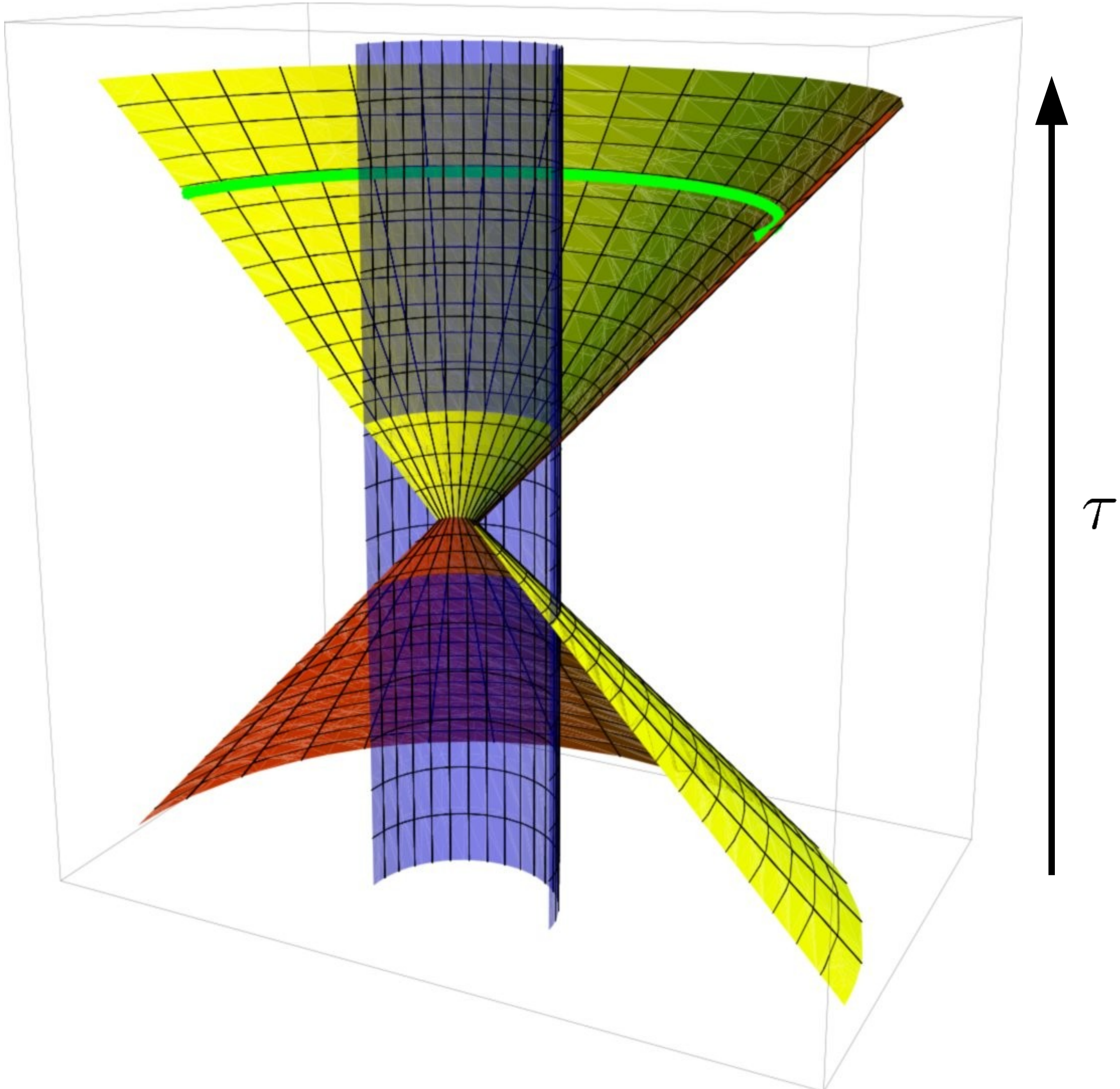
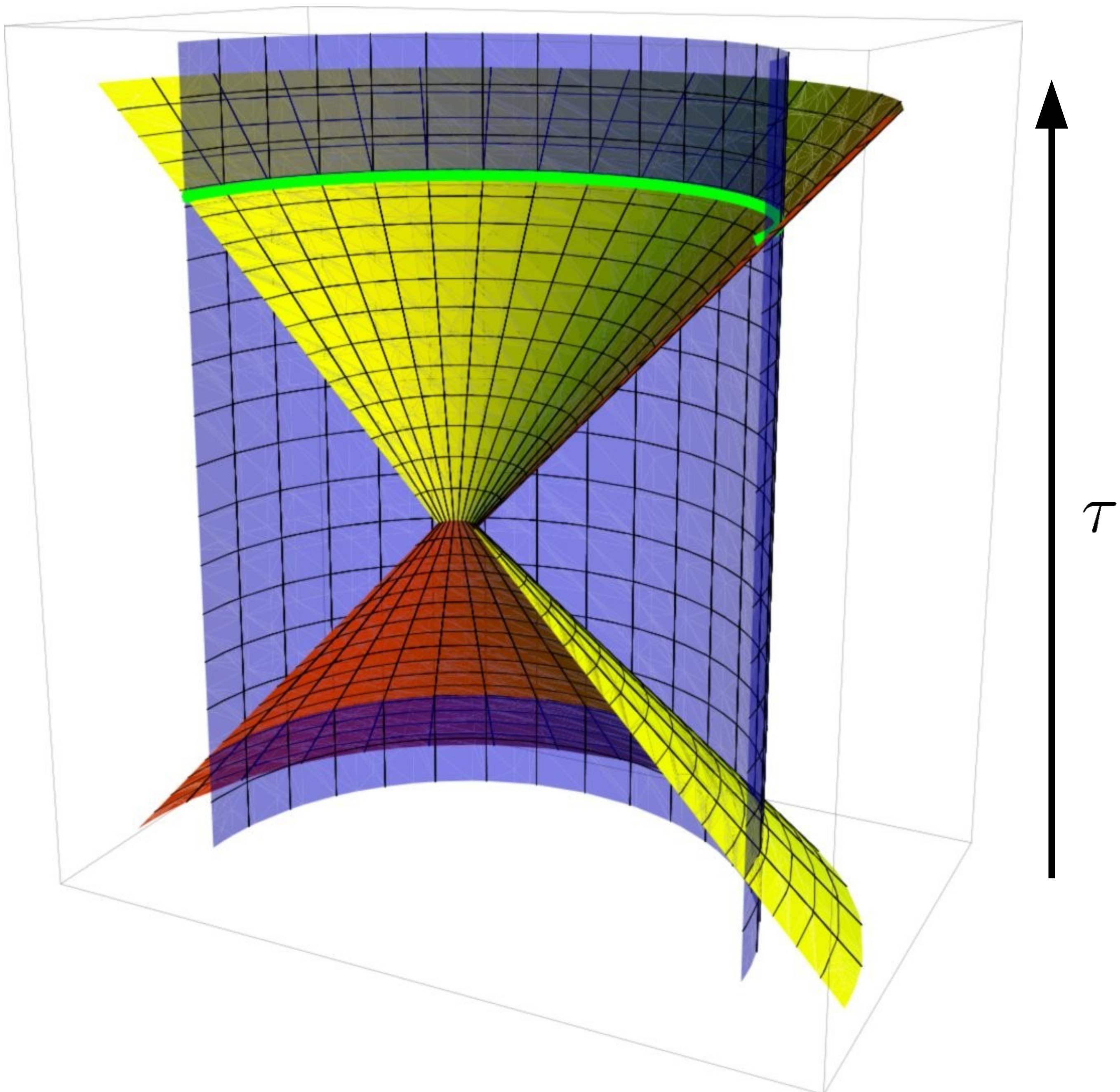

The Horizon in Inflation
Decelerating
Reheating
Accelerating
τ
$ds^2 = a^2(\tau)(d\tau^2 - d\vec{x}^2)$


Mode Exit and Reentry
re-entry
classical
τ
exit
λ
quantum

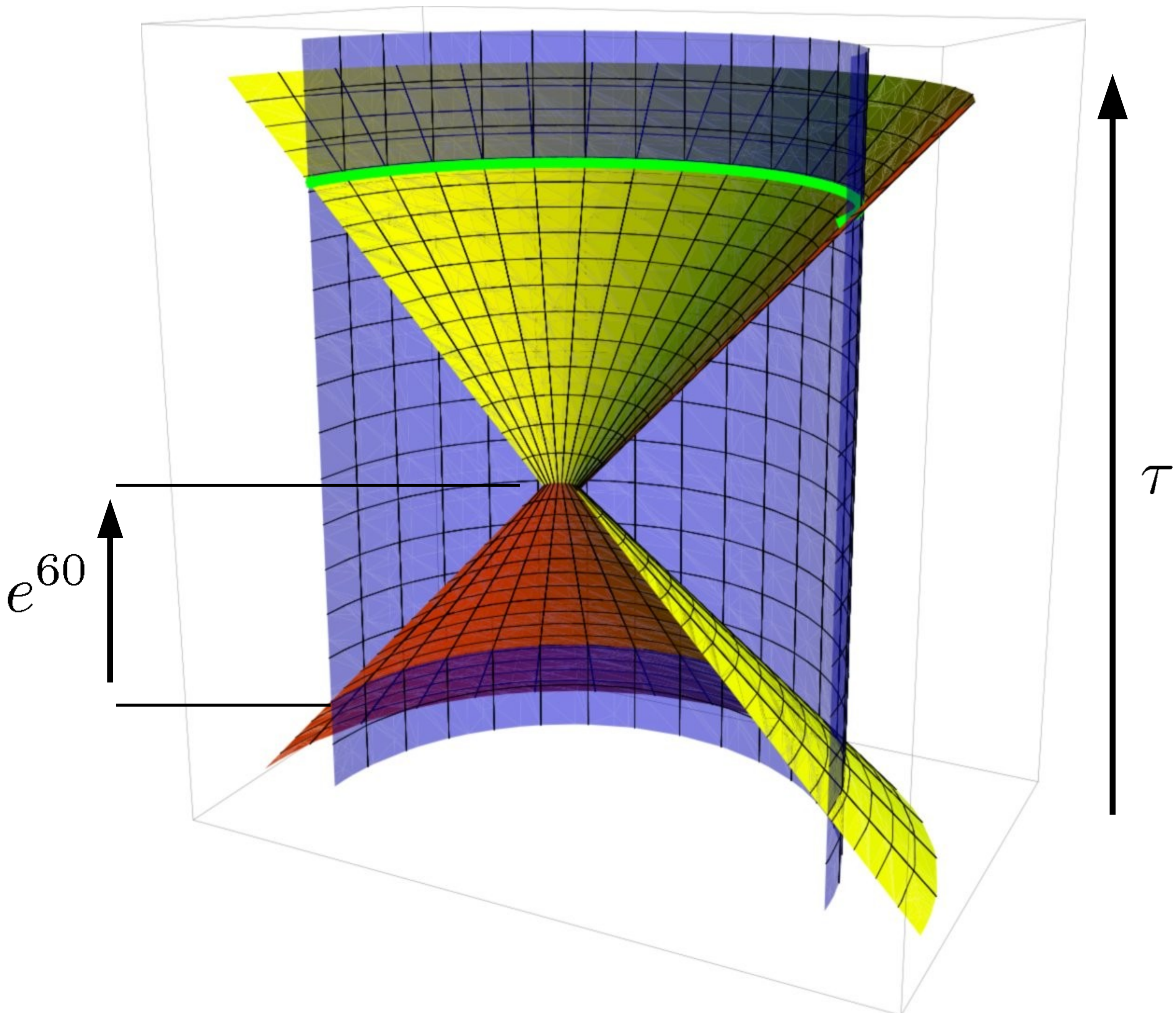
Shorter Wavelength Modes Exit Later



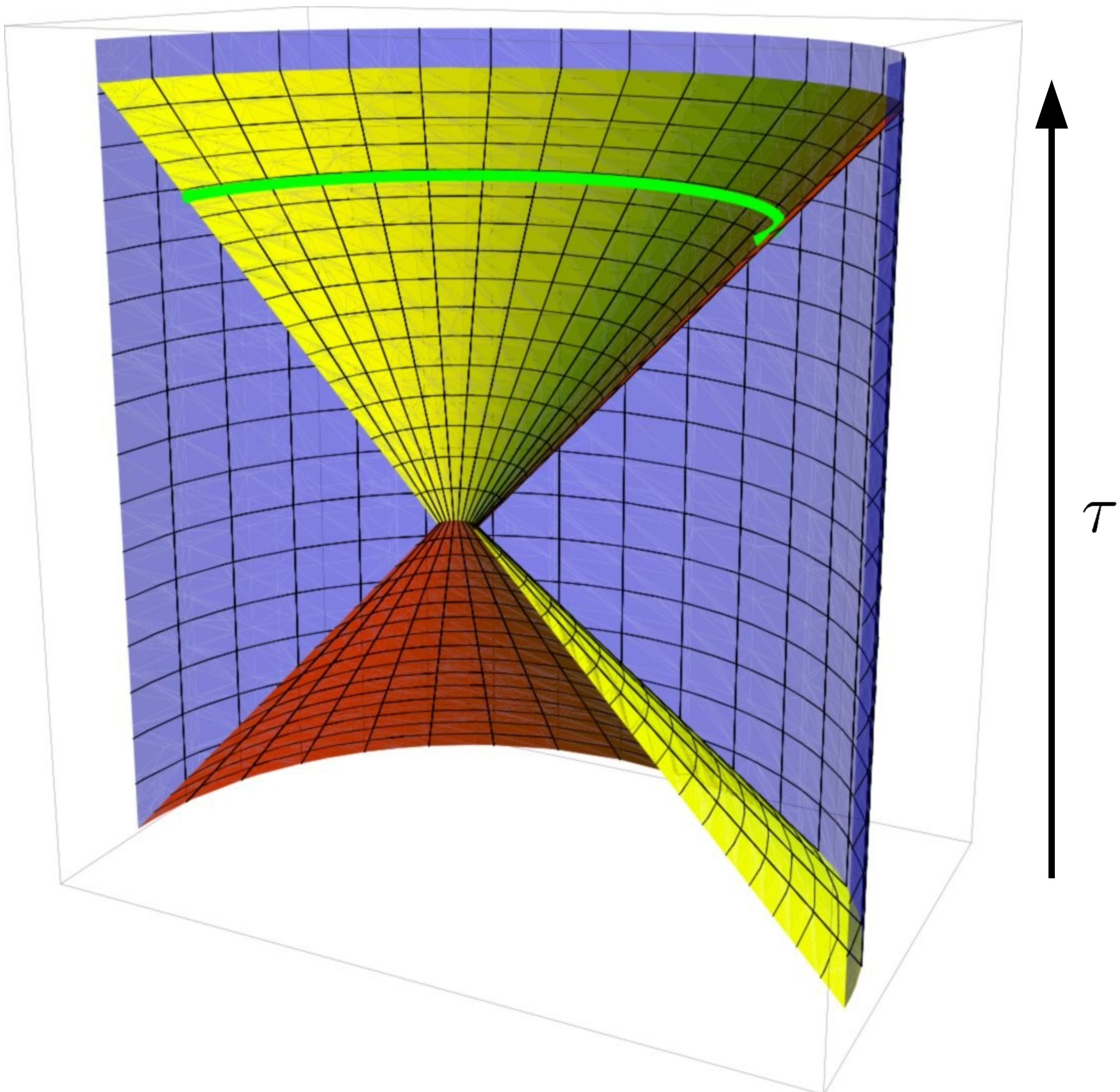
Longer Wavelength Modes Exit Earlier



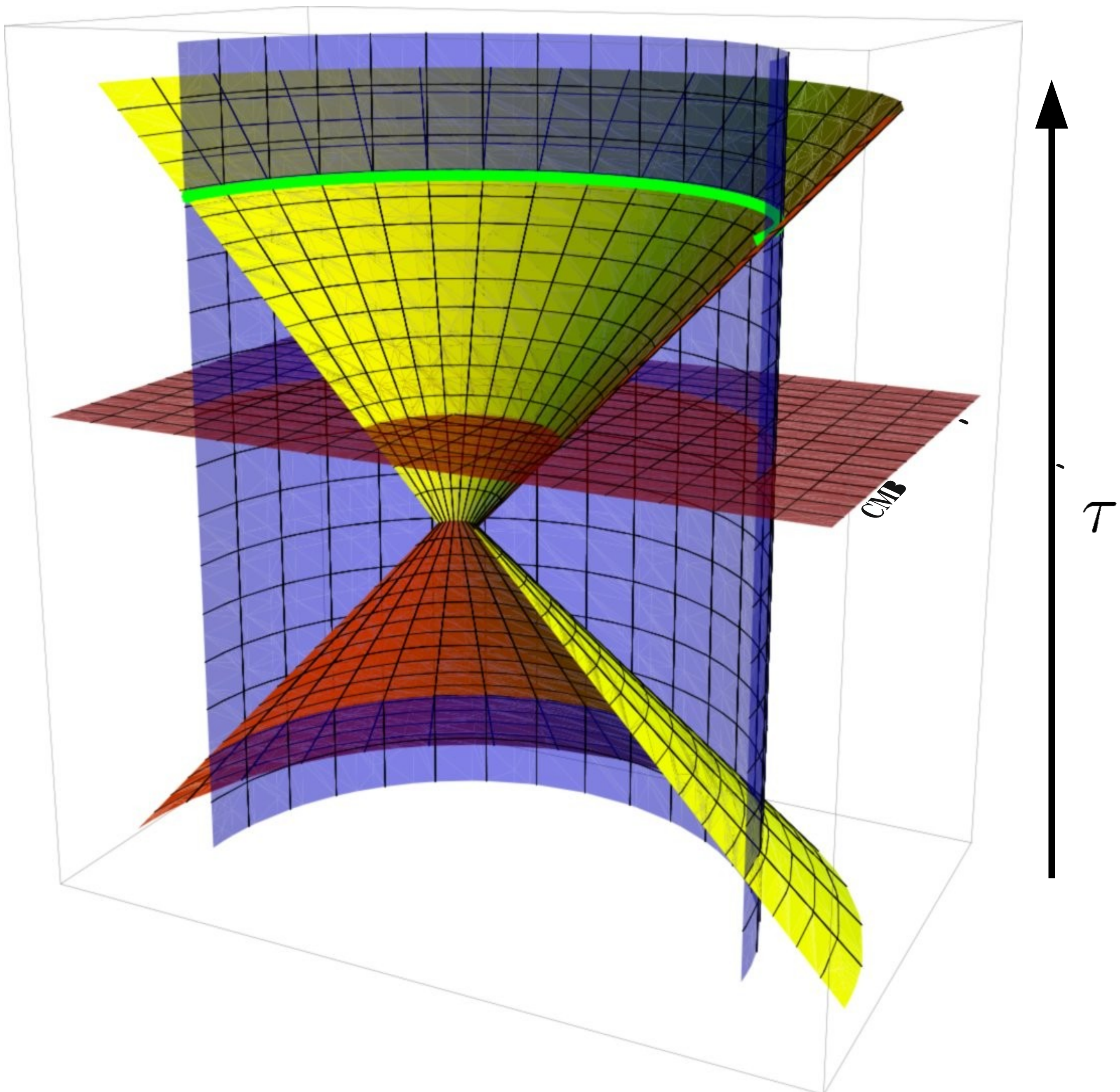
We See The *Last* 60 E-folds



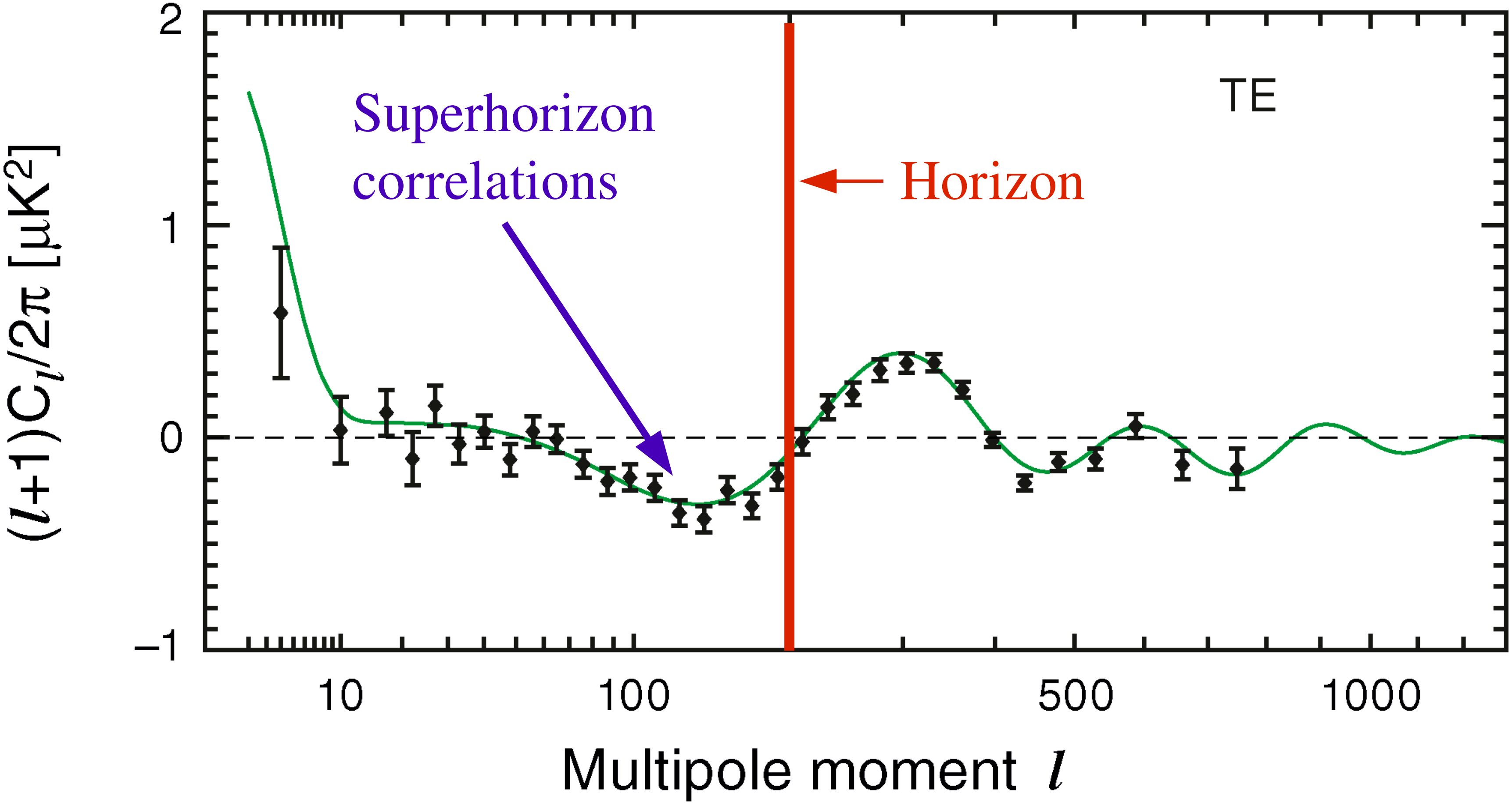
Initial Conditions: Inaccessible



Superhorizon Perturbations



Large-Scale CMB Polarization (WMAP7)



(Figure: NASA/WMAP science team)

Generating Superhorizon Perturbations

In an *expanding universe*, to generate perturbations consistent with observation, must have one of:

(1) Accelerated Expansion

(2) Superluminal Sound Speed

(3) Super-Planckian Energy Density

(Geshnizjani, WHK, Moradinezhad Dizgah, arXiv:1107.1241)

Inflation: Basic Predictions

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

Non-Canonical Lagrangians

Lagrangian with arbitrary kinetic term:

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

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

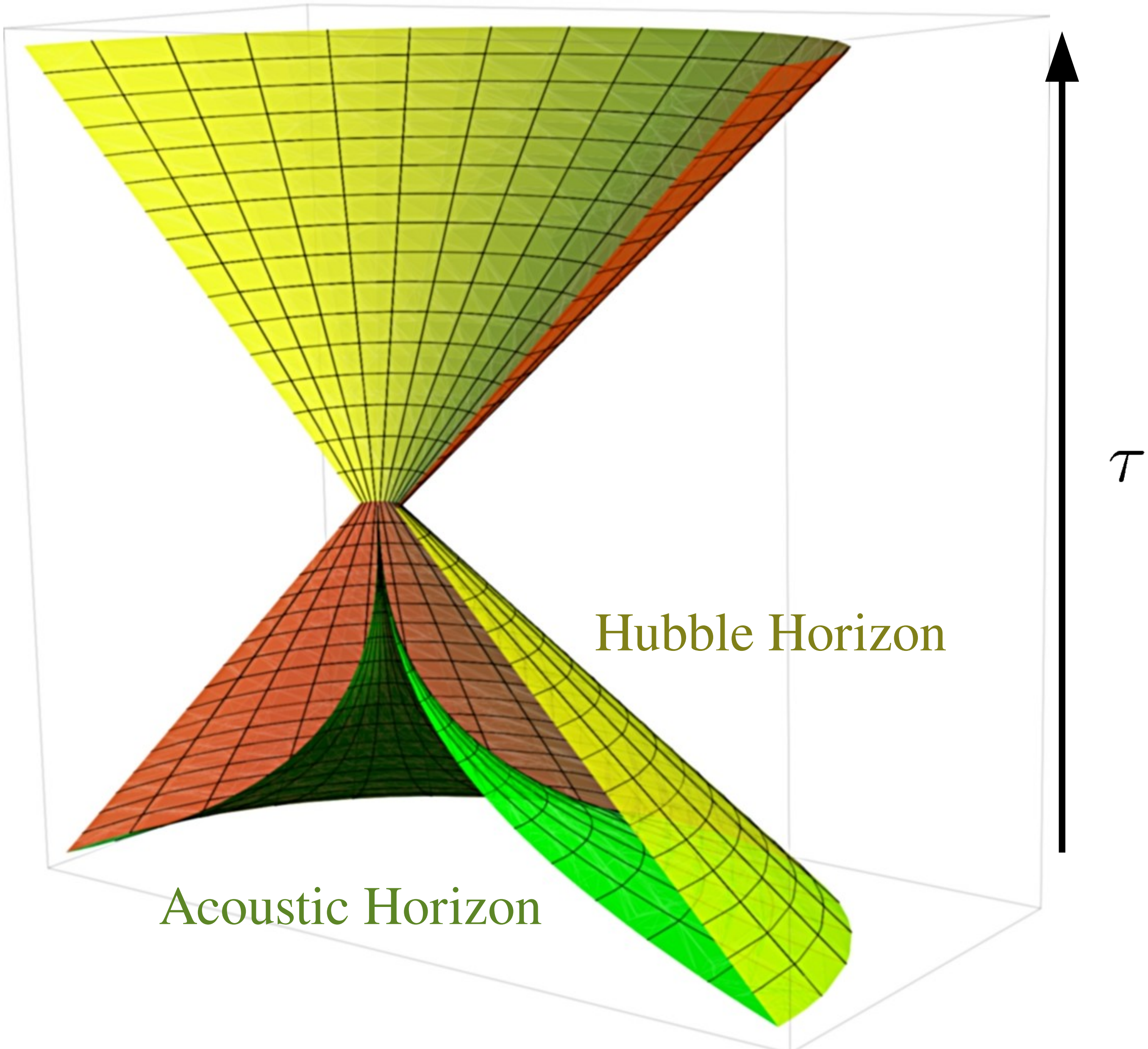
Acoustic metric

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

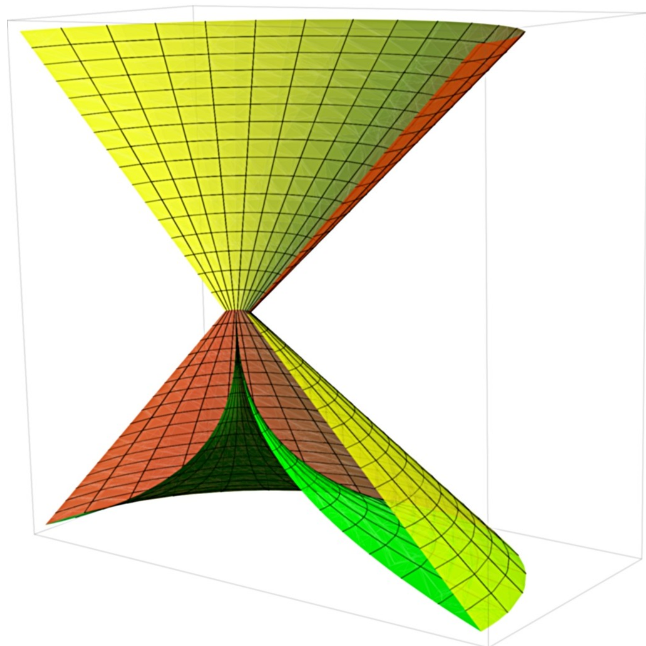
Acoustic cone: $G^{\mu\nu} dx^\mu dx^\nu = 0$

Two horizons!

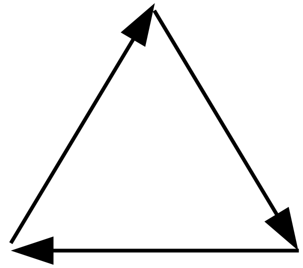
Inflation from non-Canonical Lagrangians



Inflation from non-Canonical Lagrangians

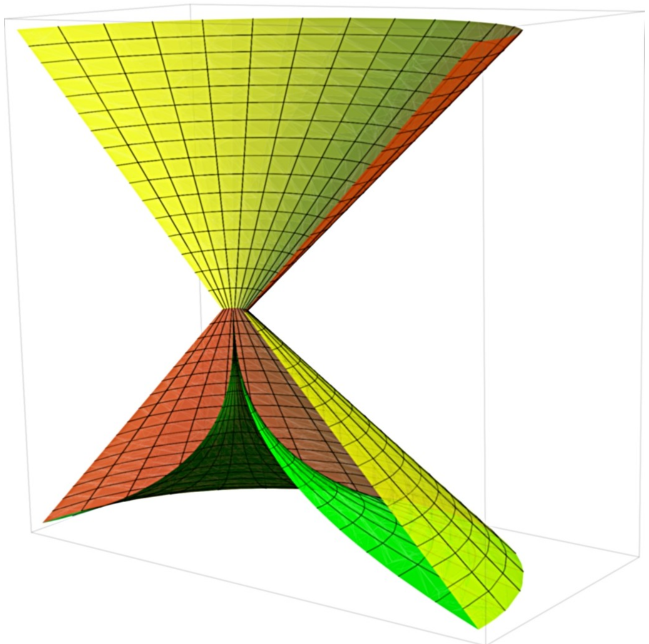


Signature: equilateral bispectrum



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

Inflation from non-Canonical Lagrangians



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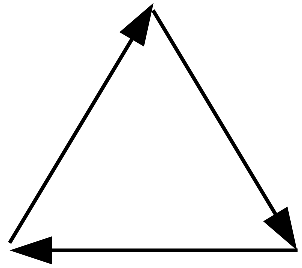


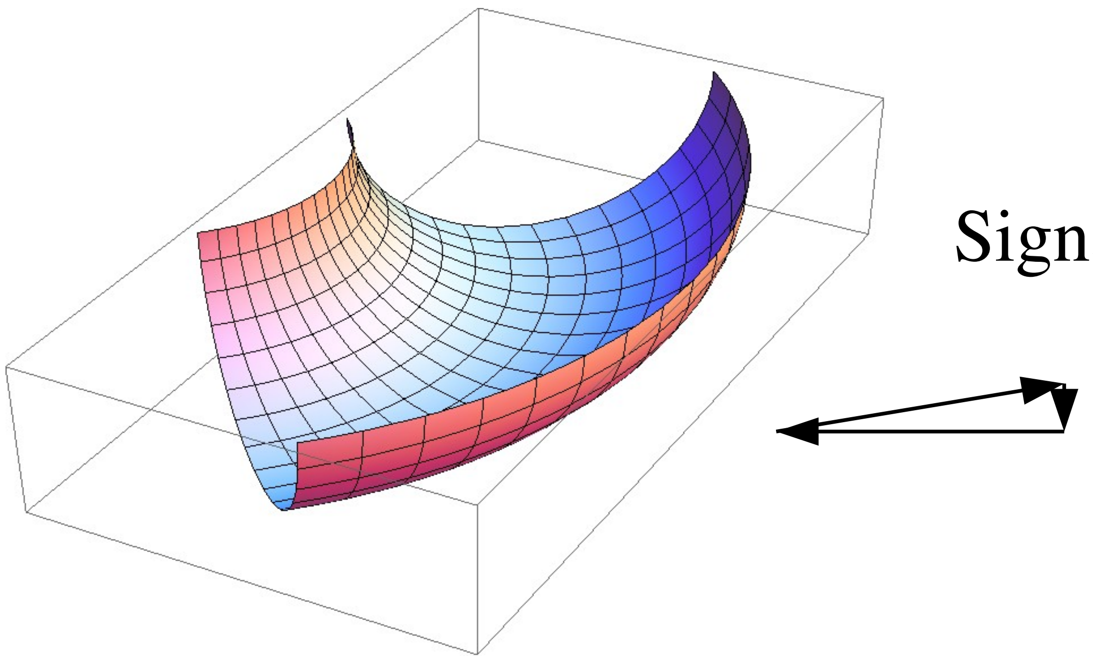
$$f_{\rm NL} \sim c_S^{-2}$$

Planck: $f_{NL}^{\rm equil} = 42 \pm 75$

No evidence for non-canonical inflation

(Planck Collaboration arXiv:1303.5084)

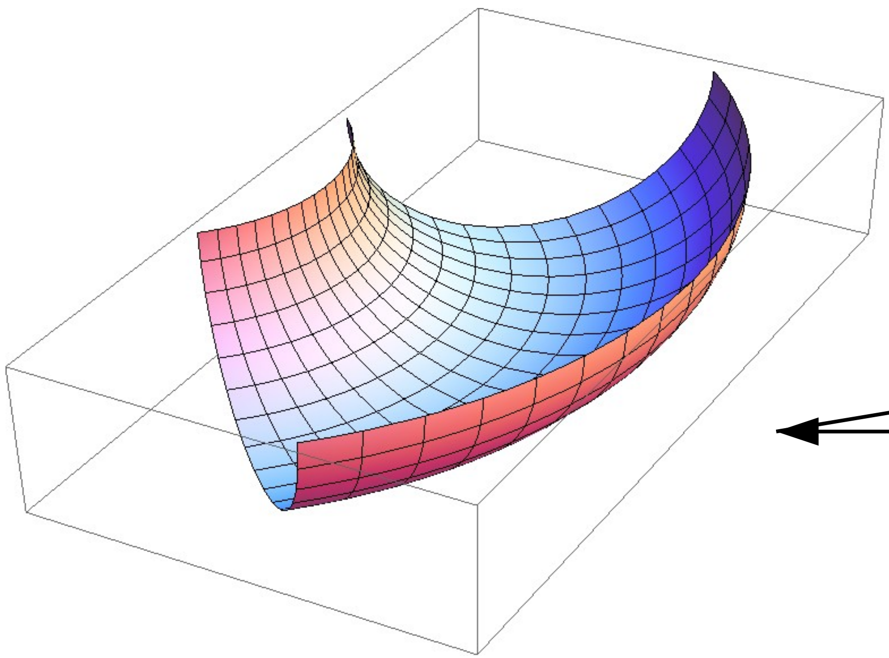
Multi-Field Inflation



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

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

Planck: $f_{NL}^{\mathrm{local}} = 2.7 \pm 5.8$

No evidence for multi-field inflation

(Planck Collaboration arXiv:1303.5084)

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.

Implications of Planck for Single-Field Inflation

- Departure from scale invariance
- Time-dependent equation of state
- Small-field models: mass suppression

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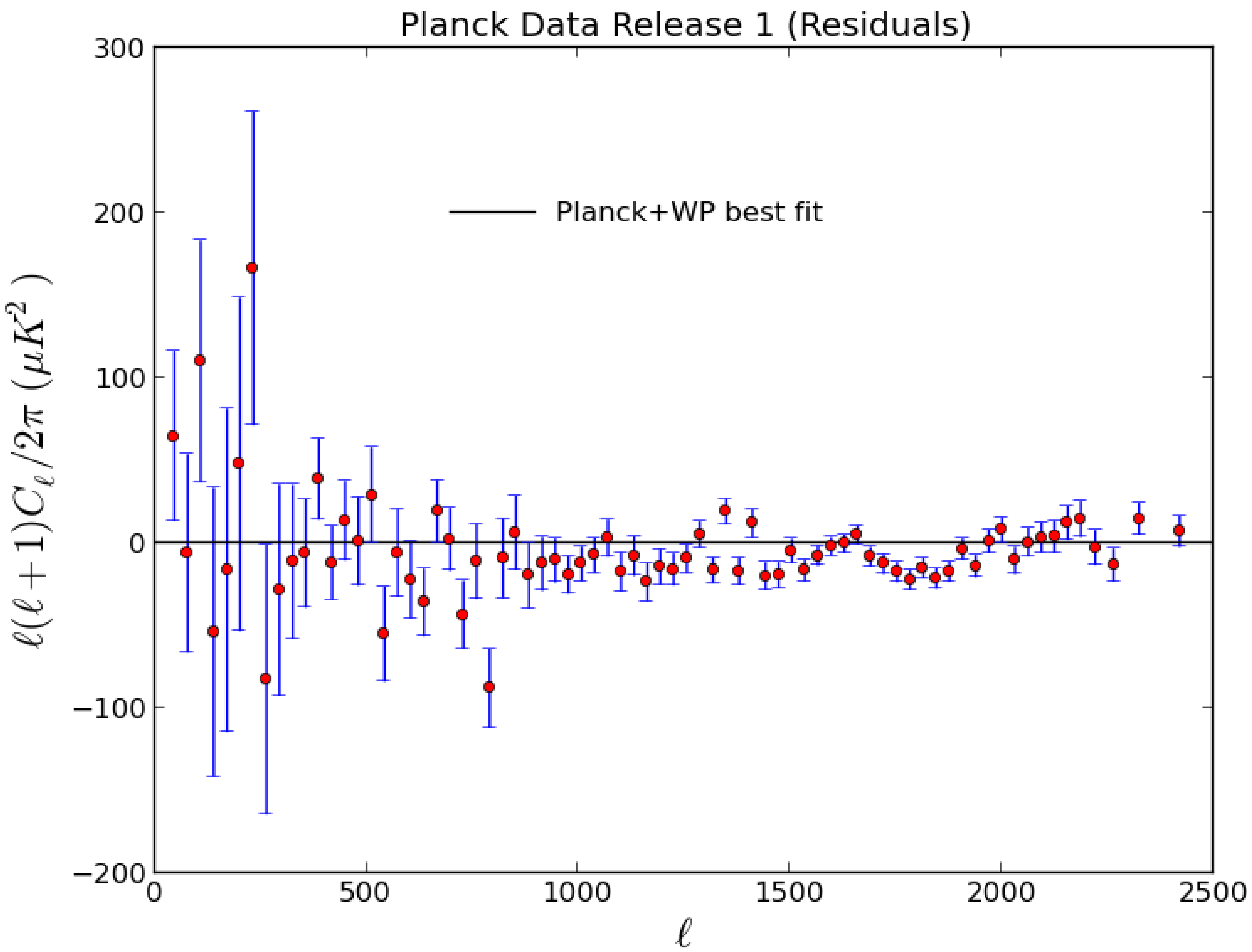
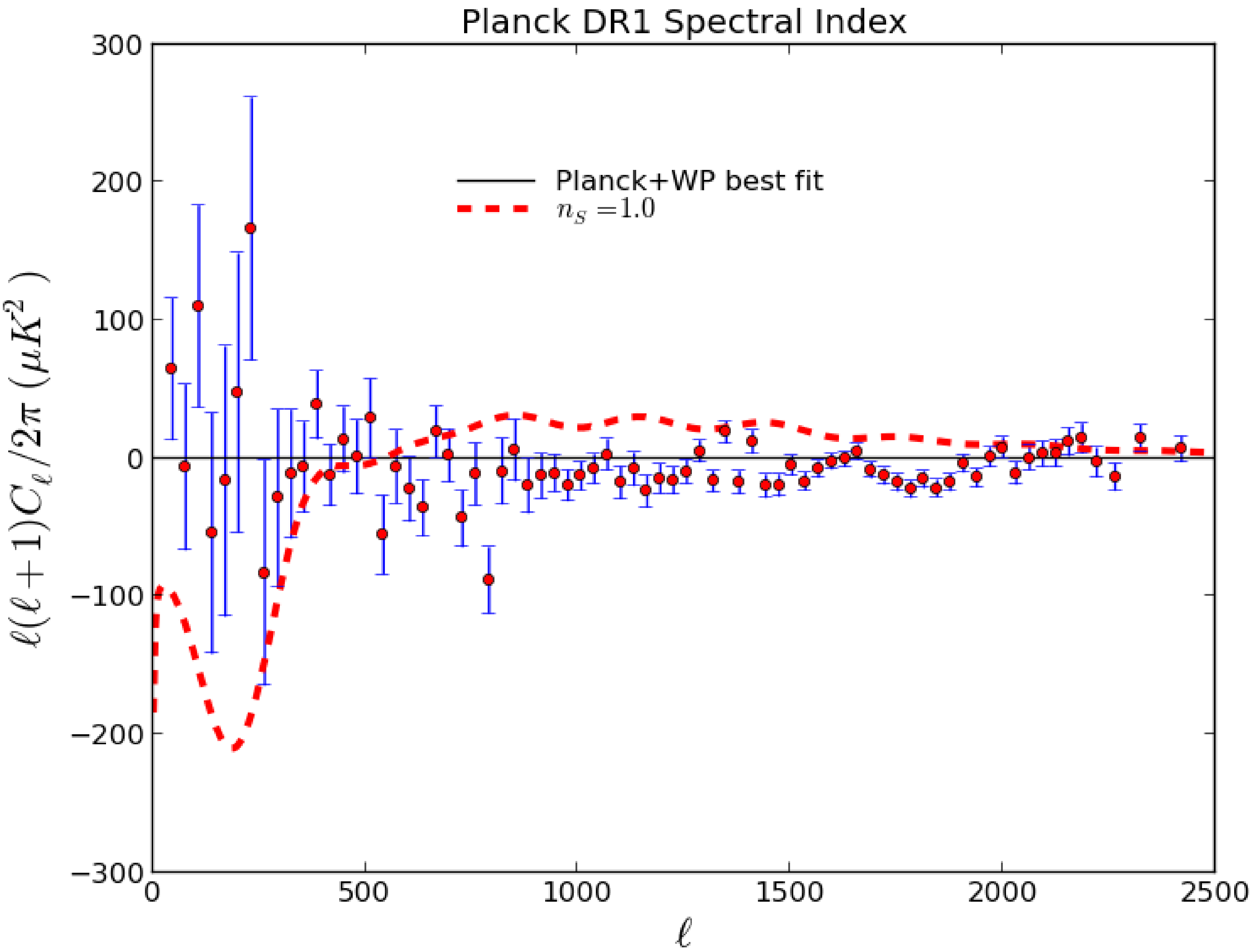


(Data: Planck Legacy Archive)



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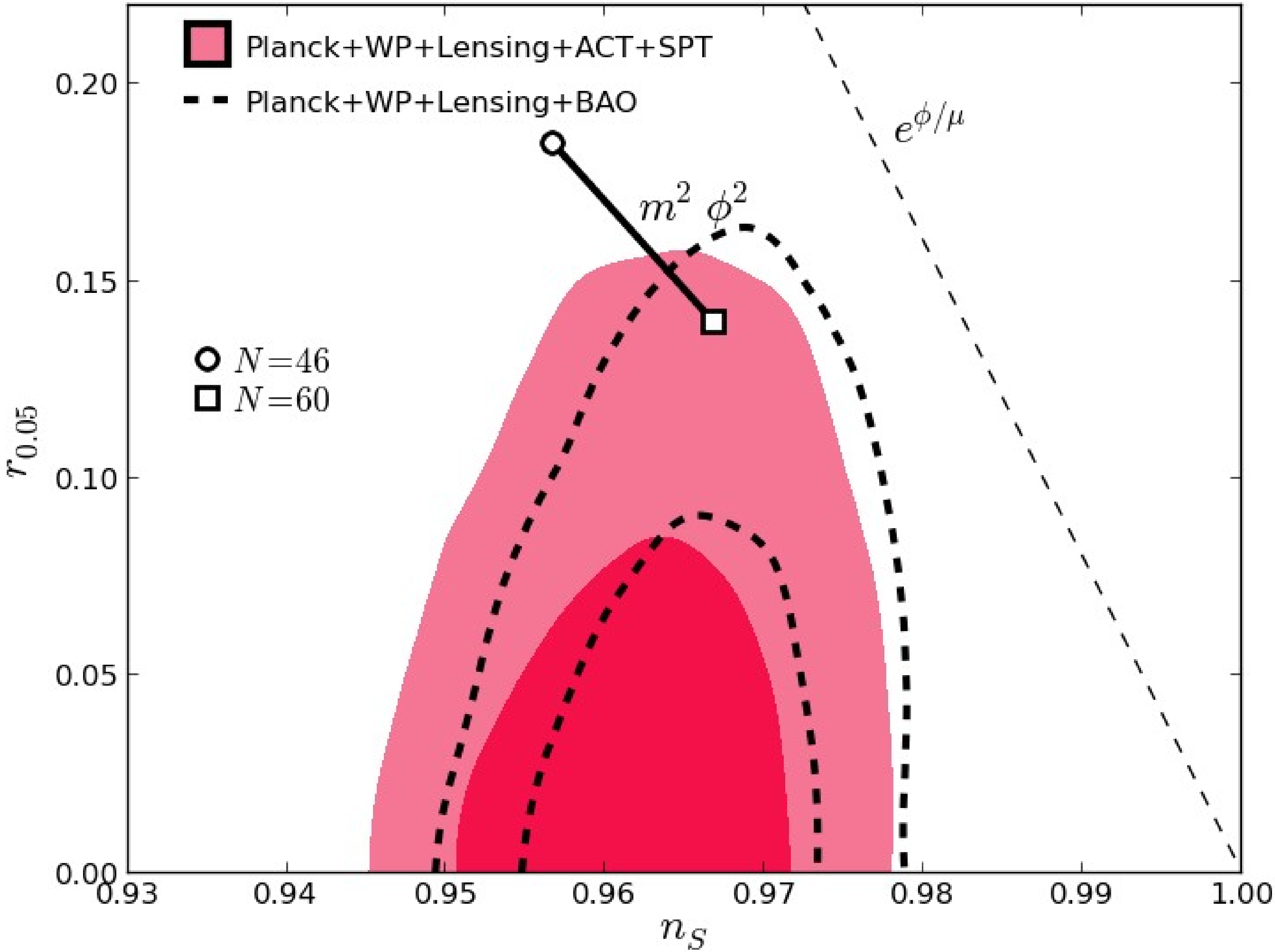


(Data: Planck Legacy Archive)

Implications of Planck for Single-Field Inflation

- Departure from scale invariance
- Time-dependent equation of state
- Small-field models: mass suppression

Power-Law Inflation

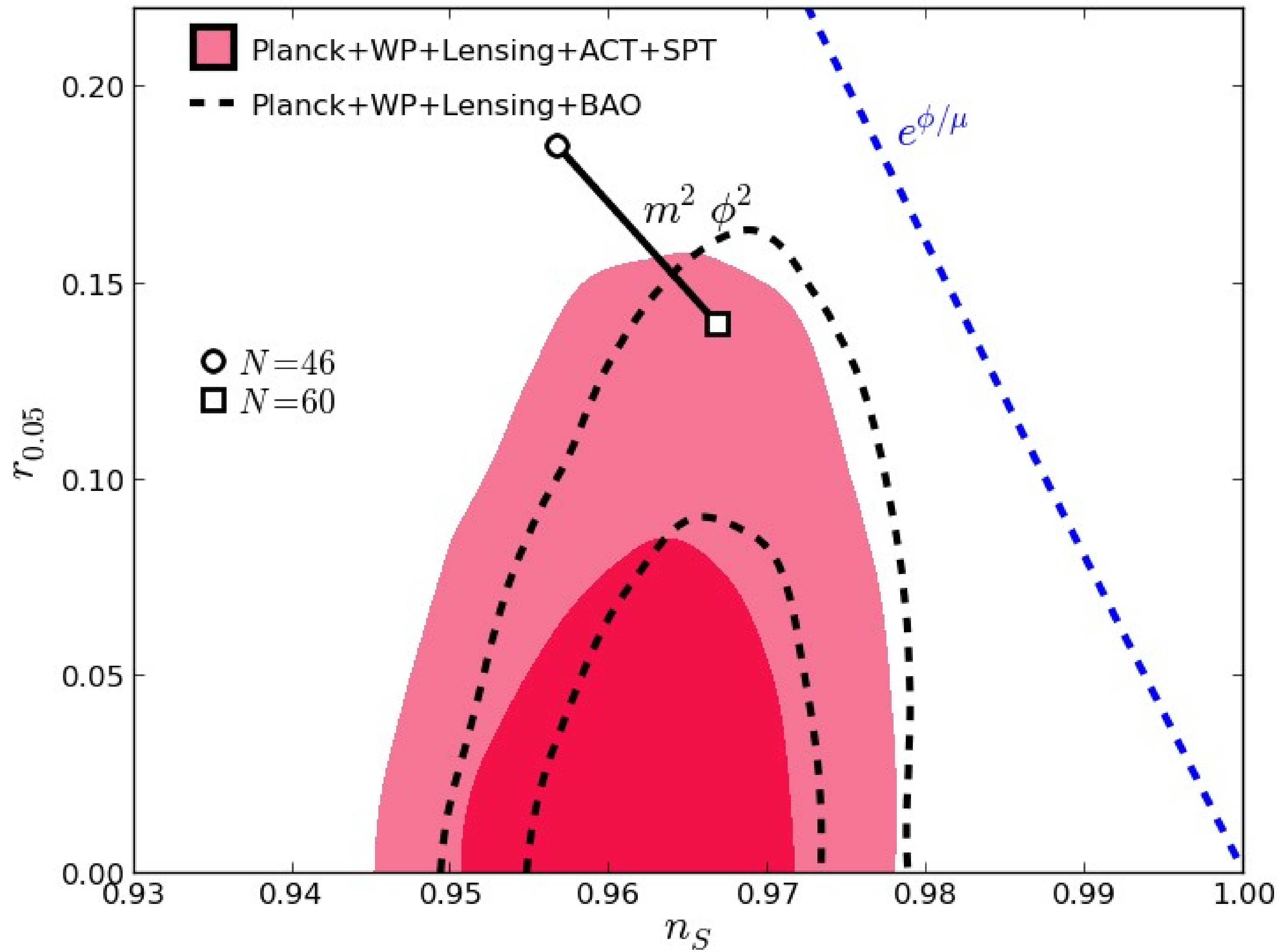
$$\epsilon = -\frac{\dot{H}}{H^2} = \frac{3\,(\rho + p)}{2\rho} = \text{const.} \qquad a(t) \propto t^{1/\epsilon}$$

$$V(\phi) = \Lambda^4 \exp\left(\frac{\sqrt{2\epsilon}\phi}{M_{\rm P}}\right)$$

Relation between n and r:

$$n - 1 = \frac{-2\epsilon}{1-\epsilon} = \frac{-r}{8-2r}$$

Constant Equation of State Excluded



(Data: Planck Legacy Archive)

Implications of Planck for Single-Field Inflation

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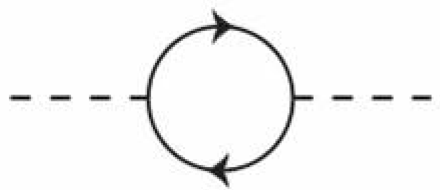
- Time-dependent equation of state
- Small-field models: mass suppression

The η Problem

Second slow roll parameter:

$$\eta \sim \frac{M_P^2}{2}\frac{V''(\phi)}{V(\phi)} \sim \frac{m_\phi^2 M_p^2}{V_0} \sim 10^{-2}$$

Radiative corrections:



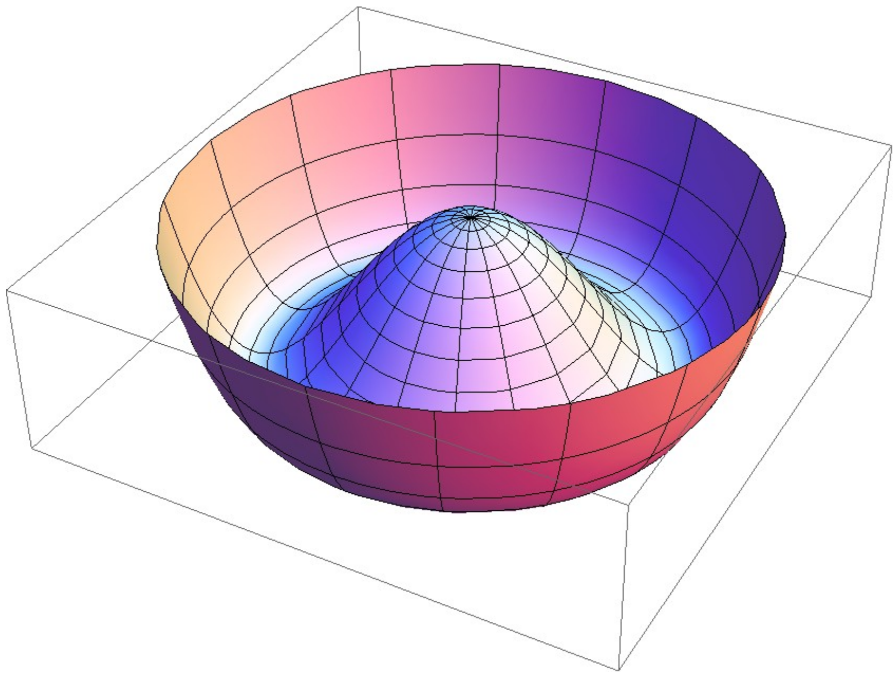
$$m_\phi^2 \sim H^2 \sim \frac{V_0}{M_{\mathrm{P}}^2} \Rightarrow \eta \sim 1$$

Shift Symmetries: Natural Inflation

Freese, Frieman & Olinto, hep-ph/9207245

The idea: introduce a weakly broken global symmetry which protects the mass term.

Shift symmetry: $\mathcal{L}(\phi, \partial_\mu \phi) \rightarrow \mathcal{L}(\phi + \text{const.}, \partial_\mu \phi)$



Shift Symmetries: Natural Inflation

- Non-perturbative axion: Freese *et al.*, hep-ph/9207245

$$V(\phi) \propto \left[1 + \cos\left(\frac{\phi}{\mu}\right)\right]$$

- Chiral symmetry breaking: WHK, Mahanthappa, hep-ph/9503331

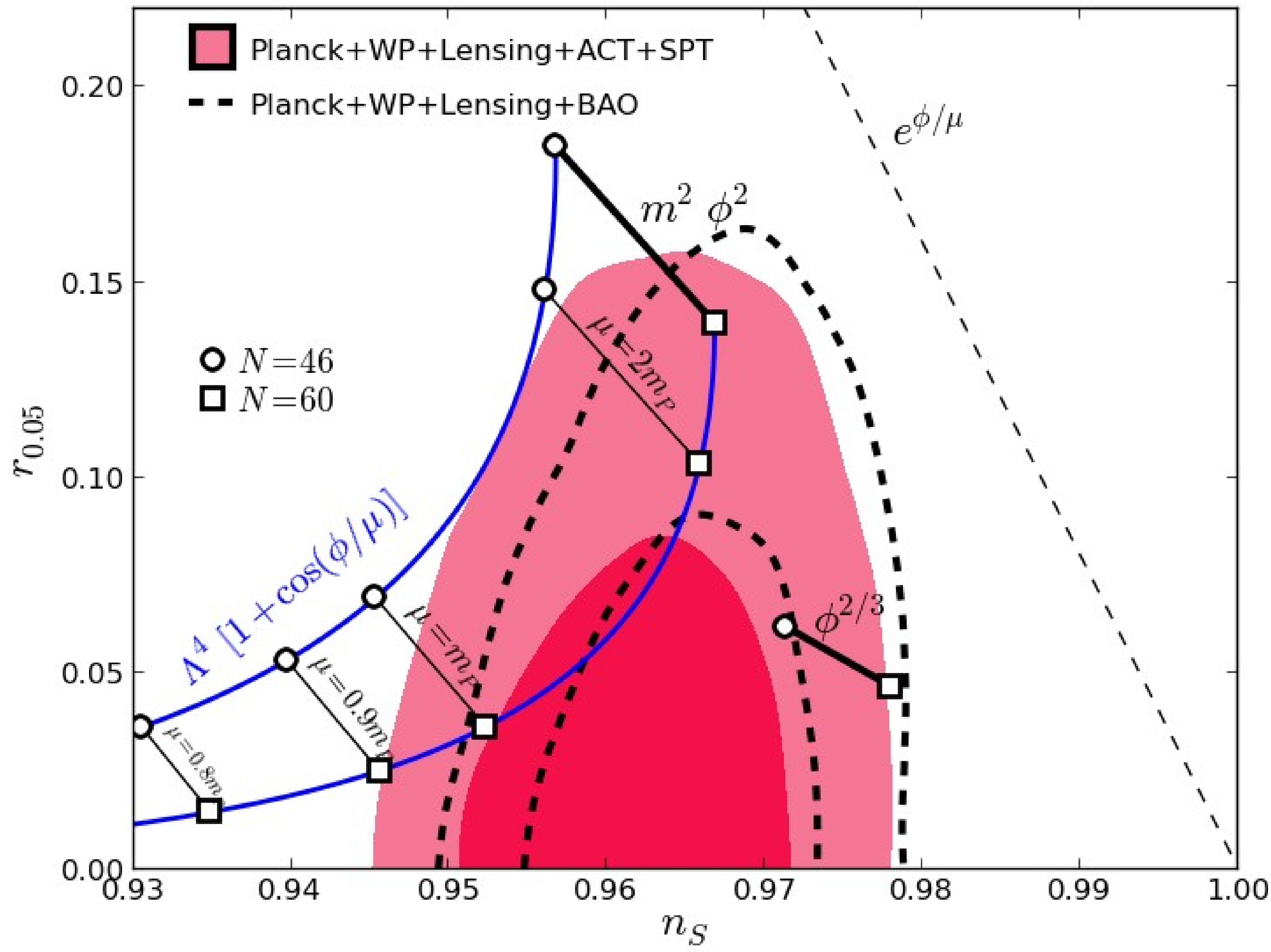
$$V(\phi) \propto \left[m_\psi^2(\phi)\right]^2 \ln\left[m_\psi^2(\phi)\right]$$

- Gauge symmetry breaking: WHK, Mahanthappa, hep-ph/9512241

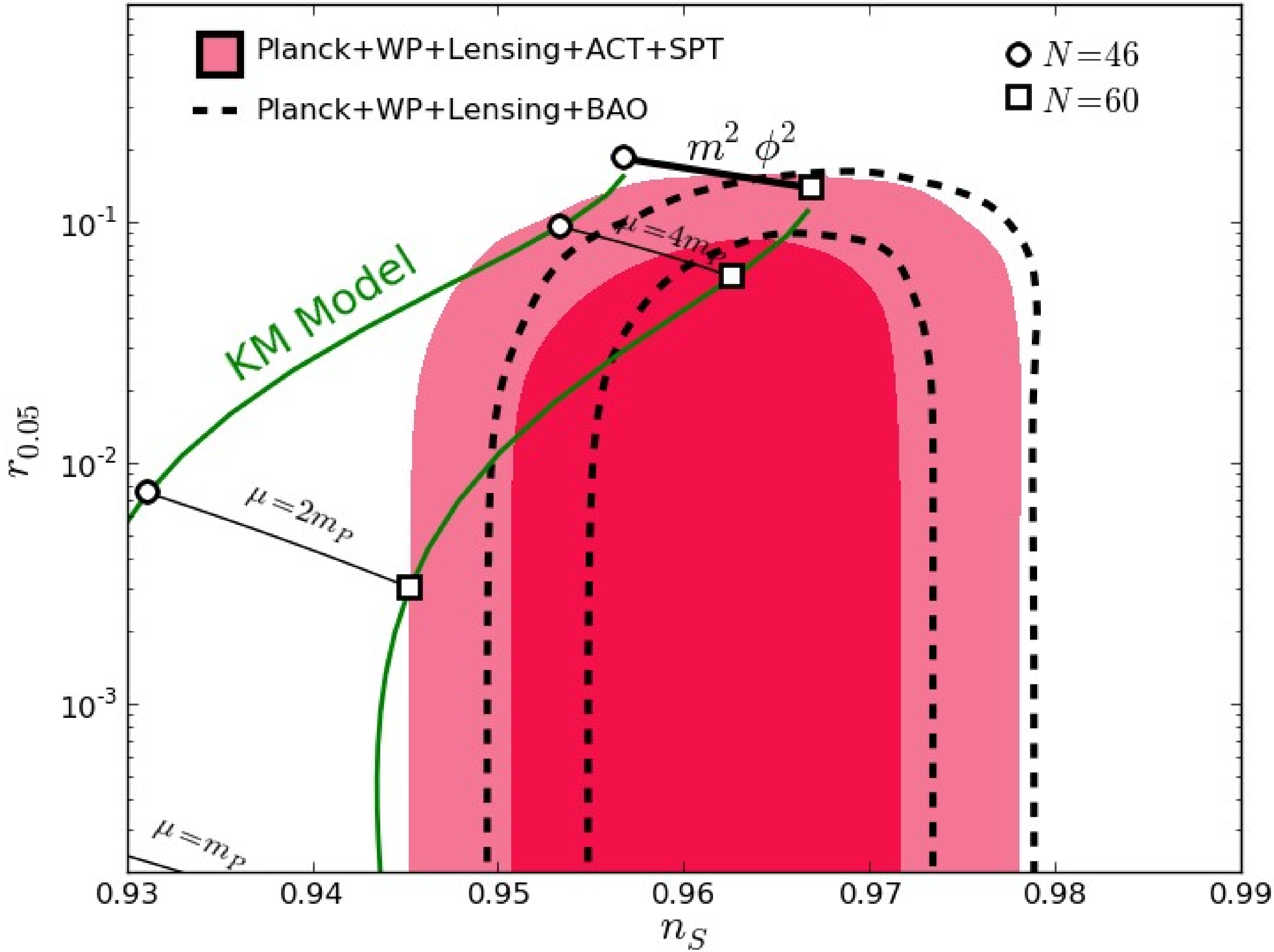
$$V(\phi) \propto \sin\left(\frac{\phi}{\mu}\right)^4 \ln\left[\sin\left(\frac{\phi}{\mu}\right)^2\right] \qquad \text{(KM Model)}$$

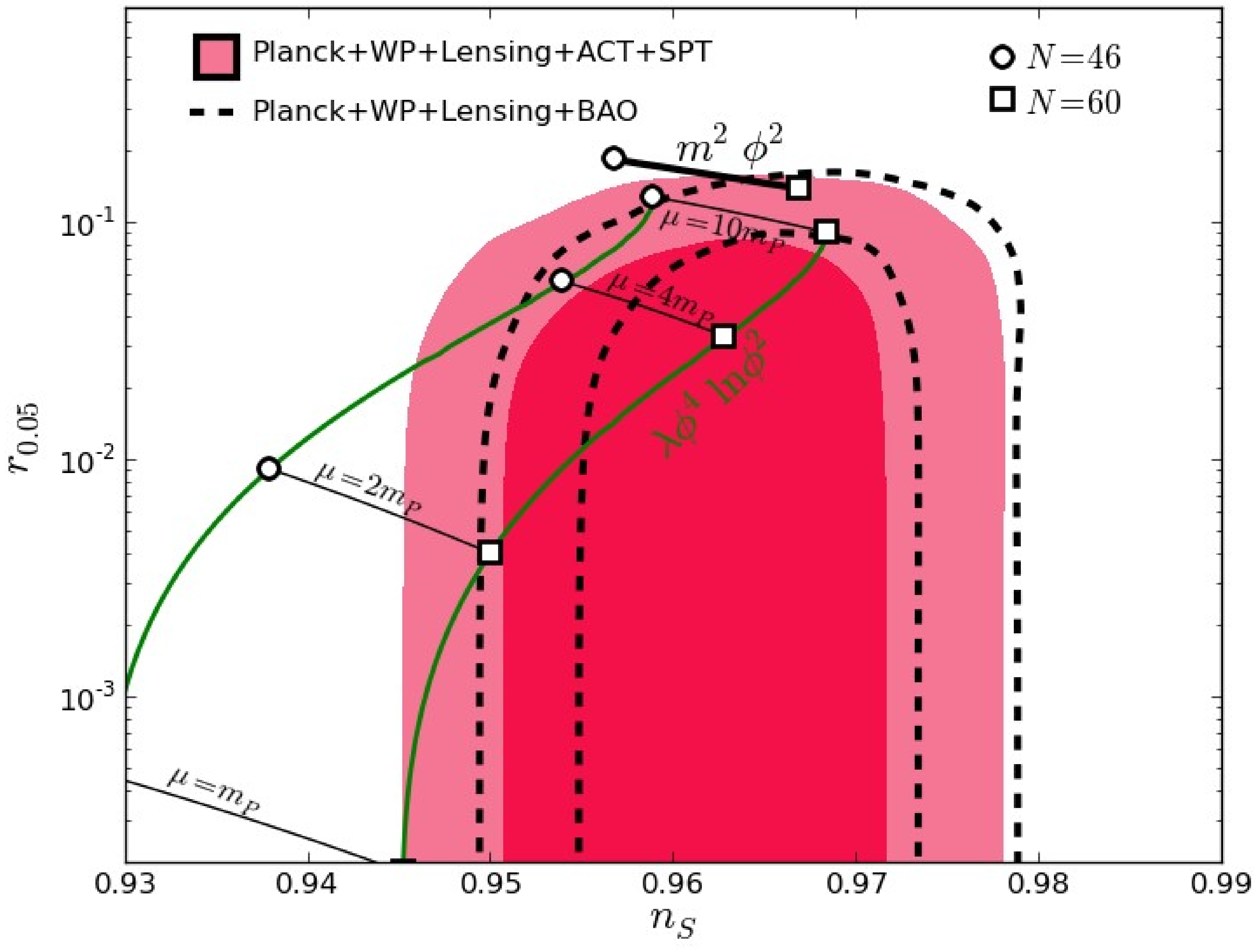
- Axion Monodromy: Silverstein, *et al.*, arXiv:0803.3085

$$V(\phi) \propto \phi^{2/3}$$



(Data: Planck Legacy Archive)


Planck+WP+Lensing+ACT+SPT
Planck+WP+Lensing+BAO
N=46
N=60
m^2 φ^2
μ=4m_P
KM Model
μ=2m_P
μ=m_P
10^-1
10^-2
10^-3
r_0.05
0.93
0.94
0.95
0.96
0.97
0.98
0.99
n_S



(Data: Planck Legacy Archive)

Natural Inflation and Effective Field Theory

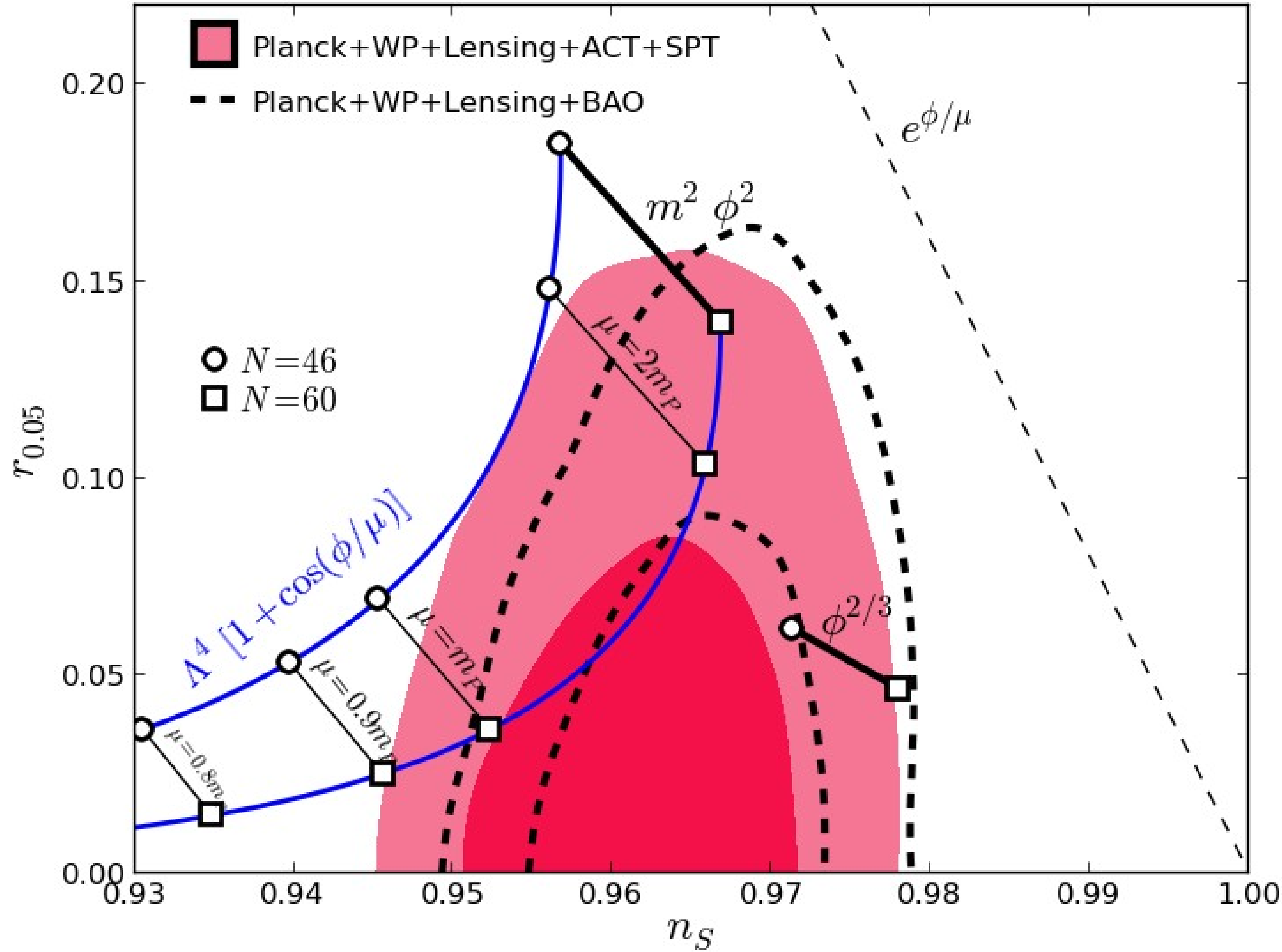
Effective potential suppressed by mass scale μ

$$V(\phi) = V_0 - \sum_p \lambda_p \left(\frac{\phi}{\mu}\right)^p$$

Lowest-order term *always* dominates near origin:

$$p = 2: \; V(\phi) \simeq V_0 - m^2\phi^2 + \cdots$$

$$p = 4: \; V(\phi) \simeq V_0 - \lambda\phi^4 + \cdots$$



(Data: Planck Legacy Archive)

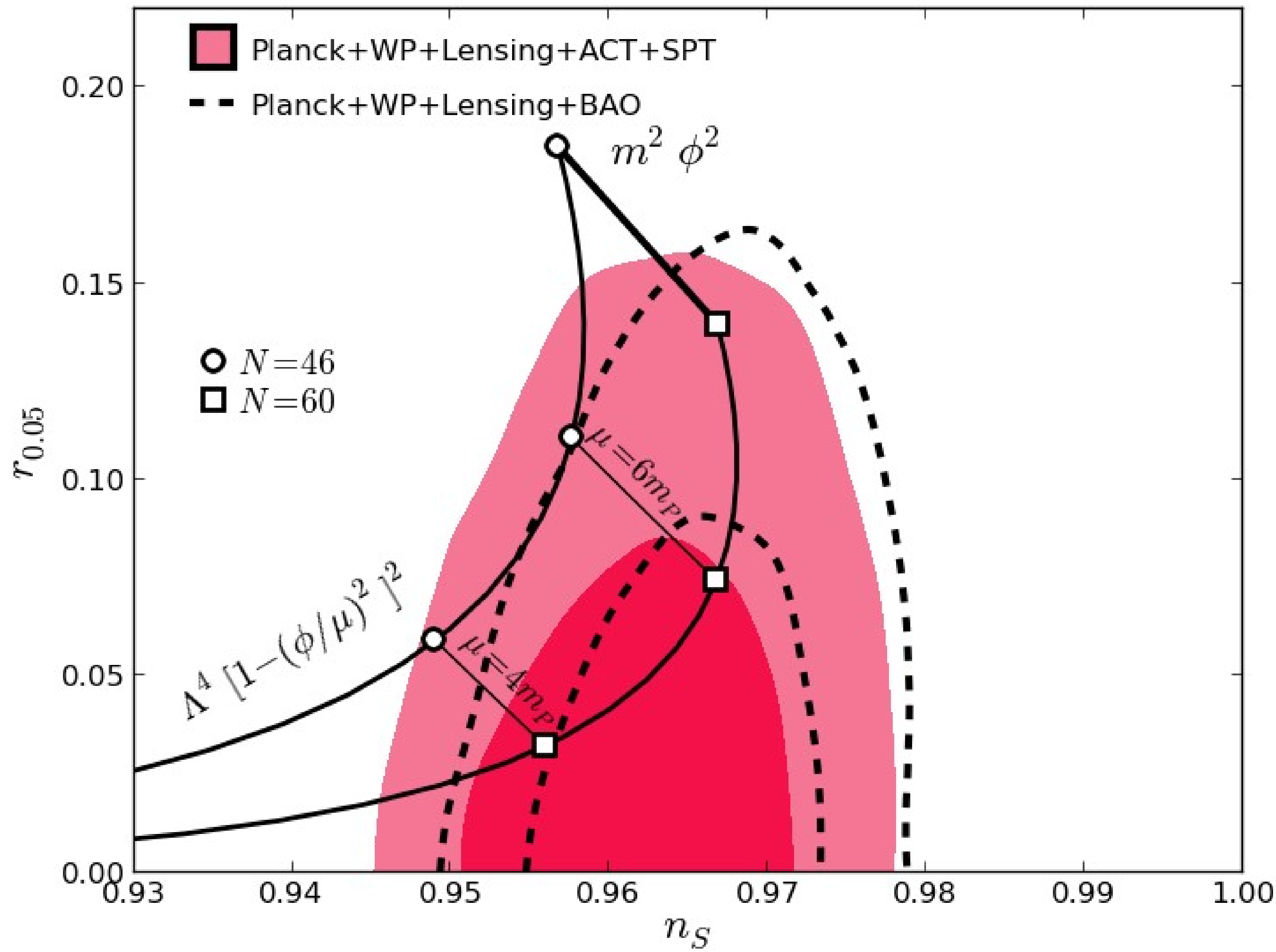
Natural Inflation and Effective Field Theory

Effective potential suppressed by mass scale μ

$$V(\phi) = V_0 - \sum_p \lambda_p \left(\frac{\phi}{\mu}\right)^p$$

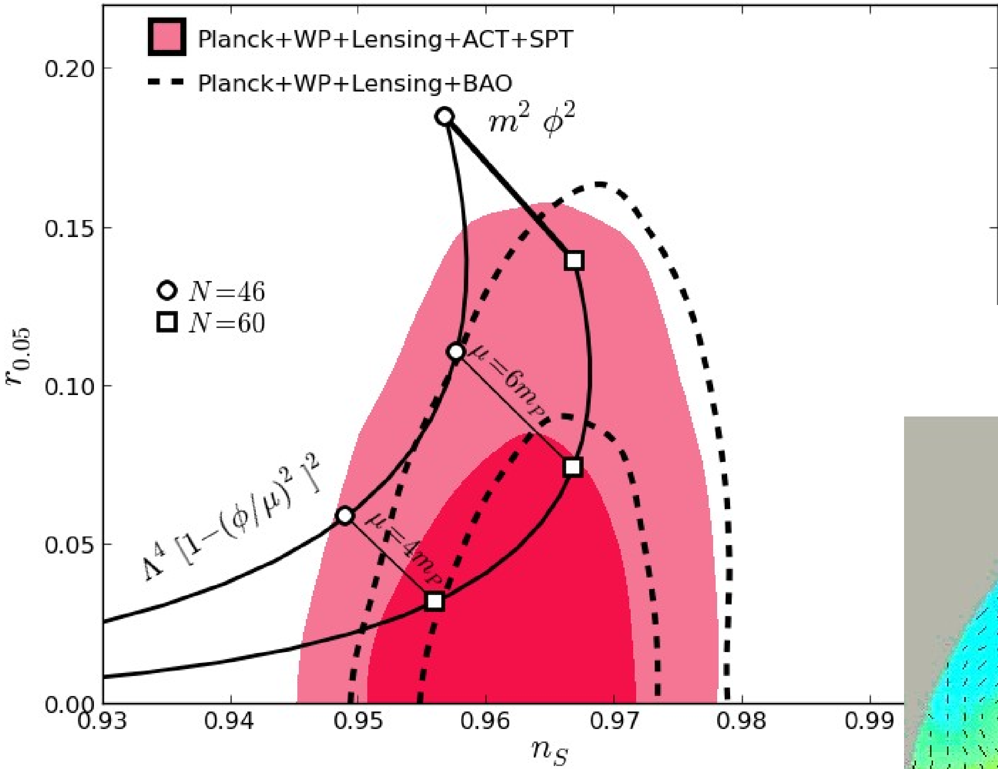
$p = 2:$ Spectral index quadratic in scale

$$n = 1 - \frac{1}{4\pi}\left(\frac{m_{\rm P}}{\mu}\right)^2$$



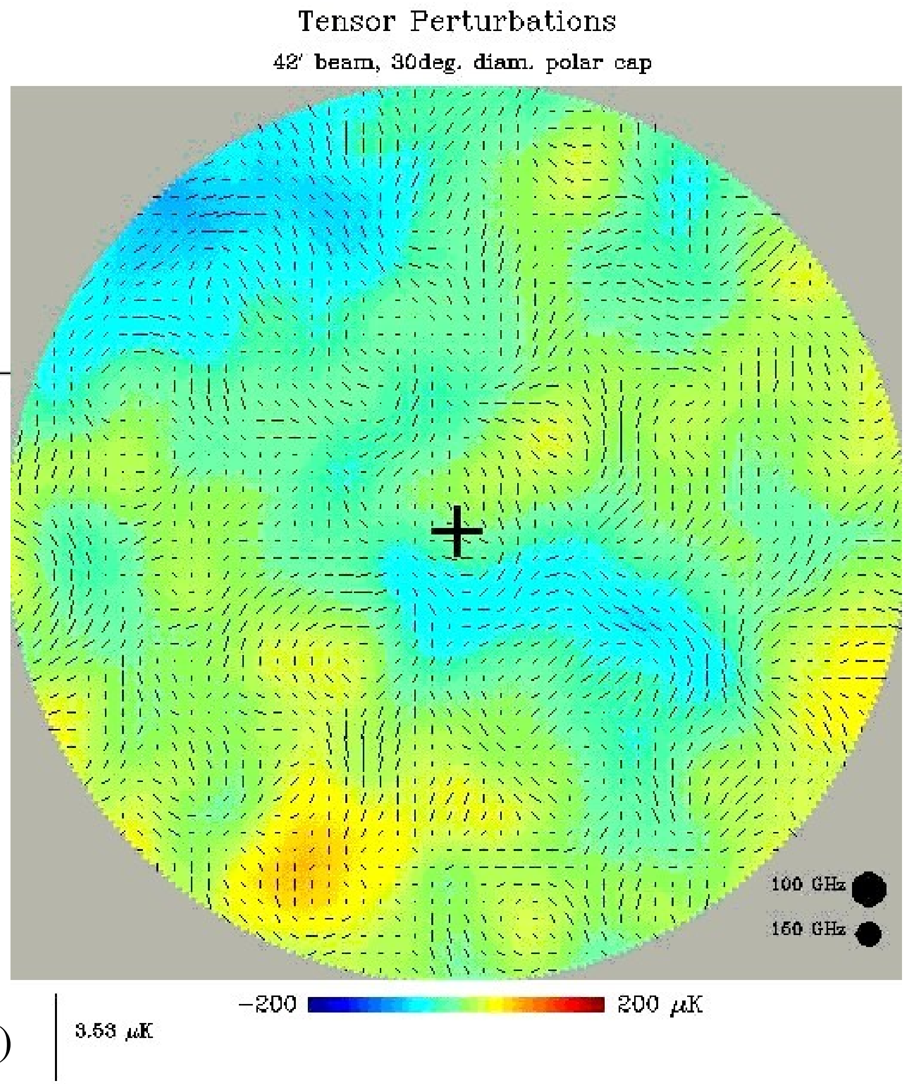
(Data: Planck Legacy Archive)

Tensors and CMB Polarization



Quadratic potentials:

$r > 0.02$



BICEP / POLAR / ABS / POLARBEAR / QUIET / SPTpol / ACTpol / SPIDER / EBEX / QUIJOTE

(Figure: BICEP collaboration)

Natural Inflation and Effective Field Theory

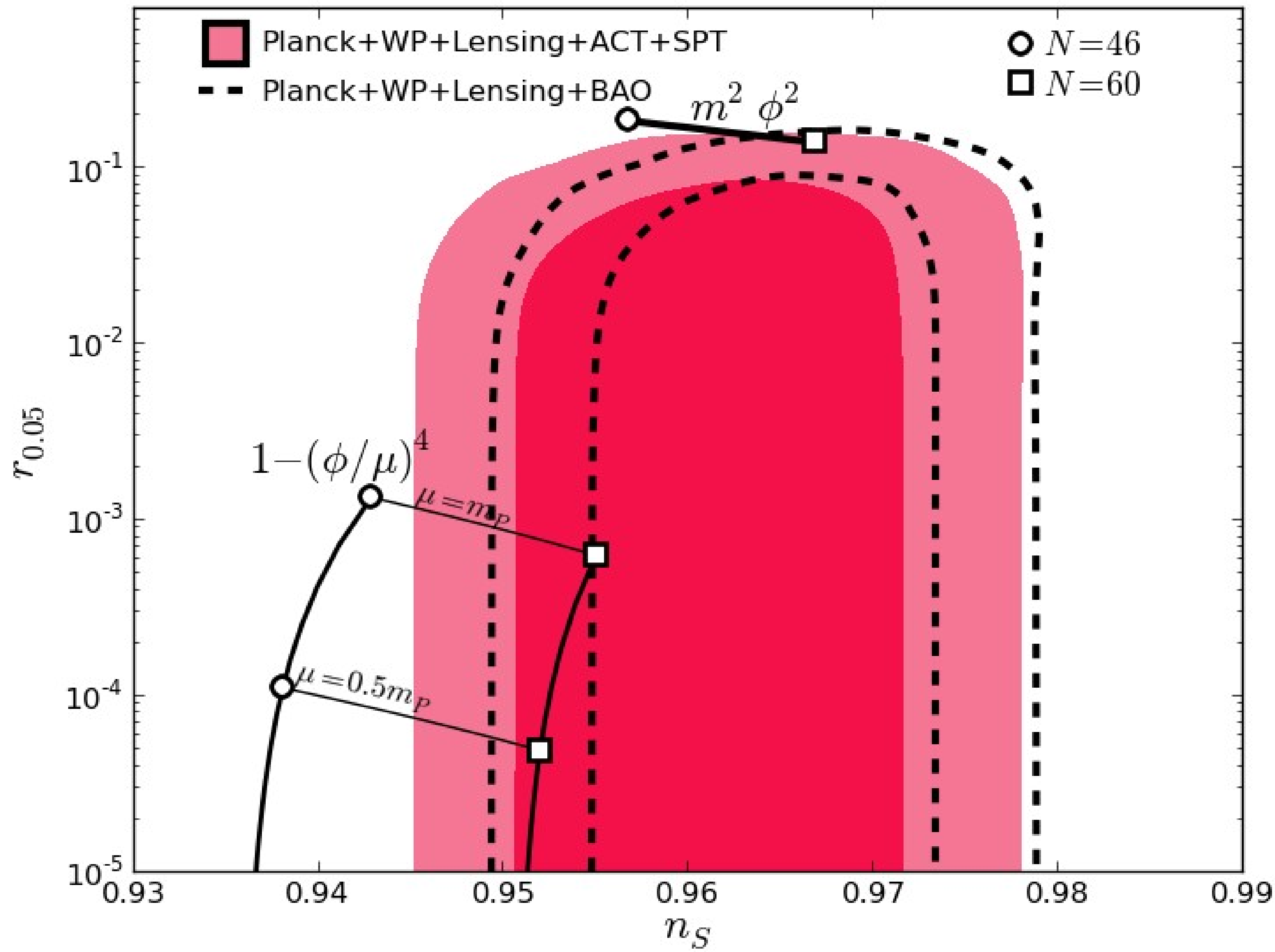
Effective potential suppressed by mass scale μ

$$V(\phi) = V_0 - \sum_p \lambda_p \left(\frac{\phi}{\mu}\right)^p$$

$p > 2:$ Spectral index *independent* of scale $\qquad p \geq 4$

$$n = 1 - \left(\frac{2}{N}\right)\frac{p-1}{p-2} = [0.935, 0.967]$$

(WHK, Mahanthappa, hep-ph/9512241)



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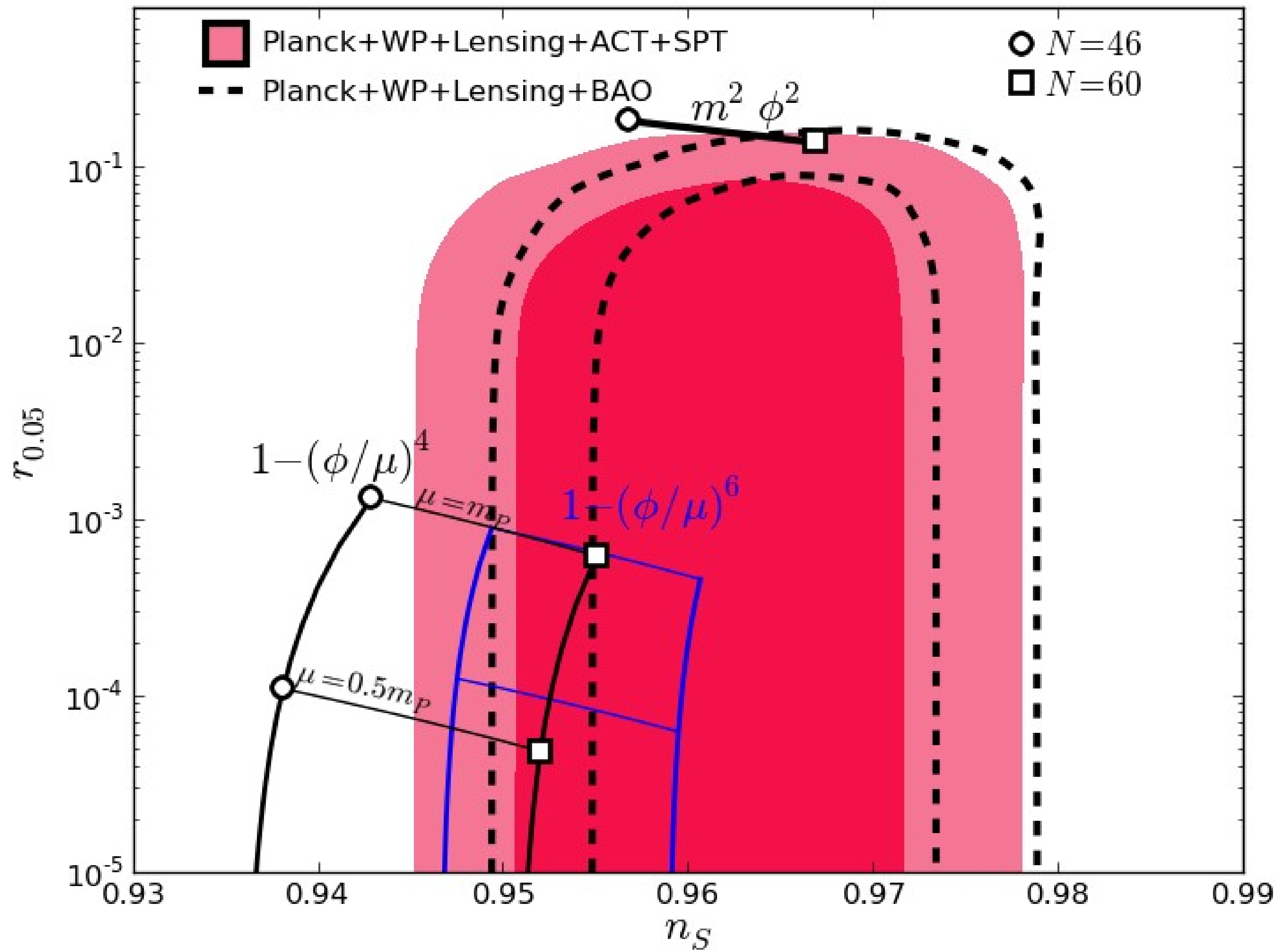

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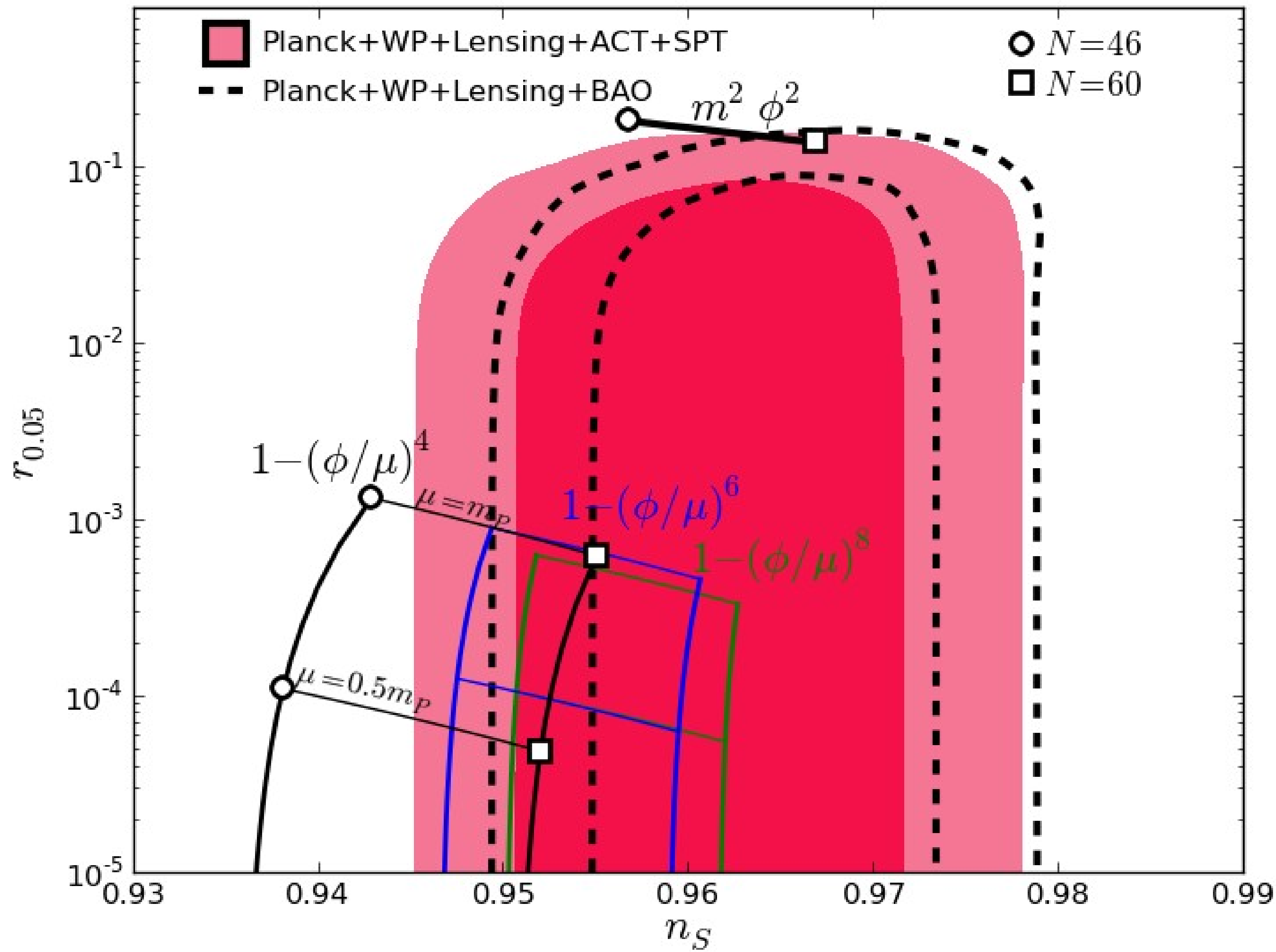
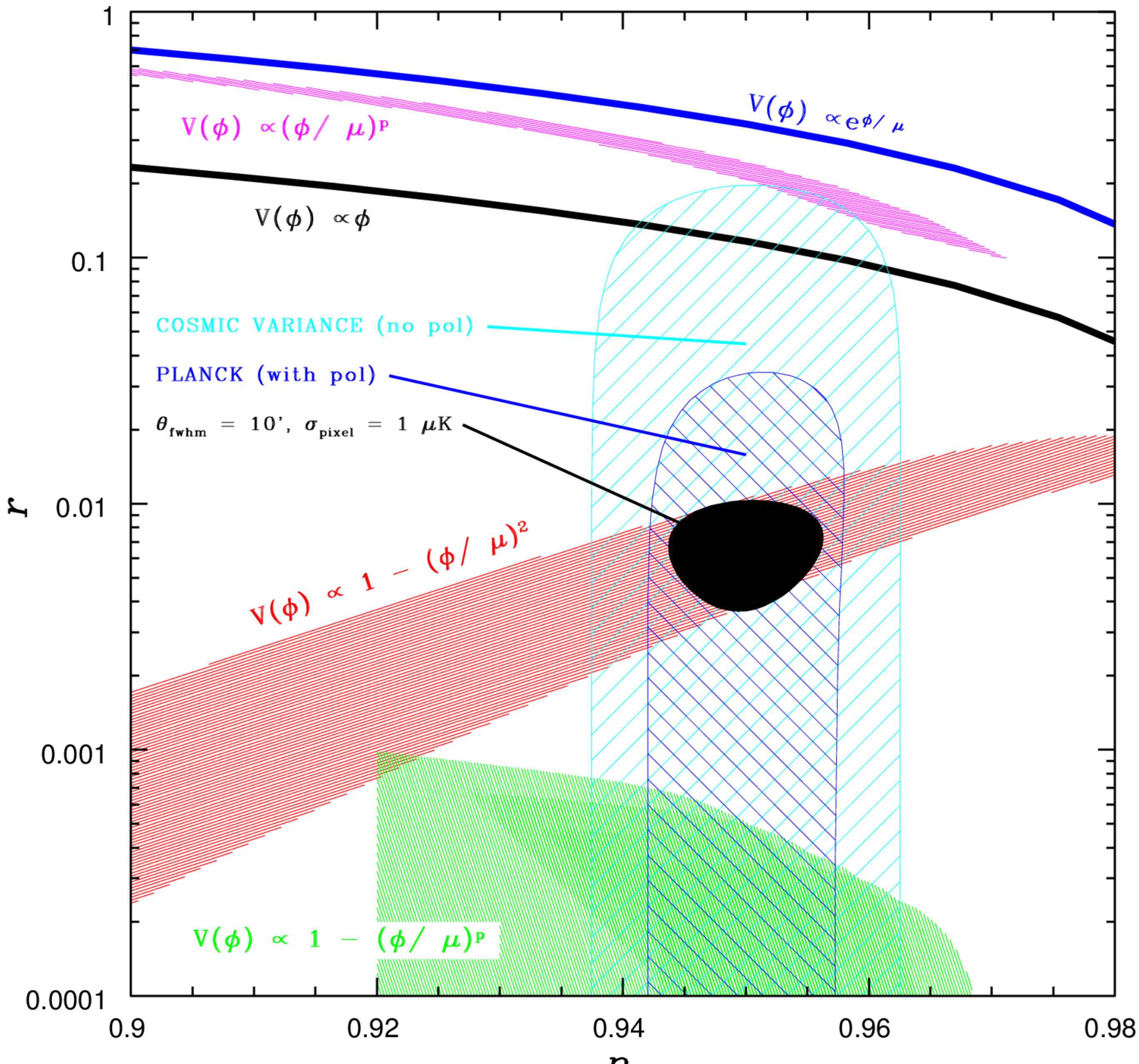


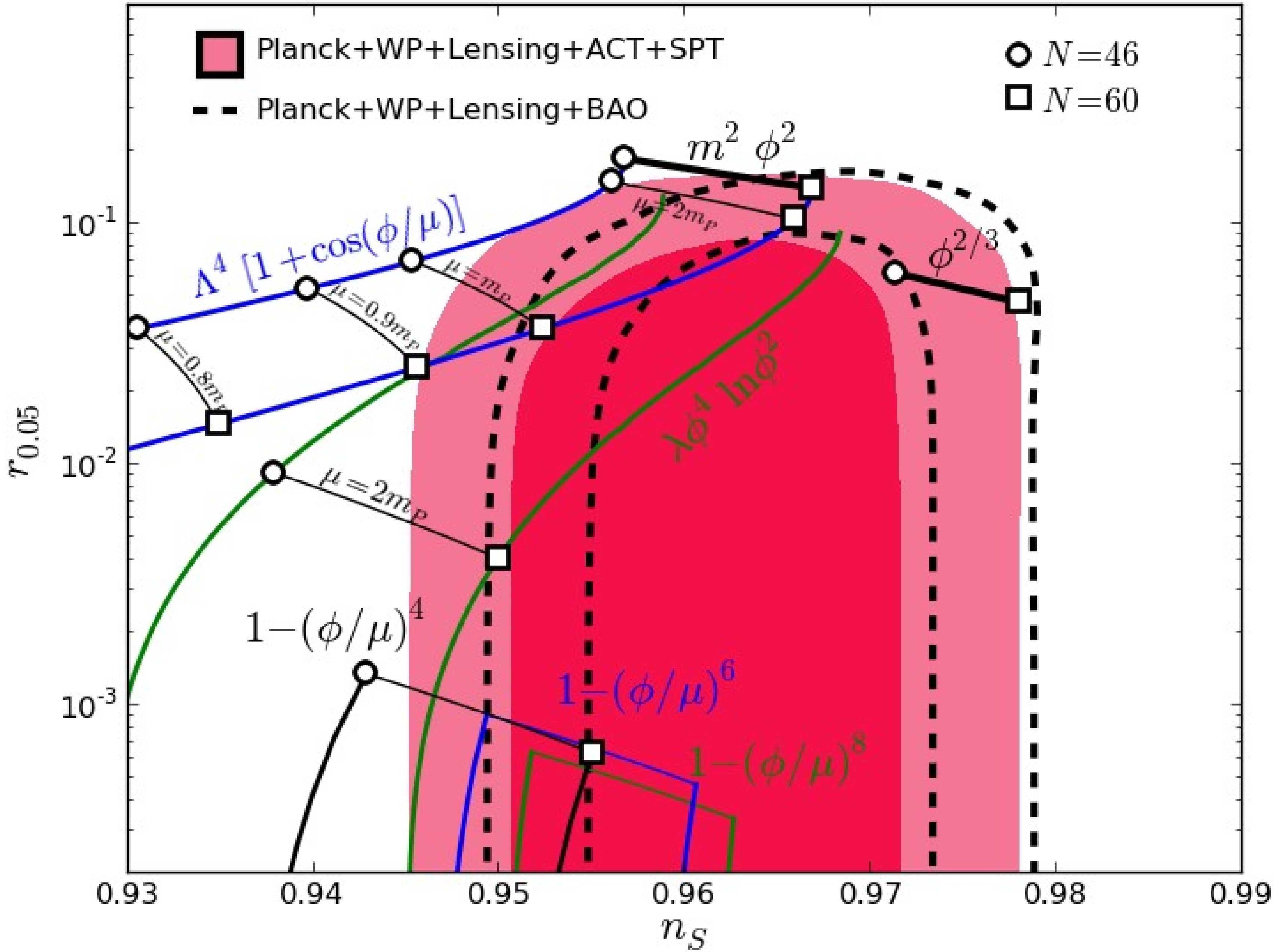
(Data: Planck Legacy Archive)

Planck: 1998 Forecast



(WHK, astro-ph/9806259)

Summary: Planck and Natural Inflation



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