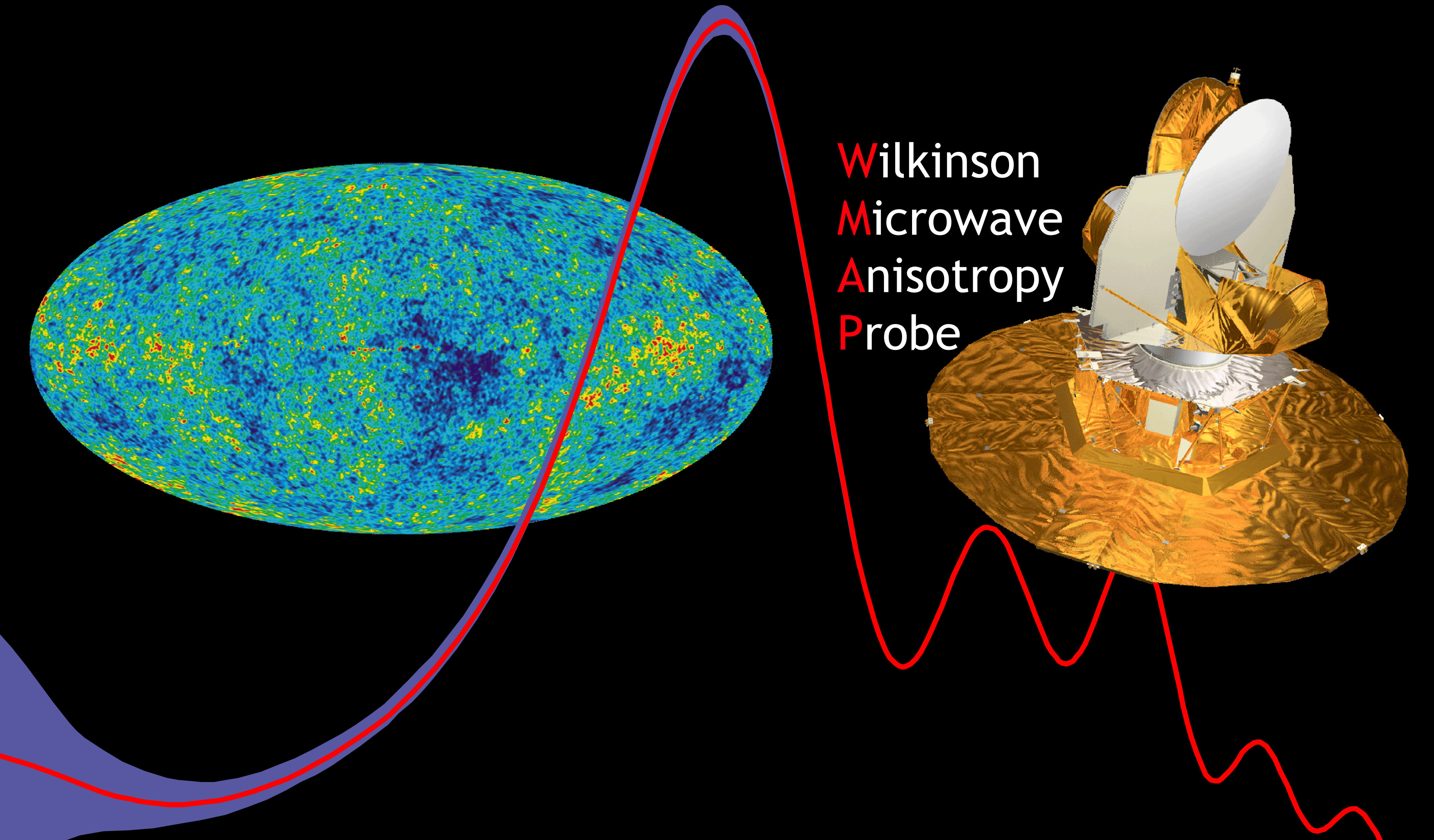
WMAP and Early Universe Cosmology



8th Paris Cosmology Colloquium, Dec 9-10 2004

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WMAP Highlights

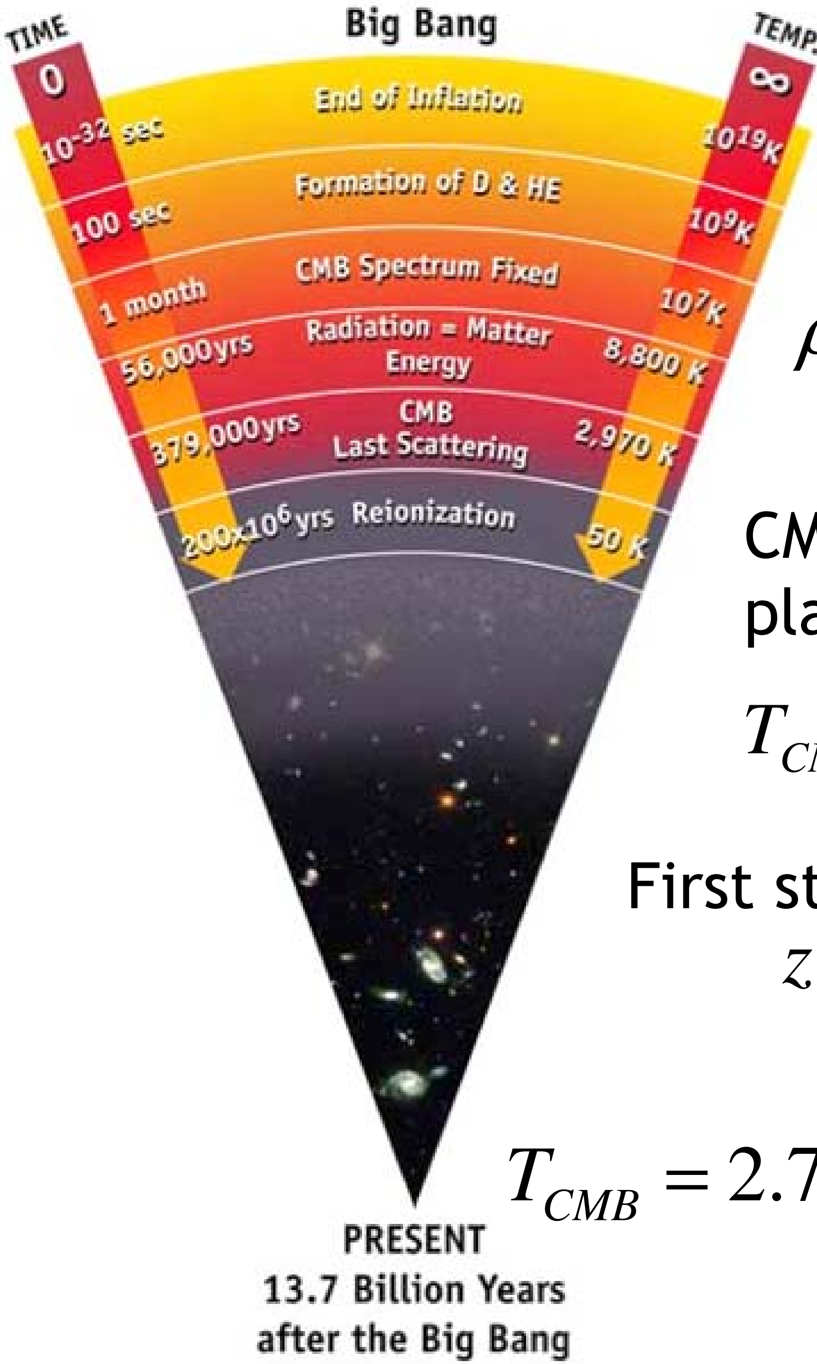
- Microwave Maps
  - High fidelity full-sky maps in five bands (23,33,41,61,94 GHz).
  - High S/N CMB maps.
  - Gaussianity of CMB.
- CMB Temperature
  - Power spectrum measured to *l*~700.
  - LCDM fits.
- CMB Polarization
  - Temp-Pol cross-power spectrum measured to *l*~400.
  - Early reionization.

A lot more…

- Galaxy model
- Point source catalogue
- etc…

Please visit

http://lambda.gsfc.nasa.gov



Cosmic History

Inflation-like epoch. new

new

$$\rho_{radiation} = \rho_{matter}$$

$$z_{eq} = 3230 \qquad t_U = 56 \text{ kyr}$$

CMB decouples from plasma new

$$z_{dec} = 1089 \qquad t_U = 380 \text{ kyr}$$

$$T_{CMB} = 2970 \text{ K}$$

First stars form new

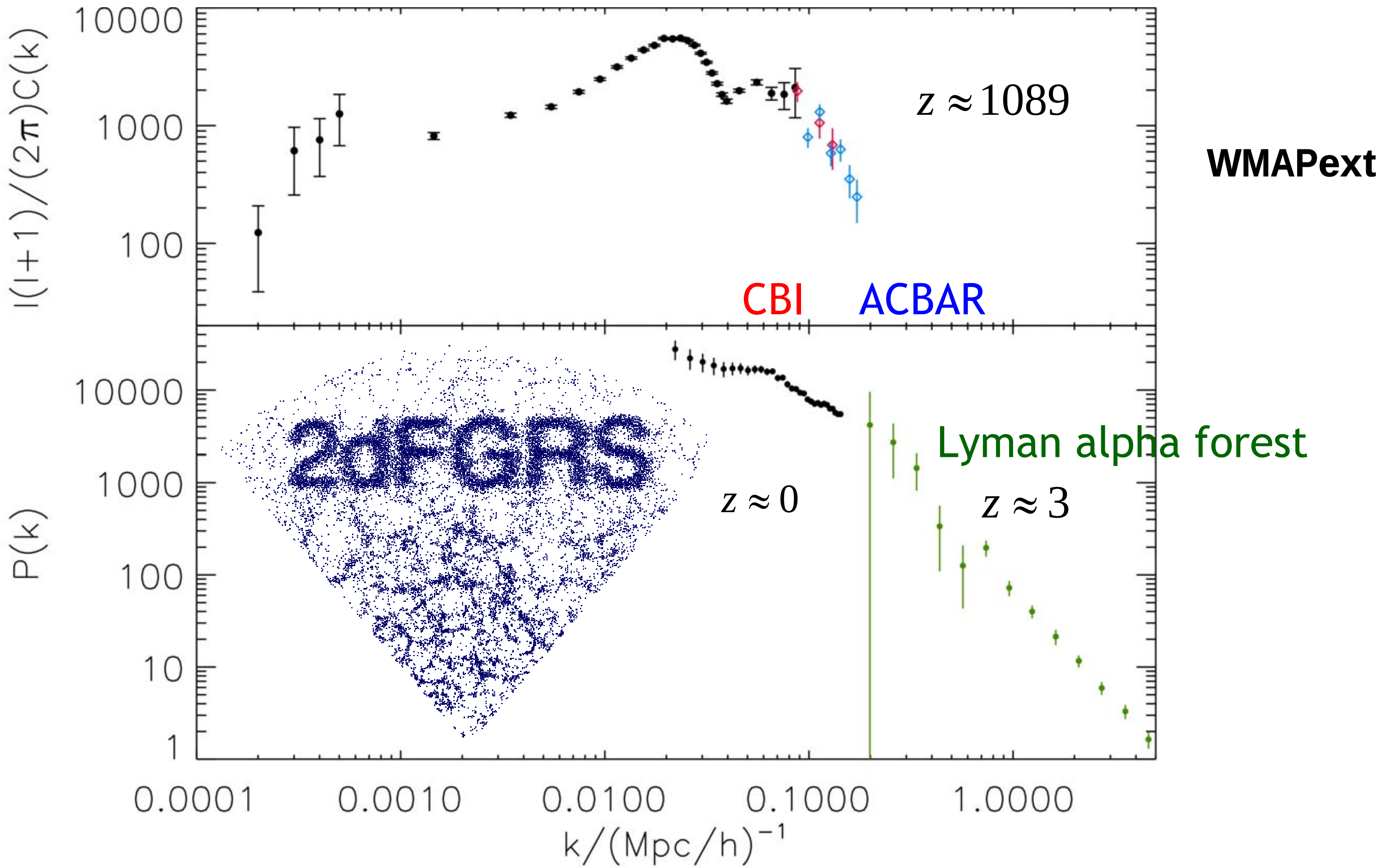
$$z_r \sim 17 \qquad t_U = 200 \text{ Myr}$$

new

$$T_{CMB} = 2.725\,\text{K}$$

$$z = 0 \qquad t_U = 13.7 \text{ Gyr}$$

TEST MODEL CONSISTENCY and LIFT DEGENERACIES



Complementary in scales-redshift

What Simple Inflationary Models predict

- Flat universe: $\Omega_{tot} = 1$
- Gaussianity: $f_{NL} \sim 1$ $$\Phi(\vec{x}) = \Phi_{gaus}(\vec{x}) + f_{NL}\Phi^2_{gaus}(\vec{x})$$

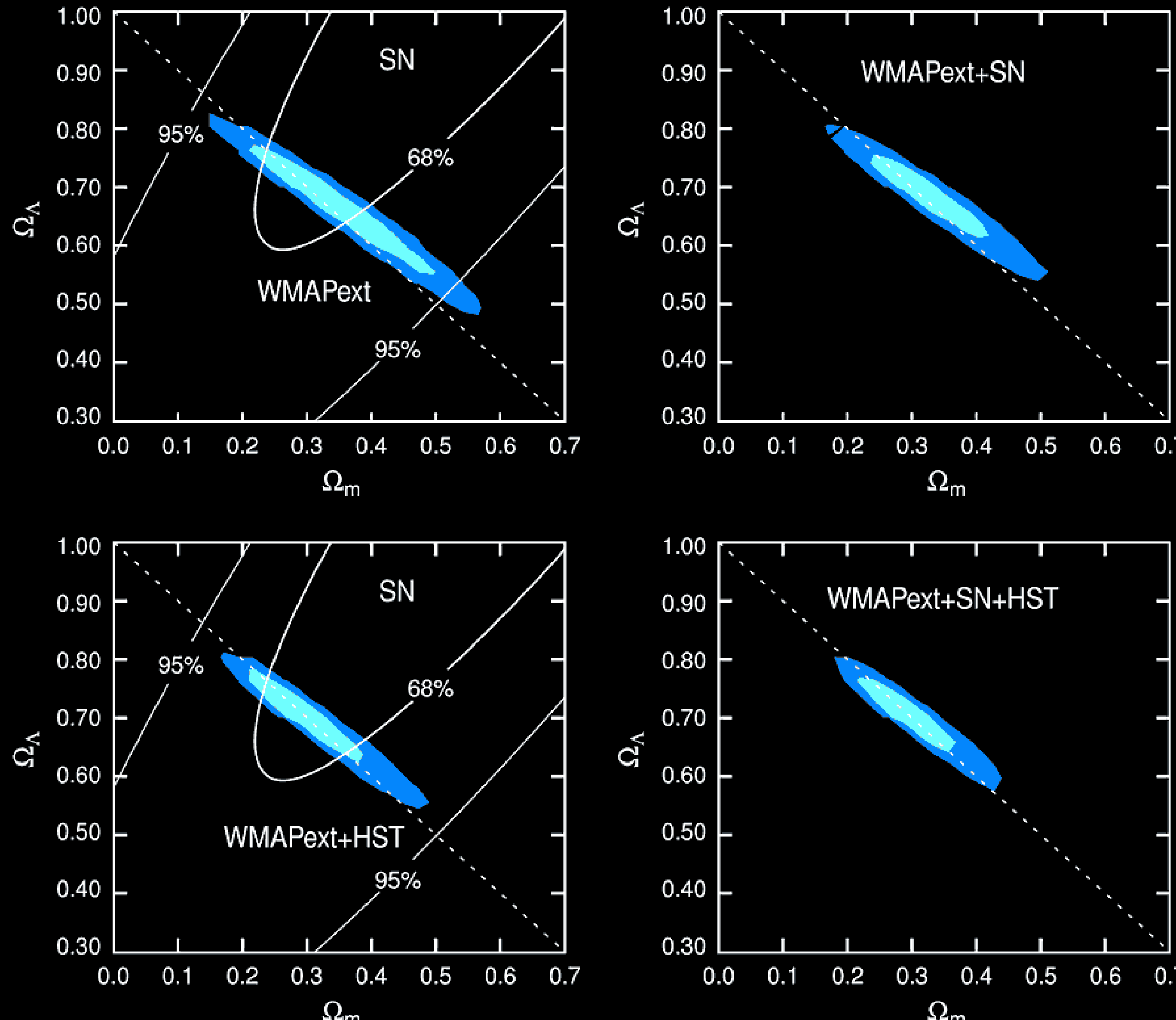
See talk by S. Matarrese

- Power Spectrum spectral index nearly scale-invariant: $n_s \sim 1$ $$k^3\langle\Phi\Phi\rangle \propto k^{n_s-1}$$
- Adiabatic superhorizon fluctuations

Guth (1981), Linde (1982), Albrecht & Steinhardt (1982), Sato (1981), Mukhanov & Chibisov (1981), Hawking (1982), Guth & Pi (1982), Starobinsky (1982), Bardeen et al. (1983), Mukhanov et al. (1992)

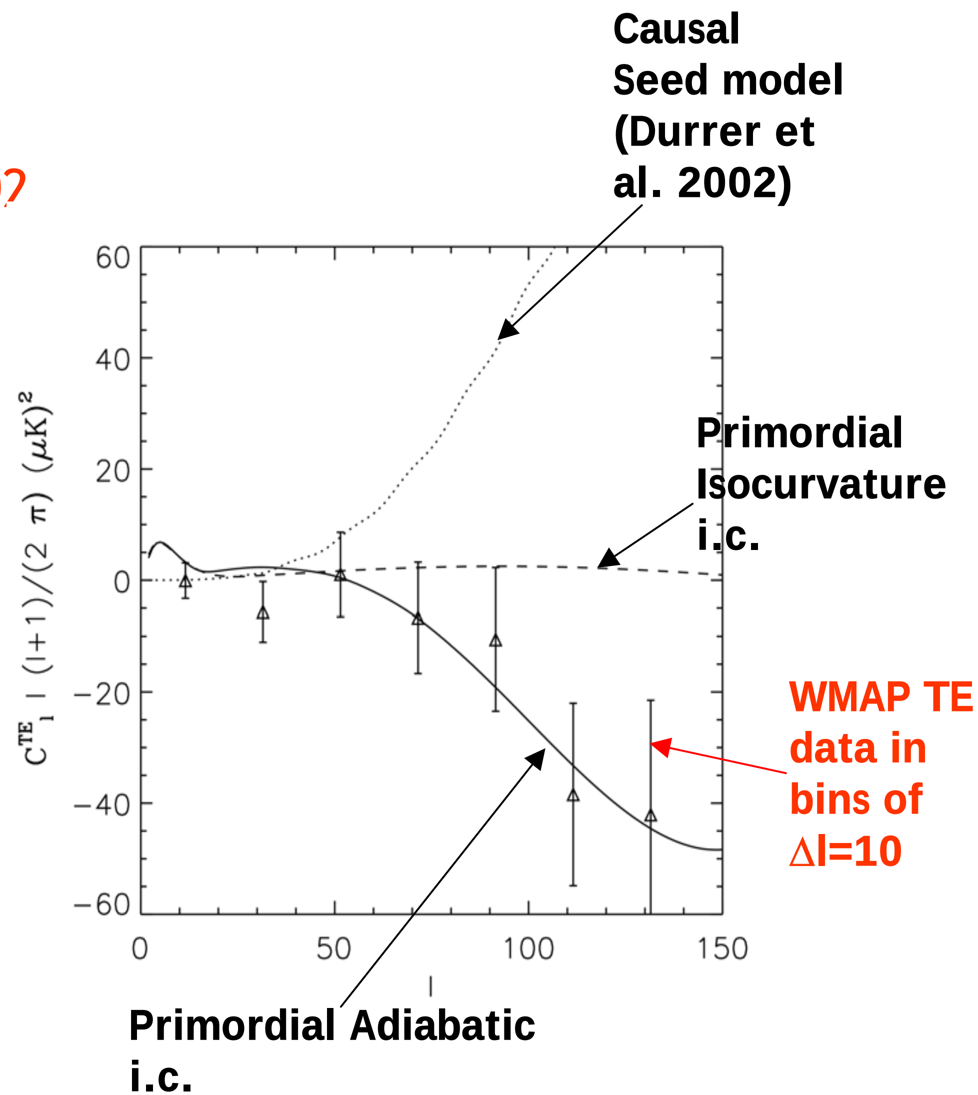
Ω_Λ vs. Ω_m

See Talk by O. Dore



WMAP Supports Single Field Inflationary Models

- Flat universe: $\Omega_{tot} = 1.02 \pm 0.02$
- Gaussianity: $-58 < f_{NL} < 134$
- Power Spectrum spectral index nearly scale-invariant: $n_s = 0.99 \pm 0.04$ (*WMAP* only)
- Adiabatic initial conditions
- Superhorizon fluctuations (TE anticorrelations)



Detailed level of confrontation

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

$$n_s(k) - 1 = n_s(k_0) - 1 + \frac{dn_s}{d\ln k}\ln\left(\frac{k}{k_0}\right)$$

"running"

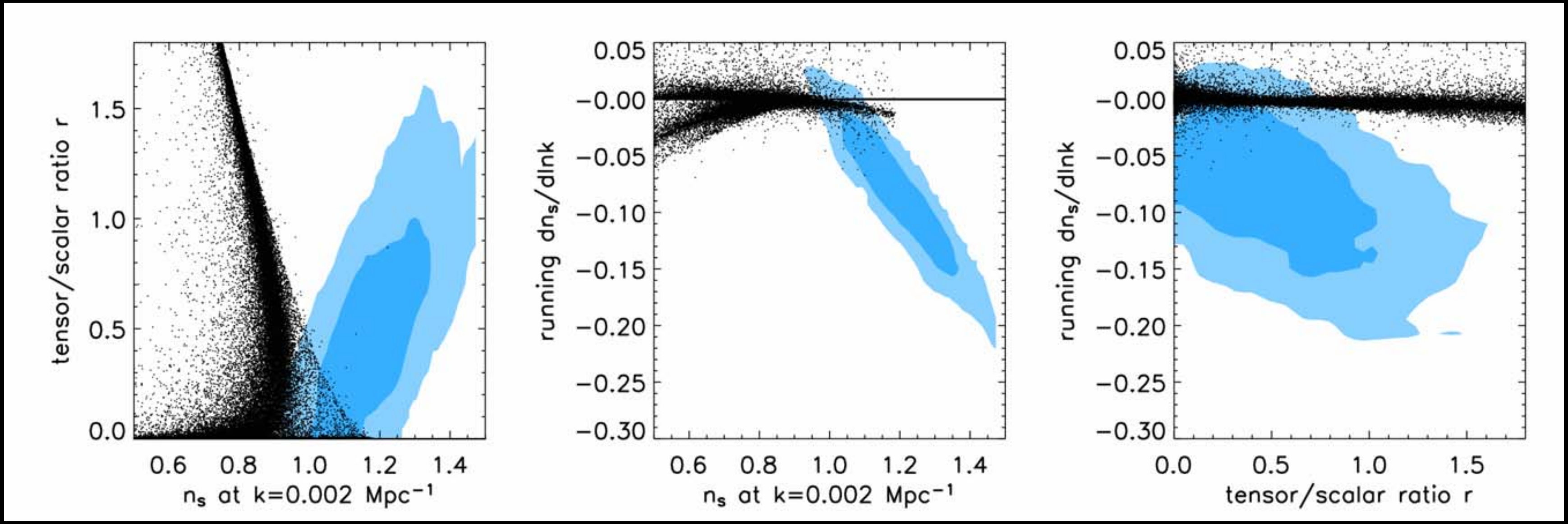
- There could be gravitational waves.

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

(The shape of the tensor power spectrum is determined by n_s and r using predictions of single field inflationary models.)

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

Generic predictions of single field slow roll models



Each point is a "viable" slow roll model, able to sustain inflation for sufficient e-foldings to solve cosmological problems.

Monte Carlo simulations following Kinney (2002) and Easther and Kinney (2002)

Classify Inflationary Models

- The shape of the scalar field potential, $V(\varphi)$, determines the observables.
- We use three parameters to characterize the shape:
  - ε: "slope" of potential, $(V'/V)^2$
  - η: "curvature" of potential, V''/V
  - ξ: "jerk" of potential, $(V'/V)(V'''/V)$

The curvature is the most important parameter in classifying the models.

Classify Inflationary Models

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

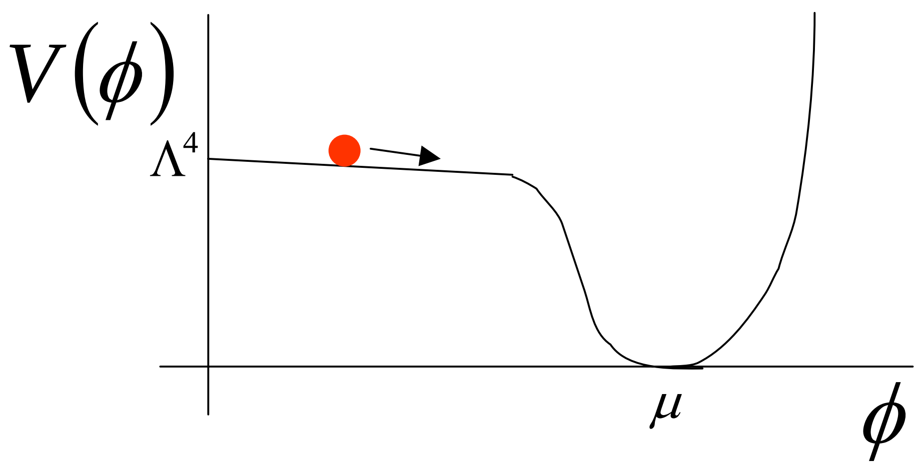
$$\Rightarrow \begin{cases} r = \frac{8}{3}(1 - n_s) + \frac{16}{3}\boxed{\eta} \\ dn_s / d\ln k + 2\xi = -\frac{2}{3}\left[(1 - n_s)^2 - 4\boxed{\eta^2}\right] \end{cases}$$

The curvature is the most important parameter in classifying the models.

Negative curvature models

$$\eta < 0$$

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



spontaneous symmetry breaking potential

e.g. new inflation

Albrecht & Steinhardt (1982), Linde (1982)

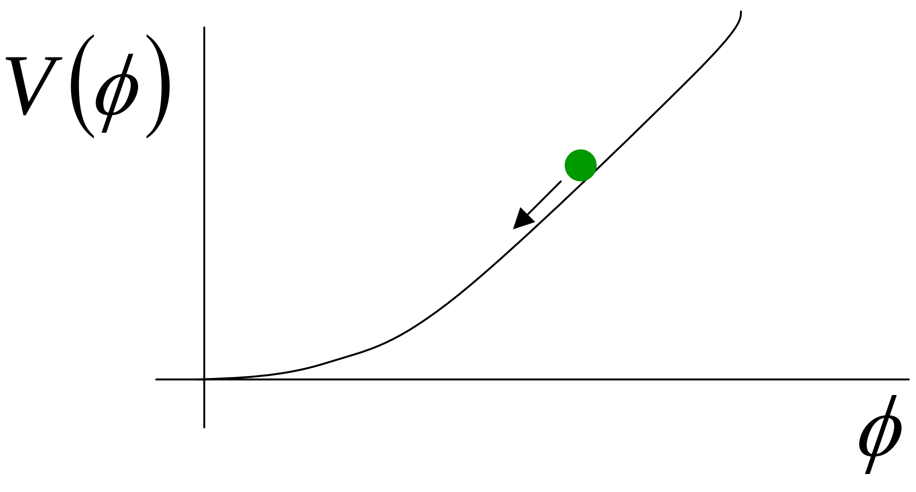
n_s<1 (red tilt) & tiny r & tiny $dn_s/d\ln k$

Small positive curvature models

$$0 \le \eta < 2\varepsilon$$

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

e.g. chaotic inflation, extended inflation



Linde (1983), La & Steinhardt (1989)

n_s<1 (red tilt) & large r & tiny dn_s/dln$k$

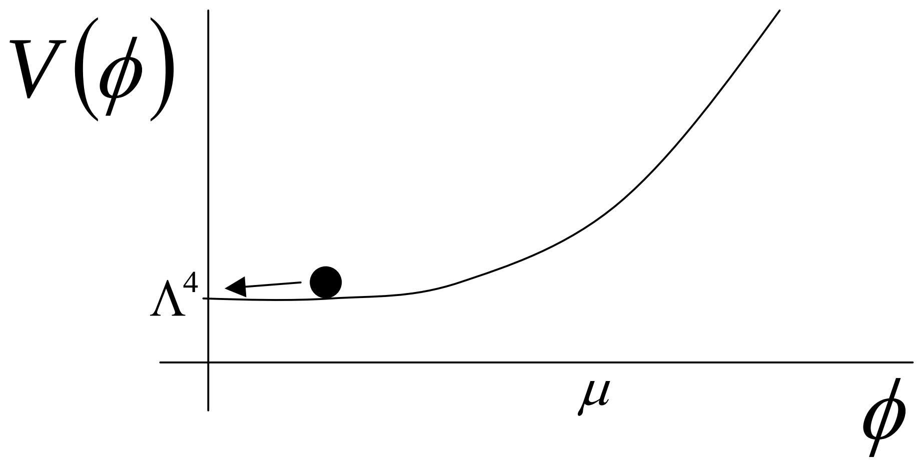
Large positive curvature models

$$\eta > 3\varepsilon$$

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

e.g. hybrid inflation

Linde (1994)



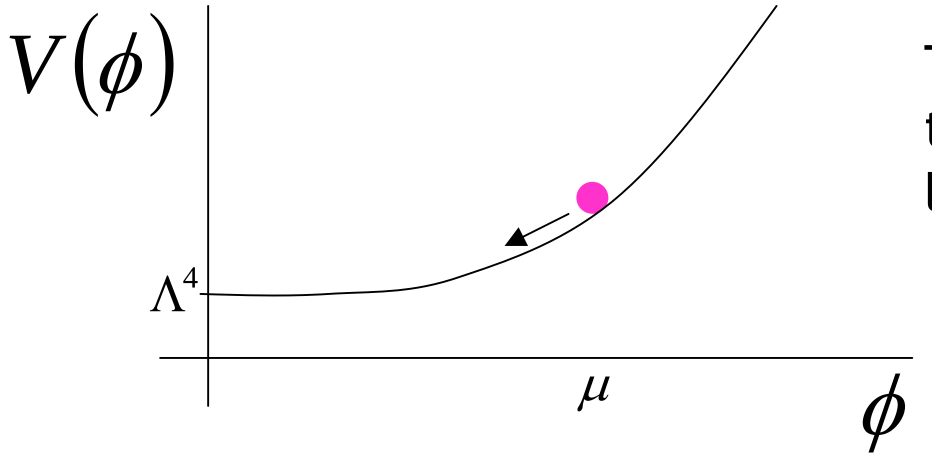
There are models in this class which give large dn_s/dln$k$.

n_s>1 (blue tilt) & tiny r & tiny dn_s/dln$k$

Intermediate positive curvature models

$$2\varepsilon \leq \eta \leq 3\varepsilon$$

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

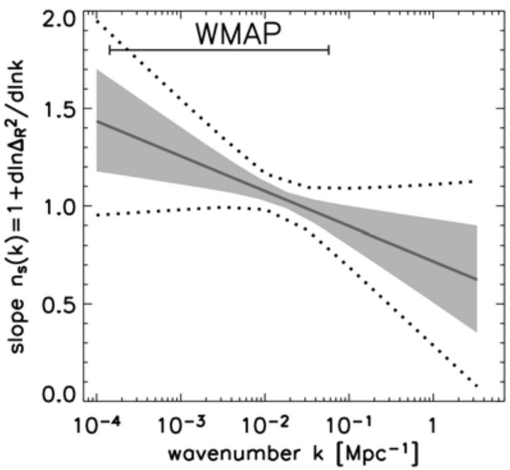


There are models in this class which give large $dn_s/d\ln k$.

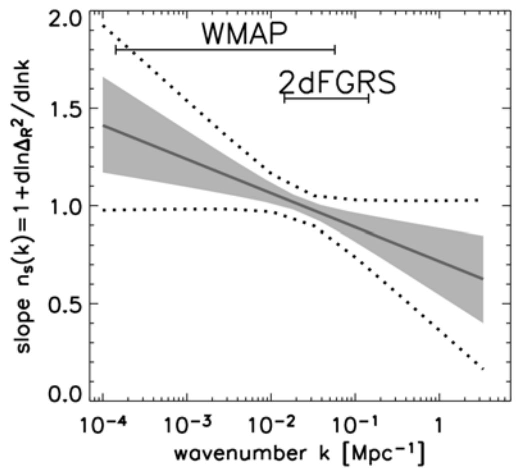
$n_s<1$ (red tilt) & large r & tiny $dn_s/d\ln k$

A hint of something unusual

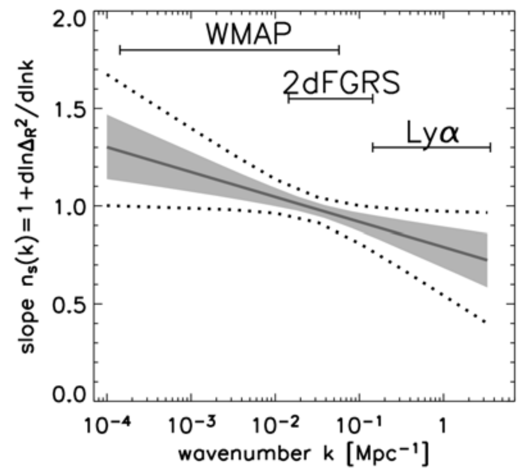
- Many inflationary models favour minimal "running".



91% runs blue-to-red



95% runs blue-to-red



96% runs blue-to-red

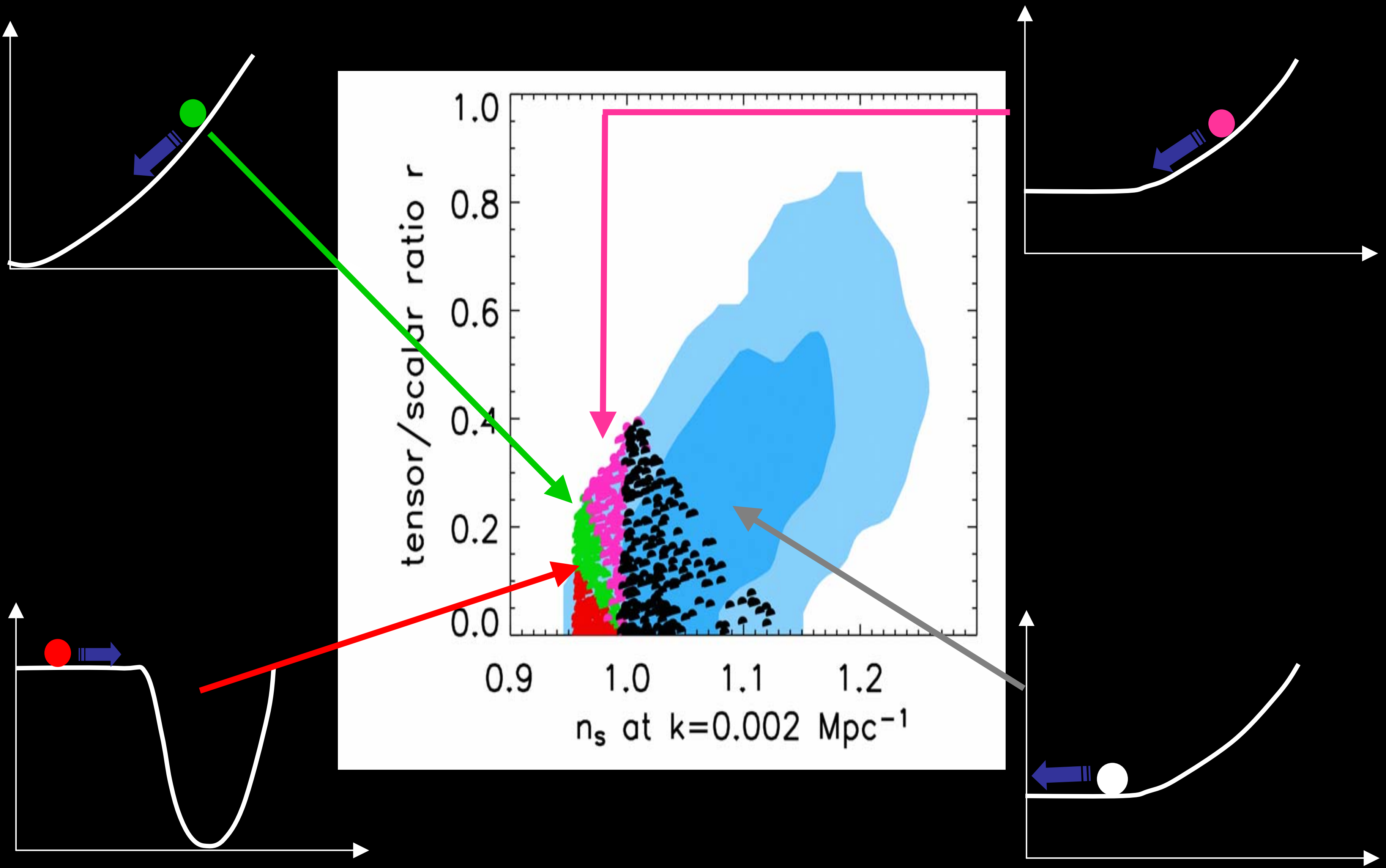
$$n_s = 1.13 \pm 0.08 \quad k=0.002\ \mathrm{Mpc}^{-1}$$

$$\frac{dn_s}{d\ln k} = -0.055 \pm 0.028$$

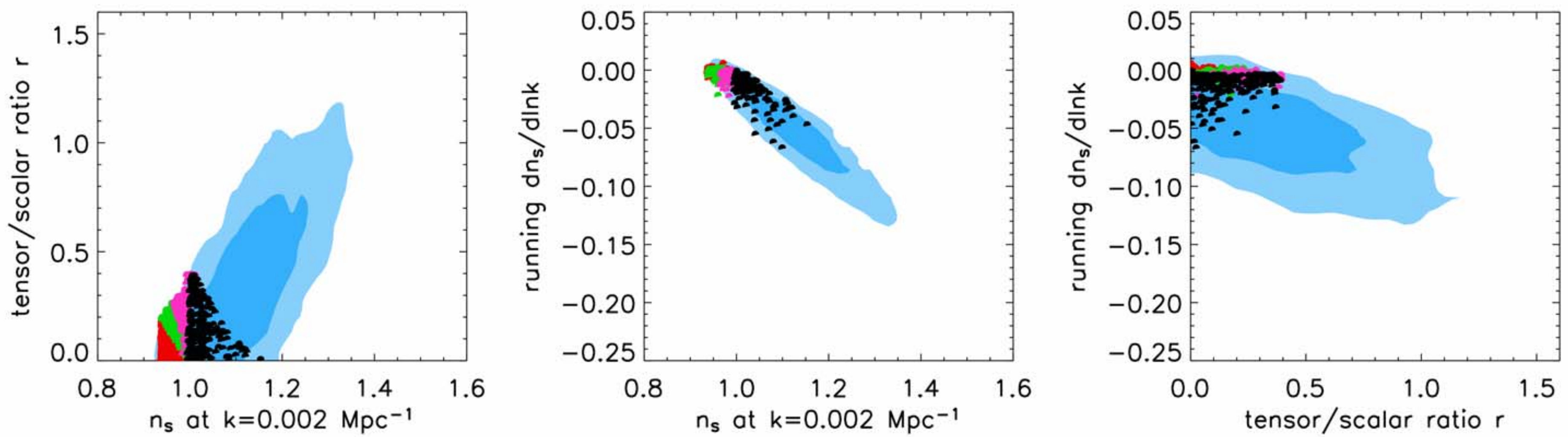
The data prefer, but do not require, a running spectral index.

If true, third derivative of potential is important.

Testing inflation at a detailed level



Categorizing single field slow roll models



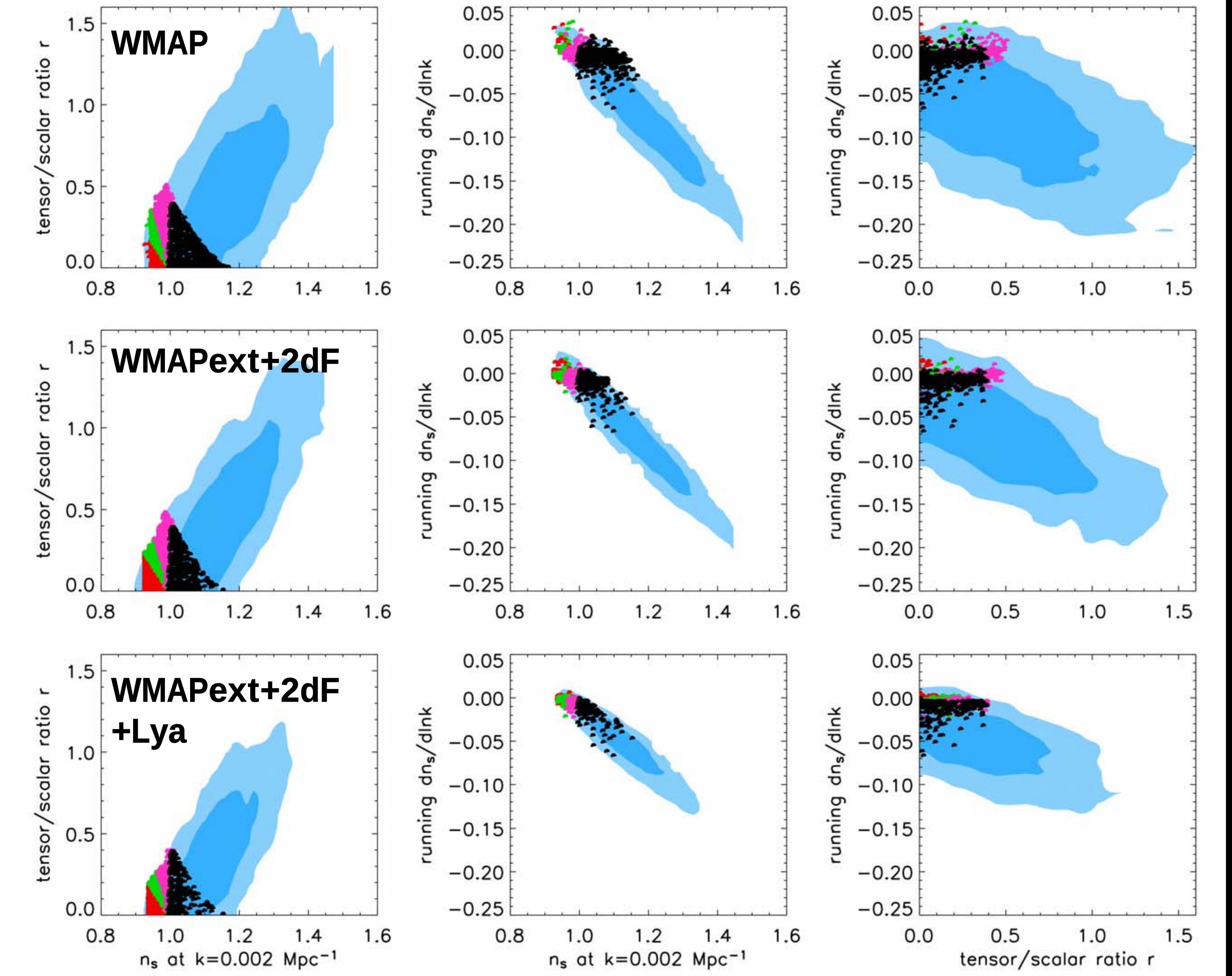
Negative curvature (e.g.: new inflation)

Small positive curvature (e.g.: chaotic inflation, extended inflation)

Intermediate positive curvature

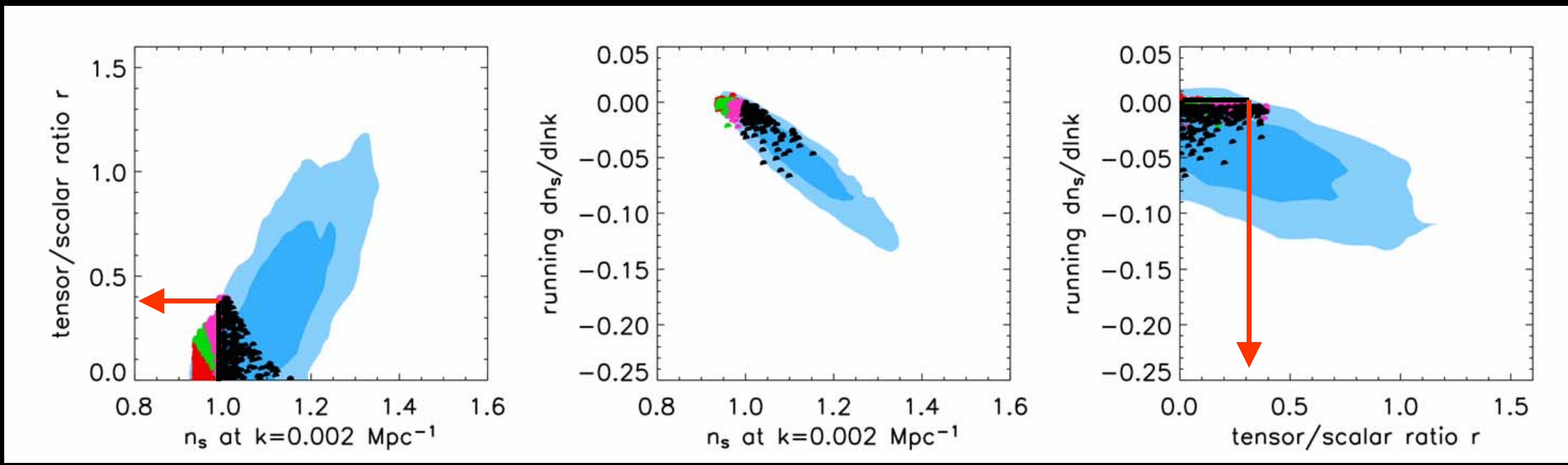
Large positive curvature (e.g.: hybrid inflation)

Recommended: For given model, sit on that point and run likelihood analysis (may need to integrate mode equation directly).



WMAP
WMAPext+2dF
WMAPext+2dF
+Lya
tensor/scalar ratio r
running dn$_s$/dlnk
n$_s$ at k=0.002 Mpc^{-1}
tensor/scalar ratio r

Constraining Inflation



95% Confidence Limits:

r<0.9 (no priors) => Energy scale of inflation $V^{1/4} < 3.3 \times 10^{16}$ GeV (95% CL)

r<0.43 (no running)

r<0.28 (red tilt)

$\lambda\phi^4$ **model, Excluded at more than 3-sigma if N<50**

Double Field Models

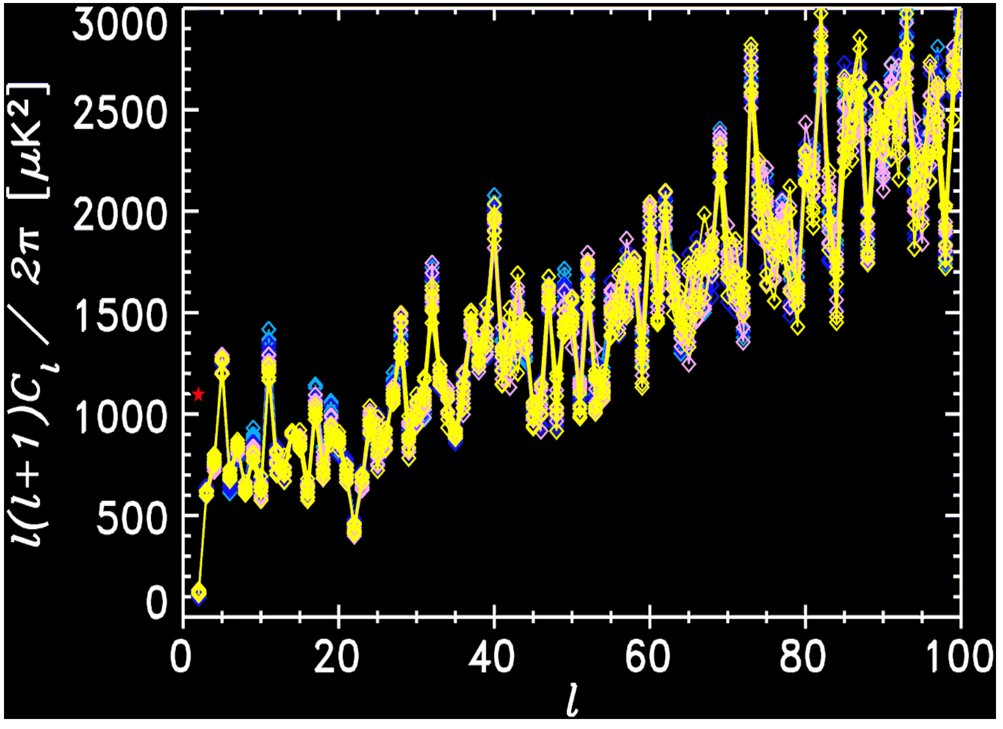
- If there is a scalar field, why not two?
- Distinctive signatures of double field models:
  - Fluctuations may not be purely adiabatic
  - Entropy (isocurvature) perturbations
- We perturb entropy between CDM and photons
  - Parameterize by two slopes (n_{ad}, n_{ent}), a fractional contribution of the entropy mode (f_{ent}), and a correlation angle ($\cos \Delta$).

See talk by J. Lesgourgues

Double field models

- Motivation: Can we reduce low l anisotropy?

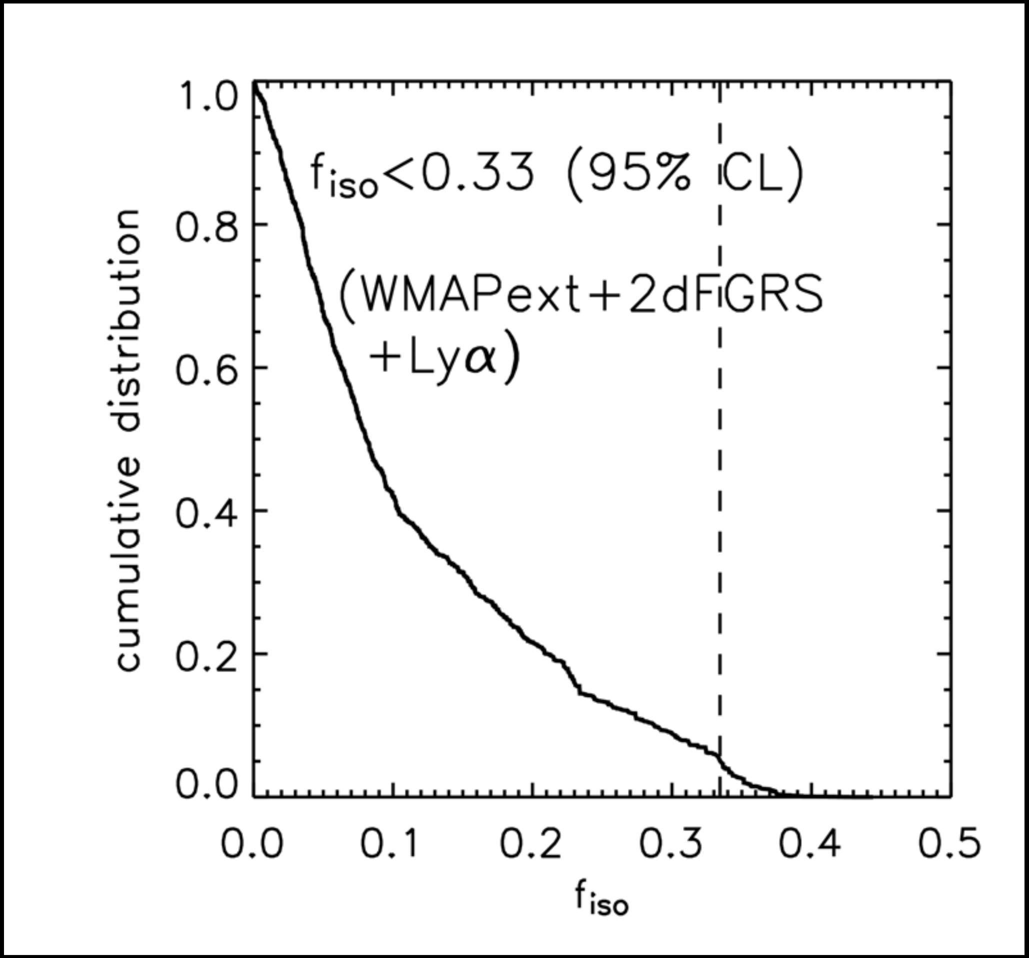
$$\frac{\Delta T}{T} = \frac{1}{5}\left(\hat{R}_{rad} - 2\hat{S}_{rad}\right)$$



- CMB anisotropy can be reduced, when *R* and *S* are correlated.

See talk by J. Lesgourgues

Constraint on correlated CDM isocurvature fraction

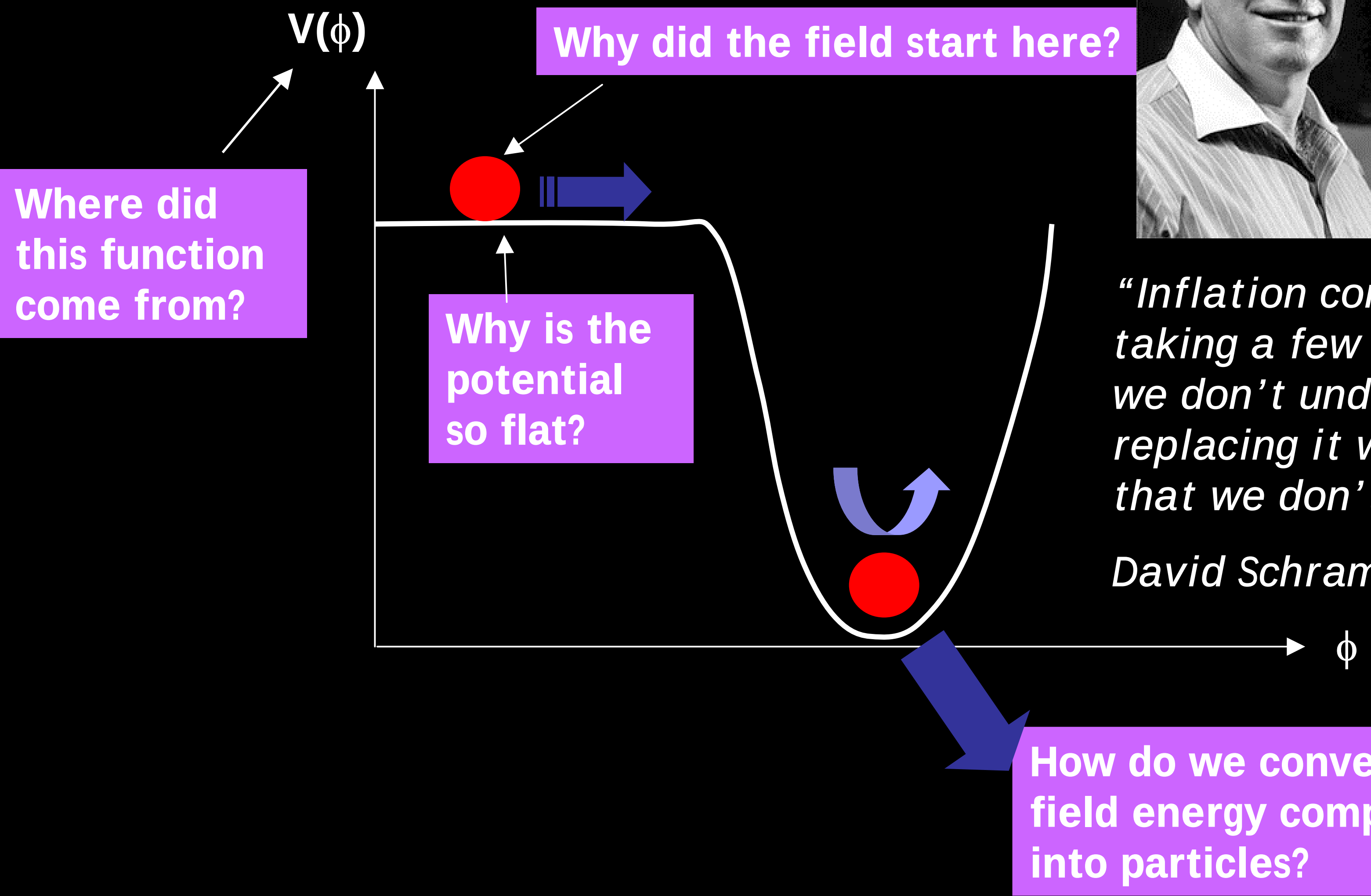


Chi-square not improved by addition of three extra parameters

What *WMAP* is telling us

- No evidence for entropy perturbations between CDM and photons.
- Primordial fluctuations seem to be purely adiabatic.
- Supporting single field (simplest) inflationary models.
- No broad classes of inflation cannot currently be ruled out (because we cannot exclude n_s=1,r=0), but specific models are starting to be able to be ruled out.

Inflation: Problems



"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

Is Inflation a Theory?

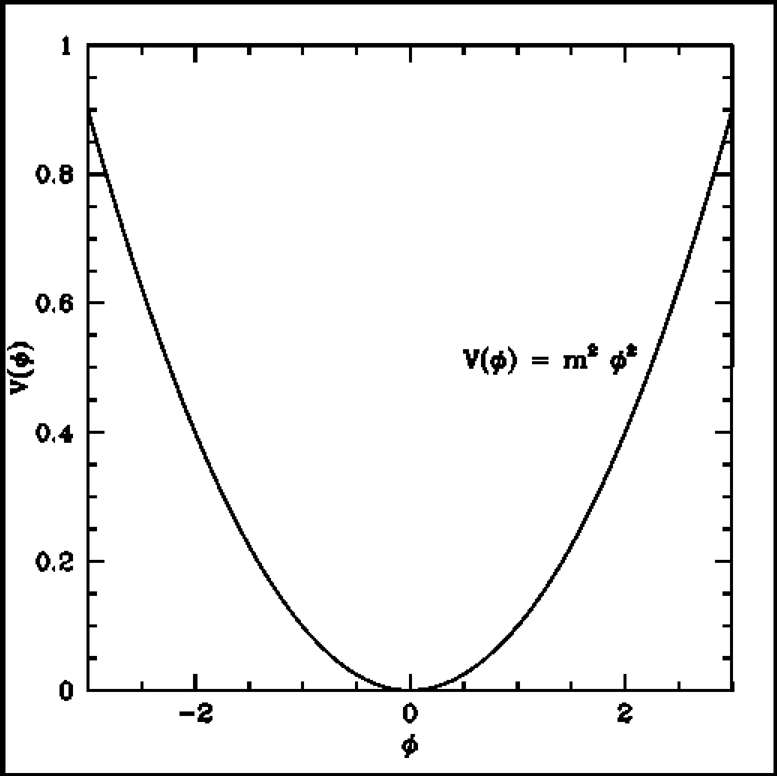
While the simplest versions of inflation have definite predictions (flat universe, Gaussian scale invariant spectrum of adiabatic fluctuations), inflationary models with more baroque forms of $V(\phi)$ can produce non-flat universes, non-Gaussian fluctuations, non-adiabatic fluctuations, and deviations from scale invariance.

INFLATION IS A PARADIGM

Testing Specific Inflationary Models

- Cosmologists need to test simplest models
- Particle theorists need to motivate models
  - String theory
  - Multiple dimensional cosmologies

See talks by H. de Vega & N. Sanchez



Testing the Simplest Models

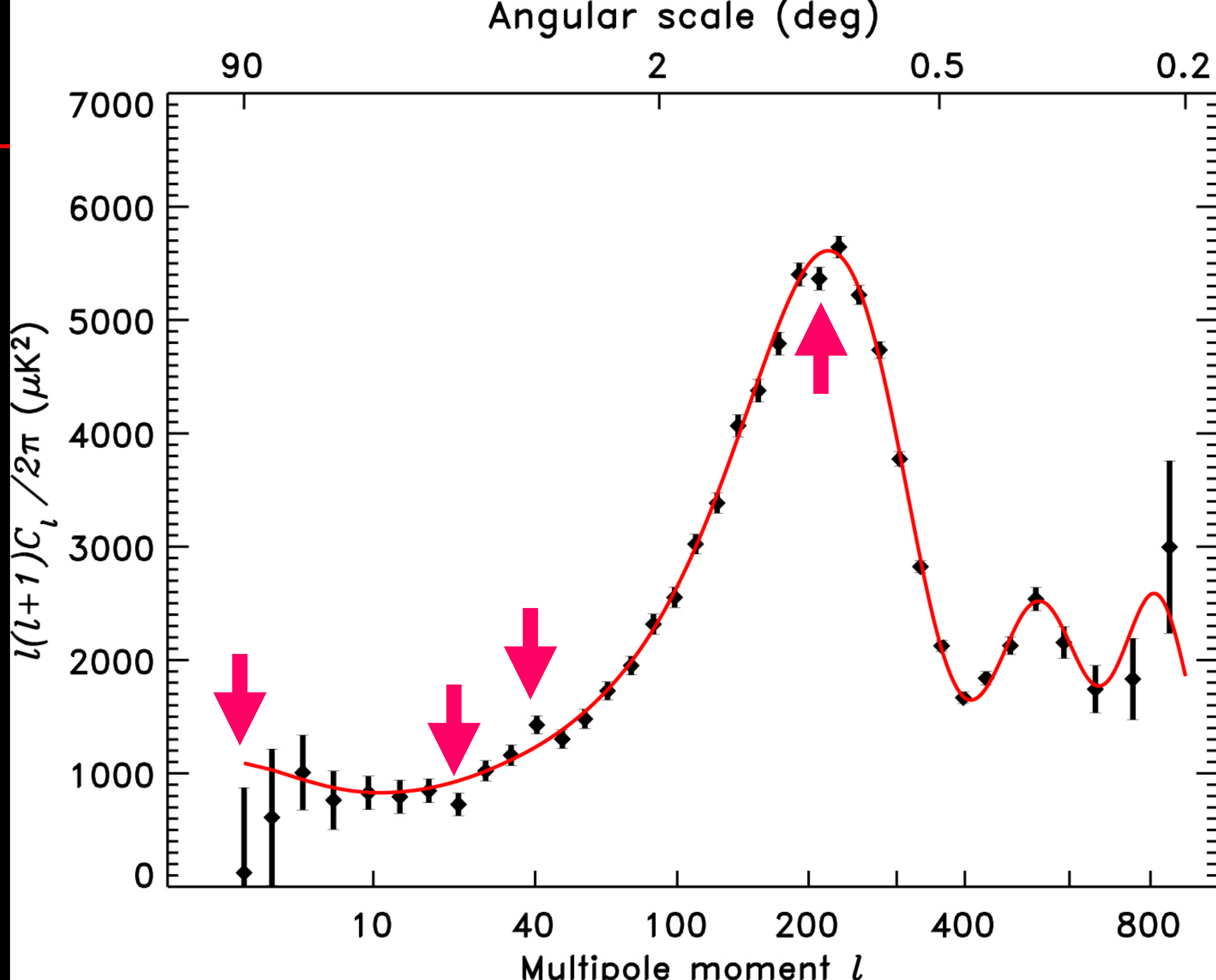
- Deviations from scale invariance
  - $m^2\phi^2$ inflation predicts $n_s = 0.97$
  - WMAP + ACT (or Planck) should detect these deviation from scale invariance at greater than 3 σ
- Further tests of non-Gaussianity (See talk by S. Matarrese)
- Gravity waves from inflation
  - $m^2\phi^2$ inflation predicts a gravity wave background at a level detectable by WMAP (with ~8 years of integration) and Planck

Current Status of Inflation

- Standard big bang models has a number of fundamental problems
- Inflationary scenario solves these problems by positing an inflaton potential
  - Inflaton potential form is currently ad-hoc

Simplest Versions of Inflation are Testable!

Glitches?



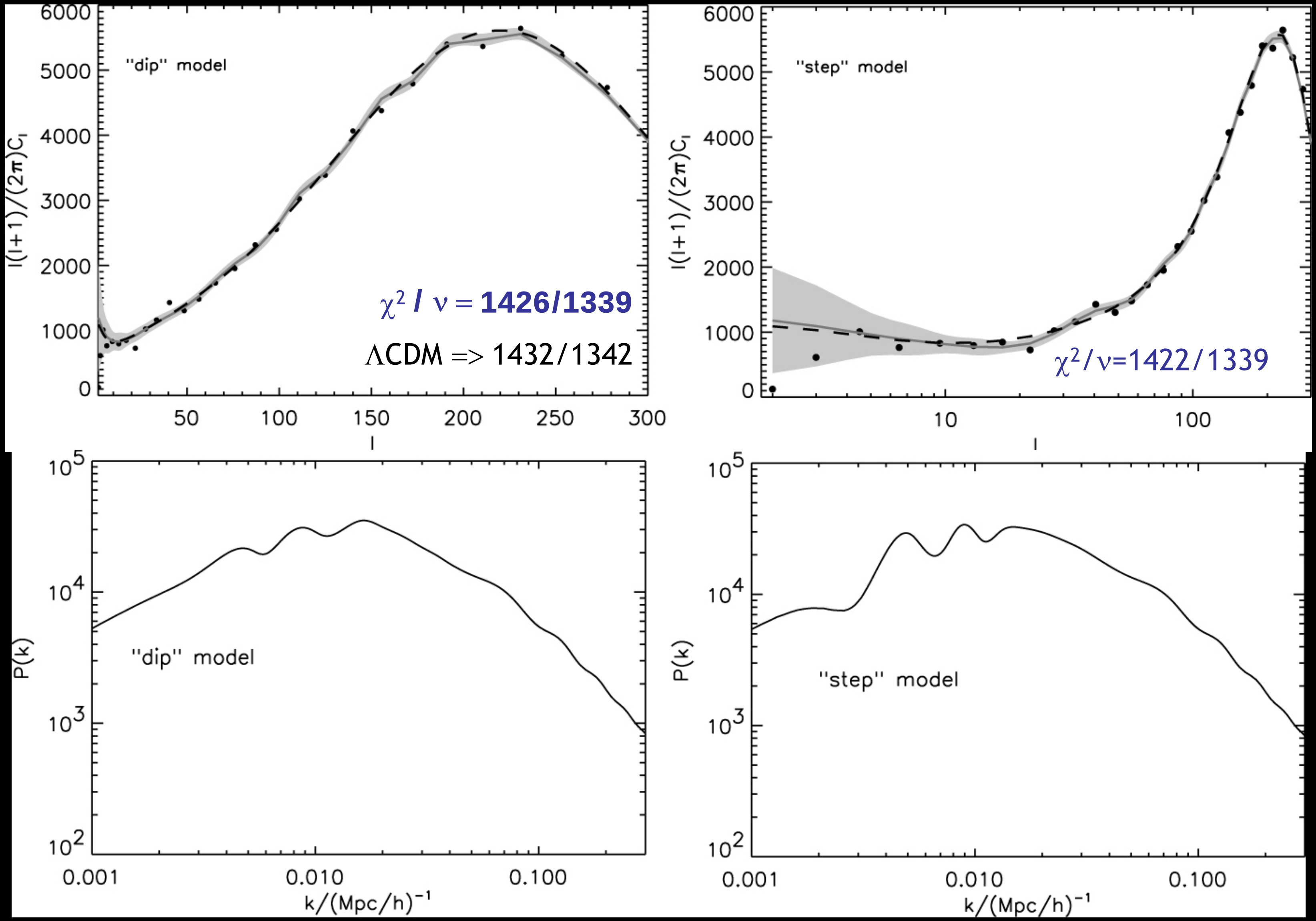
Reduced chisq for TT only 1.09

Effects neglected on covariance matrix

0.5% to 1% error on the error!

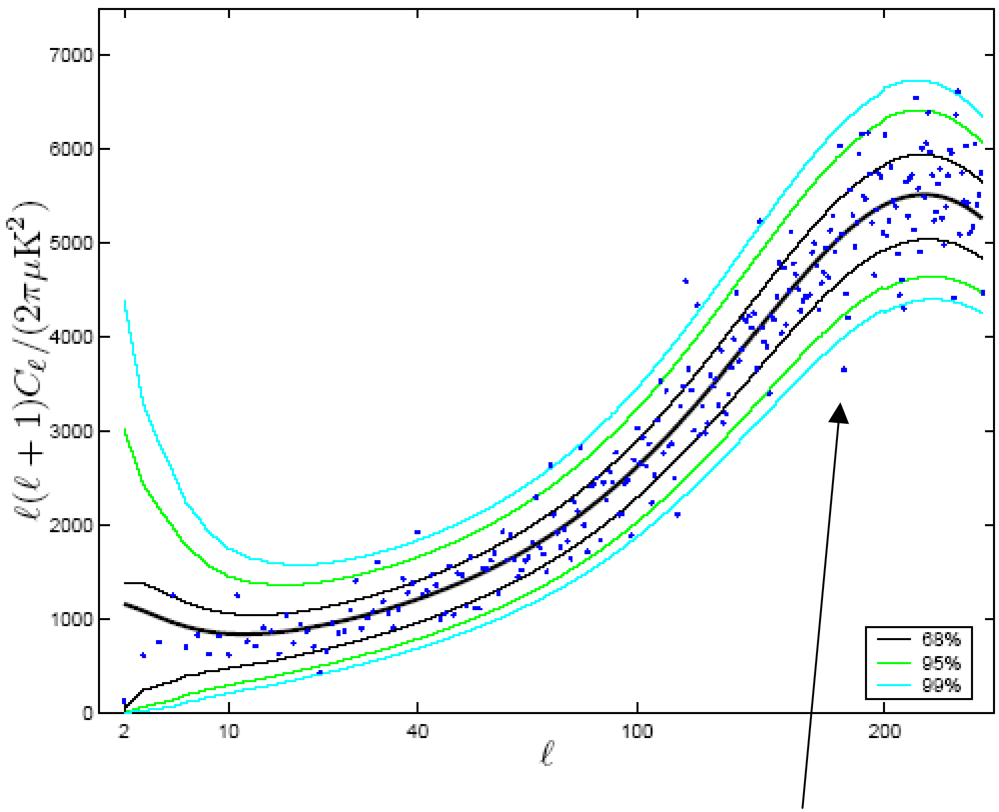
- Weak lensing
- Beam asymmetries
- Non-gaussianity of the noise (striping)
- Features in inflation potential (Peiris et al. 2003)

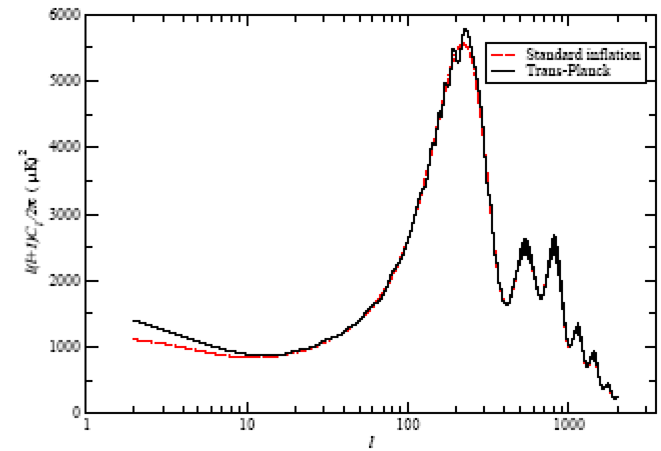
Modifying the Inflaton Potential (0.1% change in amplitude)

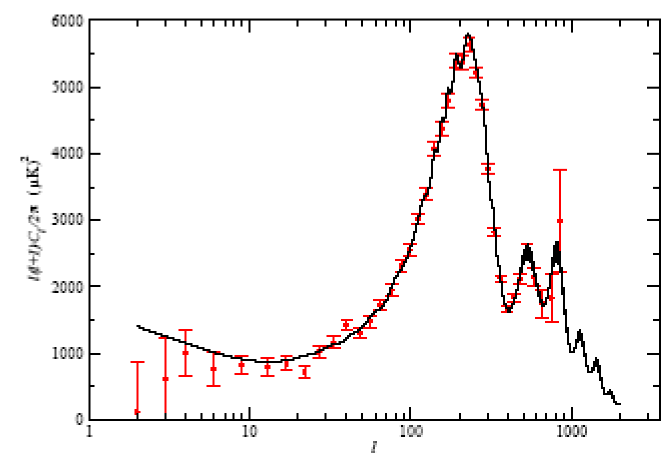


See e.g. Adams, Cresswell & Easther (astro-ph/0102236), Hunt & Sarkar (astro-ph/0408138)

More Power Spectrum Outliers







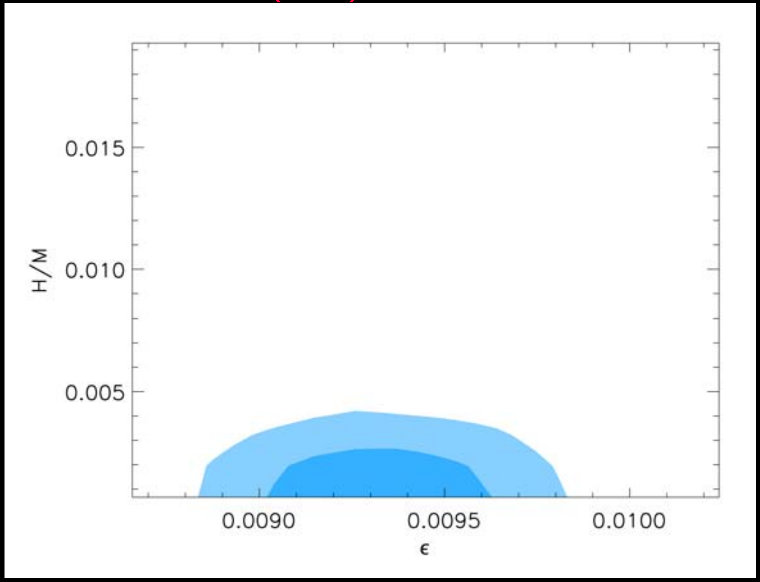
Lewis (astro-ph/0310186) observes that the number of 3σ points (above) is high. Notes that only 3/16000 simulations have a lower value of C_{181}(arrow).

See Talk by O. Dore

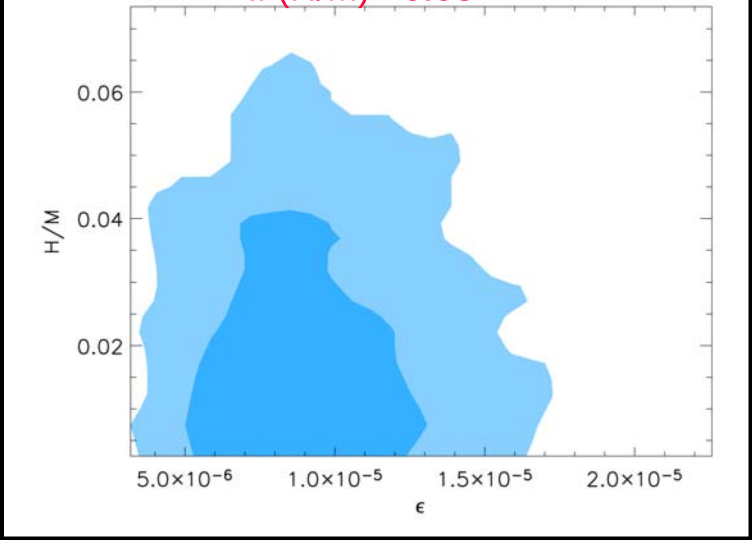
Martin & Ringeval (astro-ph/0310382) and Okamoto and Lim (astro-ph/0312284) fit toy trans-Planckian model to spectrum: $\Delta\chi^2$ = 16 for 3(?) parameters.

Are TP effects observable even in principle?

Fiducial model has r=16ε=0.15
>3σ detection of TP oscillations
if (H/M) >0.004



Fiducial model has
r=16ε=0.00013
>3σ detection of TP oscillations
if (H/M) >0.03



- Feasibility study only
- Significant theoretical uncertainties (need a proper model to test!)
- Needs favorable piece of parameter space
- Tensor detection and (H/M) detection coupled

Easther, Kinney, and Peiris (in preparation)

Standard Model fits *WMAP* data

- LCDM, Adiabatic, flat, composed of:
  - Baryonic Matter = 4.7±0.6%
  - Dark Matter = 24±7%
  - Dark Energy = 71±7%
- Power Spectrum Slope = 0.99±0.04
- Hubble Constant = 72±5 km/s/Mpc [fits HST Key Project]
- $\Omega_b h^2$ = 0.024 [fits D/H]
- σ_8 = 0.9 (0.84 for running model) [fits lensing, clusters, etc]
- Age of the Universe 13.7 ± 0.2 Gyr [fits stellar evolution]
- Fits LSS and Ly-a data

The numbers are consistent with a host of astronomical observations at different redshifts and scales.

Future observational prospects

- *Go to small scales!* Much better measurements of the primordial power spectrum shape.
  - Planck l~3000 (k~0.2/Mpc)
  - ACT l~10000 (k~0.7/Mpc) [secondary effects]
  - Galaxies k~1/Mpc [non-linearity & bias]
  - Lyman alpha k~5/Mpc [gas phys. & radiation feedback]
  - Reionization k~50/Mpc [much is unknown]
- Detecting gravitational waves
  - QUEST, QuAD, BICEP, PolarBear, EBEX ,CLOVER, QUIET, Planck, CMBpol, Inflation Probe etc… [See G. Smoot Talk]
- Detecting non-Gaussianity from 2nd order gravity
  - Can we detect f_{NL}~1?

Theoretical directions

- More detailed predictions from a specific, physically motivated model
  - More accurate reheating scenario is necessary!!
  - No slow-roll approximations
  - Test (constrain) models one by one

THE END