$U(1)_{B-L}$ Extra-Natural Inflation with Standard Model on a Brane

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Plan

- Introduction
- $U(1)_{B-L}$ Extra-Natural Inflation
- $U(1)_{B-L}$ Extension of Standard Model
- Summary

Motivations

Why extra-natural inflation?

- Natural large field inflation model
- EFT approach valid

Why $U(1)_{B-L}$?

- RH neutrinos necessitated by gauge anomaly cancellation
- Ubiquitous in beyond the SM scenarios
  - Appears in GUT and string theory embeddings
  - R-parity made exact in SUSY versions of SM

The Scenario

- (4+1)-dimensional bulk spacetime
- Extra-dimension compactified on S^1 of radius L_5
- SM on (3+1)-dimensional brane localized in extra dimension
- $U(1)_{B-L}$ gauge theory in bulk
- Inflaton from Wilson loop of $U(1)_{B-L}$ gauge field

Ingredients of Extra-Natural Inflation

The potential:

$$V(\phi) = \frac{V_0}{2}\left[1 - \cos\left(\frac{\phi}{f}\right)\right], \quad V_0 = \frac{c_0}{\pi^2}\frac{1}{(2\pi L_5)^4}$$

- c_0 "counts" $U(1)_{B-L}$-charged fields with $m \lesssim L_5^{-1}$
- **Decay constant**: $f^{-1} = g_4(2\pi L_5)$
  - g_4 **4D gauge coupling**

For small quantum gravity correction: $\ell_5^3 \equiv (L_5 M_5)^3 \gg 1$

- $M_P^2 = M_5^3(2\pi L_5)$, $M_P \simeq 2.4 \times 10^{18}$ GeV
- $\ell_5 = \frac{1}{2\pi}\left(\frac{M_P}{g_4 f}\right)^{2/3}$

Slow-roll Inflation

Slow-roll parameters:

$$\epsilon(\phi) \equiv \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2 = \frac{M_P^2}{2f^2}\frac{1+\cos\frac{\phi}{f}}{1-\cos\frac{\phi}{f}} \ll 1$$

$$\eta(\phi) \equiv M_P^2\frac{V''}{V} = \frac{M_P^2}{f^2}\frac{\cos\frac{\phi}{f}}{1-\cos\frac{\phi}{f}} \ll 1$$

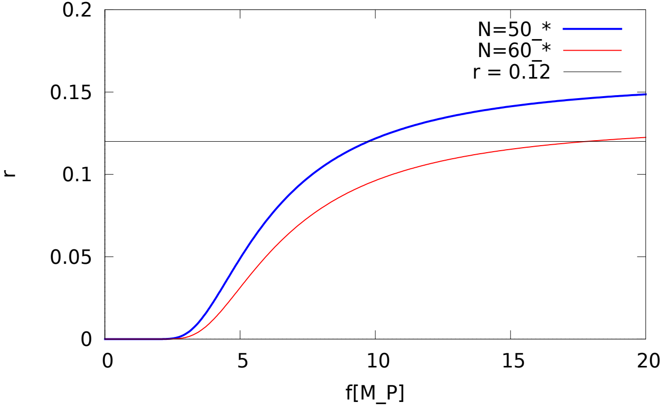
Number of e-folds:

$$N(\phi) = -\int_{\phi}^{\phi_e}\frac{d\phi}{M_P^2}\frac{V}{V'} = -\left(\frac{f}{M_P}\right)^2\log\left[\frac{1}{2}\left(1+\cos\frac{\phi}{f}\right)\right]_{\phi_e}^{\phi}$$

- ϕ_e defined by $\epsilon(\phi_e) = 1$
- $\phi = \phi(f, N)$

Scalar-to-Tensor Ratio

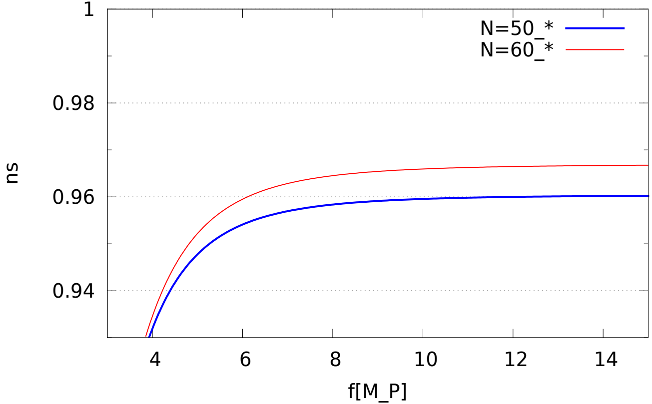
$$r = 16\epsilon$$



Pivot scale $k_* = 0.002\,Mpc^{-1}$

Spectral Index

$$n_s = 1 - 6\epsilon + 2\eta$$



Pivot scale $k_* = 0.002\,Mpc^{-1}$

Slow-roll Power Spectrum

For spatially flat universe in slow-roll approximation:

- **Friedman equation**: $3H^2 M_P^2 = \rho = V(\phi)$

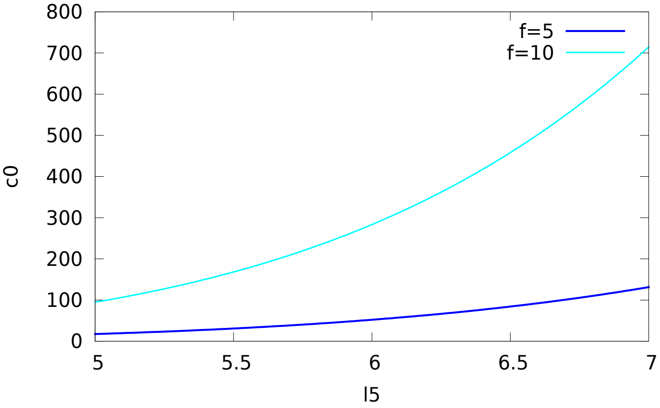
Power spectrum:

$$P_\zeta(k_*) = \frac{H^2}{8\pi^2 M_P^2 \epsilon} = \frac{V(\phi_*)}{24\pi^2 M_P^4 \epsilon_*}$$
$$= \frac{c_0}{2\pi^2} \frac{1}{(2\pi\ell_5)^6} \left[1 - \cos\frac{\phi(f, N_*)}{f}\right] \frac{1}{24\pi^2 \epsilon(f, N_*)}$$

- **Observed value**: $P_\zeta(k_*) = 2.2 \times 10^{-9}$
- c_0 determined once ℓ_5, f, N_* given

Behaviour of c_0

$$c_0 \sim \ell_5^6$$



$$N_* = 50$$

Natural Parameter Values

Naturalness:

- $N_* \simeq 50$ (from inflaton decay; see later)
- $c_0 \sim \mathcal{O}(10)$

Observational constraints:

- $r \lesssim 0.12 \Rightarrow f \lesssim 10 M_P$
- $n_s > 0.94 \Rightarrow f \gtrsim 5 M_P$

Preferred value: $\ell_5 \simeq 5,\ f \simeq 5$

$$g_4 \simeq 10^{-3},\ L_5^{-1} \simeq 10^{17}\ \text{GeV}$$

$U(1)_{B-L}$ Standard Model

Particle content and charge assignment:

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
q_L^i	**3**	**2**	$+1/6$	$+1/3$
u_R^i	**3**	**1**	$+2/3$	$+1/3$
d_R^i	**3**	**1**	$-1/3$	$+1/3$
ℓ_L^i	**1**	**2**	$-1/2$	-1
ν_R^i	**1**	**1**	0	-1
e_R^i	**1**	**1**	-1	-1
H	**1**	**2**	$-1/2$	0
Σ	**1**	**1**	0	$+2$

- **4D brane fields**: SM and RH neutrinos
- **5D bulk fields**: $U(1)_{B-L}$ gauge field A_M, complex scalar Σ

Scalar Sector

4D scalar potential:

$$V(H,\Sigma) = \mu_H^2 H^\dagger H + \mu_\Sigma^2 \Sigma_0^* \Sigma_0 + \frac{\lambda_1}{2}(H^\dagger H)^2 + \frac{\lambda_2}{2}(\Sigma_0^* \Sigma_0)^2 + \lambda_3 H^\dagger H \Sigma_0^* \Sigma_0$$

- Σ_0 zero mode of Σ in the extra dimension

After SSB: Σ breaks $U(1)_{B-L}$, m_W fixes $v_H = 246$ GeV

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_H + h \end{pmatrix}, \qquad \Sigma_0 = \frac{v_\Sigma + s}{\sqrt{2}}$$

$$\frac{v_H^2}{2} = \frac{-\mu_H^2 \lambda_2 + \mu_\Sigma^2 \lambda_3}{\lambda_1 \lambda_2 - \lambda_3^2}, \qquad \frac{v_\Sigma^2}{2} = \frac{-\mu_\Sigma^2 \lambda_1 + \mu_H^2 \lambda_3}{\lambda_1 \lambda_2 - \lambda_3^2}$$

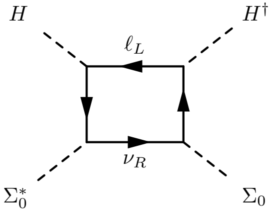
Neutrino Sector

See-saw mechanism:

$$\mathcal{L} \supset -Y_D^{ij}\,\overline{\nu_R^i}\,H^\dagger\,l_L^j - \frac{1}{2}\,Y_N^{ij}\,\overline{\nu_R^{ic}}\,\nu_R^j\,\Sigma_0 + h.c.$$

- **Active neutrino mass**: $m_\nu \sim Y_D^2 v_H^2 / M_N$
- **RH neutrino mass**: $M_N = Y_N v_\Sigma / \sqrt{2}$

Scalar mixing $H^\dagger H \Sigma_0^* \Sigma_0$ induced at one-loop:



Constraints

Higgs mass contribution:

$$\delta m_H^2 \sim \frac{Y_D^2 Y_N^2}{(4\pi)^2} \frac{v_\Sigma^2}{2} \sim \frac{m_\nu M_N^3}{(4\pi)^2 v_H^2}$$

Naturalness: $m_H = 126$ GeV, $\sqrt{\delta m_H^2} \lesssim \mathcal{O}(100)$ GeV

Bench mark: $m_\nu \sim 0.1$ eV

- **B-L breaking scale**: $M_N \lesssim 10^7$ GeV, $v_\Sigma \lesssim 10^7 / Y_N$ GeV
- $|\lambda_3| \sim \frac{m_\nu M_N}{(4\pi)^2 v_H^2} Y_N^2 \lesssim 10^{-10}\, Y_N^2$
- $m_{Z'} \sim g_4 v_\Sigma \lesssim \mathcal{O}(10)$ TeV
- **Collider limit**: $m_{Z'} \geq g_4 \times (6\,\mathrm{TeV}) \gtrsim 6$ GeV

Inflaton Decay

$\mathbb{Z}_2$ **symmetry**: $x^5 \to -x^5$, $A_5 \to -A_5$

- Inflaton absolutely stable if exact

$\mathbb{Z}_2$**-breaking Chern-Simons coupling**:

$$S_{CS} = \frac{k}{48\pi^3} \int \mathcal{A}\mathcal{F}^2 = g_4^2 \frac{k}{16\pi^2} \int d^4x \frac{\phi}{2\pi f} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Dominant decay width:

$$\Gamma_{\phi \to AA} \simeq \frac{g_4^4}{16\pi} \left(\frac{k}{32\pi^3} \right)^2 \frac{m_\phi^3}{f^2}$$

Inflaton mass: $\ell_5 \simeq 5$, $f \simeq 5 M_P$

$$m_\phi^2 = \frac{V_0}{2f^2} = \frac{c_0}{2\pi^2} g_4^4 f^2 \simeq 10^{13}\,\mathrm{GeV}$$

Reheating

Reheating temperature:

$$T_R = \left(\frac{90}{\pi^2 g_\star(T_R)}\right)^{1/4} \sqrt{\Gamma M_P}$$

$$\simeq \left(\frac{90}{g_\star(T_R)}\right)^{1/4} \frac{g_4^2}{4\pi} \frac{|k|}{32\pi^3} \sqrt{\frac{m_\phi^3 M_P}{f^2}} \simeq |k| \times 1\,\mathrm{GeV}$$

- $T_R \simeq 1 \sim 10$ GeV, $g_\star(T_R) \simeq 60 \sim 90$

Standard estimate:

$$N_* \simeq 49 + \frac{2}{3} \ln\left(\frac{\rho_*^{1/4}}{10^{16}\,\mathrm{GeV}}\right) + \frac{1}{3} \ln\left(\frac{T_R}{1\,\mathrm{GeV}}\right)$$

- $N_* \simeq 50$ natural

Summary

- Cosmological observations constrain the $U(1)_{B-L}$ gauge coupling to $g_4 \lesssim 10^{-3}$, which in turn constrains the particle physics scenario at high energy assuming naturalness.
- Allowed interaction between the inflaton and SM particles restricted by the higher-dimensional set-up, which enables a simple determination of the reheating temperature T_R.

Future directions:

- Baryon asymmetry
- Dark matter
- String theory embedding