Inflation, BICEP2, and an interesting discrepancy with Planck

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IPhT

with C. Contaldi and M. Peloso, 1403.4596
also with Kaloper and Lawrence 08, 11

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

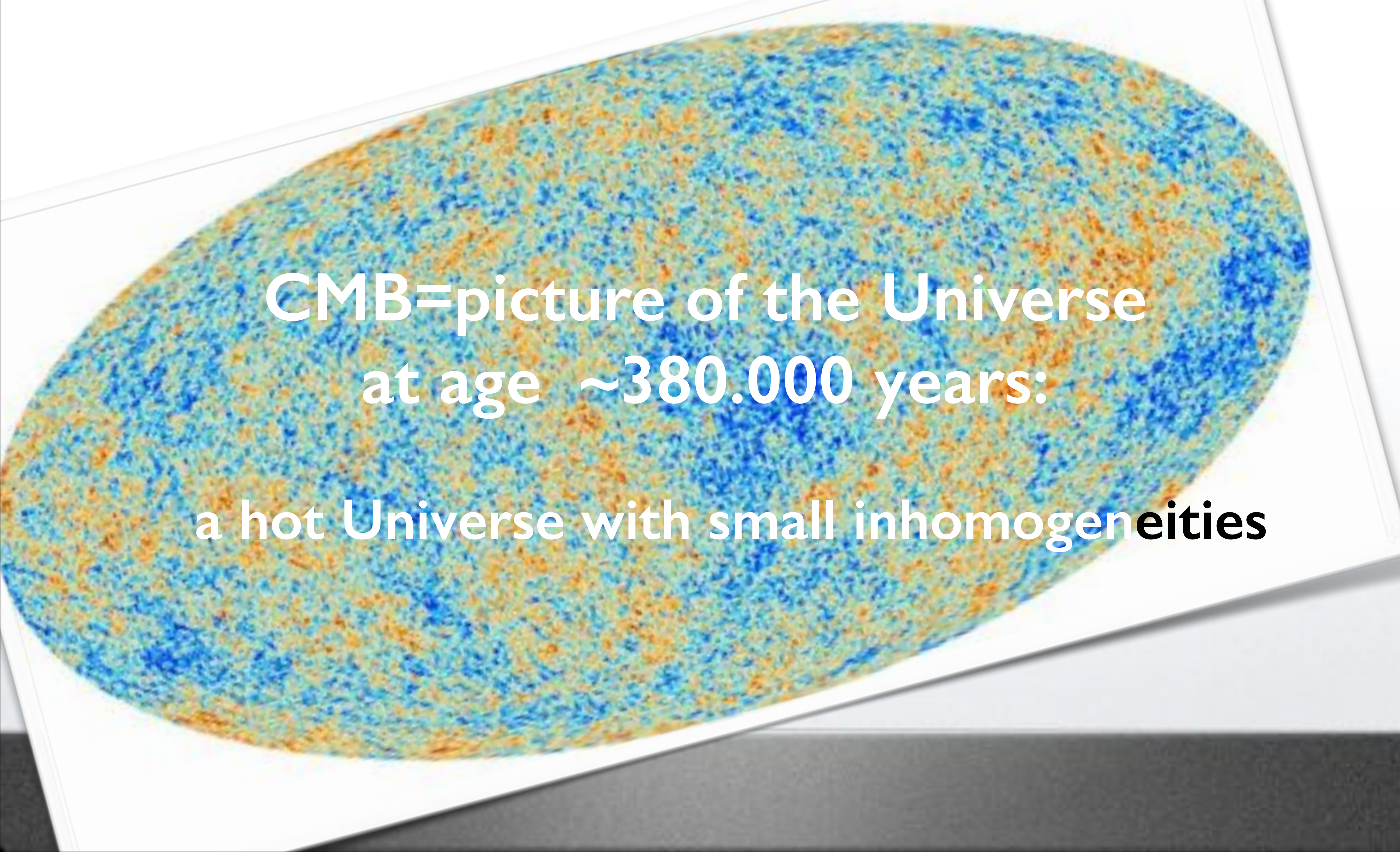
BICEP2 Collaboration (P.A.R. Ade (Cardiff U.) et al.) Show all 47 authors

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?

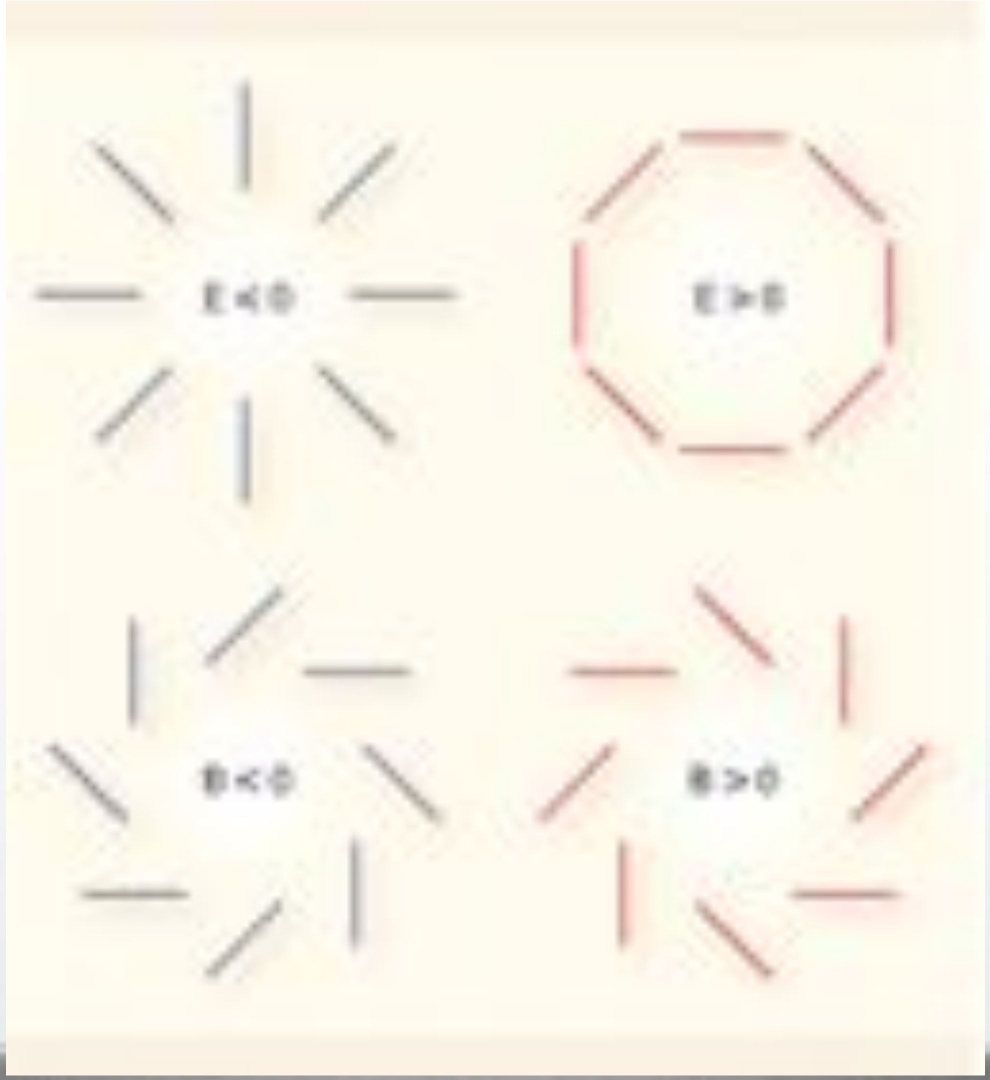


What is B-mode polarization?

The CMB light is polarized!

The polarization plane is defined wrt the gradients of CMB temperature

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

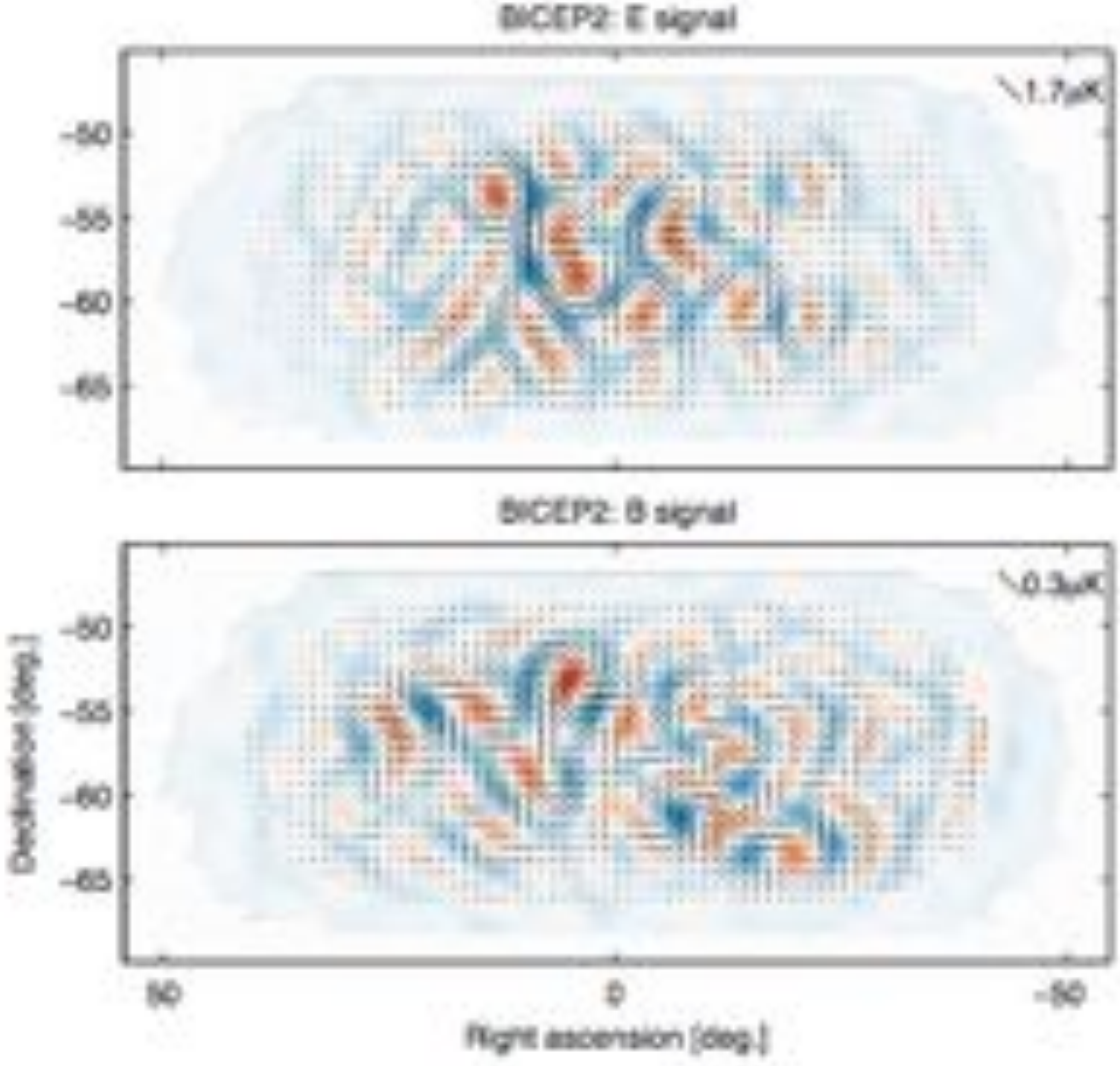


associated to
temperature gradients
(Thomson scattering)

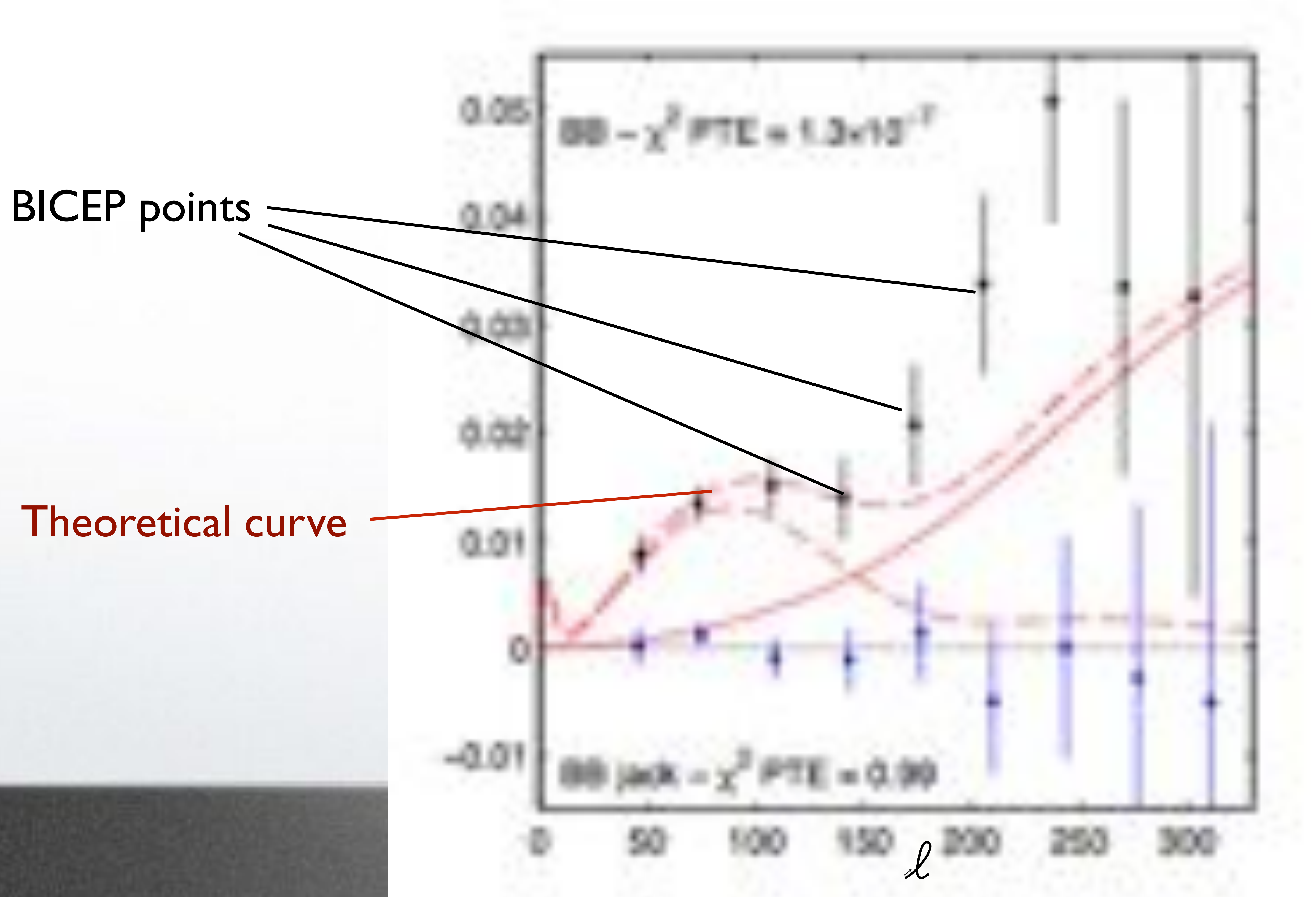
"B modes":
at 45°
to such direction
(divergence-free)

cannot be associated
to any scalar quantity
in the CMB
$\Downarrow$
TENSORS

Maps from BICEP2…



…and the <BB> power spectrum



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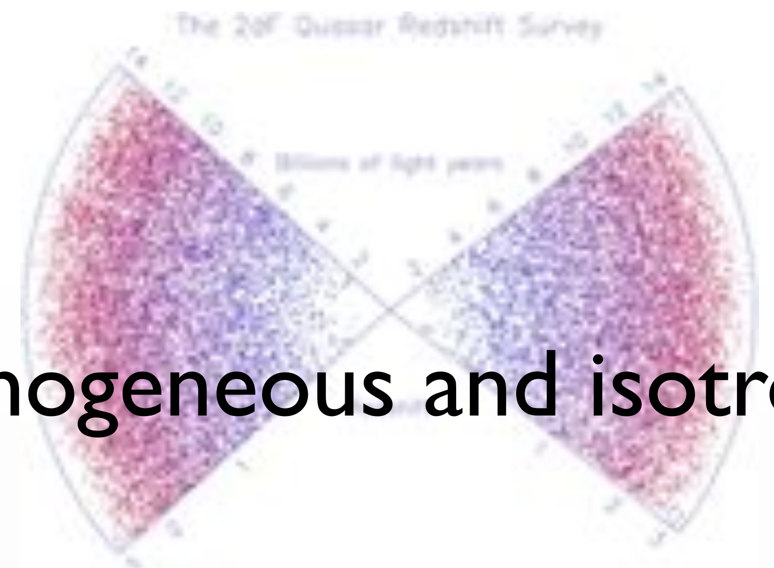
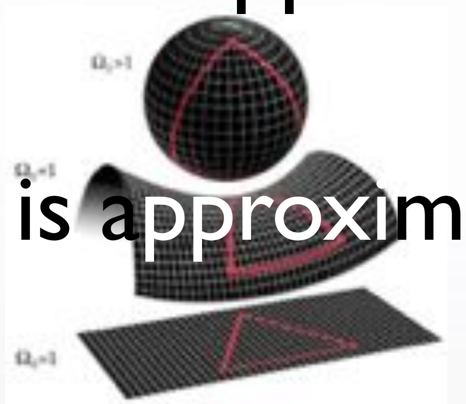
Where do these *tensor modes* come from?

5 INTERESTING FACTS ABOUT THE UNIVERSE

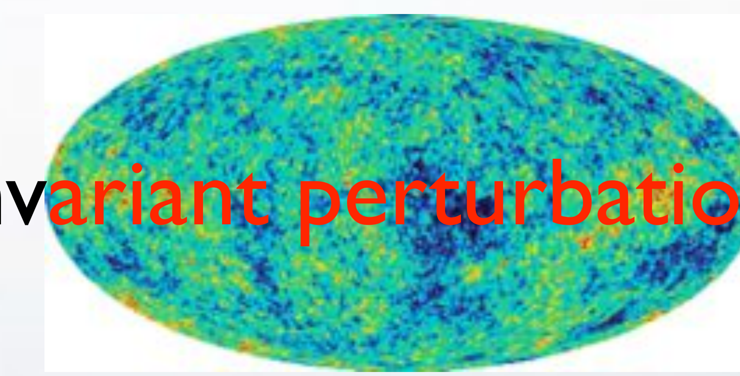
- it is old and very large



- in first approximation it is homogeneous and isotropic

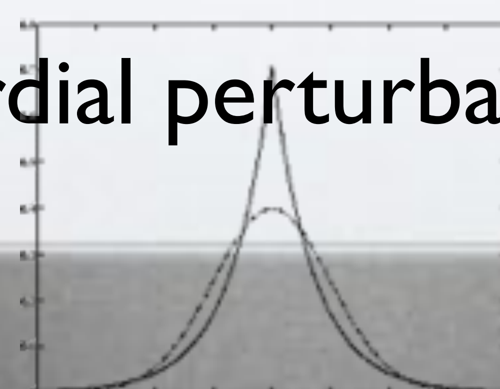


- it is approximately flat



- structure grew out of small, quasi scale invariant perturbations

- spectrum of primordial perturbations was quasi gaussian



All these facts can be explained by

INFLATION

:= period of accelerated expansion in the very early Universe

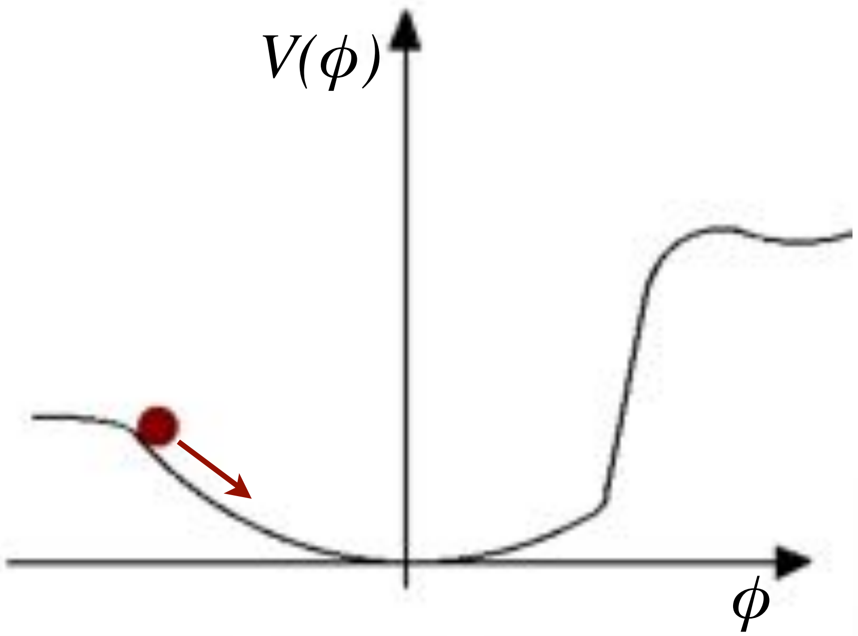
a=scale factor of the Universe. Obeys

$$H^2 = \frac{8\pi G}{3}\varrho \equiv \frac{\varrho}{3M_P^2} \qquad H \equiv \frac{\dot{a}}{a}$$

during inflation require H~constant

(not so easy, since ϱ dilutes away for ordinary matter...)

How to get some "slowly diluting" matter?



✓ very early Universe filled by scalar field ϕ, the ***inflaton***, with potential $V(\phi)>0$

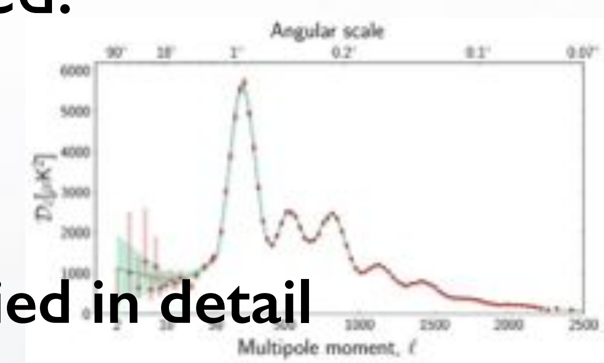
✓ to induce acceleration, $V(\phi)$ must be *flat:*

$$\epsilon \equiv \frac{M_P^2\, V'^2}{2\, V^2} \ll 1 \qquad\qquad \eta \equiv \frac{M_P^2\, V''}{V} \ll 1$$

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 people are talking about now!

Primordial gravitational waves

Let us therefore focus on
the *tensor* components of the metric:

$$ds^2 = a^2(\tau)\,\left[-d\tau^2 + \left(\delta_{ij} + h_{ij}\left(\mathbf{x},\,\tau\right)\right)\,dx^i\,dx^j\right]$$

$$\sum_{ij} \delta^{ij}\,h_{ij} = \sum_i \partial_i\,h_{ij} = 0$$

the tensor mode has two components (=helicity ±2)
so we can decompose it, in momentum space,
into left-handed and right-handed modes

$$h_{ij}\left(\mathbf{k},\,\tau\right) = \sum_{\lambda=\pm} h_\lambda\left(\mathbf{k},\,\tau\right)\,\epsilon^\lambda_{ij}\left(\mathbf{k}\right)$$

Primordial gravitational waves (II)

We then quantize h_λ on a time-dependent background

$$\hat{h}_\lambda(\mathbf{x},\, \tau) = \int \frac{d^3\mathbf{k}}{(2\pi)^{3/2}}\, e^{i\mathbf{k}\mathbf{x}}\, \left(h_\lambda(\mathbf{k},\, \tau)\, \hat{a}_\lambda(\mathbf{k}) + h_\lambda(-\mathbf{k},\, \tau)^*\, \hat{a}_\lambda(-\mathbf{k})^\dagger\right)$$

where h_λ obeys

$$\frac{d^2\, h_\lambda}{d\tau^2} + \frac{2}{a}\,\frac{d\,a}{d\tau}\,\frac{d\,h_\lambda}{d\tau} + k^2\, h_\lambda = 0$$

$$a(\tau) \simeq -\frac{1}{H\,\tau} \qquad \tau < 0$$

during inflation

with solution

$$h_\lambda(k,\, \tau) = \frac{2}{M_P}\,\frac{1}{a(\tau)}\,\frac{1}{\sqrt{2\,k}}\left(1 - \frac{i}{k\,\tau}\right)\, e^{-i\,k\,\tau}$$

important note:
quantization of gravity!

Primordial gravitational waves (III)

Observable: two point function of GWs

(related to two point function of B-modes)

$$\langle h_\lambda(\mathbf{x},\,\tau)\,h_\lambda(\mathbf{y},\,\tau)\rangle = \int \frac{d^3\mathbf{k}}{(2\pi)^3}\,e^{i\mathbf{k}(\mathbf{x}-\mathbf{y})}\;|h_\lambda(k,\,\tau)|^2$$

that for superhorizon distances $|\mathbf{x}-\mathbf{y}| \gg |\tau|$

$$\langle h_\lambda(\mathbf{x},\,\tau)\,h_\lambda(\mathbf{y},\,\tau)\rangle = \frac{4}{M_P^2}\int \frac{d^3\mathbf{k}}{(2\pi)^3}\,\frac{H^2}{2\,k^3}\,e^{i\mathbf{k}(\mathbf{x}-\mathbf{y})}$$

Scale invariant

Amplitude of tensor two point function $\propto \dfrac{H^2}{M_P^2} \propto \dfrac{V}{M_P^4}$

OK, but what is *r*?

r =tensor-to-scalar ratio

Amplitude of tensor two point function $\propto \frac{H^2}{M_P^2} \propto \frac{V}{M_P^4}$

Amplitude of scalar two point function $\propto \frac{H^2}{\epsilon\, M_P^2} \propto \frac{V}{\epsilon\, M_P^4}$

$$r \propto \epsilon$$

$$\epsilon \equiv \frac{M_P^2\, V'^2}{2\, V^2} \ll 1$$

(finally) back to 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

(in single-field inflation)

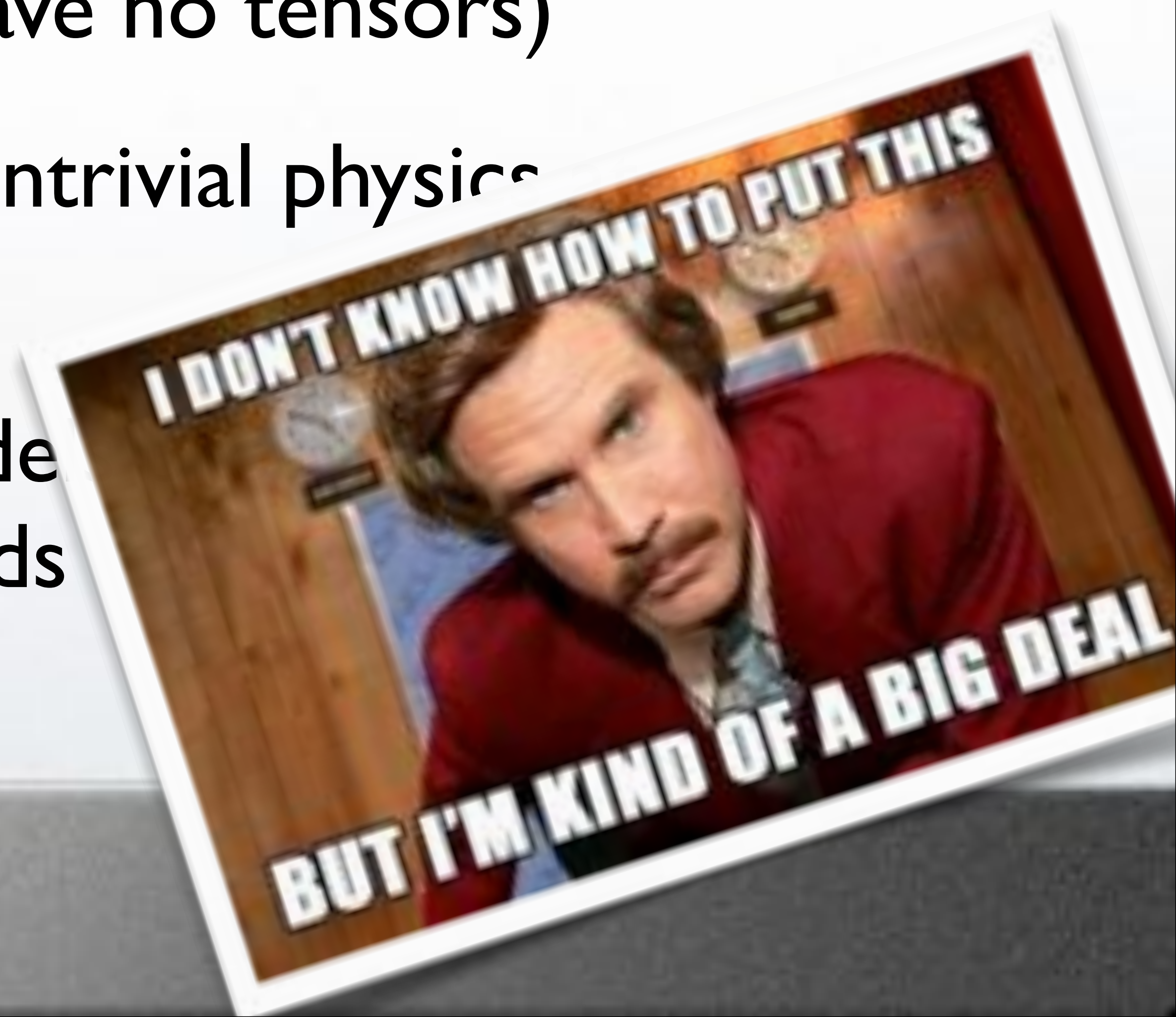
$$\frac{d\,\phi}{dt} \propto V' \propto \sqrt{\epsilon} \propto \sqrt{r}$$

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

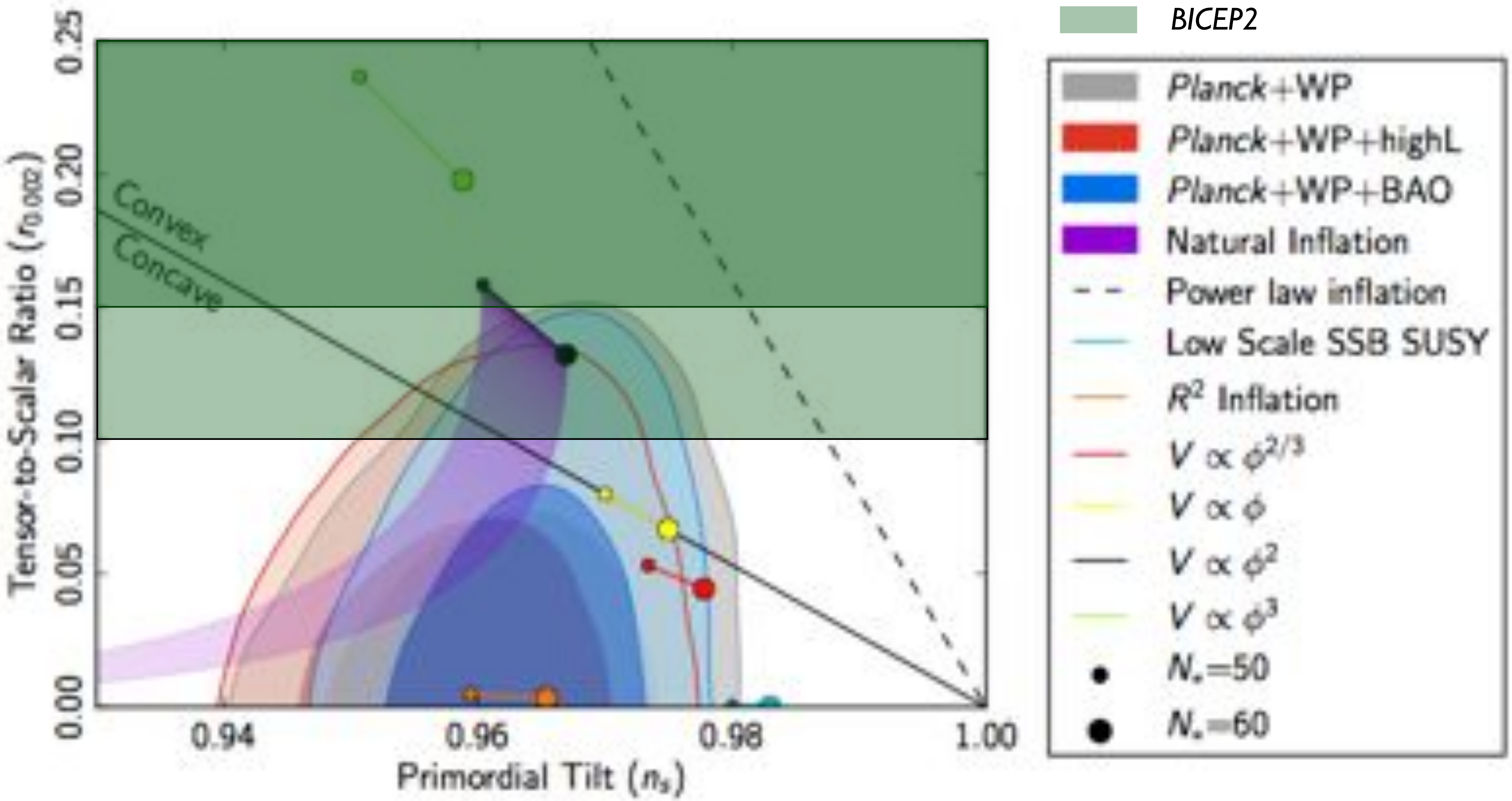
Planckian excursions of inflaton!

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!)
- Proves inflation (all alternatives have no tensors)
- Strongly supports existence of nontrivial physics
new, close to GUT, scale
- In simple (and not so simple) mode
planckian excursions of scalar fields



Space of inflationary models:



Implications for model building?

$$\Delta\phi \gtrsim M_P$$

Often-heard concern:

"Graviton loops" effects generate terms

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

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

$\Delta\phi \gtrsim M_P$

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

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

$O(1)\ V(\phi)^2/M_P^4$ and $O(1)\ V''(\phi)\ V(\phi)/M_P^2$

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)

Easy solution:

Assume an exact shift symmetry (so Yukawas are forbidden)…
…then break the symmetry a bit and generate a potential

An (important) example

If ϕ is a phase, then shift symmetry ⇔ global *U(1)*

- Theory with a spontaneously broken global *U(1)*

$$\mathcal{L} = \partial_\mu H^* \partial^\mu H - \lambda \left(|H|^2 - f^2\right)^2$$

- Decompose $H = (f + \delta H)\, e^{i\phi/f}$

  where δH is massive and φ is a massless Goldstone boson

- The global *U(1)* is broken e.g. by some strong dynamics

$$\delta\mathcal{L} = \Lambda^3 \, (H + H^*) + \ldots$$

- A potential is generated: $\delta V \sim \Lambda^3 f \cos(\phi/f)$

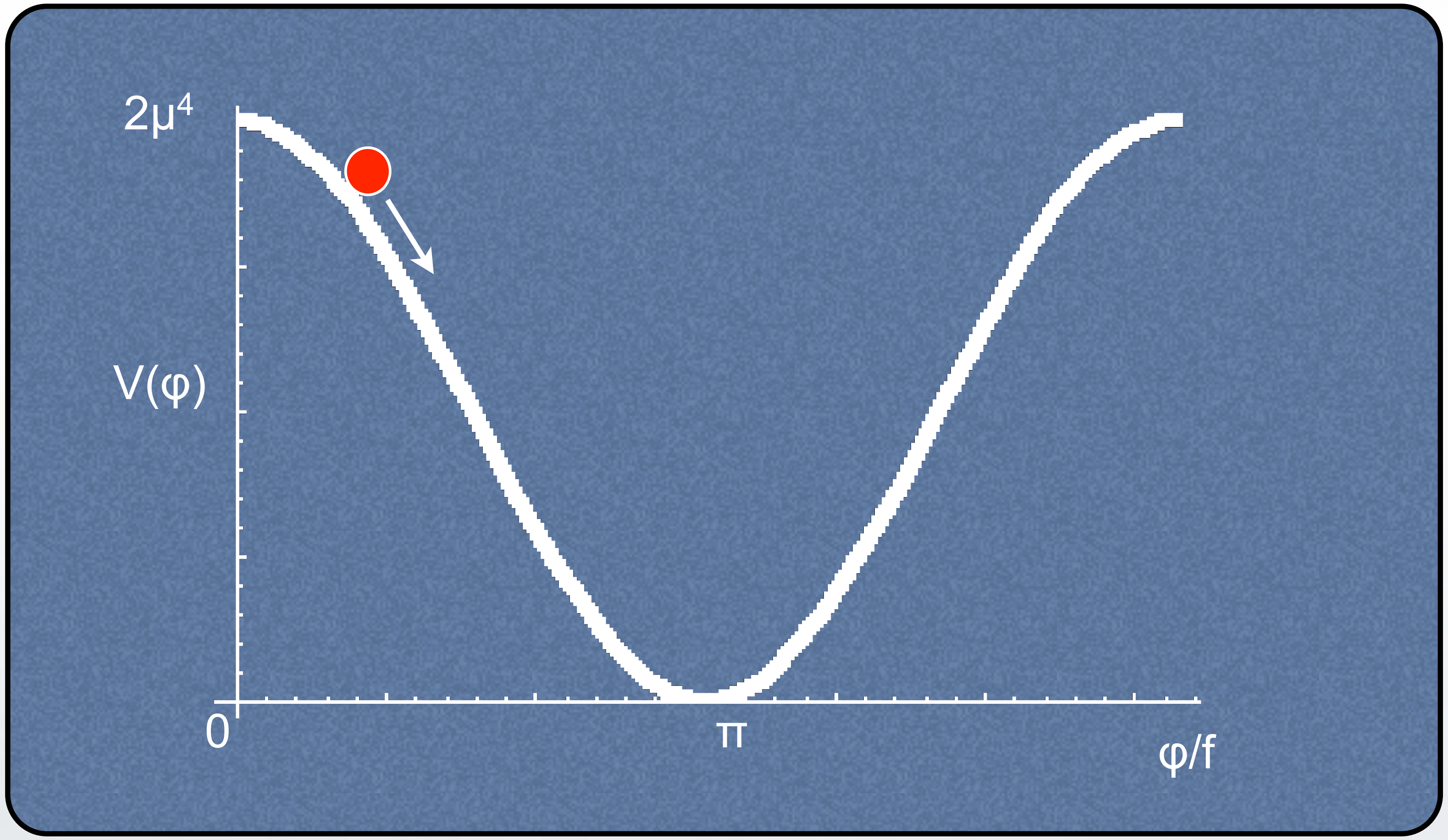
Pseudo-Nambu-Goldstone boson
PNGb

...using a pNGB as an inflaton...

Natural inflation

Freese et al 1990

$$V(\varphi)=\mu^4 \left[\cos(\varphi/f)+1 \right]$$



Data require
$f > 5\, M_P$

Everything is fine here with respect to EFT…

…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$>1/M_P$]

An example of a way out…

Enter the 4-form

(Higher rank relative of the electromagnetic field)

Kaloper, LS 08
Kaloper, Lawrence, LS 11

$$S_{4form} = -\frac{1}{48}\int F_{\mu\nu\varrho\lambda}\, F^{\mu\nu\varrho\lambda}\, d^4x$$

$$F_{\mu\nu\varrho\lambda} = \partial_{[\mu} A_{\nu\varrho\lambda]}$$

tensor structure in 4d $\Rightarrow F_{\mu\nu\varrho\lambda} = q(x^\alpha)\, \varepsilon_{\mu\nu\varrho\lambda}$

equations of motion $D^\mu F_{\mu\nu\varrho\lambda} = 0 \Rightarrow q(x^\alpha)$ = constant

(trivial dynamics)

Let us couple the 4-form to a pseudoscalar

$$\mathcal{S}_{bulk} = \int d^4x \sqrt{g} \Big(\frac{M_{Pl}^2}{2} R - \frac{1}{2} (\nabla \phi)^2 - \frac{1}{48} F_{\mu\nu\lambda\sigma}^2 + \frac{\mu \phi}{24} \frac{\epsilon^{\mu\nu\lambda\sigma}}{\sqrt{g}} F_{\mu\nu\lambda\sigma} + \ldots \Big)$$

Di Vecchia and Veneziano 1980
Quevedo and Trugenberger 1996
Dvali and Vilenkin 2001

Action invariant under shift symmetry:

under $\phi \to \phi + c$, $\mathcal{L} \to \mathcal{L} + c\, \mu\, \varepsilon^{\mu\nu\varrho\lambda} F_{\mu\nu\varrho\lambda}/24$

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$$S_{bulk} = \int d^4x \sqrt{g}\Big(\frac{M_{Pl}^2}{2}R - \frac{1}{2}(\nabla\phi)^2 - \frac{1}{48}F_{\mu\nu\lambda\sigma}^2 + \frac{\mu\phi}{24}\frac{\epsilon^{\mu\nu\lambda\sigma}}{\sqrt{g}}F_{\mu\nu\lambda\sigma} + \dots\Big)$$

Di Vecchia and Veneziano 1980
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Action invariant under shift symmetry:

under $\phi \to \phi + c$, $\mathcal{L} \to \mathcal{L} + c\,\mu\,\varepsilon^{\mu\nu\varrho\lambda} F_{\mu\nu\varrho\lambda}/24$

total derivative! $(F = dA)$

Equations of motion

Variation of the action

$$\begin{cases} \nabla^{\mu} \left(F_{\mu\nu\varrho\lambda} - \mu\, \varepsilon_{\mu\nu\varrho\lambda}\, \phi\right) = 0 \\ \nabla^2\phi + \mu\, \varepsilon^{\mu\nu\varrho\lambda} F_{\mu\nu\varrho\lambda}/24 = 0 \end{cases}$$

After simple manipulations

$$\begin{cases} F_{\mu\nu\varrho\lambda} = \varepsilon_{\mu\nu\varrho\lambda}\,(q + \mu\, \phi) \\ \nabla^2\phi - \mu^2\, (\phi + q/\mu) = 0 \end{cases}$$

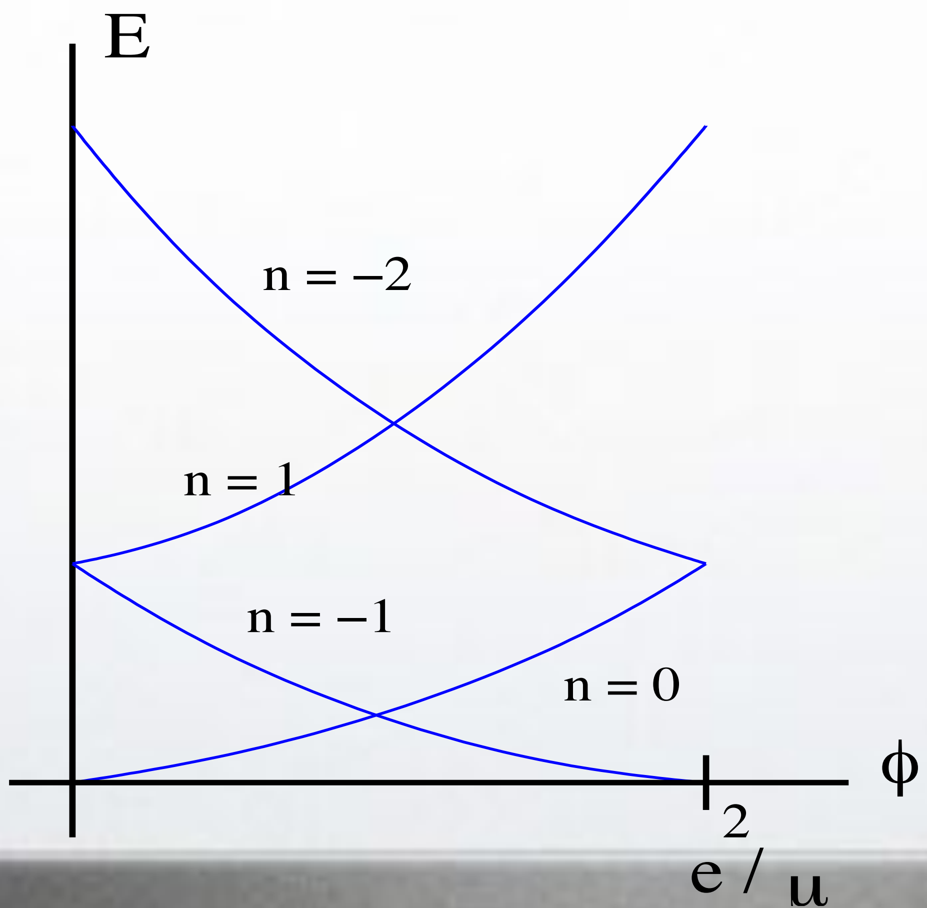
q = integration constant

The theory is massive while retaining the shift symmetry!

The symmetry is *broken spontaneously* when a solution is picked

...and by the way, wasn't ϕ an angle?

It turns out that q is quantized…



Silverstein, Westphal 08

MONODROMY

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

How about high scale inflation?

In de Sitter space, with Hubble parameter H, all scalar degrees of freedom with $m<H$ get large quantum fluctuations

☛ Planck constrains to %-level non-inflaton (isocurvature) fluctuations

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

BICEP2 ⇒ $H \sim 10^{14}\ GeV$

How about high scale inflation?

BICEP2 $\Rightarrow$ $H \sim 10^{14}\ GeV$

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

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BICEP2 I: Detection … ular Scales

Ambulance chasing

From Wikipedia, the free encyclopedia

Ambulance chasing, which is a form of barratry, refers to a lawyer using an event as a way to find legal clients. The term "ambulance chasing" comes from the stereotype of lawyers that follow ambulances to the emergency room to find clients.[1]

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An interesting 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)

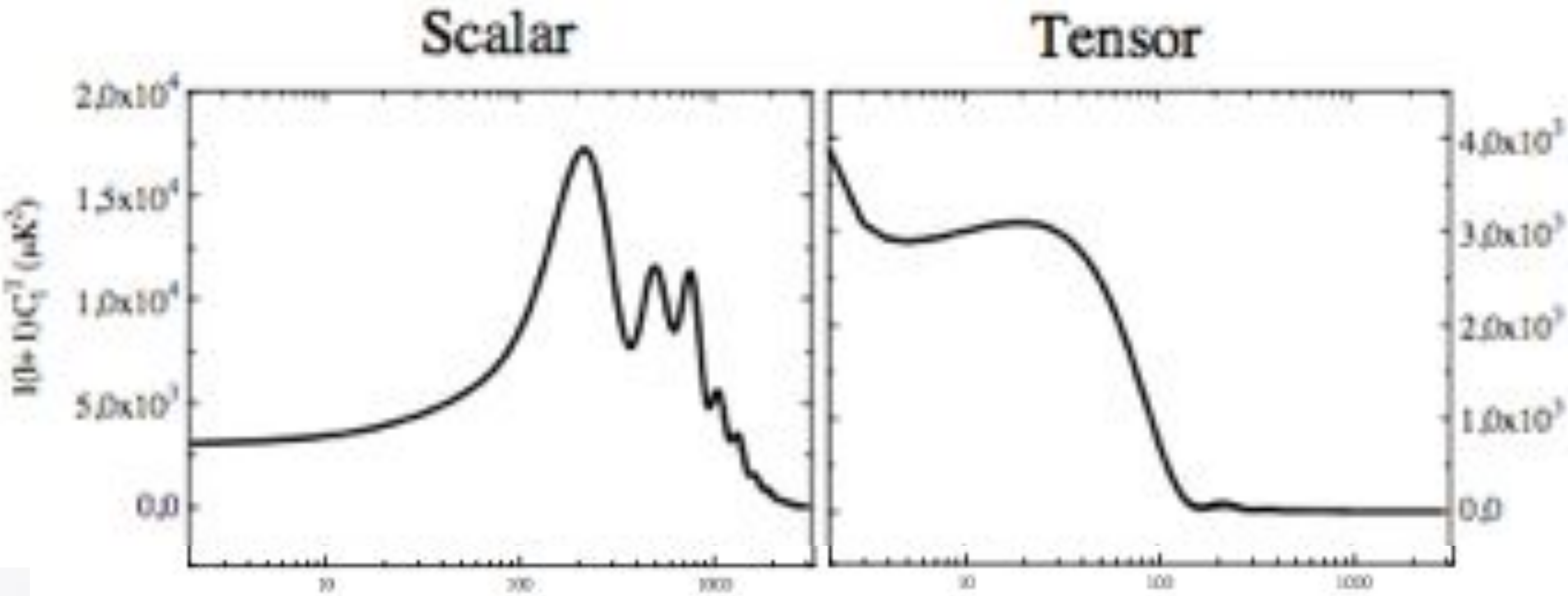
How to disentangle the scalar and the tensor contribution?

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 small scales

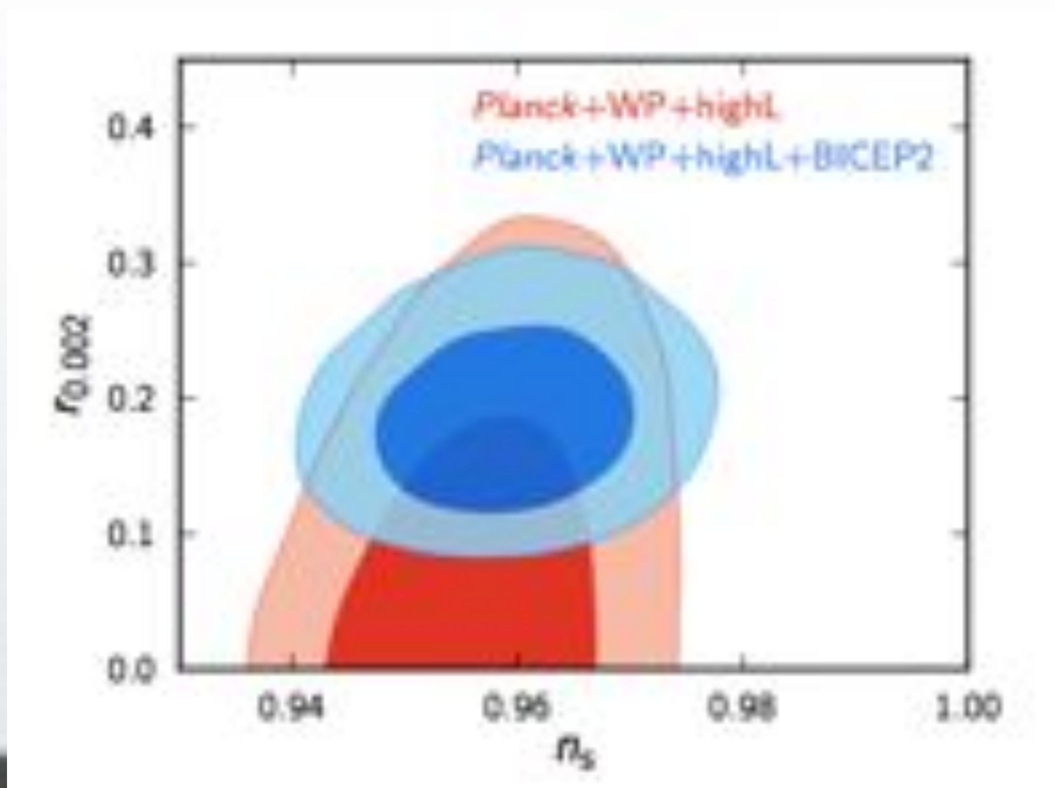
[assuming $k^3 <\zeta(k)\zeta(-k)> \propto k^{n_s-1}$, n_s=constant]

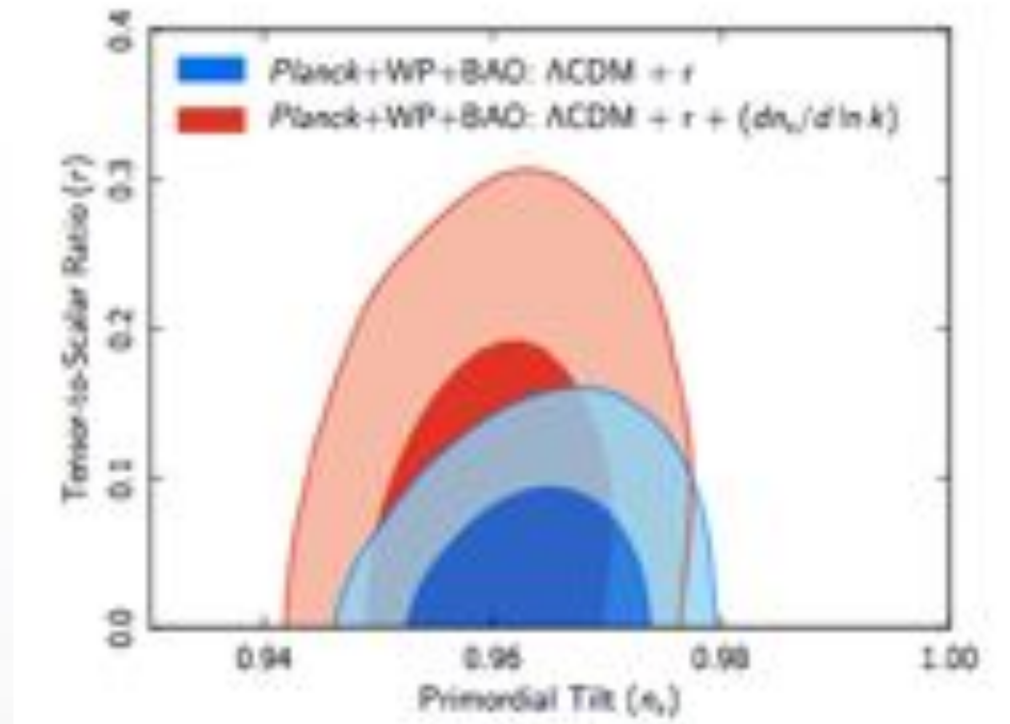
III- Infer limits on $<hh>$

Obvious solution

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

Already discussed in Planck…





…and now in BICEP

Obvious solution

Both Planck a 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 $\alpha_s \simeq O(.001)$

☛an overkill: change the spectrum at all scales $1<l<3000$ to explain phenomenon at $l<100$

Two more options

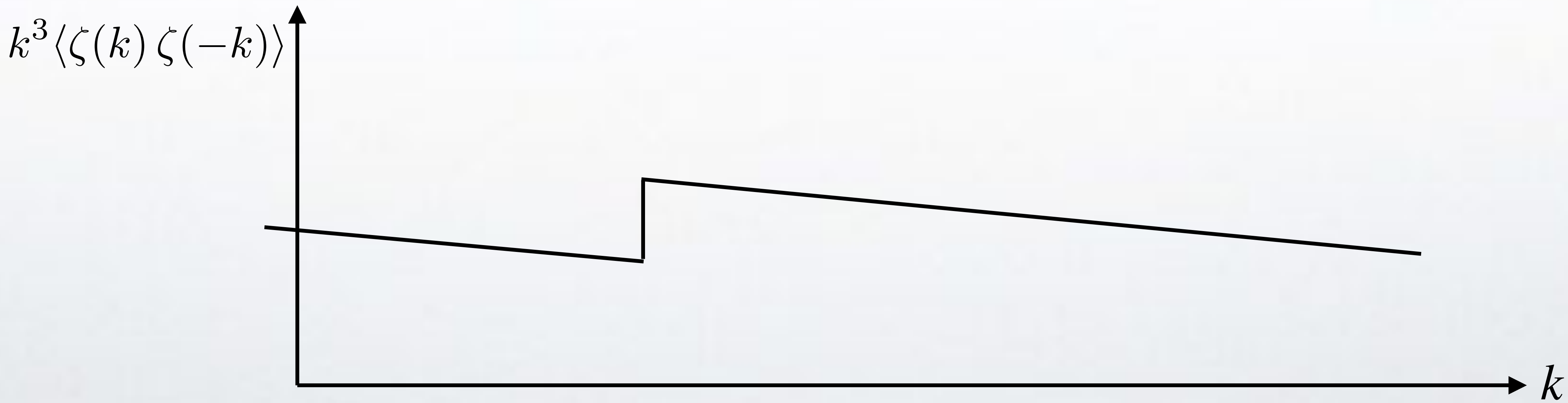
Contaldi, Peloso, LS 14

1

Assume step in primordial spectrum

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

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

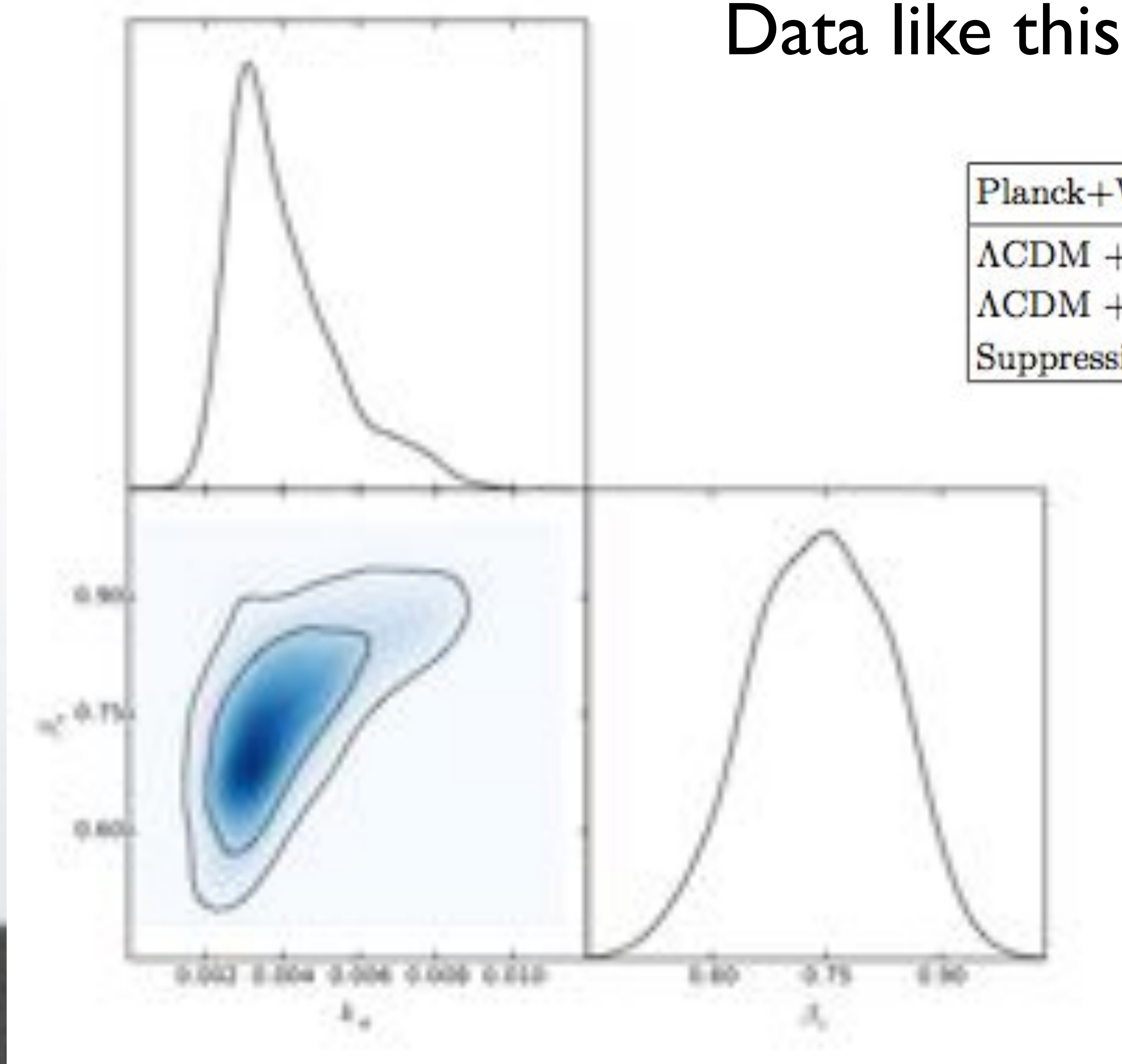


Two more options

1

Assume step in primordial spectrum

Data like this!



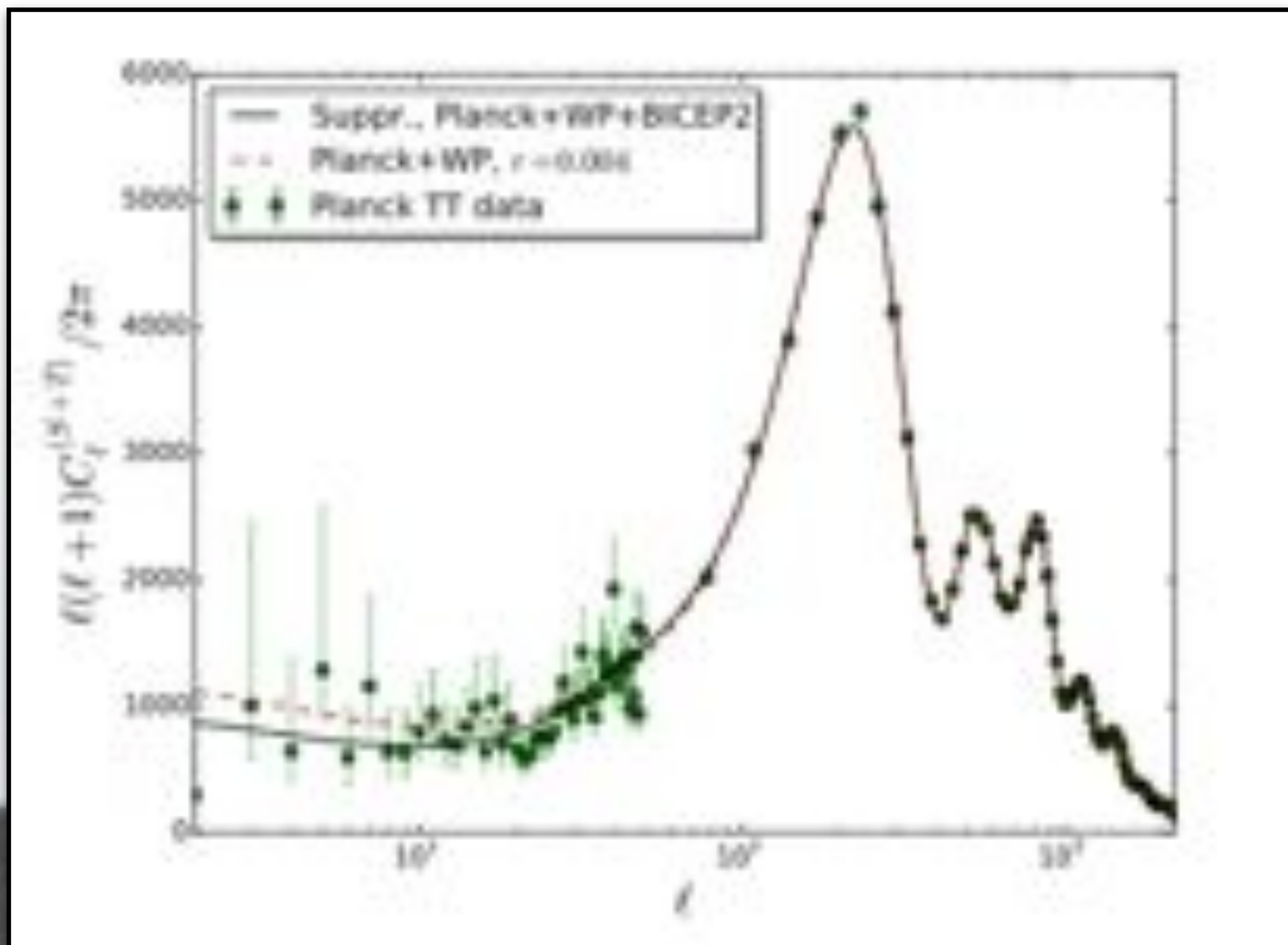
Planck+WP+BICEP2	ΔN_p	χ^2	$\Delta\chi^2$	r
ΛCDM + tensor	–	9854.83	–	0.16
ΛCDM + tensor + α_s	+1	9850.14	-4.69	0.17
Suppression	+2	9840.51	-14.32	0.20

Two more options

1

Assume step in primordial spectrum

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



Two more options

1️⃣

Assume step in primordial spectrum

And there are models that can do it…

Amplitude of scalar two point function $\propto \frac{H^2}{\epsilon M_P^2} \propto \frac{V}{\epsilon M_P^4}$

⬇

change in slope of V can change amplitude of scalar perts

Two more options

2

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

can have both signs!

Rigorously $\langle \delta T \, \delta T \rangle \sim \langle \zeta \, \zeta \rangle + \langle h \, h \rangle + 2 \, \langle \zeta \, h \rangle$

Can use scalar-tensor (anti) correlation to suppress TT fluctuations

Two more options

2

h_{ij} carries indices⇒break rotational invariance

h_{ij} affects only small ℓ⇒unbroken scale invariance

+ hints of breaking of *SO(3)* in WMAP, Planck

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
- Some intriguing discrepancies - do they point to something special that happened during inflation?