Inflation, BICEP2, and an interesting discrepancy with Planck

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Two major implications of large r

(i) the energy scale

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?

Two major implications of large r

(ii) the Lyth bound

r related to excursion of inflaton during 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!

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 $\phi \to \phi + const$.

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:

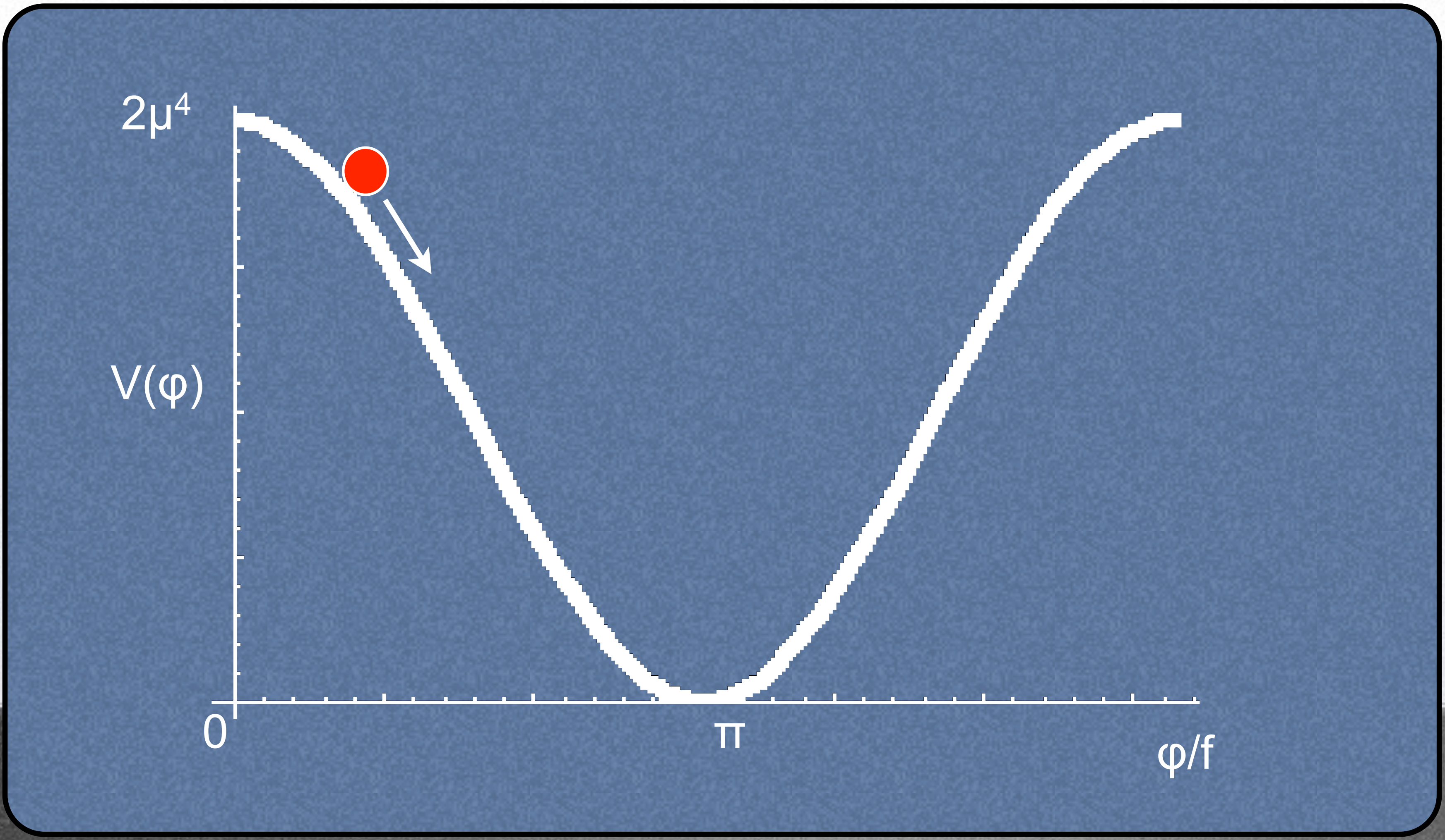
Assume an exact shift symmetry (so Yukawas are forbidden)…
…then break the symmetry a bit and generate a potential
[Pseudo-Nambu-Goldstone-Boson]

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

Natural inflation

Freese et al 1990

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



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…

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)

Sources for the 4-form: membranes

$$\mathcal{S}_{brane} \ni \frac{e}{6}\int d^3\xi \sqrt{\gamma} e^{abc}\partial_a x^\mu \partial_b x^\nu \partial_c x^\lambda A_{\mu\nu\lambda}$$

[$x^\alpha(\xi^a)$=membrane worldvolume]

$[e]$=mass^2

$q(x^\alpha)$ jumps by e across a membrane

$q(x^\alpha)$ is locally constant

and

jumps in units of e

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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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

(away from branes)

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

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

q = integration constant

- $(\mu/24)\ \phi\ \varepsilon^{\mu\nu\varrho\lambda} F_{\mu\nu\varrho\lambda}$ is actually a mass term!
- *The theory is massive while retaining the shift symmetry!*
- The symmetry is *broken spontaneously* when a solution is picked
- q changes by e across branes $\Rightarrow$ q is quantized

Where does the 4-form come from?

Kaloper and LS 2008

String theory contains a lot of p-forms!

To fix ideas, let us focus on *11d SUGRA*, that contains a 4-form $\widetilde{F}=d\widetilde{A}$

$$S_{11D\ forms} = M_{11}^9 \int *\tilde{F} \wedge \tilde{F} + M_{11}^9 \int \tilde{A} \wedge \tilde{F} \wedge \tilde{F}$$

and consider a simple compactification on $M_4 \times T^3 \times T^4$

truncating as $A_{\mu\nu\varrho}(x^\alpha) = (M_P/\sqrt{2})\, \widetilde{A}_{\mu\nu\varrho}(x^\alpha)$,
$\phi = M_P\, \widetilde{A}_{456}(x^\mu)/(V_3\, M_{11}{}^3)$, $\widetilde{A}_{789}(y^i)$

effective 4d theory

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

More explicit constructions in
Marchesano, Shiu and Uranga 14

...and by the way, wasn't ϕ an angle?

Effective potential $V(\phi) \sim (q+\mu\phi)^2$

with q quantized: discrete invariance

$$q \rightarrow q + n\, e$$

Beasley and Witten 2002

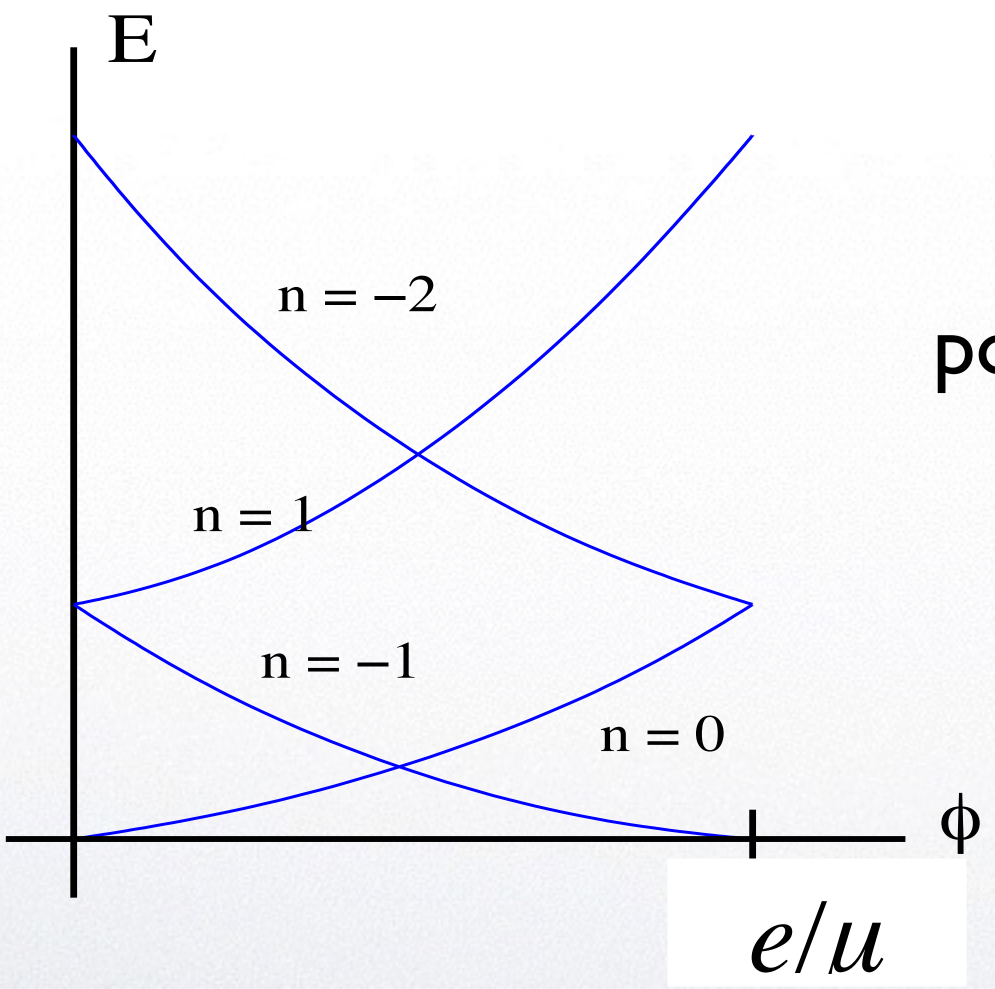
at the level of action ϕ is still an angle!

Once a vev for q is chosen, the angle unwraps:

MONODROMY

Silverstein and Westphal 2008

...and by the way, wasn't ϕ an angle?



possible tunneling between branches

$\Downarrow$

interesting phenomenology

How about high scale inflation?

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

BICEP2 ⇒ $H \sim 10^{14}\ GeV$

⇓

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

Technical problem:
stabilize moduli at high scale

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)

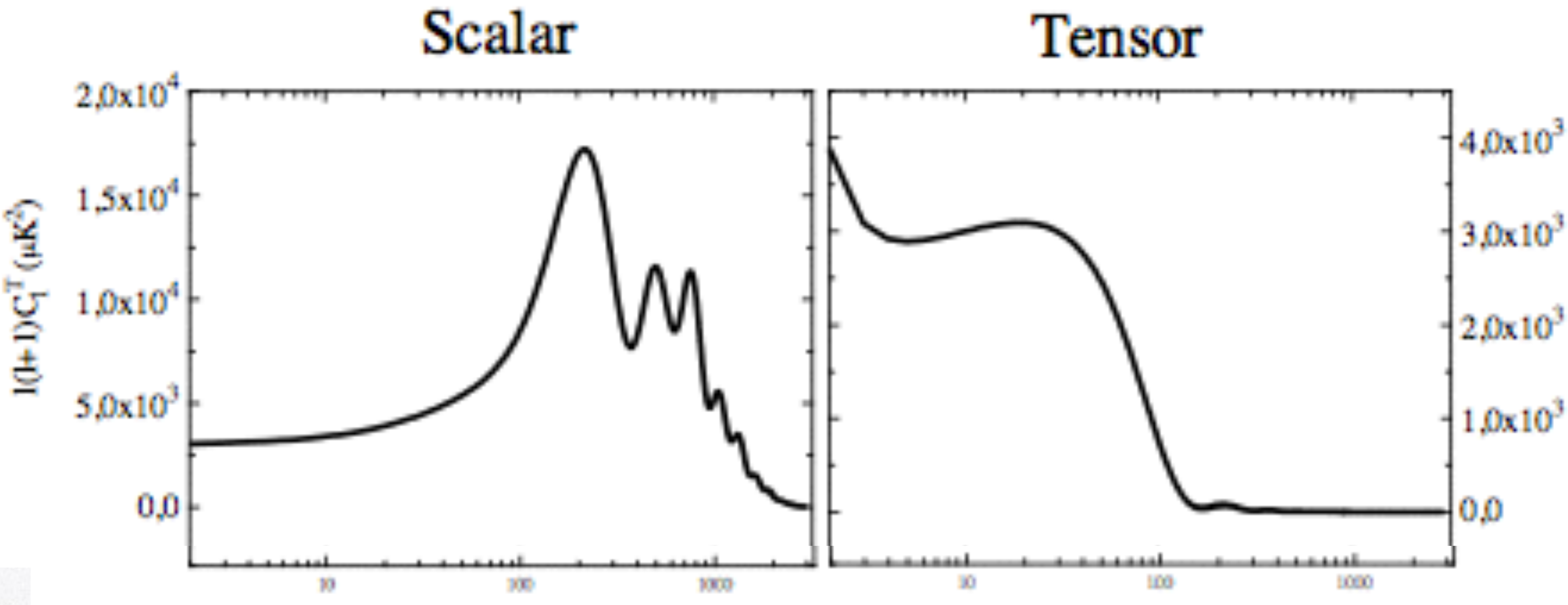
How to disentangle the scalar and the tensor contribution?

From their different scale dependence!

How does Planck measure r?

Contributions to <*TT*> 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

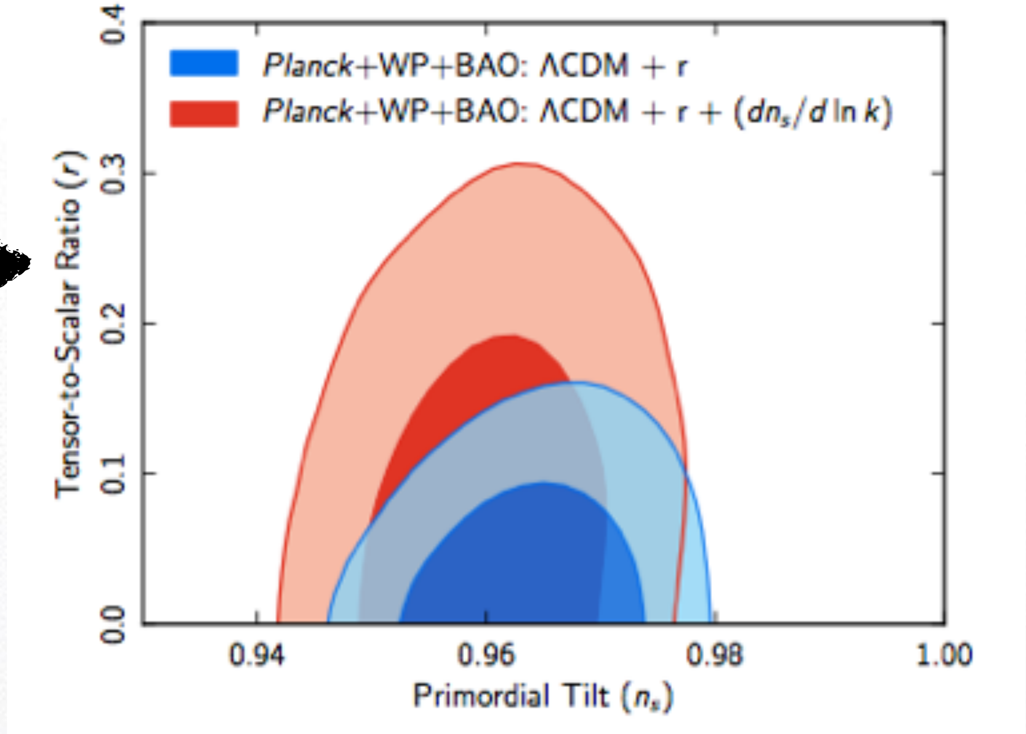
[assuming $k^3 <\zeta(k)\zeta(-k)> \propto k^{n_s-1}$, n_s=constant]

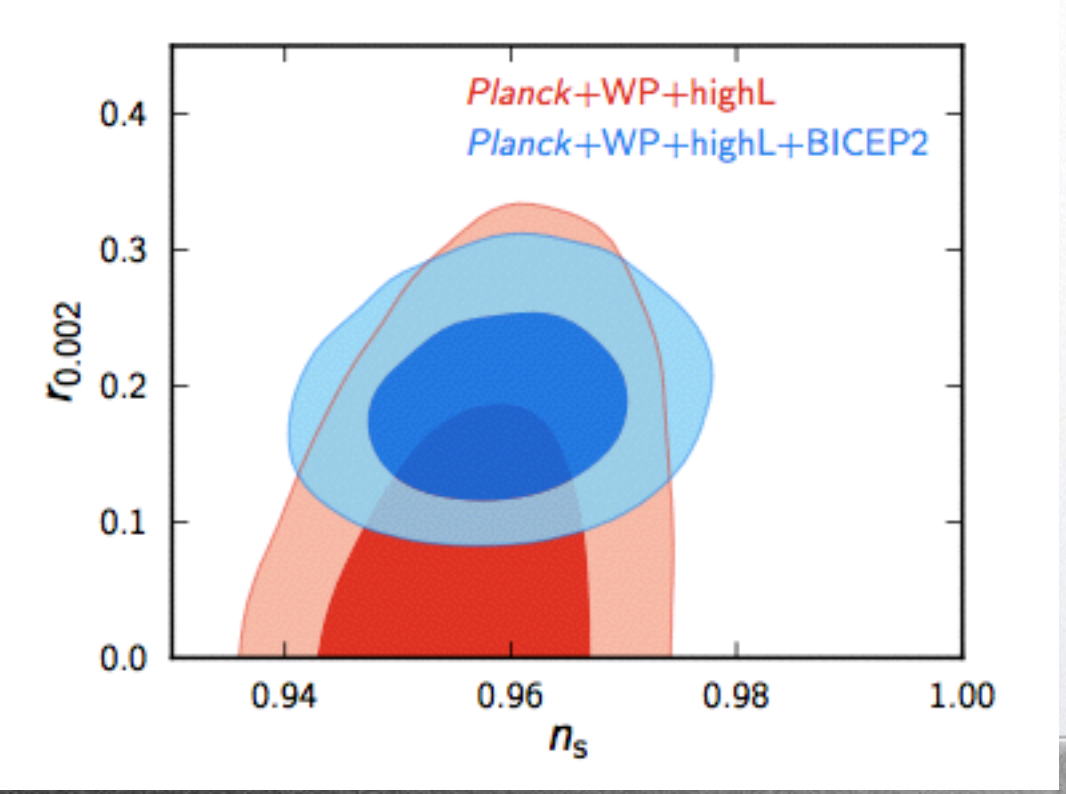
III- Infer limits on $<hh>$

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 $\alpha_s \simeq O(.0001)$

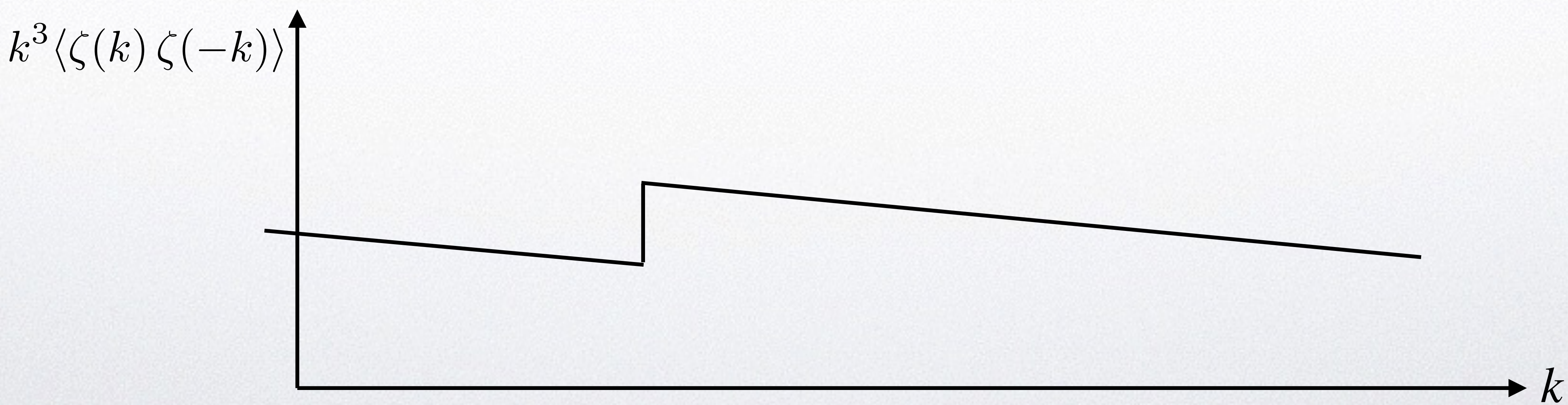
More options?

Contaldi, Peloso, LS 14

Assume step in primordial spectrum

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

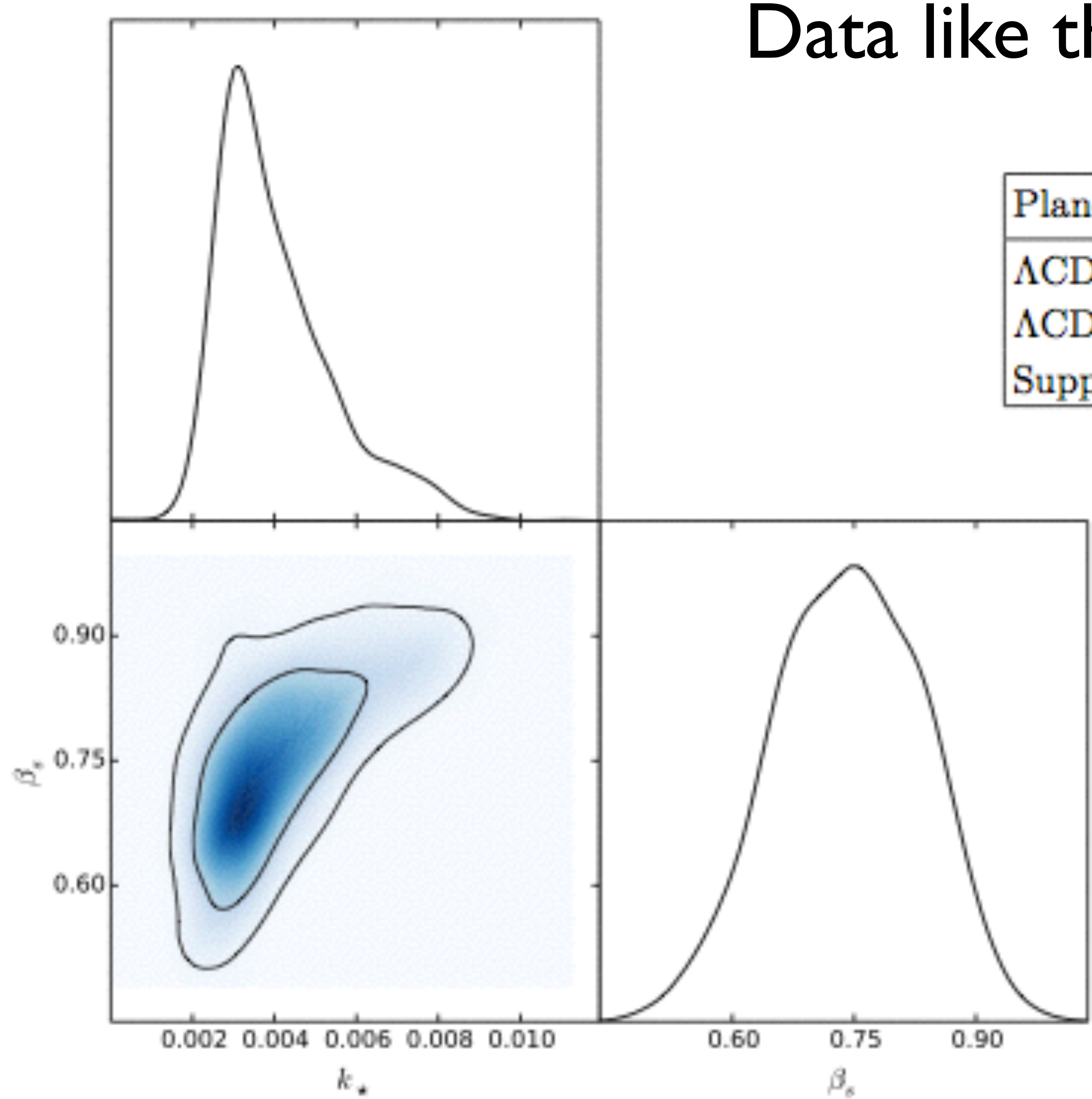
$$\beta_s = 1 \,, \quad k > k_*$$
$$\beta_s < 1 \,, \quad k < k_*$$



More options?

Assume step in primordial spectrum

Data like this!

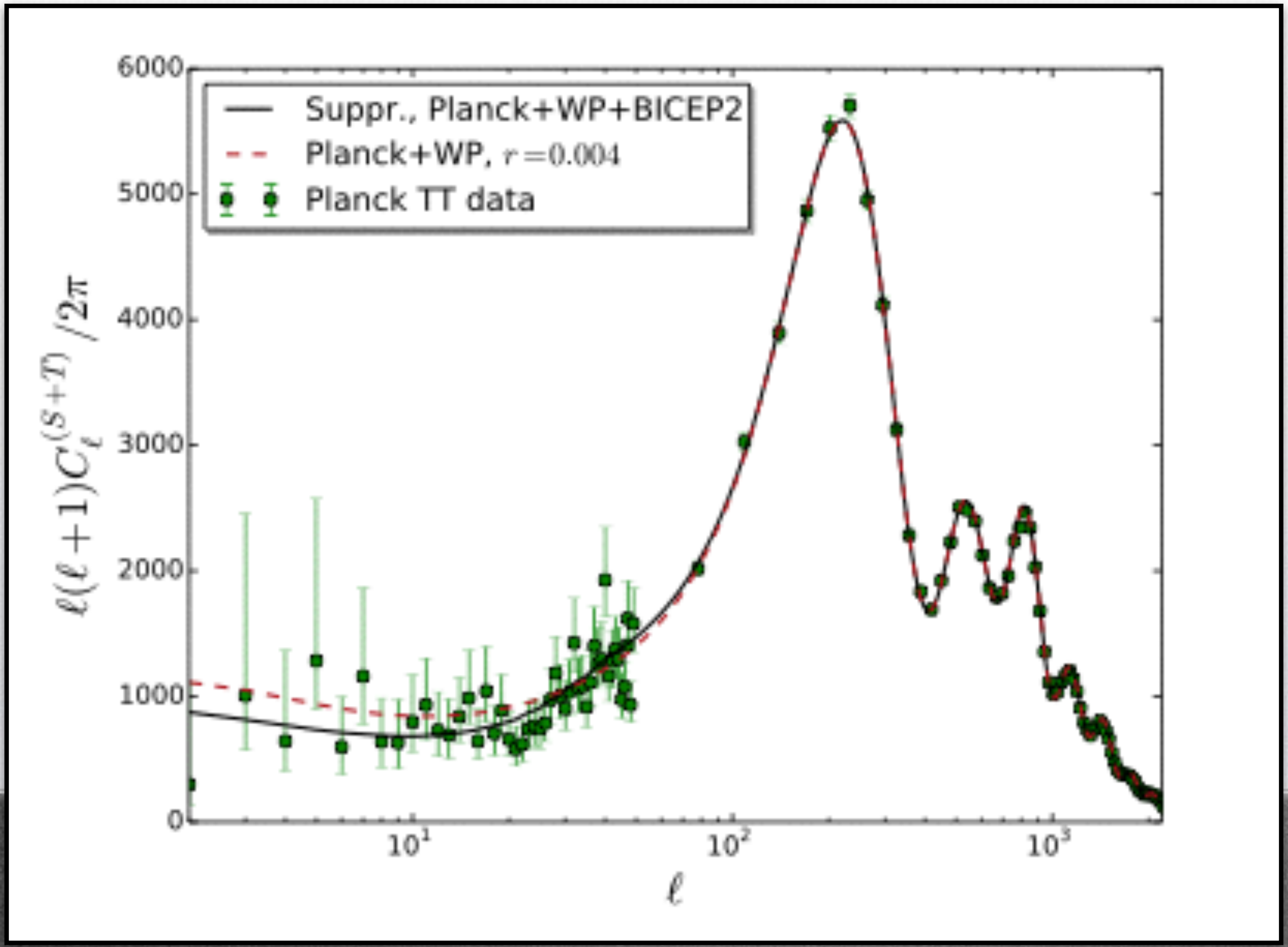


Planck+WP+BICEP2	ΔN_p	χ^2	$\Delta\chi^2$	r
ΛCDM + tensor	–	9854.83	–	0.16
ΛCDM + tensor + α_s	+1	9850.14	-4.69	0.17
Suppression	+2	9840.51	-14.32	0.20

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…

Starobinsky 92	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

- Large value of r has far reaching implications for inflation and Early Universe
- 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?

Addendum:

does it really have to be high scale inflation?

In principle inflation could happen at lower scales

Tensors produced by other mechanisms

(during inflation)

LS 10

An example: rolling pseudoscalar ϕ coupled to *U(1)* gauge field

$$\mathcal{L}_{\phi F F} = \frac{\phi}{f}\,\epsilon_{\alpha\beta\gamma\delta}\,F^{\alpha\beta}\,F^{\gamma\delta}$$

rolling ϕ excites *U(1)* gauge field that excites gravitational waves

Left- and right-handed tensor spectra...

$$\mathcal{P}_R(\mathbf{k}) = \frac{H^2}{\pi^2 M_P^2}\left(1 + 9\times 10^{-7}\,\frac{H^2}{M_P^2}\,\frac{e^{4\pi\xi}}{\xi^6}\right)$$

$$\mathcal{P}_L(\mathbf{k}) = \frac{H^2}{\pi^2 M_P^2}\left(1 + 2\times 10^{-9}\,\frac{H^2}{M_P^2}\,\frac{e^{4\pi\xi}}{\xi^6}\right)$$

$$\xi \equiv \frac{\dot{\phi}}{2\,f\,H} \gtrsim 1$$

- Large tensors in low scale inflation
- Parity-violating! Signature $<TB>, <EB> \neq 0$
- Cosmological magnetic fields? (Caprini & LS, in prep)

Space of inflationary models: