On Primordial Gravity Waves from String Inflation

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Probing the Early Universe with Gravity

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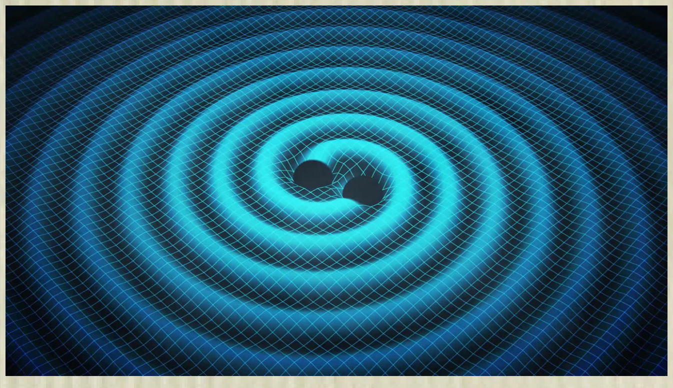
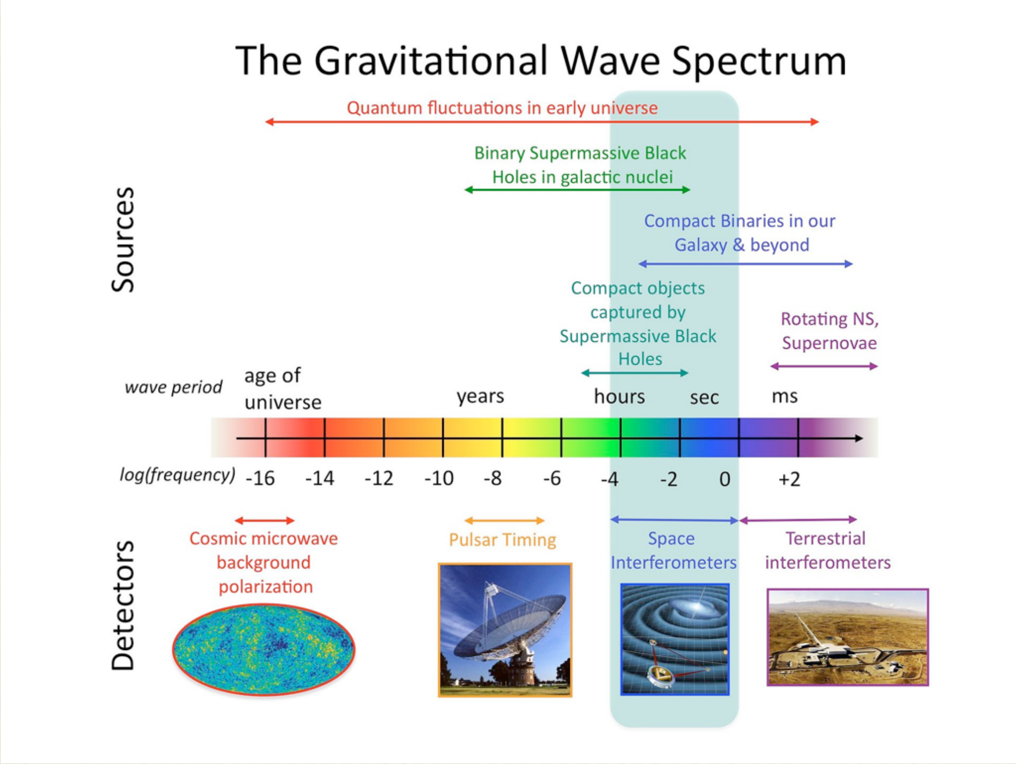
The Gravitational Universe

- The recent first detection of *gravitational waves* in the fabric of spacetime, has opened up a new way to study our Universe



[LIGO collaboration, '15]

- One very exciting, but challenging prospect, is the measurement of *primordial gravitational waves* (PGW) produced in the very early universe during *cosmological inflation* $(t \sim 10^{-34}\mathrm{sec})$ [Guth, '81; Linde, '82]



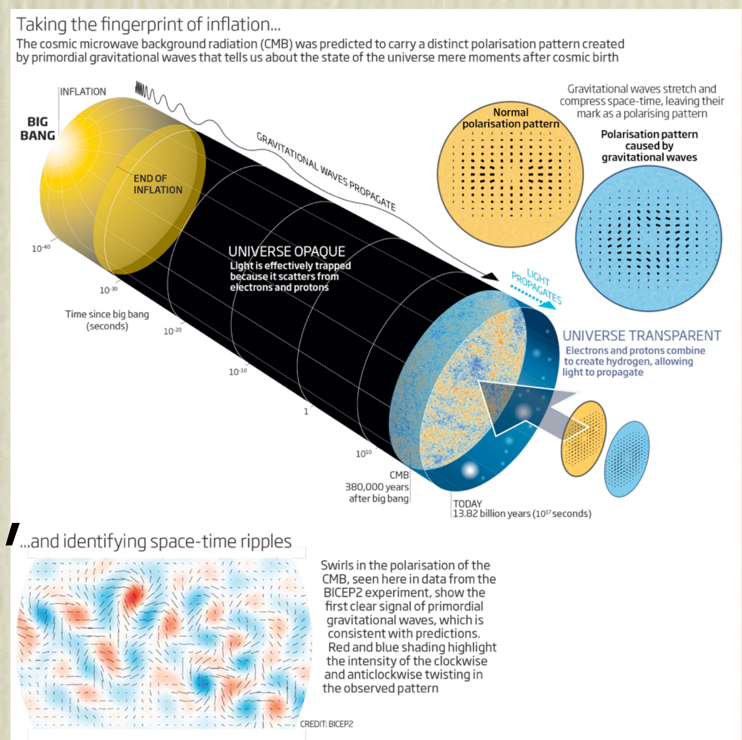
The CMB and PGW

- During an inflationary epoch, quantum fluctuations stretched to observables scales. These fluctuations seeded perturbations in the temperature of the cosmic microwave background (CMB) and ultimately lead to large scale structure formation.

[Mukhanov, Chibisov, ’81]

- The dominant contribution to the CMB temperature anisotropies are from density perturbations, while gravitational waves lead to a special pattern, *B-modes*, in the CMB polarisation.

[Zaldarriaga, Seljak, ’96]
[Kamionokowski, et al. ’96]



Primordial Gravity Waves from Inflation

- *Primordial Gravitational Waves* are a robust prediction of inflation, however their *amplitude* depends on the *inflationary model* and in particular the *inflationary scale*.

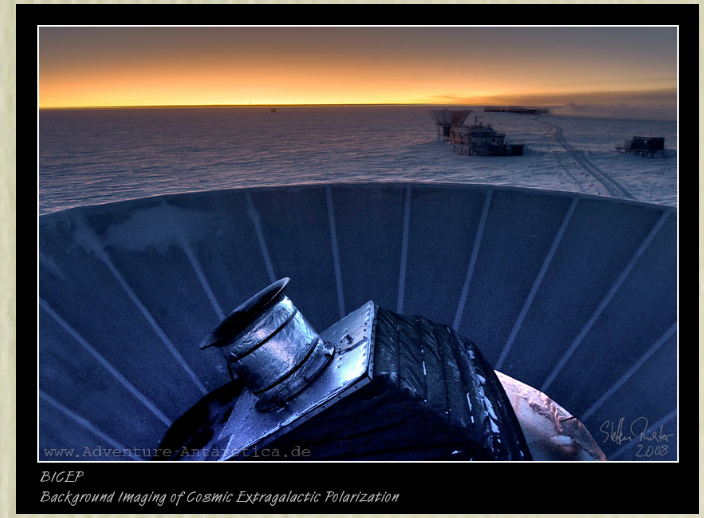
- *Their amplitude* can be encoded in *the tensor to scalar ratio of the power spectra*

$$r \equiv \frac{\mathcal{P}_t}{\mathcal{P}_\zeta} = 16\,\epsilon$$

where ϵ *is the first inflationary slow-roll parameter*

- Current bounds on the *tensor-to-scalar ratio*, r, from BICEP/Keck set at

Current bound $r < 0.07$

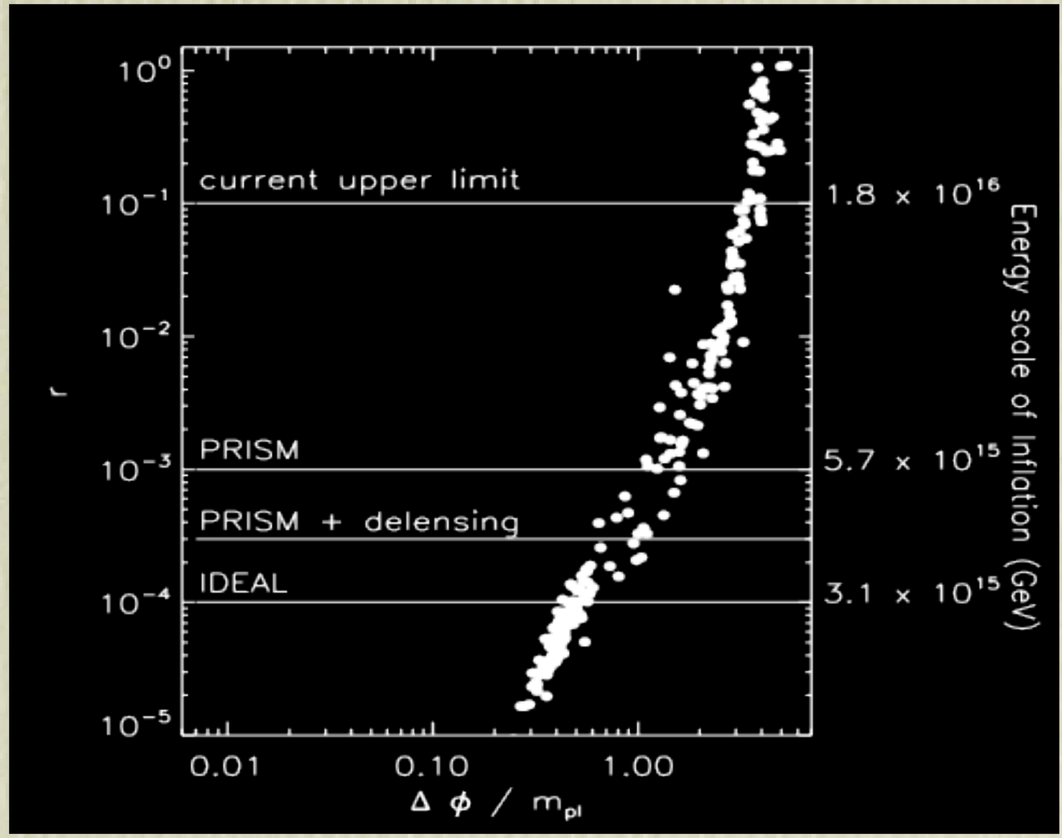


[BICEP/Keck, '15]

- Future experiments such as PRISM may reach sensitivities of

Future prospects $r \sim 10^{-4}$

[Polarized Radiation Imaging and Spectroscopy Mission, PRISM]



(B-modes in the lensing distortions of the 21 cm radiation emitted by hydrogen atoms during the reionisation epoch could reach $r \sim 10^{-9}$)

PLAN

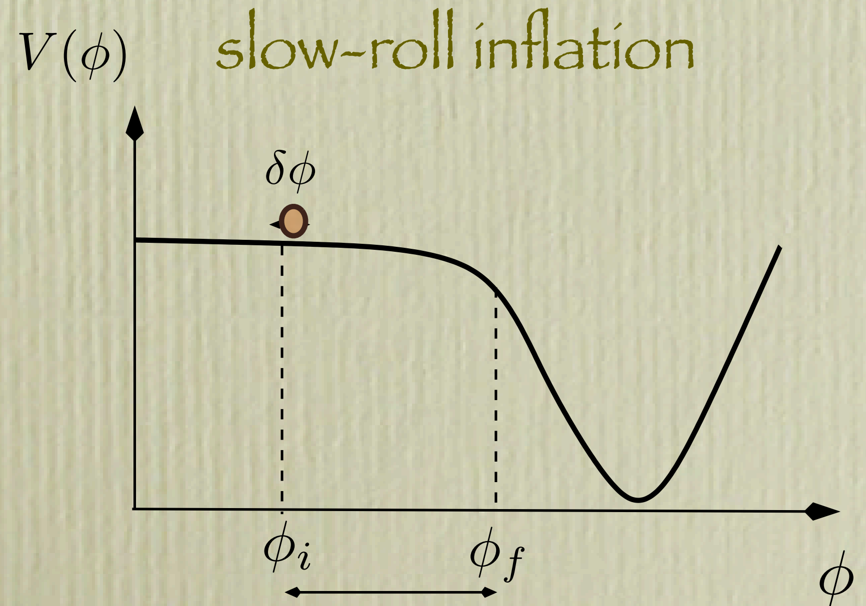
- PGW's in Inflation
- PGW's in String Inflation
- An upper bound on r

INFLATION IN EFT

- Observations are consistent with the simplest EFT inflation model with single canonically normalised scalar field, coupled minimally to gravity, whose potential

$$V(\phi) = V_{ren}(\phi) + \sum_{n=5}^{\infty} c_n \frac{\phi^n}{M_{Pl}^{n-4}}$$

drives a prolonged epoch of slow-roll inflation encoded in the potential slow-roll parameters



$$\epsilon \equiv \frac{M_{Pl}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1\,,$$

$$\eta \equiv M_{Pl}^2 \left|\frac{V''}{V}\right| \ll 1\,.$$

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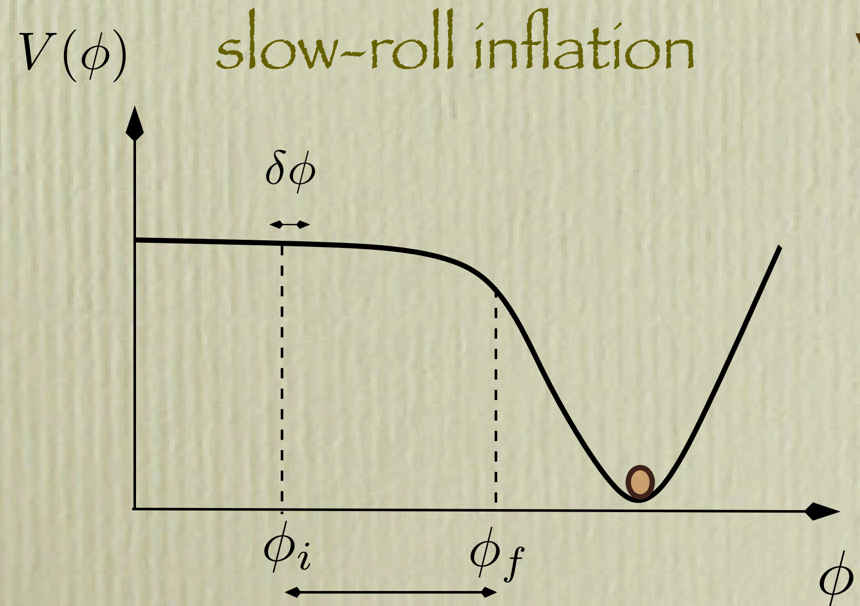
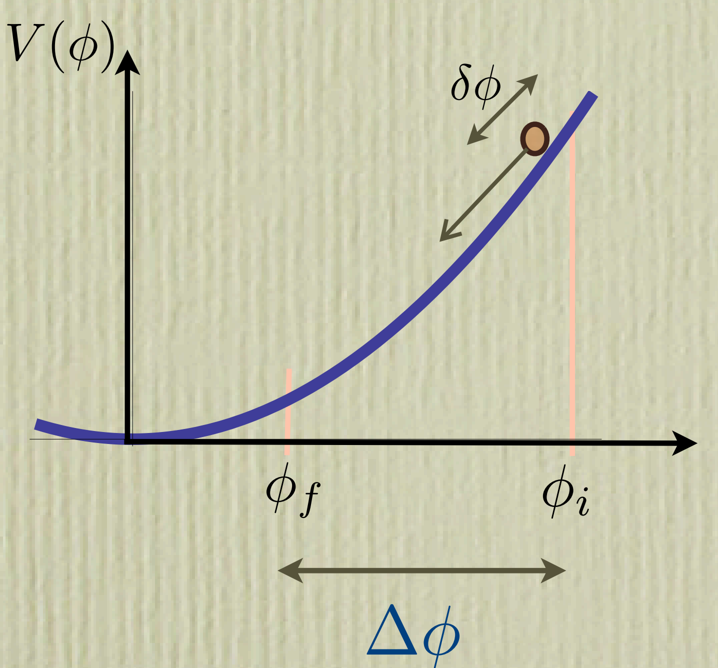


Cosmological parameters can be written in terms of slow-roll parameters:

- Spectral index $n_s = 1 - 6\epsilon + 2\eta$
- Tensor-2-scalar $r \equiv \frac{\mathcal{P}_t}{\mathcal{P}_\zeta} = 16\epsilon$

PRIMORDIAL GRAVITY WAVES AND r

The tensor to scalar ratio can be related to



- *The scale of inflation*

$$V_{inf}^{1/4} \approx 1.8 \times 10^{16}\mathrm{GeV} \left(\frac{r}{0.1}\right)^{1/4}$$

inflationary scale is close to the GUT scale for values of r as small as $r \sim 10^{-5}$!

- *The inflaton field range*

$$\frac{\Delta\phi}{M_{Pl}} \gtrsim \mathcal{O}(1) \left(\frac{r}{0.01}\right)^{1/2}$$

[Lyth, '96; Boubekeur-Lyth, '05]
[García-Bellido, Roest, Scalisi, IZ '14]

➠ inflation mechanism very sensitive to UV physics

INFLATION IS SENSITIVE TO UV PHYSICS

- Higher order corrections to $V(\phi)$ generically spoil slow roll

- Unknown physics above UV cutoff parameterised by higher dimensional operators:

$$\mathcal{O}_{p\geq 6} \quad \rightarrow \quad V(\phi)\left(\frac{\phi}{M_P}\right)^{p-4}$$

- All inflation models are sensitive Planck suppressed corrections to the potential: η-problem

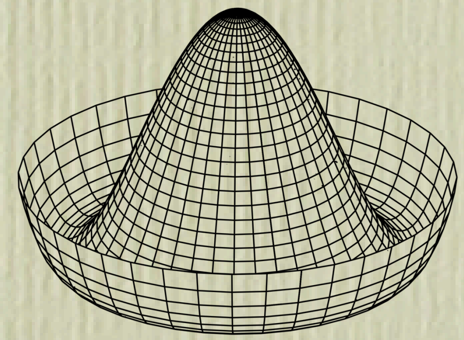
$$\Delta\eta \quad \rightarrow \quad \left(\frac{\phi}{M_P}\right)^{p-6} \gtrsim 1 \qquad\qquad \left(\eta \equiv M_{Pl}^2 \left|\frac{V''}{V}\right| \ll 1\right)$$

- *Large field inflationary models are* sensitive to *all* Planck suppressed interactions.

Opportunity to connect quantum gravity to observations

Axion Inflation

To suppress dangerous contributions to the inflaton V, invoke a symmetry: inflaton is an *axion* (PNGB) with continuous global *shift symmetry*



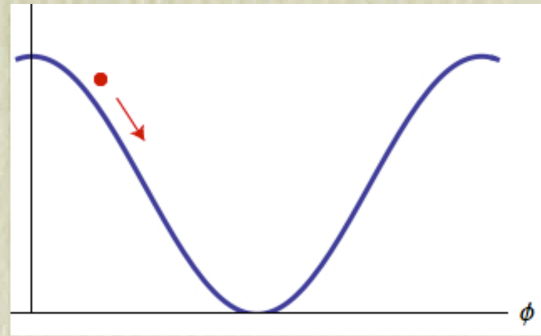
$$\phi \to \phi + a$$

Break the symmetry in a controlled way

Axion Inflation

To suppress dangerous contributions to the inflaton V, invoke a symmetry: inflaton is an *axion* (PNGB) with continuous global *shift symmetry*

- *Natural Inflation:* [Freese-Frieman-Linto, '90]

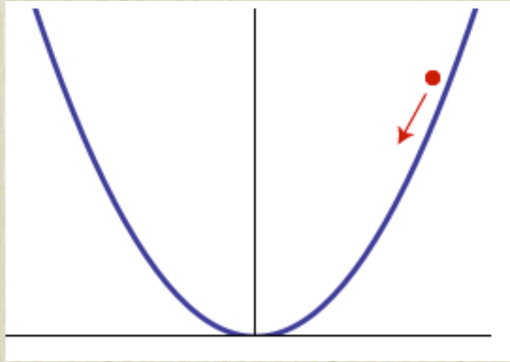


broken by non-perturbative effects to a discrete symmetry $V = V_0(1 - \cos(\phi/f))$

f *axion decay constant (~~symmetry~~ scale)*

$$f \gtrsim 7 M_{Pl}$$

- *Chaotic (monomial) Inflation:* [Kaloper-Sorbo '08]



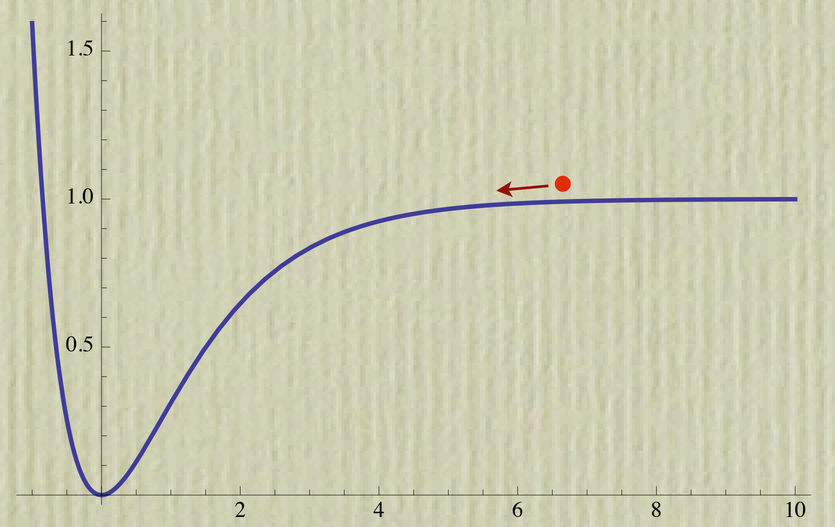
broken spontaneously (e.g. due to coupling to background fluxes) $V = V_0\, \phi^n$

$(V = V_0(q + \mu\phi)^2)$

$$\Delta\phi \sim 15 M_{Pl} \qquad (n = 2)$$

Plateau-like Inflation

Another possibility is to realise a *shift symmetry* for large values of the scalar field



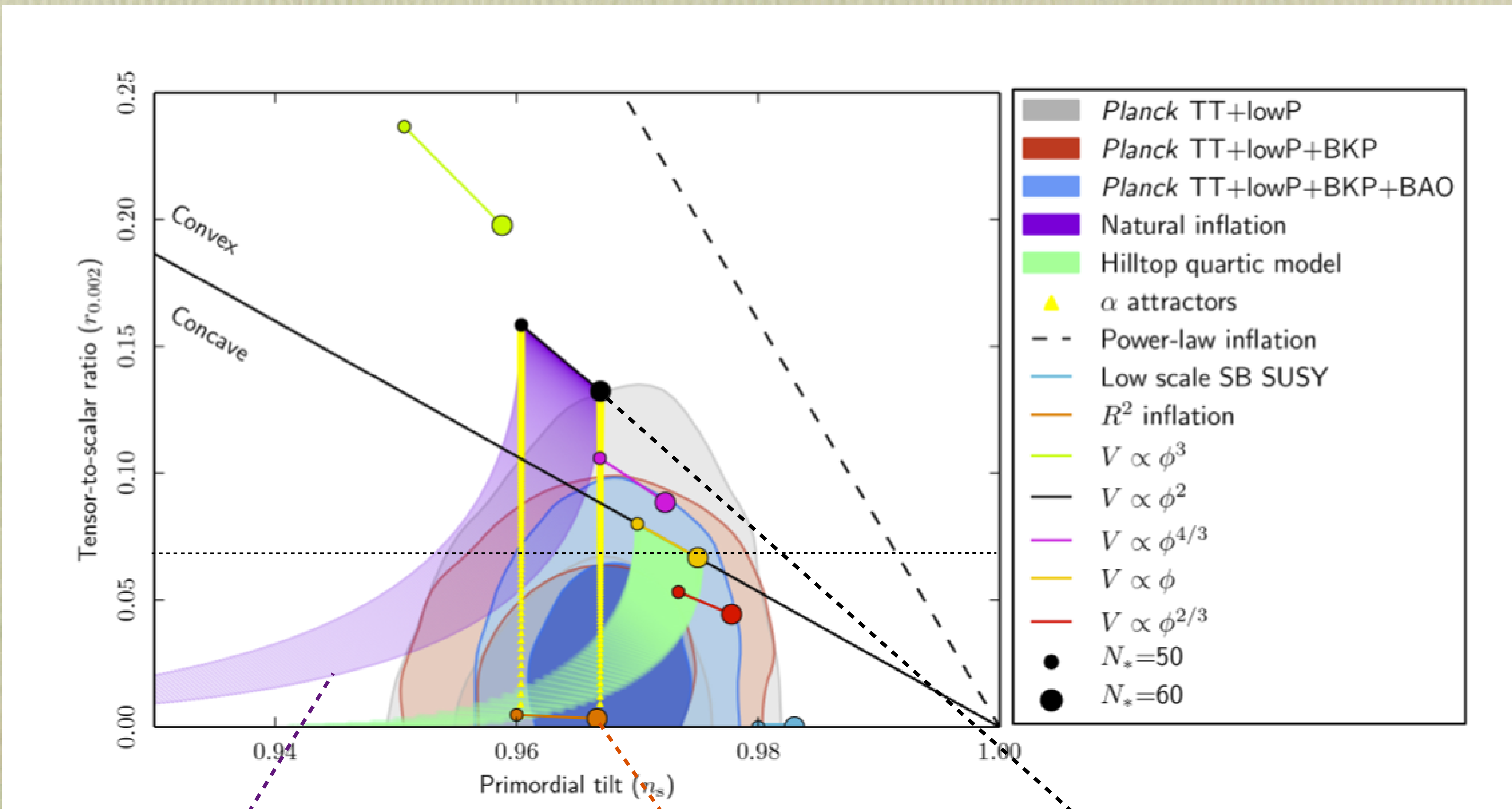
$V(\phi) \to const.$ as $\phi \gg M_{Pl}$

Starobinsky-lilke

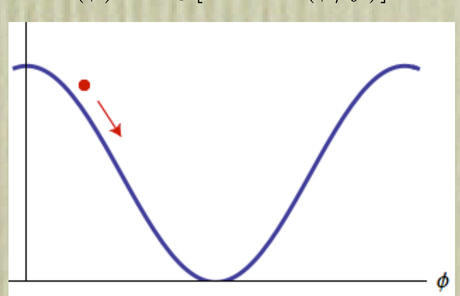
[Starobinsky, '80]

Planck-Bicep/Keck 15

$$\left(\mathcal{P}_\zeta \sim A_s\, k^{n_s - 1}\right)$$



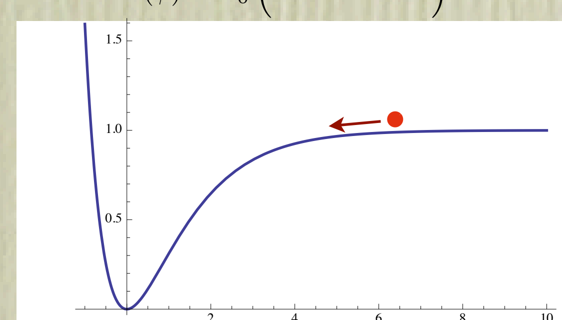
$V(\phi) = V_0\,[1 - \cos(\phi/f)]$



natural inflation

[Freese-Frieman-Linto, '90]

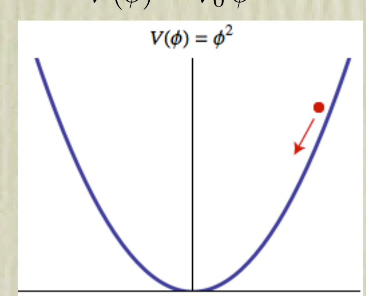
$V(\phi) = V_0\left(1 - e^{-\sqrt{2/3}\,\phi}\right)^2$



R^2 inflation

[Starobinsky, '80]

$V(\phi) = V_0\,\phi^2$



chaotic inflation

[Linde, '83]

For these models

$$r \gtrsim 10^{-3}$$

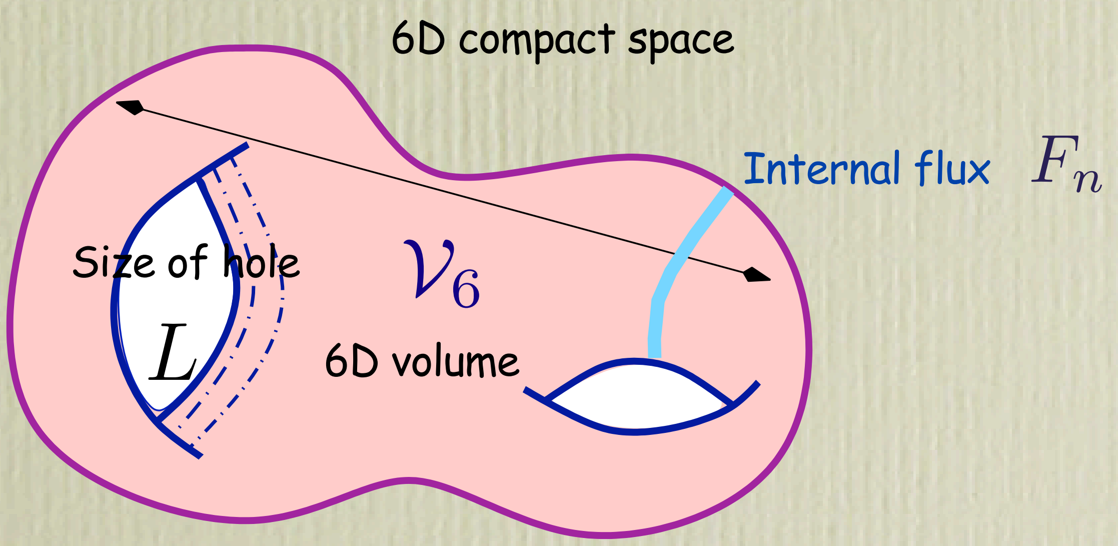
$$\Delta\phi \gtrsim 5 M_{Pl}$$

$$V_{inf}^{1/4} \gtrsim 6 \times 10^{15}\,\mathrm{GeV}$$

Inflation in String Theory

In string theory, several scalar fields arise, which can be potential candidates to drive inflation with shift symmetry

- Axions descend from gauge fields or their generalisations, p-forms wrapping p-cycles in compact 6D: A_M , $A_{M_1 \dots M_p}$
- Plateau-like potentials arise naturally for scalar fields associated to the sizes of the 6D compact space



Inflation in String Theory

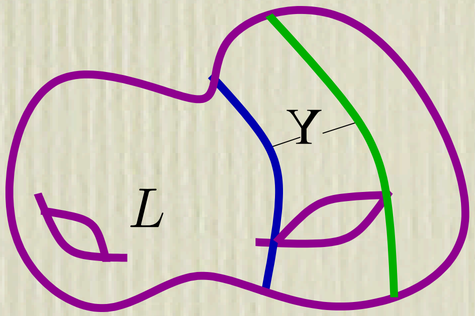
Prescription for string inflationary models:

- Start with perturbative expansion of string theory in 10D: 10D supergravity at weak coupling

- Compactify from 10D to 4D + 6D (compact)

- Stabilise all scalar fields not relevant for inflation (moduli stabilisation)

- LEEFT ingredients:



$g_s \ll 1\,,$ string weak coupling

$\alpha'/L^2 \ll 1$ perturbative string expansion

where $\mathcal{V}_6^{1/6} \sim L$ typical compactification scale

$(\alpha' = \ell_s^2/(2\pi)^2)$

Inflation in String Theory

To ensure a valid 4D EFT description throughout the inflationary epoch, any string model of inflation has to feature the hierarchy of scales

[Baumann, McAllister, '14]
[Mazumdar, Shukla, '14]
[Kooner, Parameswaran, IZ, '15]
[Burgess, Cicoli, de Alwis, Quevedo, '16]
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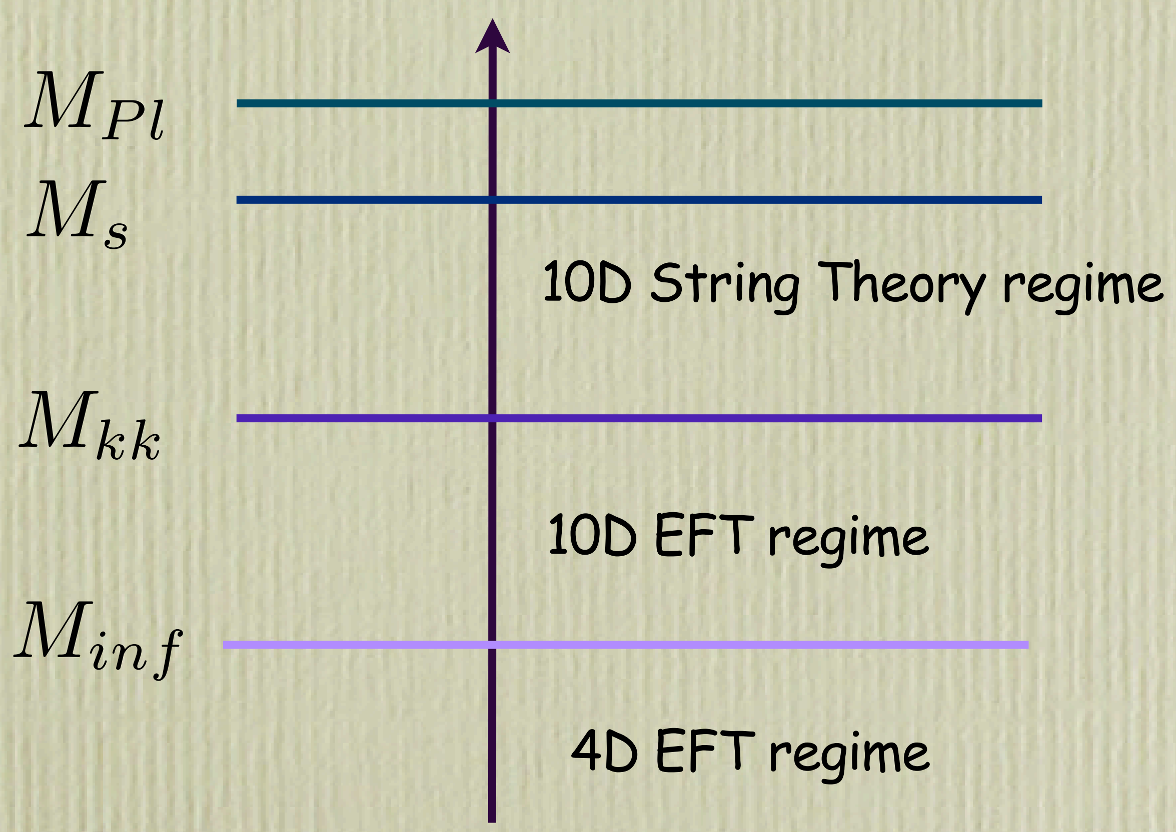

$$M_{inf} < M_{kk} \lesssim M_s \lesssim M_{Pl}$$

$$(M_s = 1/\ell_s\,, \quad \alpha' = \ell_s^2/(2\pi)^2)$$

where

$$M_s = \frac{g_s}{\sqrt{4\pi \mathcal{V}_6^w}} M_{Pl}$$

Otherwise we *cannot neglect massive string excitations, Kaluza-Klein modes* and *extra dimensions*

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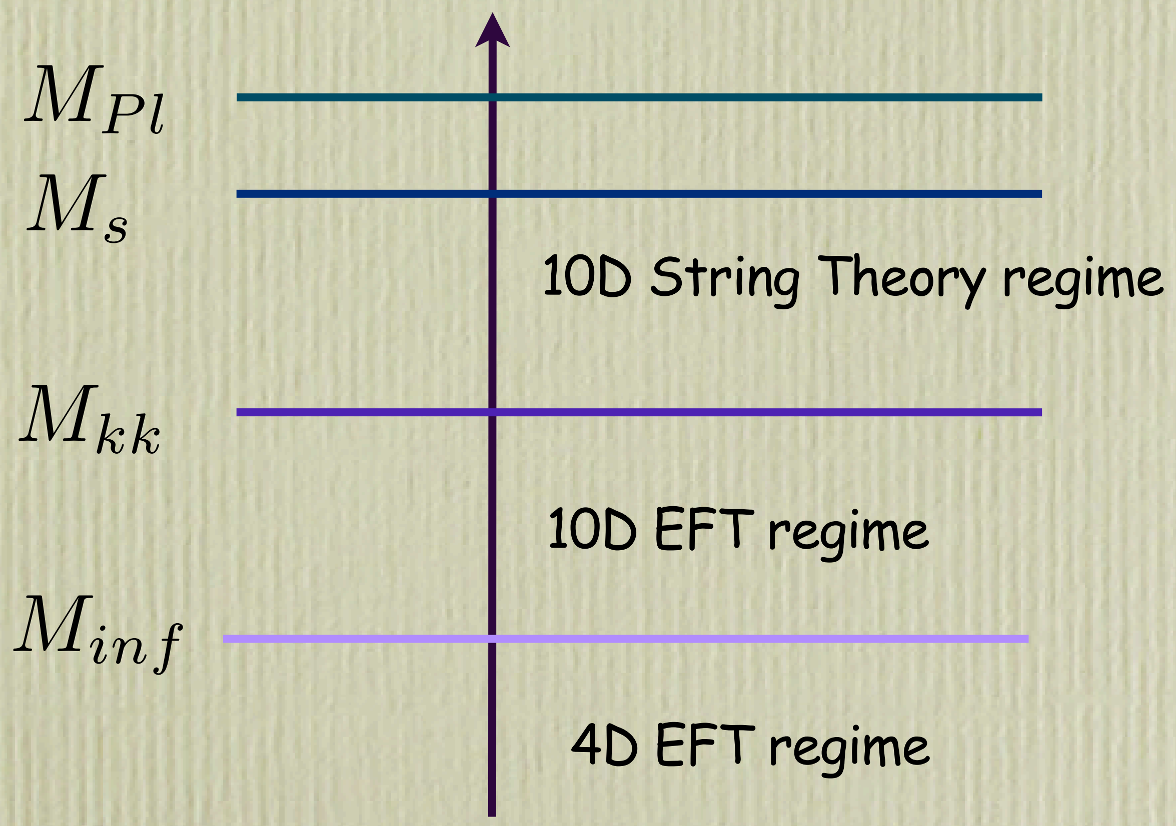

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Recalling that $\quad M_{inf} \sim 10^{-2} M_{Pl} \left(\frac{r}{0.}\right)^{1/4}, \& \quad \frac{\Delta\phi}{M_{Pl}} \gtrsim \mathcal{O}(1) \left(\frac{r}{0.01}\right)^{1/2}$

➠ tight constraints on high scale, large field inflationary models in string theory

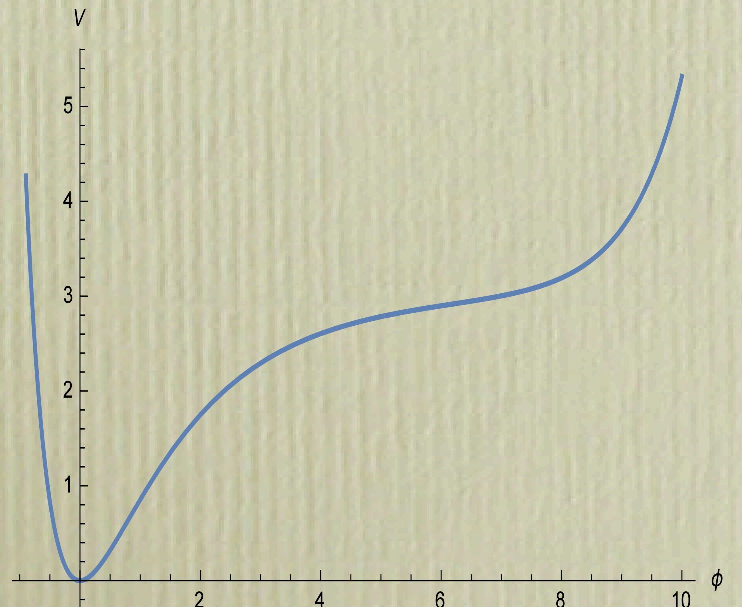
Large Field Explicit Models?

- *Natural inflation* in string theory: hard to realise as symmetry breaking scale, f, needs to be super-Planckian to drive successful inflation [Banks, Dine, Fox & Gorbatov, '03]

  Axions from closed strings tightly constrained. [Arkani-Hamed,Motl,Nicolis,Vafa, '06]

  However, open string (and multifield) axion models models may work (need explicit construction) [Kooner, Parameswaran, IZ, '15]

- Plateau-like potentials: *Fiber inflation*. A scalar field associated to size of internal cycles has potential



- Numerical control, but not parametric control. Very sensitive to numerical factors and parameter values [Burgess, Cicoli, de Alwis, Quevedo, '16] [Cicoli, Burgess, Quevedo, '08]

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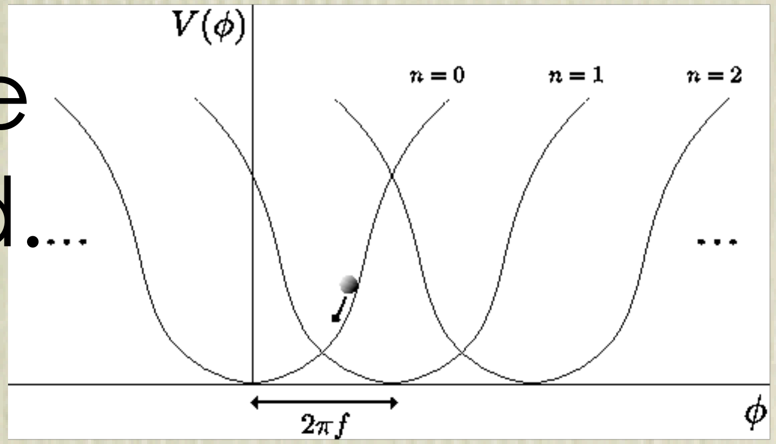
- *Plateau-like potentials*: *Fiber inflation*. A scalar field associated to size of internal cycles has potential
  [Burgess et al. '08, '16]

- *Axion monodromy*. Repeatedly traverse the sub-Planckian fundamental period.... No explicit model known



[Westphal-Silverstein, '08, '14]

UPPER BOUND ON r IN STRING INFLATION

[Parameswaran, IZ, '16]

Using relation between r, the scale of inflation and the relation between Ms and MPl we can write:

$$r = 3.1 \times 10^8 \left(\frac{M_{inf}}{m_{kk}}\right)^4 \left(\frac{m_{kk}}{m_s}\right)^4 \left(\frac{g_s}{\sqrt{\mathcal{V}_6}}\right)^4$$

$(m_s = 1/\sqrt{\alpha'})$

$(M_s = 2\pi/\sqrt{\alpha'})$

☞ very sensitive to values of parameters due to 4th power

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- Considering for example:

$$g_s \lesssim 0.1\,, \qquad \mathcal{V}_6 \gtrsim 1000\,, \qquad M_{inf} \sim 0.3\, m_{kk}\,, \qquad m_{kk} \sim 0.3\, m_s$$

gives $\quad r \lesssim 3.1 \times 10^{-6}$

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- Relaxing this to:

$$g_s \lesssim 0.2\,, \qquad \mathcal{V}_6 \gtrsim 125\,, \qquad M_{inf} \sim 0.45\, m_{kk}\,, \qquad m_{kk} \sim 0.45\, m_s$$

allows $\quad r \lesssim 0.05$

Can we evade this bound going to strong coupling and/or strong curvatures

$$g_s > 1\,, \quad L/\ell_s < 1$$

to drive $M_s\,,\ M_{kk}$ up?

In this case, $M_s = M_{Pl}\frac{g_s}{\sqrt{4\pi\mathcal{V}_6}}$ no longer valid.

But one could perform a *duality* transformation to an equivalent weak coupling weak curvature description and back to the same bound and conclusions

Comments

- The relation $V_{inf}^{1/4} \approx 1.8 \times 10^{16}\mathrm{GeV} \left(\frac{r}{0.1}\right)^{1/4}$ remains unchanged for multifield and non-standard kinetic field inflation

[Sasaki, Stewart, '95; Wands, '07]
[Garriga, Mukhanov, '99]

- The bound assumes
  i) inflation in a 4D EFT
  ii) perturbative string theory and its supergravity limit as a good description of the early Universe.

- A positive observation of PGW with $r \sim 10^{-2} - 10^{-3}$ would make convincing string realisations of inflation challenging, but very exciting!

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Universe was at the limits of string perturbation theory and sugra limit and at the limits of validity of the 4D EFT?