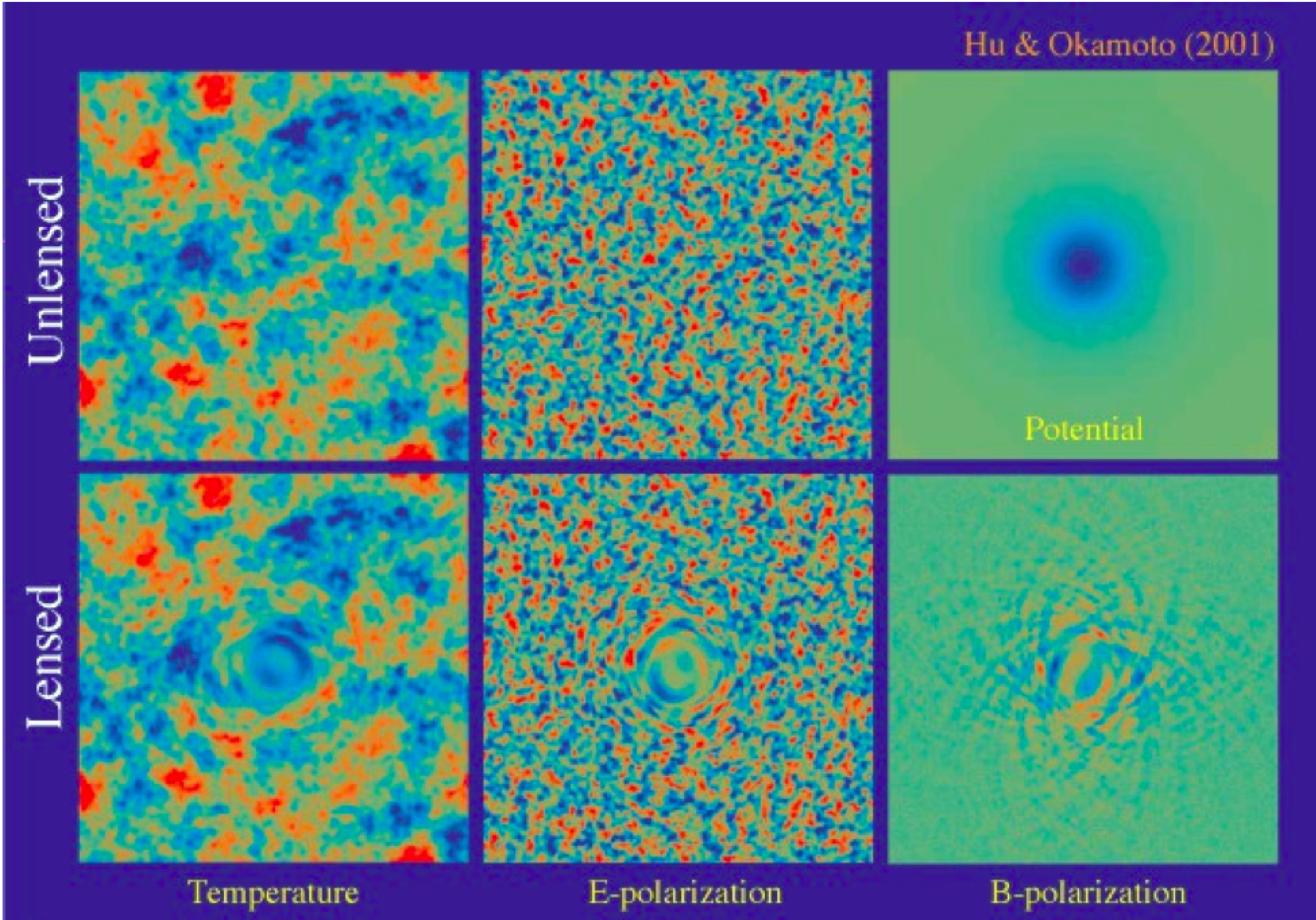
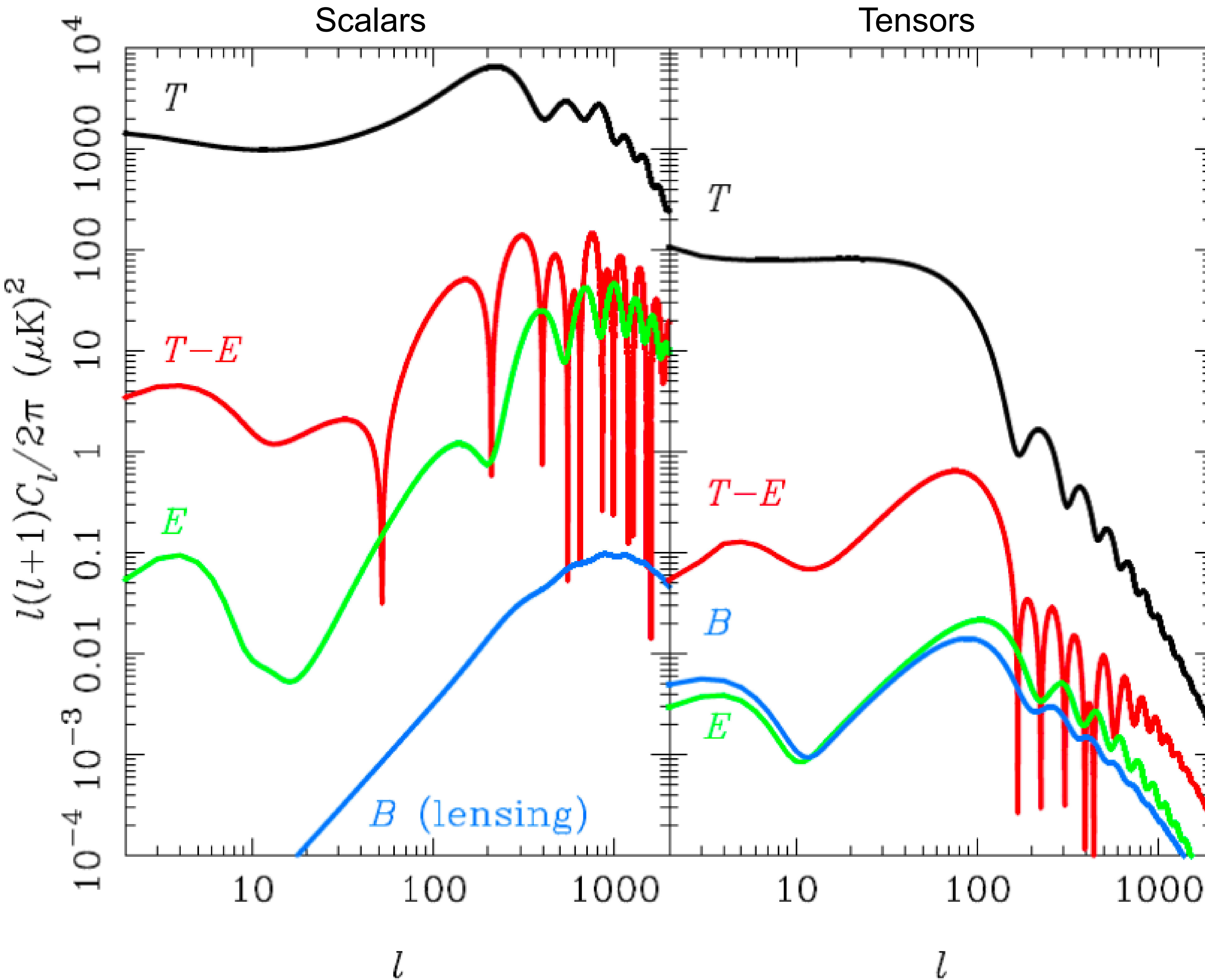

Hu & Okamoto (2001)
Unlensed
Lensed
Potential
Temperature
E-polarization
B-polarization



Scalars
Tensors
$l(l+1)C_l/2\pi\ (\mu K)^2$
10^4
1000
100
10
1
0.1
0.01
10^{-3}
10^{-4}
T
$T-E$
E
B (lensing)
B
10
100
1000
l

Planck versus Inflation

Planck at a glance

Planck (2009-2013)

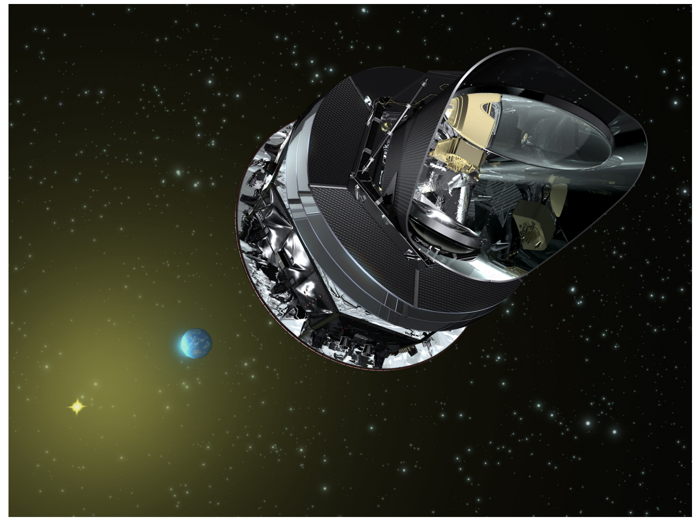
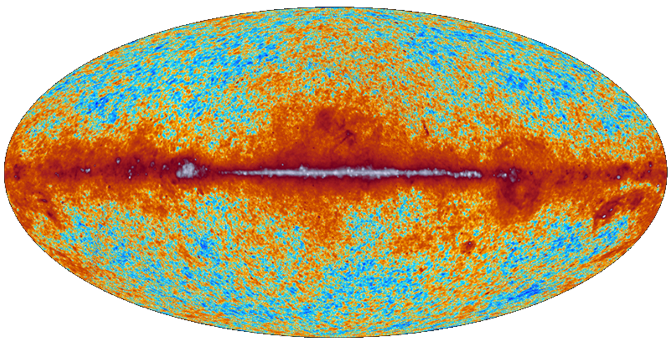


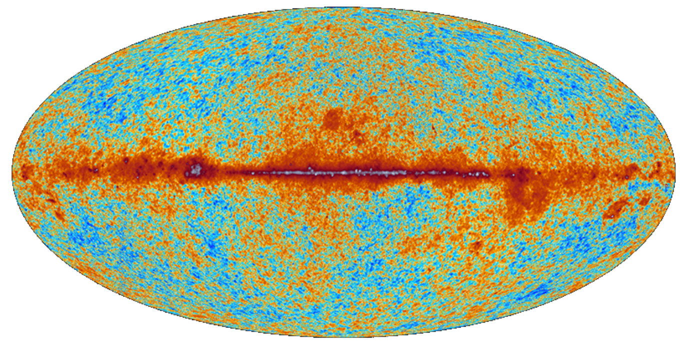
Table 2. *Planck* performance parameters determined from flight data.

	Channel	$N_{\mathrm{detectors}}$[a]	ν_{center}[b] [GHz]	Scanning Beam[c] FWHM [arcm]	Scanning Beam[c] Ellipticity	Noise[d] Sensitivity [$\mu K_{\mathrm{RJ}}\ s^{1/2}$]	Noise[d] Sensitivity [$\mu K_{\mathrm{CMB}}\ s^{1/2}$]
	30 GHz	4	28.4	33.16	1.37	145.4	148.5
LFI	44 GHz	6	44.1	28.09	1.25	164.8	173.2
	70 GHz	12	70.4	13.08	1.27	133.9	151.9
	100 GHz	8	100	9.59	1.21	31.52	41.3
	143 GHz	11	143	7.18	1.04	10.38	17.4
HFI	217 GHz	12	217	4.87	1.22	7.45	23.8
	353 GHz	12	353	4.7	1.2	5.52	78.8
	545 GHz	3	545	4.73	1.18	2.66	0.0259[d]
	857 GHz	4	857	4.51	1.38	1.33	0.0259[d]

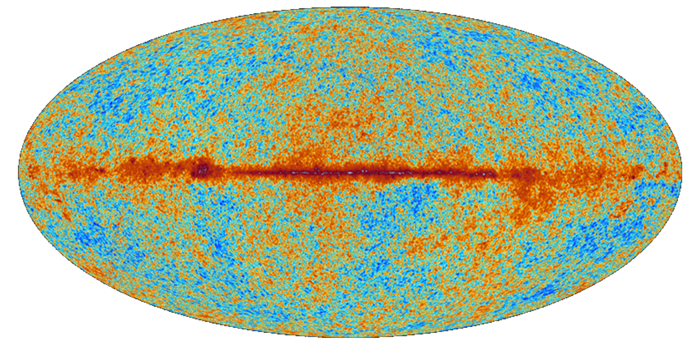
Planck's view of the microwave sky



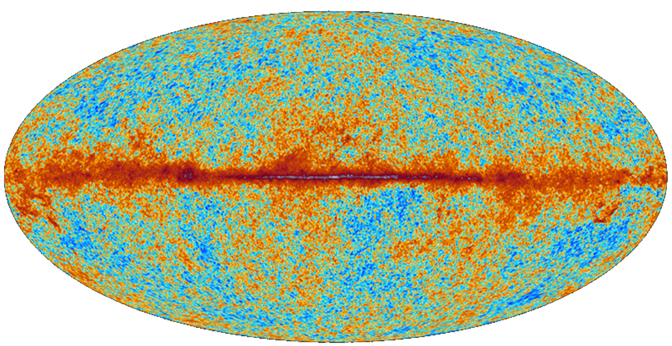
30 Ghz



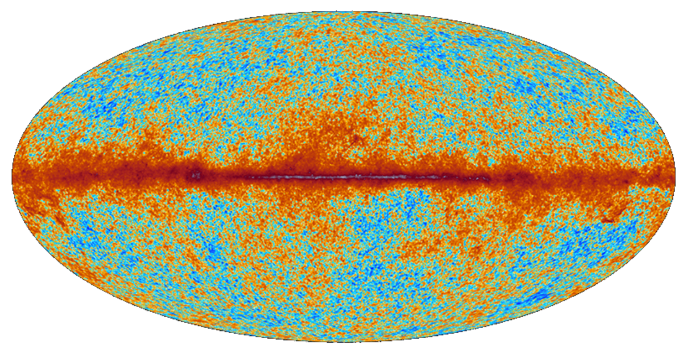
44 Ghz



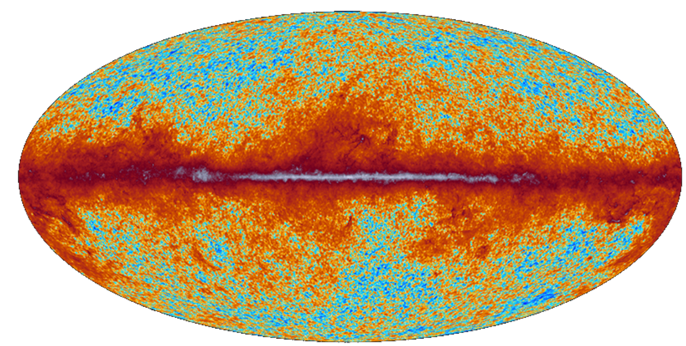
70 Ghz



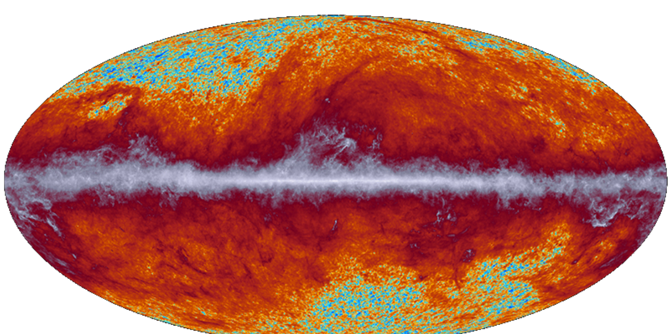
100 GHz



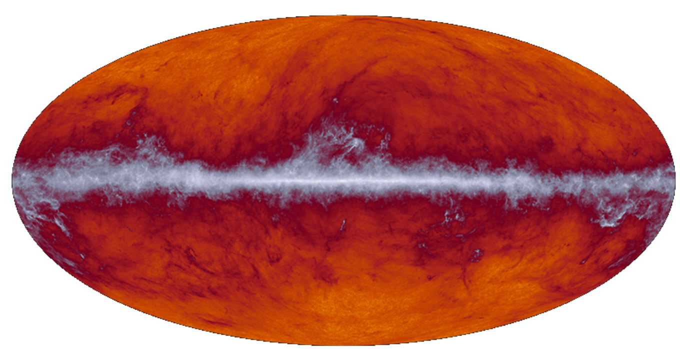
143 Ghz



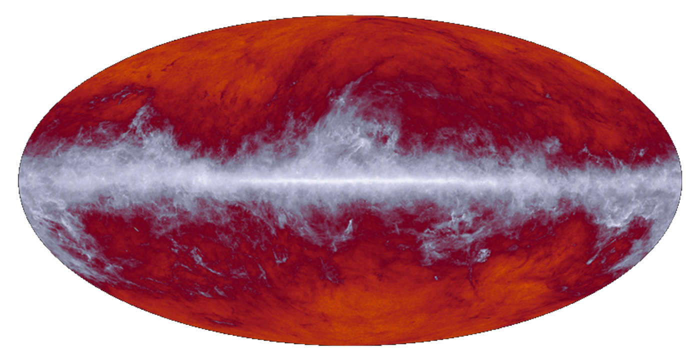
217 Ghz



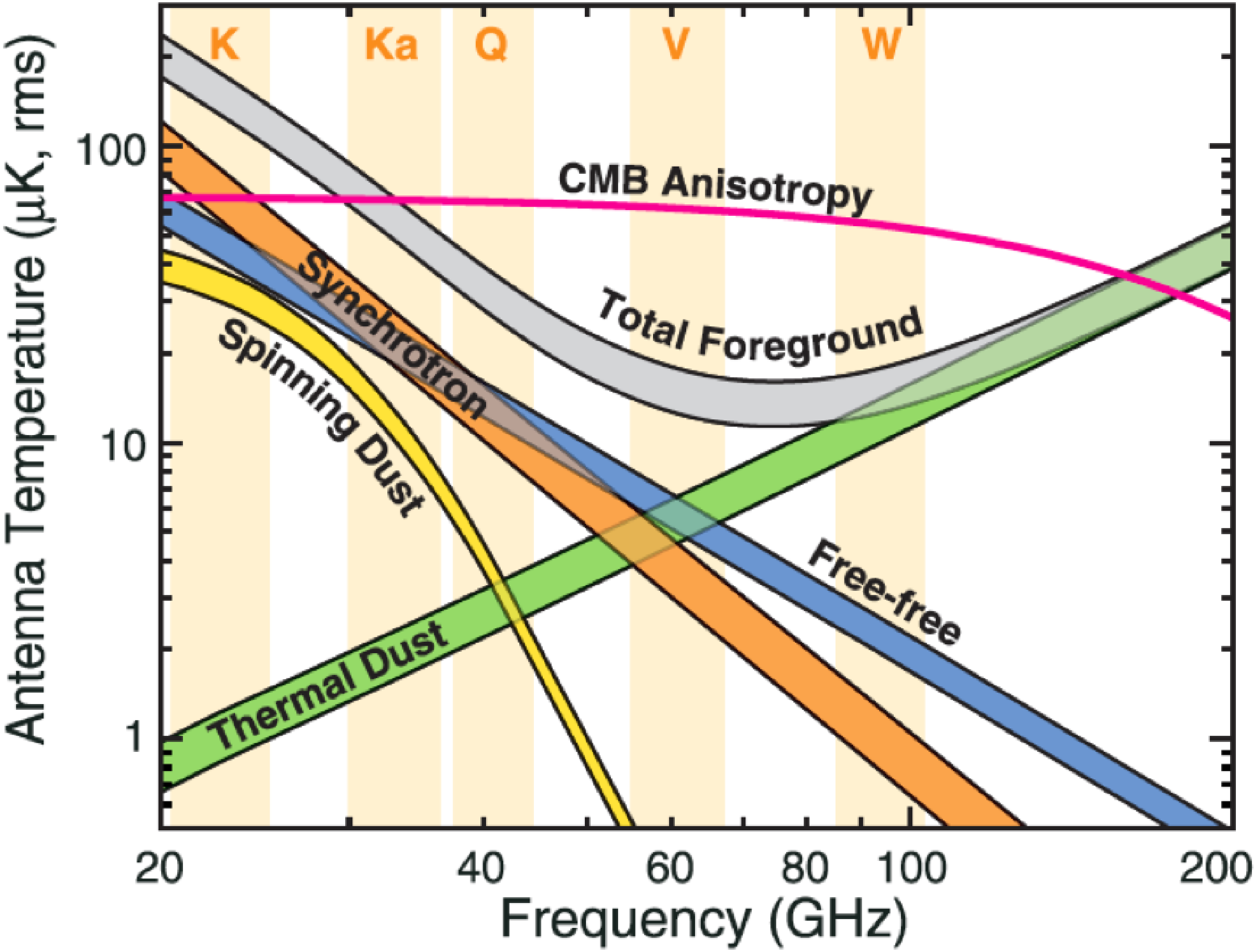
353 Ghz



545 Ghz

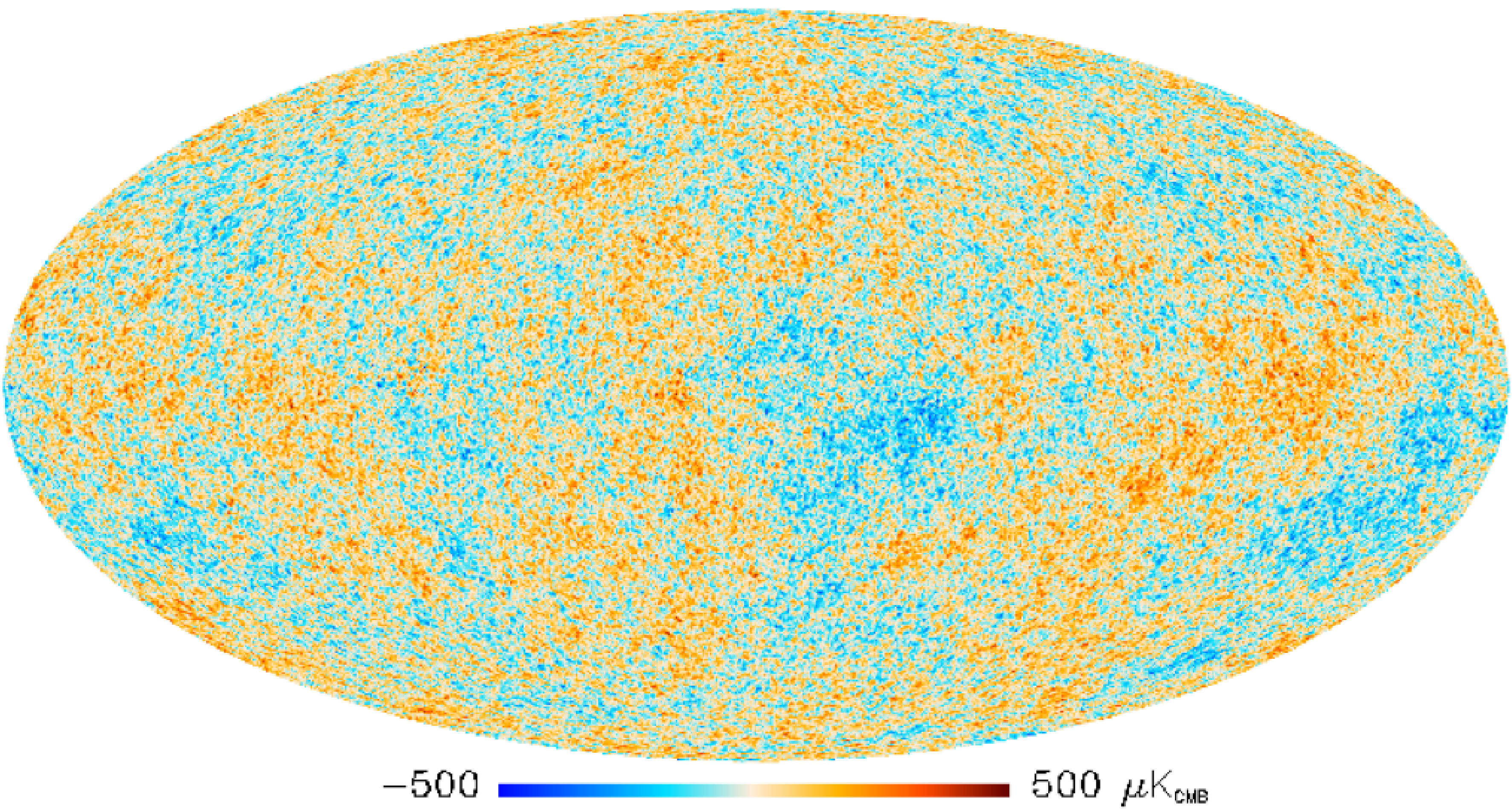


857 Ghz

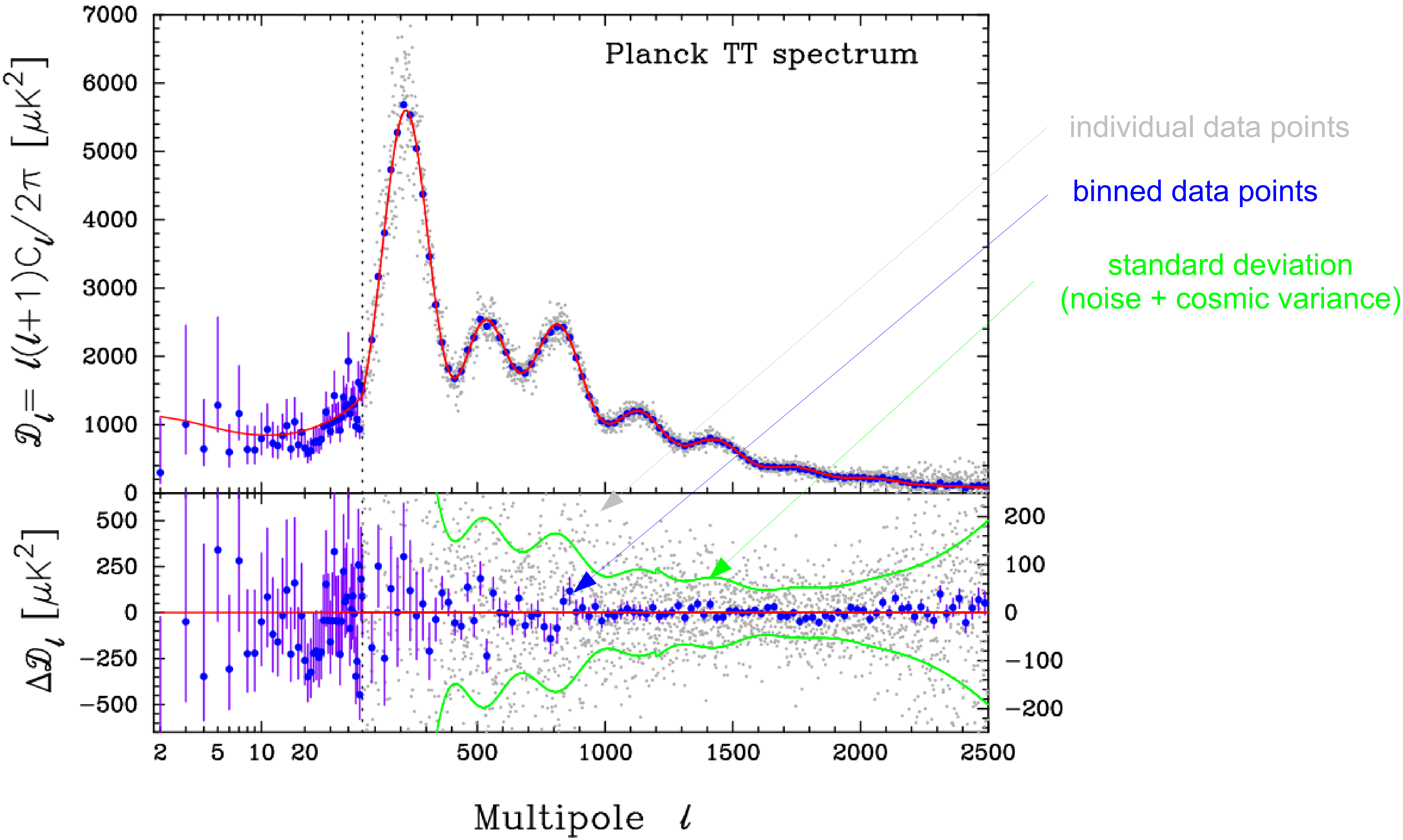

K
Ka
Q
V
W
CMB Anisotropy
Total Foreground
Synchrotron
Spinning Dust
Free-free
Thermal Dust
100
10
1
Antenna Temperature (μK, rms)
20
40
60
80
100
200
Frequency (GHz)

[WMAP 2012]

Cleaned map of CMB temperature anisotropies



Planck (temperature) angular power spectrum



Parameters of the ΛCDM model

Six cosmological parameters:

Hubble parameter

Cold dark matter density

$$A_{\mathrm{s}}, n_{\mathrm{s}}, H_0, \omega_{\mathrm{b}}, \omega_{\mathrm{c}}, \tau$$

Amplitude of initial fluctuations

Spectral index of initial fluctuations

Baryon density

Optical depth to reionisation

plus another 14 “nuisance” parameters for Planck data, describing

- perturbations from
  - the cosmic infrared background (4)
  - unresolved point sources (4)
  - the Sunyaev-Zeldovich effect (3)
- beam shape uncertainties (1)
- relative calibration uncertainties (2)

Predictions of the simplest models

single-field canonical slow-roll inflation

Adiabatic initial conditions

Nearly Gaussian initial fluctuations

$f_{NL} < 1$

Background of gravitational waves (tensor perturbations)

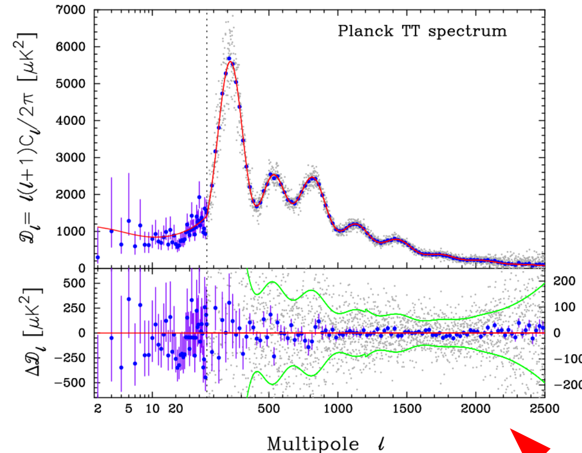
Almost (but not exactly) scale-invariant curvature perturbations

Spatial flatness

$\Omega_K \sim 10^{-5}$

Probing the predictions of inflation

CMB temperature power spectrum
(+ E-polarisation, large scale structure, ...)



Adiabatic initial conditions

Spatial flatness

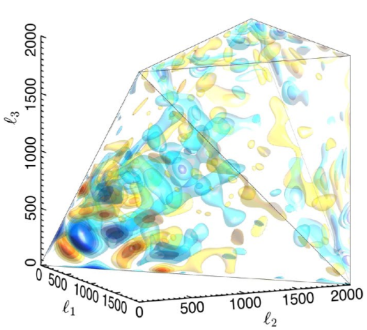
$\Omega_K \sim 10^{-5}$

Nearly Gaussian initial fluctuations

$f_{NL} < 1$

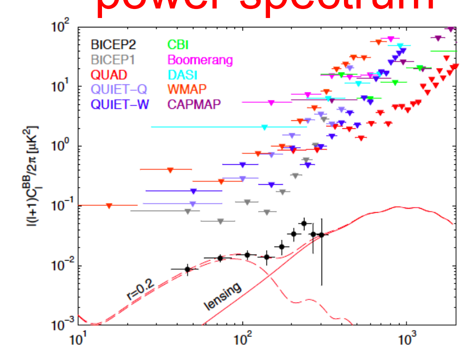
Almost (but not exactly) scale-invariant curvature perturbations

CMB bispectrum



Background of gravitational waves (tensor perturbations)

CMB B-polarisation power spectrum



Spatial curvature

sum of energy densities

Friedmann equation

$$\frac{1}{\rho_{\rm c}}\sum_i \rho_i = 1 + \Omega_k$$

critical density

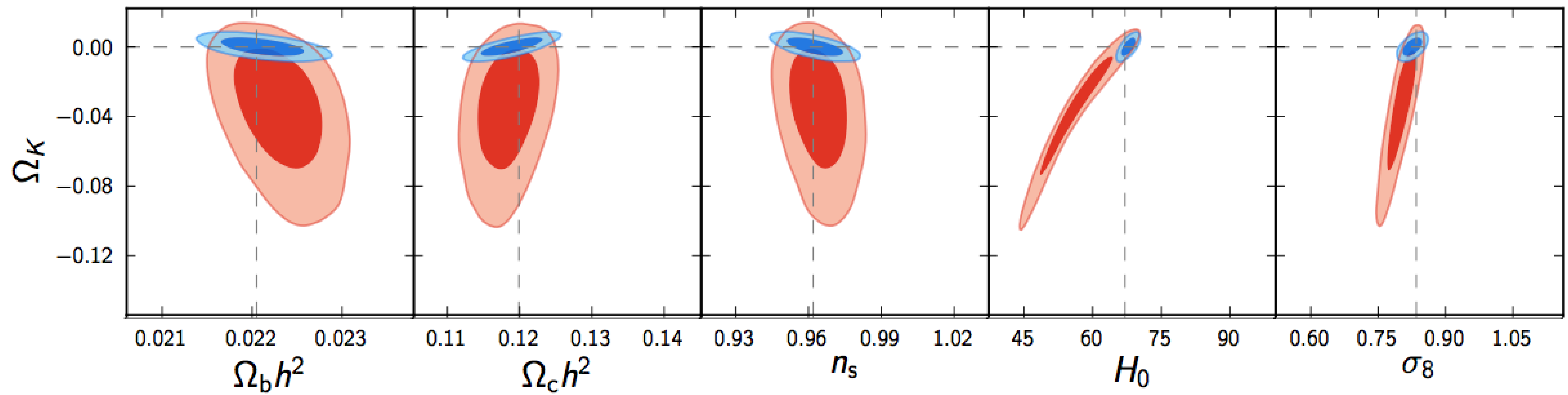
curvature parameter

Spatial flatness: $\Omega_k = 0$

Spatial curvature constraints

Planck + WP

Planck + WP + BAO



Parameter	*Planck*+WP		*Planck*+WP+BAO		*Planck*+WP+highL		*Planck*+WP+highL+BAO	
	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits
Ω_K	−0.0105	$-0.037^{+0.043}_{-0.049}$	0.0000	$0.0000^{+0.0066}_{-0.0067}$	−0.0111	$-0.042^{+0.043}_{-0.048}$	0.0009	$-0.0005^{+0.0065}_{-0.0066}$

No evidence for non-zero spatial curvature

[Planck 2013]

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$\Omega_K \sim 10^{-5}$

The scale-invariant (HZ-) spectrum

Planck + WP data

	HZ	ΛCDM
$10^5\Omega_b h^2$	2296 ± 24	2205 ± 28
$10^4\Omega_c h^2$	1088 ± 13	1199 ± 27
$100\,\theta_{MC}$	1.04292 ± 0.00054	1.04131 ± 0.00063
τ	$0.125^{+0.016}_{-0.014}$	$0.089^{+0.012}_{-0.014}$
$\ln\left(10^{10} A_s\right)$	$3.133^{+0.032}_{-0.028}$	$3.089^{+0.024}_{-0.027}$
n_s	—	0.9603 ± 0.0073
N_{eff}	—	—
Y_P	—	—
$-2\Delta\ln(\mathcal{L}_{max})$	27.9	0

Scale-invariant spectrum ($n_s = 1$, "white noise") is now ruled out at more than 5σ from *Planck* + WP data alone

Even for extended models, still disfavoured at 3σ, when combined with BAO data

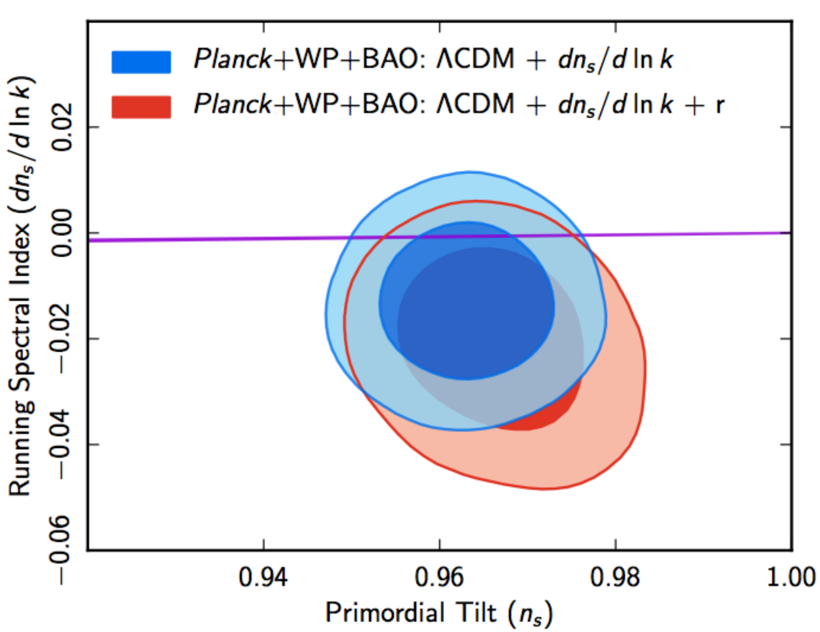
→ strong argument for dynamical generation of primordial perturbation

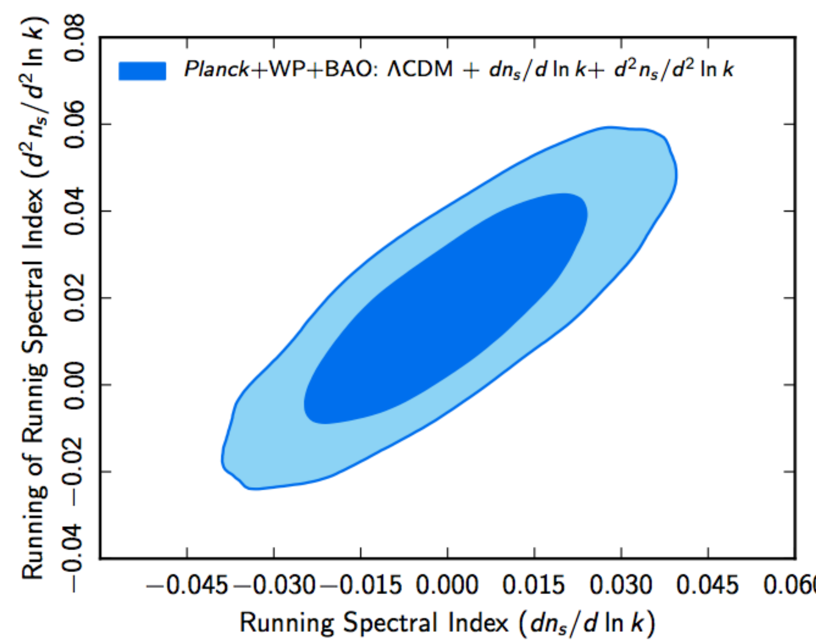
Higher order terms in the power spectrum

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

running
of the spectral index

running of the running
of the spectral index





Predictions of the simplest models

single-field canonical slow-roll inflation

Adiabatic initial conditions

Nearly Gaussian initial fluctuations

$f_{NL} < 1$

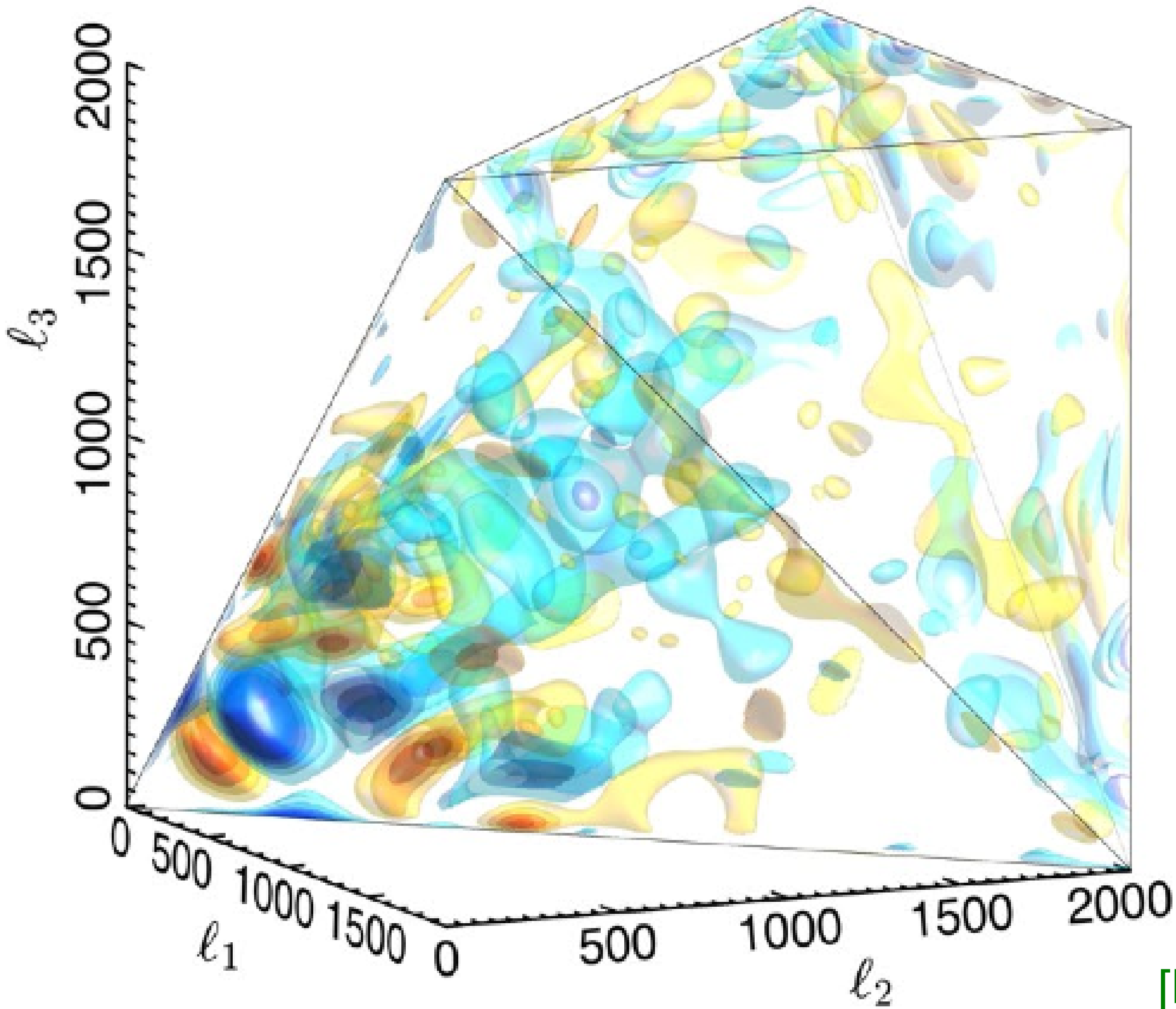
Background of gravitational waves (tensor perturbations)

Almost (but not exactly) scale-invariant curvature perturbations

Spatial flatness

$\Omega_K \sim 10^{-5}$

Non-Gaussianity: CMB angular bispectrum



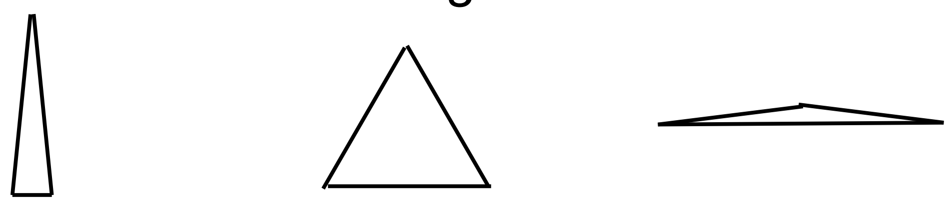
[Planck 2013]

Non-Gaussianity

$$\underbrace{\langle\Phi(\vec{k}_1)\Phi(\vec{k}_2)\Phi(\vec{k}_3)\rangle}_{\text{Three-point correlation}} = (2\pi)^3\,\delta^{(3)}(\vec{k}_1+\vec{k}_2+\vec{k}_3)\;\underbrace{f_{\rm NL}\;F(k_1,k_2,k_3)}_{\text{Bispectrum}}$$

enforces triangular configurations

Three limiting cases

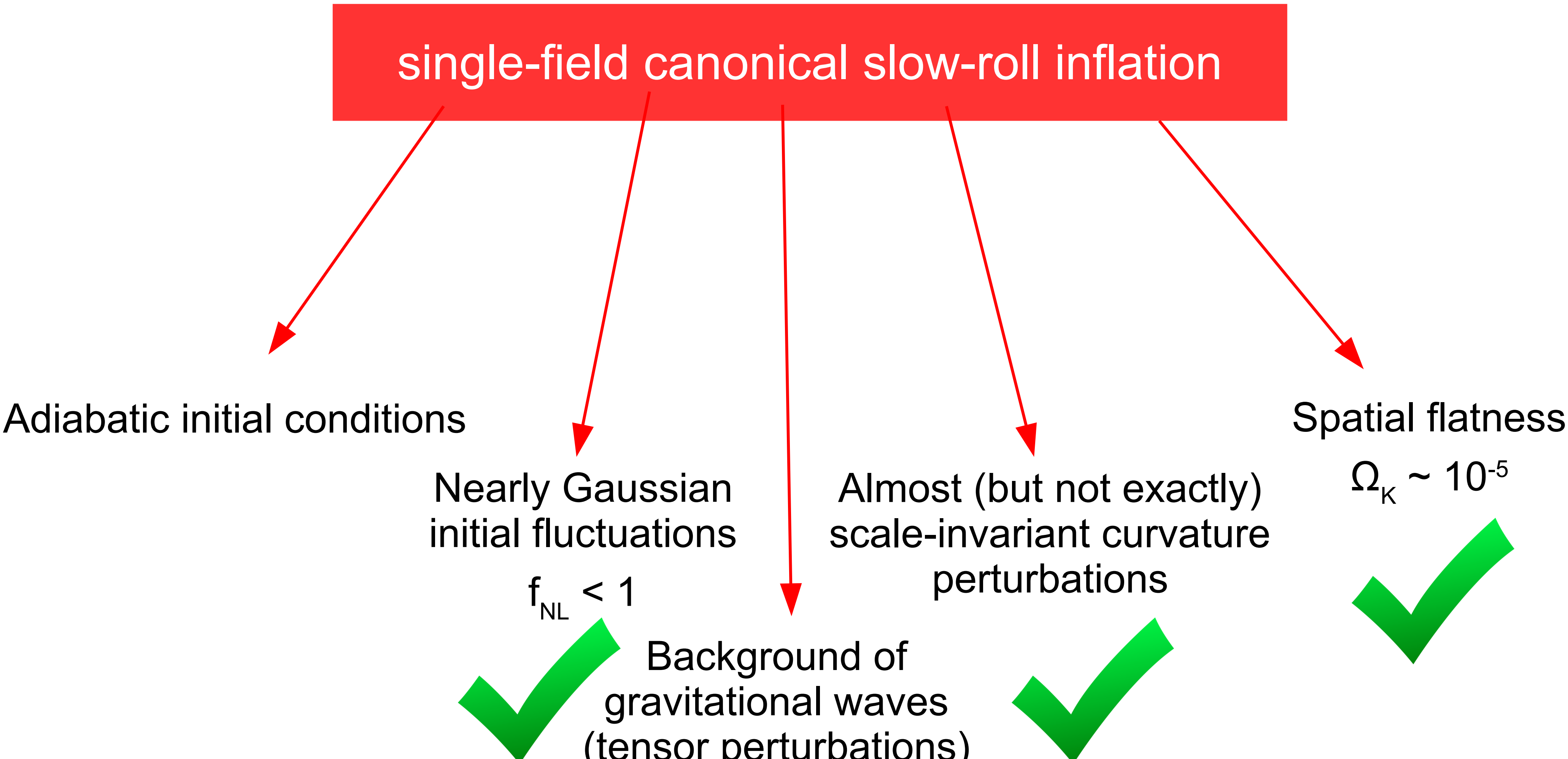


$f_{\rm NL}$		
Local	Equilateral	Orthogonal
2.7 ± 5.8	-42 ± 75	-25 ± 39

No evidence for non-Gaussianity

[Planck 2013]

Predictions of the simplest models



Adiabaticity: constraints on isocurvature perturbations

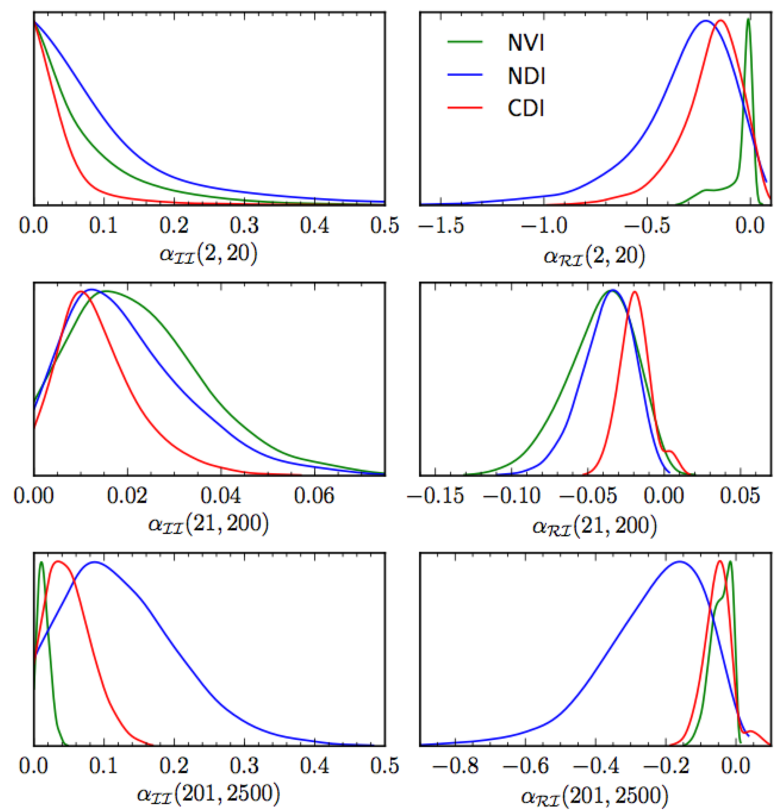
Isocurvature fraction at ...

Types of isocurvature

Large scales

Intermediate scales

Small scales



Neutrino velocity
Neutrino density
CDM density

Planck data are perfectly compatible with adiabatic initial conditions

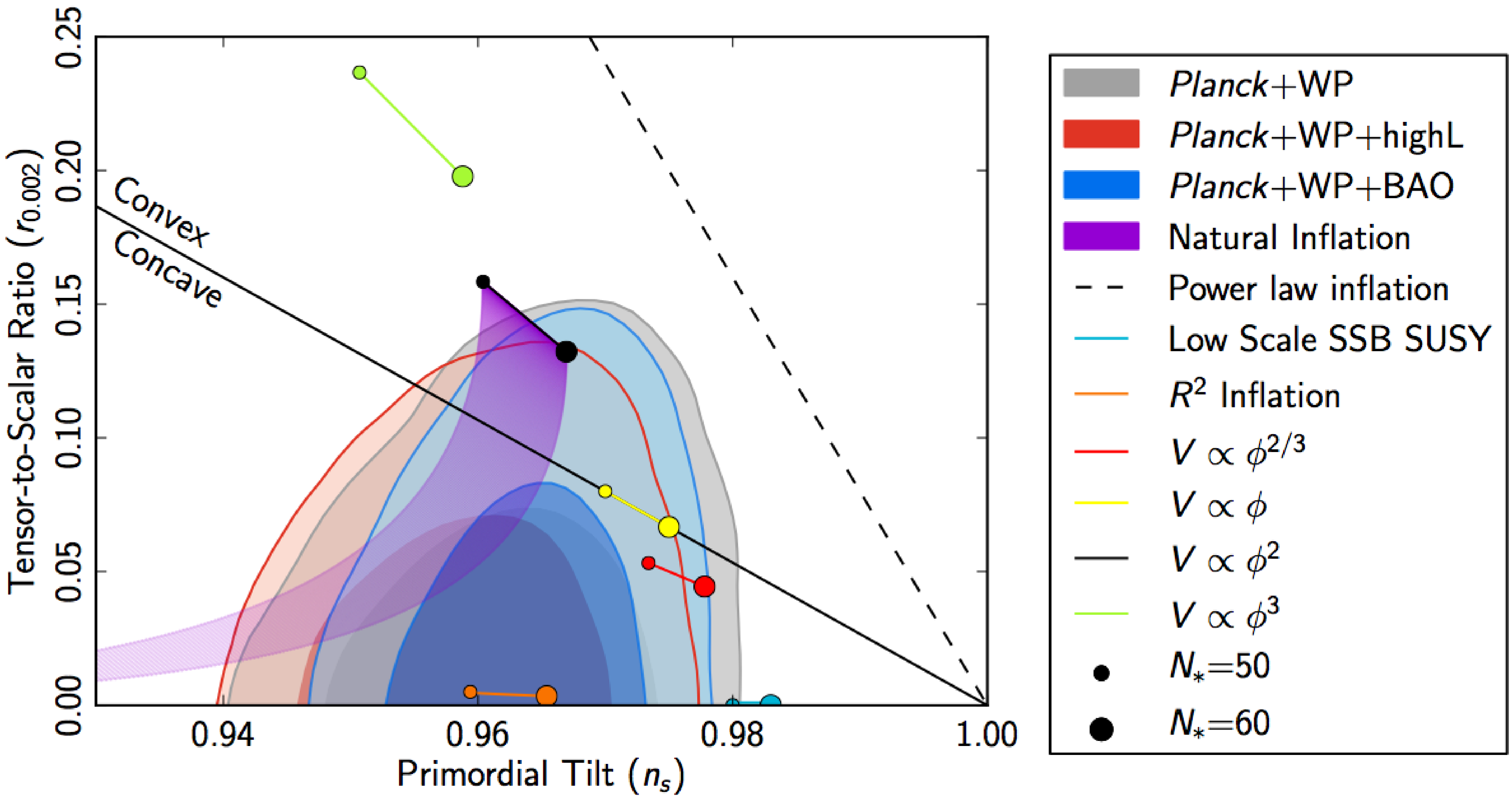
[Planck 2013]

Status of inflation pre BICEP2

single-field canonical slow-roll inflation

- Adiabatic initial conditions ✓
- Nearly Gaussian initial fluctuations $f_{NL} < 1$ ✓
- Background of gravitational waves (tensor perturbations)
- Almost (but not exactly) scale-invariant curvature perturbations ✓
- Spatial flatness $\Omega_K \sim 10^{-5}$ ✓

Constraints on a selection of inflation models



Status of inflation pre BICEP2

single-field canonical slow-roll inflation

Adiabatic initial conditions

Nearly Gaussian initial fluctuations

$f_{NL} < 1$

Background of gravitational waves (tensor perturbations)

Almost (but not exactly) scale-invariant curvature perturbations

Spatial flatness

$\Omega_K \sim 10^{-5}$

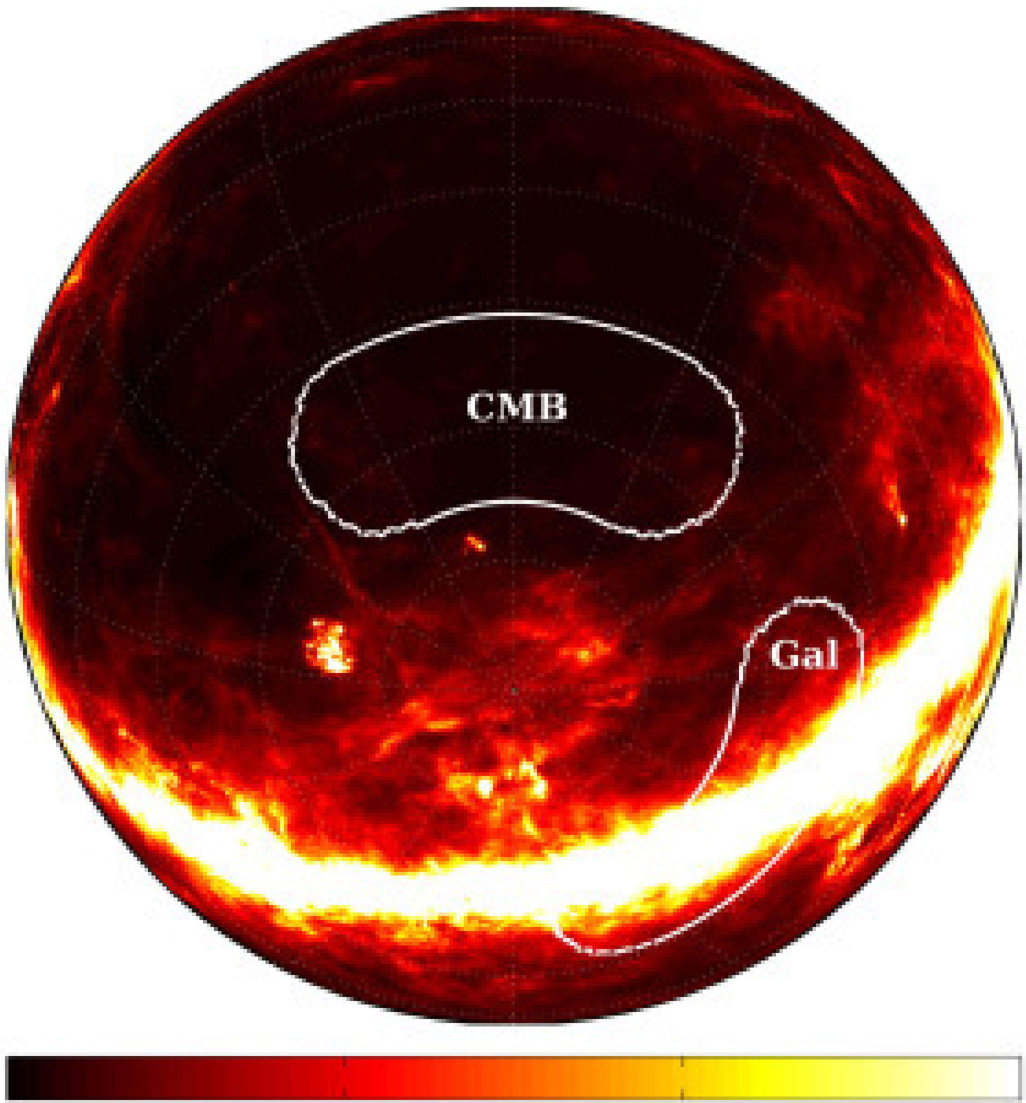
$r < 0.11$ (@95% c.l.)

BICEP2

BICEP2

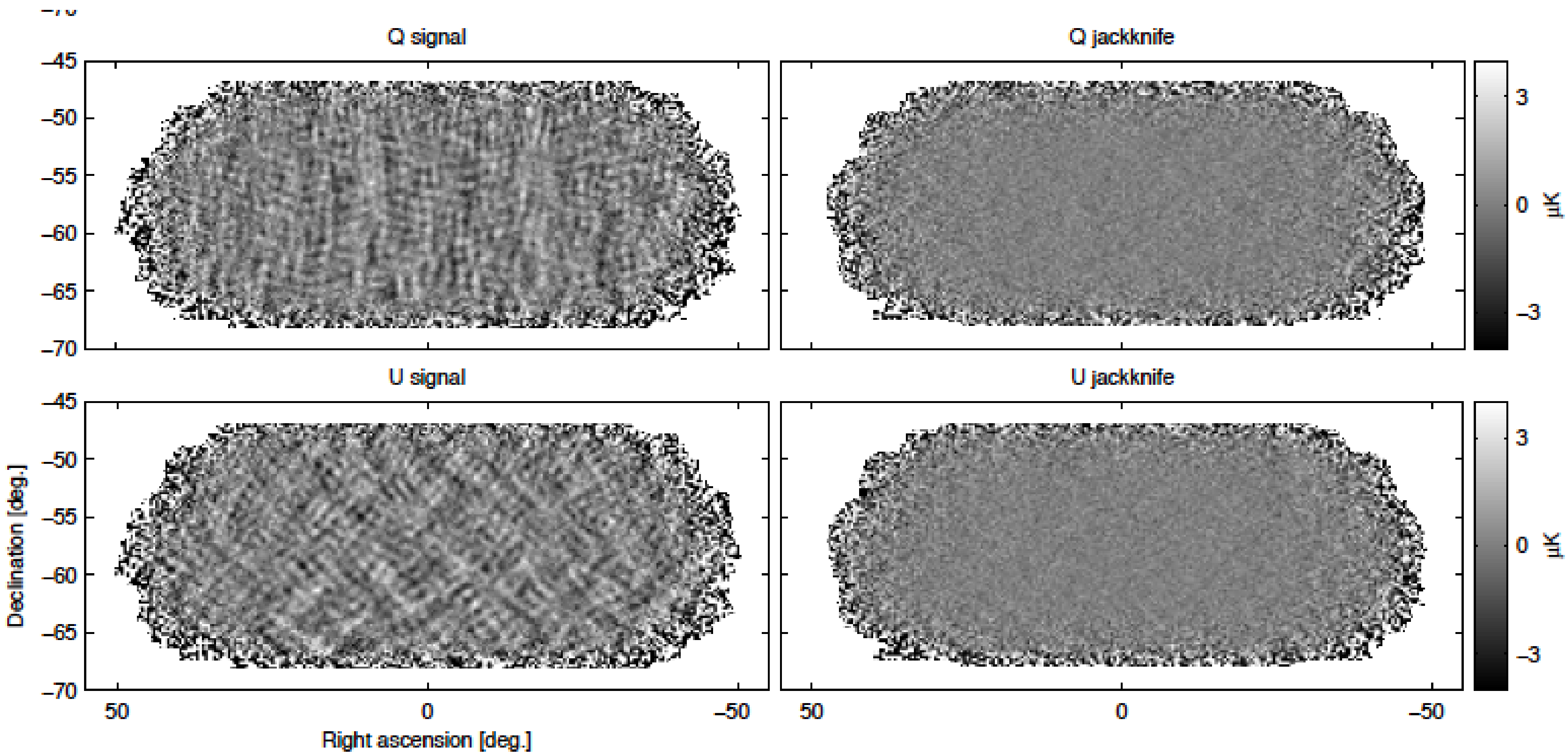
BICEP2 is a microwave telescope at the south pole, and measured the CMB at a frequency of 150 GHz

BICEP2: survey area



[BICEP2 2014]

BICEP2: polarisation maps Q/U



[BICEP2 2014]

BICEP2: polarisation maps E/B

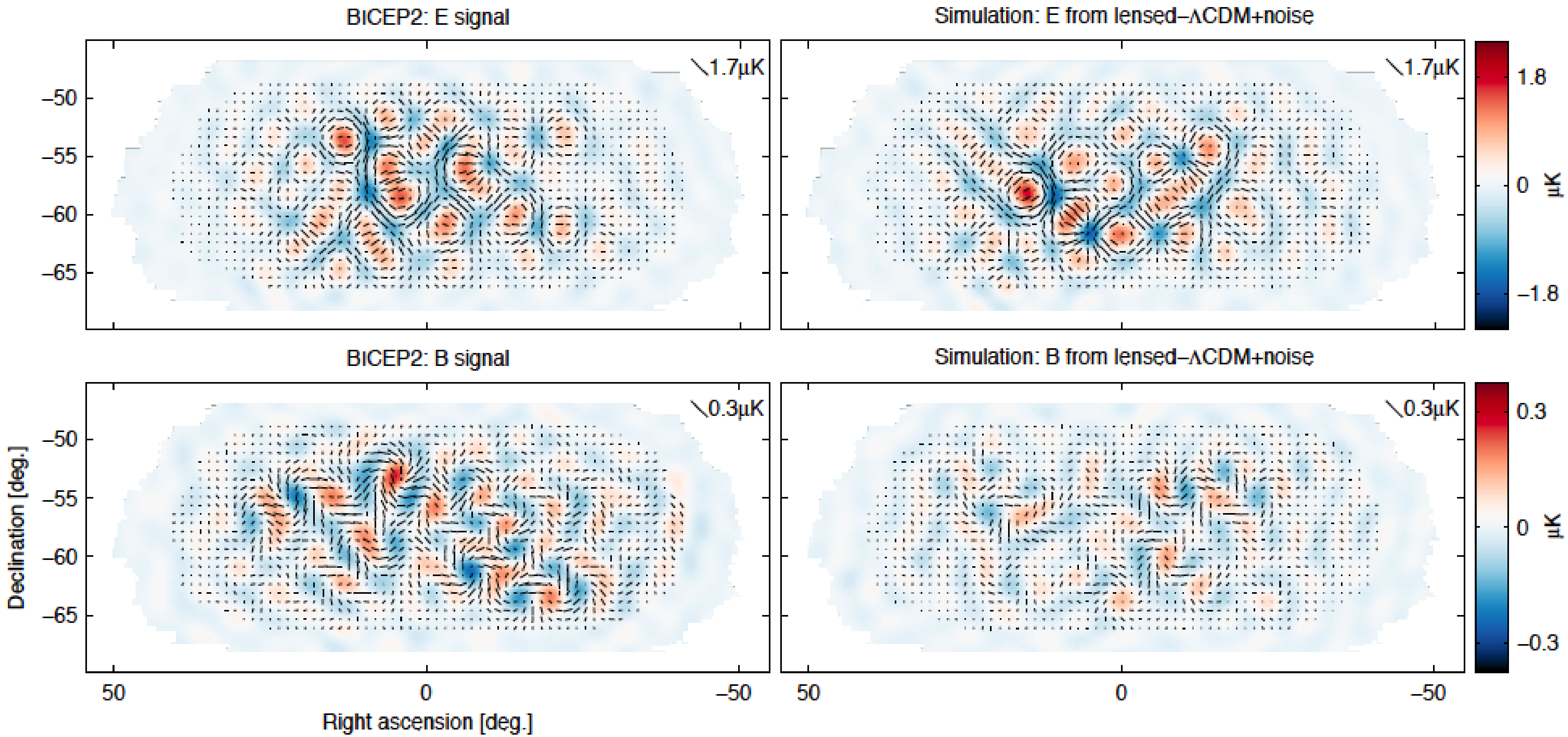


FIG. 3.— *Left:* BICEP2 apodized *E*-mode and *B*-mode maps filtered to $50 < \ell < 120$. *Right:* The equivalent maps for the first of the lensed-ΛCDM+noise simulations. The color scale displays the *E*-mode scalar and *B*-mode pseudoscalar patterns while the lines display the equivalent magnitude 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.)

[BICEP2 2014]

BICEP2: angular power spectra

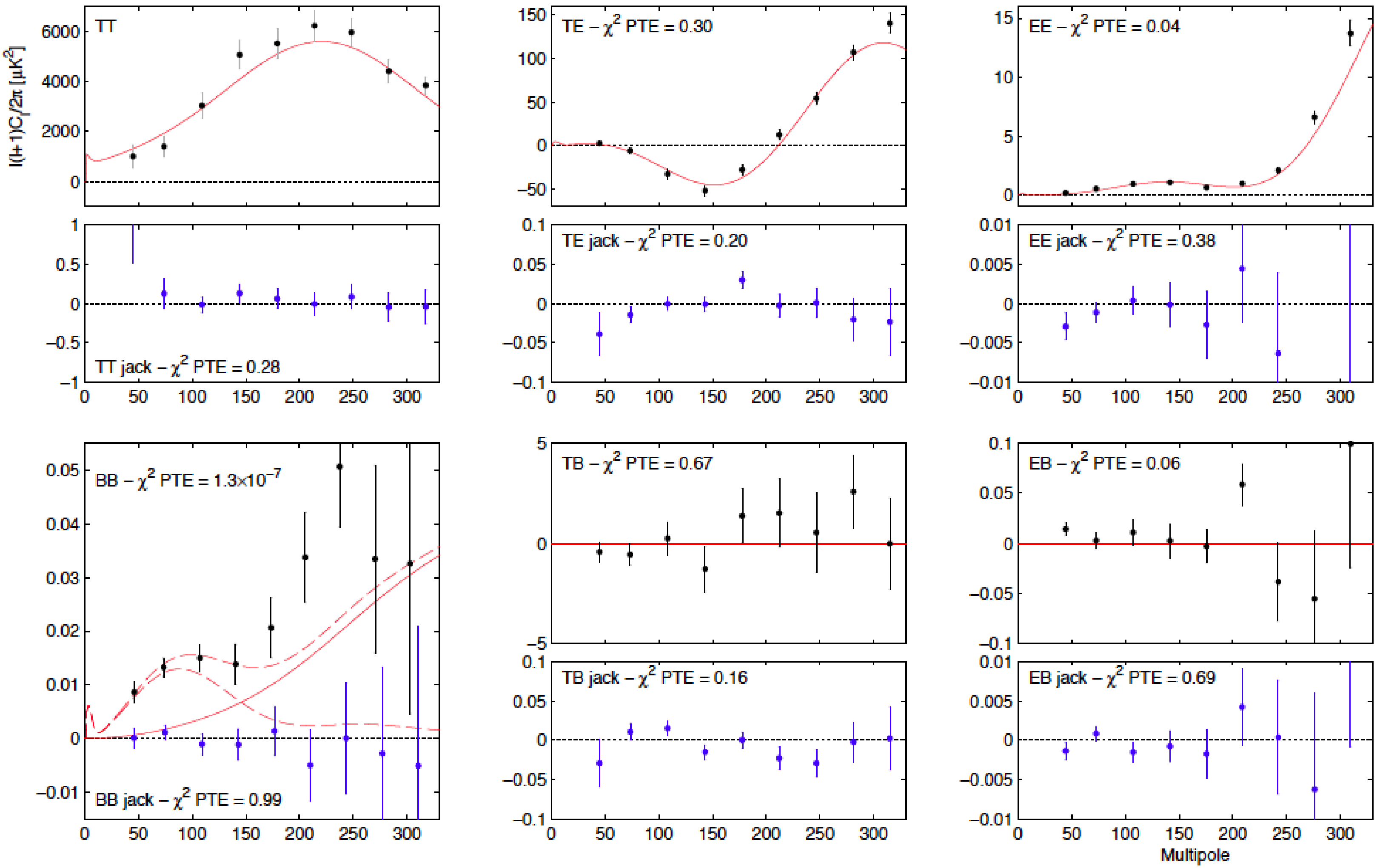
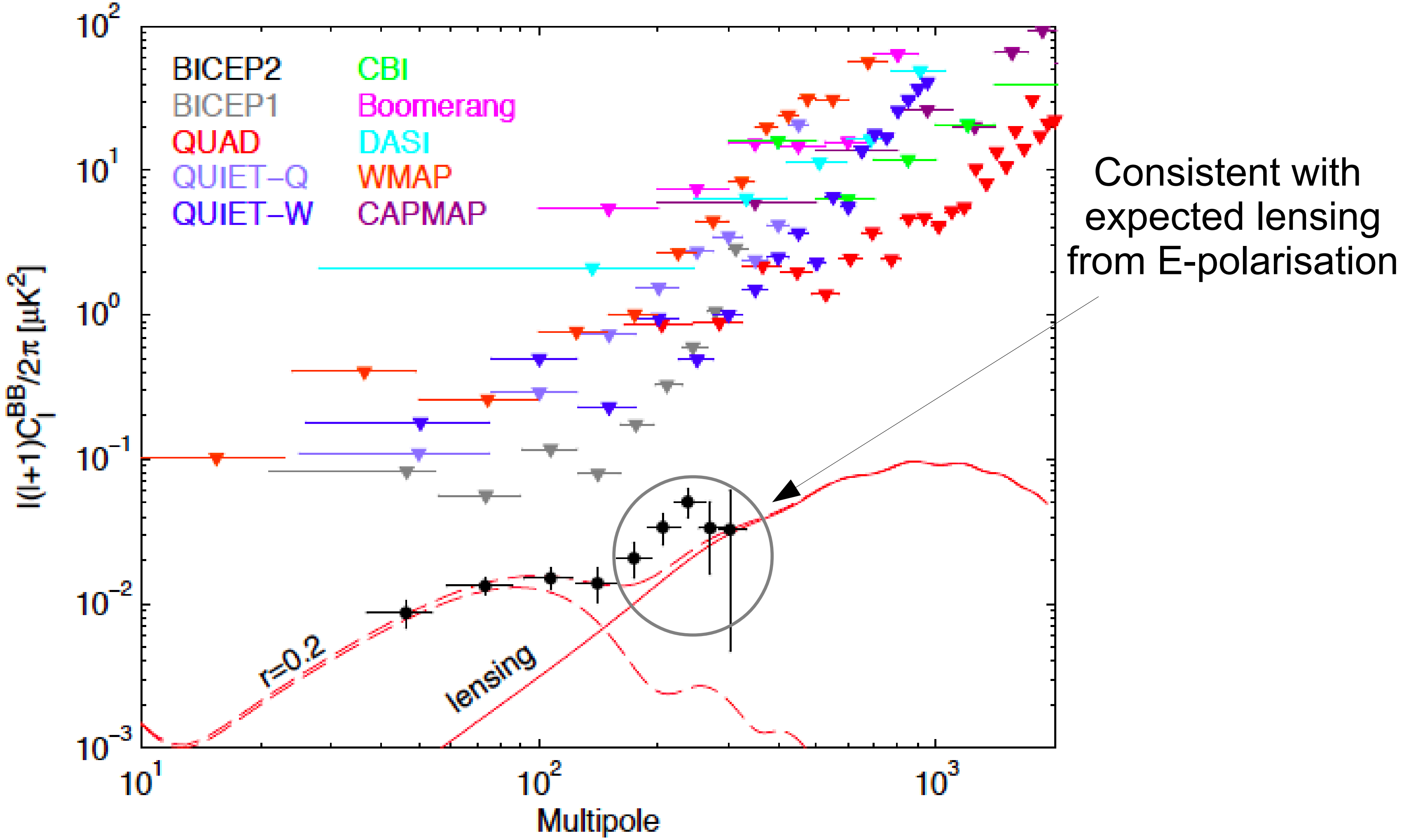


FIG. 2.— BICEP2 power spectrum results for signal (black points) and temporal-split jackknife (blue points). The red curves show the lensed-ΛCDM theory expectations — in the case of *BB* an $r = 0.2$ spectrum is also shown. The error bars are the standard deviations of the lensed-ΛCDM+noise simulations. The probability to exceed (PTE) the observed value of a simple χ^2 statistic is given (as evaluated against the simulations). Note the very different y-axis scales for the jackknife spectra (other than *BB*). See the text for additional discussion of the *BB* spectrum.

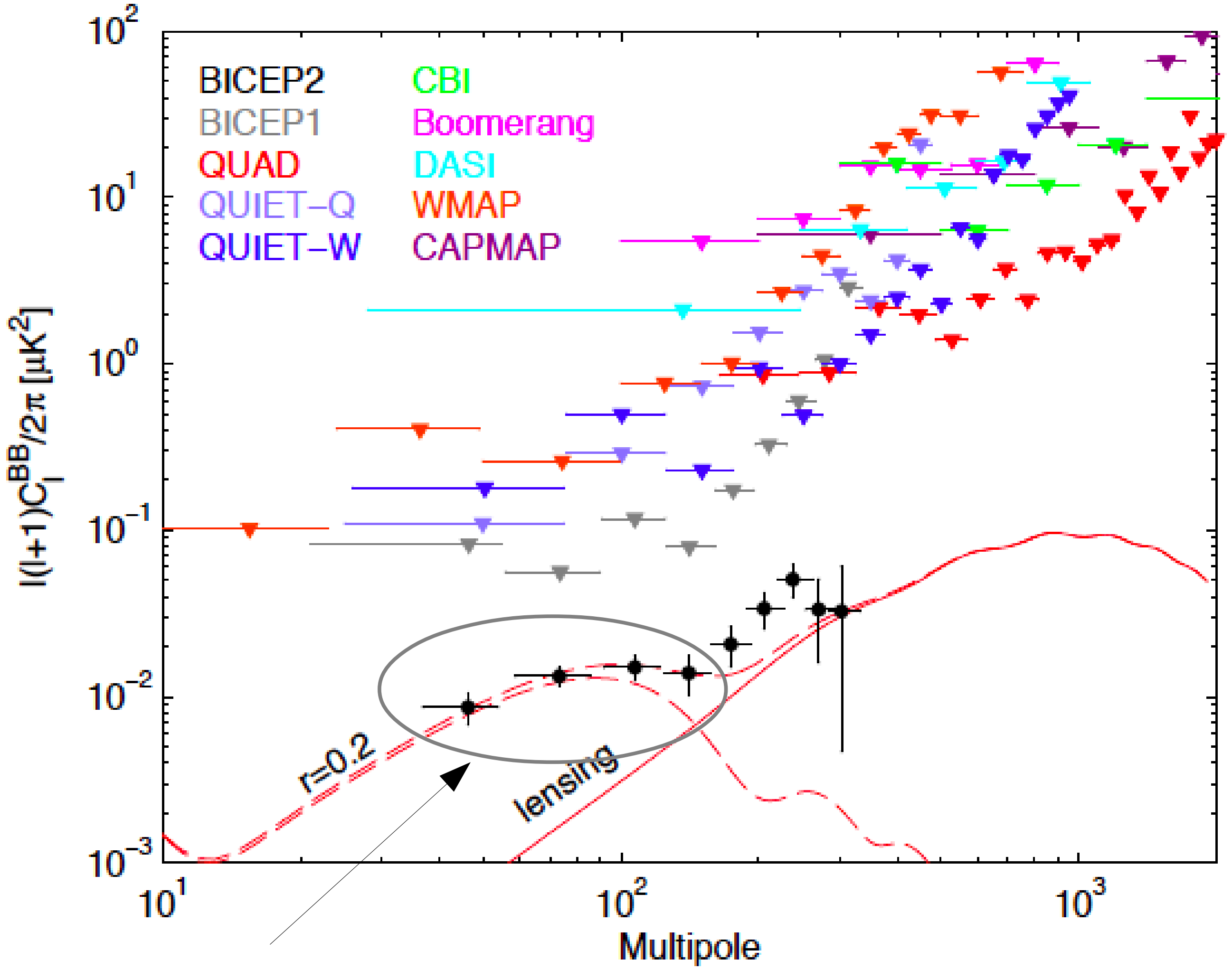
[BICEP2 2014]

BB angular power spectrum measured by BICEP2



[BICEP2 2014]

BB angular power spectrum measured by BICEP2



Excess signal
due to tensor modes (?!)

[BICEP2 2014]

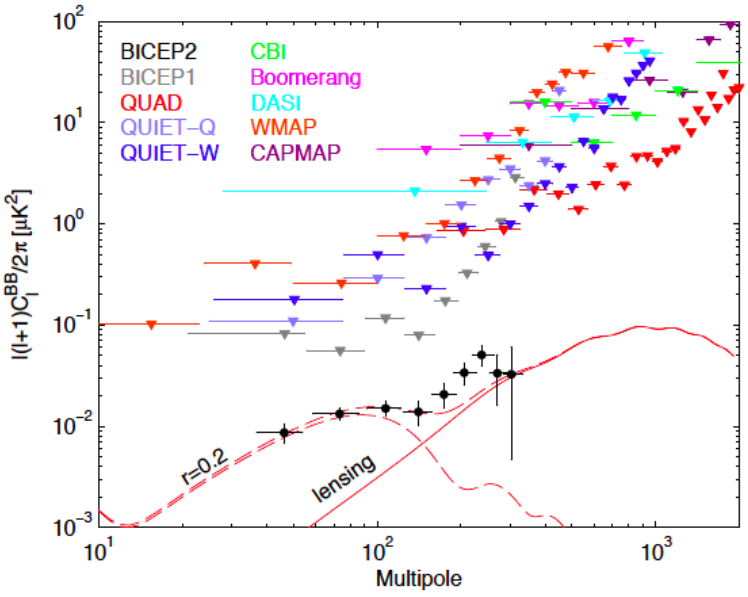
Is the signal real?

Experimental systematics?

- Pointing error
- Beam uncertainty

Passed consistency checks:

- jackknife tests
- no EB- and TB-signal

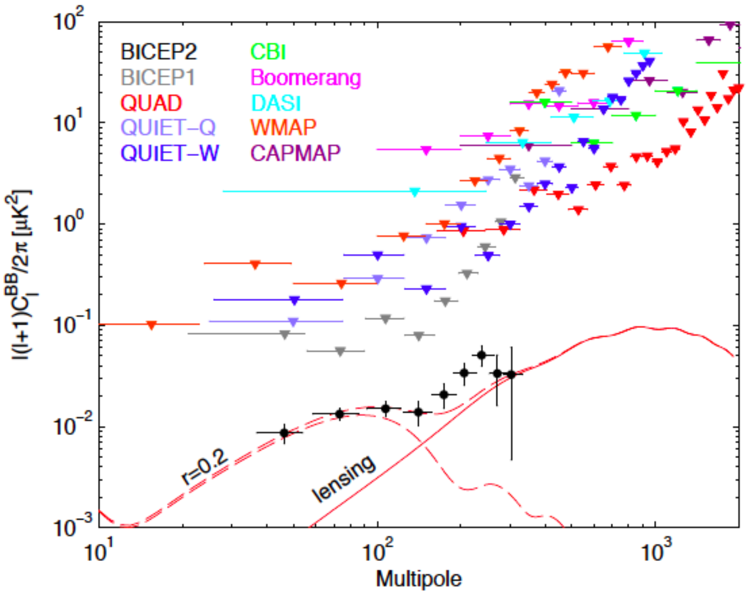


$\longrightarrow$ very unlikely to account for excess signal

Is the signal of cosmological origin?

Astrophysical foregrounds

- Polarised point sources
- Synchrotron emission
- Polarised dust emission



negligible; contribution corresponding to r ~ $O(10^{-3})$

Is the signal of cosmological origin?

Astrophysical foregrounds

- Polarised point sources
- Synchrotron emission
- Polarised dust emission

Where is the uncertainty?!

Different foreground models

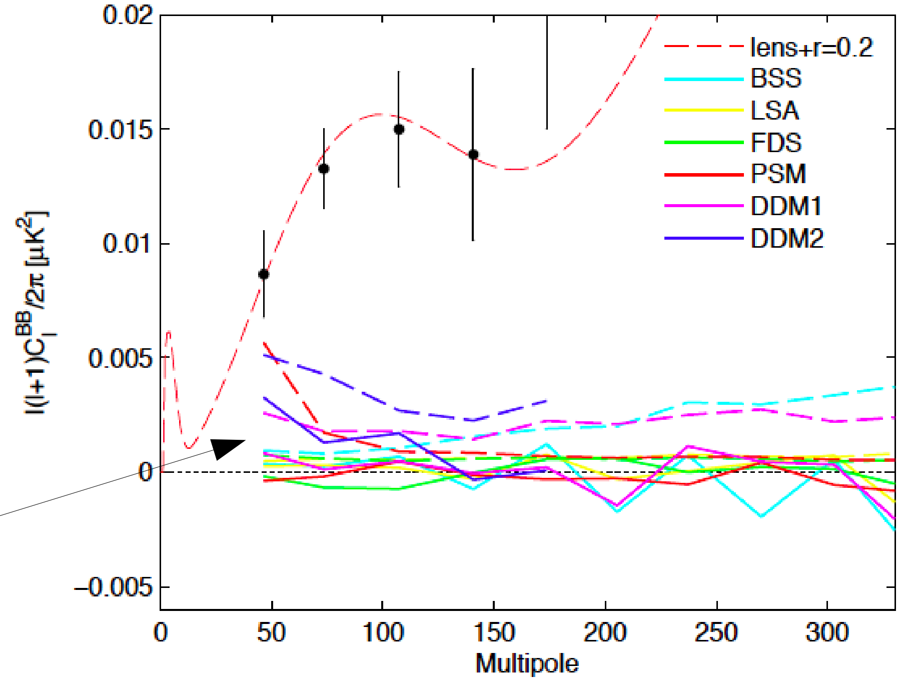


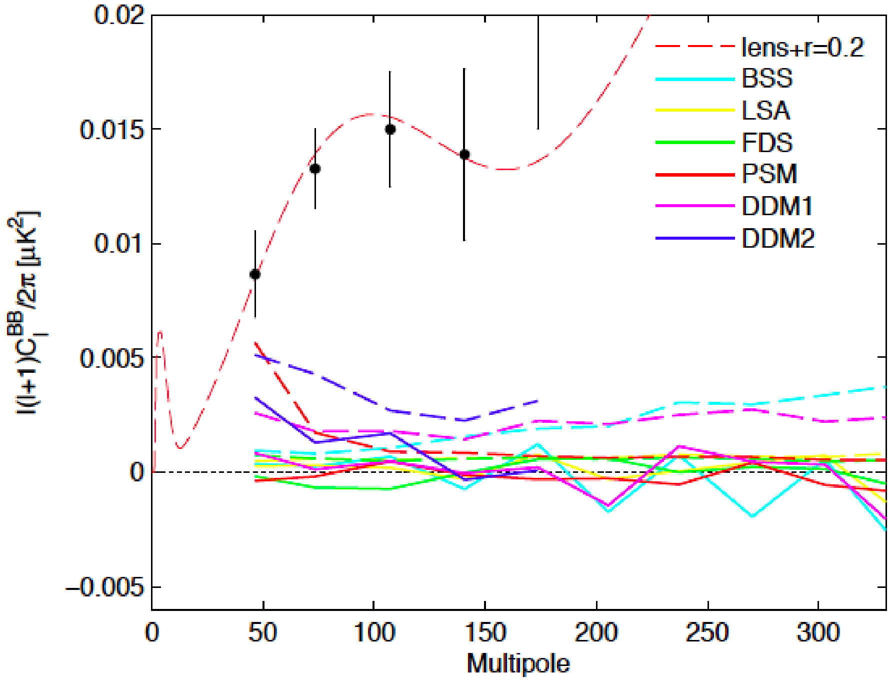
FIG. 6.— Polarized dust foreground projections for our field using various models available in the literature, and two new ones formulated using publically available information from *Planck*. Dashed lines show autospectra of the models, while solid lines show cross spectra between the models and the BICEP2 maps. The cross spectra are consistent with zero, and the DDM2 auto spectrum (at least) is noise biased high (and is hence truncated to $\ell < 200$). The BICEP2 auto spectrum from Figure 2 is also shown with the lensed-ΛCDM+$r = 0.2$ spectrum.

Is the signal of cosmological origin?

Polarised dust emission

- DDM1/2 models based on digitised, unpublished Planck data
- Other models assume (unrealistically?) low polarisation fraction f_p
- Foreground signal ~ f_p^2

Different foreground models



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Dusty foregrounds revisited

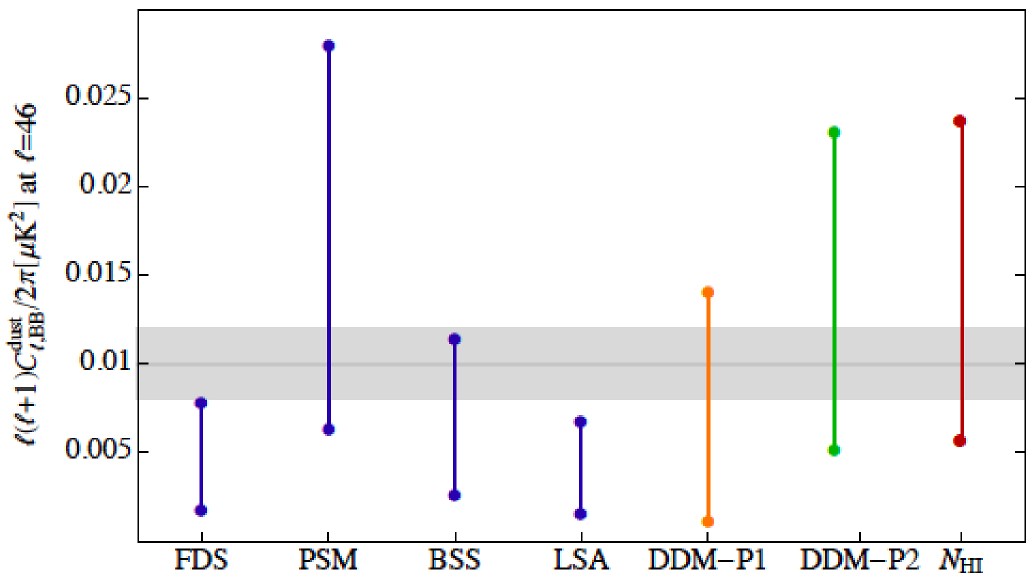


FIG. 3: Predicted contribution of polarized dust emission to the B-mode angular power spectrum for our models discussed in section III, and for the pre-*Planck* models studied by BICEP2 (blue) after taking into account the increase in polarization fraction. The range for the FDS, PSM, BSS, and LSA models, shown in blue, is based on a variation of the polarization fraction between 8 and 17%, while the range for the DDM-P1 and DDM-P2 models is based on our set of 96 models (see section III). The range for the HI estimate reflects the uncertainty in the extrapolation to low column densities and the uncertainty in frequency extrapolation. The gray band shows the best-fit amplitude of $0.010 \pm 0.002\,\mu{\rm K}^2$ at $\ell = 46$ determined in section II. If the dust foreground amplitude lies in this gray band, then the best-fit model to the data will have a negligible gravitational wave contribution.

[Flauger, Hill, Spergel 2014]

Dusty foregrounds revisited

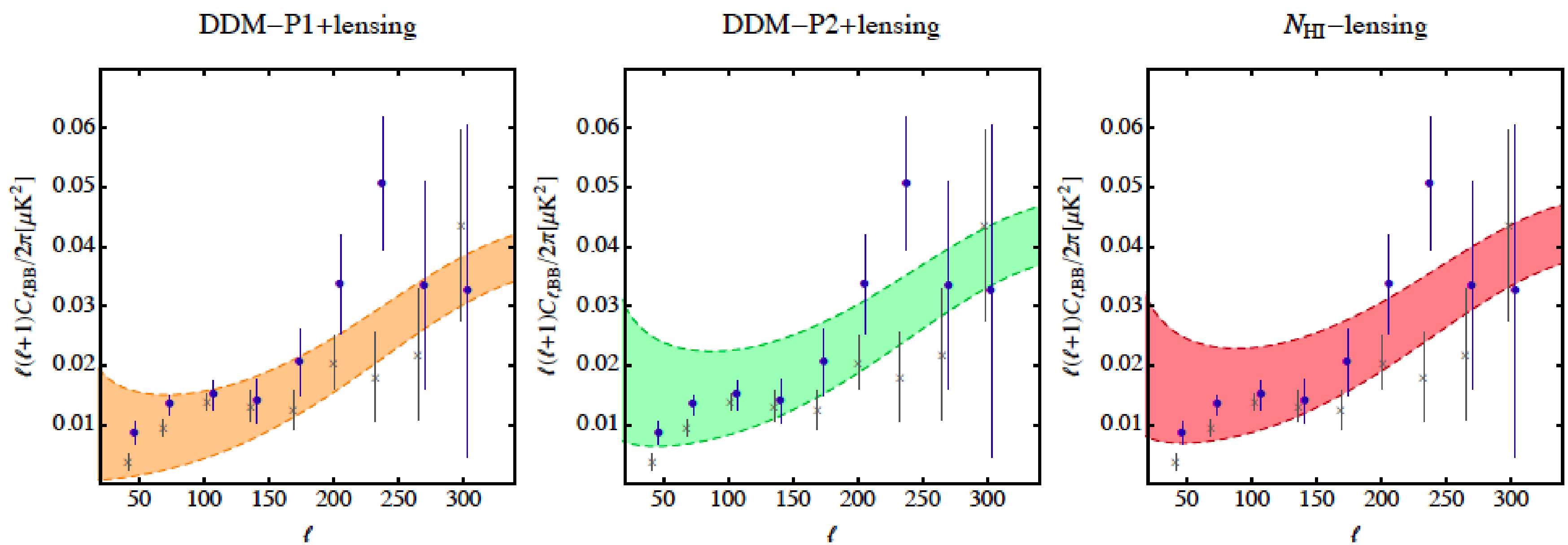


FIG. 4: Comparison of several predictions for the 150 GHz signal versus the reported BICEP2 × BICEP2 and the preliminary BICEP2 × Keck measurements. The predictions are a combination of the dust polarization signal and the predicted lensing signal for standard cosmological parameters. Panel (a) is based on DDM-P1, which assumes that the dust polarization signal is proportional to the dust intensity (extrapolated from 353 GHz) times the mean polarization fraction (based on our CIB-corrected map; see section III). The band represents the 1σ countours derived from a set of 48 DDM-P1 models. Panel (b) shows DDM-P2, with polarization fractions from our CIB-corrected map, and polarization direction based on starlight measurements, the PSM, or [33]. Panel (c) uses the column density of neutral hydrogen in the BICEP2 region inferred from the optical depth at 353 GHz to estimate the dust foreground. In this panel, the band reflects the uncertainty in the extrapolation of the scaling relation to low column densities as well as the uncertainty in the rescaling from 353 GHz to 150 GHz.

[Flauger, Hill, Spergel 2014]

Is the signal of cosmological origin?

Adding BICEP1 data to determine frequency-dependence of the signal

→ *total* signal consistent with CMB expectation

(but signal is dominated by lensing contribution!)

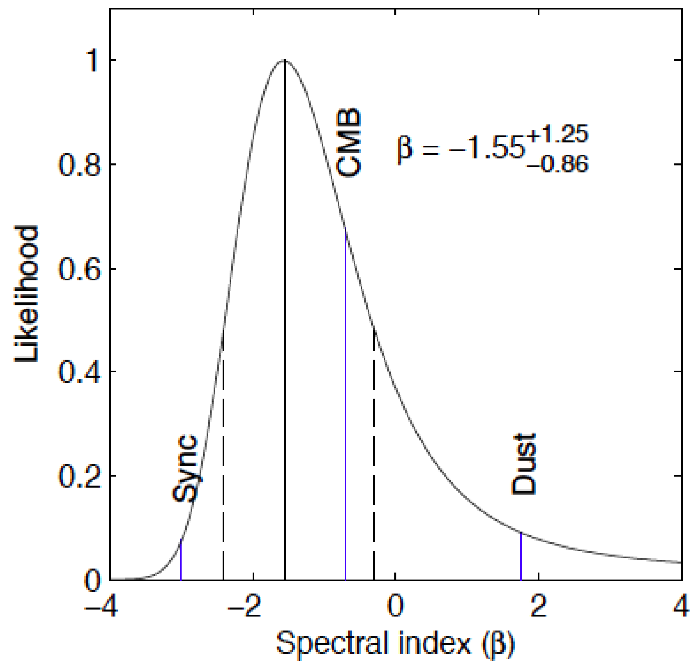
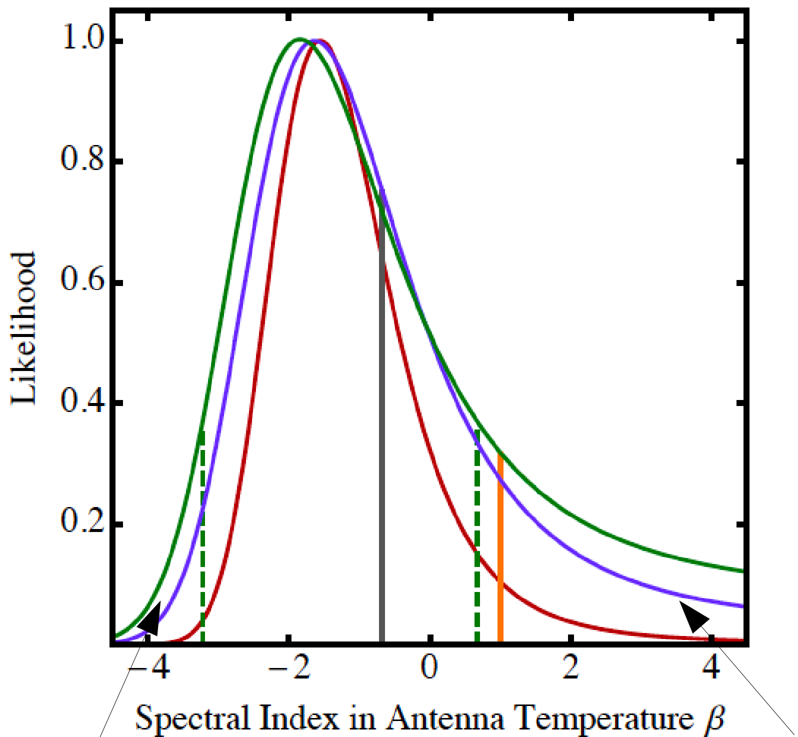


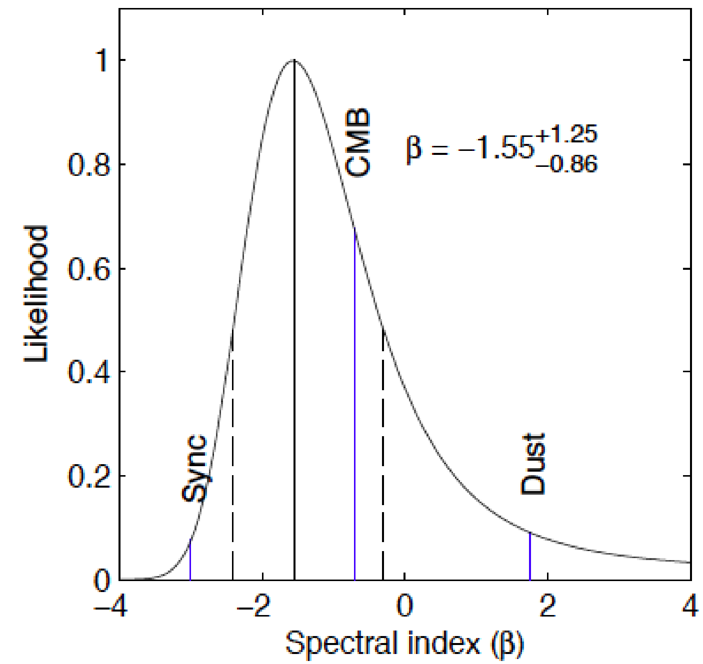
FIG. 8.— The constraint on the spectral index of the *BB* signal based on joint consideration of the BICEP2 auto, BICEP1$_{100}$ auto, and BICEP2×BICEP1$_{100}$ cross spectra. The curve shows the marginalized likelihood as a function of assumed spectral index. The vertical solid and dashed lines indicate the maximum likelihood and the $\pm 1\sigma$ interval. The blue vertical lines indicate the equivalent spectral indices under these conventions for the CMB, synchrotron, and dust. The observed signal is consistent with a CMB spectrum, while synchrotron and dust are both disfavored by $\gtrsim 2\sigma$.

Is the signal of cosmological origin?



lensing removed

lensing removed
+ foreground with
cosmic variance



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[Flauger, Hill, Spergel 2014]

Planck

- Planck has measured polarisation in 7 frequency bands
- Data are currently being analysed, probable release this summer
- Planck data will allow accurate determination of polarised foreground emission
- Also: Planck measurement of BB-spectrum (but sensitivity to *r* will be lower than BICEP2's)

Planck 353 Ghz polarisation map

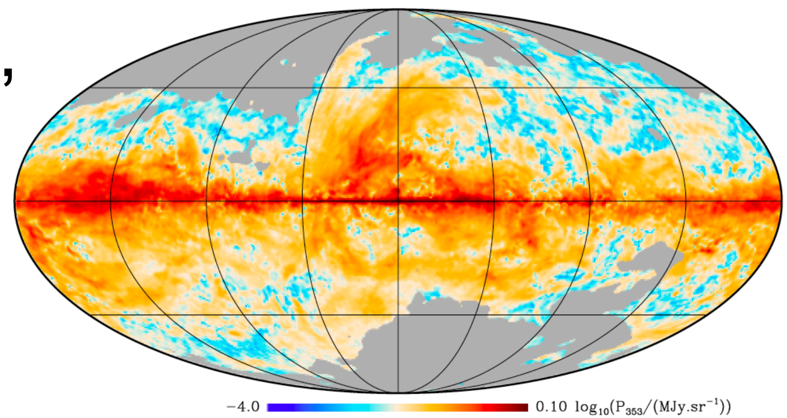


Fig. 2. *Planck* 353 GHz polarized intensity (P) map at 1° resolution in $\log_{10}$ scale. The values shown have been bias corrected as described in Sect. 2.3. The same mask as in Fig. 1 is applied. The full sky map of the unpolarized intensity I entering the calculation of P is shown in Fig. 5.

[Planck 2014]

Is the signal really from inflationary tensor modes?

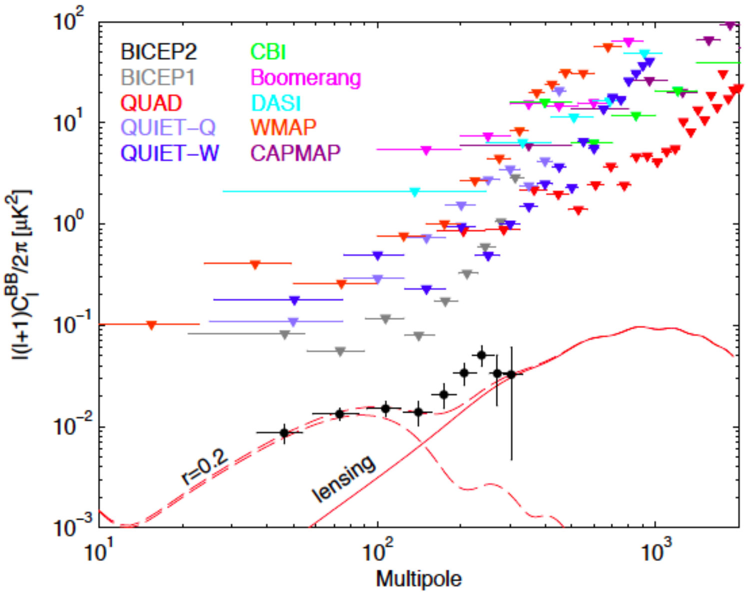
Alternative mechanisms:

- Topological defects
  → too much small scale power

  [Lizarraga et al. 2014]

- Primordial magnetic fields
  → possible, but simplest models predict too much NG

  [Bonvin et al. 2014]



→ inflation remains most likely origin

Implications of BICEP2

DISCLAIMER:

In the following, I will assume this signal is real and that it is caused by primordial tensor perturbations from inflation

Status of inflation after BICEP2

single-field canonical slow-roll inflation

Adiabatic initial conditions ✓

Nearly Gaussian initial fluctuations

$f_{NL} < 1$ ✓

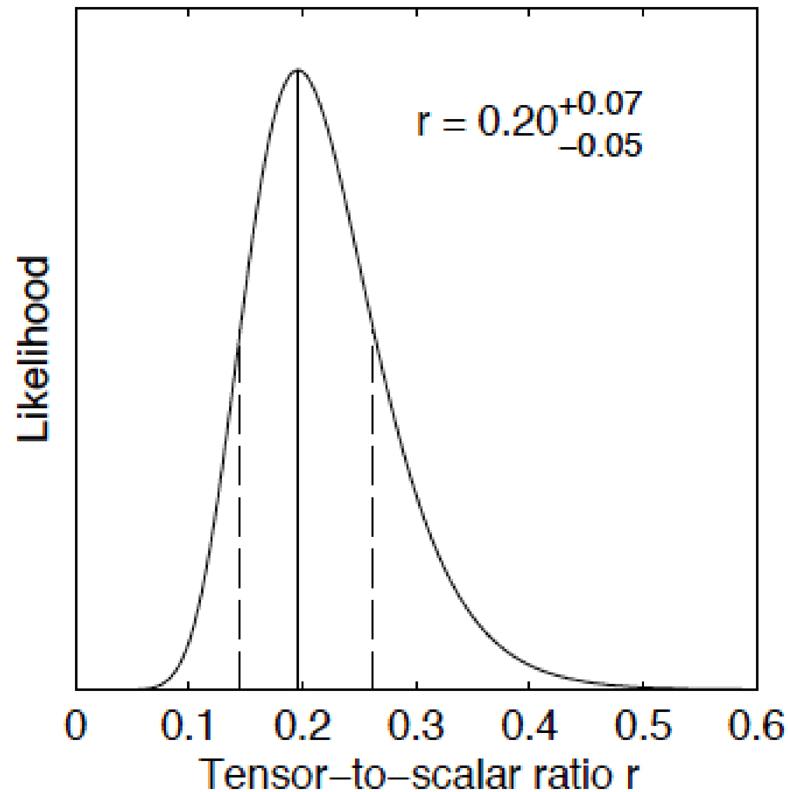
Background of gravitational waves (tensor perturbations) ✓

Almost (but not exactly) scale-invariant curvature perturbations ✓

Spatial flatness

$\Omega_K \sim 10^{-5}$ ✓

Implications of BICEP2 results



[BICEP2 2014]

Energy scale of inflation:

$$V_{\inf}^{1/4} \approx 2.2 \cdot 10^{16} \left(\frac{r}{0.2}\right)^{1/4} \text{ GeV}$$

(This could in principle have been as low as O(10) MeV, we are incredibly lucky!)

Implications of BICEP2 results

- Lyth bound:
large r $\rightarrow$ large ε $\rightarrow$ large V'/V $\rightarrow$ large $d\phi/dN$
For inflation to last sufficiently long, ϕ has to take on super-Planckian values

$$\Delta\phi \gtrsim m_{\rm Pl}\,(r/0.01)^{1/2}$$

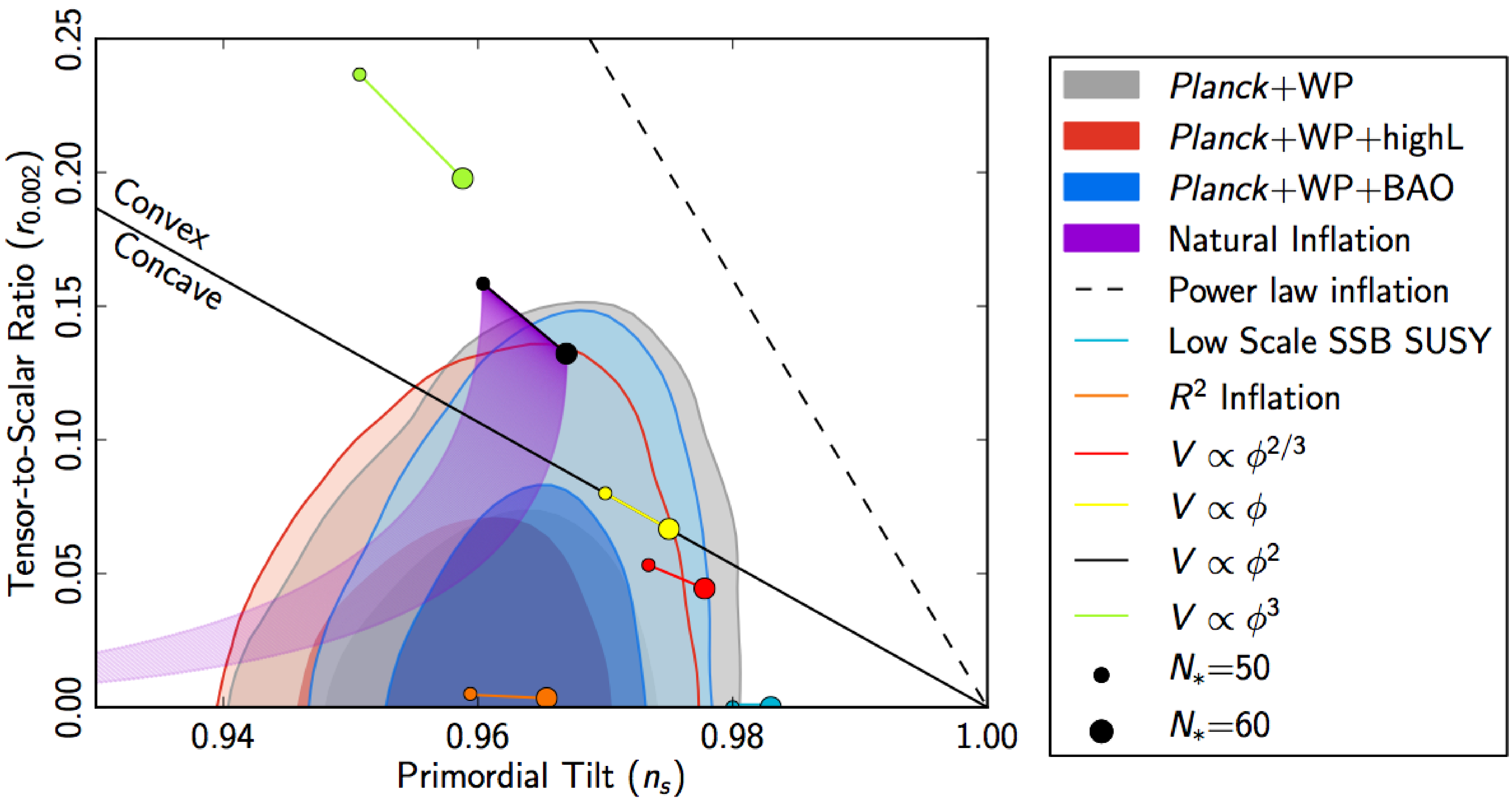
[Lyth 1997]

- In effective field theory, Planck-mass suppressed higher order operators would mess up things...

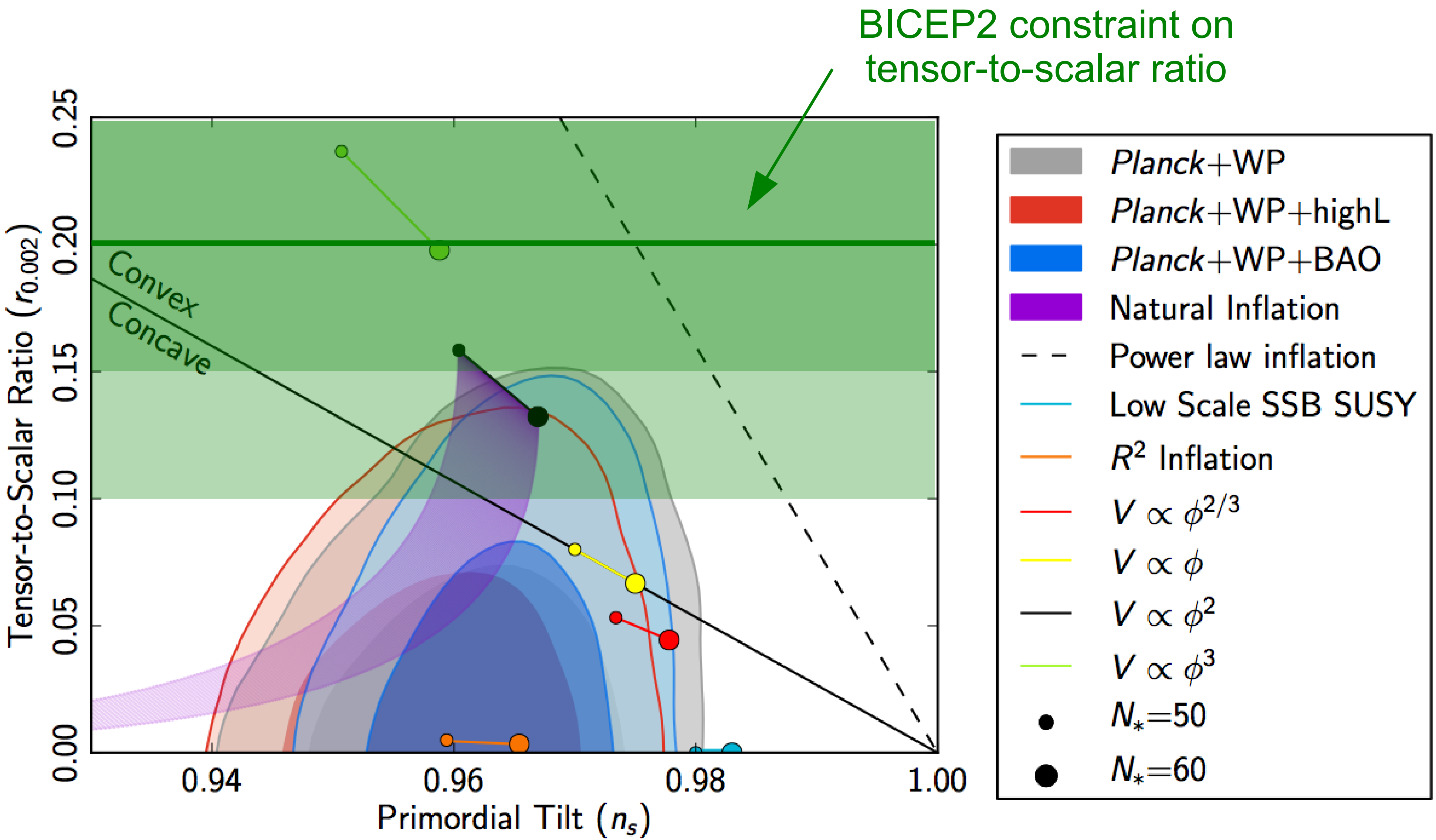
$$\mathcal{L} = \mathcal{L}_{\rm renormalisable} + \underbrace{\sum_{i=1}^{\infty}\sum_{j} c_{ij}\left(\frac{1}{m_{\rm Pl}}\right)^{i} \mathfrak{O}_j(4+i)}$$

e.g., $c\left(\dfrac{1}{m_{\rm Pl}}\right)^2 \phi^6$ ..., etc.

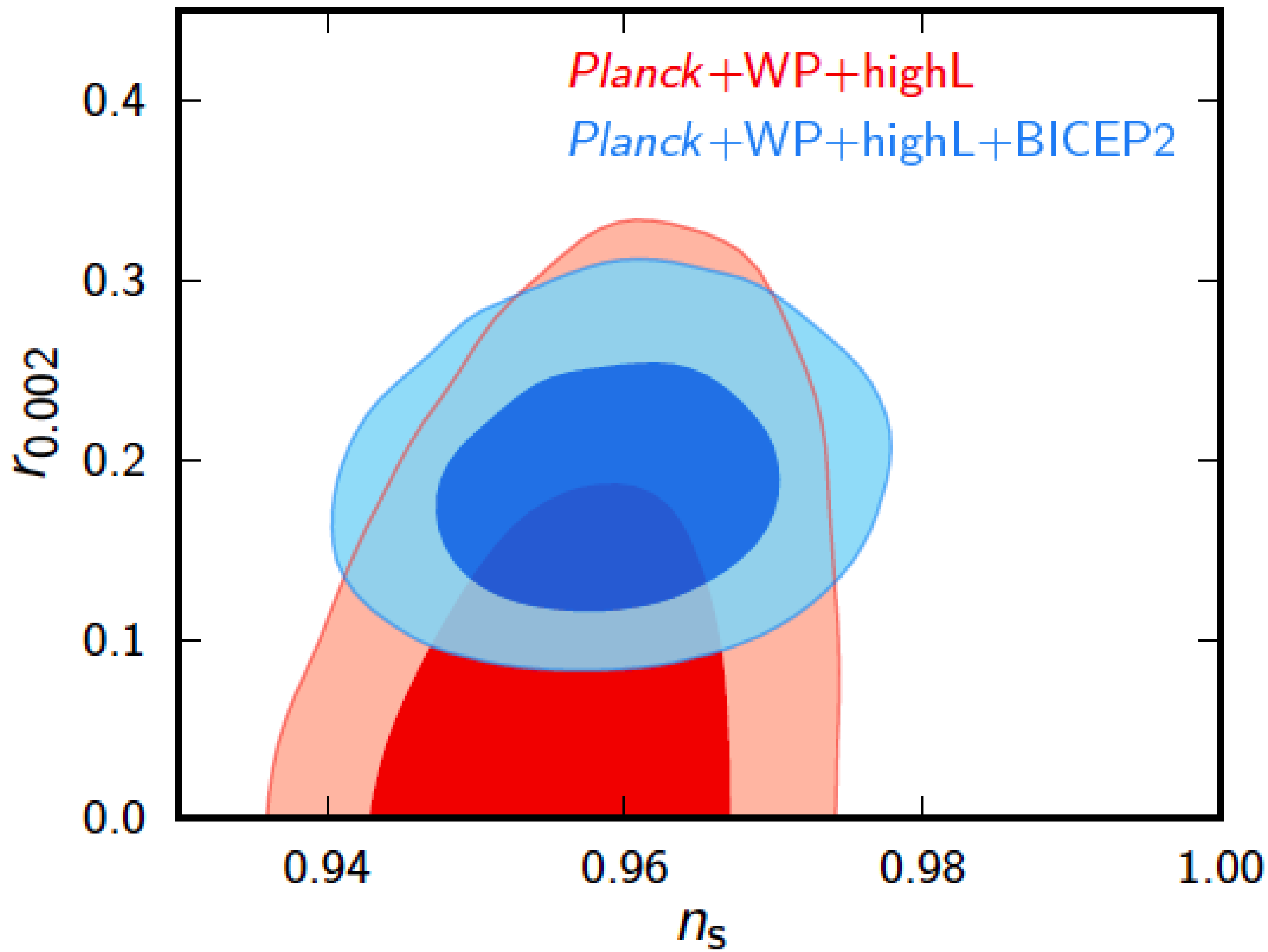
Inflation model constraints (post BICEP2)



Inflation model constraints (post BICEP2)

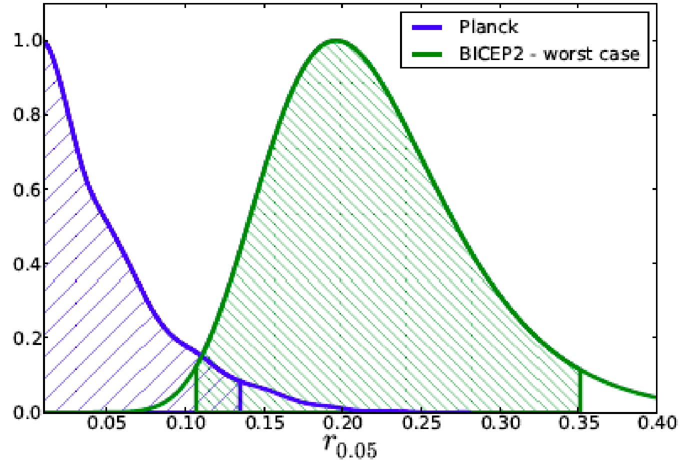


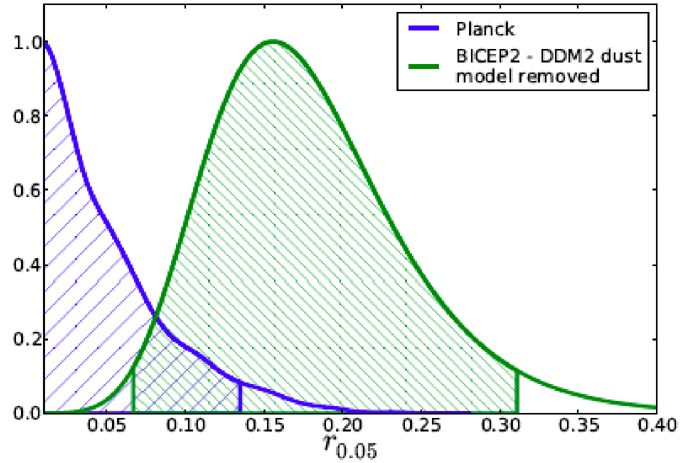
Inflation model constraints (post BICEP2)



Tension with Planck temperature data?

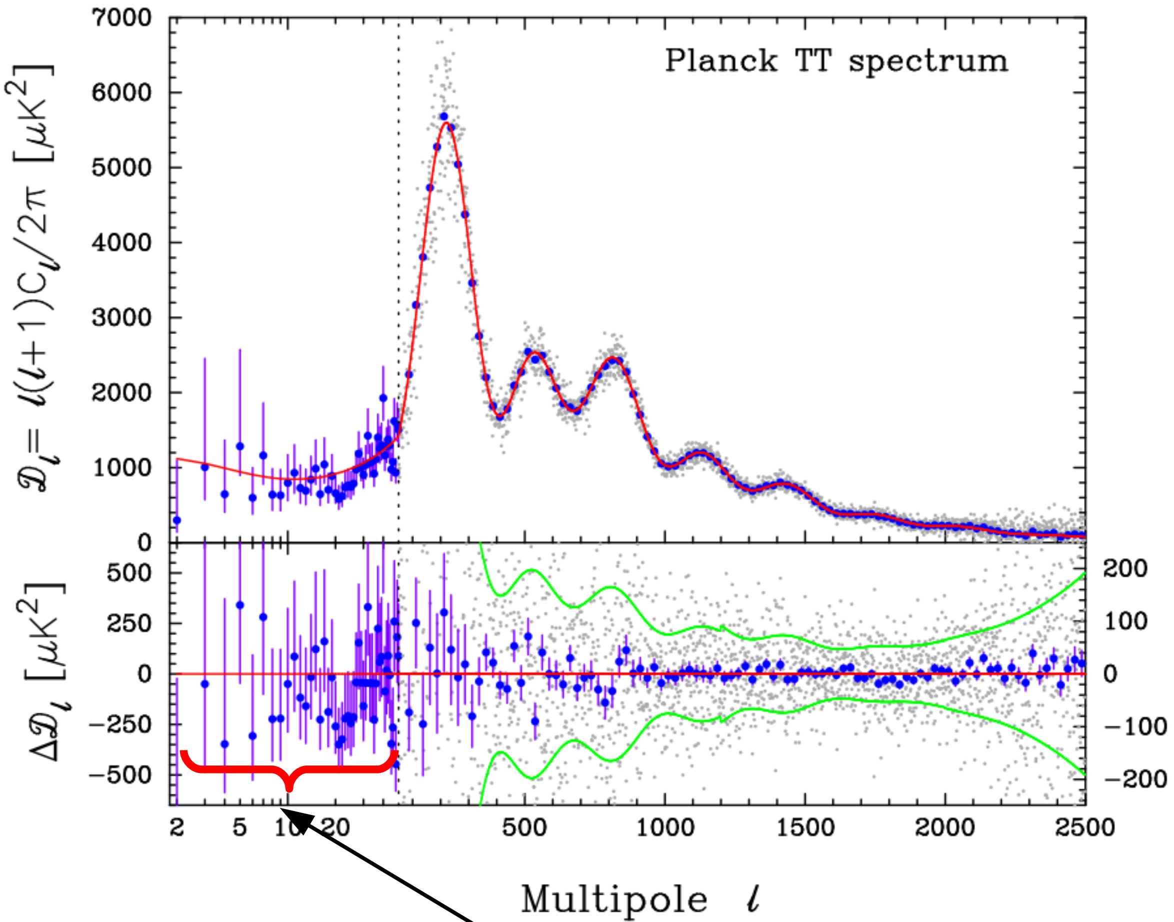
Perhaps not much of a problem at all?





[Audren, Figueroa, Tram 2014]

Tension with Planck temperature data?



Even in ΛCDM with r=0, there is a lack of power at the largest scales
Adding a tensor contribution would exacerbate the problem

Possible solutions:

- Suppress primordial scalar power at large scales
- Suppress late integrated Sachs-Wolfe effect (DE)
- Anticorrelated isocurvature perturbations
  [Kawasaki et al. 2014]
- Anticorrelated tensor perturbations
  [Contaldi, Peloso, Sorbo 2014]
- Extra radiation (e.g., $\Delta N_{\rm eff} \approx 1$ sterile neutrinos)
  [Zhang et al., Dvorkin et al. 2014]

Or maybe dust after all...?

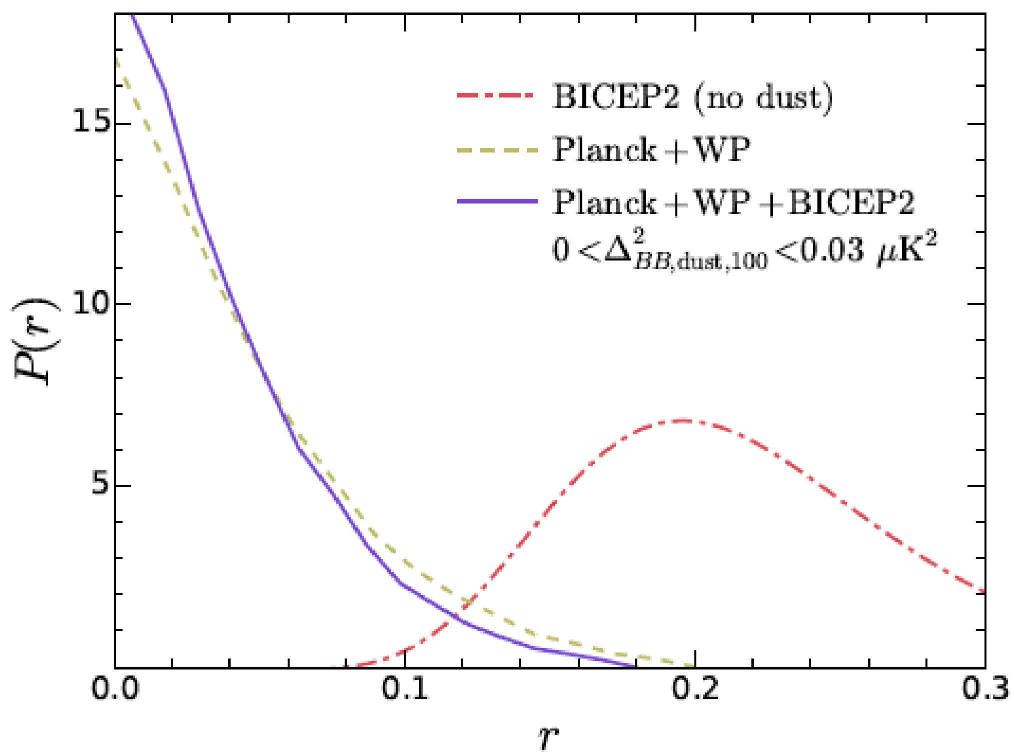


Figure 2. Marginalized constraints on r from Planck+WP and Planck+WP+BICEP2 with free dust polarization amplitude (dashed and solid curves), and the BICEP2 likelihood (dot-dashed curve).

[Mortonson & Hu 2014]

Conclusions

- Predictions of simplest inflationary models pass all challenges thrown at them by Planck data
- BICEP2 measurement of the CMB's BB angular power spectrum (*if confirmed!*) probably most spectacular result in cosmology in last 15 years
  - Can be interpreted as gravitational wave signal from inflation
  - Energy scale of inflation ~ GUT scale
  - Inflation was large-field
  - Possibly signs of further new physics
- These measurements do not prove inflation happened, but certainly make it look even more attractive than before!