Slow-roll inflation model from higher-dimensional gravity with a U(1) gauge theory

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1. Motivation: Fine-tuning problem in slow-roll inflation

Slow-roll inflation model : **Basic inflation parameters are known.** Planck (2013)

$$\epsilon \sim \left(\frac{V'}{V}\right)^2, \quad \eta \sim \frac{V''}{V} \ll 1 \quad (n_s \simeq 0.96) \qquad \mathcal{P}_\zeta \sim \frac{V}{M_P^4 \epsilon} \sim 10^{-9}$$

→ **nearly flat potential** → **small-sized potential**

Severe restrictions on the couplings in inflaton potential $V(\phi)$

i) Huge quantum correction → **Fine-tuning of** c_n **(like in Higgs potential,** $\delta m^2 \sim \lambda\Lambda^2$**)**

ii) BICEP2: tensor to scalar ratio $r \gtrsim 0.1$ → **Large field inflation** $\Delta\phi > M_P$

Dangerous higher-dim. operators

$$V(\phi) \sim \Sigma_n c_n \frac{\phi^n}{M_P^{n-4}}$$

fine-tuning problem in inflation

A solution for the fine-tuning problem in inflation

Inflation from higher dimensional theories:

Bottom-up = our approach

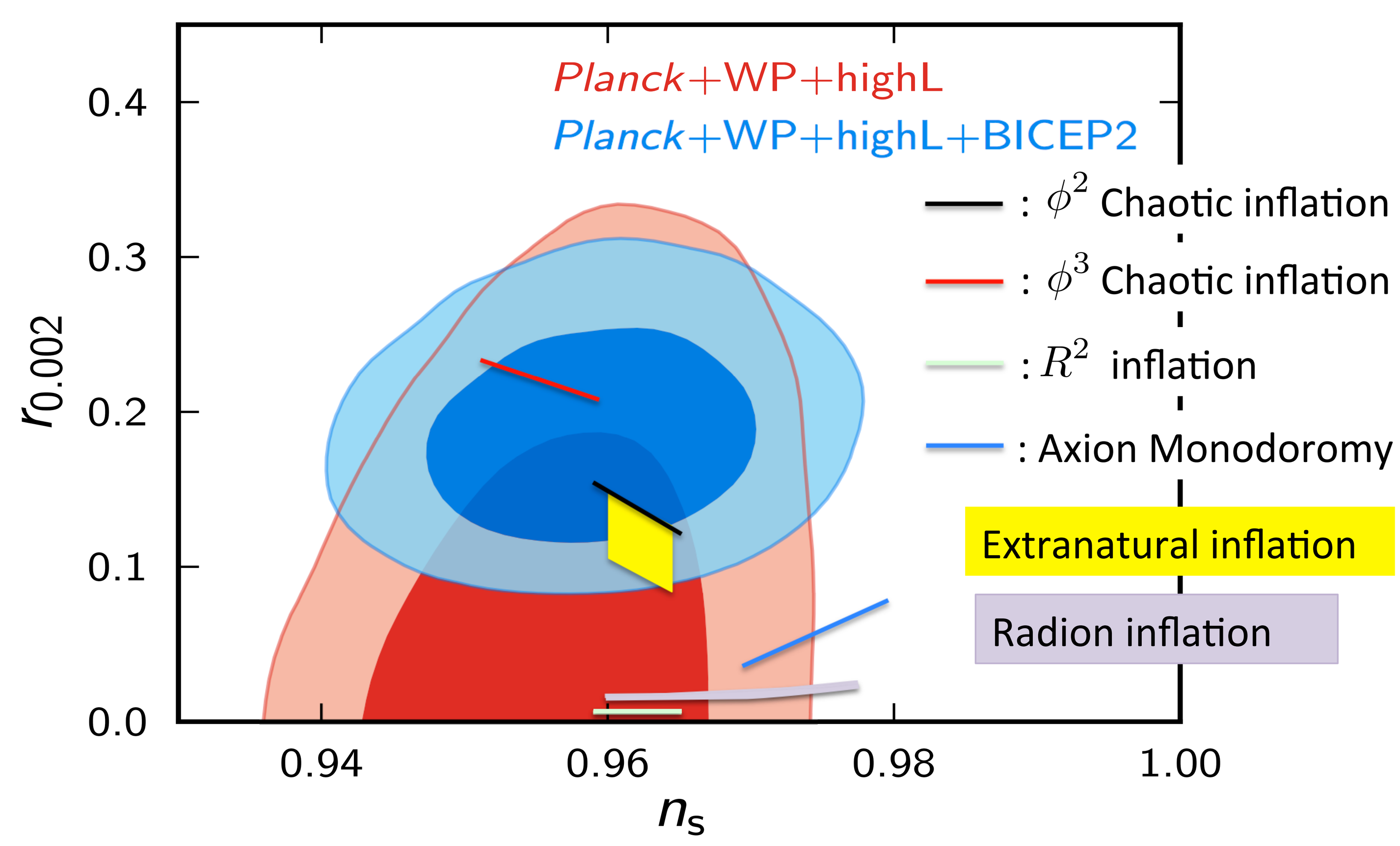
Scalar potential is protected by the gauge symmetry in the extra dimensions from huge quantum corrections.

···· **Naturalness** 't Hooft (1980)

The potential of the inflaton begins to be generated at loop level.

- **The potential is finite.**
- **No dangerous higher operators.**

~comparison with other inflation model~



Spectral index and tensor to scalar ratio

Planck & BICEP2 (13,14)

• Extranatural inflation

Arkani-Hamed et al(2003)

$$A_5^{(0)} = \phi$$

$$V(\phi) = \frac{3}{\pi^2 L^4} \sum_{n=1}^{\infty} \frac{1}{n^5} \cos(n\phi/f)$$

$f = \frac{1}{gL}$ **: an important parameter in extranatural**

• Radion inflation

Fukazawa et al(2012)

$$g_{55}^{(0)} = \phi$$

$$V(\phi) = \frac{3}{4\pi^2} \frac{1}{\phi^2 L^4} \left(-5\zeta(5) + 4c[\mathrm{Li}_5(e^{-Lm\phi^{1/3}}) + \cdots]\right)$$

S^1 **circumference** $L = 2\pi R$ $\qquad \mathrm{Li}_n(x) = \sum_{k=1}^{\infty} \frac{x^k}{k^n}$

Cf. Slow-roll (axion) inflation from string theory : (Top-down)

axion monodromy Silverstein et al(2008), **Multi axion …**

It is natural to ask what happens when the both scalars contribute to the potential energy of the universe.

Question: **Which scalar is responsible for inflation? Radion or gauge scalar?**

2. Our model: 5D gravity + $U(1)$ gauge theory

Model, radion and gauge scalar $M_5 \to M_4 \times S^1$

$$S_{5D} = \int d^5x\sqrt{-\hat{g}_5}\left[\frac{1}{16\pi G_5}\hat{R}_5 - \frac{1}{4}\hat{g}^{MP}\hat{g}^{NL}F_{MN}F_{PL} + \bar{\psi}_i(i\hat{g}^{MN}\Gamma_M D_N - m)\psi_i + \bar{\eta}_l(i\hat{g}^{MN}\Gamma_M\partial_N - \mu)\eta_l\right]$$

$\langle\Phi^{(0)}\rangle = \phi$: radion $\qquad \langle B_5^{(0)}\rangle = \theta f$: gauge-scalar (Higgs)

$L_{\rm phys} = \int dy\sqrt{\hat{g}_{55}} = \phi^{1/3}L$: physicl size of the 5th dimension

Field content:

$$\hat{g}_{MN} = \Phi^{-\frac{1}{3}}\begin{pmatrix} g_{\mu\nu} + A_\mu A_\nu \Phi & A_\mu\Phi \\ A_\nu\Phi & \Phi \end{pmatrix}$$

$B_M = (B_\mu, B_5)$: $U(1)$ gauge boson

ψ_i : $U(1)$ charged fermion $(i = 1, \ldots, c_1)$

η_l : neutral fermion $(l = 1, \ldots, c_2)$

One-loop effective potential for radion and gauge scalar

$$V(\phi,\theta) = -\frac{6}{\pi^2}\frac{1}{\phi^2L^4}\zeta(5) + c_1\frac{3}{\pi^2}\frac{1}{\phi^2L^4}{\rm Re}\left[{\rm Li}_5(e^{-Lm\phi^{1/3}}e^{i\theta}) + Lm\phi^{1/3}{\rm Li}_4(e^{-Lm\phi^{1/3}}e^{i\theta}) + \frac{1}{3}L^2m^2\phi^{2/3}{\rm Li}_3(e^{-Lm\phi^{1/3}}e^{i\theta})\right]$$
$$+c_2\frac{3}{\pi^2}\frac{1}{\phi^2L^4}\left[{\rm Li}_5(e^{-L\mu\phi^{1/3}}) + L\mu\phi^{1/3}{\rm Li}_4(e^{-L\mu\phi^{1/3}}) + \frac{1}{3}L^2\mu^2\phi^{2/3}{\rm Li}_3(e^{-L\mu\phi^{1/3}})\right].$$

$${\rm Li}_n(x) = \sum_{k=1}^{\infty}\frac{x^k}{k^n}$$

Radion and gauge scalar couple through the charged fermion loop.

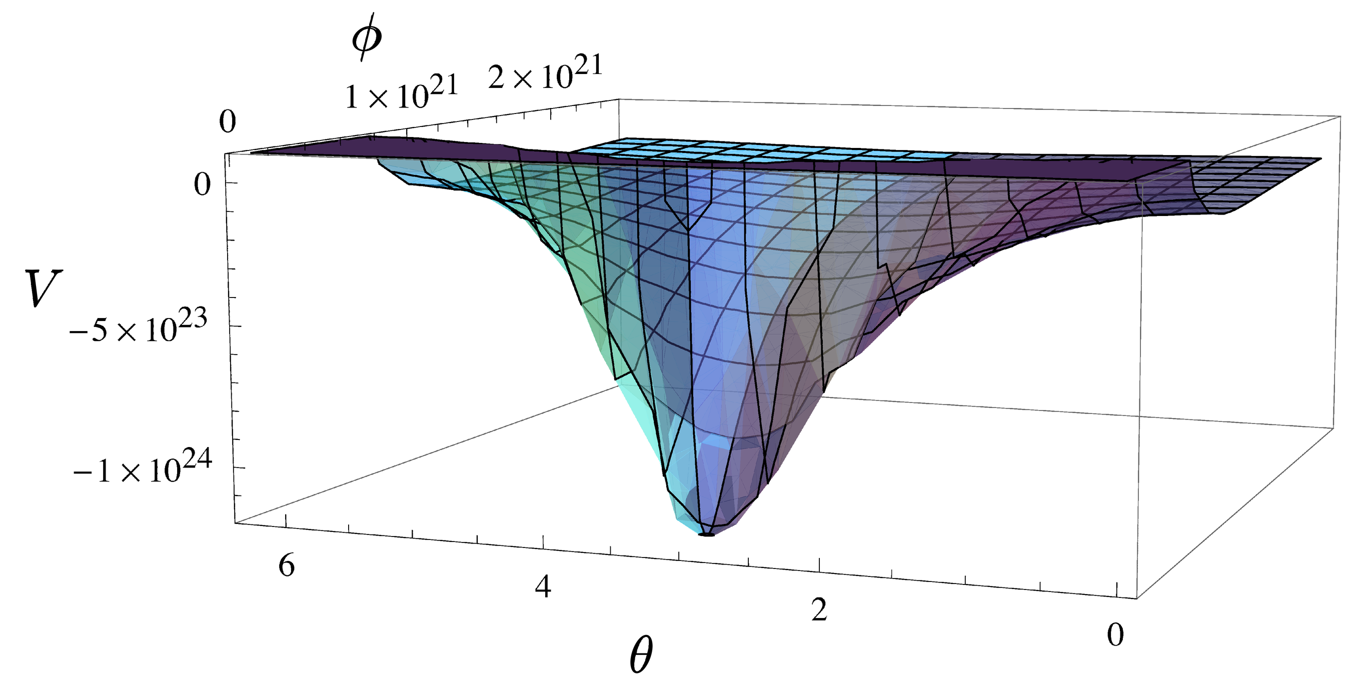
For $\theta > \pi/2$ the gauge scalar potential becomes attractive.

Radion stabilization in the presence of Wilson line phase

Neutral fermions play an important role in making a stable minimum perturbatively. Namely we impose

$$c_2 > 2 + c_1$$

Cf. moduli stabilization in string theory.
Flux compactification (non-perturbative)..



One-loop effective potential

3. Application to slow-roll inflation: Hybrid model

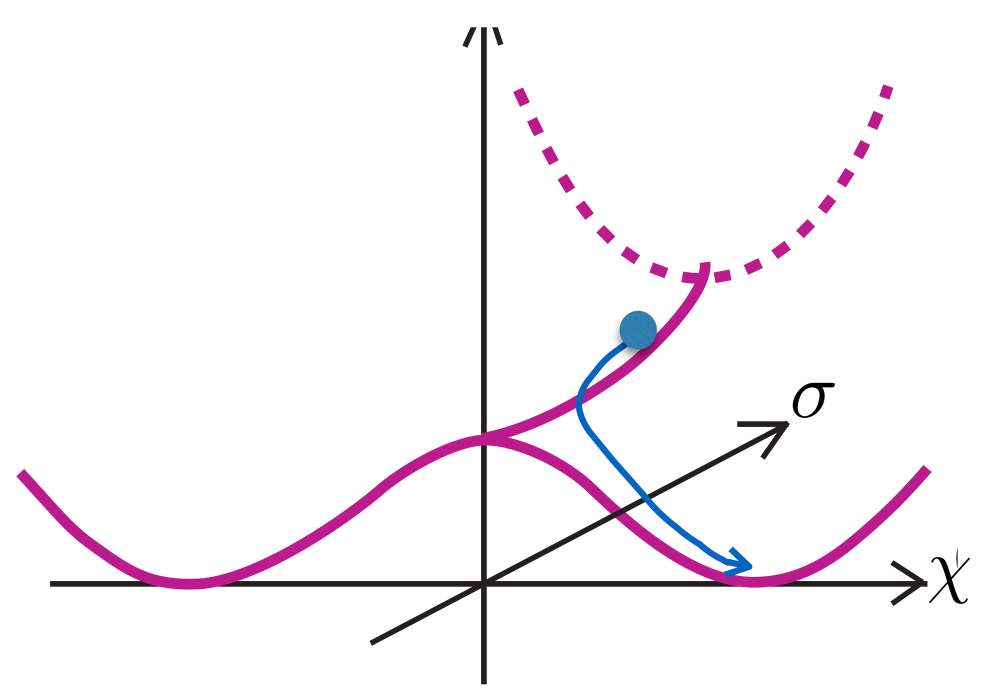
The most interesting possibility is hybrid inflation.

Gauge scalar = Inflaton σ

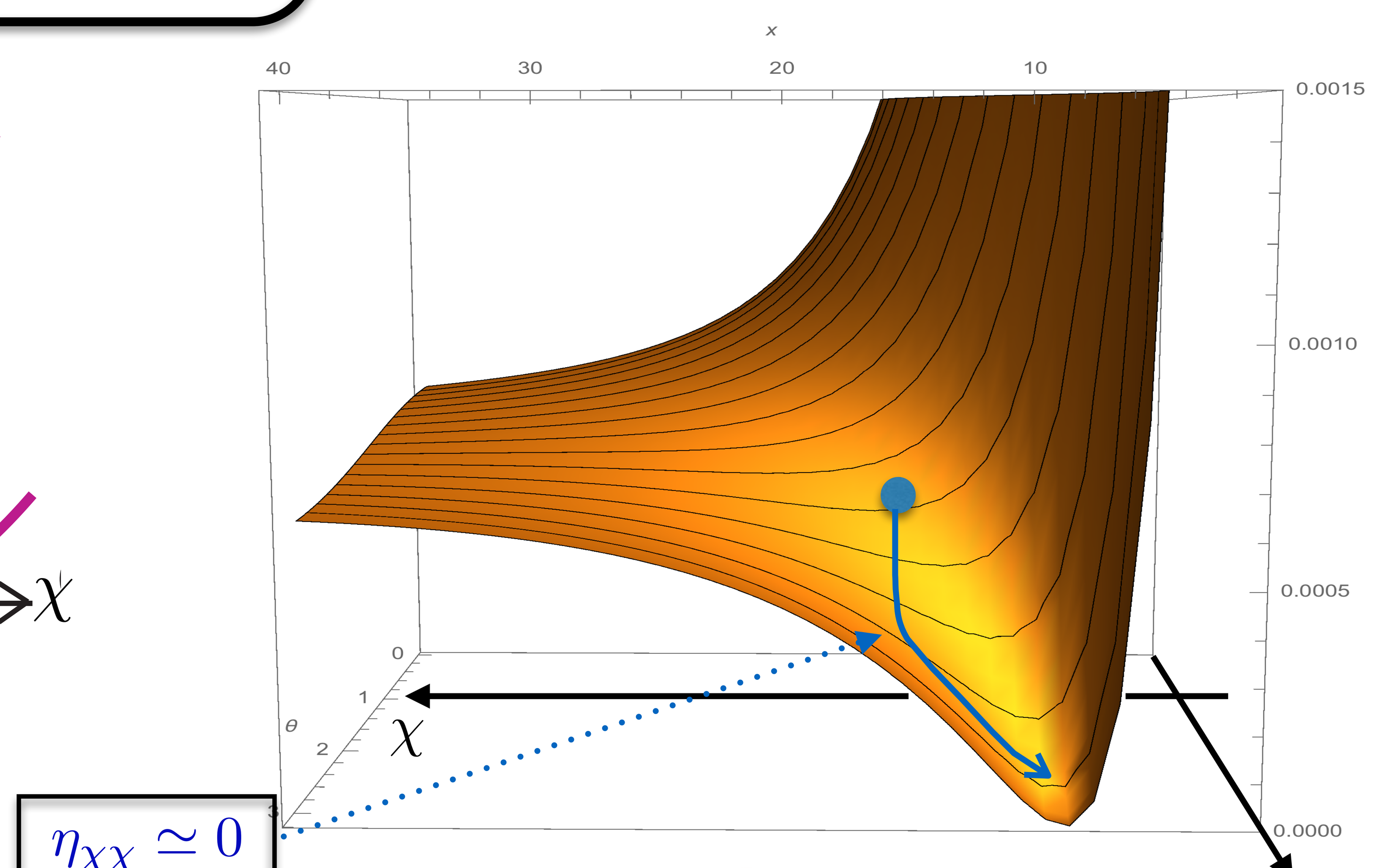
$$\sigma = \theta f \qquad f = \frac{1}{gL}$$

Radion = Waterfall field χ

$$\chi = \frac{M_P}{\sqrt{3}}\ln\phi$$



Trajectory: original hybrid



Trajectory: Our potential

- To achieve nearly zero vaccum energy

5D cosmological constant term $aL\phi^{-1/3}$ ➡ $V_{\rm min} \sim 0$ (We need a fine-tuning in a.)

Model parameters
$a,\ c_1,\ c_2,\ g,\ L,\ m,\ \mu$

The simplest case:
$c_1 = 1,\ c_2 = 4,\ \mu = m$

Free parameters:
$g,\ L,\ m$

Inflation parameters are determined by inflaton slow-roll parameters (Instantaneous waterfall)

$$n_s = 1 - 6\epsilon_{\sigma_*} + 2\eta_{\sigma\sigma_*} = 0.96 \Longrightarrow f, m$$

$$N = M_P^{-1}\int_{\sigma_e}^{\sigma_*}\frac{1}{\sqrt{2\epsilon_\sigma}}d\sigma = 50 - 60 \Longrightarrow \sigma_*$$

$$\mathcal{P}_\zeta = \frac{V_*}{24\pi^2M_P^4\epsilon_{\sigma_*}} \simeq 2.2\times10^{-9}$$
$$r = 16\epsilon_{\sigma_*} \qquad \Longrightarrow g, f, m \quad (m_\sigma)$$

We are investigating if the hybrid inflation actually occurs in our toy model and whether the values of g, L, m are natural or not.