Natural cliff inflation

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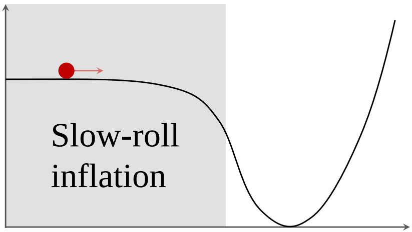
Based on JG and C. S. Shin, arXiv:1711.08270 [hep-ph]

Outline

Managing flat inflaton potential

Successful slow-roll inflation needs flat potential



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

(potential is flat)

$$\eta \equiv m_{\rm Pl}^2 \frac{V''}{V} \ll 1$$

(flatness lasts long enough)

Flatness is fragile under corrections, e.g. η problem (Copeland et al. 1994)

$$\Delta V \sim \frac{\phi^2}{\Lambda^2} V_0 \to \Delta\eta \sim \frac{m_{\rm Pl}^2}{\Lambda^2} \gtrsim 1$$

Inflaton with symmetry

Inflaton protected by symmetry is good, e.g. shift symmetry

Shift symmetry $\phi \to \phi + c$

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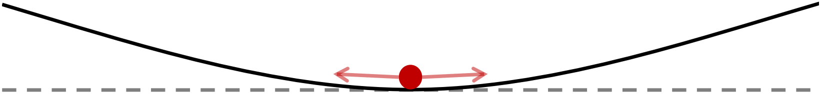

Shift symmetry $\phi \to \phi + c$ is (softly) broken at a scale f so that

$$V(\phi) = \Lambda^4 \left[1 + \cos\left(\frac{\phi}{f} \right) \right]$$

"Natural inflation" (Freese, Frieman & Olinto 1990; Adams et al. 1993)

But CMB observations prefer $f \sim 5 m_{\rm Pl}$, so EFT is doubtful

How to realize natural inflation

We can realize natural inflation by either

1. obtaining (effective) super-Planckian f
   - Extranatural inflation (Arkani-Hamed, Cheng, Creminelli & Randall 2003)
   - Aligned axion (Kim, Nilles & Peloso 2005)
   - N-flaton (Dimopoulos, Kachru, McGreevy & Wacker 2008)
2. finding working models with sub-Planckian f
   - ✓ We present an explicit model that allows $f \ll m_{\rm Pl}$

5D angular field with a zero mode

A 5D angular field $\theta(x, y)$ with shift symmetry ($\theta \to \theta + c$)

$$S[\theta] = \int d^5x \, f_5^3 \left[-\frac{1}{2} (\partial_M \theta)^2 \right]$$

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   - Shift symmetry is (softly) broken
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2. $V_{\text{boundary}}(\theta)$: Potential localized at boundaries
   - With S_1/Z_2, $y_b = 0$ and $y_b = \pi R$
   - Massless mode with a non-trivial profile along y

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Consider e.g. the following potential (Choi, Im & Shin 2017):

$$V_{\rm bulk} + V_{\rm boundary} = -\frac{1}{4}m^2\cos(2\theta) + \frac{1}{4}m^2 - 2m\cos\theta\left[\delta(y) - \delta(y-\pi R)\right]$$

Profile of zero mode in 5D

- Massless mode can be found from 5D action

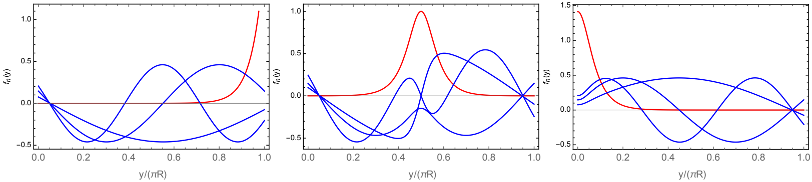
$$S[\theta] = \int d^5x \frac{-f_5^3}{2}\left[(\partial_\mu\theta)^2 + \left(\partial_y\theta + m\sin\theta\right)^2\right]$$

- Mode expansion: $\theta(x,y) = \langle\theta\rangle + \sum_{n=0} f_n(y)\phi_n(x)$ with

$$\langle\theta\rangle = 2\tan^{-1}\left[e^{-my}\langle u(\phi)\rangle\right] \equiv 2\tan^{-1}\left[e^{-m(y-y_0)}\right]$$

  Zero mode is localized according to $\langle\phi\rangle$
- Higher order profiles could be found iteratively

$$f_0(y) \sim \text{sech}[m(y-y_0)]\,, \text{ and so on}$$



Zero mode as a 4D massless field

From the zero mode action (suppressing 4D integral notation)

$$S = \int_0^{\pi R} dy \frac{-f_5^3}{2} (\partial_\mu \theta) = -\frac{1}{2} (\partial_\mu \phi)^2$$

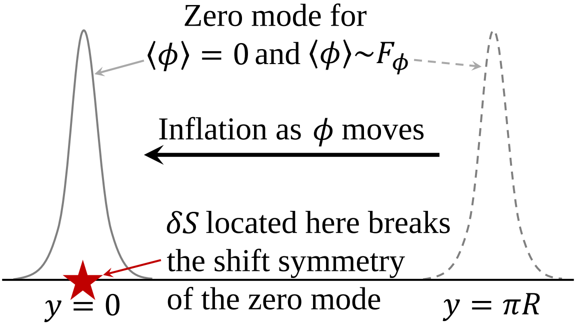
Zero mode θ_0 is eplicitly

$$\theta_0(x,y) = 2\tan^{-1}\left[ie^{-my} \mathrm{sn}\left(\frac{\phi(x)}{2if} \middle| e^{-2m\pi R} \right) \right] \quad \text{with} \quad f \equiv \sqrt{\frac{f_5^3}{2m}\left(1 - e^{-2m\pi R}\right)}$$

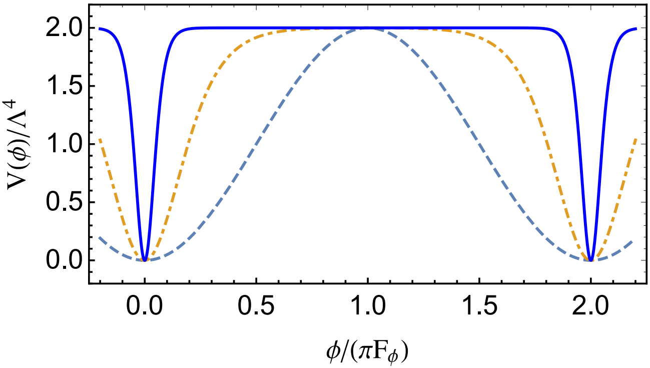
Generation of the potential

Introducing a small perturbation ($\Lambda^4 \ll 2f_5^3 m$) at $y_b = 0$

$$\delta S[\theta] = \int \delta(y)\Lambda^4\left[1-\cos\theta(x,y)\right] \quad \rightarrow \quad V(\phi) = -\Lambda^4 \frac{\mathrm{sn}^2\left(\frac{\phi}{2if}\middle|e^{-2m\pi R}\right)}{1-\mathrm{sn}^2\left(\frac{\phi}{2if}\middle|e^{-2m\pi R}\right)}$$



Shape of the potential



- Half period $\pi F_\phi = 2fK\left(1 - e^{-2m\pi R}\right)$
- Shape is exponentially sensitive to mR

Full analytic results

Given the potential for a canonical field we can find

$$A_{\mathscr{R}} = \frac{1}{6\pi^2}\frac{\Lambda^4}{m_{\rm Pl}^4}\frac{f^2}{m_{\rm Pl}^2}\frac{\mathrm{sn}^4(1-\mathrm{sn}^2)}{\mathrm{cn}^2\mathrm{dn}^2} \approx 2.21\times10^{-9}$$

$$n_{\mathscr{R}} = 1 + \frac{m_{\rm Pl}^2}{f^2}\frac{(1-\mathrm{sn}^2)(\mathrm{cn}^2+\mathrm{dn}^2+\mathrm{cn}^2\mathrm{dn}^2)-\mathrm{cn}^2\mathrm{dn}^2}{\mathrm{sn}^2(1-\mathrm{sn}^2)^2} \approx 0.96$$

$$r = \frac{m_{\rm Pl}^2}{f^2}\frac{-8\mathrm{cn}^2\mathrm{dn}^2}{\mathrm{sn}^2(1-\mathrm{sn}^2)^2} \lesssim 0.07$$

But not very illuminating...

Simplified potential

For $mR = \mathcal{O}(10)$ the potential is approximately

$$V(\phi) \approx \Lambda^4 \tanh^2\left(\frac{\phi}{2f}\right)$$

$$\text{for} \quad |\phi| < \pi F_\phi \approx 2m\pi Rf \approx \sqrt{2m\pi R}\left(\frac{f_5}{M_5}\right)^{3/2} m_{\rm Pl}$$

Half period may well be sub-Planckian for $f_5 \ll M_5$

Inflationary predictions

- Number of e-folds

$$N = \frac{1}{m_{\rm Pl}} \int_{\phi_e}^{\phi_i} \frac{d\phi}{\sqrt{2\epsilon}} \approx \left(\frac{f}{2m_{\rm Pl}} \right)^2 e^{\phi_i/f}$$

- Spectral index

$$n_{\mathcal{R}} - 1 = 1 - \frac{4[1+\cosh(\phi_i/f)]\mathrm{csch}^2(\phi_i/f)}{(f/m_{\rm Pl})^2} \approx 1 - \frac{2}{N}$$

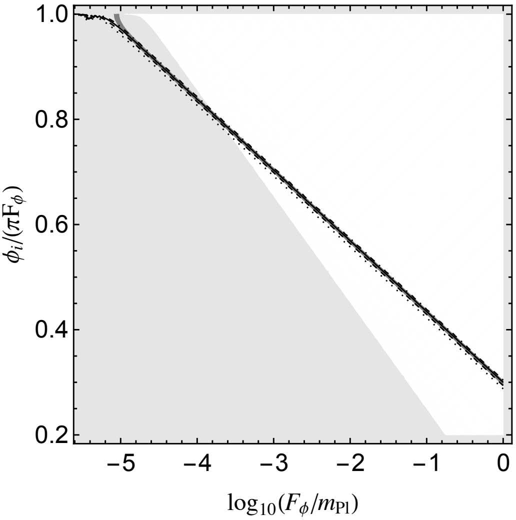
The same as many favoured models

- Tensor-to-scalar ratio

$$r = \frac{32\mathrm{csch}^2(\phi_i/f)}{(f/m_{\rm Pl})^2} \approx \frac{8}{N^2} \left(\frac{f}{m_{\rm Pl}} \right)^2$$

Compared to R^2 model, further suppressed by $(f/m_{\rm Pl})^2$

Parameter space

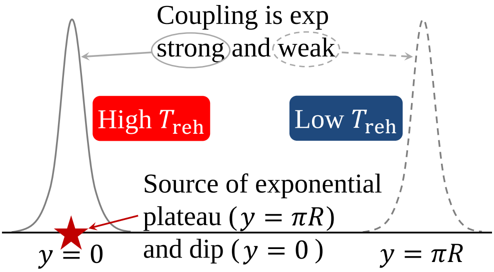


Sub-Planckian field range can do the job

Reheating after inflation

Anormalous coupling gives interaction bet inflaton and gauge fields

$$\int d^5x\,\delta(\text{SM location})c_\gamma\theta(x,y)F_{\mu\nu}(x)\widetilde{F}^{\mu\nu}(x) \rightarrow \delta\mathscr{L}\sim\frac{c_\gamma}{f}\delta\phi F\widetilde{F}$$



For fiducial values $F_\phi\sim10^{-3}m_{\rm Pl}$ and $mR=5$, if SM lives at...

- $y=0$: $T_{\rm reh}=\sqrt{\Gamma_\phi m_{\rm Pl}}\sim10^{13}$ GeV
- $y=\pi R$: suppressed by $e^{-m\pi R}\sim10^{-7}$ and $T_{\rm reh}\sim10^6$ GeV

1 Introduction

2 Model

3 Prediction

4 Conclusions

Conclusions

- Realizing natural inflation concerns the value of f
- Setup
  - Zero mode of 5D angular field
  - Exponentially flat hilltop and cliff-like minimum
- Inflation
  - Simple analytic results for reasonable parameters
  - Sub-Planckian field excursion