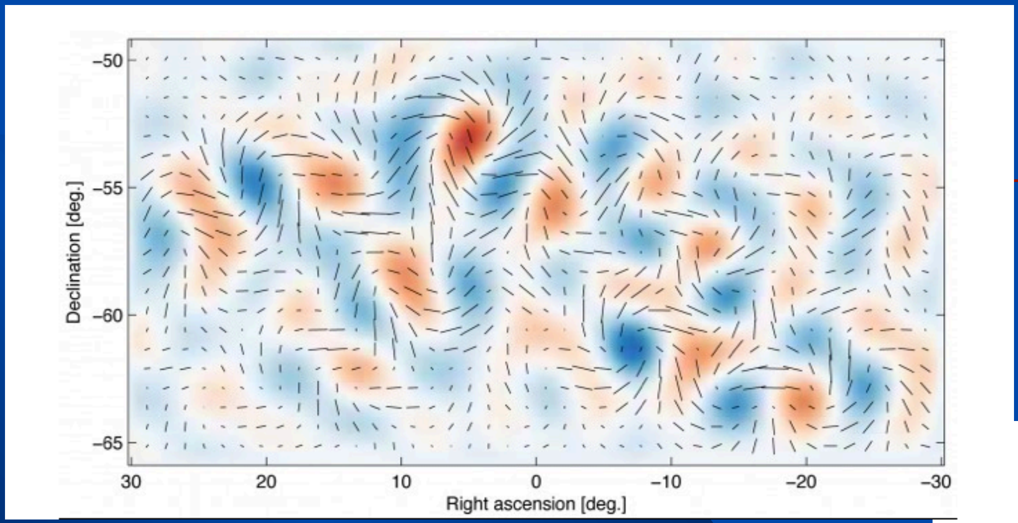
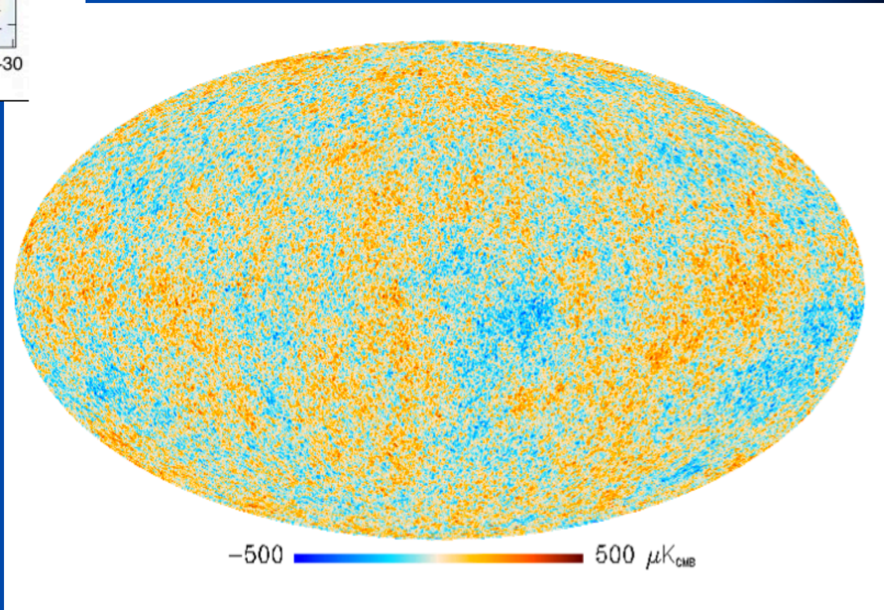
WHAT WILL BE THE NEXT GREAT DISCOVERY IN COSMOLOGY?





Katherine Freese
University of Michigan

We just had a major discovery!

- Primordial gravity waves in the BICEP2 detector : quantum fluctuations in inflation should produce gravitational waves that would appear as B-modes in polarization data. BICEP2 reported the first discovery of these gravity waves. SMOKING GUN FOR INFLATION.
- The earliest probe of the Universe, back to the scale of Grand Unification, almost back to the Big Bang.
- First direct detection of gravity waves predicted by Einstein

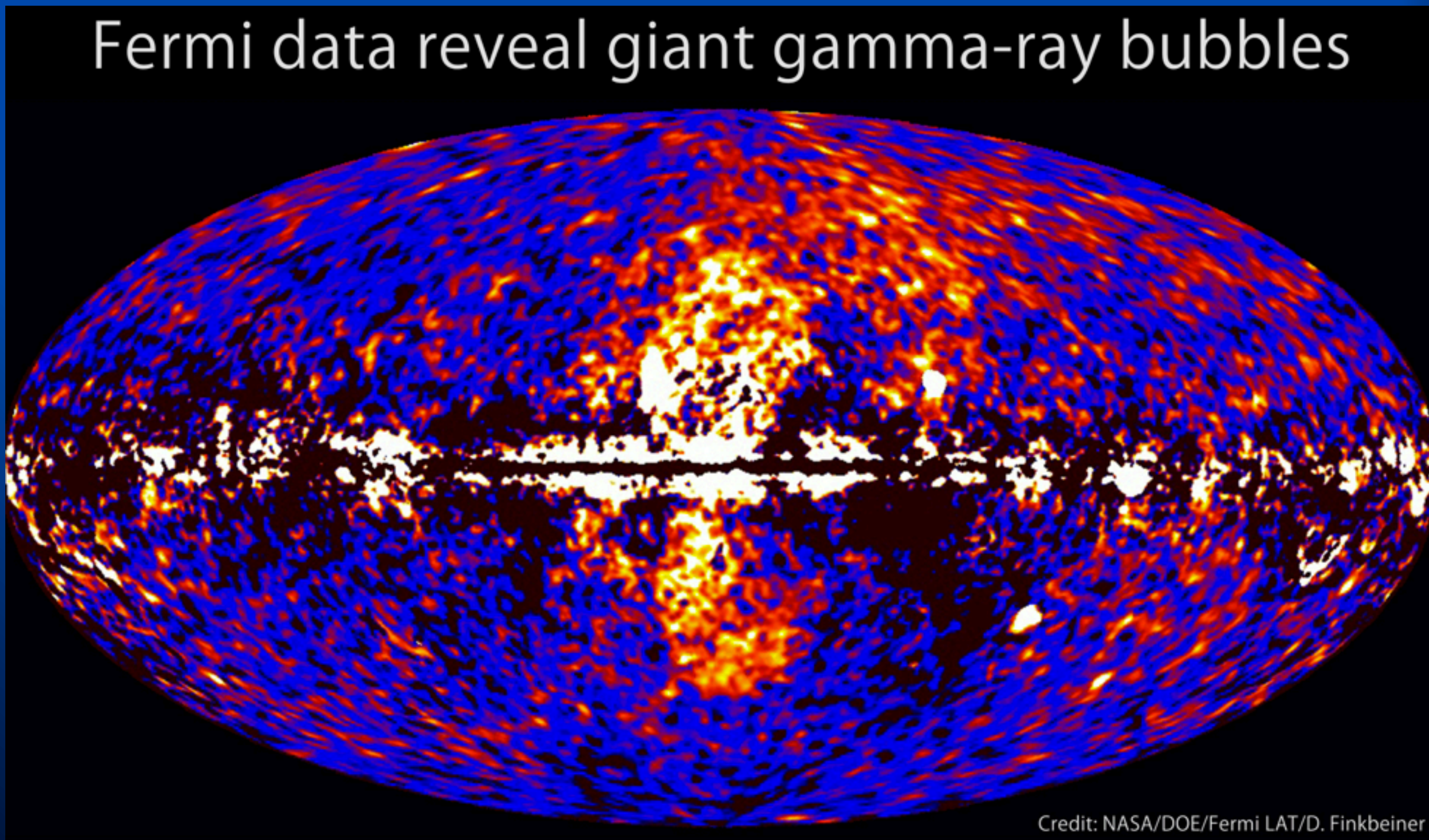
We expect another one very soon:

The identity of the dark matter particle.

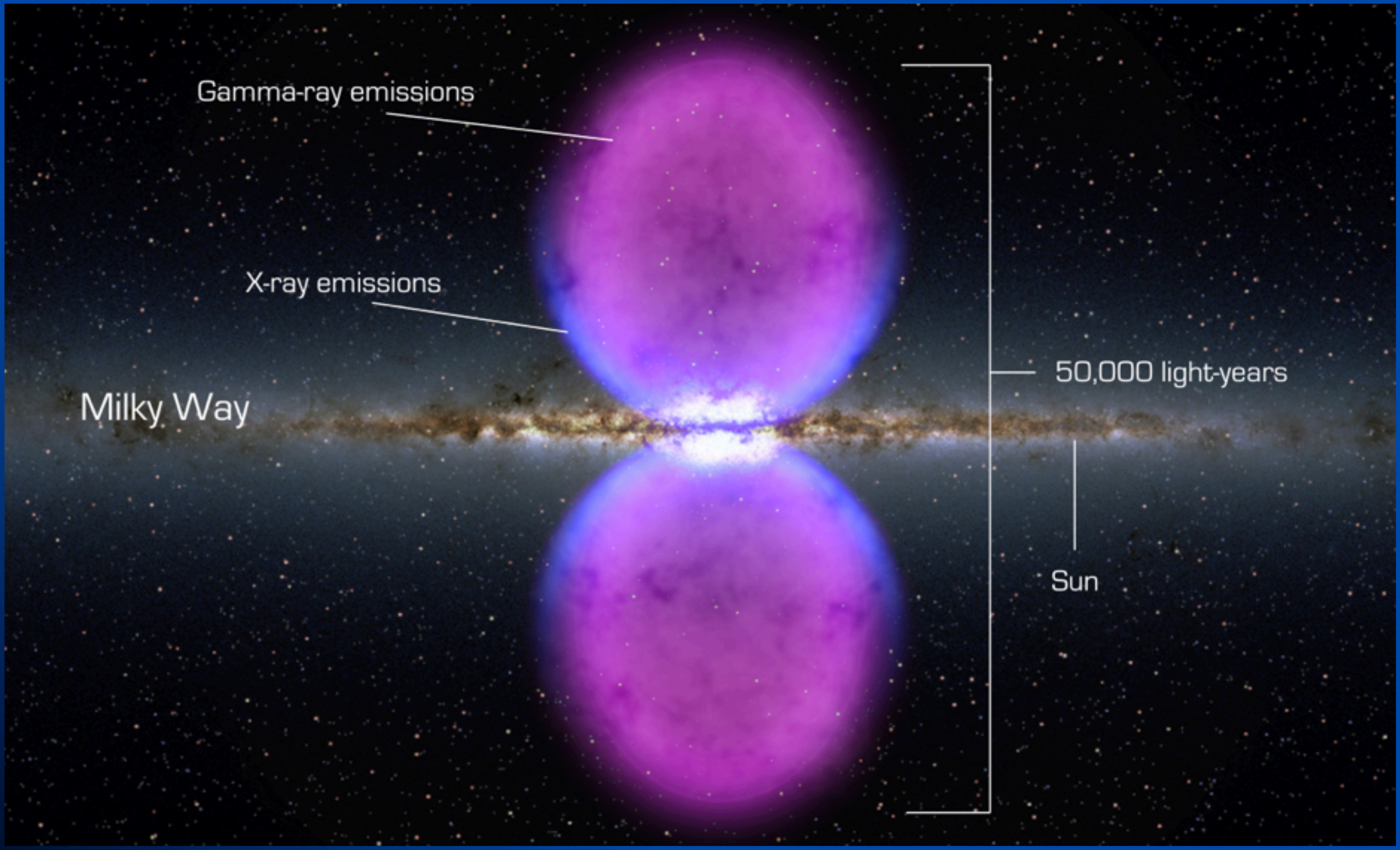
Current Hints of Dark Matter

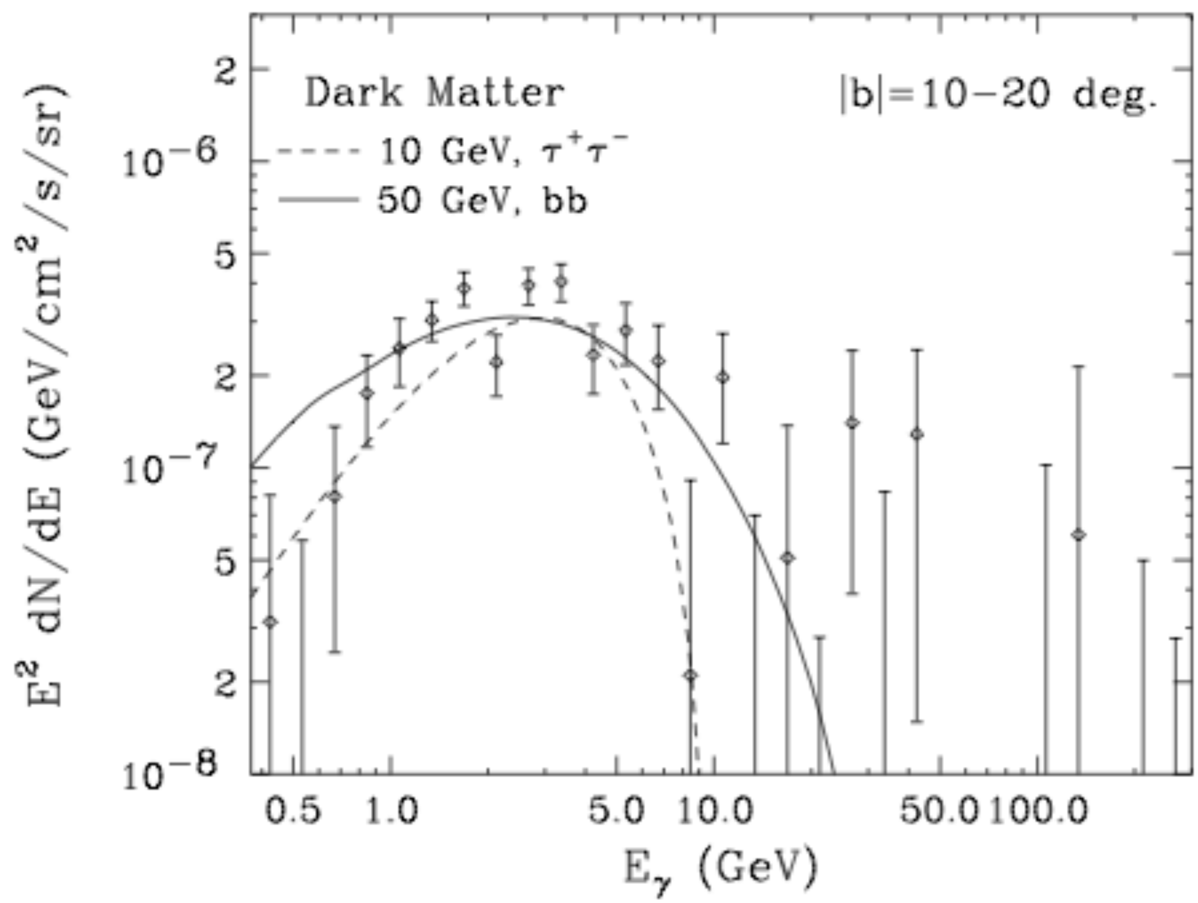
- 1) Gamma Rays from Galactic Center due to DM annihilation (around 30 GeV)
- 2) Sterile Neutrinos (17keV)

Dark Matter at Galactic Center annihilating to Gamma Rays?



Fermi Bubble





Dark Matter
|b|=10−20 deg.
10 GeV, τ⁺τ⁻
50 GeV, bb
E² dN/dE (GeV/cm²/s/sr)
E_γ (GeV)

Possible Detections

two different X-ray astronomy groups see a **3.5 keV** line in **clusters of galaxies** and in M31, and this line is ***consistent with a dark matter decay origin***, corresponding to a **7 keV rest mass sterile neutrino** with vacuum mixing with active neutrinos $\sin^2 2\theta = (2 - 20) \times 10^{-11}$

E. Bulbul, M. Markevitch, A. Foster, R. Smith, M. Lowenstein, S. Randall
"*Detection of an unidentified emission line in the stacked X-ray spectrum of Galaxy Clusters*" arXiv:1402.2301

A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi, J. Franse
"An unidentified line in the X-ray spectrum of the Andromeda galaxy and Perseus galaxy cluster" arXiv:1402.4119

Status of Inflation in Light of Data

- **I. The predictions of inflation are right:**

  (i) the universe is flat with a critical density $\Omega = 1$

  (ii) superhorizon fluctuations

  (iii) density perturbation spectrum nearly scale invariant

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

  (v) GRAVITY WAVES

- **II. Data differentiate between models**

- -- each model makes specific predictions for density perturbations and gravity modes
- -- WMAP, Planck and BICEP2 rule out most models

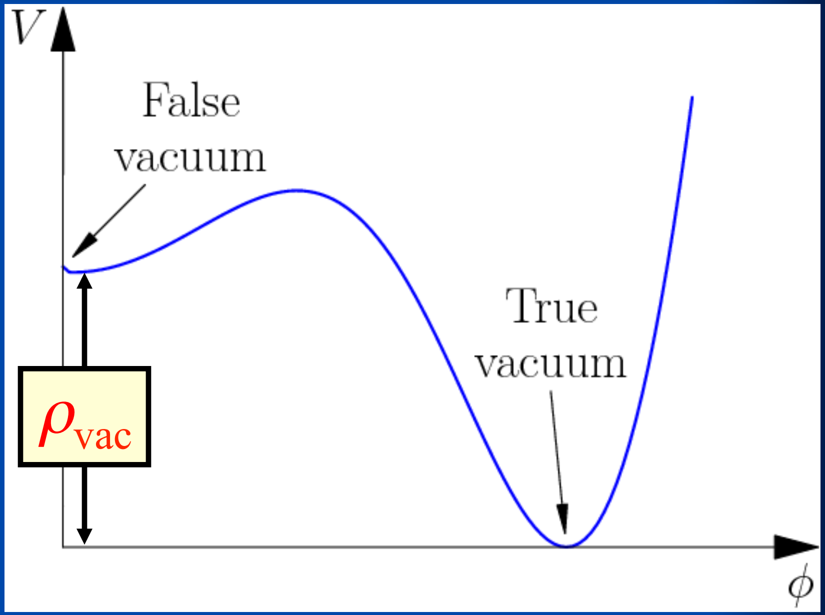
  -- **Natural Inflation** (shift symmetries) is great fit to data

WHY INFLATION?

- Cosmological Puzzles unresolved by standard Hot Big Bang:
- 1) Large-scale ‘smoothness’ -- homogeneity and isotropy
- 2) flatness and oldness
- 3) GUT magnetic monopoles

- The idea of inflation was proposed to resolve these puzzles
- BONUS: causal generation of density fluctuations required for galaxy formation

Basic Mechanism of Inflation



- The universe resides in a false vacuum for a long time, either trapped by a barrier or rolling along flat potential

- The vacuum energy dominates over matter and radiation
  $\Rightarrow$ de Sitter-like expanding universe

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho_{\text{vac}} = \text{constant}$$

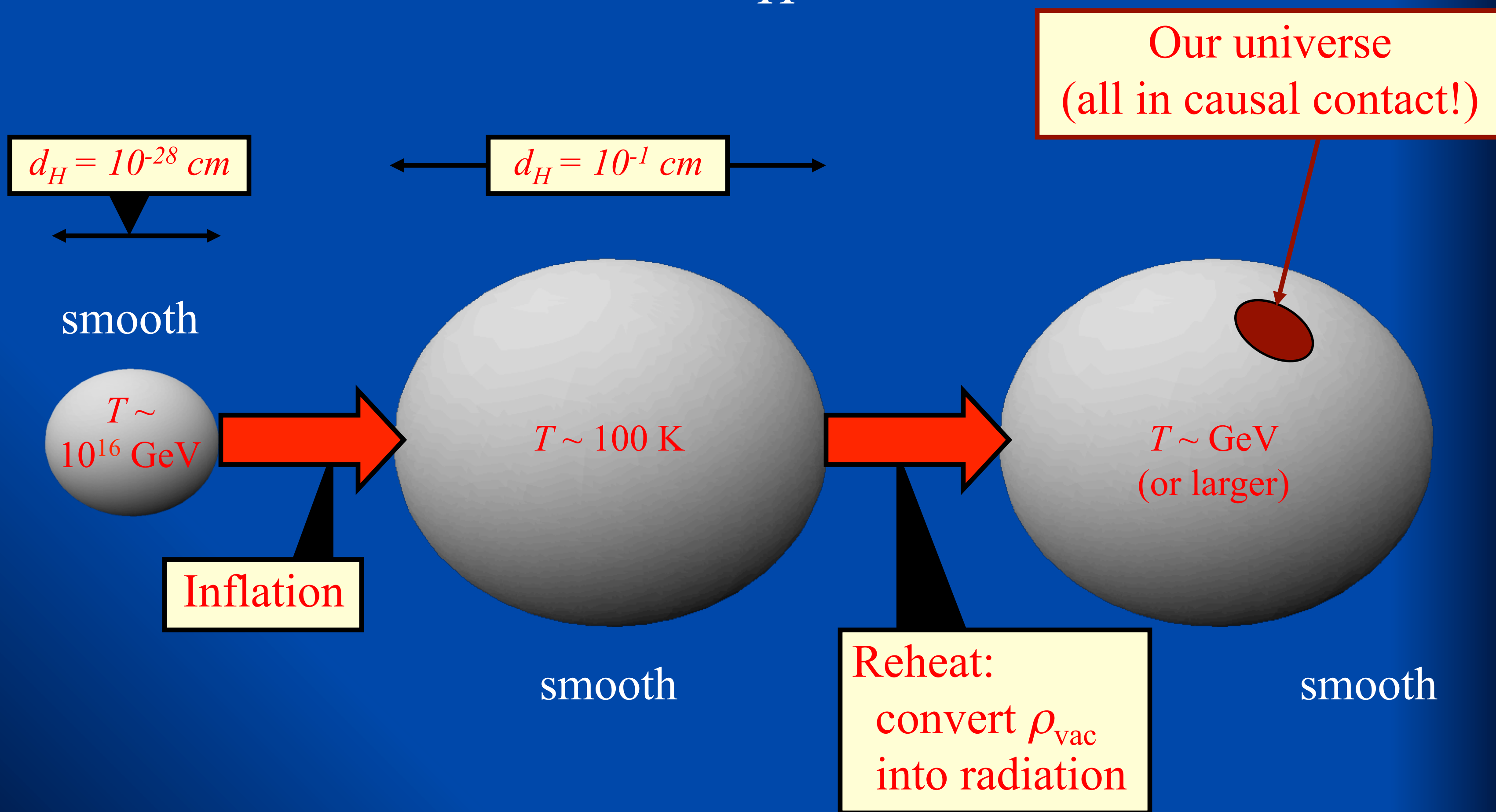
$$\text{solution}: \quad a \sim e^{Ht}, \quad H = \left[\frac{8\pi G}{3}\rho_{\text{vac}}\right]^{1/2}$$

- Enough inflation to solve problems:

$$a_{\text{end}} = a_{\text{begin}} \times 10^{27} = a_{\text{begin}} \times e^{65}$$

Horizon Volume

$$d_H = ct$$



Inflation Resolves Cosmological Problems

- Horizon Problem (homogeneity and isotropy): small causally connected region inflates to large region containing our universe
- Flatness Problem $k/a^2 \rightarrow \text{small}$ $\Omega \rightarrow 1$
- Monopole Problem: monopoles inflated away (outside our horizon)
- BONUS: Density Perturbations that give rise to large scale structure are generated by inflation

Rolling Models of Inflation

Linde (1982)
Albrecht & Steinhardt (1982)

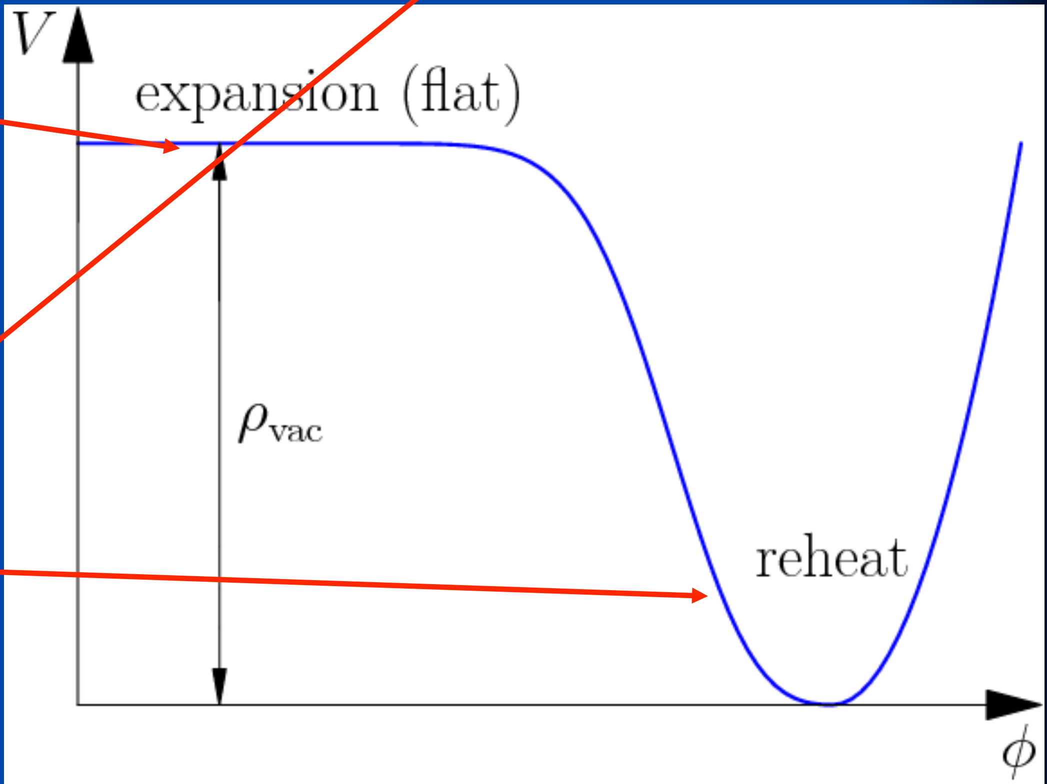
- Equation of motion:

$$\ddot{\phi} + 3H\dot{\phi} + \Gamma\dot{\phi} + V'(\phi) = 0$$

- Flat region:
  - *V* almost constant
  - ρ_{vac} dominates energy density

$$\rightarrow a \approx a_i \, e^{Ht}$$

- Decay of ϕ:
  - Particle production
  - Reheating



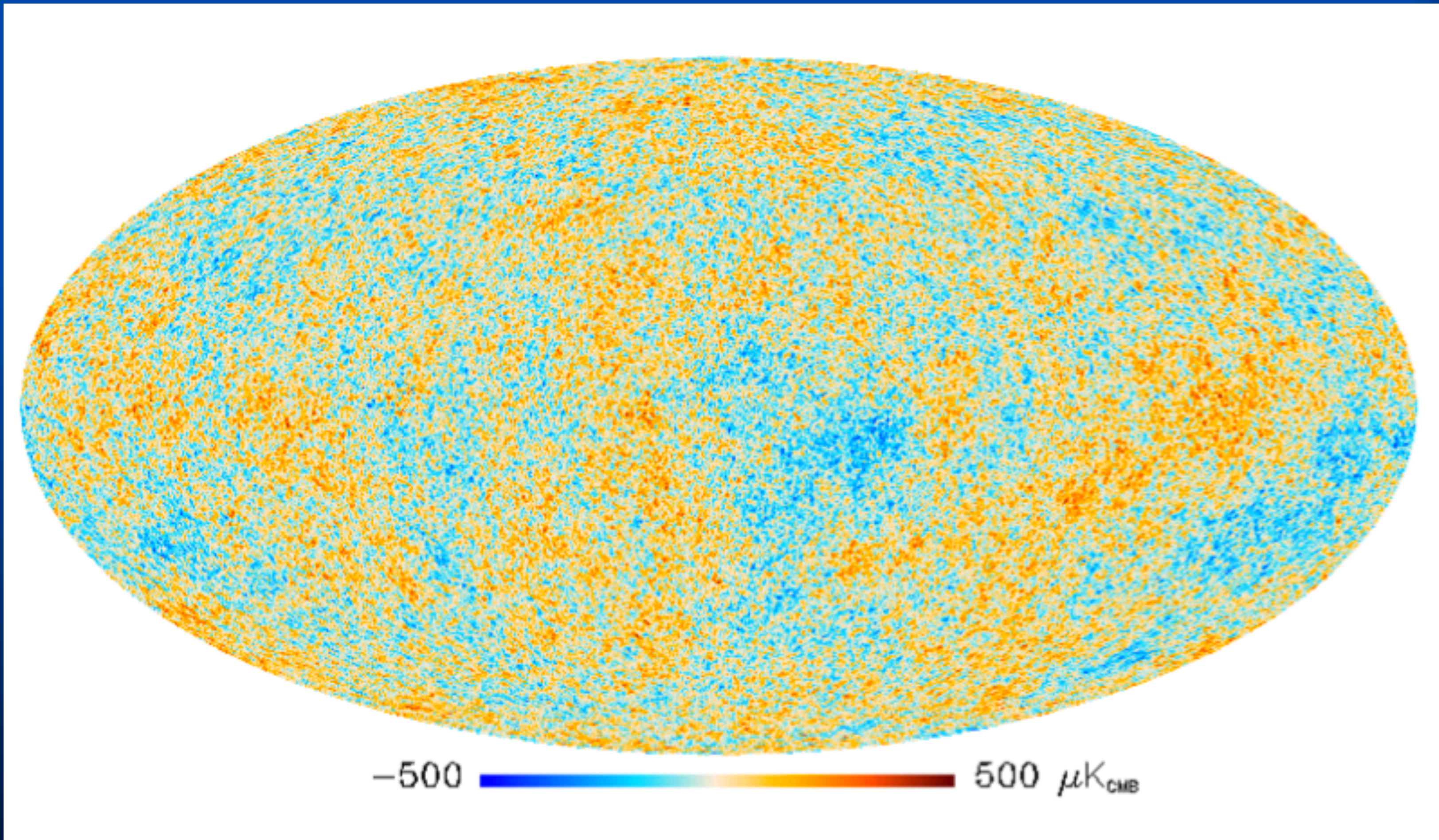
From Theory to Observation: Predictions of Inflation

- 1) flat universe: $\Omega = 1$
- 2) Spectrum of density perturbations:

$$|\delta_k|^2 \propto k^n, \; n \sim 1$$

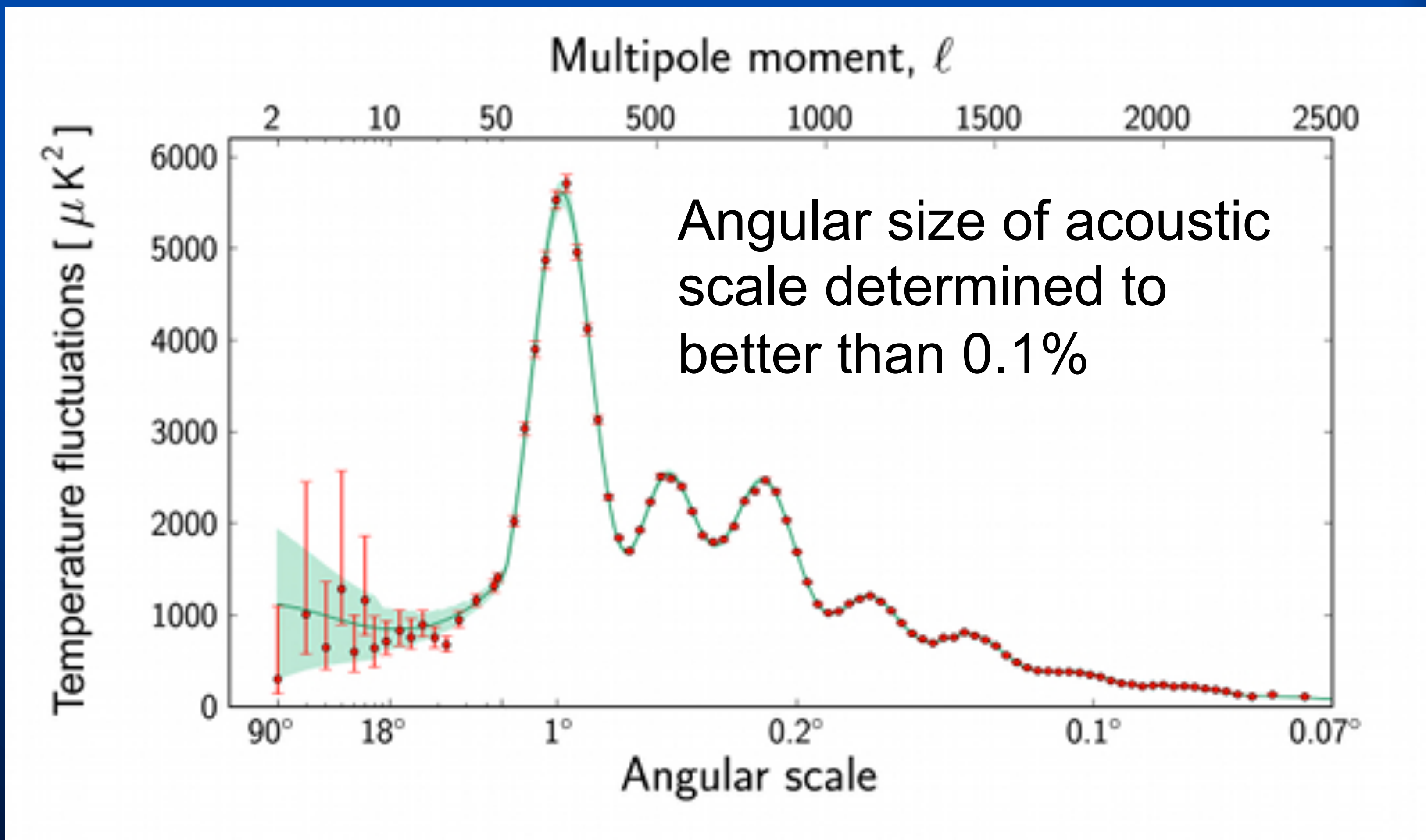
- 3) gravitational wave modes
- Individual models make specific predictions.
- Can test inflation as a concept and can differentiate between models.

The Universe according to Planck



Planck Data

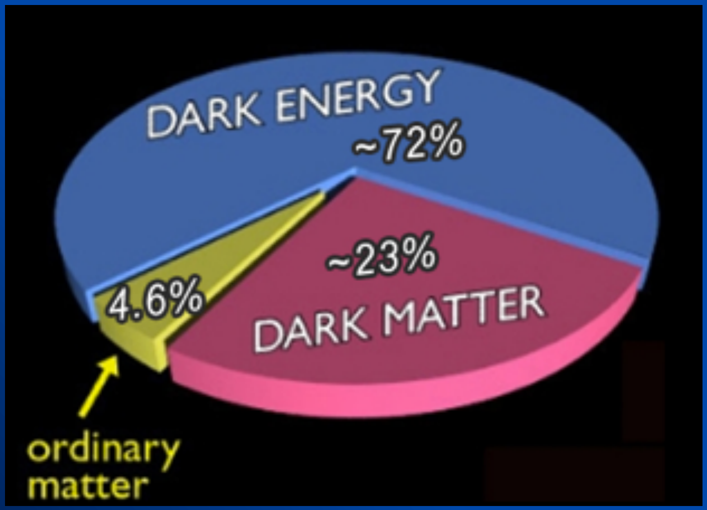
$$\Omega = 1$$

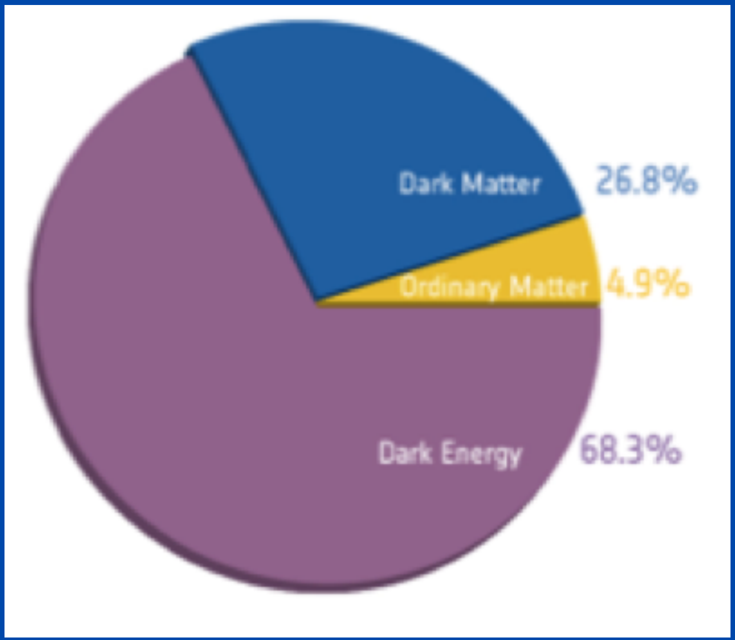


Seven acoustic peaks

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).

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

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

Cosmological Parameters from Planck

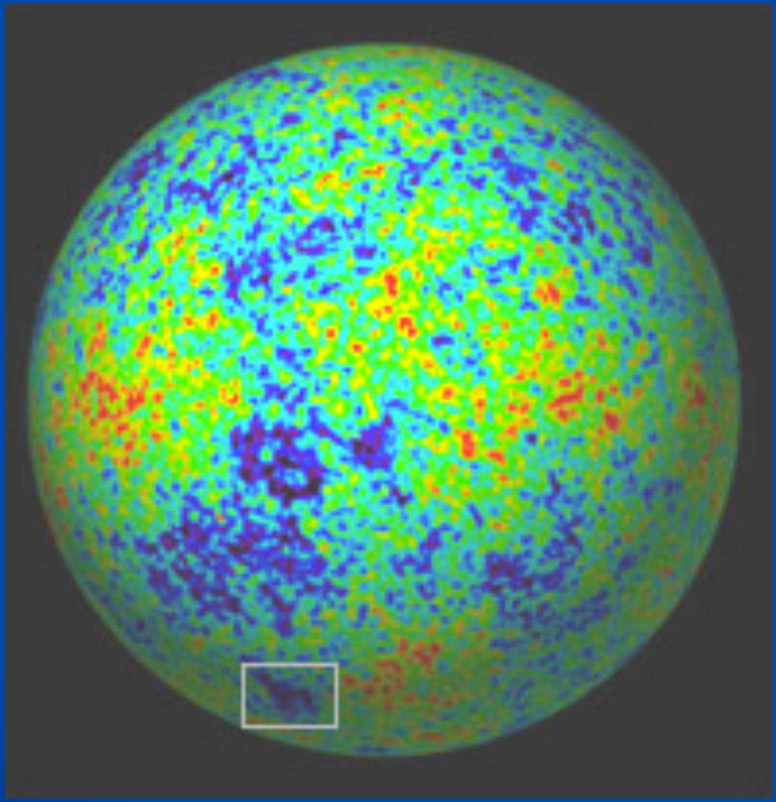
Parameter	*Planck* (CMB+lensing) Best fit	*Planck* (CMB+lensing) 68 % limits	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 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		

Weird Anomalies of WMAP hold up

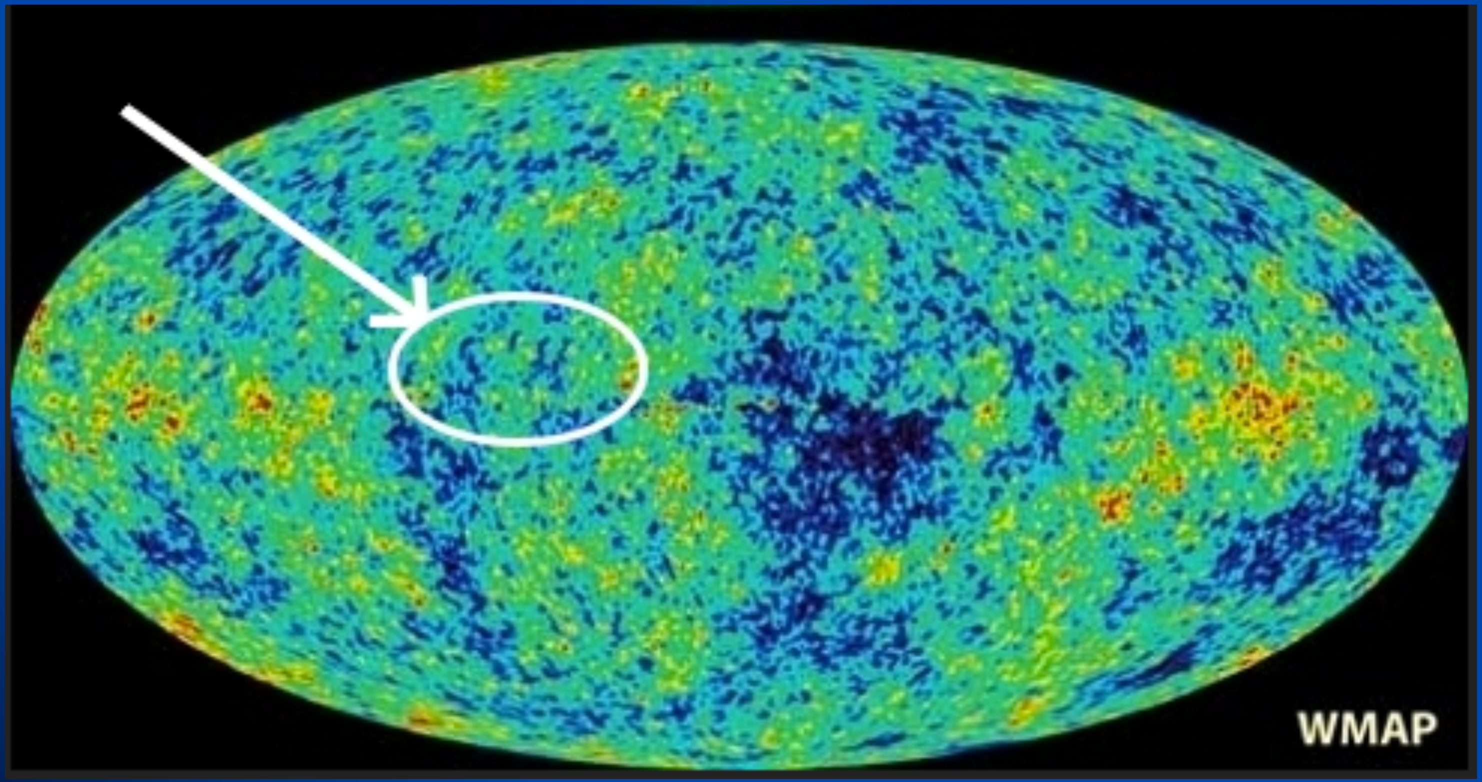
- Alignment between quadrupole and octopole moments (axis of evil)
- Asymmetry of power between two hemispheres
- The Cold Spot
- Deficit of power in low-l modes (below l=30)

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

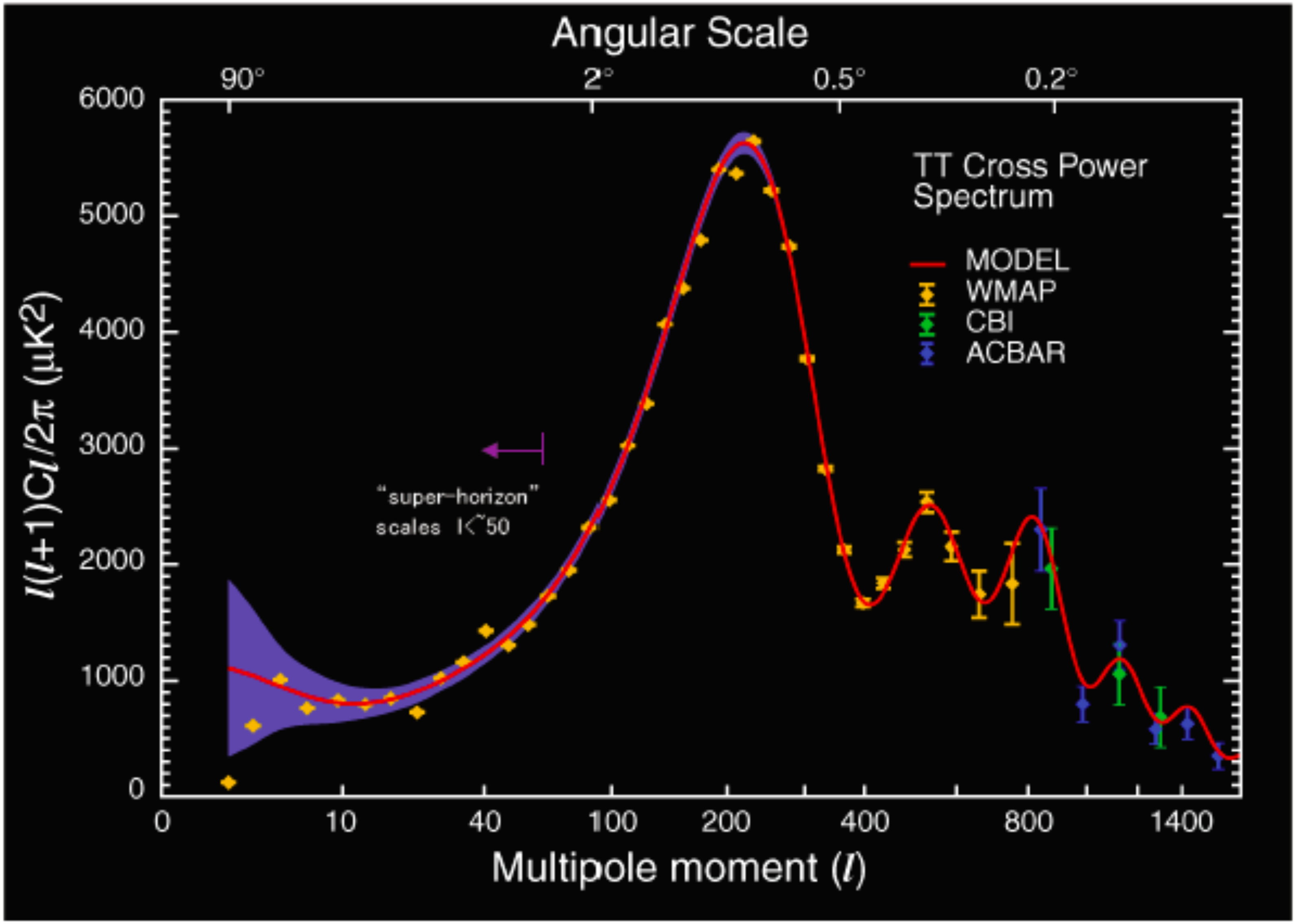
WMAP cold spot (also in Planck)



SH initials in WMAP satellite data

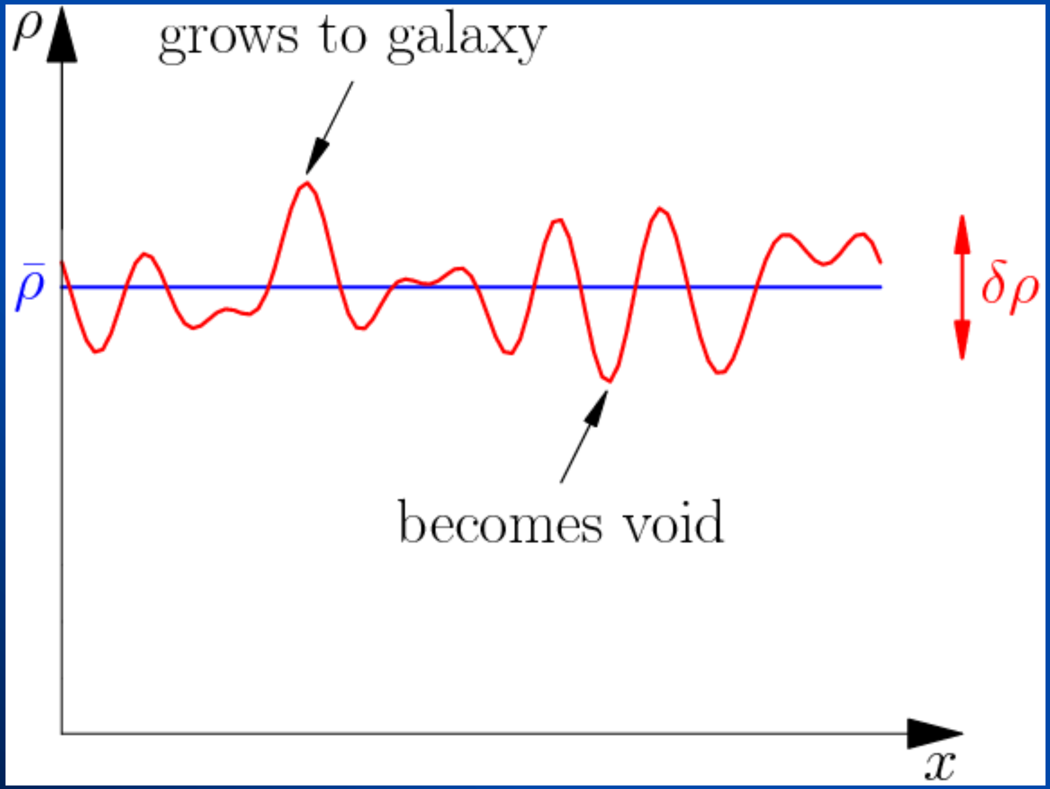


PREDICTION OF INFLATION: SUPERHORIZON MODES



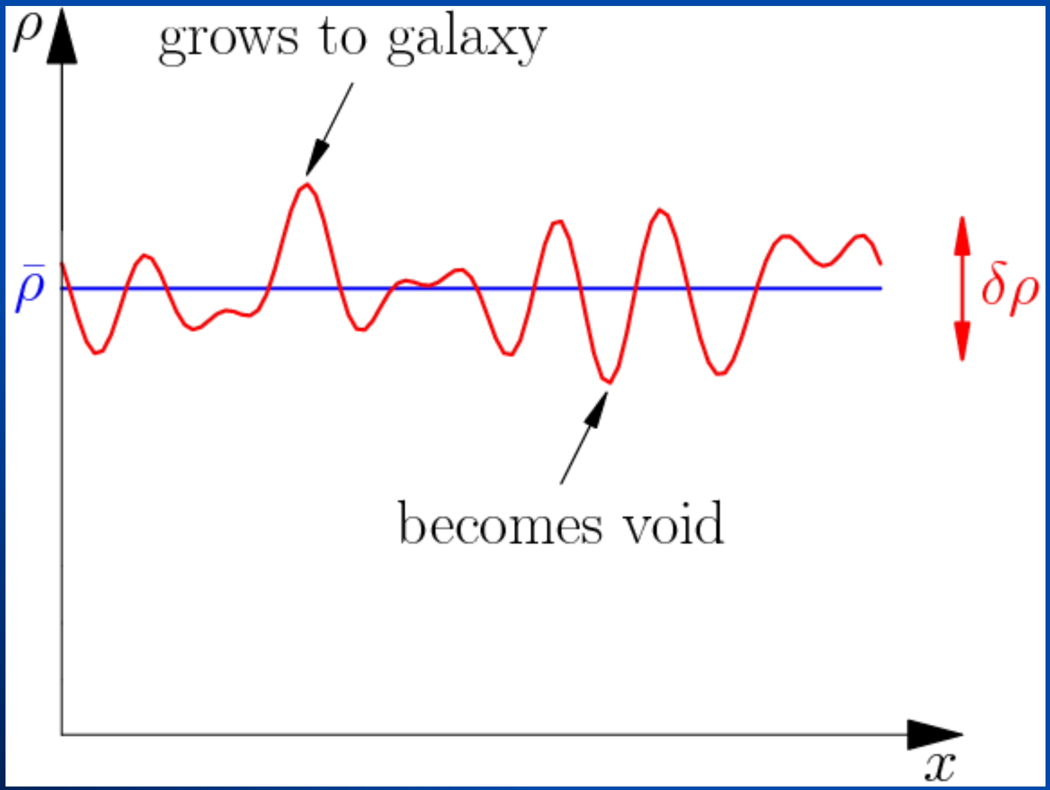
Prediction 2 of Inflation: Density Fluctuations

- Density fluctuations are produced in rolling models of inflation $\delta\rho/\rho$
  - Origin: quantum fluctuations $\langle \Delta\phi^2 \rangle \sim H / 2\pi$



Density Fluctuations

- Different regions of the universe start at different values of ϕ, take different times to reach bottom
  $\Rightarrow$ end at different energy densities



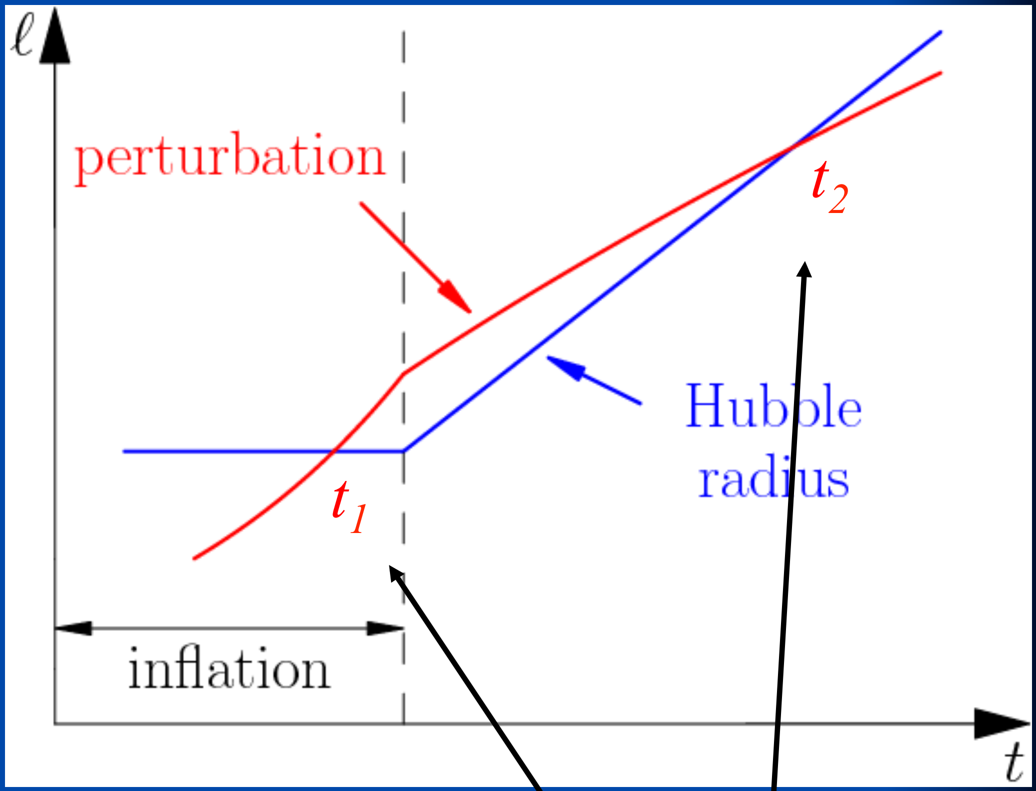
Density Perturbations

Hubble radius

$$\ell_H \sim \frac{1}{H} \sim \begin{cases} \text{constant} & \text{during inflation} \\ t & \text{post inflation} \end{cases}$$

Perturbation

$$\lambda_{\text{pert}} \sim \begin{cases} e^t & \text{during inflation} \\ t^{2/3} & \text{post inflation} \end{cases}$$



Two horizon crossings

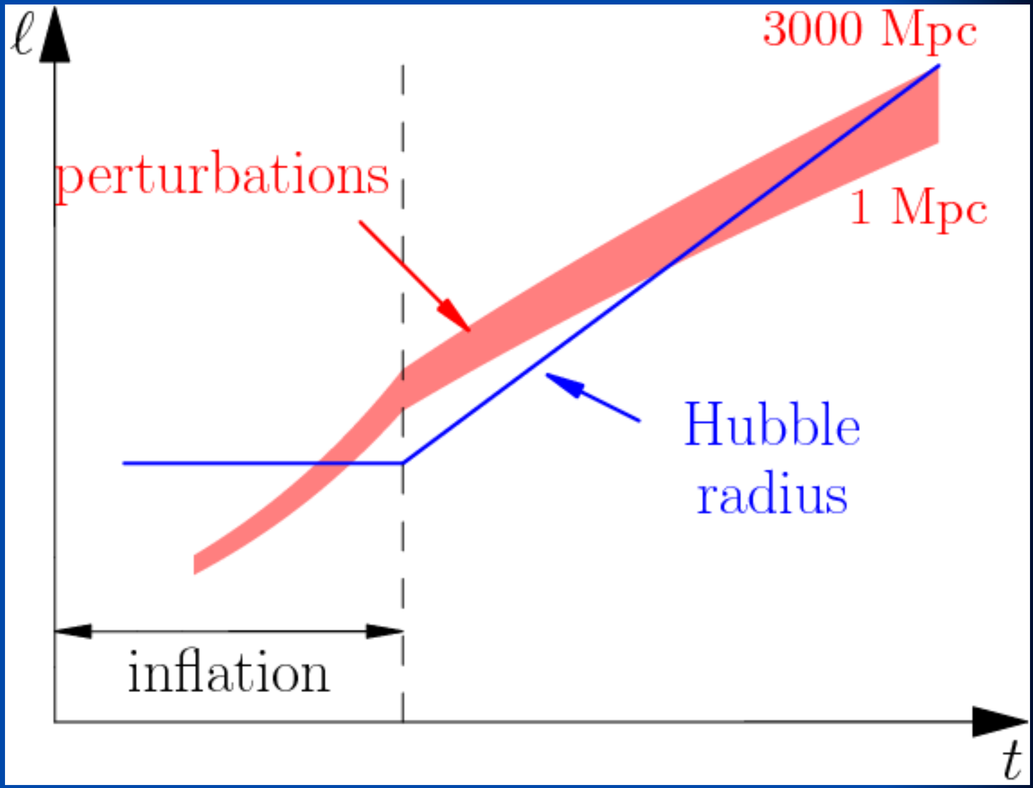
Causal microphysics before t_1 describes density perturbations at t_2

$$\left.\frac{H^2}{\dot{\phi}}\right|_{t_1} = \left.\frac{\delta\rho}{\rho}\right|_{t_2}$$

Density Perturbations

Scales of structure in Universe:

- Distance between galaxies
  ~ 1 Mpc
- Horizon size (size of our observable universe)
  ~ 3000 Mpc



Density Perturbations

Lead to test of inflation theory:

- Must match amplitude of observations

$$\frac{\delta\rho}{\rho} \sim \frac{\delta T}{T} \sim 10^{-5}$$

- Must match spectrum of observations (amplitude on all length scales)

Spectrum of Perturbations

- Fourier Transform $$\frac{\delta\rho}{\rho} \xrightarrow[F.T.]{} \delta_k$$
- Power Spectrum $$P_k = |\delta_k|^2 \sim k^n$$
  - *n* = 1: equal power on all scales
    (when perturbations enter the horizon)
    Harrison-Zel'dovich-Peebles-Yu
  - *n* < 1: extra power on large scales

Spectrum of Perturbations

- Power Spectrum $P_k = |\delta_k|^2 \sim k^n$

- During inflation, *H* and dϕ/d*t* vary slowly

$$\frac{\delta\rho}{\rho}\text{(when entering horizon)} = \frac{H^2}{\dot{\phi}}\text{(exiting horizon during inflation)}$$

  ~ same on all scales

- Predicts *n* ~ 1: CORRECT

- Precise predictions of *n* in different models leads to test of models. It's found that n<1 and the exact number is important.

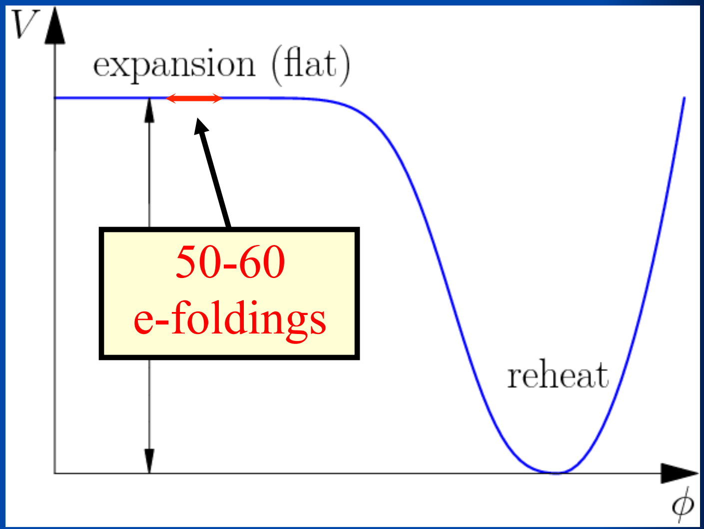
Spectrum of Perturbations

- Total number of inflation e-foldings $N_{tot} \geq 60$

- Spectrum of observable scales is produced ~ 50 – 60 e-foldings before the end of inflation

  - 50: later during inflation
    → smaller scales (~1 Mpc)

  - 60: earlier during inflation
    → larger scales (~3000 Mpc)



Prediction 2 of inflation is confirmed

- Multiple data sets (WMAP, large scale structure, etc) confirm n is near 1.
- More detail shown in a minute to differentiate between models
- Best fit to Planck + hi L + BAO:
- n_s = 0.9608 +- 0.0054
- Pure scale invariant ruled out to 5 sigma

Cosmological Parameters from Planck

	Planck (CMB+lensing)		*Planck*+WP+highL+BAO	
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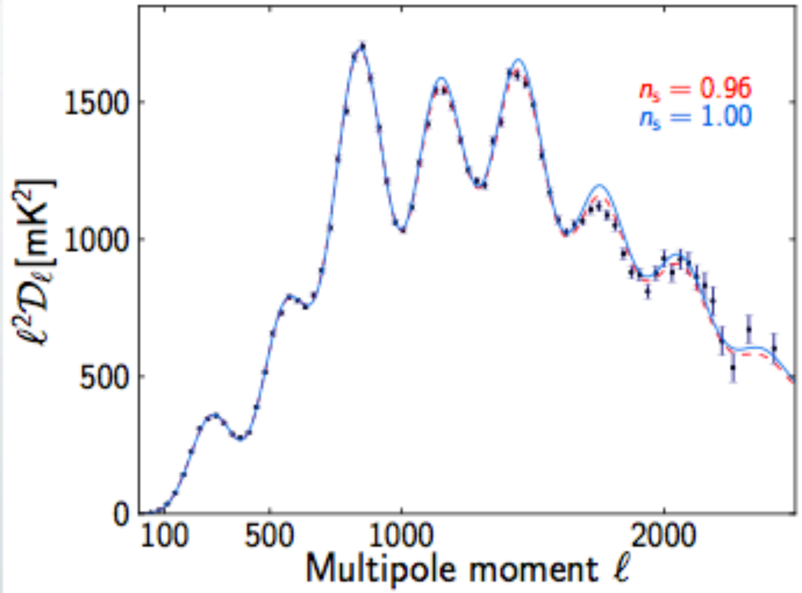
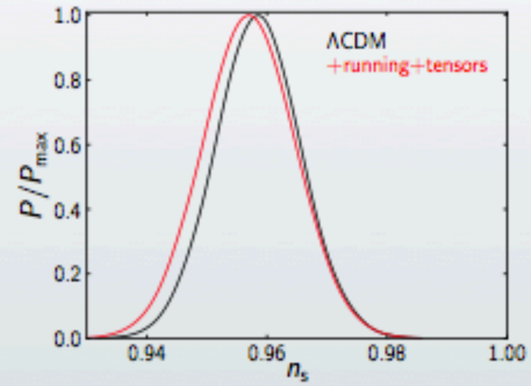
r_{drag}	147.74	147.70 ± 0.63	147.611	147.68 ± 0.45
$r_{drag}/D_V(0.57)$	0.07207	0.0719 ± 0.0011		

Extensions to ΛCDM model
Early-Universe physics: ns, dn$_s$/dk and r



6σ departure from scale invariance

$$n_s = 0.9603 \pm 0.0073$$

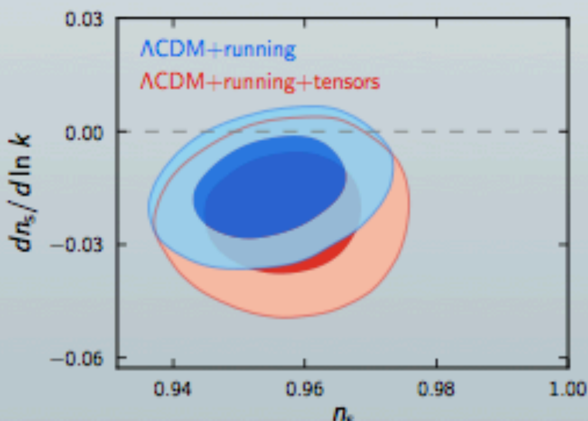


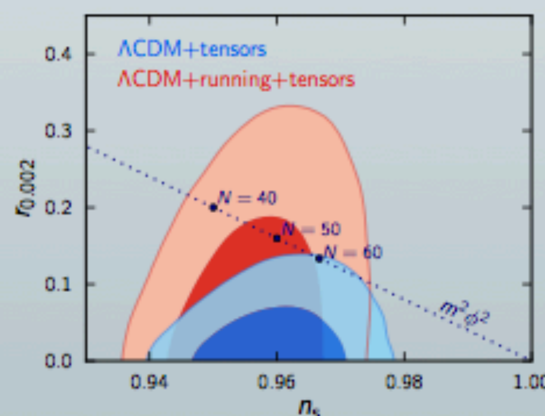
l<50

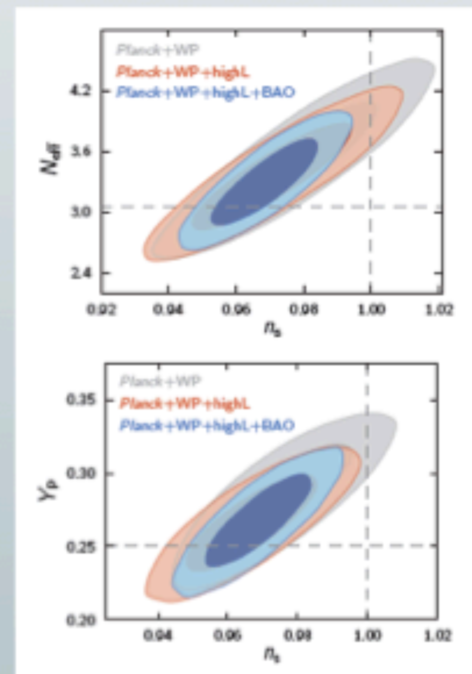
$$dn_s / d\ln k = -0.0134 \pm 0.0090$$

$$r < 0.11 \qquad V_*$$

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







3σ

Slide from Graca Rocha

Prediction 3 of Inflation

Existence of gravitational wave perturbations (tensor modes) with amplitude

$$P_{\mathrm{T}}^{1/2} = \frac{H}{2\pi}.$$

Perturbations

Field perturbations:

$$\phi = \phi_0 + \delta\phi$$

Metric perturbations:

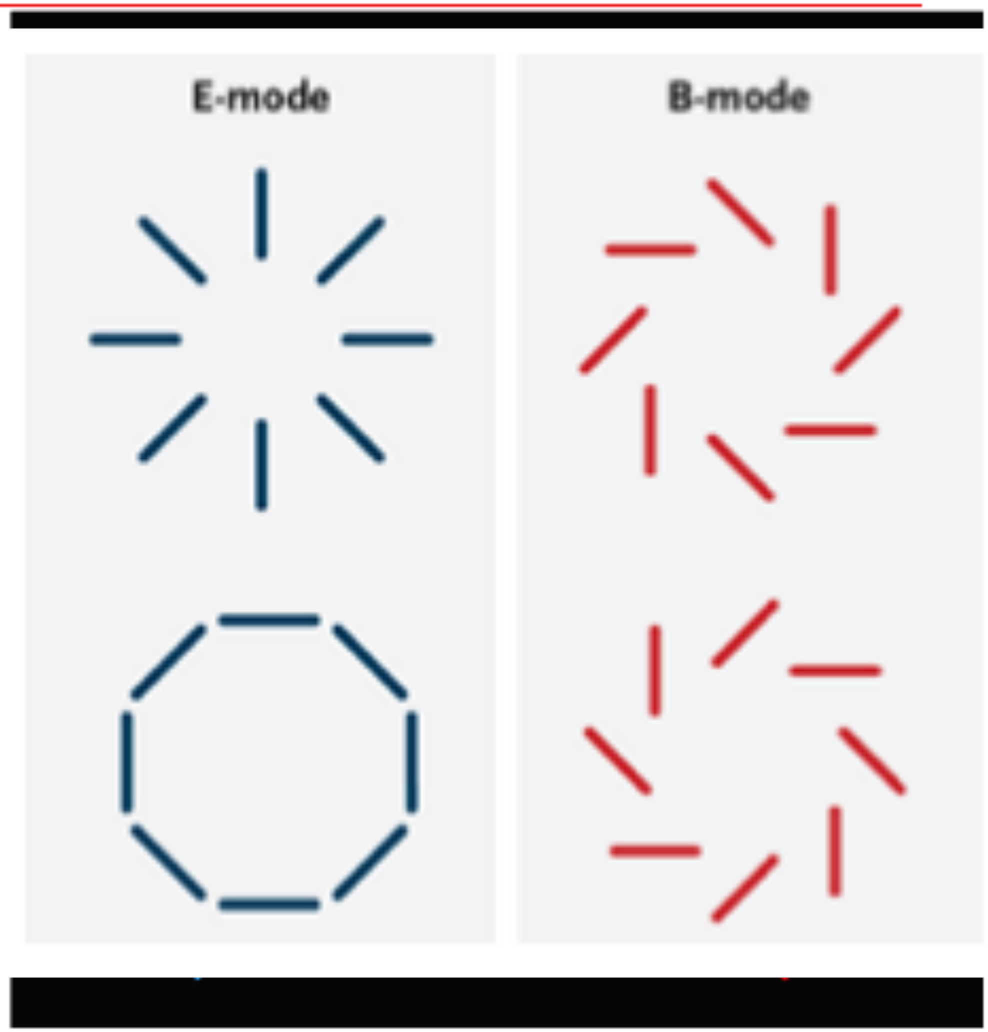
$$g_{\mu\nu} = g_{\mu\nu}^{(0)} + \delta g_{\mu\nu}$$

Modes: scalar ~~vector~~ tensor

none in inflation
(no rotational velocity fields)

The E's and B's of Polarization Spectra

- Polarization decomposable into E mode (gradient) and B mode (curl) components.
- Tensor fluctuations produce both E and B mode components.
- Scalar fluctuations produce only E mode component (except for transformation by gravitational lensing).
- B modes directly probe gravity waves.



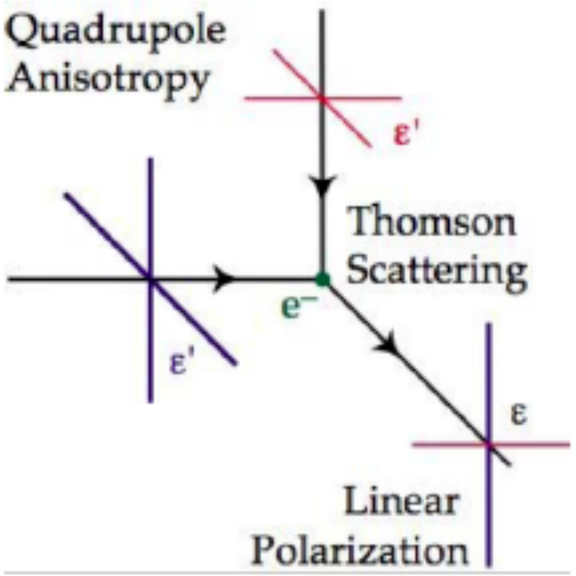
Sources of Polarization

Two ingredients

1. Free electrons
2. Incident quadrupole anisotropy

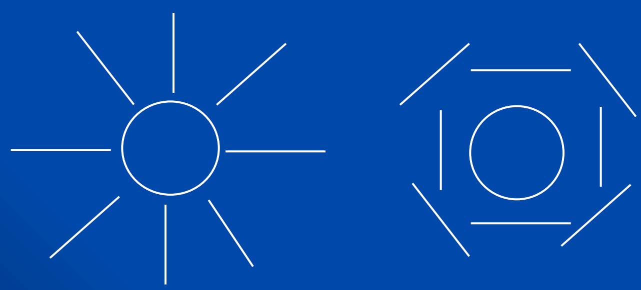
Scattering at z~1100 produces signal on degree scales

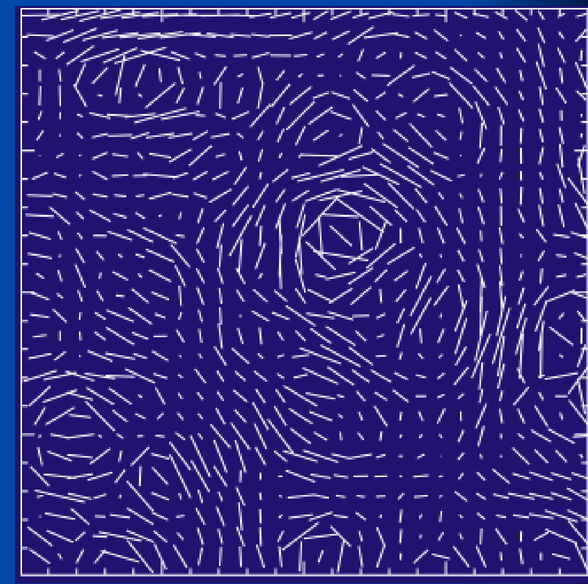
Scattering at z~10 produces signal on 10 degree scales - probes reionization from first stars.



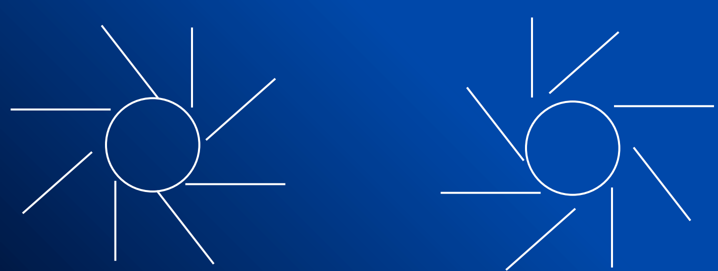
E and B modes polarization

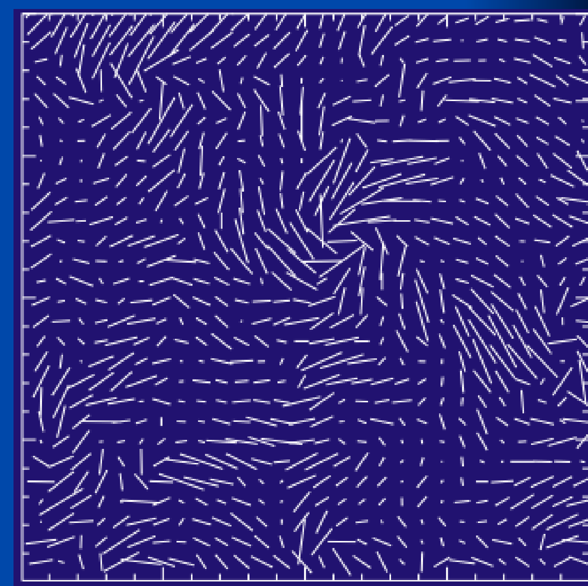
E polarization
from scalar, vector and tensor modes





B polarization only from (vector)
tensor modes

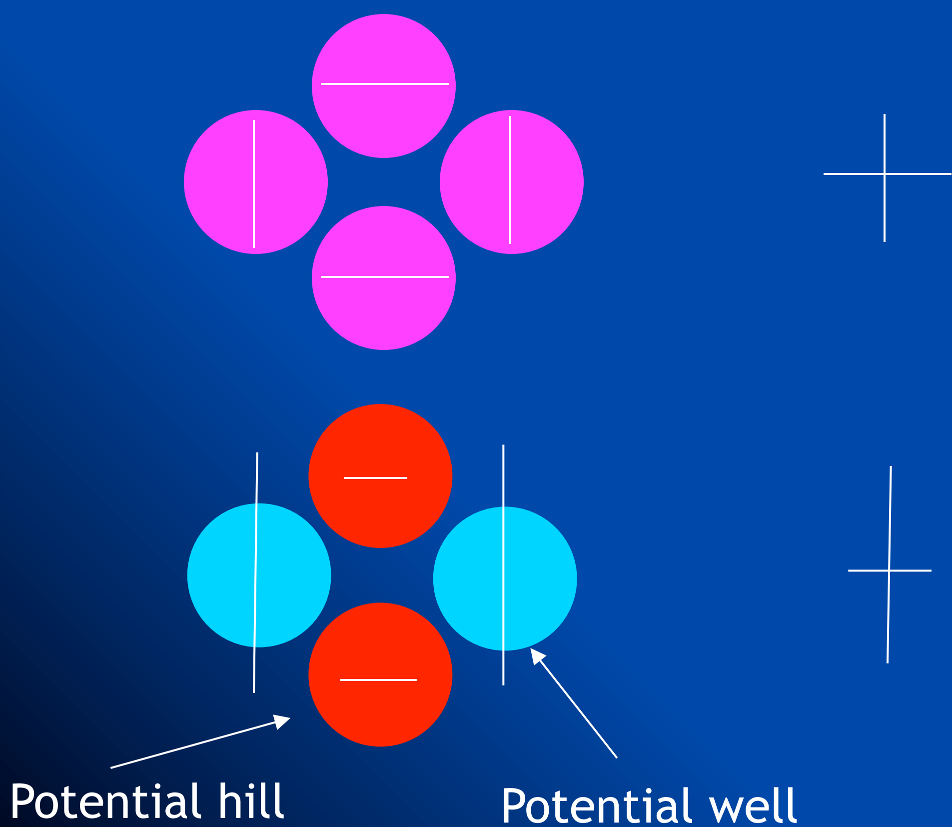


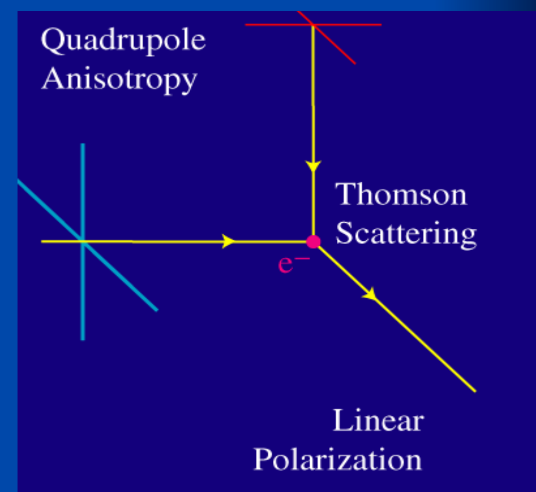


Kamionkowski, Kosowsky, Stebbings 1997, Zaldarriga & Seljak 1997

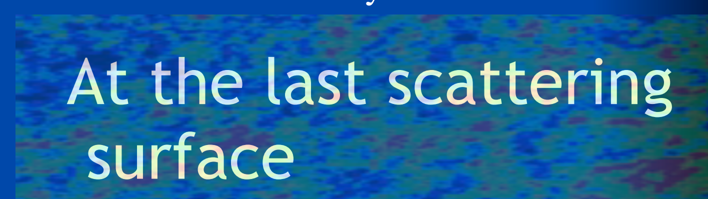
Generation of CMB polarization

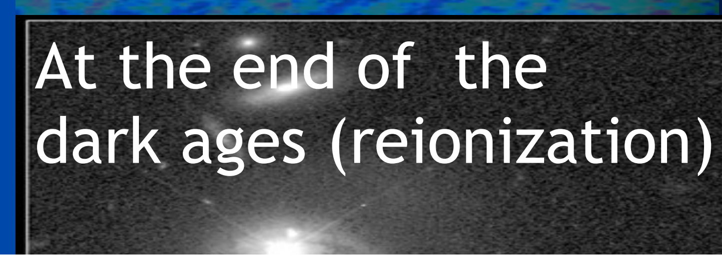
- Temperature quadrupole at the surface of last scatter generates polarization.





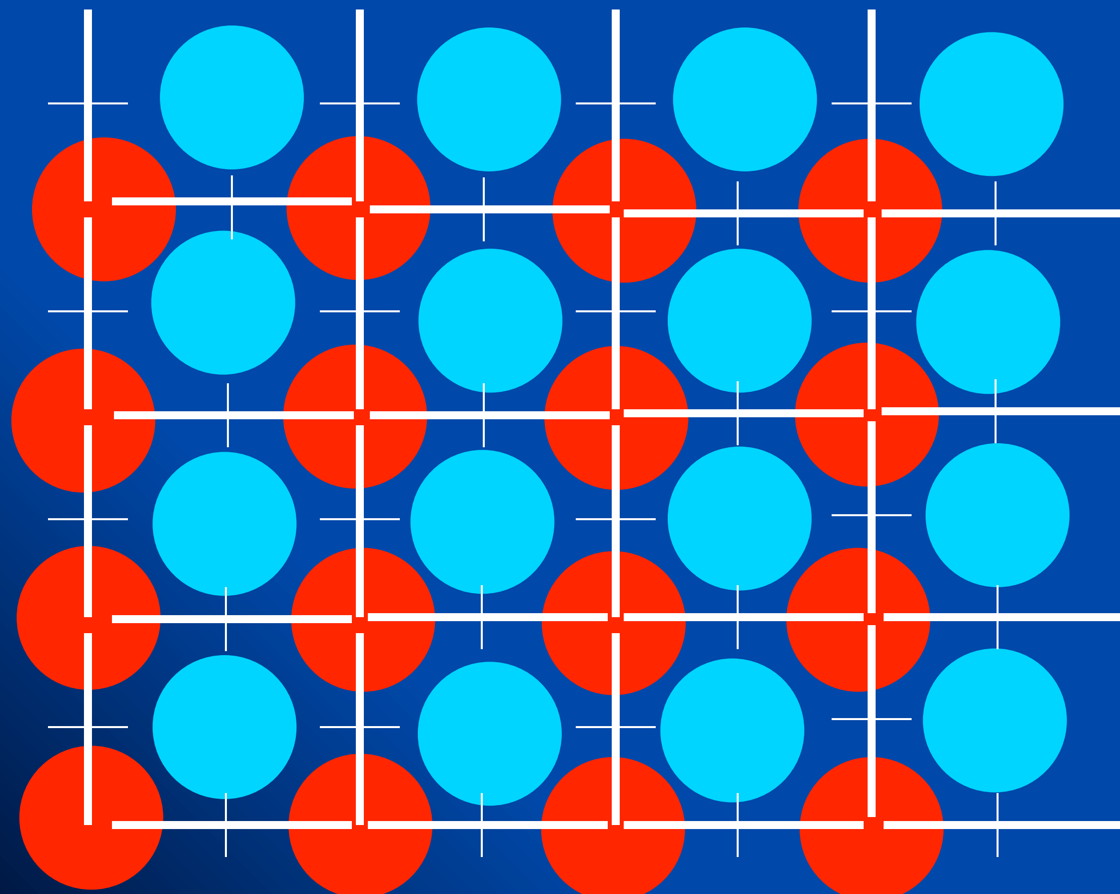
From Wayne Hu

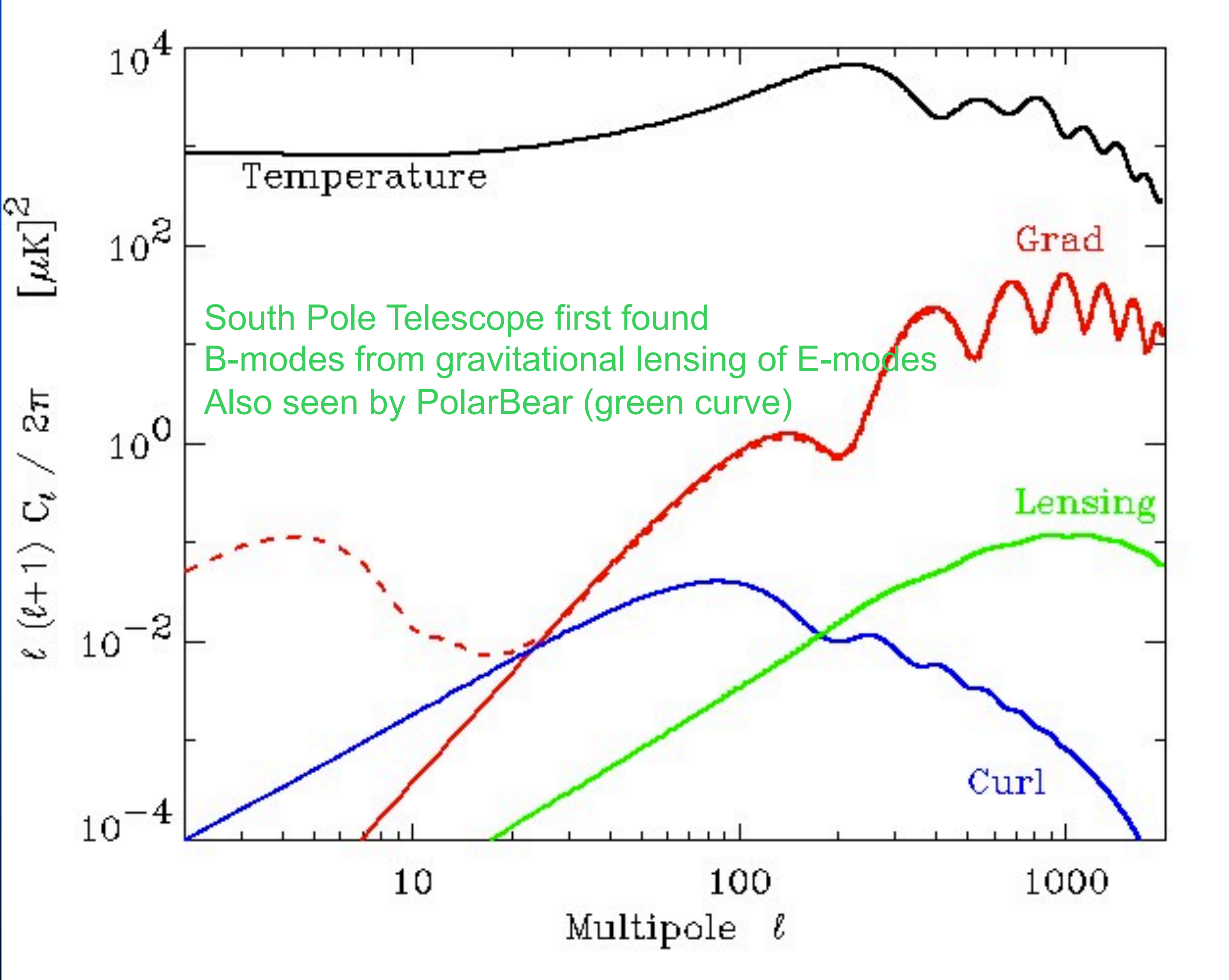




Polarization for density perturbation

- Radial (tangential) pattern around hot (cold) spots.





South Pole Telescope first found
B-modes from gravitational lensing of E-modes
Also seen by PolarBear (green curve)
Temperature
Grad
Lensing
Curl
10^4
10^2
10^0
10^{-2}
10^{-4}
$\ell\ (\ell+1)\ C_\ell\ /\ 2\pi\quad [\mu K]^2$
10
100
1000
Multipole ℓ

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

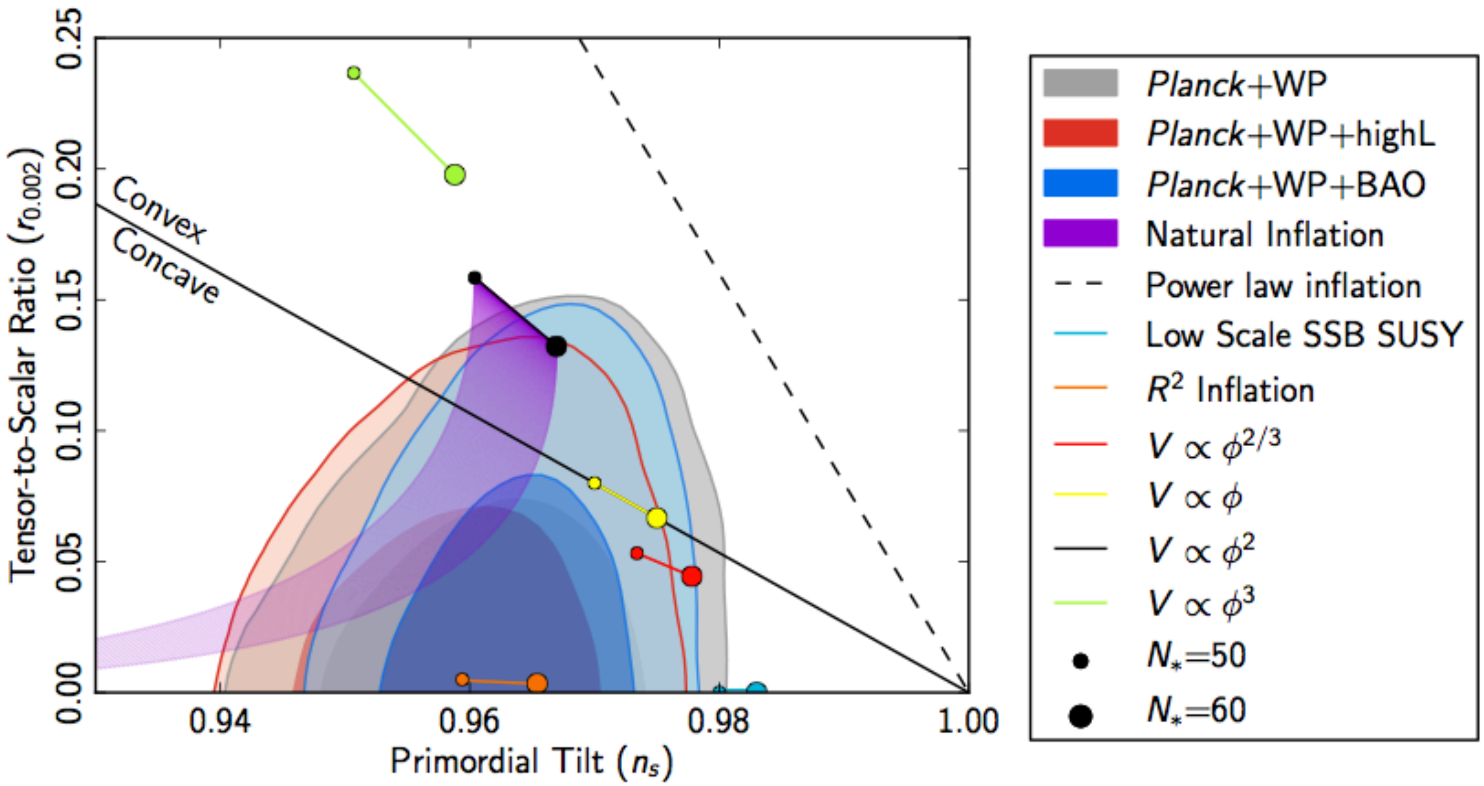


Fig. 1. Marginalized joint 68% and 95% CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets compared to the theoretical predictions of selected inflationary models.

Purple swath is cosine natural inflation model of Freese, Frieman, and Olinto 1990. Prediction: r>0.02

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:

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

- Here Phi is comoving curvature perturbation (density pert)

Bispectrum

- Measures correlation among three perturbation modes.

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

- Assuming translational and rotational invariance, it depends only on the magnitudes of the three wavevectors.

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

- The quantity f_NL is known as the nonlinearity parameter.

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 models 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

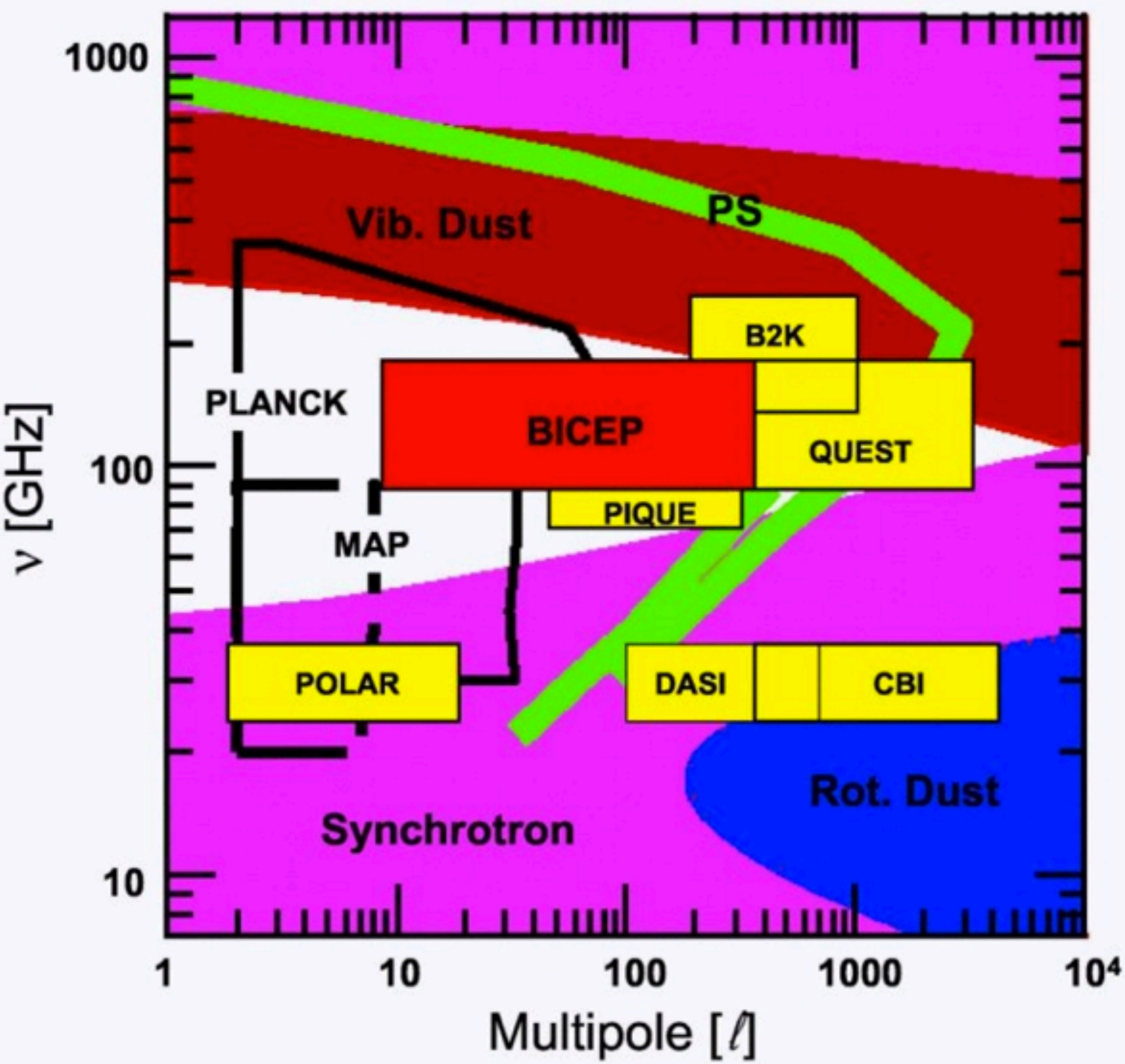
$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1 + \frac{1}{2}\, dn_s/d\ln k \ln(k/k_*) + \frac{1}{6}\, d^2 n_s/d\ln k^2 (\ln(k/k_*))^2 + \ldots}$$

$$\mathcal{P}_t(k) = A_t \left(\frac{k}{k_*}\right)^{n_t + \frac{1}{2}\, dn_t/d\ln k \ln(k/k_*) + \ldots},$$

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

BICEP2 at the South Pole

BICEP2 at the South Pole.



1000
100
10
ν [GHz]
1
10
100
1000
10^4
Multipole [ℓ]
Vib. Dust
PS
B2K
PLANCK
BICEP
QUEST
PIQUE
MAP
POLAR
DASI
CBI
Rot. Dust
Synchrotron

TO BE SUBMITTED TO A JOURNAL TBD
Preprint typeset using LaTeX style emulateapj v. 04/17/13

BICEP2 I: DETECTION OF *B*-mode POLARIZATION AT DEGREE ANGULAR SCALES

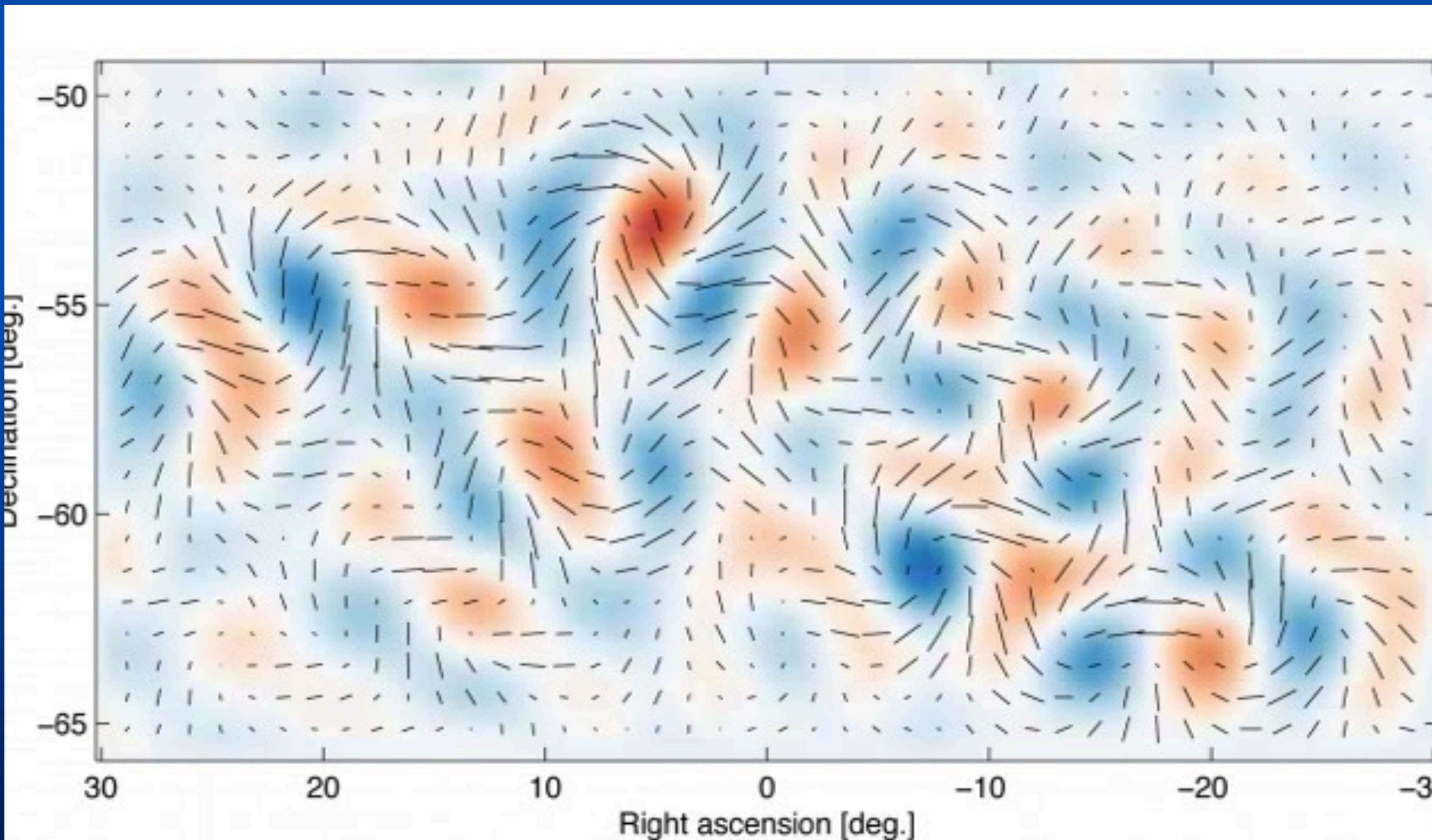
BICEP2 COLLABORATION - P. A. R. ADE[1], R. W. AIKIN[2], D. BARKATS[3], S. J. BENTON[4], C. A. BISCHOFF[5], J. J. BOCK[2,6], J. A. BREVIK[2], I. BUDER[5], E. BULLOCK[7], C. D. DOWELL[6], L. DUBAND[8], J. P. FILIPPINI[2], S. FLIESCHER[9], S. R. GOLWALA[2], M. HALPERN[10], M. HASSELFIELD[10], S. R. HILDEBRANDT[2,6], G. C. HILTON[11], V. V. HRISTOV[2], K. D. IRWIN[12,13,11], K. S. KARKARE[5], J. P. KAUFMAN[14], B. G. KEATING[14], S. A. KERNASOVSKIY[12], J. M. KOVAC[5,16], C. L. KUO[12,13], E. M. LEITCH[15], M. LUEKER[2], P. MASON[2], C. B. NETTERFIELD[4], H. T. NGUYEN[6], R. O'BRIENT[6], R. W. OGBURN IV[12,13], A. ORLANDO[14], C. PRYKE[9,7,16], C. D. REINTSEMA[11], S. RICHTER[5], R. SCHWARZ[9], C. D. SHEEHY[9,15], Z. K. STANISZEWSKI[2,6], R. V. SUDIWALA[1], G. P. TEPLY[2], J. E. TOLAN[12], A. D. TURNER[6], A. G. VIEREGG[5,15], C. L. WONG[5], AND K. W. YOON[12,13]

to be submitted to a journal TBD

ABSTRACT

We report results from the BICEP2 experiment, a Cosmic Microwave Background (CMB) polarimeter specifically designed to search for the signal of inflationary gravitational waves in the *B*-mode power spectrum around $\ell \sim 80$. The telescope comprised a 26 cm aperture all-cold refracting optical system equipped with a focal plane of 512 antenna coupled transition edge sensor (TES) 150 GHz bolometers each with temperature sensitivity of $\approx 300\ \mu\mathrm{K}_{\mathrm{CMB}}\sqrt{\mathrm{s}}$. BICEP2 observed from the South Pole for three seasons from 2010 to 2012. A low-foreground region of sky with an effective area of 380 square degrees was observed to a depth of 87 nK-degrees in Stokes Q and U. In this paper we describe the observations, data reduction, maps, simulations and results. We find an excess of *B*-mode power over the base lensed-ΛCDM expectation in the range $30 < \ell < 150$, inconsistent with the null hypothesis at a significance of $> 5\sigma$. Through jackknife tests and simulations based on detailed calibration measurements we show that systematic contamination is much smaller than the observed excess. We also estimate potential foreground signals and find that available models predict these to be considerably smaller than the observed signal. These foreground models possess no significant cross-correlation with our maps. Additionally, cross-correlating BICEP2 against 100 GHz maps from the BICEP1 experiment, the excess signal is confirmed with 3σ significance and its spectral index is found to be consistent with that of the CMB, disfavoring synchrotron or dust at 2.3σ and 2.2σ, respectively. The observed *B*-mode power spectrum is well-fit by a lensed-ΛCDM + tensor theoretical model with tensor/scalar ratio $r = 0.20^{+0.07}_{-0.05}$, with $r = 0$ disfavored at 7.0σ. Subtracting the best available estimate for foreground dust modifies the likelihood slightly so that $r = 0$ is disfavored at 5.9σ.

Polarization in BICEP2



BICEP2 revealed a faint but distinctive twist in the polarization pattern of the CMB. Here the lines represent polarization; the red and blue shading show the degree of the clockwise and counter-clockwise twist.

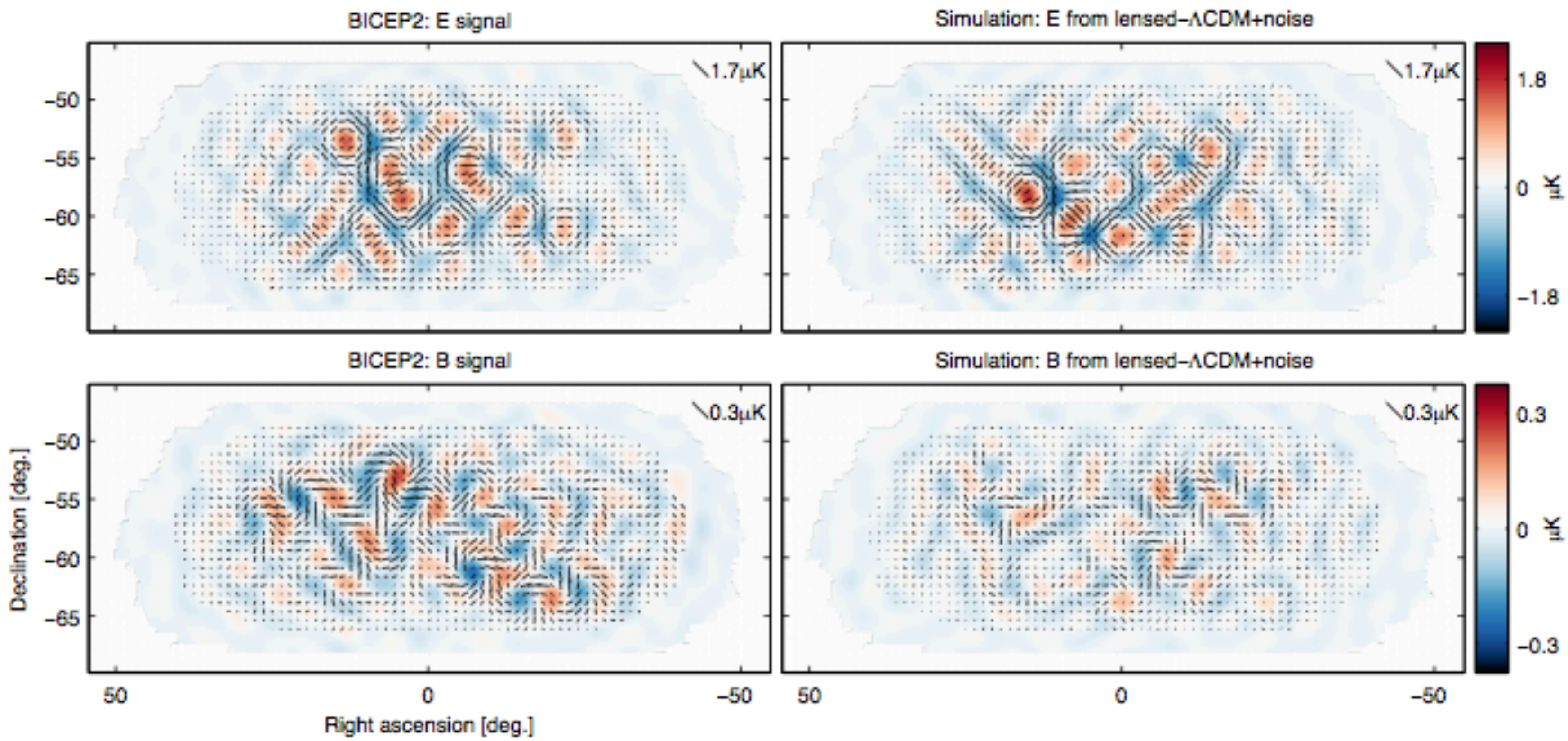
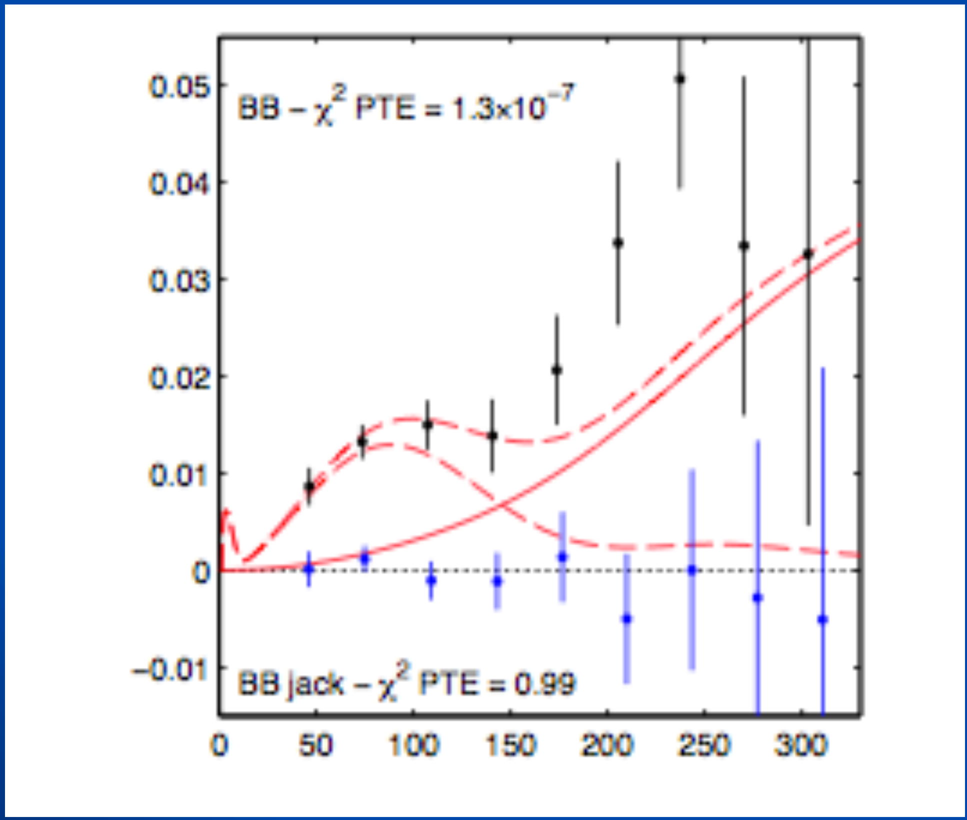


FIG. 3.— *Left:* BICEP2 apodized E-mode and B-mode maps filtered to $50 < \ell < 120$. *Right:* The equivalent maps for the first of the lensed-ΛCDM+noise simulations. The color scale displays the E-mode scalar and B-mode pseudoscalar patterns while the lines display the equivalent magnitude and orientation of linear polarization. Note that excess B-mode is detected over lensing+noise with high signal-to-noise ratio in the map ($s/n > 2$ per map mode at $\ell \approx 70$). (Also note that the E-mode and B-mode maps use different color/length scales.)



BB – χ² PTE = 1.3×10⁻⁷
BB jack – χ² PTE = 0.99
0.05
0.04
0.03
0.02
0.01
0
−0.01
0
50
100
150
200
250
300

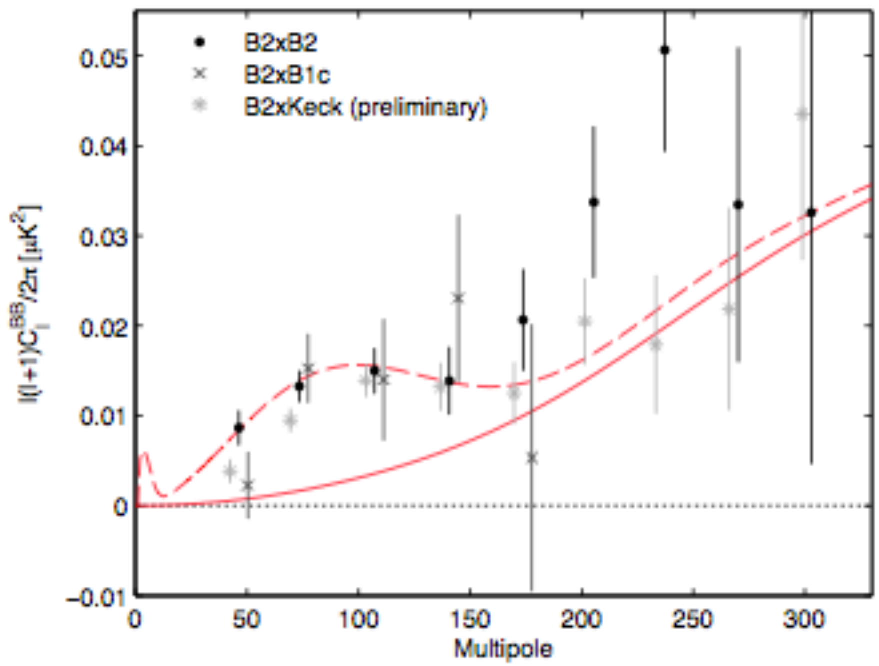


FIG. 9.— Comparison of the BICEP2 *BB* auto spectrum and cross spectra taken between BICEP2 and BICEP1 combined, and BICEP2 and *Keck Array* preliminary. (For clarity the cross spectrum points are offset horizontally and the BICEP2×BICEP1 points are omitted at $\ell > 200$.)

BICEP results compared to previous upper limits

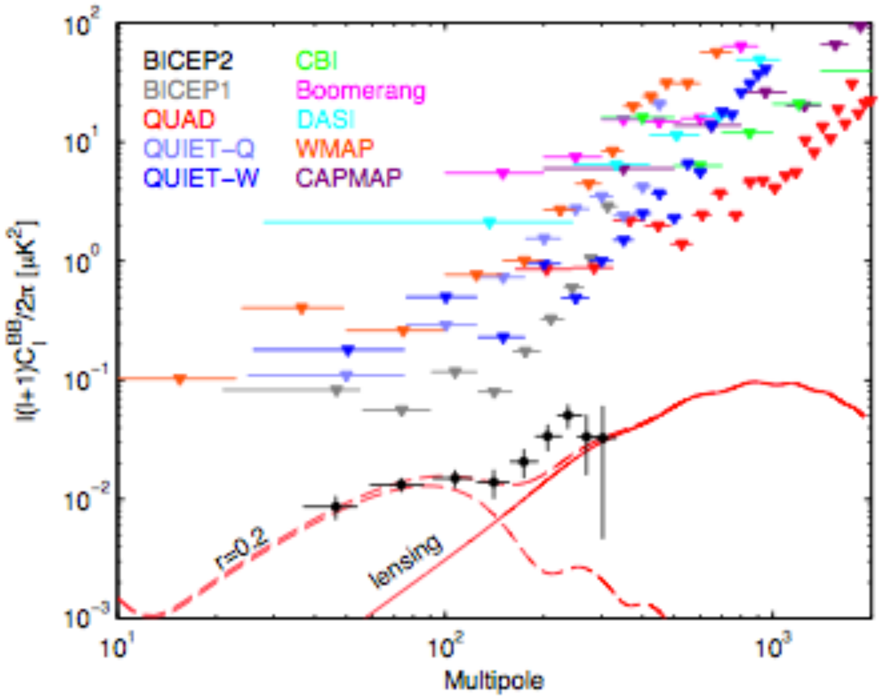


FIG. 14.— BICEP2 *BB* auto spectra and 95% upper limits from several previous experiments (Leitch et al. 2005; Montroy et al. 2006; Sievers et al. 2007; Bischoff et al. 2008; Brown et al. 2009; QUIET Collaboration et al. 2011, 2012; Bennett et al. 2013; Barkats et al. 2014). The curves show the theory expectations for $r = 0.2$ and lensed-ΛCDM.

- "The long search for tensor *B-modes* is apparently over, and a new era of *B-mode* cosmology has begun." (BICEP2 paper)

BICEP2 result

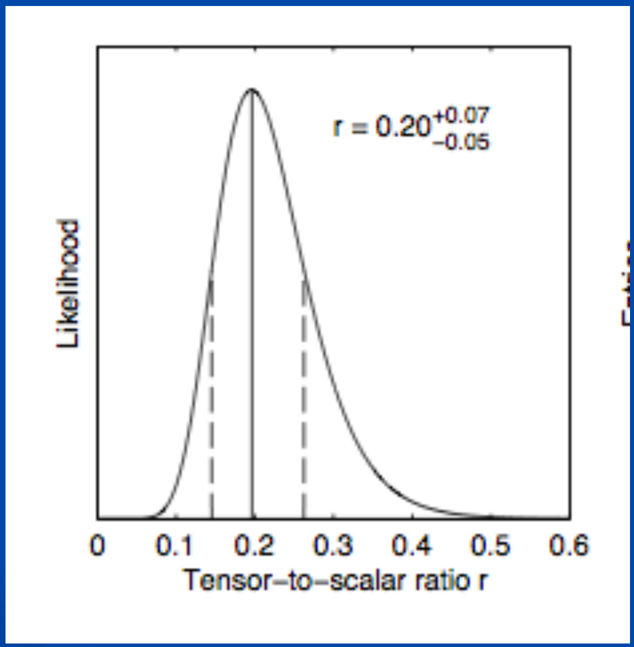
- The observed *B-mode* power spectrum is well- fit by a lensed-Lambda CDM + tensor theoretical model with tensor/scalar ratio *r* = 0.20+0.07-0.05 , with *r* = 0 disfavored at 7.0 sigma.
- Since r is determined by the value of the Hubble constant during inflation, and therefore the height of the potential, the height of the potential must be high scale, comparable to the GUT scale

$$V = (2.2 \times 10^{16}\mathrm{GeV})^4 \frac{r}{0.2}.$$

- Lyth bound: the excursions of the field which implies that inflation is probing the Planck scale

$$\Delta\phi \geq m_{\mathrm{Pl}} \sqrt{\frac{r}{4\pi}}.$$

BICEP result on r=tensor-to-scalar ratio



IMPACT of BICEP2 Results

- First real discovery of gravitational waves predicted by Einstein’s relativity
- B mode polarization results from quantum fluctuations of the two polarization modes of the gravitational field: QM of gravity.
- Height of the potential at the GUT scale: Opens new window on new regime of physics: the physics of what happens in the first tiny fraction of the history of the Universe, in particular the physics of the unification of the four forces.
- Width of the potential at the Planck scale: Many thought that large field models didn’t work because of instability due to quantum physics. But that they do work, so we learn about quantum gravity.
- We are left with a focus on a small range of inflation models

Tension between Planck vs. BICEP2 on the value of r

- Planck: r<0.17 at 95% C.L. in the case of no running of ns
- BICEP r = 0.20+0.07-0.05 (no constraint on ns)
- Here r is the tensor to scalar ratio, i.e. the ratio of the amplitude of gravitational wave modes to density perturbations
- Consistent at 2 sigma; discrepant at 1 sigma.
- Possible resolution:
- 1) Details of foreground removal in BICEP2
- 2) Extra neutrino species
- 3) Running of spectral index ns (bad for single rolling fields)

BICEP2 + Planck with running of ns

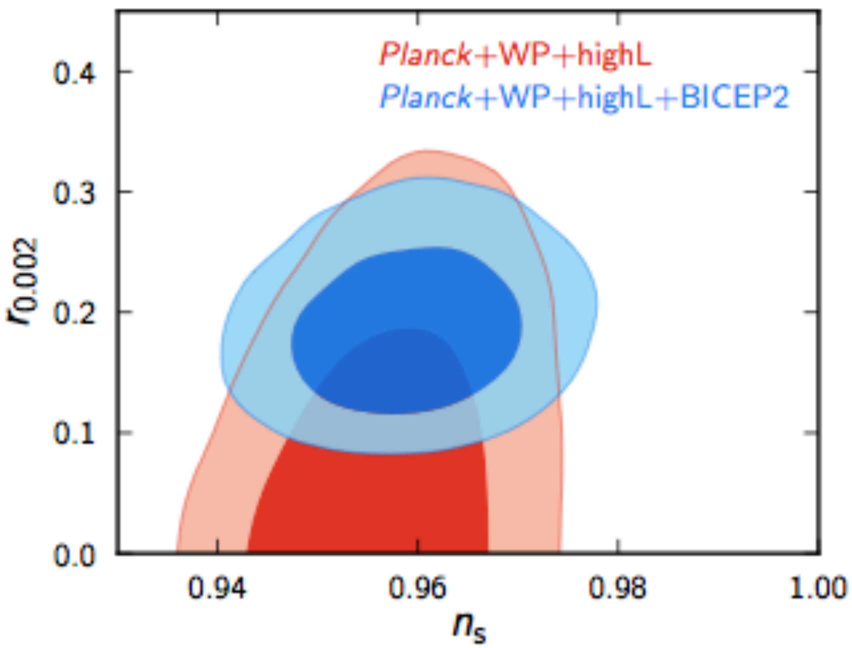


FIG. 13.— Indirect constraints on r from CMB temperature spectrum measurements relax in the context of various model extensions. Shown here is one example, following Planck Collaboration XVI (2013) Figure 23, where tensors and running of the scalar spectral index are added to the base ΛCDM model. The contours show the resulting 68% and 95% confidence regions for r and the scalar spectral index n_s when also allowing running. The red contours are for the "Planck+WP+highL" data combination, which for this model extension gives a 95% bound $r < 0.26$ (Planck Collaboration XVI 2013). The blue contours add the BICEP2 constraint on r shown in the center panel of Figure 10. See the text for further details.

PLANCK without BICEP2:

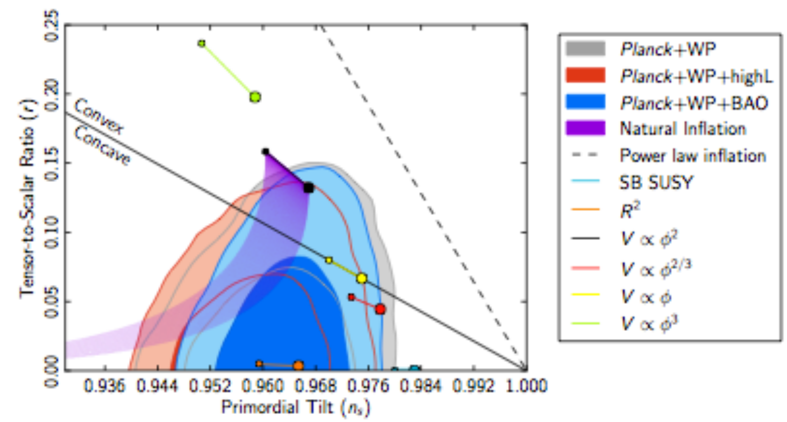


Fig. 26. Marginalized 68 % and 95 % confidence levels for n_s and r from Planck+WP and BAO data, compared to the theoretical predictions of selected inflationary models.

Planck with and without running (from Planck inflation paper)

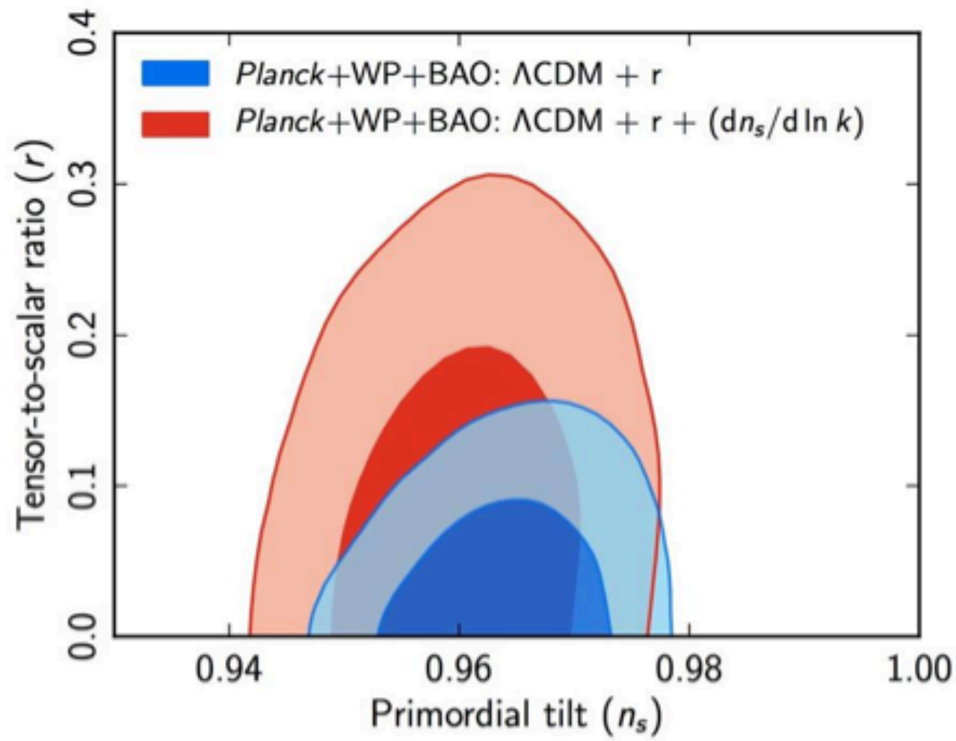


Fig. 4. Marginalized joint 68% and 95% CL regions for (r, n_s), using *Planck*+WP+BAO with and without a running spectral index.

arXiv:1303.5082

Where are we?

- General idea of inflation compares well to data: critical density, nearly scale invariant perturbations, superhorizon fluctuations, gravity waves.
- Single field models holding up
- Now the data are becoming good enough to differentiate between models.
- Theorists constructed thousands of models in the absence of data. The number of inflation models we now have, after data, are very few.

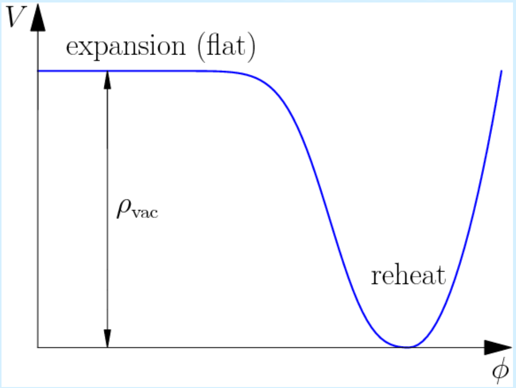
Natural Inflation after Planck

Theoretical motivation: no fine-tuning
Recent interest in light of theoretical developments
Unique predictions:
Looks good compared to data

(Freese, Frieman, Olinto 1990)

The Fine Tuning Problem in Inflation

- The potential must be very flat:



$$\frac{\Delta V}{(\Delta \Phi)^4} = \frac{\text{height}}{\text{width}^4} \leq 10^{-8},$$
$$e.g. V(\phi) = \lambda \Phi^4, \lambda \leq 10^{-12}$$

(Adams, Freese, and Guth 1990)

But particle physics typically gives this ratio = 1!

Inflationary Model Constraints

Success of inflationary models with rolling fields
$\Rightarrow$ constraints on $V(\phi)$

- Enough inflation

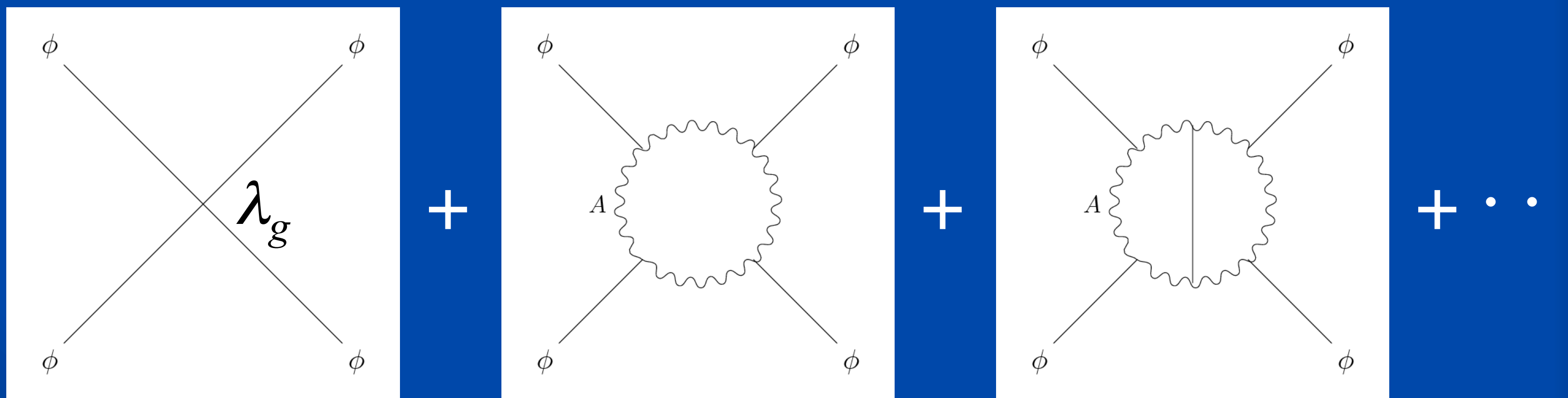
  Scale factor *a* must grow enough

$$\ln\left(\frac{a_{\text{end}}}{a_{\text{begin}}}\right) = \int_{t_{\text{begin}}}^{t_{\text{end}}} H\,dt = -8\pi G \int \frac{V(\phi)}{V'(\phi)}\,d\phi \geq 60$$

- Amplitude of density fluctuations not too large

$$\left.\frac{\delta\rho}{\rho}\right|_{\substack{\text{enter}\\ \text{horizon}}} \sim \left.\frac{H^2}{\dot{\phi}}\right|_{\substack{\text{exit}\\ \text{horizon}}} \leq \frac{\delta T}{T} \sim 10^{-5}$$

Fine Tuning due to Radiative Corrections



- Perturbation theory: 1-loop, 2-loop, 3-loop, etc.

- To keep $\lambda \sim 10^{-12}$ must balance tree level term against corrections to each order in perturbation theory. Ugly!

Inflation needs small ratio of mass scales

$$\frac{\Delta V}{(\Delta\Phi)^4} = \frac{\text{height}}{\text{width}^4} \leq 10^{-8},$$

- Two attitudes:

1) We know there is a heirarchy problem, wait until it's explained

2) Two ways to get small masses in particles physics:

(i) supersymmetry

(ii) Goldstone bosons (shift symmetries)

Natural Inflation: Shift Symmetries

- Shift symmetries protect flatness of inflaton potential
  $\Phi \longrightarrow \Phi + \mathrm{constant}$ (inflaton is Goldstone boson – an “axion”)
- 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

Shift Symmetries

$\rightarrow$ "Natural Inflation"
Freese, Frieman & Olinto (1990)

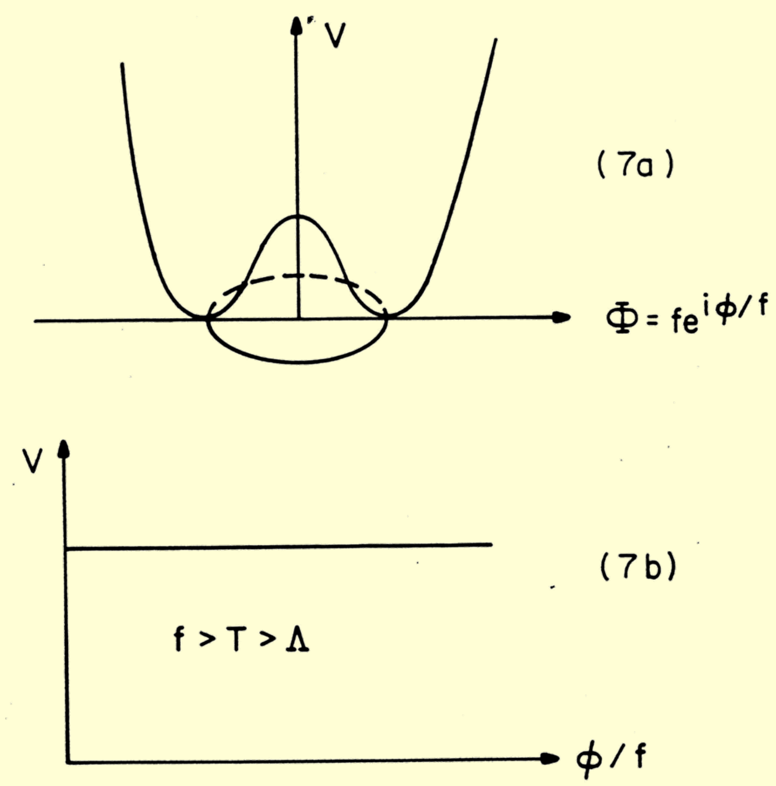
- We know of a particle with a small ratio of scales:
  the **axion**

$$\lambda_a \sim \left(\frac{\Lambda_{\text{QCD}}}{f_{\text{PQ}}}\right)^4 \sim 10^{-64}$$

- IDEA: use a potential similar to that for axions in inflation
  $\Rightarrow$ natural inflation (no fine-tuning)

  - Here, we do ***not*** use the QCD axion.
    In original Natural inflation, we use a heavier particle with similar behavior.

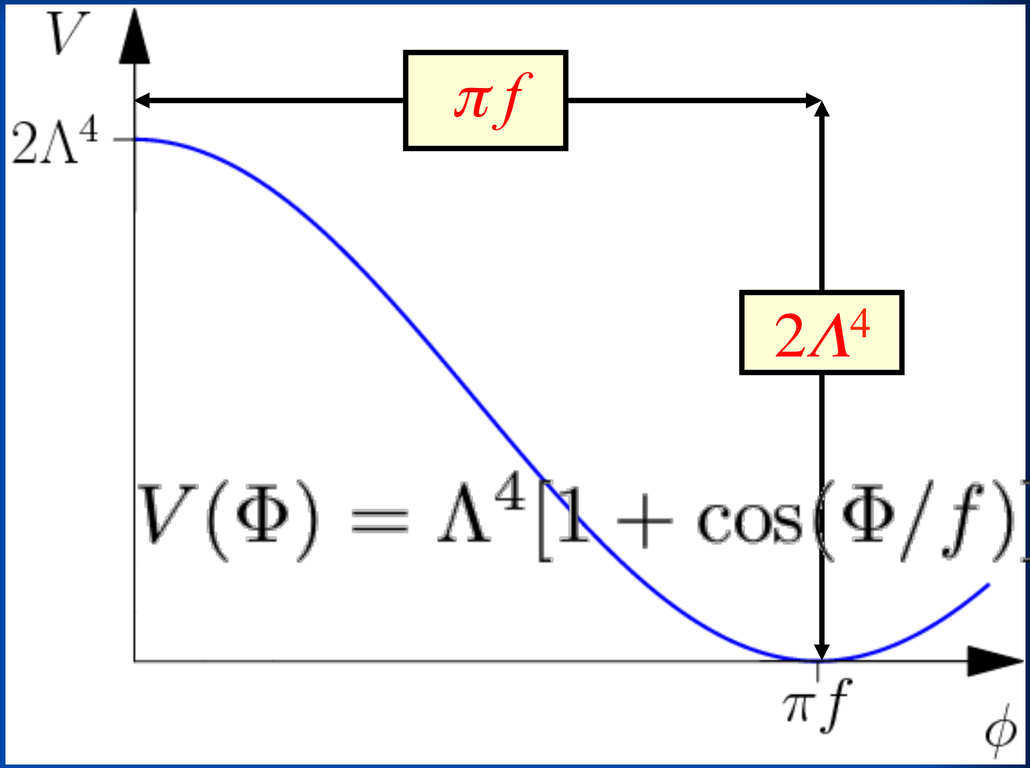
e.g., mimic the physics of the axion (Weinberg; Wilczek)



Original Natural Inflation

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

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



- Width f :
  - Scale of spontaneous symmetry breaking of some global symmetry
  - Enough inflation requires width f to be roughly Mpl
- Height Λ:
  - Scale at which gauge group becomes strong
  - Amplitude of density fluctuations requires $\Lambda \sim m_{GUT}$

Two Mass Scales Provide required heirarchy

- For QCD axion,

$$\Lambda_{\mathrm{QCD}} \sim 100\mathrm{MeV}, f_{PQ} \sim 10^{12}\mathrm{GeV}, \frac{\mathrm{height}}{\mathrm{width}} \sim 10^{-64}!!$$

- For inflation, need $\Lambda \sim m_{GUT}, f \sim m_{pl}$

Enough inflation requires width = f ≈ mpl,
Amplitude of density fluctuations requires height = $\Lambda \sim m_{GUT}$

Density Fluctuations

Largest at 60 efolds
before end of inflation

$$\frac{\delta\rho}{\rho} \approx \frac{H^2}{\dot{\phi}} \approx \frac{3\Lambda^2 f}{M_{\mathrm{Pl}}^3} \frac{\left[1+\cos(\phi_1^{\max}/f)\right]^{3/2}}{\sin(\phi_1^{\max}/f)} \sim 10^{-5}$$

$\Rightarrow \Lambda \sim 10^{15}$ GeV – 10^{16} GeV (height of potential)

$\Rightarrow m_\phi = \Lambda^2/\phi \sim 10^{11}$ GeV – 10^{13} GeV

- Density fluctuation spectrum is non-scale invariant with extra power on large length scales

$$P_k = |\delta_k|^2 \sim k^{n_s}$$

$$\text{with} \quad n_s \approx 1 - \frac{M_{\mathrm{Pl}}^2}{8\pi f^2} \quad (\text{for } f < M_{\mathrm{Pl}})$$

WMAP + Planck $\Rightarrow$ f > 0.8 M_{PL}

Implementations of natural inflation's shift symmetry

- Natural chaotic inflation in SUGRA using shift symmetry in Kahler potential (Gaillard, Murayama, Olive 1995; Kawasaki, Yamaguchi, Yanagida 2000)
- In context of extra dimensions: Wilson line with (Arkani-Hamed et al 2003) but Banks et al (2003) showed it fails in string theory. $f \gg m_{pl}$
- "Little" field models (Kaplan and Weiner 2004)
- In brane Inflation ideas (Firouzjahi and Tye 2004)
- Gaugino condensation in SU(N) $\times$ SU(M):

Adams, Bond, Freese, Frieman, Olinto 1993;

Blanco-Pillado et al 2004 (Racetrack inflation)

Legitimacy of large axion scale?

Natural Inflation needs f>mpl

Is such a high value compatible with an effective field theory description? Do quantum gravity effects break the global axion symmetry?

Kinney and Mahantappa 1995: symmetries suppress the mass term and $f \ll m_{pl}$ is OK.

Arkani-Hamed et al (2003):axion direction from Wilson line of U(1) field along compactified extra dimension provides $f \gg m_{pl}$

However, Banks et al (2003) showed it does not work in string theory.

Multiple axions with a large effective axion scale

- Two or more axions with low PQ scale can provide large $f_{eff} \sim m_{pl}$ (Kim, Nilles, Peloso 2004)
- Two axions $\theta \text{ and } \rho$

$$V = \Lambda_1^4[1 - \cos(\frac{\theta}{f} + \frac{\epsilon_1 \rho}{g})] + \Lambda_2^4[1 - \cos(\frac{\theta}{f} + \frac{\epsilon_2 \rho}{g})]$$

Mass eigenstates are linear combinations of the two axions. Effective axion scale can be large,

$$f_\xi = \frac{\sqrt{\epsilon_1^2 f^2 + g^2}}{\epsilon_1 - \epsilon_2} >> f \ \text{ if } \ |\epsilon_1 - \epsilon_2| << 1$$

N-flation has a large number of axions (Dimopolous et al 2005)
Axion Inflation in Type II String Theory (Thomas Grimm 2008)

(McAllister, Silverstein, and Westphal 2011)

Monodromy: a way to get large "f" in natural inflation

- Multiple circuits of a single axion
- Axions arise in string compactifications from integrating gauge potentials over nontrivial cycles. Typically flat potentials exactly as we've discussed. However branes wrapping cycles have a potential that is not periodic and instead increases without bound.
- Resulting linear potential: V \sim Phi
- Or Phi^2/3

Differentiating between Models

Density Fluctuations and Tensor Modes can determine which inflationary model is right

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

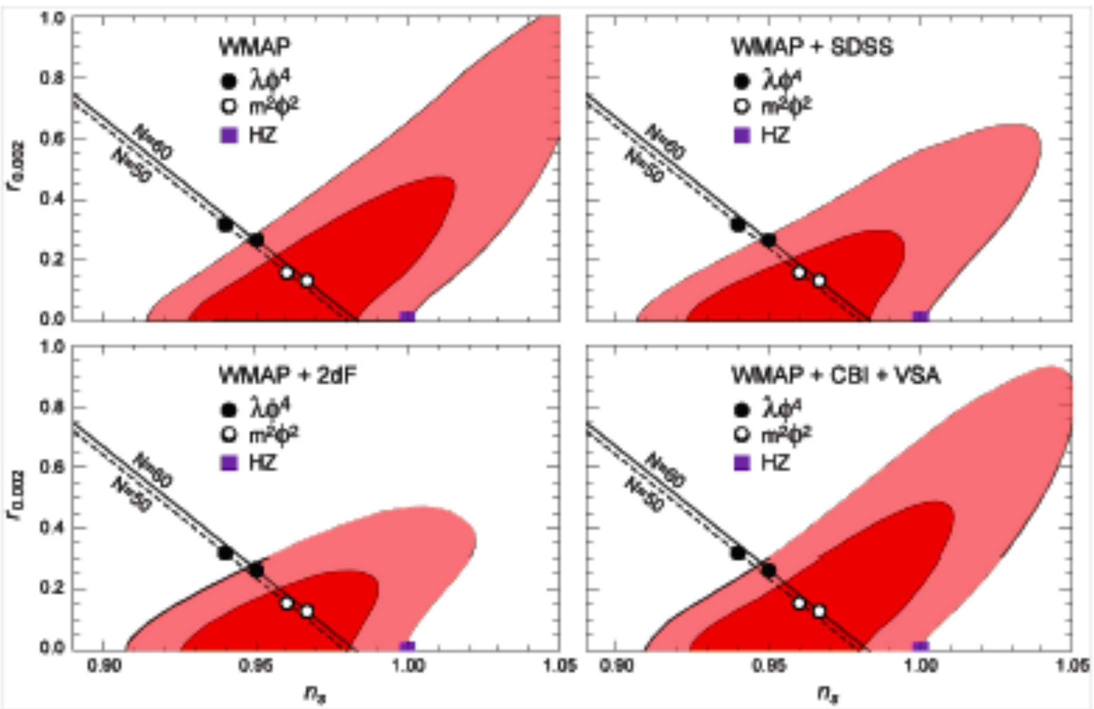
Expressed as $r \equiv \dfrac{P_T^{1/2}}{P_S^{1/2}}$

Inflationary consistency condition: $r = -8n_T$

Plot in r-n plane (two parameters)

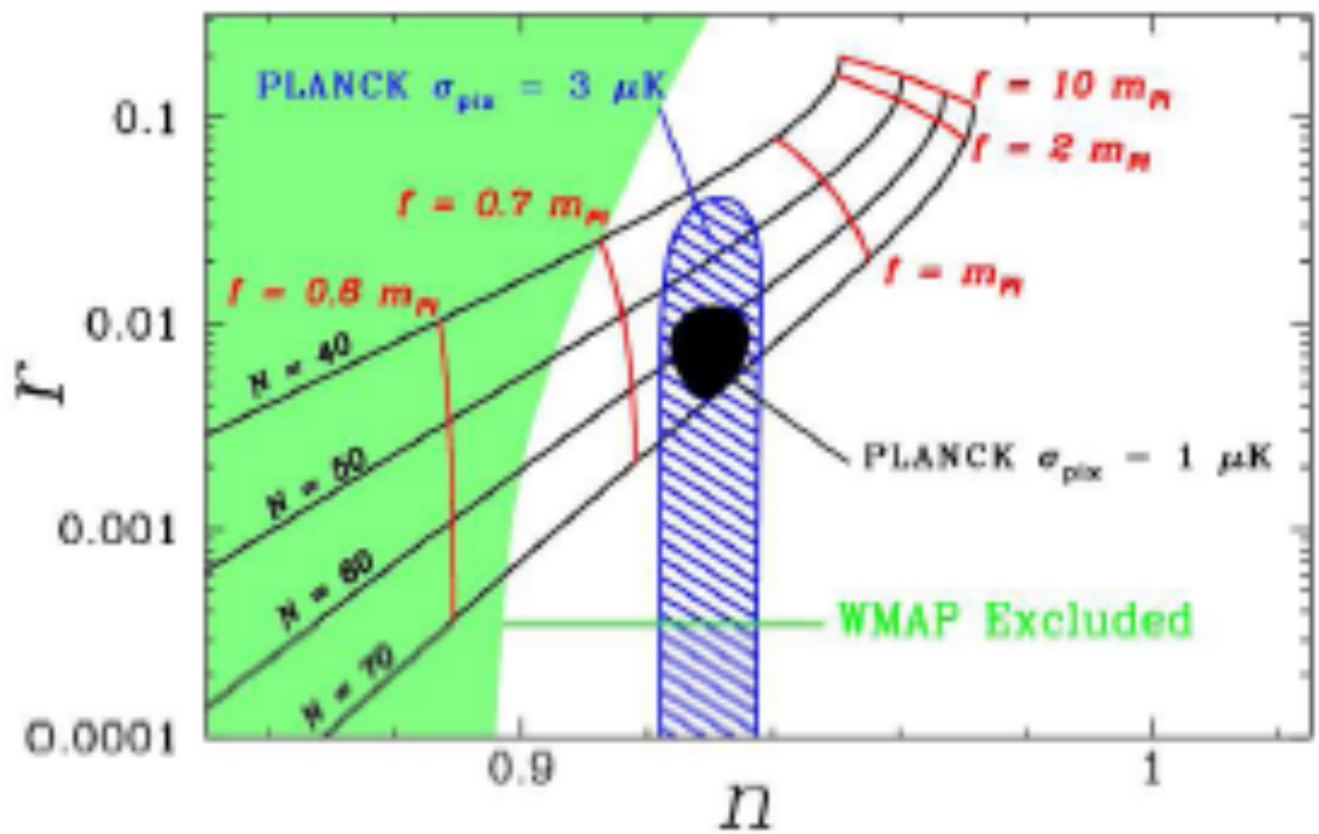
WMAP 1 already ruled out models: Harrison-Zeldovich n=1 and Phi^4 potentials

Testing Inflation with Tensors



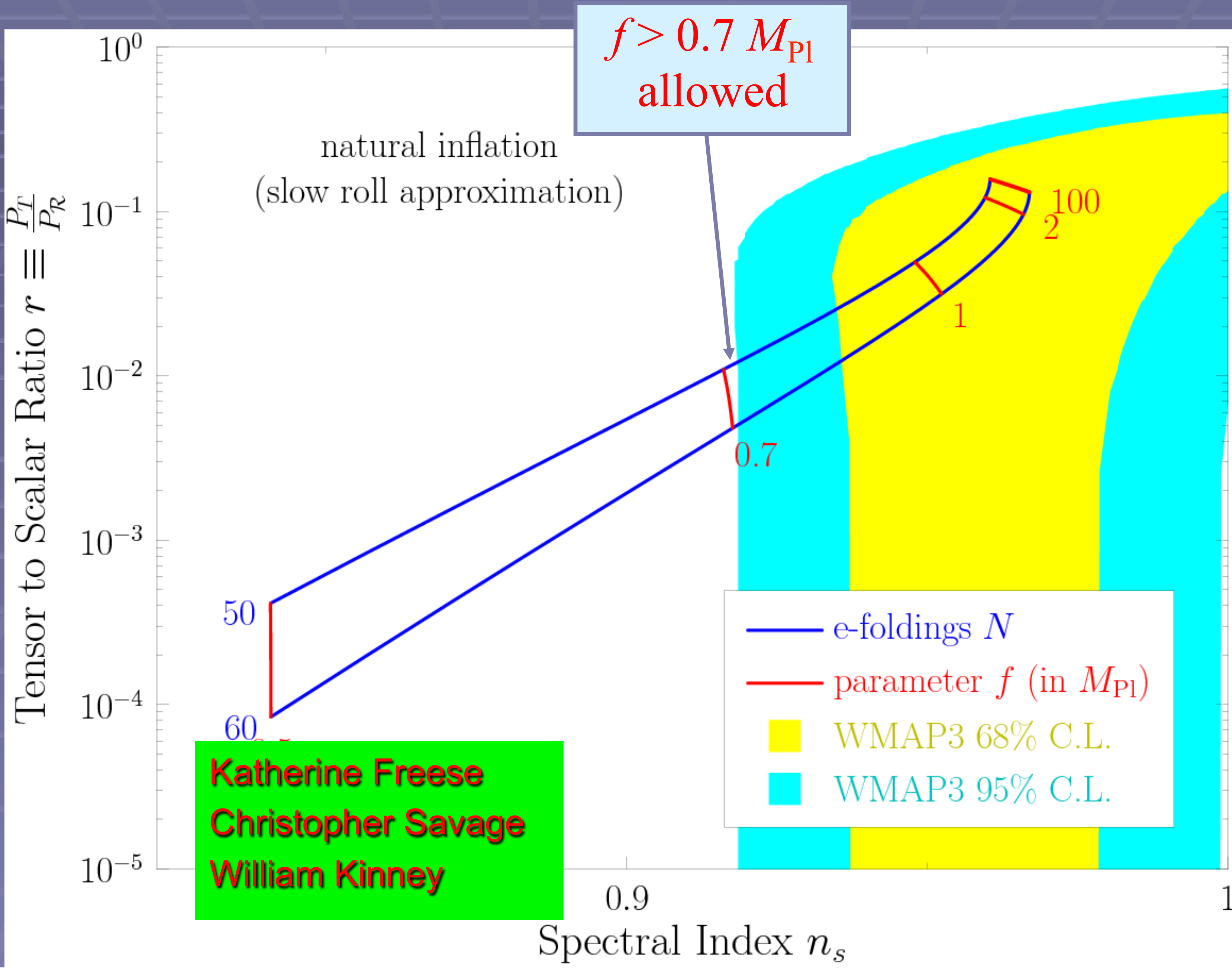
Spectral index vs. tensors

Natural Inflation agreed well w WMAP1



White region is where natural inflation agrees with WMAP1

r-n plane: Natural inflation after WMAP 3



Katherine Freese
Christopher Savage
William Kinney

- What point during inflation corresponds to structures on scale k today?
- e-foldings <u>before</u> the end of inflation *N(k)*: $a = a_e \, \mathrm{e}^{-N}$
- Depends on post-inflation physics

$$N(k) \approx 62 - \ln\frac{k}{a_0 H_0} - \ln\frac{10^{16}\,\mathrm{GeV}}{V_k^{1/4}} + \ln\frac{V_k^{1/4}}{V_e^{1/4}} - \frac{1}{3}\ln\frac{V_e^{1/4}}{\rho_{\mathrm{RH}}^{1/4}}$$

Potential when mode leaves horizon

Potential at end of inflation

energy density after reheating

Instantaneous reheating gives the minimum number of e-folds as one looks backwards to the time of perturbation production while a prolonged period of reheating gives larger N(k).

Inflation after Planck

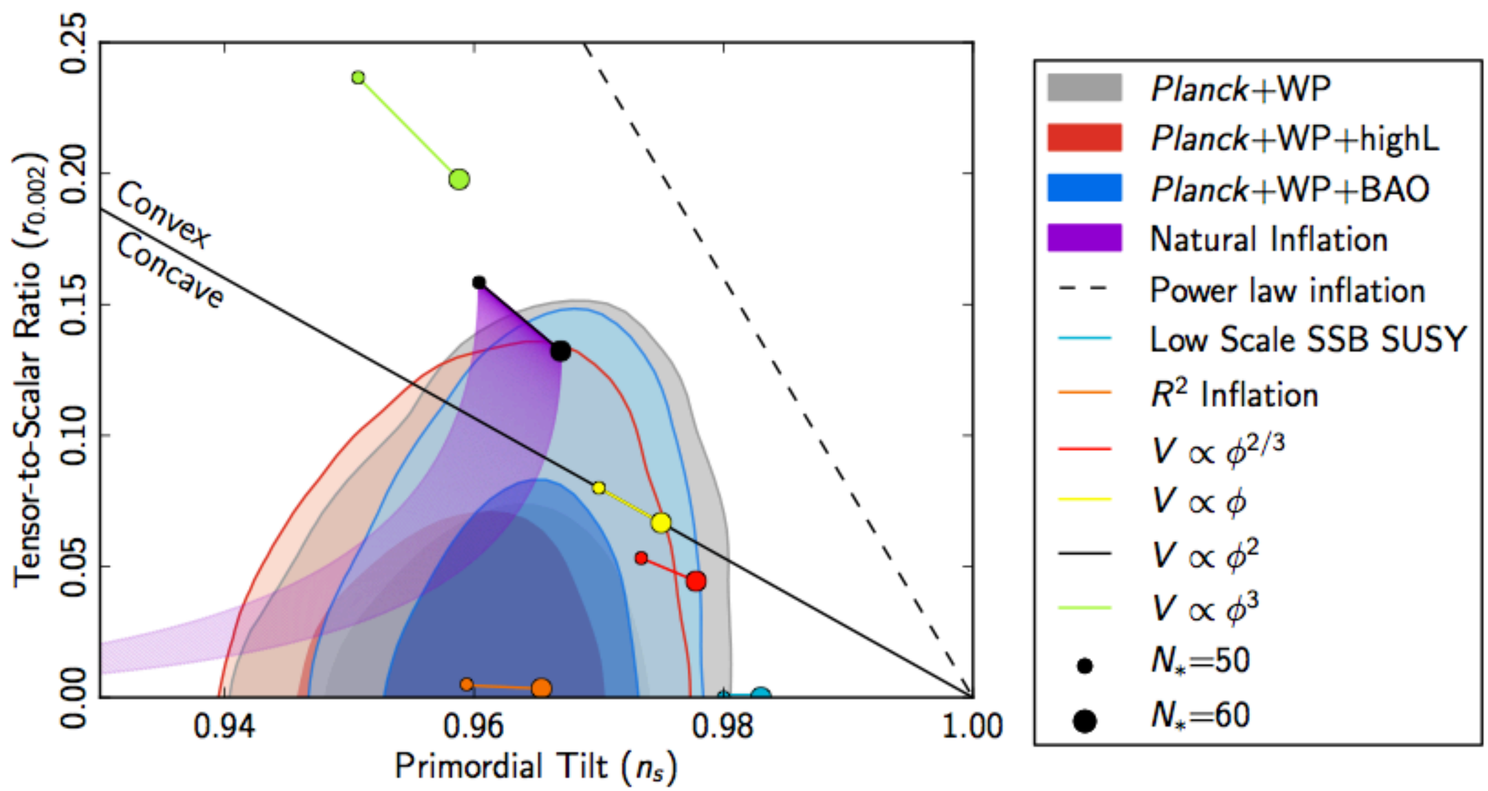
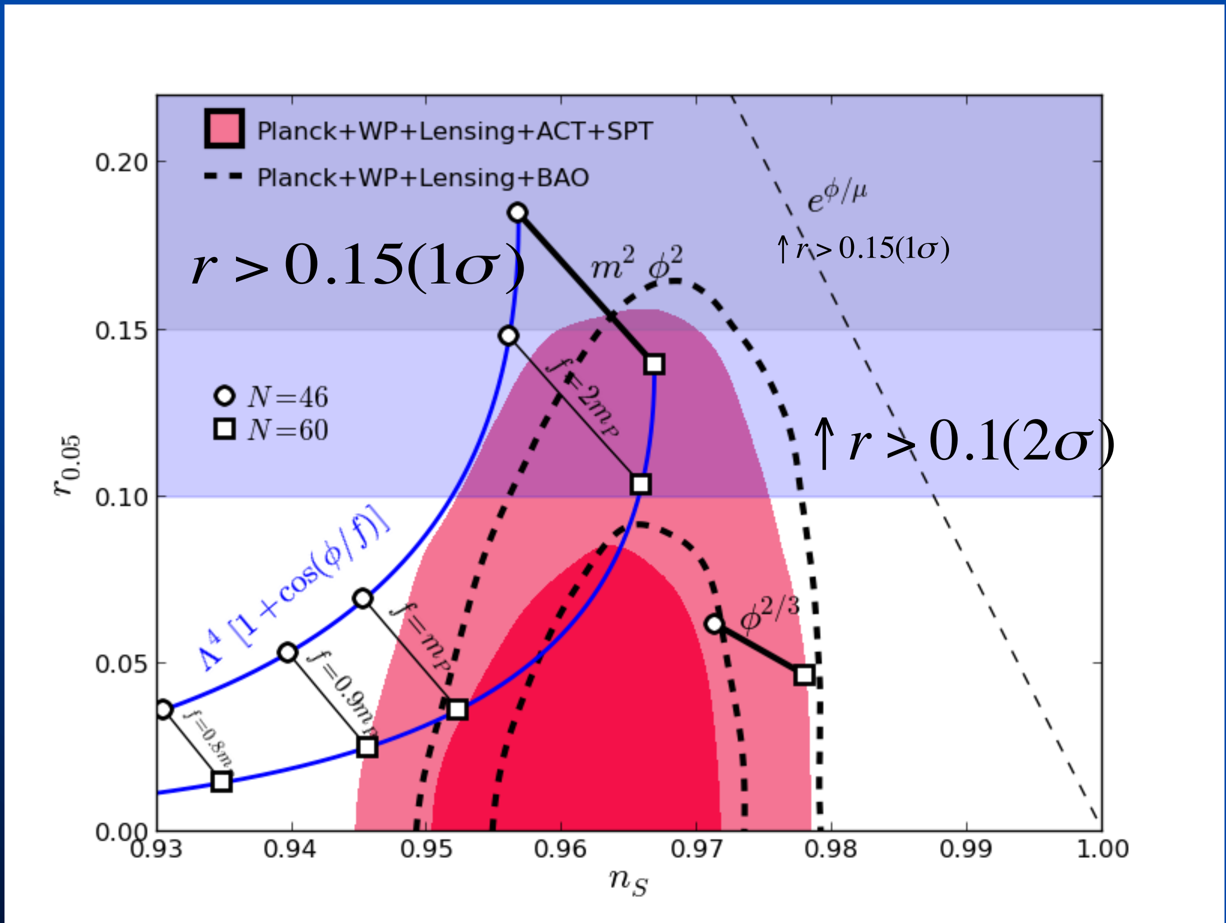


Fig. 1. Marginalized joint 68% and 95% CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets compared to the theoretical predictions of selected inflationary models.

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

Cosine Natural Inflation after BICPE2: good fit for f>mpl

Freese and Kinney 2014

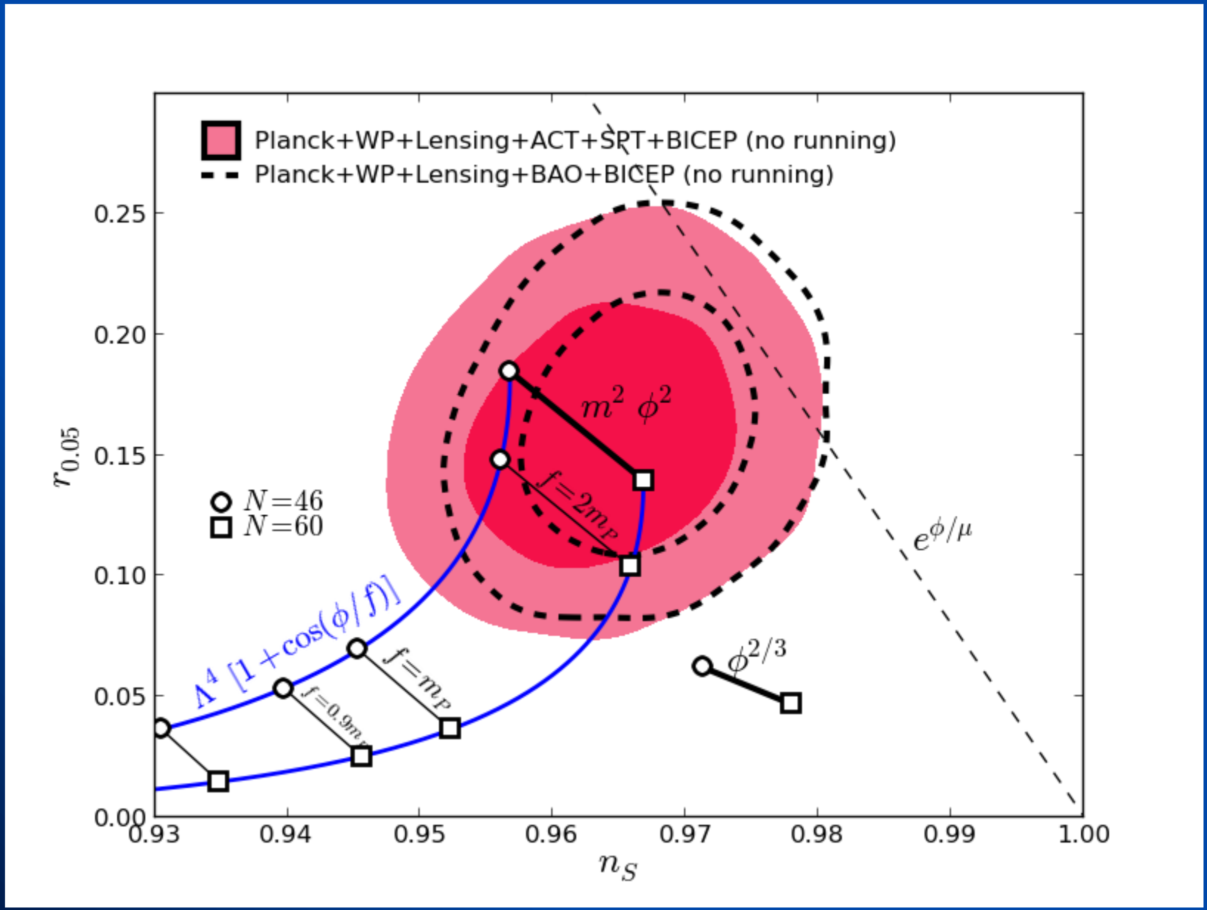


Blue regions indicate BICEP2 data: r>0.15 (1 sigma) and r>0.1 (2 sigma)

V=m^2 phi^2 is limiting case of cosine for large f

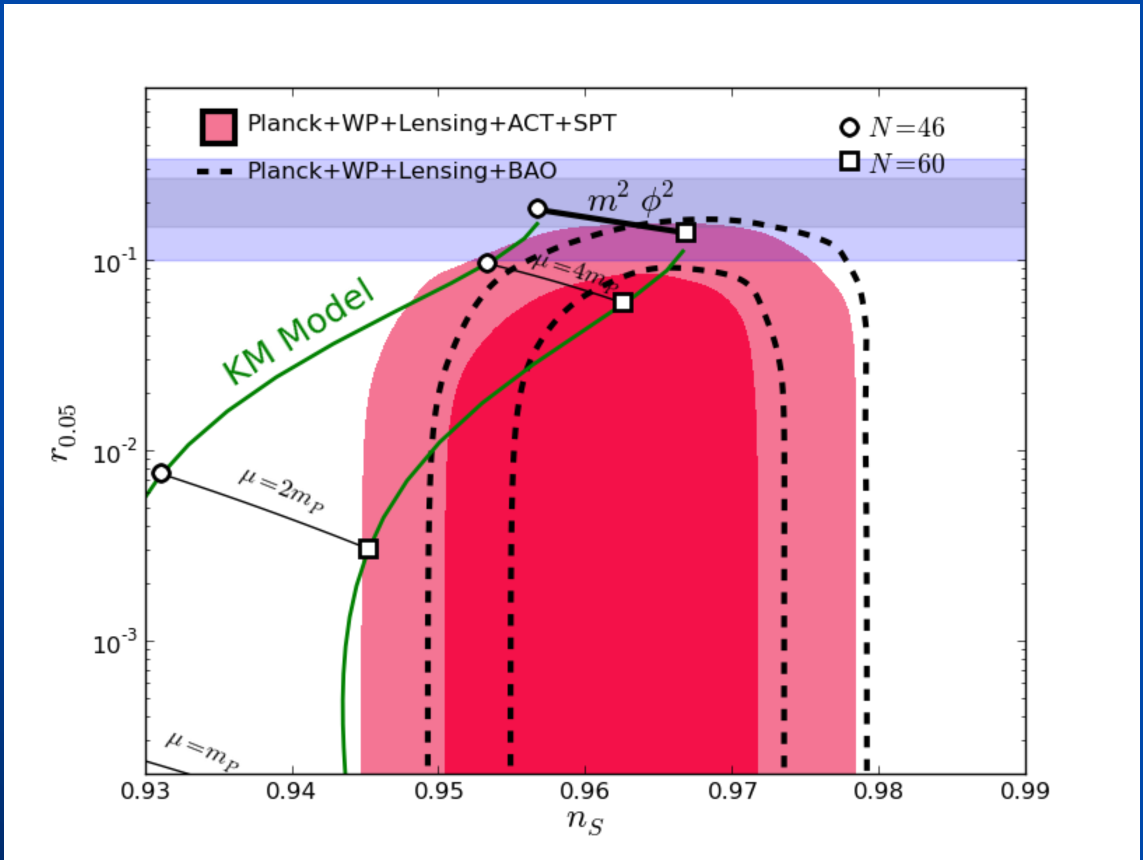
Axion monodromy with linear or phi^2/3 potentials are in tension with BICEP2 at sigma

Cosine Natural Inflation using joint likelihood analysis of Planck and BICEP2

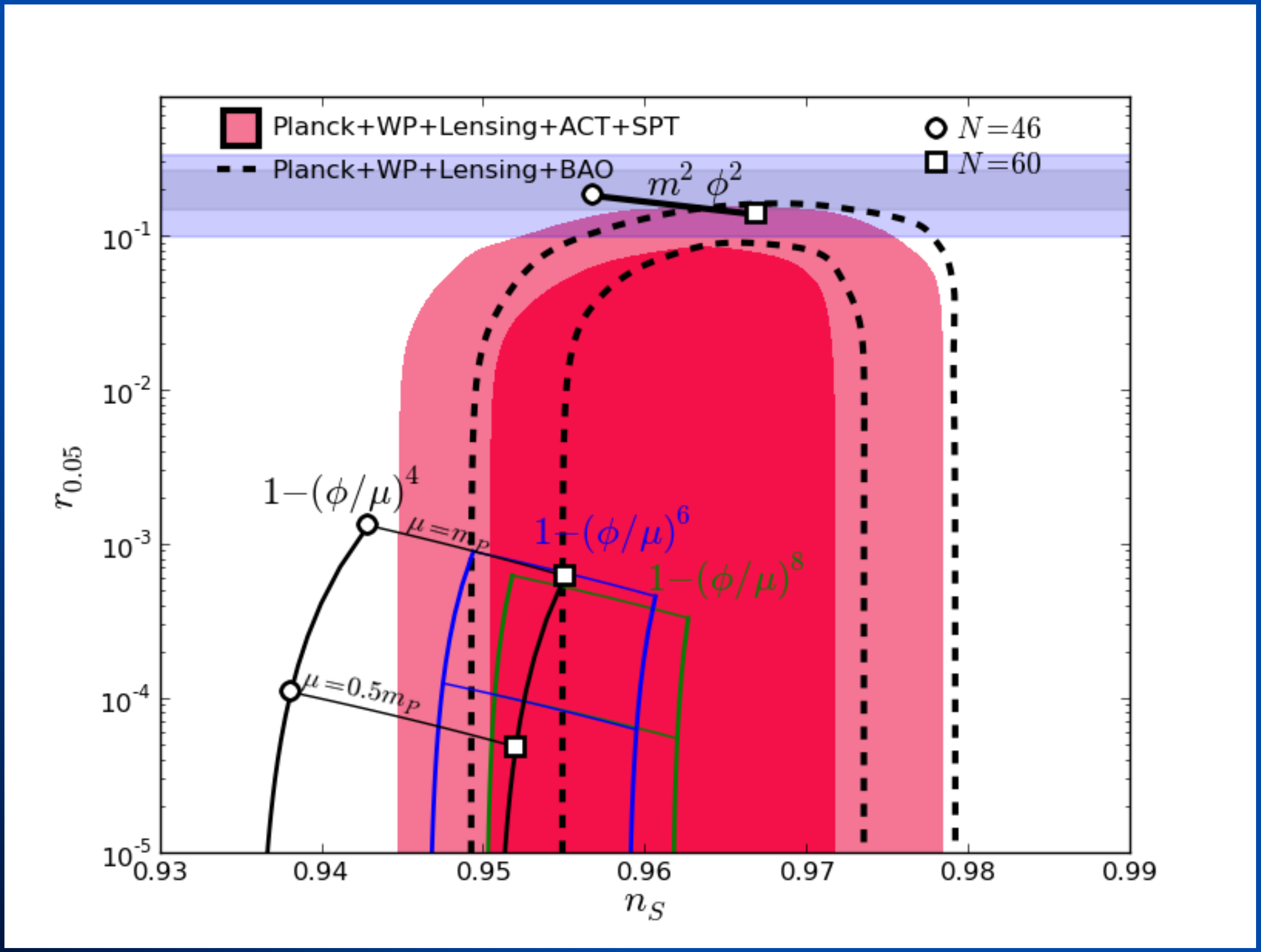


Freese and Kinney 2014

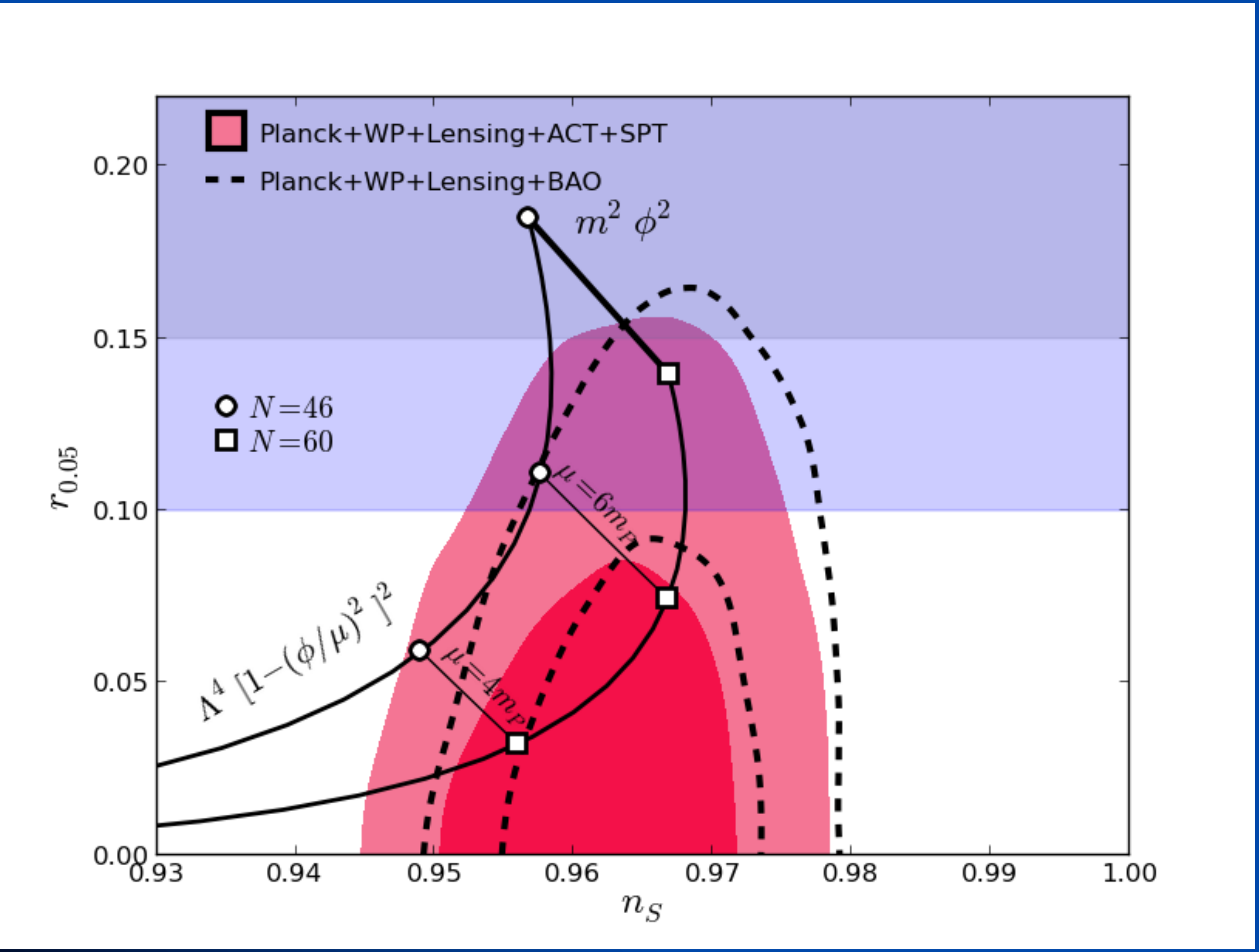
Kinney/Mahantappa NI



Low Scale Inflation (ruled out)



Higgs-like inflation (GUT scale Higgs)



Models remaining after Planck and BICEP2

- Of the thousands of models existing in 2013, most have been ruled out. Simple remaining models:
- 1) $m^2\phi^2$ (Andrei Linde) Flatness of potential remains unexplained (unless motivated by shift symmetry)
- 2) Shift symmetries (natural inflation) are a winning mechanism for generating the inflationary potential

    Original model had cosine-shaped potential

    Today many variants exist

Natural Inflation Summary (for classical cosine model)

- No fine tuning,
  naturally flat potential

- Planck data:

  $f < 0.8\ M_{\rm Pl}$ excluded

  $f > 0.8\ M_{\rm Pl}$ consistent
  - Tensor/scalar ratio r
  - Spectral index n_s
  - Spectral index running $dn_s/d\ln k$

SUMMARY:

- I. The predictions of inflation are right:

  (i) the universe is flat with a critical density $\Omega = 1$

  (ii) superhorizon fluctuations

  (iii) density perturbation spectrum nearly scale invariant

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

  (v) Gravitational wave modes

- II. Data differentiate between models

- -- each model makes specific predictions for density perturbations and gravity modes
- -- WMAP, Planck and BICEP2 rule out most models

  -- **Natural Inflation** (shift symmetries) is great fit to data

Models that survive after Planck and BICEP2 data:

- Of the thousands of models existing in 2013, most have been ruled out. Simple remaining potentials:

- 1) $m^2\phi^2$ Yet the flatness of the potential remains unexplained (unless motivated by shift symmetry)

- 2) Shift symmetries (natural inflation) are a winning mechanism for generating a flat inflationary potential

  Original model had cosine-shaped potential

  Today many variants exist

IMPACT of BICEP2 Results

- First real discovery of gravitational waves predicted by Einstein's relativity
- B mode polarization results from quantum fluctuations of the two polarization modes of the gravitational field.
- Height of the potential at the GUT scale: Opens new window on new regime of physics: the physics of what happens in the first tiny fraction of the history of the Universe, in particular the physics of the unification of the four forces.
- Width of the potential at the Planck scale: Many thought that large field models didn't work because of instability due to quantum physics. But that they do work, so we learn about quantum gravity.
- We are left with a focus on a small range of inflation models

- The tensor perturbations responsible for primordial B-mode polarization are the result of quantum fluctuations of the two polarization modes of the gravitational field. To belabor the point: the inflationary prediction is derived by promoting the fluctuations of the gravitational field operators, imposing canonical commutation relations, specifying the vacuum state, and computing the correlation functions. The tensor fluctuations write quantum gravity on the sky.

Other CMB experiments should test primordial B-modes soon

- Planck polarization to be released next fall (if it’s r=0.2 they should see it)
- South Pole Telescope and Polarbear (already found lensing B-modes)
- the ABS, ACTPOL, and CLASS ground-based telescopes
- the EBEX, SPIDER, and PIPER balloon experiments,

Keck Array Overview

The Keck Array is a suite of telescopes designed to measure the Cosmic Microwave Background polarization at high precision in search of the B-mode signature of inflation. Each Keck telescope duplicates the BICEP2 detector and optical design inside a compact, pulse tube cooled cryostat. This design allows up to five identical telescopes to be deployed on the DASI mount, located at the Martin A. Pomerantz Observatory at Amundsen-Scott South Pole Station.

News from the Pole

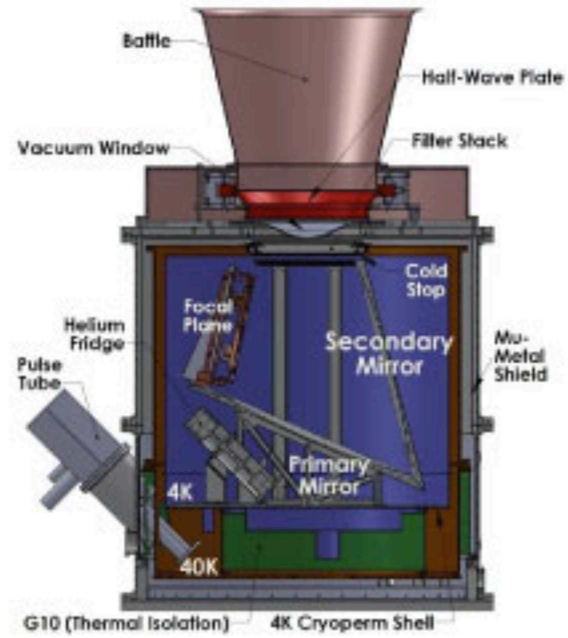
The Keck Array was deployed during the Austral summer of 2010-2011. Three receivers were installed in 2011, with two additional receivers following in 2012. From 2011 to 2013, all receivers observed at 150 GHz. In the 2013-2014 summer season, two out of the five were converted to 100 GHz.

ABS Experiment

Atacama B-mode Search (ABS)

Princeton NIST UBC

The **Atacama B-mode Search** (ABS) is a new experiment to probe the inflationary epoch in the early universe by measuring the patterns of polarization anisotropy in the cosmic microwave background (CMB) at large angular scales. The polarization of the CMB observed on the celestial sphere can be described with a tensor field. Gravitational waves from inflation, if it occurred, lead to a pseudoscalar component of that tensor field, which is quantified versus angular wavenumber as B-modes [1, 2]. ABS is designed to measure the CMB polarization over a wide frequency band at 145 GHz, using novel detectors optimized for polarization, fabricated at NIST. The detectors are bolometers, based on transition-edge sensors (TES), coupled to feedhorns. ABS features a large focal plane array of detectors illuminated by two ≈ 60 cm mirrors cooled to 4 K. The incoming polarization of the CMB is rotated with a warm half-wave plate (HWP) at the dewar aperture. ABS will make observations at a high-altitude site in the Atacama Desert of Chile.



- **Built for rapid deployment to the Atacama Desert, Chile**
- **Targeted at primordial B-modes**
- **Designed for minimal foreground contamination**