Modulated Natural Inflation in the CMB

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Natural Inflation

- global $U(1)$ symmetry
  \[ \Phi = f e^{i\varphi/f} \]

- inflaton = goldstone boson (axion)

- shift symmetry broken via $\varphi F\tilde{F}$

\[ V = \Lambda^4 \left( 1 - \cos \left[ \frac{\varphi}{f} \right] \right) \quad f = \text{axion decay constant} \]

- string axions inherit shift symmetries from gauge symmetries

- breaking via gaugino condensation or string instantons, e.g. KKLT
Natural Inflation and the CMB

- Tension with CMB data
- $f > M_P$ does not arise in controllable regime of string theory

Banks, Dine, Fox, Gorbatov, JCAP 0306 (2003), Svrcek, Witten, JHEP 0606 (2006)
Natural Inflation and the CMB

- **tension with CMB data**
- **$f > M_P$ does not arise in controllable regime of string theory**

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Two-axion model

\[ V = \Lambda_1^4 \left[ 1 - \cos \left( \frac{\varphi_1}{f_1} + \frac{\varphi_2}{f_2} \right) \right] \]

\[ + \Lambda_2^4 \left[ 1 - \cos \left( \frac{\varphi_1}{g_1} + \frac{\varphi_2}{g_2} \right) \right] \]

Integrate out

\[ V \sim \Lambda^4 \left( 1 - \cos \frac{\varphi}{f} \right) \]

\[ f \propto \frac{1}{\frac{f_1 g_2}{g_1 f_2} - \frac{g_1}{g_2}} > 1 \]
Axion Alignment Mechanism with Higher Harmonics

- **two-axion model**
  
  \[ V = \Lambda_1^4 \left[ 1 - \cos \left( \frac{\varphi_1}{f_1} + \frac{\varphi_2}{f_2} \right) \right] \times \mathcal{F}_1 + \Lambda_2^4 \left[ 1 - \cos \left( \frac{\varphi_1}{g_1} + \frac{\varphi_2}{g_2} \right) \right] \times \mathcal{F}_2 \]

  \[ \eta(T) = e^{-\pi T/12} - e^{-25\pi T/12} + \ldots \]

- **misalignment**
  
  \[ \frac{f_1}{f_2} \neq \frac{g_1}{g_2} \]

- **alignment**
  
  \[ \frac{f_1}{f_2} \approx \frac{g_1}{g_2} \]

- **integrate out**
  
  \[ V \sim \Lambda^4 \left( 1 - \cos \frac{\varphi}{f} \right) \times \left( 1 - \delta \cos \frac{\varphi}{f_{\text{mod}}} \right) \]
  
  \[ f \propto \frac{1}{f_1 g_2 - g_1 f_2} > 1 \]
Modulations

$V$, $V'$, $V''$

- slow roll parameters
- CMB observables
  \[ r \approx 16\epsilon \]
  \[ n_s \approx 1 - 4\epsilon + 2\eta \]

Modulations mainly affect $n_s$

other inflation models with higher harmonics: Abe, Kobayashi, Otsuka, JHEP 04 (2015), Higaki, Takahashi, JHEP 03 (2015)
\[ V = \Lambda^4 \left( 1 - \cos \frac{\varphi}{f} \right) \times \left( 1 - \delta \cos \frac{\varphi}{f_{\text{mod}}} \right) \]

\[ f_{\text{mod}} = 0.1 M_P \]
$$\delta = 10^{-5}$$

$$V = \Lambda^4 \left( 1 - \cos \frac{\varphi}{f} \right) \times \left( 1 - \delta \cos \frac{\varphi}{f_{\text{mod}}} \right) \quad \text{f}_{\text{mod}} = 0.1 \, \text{M}_\text{P}$$
$\delta = 10^{-4}$

\[ V = \Lambda^4 \left(1 - \cos \frac{\varphi}{f}\right) \times \left(1 - \delta \cos \frac{\varphi}{f_{\text{mod}}}\right) \quad f_{\text{mod}} = 0.1 \, M_P \]
\[ V = \Lambda^4 \left( 1 - \cos \frac{\varphi}{f} \right) \times \left( 1 - \delta \cos \frac{\varphi}{f_{\text{mod}}} \right) \]

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in string/supergravity model modulations grow with increasing $f$

modulations induce running of the spectral index

observable tensor modes predicted $r \sim 0.001 - 0.05$
Running of the Spectral Index

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- modulations induce running of the spectral index

- observable tensor modes predicted $r \sim 0.001 - 0.05$
Primordial Scalar Power Spectrum

small scale suppression hardly visible in CMB power spectrum

- suppressed $\mu$-distortion in CMB

impact on $H_0$, $m_\nu$, ...?
in string realization of natural inflation higher harmonics cause modulations on the potential

this leads to a primordial power spectrum which is observationally distinguishable from $\Lambda$CDM
Backup Slides
Model

- instanton-induced coupling between matter fields $\psi_i$
  $$W = \psi_1 \psi_2 \psi_3 \cdot \eta^n(T) + \psi_1 \psi_4 \psi_5 \quad (\psi_{2\ldots4} \text{ get vev})$$

  $T$: Kähler modulus,
  $$\eta(T) = e^{-\pi T/12}(1 - e^{-2\pi T} + \ldots)$$

- resulting potential for $T = T_0 + \chi + i\varphi$
  $$V \simeq \Lambda^4 \frac{e^{-\chi/f}}{T_0 + \chi} \left( \cosh \left[ \frac{\chi}{f} \right] - \cos \left[ \frac{\varphi}{f} \right] \right)$$
  $$f = \frac{6\sqrt{2}}{n\pi T_0}$$
The Weak Gravity Conjecture

- U(1) gauge symmetry requires particle with \( q/m > 1 \)

- two U(1)s: convex hull of vectors \( \left( \frac{q_1}{m}, \frac{q_2}{m} \right) \) must contain unit ball

- axion related to U(1) via chain of dualities \( q \rightarrow f^{-1}, \ m \rightarrow S \)

- alignment mechanism seems to violate convex hull condition
\begin{itemize}
  \item \textbf{U(1) gauge symmetry requires particle with }$q/m > 1$
    
  
  \item two U(1)s: convex hull of vectors $\left(\frac{q_1}{m}, \frac{q_2}{m}\right)$ must contain unit ball
  
  \item axion related to U(1) via chain of dualities $q \rightarrow f^{-1}, \ m \rightarrow S$
    
  
  \item alignment mechanism seems to violate convex hull condition
  
  \item resolved by subleading instantons
    
    \[ \eta(T) = e^{-\pi T/12}(1 - e^{-2\pi T} + \ldots) \]
\end{itemize}