B modes
and
High Energy Physics
Inflationary cosmology

- Accelerated expansion driven by potential energy

\[ V(\phi) \]

\[ \sim \text{scalar inflaton} \]

\[ -dt^2 + a(t)^2 d\vec{x}^2 \]

\[ a(t) \approx a_0 e^{Ht} \]

- Quantum fluctuations \( \delta \phi(t, \vec{x}) \) 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 \[ \rightarrow \]
\[ \langle \gamma_s \gamma_{s'} \rangle = \frac{2H^2}{M_p^2} \int_{ss'} \mathcal{D} \mathcal{E} \mathcal{E}' \] tensor
\[ \langle s s \rangle \sim \frac{H^4}{\phi^2} \int \mathcal{D} \mathcal{E} \mathcal{E}' \] scalar

\[ ds^2 = -dt^2 + e^{2Ht} dx^i dx^j \left( e^{2s} \delta_{ij} + \gamma_{ij} \right) \]

\[ r = \frac{\langle \gamma \gamma \rangle}{\langle ss \rangle} \] detected via CMB polarization (B-modes)
Significance

(1) Quantum mechanical fluctuations of the gravitational field!

\[ <r> = 0 \quad <\phi^2> \neq 0 \]

(2) \[ r \propto H^2 = \frac{V}{M_p^2} \sim V^\frac{1}{4} \frac{\text{not a wide range available}}{\left(\frac{r}{0.01}\right)^{\frac{7}{4}} \times 10^{-16} \text{ GeV}} \]

Inflatimary potential energy

GUT scale

(3) \* Lyth: \ r \ is \ related \ to \ field \ range

\[ \frac{\Delta Q}{M_p} \sim \left(\frac{r}{0.01}\right)^{\frac{7}{4}} \]

highly UV sensitive

observable \ (at 5 \sigma \ level!\) \n
if \ \geq 1 \ (as \ we'll \ review \ here)
To see this:

\[ N_e = \log \left( \frac{a_{\text{end}}}{a_{\text{start}}} \right) = \int_{\text{start}}^{\text{end}} \frac{da}{a} = \int \frac{da}{a} \frac{dt}{H} \]

\[ = \int H \frac{dt}{d\phi} d\phi = \int \frac{H M_p}{\phi} \frac{d\phi}{M_p} \sqrt{8} r^{-\frac{1}{2}} \]

\[ N_e = \sqrt{8} r^{-\frac{1}{2}} \frac{\Delta \phi}{M_p} \]

\[ \text{max} \quad \text{Treheating} \quad \rightarrow \quad N_e = 60, \quad \frac{\Delta \phi}{M_p} \sim \left( \frac{r}{.01} \right)^{-\frac{1}{2}} \]

\[ \text{min} \quad \text{Treheating} \quad \rightarrow \quad N_e = 30, \quad \frac{\Delta \phi}{M_p} \sim \left( \frac{r}{.002} \right)^{\frac{3}{2}} \]
As B-mode detectors scan from $r \gtrsim 0.1$ (current $2\sigma$ limit) down to $r = .01$ and then $r \approx 0.001$.

They cover a wide range of $\Delta \phi$ from $\Delta \phi \gtrsim 10 M_p$ to $\Delta \phi \sim M_p \approx$ important threshold in which inflation is sensitive to an infinite sequence of quantum gravity corrections!
Recall Wilsonian effective field theory

General Relativity describes gravity accurately at long distances

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

GR breaks down for \( \lambda_g \rightarrow 1 \) (or before)

Quantum fluctuations + classical UV physics \( \rightarrow \)

\[ S' = \int \left( \frac{R}{G_N} - V(\phi) \right) \left( 1 + R \left( \frac{C_1}{M^2_k} + \tilde{C}_1 G_N \right) + \ldots \right) \]

\[ + \int (\partial \phi)^2 + k_1 (\partial \phi)^4 \frac{1}{M^2_k} + \ldots \]

\( \leftarrow \) 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 $\phi(x)$.

\[ \mathcal{E} \equiv \frac{M_p^2}{2} \left( \frac{V'}{V} \right)^2 \ll 1 \quad \eta \equiv \frac{M_p^2 |V''|}{V} \ll 1 \]

However, corrections from the UV physics can generate substructure in $\mathcal{L}(\alpha, \phi_0) : \frac{V(\alpha - \phi_0)^2}{M_p^2} \to \Delta \eta \sim 1$
The UV Sensitivity is greatest in cases like "chaotic inflation" A. Linde '83 where the inflaton ce ranges over more than a distance $M_P$, e.g. $V(\alpha) = \pm m^2 \alpha^2$

\[
\begin{aligned}
\epsilon &= \pm \left(\frac{V'}{V}\right)^2 \\
\eta &= M_P^2 \left|\frac{V''}{V}\right|
\end{aligned}
\Rightarrow \alpha \sim 15 M_P
\]

- An infinite sequence of possible terms $N \rightarrow V(1 + \sum n C_n (\phi - \phi_o)^n / M_P^n)$ would ruin inflation $\Rightarrow$ "UV-sensitive"
- Can control with approximate shift symmetry (Wilsonian 'natural') if such a symmetry exists in Quantum Gravity
Axions naturally respect an (approximate) shift symmetry $\Phi \rightarrow \Phi + \alpha$ (couple via their derivatives).

$\rightarrow$ "Natural Inflation"

$- e^{-\frac{\text{const}}{\ell^2}}$

$\Rightarrow$ Naturally small

$\Phi_a = f_a a$

canonical scalar field

$\Rightarrow$ Does $\frac{\Delta \Phi}{M_p} \gg 1$, protected by shift symmetry, arise in string theory?

* Basic period small compared to $M_p$
For axions, \( f \ll \text{M}_\text{p} \) in currently controlled regions of the landscape. (size \( L \gg \text{M}_\text{p}^{-1} \))

\[
\int d^4x \sqrt{-g} \left| \mathcal{C}_i \right|^2 = \int d^4x \sqrt{g} \frac{\text{M}_\text{p}^2}{(\text{L}_\text{M}_\text{p})^4} (\partial \Theta)^2 \]

\[\sim g^{\mu \nu} \ldots g^{\rho \tau} (\partial \Theta)^2\]

* 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 $\to$ large field range with distinctive potential, with $V(\Omega > M_p) \sim \left\{ \begin{array}{ll}
\Omega^{2/3} & \text{twisted torus} \\
\Omega & \text{axions}
\end{array} \right.$

the so far worked out examples.
The basic mechanism is very simple:

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

\[
V(\phi) \sim m^3 \sqrt{Q^2 + M_*^2}
\]

\[
\sim m^3 \phi
\]

\[
\left( e^{-\frac{m^2 \phi^2}{2g^2}} \cos \frac{\phi}{\phi_0} \right)
\]

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

QFT toy model

$$V(\phi_L, \phi_H) = g^2 \phi_L^2 \phi_H^2 + m^2 (\phi_H - \phi_0)^2$$

$$\frac{\partial V}{\partial \phi_H} = 0 \Rightarrow V = \frac{g^2 \phi_L^2}{g^2 \phi_L^2 + m^2} \phi_0^2$$

($\phi_H$ term subdominant) flatter: energetically favorable.

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

$V \propto \phi^{p<2}$
\[ V = \frac{1}{2} m^2 \phi^2 \]

is eventually ruled out, then

- new physics beyond \( \Lambda \)CDM (more parameters in inflaton sector)

- Opportunity to discover flattened potentials

\[ 0.01 < r \leq 0.1 \]

suggesting UV origin (e.g. monodromy)

- If exclude \( .002 < r < .1 \), 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 $\to$ 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

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

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

\( \Rightarrow \) e.g. brane motion limited by XD Speed of light (DBI)

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