BICEP2, and its implications for cosmology and particle physics

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BICEP2 I: Detection Of B-mode Polarization at Degree Angular Scales

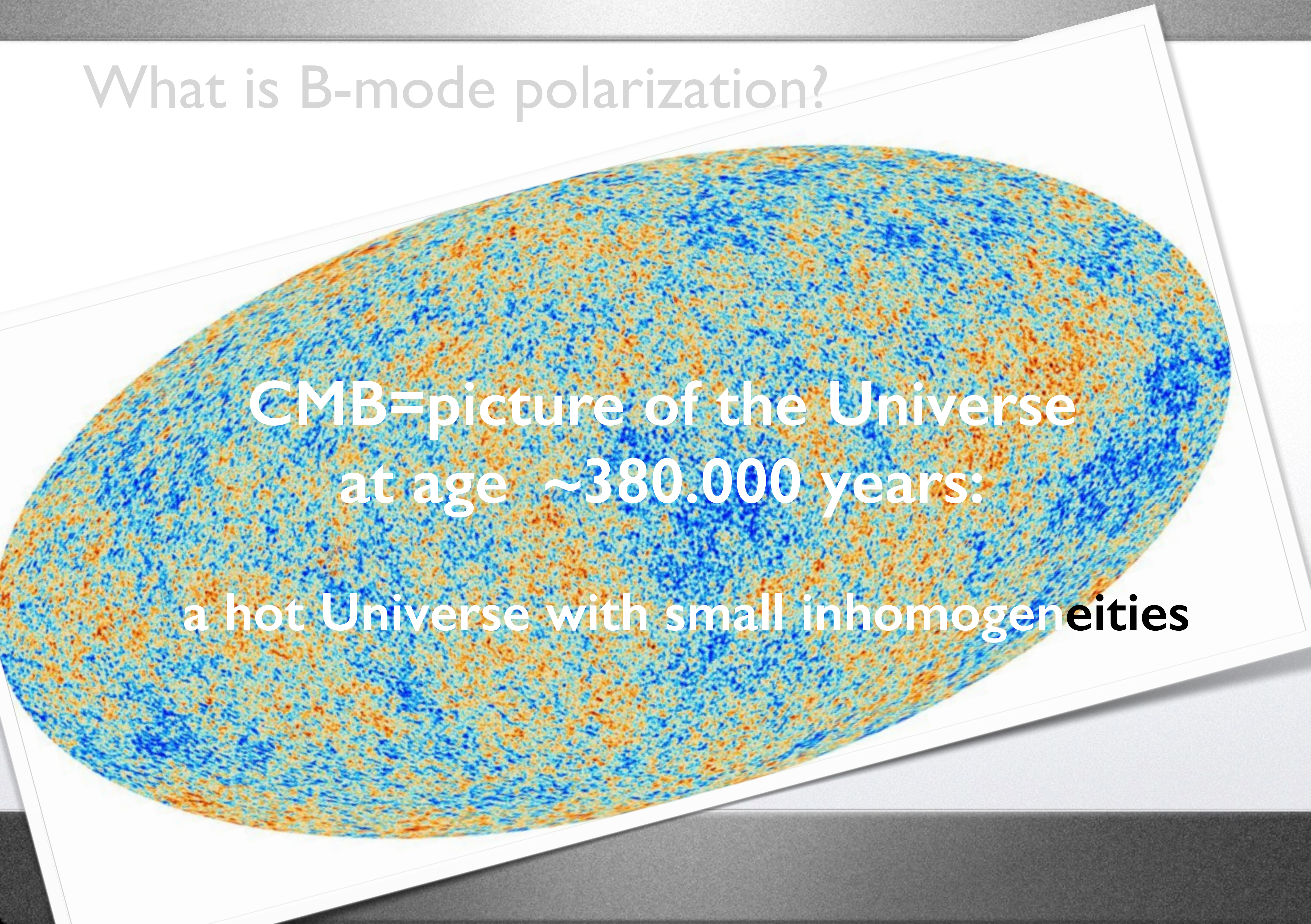
BICEP2 Collaboration (P.A.R. Ade (Cardiff U.) et al.) Show all 47 authors

Mar 16, 2014 - 19 pages

e-Print: arXiv:1403.3985 [astro-ph.CO] | PDF
Experiment: BICEP2

Abstract (arXiv)
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 l=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 uk.sqrt(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-LCDM expectation in the range 30<l<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-LCDM + 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.

What is B-mode polarization?



CMB=picture of the Universe at age ~380.000 years:

a hot Universe with small inhomogeneities

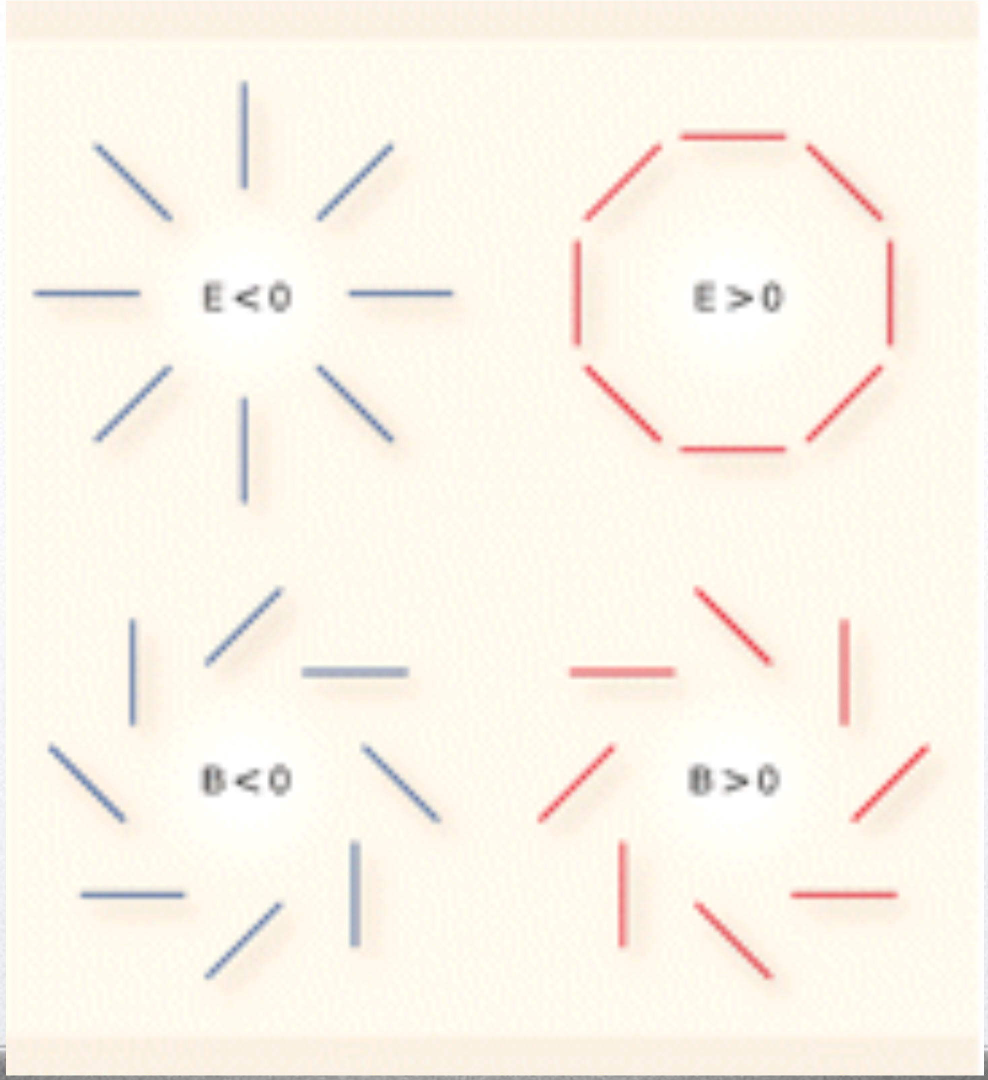
What is B-mode polarization?

The CMB light is polarized!

The polarization plane is related to the gradients of CMB temperature

"E modes":
parallel/orthogonal
to such direction
(curl-free)

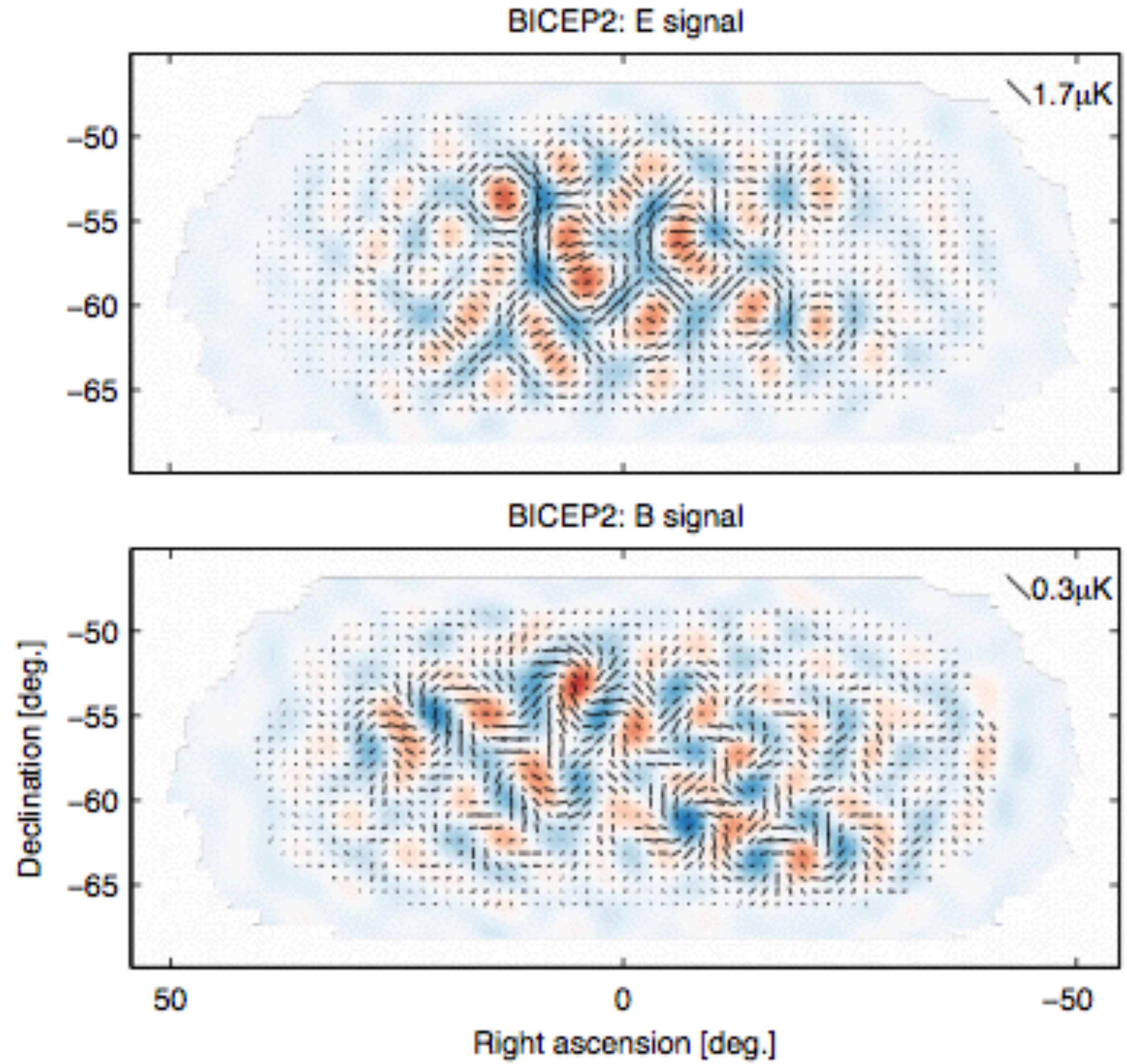
associated to
temperature gradients
(Thomson scattering)



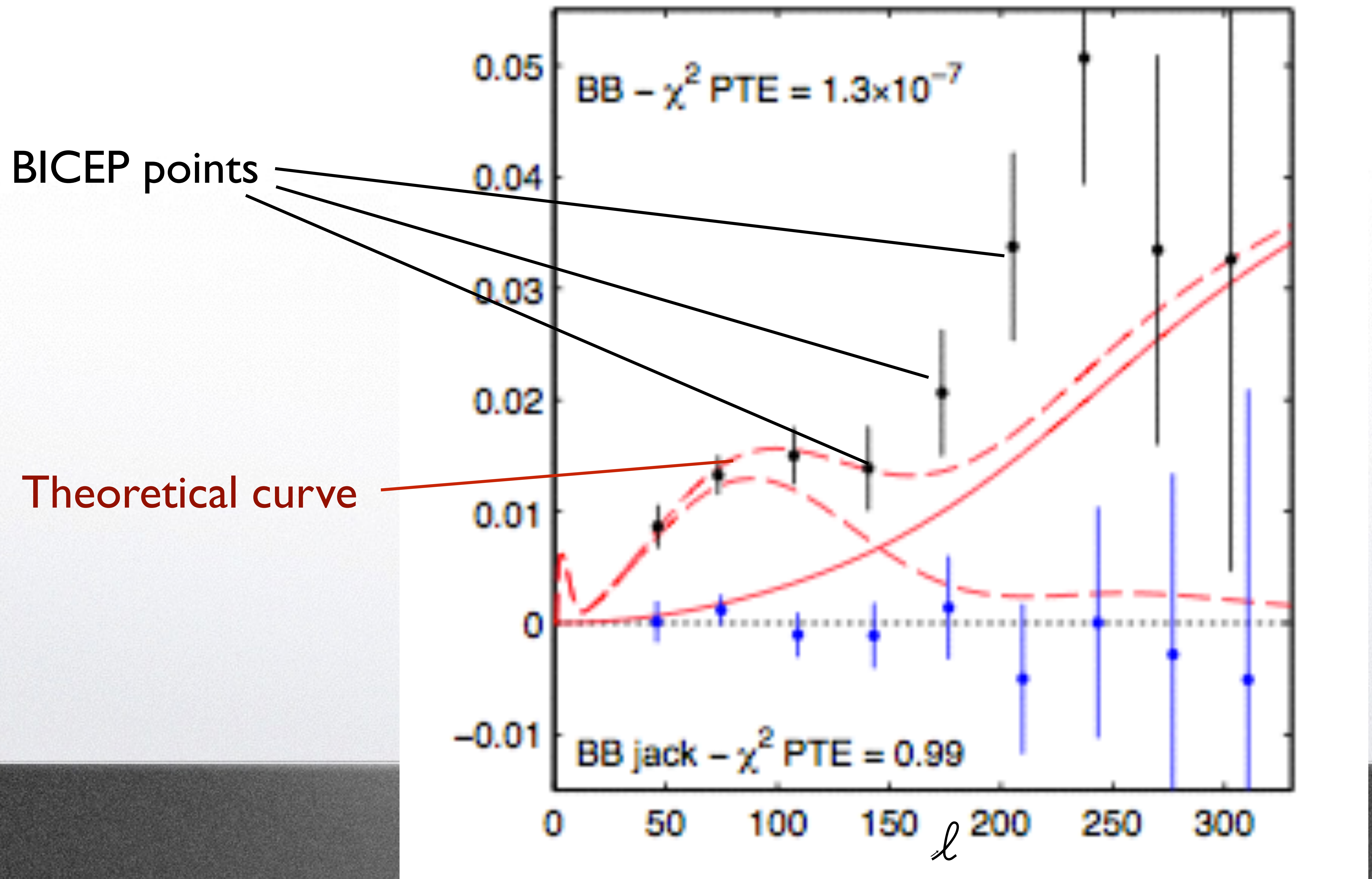
"B modes":
at 45°
to such direction
(divergence-free)

cannot be associated
to any scalar quantity
in the CMB
⇓
TENSORS

Maps from BICEP2…



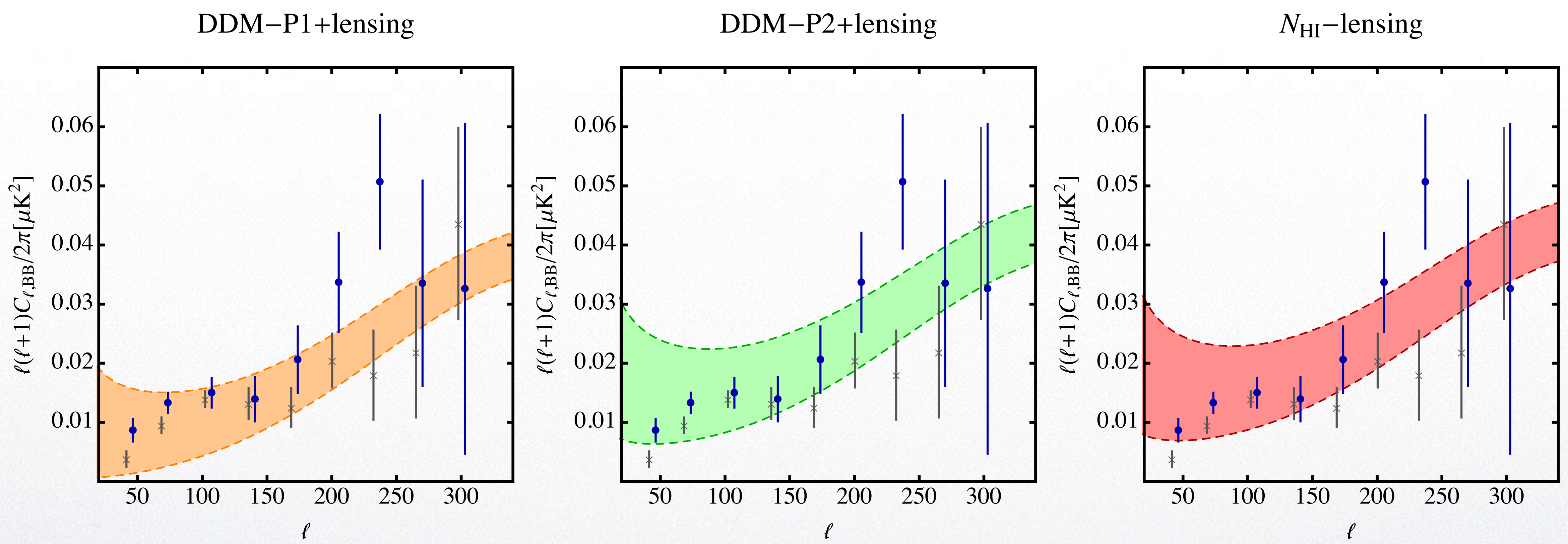
…and the <BB> power spectrum



Is it primordial?

Estimating of effect of foregrounds…
(note the errorbar on the errorbar)

Flauger, Hill and Spergel 14



In the rest of talk talk I will assume that the signal *is* primordial

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Where do these *tensor modes* come from?

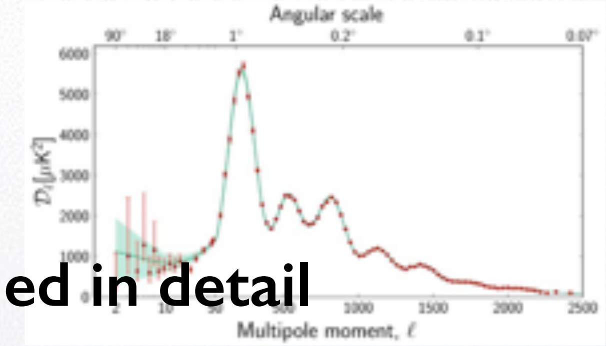
Inflation:

accelerated expansion

- counters Jeans instability and produces a large, homogeneous and spatially flat Universe

- pulls quantum fluctuations out of vacuum (cf. Schwinger effect): at least two forms of “particles” are created:

scalar modes (quanta of inflaton) → Observed, studied in detail



tensor modes (quanta of gravity) → This is what we care about here

r=amplitude of tensors over scalars

BICEP2

Amplitude of scalar perturbations well measured by COBE

$r \Longleftrightarrow V$ during inflation

$$V^{1/4} \simeq 2.25 \cdot 10^{16}\,\mathrm{GeV}\ \left(\frac{r}{0.2}\right)^{1/4}$$

High scale (GUT!) inflation!

…more properties?

The Lyth bound

r related to excursion of inflaton during inflation

$$\Delta\phi \sim M_P \sqrt{\frac{r}{0.01}}$$

Planckian excursions of inflaton!

To sum up, if BICEP2 result is true:

- It means that we "saw" gravitational waves
- Direct test of canonical quantization of gravity (on a time-dependent background!)
- Rules out a bunch of alternatives to inflation (that have no tensors)
- Strongly supports existence of nontrivial physics at a new, close to GUT, scale
- In simple (and not so simple) models proves planckian excursions of scalar fields

NOTA BENE: none of these statements is a theorem!

Implications for model building?

$\Delta\phi \gtrsim M_P$

A possible concern?

“Graviton loops” effects generate terms

$$\propto M_P^4 \left(\frac{\phi}{M_P} \right)^n$$

in $V(\phi)$, that are uncontrollable corrections for $\phi > M_P$

Not really...

$\Delta\phi \gtrsim M_P$

(Quantum) gravity interacts with energy, not with ϕ!

Indeed: for potential $V(\phi)$, perturbative quantum gravity effects are

$$O(1)\, V(\phi)^2/M_P^4 \quad \text{and} \quad O(1)\, V''(\phi)\, V(\phi)/M_P^2$$

Smolin 80
Linde 88

negligible during inflation

$V(\phi)$ breaks softly the shift symmetry $\phi \rightarrow \phi + const.$
that protects $V(\phi)$ against gradients

$$\Delta\phi \gtrsim M_P$$

Perturbatively dangerous operators are those that break shift symmetry in a hard way (e.g., sufficiently large Yukawas)

Solution:

Assume an exact shift symmetry (so Yukawas are forbidden)…
…then break the symmetry a bit and generate a potential
[Pseudo-Nambu-Goldstone-Boson]

Prototypical example: **Natural Inflation** Freese et al 90

$$V(\phi) = \Lambda^4(1 - \cos\phi/f\ \ )$$

BICEP requires
$f > 10\ M_P$

…what about UV-complete theories?

(e.g., string theory)

A problem…

Banks, Dine, Fox and Gorbatov 03
Arkani-Hamed, Motl, Nicolis and Vafa 06

String Theory appears to require $f < M_P$

[ϕ=angle, with periodicity determined by size of internal space$> 1/M_P$]

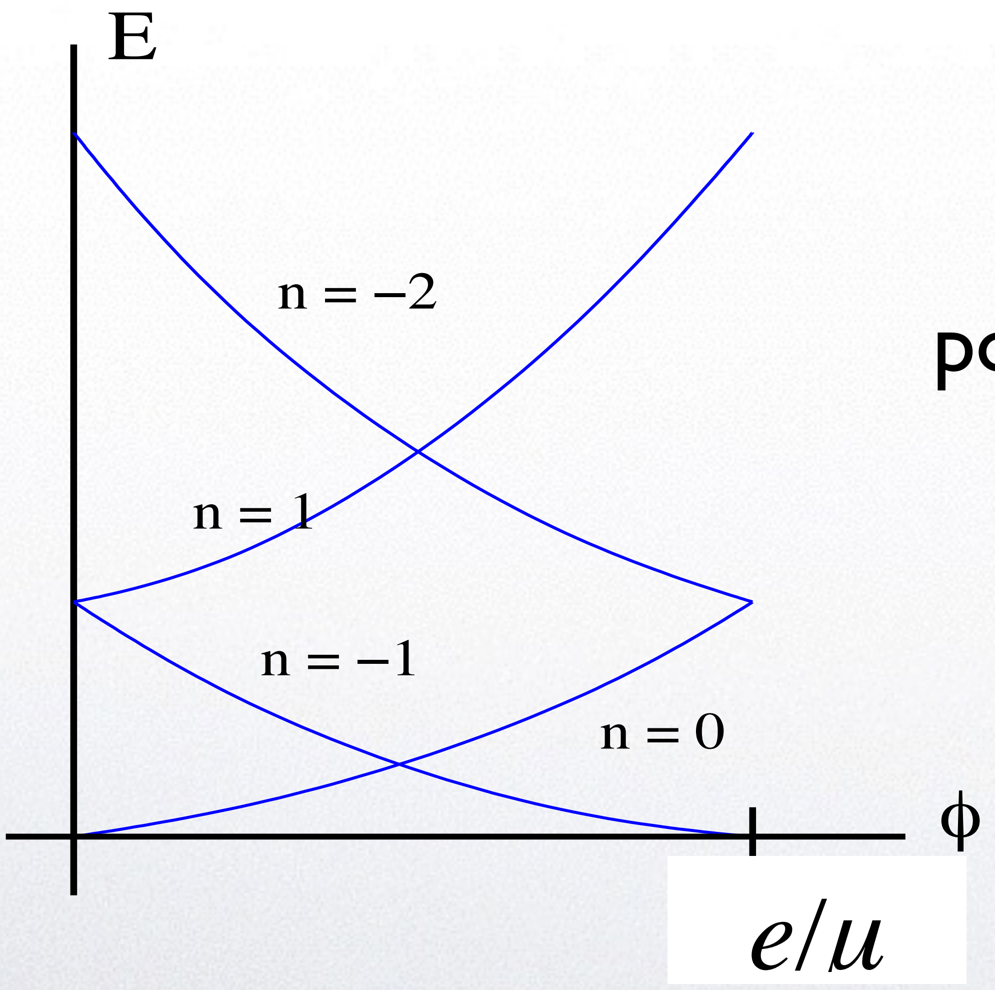
[instanton corrections unsuppressed for $f > M_P$]

An example of a way out…

Monodromy

Silverstein and Westphal 08
Kaloper, LS 08
Kaloper, Lawrence, LS 11

The potential is not a single valued function of the inflaton!



possible tunneling between branches

$\Downarrow$

interesting phenomenology

How about high scale inflation?

☛ In string th, moduli better be stabilized during inflation (decompactification!)

BICEP2⇒ $H\sim10^{14}\ GeV$

Need to stabilize moduli at high scale (above usual SUSY breaking scale $10^{11}\ GeV$)

Bottom line…

From an Effective Field Theory approach
Planckian excursions are not a problem

Even in more constrained setups,
like string theory, there are ways out

More implications for particle physics?

How about high scale inflation?

☛ Axion dark matter

If axion exists during inflation,
gets fluctuations $\delta a \simeq H_I/2\pi$

DM isocurvature perturbations!

Planck requires

$$H_I \leq 2.4 \times 10^9 \ \mathrm{GeV} \left(\frac{f_a}{10^{16} \ \mathrm{GeV}} \right)^{0.408}$$

Ways out exist

BICEP2⇒ $H \sim 10^{14}$ GeV

How about high scale inflation?

☛ Metastable EW vacuum

(From Lebedev and Westphal 12)

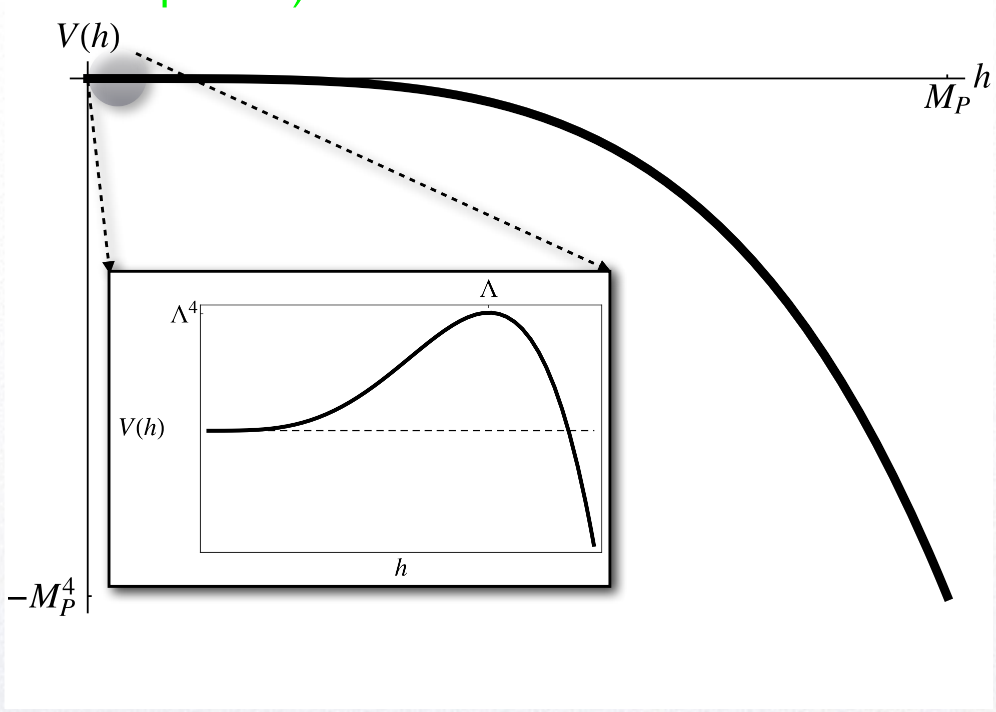


Figure 1: A *schematic* view of the Higgs potential ($\Lambda \sim 10^{10}$ GeV $\ll M_{\rm Pl}$).

BICEP2⇒ $H \sim 10^{14}$ GeV

Quantum fluctuations bring Higgs into region unbounded from below!

Ways out exist

Conclusions

- If BICEP2 results hold true (and we will know within months!) this is a huge result: (new) evidence for GWs, for quantization of gravity, for inflation, for a new scale in physics
- No real problem with large inflaton excursions…
- …provided one does not forget about (approximate) shift symmetries
- Implications for particle physics. Nothing that cannot be evaded, but at what price?

An intriguing discrepancy…

BICEP: $.15 < r < .27$ @ 68%

Planck: $r < .11$ @ 95%

Probably this will go away with more data.
But what if…?

How does Planck measure r?

scalar metric perturbations

tensor metric perturbations

Planck measures $\delta T \sim \zeta + h$

(cf. BICEP2 measures $B \sim h$)

$$\langle \delta T \, \delta T \rangle \sim \langle \zeta \, \zeta \rangle + \langle h \, h \rangle$$

(assuming no tensor-scalar correlation)

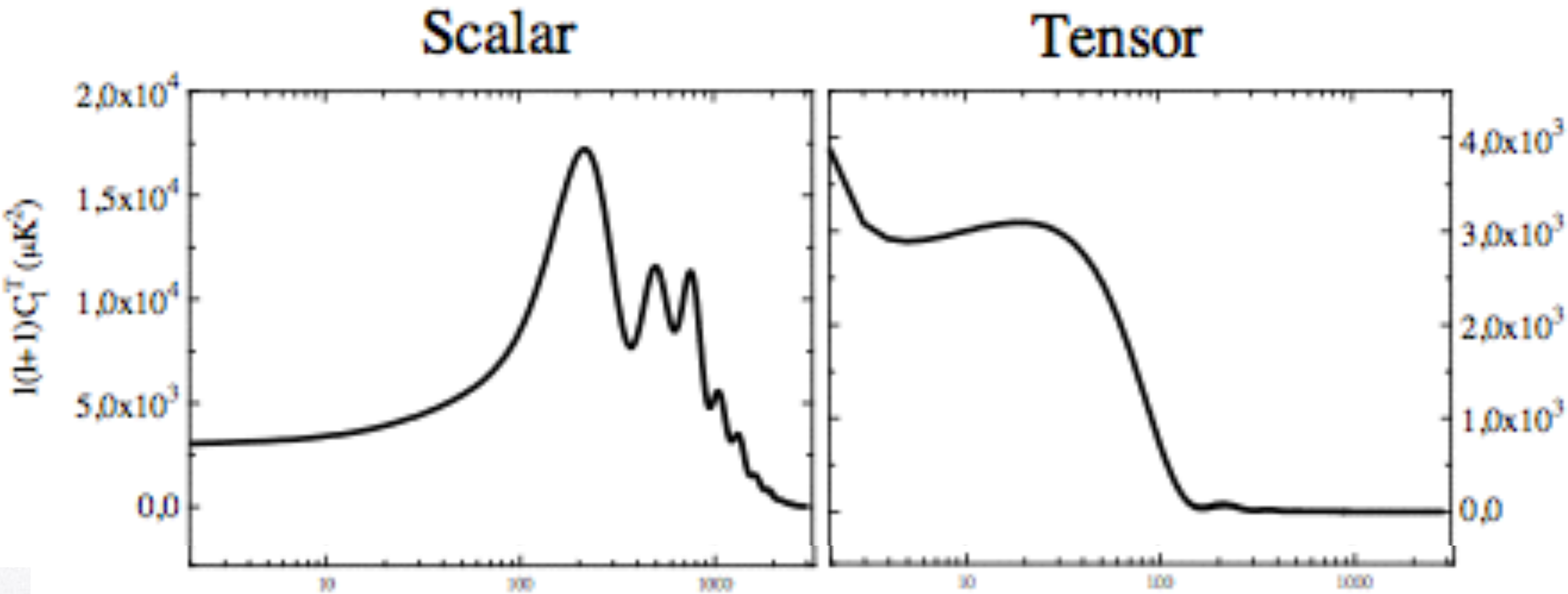
How to disentangle the scalar and the tensor contribution?

From their different scale dependence!

How does Planck measure r?

Contributions to $\langle TT \rangle$ power spectrum:

from Melchiorri, Vittorio 96



How to disentangle the scalar and the tensor contribution?

From their different scale dependence!

How does Planck measure r?

How to disentangle the scalar and the tensor contribution?

From their different scale dependence!

I- Compute spectrum of $< \zeta\zeta >$ at small scales where effect of $<hh>$ is negligible

II- ***Extrapolate*** spectrum of $< \zeta\zeta >$ to large scales

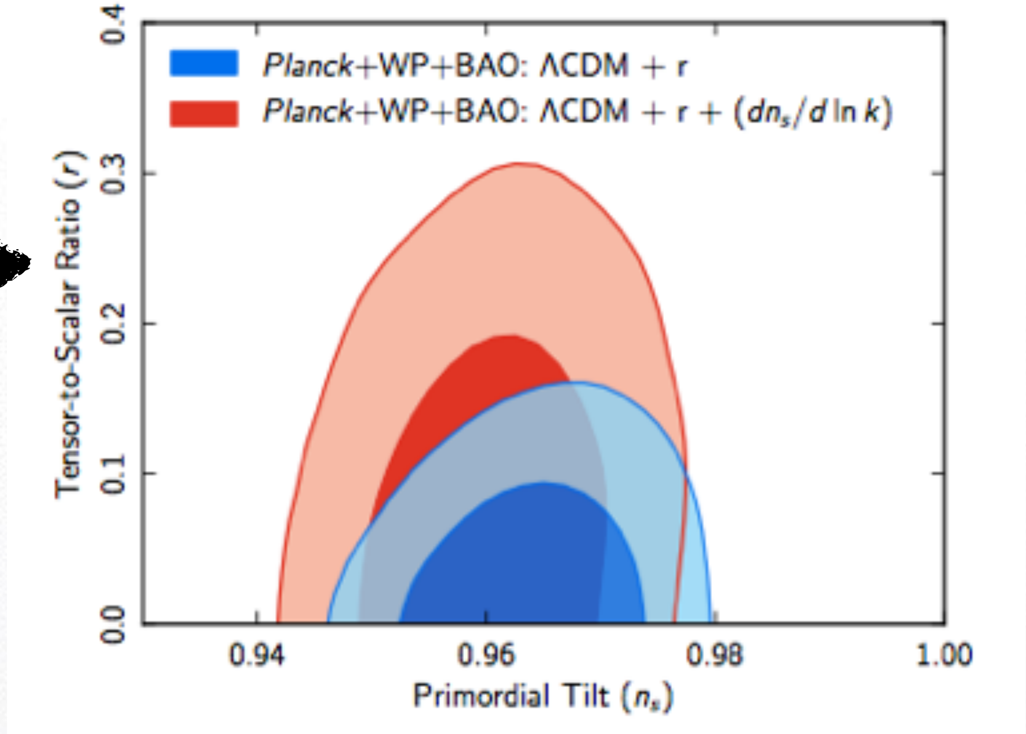
[assuming $k^3 <\zeta(k)\zeta(-k)> \propto k^{n_s-1}$, n_s=constant]

III- Infer limits on $<hh>$

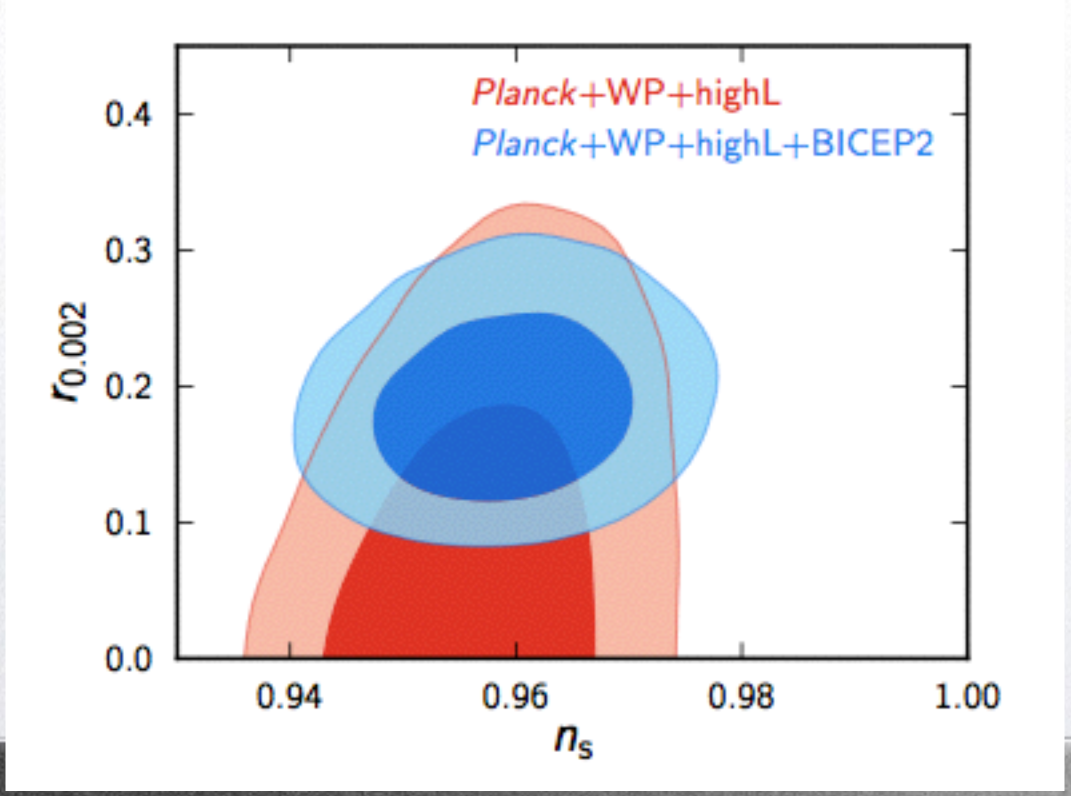
One possible solution

Change the way you extrapolate.
I.e., relax assumption of constant spectral index!

Already discussed in Planck…



…and now in BICEP



One possible solution

Both Planck and BICEP assume *constant* running of n_s:

$$\alpha_s \equiv \frac{d\,n_s}{d\log k} = \text{constant}$$

Best fit:

$\alpha_s \simeq -.02$

very large wrt prediction from inflation $\alpha_s \simeq O(.0001)$

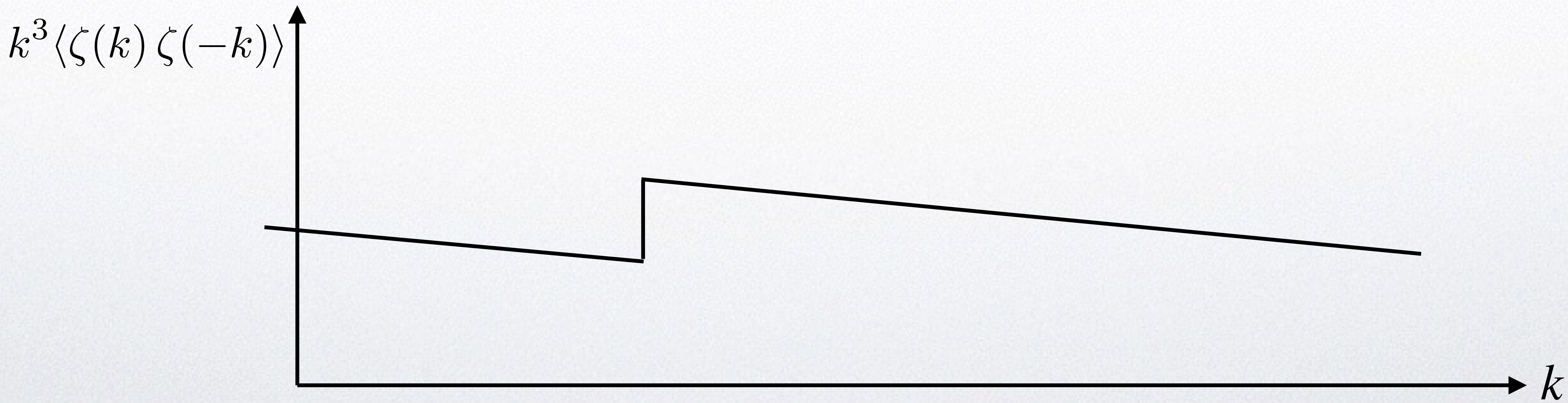
More options?

Contaldi, Peloso, LS 14

Assume step in primordial spectrum

$$k^3 \langle \zeta(k)\, \zeta(-k) \rangle = \beta_s\, A\, k^{n_s - 1}$$

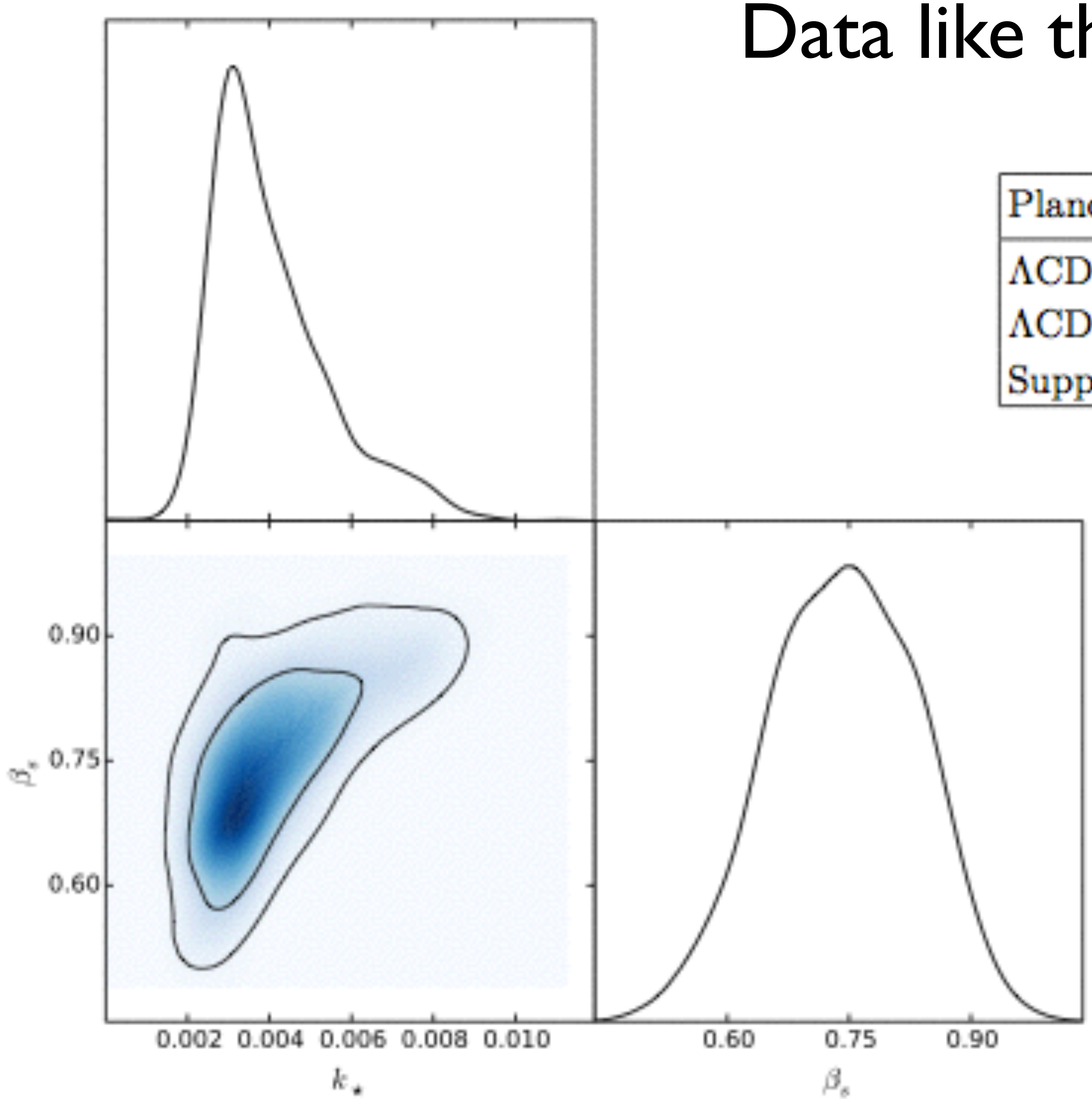
$$\beta_s = 1\,, \quad k > k_*$$
$$\beta_s < 1\,, \quad k < k_*$$



More options?

Assume step in primordial spectrum

Data like this!

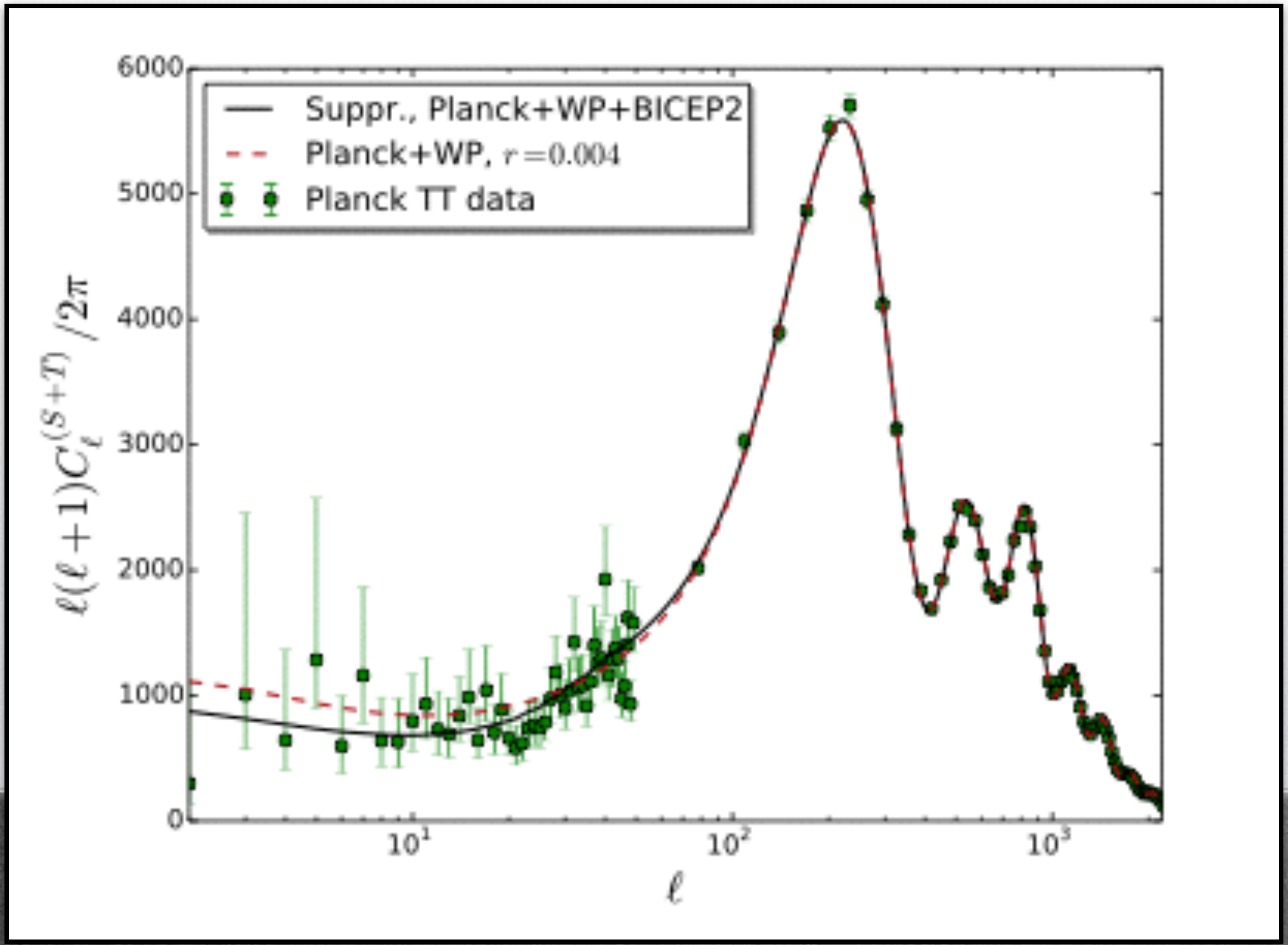


Planck+WP+BICEP2	ΔN_p	χ^2	$\Delta\chi^2$	r
ΛCDM + tensor	–	9854.83	–	0.16
ΛCDM + tensor + α_s	+1	9850.14	-4.69	0.17
Suppression	+2	9840.51	-14.32	0.20

More options?

Assume step in primordial spectrum

$$k^3 \langle \zeta(k)\, \zeta(-k) \rangle = \beta_s\, A\, k^{n_s - 1}$$



More options?

Assume step in primordial spectrum
And there are models that can do it…

Contaldi et al 03	sudden change in the slope of the potential
Park, LS 12	sudden change in the speed of sound
D'Amico et al 13	particle production
…	…

Conclusions

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- No real problem with large inflaton excursions…
- …provided one does not forget about (approximate) shift symmetries
- Implications for particle physics. Nothing that cannot be evaded, but at what price?
- Hints of anomalies exist