Inflation after Planck and BICEP2

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Theory seminar @ DESY

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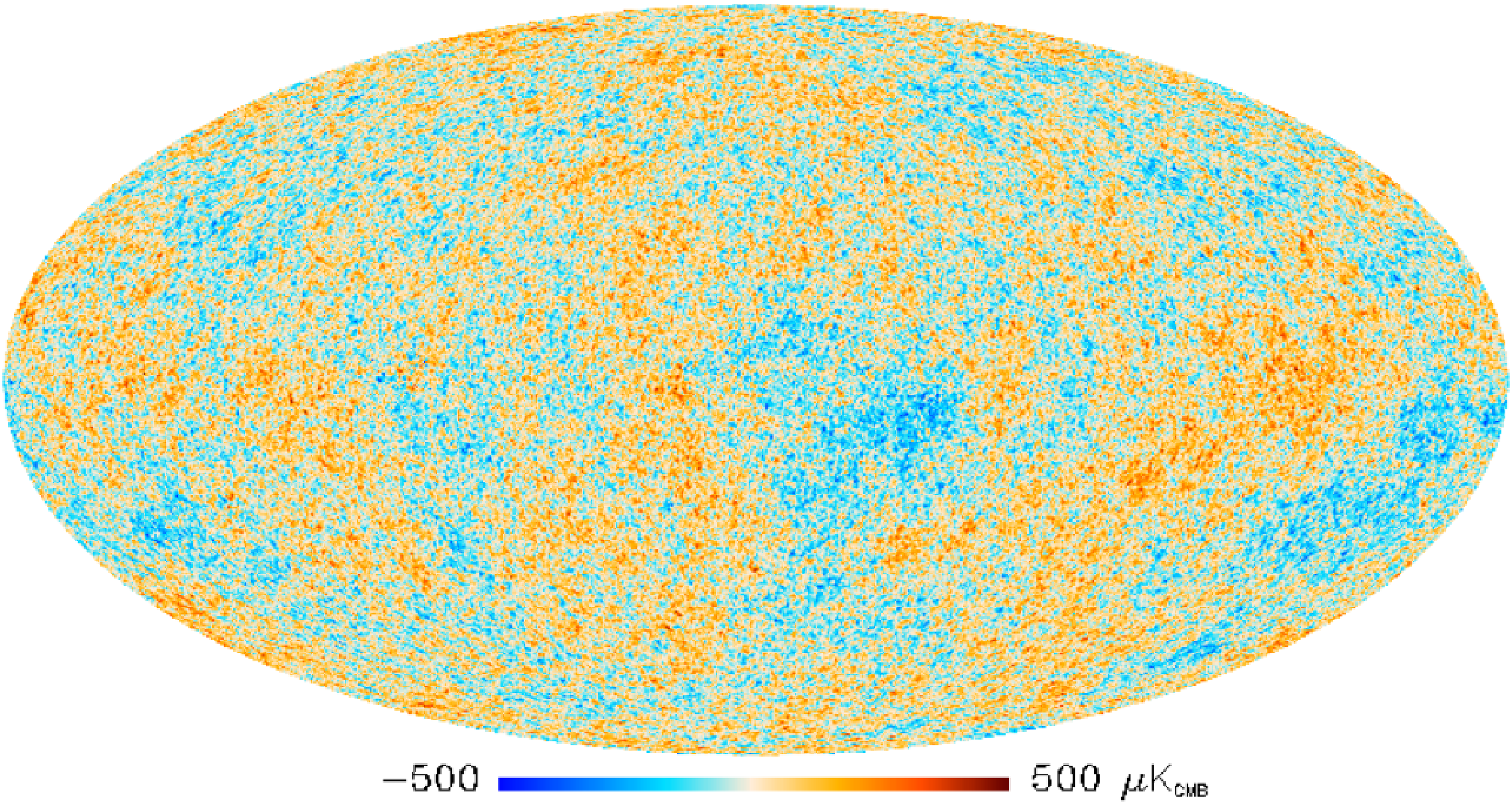
Outline

1. Inflation and its generic predictions (brief reminder)
2. Inflation vs. Planck data
3. Polarisation of the Cosmic Microwave Background
4. BICEP2
5. Theoretical implications of BICEP2's results

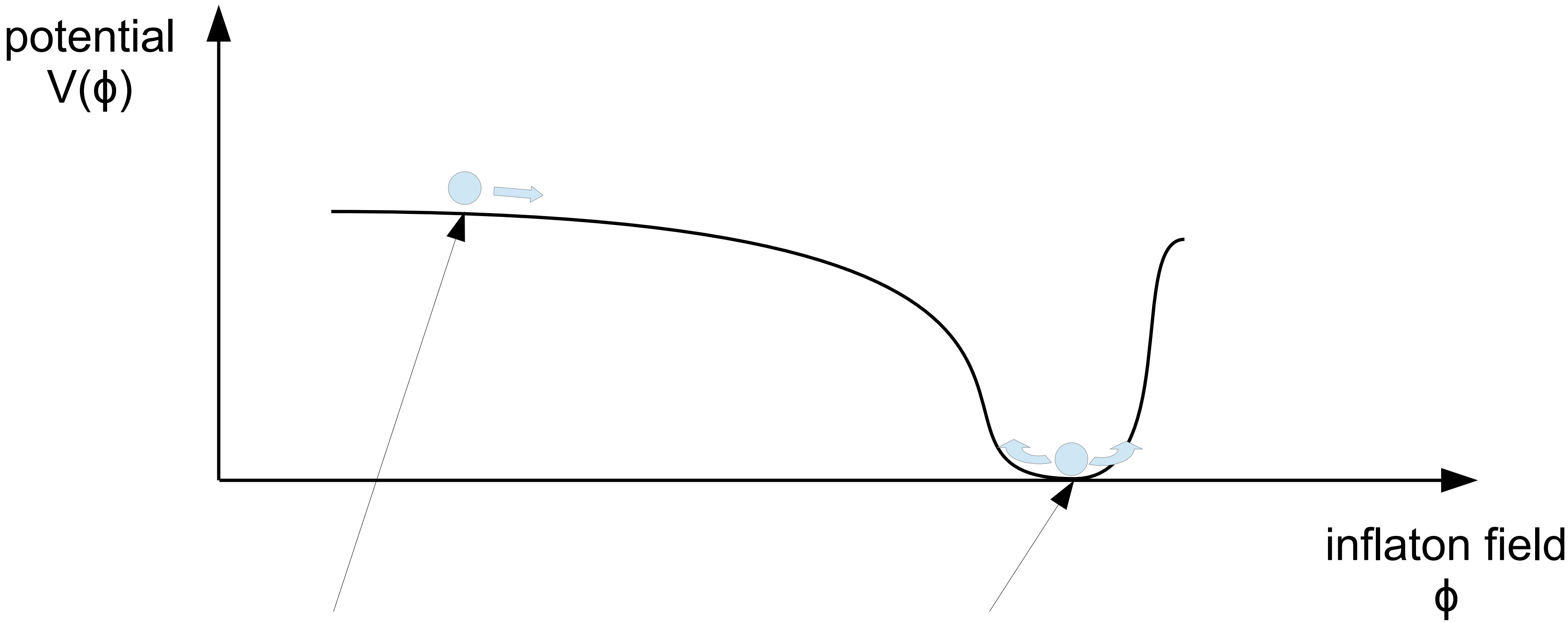
Inflation

Planck's CMB temperature map



Where do the anisotropies come from?

Inflation



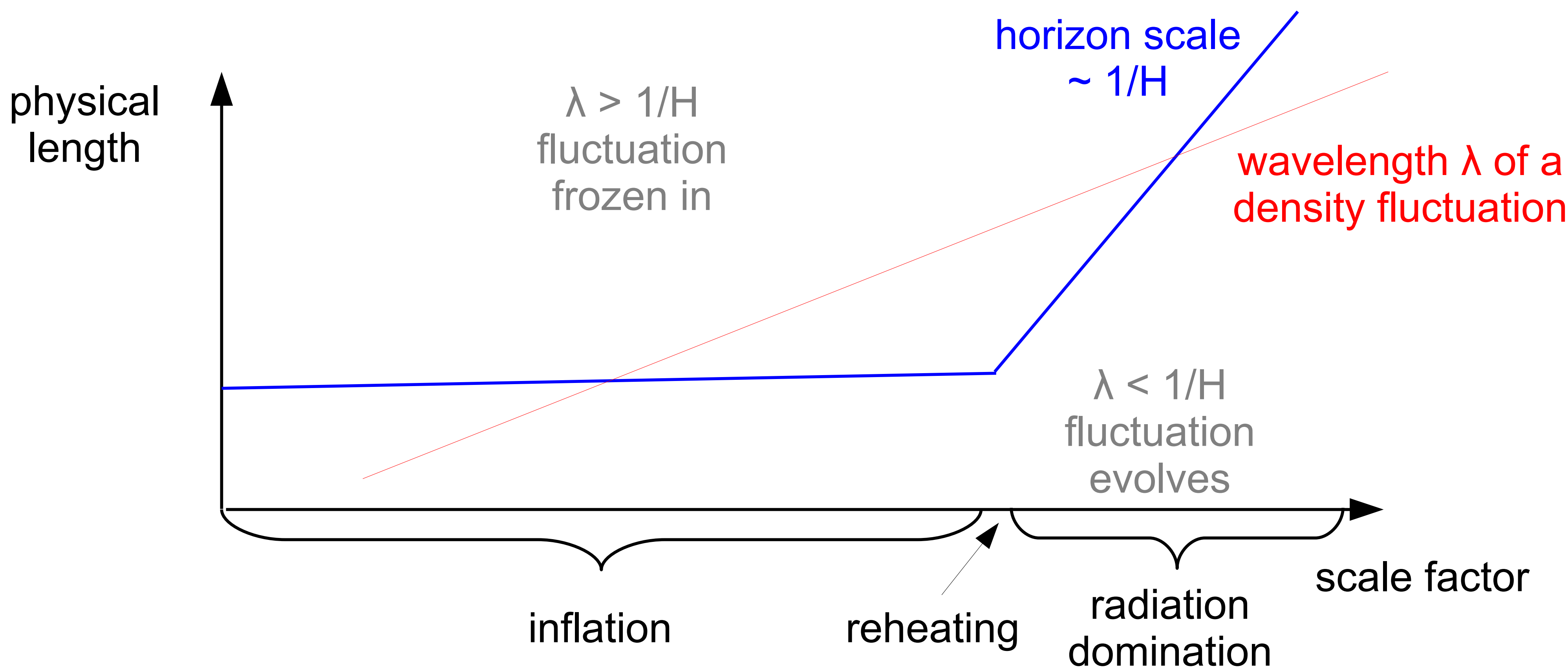
Potential energy domination
("slow-roll" inflation)

- Attractor solution
- Scale factor grows exponentially with time
- Hubble parameter close to constant
- Space is flattened

Reheating

- Potential energy is converted to standard model particles

The origin of the primordial perturbations: inflation



Quantum fluctuations of ϕ are stretched beyond the horizon and freeze in

Perturbations of the metric

- In General Relativity, need to take into account perturbations of the whole metric, not just the inflaton field
- Decompose metric perturbations into scalar, vector and tensor perturbations
- Inflation generates scalar (curvature) and tensor perturbations (gravitational waves), but no vector perturbations
- Properties of the perturbations depend on the inflaton potential

Inflationary perturbations

Scalar (curvature) perturbations

$$\mathcal{P}_{\mathcal{R}}(k) \propto \left.\frac{V}{\epsilon}\right|_{k=aH} \approx A_{\rm s}\left(\frac{k}{k_*}\right)^{n_{\rm s}-1+\ldots}$$

$$\epsilon \propto \left(\frac{V'}{V}\right)^2$$

scalar/tensor amplitude

scalar/tensor spectral index

Tensor perturbations (gravitational waves)

$$\mathcal{P}_t(k) \propto V|_{k=aH} \approx A_{\rm t}\left(\frac{k}{k_*}\right)^{n_{\rm t}+\ldots}$$

Tensor-to-Scalar ratio

$$r \equiv \left.\frac{\mathcal{P}_{\rm t}}{\mathcal{P}_{\mathcal{R}}}\right|_{k=0.002\ {\rm Mpc}^{-1}}$$

Inflationary perturbations

Scalar (curvature) perturbations

$$\mathcal{P}_{\mathcal{R}}(k) \propto \left.\frac{V}{\epsilon}\right|_{k=aH} \approx A_{\rm s}\left(\frac{k}{k_*}\right)^{n_{\rm s}-1+\ldots}$$

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scalar/tensor amplitude

scalar/tensor spectral index

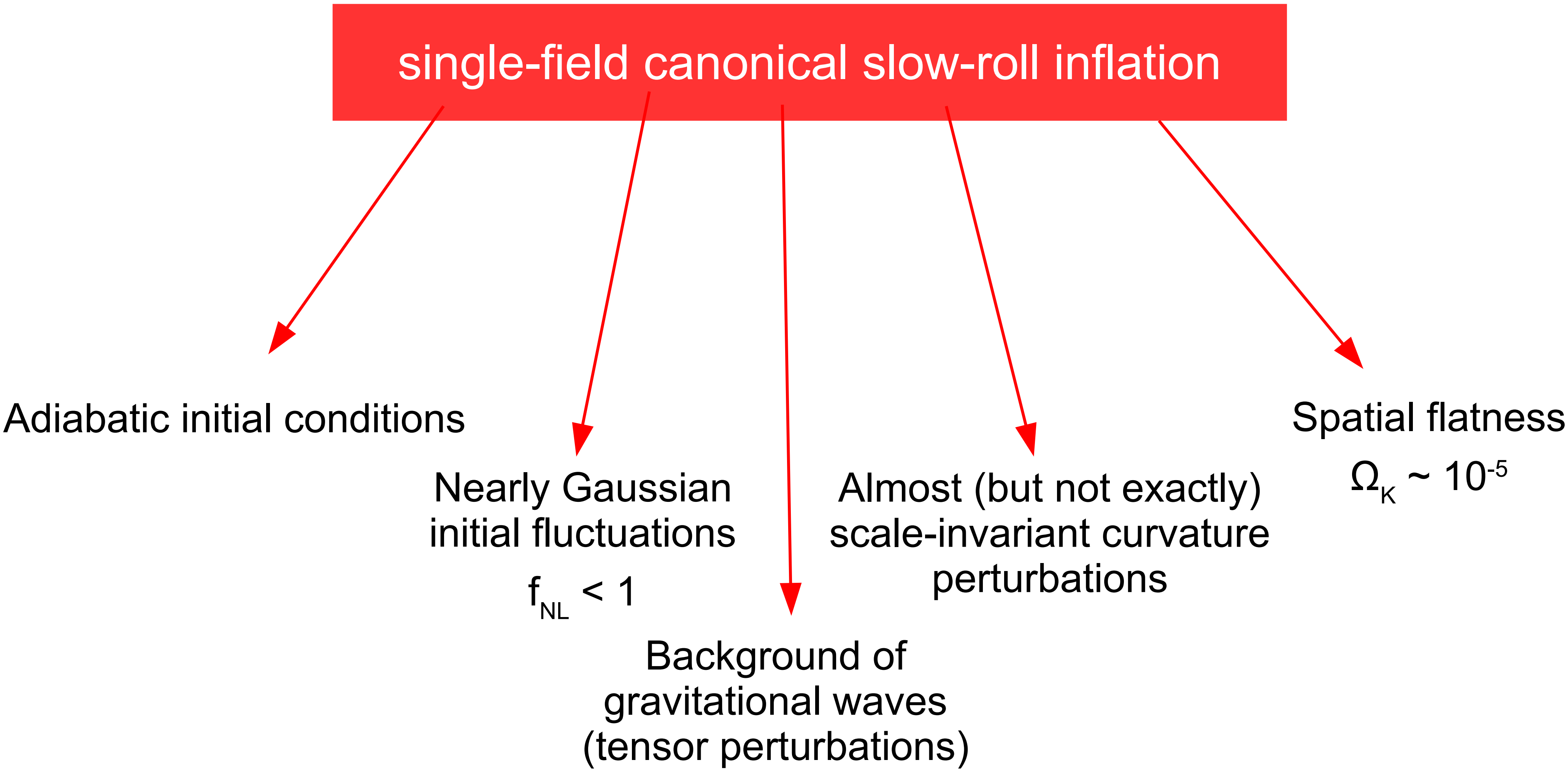
Tensor perturbations (gravitational waves)

$$\mathcal{P}_t(k) \propto V|_{k=aH} \approx A_{\rm t}\left(\frac{k}{k_*}\right)^{n_{\rm t}+\ldots}$$

Also, generically:

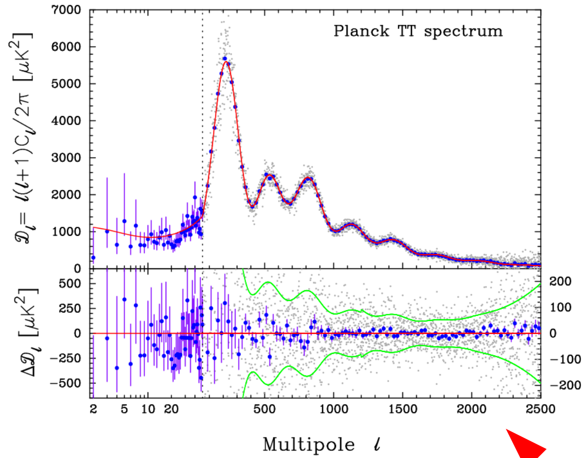
- no significant non-trivial higher-order correlations (*non-Gaussianities*)
- if single field: *adiabatic* perturbations (i.e., no isocurvature modes)

Predictions of the simplest models



Probing the predictions of inflation

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



Adiabatic initial conditions

Spatial flatness

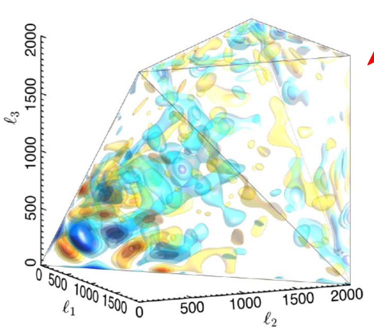
$\Omega_K \sim 10^{-5}$

Nearly Gaussian
initial fluctuations

$f_{NL} < 1$

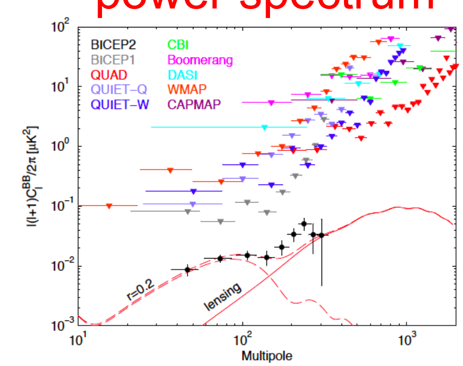
Almost (but not exactly)
scale-invariant curvature
perturbations

CMB bispectrum



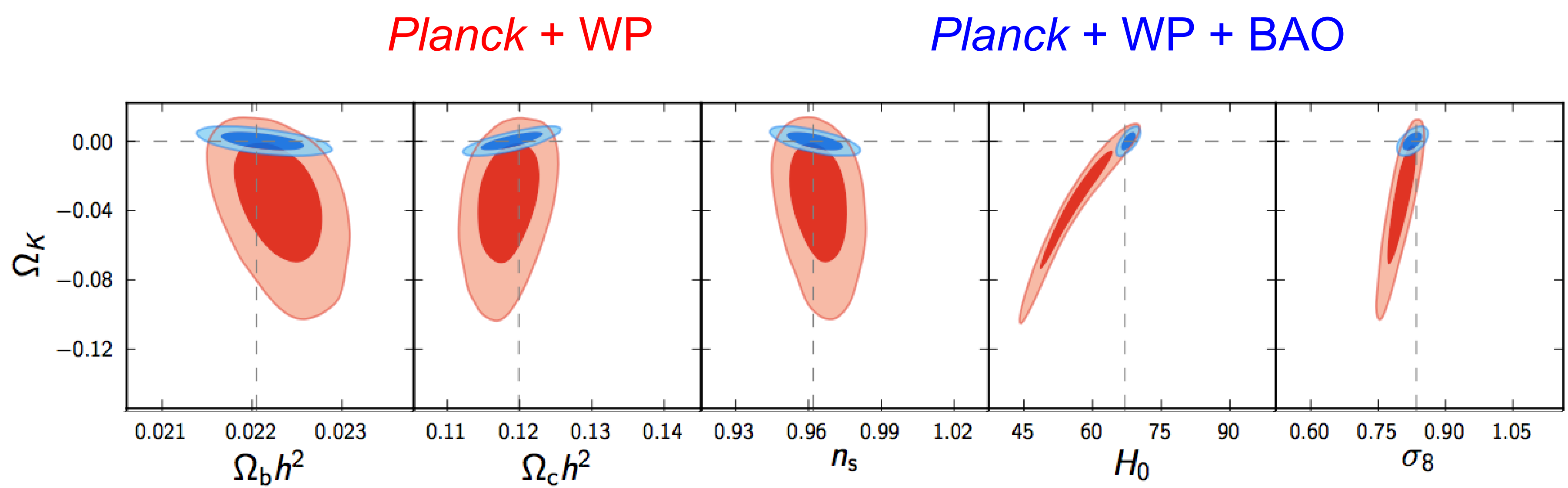
Background of
gravitational waves
(tensor perturbations)

CMB B-polarisation
power spectrum



Inflation vs. Planck

Spatial curvature constraints



	Planck+WP		*Planck*+WP+BAO		*Planck*+WP+highL		*Planck*+WP+highL+BAO	
Parameter	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

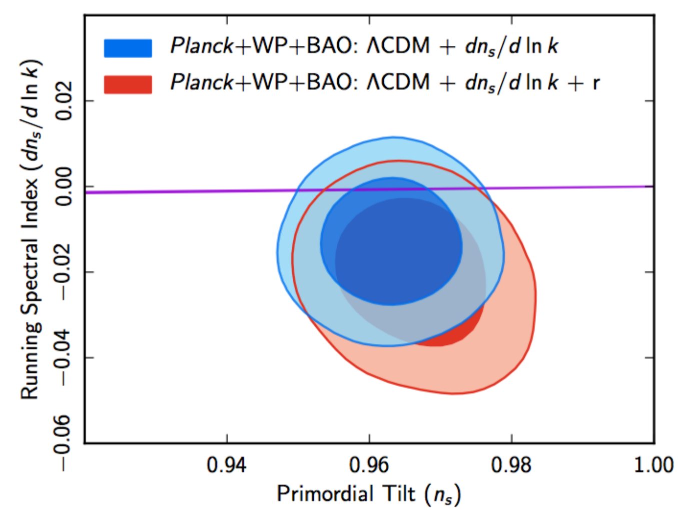
[Planck 2013]

Constraints on scalar power spectrum

- Scale dependence clearly required
- No hints for anything more complicated than power-law

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	$0.125^{+0.016}_{-0.014}$	$0.089^{+0.012}_{-0.014}$
$\ln(10^{10}A_s)$	$3.133^{+0.032}_{-0.028}$	$3.089^{+0.024}_{-0.027}$
n_s	—	0.9603 ± 0.0073
N_{eff}	—	—
Y_P	—	—
$-2\Delta\ln(\mathcal{L}_{max})$	27.9	0



Power-law scalar spectrum fits Planck data very well

[Planck 2013]

Adiabaticity: constraints on isocurvature perturbations

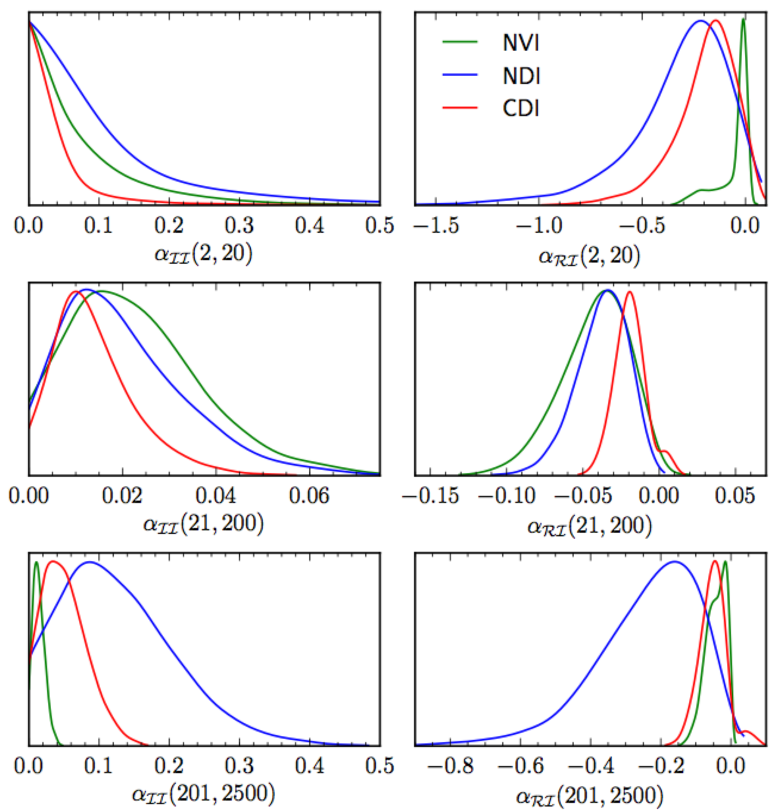
Isocurvature fraction at ...

Types of isocurvature

Large scales

Intermediate scales

Small scales

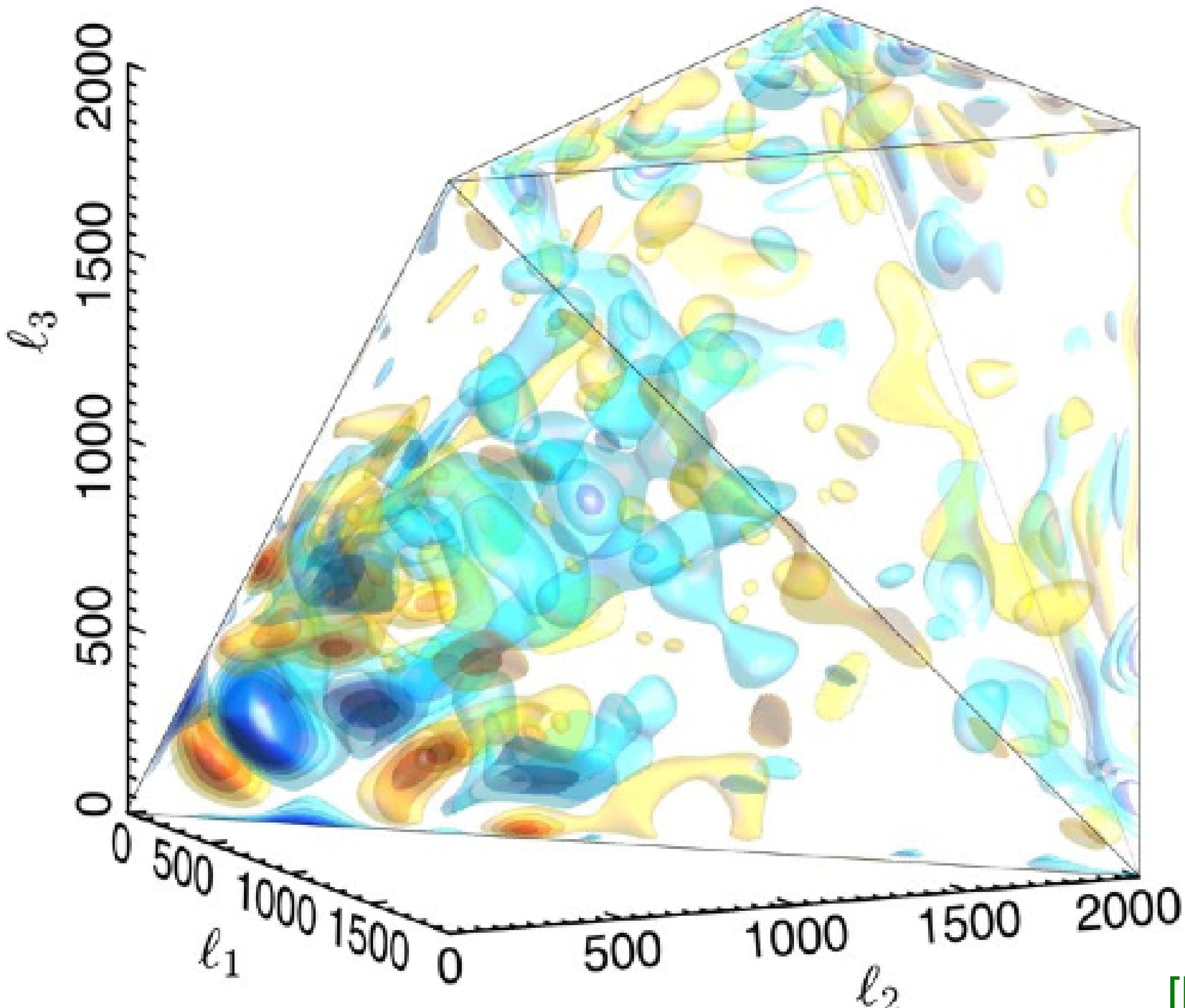


Neutrino velocity
Neutrino density
CDM density

Planck data are perfectly compatible with adiabatic initial conditions

[Planck 2013]

Non-Gaussianity: CMB angular bispectrum



[Planck 2013]

Non-Gaussianity

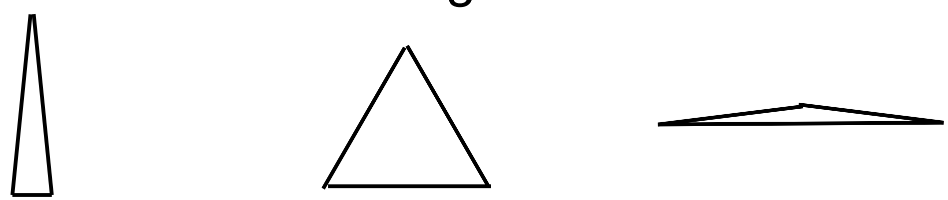
$$\underbrace{\langle \Phi(\vec{k}_1)\Phi(\vec{k}_2)\Phi(\vec{k}_3)\rangle}_{\text{Three-point correlation}} = (2\pi)^3\,\delta^{(3)}(\vec{k}_1+\vec{k}_2+\vec{k}_3)\;\underbrace{f_{\rm NL}\;F(k_1,k_2,k_3)}_{\text{Bispectrum}}$$

Three-point correlation

enforces triangular configurations

Bispectrum

Three limiting cases

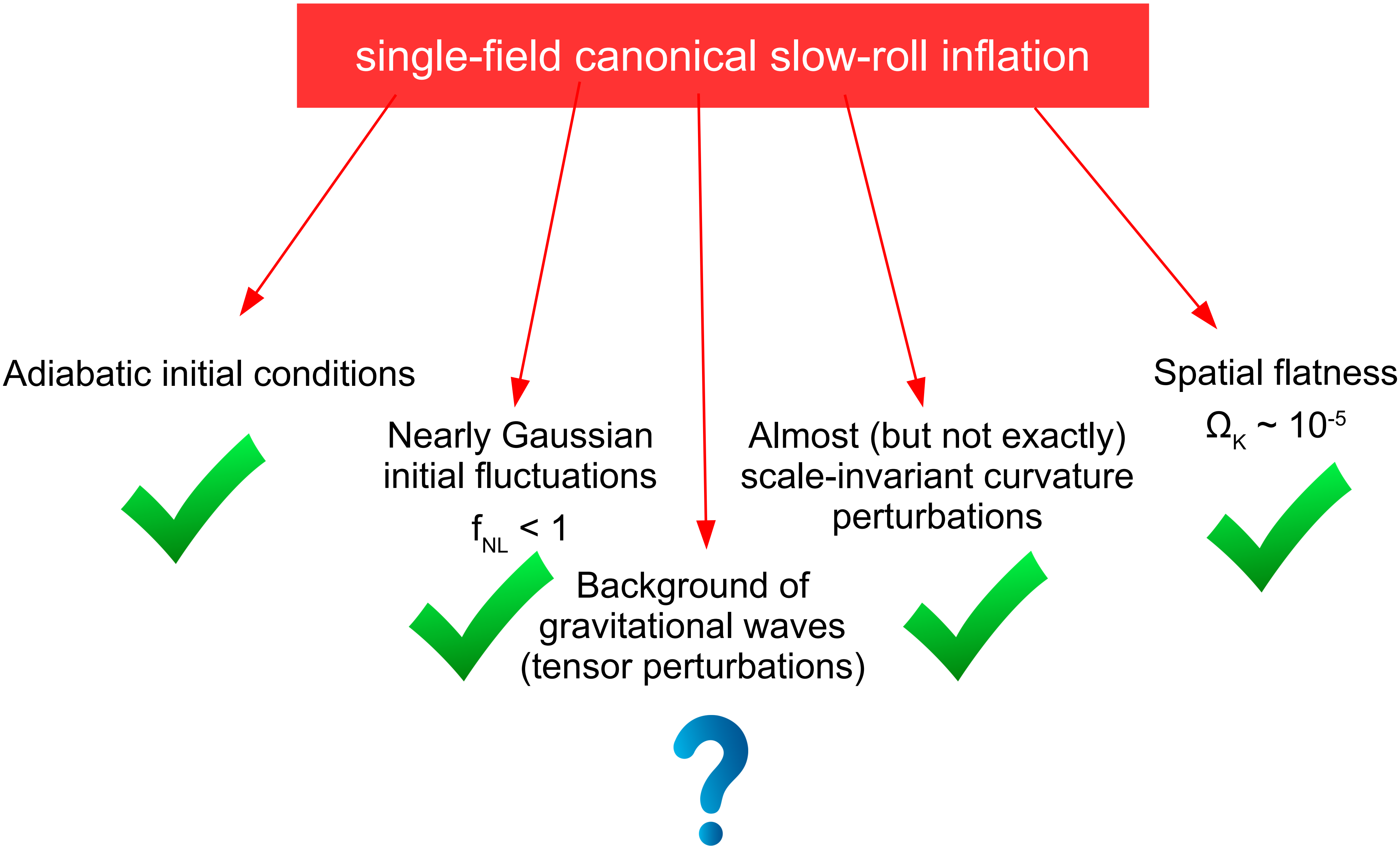


$f_{\rm NL}$		
Local	Equilateral	Orthogonal
2.7 ± 5.8	-42 ± 75	-25 ± 39

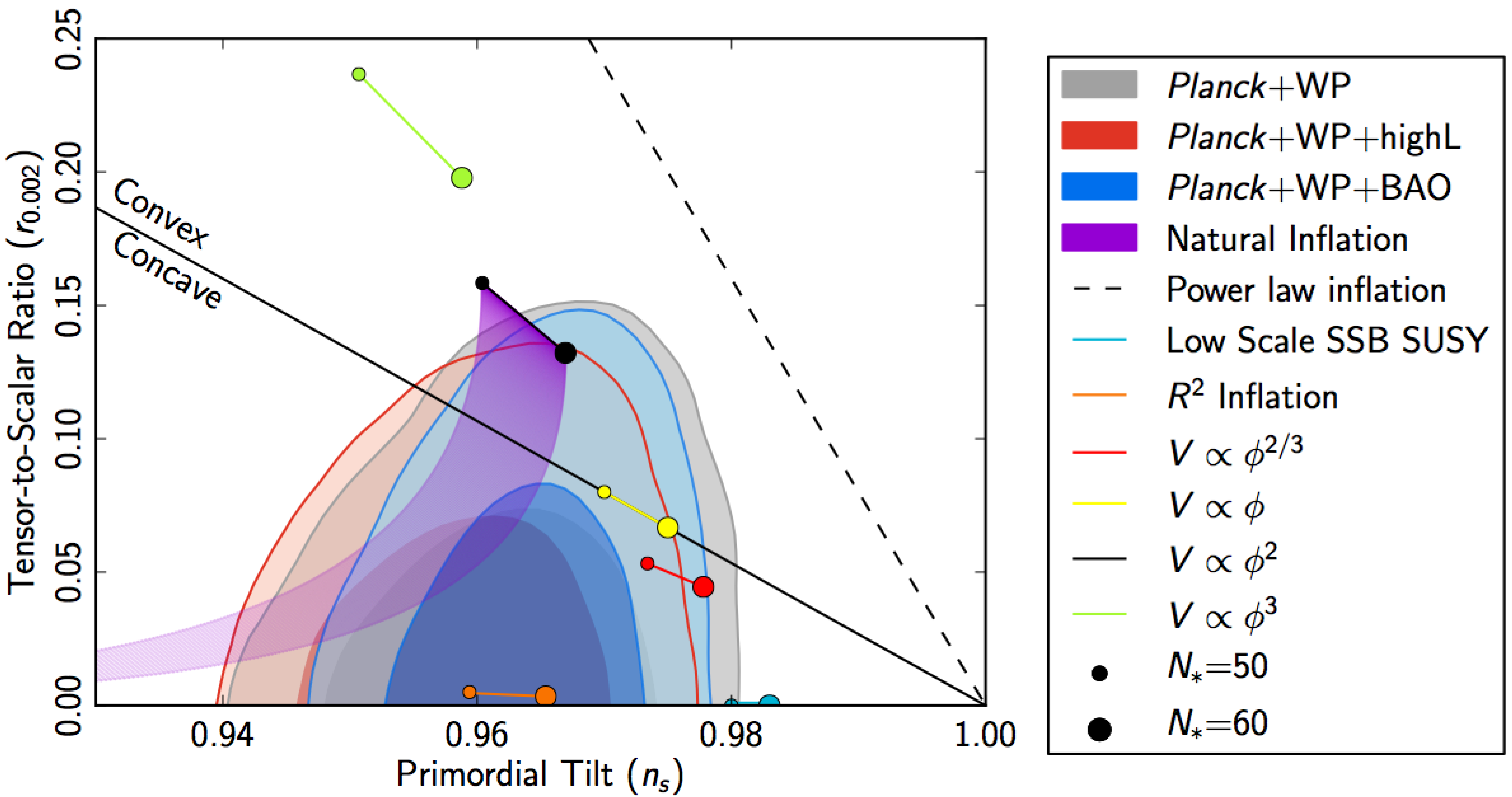
No evidence for non-Gaussianity

[Planck 2013]

Status of inflation last month



Inflation model constraints (pre BICEP2)

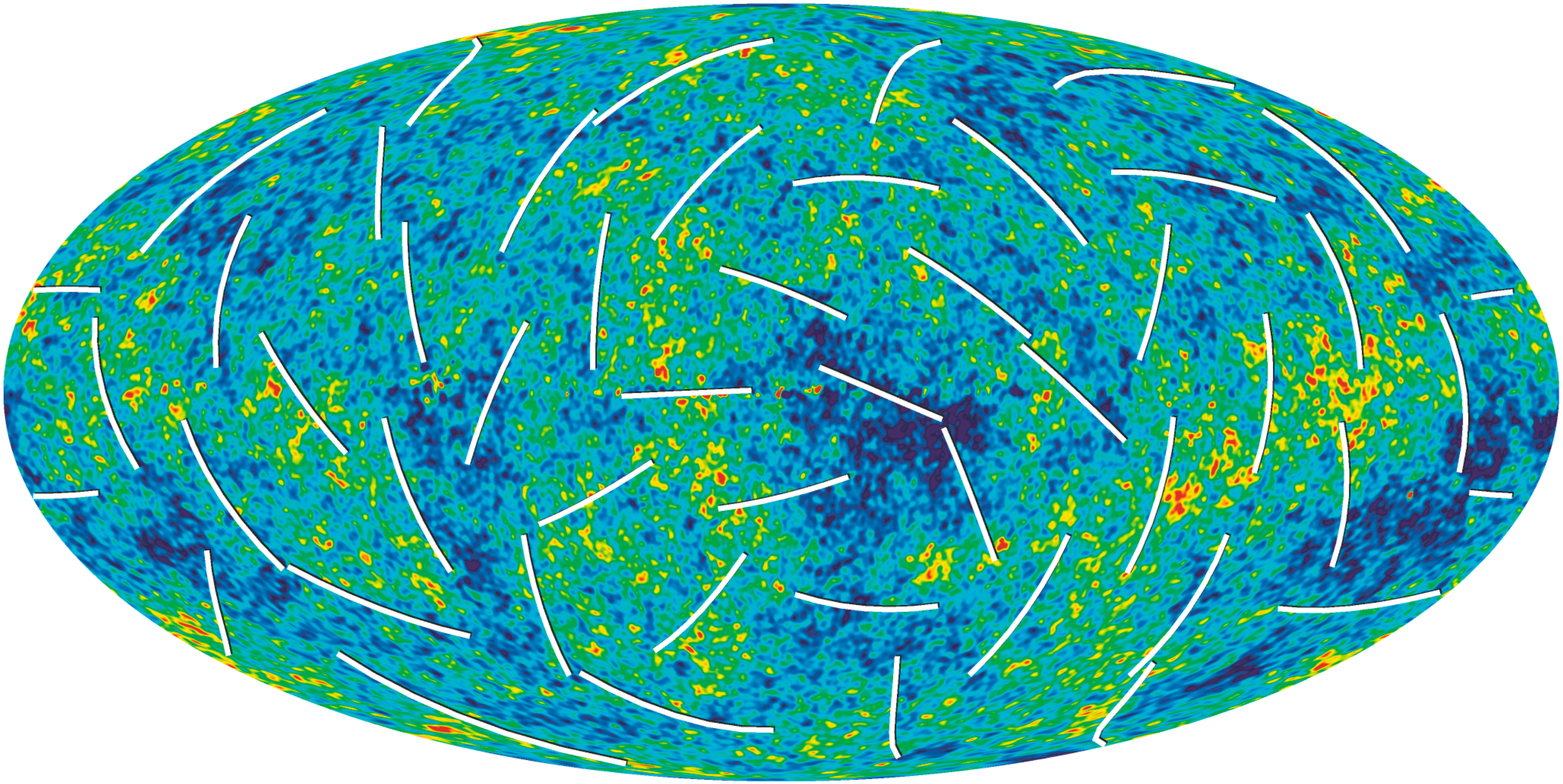


[Planck 2013]

Polarisation of the CMB

CMB polarisation

- The CMB is weakly linearly polarised:

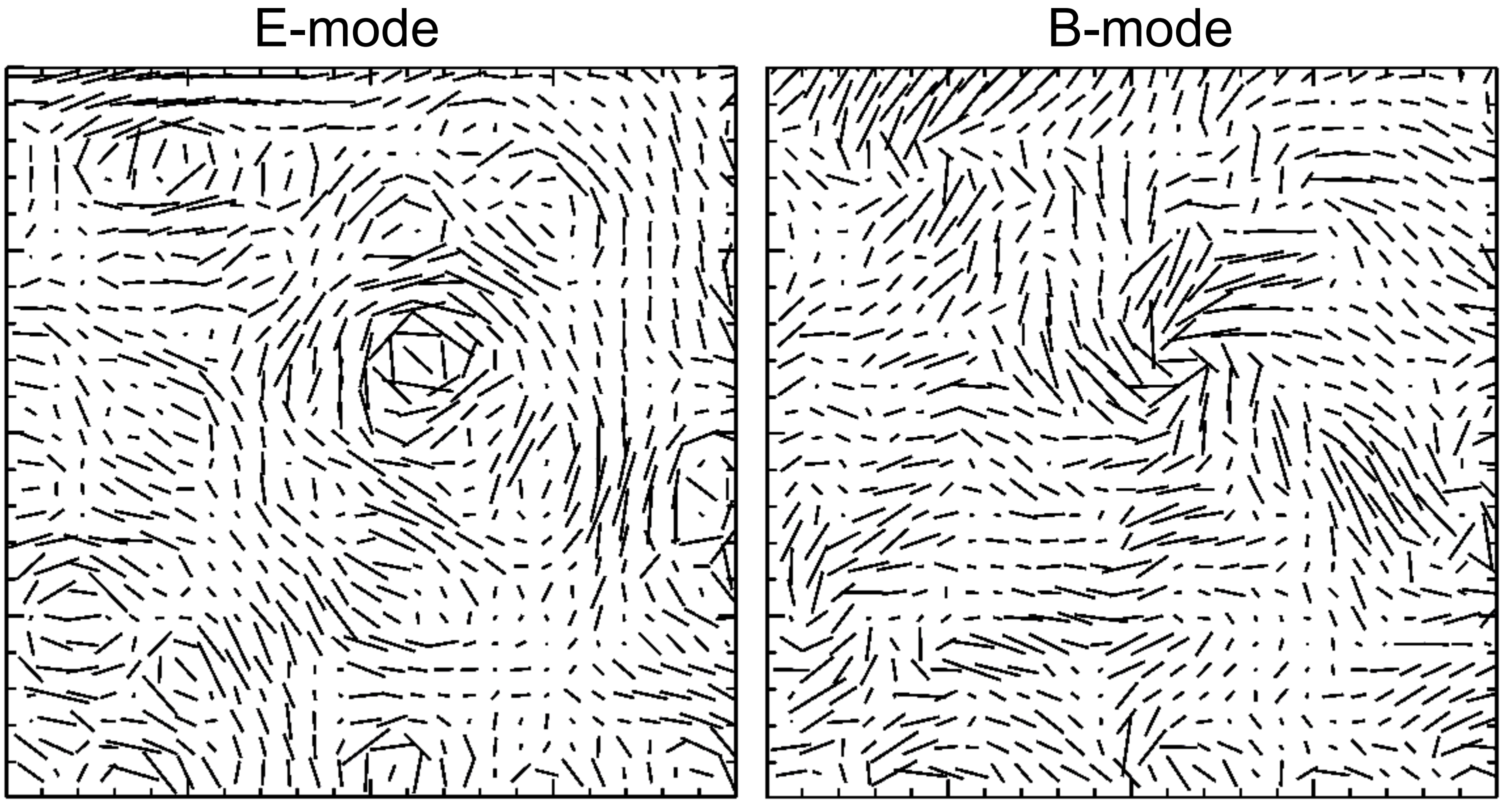


[WMAP 2006]

E- and B-modes

Polarisation pattern can be described in terms of

- Stokes parameters Q and U (easier to measure)
- Parity-even, curl-free E-mode and parity-odd, grad-free B-mode (easier to handle theoretically)

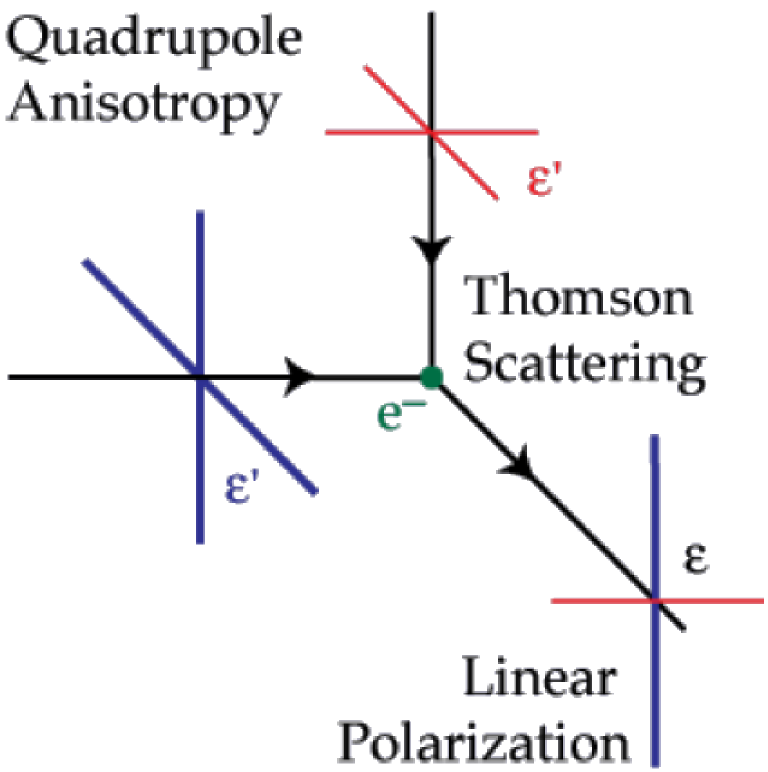


taken from [Hu 2001]

Why is the CMB polarised?

- Thomson scattering results in linear polarisation

(which is cancelled unless there is a quadrupole anisotropy)



taken from [Hu 2001]

Why is the CMB polarised?

- Thomson scattering results in linear polarisation

(which is cancelled unless there is a quadrupole anisotropy)

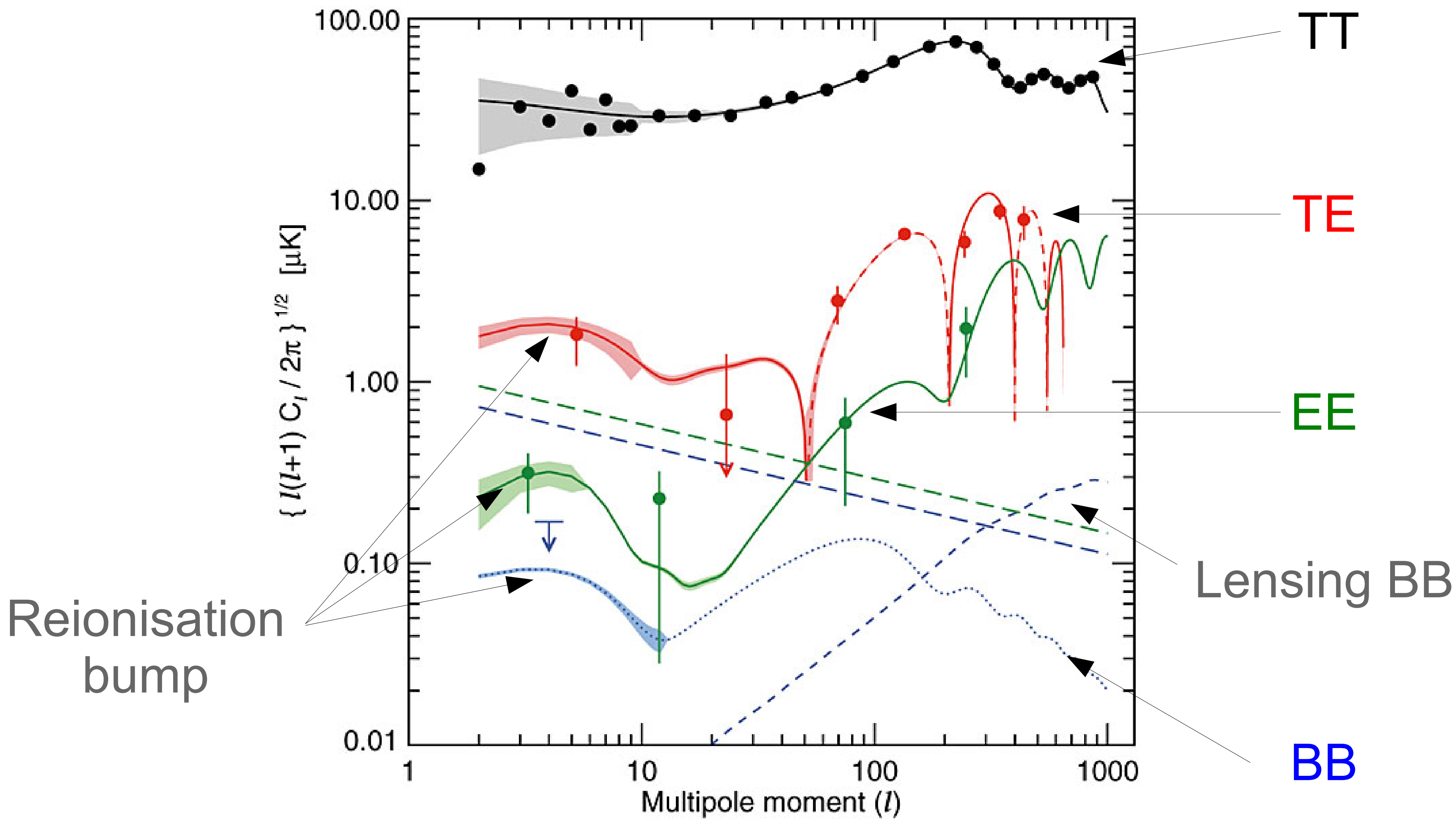
Polarisation signal survives:

- from last scattering surface
- from reionisation

→ expect contributions on the largest scales (reionisation) and intermediate to small ($\ell > 100$) scales (last scattering)

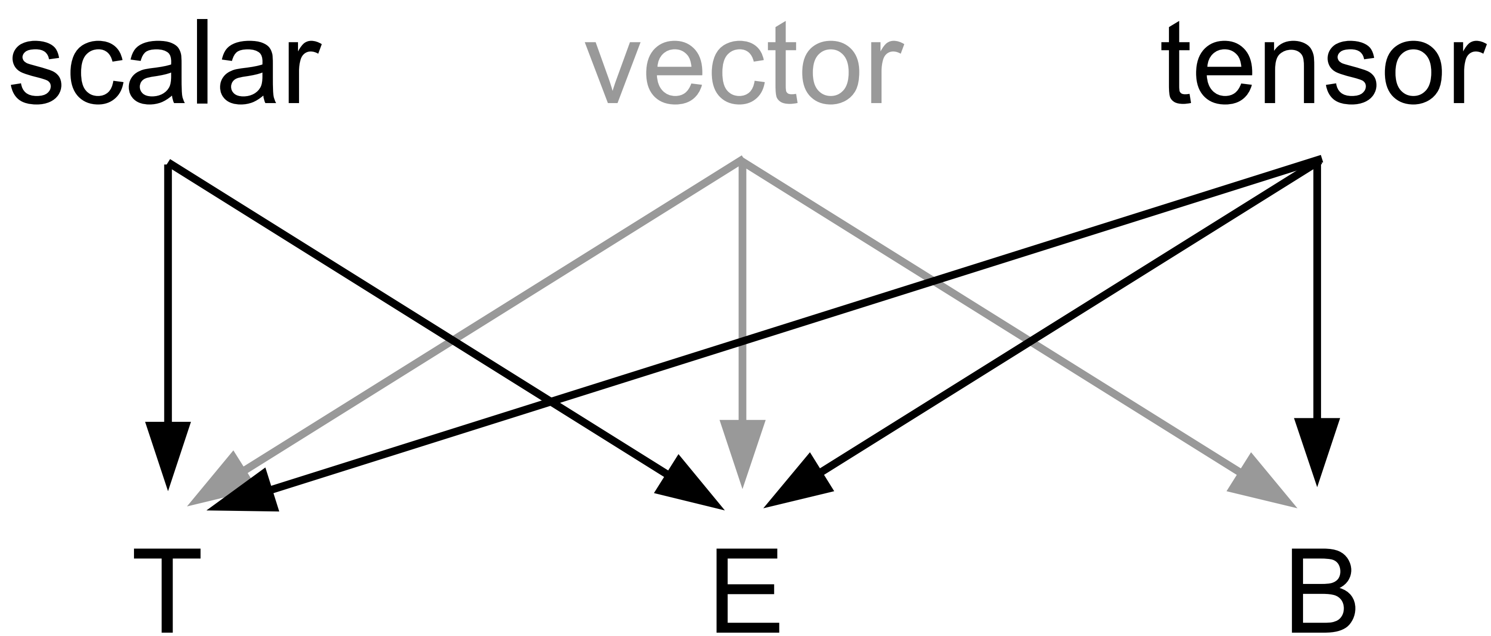
Also: gravitational lensing can generate B-mode from initial E-mode polarisation

Polarisation spectra



[WMAP 2006]

CMB signals from primordial perturbations



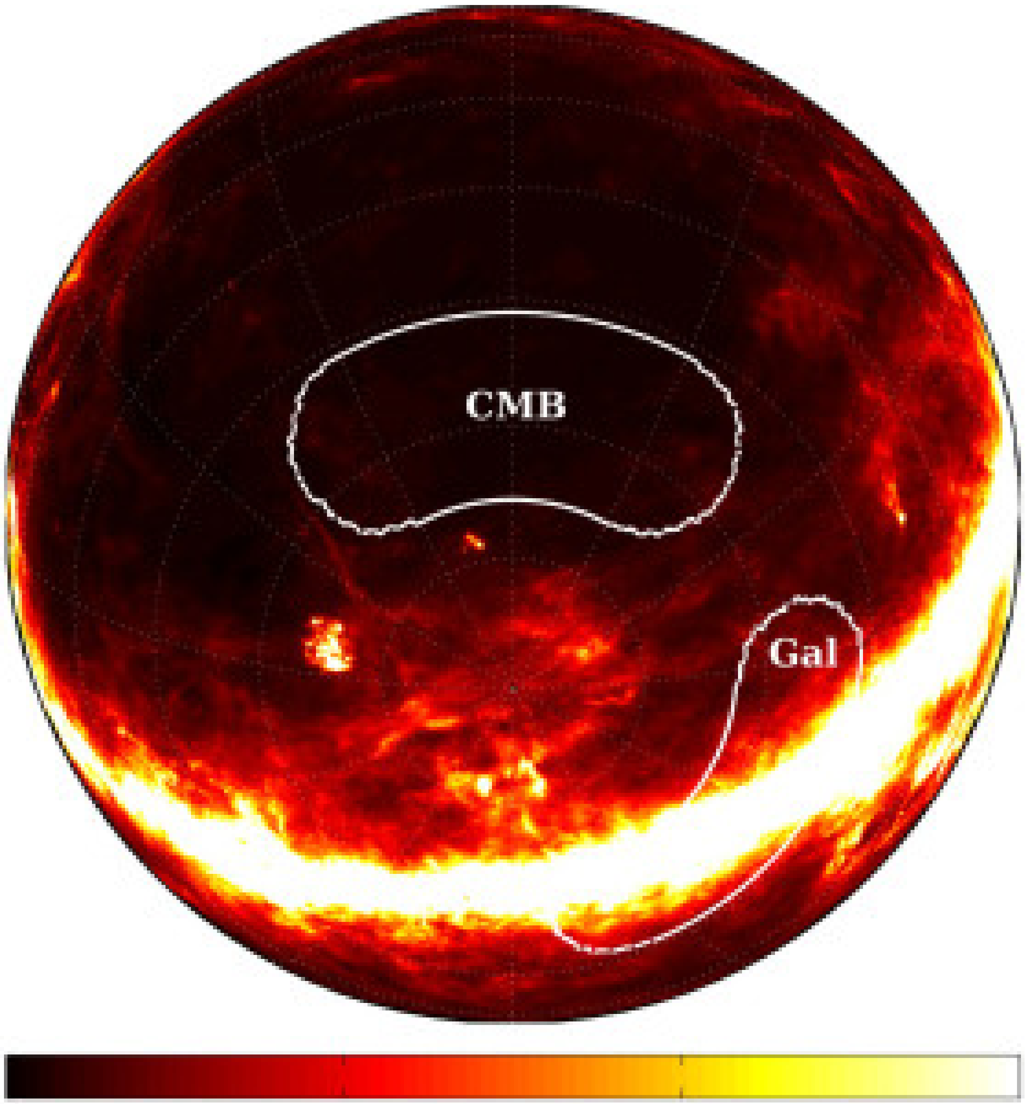
B-polarisation is the ideal probe of tensor perturbations

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

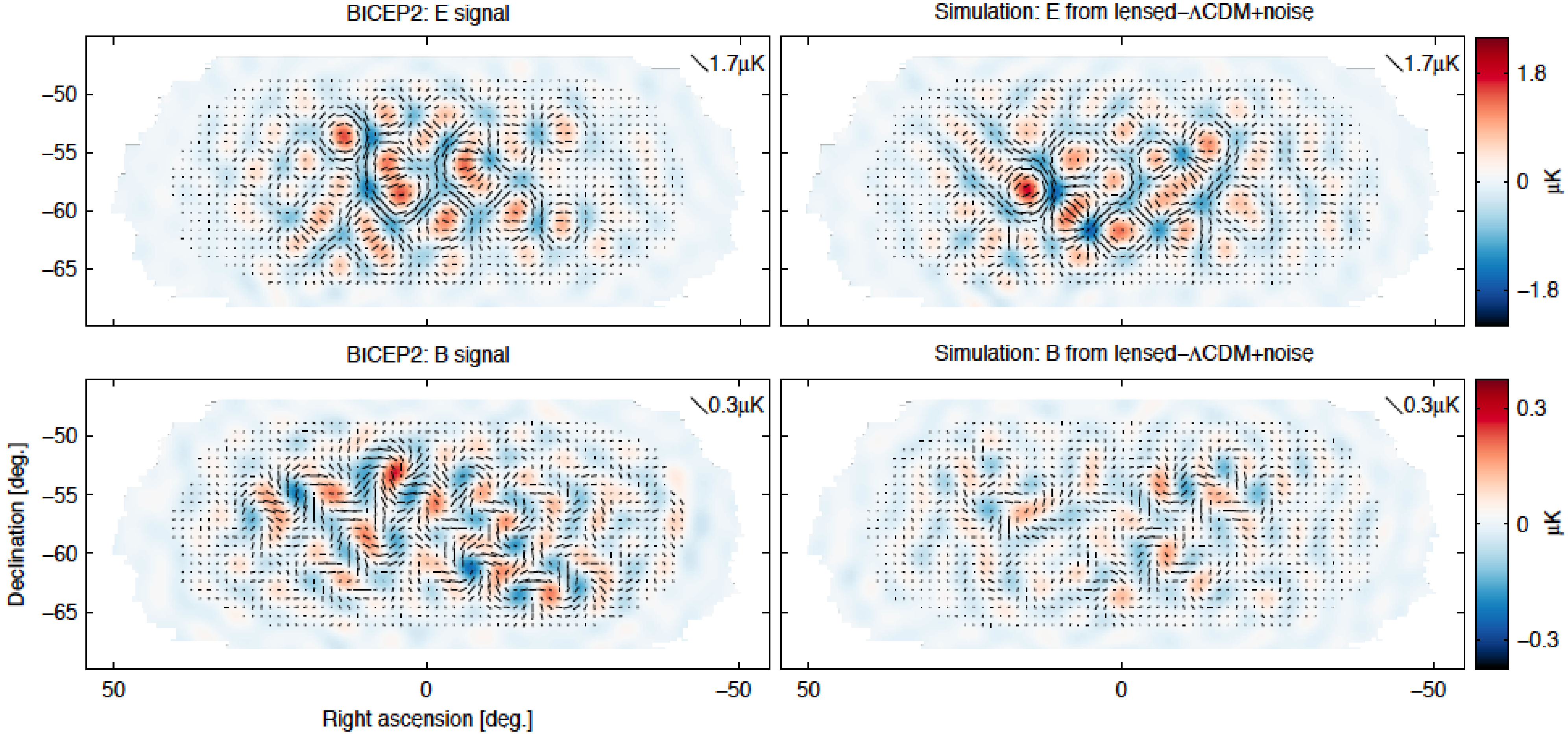


FIG. 3.— *Left:* BICEP2 apodized E-mode and B-mode maps filtered to $50 < \ell < 120$. *Right:* The equivalent maps for the first of the lensed-ΛCDM+noise simulations. The color scale displays the E-mode scalar and B-mode pseudoscalar patterns while the lines display the equivalent magnitude and orientation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

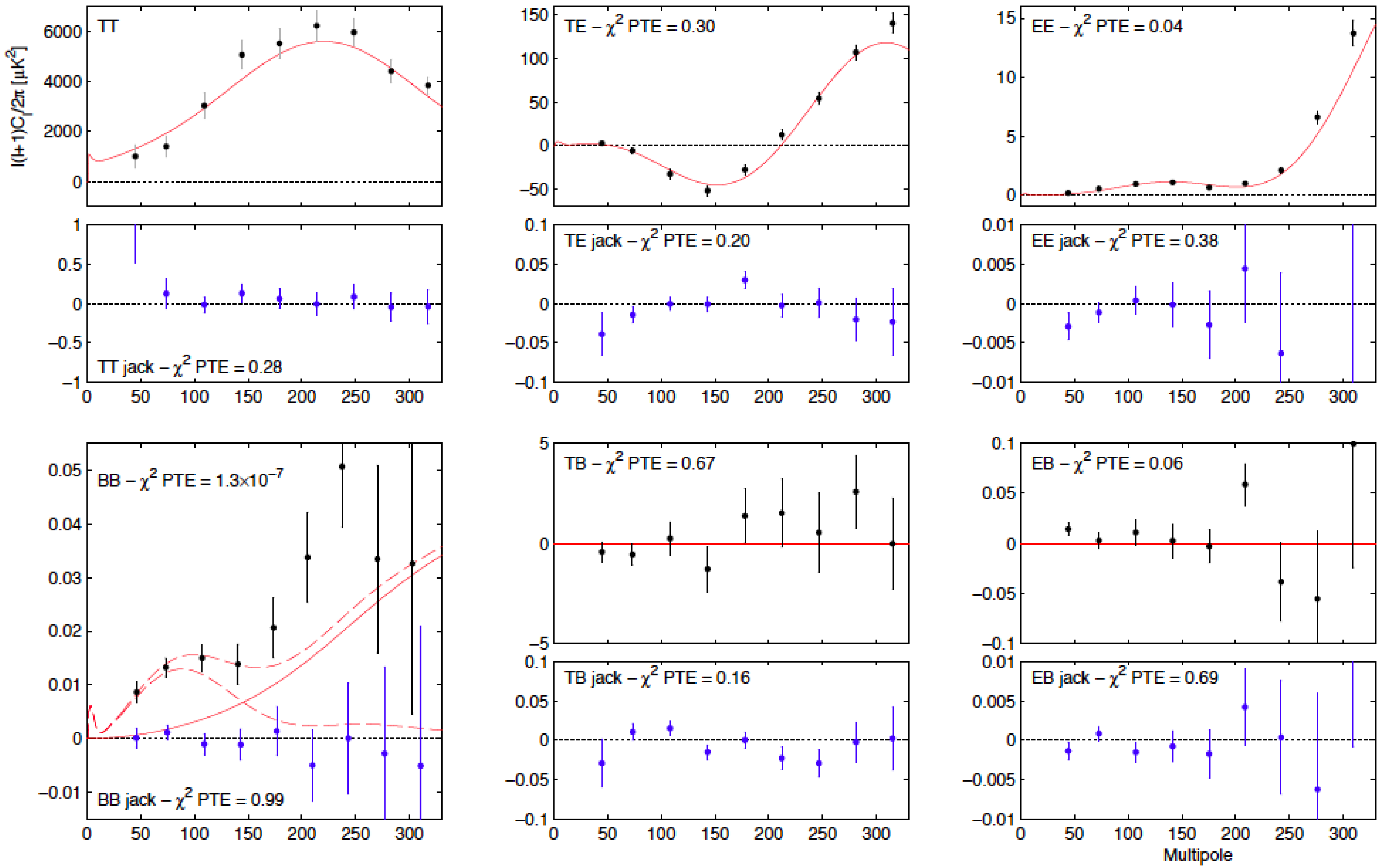
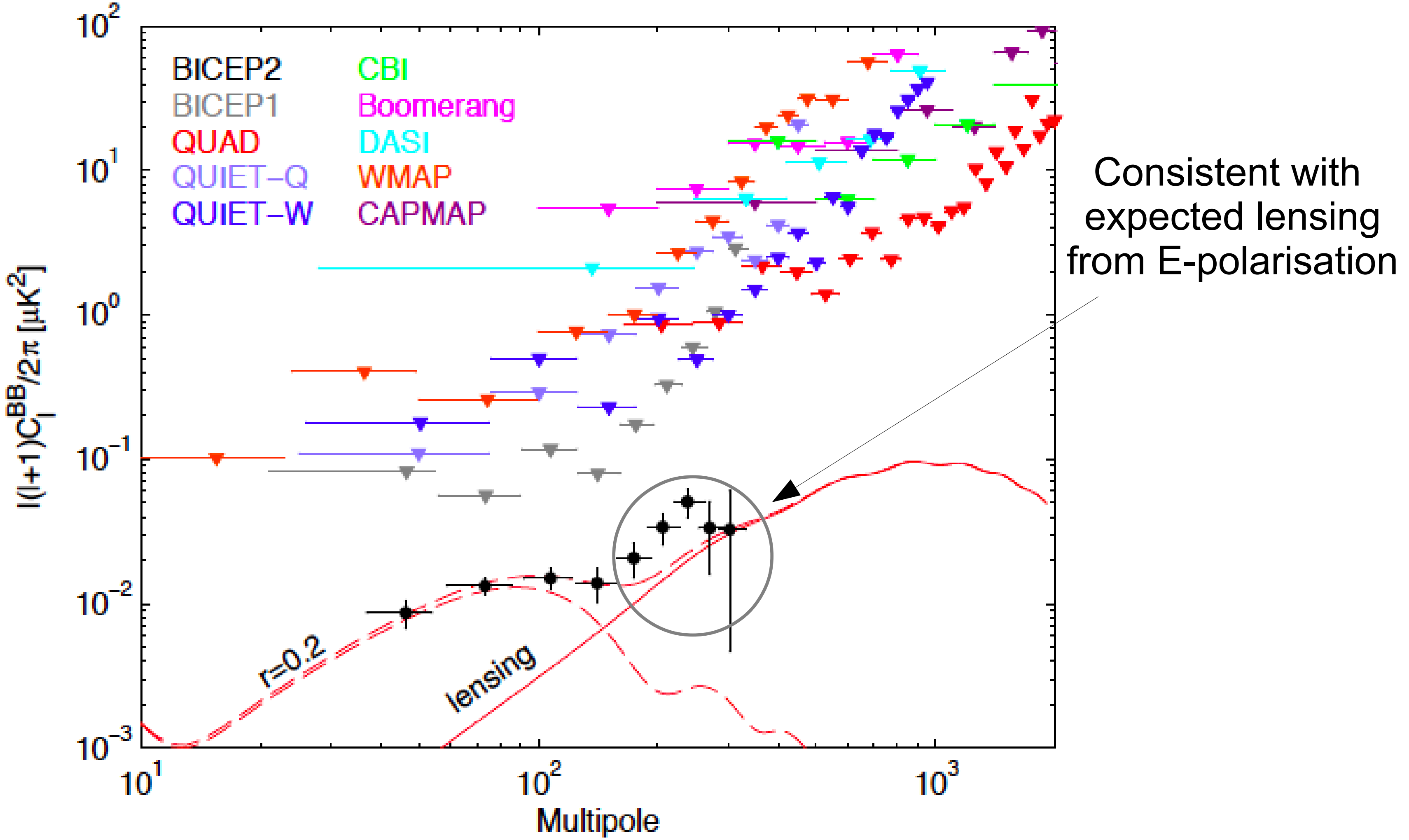


FIG. 2.— BICEP2 power spectrum results for signal (black points) and temporal-split jackknife (blue points). The red curves show the lensed-ΛCDM theory expectations — in the case of *BB* an $r = 0.2$ spectrum is also shown. The error bars are the standard deviations of the lensed-ΛCDM+noise simulations. 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]

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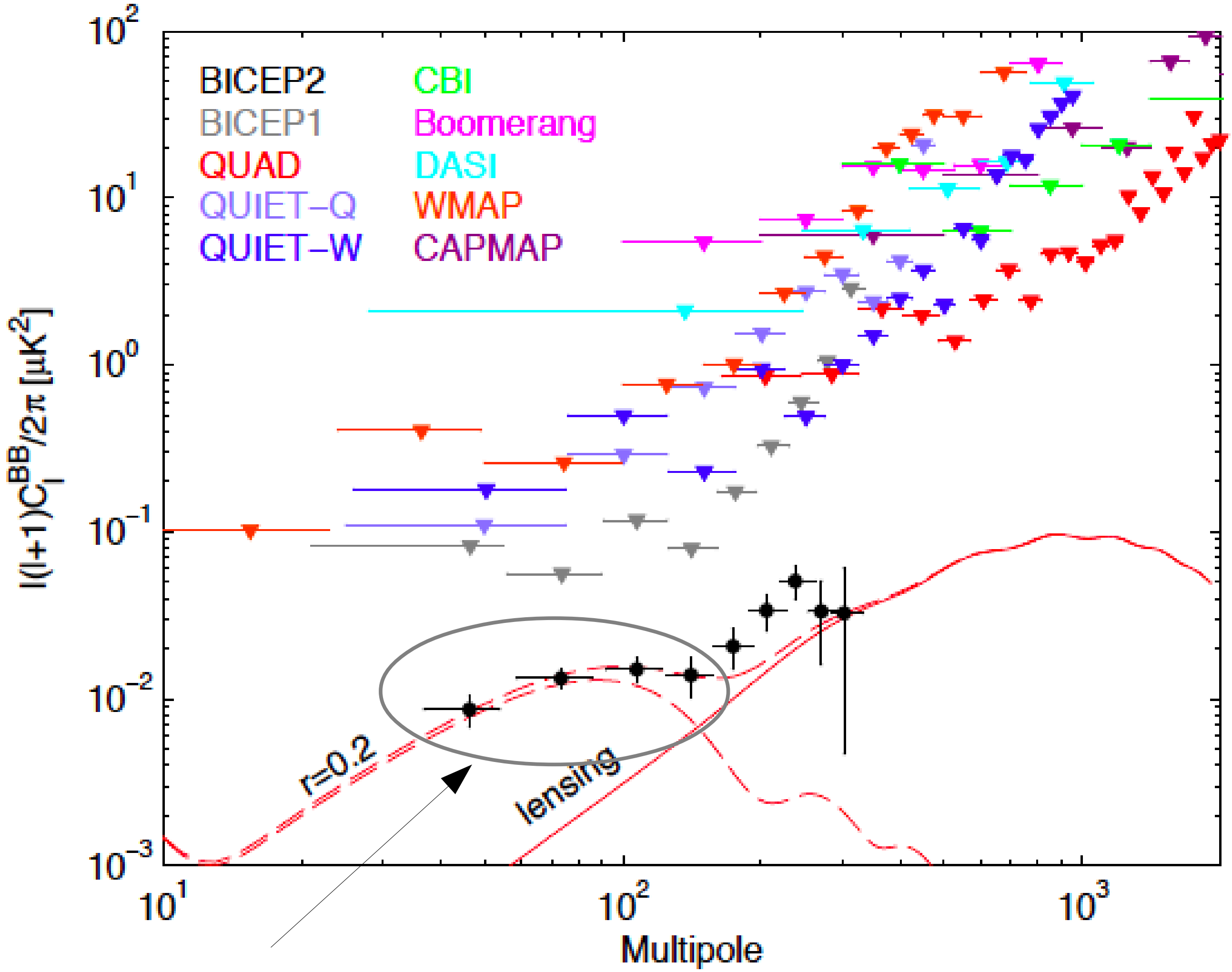


Excess signal
Due to tensor modes (?!)

[BICEP2 2014]

Is the signal real?

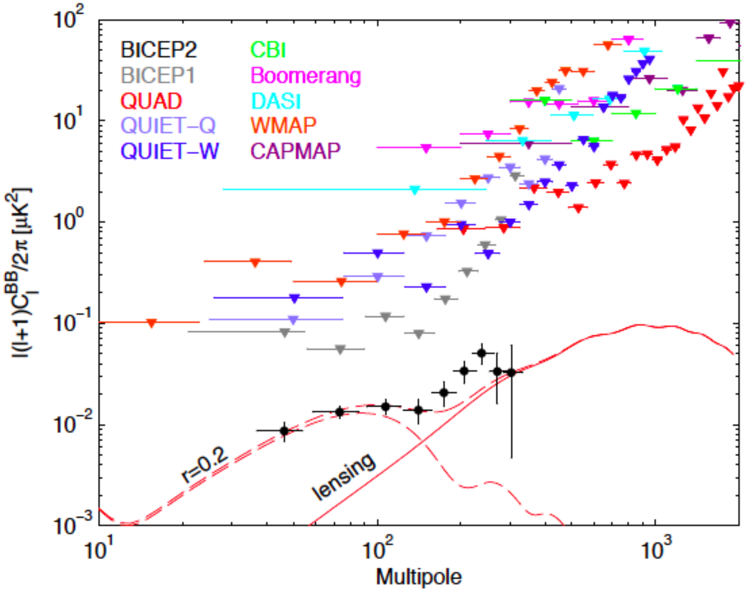
Experimental systematics?

- Pointing error
- Beam uncertainty

Passed consistency checks:

- jackknife tests
- no EB- and TB-signal

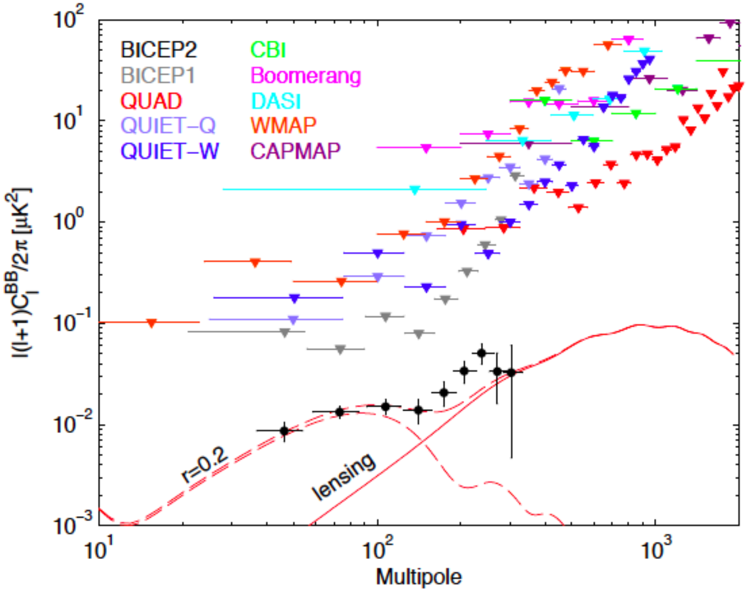
→ very unlikely to account for excess signal



Is the signal of cosmological origin?

Astrophysical foregrounds

- Polarised point sources
- Synchrotron emission
- Polarised dust emission



Is the signal of cosmological origin?

Astrophysical foregrounds

- Polarised point sources
- Synchrotron emission
- Polarised dust emission

→ likely some contribution to signal, not very likely to account for all of it

Ideally:
Want multi-frequency information

Different foreground models

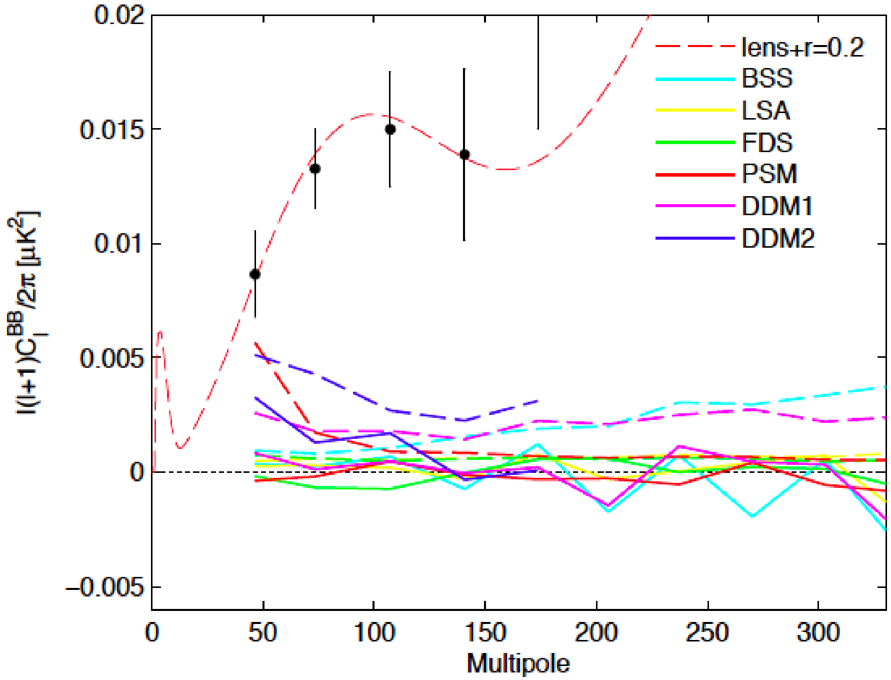


FIG. 6.— Polarized dust foreground projections for our field using various models available in the literature, and two new ones formulated using publically available information from *Planck*. Dashed lines show autospectra of the models, while solid lines show cross spectra between the models and the 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?

Adding BICEP1 data to determine frequency-dependence of the signal

→ signal consistent with CMB expectation

Foreground removal will greatly benefit from Planck polarised dust maps

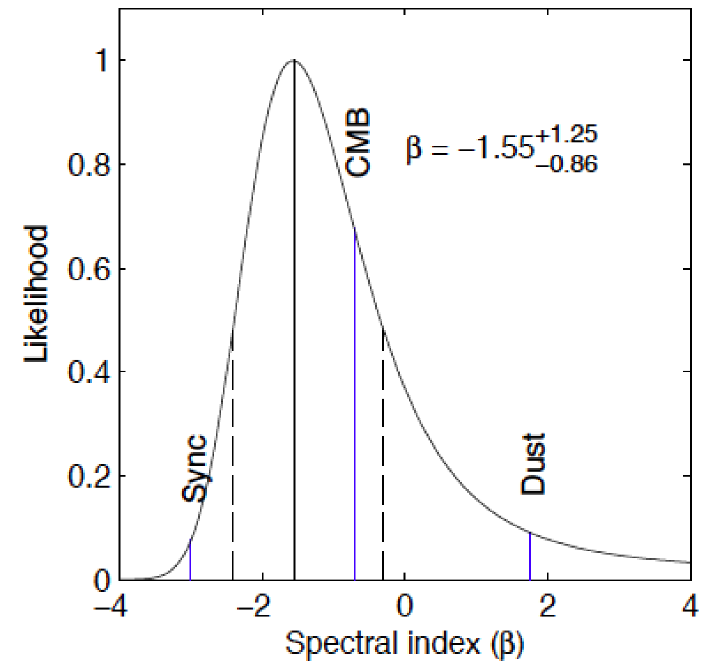


FIG. 8.— The constraint on the spectral index of the *BB* signal based on joint consideration of the BICEP2 auto, BICEP1$_{100}$ auto, and BICEP2×BICEP1$_{100}$ cross spectra. The curve shows the marginalized likelihood as a function of assumed spectral index. The vertical solid and dashed lines indicate 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 really from inflationary tensor modes?

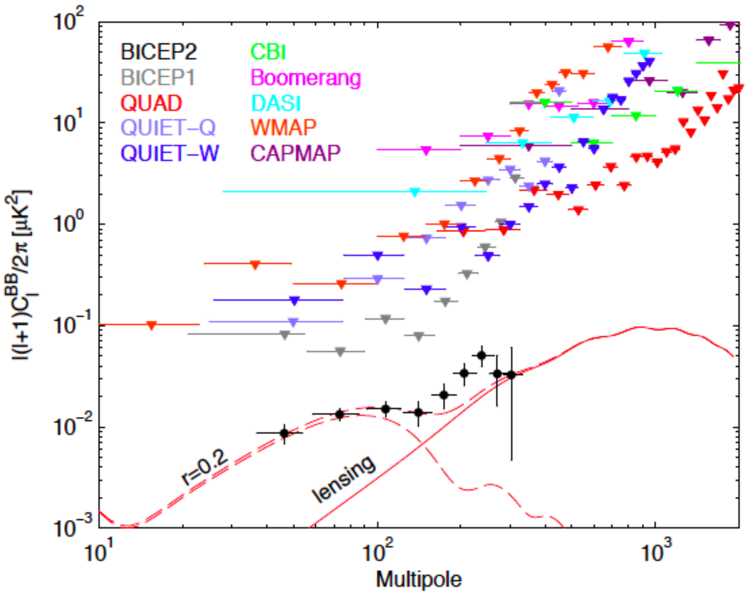
Alternative mechanisms:

- 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]



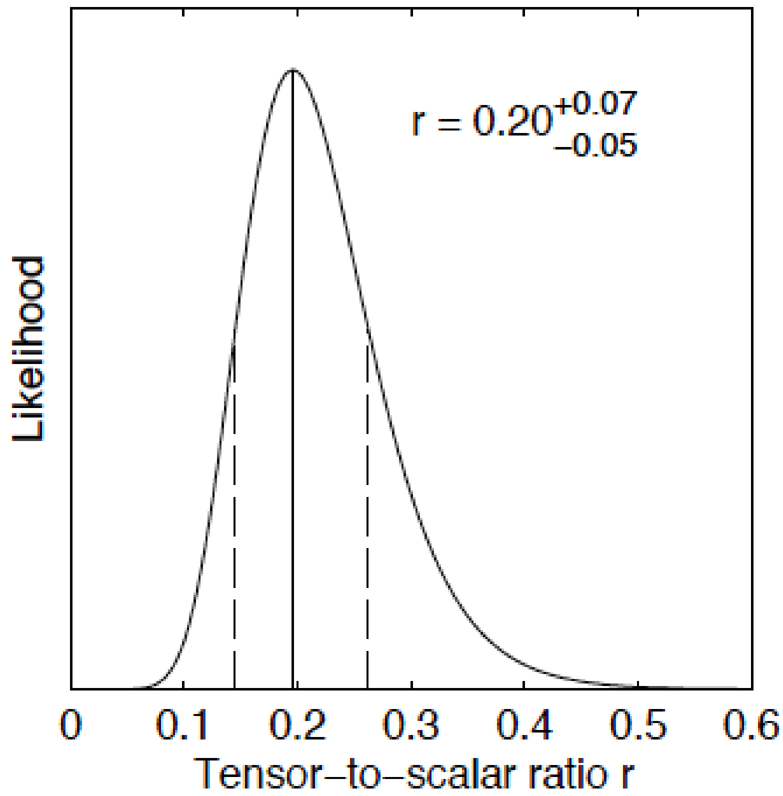
→ inflation remains most likely origin

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

Implications of BICEP2 results



[BICEP2 2014]

Energy scale of inflation:

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

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

Implications of BICEP2 results

- Lyth bound:
  For inflation to last sufficiently long, ϕ has to take on super-Planckian values

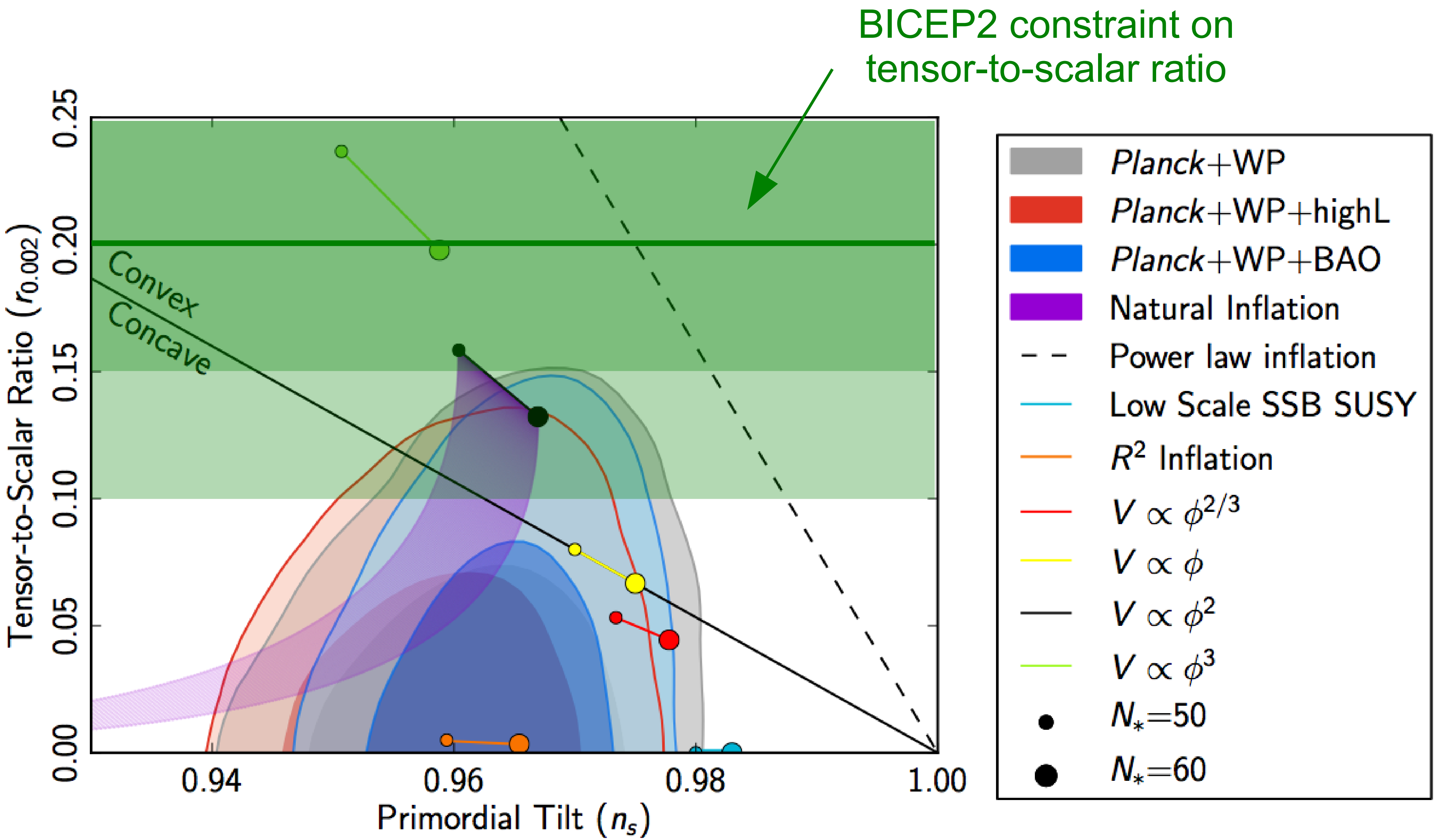
$$\Delta\phi \gtrsim m_{\mathrm{Pl}}\,(r/0.01)^{1/2}$$

[Lyth 1997]

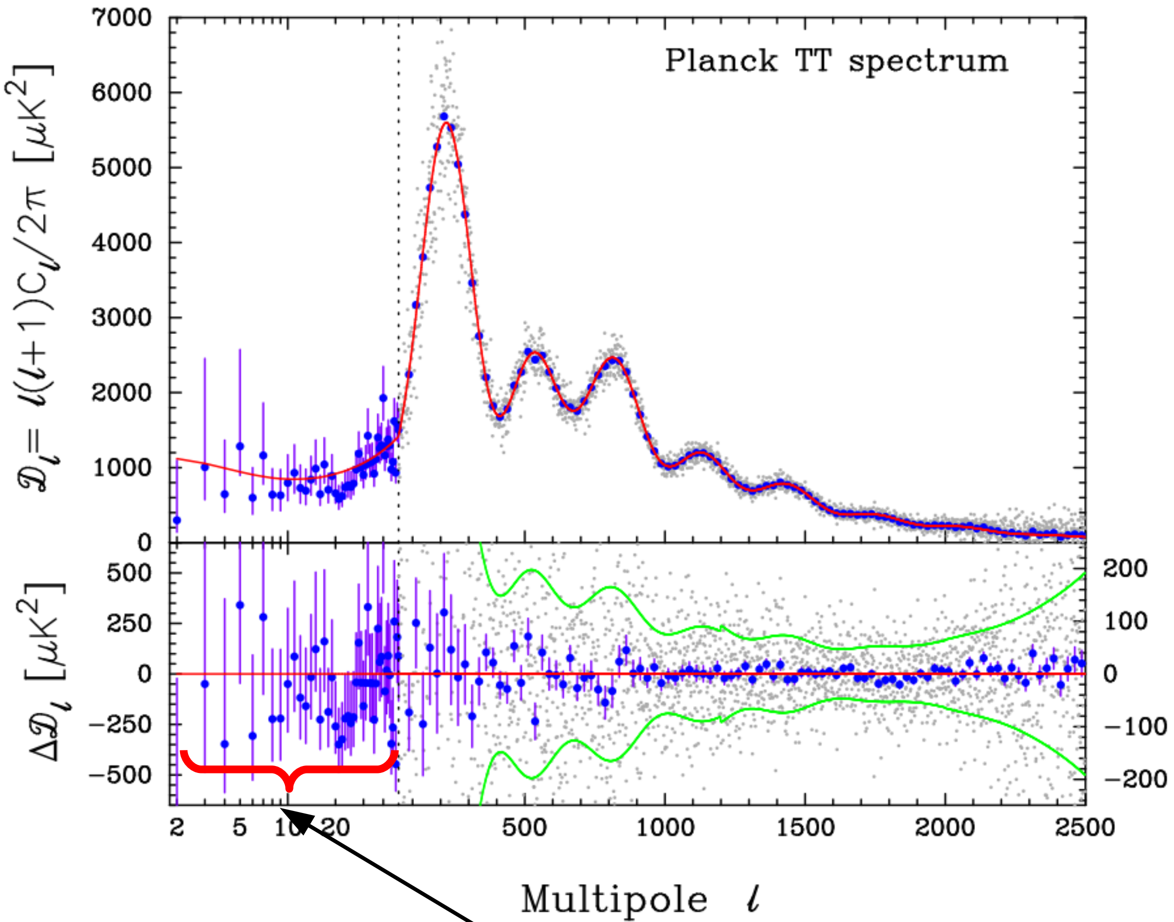
- In effective field theory, Planck-mass suppressed higher order operators would mess up things...

  → Challenge for inflation model-builders

Inflation model constraints (post BICEP2)



Tension with 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
- Anticorrelated tensor perturbations

[Contaldi, Peloso, Sorbo 2014]

- Extra radiation (e.g., $\Delta N_{eff} \approx 1$ sterile neutrinos)

[Zhang et al., Dvorkin et al. 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
  - Quite possibly signs of further new physics
- These measurements do not prove inflation happened, but certainly make it look even more attractive than before!