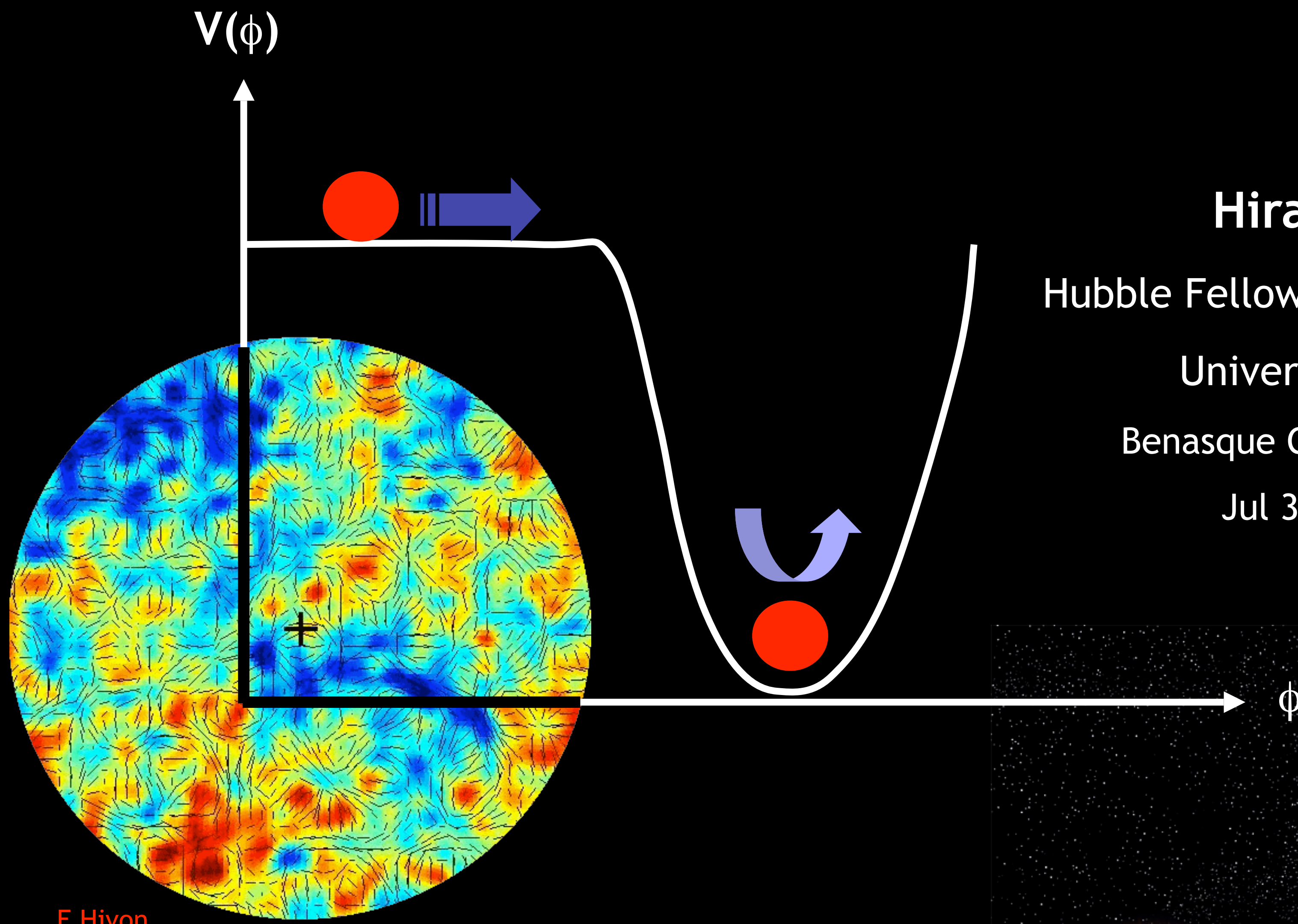
Inflation after 3 years of WMAP



E Hivon

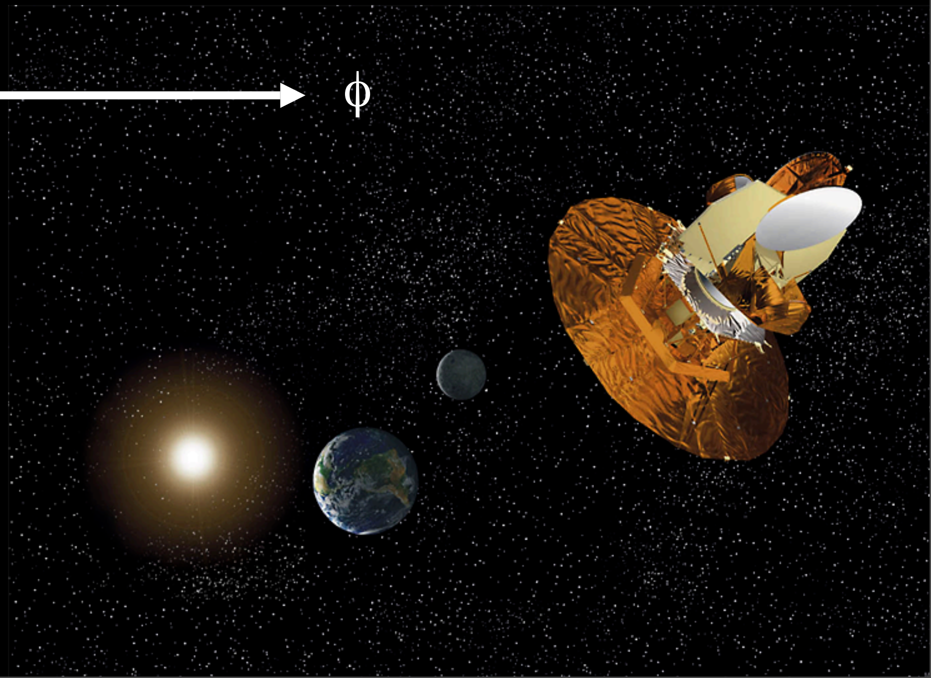
Hiranya Peiris

Hubble Fellow/ Enrico Fermi Fellow

University of Chicago

Benasque Cosmology Workshop

Jul 31 - Aug 18 2006



Kavli Institute
for Cosmological Physics
at The University of Chicago

Credits:
WMAP Science Team (2003, 2006)
Peiris & Easther (2006)
Easther & Peiris (2006)
Peiris & Easther (in prep)

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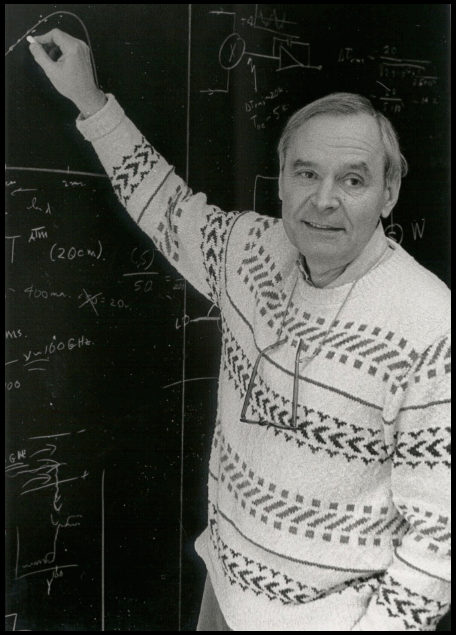

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Licia Verde

U. Toronto

Michael Nolta
Olivier Dore

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- Alabidi & Lyth, astro-ph/0603539
- Peiris & Easther, astro-ph/0603587
- de Vega & Sanchez, astro-ph/0604136
- Easther & Peiris, astro-ph/0604214
- Kinney, Kolb, Melchiorri & Riotto, astro-ph/0605338
- Martin & Ringeval, astro-ph/0605367
- Peiris & Easther (2006), in prep

WMAP Returns! What's New?

In a nutshell:

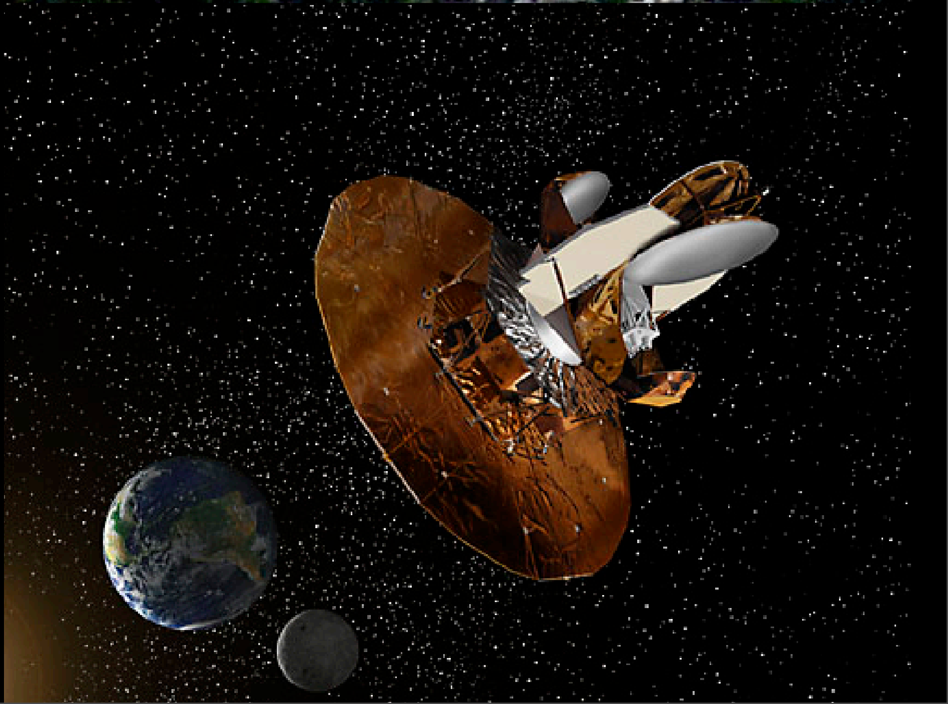
- more data

- lower noise

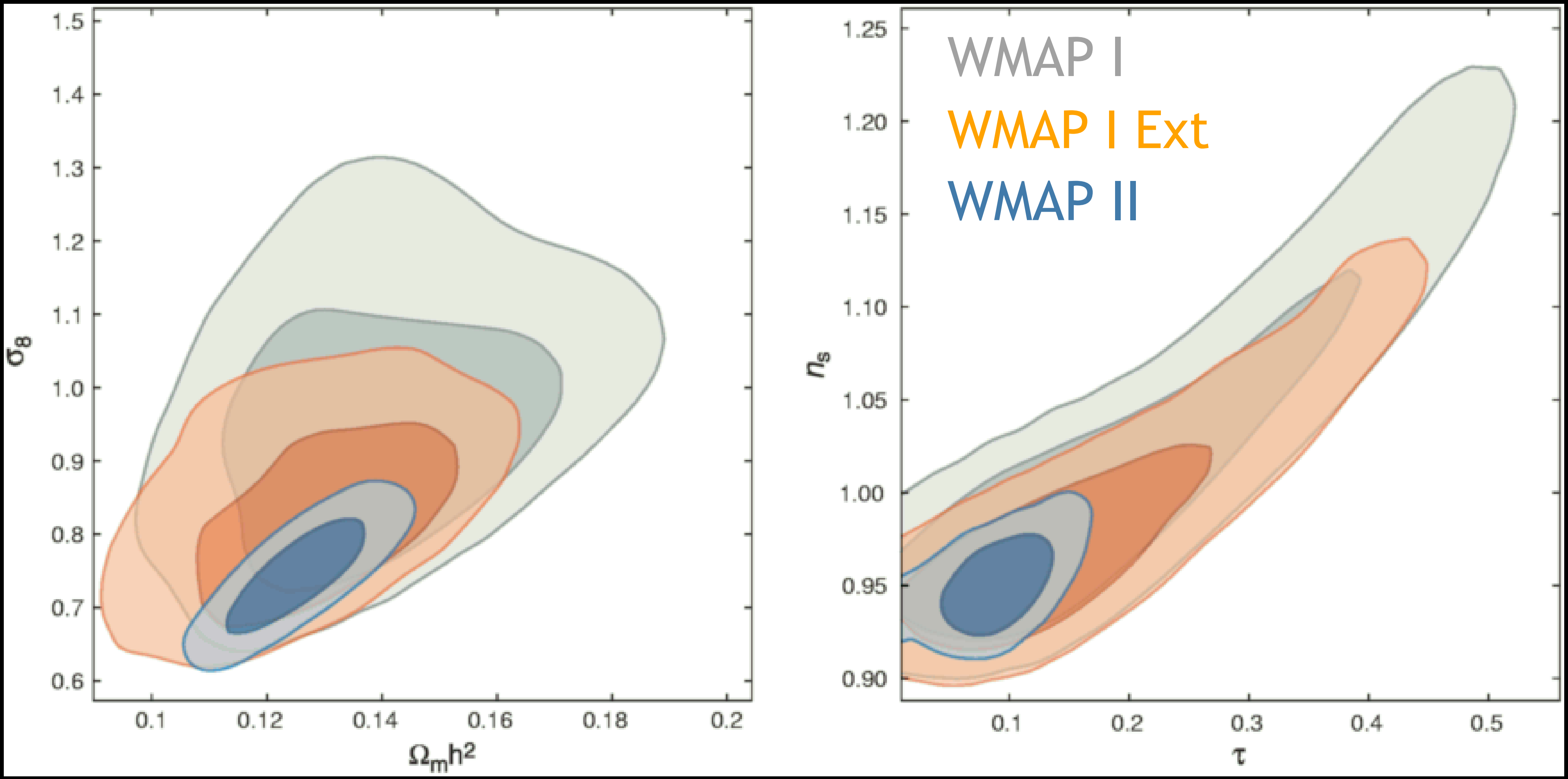
- improved foreground analysis

- 200 article pages describing the analysis:

    - Jarosik et al (2006)
    - Hinshaw et al (2006)
    - Page et al (2006)
    - Spergel et al (2006)



The effect of 3 years of WMAP data: LCDM model

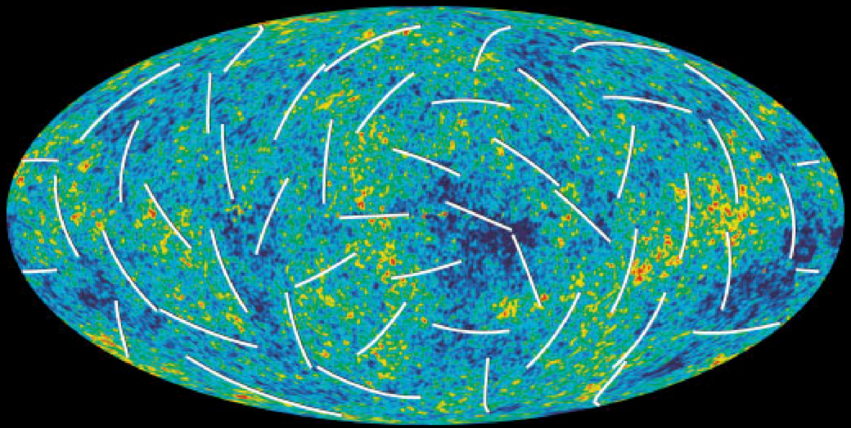


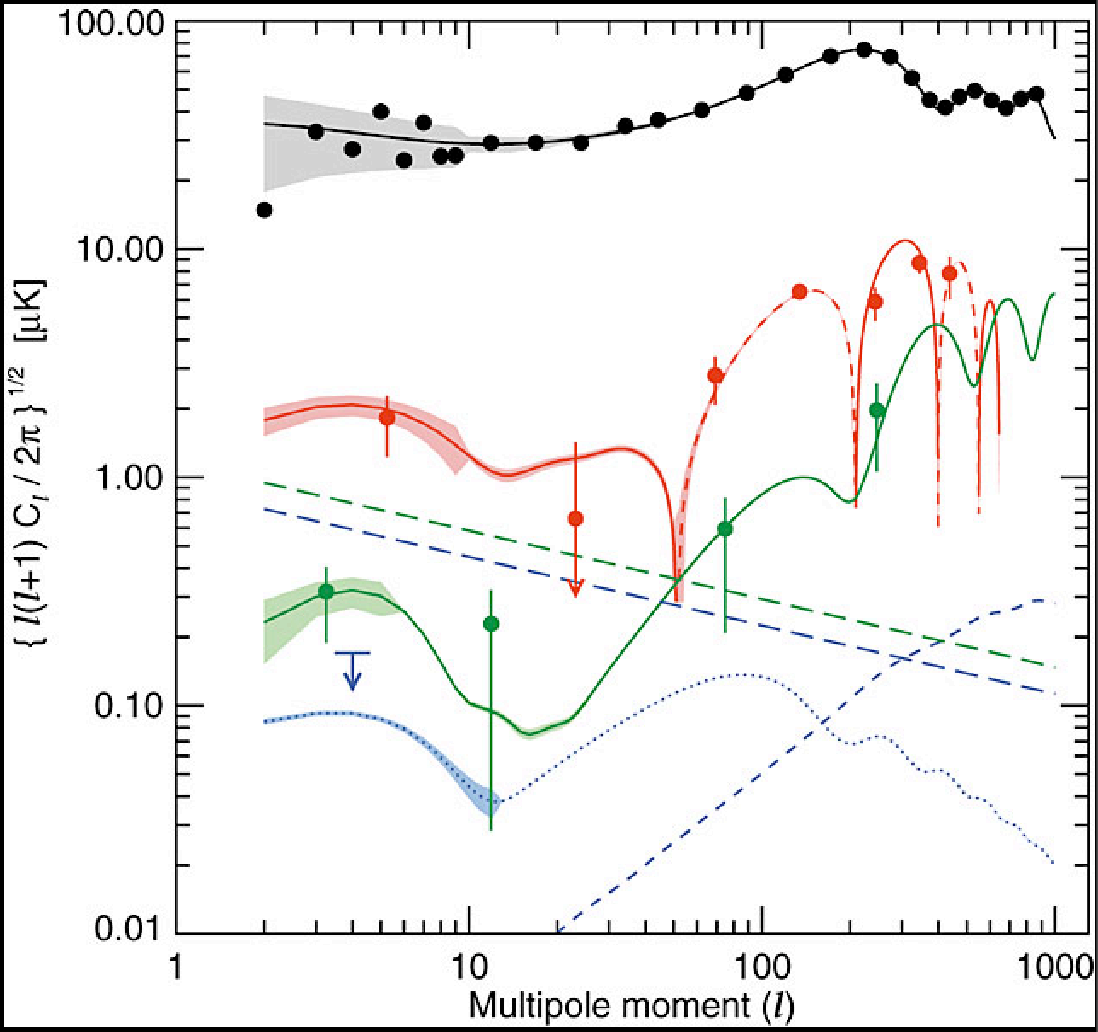
Reducing the noise by sqrt(T) → degeneracies broken

Jarosik et al (2006), Hinshaw et al (2006), Page et al (2006), Spergel et al (2006)

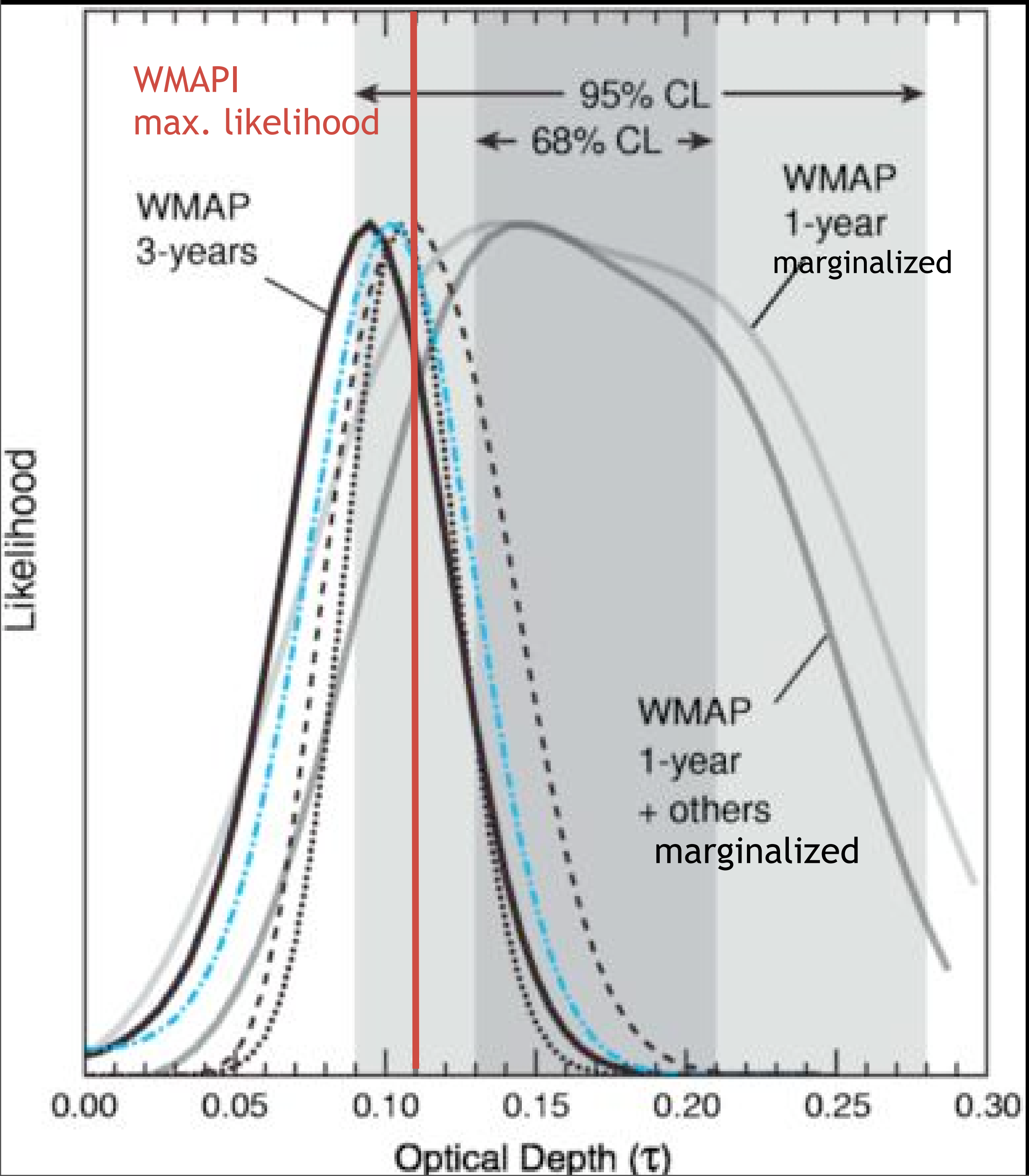
WMAP 3 year polarization data

- Three Years (TE,EE,BB)
  - Foreground Removal
    - Done in pixel space
  - Null Tests
    - Year Difference & TB, EB, BB
  - Data Combination
    - Only Q and V are used
  - Data Weighting
    - Optimal weighting (C^{-1})
  - Likelihood Form
    - Gaussian for the pixel data
    - C_l not used at l<23





Stand-alone τ

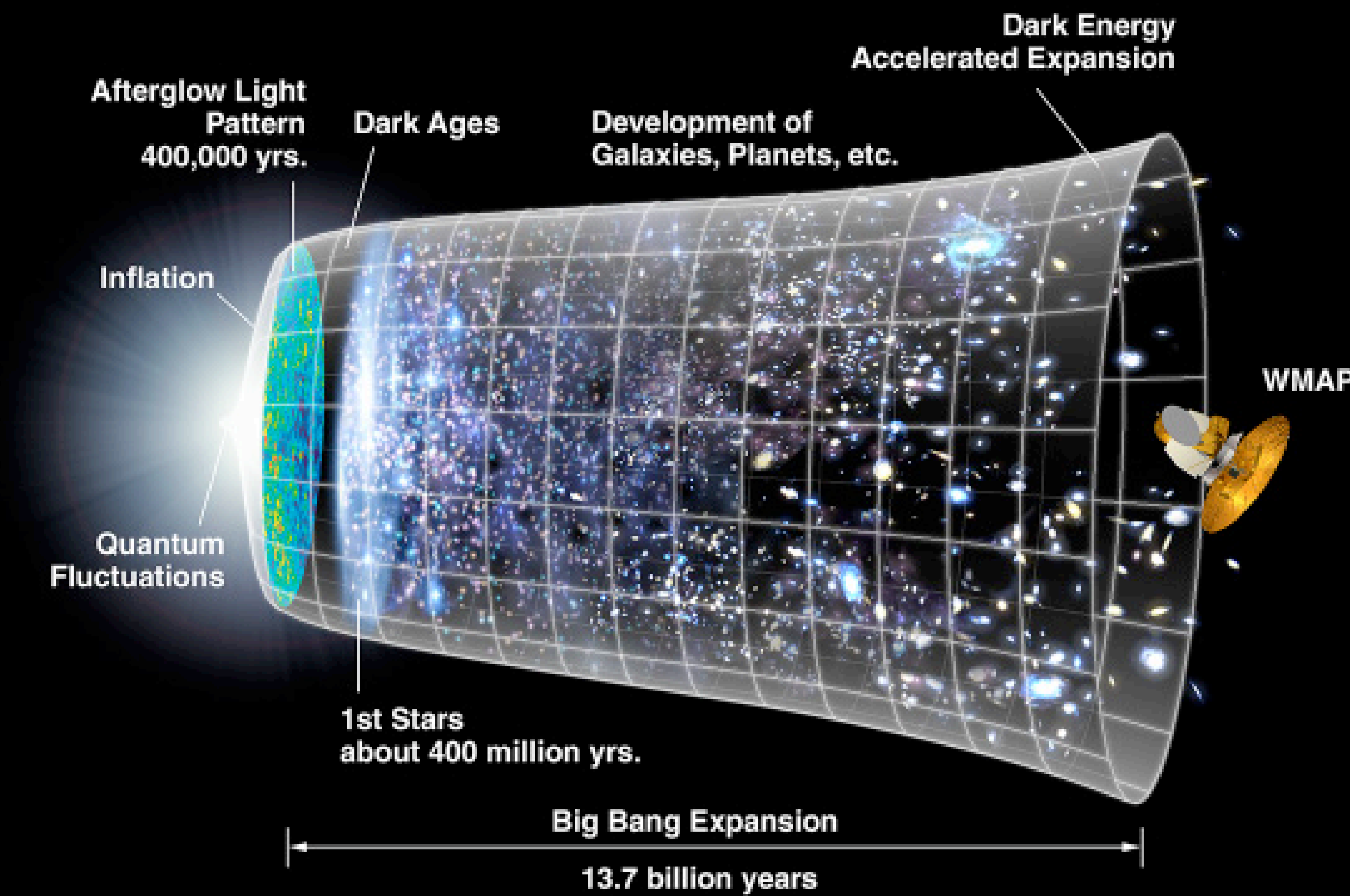


- Tau is almost entirely determined by the EE data.
- TE adds very little.
- Black Solid: TE+EE
- Cyan: EE only
- Dashed: Used C_l
- Dotted: TE+EE from KaQVW
- Shaded: Kogut et al.'s stand-alone tau analysis from TE
- Grey: 1-yr full analysis (Spergel et al. 2003)

The 3-yr polarization data essentially fixes tau independent of the other parameters.

Cosmological Parameter Estimation: An Inference Problem

early time parameters $P(k)$: n_s, r, $dn_s/d\ln k$, A_s, ...

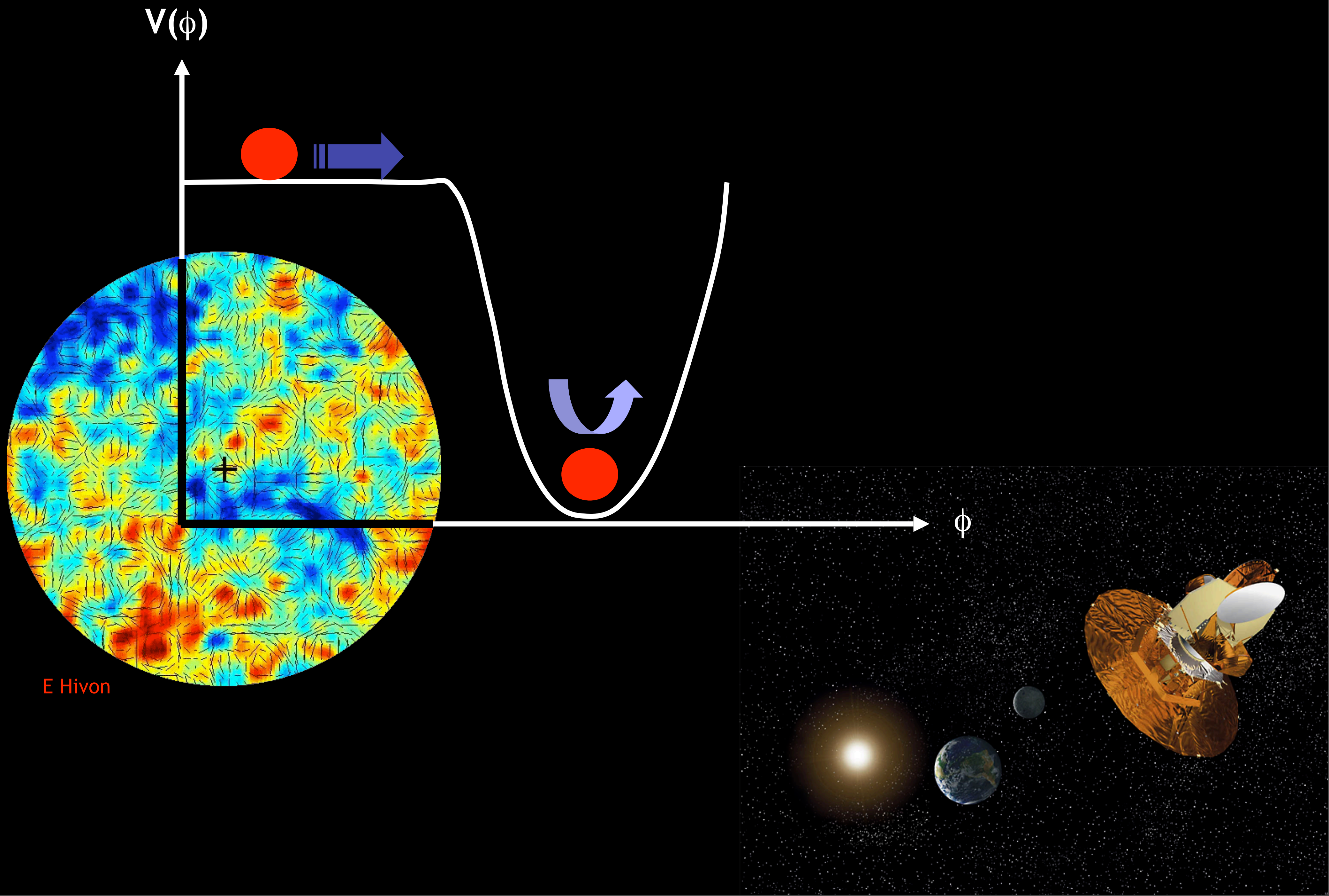


late time parameters: τ, w, H_0, ω_b, ω_c, ...

Generic predictions of simplest inflation models

- Nearly scale invariant primordial fluctuations [COBE]:
  - $P(k) \propto k^{n-1}$
- Flatness of the universe [TOCO, BOOMERanG, Maxima, Archeops, ..., WMAPI]
  - WMAPII: $\Omega_k = -0.064 \pm 0.07$
- Gaussianity of primordial perturbations [WMAPI]
  - WMAPII $-54 < f_{NL} < 114$
- Adiabatic initial conditions and superhorizon fluctuations [large scale TE anticorrelation, WMAPI]

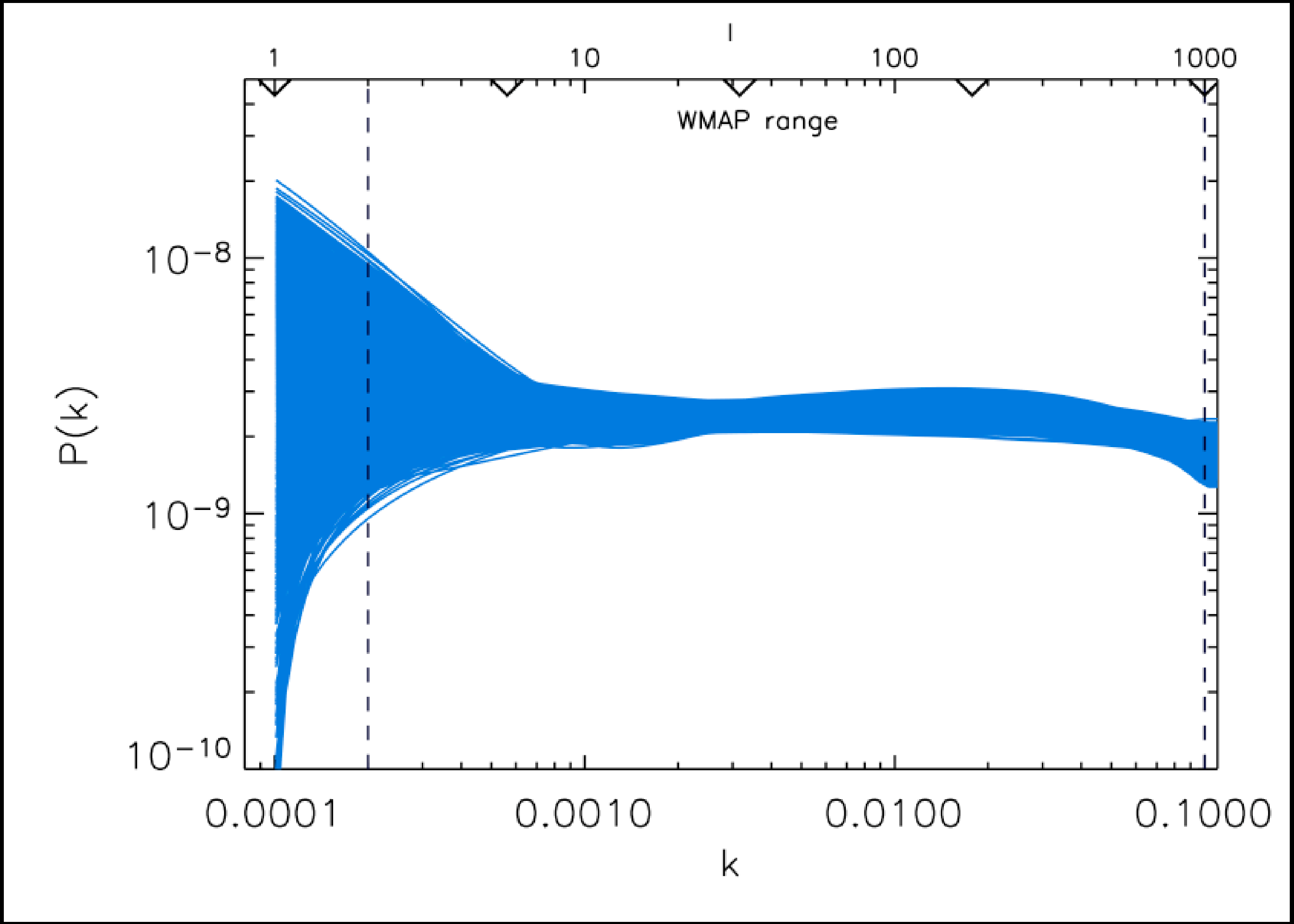
Constraints on the Scalar Power Spectrum



Constraints on the scalar power spectrum

- WMAPII data prefers a scalar spectral index that is significantly less than the Harrison-Zel'dovich scale invariant spectrum ($n_s = 1$, $r = 0$) in the LCDM model.
  - WMAPII: $n_s = 0.95 \pm 0.016$, $\Delta\chi^2 = 8$ from HZ case
- As CMB data continues to improve, this would be a major clue to how inflation proceeded, and its underlying physics.
- The error on the spectral index and its centroid is somewhat sensitive to:
  - The treatment of the beam error propagation in the likelihood function
  - The prior placed on the SZ amplitude in marginalization
  - Using the larger set KaQVW of WMAP bands for the polarization data rather than QV - stronger upper limit on τ cuts off residual degeneracy with n_s
  - Relaxing the assumption of instantaneous reionization
  - Adding external small scale data increases the significance

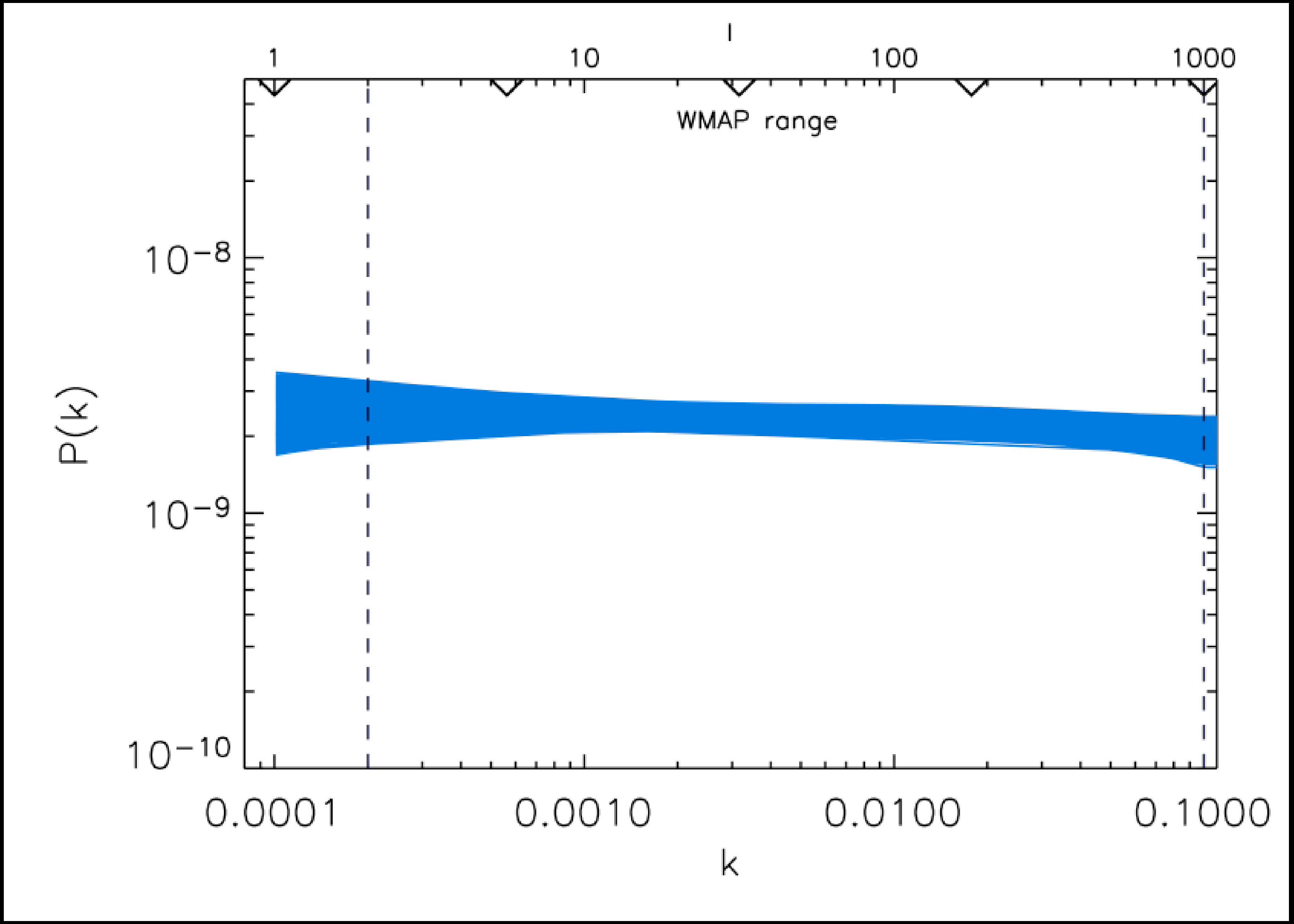
Minimally-parametric constraints on P(k)



Constraints from fitting a 5-knot spline to the primordial scalar power spectrum (minimal smoothness penalty)

Preliminary results, in collaboration with Licia Verde

Minimally-parametric constraints on P(k)



Constraints from fitting a 5-knot spline to the primordial scalar power spectrum (smoothness penalty imposed)

Preliminary results, in collaboration with Licia Verde

Detailed Predictions of Inflation Models

- The primordial power spectrum is not a perfect power law.

$$n_s(k) = n_s(k_0) + \alpha \ln\left(\frac{k}{k_0}\right)$$

"running": $dn_s/d\ln k$

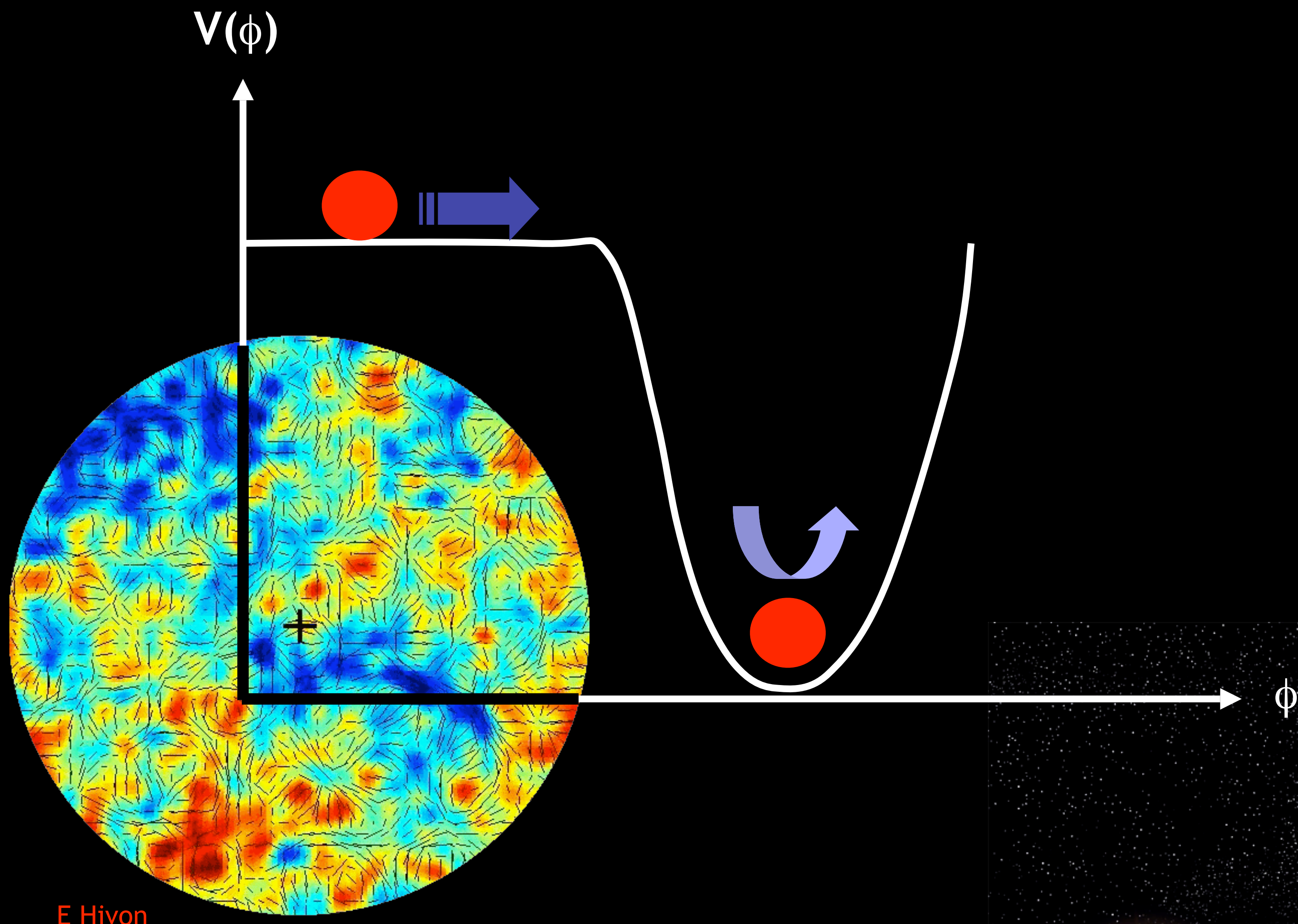
- There could be gravitational waves.

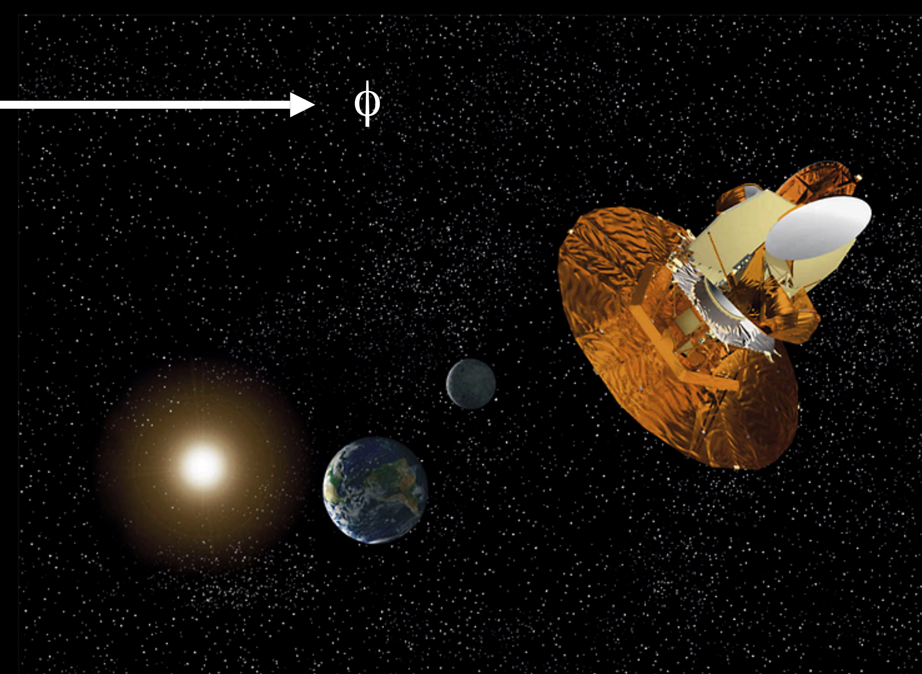
$$r \equiv \text{tensor-to-scalar ratio} = \frac{\langle h_{ij}h^{ij}\rangle(k_0)}{\langle \mathcal{R}\mathcal{R}\rangle(k_0)}$$

(The shape of the tensor power spectrum is determined by $n_t = -r/8$ using predictions of single field inflationary models.)

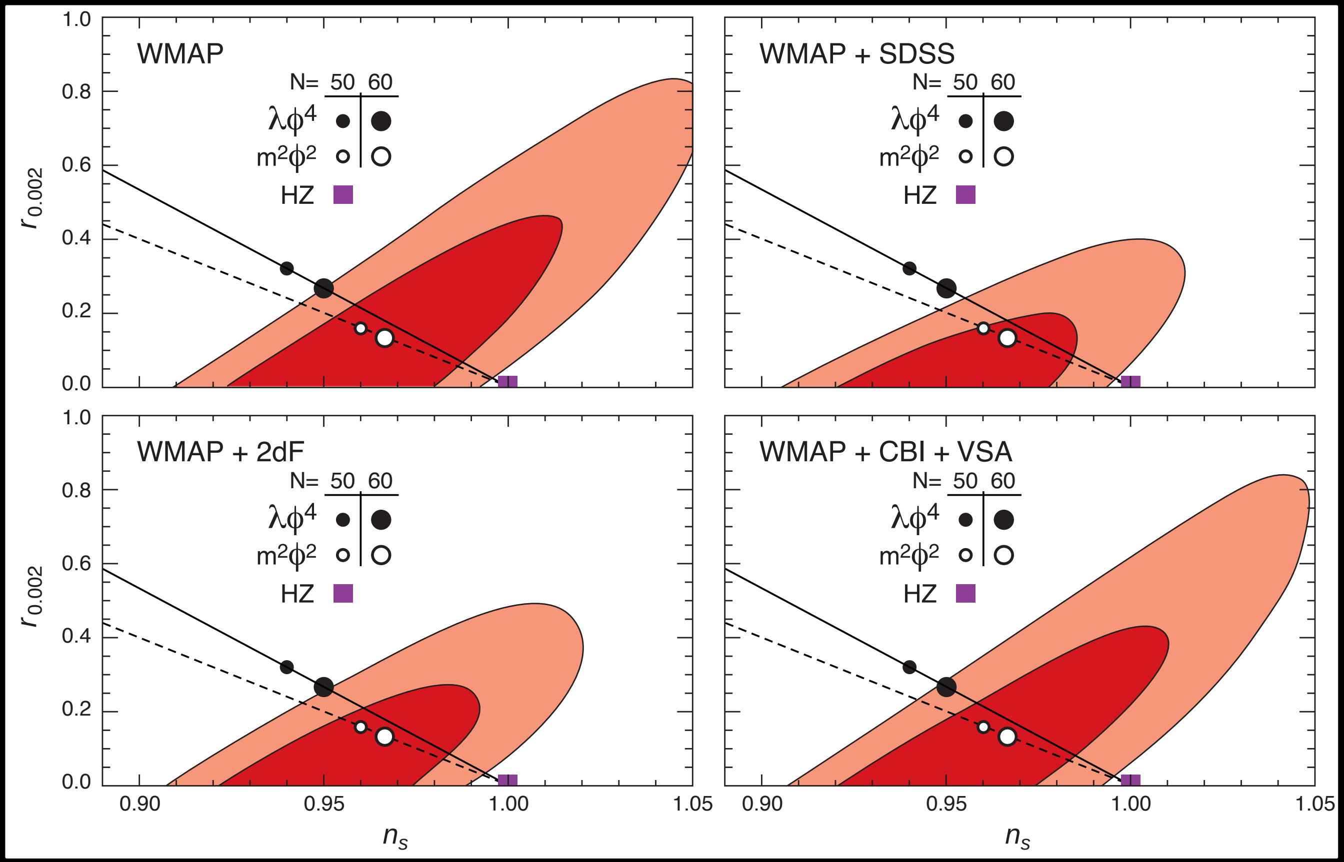
We use k_0=0.002 Mpc^{-1} (l ~ 30)

Constraints on Tensor Modes





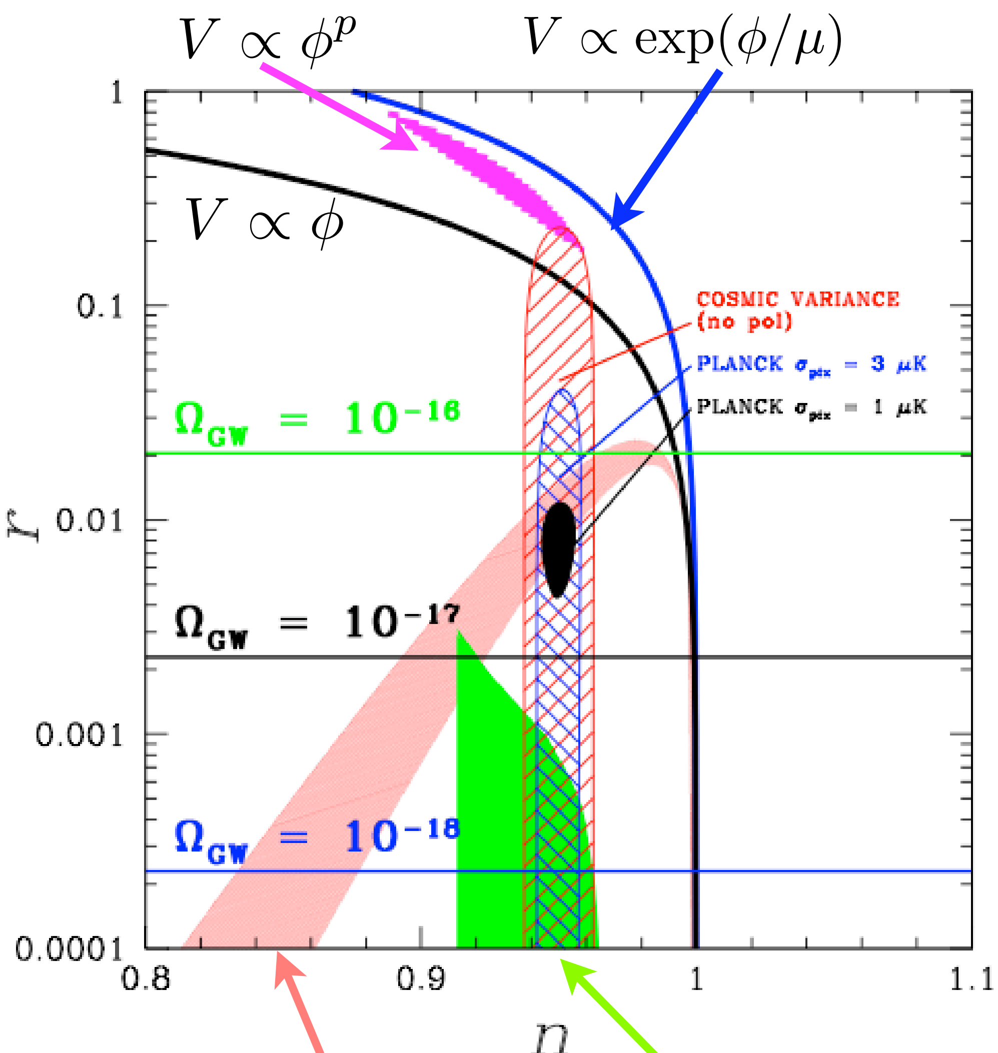
Constraints on tensor modes



Spergel et al (2006)

- Both the scale-invariant Harrison-Zel'dovich power spectrum and the $\lambda\, \phi^4$ model are disfavoured w.r.t. to the $m^2\, \phi^2$ model by likelihood ratios greater than 50.

Theoretical Uncertainties in Inflationary Predictions



Kinney & Riotto (astro-ph/0511127)

$$N \simeq 60 + \frac{1}{6}\ln(-n_T) + \frac{1}{3}\ln(T_{RH}/10^{16}\mathrm{GeV}) - \frac{1}{3}\ln\gamma$$

- Reheat temperature can vary from GUT scale (10^{15} GeV) to nucleosynthesis scale (1 MeV)
- Resulting uncertainty in N about 14 efolds gives uncertainties in observables:

$$\frac{\Delta r}{r} \sim 1$$

$$\Delta n \sim 0.02$$

Measuring these "observables" from the data may not be the best way to learn about inflation!

An alternative description: Hubble Slow Roll Formalism

- Starting point:
  - Single Field Inflation
  - Minimally coupled; model specified via potential
- "Slow Roll" introduced with new inflation.
  Albrecht & Steinhardt; Linde (1980s)
- Expressed via the Hamilton-Jacobi Formalism (1990s)
  - Used to organize inflationary parameter space (1990s-2000s)
  - Inflaton field used as a "clock"

Hubble Slow Roll Formalism for Single Field Inflation: Review

Assume Hubble parameter during inflation is a function of field rather than time (i.e. field is monotonic in time). Leads to Hamilton-Jacobi Equation:

$$[H'(\phi)]^2 - \frac{12\pi}{m_{\rm Pl}^2} H^2(\phi) = -\frac{32\pi^2}{m_{\rm Pl}^4} V(\phi)$$

Define HSR parameters:

$$\epsilon(\phi) \equiv \frac{m_{\rm Pl}^2}{4\pi} \left[\frac{H'(\phi)}{H(\phi)}\right]^2$$

$${}^\ell\lambda_H \equiv \left(\frac{m_{\rm Pl}^2}{4\pi}\right)^\ell \frac{(H')^{\ell-1}}{H^\ell} \frac{d^{(\ell+1)} H}{d\phi^{(\ell+1)}};\ \ \ell \geq 1$$

Then the potential is given by:

$$H^2(\phi)\left[1 - \frac{1}{3}\epsilon(\phi)\right] = \left(\frac{8\pi}{3m_{\rm Pl}^2}\right) V(\phi)$$

Barrow, Parsons & Liddle (1994), Hoffman & Turner (2001), Kinney (2002), Kinney & Easther (2003)

Evolution of HSR parameters described by an infinite set of coupled first order DEs. In practice, must truncate this series at order M:

$$ {}^{M+1}\lambda_H = 0 $$

$$ \Rightarrow \frac{d^{(M+2)}H}{d\phi^{(M+2)}} = 0 $$

This leads to an analytic solution for the motion:

$$ H(\phi) = H_0 \left[1 + A_1 \left(\frac{\phi}{m_{\rm Pl}} \right) + ... + A_{M+1} \left(\frac{\phi}{m_{\rm Pl}} \right)^{M+1} \right] $$

$$ \epsilon(\phi) = \frac{m_{\rm Pl}^2}{4\pi} \left[\frac{(A_1/m_{\rm Pl}) + ... + (M+1)\,(A_{M+1}/m_{\rm Pl})\,(\phi/m_{\rm Pl})^M}{1 + A_1\,(\phi/m_{\rm Pl}) + ... + A_{M+1}\,(\phi/m_{\rm Pl})^{M+1}} \right]^2 $$

$$ A_1 = \sqrt{4\pi\epsilon_0} $$

$$ A_{\ell+1} = \frac{(4\pi)^{\ell}\ {}^{\ell}\lambda_{H,0}}{(\ell+1)!\ A_1^{\ell-1}};\ \ \ell \geq 1 $$

Liddle (2003), Ramirez & Liddle (2005)

Hubble Slow Roll Formalism: Summary I

The time-evolution of inflation can be described by infinite hierarchy of derivatives of the Hubble parameter H[ϕ(t)] during inflation (where primes denote d/dϕ) :

$$\epsilon \propto \left(\frac{H'}{H}\right)^2 \qquad \eta \propto \frac{H''}{H} \qquad \xi \propto \frac{H'''H'}{H^2} \qquad \text{etc.}$$

SLOPE　　CURVATURE　　JERK

- Truncated hierarchy is closed (truncate a point, truncate everywhere).
- HSR hierarchy captures full inflationary dynamics. Truncate it, get an approximate potential.
- Truncated hierarchy has an exact solution.

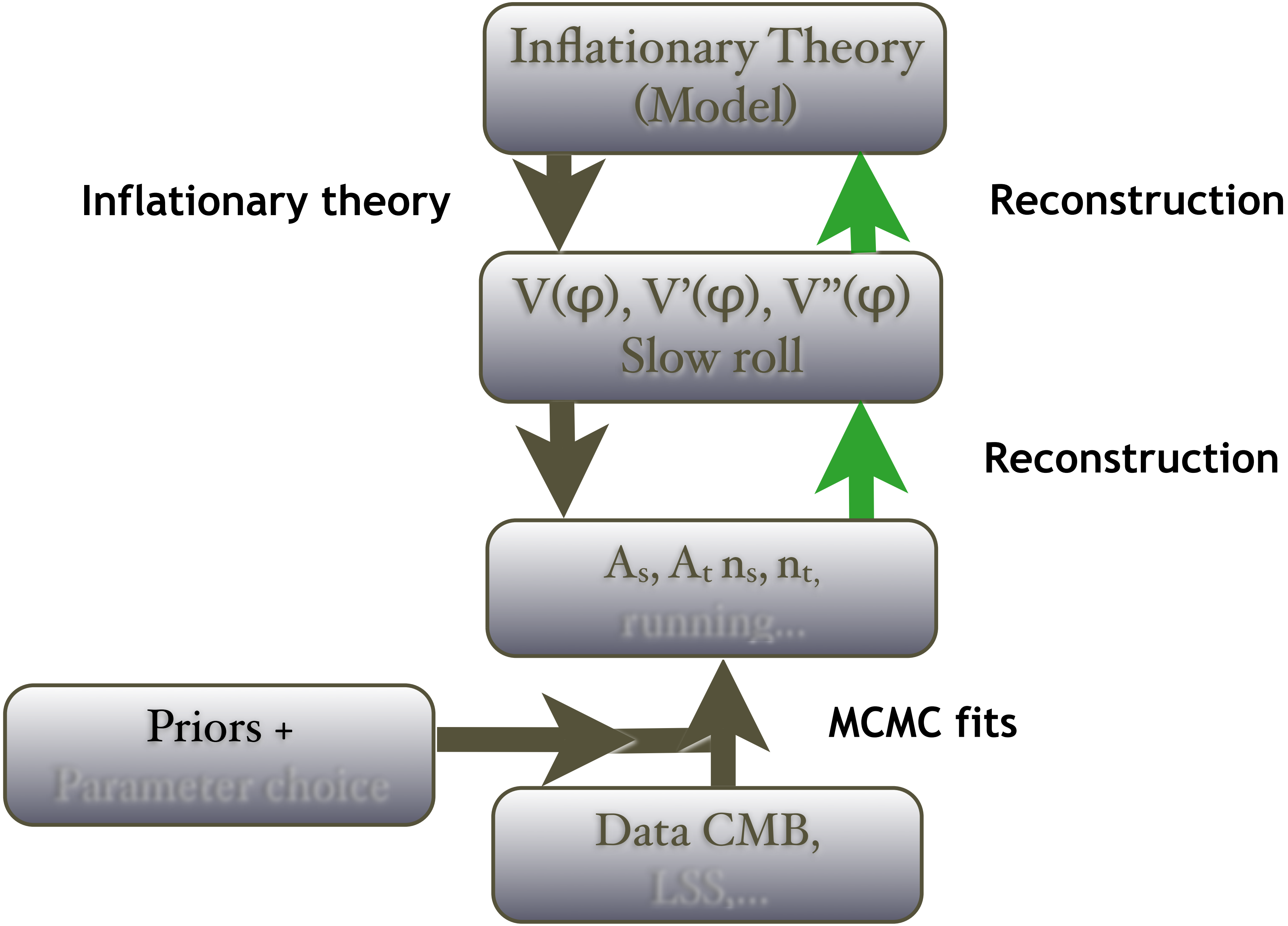
Hubble Slow Roll Formalism: Summary II

- The slow roll parameters are functions of scale k (since amplitude of primordial fluctuations at each scale is imprinted when that scale exits the horizon during inflation).

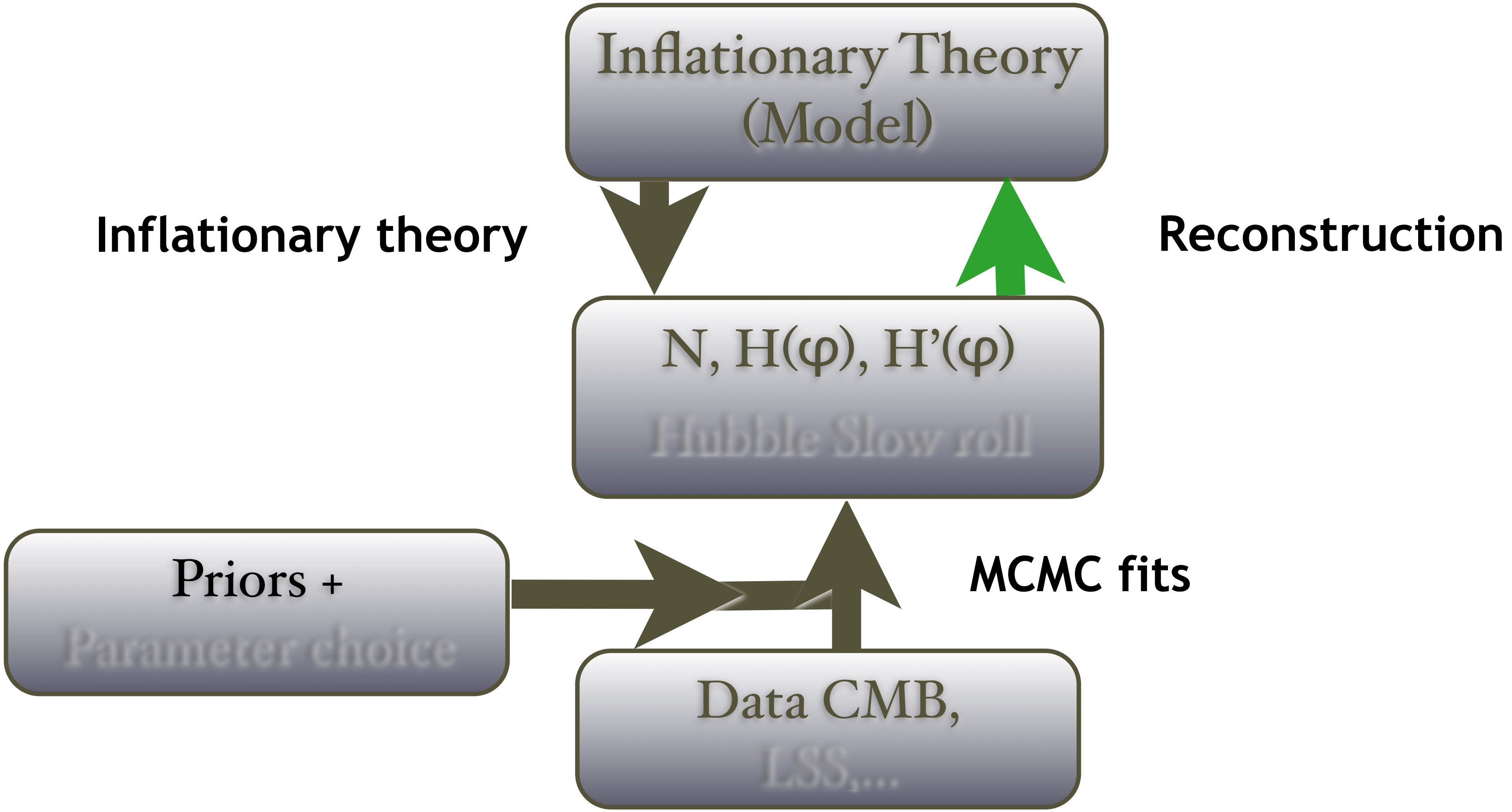
- Hence the slow roll parameters describe the primordial power spectra.

- Link values of slow roll parameters at a measurable fiducial scale directly to the field value there ($k=0.002\ \mathrm{Mpc}^{-1}$)- analytic expressions for the slow roll parameters at all other scales follow.

Fit to data: Standard process



Fit to data: Slow Roll Reconstruction



Modelling Methods

- Approach 1: Fit power law form n_s, r, $dn_s/d\ln k$, ... etc for shapes of primordial power spectra.
  - These are empirical quantities
  - No fundamental significance
  - No immediate correlation with theoretical predictions
  - Implicitly assume smoothness

- Approach 2: Fit functions $P_R(\epsilon, \eta, \ldots)$, $P_h(\epsilon, \eta, \ldots)$ directly for primordial power spectra.
  - From these we can rebuild the potential
  - "Thorough" inflationary prior
  - Do not explicitly drop smoothness
  - Automatically encapsulates scale-dependence; could compute spectrum exactly if needed
  - Can easily impose N_{efold} prior
  - Ambiguities about "measure of initial conditions" minimized as long as data constraints are stronger than prior
  - Taylor expansion around a moving point (avoids use of a pivot)
  - Ideal for use with heterogeneous datasets (e.g. CMB+21cm, CMB+GWO)

Hubble Slow Roll Formalism as Potential Generator for Markov Chain-based Parameter Estimation

Algorithm:

- Pick HSR parameters at fiducial wavenumber corresponding to phi=0
- Calculate k as a function of phi
- Use analytic solutions to H, epsilon and eta to calculate the primordial power spectra
- Feed into e.g. CAMB to calculate CMB power spectra
- Models where inflation ends within the k-range accessible by CMB and LSS are rejected
- Have option of applying an a posteriori “sufficient e-folds” prior

$$\frac{d\phi}{d\ln k} = -\frac{m_{\rm Pl}}{2\sqrt{\pi}}\frac{\sqrt{\epsilon}}{1-\epsilon}$$

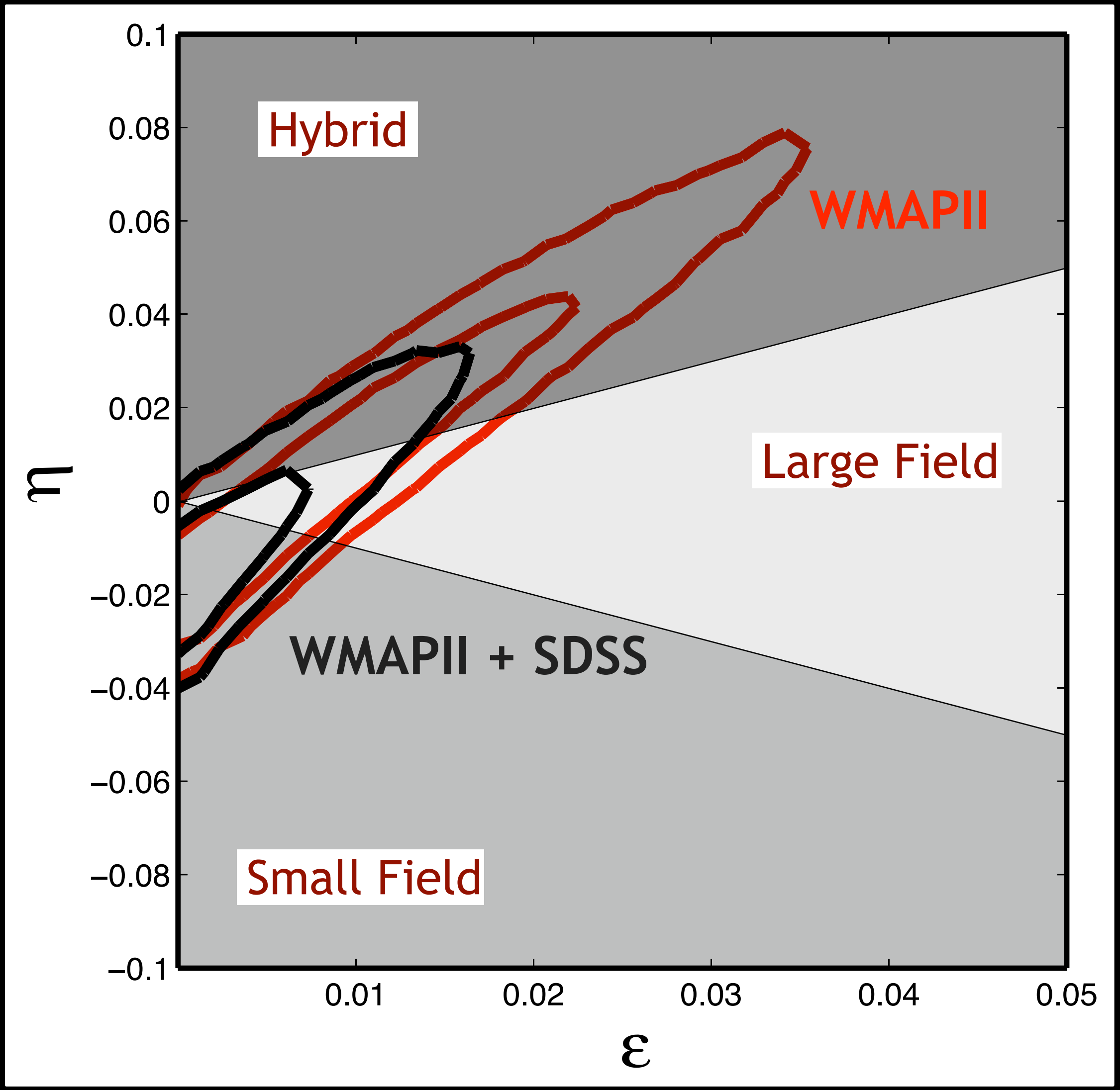
$$P_{\mathcal{R}} = \frac{\left[1-(2C+1)\epsilon + C\eta\right]^2}{\pi\epsilon}\left(\frac{H}{m_{\rm Pl}}\right)^2 |_{k=aH}$$

$$P_h = \left[1-(C+1)\epsilon\right]^2 \frac{16}{\pi}\left(\frac{H}{m_{\rm Pl}}\right)^2 |_{k=aH}$$

$$A_s = \frac{\left[1-(2C+1)\epsilon_0 + C\eta_0\right]^2}{\pi\epsilon_0}\left(\frac{H_0}{m_{\rm Pl}}\right)^2$$

Lidsey et al (1995)

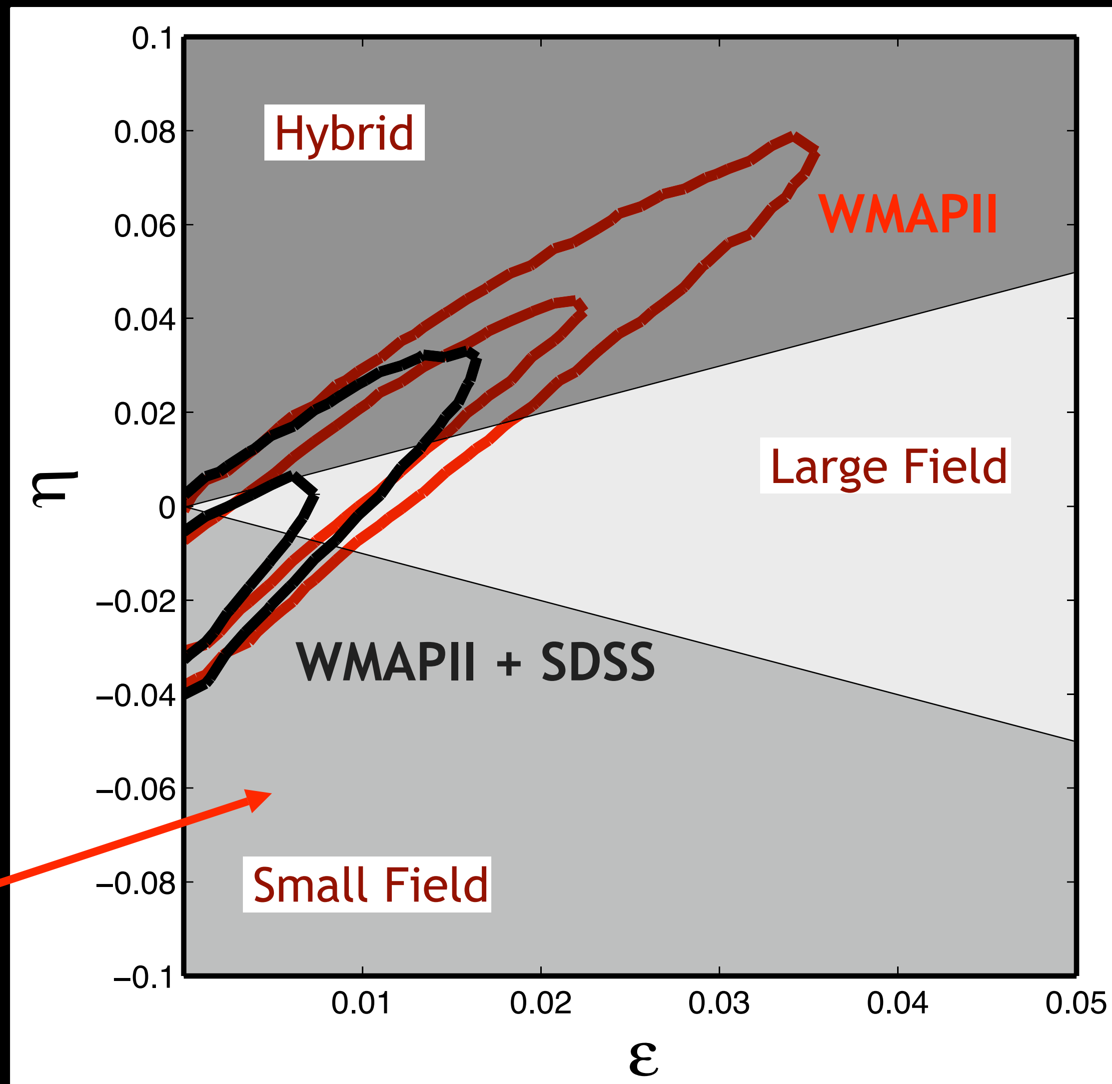
The Inflationary Zoo

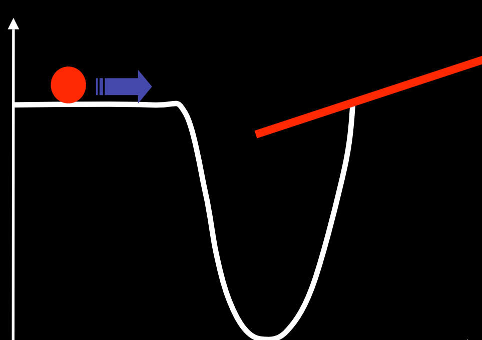


Peiris & Easther (2006)

Constraints on first two HSR parameters at k=0.002 Mpc^{-1}

The Inflationary Zoo





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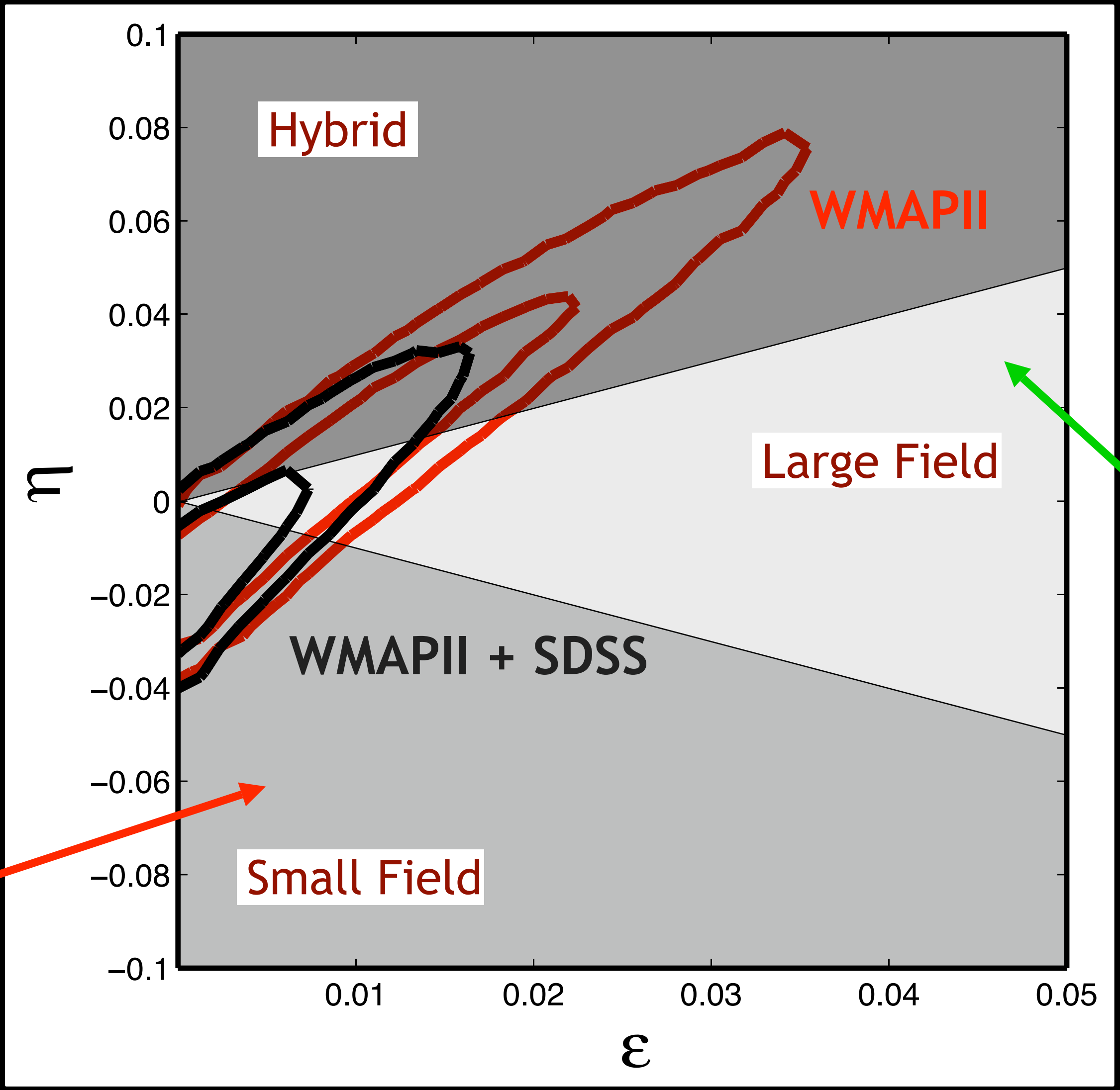
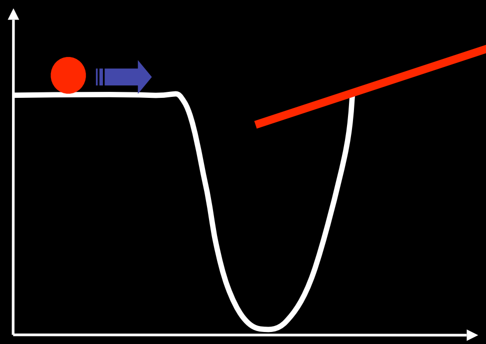
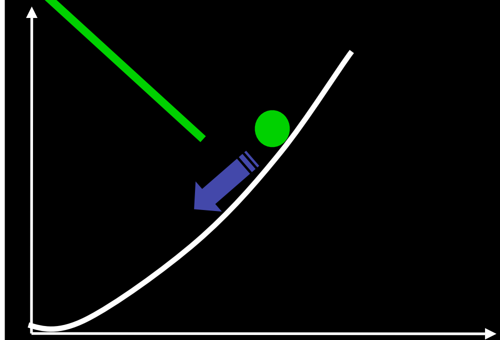


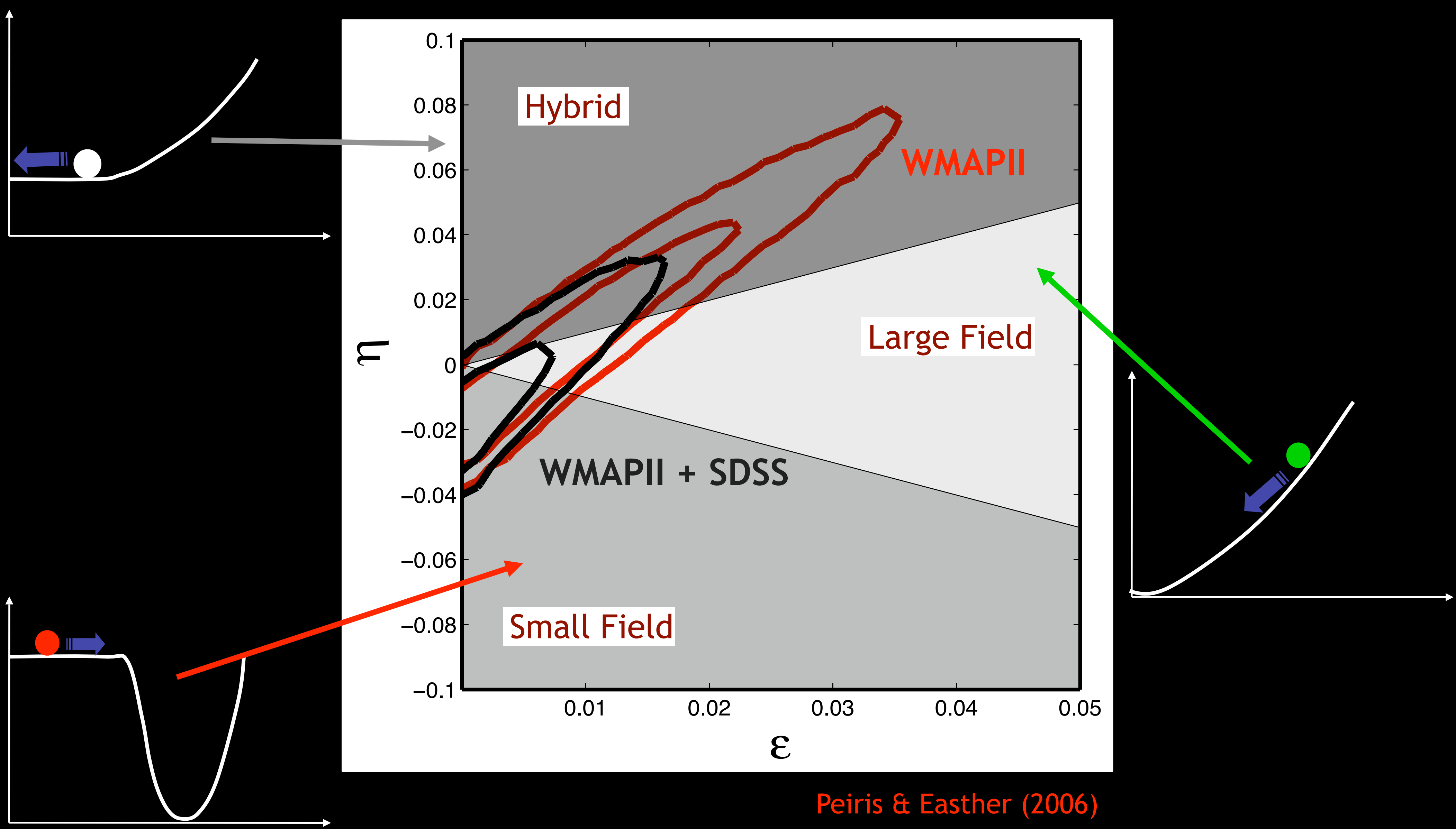




Peiris & Easther (2006)

Constraints on first two HSR parameters at $k = 0.002\ \mathrm{Mpc}^{-1}$

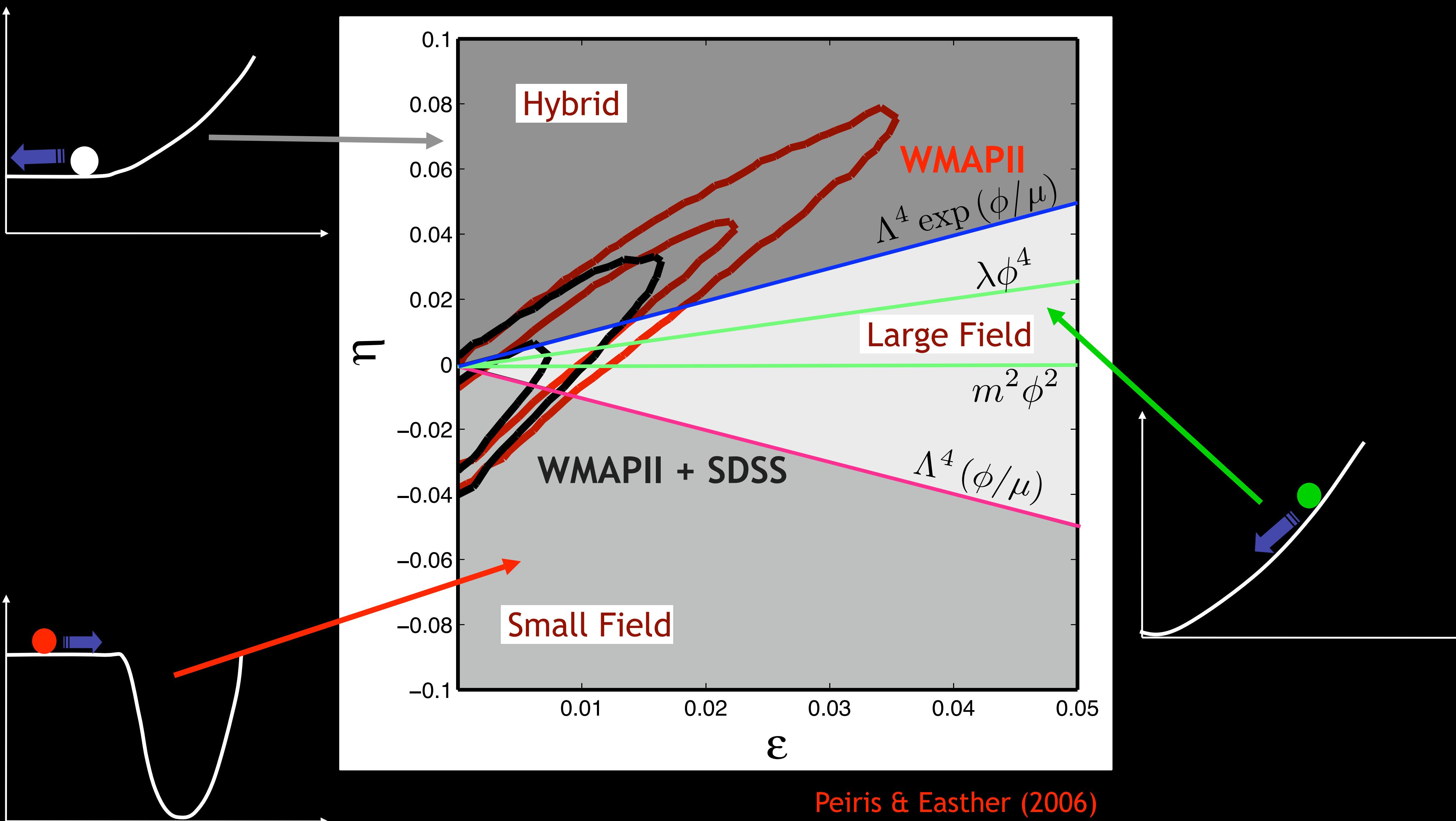
The Inflationary Zoo



Peiris & Easther (2006)

Constraints on first two HSR parameters at k=0.002 Mpc^{-1}

Denizens of the Inflationary Zoo



Peiris & Easther (2006)

Constraints on first two HSR parameters at k=0.002 Mpc^{-1}

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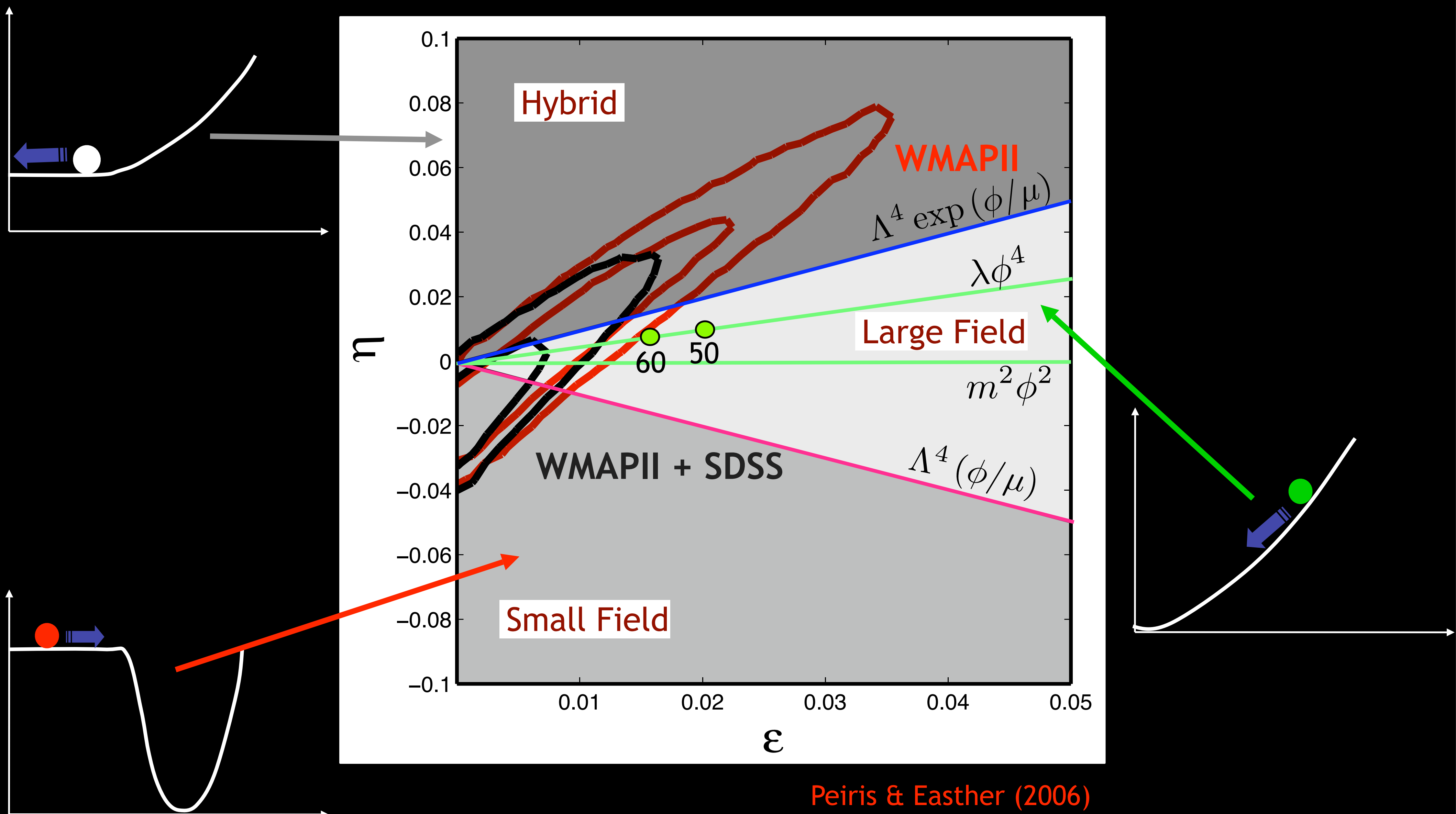

Peiris & Easther (2006)

Constraints on first two HSR parameters at k=0.002 Mpc^{-1}

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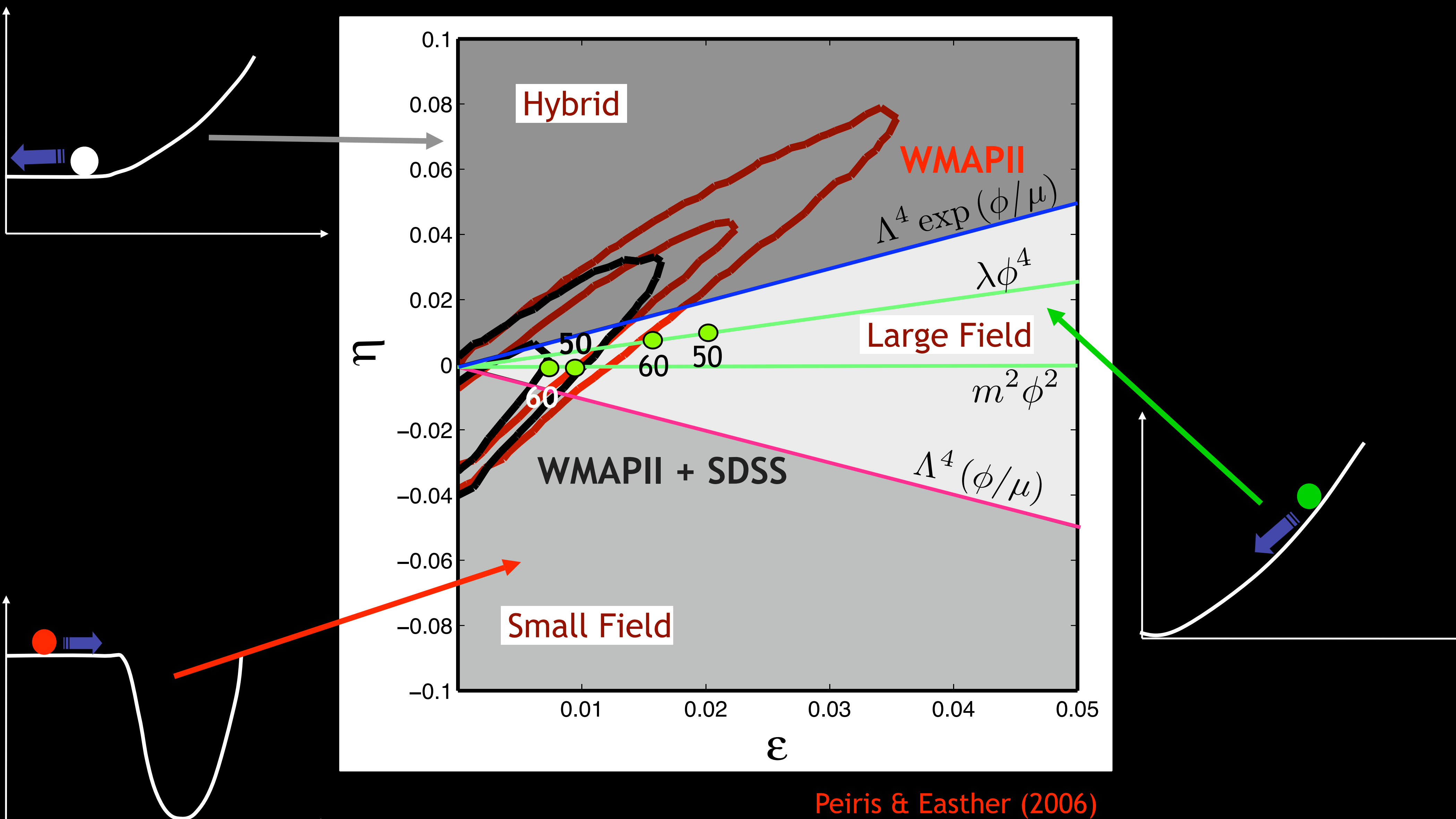
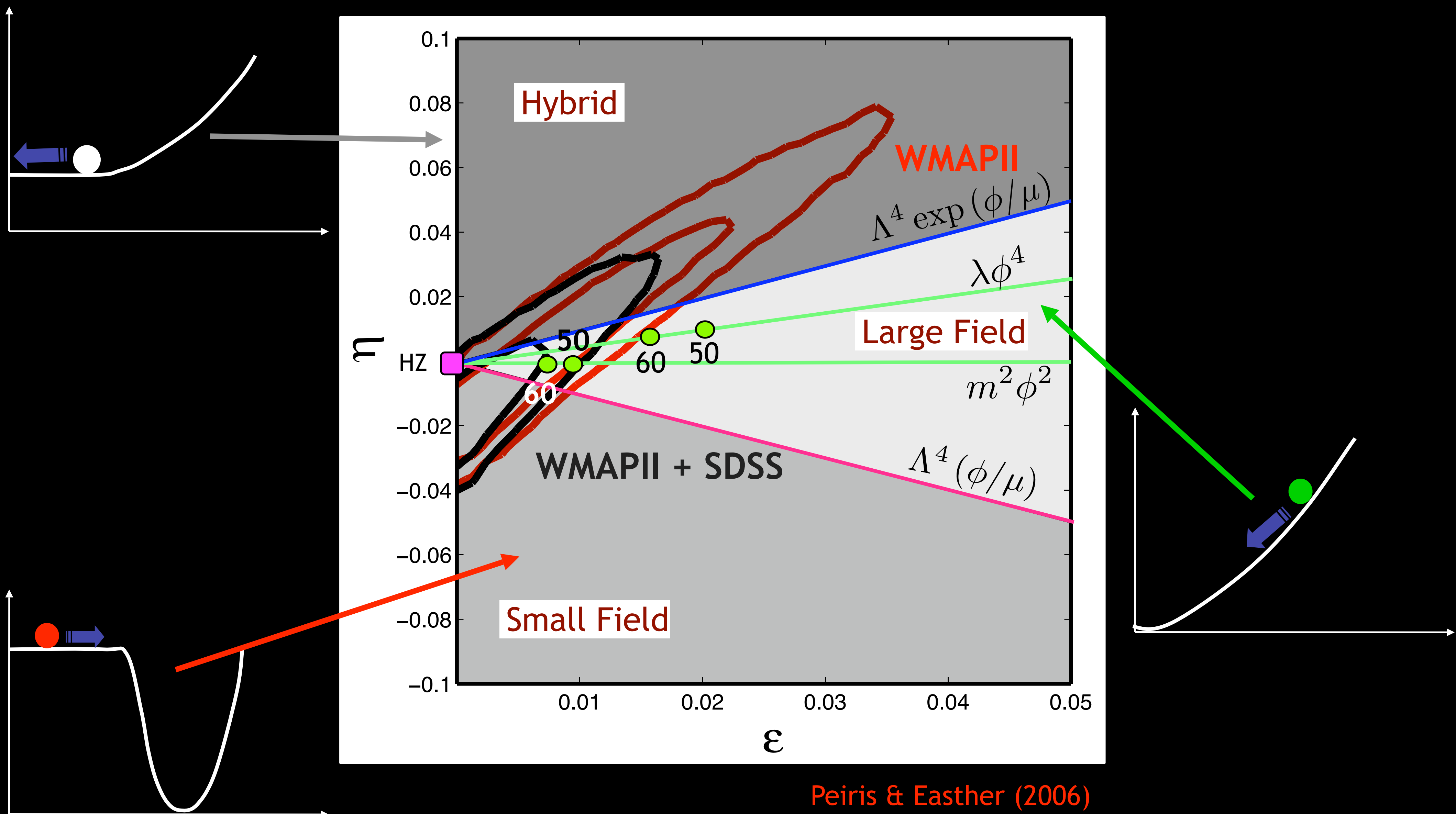


Peiris & Easther (2006)

Constraints on first two HSR parameters at $k=0.002\ \mathrm{Mpc}^{-1}$

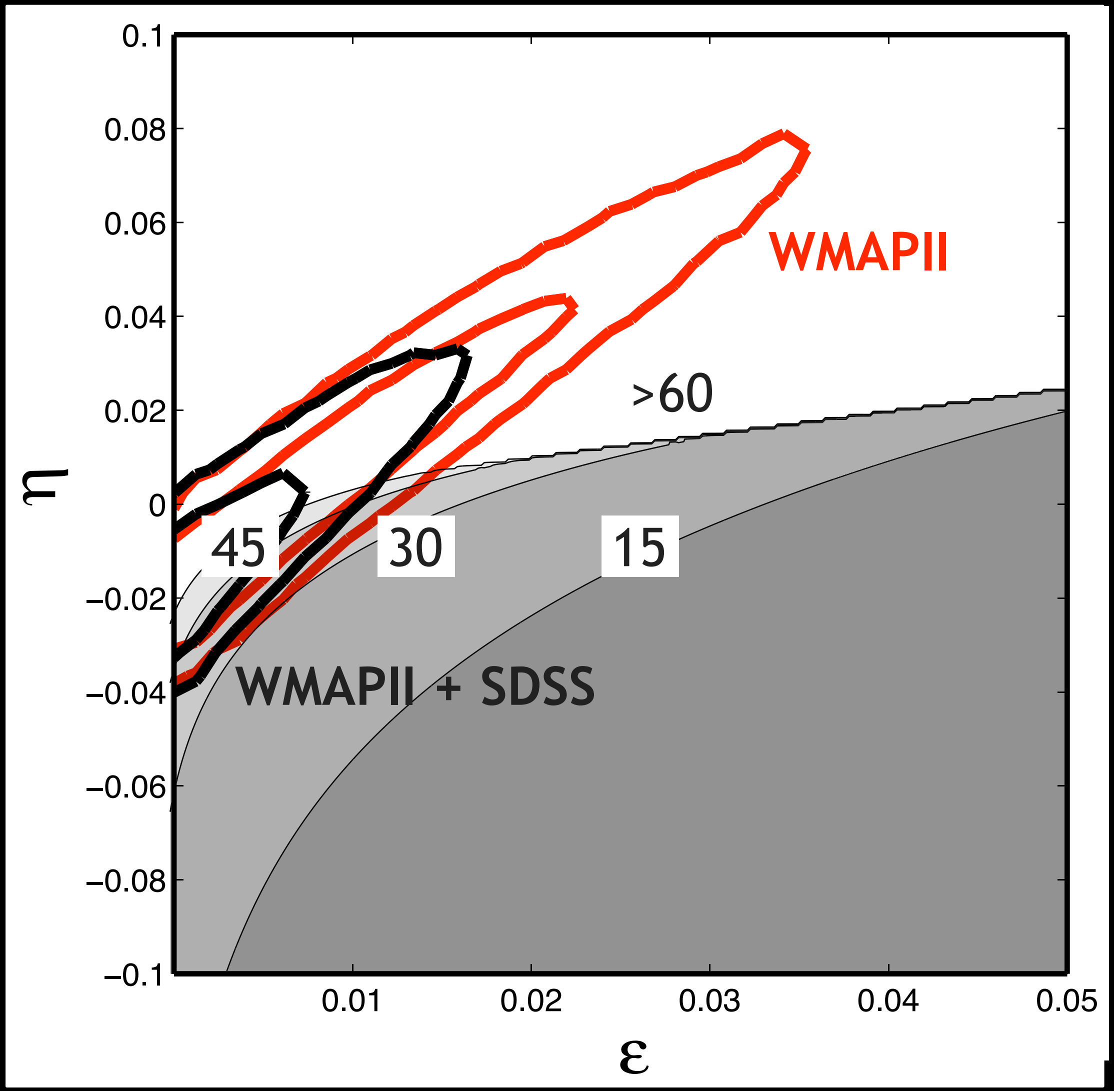
Denizens of the Inflationary Zoo



Peiris & Easther (2006)

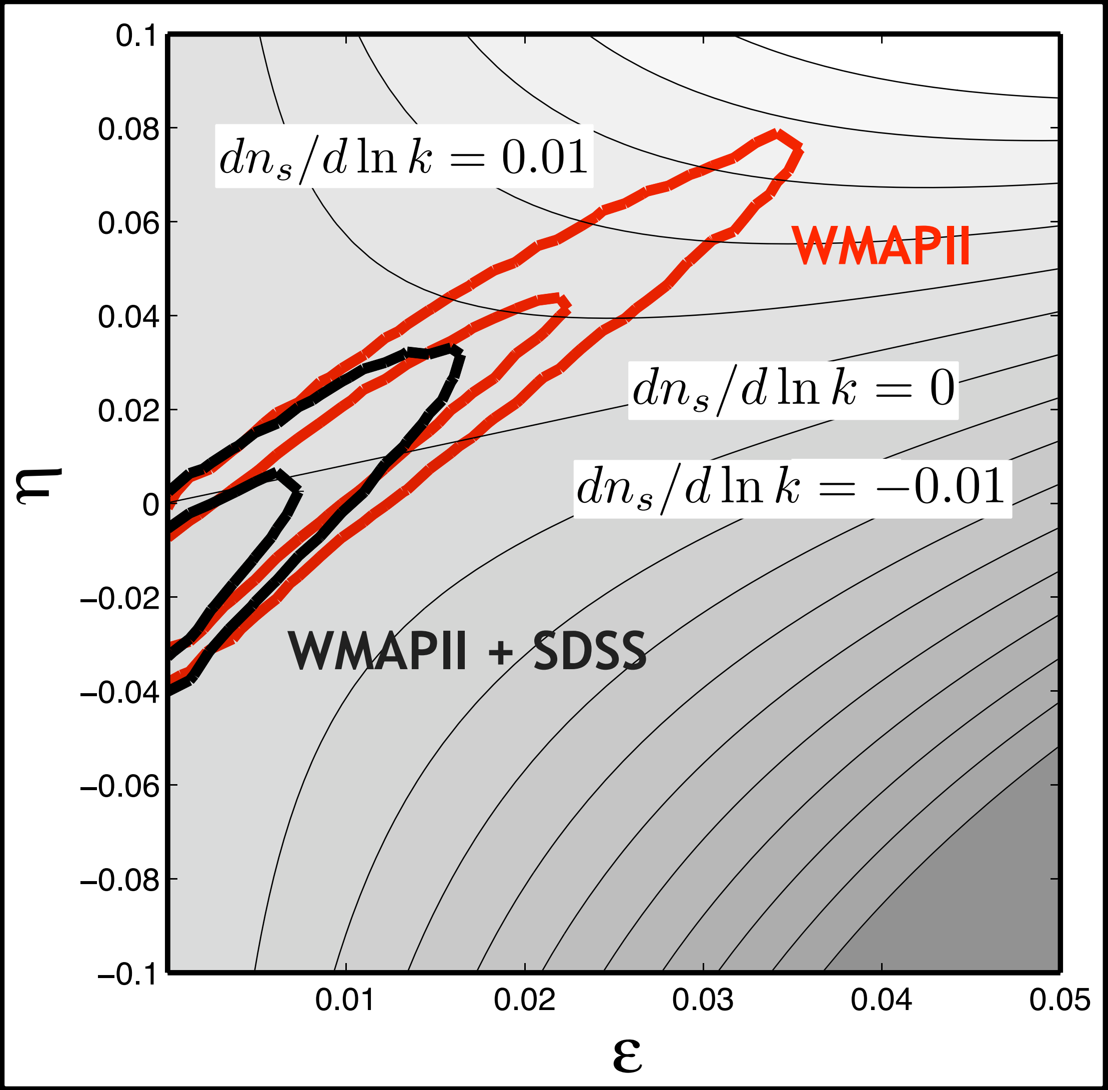
Constraints on first two HSR parameters at k=0.002 Mpc^{-1}

The duration of inflation



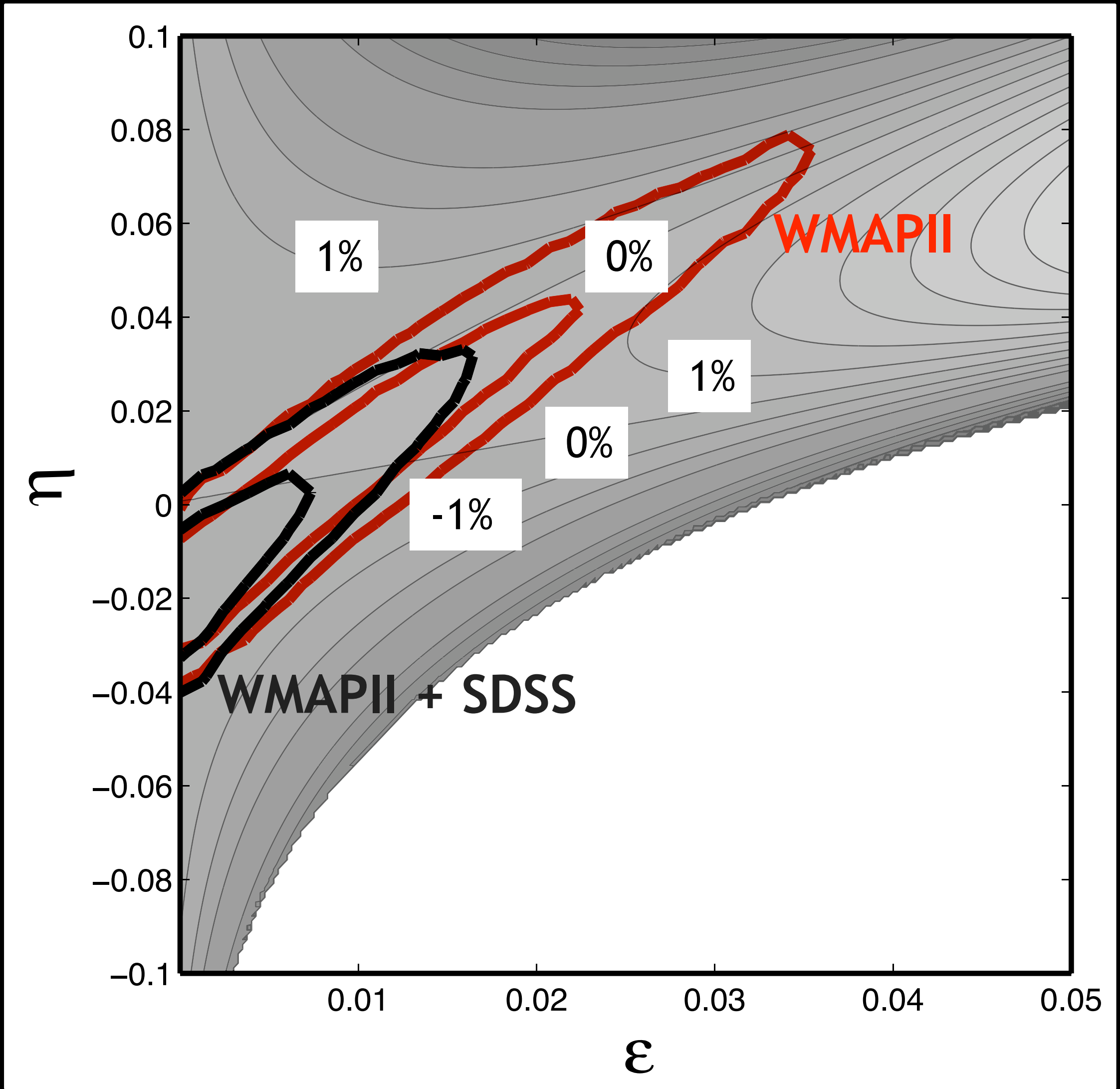
Peiris & Easther (2006)

Inflation and a running spectral index?



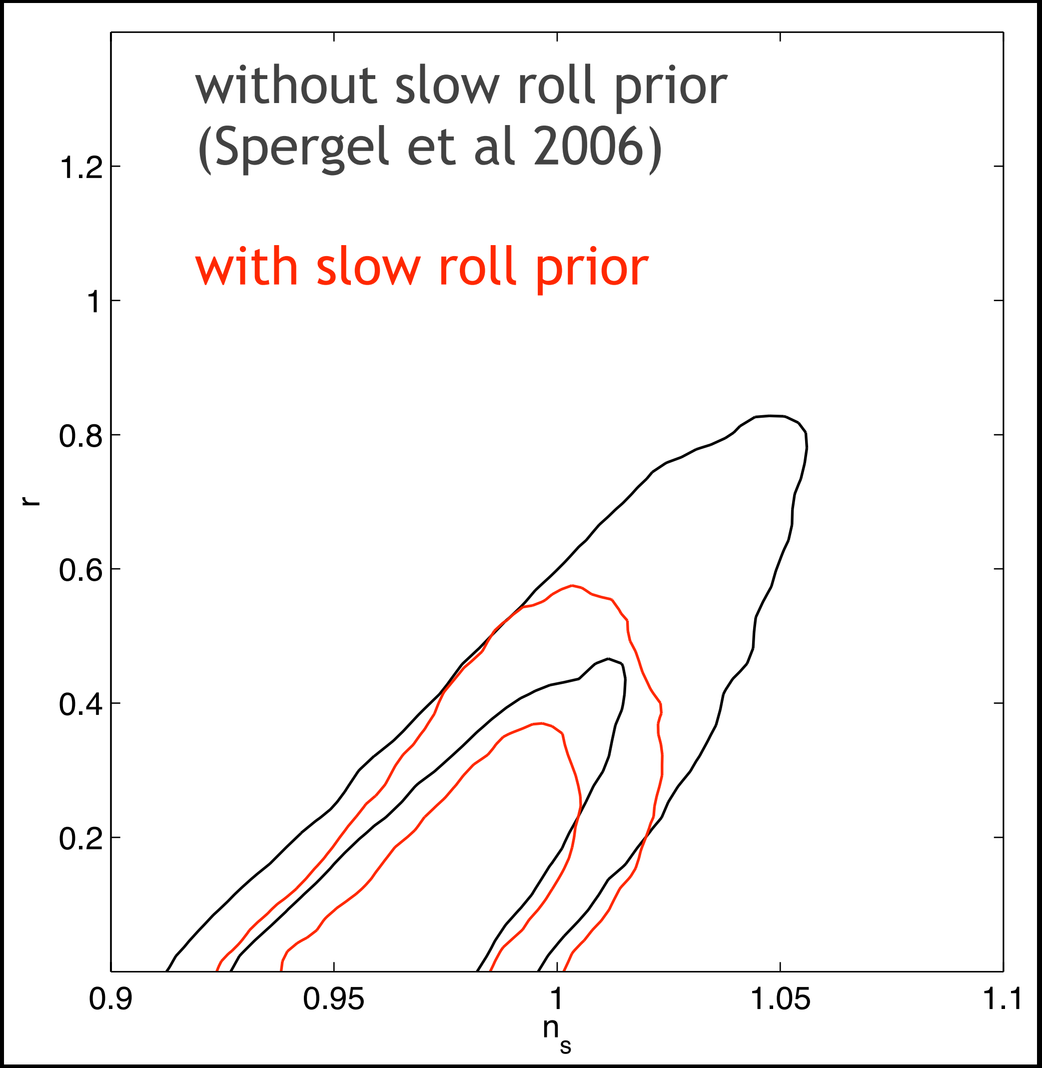
Peiris & Easther (2006)

Analytic vs Semianalytic formalisms



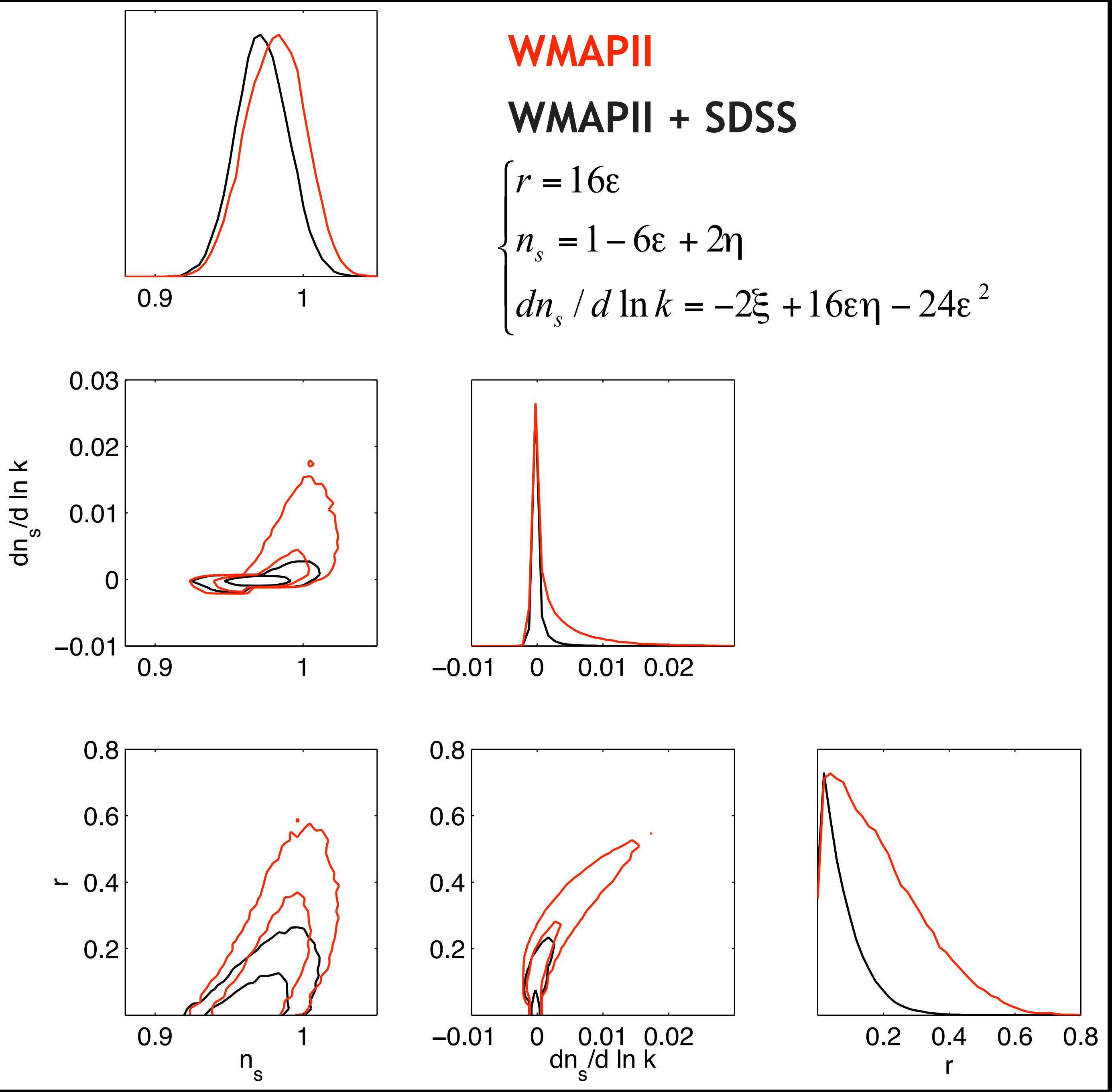
- HSR approach compared compared to $n_s(\epsilon, \eta, \ldots)$, $r(\epsilon, \eta, \ldots)$ approach, truncating the series at ξ
- Differences increase when including higher order parameters

The effect of applying a “slow roll prior”



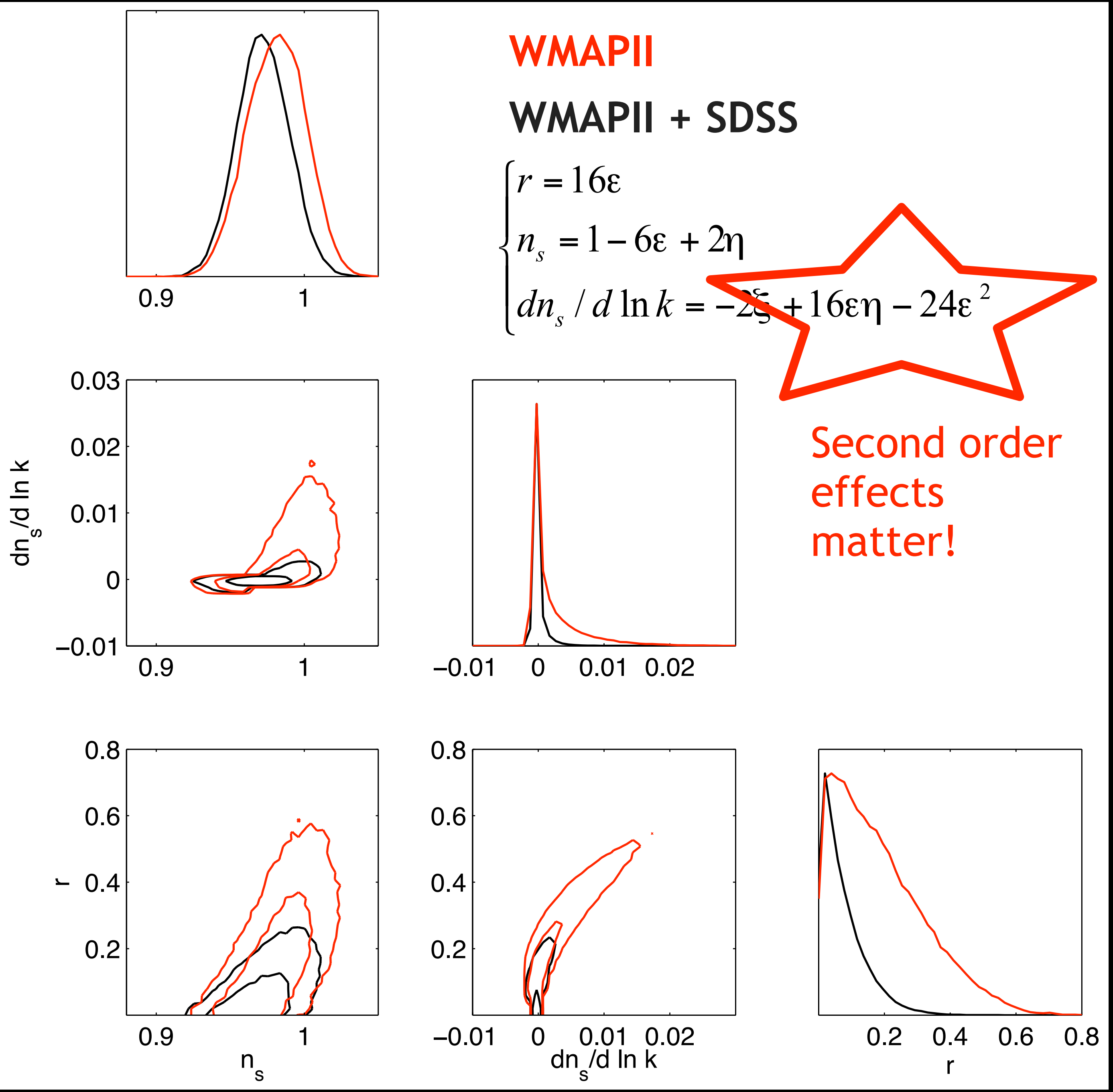
Peiris & Easther (2006)

Why are "slow roll prior" constraints tighter?



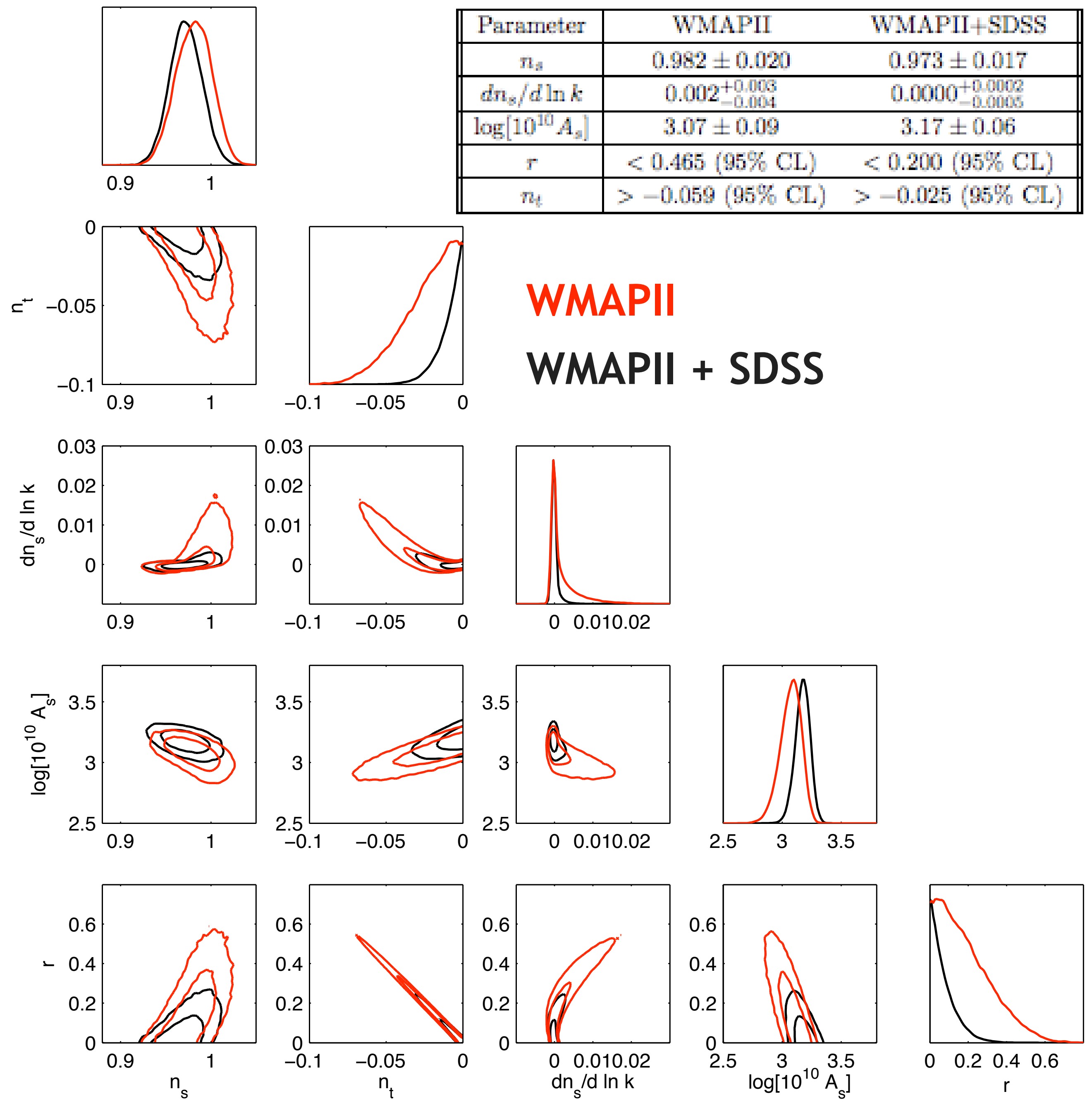
$$\begin{cases} r = 16\varepsilon \\ n_s = 1 - 6\varepsilon + 2\eta \\ dn_s / d\ln k = -2\xi + 16\varepsilon\eta - 24\varepsilon^2 \end{cases}$$

Why are "slow roll prior" constraints tighter?



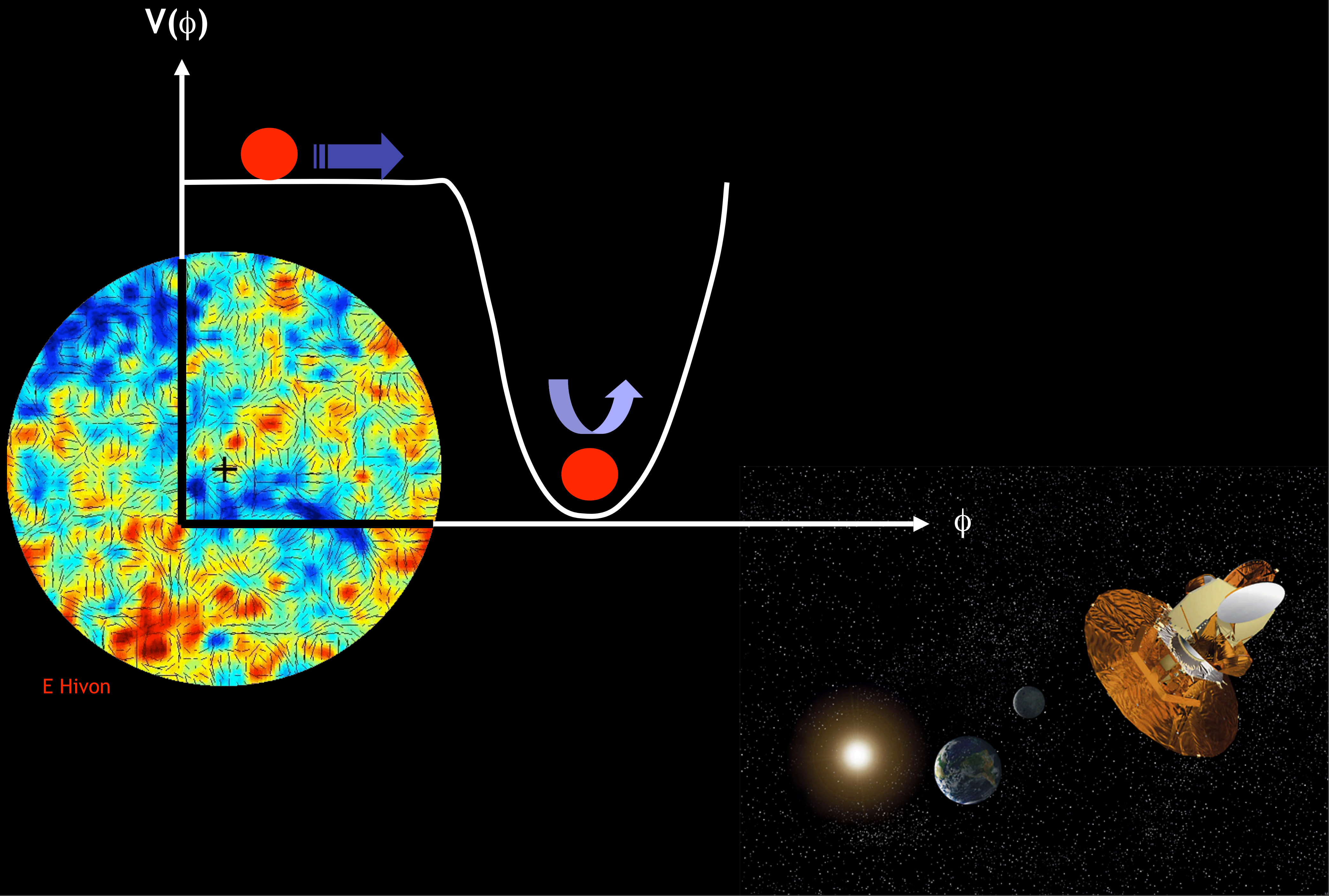
Constraints on primordial parameters

Parameter	WMAPII	WMAPII+SDSS
n_s	0.982 ± 0.020	0.973 ± 0.017
$dn_s/d\ln k$	$0.002^{+0.003}_{-0.004}$	$0.0000^{+0.0002}_{-0.0005}$
$\log[10^{10} A_s]$	3.07 ± 0.09	3.17 ± 0.06
r	< 0.465 (95% CL)	< 0.200 (95% CL)
n_t	> -0.059 (95% CL)	> -0.025 (95% CL)

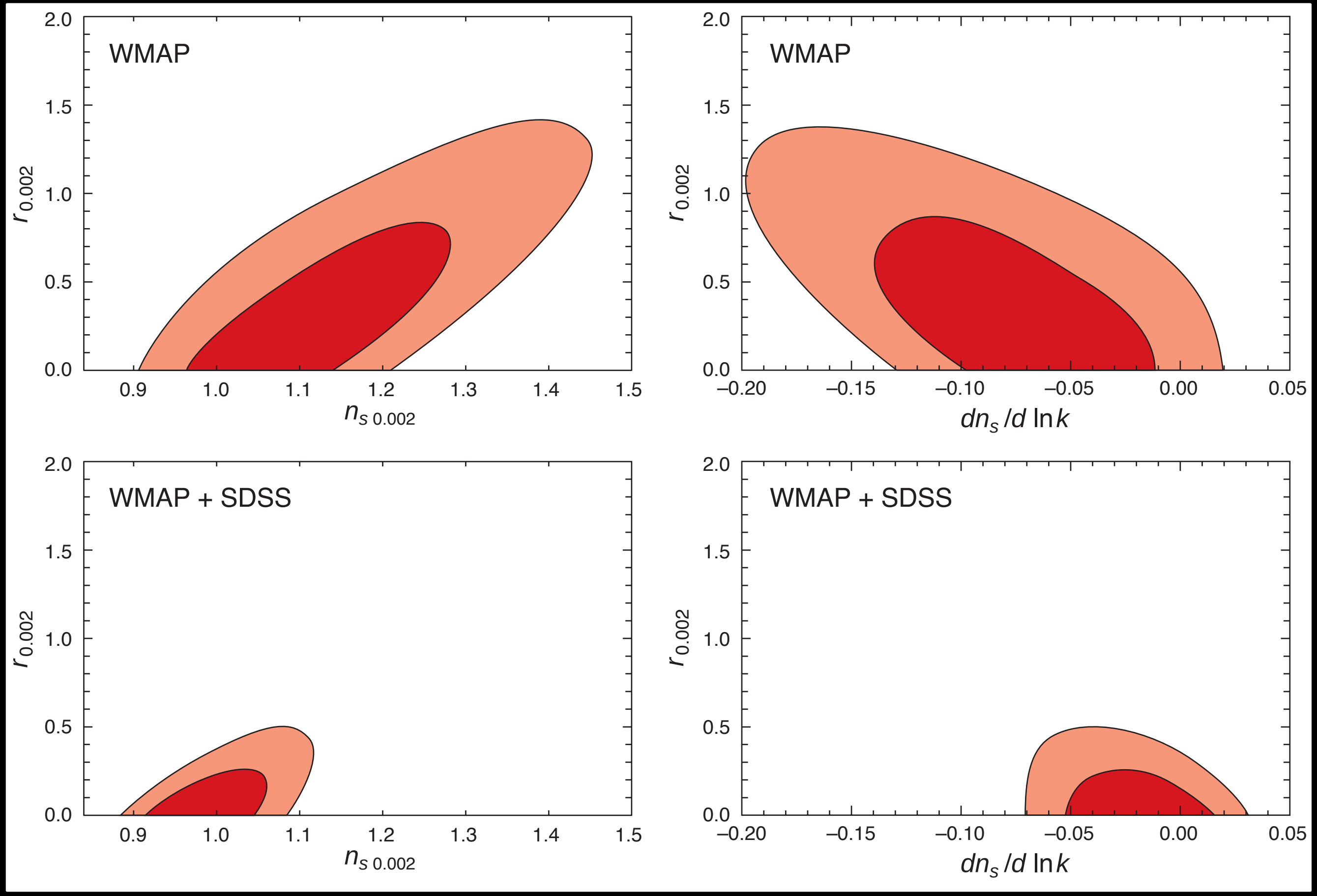


Peiris & Easther (2006)

The Effect of a Running Scalar Spectral Index



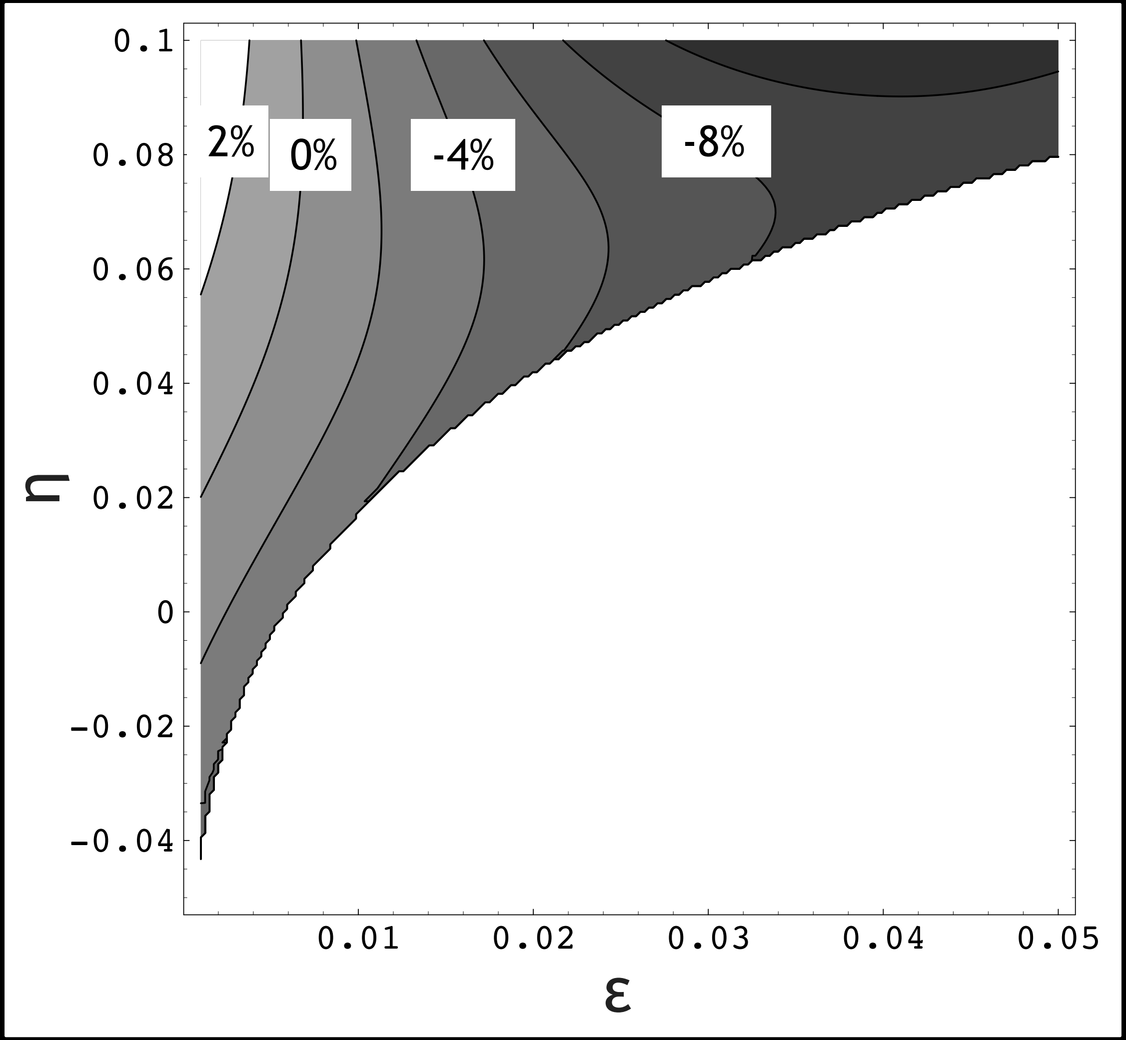
Constraints on tensor modes and a running index



Spergel et al (2006)

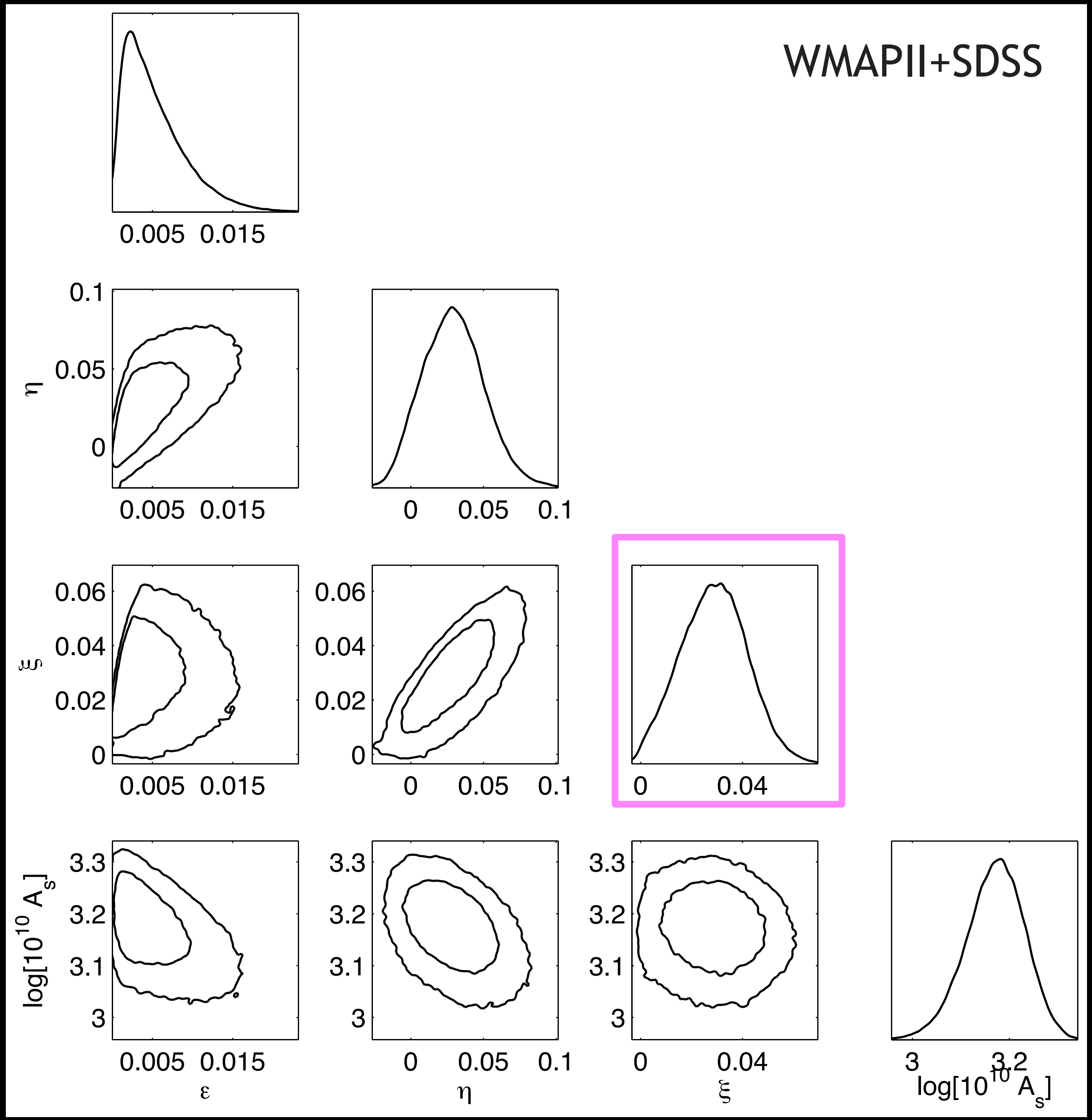
$$\alpha \simeq -2\xi + 16\epsilon\eta - 24\epsilon^2$$

Analytic vs Semianalytic formalisms



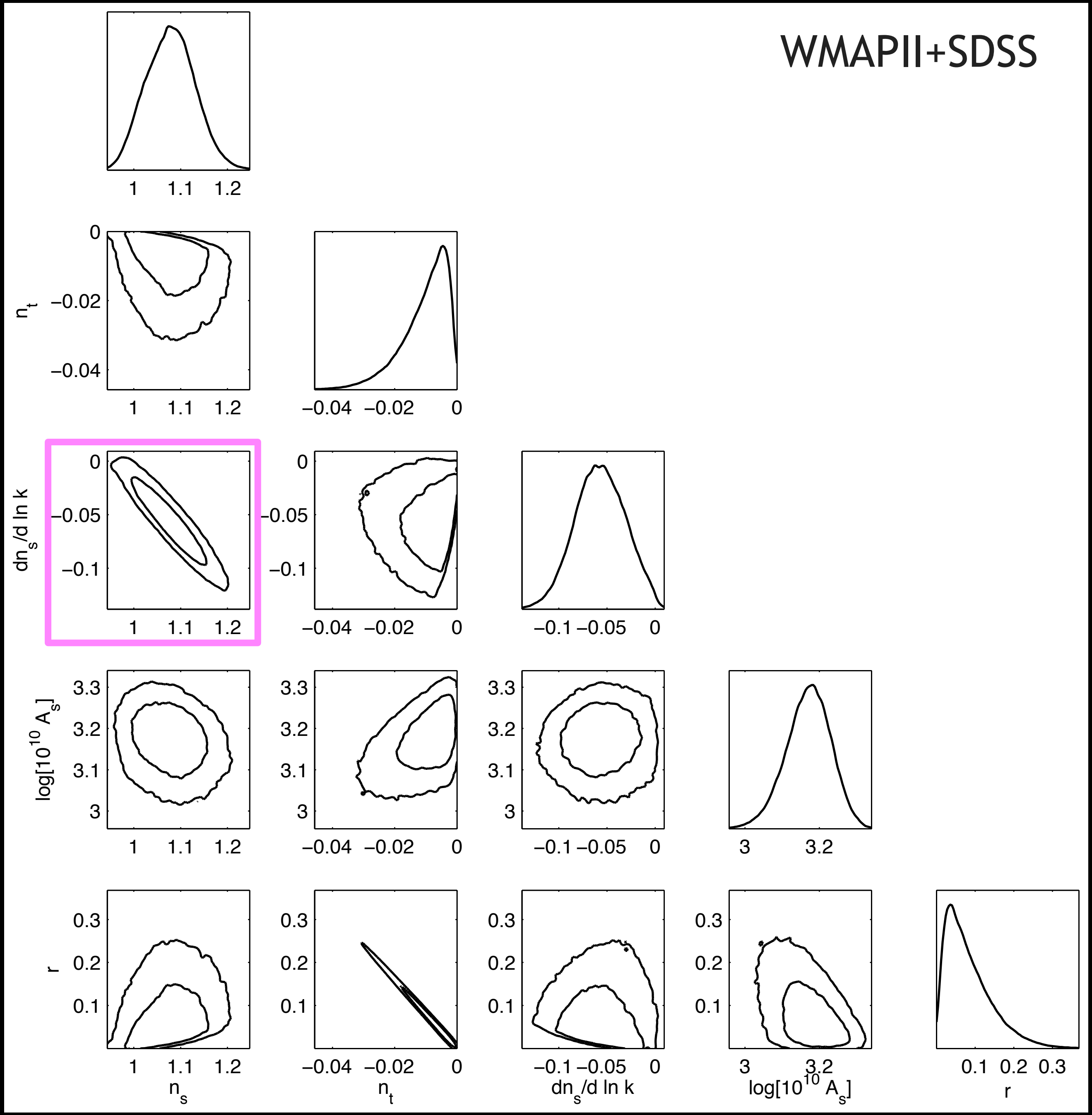
- HSR approach compared compared to $n_s(\epsilon, \eta, \ldots)$, $r(\epsilon, \eta, \ldots)$ approach, truncating the series at ${}^3\lambda$.
- Difference at 1 Mpc^{-1} for $\xi = 0.01$: only points with $N_{efold}>10$ are plotted.

Constraints on HSR variables (no N_{efold} prior)



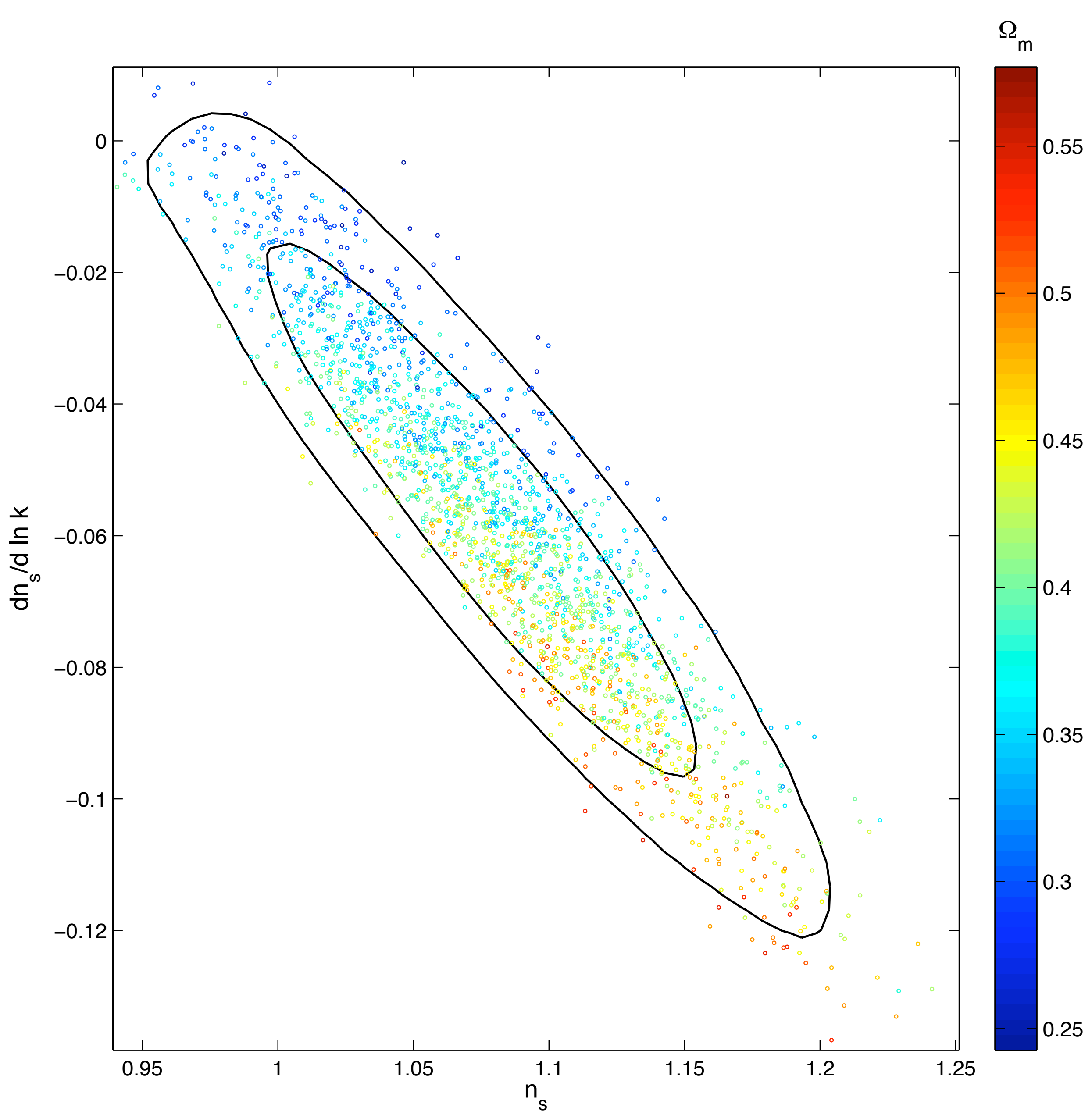
Peiris and Easther (in prep ,2006)

Constraints on “power law” variables (no N_{efold} prior)

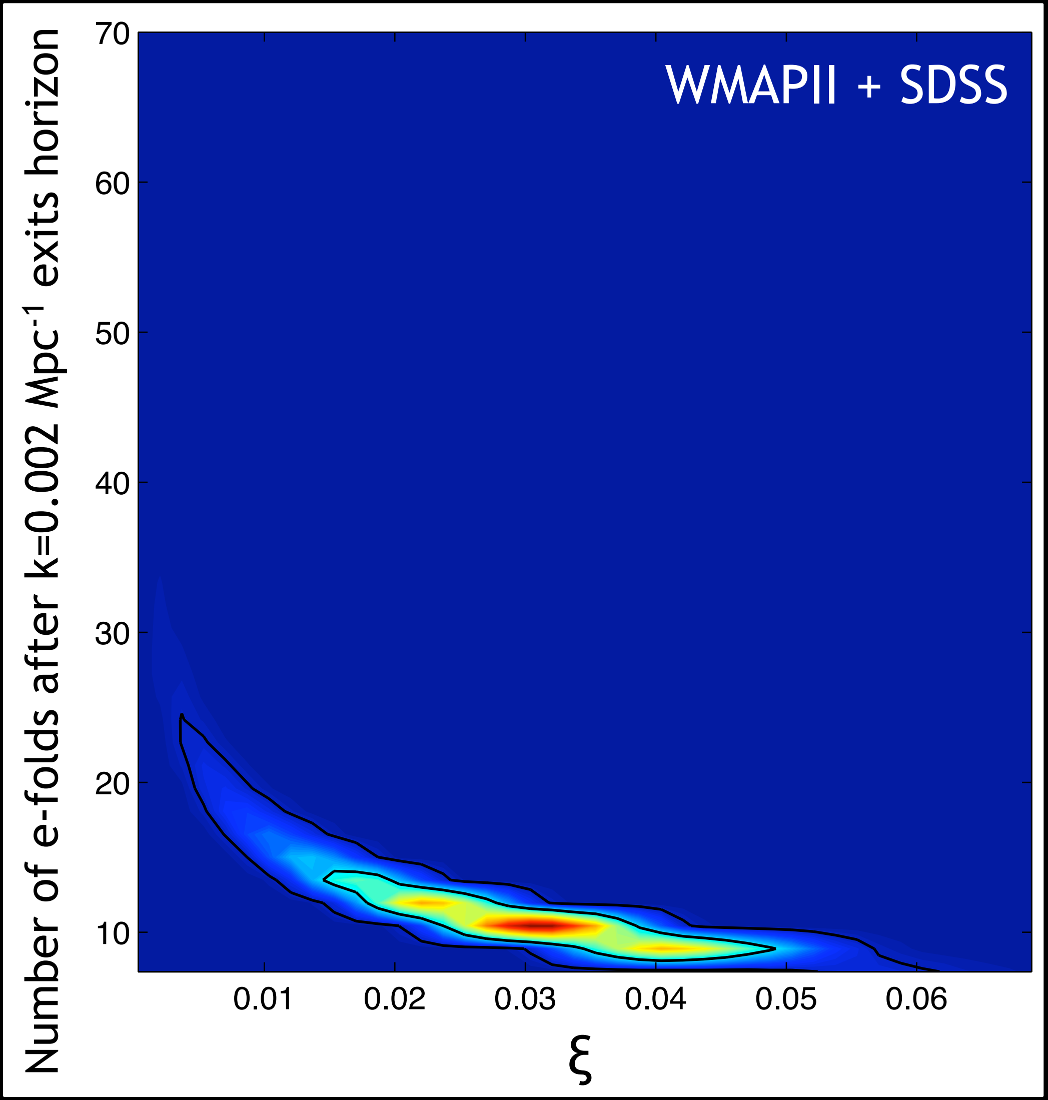


Peiris and Easther (in prep ,2006)

“Late time” parameter correlations



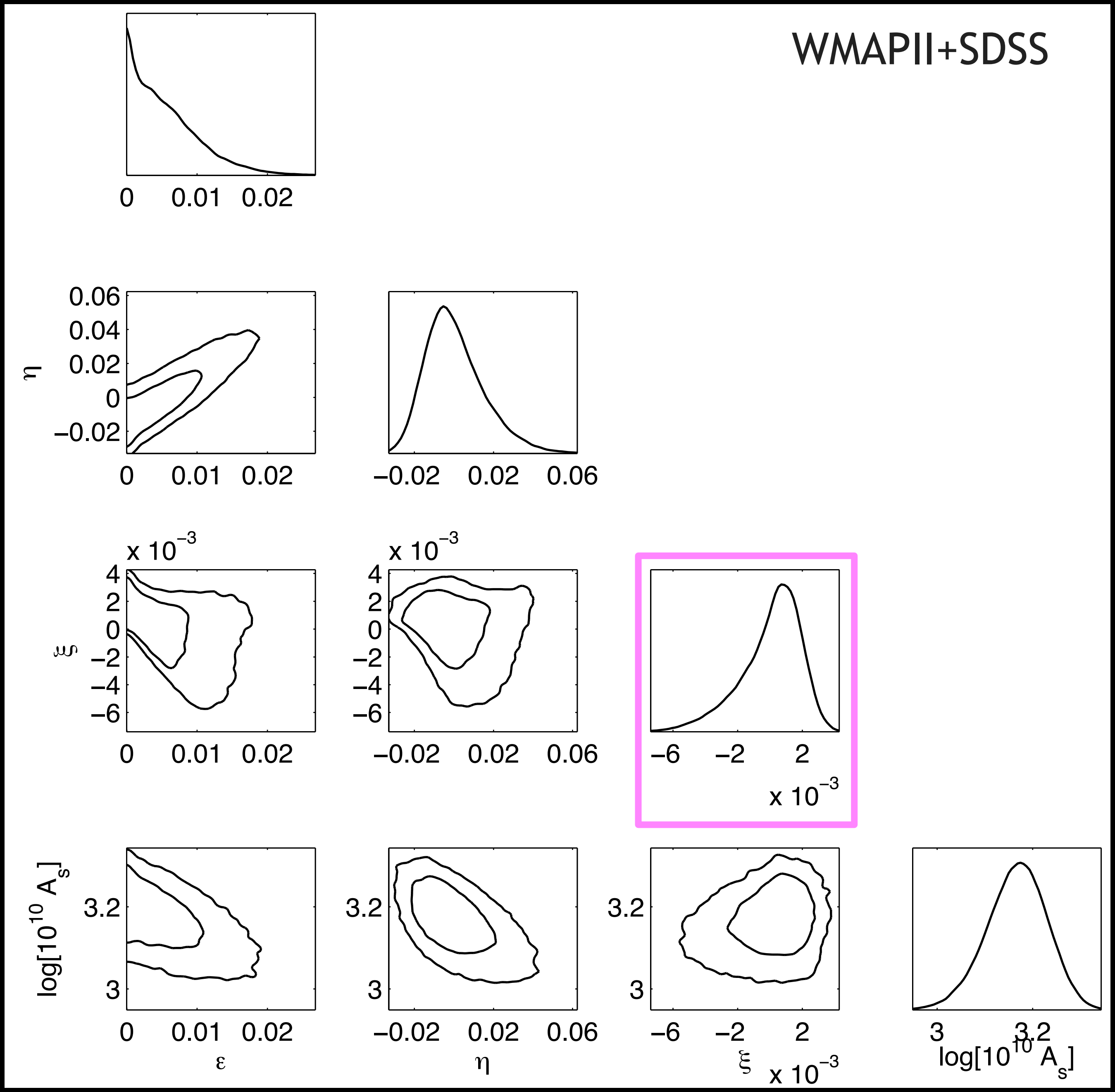
The effect of a running index (no N_{efold} prior)



$$\alpha \simeq -2\xi + 16\epsilon\eta - 24\epsilon^2$$

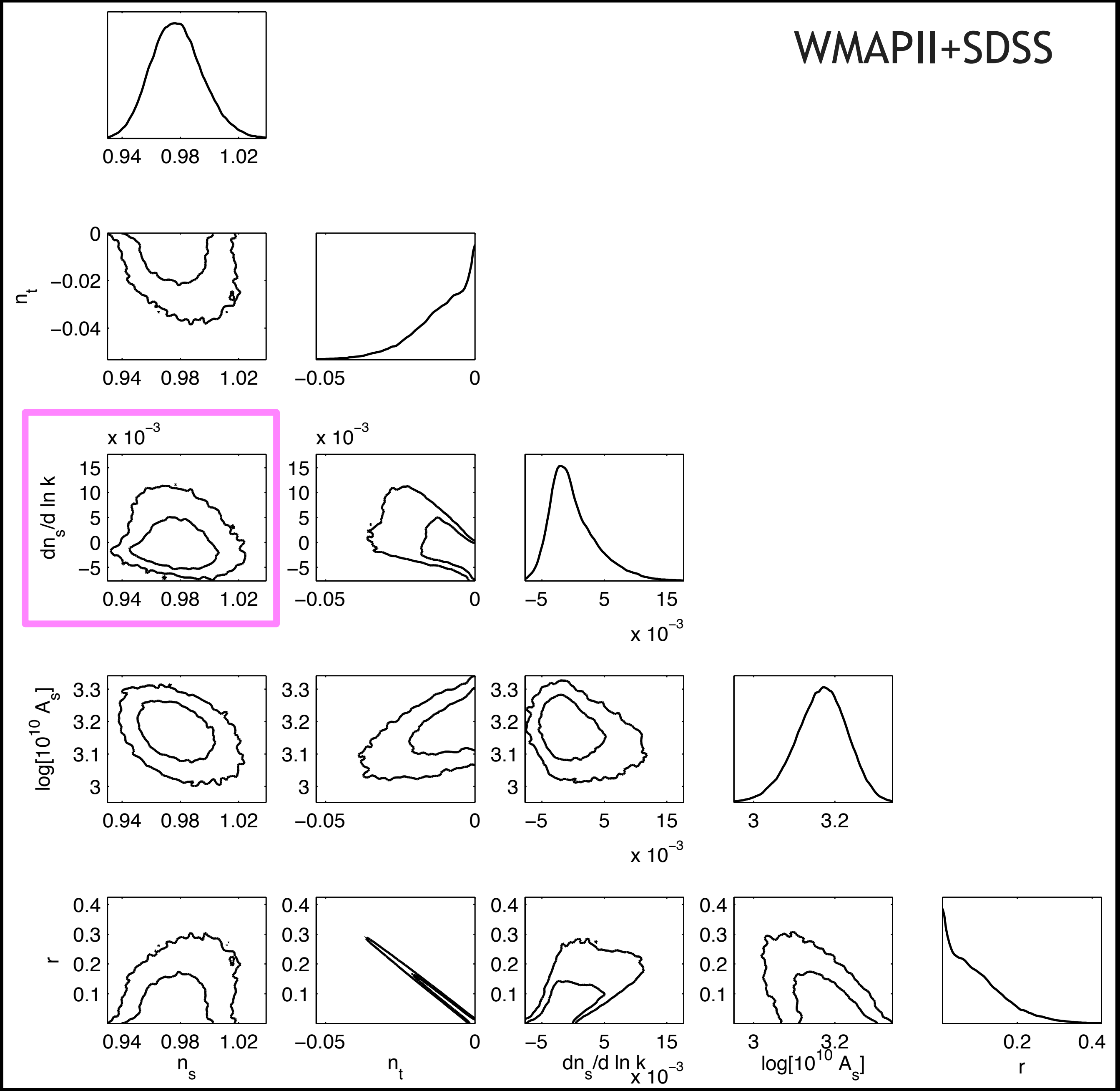
Peiris and Easther (in prep, 2006)

Constraints on HSR variables (N_{efold}>30)



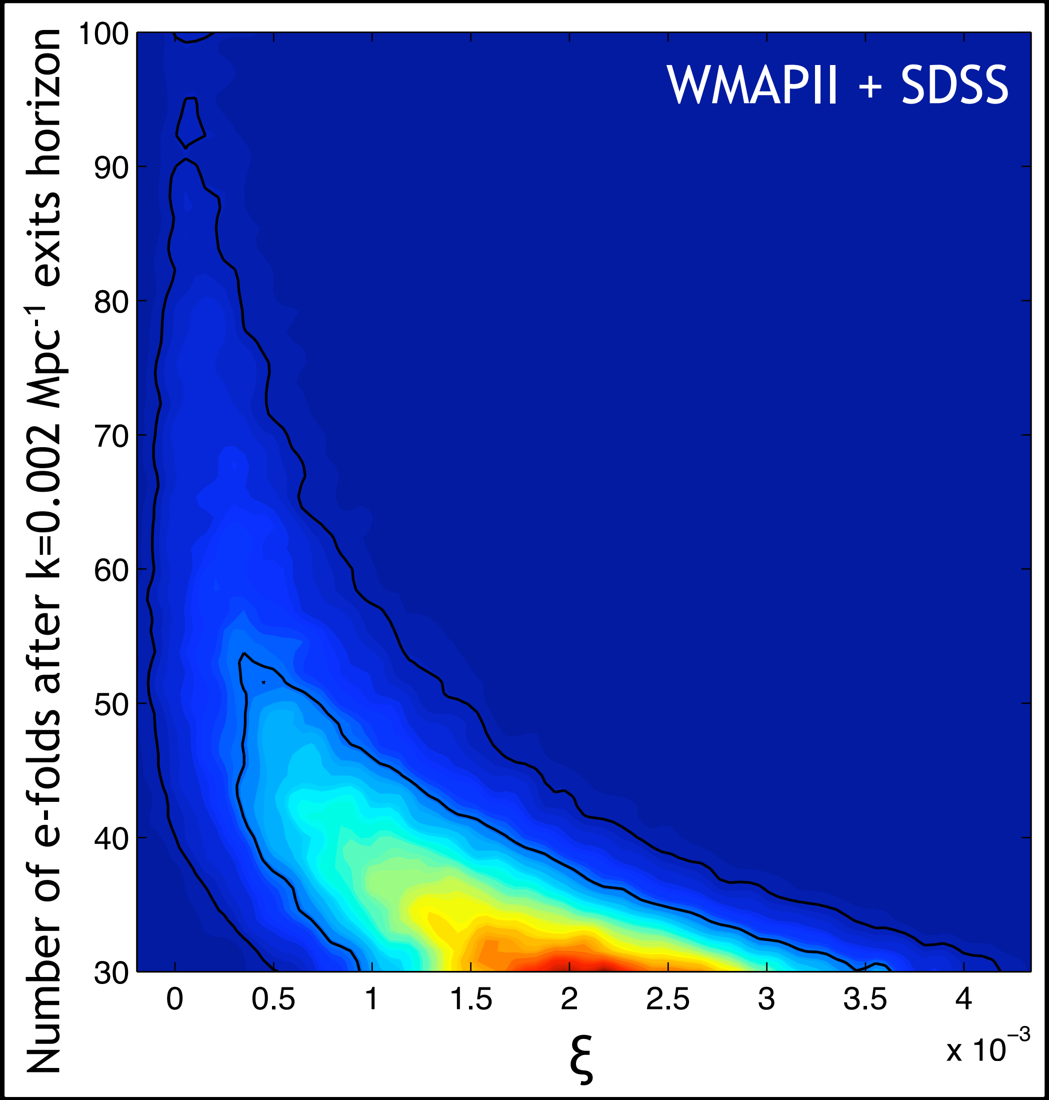
Peiris and Easther (in prep, 2006)

Constraints on “power law” variables (N_{efold}>30)



Peiris and Easther (in prep, 2006)

The effect of a running index (N_{efold}>30)



$$\alpha \simeq -2\xi + 16\epsilon\eta - 24\epsilon^2$$

Peiris and Easther (in prep, 2006)

Implications of large negative running

- WMAP data suggests a large negative running index at the 2 sigma level (needs to be verified!).

- No inflation model can simultaneously satisfy:
    - validity of slow roll expansion
    - large negative running
    - sufficient number of e-folds

- Theoretical “outs”: cancellation between higher order HSR parameters? local violation of slow roll? More than one inflaton field? Complicates theoretical understanding...

- Most prosaic explanation: with more data, central value of running will move much closer to zero (Lyman alpha already indicates this).

- Best test is with a single experiment that spans the whole k-range with tightly-controlled systematics. (Planck?)

B-modes and Inflation

Measurement of the amplitude of tensor modes fixes Hubble parameter H during inflation when relevant scales are leaving horizon; alternatively, fixes scalar field potential and first derivative. e.g. Liddle & Lyth (1993), Copeland et al. (1993), Liddle (1994)

$$H \equiv \dot{a}/a \approx \frac{1}{M_{Pl}}\sqrt{\frac{V}{3}}$$

$$r = \frac{2V}{3\pi^2 M_{Pl}{}^4 \Delta_R{}^2(k_0)} = 8M_{Pl}{}^2\left(\frac{V'}{V}\right)^2$$

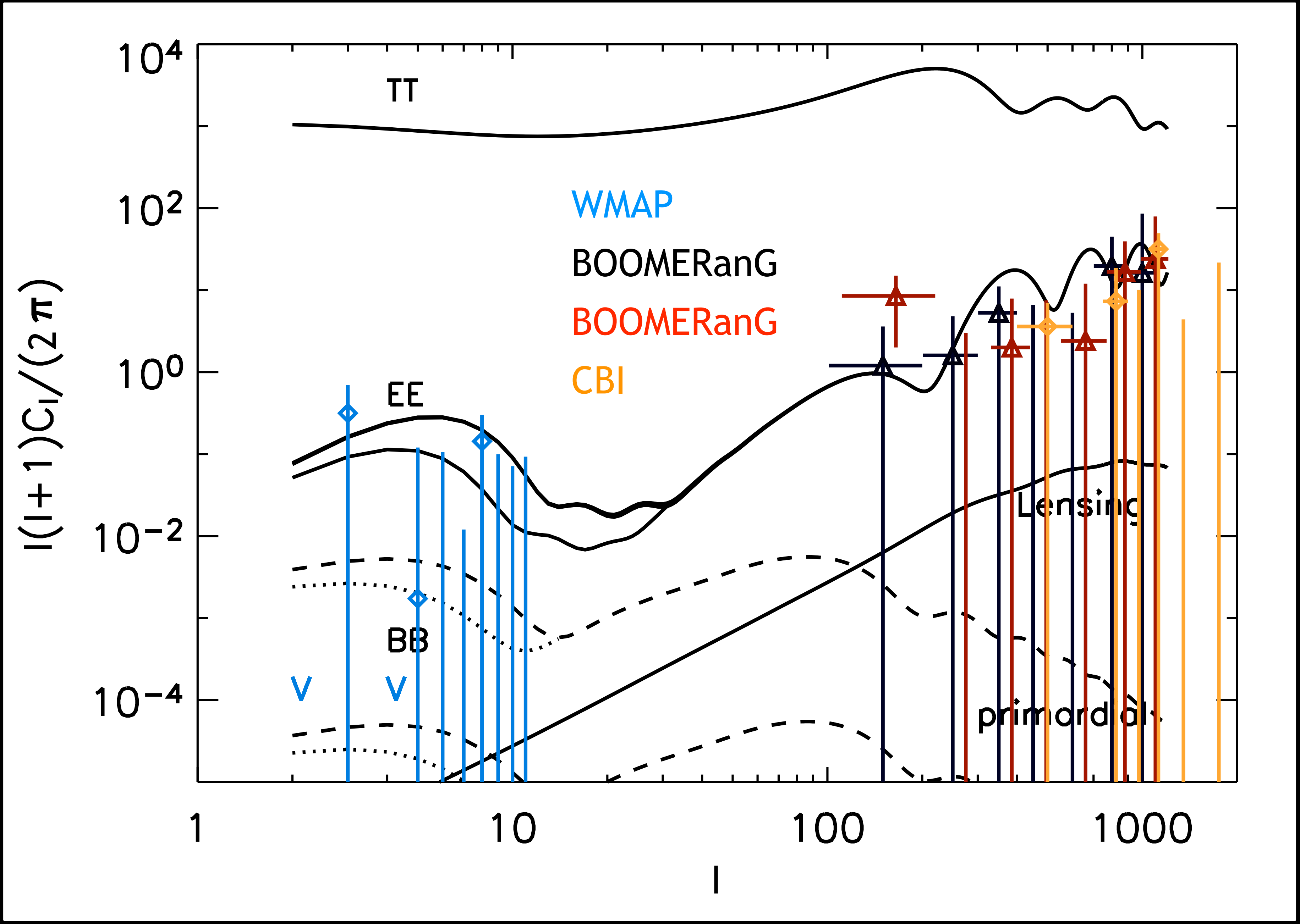
$$V^{1/4} \leq 3.3 \times 10^{16}\, r^{1/4}\ \text{GeV}$$

Current compilation of WMAPII+SDSS Spergel et al. (2006) gives a 95% upper limit (for dn/d ln k = 0):

$$r < 0.4$$

$$V^{\frac{1}{4}} \leq 2.6 \times 10^{16}\ \text{GeV}$$

Current limits on B modes



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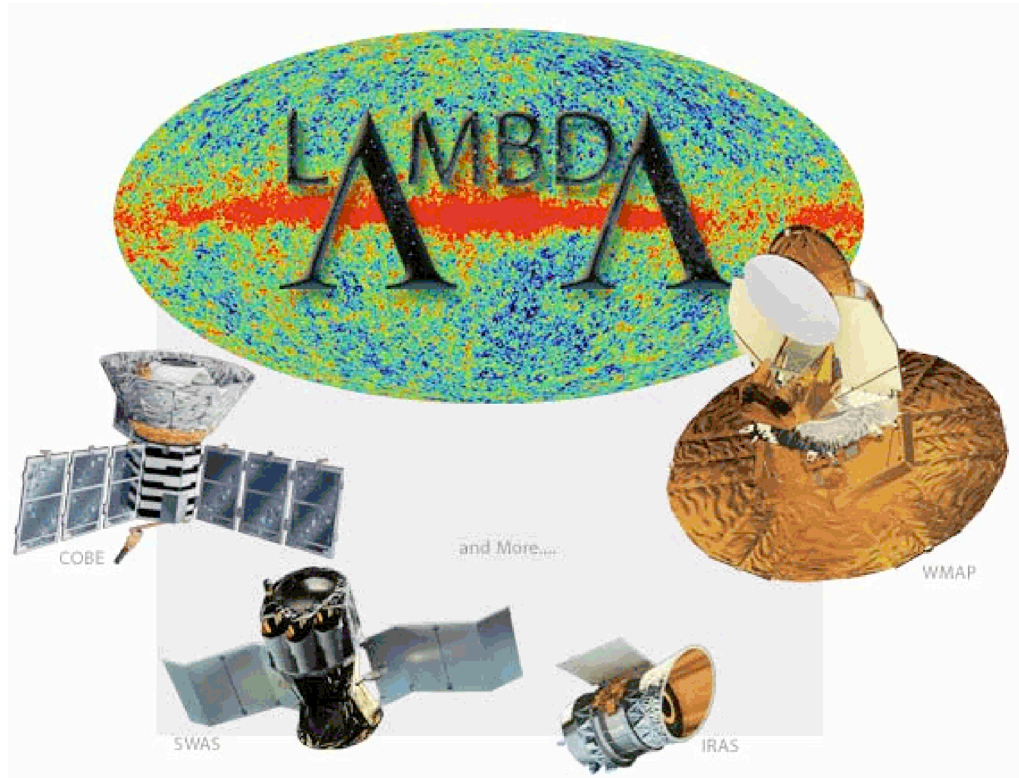

http://lambda.gsfc.nasa.gov

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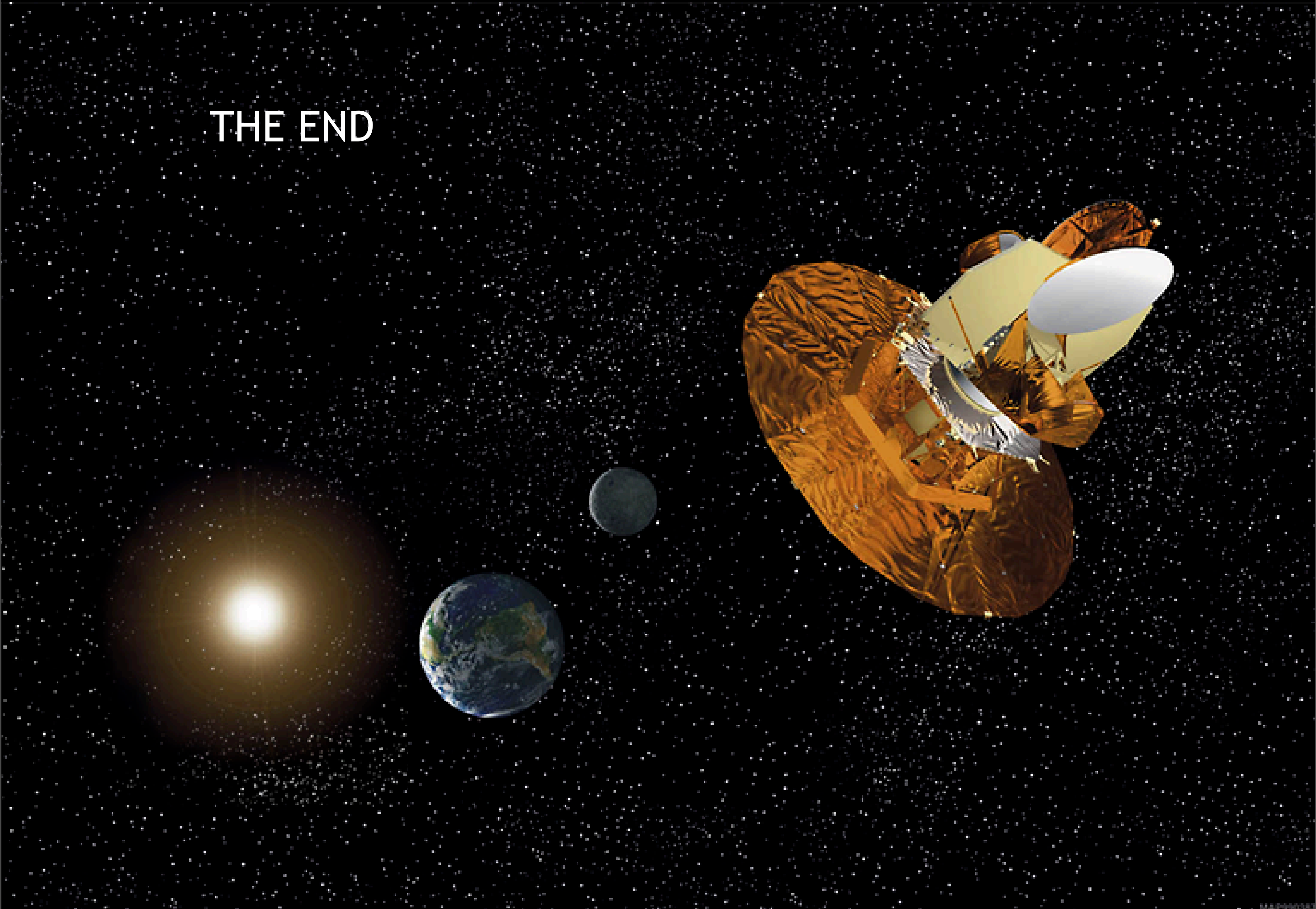
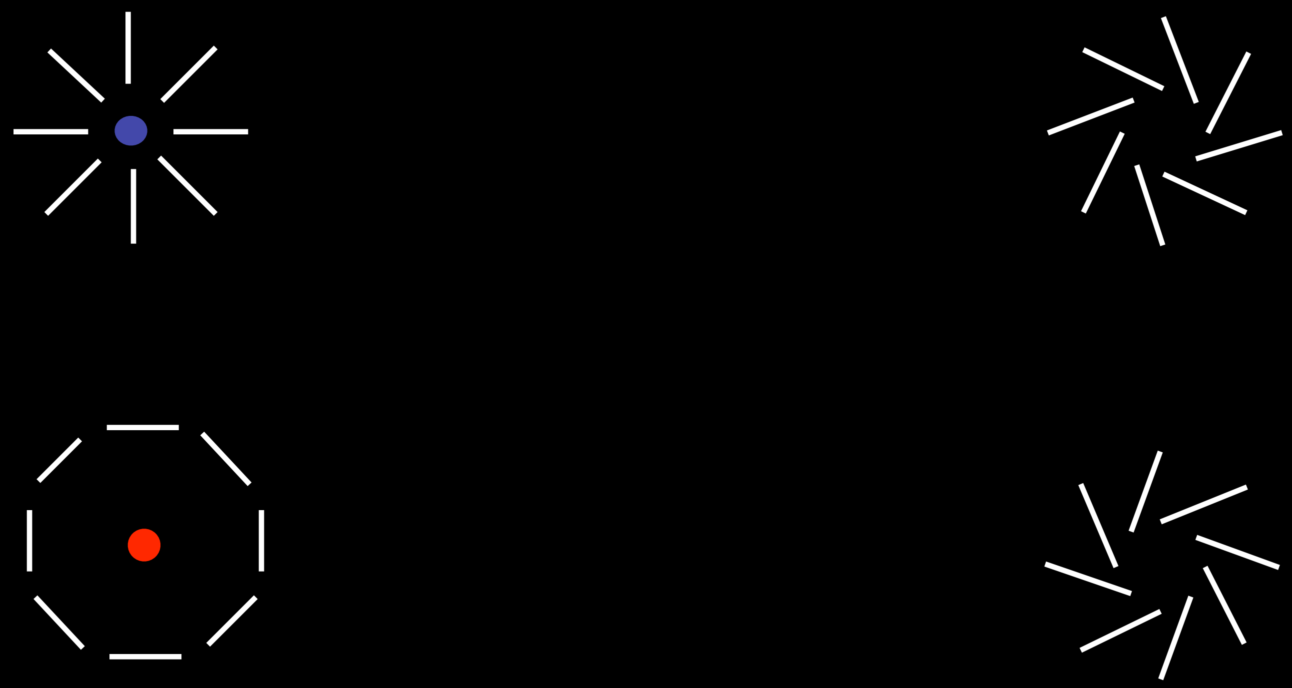

THE END

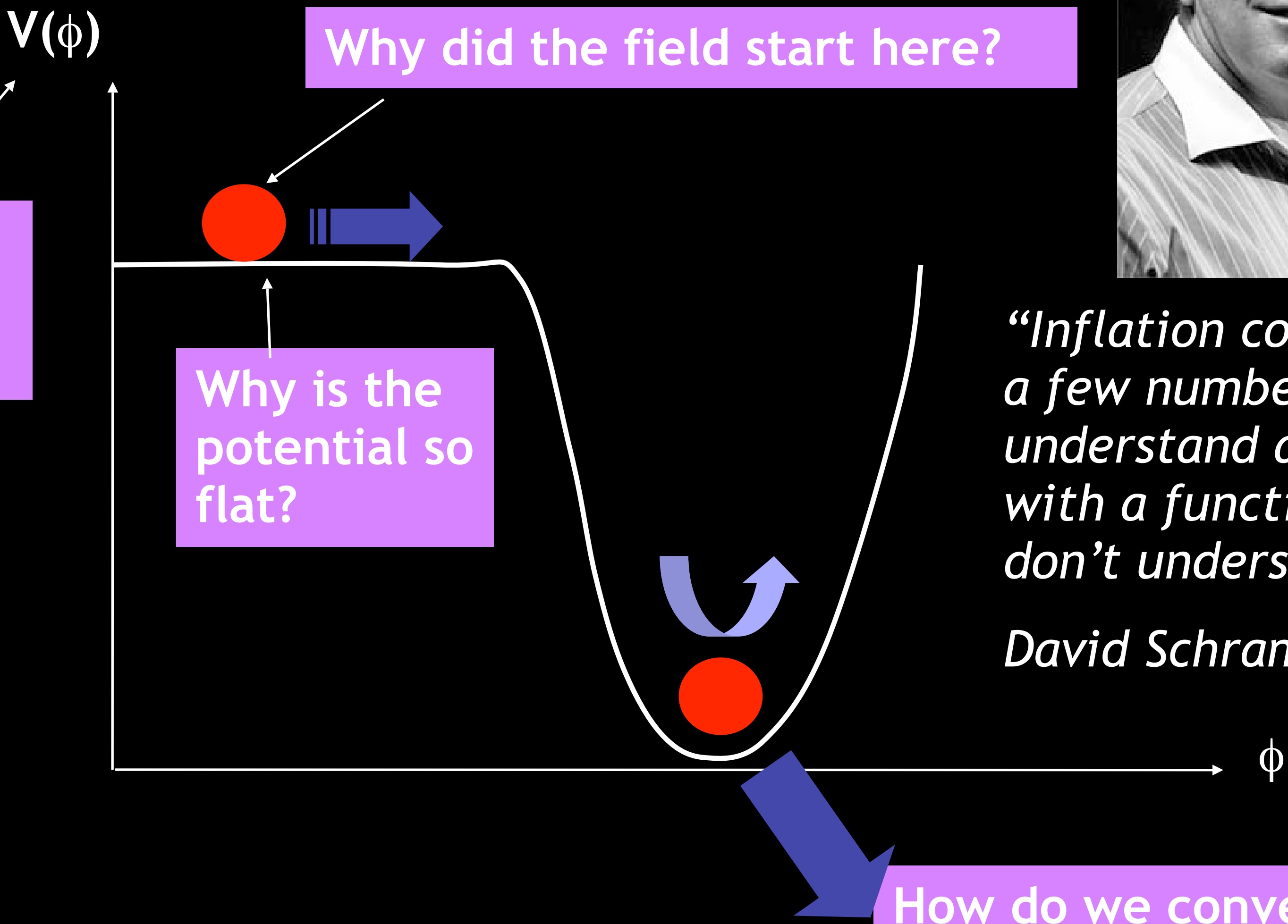
Types of CMB polarization

CMB polarization can be decomposed into two orthogonal modes. E-mode is the curl-free mode (“Electric”). B-mode is the divergence-free mode (“Magnetic”).



E-mode B-mode

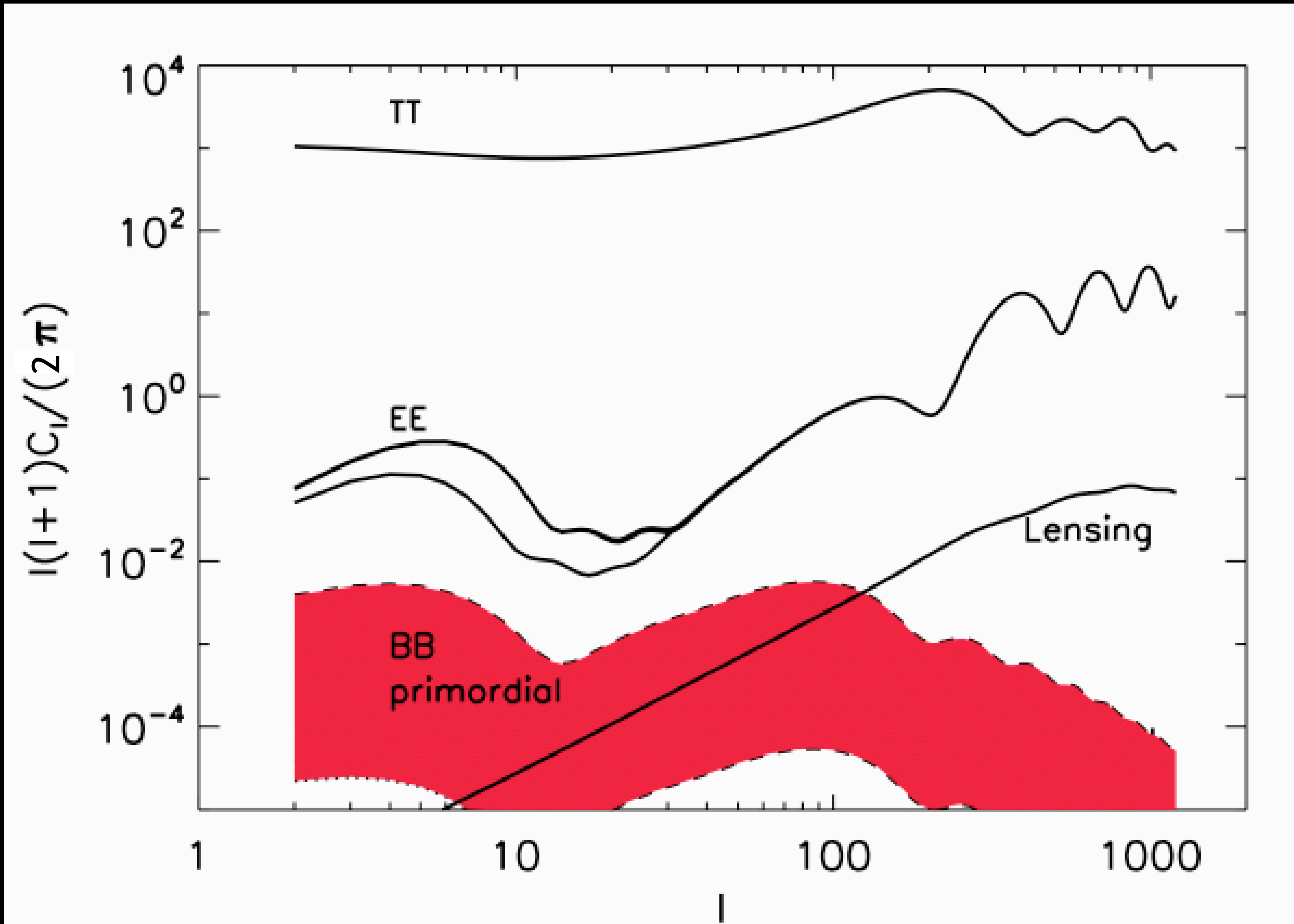
Inflation: Theoretical Front



"Inflation consists of taking a few numbers that we don't understand and replacing it with a function that we don't understand"

David Schramm 1945 -1997

Approximate range of primordial B-modes accessible to upcoming experiments

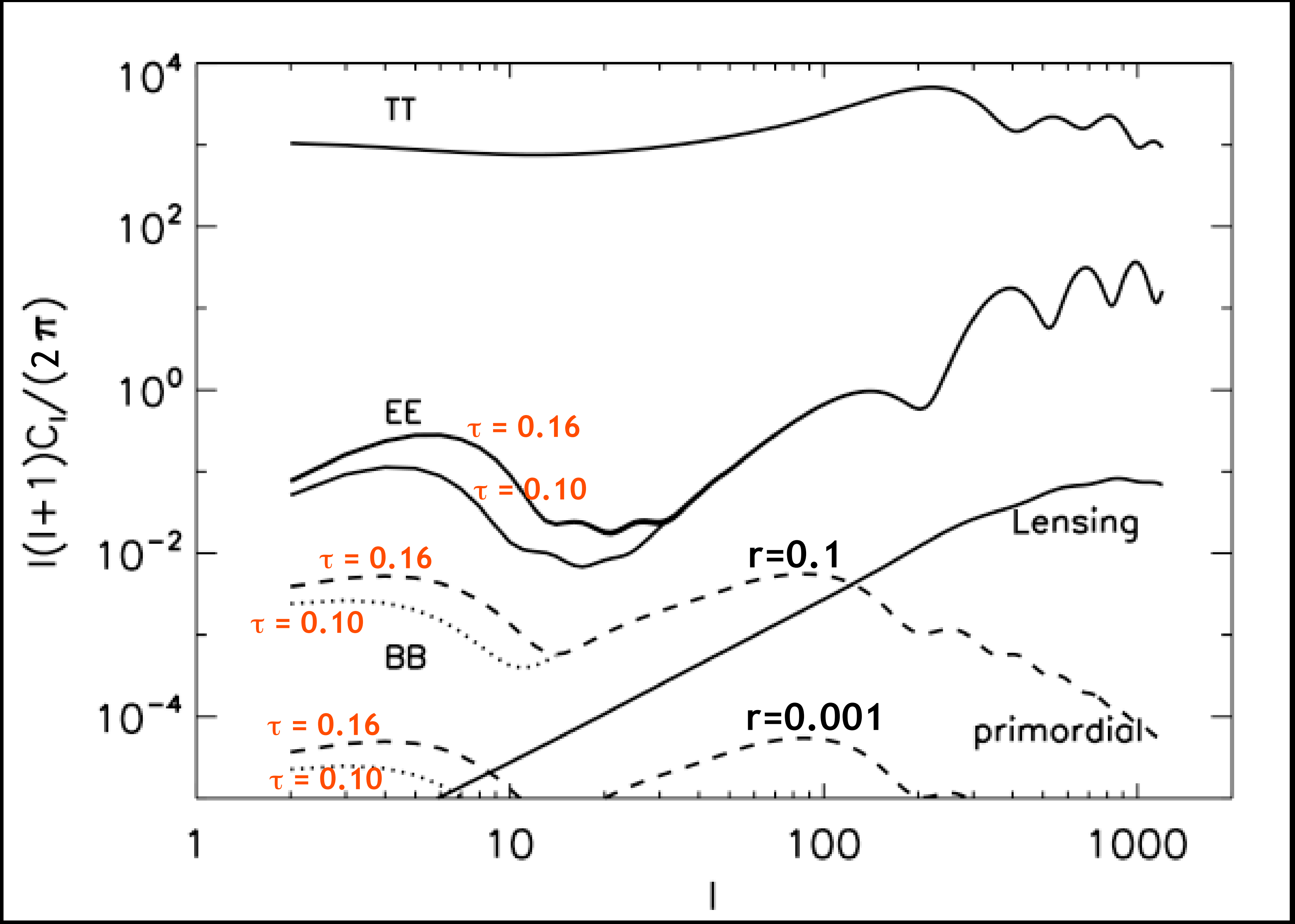


Obstacles to detecting primordial gravity waves

- **Fundamental complications:**
  - B-modes also generated by weak lensing of the E-mode by large scale structure
  - Primordial signal not significantly contaminated by lensing only on largest scales where cosmic variance is important; lensing dominates on small scales.
  - Polarized FG emission on large scales likely dominate the signal at all frequencies

- **Practical complications:**
  - For signal to be detected in a reasonable timescale, instrumental noise needs to be well below the photon noise limit for a single detector $\Rightarrow$ need multiple detectors
  - Polarized FG not yet well known $\Rightarrow$ FG subtraction uncertainties seriously affect the goal

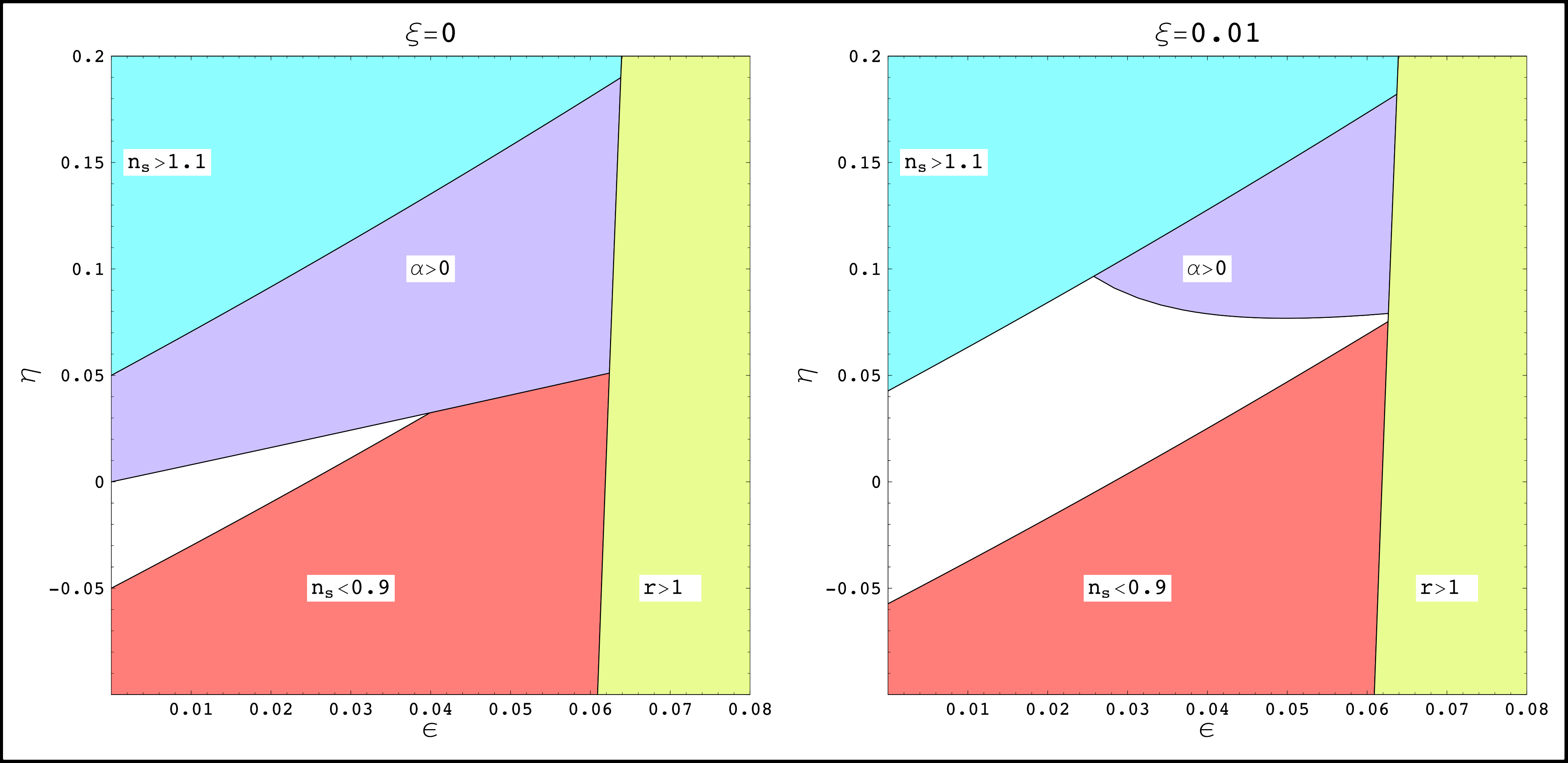
Relative Amplitudes of CMB power spectra



Next Generation Observational Prospects

- Space-based
  - Planck $l\sim3000$ ($k\sim0.2$/Mpc), ACT
  - CMBPol/Inflation Probe?
- Ground-based
  - e.g. BICEP, CLOVER, EBEX, PolarBeaR, QuAD, QUIET
- Balloon-borne
  - SPIDER

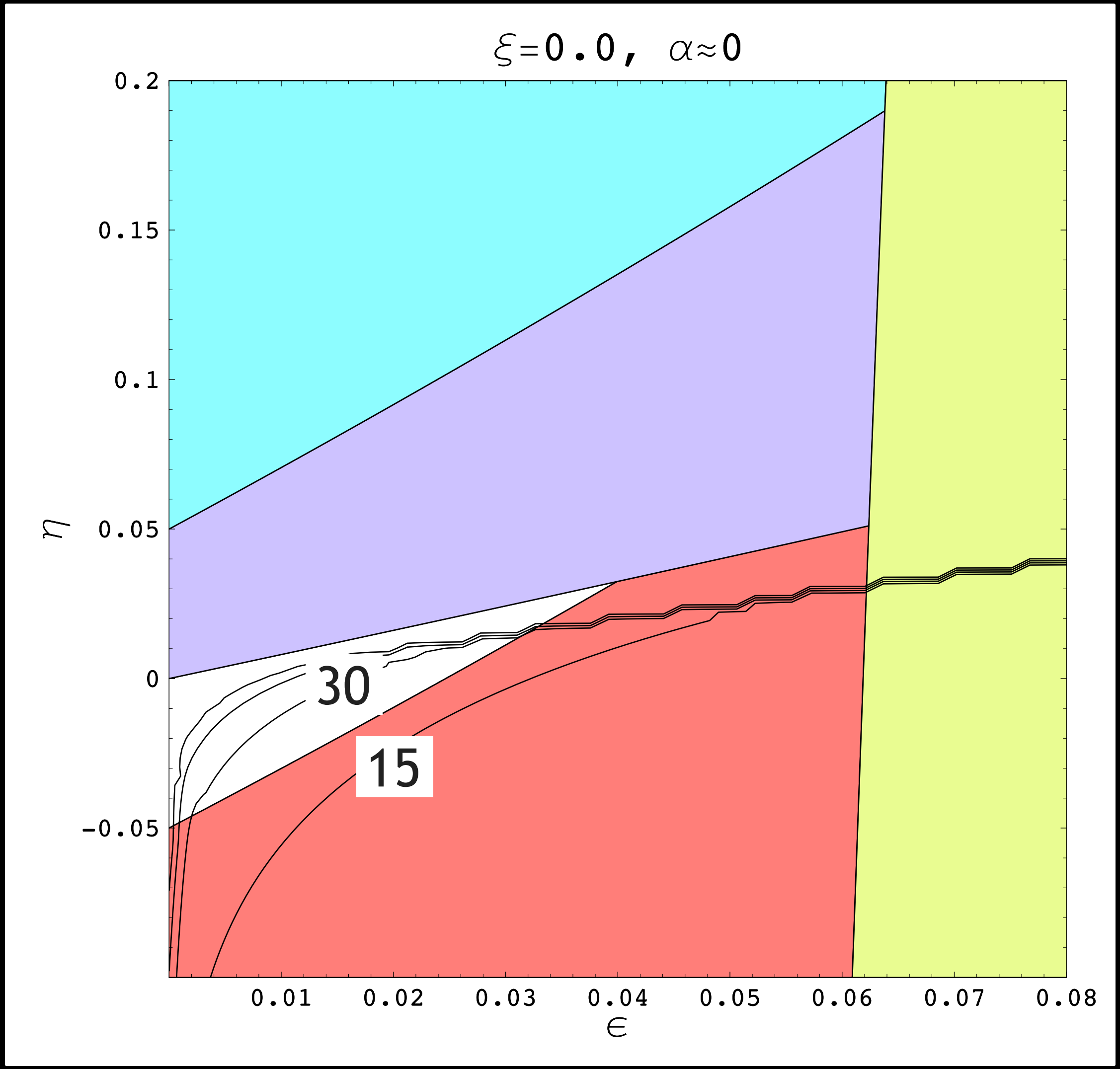
The Effect of a Running Spectral Index



Easther & Peiris (2006)

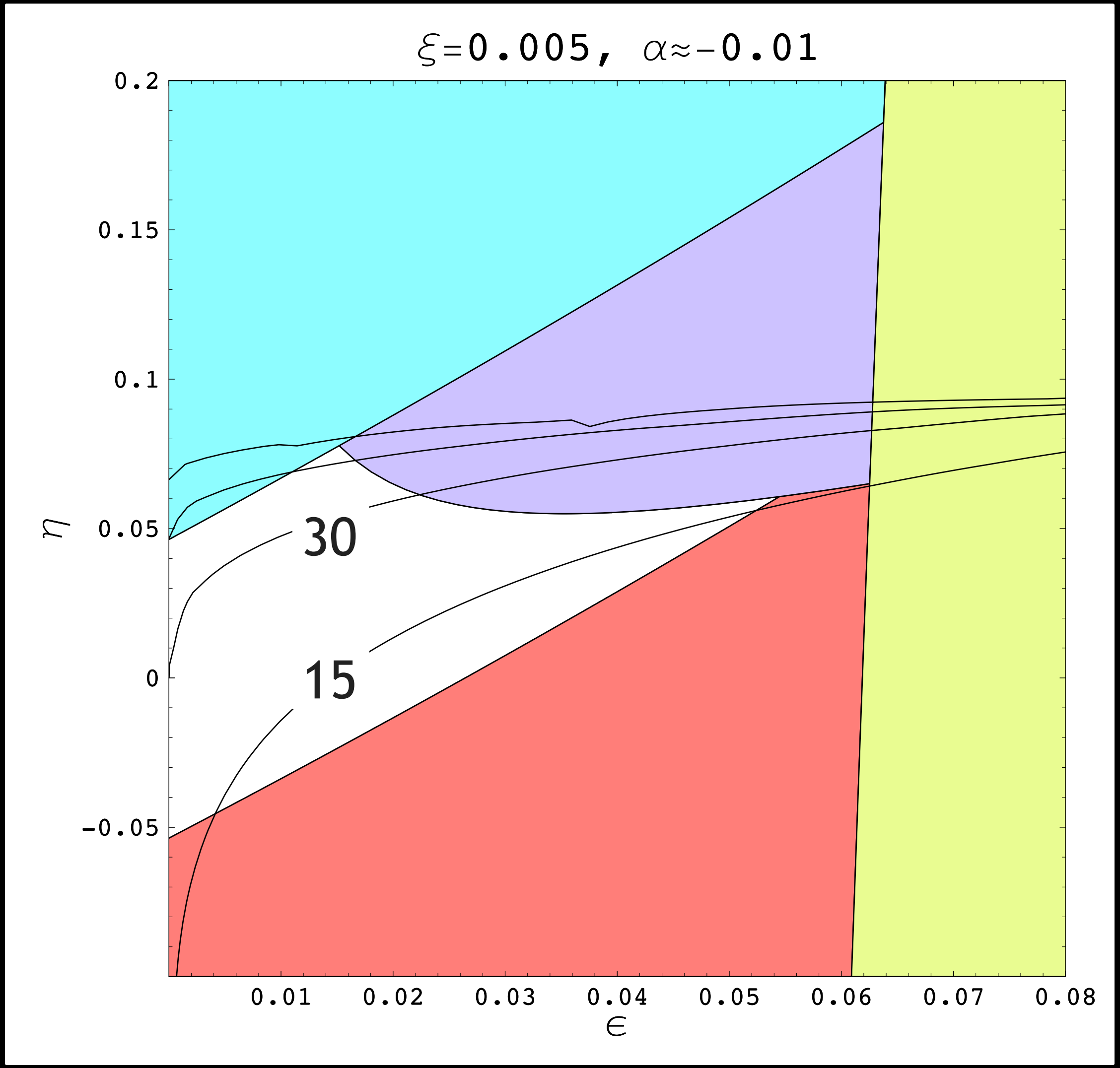
$$\alpha \simeq -2\xi + 16\epsilon\eta - 24\epsilon^2$$

running ≈ 0



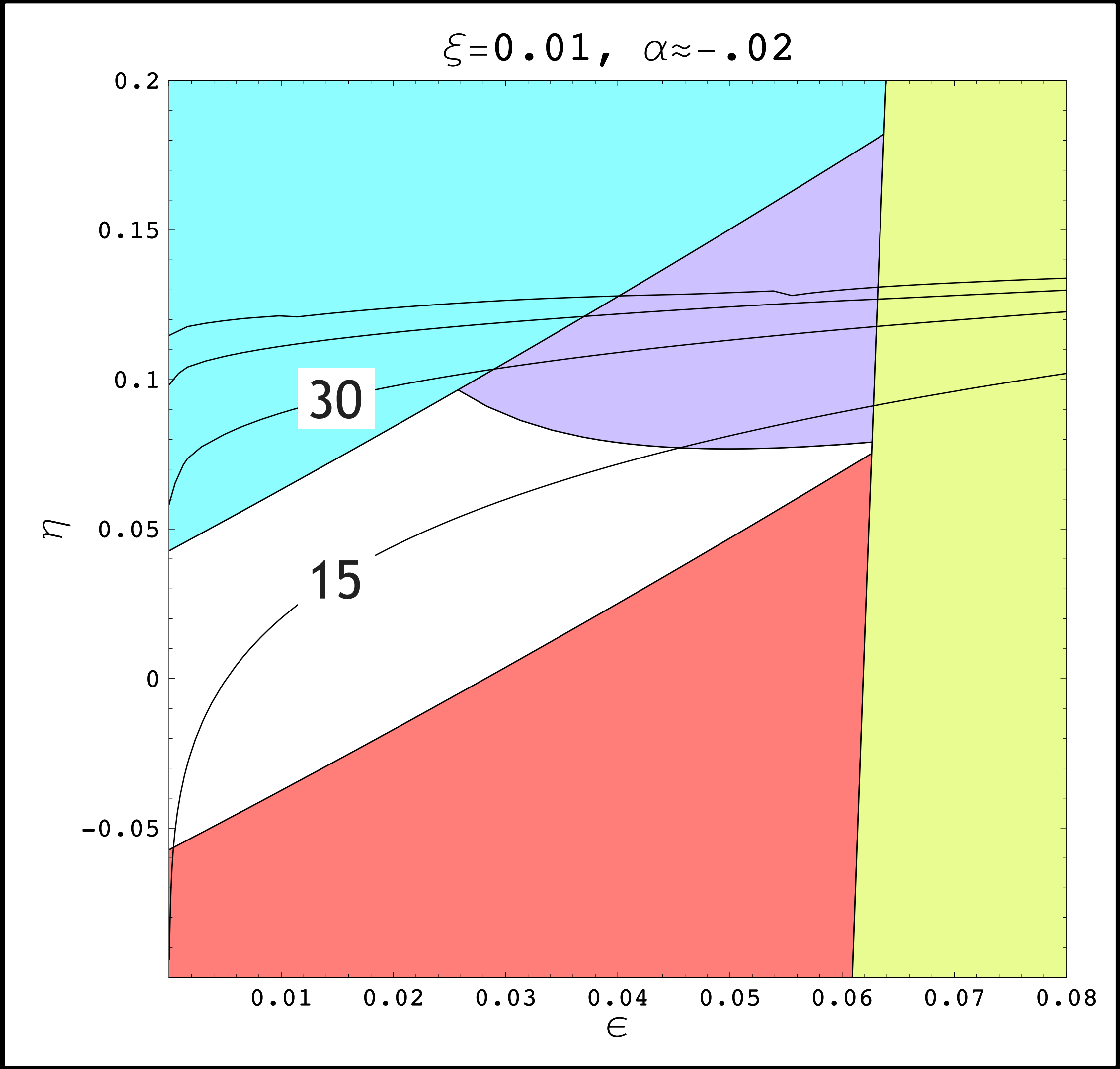
Easther & Peiris (2006)

running ≈ -0.01



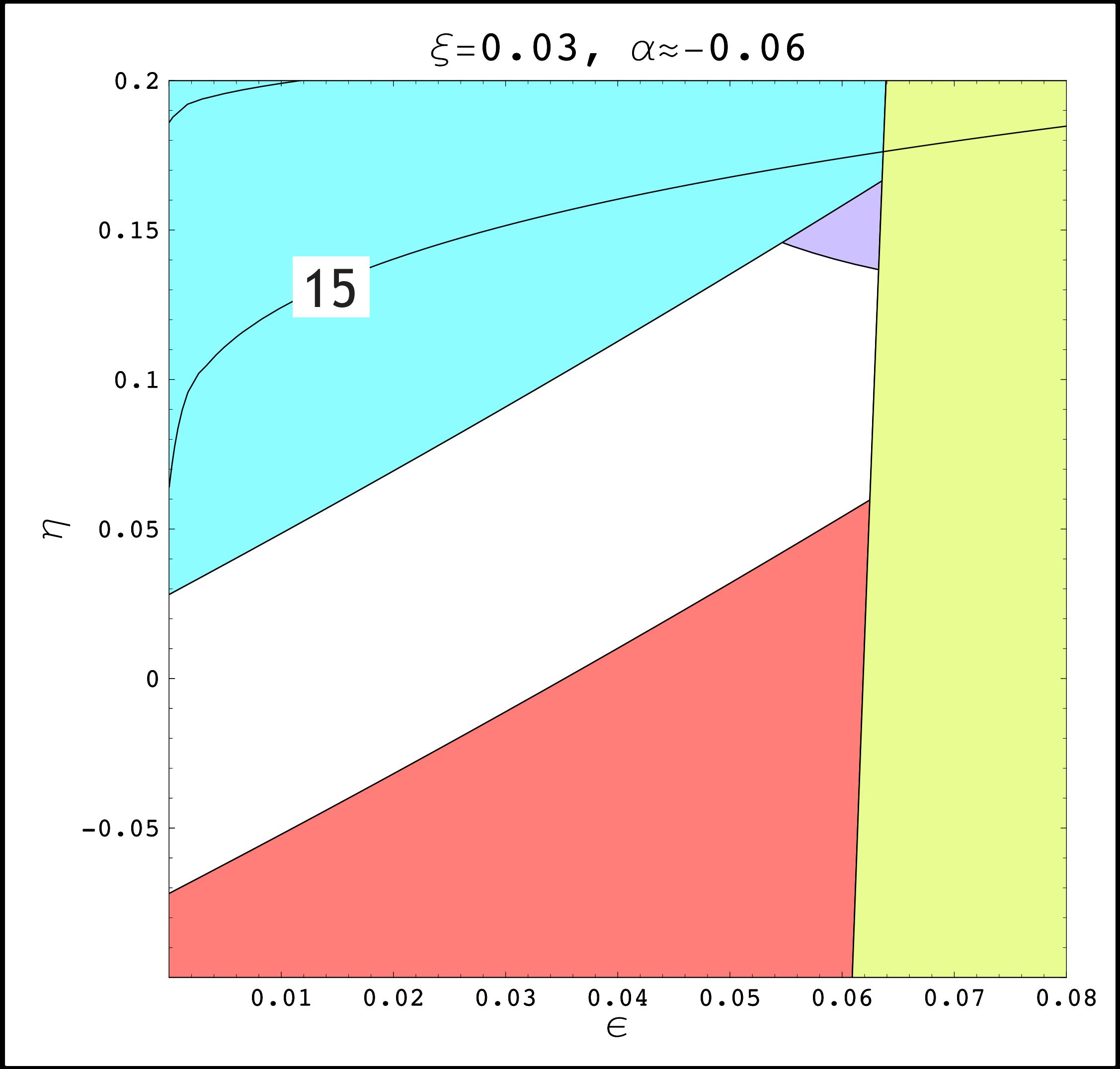
Easther & Peiris (2006)

running ≈ -0.02



Easther & Peiris (2006)

running ≈ -0.06



Easther & Peiris (2006)