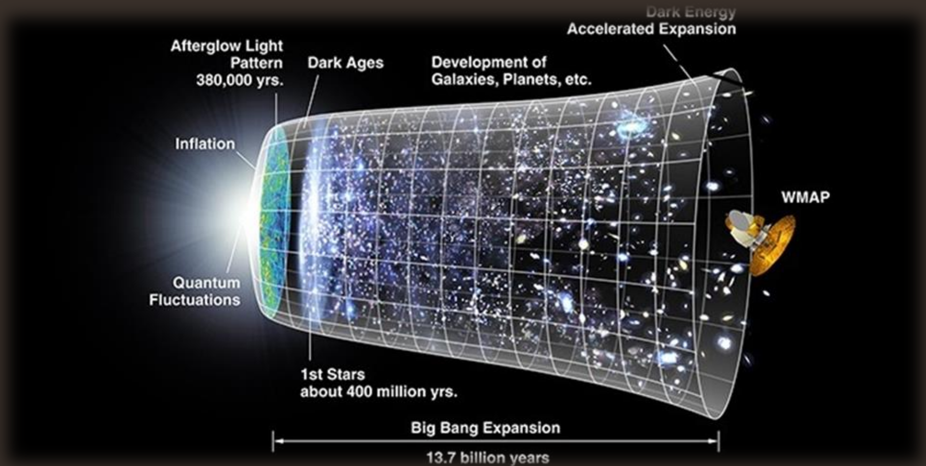

Inflection-point $U(1)_X$ Higgs Inflation

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[1] N. Okada and D. Raut, *"Inflection-point B-L Higgs Inflation,"* Phys. Rev. D 95, 035035 (2017), [arXiv:1610.09362 [hep-ph]] .

[2] N. Okada, S. Okada and D. Raut, *"Inflection-point inflation in hyper-charge oriented $U(1)_X$ model,"* Phys. Rev. D 95, 055030 (2017), [arXiv:1702.02938 [hep-ph]] .

Inflation Scenario

- Solves problems in Big Bang Cosmology
  - Horizon Problem
  - Flatness Problem
- Generates Primordial Density Fluctuations
  - Primordial Density Fluctuation ⟺ CMB Temperature Fluctuation

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

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

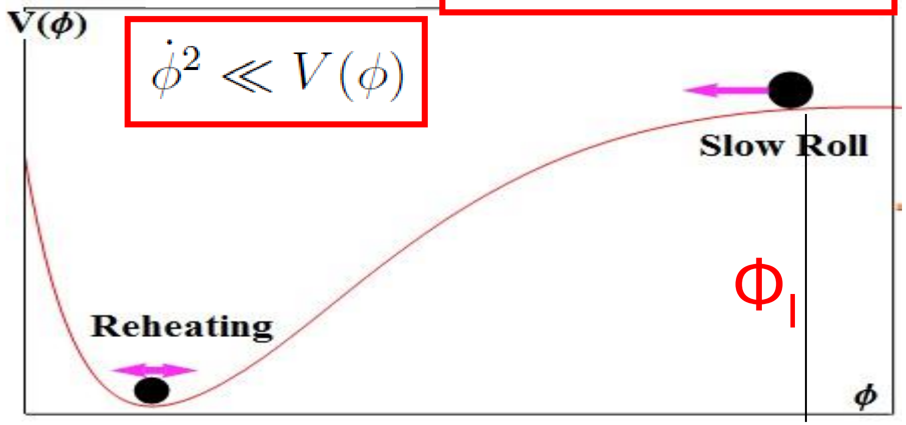
Single Scalar Field: Slow Roll Inflation Scenario

- Slow Roll Inflation

$$\epsilon(\phi) = \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2$$
$$\eta(\phi) = M_P^2\left(\frac{V''}{V}\right)$$
$$\zeta^2(\phi) = M_P^4\left(\frac{V'V'''}{V^2}\right)$$

Slow Roll $\{\epsilon,\ |\eta|,\ \zeta^2\} \ll 1$

$\dot{\phi}^2 \ll V(\phi)$



- e-folds: $$N = \frac{1}{M_P^2}\int_{\phi_E}^{\phi_I}\left(\frac{V}{V'}\right)\mathrm{d}\phi$$

N ≃ 60

To solve the horizon problem

- Observables

$$r = 16\epsilon$$
$$n_s = 1 - 6\epsilon + 2\eta$$
$$\alpha = \frac{dn_s}{d\ln k} = 16\epsilon - 24\epsilon^2 - 2\zeta$$
$$\Delta_{\mathcal{R}}^2 = \frac{1}{24\pi^2}\frac{1}{M_P^4}\frac{V}{\epsilon}\Big|_{k_0=0.002\ \mathrm{Mpc}^{-1}}$$

Planck 2015 Measurements

$$r \leq 0.11$$
$$n_s \simeq 0.9655 \pm 0.0062$$
$$\alpha = -0.0057 \pm 0.0071$$
$$\Delta_{\mathcal{R}}^2 = 2.195 \times 10^{-9}$$

Inflection-point Inflation $(\phi_I < m_{pl})$

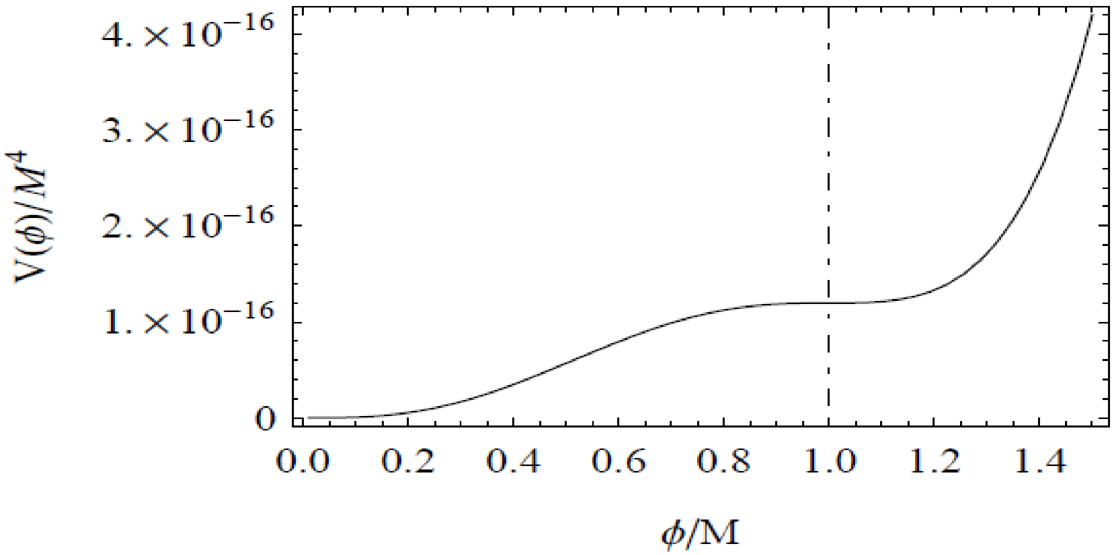
- Inflection-point inflation is a unique realization for small field inflation when inflation is driven by single scalar field .

Inflection-point conditions

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

- Potential expansion around the inflection-point

$$V(\phi) \simeq V_0 + V_1(\phi - M) + \frac{V_2}{2}(\phi - M)^2 + \frac{V_3}{6}(\phi - M)^3$$



$M = \phi_I$

- Summary of Inflection-point inflation analysis:

Constraint on Potential to satisfy Planck 2015 inflationary measurements

$$\frac{V_1}{M^3} \simeq 1961 \left(\frac{M}{M_P}\right)^3 \left(\frac{V_0}{M^4}\right)^{3/2},$$

$$\frac{V_2}{M^2} \simeq -1.725 \times 10^{-2} \left(\frac{M}{M_P}\right)^2 \left(\frac{V0}{M^4}\right)$$

$$\frac{V_3}{M} \simeq 6.989 \times 10^{-7} \left(\frac{M}{M_P}\right) V_0^{1/2}$$

$M = \phi_I$

N = 60 ; n_s = 0.9655

r = 0.11 ; Δ_R^2 = 2.195 *10 $^{-9}$

Free Parameters:

V_0 , M

- Model-independent Prediction for the Running of the Spectral Index

$$\alpha \simeq -2\zeta^2(M) = -\, 2.742 \times 10^{-3} \left(\frac{60}{N}\right)^2$$

Planck 2015

$$\alpha \; = \; -0.0057 \pm 0.0071$$

  - The future experiments can reduce the error to ±0.002.

(*Abazajian et. al. , arXiv:1309.5381*)

  - Hence this prediction can be tested in the future.

Inflection-point $U(1)_X$ Higgs Inflation

- Compelling inflation scenario:
  If the inflaton field plays another important role in particle physics.

- It may be interesting to identify the inflaton (scalar) field with a Higgs field in a general Higgs model, which plays a crucial role to spontaneously break a gauge symmetry of the model.

- We consider inflection-point inflation in the context of the minimal gauged $U(1)_X$ extended Standard Model (SM).

- We identify $U(1)_X$ Higgs field with the inflaton.

$V_0 \simeq \frac{1}{4}\lambda(M)M^4$ is $U(1)_X$ Higgs/Inflaton potential at $M = \phi_I$.

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

- Minimal Gauged B-L(Baryon-Lepton) Extension of Standard Model

  - Gauge Anomaly Free:
    3 generation of right handed Neutrinos (N_i).

  - B-L Higgs Field :
    Breaks B-L gauge symmetry.

  - B-L Symmetry Breaking:
    Generates Z' boson mass and Majorana mass for N_i.

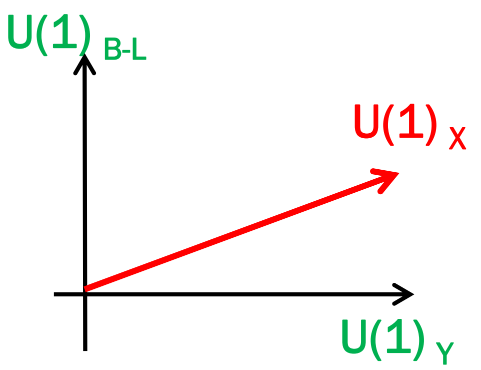
$$\mathcal{L} \supset -\frac{1}{2}\sum_{i=1}^{3} Y\,\varphi\,\overline{N^c}N + \text{h.c.}$$

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
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	$+2$

  - See-Saw Mechanism

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

$U(1)_X$ Model $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$



- Generalization of the minimal B-L model.
- $U(1)_X$ is defined as a linear combination of $U(1)_Y$ and $U(1)_{B-L}$.

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_X = Q_Y x_H + Q_{B-L} x_\Phi$
q_L^i	**3**	**2**	$1/6$	$(1/6)x_H + (1/3)x_\Phi$
u_R^i	**3**	**1**	$2/3$	$(2/3)x_H + (1/3)x_\Phi$
d_R^i	**3**	**1**	$-1/3$	$(-1/3)x_H + (1/3)x_\Phi$
ℓ_L^i	**1**	**2**	$-1/2$	$(-1/2)x_H - x_\Phi$
e_R^i	**1**	**1**	-1	$(-1)x_H - x_\Phi$
H	**1**	**2**	$-1/2$	$(-1/2)x_H$
N_R^i	**1**	**1**	0	$-x_\Phi$
Φ	**1**	**1**	0	$+2x_\Phi$

Parameterization

$x_\Phi = 1$

x_H (Free)

B-L limit: $x_H = 0$

$U(1)_Y$ limit: $x_H \Rightarrow \infty$

Gauged U(1)$_X$ Scenario

- Gauge anomaly free: 3 generation of right handed Neutrinos (N_i).
- U(1)$_X$ Higgs field (Φ) :

  VEV of U(1)$_X$ $\langle\Phi\rangle = v_X/\sqrt{2}$ breaks U(1)$_X$ gauge symmetry.

- U(1)$_X$ symmetry breaking: Generates Z' boson and Majorana mass for N_i.

$$\mathcal{L}_{Yukawa} \supset -\sum_{i=1}^{3}\sum_{j=1}^{3} Y_D^{ij}\overline{\ell_L^i} H N_R^j - \frac{1}{2}\sum_{k=1}^{3} Y_M^k \Phi \overline{N_R^{k\,C}} N_R^k + \text{h.c.}$$

- See-saw mechanism is implemented.
- Mass spectrum : $v_X^2 \gg v_h^2 \qquad v_h = 246\ \text{GeV}$

$$m_{Z'} = 2g_X v_X\sqrt{1+\frac{1}{16}x_H^2\frac{v_h^2}{v_X^2}} \simeq 2g_X v_X,\quad m_{N^i} = \frac{1}{\sqrt{2}}Y_M^i v_X,\quad m_\phi = \sqrt{2\lambda_\Phi}v_X$$

Almost Identical to B-L Scenario

U(1)$_X$ Higgs/Inflaton Potential

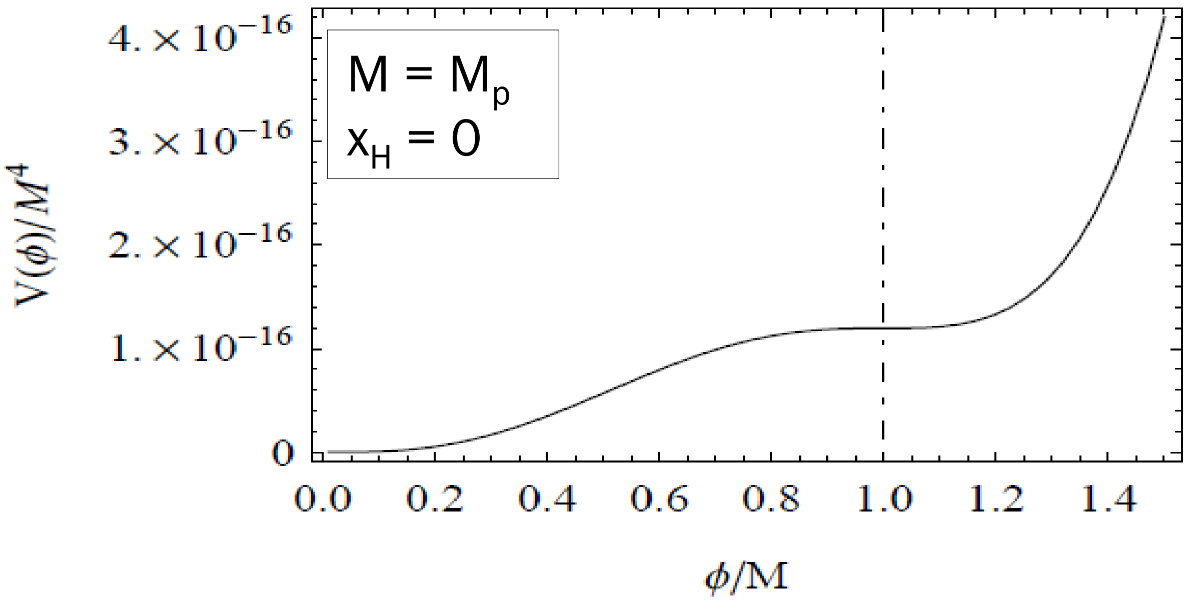
- RG improved U(1)$_X$ Higgs/Inflaton potential: $V(\phi) = \frac{1}{4}\lambda_\Phi(\phi)\,\phi^4$

Constraint on U(1)$_X$ couplings for a successful inflection-point inflation

$$\lambda_\Phi(M) \simeq 4.770 \times 10^{-16}\left(\frac{M}{M_P}\right)^2,$$

$$Y(M) \simeq 32^{1/4} g_X(M)$$

$$g_X(M, x_H) \simeq \frac{1.511 \times 10^{-2}}{(93 + 256 x_H + 164 {x_H}^2)^{1/6}}\left(\frac{M}{M_P}\right)^{1/3}.$$



Free Parameters:

x_H , M

Constraint on Low Energy Observables

- Low Energy Observables evaluated at VEV

Inflection-point condition leads to a relation between low energy observables!

$$Y \equiv Y_1 = Y_2 = Y_3$$

$$\frac{m_N}{m_{Z'}} \simeq 0.84, \qquad (m_{Z'} > m_N)$$

$$\frac{m_\phi}{m_{Z'}} \simeq 2.911 \times 10^{-6} \left(\frac{M}{M_P}\right)^{2/3} \left(87 + 256 x_H + 164 x_H^2\right)^{1/6} \ln\left[2 g_X \frac{M}{m_{Z'}}\right].$$

$$g_X(M, x_H)$$

- Free Parameters

X_H, M, $m_{Z'}$

Decay of Inflaton and Reheating

- Φ decays into the SM particle
- Themalization of decay products recreates Standard Big Bang Scenario.

Reheating Temperature

$$T_R \simeq 0.55 \left(\frac{100}{g_*}\right)^{1/4} \sqrt{\Gamma_\phi M_P},$$

BBN Constraint

T_R > 1 MeV

- Inflaton being very light, it can only decay through SM Higgs coupling

$$V = \lambda_H \left(H^\dagger H - \frac{v_h^2}{2}\right)^2 + \lambda_\Phi \left(\Phi^\dagger \Phi - \frac{v_X^2}{2}\right)^2 + \lambda_{\rm mix}\left(H^\dagger H - \frac{v_h^2}{2}\right)\left(\Phi^\dagger \Phi - \frac{v_X^2}{2}\right)$$

$$\Gamma_\phi(m_\phi, \xi) \simeq \theta^2 \, \Gamma_h(m_\phi)$$

$$m_\phi(x_H, M, m_{Z'})$$

$$\lambda_{mix} = \left(\frac{m_H^2}{v_H \ v_X}\right)\theta$$

Additional Constraint

$$\theta^2 = \left(\frac{m_\phi}{m_H}\right)^2 \xi$$

$$\xi < 1$$

- Free Parameters: ξ , X_H, M , $m_{Z'}$

Collider Z' Phenomenology

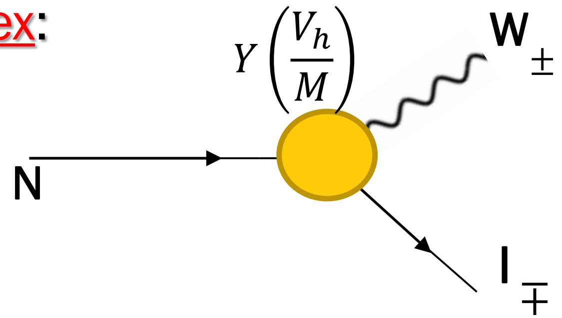
- Z' boson direct search :

$$pp \to Z' + X \to \ell^+ \ell^- + X$$

- Heavy Neutrino search via displaced vertex:

$$Z' \to N\ N$$

$$N \to W^{\pm} + l^{\mp}$$



The partial decay width of heavy neutrinos is suppressed by See-Saw mechanism.

$$\Gamma_N \sim Y^2 \left(\frac{V_h}{M}\right)^2 M \sim \frac{{m_D}^2}{M} \sim m_v$$

- Kinematic Constraint:

$$ {m_{Z'}}^2 > 4\, {m_N}^2 $$

Non-degenerate Yukawa

$$Y_2 = Y_3$$

$$m_{Z'}/m_{N^1} = 3$$

$$\frac{m_{N^{2,3}}}{m_{Z'}} \simeq 0.929$$

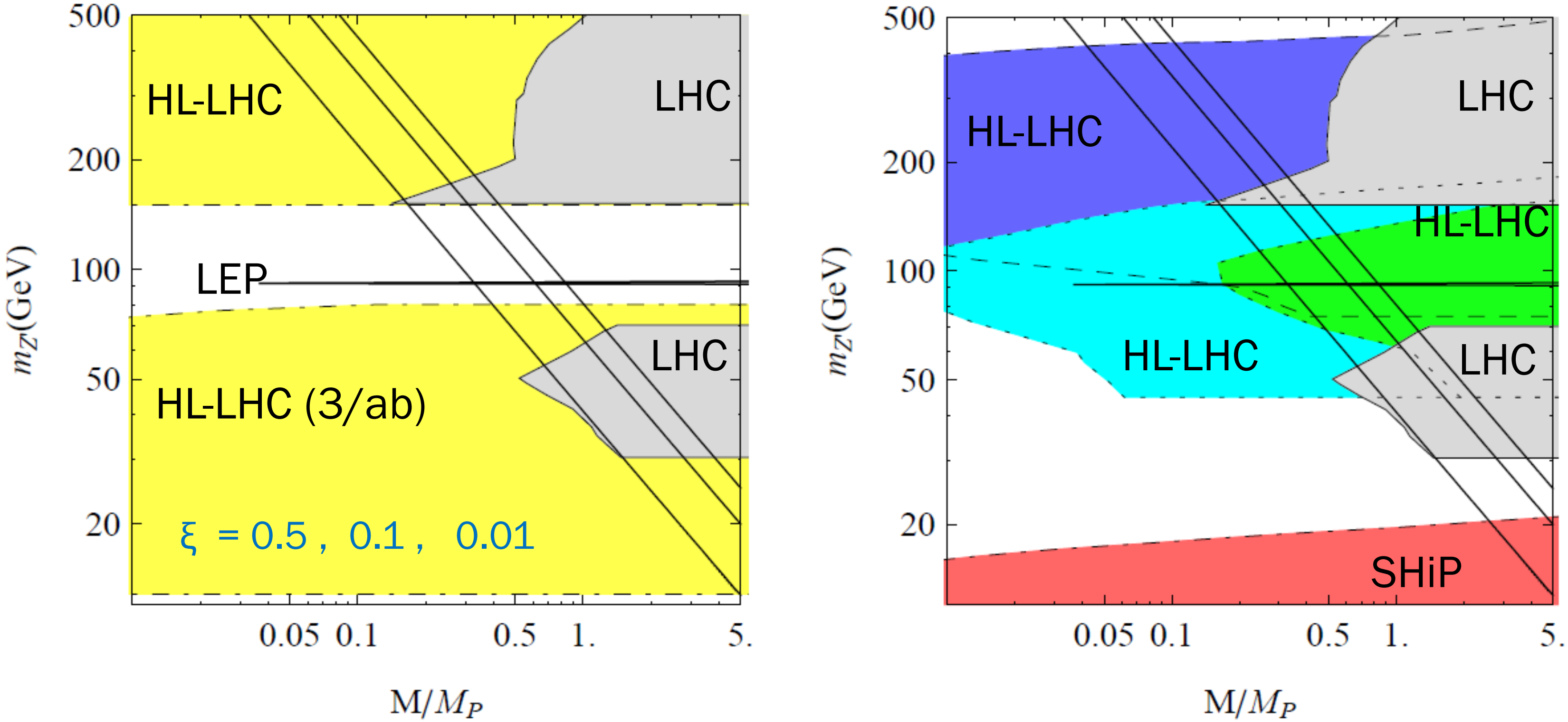
Batell, Pospelov and Shuve, JHEP 1608 (2016) 052

- <u>Z' and Heavy Neutrino Search in Current /Future Experiments (B-L)</u>

B-L: (x_H =0) Low Mass Z'

Batell, Pospelov and Shuve, JHEP 1608 (2016) 052

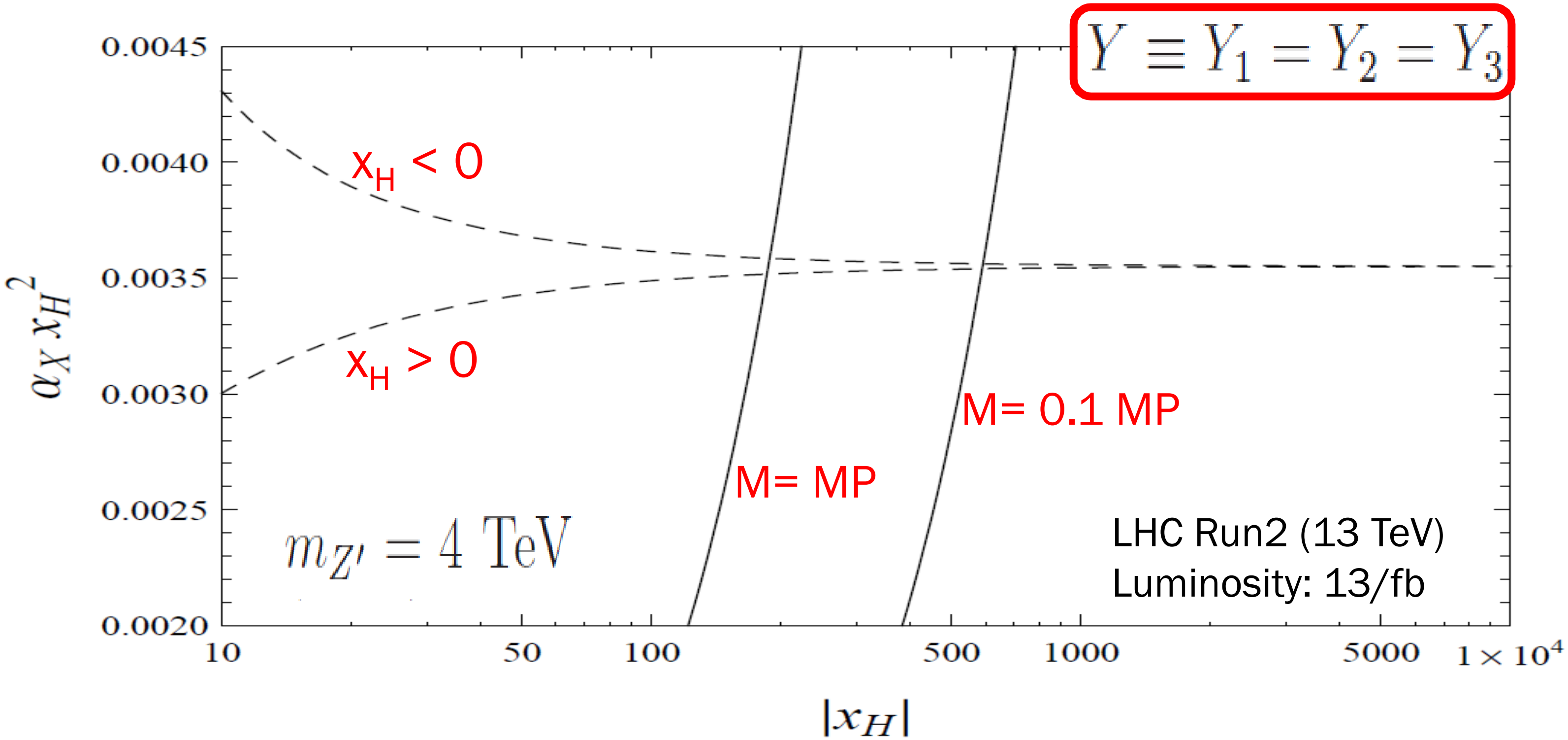
We re-interpret the gauge coupling terms of M/M_P



- Along the diagonal lines Reheating Temperature (T_R) = 1 MeV .
- The regions to the right of the diagonal lines are excluded.
- All allowed regions will be covered by Future High-Luminosity LHC and SHiP experiments.

Collider phenomenology: $U(1)_X$: large $|x_H|$

- CMS Z' Boson Search (combined di-electron and di-muon)



- Along the diagonal lines, inflection-point U(1)x Higgs inflation is possible.
- Lower bound on x_H :

$$x_H \lesssim 200 \quad (M = M_P)$$

$$x_H \lesssim 600 \quad (M = 0.1\, M_P)$$

Summary

- We have investigated inflection-point inflation in the context of the minimal $U(1)_X$ extended SM with identification of $U(1)_X$ Higgs as Inflaton.

- Successful inflection-point inflation requires both inflaton quartic coupling and its beta-function to be vanishingly small during the inflation.

$$\lambda_\Phi(M) \simeq 0 \qquad \beta_{\lambda_\Phi}(M) \simeq 0$$

- Because of this condition, the gauge, the Yukawa and the quartic coupling are all related. As a result the low energy observables have a relation to the inflationary predictions.

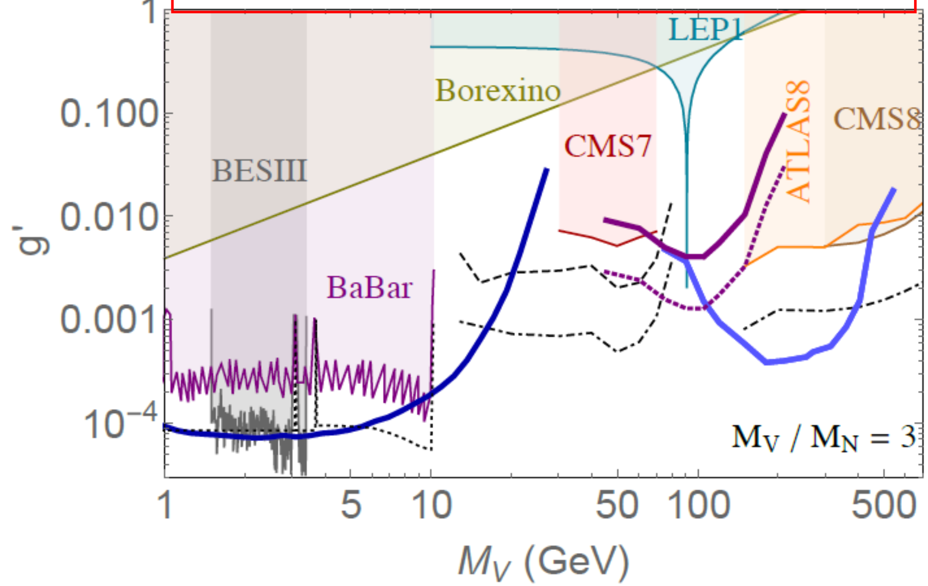
- We have investigated the collider phenomenology of this model and shown that the parameter regions for successful inflection-point inflation can be explored in the future.

- In addition, we have found that the inflection-point inflation has a model-independent prediction for the running of the spectral index, which can be tested in the future cosmological observations.

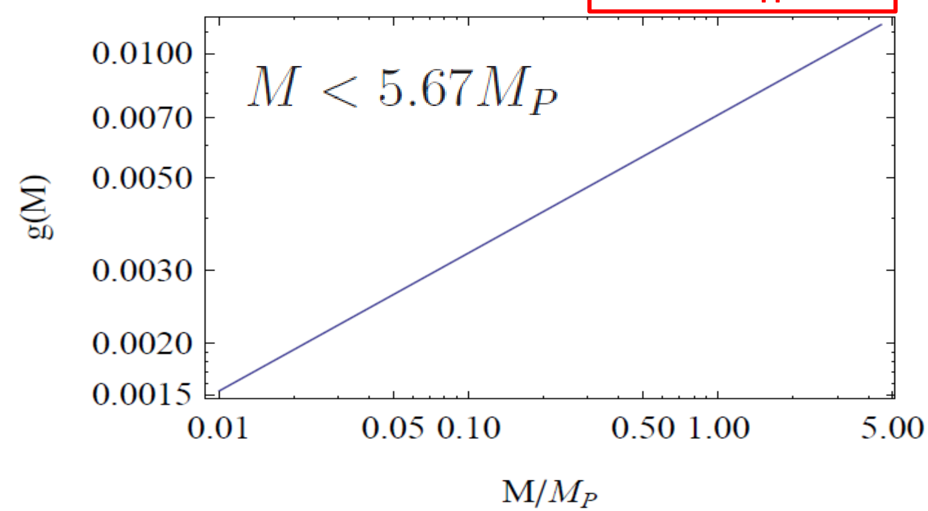
Thank You

Back-Up Slides

Batell, Pospelov and Shuve, JHEP 1608 (2016) 052



B-L: (x_H =0)



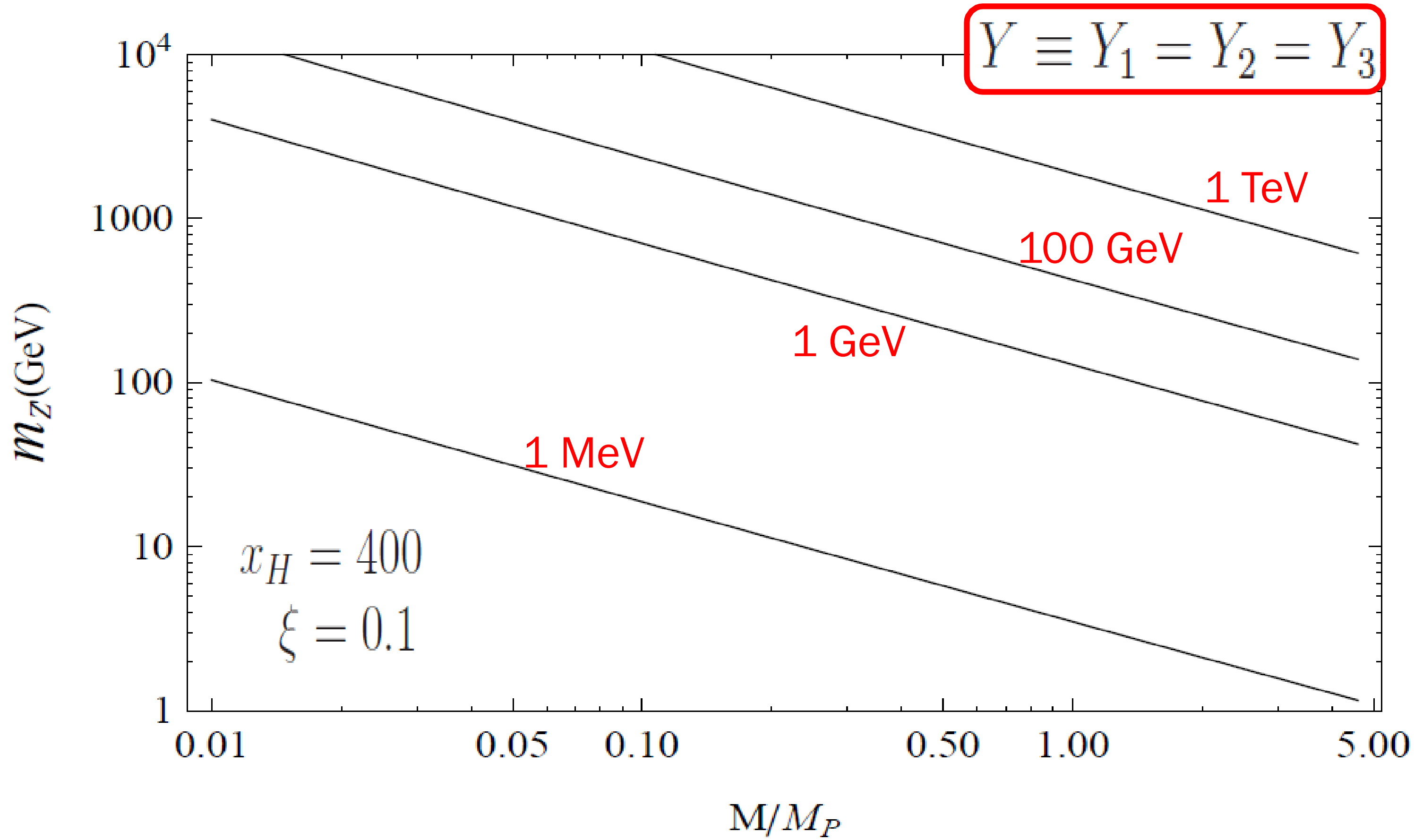
Upper Bounds on Coupling

$$g(M) < 1.261 \times 10^{-2}$$

$$\lambda(M) < 1.486 \times 10^{-14}$$

$$Y(M) < 3.001 \times 10^{-2}$$

Reheating temperature for large $|x_H|$ case



- For large xH case, the reheating temperature is high enough.
  Example:
  TR ~ 10 TeV ⟺ $m_{Z'}$ = 4 TeV & M = MP.

Collider phenomenology

- Z' Boson Search
  - Cross-section $pp \to Z' + X \to \ell^+\ell^- + X$

$$\hat{\sigma}(q\bar{q} \to Z' \to \ell^+\ell^-) = \frac{\pi}{1296}\alpha_X^2 \frac{M_{\ell\ell}^2}{(M_{\ell\ell}^2 - m_{Z'}^2)^2 + m_{Z'}^2\Gamma_{Z'}^2} F_{q\ell}(x_H)$$

$$\begin{aligned} F_{u\ell}(x_H) &= (8 + 20x_H + 17x_H^2)(8 + 12x_H + 5x_H^2), \\ F_{d\ell}(x_H) &= (8 - 4x_H + 5x_H^2)(8 + 12x_H + 5x_H^2). \\ F(x_H) &= 13 + 16x_H + 10x_H^2. \end{aligned}$$

  - Total decay width

$$\Gamma_{Z'} = \frac{\alpha_X}{6} m_{Z'} \left[F(x_H) + 3\left(1 - \frac{4m_N^2}{m_{Z'}^2}\right)^{\frac{3}{2}} \theta\left(\frac{m_{Z'}}{m_N} - 2\right) \right]$$

Collider phenomenology

- Z' Boson Search
  - Cross-section $pp \to Z' + X \to \ell^+\ell^- + X$

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Bound on M

- End of inflation $(\phi_I < m_{pl})$ $\phi_E \lesssim M$ $\phi_E/M = 1 - \delta_E$ $0 < \delta_E < 1$

$$\epsilon(\phi_E) = \frac{M_P{}^2}{2V_0^2}\left(V_1 - V_2\, M\delta_E + \frac{V_3}{2}M^2\delta_E{}^2\right)^2 \simeq \frac{M_P{}^2\, M^6\, \delta_E{}^2}{2\, V_0^2}\left(-\frac{V_2}{M^2} + \frac{V_3}{2M}\delta_E\right)^2 = 1$$

$$\delta_E \simeq 0.210\left(\frac{M}{M_P}\right)^{1/2}$$

- RG improved inflaton potential

$$V(\phi) = \sum_{n=0} \frac{V^{(n)}}{n!}(\phi - M)^n \qquad \delta_E{}^{(p-3)} < \left|\frac{(p-1)!}{2}\frac{V^{(3)}}{V^{(p)}}M^{3-p}\right|_{p\,\geq\,4}$$

Consistency: Terms $V^{(4)}$ and should be small.

$$V^{(n)}M^{n-4} \simeq C_n\lambda(M)$$

Example: $C_4 = 96$, $C_5 = 184$,

→ $M < 5.67\, MP$ $M < 5.91\, MP$

Consistency leads to upper bound on $M < 5.67\, MP$