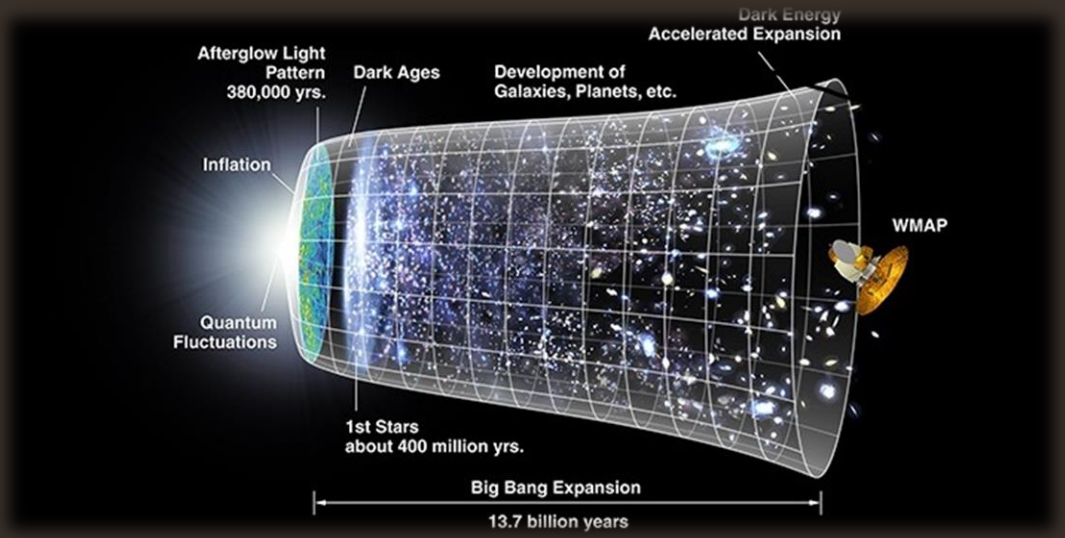


Inflection-point B-L Higgs Inflation

Digesh Raut
University of Alabama

"Inflection-point B-L Higgs Inflation,"

By *Nobuchika Okada* and *Digesh Raut*.
(Work in progress)

Standard Big-Bang Cosmology and Inflation

- Flatness Problem (Fine-tuning Problem)
  - Our universe is very flat today. : $\Omega(t_0) = 1.02 \pm 0.02$.
  - Requires Extreme Fine-Tuning : 10^{-4} (recombination) and 10^{-16} (BBN)
- Horizon Problem
  - Angular size of causally connected patches at CMB $\simeq$ 1.6^{0}

- Inflationary Solution
  - Phase of accelerated expansion before BBN era

Inflation: ⟶ $a(t_E) = a(t_I)\, e^{\sim 60}$

- Primordial Density Fluctuation
  - CMB Temperature Fluctuation ⟺ Primordial Density Fluctuation

$$\frac{\delta T}{T} \cong 10^{-5} \quad \text{(Planck +WMAP)}$$

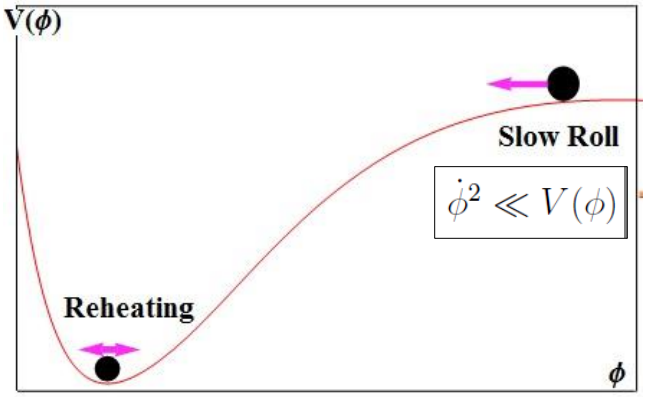
  - Standard Big Bang Cosmology does not explain the origin of these fluctuations
  - Inflation scenario naturally generates such density fluctuation

Single Scalar Field: Slow Roll Inflation Scenario

- Slow Roll Inflation

$$\epsilon(\phi) = \frac{Mp^2}{2}\left(\frac{V'}{V}\right)^2$$
$$\eta(\phi) = Mp^2\left(\frac{V''}{V}\right)$$

Slow Roll Conditions $\{\epsilon,\ |\eta|\} \ll 1$



- E-folding Number : $N = \int_{\phi_E}^{\phi_I}\left(\frac{V}{V'}\right)\mathrm{d}\phi$ N ≃ 60

- Observables

$$n_s = 1 - 6\epsilon + 2\eta$$
$$r = 16\epsilon$$
$$\Delta^2_{\mathcal{R}} = \frac{1}{24\pi^2}\frac{1}{Mp^4}\frac{V}{\epsilon}\Big|_{k_0}$$

$$n_s \simeq 0.9603 \pm 0.0073$$
$$r \leq 0.11$$
$$\Delta^2_{\mathcal{R}} = 2.95 \times 10^{-9}$$

Planck 2015 Measurements

Small Field Inflation : $\phi_I < m_{pl}$

- Inflection point inflation is unique realization for small field inflation when inflation is driven by single scalar field .

Inflection Conditions $V'(\phi_I) \simeq 0 \qquad V''(\phi_I) \simeq 0$

Inflection Point Analysis

- Potential Expansion

$$V(\phi) = V0 + V1(\phi - M) + \frac{V2}{2}(\phi - M)^2 + \frac{V3}{6}(\phi - M)^3$$

M = ϕ_I

- Inflationary parameters and Power-Spectrum

$$\epsilon(M) = \frac{Mp^2}{2}\left(\frac{V1}{V0}\right)^2$$
$$\eta(M) = Mp^2\left(\frac{V2}{V0}\right)$$

$$\Delta^2_{\mathcal{R}} = \frac{1}{12\pi^2}\frac{1}{Mp^6}\frac{V0^3}{V1^2}$$

V1

Small Field Inflation : $\phi_I < m_{pl}$

- End of Inflation

$$\frac{\phi_E}{M} \simeq (1-\delta)\,, \qquad \delta << 1$$

$$\eta(\phi) \simeq Mp^2 \frac{V3(\phi - M)}{V0}$$

$$V2 \ll V3(\phi - M)$$

$$\delta = \frac{1}{Mp^2}\frac{V0}{M\,V3}.$$

- E-folding Number

$$N \simeq \frac{1}{Mp^2}\left(\frac{V0}{V'}\right)\Delta\phi = \frac{1}{Mp^4}\frac{V0^2}{V1\,V3}$$

V3

- Spectral Index

$$\epsilon \ll 1$$

$$n_s \simeq 1 + 2\eta$$

V2

Small Field Inflation : $\phi_I < m_{pl}$

- Constraints on Potential

$$V0 \simeq \frac{1}{4}\lambda M^4$$

$$\begin{aligned}
\frac{V1}{M^3} &\simeq 211\left(\frac{M}{Mp}\right)^3\lambda^{3/2}, \\
\frac{V2}{M^2} &\simeq -4\times 10^{-3}\left(\frac{M}{Mp}\right)^2\lambda, \\
\frac{V3}{M} &\simeq 5\times 10^{-6}\frac{N0}{N}\left(\frac{M}{Mp}\right)\lambda^{1/2}.
\end{aligned}$$

N0 ≃ 60

- Successful Small-field Inflation Requires,
  - Realization of almost Inflection-like behavior.
  - $\lambda << 1$.

B-L Particle Content

- Minimal B-L(Baryon-Lepton) Extension of Standard Model
  - 3 generation of right handed Neutrinos (N_i) to make theory free of gauge anomaly.
  - B-L Higgs Field (φ) to break the B-L gauge symmetry.
  - B-L symmetry breaking generates Z' boson mass and Majorana mass for N_i.

$$\mathcal{L} \supset -\frac{1}{2}\sum_{i=1}^{3} Y\ \varphi\ \overline{N^c} N + \text{h.c.}$$

  - See-Saw Mechanism
  - Mass Spectrum : $m_{NR} = \frac{1}{\sqrt{2}} Y_N v_{BL},\ m_{Z'} = 2 g v_{BL},\ m_\phi^2 = 2\lambda v_{BL}^2$

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
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
NR^i	1	1	0	-1
e_R^i	1	1	-1	-1
H	1	2	$-1/2$	0
φ	1	1	0	$+2$

Model: N with degenerate mass spectrum

RGE Improved B-L Higgs Potential

- Tree Level B-L Higgs Potential

$$V_{tree}(|\varphi|) = \lambda_{tree}\left(\varphi^{\dagger}\varphi - \frac{v_{BL}^2}{2}\right)^2, \qquad \varphi = \frac{1}{\sqrt{2}}(\phi + v_{BL}).$$

- RGE B-L Higgs Potential

$$V(\phi) = \frac{1}{4}\lambda(\phi)\phi^4$$

- B-L RGE Running

$$\begin{aligned}
16\pi^2\mu\frac{dg}{d\mu} &= 12g^3, \\
16\pi^2\mu\frac{dY}{d\mu} &= -6g^2Y + \frac{5}{2}Y^3, \\
16\pi^2\mu\frac{d\lambda}{d\mu} &= 20\lambda^2 - (48g^2 - 6Y^2)\lambda + 96g^4 - 3Y^4.
\end{aligned}$$

RGE Improved B-L Higgs Potential

- RGE Improved Quartic Coupling (λ)

$$16\pi^2\mu\frac{d\lambda}{d\mu} = \beta_\lambda$$

$$\beta_\lambda(M) = \frac{1}{16\pi^2}\left[20\lambda^2 - 48g^2\lambda + 96g^4 + 6\lambda Y^2 - 3Y^4\right] \qquad \lambda \ll 1$$

- Inflection Analysis

$$\begin{aligned}
\frac{V'}{\mu^3} &= \frac{1}{4}(4\lambda + \beta_\lambda), \\
\frac{V''}{\mu^2} &= \frac{1}{4}(12\lambda + 7\beta_\lambda + \mu\beta'_\lambda), \\
\frac{V'''}{\mu} &= \frac{1}{4}(24\lambda + 26\beta_\lambda + 10\mu\beta'_\lambda + \mu^2\beta''_\lambda)\ .
\end{aligned}$$

Inflection Constraint on RGE Improved B-L Potential

- λ and Inflation-scale (M)

Inflationary Analysis

$$\frac{V3}{M} \simeq 5 \times 10^{-6} \frac{N0}{N} \left(\frac{M}{Mp}\right) \lambda^{1/2}$$

RGE Analysis

$$\frac{V3}{M} = \frac{1}{4}(24\lambda + 26\beta_\lambda + 10M\beta'_\lambda + M^2\beta''_\lambda)$$

$$V1 \simeq 0, \qquad V2 \simeq 0, \qquad M^2\beta''_\lambda(M) \ll M\beta'_\lambda(M), \qquad \lambda \simeq 4.53 \times 10^{-14} \frac{M}{Mp}$$

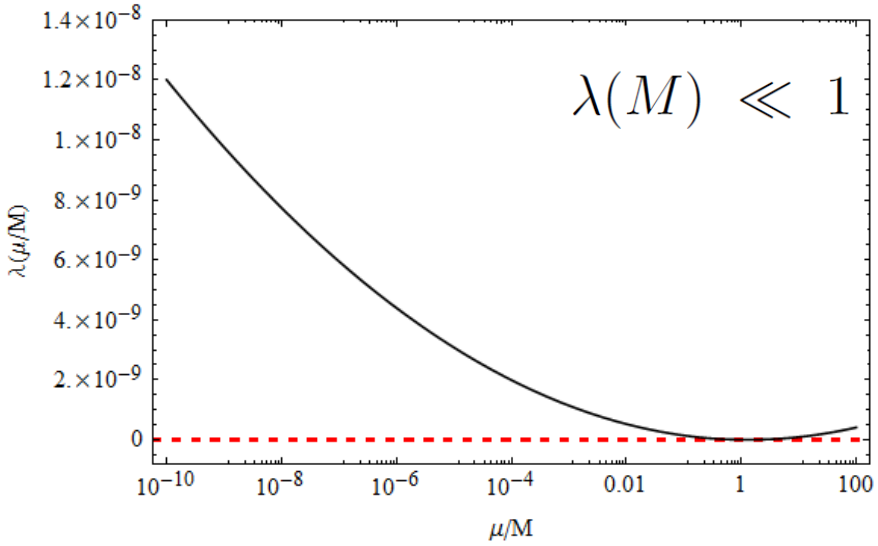
- λ and Gauge Coupling

$$V1 \simeq 0, \qquad V2 \simeq 0. \qquad \Rightarrow \qquad \lambda \simeq \frac{1}{16} M\beta'_\lambda(M)$$

$$\beta_\lambda(M) \simeq 0, \qquad \lambda \ll 1. \qquad \Rightarrow \qquad Y \simeq 2^{5/4} g \qquad \lambda \simeq 3.71 \times 10^{-3} g^6$$

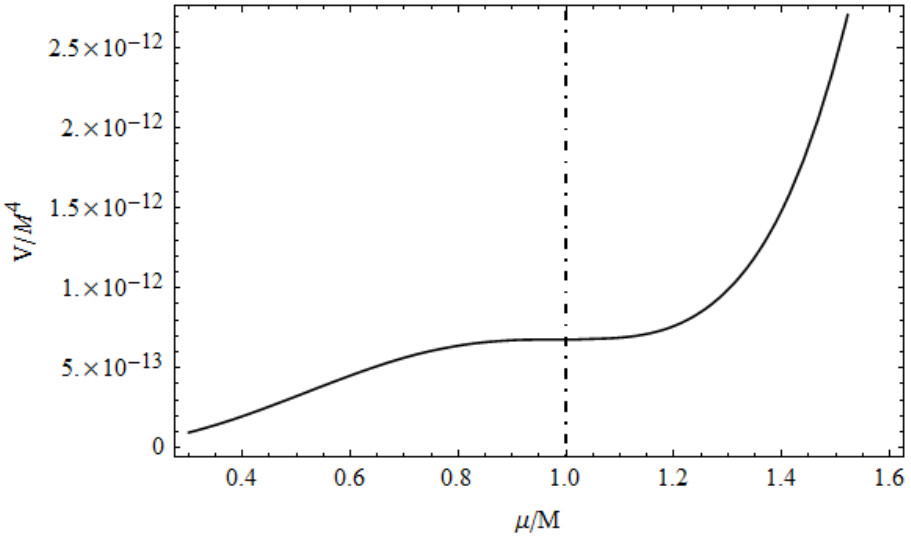
RGE Improved B-L Higgs Potential w/Inflection Point

RGE Running of Quartic Coupling



M = ϕ_I

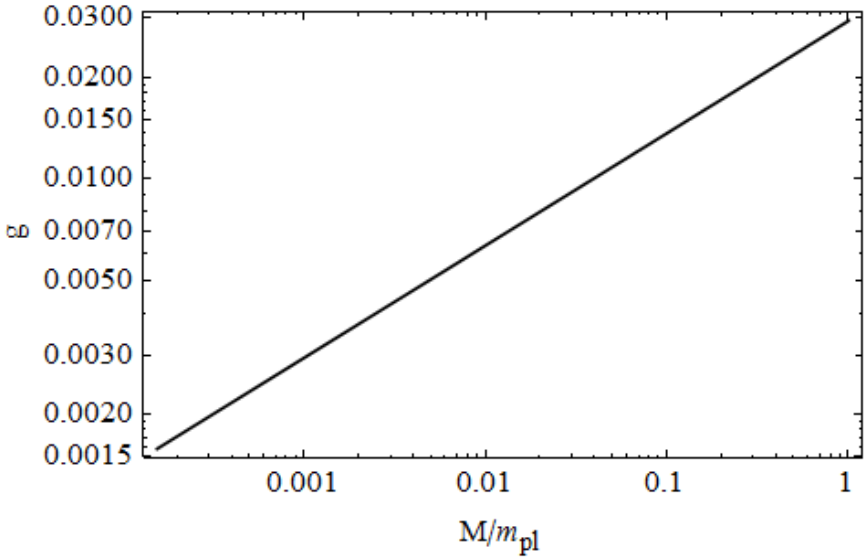
RGE improved potential w/ Inflection Point



$$\begin{aligned} V'(M) &\simeq 0, \\ V''(M) &\simeq 0, \\ V'''(M) &\simeq 0. \\ \hline \lambda(M) &\ll 1 \end{aligned}$$

Inflection Point Conditions

RGE Improved B-L Higgs Potential w/Inflection Point



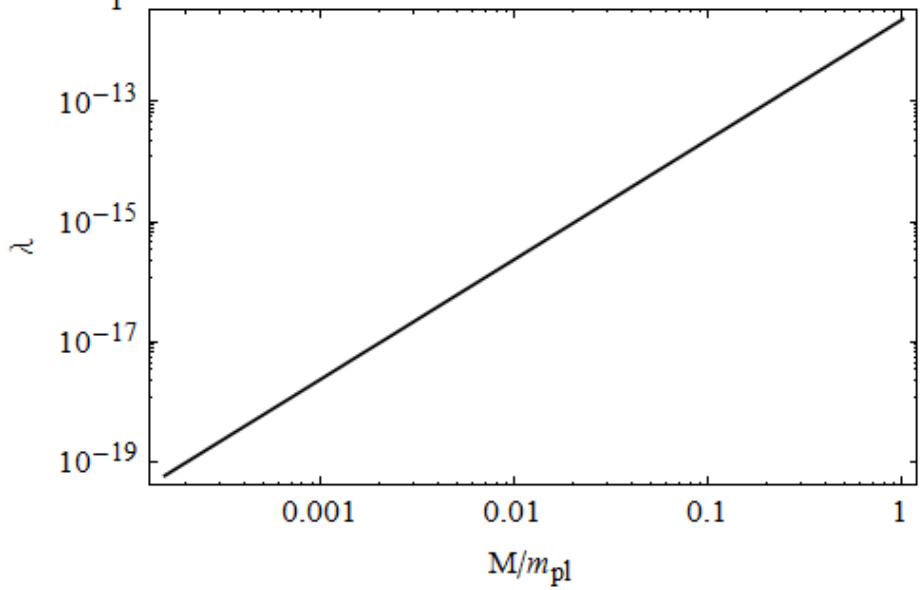
$M \leq m_{pl}$

g(max) ≈ 0.03

Inflection Point Constraints

$$\lambda \simeq 3.71 \times 10^{-3} g^6$$

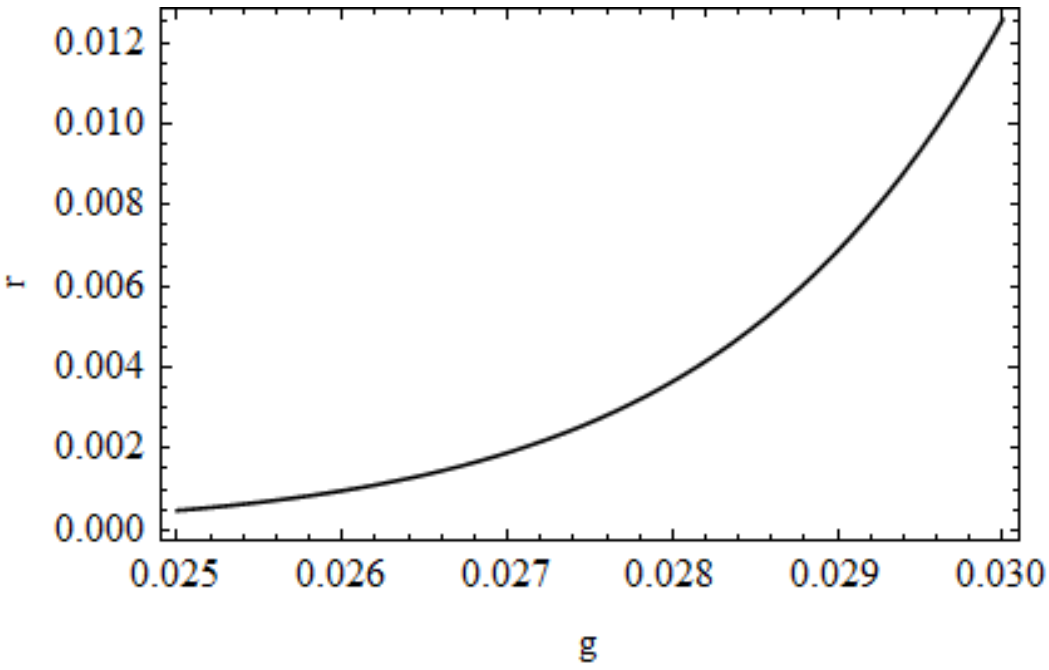
$$\lambda \simeq 4.53 \times 10^{-14} \frac{M}{Mp}$$



Inflationary Predictions

Spectral Index (ns) :
0.968 (free parameter)

Power Spectrum (Δ_R^2) :
$2.95 * 10^{-9}$



Low Energy Predictions

$$\frac{m_{NR}}{m_{Z'}} \sim 0.84$$

Conclusions

- We considered $\lambda \phi^4$ context of B-L extension of SM with identification of B-L Higgs as Inflaton.
- Inflection point inflation is unique realization for small field inflation when inflation is driven by single scalar field .
- Spectral Index consistent to the Planck measurement can be realized independent of low energy phenomenology.
- Successful Inflection point provide unique boundary condition around inflection scale

$$\beta_\lambda(M) \simeq 0, \qquad \lambda \ll 1.$$

- The boundary condition provide uniquely fixes the parameter for low energy phenomenology

$g(\text{max}) \approx 0.03$ $\qquad \frac{m_{NR}}{m_{Z'}} \sim 0.84$

Thank You