B-modes and the Nature of Inflation

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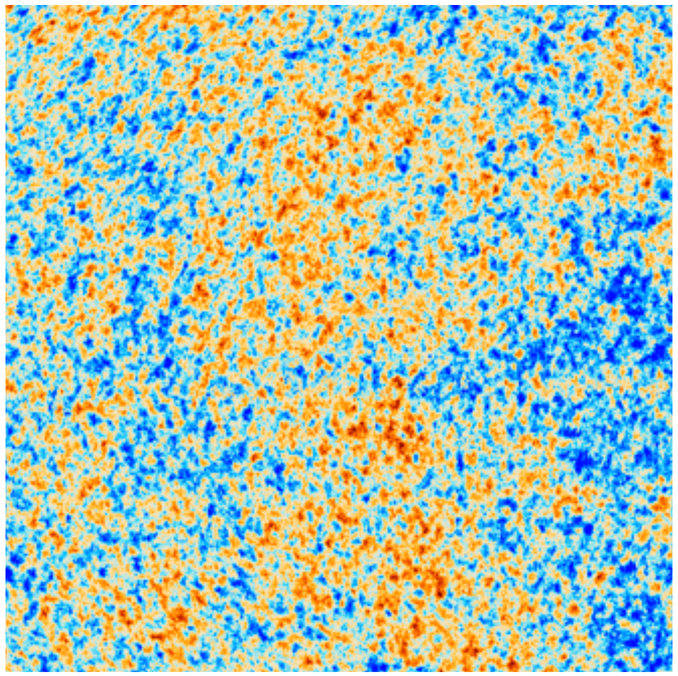
with Daniel Green and Rafael Porto

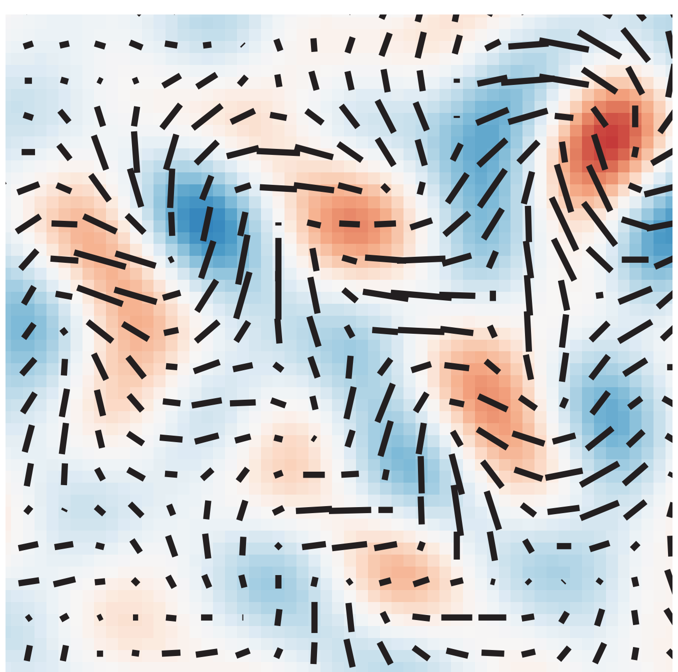
STRINGS 2014

Data-Driven Cosmology


Planck

Primordial density perturbations are:

- superhorizon
- scale-invariant
- Gaussian
- adiabatic


BICEP2

$$r \sim 0.1 \ ?$$

Have primordial gravitational waves been detected?

What does this teach us about the UV-completion of inflation?

In **effective field theory**, we parameterize the effects of the UV-completion by higher-dimension operators.

In this talk, I will consider the leading **higher-derivative corrections** to the slow-roll action:

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

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In this talk, I will consider the leading **higher-derivative corrections** to the slow-roll action:

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

This induces a non-trivial **speed of sound** for the inflaton fluctuations:

$$\mathcal{L} = -\frac{1}{2}\left[(\partial_t\delta\phi)^2 - c_s^2(\partial_i\delta\phi)\right] + \cdots$$

I will discuss what the data from Planck and BICEP teaches us about this important class of deformations of slow-roll inflation.

Higgs vs. Technicolor

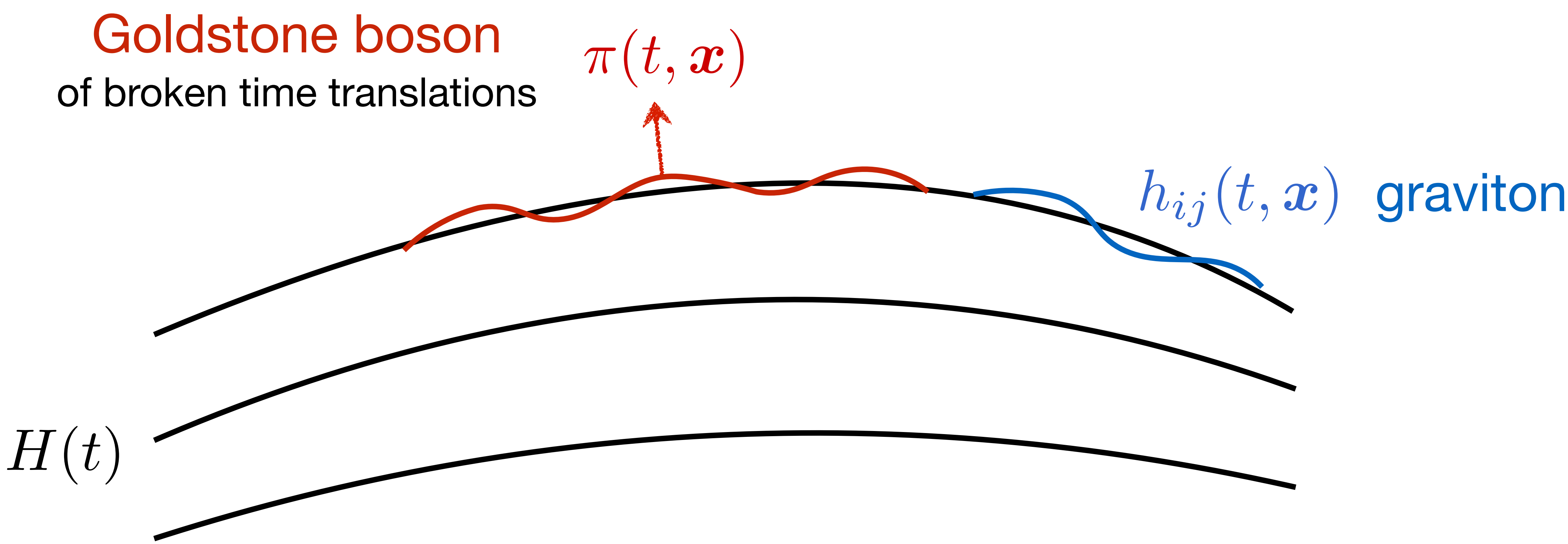
$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{(\partial\phi)^4}{\Lambda^4} + \cdots$$

perturbative		*non-perturbative*	
$\Lambda^2 \gg \dot{\phi}$		$\Lambda^2 \sim \dot{\phi}$	
$\updownarrow$	or	$\updownarrow$	?
$c_s \sim 1$		$c_s \ll 1$	

can't be described by small corrections to slow-roll inflation

Effective Theory of Inflation

Cheung et al.



The Goldstone and the graviton are massless, so their quantum fluctuations are amplified during inflation.

Effective Theory of Inflation

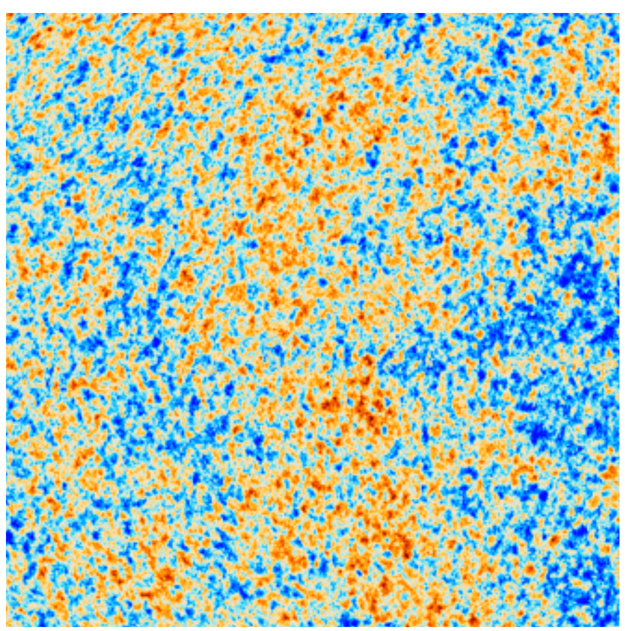
Cheung et al.

Goldstone boson

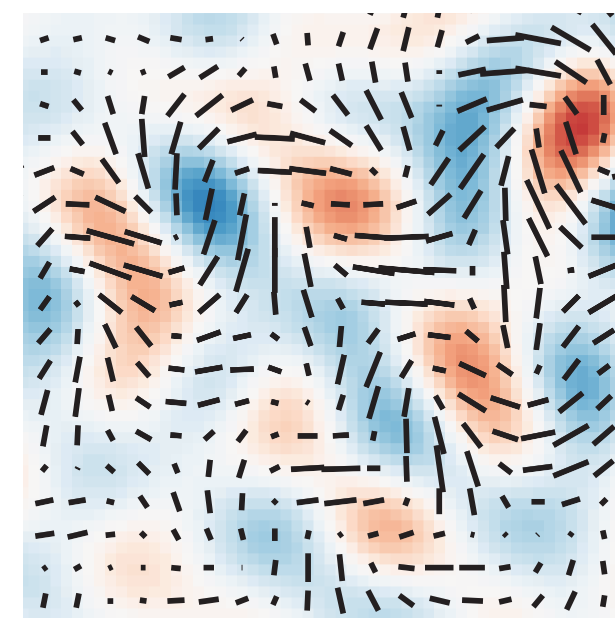
$\pi(t, \boldsymbol{x})$

graviton

$$g_{ij} = a^2(t)\Big[(1 + 2\zeta(t, \boldsymbol{x}))\delta_{ij} + 2h_{ij}(t, \boldsymbol{x})\Big]$$



temperature anisotropies



B-mode polarization

Slow-Roll Inflation

Slow-roll inflation corresponds to nearly free
Goldstone bosons with relativistic dispersion relation:

$$\mathcal{L}_\pi = M_{\rm pl}^2|\dot{H}|\Big[\dot{\pi}^2 - (\partial_i\pi)^2\Big]$$

$$\mathcal{L}_h = \frac{1}{8}M_{\rm pl}^2\Big[(\dot{h}_{ij})^2 - (\partial_k h_{ij})^2\Big]$$

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symmetry breaking scale $f_\pi^4 = \dot{\phi}^2$

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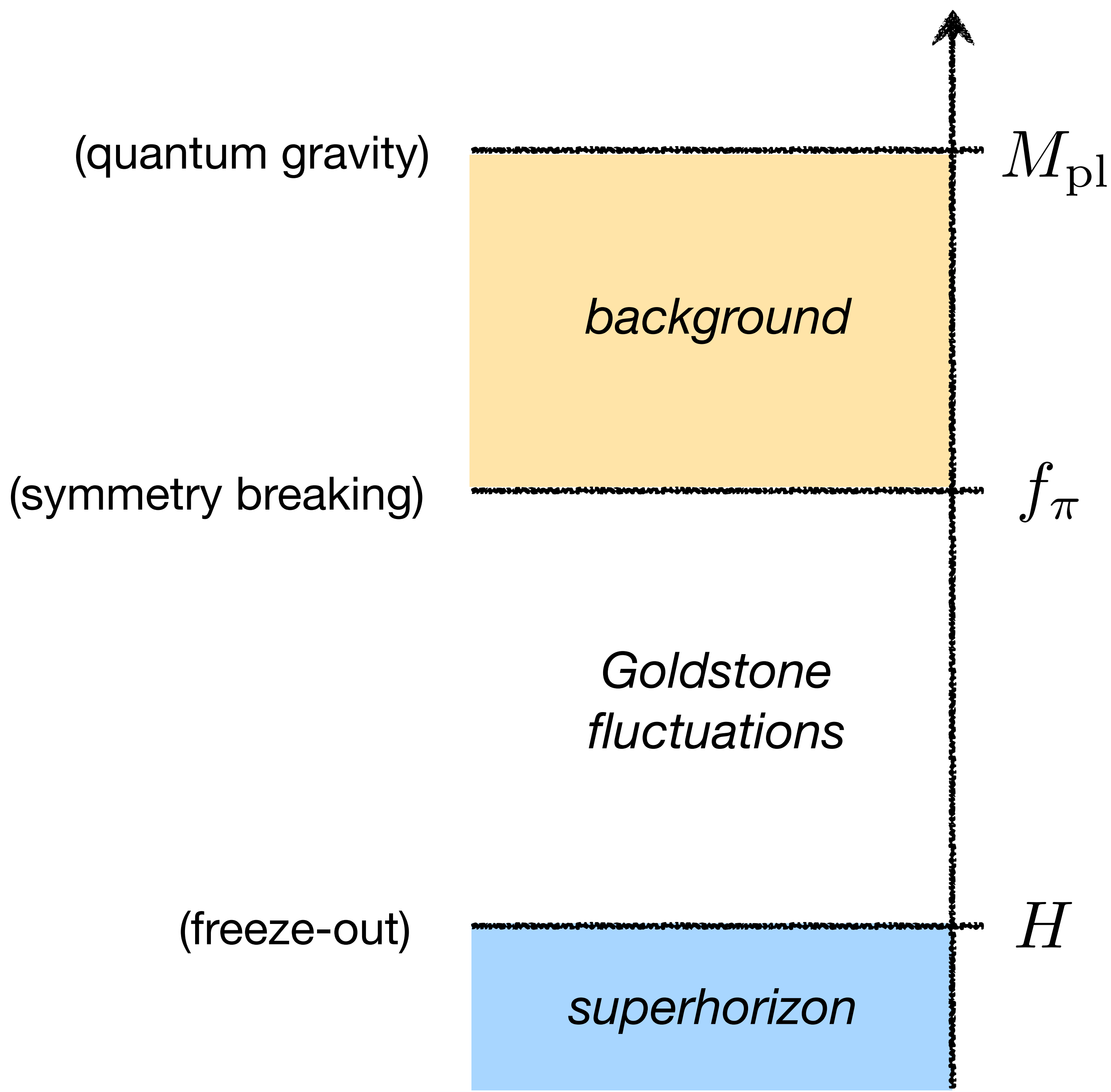
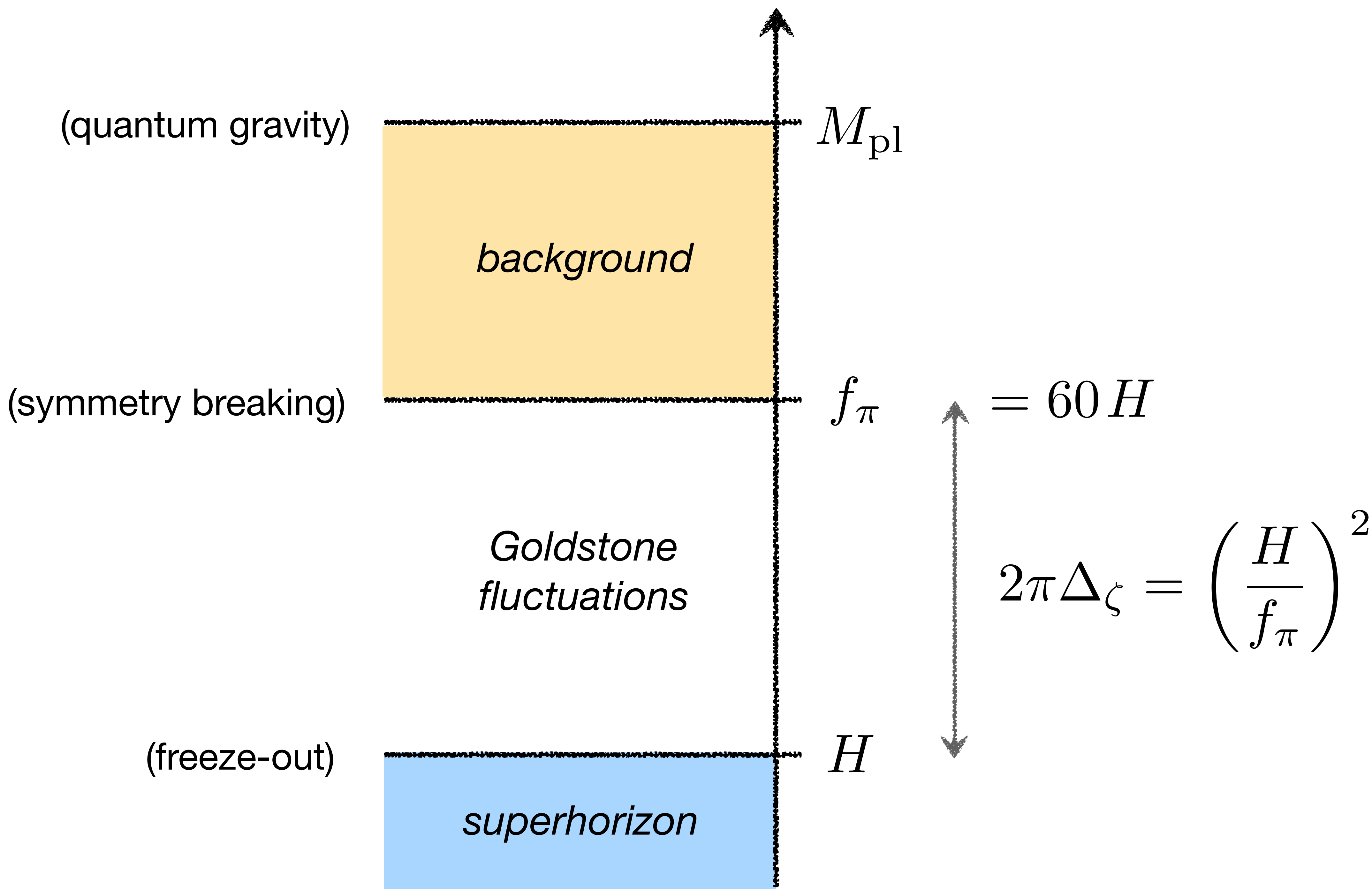
quantum gravity scale

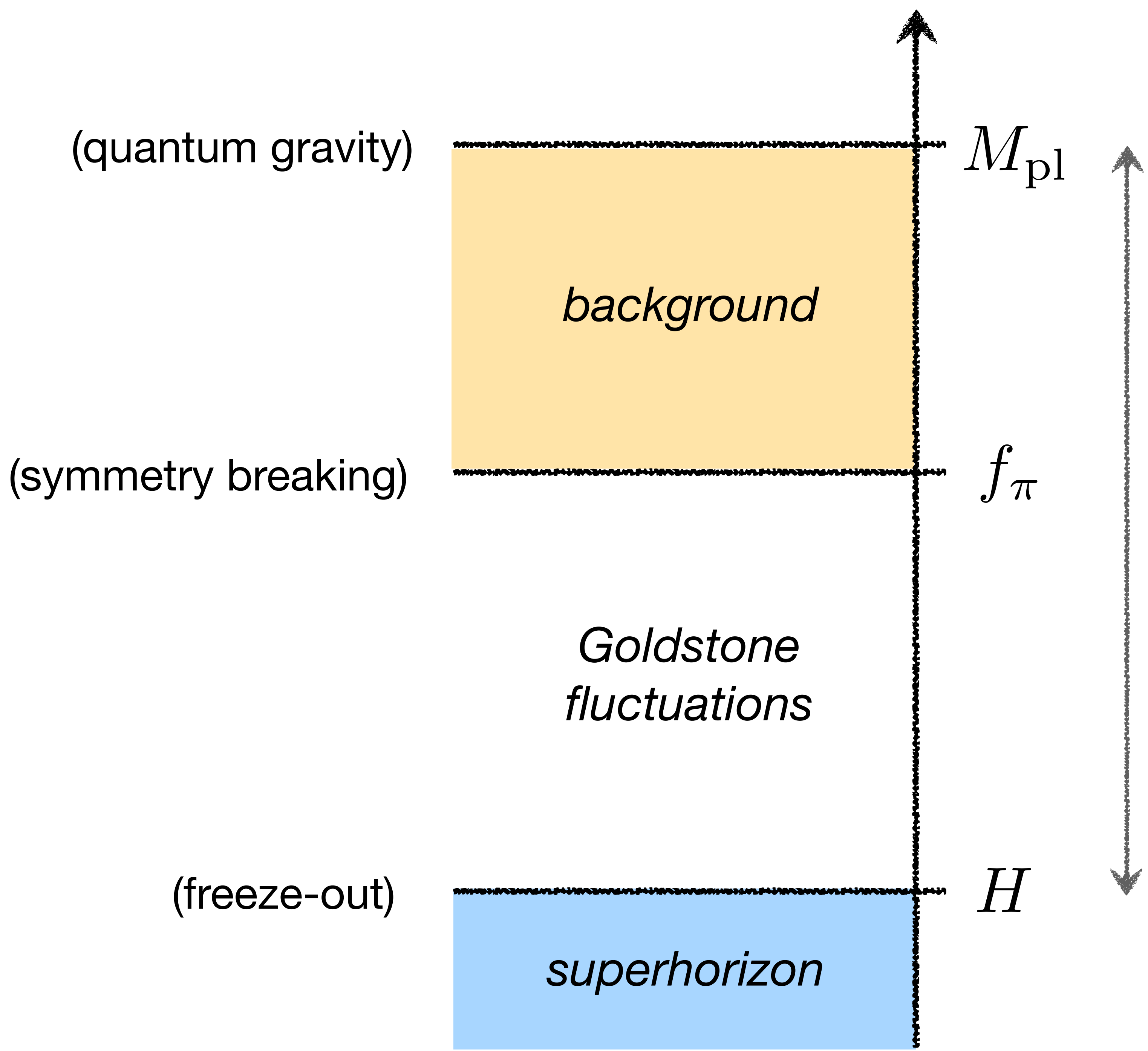
Slow-Roll Inflation



Slow-Roll Inflation



Slow-Roll Inflation



$$= 3 \times 10^4 \left(\frac{r}{0.1}\right)^{-1/2} H$$

$$2\pi\Delta_h = \frac{H}{M_{\rm pl}}$$

Beyond Slow-Roll

Deviations from slow-roll inflation are parameterized by higher-order self-interactions and/or a non-trivial dispersion relation.

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A well-motivated possibility is a non-trivial **sound speed**:

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non-linearly realized symmetry

allows power spectrum measurements to constrain the interacting theory.

Beyond Slow-Roll

Writing

$$x \mapsto \tilde{x} \equiv c_s x$$

$$\pi_c \equiv (2M_{\rm pl}^2 |\dot{H}| c_s)^{1/2} \pi \equiv f_\pi^2 \pi$$

symmetry breaking scale

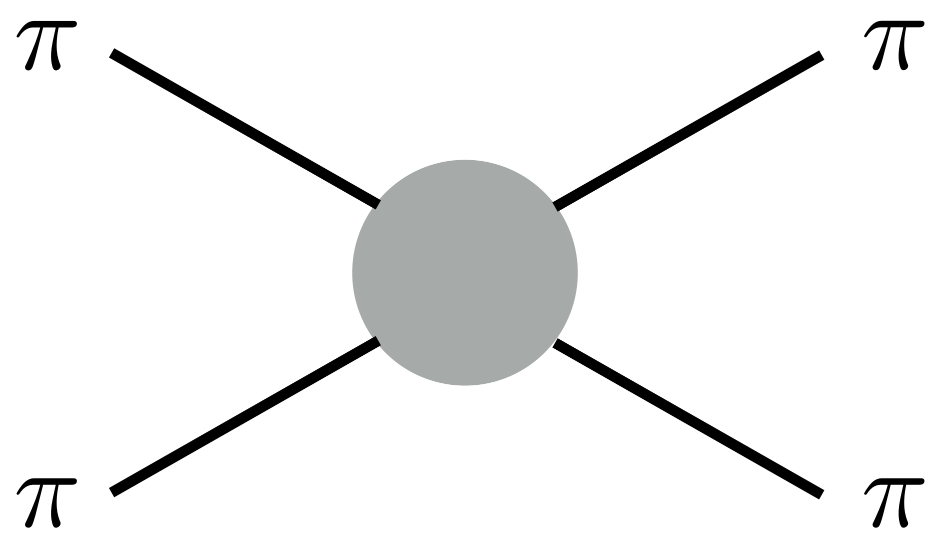
gives

$$\boxed{\mathcal{L}_\pi = -\frac{1}{2}(\tilde{\partial}_\mu \pi_c)^2 - \frac{\dot{\pi}_c (\tilde{\partial}_i \pi_c)^2}{\Lambda^2} + \cdots}$$

strong coupling scale

$$\Lambda^2 = f_\pi^2 \frac{c_s^2}{1 - c_s^2}$$

Unitarity Bound



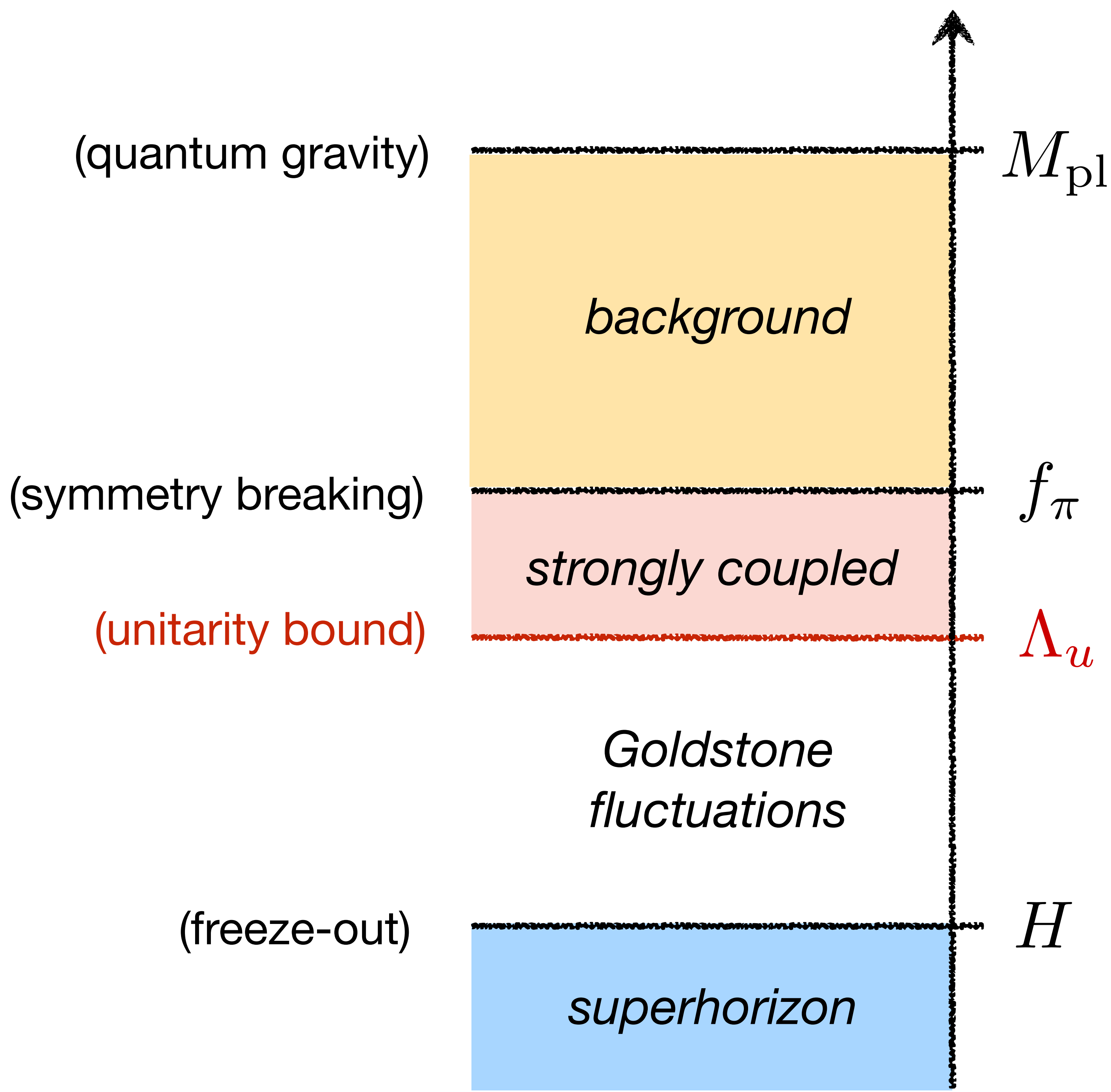
2-to-2 Goldstone scattering violates **unitarity** when

$$E^4 > \frac{24\pi}{5}\Lambda^4 \equiv \Lambda_u^4$$

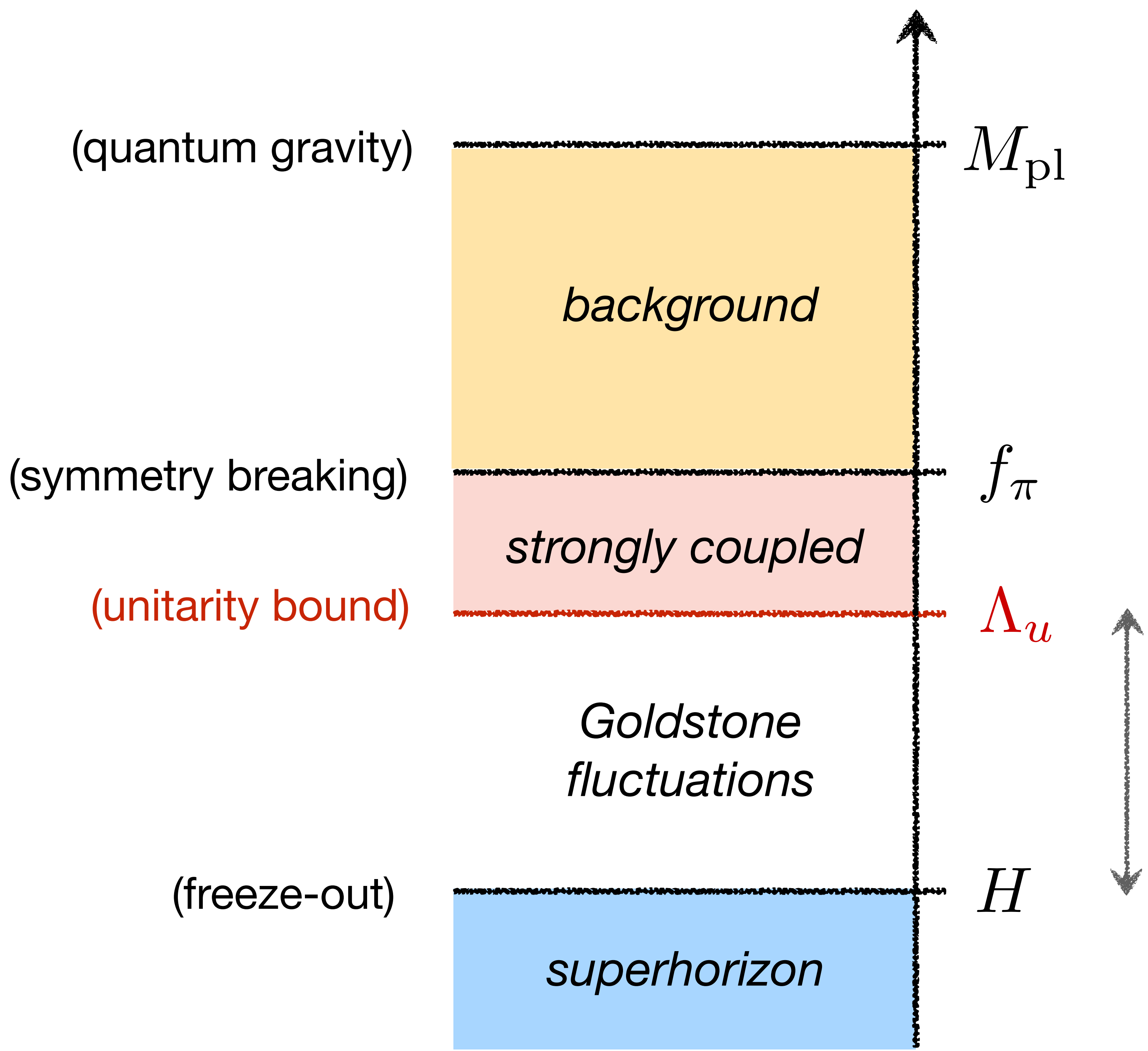
DB and Green

DB, Green and Porto

Beyond Slow-Roll



Beyond Slow-Roll

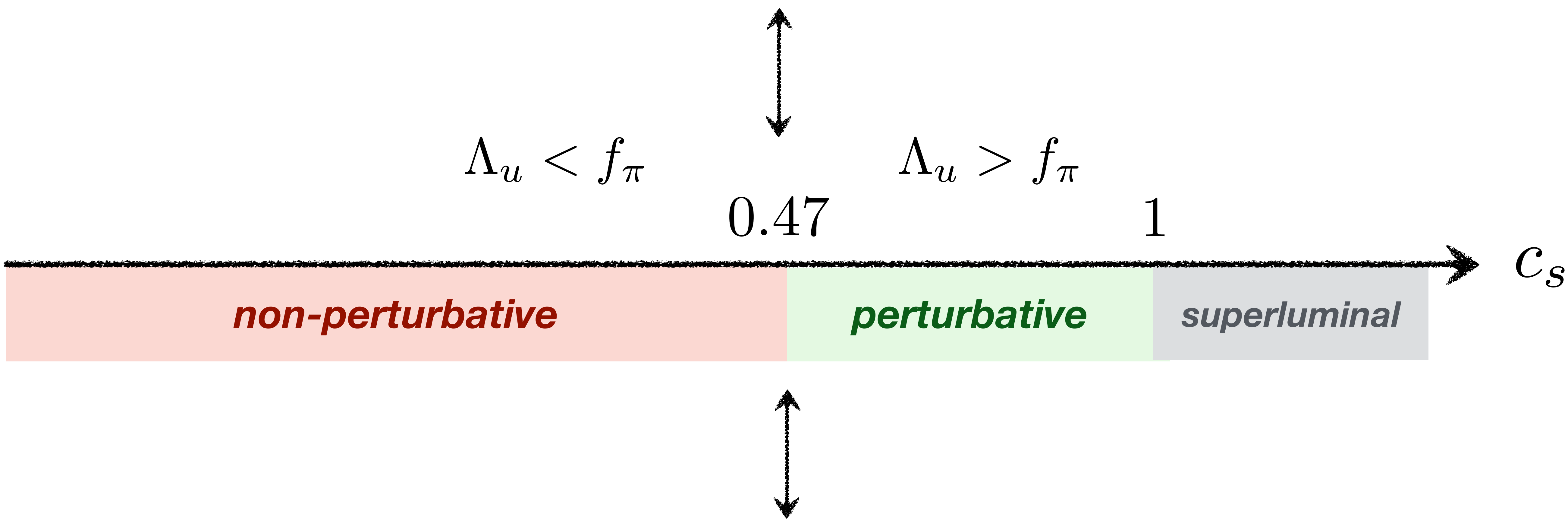


$$\Delta_\zeta \, f_{\rm NL} = \left(\frac{H}{\Lambda_u}\right)^2$$

non-Gaussianity $\quad f_{\rm NL} \propto \dfrac{1}{c_s^2}$

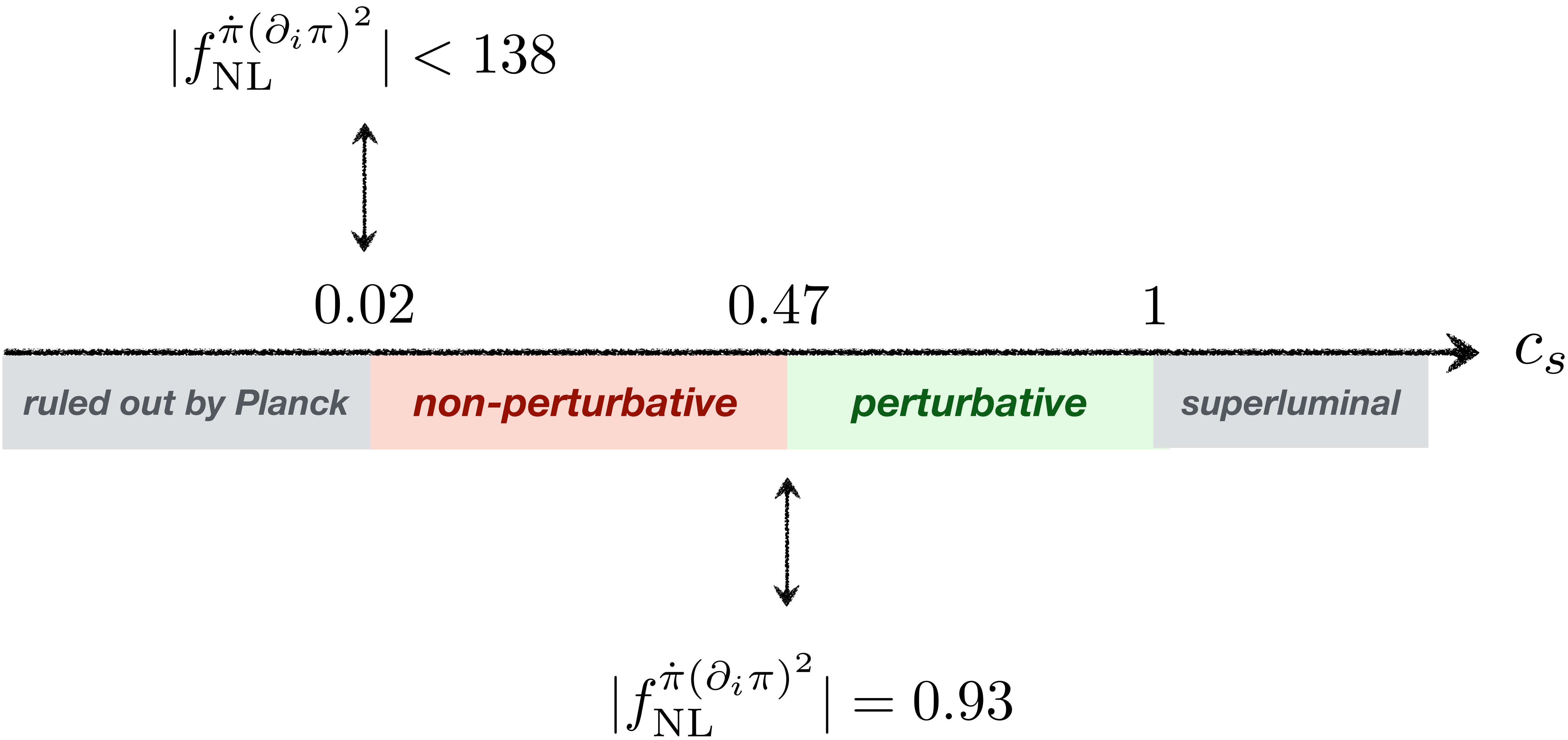
A Theoretical Threshold

$$\Lambda_u = f_\pi$$



$$|f_{\rm NL}^{\dot{\pi}(\partial_i \pi)^2}| = 0.93$$

A Theoretical Threshold



A New Bound on the Sound Speed

DB, Daniel Green and Rafael Porto

see also: Creminelli et al. [arXiv:0404.1065]

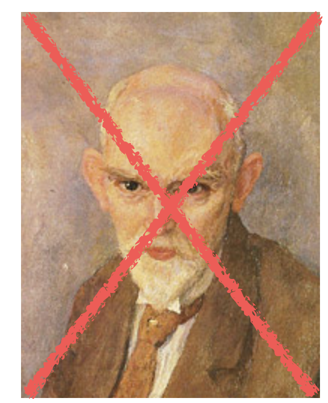
D'Amico and Kleban [arXiv:0404.6478]

A small sound speed enhances the scalar power spectrum and suppresses the tensor-to-scalar ratio:

$$\Delta_\zeta^2 = \frac{1}{8\pi^2}\frac{H^4}{M_{\rm pl}^2|\dot{H}|\,c_s}$$

$$\Delta_h^2 = \frac{2}{\pi^2}\frac{H^2}{M_{\rm pl}^2}$$

$$r \equiv \frac{\Delta_h^2}{\Delta_\zeta^2} = 16\,\varepsilon\,c_s$$



$$\varepsilon \equiv \frac{|\dot{H}|}{H^2}$$

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$$\left.\begin{aligned}\Delta_\zeta^2 &= \frac{1}{8\pi^2}\frac{H^4}{M_{\rm pl}^2|\dot H|\,c_s} \\ \Delta_h^2 &= \frac{2}{\pi^2}\frac{H^2}{M_{\rm pl}^2}\end{aligned}\right\}\qquad r \equiv \frac{\Delta_h^2}{\Delta_\zeta^2} = 16\,\varepsilon\, c_s$$

$$\varepsilon \equiv \frac{|\dot H|}{H^2}$$

BICEP2 then implies a lower bound on the sound speed:

$$c_s = \frac{r}{16\varepsilon} > \frac{0.01}{\varepsilon}$$

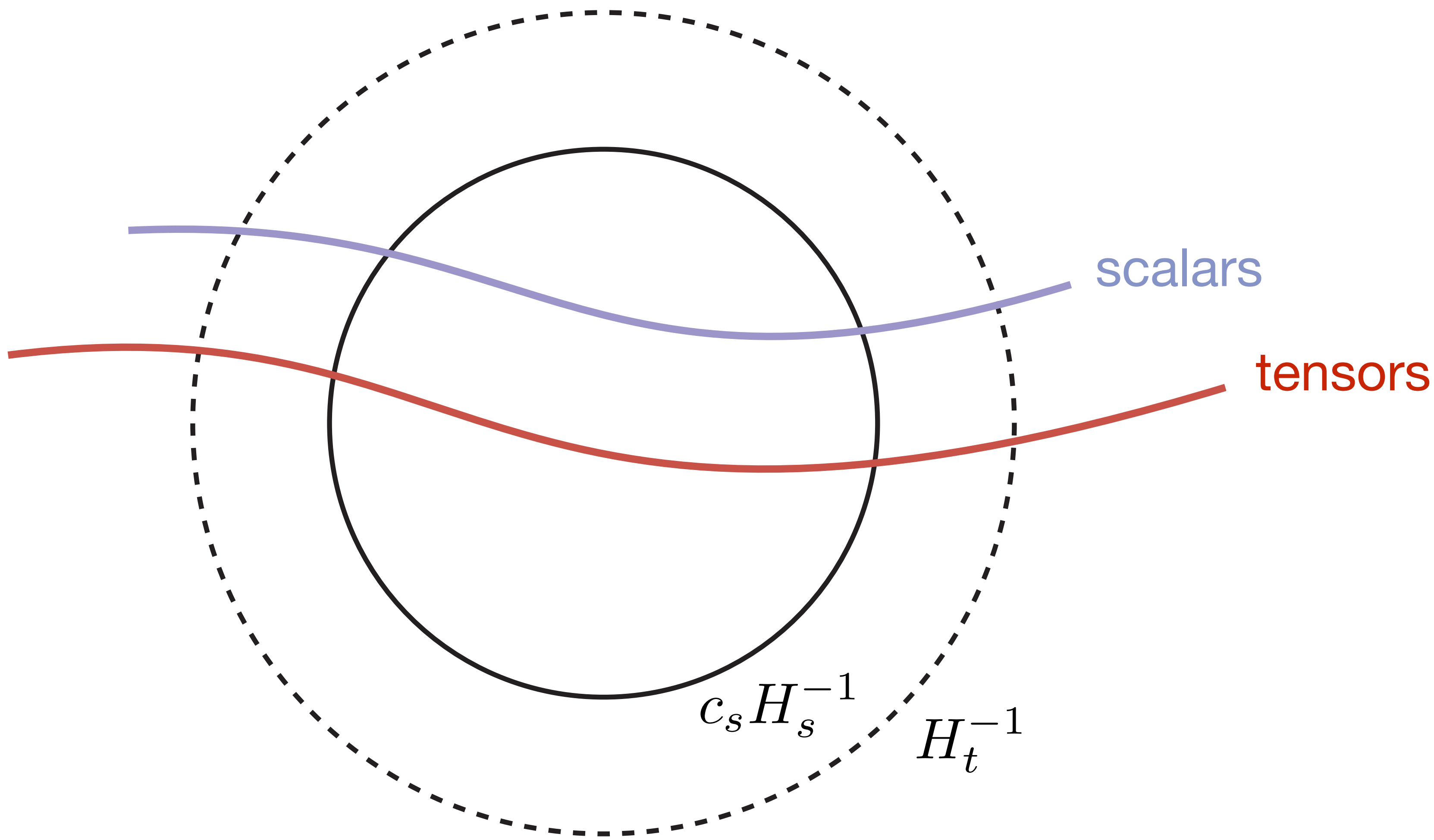
Creminelli et al.
D'Amico and Kleban

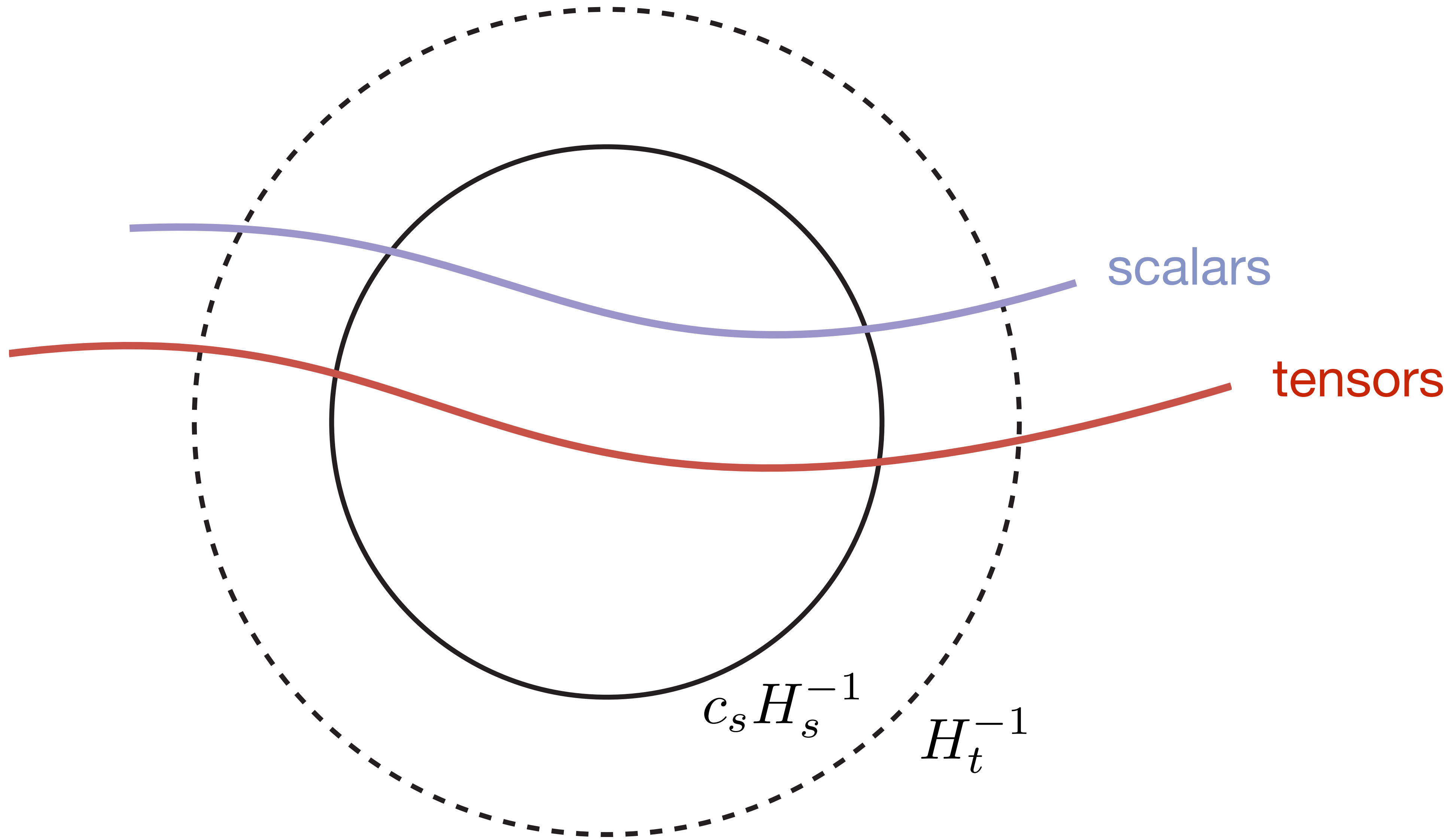
Naively, the bound weakens for large ε.

But, for $\varepsilon > 0.1$ new effects kick in:

1. scale-invariance of the scalars is in danger

2. tensors and scalars freeze at different times





This leads to an extra suppression in the tensor-to-scalar ratio:

$$r = 16\varepsilon c_s \left(\frac{H_t}{H_s} \right)^2$$

Summing Large Logs

At next-to-leading order in slow-roll, one finds:

$$r = 16\varepsilon c_s \left(\frac{H_t}{H_s}\right)^2 = 16\varepsilon c_s \left[1 + 2\varepsilon \ln c_s + \cdots\right]$$

↑

This is large in the regime of interest.

Summing Large Logs

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$$r = 16\varepsilon c_s \left(\frac{H_t}{H_s}\right)^2 = 16\varepsilon c_s \left[1 + 2\varepsilon \ln c_s + \cdots\right]$$

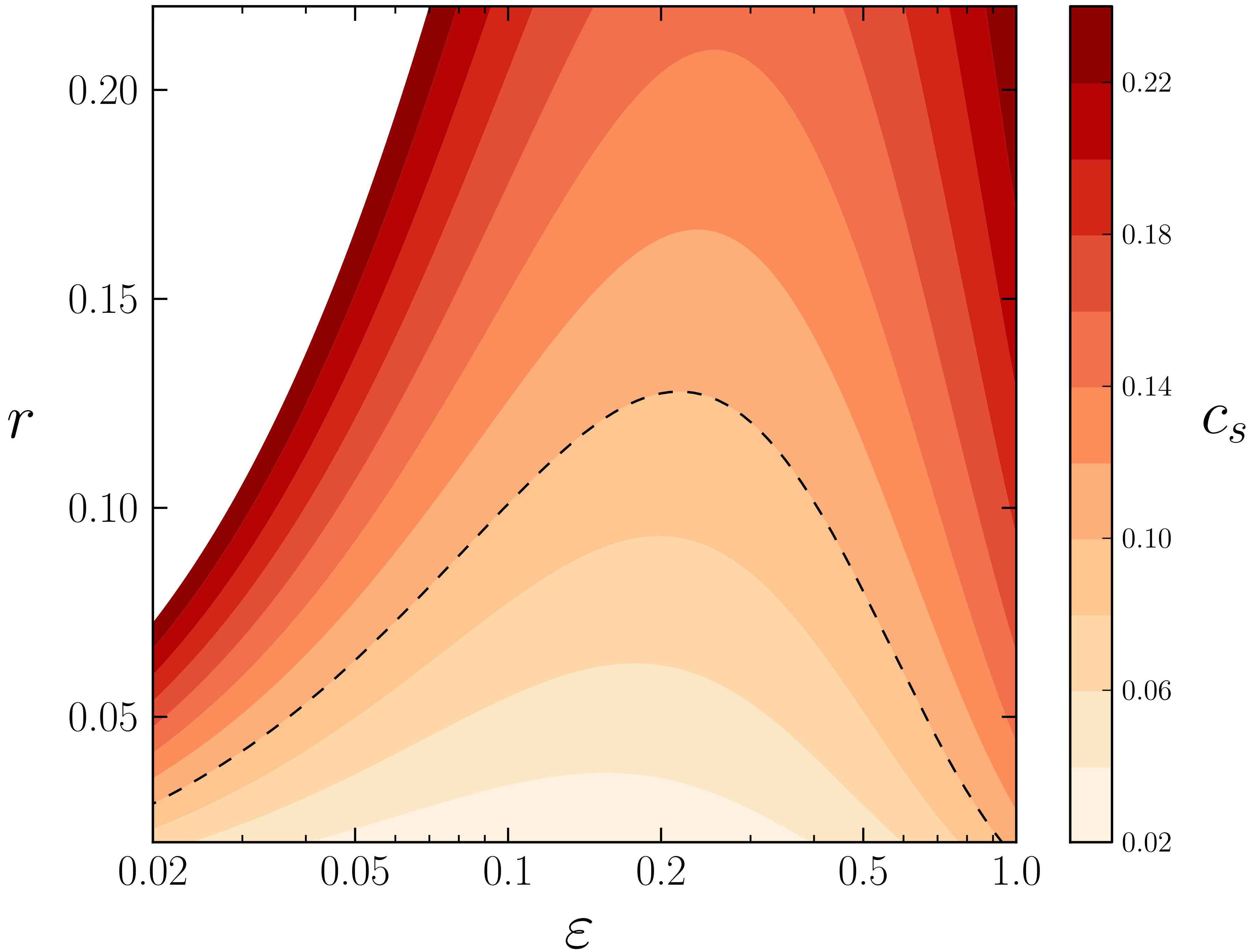
This is large in the regime of interest.

For $\varepsilon \approx const.$ we can solve the evolution exactly:

$$\boxed{r = 16\varepsilon c_s^{\frac{1+\varepsilon}{1-\varepsilon}}}$$

DB, Green and Porto

A New Bound on the Sound Speed



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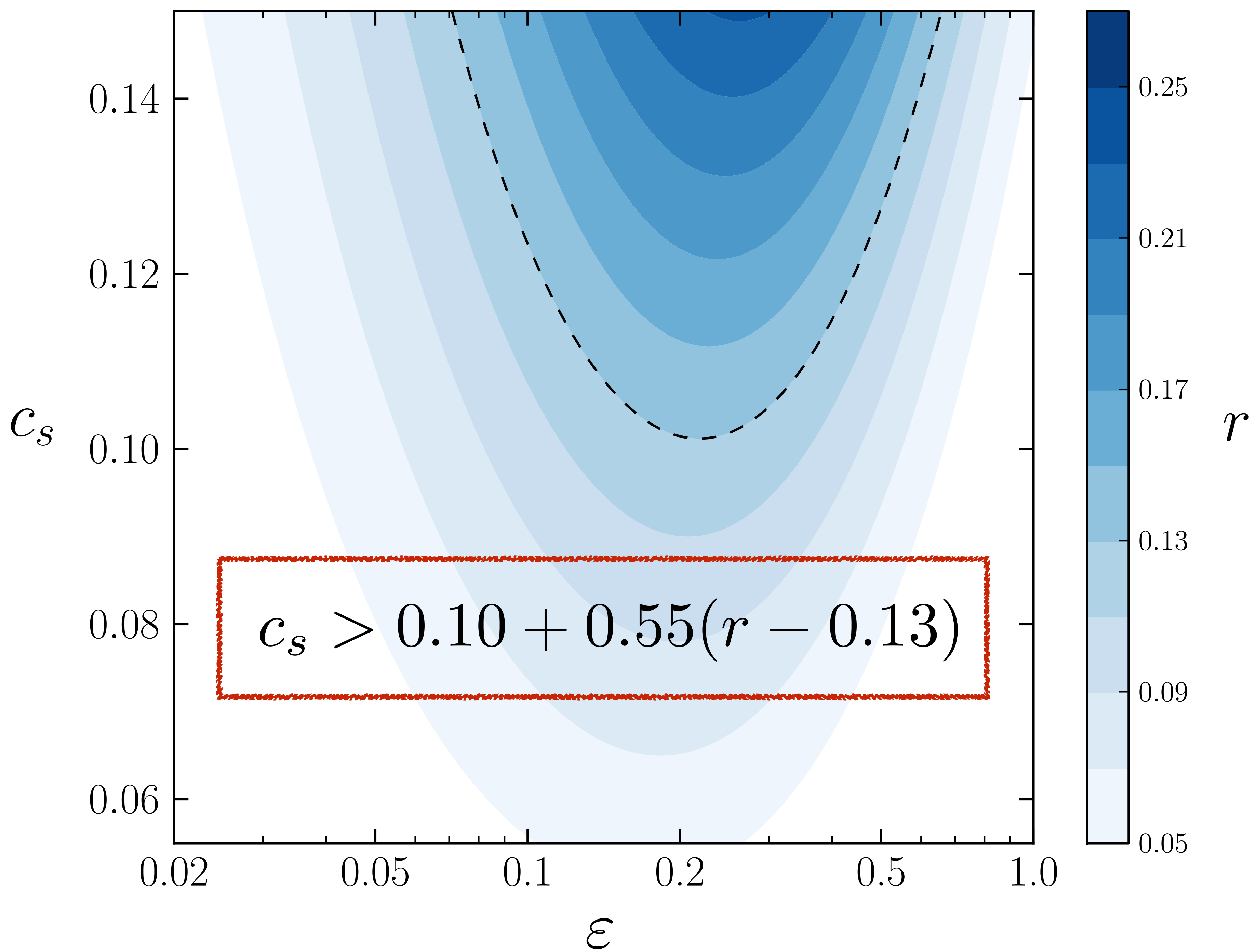

DB, Green and Porto

Summing Large Logs

Extending to $\eta \equiv \frac{\dot{\varepsilon}}{H\varepsilon} \neq 0$ and $s \equiv \frac{\dot{c}_s}{Hc_s} \neq 0$, we find:

tensors

$$r = 16\varepsilon c_s^{1+2\varepsilon\cdot(1-c_s^{-\eta})/(\eta \ln c_s)} \Big[1 - \mathcal{C}\eta + 2(1-\mathcal{C})s\Big]$$

scalars

$$\Delta_\zeta^2(k) \propto \left(\frac{k}{k_\star}\right)^{\overbrace{-2\varepsilon-\eta-s}^{n_s-1} + \overbrace{(-2\varepsilon\eta)}^{\alpha_s} \ln(k/k_\star)}$$

DB, Green and Porto

Expected Degeneracies

Our bound would weaken if large ε is possible.

But this has to be consistent with the scalar spectrum:

$$n_s - 1 = -2\varepsilon - \eta - s$$

$$\alpha_s = -2\varepsilon\eta$$

Expected Degeneracies

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But this has to be consistent with the scalar spectrum:

$$n_s - 1 = -2\varepsilon - \eta - s$$
$$\alpha_s = -2\varepsilon\eta$$

Taking this into account strengthens the bound:

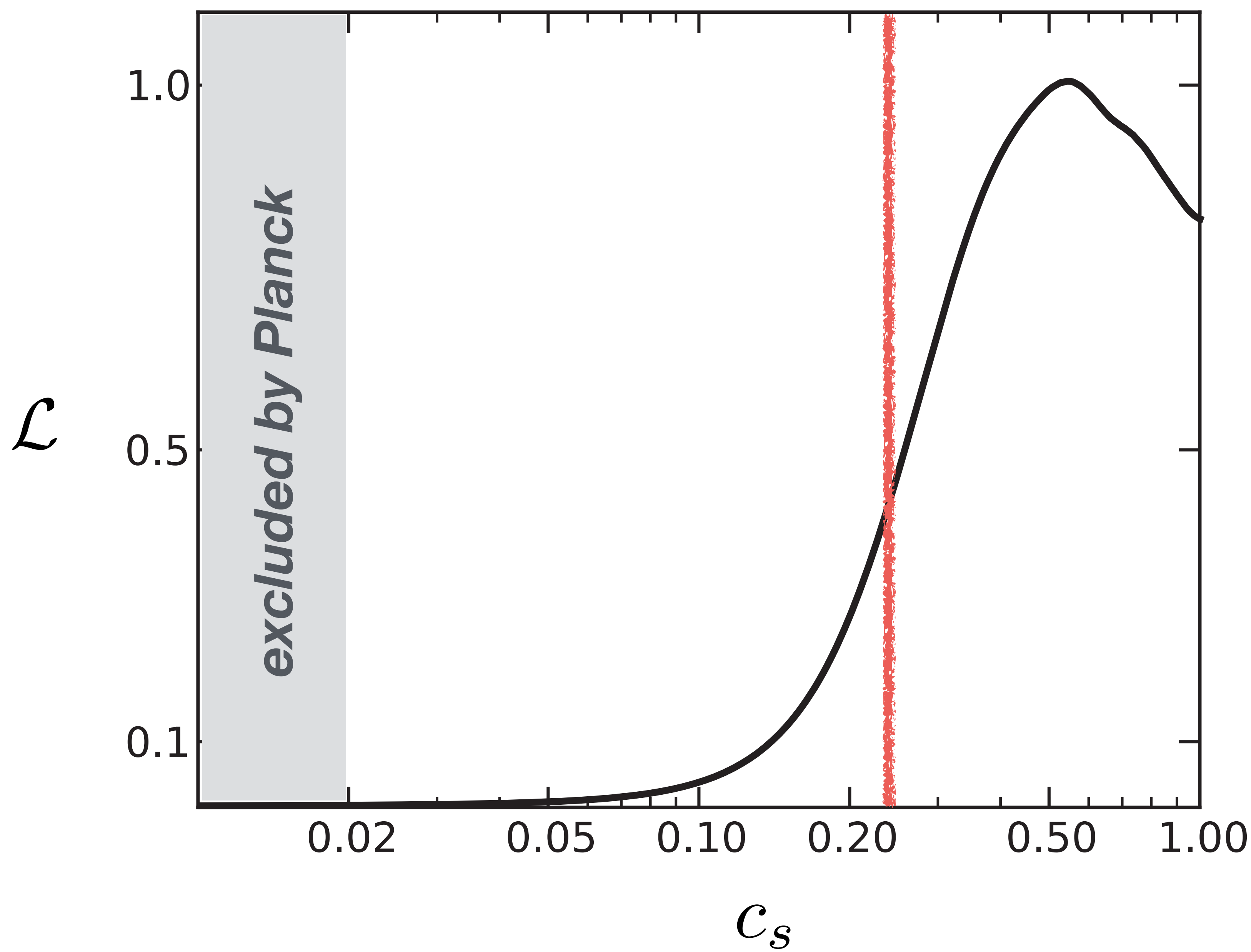
I. $\eta \approx -2\varepsilon \xrightarrow{|\alpha_s| \lesssim 0.01} \varepsilon < 0.05 \xrightarrow{r > 0.13}$ $\boxed{c_s > 0.17}$

II. $s \approx -2\varepsilon \longrightarrow r \approx 16\varepsilon c_s^{1+2\varepsilon}\underbrace{\left[1 - 2.5\varepsilon\right]} \xrightarrow{r > 0.13}$ $\boxed{c_s > 0.15}$

strengthens the bound

Data Analysis

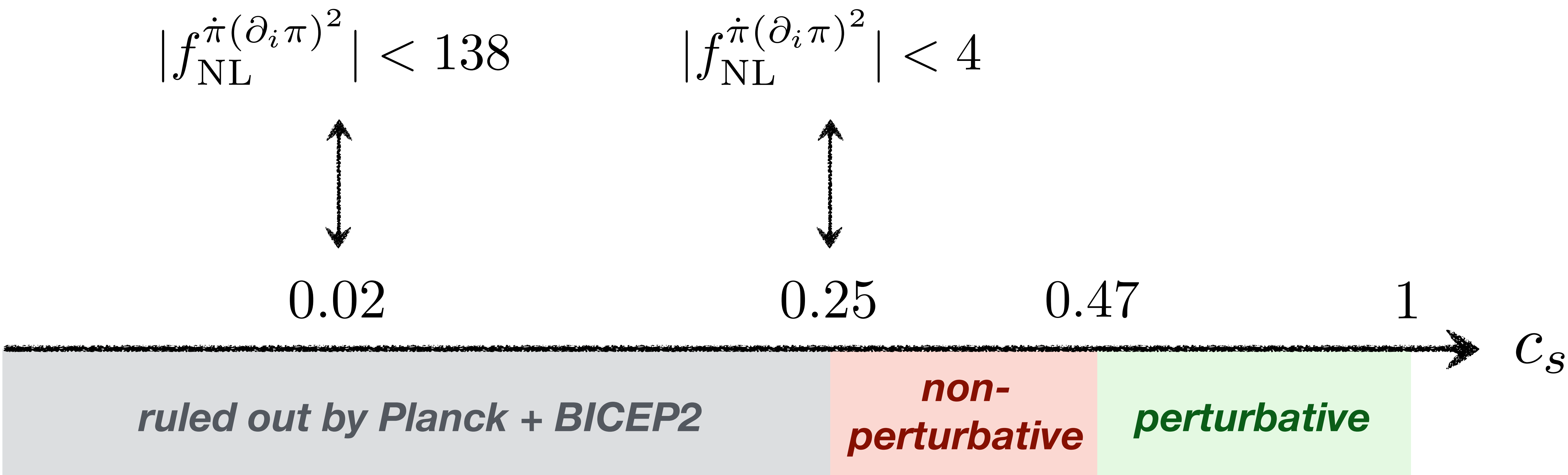
A joint likelihood analysis of Planck and BICEP2 * gives: $c_s > 0.25$

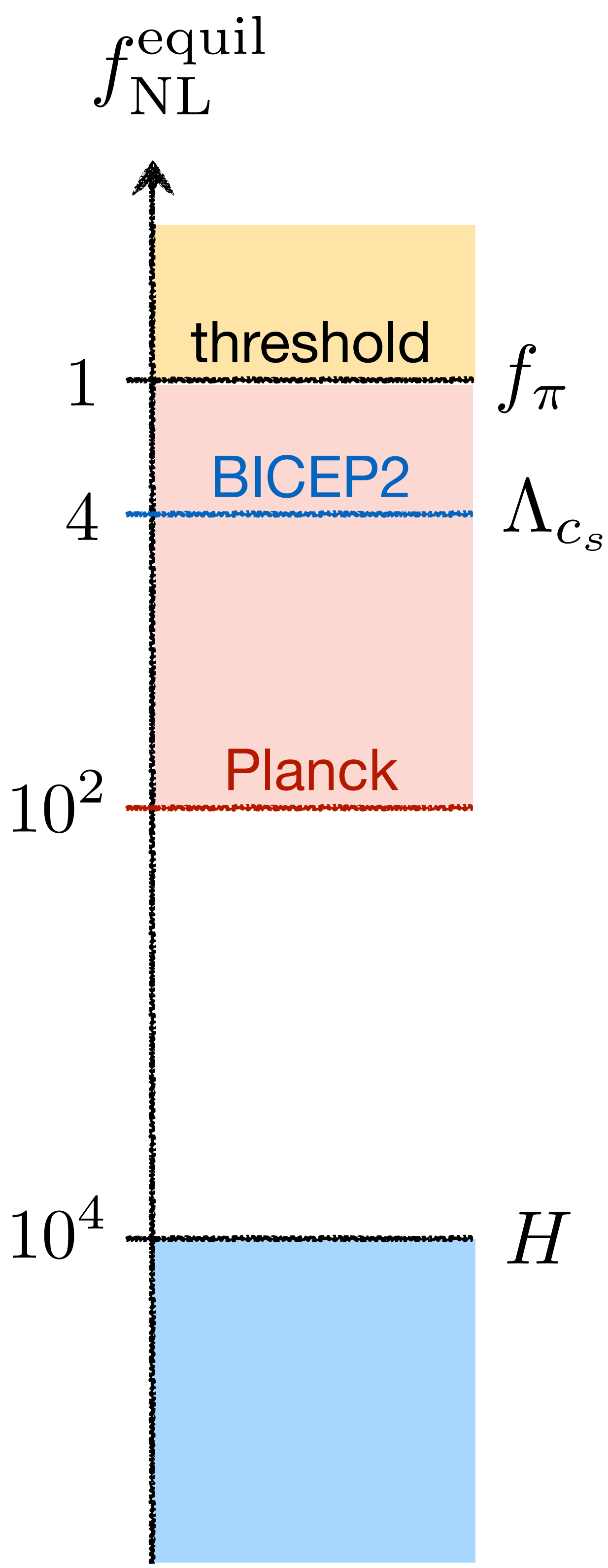


* warning: no foreground subtraction

CosmoMC

A New Bound on the Sound Speed





Conclusions

- If the BICEP2 result survives, then $c_s > 0.25$ almost reaching the unitarity threshold $(c_s)_\star = 0.47$.

- This corresponds to $|f_{\rm NL}^{\dot\pi(\partial_i\pi)^2}| < 3.3$, two orders of magnitude stronger than the Planck-only bound.

- This does not rule out large equilateral non-Gaussianity from other operators in the EFT of inflation:

  e.g. $$\mathcal{L}_\pi^{(3)} = -\frac{\dot\pi_c(\tilde\partial_i\pi_c)^2}{\Lambda_{c_s}^2} - \frac{\dot\pi_c^3}{\Lambda^2}$$ with $\Lambda \ll \Lambda_{c_s}$, is radiatively stable!

- Order-one equilateral non-Gaussianity remains a well-motivated experimental target.

$$f_{\rm NL}^{\rm equil} = 1$$

"If you build it they will come."

Thank you for your attention!

Robustness of the Bound