B-modes and the Nature of Inflation

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arXiv:1407.2621 with Baumann and Porto

Outline

The Nature of Inflation

Limits from Planck

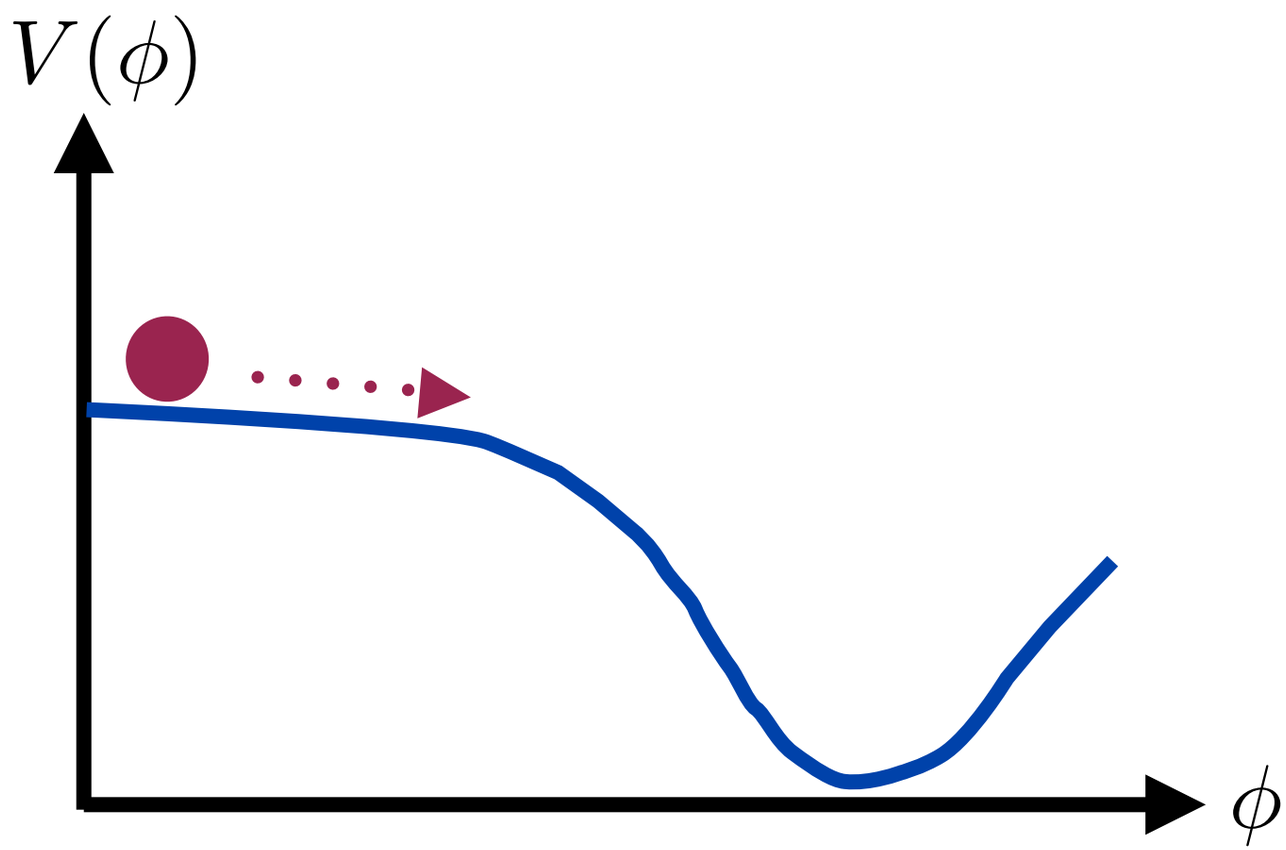
B-modes

Conclusions

The Nature of Inflation

What is Inflation?

The conventional picture of inflation is slow-roll:



$$\mathcal{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)$$

Cosmological data is compatible with this picture

What is Inflation?

Inflation is a more general framework:

e.g. $\mathcal{L} = P(X, \phi) - V(\phi)$ where $X \equiv \partial_\mu \phi \partial^\mu \phi$

Armendariz-Picon et al.

This is very closely related to a superfluid with:

$X \to \mu$	chemical potential
$\delta\phi \to \pi$	superfluid phonon
$P(\mu) \to$	equation of state

Can inflation have a more exotic origin?

What is Inflation?

A definition:

1. A period of quasi-dS expansion

$$\frac{\dot{H}}{H^2} \ll 1$$

2. A physical clock

Needed to define the end of inflation Cheung et al.

In slow roll, the clock is defined by $\phi(t)$

What is Inflation?

No clock is perfect (uncertainty principle)

The amount of inflation will vary from place to place:

$$\zeta(x) \sim \frac{\delta a(x)}{a} \sim \frac{\dot{a}\delta t(x)}{a} \equiv H\delta t$$

RMS fluctuations of the clock $\sqrt{\langle(\delta t)^2\rangle} \sim \frac{H}{f_\pi^2}$

Time between "ticks" defines an energy scale f_π

For slow-roll inflation $\delta t \sim \frac{\delta\phi}{\dot{\phi}}$ and $f_\pi^2 = \dot{\phi}$

What is Inflation?

Raises the question: what was the clock?

We have lots of ways to make clocks

Slow-roll inflation is easiest to construct, because it is weakly coupled (like Higgs versus technicolor)

But, does the data prefer slow-roll inflation?

Can we rule out slow-roll?

Hard to produce large NG in single-field slow-roll

$$\mathcal{L} = -\tfrac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) + \frac{1}{\Lambda^4}(\partial_\mu\phi\partial^\mu\phi)^2$$

Creminelli

Changes the sound speed for fluctuations

$$\mathcal{L} \supset \frac{\dot\phi^2}{\Lambda^4}\delta\dot\phi^2 \simeq \frac{1-c_s^2}{c_s^2}\delta\dot\phi^2$$

and introduces interactions (bi & tri-spectra)

$$\mathcal{L} \supset \frac{4\dot\phi}{\Lambda^4}\delta\dot\phi\partial_\mu\delta\phi\partial^\mu\dot\phi + \frac{1}{\Lambda^4}(\partial_\mu\delta\phi\partial^\mu\delta\phi)^2$$

Can we rule out slow-roll?

Single-field slow-roll is very gaussian

$$\mathcal{L} = -\tfrac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) + \frac{1}{\Lambda^4}(\partial_\mu\phi\partial^\mu\phi)^2$$

Creminelli

This is essentially slow-roll if $\dot{\phi}^2 \ll \Lambda^4$

Implies that $f_{\rm NL}^{\rm equil.} \ll 1$ (or $c_s^2 \sim 1$)

Essence of have a weakly coupled description

(at all energy scales)

Can we rule out slow-roll?

The speed of sound is a very useful parametrization

$$P_\zeta = \frac{1}{k^3}\frac{H^4}{4M_{\rm pl}^2|\dot{H}|c_s} \qquad f_{\rm NL}^{\rm eq.} = (1-\tfrac{1}{c_s^2})(\tfrac{85}{324}+c_s^2\tfrac{5}{81})$$

EFT for the "clock" makes sense for any c_s Cheung et al.

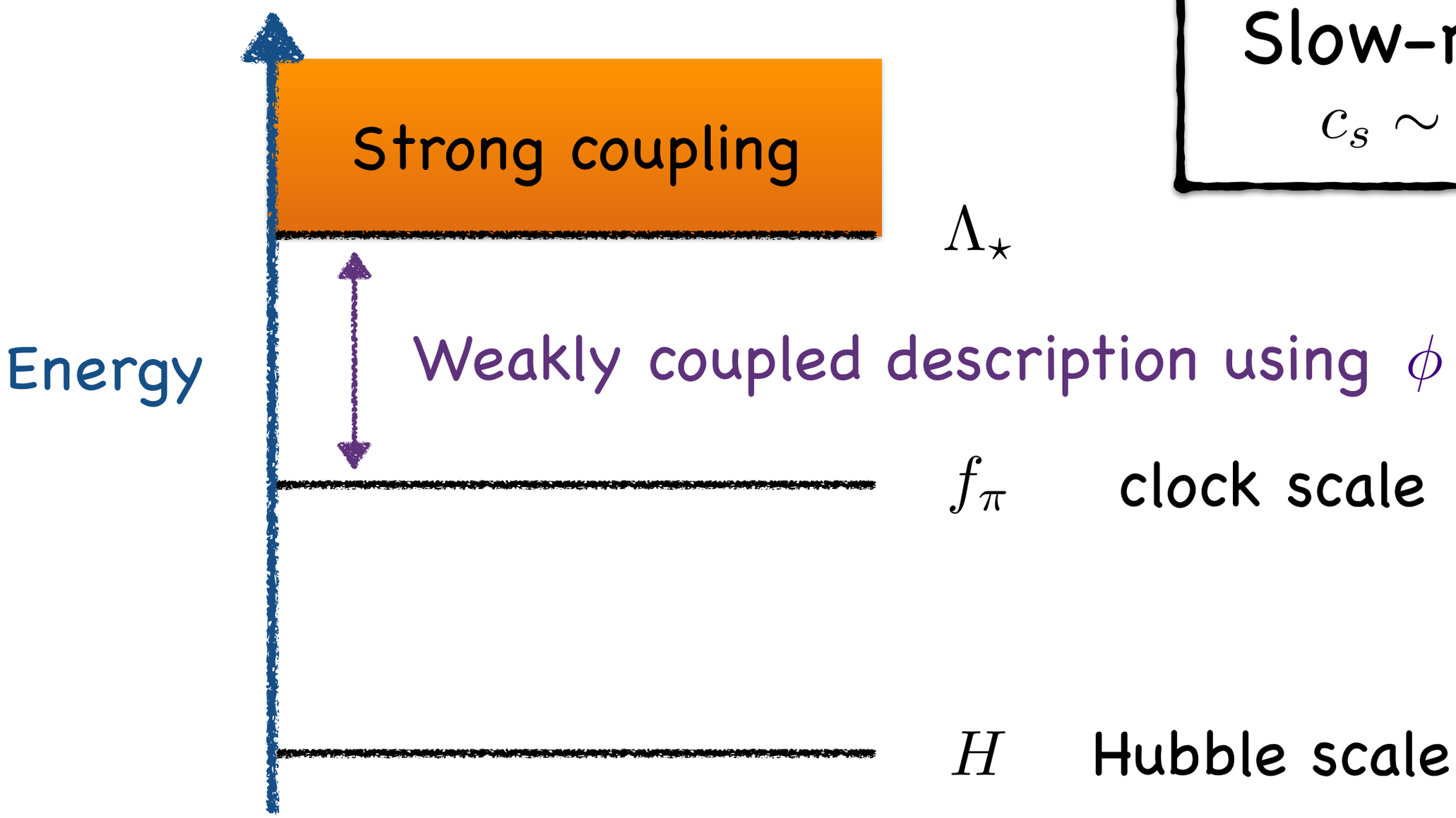
Violates perturbative unitarity (strongly coupled) when

$$E^4 > \Lambda_\star^4 = \frac{48\pi}{5}M_{\rm pl}^2|\dot{H}|\frac{c_s^5}{(1-c_s^2)}$$

Baumann & DG; Baumann, DG & Porto

Can we rule out slow-roll?

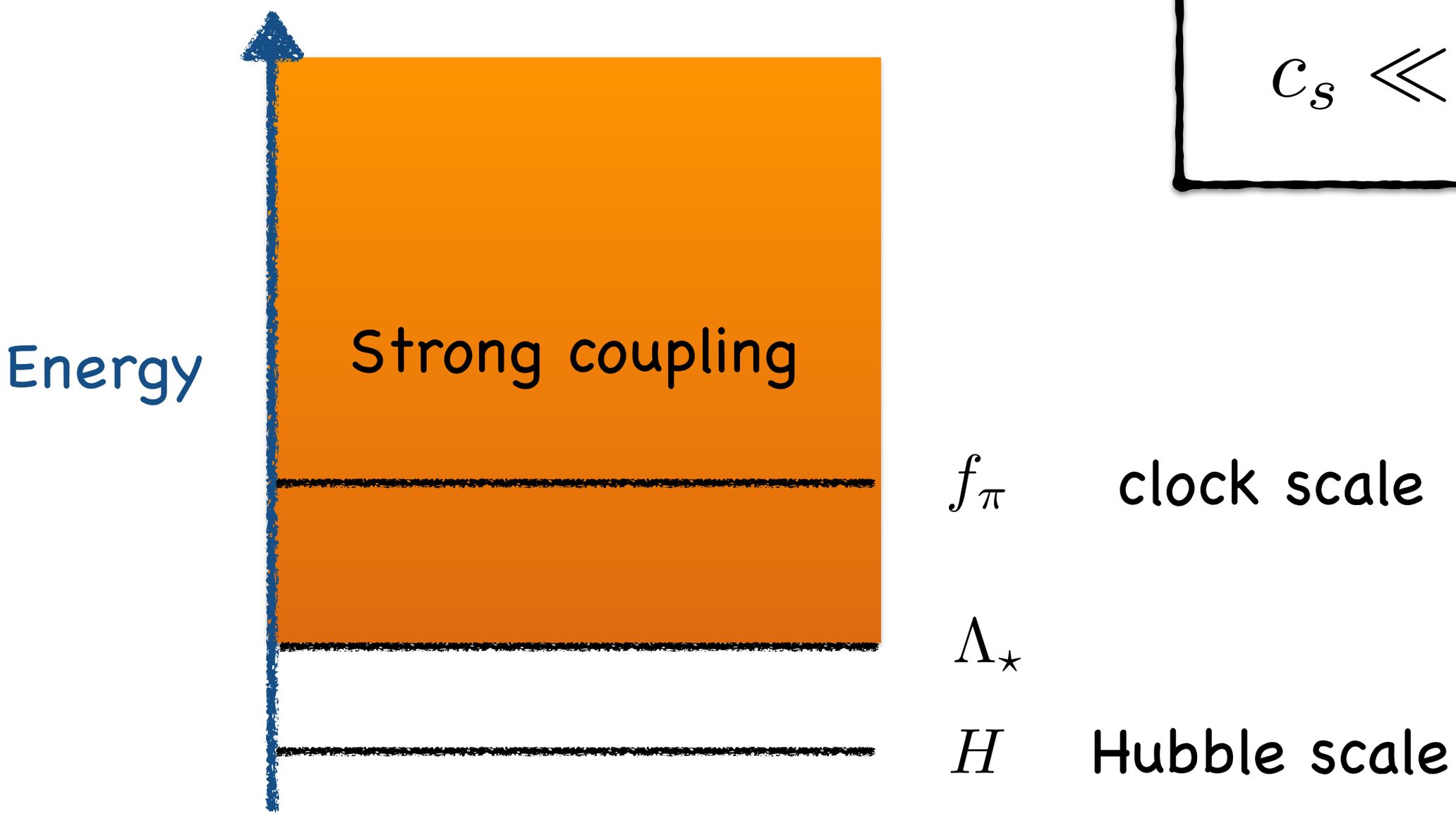
Leads to two qualitatively different pictures:



Can we rule out slow-roll?

Leads to two qualitatively different pictures:

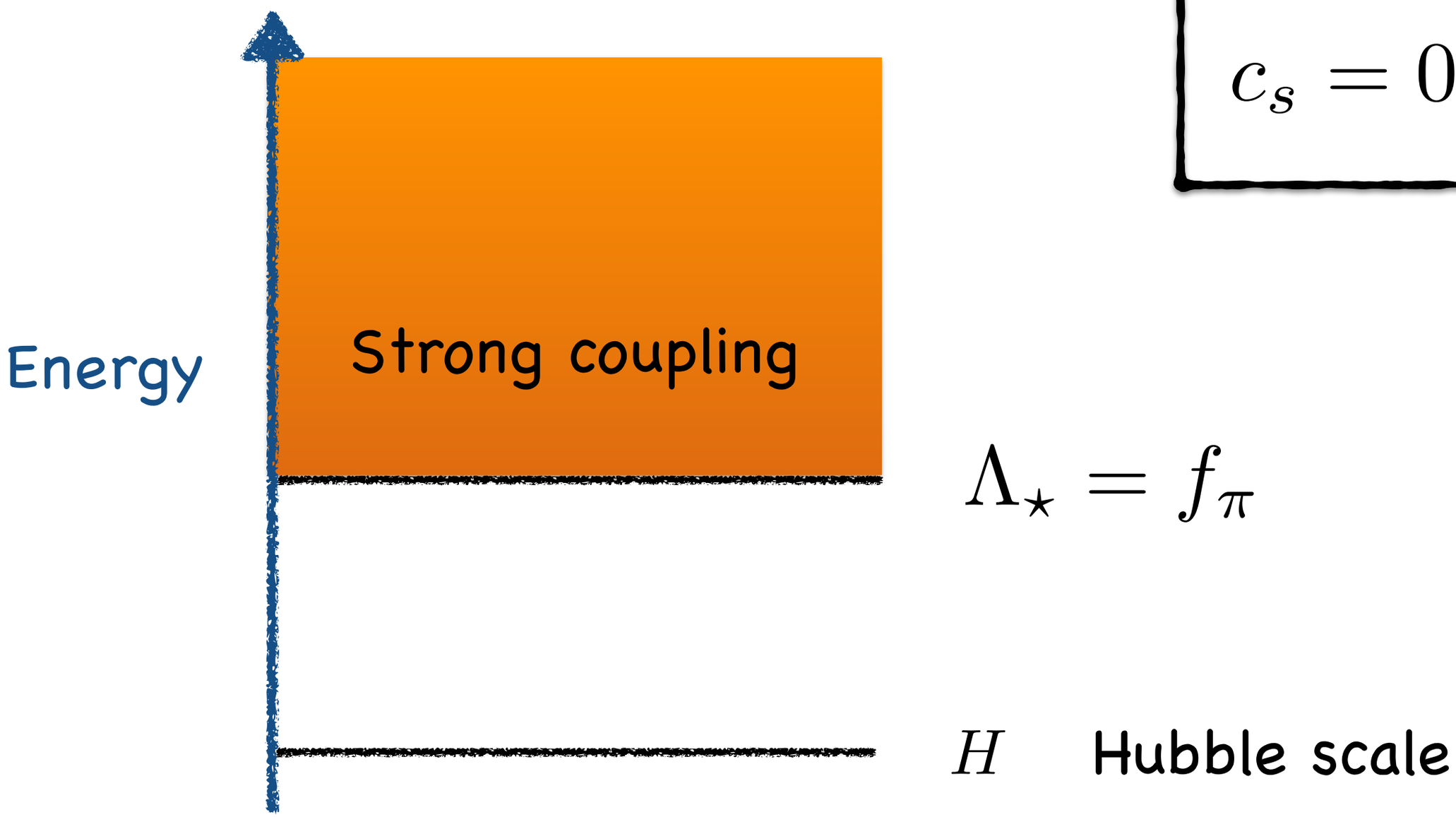
$$c_s \ll 1$$



Can we rule out slow-roll?

Natural boundary between the pictures

$$c_s = 0.47$$



Can we rule out slow-roll?

Single-field slow-roll ruled out if

$$c_s < 0.47$$

In terms of bispectrum this means

$$|f_{\rm NL}^{\rm equilateral}| > 0.97.$$

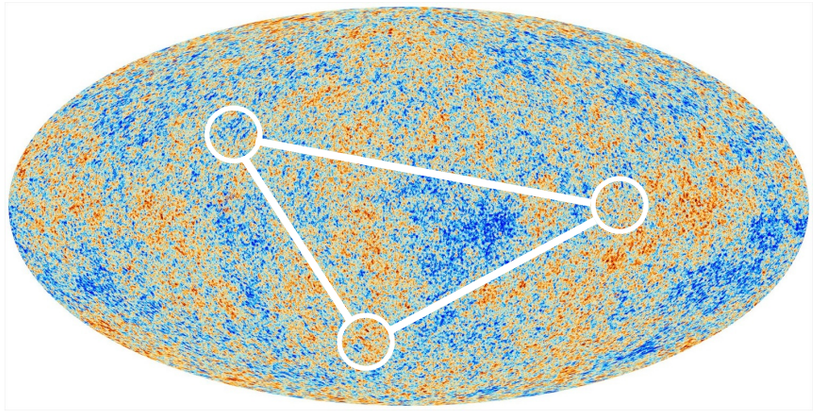
Similar threshold in NG exist for most deformations

It might be fair to call inflation "slow-roll" if we find

$$|f_{\rm NL}^{\rm equilateral}| < 1 \quad (5\sigma)$$

Results from Planck

Planck Limits



Constraint given in terms of individual templates

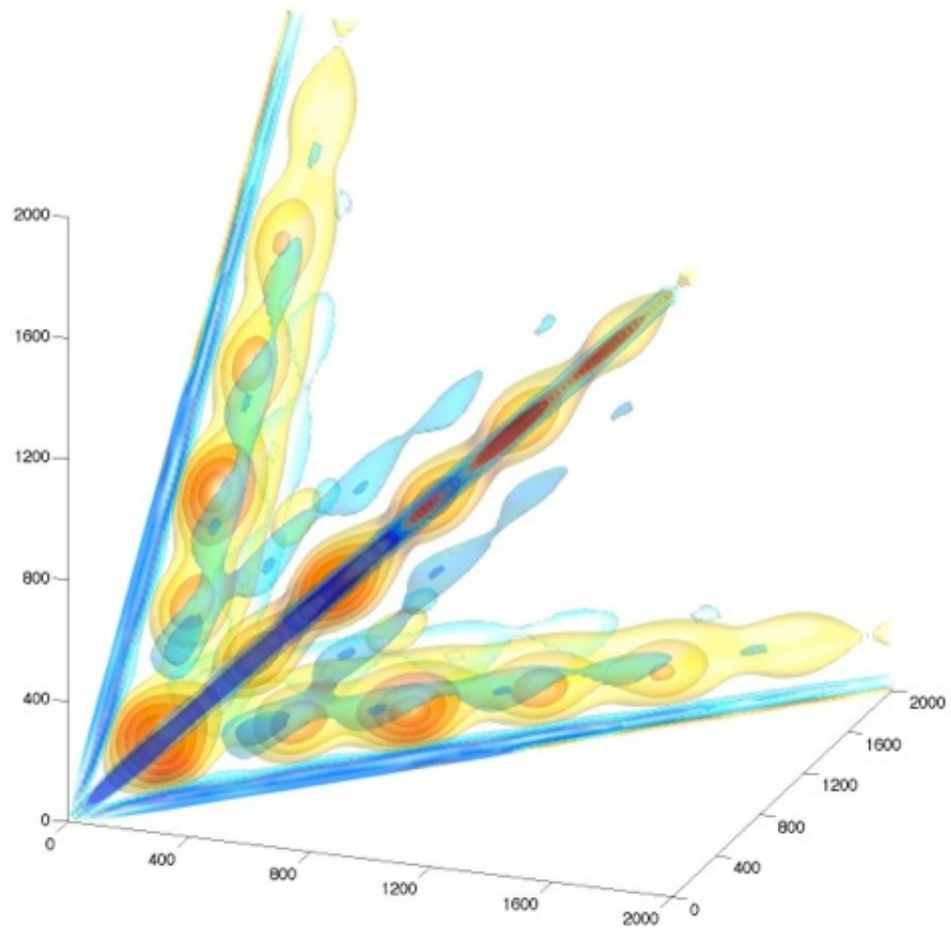
$$\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle = B(k_1, k_2, k_3)(2\pi)^2 \delta^3(\mathbf{k}_1 + \mathbf{k_2} + \mathbf{k}_3)$$

For a given template, bound $f_{\rm NL} \equiv \frac{5}{18} \frac{B(k,k,k)}{P_\zeta(k)^2}$

With this definition: non-gaussian = $f_{\rm NL} \sim 10^5$

Planck Limits

Planck reports limits on 3 templates:



Peaked at:

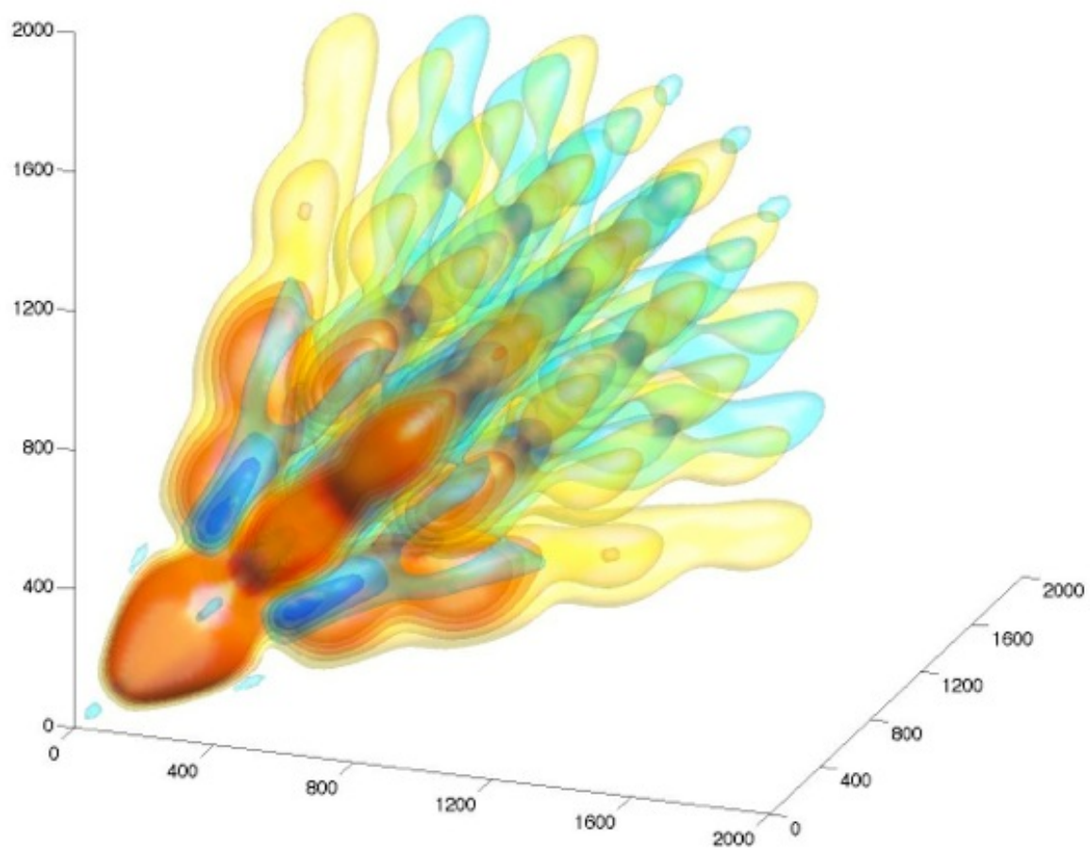
$$k_1 \ll k_2 \sim k_3$$

$$f_{\rm NL}^{\rm local} = 2.7 \pm 5.8 \quad \text{(68\% C.I.)}$$

Courtesy of Fergusson & Shellard

Planck Limits

Planck reports limits on 3 templates:



Peaked at:

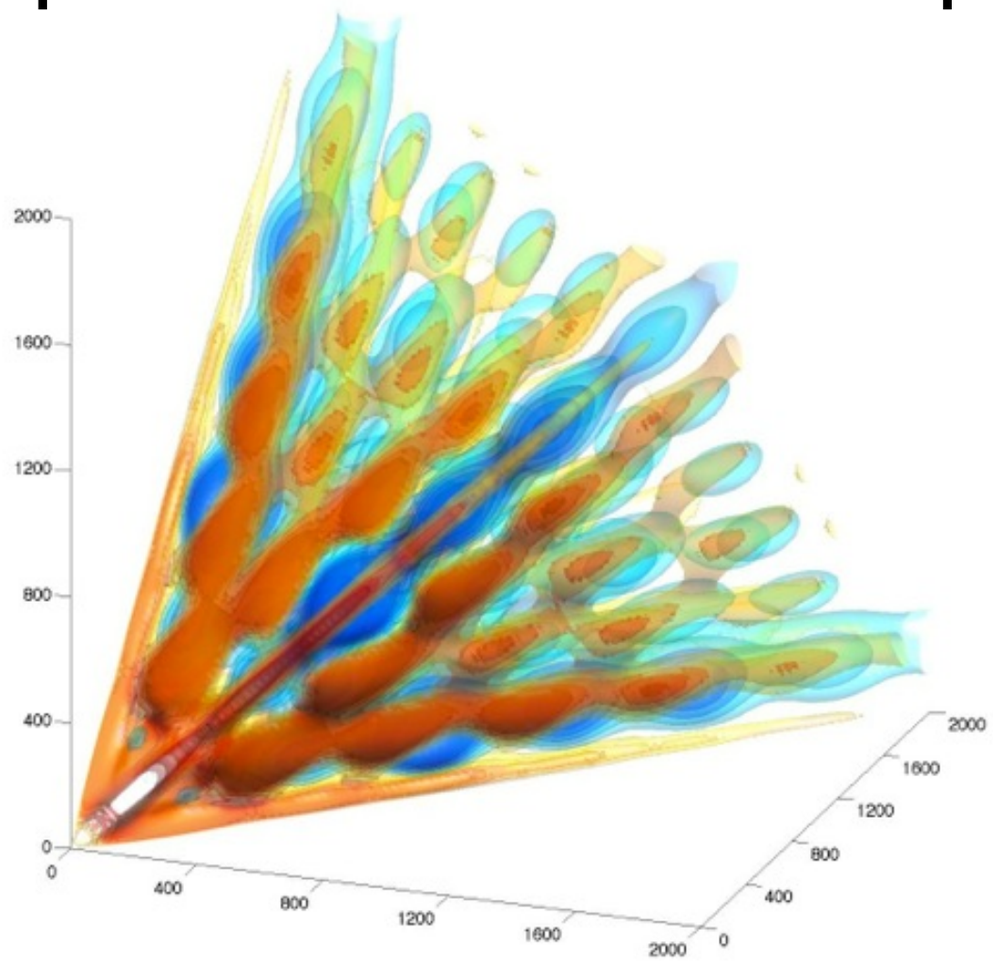
$$k_1 = k_2 = k_3$$

$$f_{\rm NL}^{\rm equil} = -42 \pm 75 \quad \text{(68\% C.I.)}$$

Courtesy of Fergusson & Shellard

Planck Limits

Planck reports limits on 3 templates:



Peaked at:

$$k_1 = k_2 = k_3$$

&

$$k_1 = k_2 = \frac{1}{2} k_3$$

$$f_{\rm NL}^{\rm ortho} = -25 \pm 39 \quad \text{(68\% C.I.)}$$

Courtesy of Fergusson & Shellard

Planck Limits

Given a combined constraint on sound speed

$$c_s > 0.02 \ (95\%)$$

To reach threshold with NG will require

$$N_{\rm modes} \sim 10^4 \times N_{\rm modes}^{\rm Planck}$$

Reaching $\Delta f_{\rm NL}^{\rm eq.} < 1$ is very well motivated target

Need large scale structure surveys to get there

(if we are up for the challenge)

B-modes

Sound Speed and r

The power spectrum is very sensitive to c_s

$$P_\zeta = \frac{1}{k^3} \frac{H^4}{4M_{\rm pl}^2 |\dot{H}| c_s}$$

It should me much easier to measure this way

$$\left(\frac{S}{N}\right)_2 \sim \frac{1}{\sqrt{N_{\rm modes}}} \qquad \left(\frac{S}{N}\right)_3 \sim \frac{\Delta_\zeta}{\sqrt{N_{\rm modes}}} \frac{(1-c_s^2)}{4c_s^2}$$

A huge suppression for using the bispectrum

Sound Speed and r

Can we constraint c_s using the power spectrum?

$$P_\zeta = \frac{1}{k^3} \frac{H^4}{4M_{\rm pl}^2 |\dot{H}| c_s}$$

Determines c_s if we can measure H and $\dot{H}$

Scalar power alone cannot determine H

We can rescale parameters leaving observables fixed

Sound Speed and r

Can we constraint c_s using the power spectra?

$$P_\zeta = \frac{1}{k^3}\frac{H^4}{4M_{\rm pl}^2|\dot{H}|c_s} \qquad P_T = \frac{1}{k^3}\frac{4H^2}{M_{\rm pl}^2}$$

A detection of tensors would determine H

We still need to determine $\dot{H}$

Can we use the tilt and/or running ?

see also: Creminelli et al. ; D'Amico & Kleban

Sound Speed and r

Define "generalized slow-roll" parameters

$$\epsilon_1 \equiv -\frac{\dot{H}}{H^2} \qquad \epsilon_n \equiv \frac{\dot{\epsilon}_{n-1}}{\epsilon_{n-1} H}$$

$$\delta_1 \equiv \frac{\dot{c}_s}{c_s H} \qquad \delta_n \equiv \frac{\dot{\delta}_{n-1}}{\delta_{n-1} H}$$

We will assume that $\epsilon_n, \delta_n \ll 1$

Consistent with broader definition of inflation

Sound Speed and r

Start by looking at the tilt

To leading order in $\epsilon_n, \delta_n \ll 1$

$$r = 16\epsilon_1 c_s$$

$$n_s - 1 = -2\epsilon_1 - \epsilon_2 - \delta_1$$

It looks like there is a degeneracy along

$$\epsilon_1 = r/16c_s \qquad \delta_1 = -2\epsilon_1 - (n_s - 1)$$

Leaves r and n_s fixed while taking $c_s \to 0$

Summing large logs

This argument seems valid unless slow-roll fails

<u>But</u> $c_s \to 0$ introduces a new large number

In fact, the leading correction to r is

$$r = 16\epsilon_1 c_s(1 + 2\epsilon_1 \log c_s - 0.73\epsilon_2 + 0.54\delta_1)$$

This "degeneracy" will reach a point where

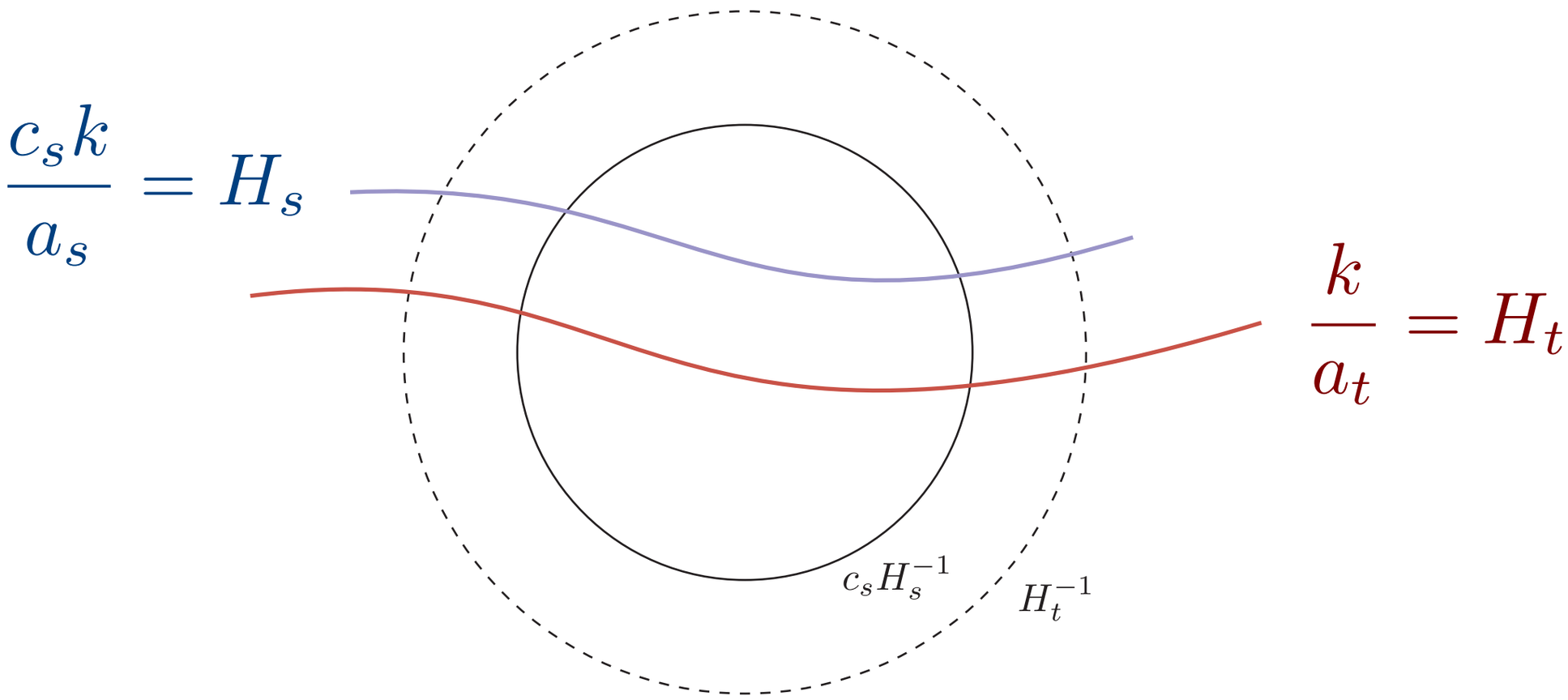
$$\epsilon_1 \ll 1 \quad \text{but} \quad 2\epsilon_1 \log c_s \sim -1$$

Our argument fails without violating $\epsilon_n, \delta_n \ll 1$

Summing large logs

Where did the large logs come from ?

Tensor and scalar freeze-out time is different



Gravitons move at the speed of light Creminelli et al.

Summing large logs

Where did the large logs come from ?

Tensor and scalar freeze-out time is different

$$P_\zeta = \frac{1}{k^3}\frac{H^4}{4M_{\rm pl}^2|\dot{H}|c_s}\Big|_{c_s k=aH} \qquad P_h = \frac{1}{k^3}\frac{4H^2}{M_{\rm pl}^2}\Big|_{k=aH}$$

$$r = 16\epsilon_1 c_s \times \left(\frac{H_t \equiv H|_{k=aH}}{H_s \equiv H_{c_s k=aH}}\right)^2$$

Exponentially sensitive to freeze-out $H_t \sim H_s e^{-\epsilon_1 \Delta N}$

Summing large logs

Leads to additional suppression of r

$$H_t = H_s e^{-\bar{\epsilon}_1 \Delta N}$$

Increasing ϵ_1 means faster change to Hubble

Decreasing c_s increases separation of freeze-out

$$\Delta N \sim -\log c_s$$

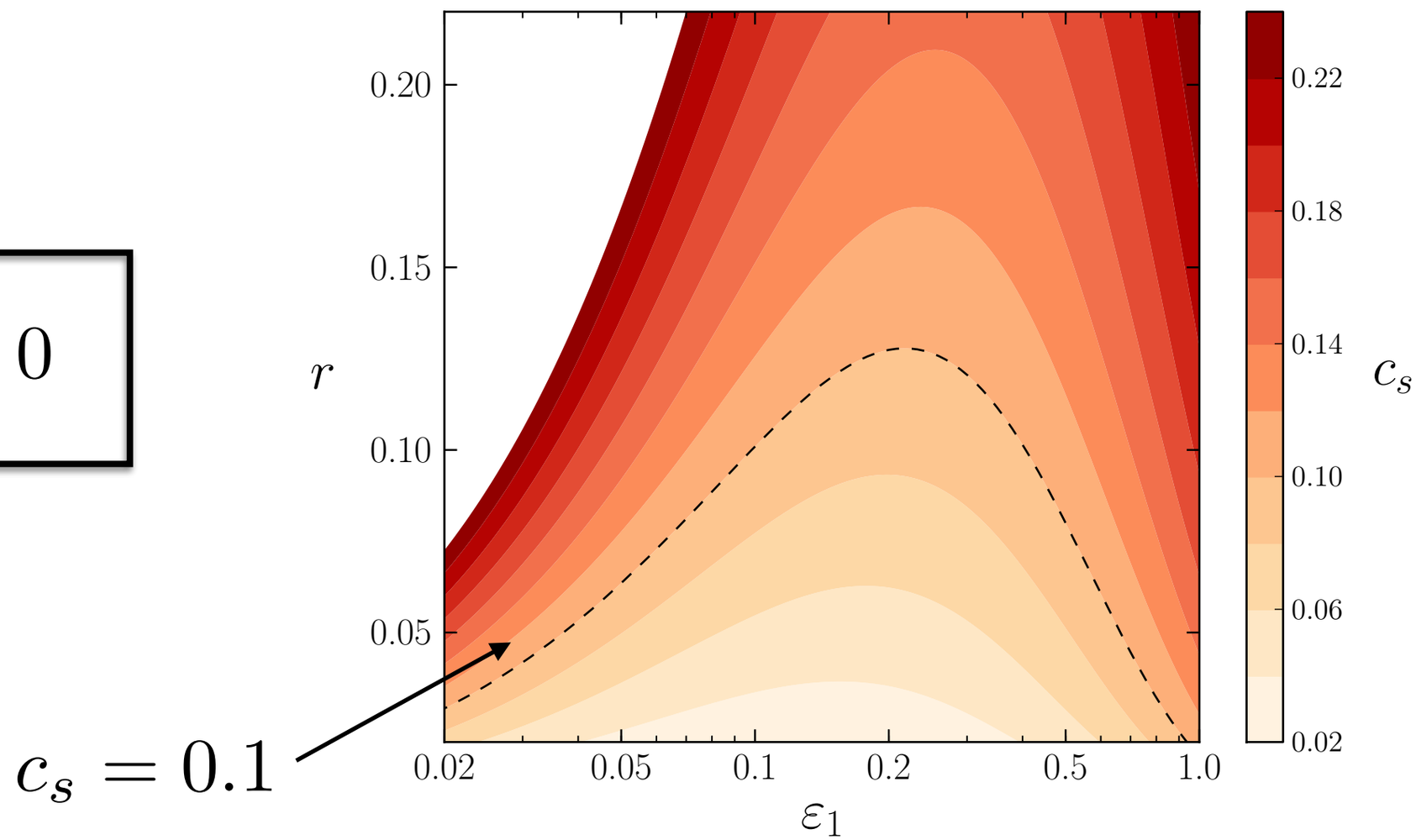
This additional suppression breaks “degeneracy”

Summing large logs

Taking these effects into account (summing logs)

$$r = 16\epsilon_1 c_s^{1+2\epsilon_1(1-c_s^{-\epsilon_2})/(\epsilon_2 \log c_s)}$$

$$\boxed{\epsilon_2 \to 0}$$



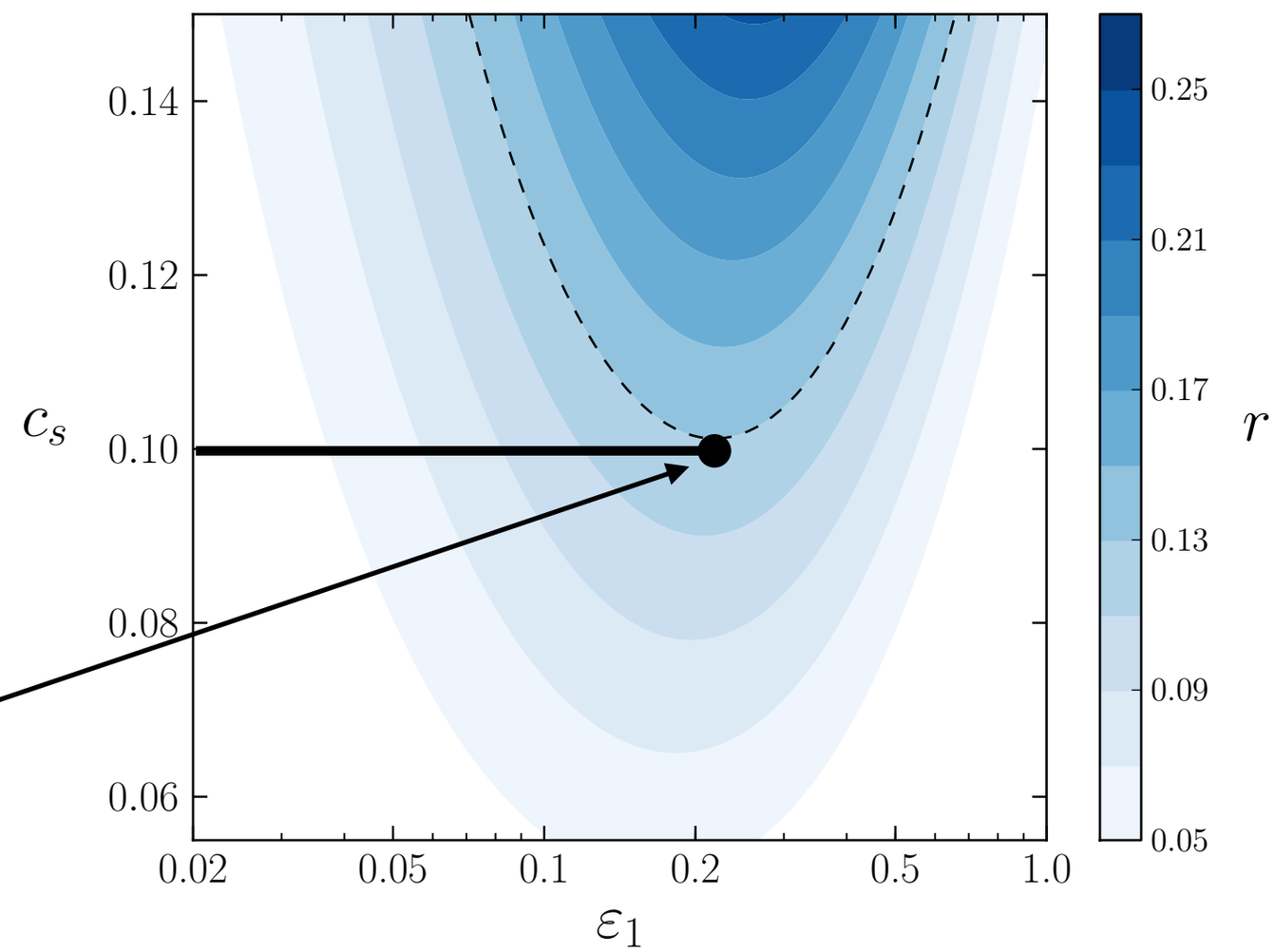
Summing large logs

Taking these effects into account (summing logs)

$$r = 16\epsilon_1 c_s^{1+2\epsilon_1(1-c_s^{-\epsilon_2})/(\epsilon_2 \log c_s)}$$

$$\epsilon_2 \to 0$$

$$r_{\max} = 0.13$$



Summing large logs

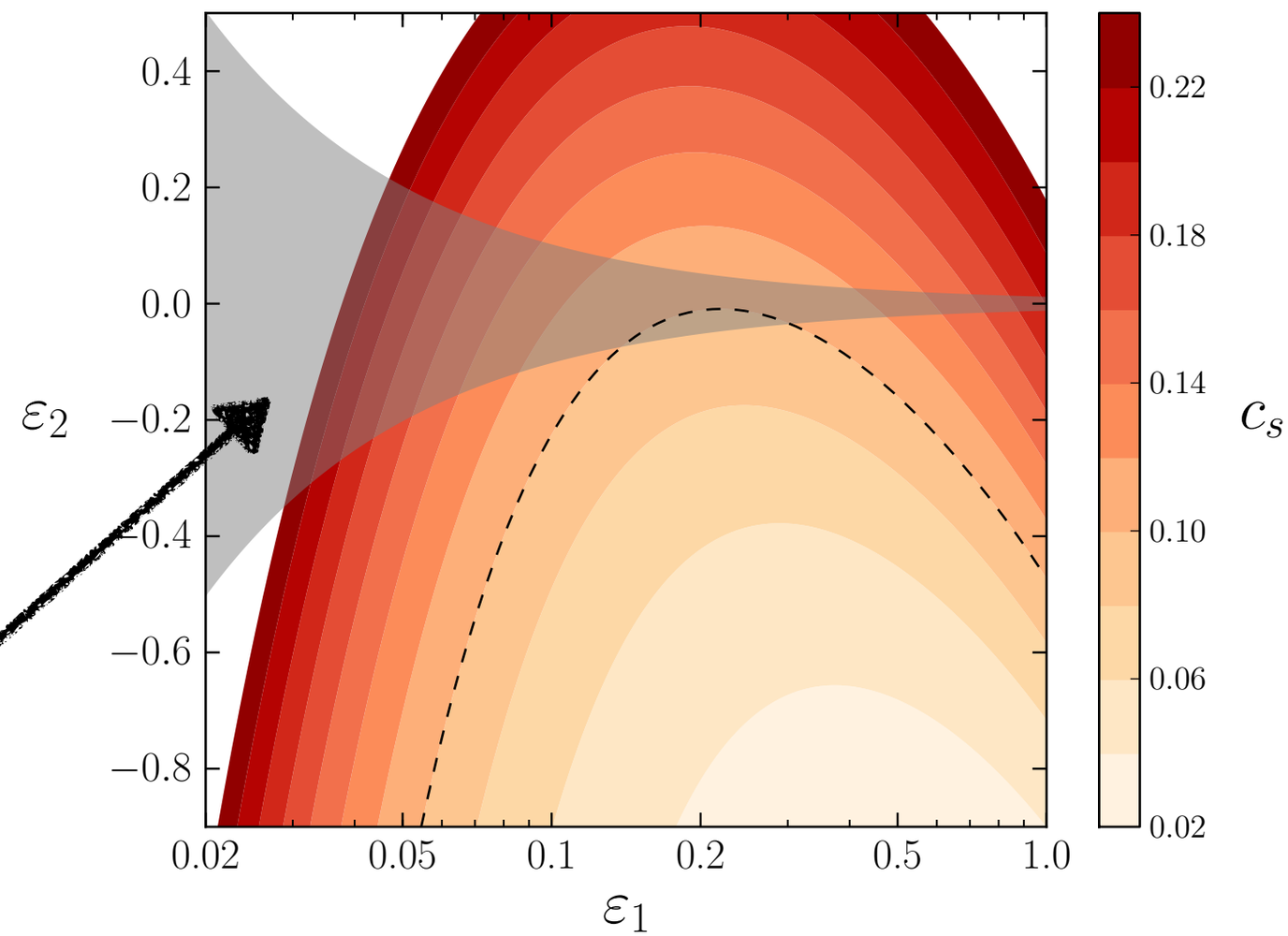
Taking these effects into account (summing logs)

$$r = 16\epsilon_1 c_s^{1+2\epsilon_1(1-c_s^{-\epsilon_2})/(\epsilon_2 \log c_s)}$$

$$r = 0.13$$

Consistent with running:

$$|\alpha_s| < 2 \times 10^{-2}$$



Analytic Bounds

From simple analytic arguments we find

A detection of $r > 0.13$ implies

$$c_s > 0.14$$

A detection of $r > 0.01$ implies

$$c_s > 0.02$$

Tensors at a detectable level imply a stronger constraint than from Planck NG

Analysis with Planck and Bicep2

There are two problems with the analytic arguments

1. Can miss additional degeneracies
   (the real bound could be weaker)

2. Can miss additional constraints
   (the real bound could be stronger)

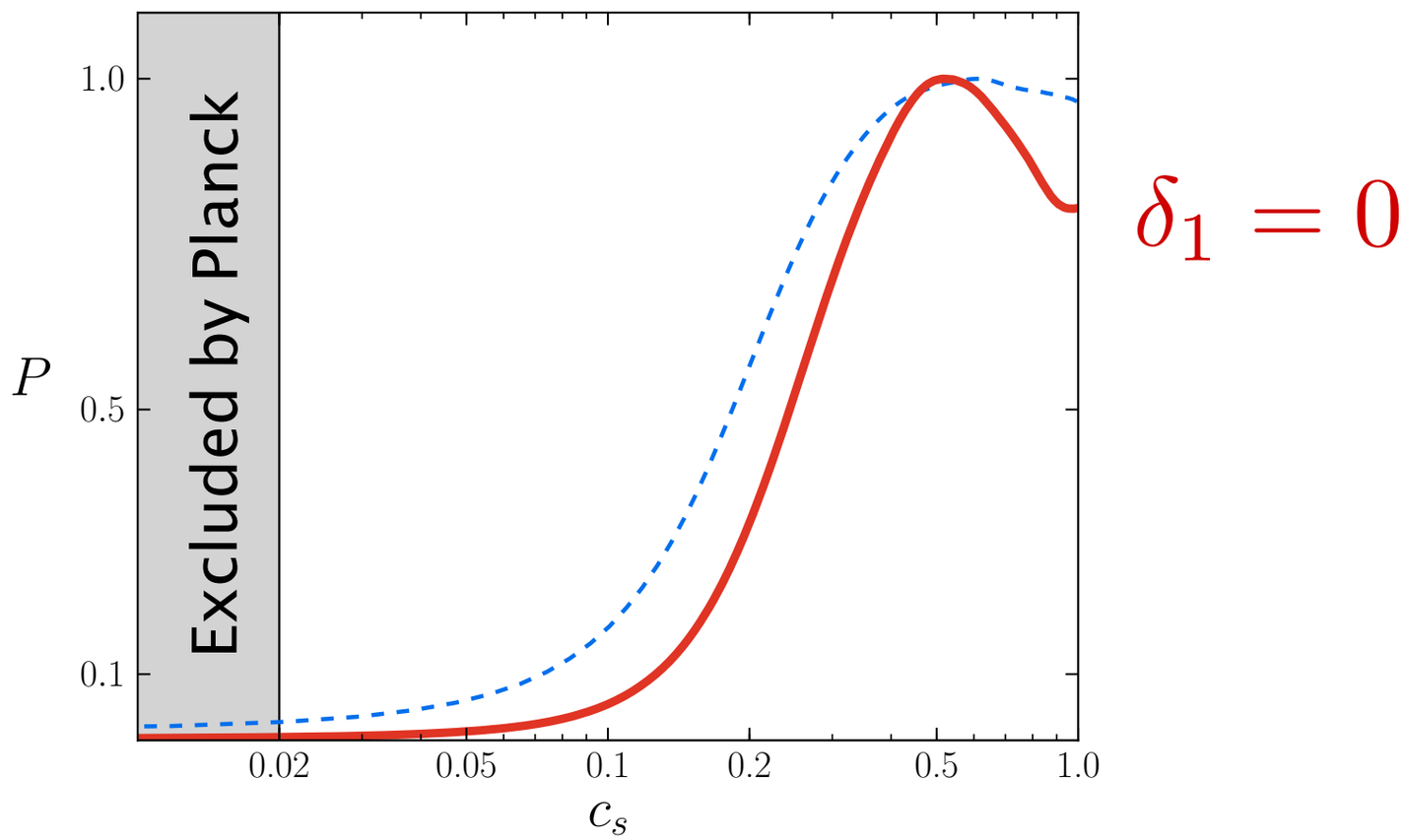
Ultimately we want to get a bound from data

We will do this with Planck and Bicep2

Analysis with Planck and Bicep2

Combining all available data we get

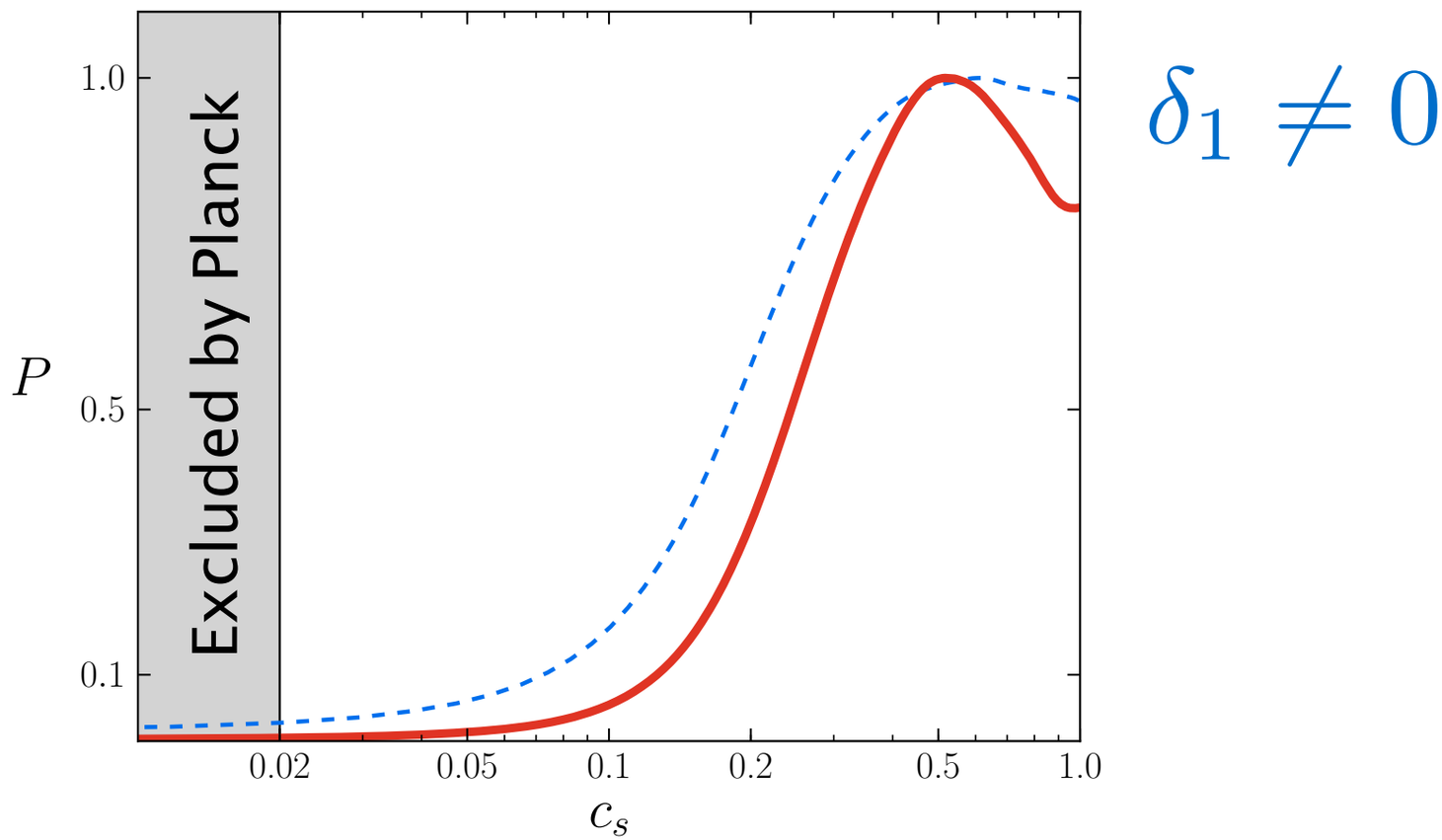
$$c_s > 0.25 \quad (95\%)$$



Analysis with Planck and Bicep2

Combining all available data we get

$$c_s > 0.21 \quad (95\%)$$



Analysis with Planck and Bicep2

To compare directly to Planck use $\delta_1 = 0$

If we keep everything at linear order, use $\delta_1 \neq 0$

$$n_s - 1 = -2\epsilon_1 - \epsilon_2 - \delta_1$$

Including $\delta_1 \neq 0$ qualitatively changes contours

$$\alpha_s = -2\epsilon_1\epsilon_2$$

Unconstrained by running

Analysis with Planck and Bicep2

Why are they stronger than our analytic bounds?

Low ℓ data prefers negative running

$$\alpha_s = -2\epsilon_1\epsilon_2 < 0$$

Null energy condition requires $\epsilon_1 > 0$

Forces $\epsilon_2 > 0$: Hubble decreases even faster

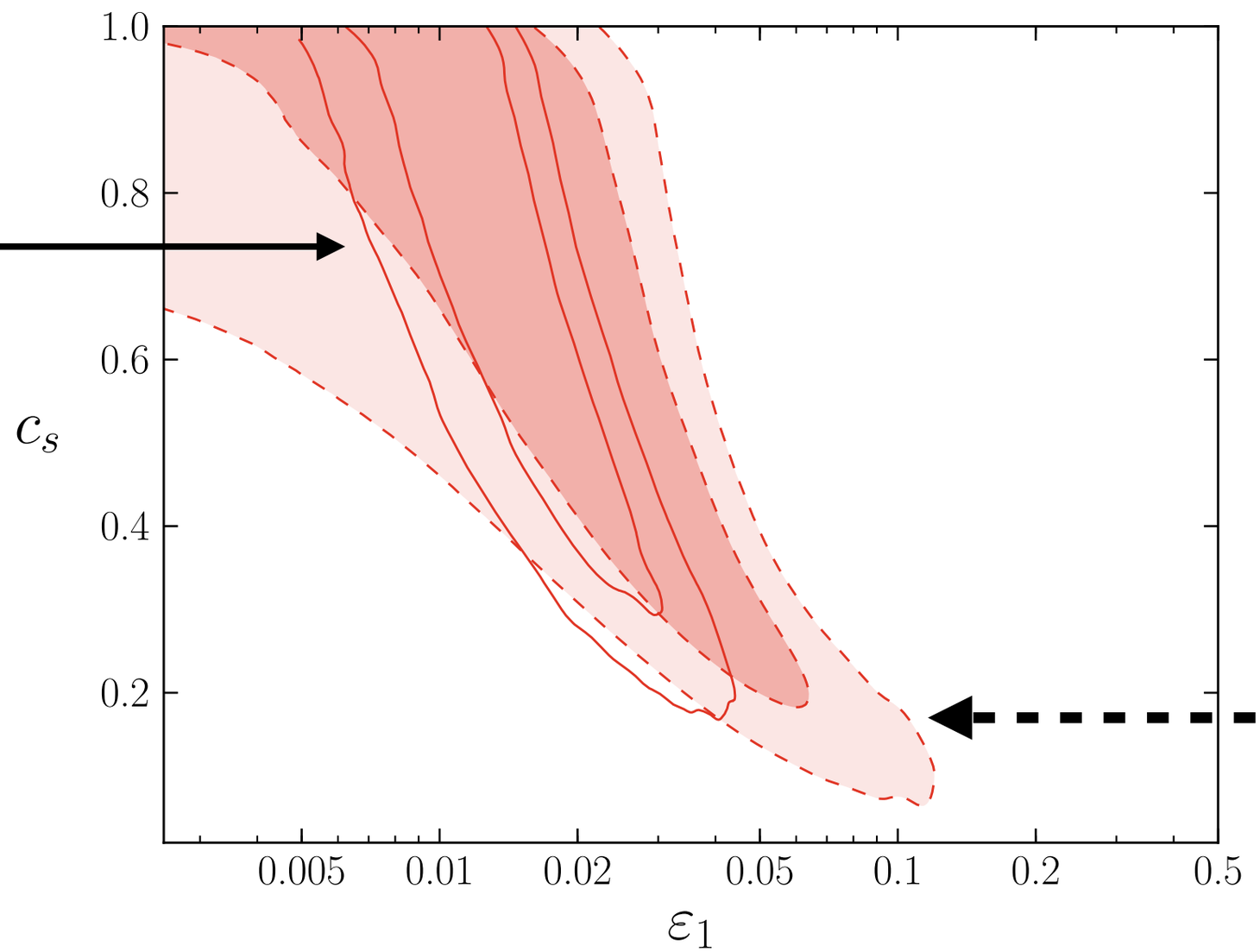
Further suppression of r

Analysis with Planck and Bicep2

We can repeat analysis with $\ell \geq 50$

$\delta_1 = 0$

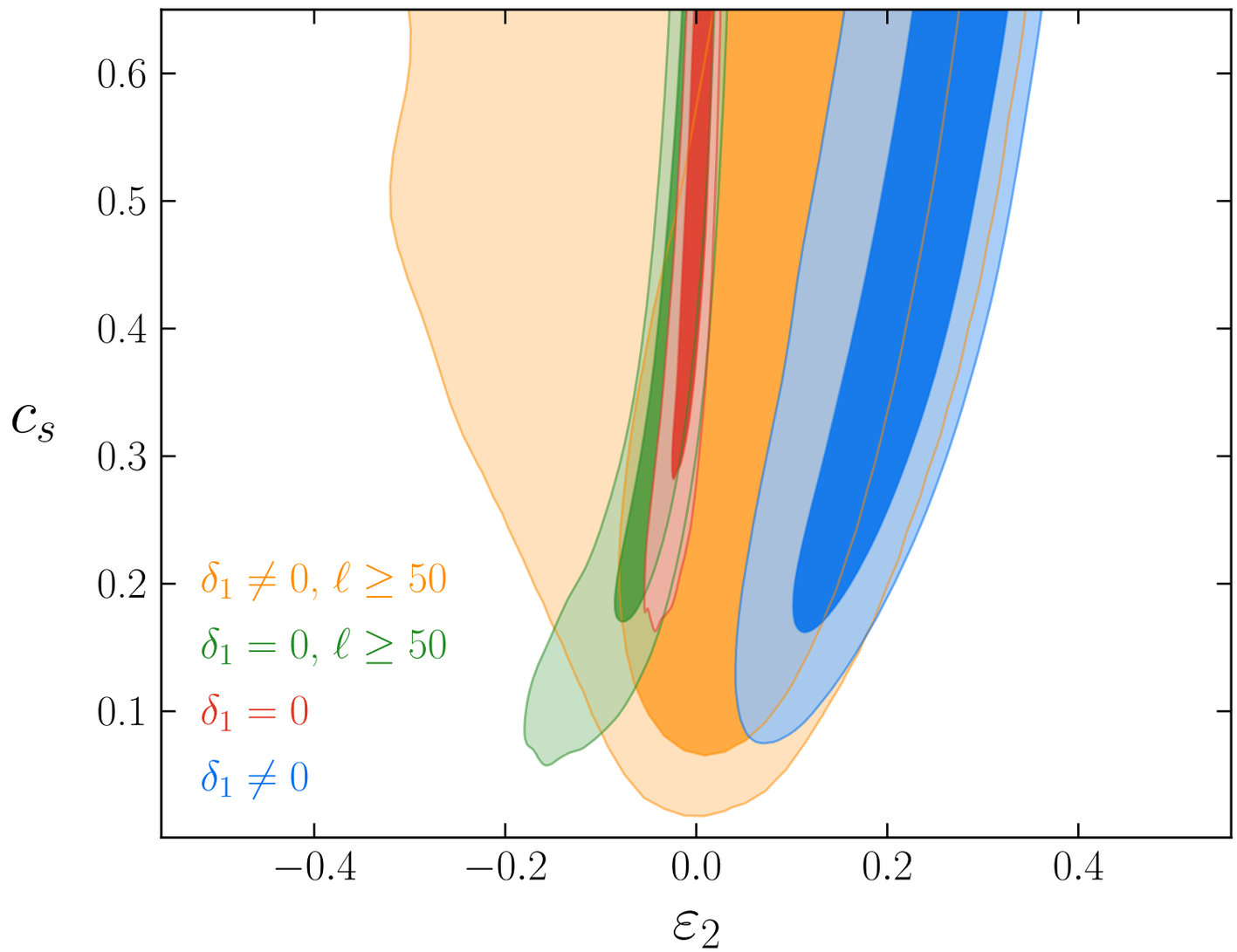
All data



$\ell \geq 50$

Analysis with Planck and Bicep2

We can repeat analysis with $\ell \geq 50$



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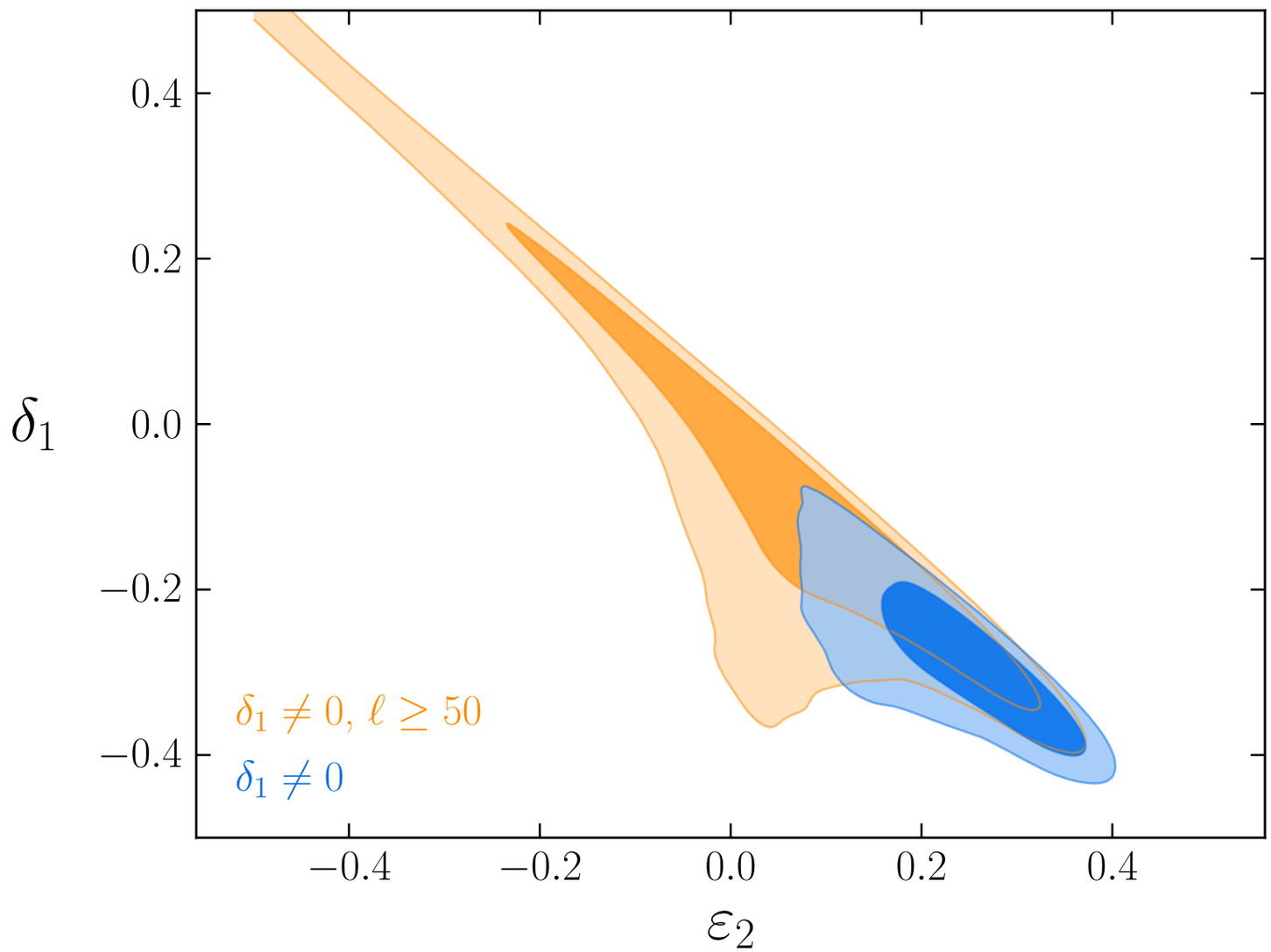

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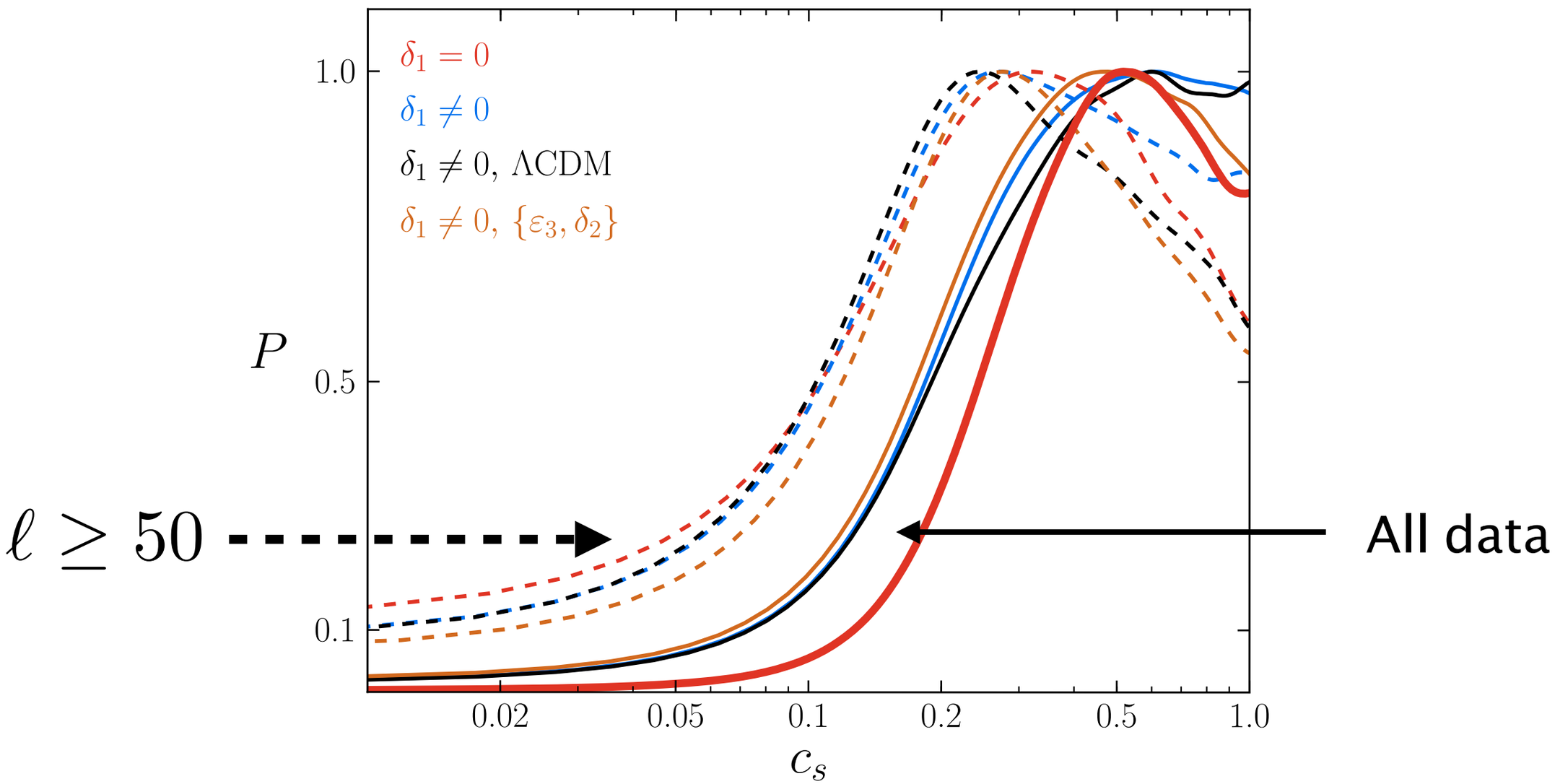
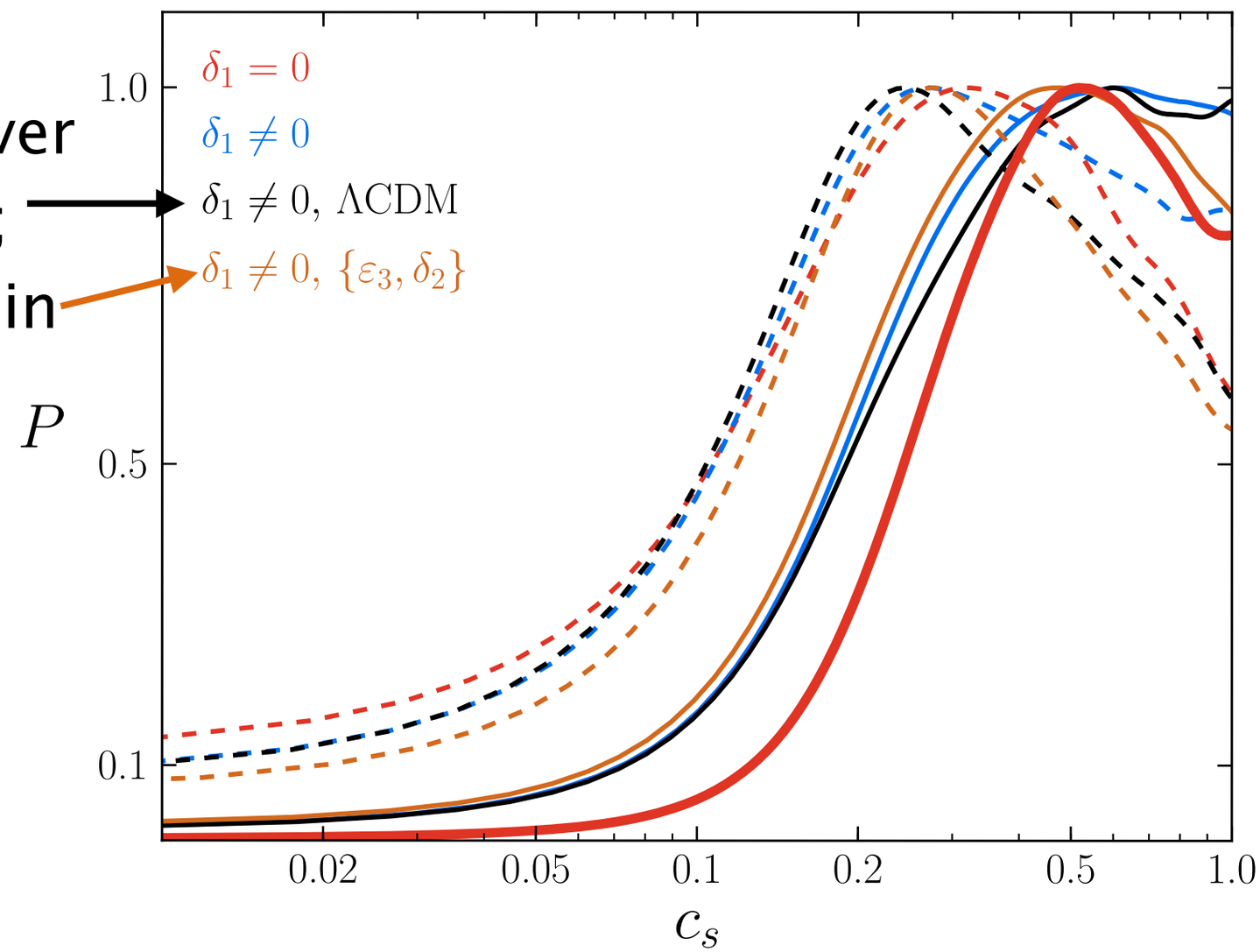


Analysis with Planck and Bicep2

We can repeat analysis with $\ell \geq 50$

Marginalize over cosmology ; higher order in slow-roll



Analysis with Planck and Bicep2

We can repeat analysis with $\ell \geq 50$

	CMBAll	~~LowLike~~
$\delta_1 = 0$	$c_s > 0.25$	$c_s > 0.14$
$\delta_1 \neq 0$	$c_s > 0.21$	$c_s > 0.15$
$\delta_1 \neq 0, \Lambda\mathrm{CDM}$	$c_s > 0.21$	$c_s > 0.13$
$\delta_1 \neq 0, \{\varepsilon_3, \delta_2\}$	$c_s > 0.20$	$c_s > 0.13$

Results look consistent with analytic bounds

Conclusions

Conclusions

To date, NG is the strongest test of slow-roll

Limits are still very far from slow-roll limit

Speed of sound is one very natural alternative

A confirmed B-modes detection would give a much stronger constraint on the speed of sound

NG remains very interesting for many other non-single-field slow-roll scenarios

Conclusions

If the results of Bicep2 are confirmed:

$$c_s > 0.25 \quad (95\%)$$

This is an order of magnitude better than Planck:

$$c_s > 0.02 \ (95\%)$$

This is two orders of magnitude in $f_{\rm NL}^{\rm eq.}$

Still short of the threshold for slow-roll:

$$c_s > (c_s)_\star = 0.47$$

Conclusions

What would help us reach the threshold

1. Better constraints on running $\alpha_s = -2\epsilon_1\epsilon_2$

Breaks degeneracy between ϵ_1 and ϵ_2

Can reach the threshold with $\Delta\alpha_s \sim 4 \times 10^{-4}$

$$(\Delta\alpha_s)_{\rm Planck} \sim 2 \times 10^{-2} \quad (\Delta\alpha_s)_{\rm CMBS4} \sim 10^{-3}$$

Wu et. al.

Potentially within reach

Conclusions

What would help us reach the threshold

2. Better measurement of NG on small scales

Breaks degeneracy between ϵ_1 and $\delta_1 < 0$

NG is dominated by speed of sound on small scales

$$\dot{c}_s < 0 \rightarrow c_s(\ell \sim 3000) \ll c_s(\ell \sim 100)$$

Can reach the threshold with $\Delta f_{\rm NL} \sim 5$

Conclusions

What would help us reach the threshold

3. Measure the tilt of the tensors

Directly determines ϵ_1 : $n_t = -2\epsilon_1$

Would reach threshold with $\Delta n_t \sim 10^{-2}$

Whether this is achievable is very sensitive to r

Caligiuri & Kosowsky; Dodelson; Boyle et al.


Thank you