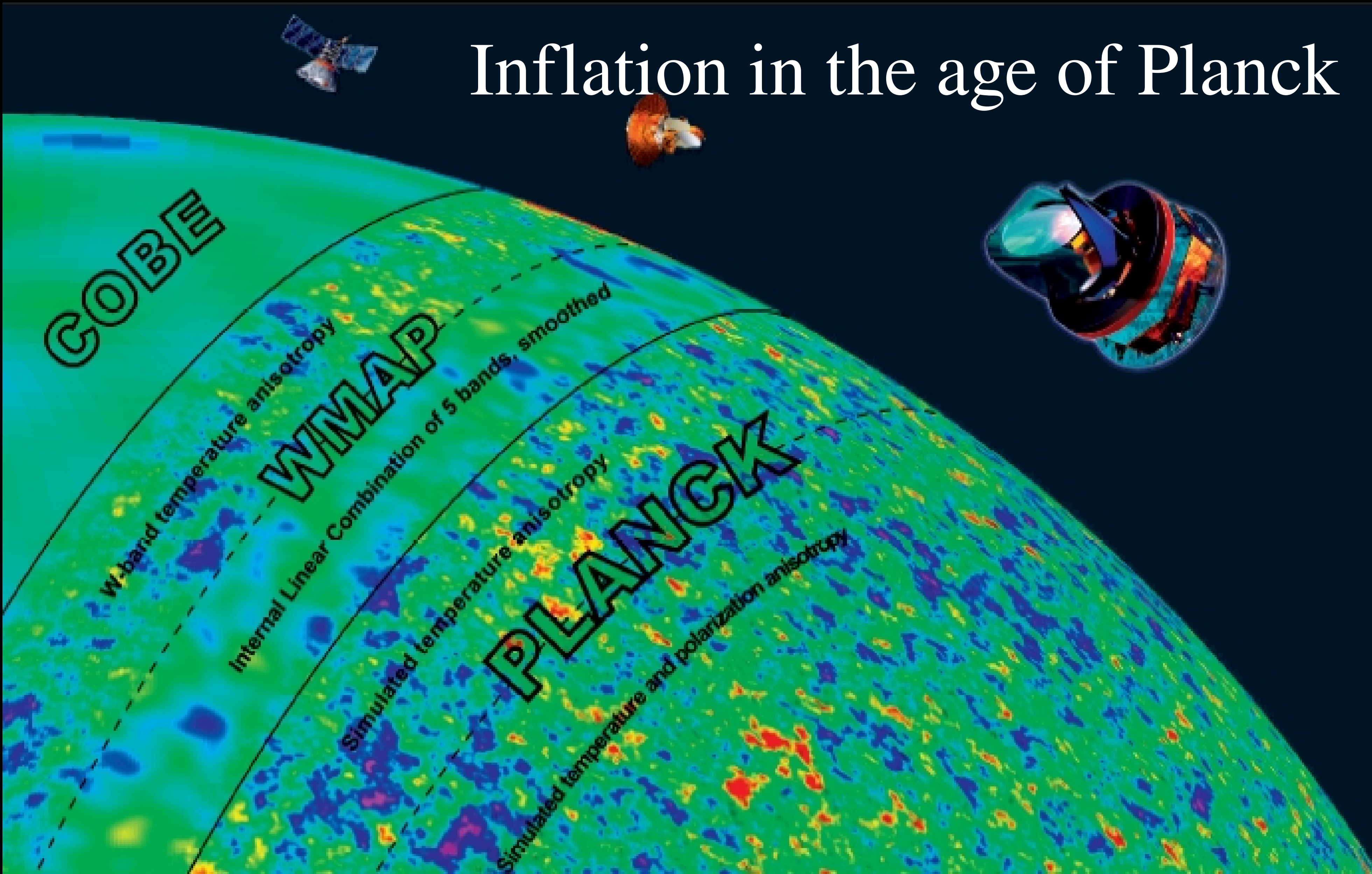
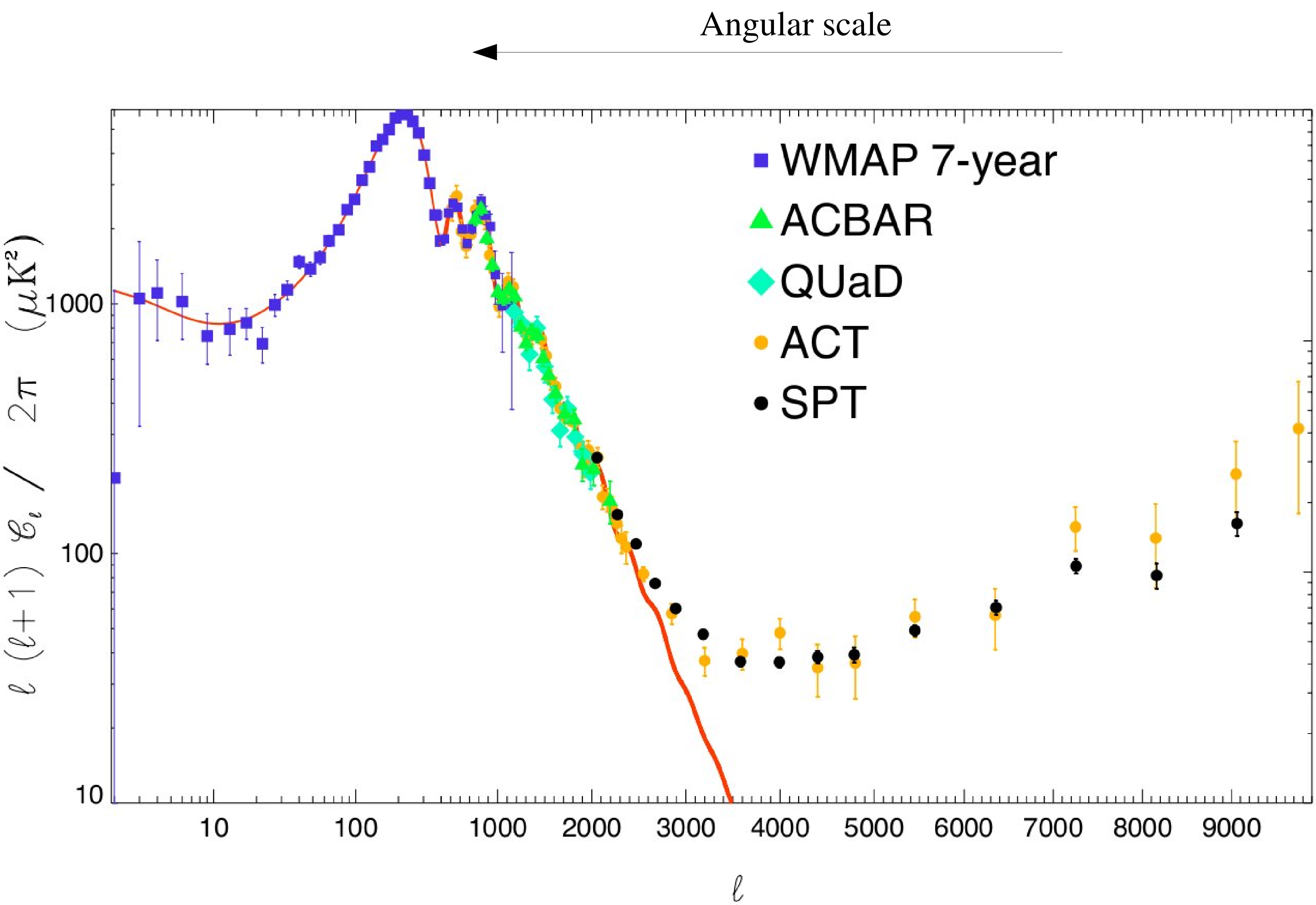
Inflation in the age of Planck



Will Kinney
University at Buffalo *The State University of New York*

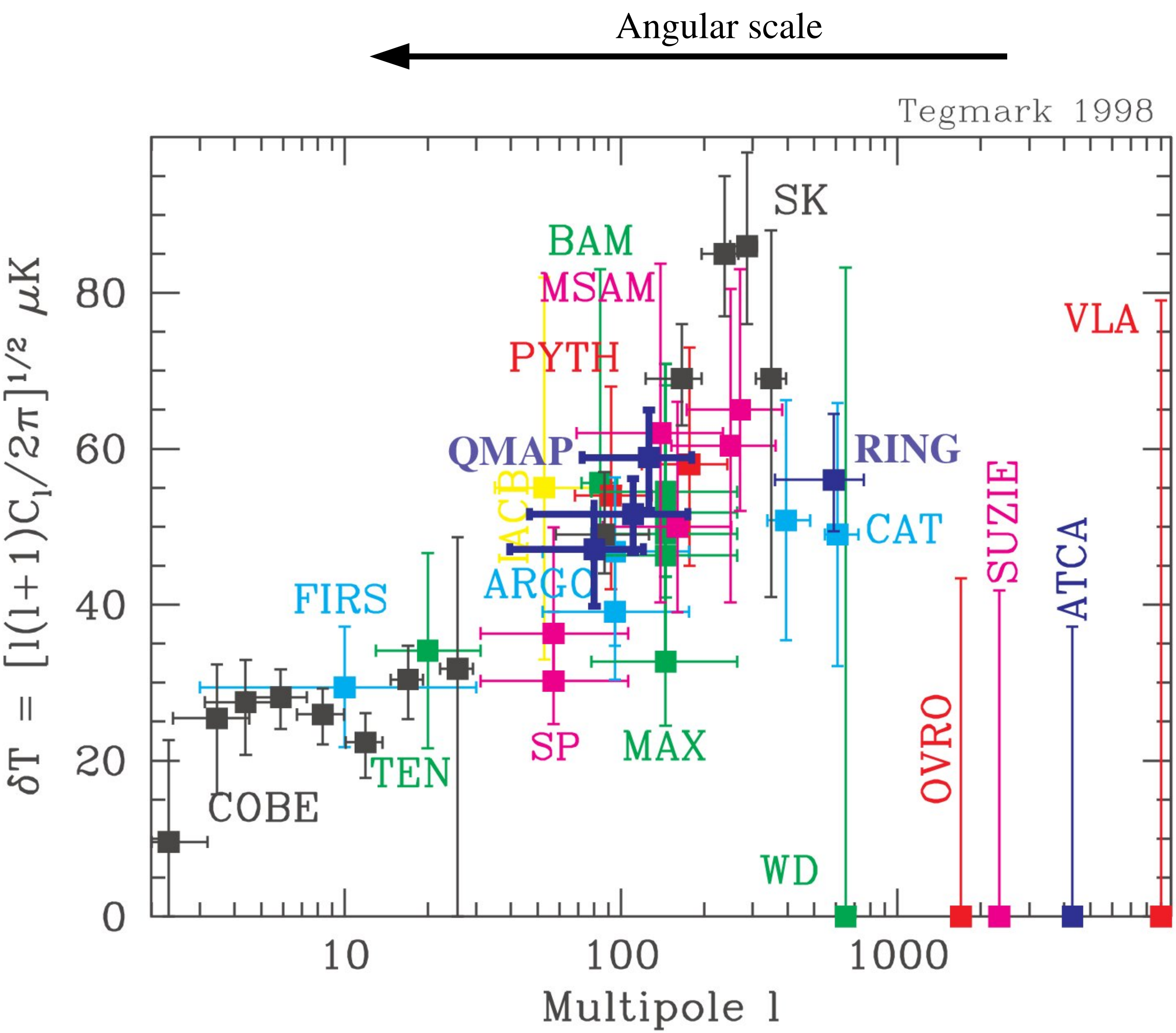
Workshop on Cosmic Acceleration
Carnegie Mellon University
25 August 2012

The CMB Angular Power Spectrum (2012)



(Shirokoff, *et al.*, arXiv:1012.4788)

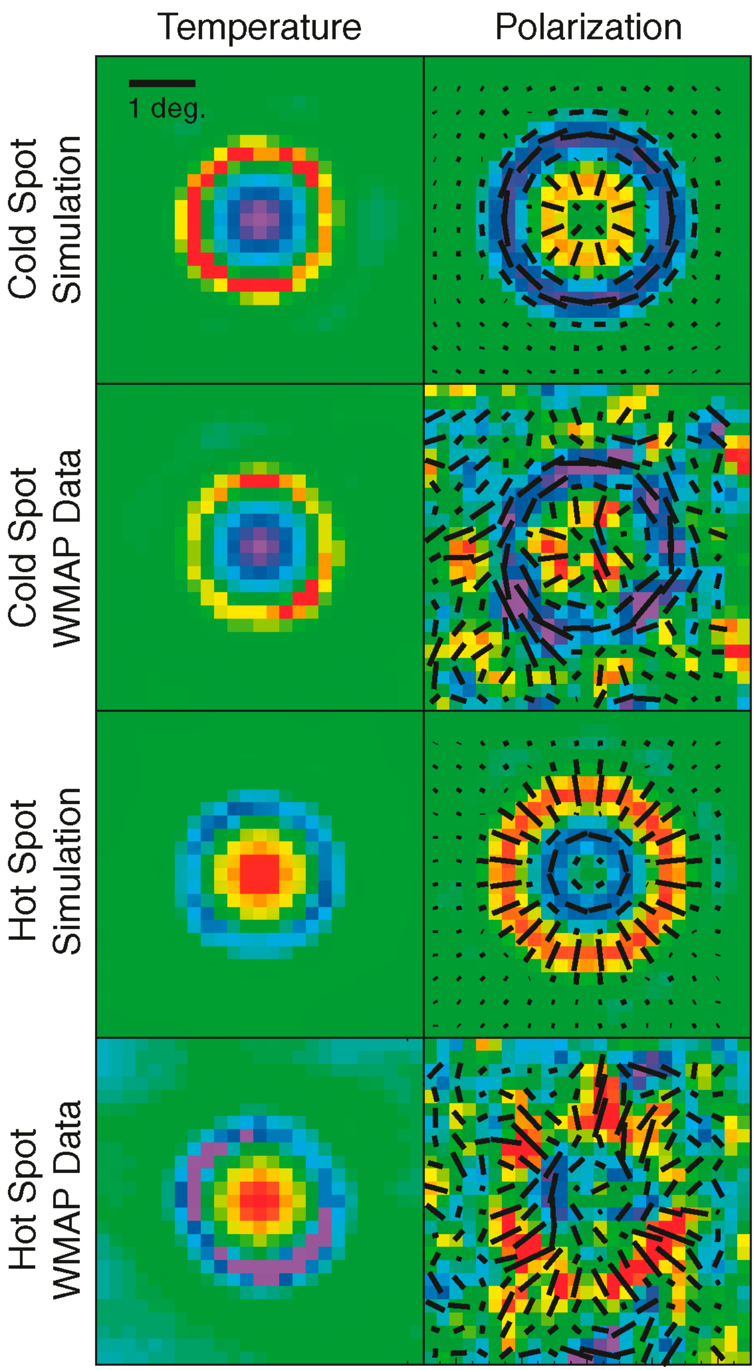
The CMB Angular Power Spectrum (1998)



Inflation: Basic Predictions

- Adiabatic density perturbations
- Superhorizon correlations
- Gaussian statistics

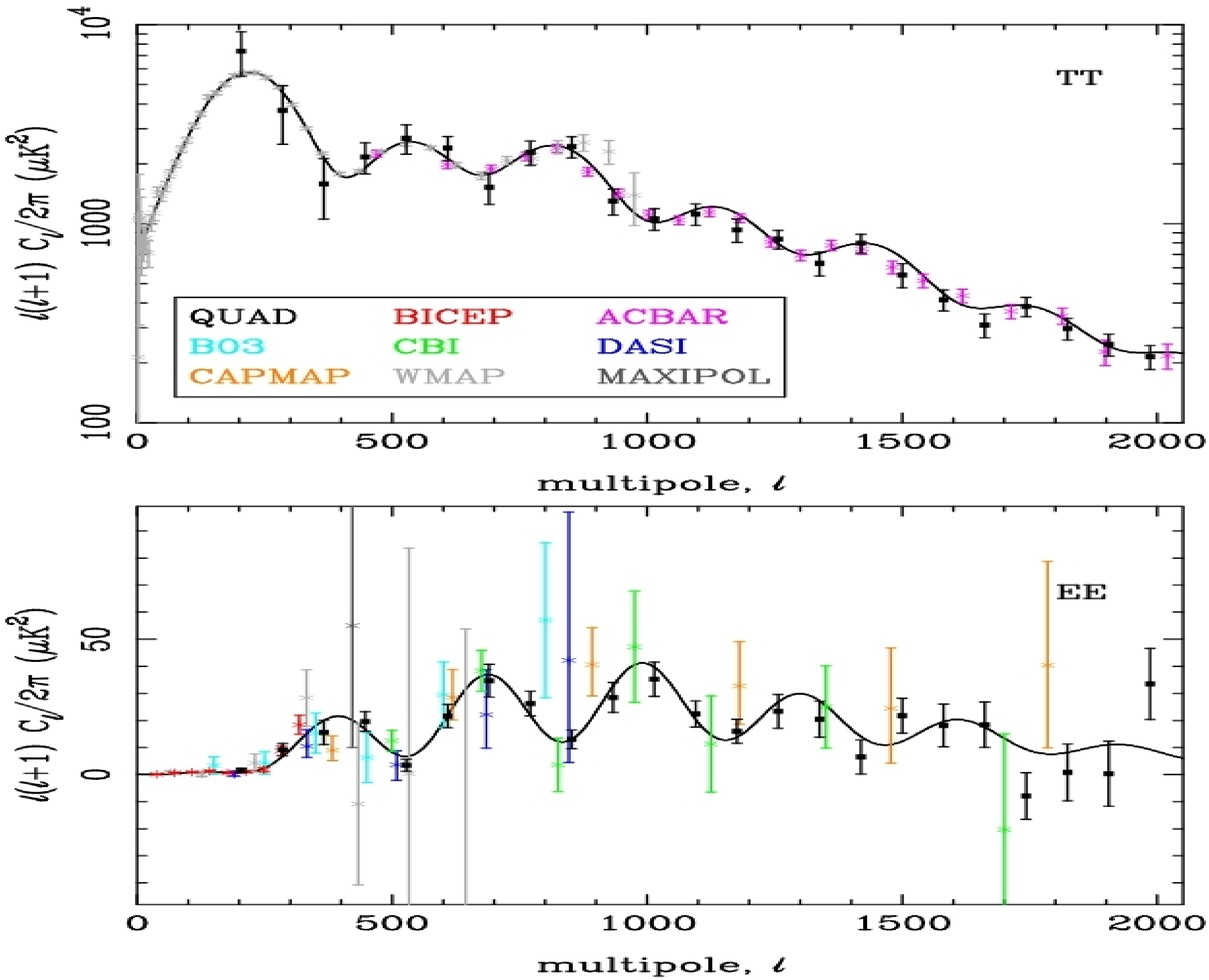
Polarization: Test of Adiabaticity



Polarization strongest along *gradients* in temperature

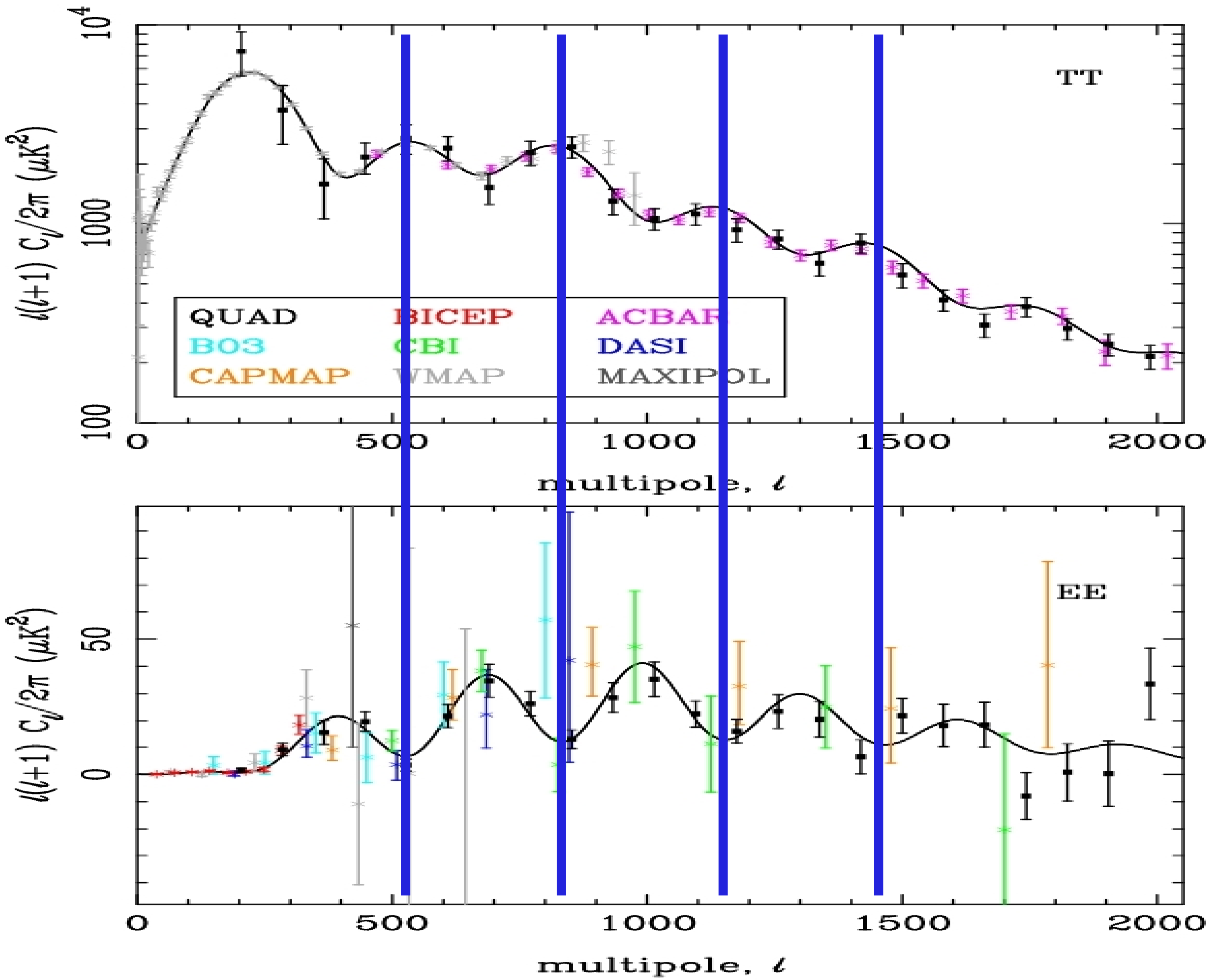
(Komatsu, *et al.*, arXiv:0912.0522)

Adiabatic Perturbations:
Temperature and Polarization Spectra Anticorrelated



(QuaD Collaboration, arXiv:0906.1003)

Adiabatic Perturbations:
Temperature and Polarization Spectra Anticorrelated

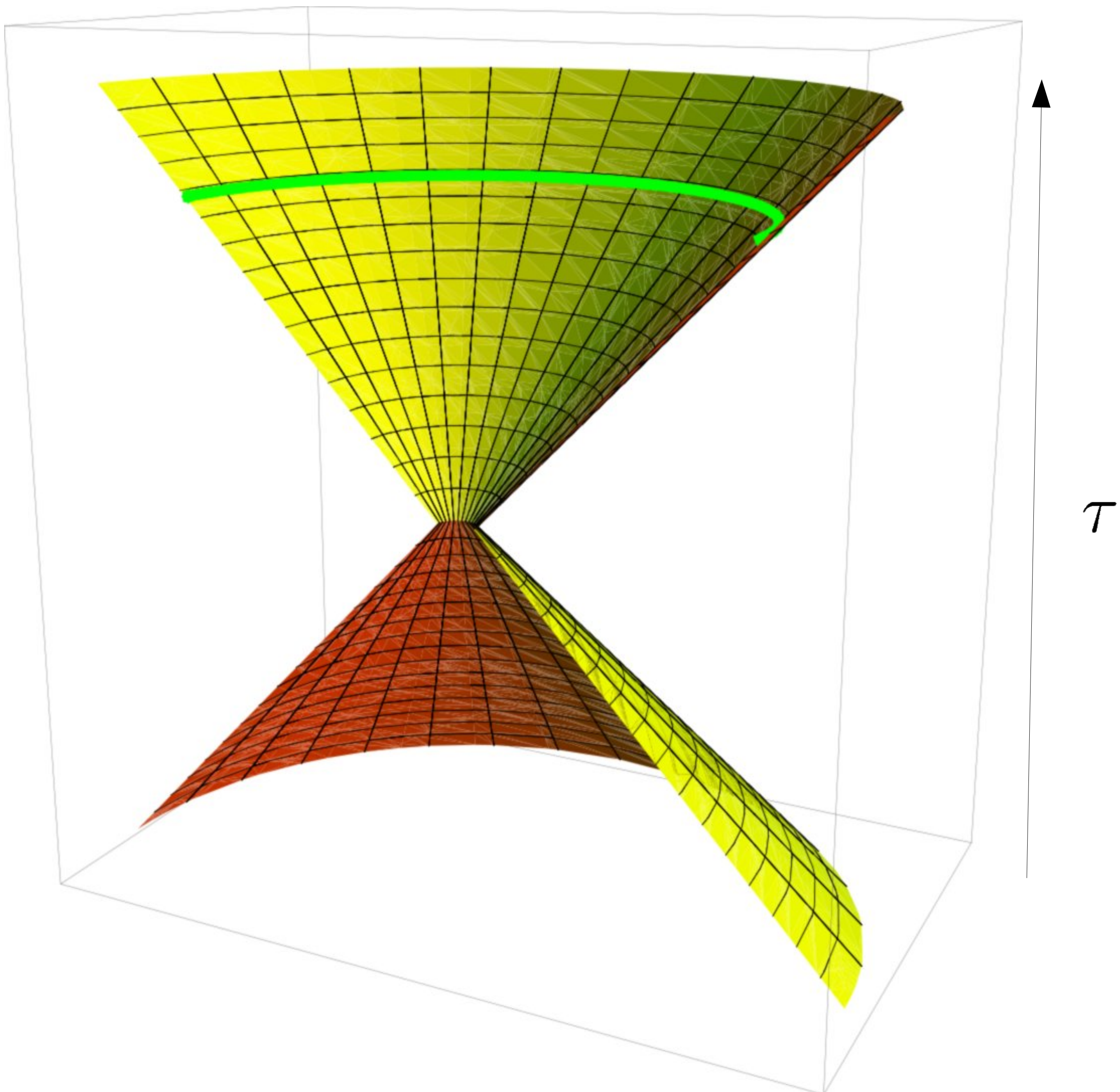


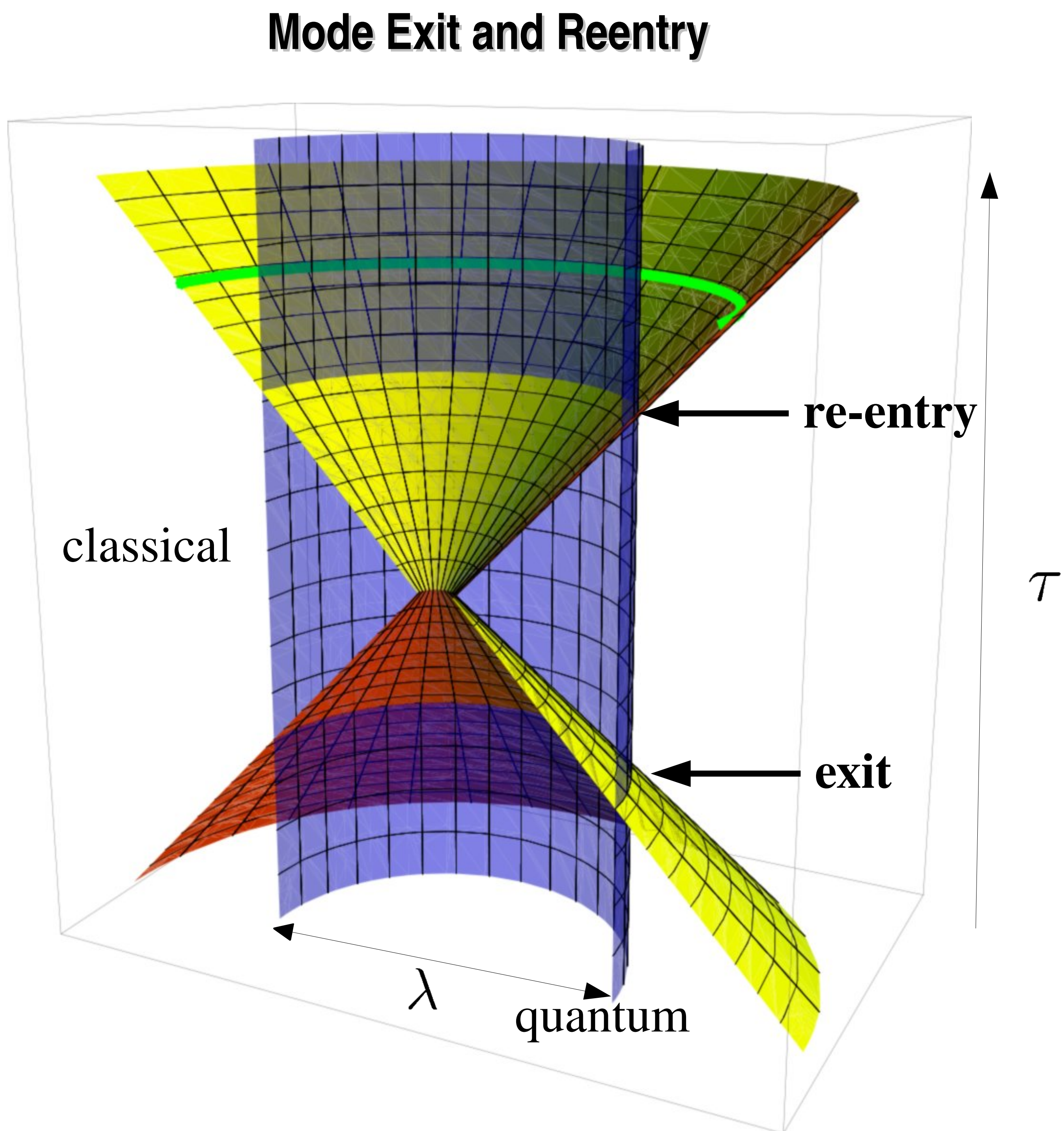
(QuaD Collaboration, arXiv:0906.1003)

Inflation: Basic Predictions

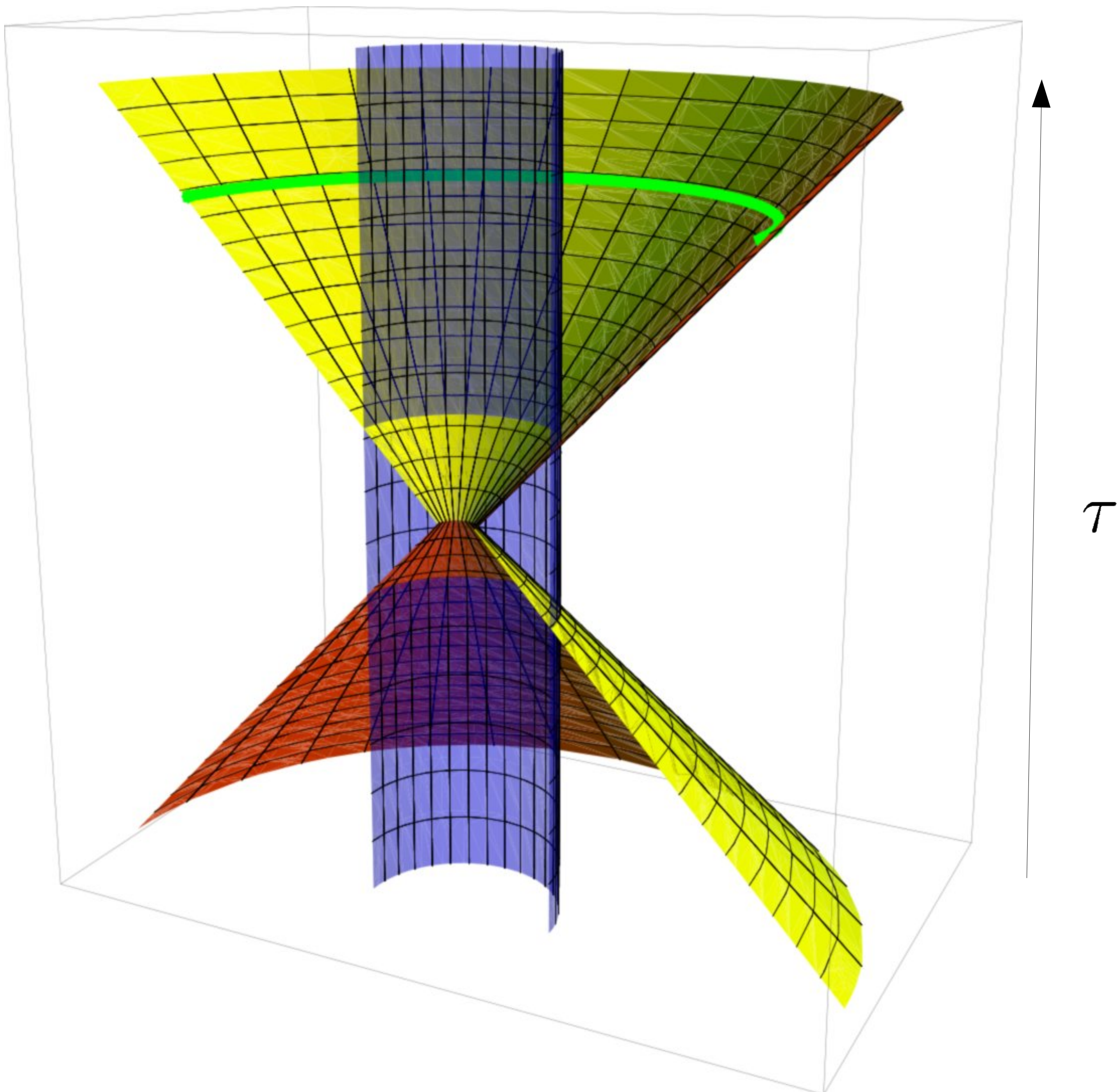
- Adiabatic density perturbations ✓
- Superhorizon correlations
- Gaussian statistics

The Horizon in Inflation

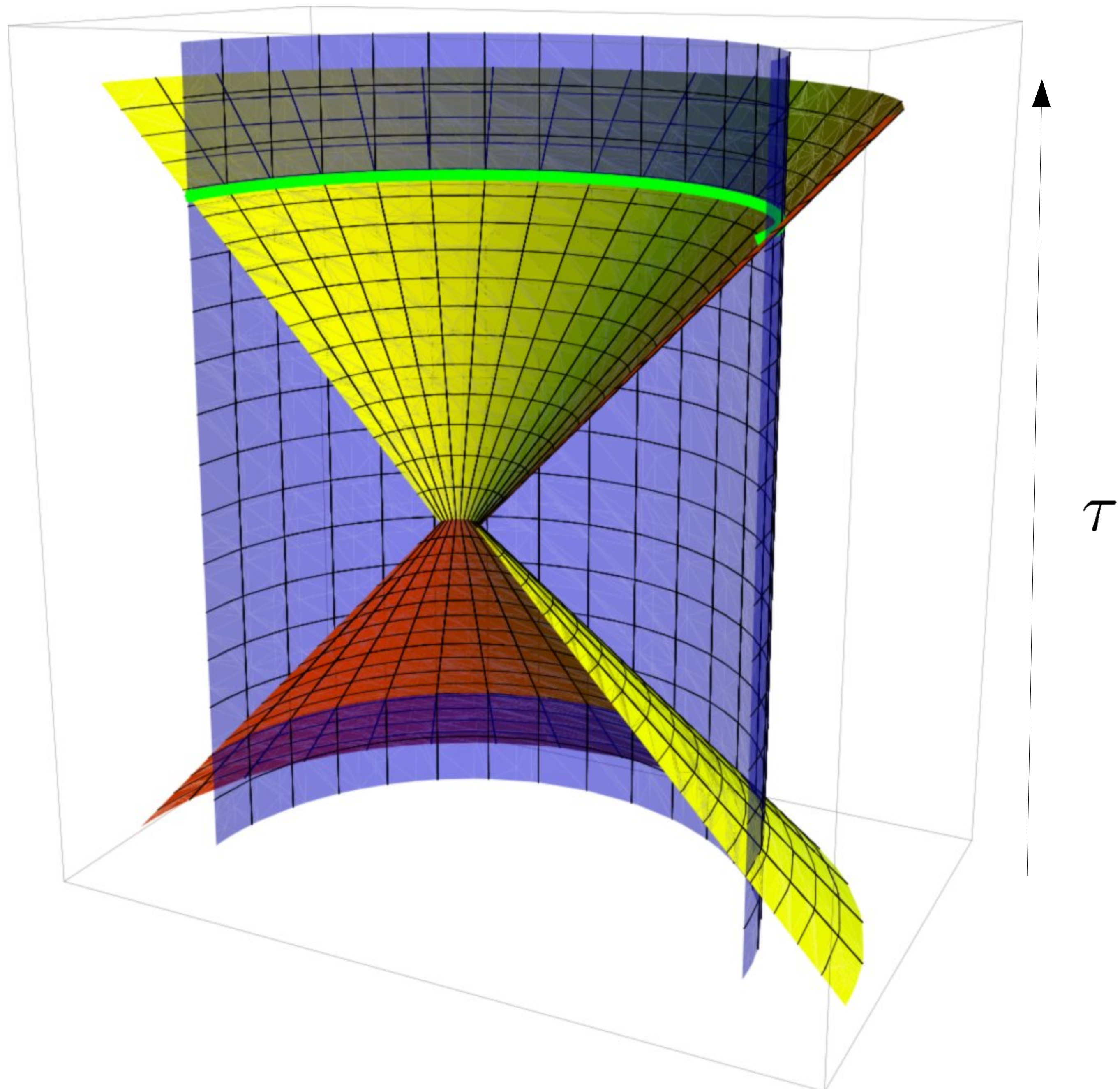



Mode Exit and Reentry
re-entry
classical
τ
exit
λ
quantum

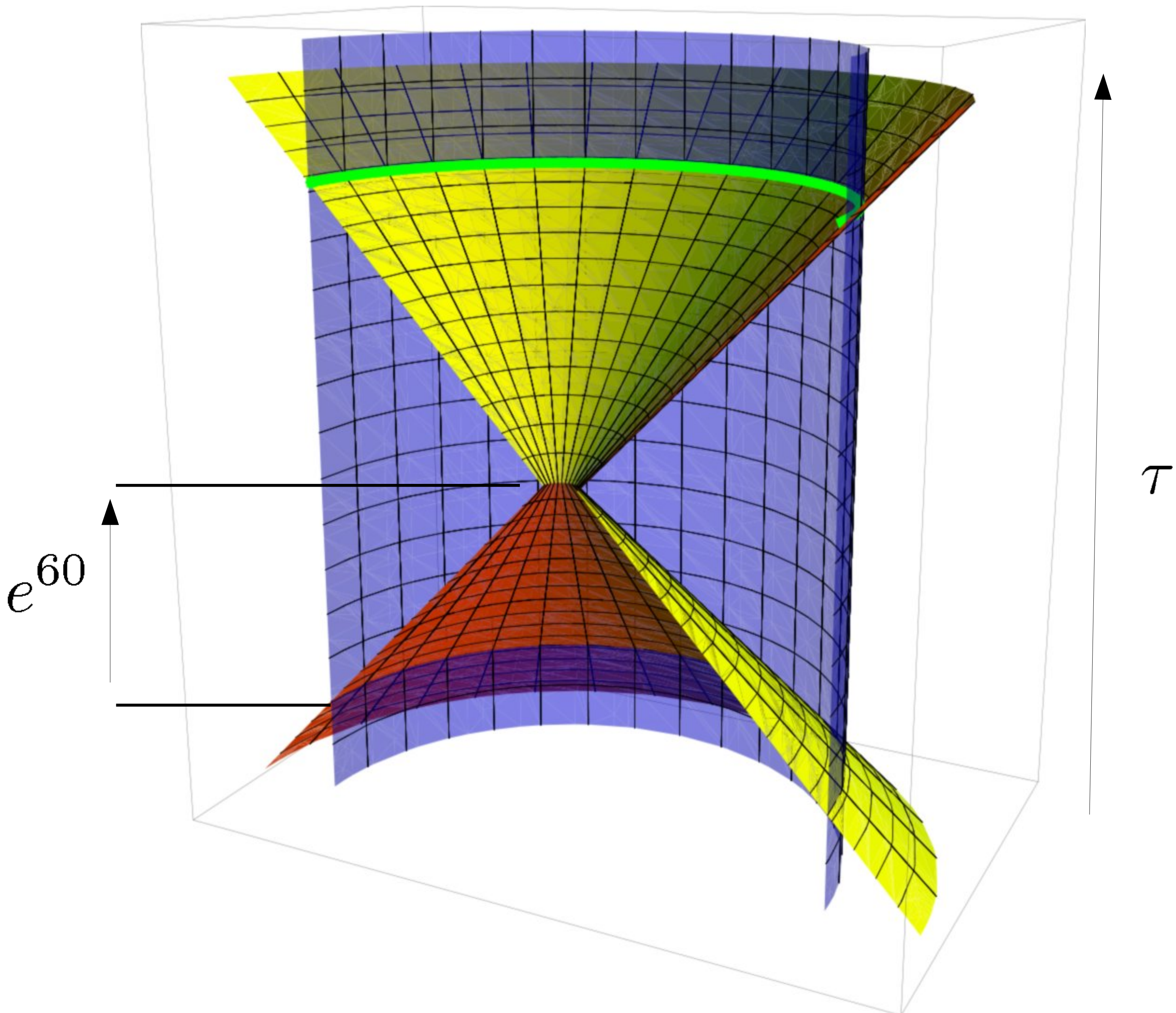
Shorter Wavelength Modes Exit Later



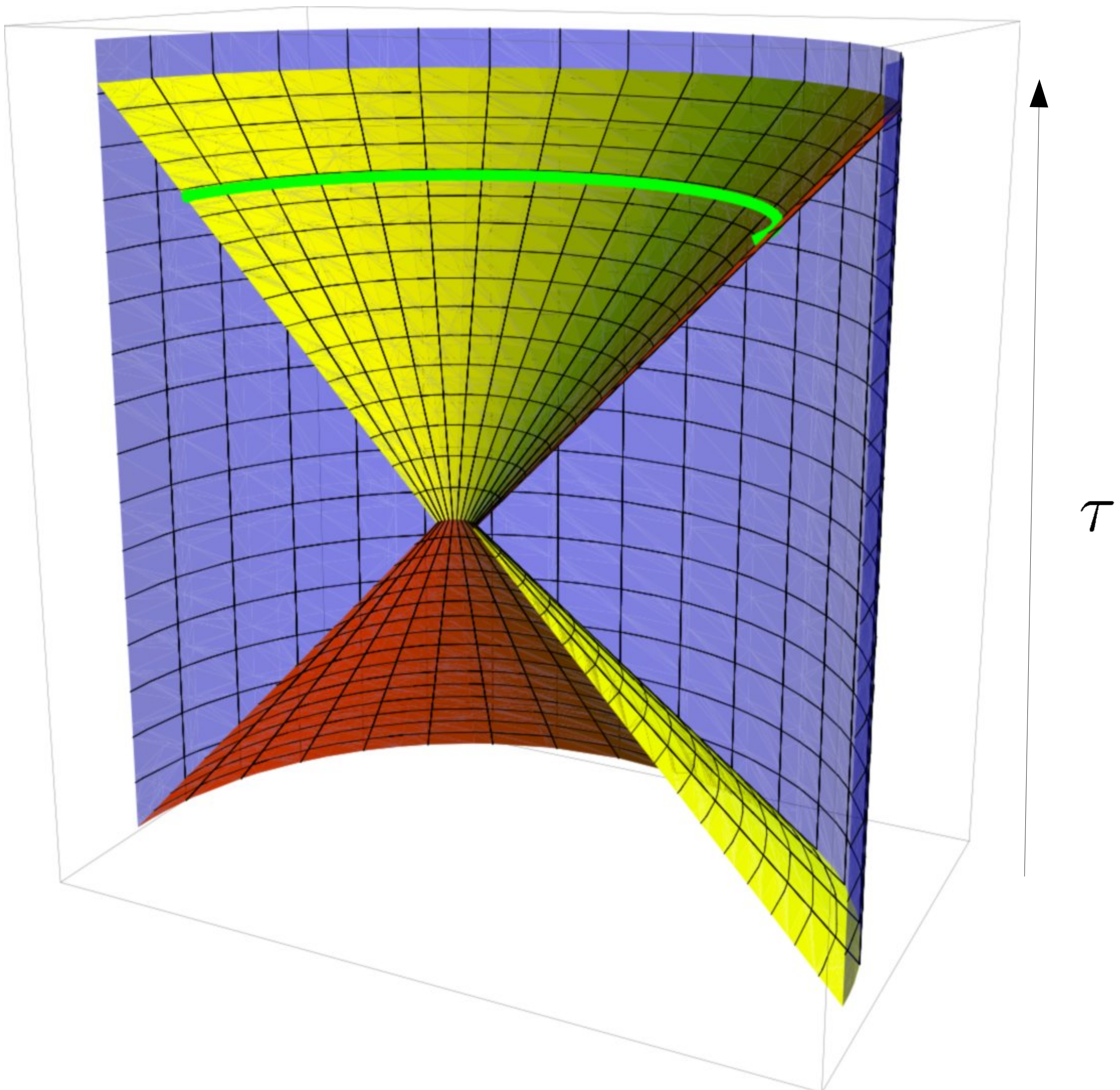
Longer Wavelength Modes Exit Earlier



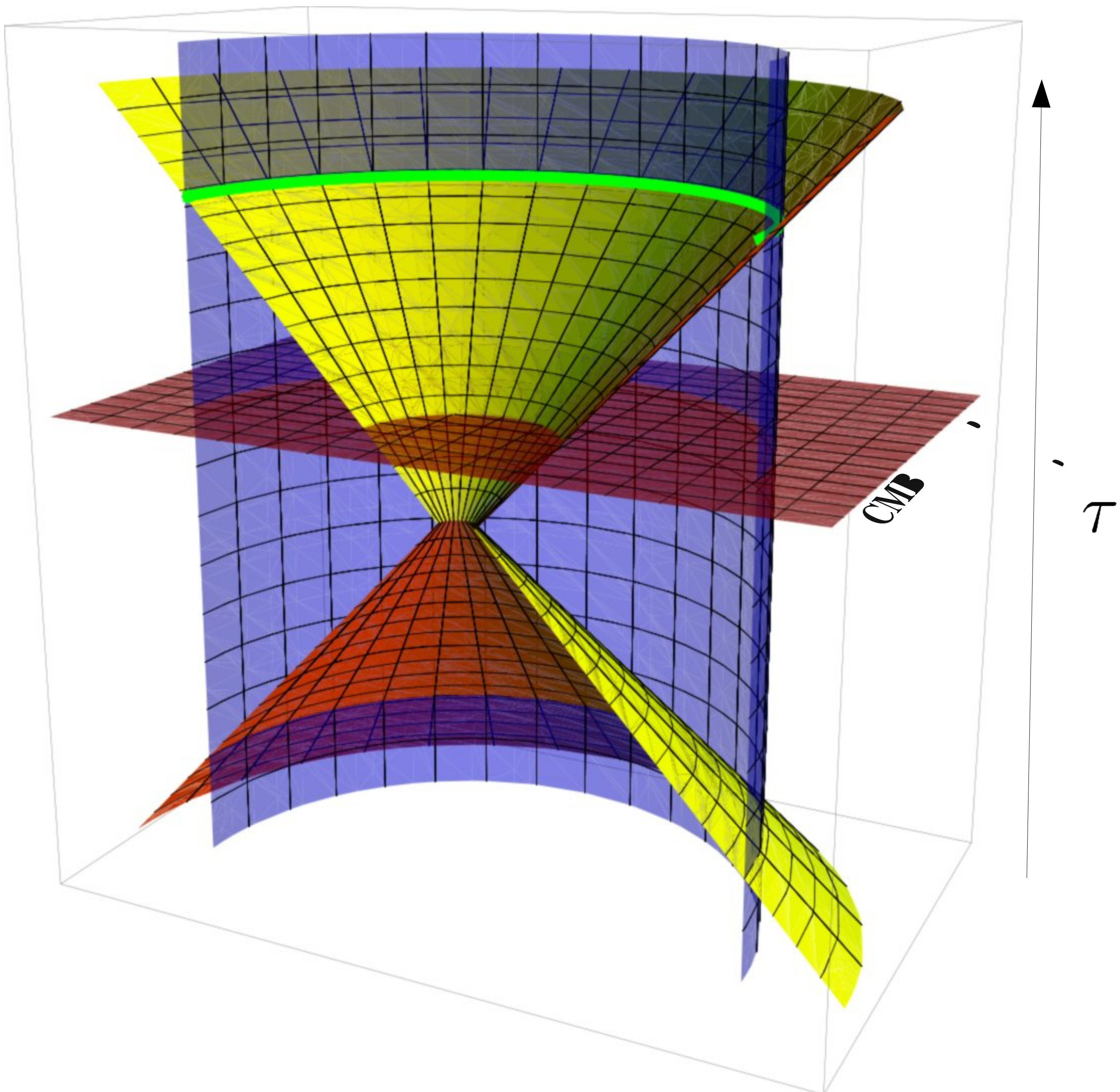
We See The *Last* 60 E-folds



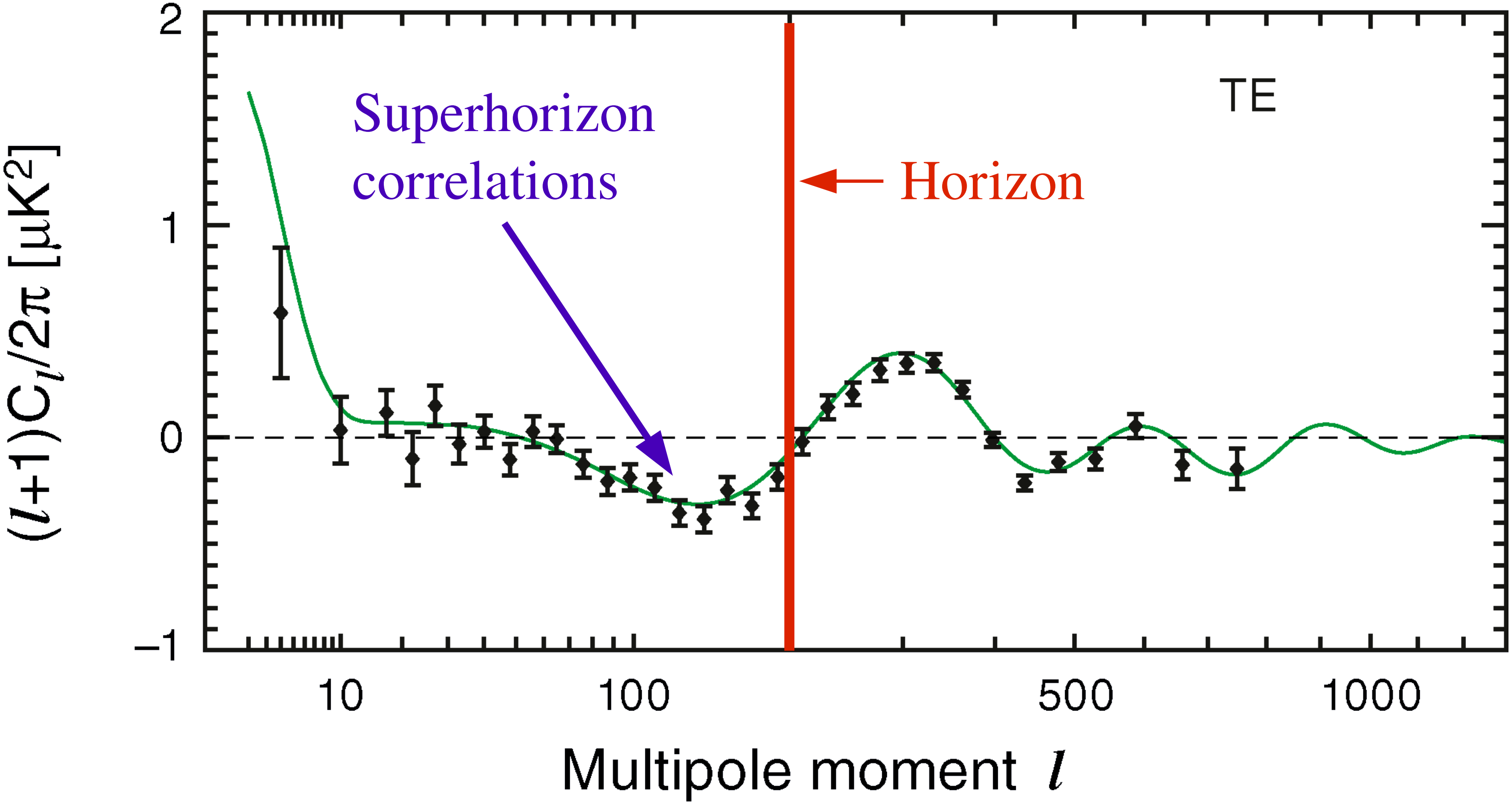
Initial Conditions: Inaccessible



Superhorizon Perturbations



Large-Scale CMB Polarization (WMAP7)



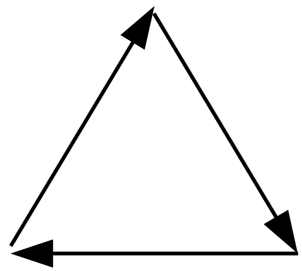
(Figure: NASA/WMAP science team)

Inflation: Basic Predictions

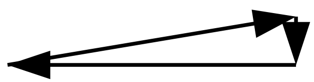
- Adiabatic density perturbations ✓
- Superhorizon correlations ✓
- Gaussian statistics

Three-point Correlation: WMAP7 Limits

Bispectrum: *three-point* correlation function



$$-214 < f_{NL}^{\text{equil}} < 266$$

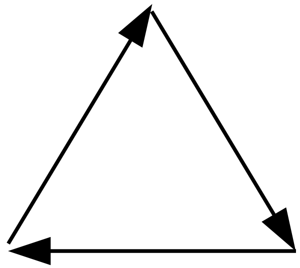


$$-10 < f_{NL}^{\text{local}} < 74$$

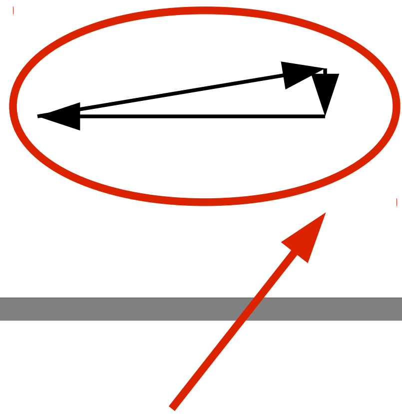
(Komatsu, *et al.*, arXiv:0912.0522)

Three-point Correlation: WMAP7 Limits

Bispectrum: *three-point* correlation function



$$-214 < f_{NL}^{\text{equil}} < 266$$



$$-10 < f_{NL}^{\text{local}} < 74$$

Single-field inflation: $f_{\text{NL}}^{\text{local}} = -\frac{5}{16}(n-1)$

(Maldacena, astro-ph/0210603, Creminelli & Zaldarriaga, astro-ph/0407059)

Inflation: Basic Predictions

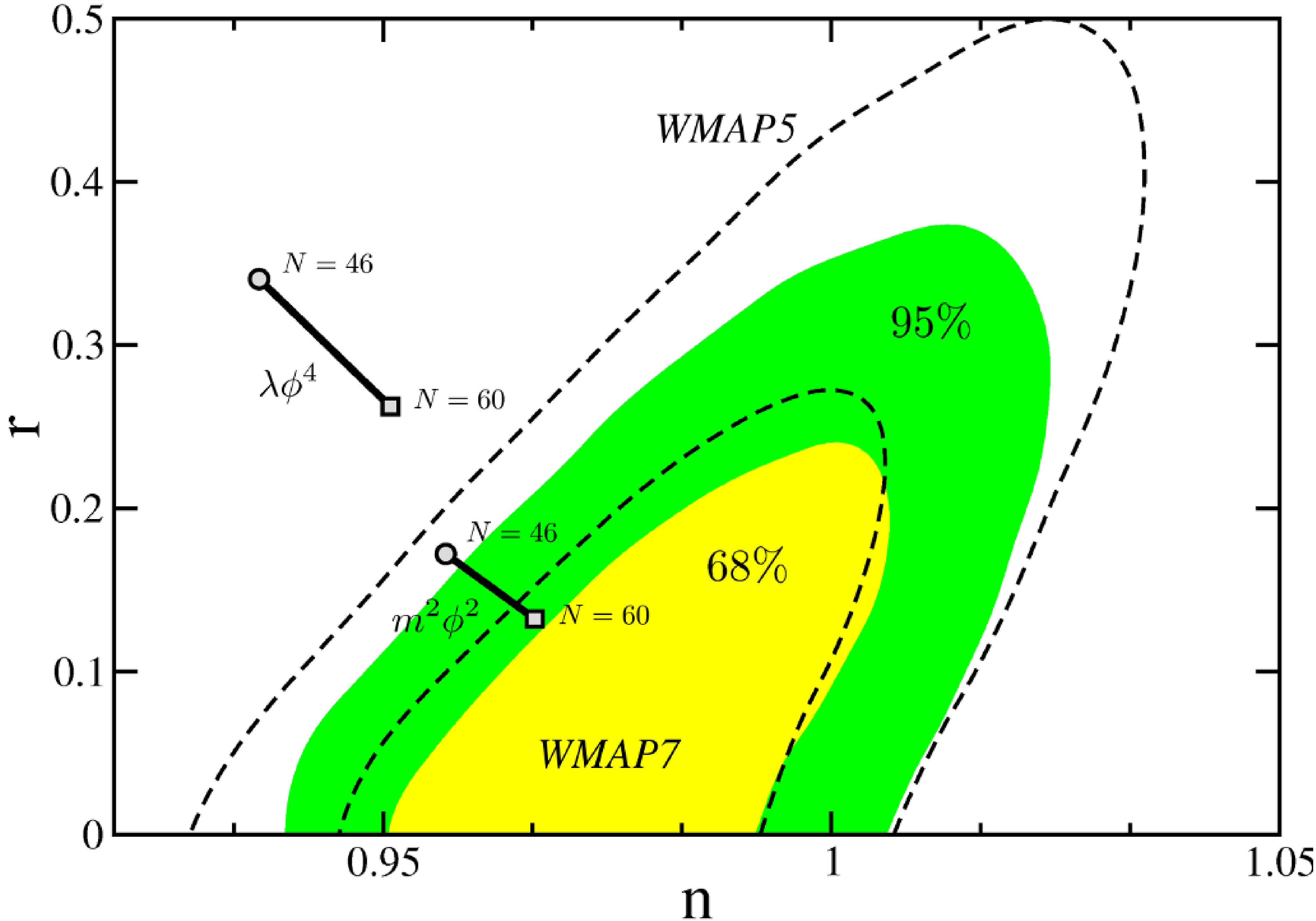
- Adiabatic density perturbations ✓
- Superhorizon correlations ✓
- Gaussian statistics ✓

Generic tests all ok!

Inflation: Basic Predictions

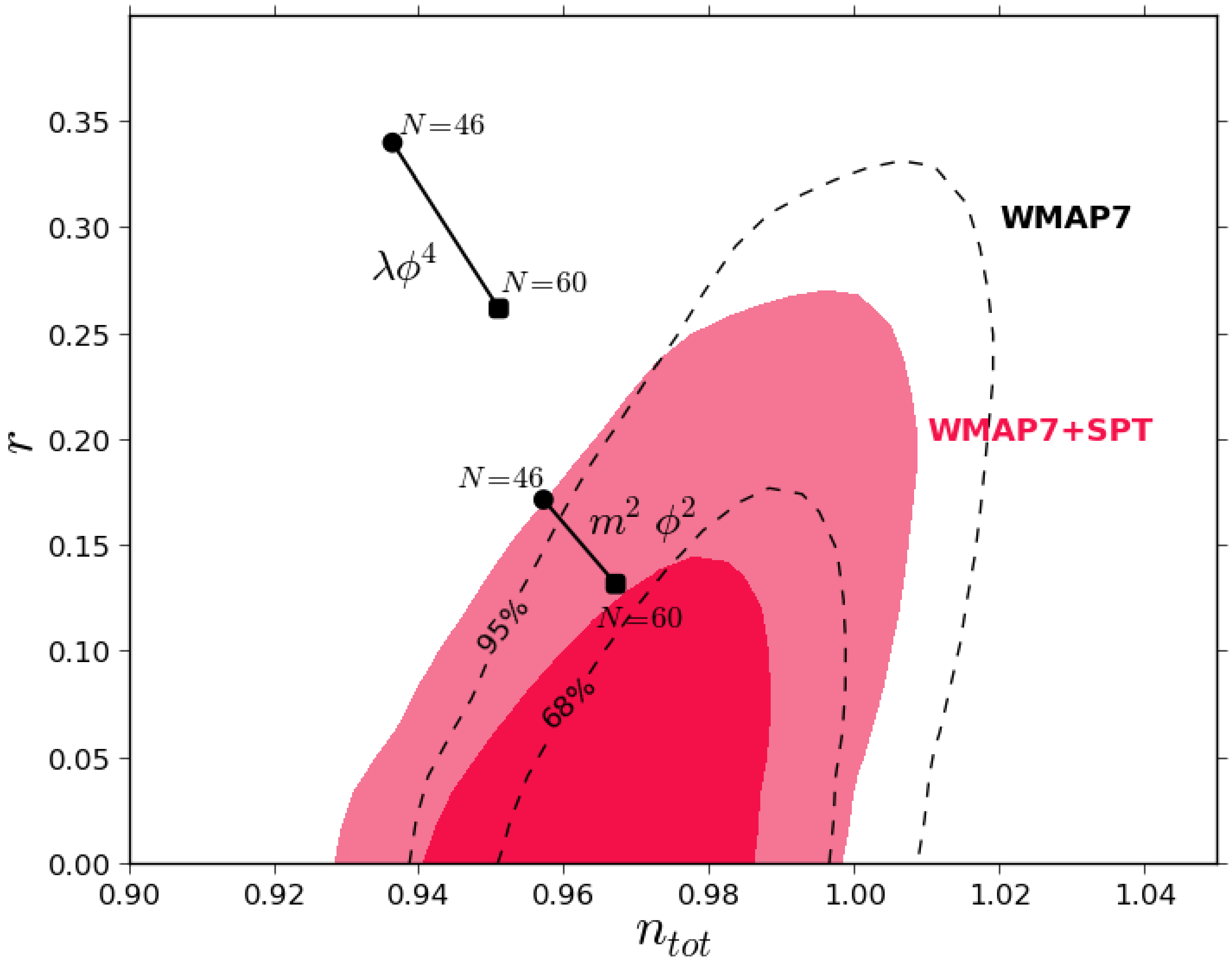
- Adiabatic density perturbations ✓
- Superhorizon correlations ✓
- Gaussian statistics ✓
- (Almost) scale-invariant spectrum
- Primordial gravitational waves

WMAP Limits on Inflation (Large-Field)

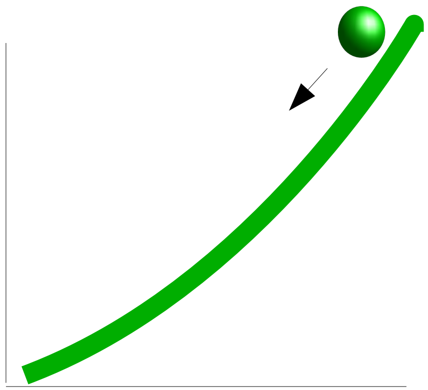


(WHK, astro-ph/9806259)

WMAP+SPT Limits on Inflation (Large-Field)



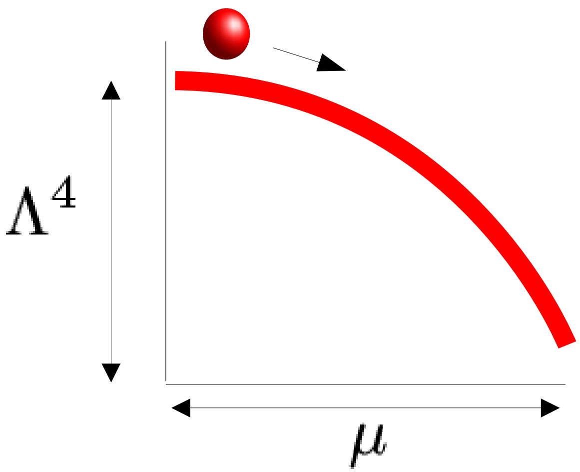
WMAP Constraints



Large field

$$V(\phi) = \Lambda^4 (\phi/\mu)^p$$

$$V(\phi) = \Lambda^4 e^{\phi/\mu}$$

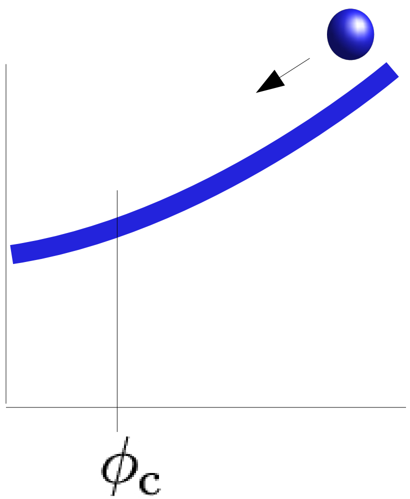


Small field

$$V(\phi) = \Lambda^4 [1 - (\phi/\mu)^p]$$

$$r = 0$$

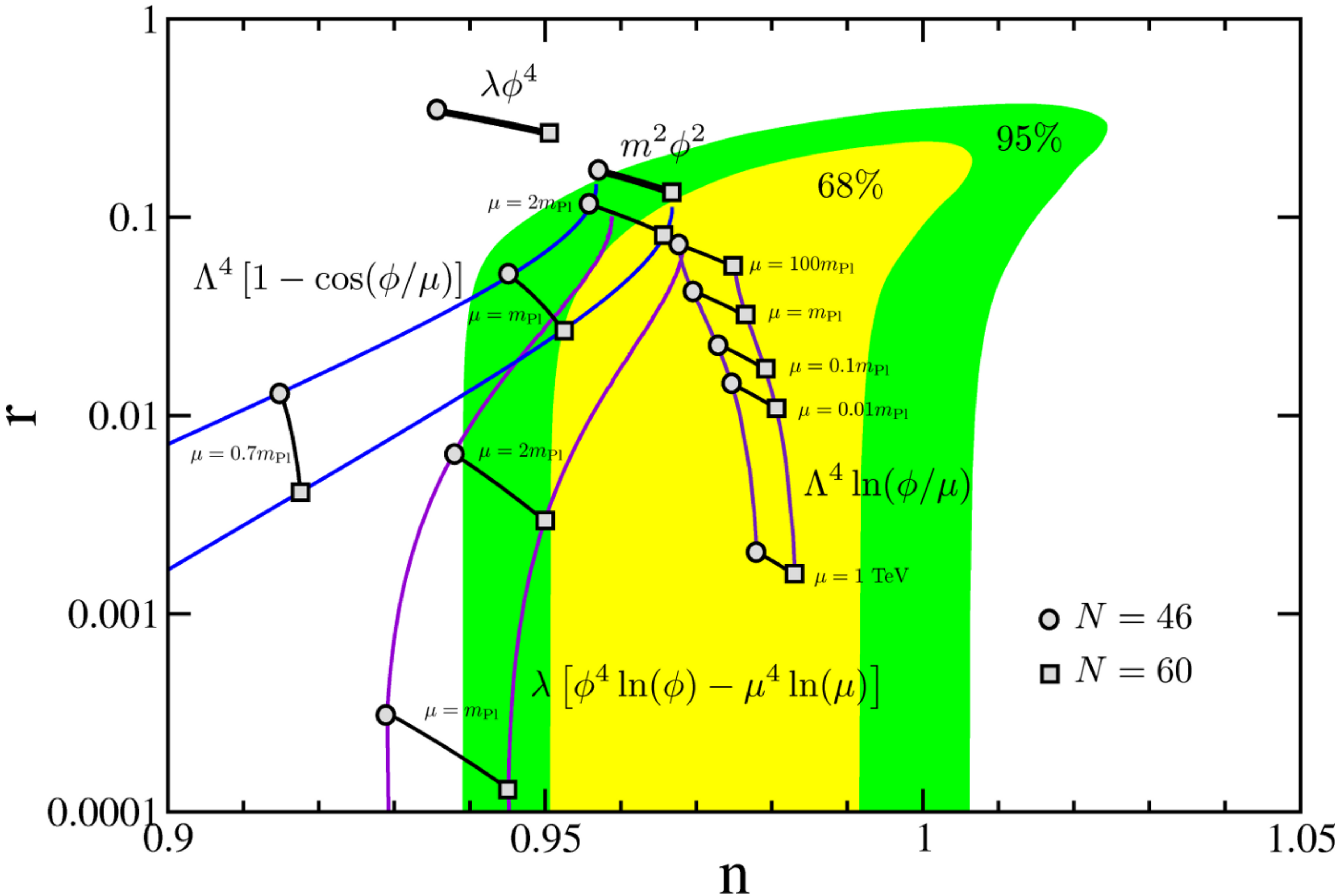
$$n > 1$$



Hybrid

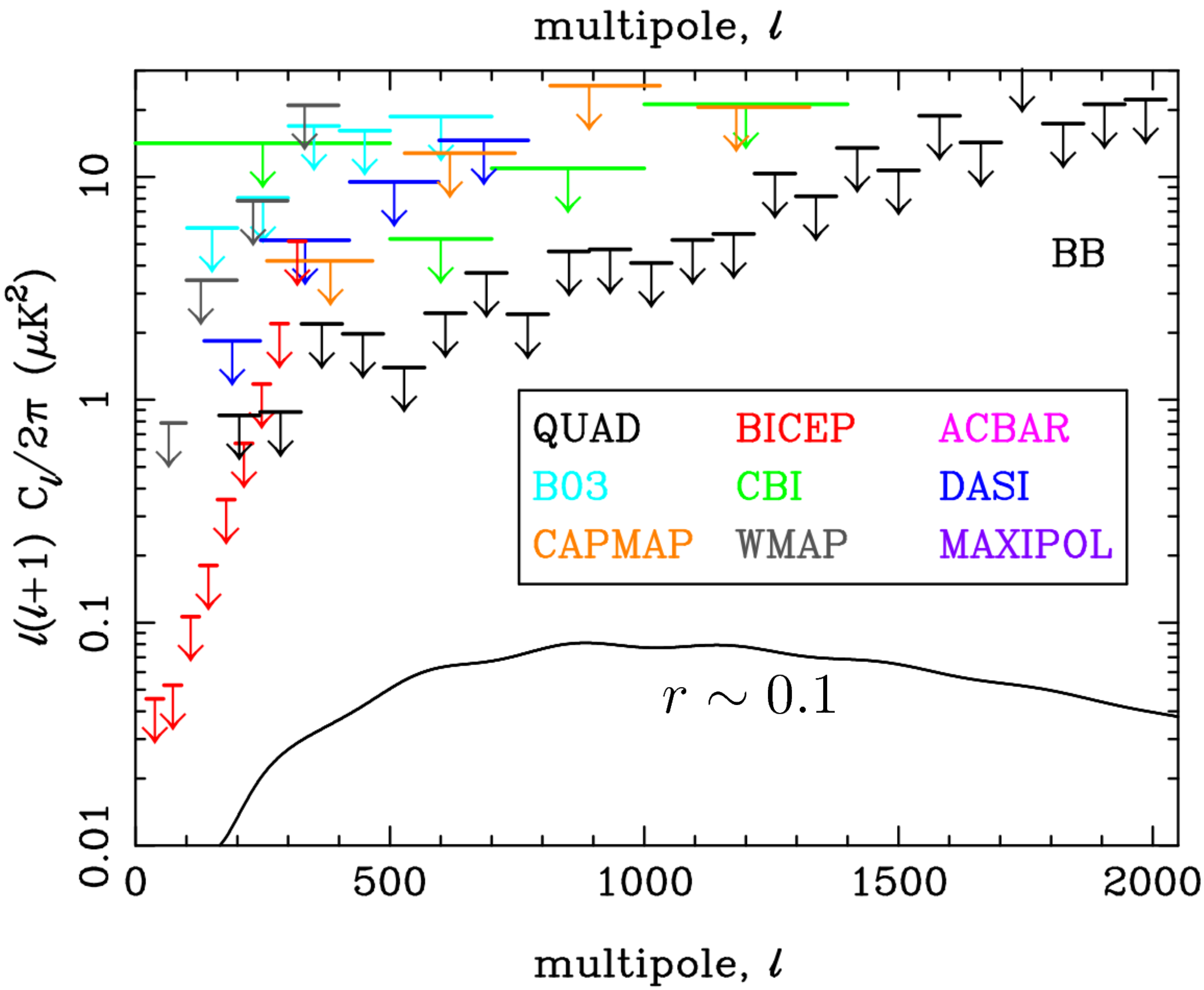
$$V(\phi) = \Lambda^4 [1 + (\phi/\mu)^p]$$

WMAP7 Limits on Inflation (Small-field)



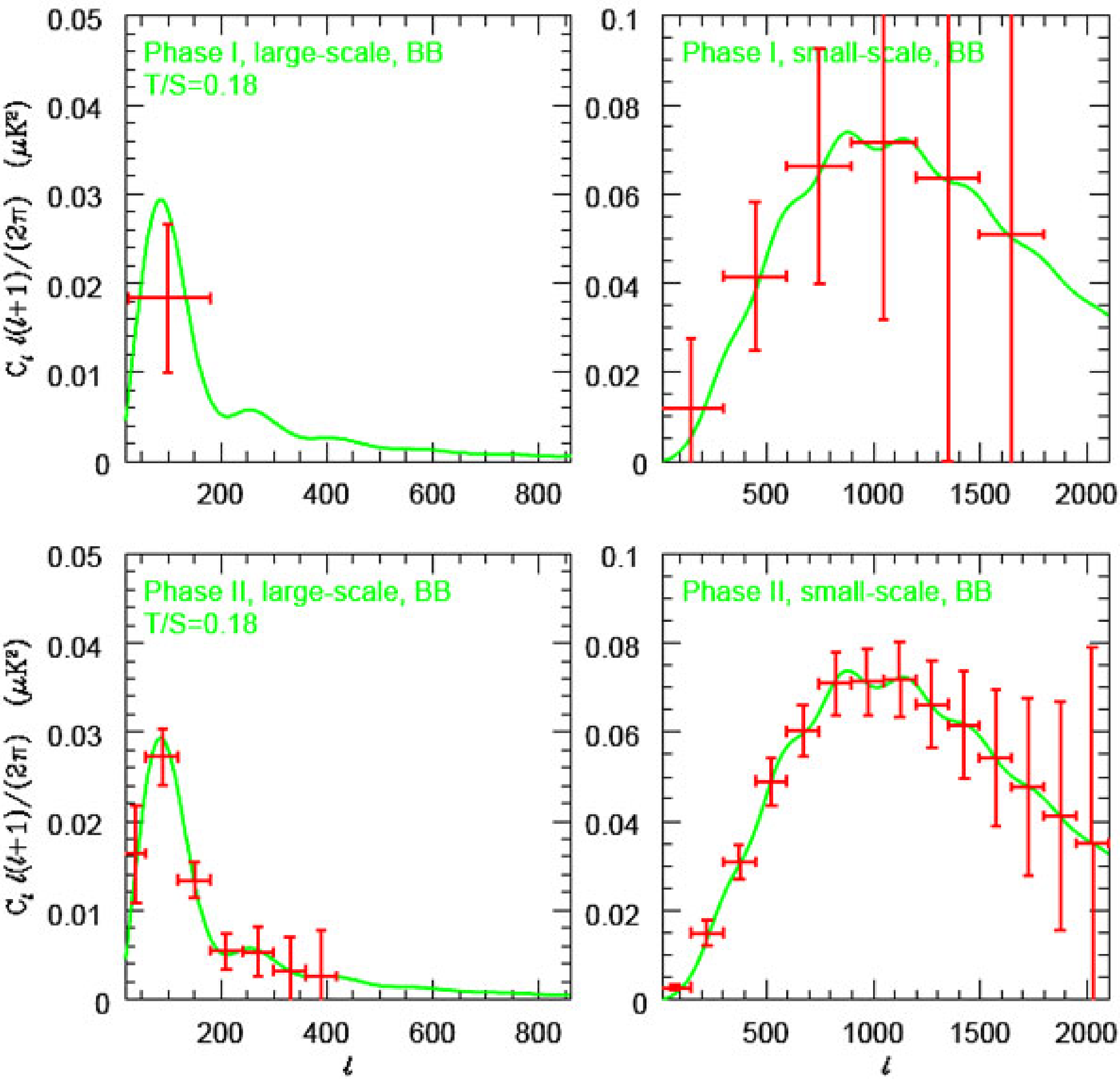
(WHK, astro-ph/9806259)

B-Mode Polarization: Current Status



(QuaD Collaboration, arXiv:0906.1003)

B-Mode Polarization: QUIET Experiment (projected)



$r = 0.18$

$r = 0.18$

(QUIET Collaboration, http://quiet.uchicago.edu/)

Inflation: Basic Predictions

- Adiabatic density perturbations ✓
- Superhorizon correlations ✓
- Gaussian statistics ✓
- (Almost) scale-invariant spectrum ✓
- Primordial gravitational waves ?

CMB: Basic Properties

- Adiabatic density perturbations
- Superhorizon correlations
- Gaussian statistics
- Scale Invariance

Q: What does this really tell us?

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

See: Moradinezhad Dizgah talk this afternoon

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

Going Forward: What to Look For

- Tensor modes (Key: CMB BB Spectrum)
- Features / running in power spectrum
- Non-Gaussianity
- Isocurvature perturbations

None of these signals is guaranteed

Lyth Bound

$$\frac{\Delta\phi}{M_{\rm P}} \geq \sqrt{\frac{r}{4\pi}}$$

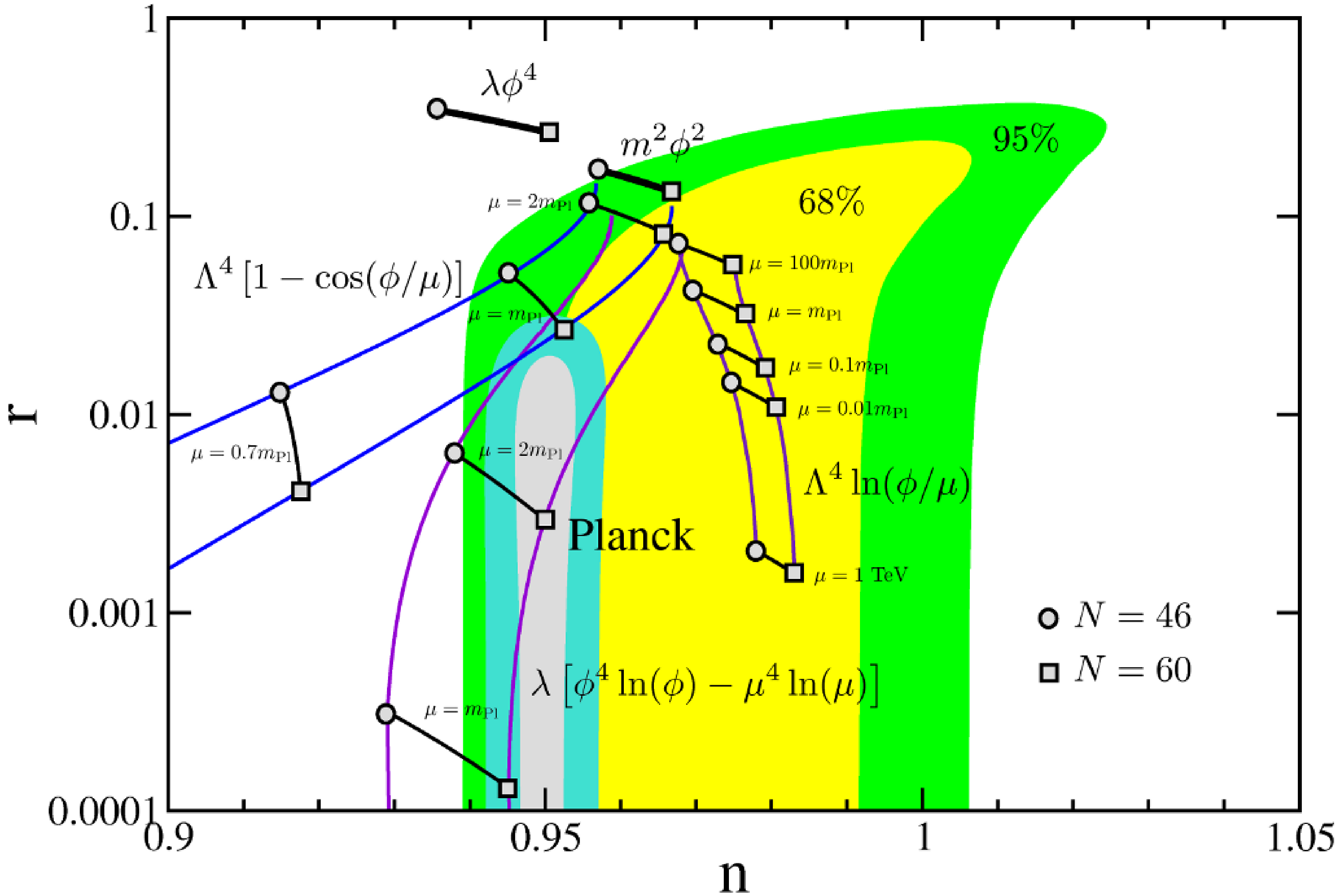
$$\Delta\phi < M_p \Rightarrow r < 0.01 \Rightarrow \frac{H}{M_p} < 10^{-5}$$

Observable effect from Planck-suppressed operators suggests a high scale for H and a large tensor contribution.
(EFT for inflaton?)

The Single-Field Model Space

Tensor/Scalar Ratio	Experiment	$V(\phi)$	Physics Probed
$r \sim \mathcal{O}(0.1)$	Planck	$m^2\phi^2$	Potential reconstruction Transplanckian Physics
$r \sim \mathcal{O}(0.01)$	CMBPOL	$V_0 - m^2\phi^2$	Inflaton mass
$r \leq \mathcal{O}(0.001)$	BBO	$V_0 - \lambda\phi^4$	Reheating scale (from spectral index)

Planck vs. WMAP (Small-field)



(WHK, astro-ph/9806259)

What to look for

Possible signals of new physics

- Tensor modes

  GUT-scale inflation, Transplanckian physics
  non-slow roll dynamics, potential reconstruction

- Features / running in power spectrum

  Non-slow roll dynamics, landscape inflation

- Non-Gaussianity

  Non-slow roll dynamics, DBI / string inflation
  Curvaton, Ekpyrotic models

- Isocurvature perturbations

  Multi-field inflation, topological defects