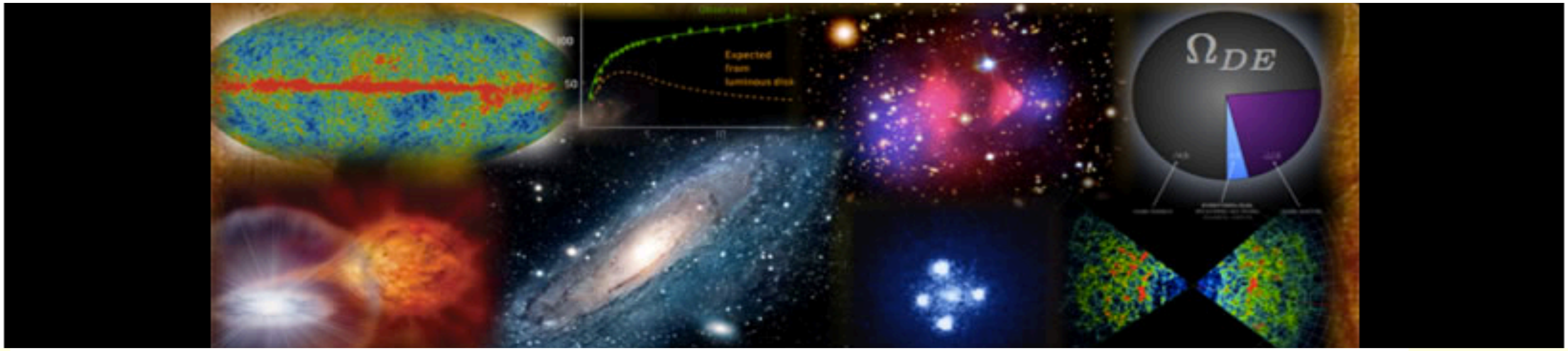

Cosmology After Planck Workshop

September 23-25, 2013

340 West Hall

University of Michigan, Ann Arbor, Central Campus

Sponsored by:

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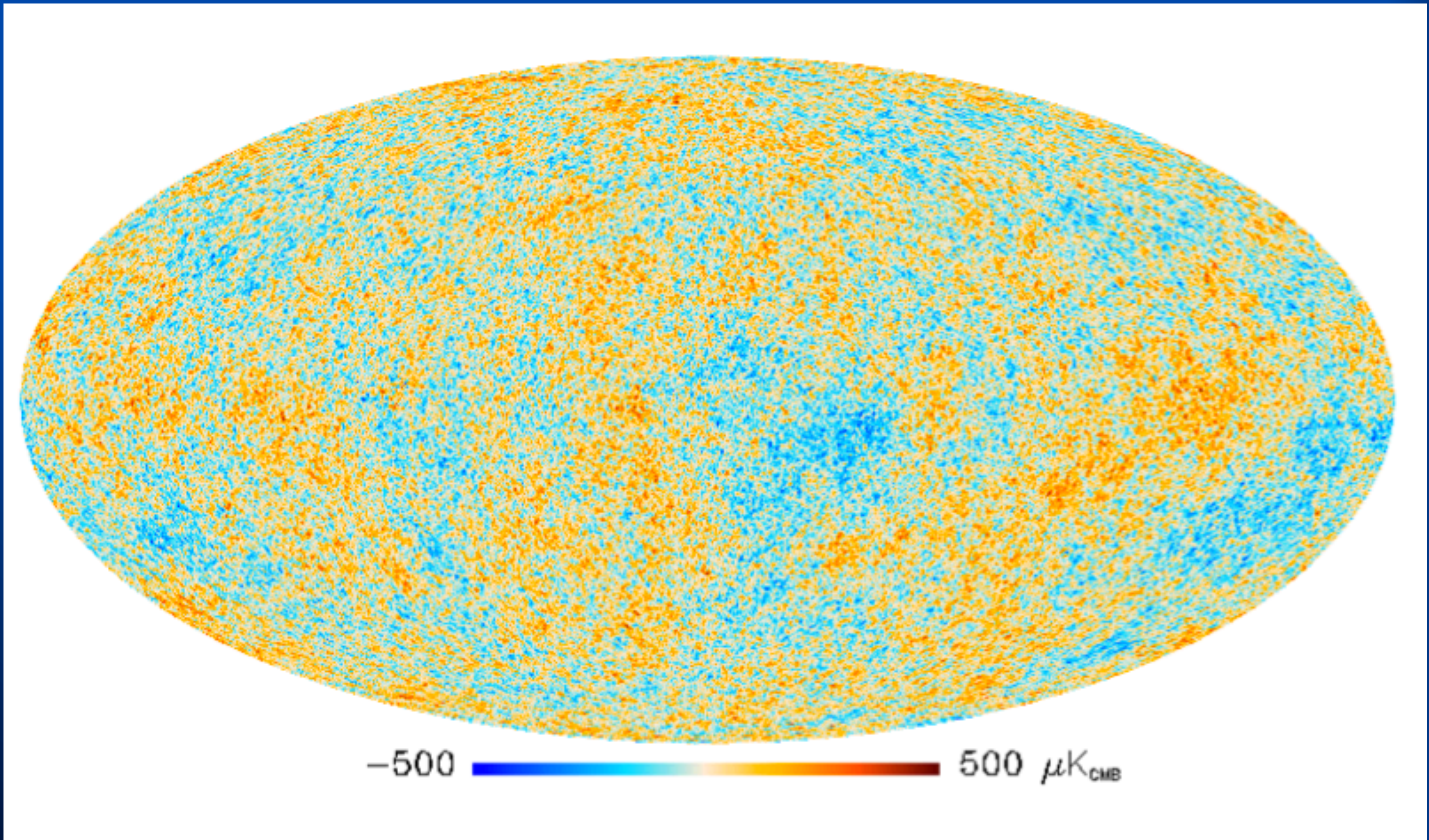
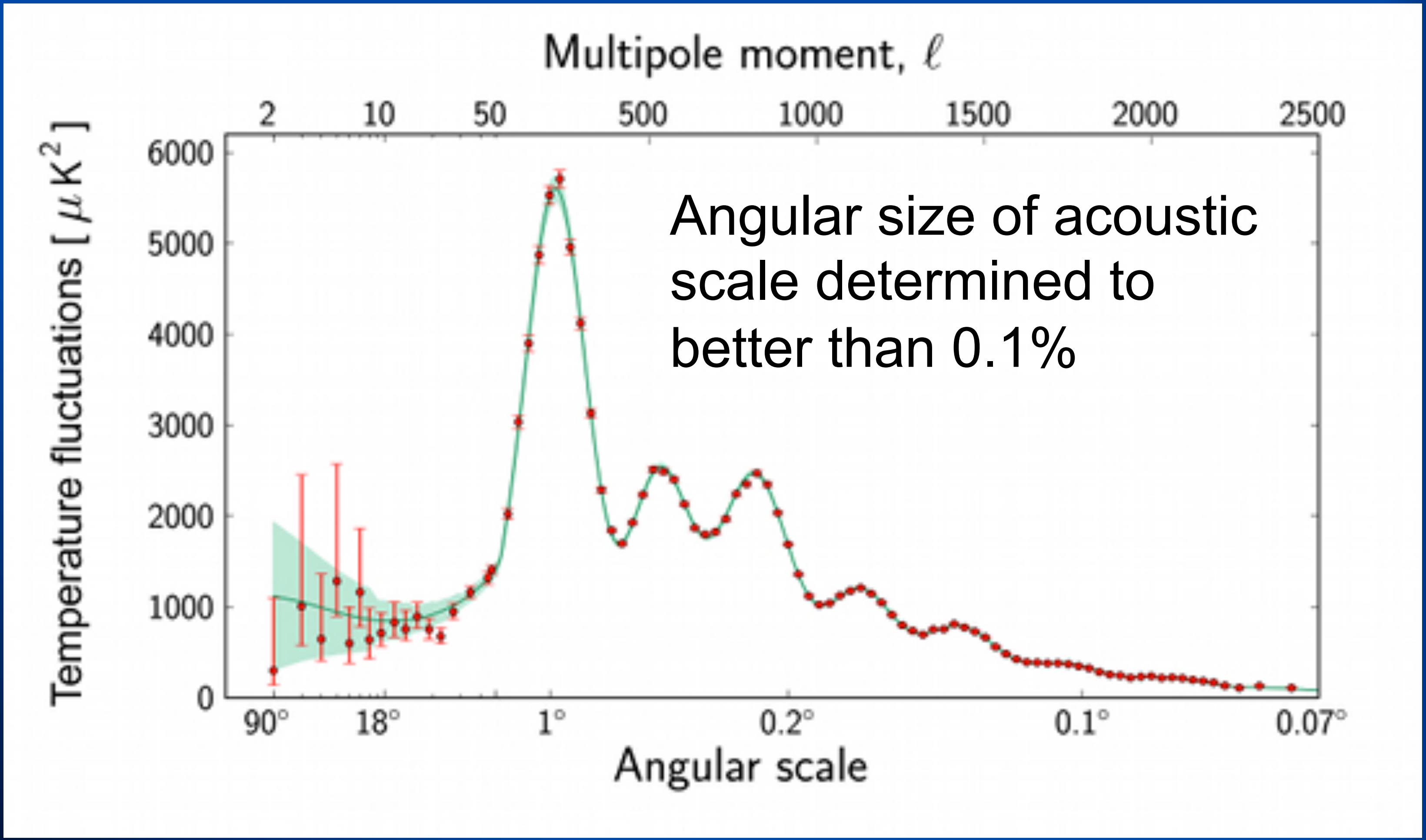
Inflationary cosmology has become an integral part of the standard model of the early Universe. Inflationary models and other signatures of of the early-Universe physics have become stringently constrained by WMAP and Planck, as well as powerful new large-scale structure surveys. This workshop will discuss the theoretical, observational, and experimental aspects of inflation and primordial physics, interpreted broadly. We plan to gather 20-30 of the top experts in the field.

Mysteries of the Dark Universe Public Lecture - Monday, September 23, 2013
TIME: 7:00pm. Refreshments will be served prior to talk at 6:30pm.
VENUE: Edward Henry Kraus Building (Natural Science) #2140, 830 North University, Ann Arbor,

The Universe according to Planck



Planck Data



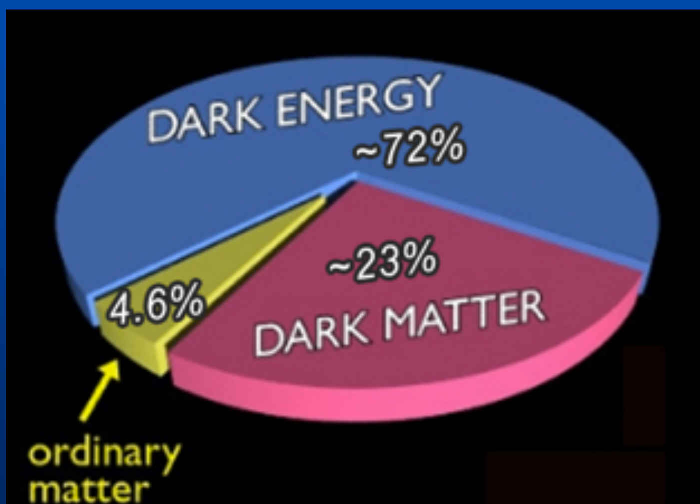
Seven acoustic peaks

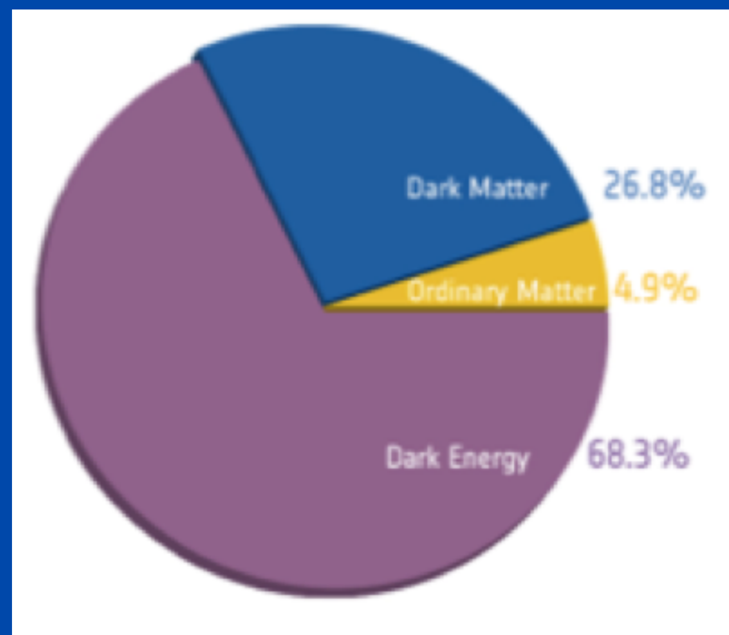
Cosmological Parameters from Planck

	Planck (CMB+lensing)		*Planck*+WP+highL+BAO	
Parameter	Best fit	68 % limits	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	1.04147 ± 0.00056
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025
Ω_Λ	0.6964	0.693 ± 0.019	0.6914	0.692 ± 0.010
σ_8	0.8285	0.823 ± 0.018	0.8288	0.826 ± 0.012
z_{re}	11.45	$10.8^{+3.1}_{-2.5}$	11.52	11.3 ± 1.1
H_0	68.14	67.9 ± 1.5	67.77	67.80 ± 0.77
Age/Gyr	13.784	13.796 ± 0.058	13.7965	13.798 ± 0.037
$100\theta_*$	1.04164	1.04156 ± 0.00066	1.04163	1.04162 ± 0.00056
r_{drag}	147.74	147.70 ± 0.63	147.611	147.68 ± 0.45
$r_{drag}/D_V(0.57)$	0.07207	0.0719 ± 0.0011		

New Pie Picture: more dark matter

- WMAP: 4.7% baryons, 23% DM, 72% dark energy
- PLANCK: 4.9% baryons, 26% DM, 69% dark energy





For discussion: is the difference due to instrumental effects? Is it due to 217 X 217 spectra?

Effective Number of Neutrino Species

- In the Standard Model, *Neff* = 3.046, due to non- instantaneous decoupling corrections (Mangano et al. 2005).

$$N_{\rm eff} = 3.52^{+0.48}_{-0.45} \quad (95\%; \textit{Planck}+\text{WP}+\text{highL}+H_0+\text{BAO}).$$

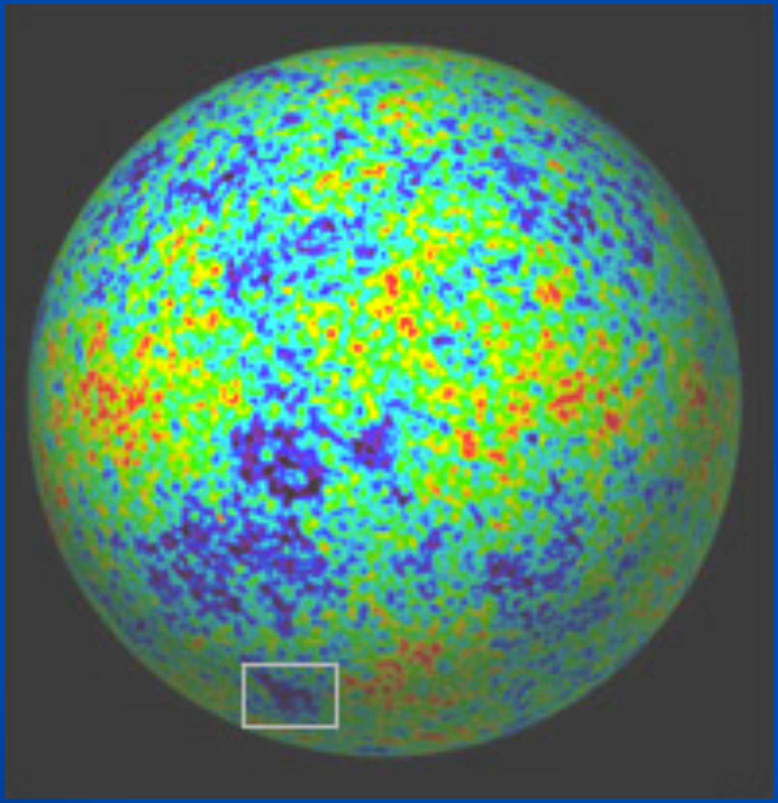
Increasing the radiation density increases the expansion rate before recombination and reduces the age of the Universe at recombination.

Weird Anomalies of WMAP hold up

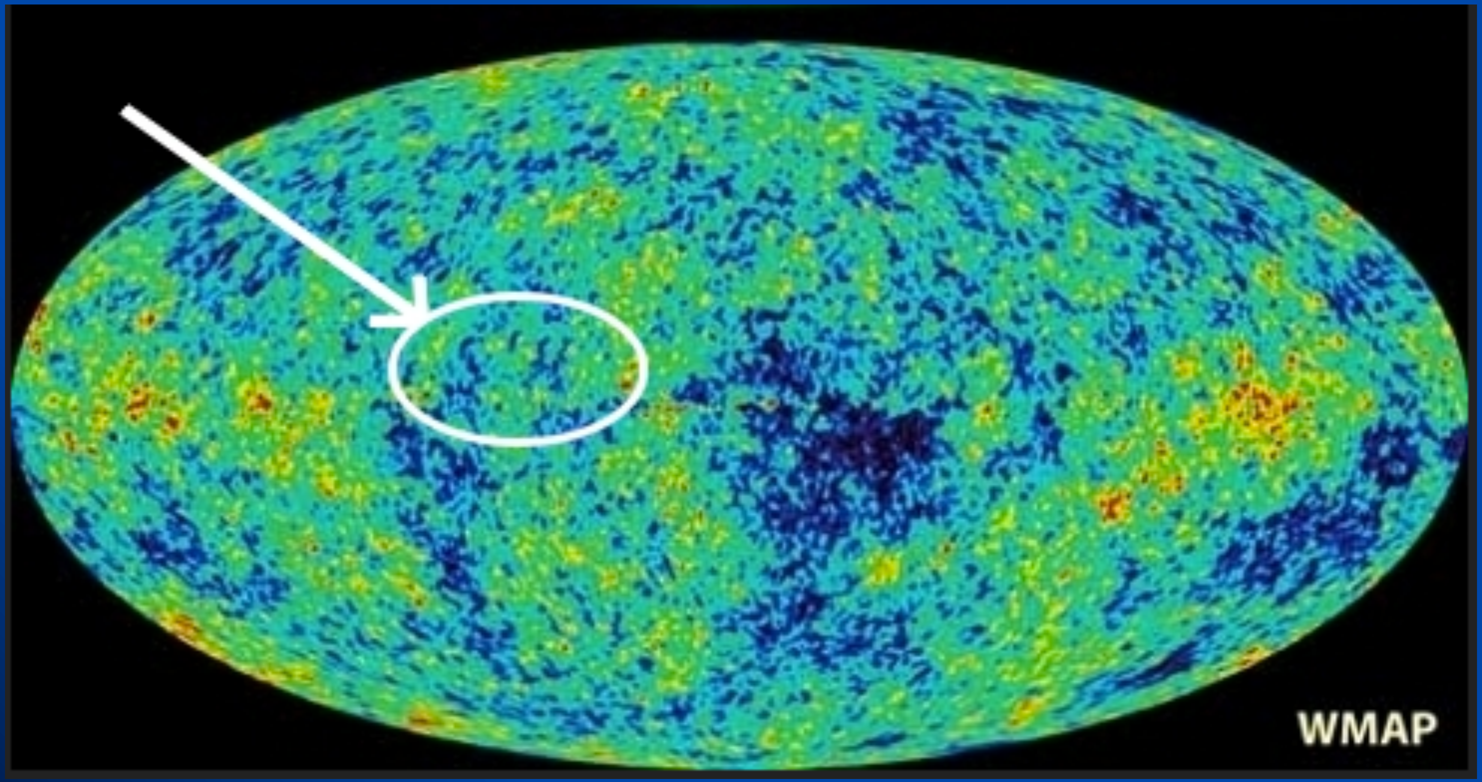
- Alignment between quadrupole and octopole moments (axis of evil)
- Asymmetry of power between two hemispheres
- The Cold Spot
- Deficit of power in low-l modes (below l=30)

- All confirmed to 3 sigma
- Cosmological origin favored (consistency between different CMB maps)

WMAP cold spot (also in Planck)



SH initials in WMAP satellite data



Minimal inflation:

- 1) a single weakly-coupled neutral scalar field, the inflaton, drives the inflation and generates the curvature perturbation
- 2) with canonical kinetic term
- 3) slowly rolling down featureless potential
- 4) initially lying in a Bunch-Davies vacuum state

- If any one of these conditions is violated, detectable amplitudes of nonGaussianity should have been seen.

$$\langle \Phi(\boldsymbol{k}_1)\Phi(\boldsymbol{k}_2)\Phi(\boldsymbol{k}_3)\rangle = (2\pi)^3\delta^{(3)}(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3)B_\Phi(k_1,k_2,k_3).$$

$$B_\Phi(k_1,k_2,k_3) = f_{\rm NL}F(k_1,k_2,k_3)\,.$$

Primordial nonGaussianities

- If primordial fluctuations are Gaussian distributed, then they are completely characterized by their two-point function, or equivalently by the power spectrum. All odd-point functions are zero.
- If nonGaussian, there is additional info in the higher order correlation functions
- The lowest order statistic that can differentiate is the 3-point function, or bispectrum in Fourier space:

$$\langle \Phi(\mathbf{k}_1)\Phi(\mathbf{k}_2)\Phi(\mathbf{k}_3)\rangle = (2\pi)^3\delta^{(3)}(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)B_\Phi(k_1,k_2,k_3).$$

- Here Phi is comoving curvature perturbation (density pert)

No primordial nonGaussianities in Planck

- Single field models: so small as to be undetectable
- Other models: three shapes (configurations of triangles formed by the three wavevectors)
- Any detection of nonGaussianity would have thrown out all single field models
- Data show no evidence of nonGaussianity, implying single field models work

f_{NL}		
Local	Equilateral	Orthogonal
2.7 ± 5.8	-42 ± 75	-25 ± 39

- Data bound the speed of sound c_s>0.02

Models with NG: f_NL>>1

- Local NG: squeezed triangles, k1<<k2 = k3,
  e.g. multifield models, curvaton
- Equilateral NG, k1=k2=k3, e.g. non-canonical kinetic terms as in k-inflation or DBI inflation, models with general higher-derivative interactions of the inflaton field such as ghost inflation, and models arising from effective field theories
- Folded NG, e.g. single-field models w non-Bunch-Davies vacuum, and modesl with general higher derivative interactions.
- Orthogonal NG, e.g. non-canonical kinetic terms.

No evidence for any of these nonGaussianities in Planck.
Disfavored: EKPYROTIC with exponential potential

Predictions of Single Field Models

- 1) no nonGaussianities
- 2) no running of spectral index of scalar perturbations

- Scalar
- modes
- Tensor

  modes

$$\mathcal{P}_{\mathcal{R}}(k) = A_{\mathrm{s}} \left(\frac{k}{k_*} \right)^{n_{\mathrm{s}} - 1 + \frac{1}{2}\, \mathrm{d}n_{\mathrm{s}}/\mathrm{d}\ln k \ln(k/k_*) + \frac{1}{6}\, \mathrm{d}^2 n_{\mathrm{s}}/\mathrm{d}\ln k^2 (\ln(k/k_*))^2 + \ldots}$$

$$\mathcal{P}_{\mathrm{t}}(k) = A_{\mathrm{t}} \left(\frac{k}{k_*} \right)^{n_{\mathrm{t}} + \frac{1}{2}\, \mathrm{d}n_{\mathrm{t}}/\mathrm{d}\ln k \ln(k/k_*) + \ldots},$$

- Both predictions proven true by Planck

- “With these results, the paradigm of standard single-field inflation has survived its most stringent tests to date”

Four parameters from inflationary perturbations:

I. Scalar perturbations:

amplitude $(\delta\rho/\rho)|_s$ spectral index n_s

II. Tensor (gravitational wave) modes:

amplitude $(\delta\rho/\rho)|_T$ spectral index n_T

Expressed as $r \equiv \frac{P_T^{1/2}}{P_S^{1/2}}$

Inflationary consistency condition: $r = -8n_T$

Plot in r-n plane (two parameters)

Inflation after Planck

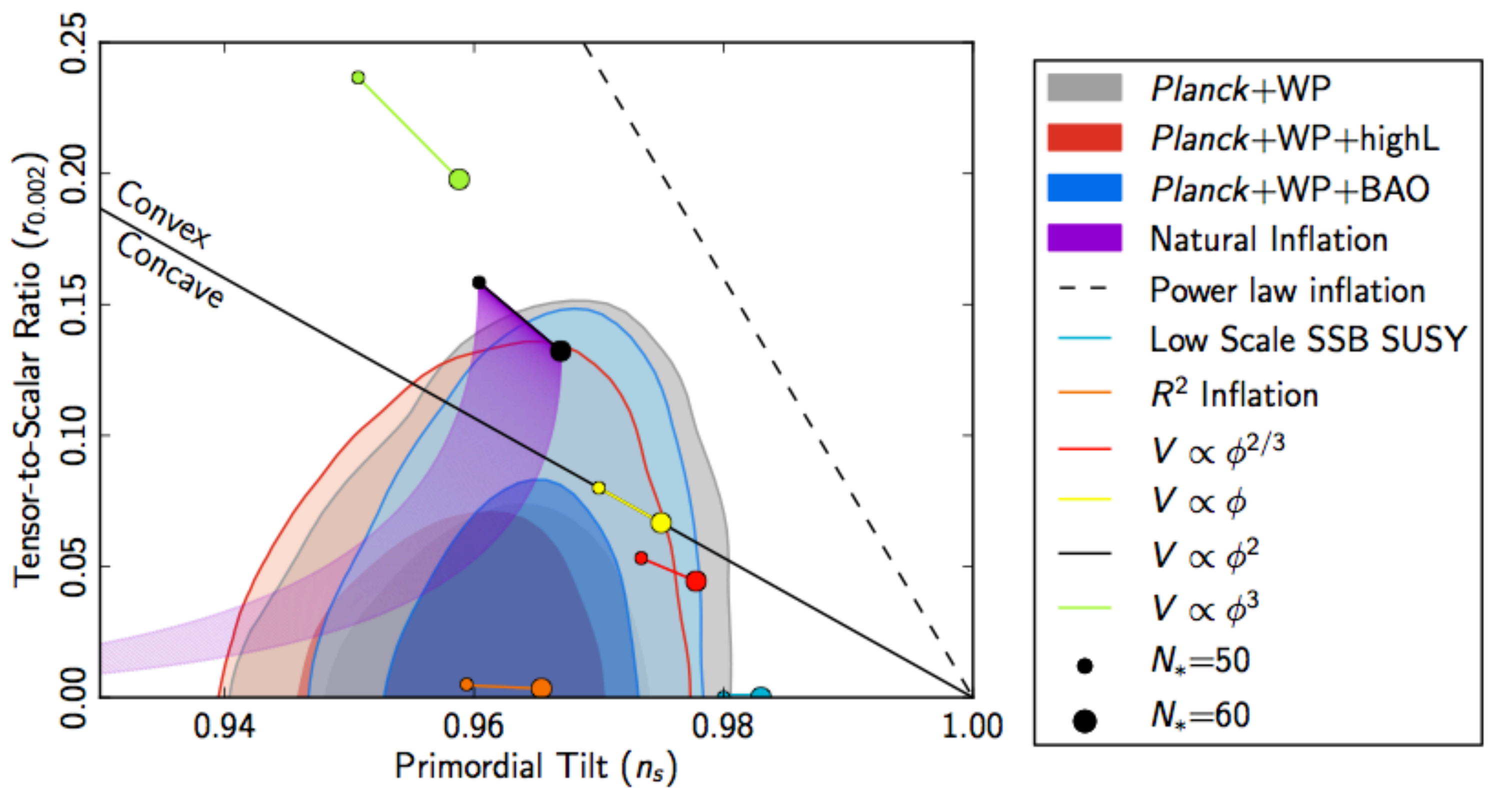
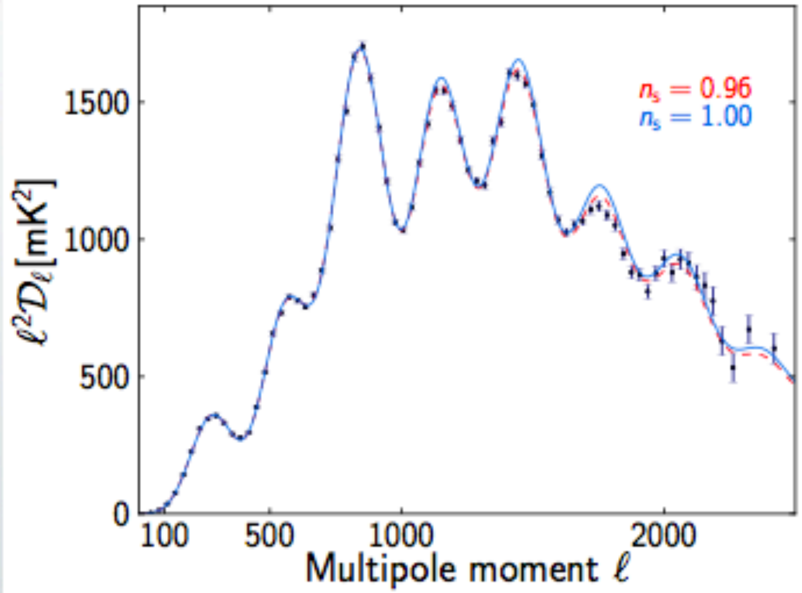


Fig. 1. Marginalized joint 68% and 95% CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets compared to the theoretical predictions of selected inflationary models.

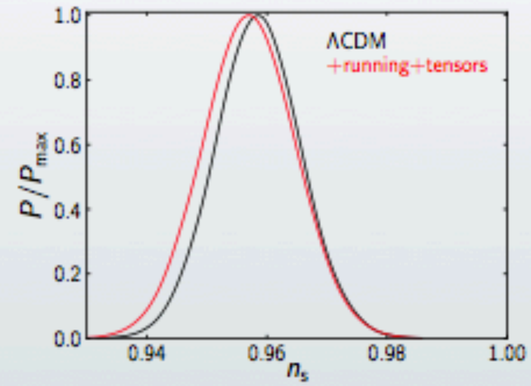
Purple swath is natural inflation model of Freese, Frieman, and Olinto 1990

Extensions to ΛCDM model
Early-Universe physics: ns, dn_s/dk and r



6σ departure from scale invariance

$$n_s = 0.9603 \pm 0.0073$$

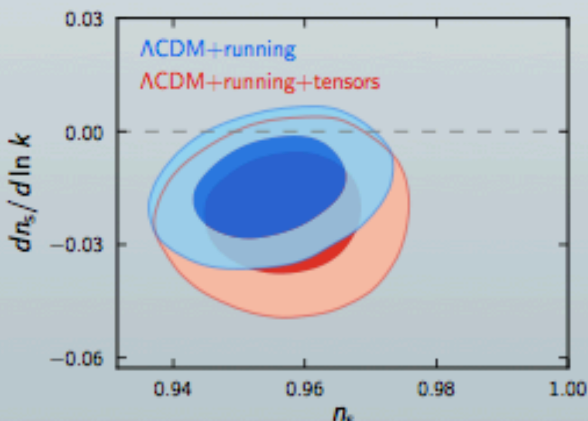


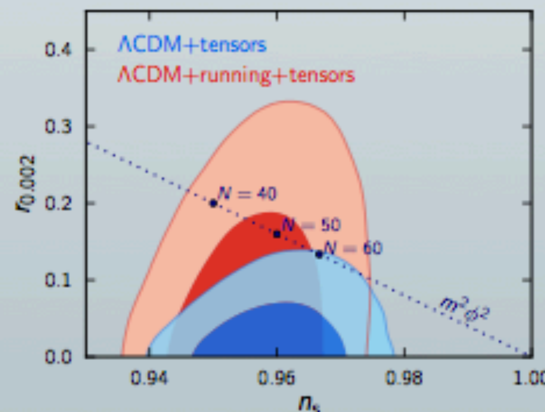
l<50

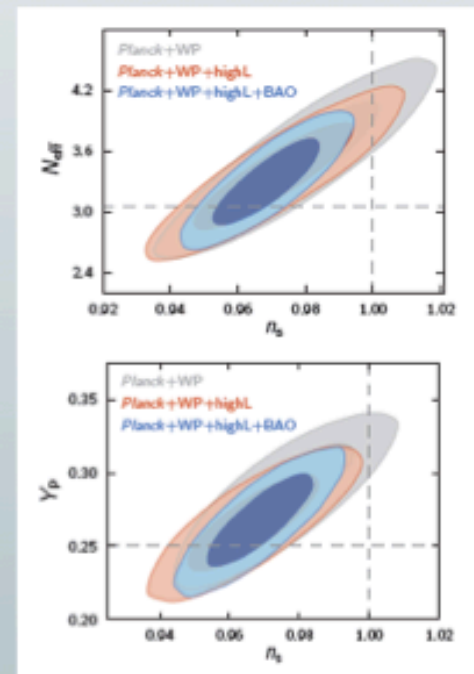
$$dn_s / d\ln k = -0.0134 \pm 0.0090$$

$$r < 0.11 \qquad V_*$$

$$V = (1.94 \times 10^{16} GeV)^4 (r_{0.02} / 0.12)$$







3σ

Slide from Graca Rocha

Natural Inflation: Shift Symmetries

- Shift symmetries (e.g. axionic) protect flatness of inflaton potential

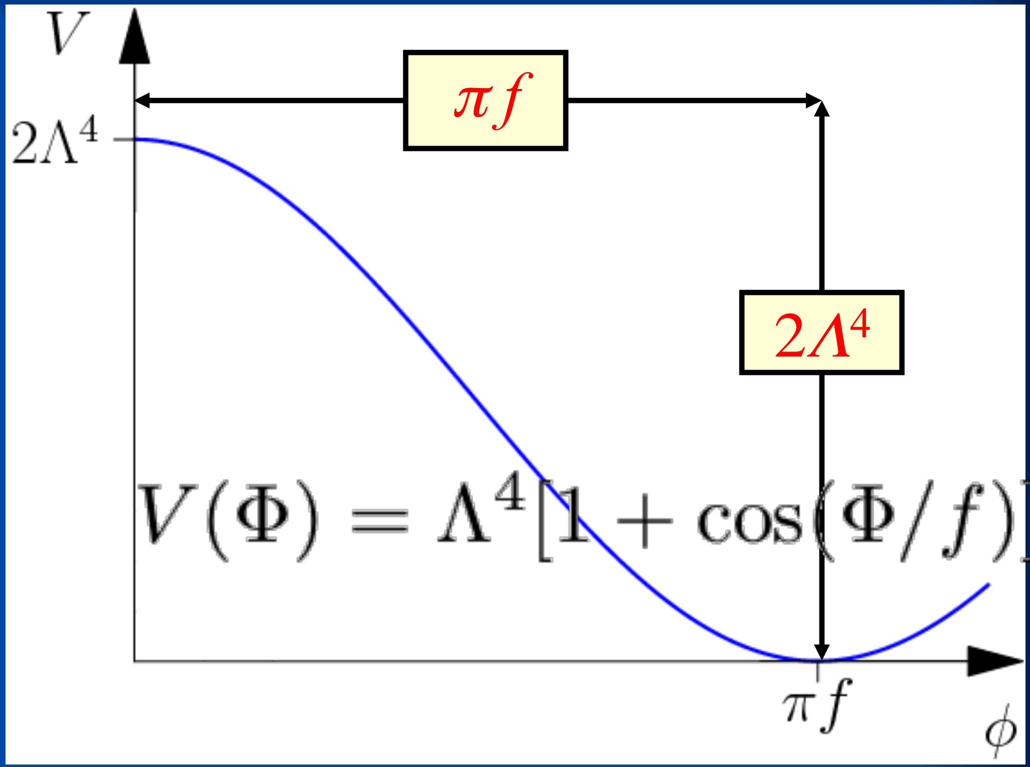
  $\Phi \rightarrow \Phi + \mathrm{constant}$ (e.g. inflaton is Goldstone boson)
- Additional explicit breaking allows field to roll.
- This mechanism, known as natural inflation, was first proposed in

Freese, Frieman, and Olinto 1990;
Adams, Bond, Freese, Frieman and Olinto 1993

Original Natural Inflation

For QCD axion:
$f \sim 10^{12}$ GeV
$\Lambda \sim 100$ MeV

For natural inflation:
$f \sim M_{\rm Pl}$
$\Lambda \sim M_{\rm GUT}$



- Width f :
  Scale of spontaneous symmetry breaking of some global symmetry
- Height Λ:
  Scale at which gauge group becomes strong

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

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

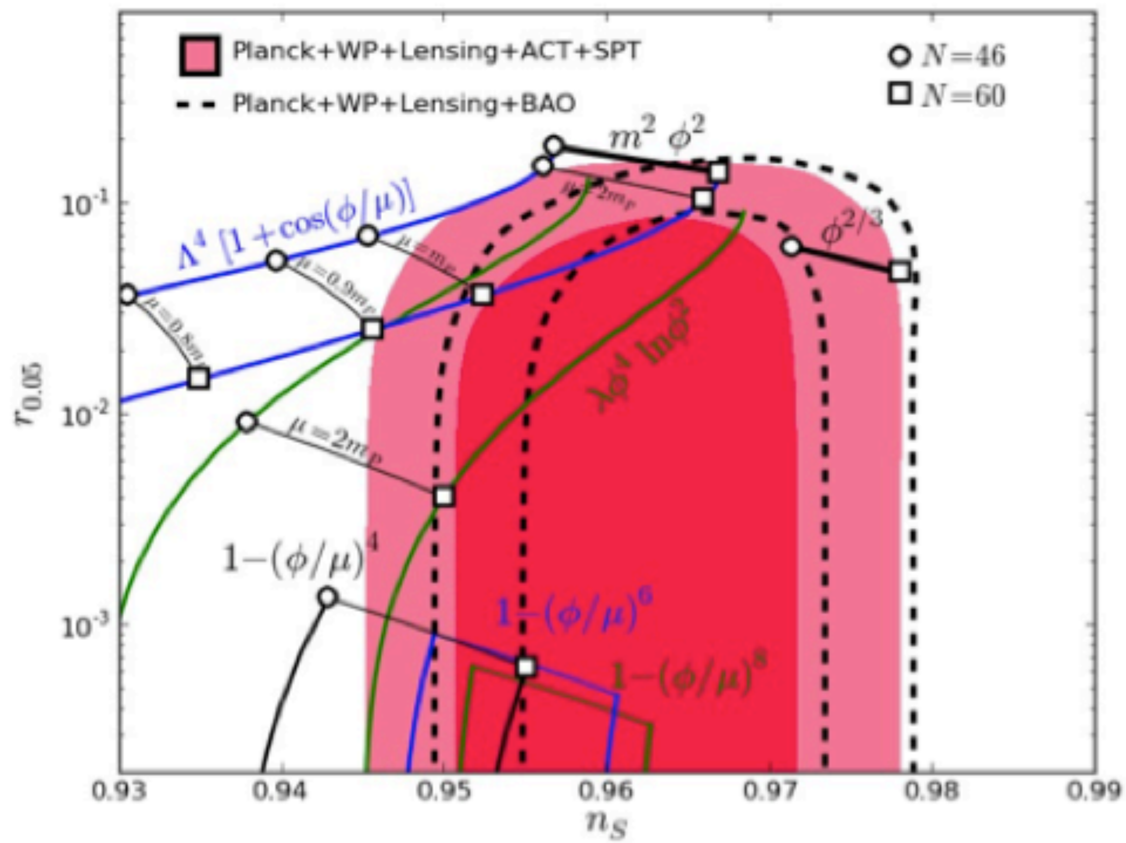
- Gauge symmetry breaking: WHK, Mahanthappa, hep-ph/9512241

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

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

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

Summary: Planck and Natural Inflation



Slide from Will Kinney

A lesson from Planck

- Shift symmetries are a winning mechanism for generating the inflationary potential!

Shift symmetries were the point of natural inflation

Original model had cosine-shaped potential

Today many variants exist

Nice review by Pajer and Peloso

We eagerly await Planck polarization data

- To date: r<0.12 (k=0.002Mpc^-1) at 95% C.L.

The *Planck* constraint on r corresponds to an upper bound on the energy scale of inflation

$$V_* = \frac{3\pi^2 A_s}{2} r M_{\rm pl}^4 = (1.94 \times 10^{16}\ {\rm GeV})^4 \frac{r_*}{0.12}, \qquad (33)$$

at 95% CL. This is equivalent to an upper bound on the Hubble parameter during inflation of $H_*/M_{\rm pl} < 3.7 \times 10^{-5}$. In terms of slow-roll parameters, *Planck*+WP constraints imply $\epsilon_V < 0.008$ at 95% CL, and $\eta_V = -0.010^{+0.005}_{-0.011}$.

- If cosine (original variant of natural inflation) is right, then r >0.02 is predicted (given bounds on n_s)

Summary of Inflation after Planck:

- I. The predictions of inflation are right:

(i) the universe has a critical density

(ii) superhorizon fluctuations

(iii) density perturbation spectrum nearly scale invariant

(iv) Single rolling field models look good: Gaussian perturbations, not much running of spectral index

- II. Data differentiate between models
- -- gravitational wave modes detectable in upcoming polarization experiments
- -- WMAP and Planck rule out many models

-- Natural Inflation (shift symmetries) is good fit to data

Provocative Point: Hints of NonGaussianity in data

- There is nonGaussianity in the Planck data at almost 4 sigma.
- It doesn't correspond to familiar shapes or templates.
- i.e. not characterized well by fNL or from point sources
- Buried deep in the paper
- More work to be done
- Nature might surprise us!

Provocative Questions

- What is the target sensitivity that LSS/CMB surveys should be trying to reach in tests of inflation (e.g. r=0.001, fNL=O(1), curvature = O(10^{-4})? This is a very important question: it's easier for surveys to get funded provided there is a clear target from theory.
- Do we need a CMB *temperature* survey beyond Planck? For CMB polarization, do we need a space telescope, or is ground sufficient?
- Can LSS systematics be controlled sufficiently so that LSS reaches its full potential?

Large Scale Structure

- Provides complementary and/or competing info w/ CMB
- Different temporal (later) and spatial (smaller) scales
- LSS has more modes and in principle more info:
  - CMB is 2D
  - LSS is 3D
- Yet: can systematic errors be controlled?
- LSS has great potential: can it be tapped?

Provocative Questions II

- Can a convincing case be made that inflationary acceleration is somehow related to the present-day acceleration of the universe?
- One can fit any observational data with inflation theory - true or false
- From the theory side, should we be trying to get a "prior" for measured parameter distribution/values? Is this even possible?