# B modes

# and

# High Energy Physics

# Inflationary cosmology

- Accelerated expansion driven by potential energy

$$V(\phi)$$

$\uparrow$ scalar inflaton

$$-dt^2 + a(t)^2 d\tilde{x}^2 \qquad a(t) \simeq a_0 e^{Ht}$$

- Quantum fluctuations $\delta\phi(t, \tilde{x})$ seed structure
- Fluctuations of the gravitational field are also generated

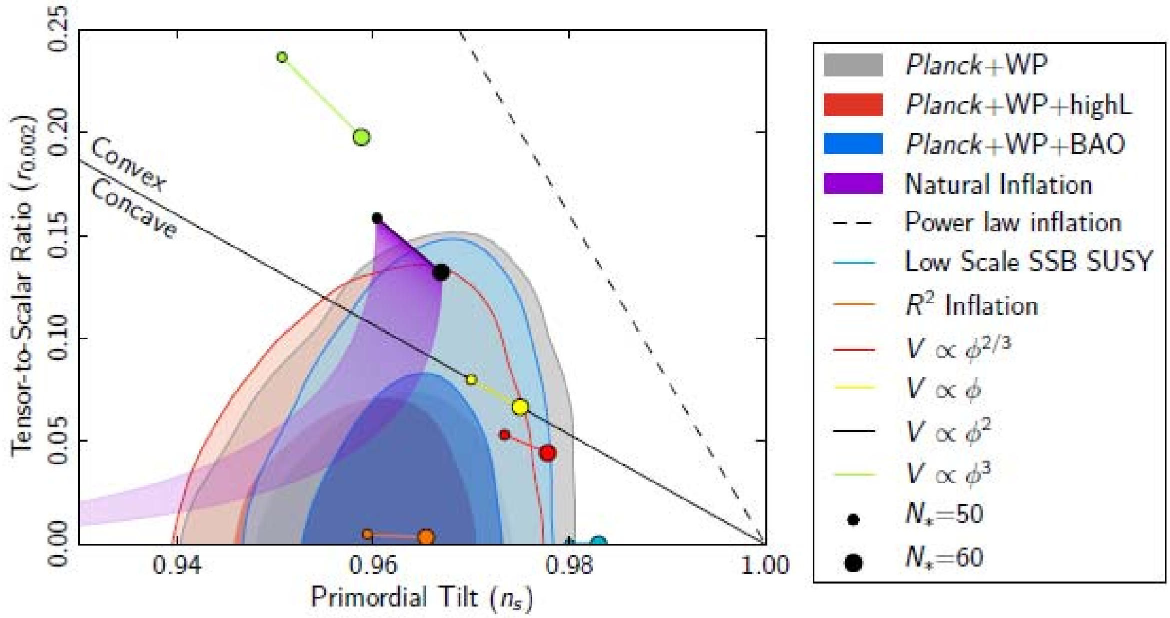



**Figure 1-1.** *Current CMB constraints on the combined $n_s$-$r$ parameter space [18].*

Inflation + Quantum mechanics $\rightarrow$

$$\langle \gamma_s \gamma_{s'} \rangle = \frac{2H^2}{M_p^2}\,\delta_{ss'}\,\delta(\vec{k}+\vec{k}')$$ tensor

$$\langle \zeta \zeta \rangle \sim H^4/\dot{\phi}^2\,\delta(\vec{k}+\vec{k}')$$ scalar

$$ds^2 = -dt^2 + e^{2Ht}\,dx^i dx^j \left(e^{2\zeta}\delta_{ij} + \gamma_{ij}\right)$$

$$r = \frac{\langle \gamma\gamma \rangle}{\langle \zeta\zeta \rangle}$$ detected via CMB polarization (B-modes)

# Significance

(1) Quantum mechanical fluctuations of the gravitational field !

$\langle \gamma \rangle = 0 \qquad \langle \gamma\gamma \rangle \neq 0$

(2) $r \propto H^2 = \frac{V}{M_p^2}$ : $\underbrace{V^{\frac{1}{4}}}_{\text{Inflationary potential energy}} \sim \left(\frac{r}{.01}\right)^{\frac{1}{4}} \times 10^{16}\,\text{GeV}$

not a wide range available

☆ GUT scale

(3) ☆ Lyth: r is related to field range

$$\frac{\Delta\phi}{M_p} \sim \left(\frac{r}{0.01}\right)^{\frac{1}{2}}$$

observable (at $5\sigma$ level!)

highly UV sensitive if $\gtrsim 1$ (as we'll review here)

To see this :

$$N_e = \log\left(\frac{a_{end}}{a_{start}}\right) = \int_{start}^{end} \frac{da}{a} = \int \underbrace{\frac{\frac{da}{dt}}{a}}_{H} dt$$

$$= \int H \frac{dt}{d\phi} d\phi = \int \frac{H M_p}{\underbrace{\dot{\phi}}_{\sqrt{8}\, r^{-\frac{1}{2}}}} \frac{d\phi}{M_p}$$

$$N_e \simeq \sqrt{8}\, r^{-\frac{1}{2}} \frac{\Delta\phi}{M_p}$$

- $T^{max}_{reheating} \to N_e \simeq 60, \quad \frac{\Delta\phi}{M_p} \sim \left(\frac{r}{.01}\right)^{-\frac{1}{2}}$
- $T^{min}_{reheating} \to N_e \simeq 30, \quad \frac{\Delta\phi}{M_p} \sim \left(\frac{r}{.002}\right)^{\frac{1}{2}}$

As B-mode detectors

scan from

$r \gtrsim .1$ (current $2\sigma$ limit)

down to $r = .01$

and then $r \gtrsim .001$

They cover a wide range of $\Delta\phi$

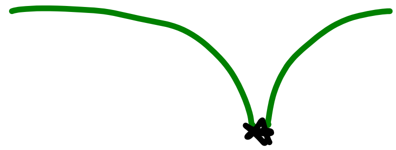
from $\Delta\phi \gtrsim 10 M_p$

to $\Delta\phi \sim M_p$ ← important threshold

in which inflation is sensitive to an $\infty$ sequence of quantum gravity corrections!

Recall Wilsonian effective field theory

General Relativity describes gravity accurately at long distances



$$S = \int d^4x \sqrt{g}\,\frac{R}{G_N} + S_{\text{matter}} \rightarrow R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G_N T_{\mu\nu}$$

GR breaks down for $\lambda_G \rightarrow 1$ (or before)

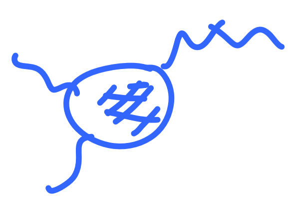
Quantum fluctuations & classical UV physics $\rightarrow$

$$S = \int \left(\frac{R}{G_N} - V(\phi)\right)\left(1 + R\left(\frac{c_1}{M_*^2} + \tilde{c}_1 G_N\right) + \dots\right)$$

$$+ \int (\partial\phi)^2 + k_1 \frac{(\partial\phi)^4}{M_*^2} + \dots$$

$\leftarrow$ scale of "new physics"

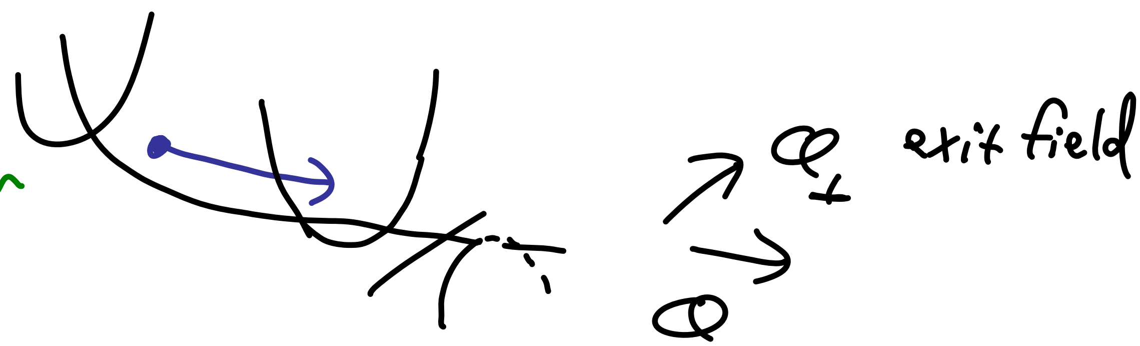
with corrections sensitive to short-distance physics



2) These corrections matter for inflation in general

e.g. A seemingly simple way to obtain inflation is to postulate a very flat potential for the inflaton $\phi(x)$.

Linde '93
hybrid inflation



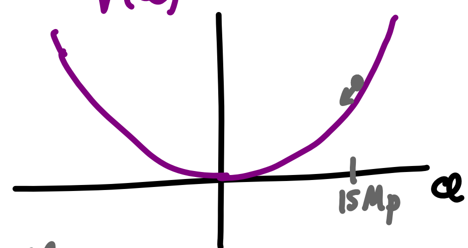

$$\varepsilon \equiv \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2 << 1 \qquad \eta \equiv M_p^2\left|\frac{V''}{V}\right| << 1$$

However, corrections from the UV physics can generate substructure in $\mathcal{L}(\phi, \partial\phi)$ :

$$\frac{V(\phi-\phi_0)^2}{M_p^2} \to \Delta\eta \sim 1$$

The UV Sensitivity is greatest in cases like "chaotic inflation" A. Linde '83 where the inflaton $\phi$ ranges over more than a distance $M_p$

e.g. $V(\phi) = \frac{1}{2} m^2 \phi^2$




$$\begin{Bmatrix} \epsilon = \frac{1}{2}\left(\frac{V'}{V} M_p\right)^2 \\ \eta = M_p^2 \left|\frac{V''}{V}\right| \end{Bmatrix} \sim \left(\frac{M_p}{\phi}\right)^2 \Rightarrow \phi \sim 15 M_p$$

- An $\infty$ sequence of possible terms

$$V \to V\left(1 + \sum_n c_n \frac{(\phi - \phi_0)^n}{M_p^n}\right)$$

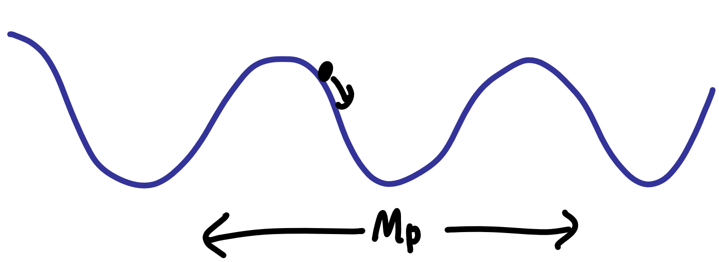
would ruin inflation $\Rightarrow$ infinitely "UV-sensitive"

- Can Control with approximate shift symmetry (Wilsonian 'natural') IF such a symmetry exists in Quantum Gravity

<u>Axions</u> naturally respect an (approximate) shift symmetry $\phi \to \phi + \alpha$

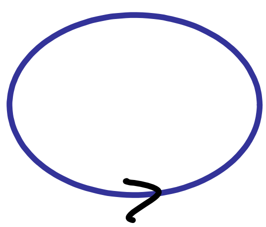
(couple via their derivatives)

→ "Natural Inflation"




$\Lambda^4 \sim e^{-\frac{\text{const}}{g^2}}$

<u>Naturally small</u>



$a \cong a + (2\pi)^2$

$\phi_a = f_a a$ — canonical scalar field

→ Does $\dfrac{\Delta\phi}{M_p} \gtrsim 1$, protected by shift symmetry, arise in string theory?

* Basic <u>period</u> small compared to $M_p$

For axions, $f \ll M_p$

in currently controlled regions of the landscape. (size $L \gg M_p^{-1}$)

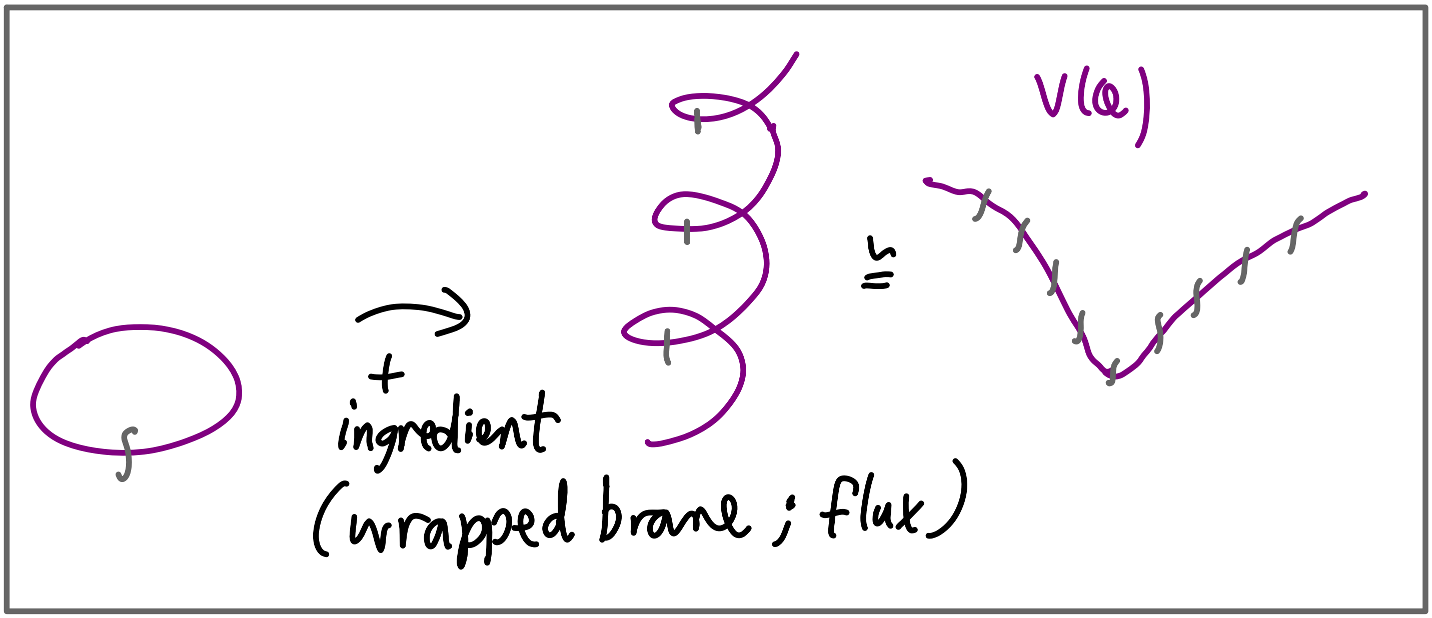
$$\int d^4x\sqrt{-G}\,\underbrace{|dC_p|^2}_{g^{i_1 j_1}\cdots g^{i_{p+1} j_{p+1}}} = \int d^4x\sqrt{-g}\,\frac{M_p^2}{(LM_p)^{2p}}(\partial\theta)^2$$

* Not "anything goes" in the landscape!

- Multiple Axions mitigates this...

  'N-Flation'

... But must take into account Monodromy in string compactifications

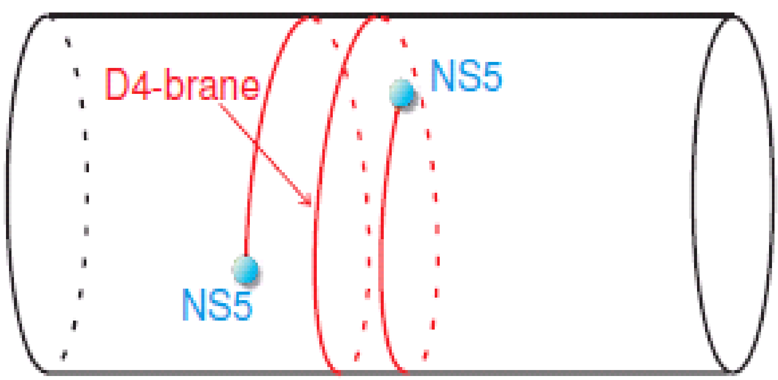



unwraps the would-be periodic direction. → Large field range with distinctive potential, with

$$V(\varphi > M_p) \sim \begin{cases} \varphi^{2/3} & \text{twisted torus} \\ \varphi & \text{axions} \end{cases}$$

the so far worked out examples.

The basic mechanism is very simple :

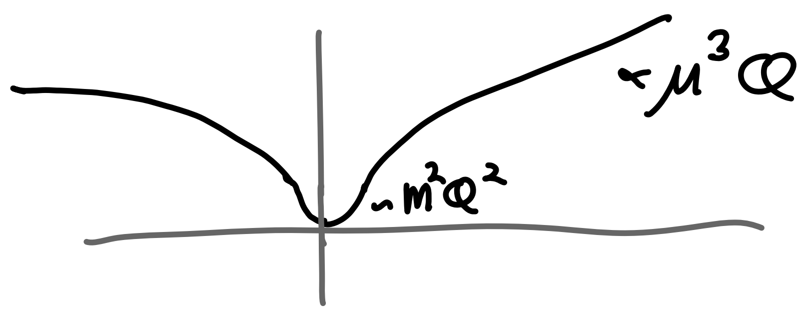



[ "T-dual" to axions ]

- "NS5" branes position periodic on this circle, until add stretched "D4" brane

$$V(\phi) \sim \mu^3 \sqrt{\phi^2 + M_*^2}$$

→ Novel prediction for inflaton potential

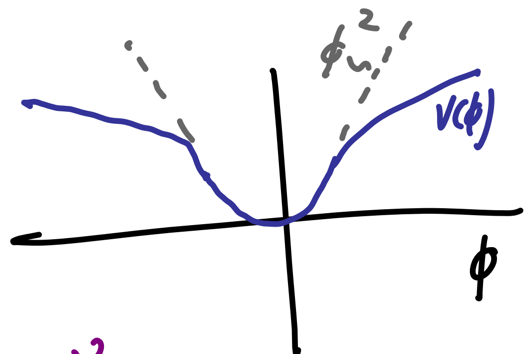



$+$

$$\left( e^{-\frac{8\pi^2}{g^2}} \cos \frac{\phi}{f} \right.$$

General Lesson: Heavy fields (mass > H) adjust in response to inflationary potential energy, flattening $V(\phi)$:

QFT toy model




$$V(\varphi_L, \varphi_H) = g^2\varphi_L^2\varphi_H^2 + m^2(\varphi_H - \varphi_0)^2$$

$$\frac{\partial V}{\partial \varphi_H} \equiv 0 \Rightarrow V = \frac{g^2\varphi_L^2}{g^2\varphi_L^2 + m^2} m^2\varphi_0^2$$

($\dot{\varphi}_H^2$ term subdominant)

flatter: energetically favorable.

String theory large-field inflation (monodromy) has flattened $V(\phi)$ for essentially this reason.

$$\rightarrow V \propto \phi^{p<2}$$

<u>If</u> $V = \frac{1}{2} m^2 \phi^2$ is eventually ruled out, then

- new physics beyond $\Lambda$CDM (more parameter(s) in inflaton sector)
- Opportunity to <u>discover</u> flattened potentials

  $$.01 < r \lesssim .1$$

  suggesting UV origin (e.g. Monodromy)
- If <u>exclude</u> $.002 < r < .1$, we learn that inflation was small-field

# Large-Field Summary

- Neither tradition QFT axions (Natural Inflation, $f > M_p$)

  nor $V = \frac{1}{2} m^2 \phi^2$ inflation

  appear generic (possible?) in string theory

- But string theory axion monodromy

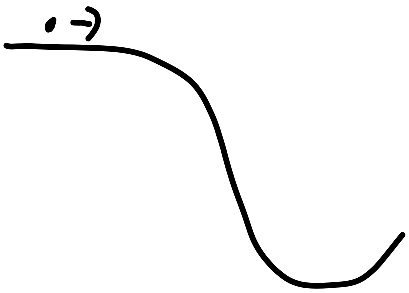
  $\Rightarrow$ flattened-potential versions of chaotic inflation

- In any case, B-modes probe $\Delta\Phi$ down to $M_p$ !

## Non-Gaussianity

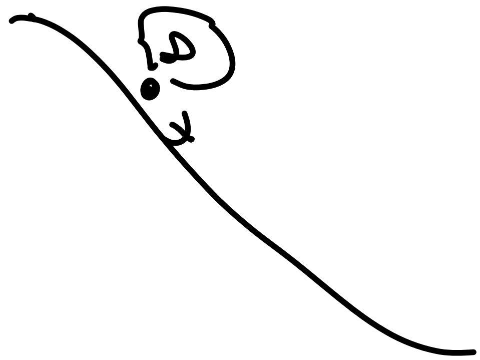
Roughly Speaking,
2 classes of Inflation Mechanisms:

Slowly diluting potential energy



Flat potential

NG only from substructure, e.g. oscillations, in $V(\phi)$



Steep potential, but interactions slow the field. $\Rightarrow$ NG.

↳ e.g. brane motion limited by XD speed of light (DBI)

Now Systematic (EFT) understanding for single-field; new effects for multiple fields