Targets for B-mode searches

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Introduction

If primordial B-mode polarization is detected in the CMB, inflation is our best candidate to explain it.

In the context of inflation a detection would imply that we have seen quantum fluctuations in the spacetime metric.

A detection would consequently provide us with an independent and more direct look at the early universe.

Precision measurements of the CMB are our only way to detect primordial gravitational waves, at least for the foreseeable future.

Introduction

More quantitatively, a detection of primordial gravitational waves from inflation would imply

- $H \approx 10^{14} GeV$ or $V^{1/4} \approx 2 \times 10^{16} GeV$

allowing us to probe interactions of matter at energies 10 orders of magnitude higher than at LHC.

These energy scales roughly coincide with the energy scales associated with grand unified theories and the scale naturally associated with the origin of the mass of the neutrinos.

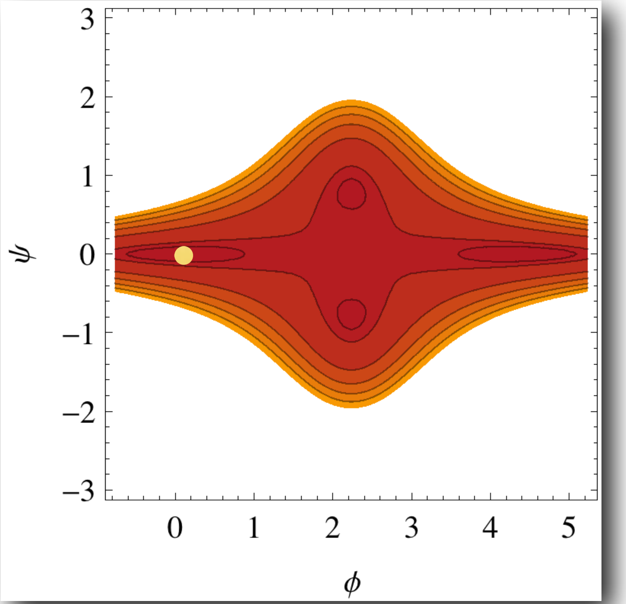
Introduction

In addition, a detection would imply that

- The range traveled by the inflaton is Planckian

Super-Planckian displacements are not expected in a *generic* low energy effective field theory.

$$V(\phi) = V_0 + \frac{1}{2}m^2\phi^2 + \frac{1}{3}\mu\phi^3 + \frac{1}{4}\lambda\phi^4 + \phi^4\sum_{n=1}^{\infty} c_n\,(\phi/\Lambda)^n$$



Introduction

We can invoke a shift symmetry and break the shift symmetry in a controlled way.

e.g. Linde's chaotic inflation

$$V(\phi) = \frac{1}{2}m^2\phi^2 \qquad \text{with} \qquad m \ll M_p$$

natural inflation

$$V(\phi) = \Lambda^4 \left[1 - \cos\left(\frac{\phi}{f}\right)\right] \qquad \text{with} \qquad f \gtrsim M_p$$

It is not obvious that such shift symmetries exist in a theory of quantum gravity so that a detection would provide us with information about the symmetries of nature.

Introduction

In addition, a detection would contain important information about

- moduli
- axions
- graviton mass
- ...

and many other aspects of fundamental physics

Targets

The "simplest" models of inflation have monomial potentials

$$V(\phi) = \mu^{4-2p}\phi^{2p}$$

They predict

$$n_{\rm s}(\mathcal{N}) - 1 = -\frac{p+1}{\mathcal{N}}$$

$$\alpha_{\rm s} = -\frac{1+p/2}{\mathcal{N}^2} = -\frac{(n_{\rm s}-1)^2}{1+p/2}$$

$$r(\mathcal{N}) = \frac{8p}{\mathcal{N}}$$

$\mathcal{N}$: number of e-folds before the end of inflation

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Consistent with Planck

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Just too small for S4 or PICO

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Targets

The "simplest" models of inflation have monomial potentials

$$V(\phi) = \mu^{4-2p}\phi^{2p}$$

For p of order unity and $\mathcal{N} \sim 50 - 60$

$$r \gtrsim 0.1$$

Stringy large field models protected by shift symmetries display similar behavior, possibly with smaller p

In this case typically

$$r \gtrsim 0.01$$

Targets

At much smaller amplitudes, and not directly related to inflation, second order, density perturbations in the plasma generate gravitational waves.

Around the recombination peak, this contribution amounts to

$$r \sim 10^{-7}$$

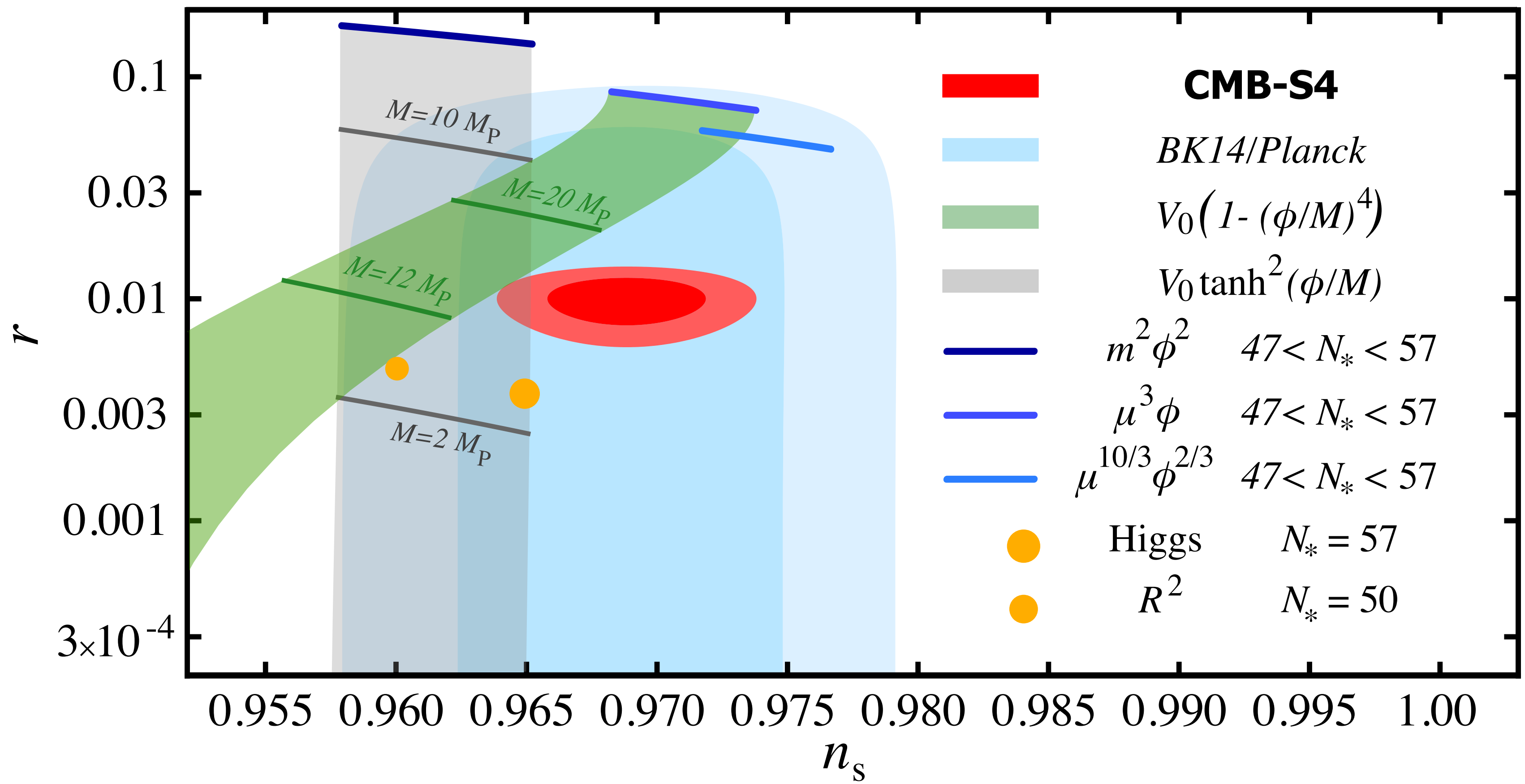
This is an interesting target to keep in mind, but certainly too low for PICO.

So we must explore the range in between.

Targets

CMB-S4 would detect r=0.01 at high significance

CMB-S4 Science Book (http://www.cmbs4.org)



Targets

Even an upper limit from CMB-S4 is interesting

If the inflationary model naturally explains the observed value of the spectral index, i.e.

$$n_{\mathrm{s}}(\mathcal{N}) - 1 = -\frac{p+1}{\mathcal{N}}$$

then the differential equation

$$\frac{d \ln \epsilon}{d\mathcal{N}} - (n_{\mathrm{s}}(\mathcal{N}) - 1) - 2\epsilon = 0$$

only has four classes of solutions

Targets

They are

$$\epsilon(\mathcal{N}) = \frac{p}{2\mathcal{N}}$$

$$\epsilon(\mathcal{N}) = \frac{p}{2\mathcal{N}}\left(\frac{\mathcal{N}_{\rm eq}}{\mathcal{N}}\right)^{p} \qquad\qquad p > 0 \quad \text{and} \quad \mathcal{N}_{\rm eq} \ll \mathcal{N}_*$$

$$\epsilon(\mathcal{N}) = \frac{|p|}{2\mathcal{N}}\left(\frac{\mathcal{N}}{\mathcal{N}_{\rm eq}}\right)^{|p|} \qquad\qquad p < 0 \quad \text{and} \quad \mathcal{N}_{\rm eq} \gg \mathcal{N}_*$$

$$\epsilon(\mathcal{N}) = \frac{1}{2\mathcal{N}\ln \mathcal{N}_{\rm eq}/\mathcal{N}} + \frac{p}{4\mathcal{N}} + \dots \quad |p| \ll \frac{1}{\ln \mathcal{N}_{\rm eq}/\mathcal{N}_*}$$

Targets

With

$$\frac{d\phi}{d\mathcal{N}} = M_{\rm P}^2 \frac{V'}{V} \qquad \text{and} \qquad \left(\frac{d\phi}{d\mathcal{N}}\right)^2 = 2\epsilon M_{\rm P}^2$$

the inflationary part of the potential either corresponds to monomial models

$$V(\phi) = \mu^{4-2p}\phi^{2p}$$

Targets

Starobinsky model, Higgs inflation, Kähler moduli inflation, fibre inflation, α-attractors, ...

$$V(\phi) \simeq V_0 \left(1 - \exp\left(-\phi/M\right)\right) \qquad (p = 1)$$

or hilltop models

$$V(\phi) = V_0 \exp\left[-\left(\frac{\phi}{\Lambda}\right)^{\frac{2p}{p-1}}\right] \qquad (p \neq 1)$$

The characteristic scale in latter case is $M = \Lambda \dfrac{|1-p|}{p}$

Targets

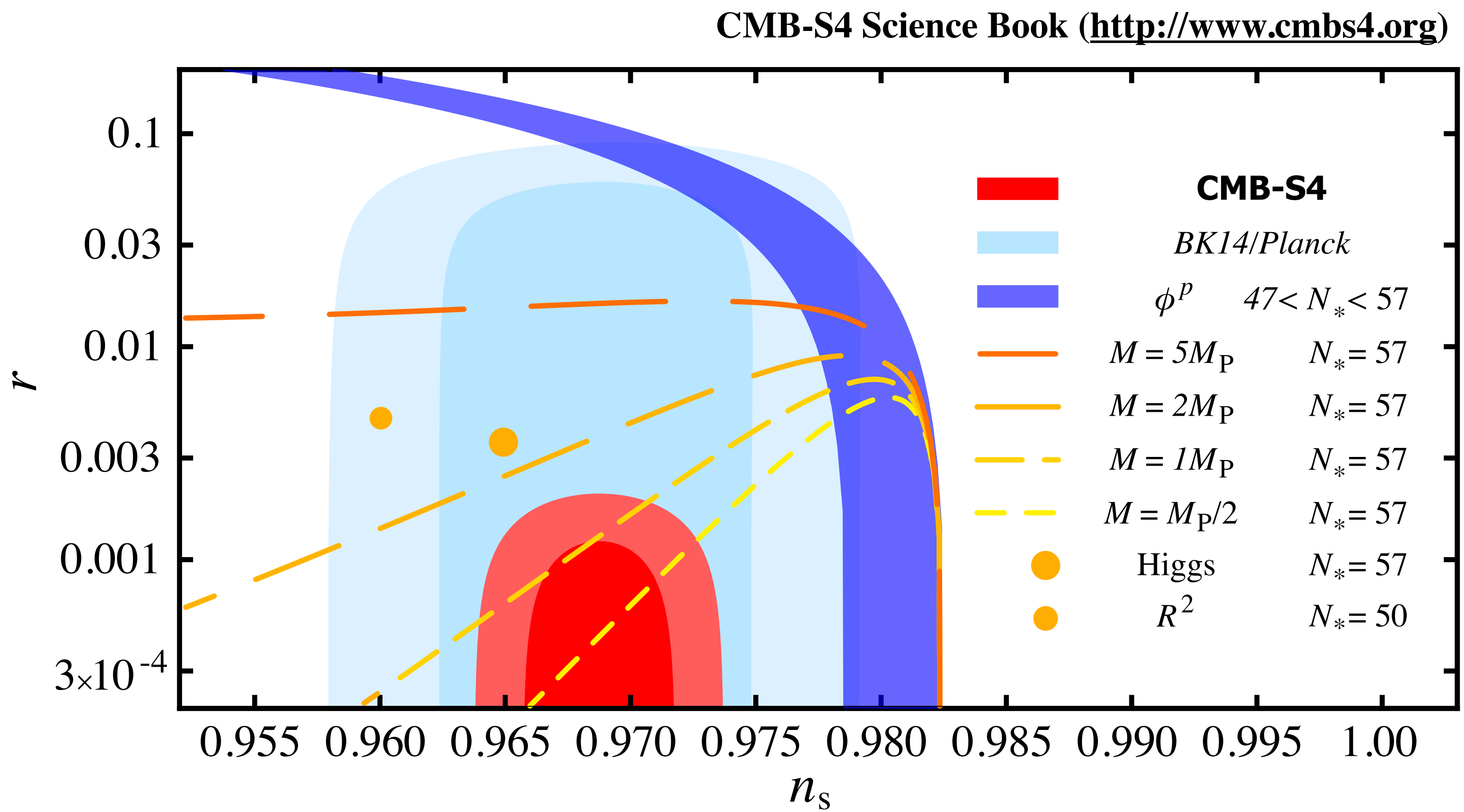
In many models the characteristic scale is of order

$$M \approx M_{\mathrm{P}}$$

Targeting the Planck scale and excluding $M \geq M_{\mathrm{P}}$ at 95% CL in part motivates S4 sensitivities

$$\sigma(r) = 5 \times 10^{-4} \quad \text{for} \quad r = 0$$

Targets



An upper limit with CMB-S4 would disfavor all models of inflation that naturally explain n_s with super-Planckian characteristic scale M

Targets

While $M \geq M_{\rm P}$ is a natural target, there are certainly models with

$$M < M_{\rm P}$$

Goncharov-Linde (1984)

$$M = M_{\rm P}/\sqrt{6}$$

$r \simeq 4 \times 10^{-4}$ for $\mathcal{N} = 57$

α -attractors, ...

Targets

Unrelated to inflation, patchy reionization provides a target around $r \sim 10^{-4}$

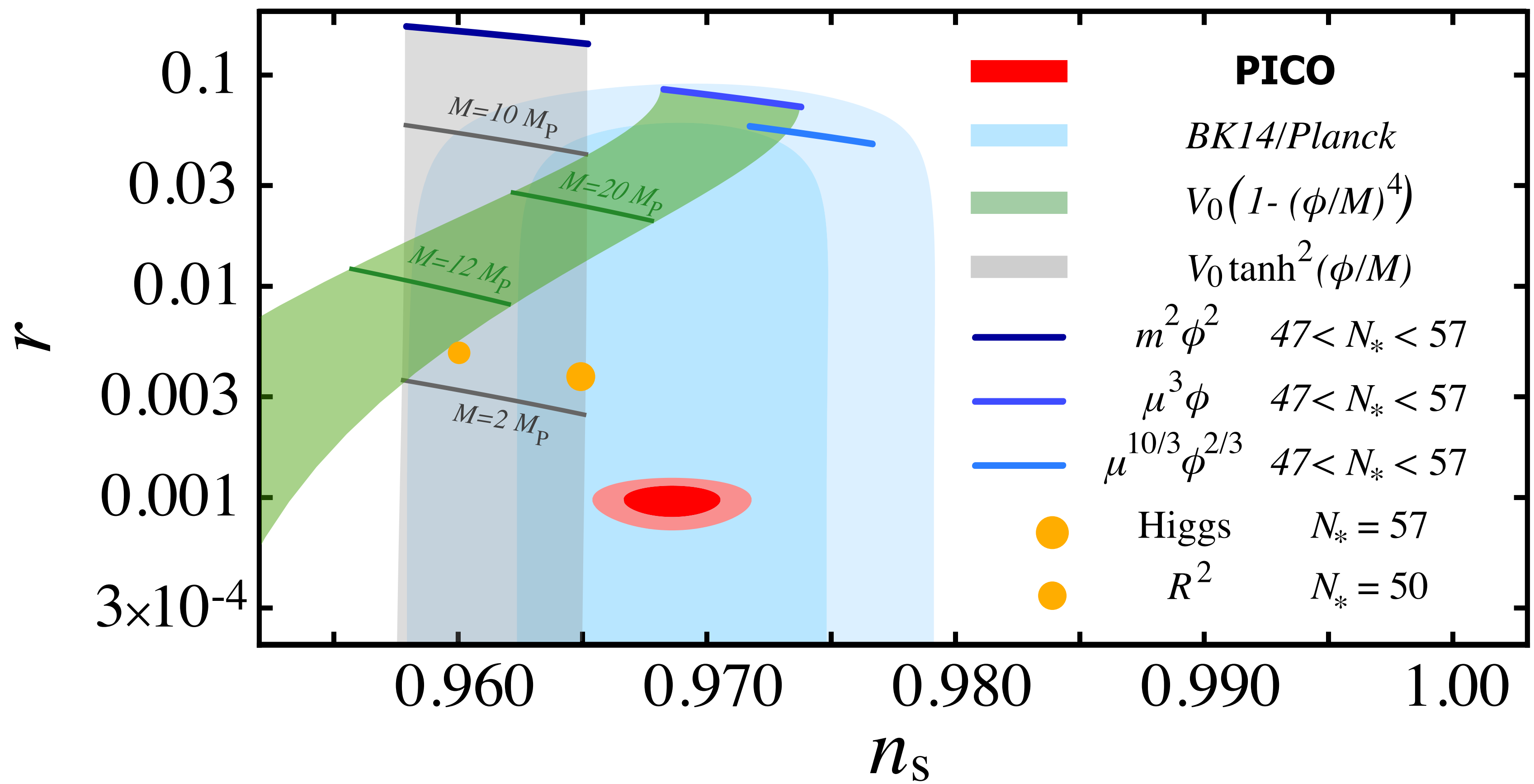
This is an order of magnitude improvement over what appears possible from the ground.

This is only possible if the reionization bump is observed.

At least to me, $r \sim 10^{-4}$ is a scientifically interesting target that appears feasible with a space mission and only with a space mission.

Targets

PICO sensitivity



Thank you