Affleck-Dine Leptogenesis from Higgs Inflation

Neil D. Barrie

IBS-CTPU

NDB, Chengcheng Han, Hitoshi Murayama, arxiv: 2106.03381

Matter-antimatter Asymmetry

The asymmetry is described quantitatively by,

$$\eta = \frac{n_b - n_{\bar{b}}}{s} \simeq 8.5 \times 10^{-11}$$

The Sakharov Conditions

1. Baryon number violation
2. $\mathcal{C}$ and $\mathcal{CP}$ violation
3. Period of non-equilibrium

Standard Model $\rightarrow \eta_{sm} \sim 10^{-18}$,

Possible path: Angular motion of a complex scalar field.

Charge Asymmetry from a Complex Scalar

Consider a complex field ϕ with a global $U(1)$ charge Q. The charge density of ϕ is,

$$n_\phi = j^0 = 2Q\mathrm{Im}[\phi^\dagger \dot{\phi}] = Q\phi_r^2\dot{\theta} \ ,$$

where $\phi = \frac{1}{\sqrt{2}}\phi_r e^{i\theta}$.

The equation of motion for n_ϕ,

$$\dot{n}_\phi + 3Hn_\phi = \mathrm{Im}\left[\phi\frac{\partial V}{\partial \phi}\right] \ .$$

The potential V must contain an explicit $U(1)$ breaking term to generate a non-zero $\dot{\theta}$ and n_L.

We want to identify ϕ with the Triplet Higgs.

Triplet Higgs and Type II Seesaw Mechanism

SM Higgs doublet and Triplet Higgs,

$$H = \begin{pmatrix} h^+ \\ h \end{pmatrix}, \quad \Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix} ,$$

Consider the Δ doubly charged under $U(1)_L$, through,

$$\mathcal{L}_{\rm yukawa} = -\frac{1}{2} y_{ij} \bar{L}_i^c \Delta L_j + h.c.$$

Lepton violation terms,

$$\mathcal{L}_{\not{L}} = \mu h^2 \Delta^{0*} + \frac{1}{M_P}\left(\lambda_5 |h|^2 h^2 \Delta^{0*} + \lambda_5' |\Delta^0|^2 h^2 \Delta^{0*}\right) + h.c.$$

In the limit $M_\Delta \gg v_{\rm EW}$,

$$\langle \Delta^0 \rangle \simeq \frac{\mu v_{\rm EW}^2}{2 m_\Delta^2} \ .$$

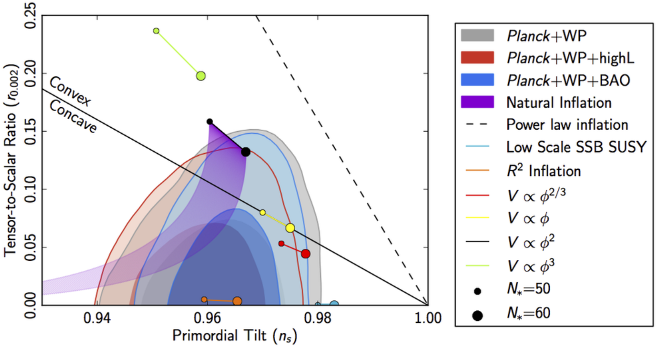
Higgs Inflation

Flattening by non-minimal couplings of higgs'

$$M_p^2\left(1+\frac{\xi_H|h|^2}{M_p^2}+\frac{\xi_\Delta|\Delta^0|^2}{M_p^2}\right)R$$

Giving the Starobinsky potential in Einstein frame,

$$\frac{3}{4}m_S^2M_p^2(1-e^{-\sqrt{2/3}\chi/M_p})^2$$



Model Framework

Motivated by the unknown origins of Inflation, Baryogenesis, and the neutrino masses.

Explain by addition of a Triplet Higgs to SM,

- Two-field inflation, with Starobinsky-like observables,
- Lepton number phase motion, n_L, induced during inflationary phase,
- Baryon asymmetry via sphaleron redistribution,
- Neutrino masses via triplet higgs vacuum expectation value,
- Possible collider signatures.

Model Framework

Lagrangian:

$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{1}{2}M_P^2 R - f(H,\Delta)R - g^{\mu\nu}(D_\mu H)^\dagger(D_\nu H) \\ -g^{\mu\nu}(D_\mu\Delta)^\dagger(D_\nu\Delta) - V(H,\Delta) + \mathcal{L}_{\rm Yukawa},$$

where in the unitary gauge,

$$V(h,\Delta^0) = -m_H^2|h|^2 + m_\Delta^2|\Delta^0|^2 + \lambda_H|h|^4 + \lambda_\Delta|\Delta^0|^4 + \lambda_{H\Delta}|h|^2|\Delta^0|^2 \\ -\mu h^2\Delta^{0*} - \frac{1}{M_P}\left(\lambda_5|h|^2h^2\Delta^{0*} + \lambda_5'|\Delta^0|^2h^2\Delta^{0*}\right) + \dots ,$$

and

$$f(H,\Delta) = \xi_H|h|^2 + \xi_\Delta|\Delta^0|^2 ,$$

Reparametrise in polar coordinates $h \equiv \frac{1}{\sqrt{2}}\rho_H e^{i\eta}$, $\Delta^0 \equiv \frac{1}{\sqrt{2}}\rho_\Delta e^{i\theta}$.

Inflationary Setting

Reparametrising,

$$\rho_H = \varphi \sin\alpha,\ \ \rho_\Delta = \varphi\cos\alpha,\ \ \xi \equiv \xi_H \sin^2\alpha + \xi_\Delta \cos^2\alpha\ .$$

Giving the Lagrangian,

$$\begin{aligned}\frac{\mathcal{L}}{\sqrt{-g}} &= -\frac{1}{2}M_P^2 R - \frac{1}{2}\xi\varphi^2 R - \frac{1}{2}g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi \\ &\quad -\frac{1}{2}\varphi^2\cos^2\alpha\ g^{\mu\nu}\partial_\mu\theta\partial_\nu\theta - V(\varphi,\theta)\ ,\end{aligned}$$

where

$$V(\varphi,\theta) = \frac{1}{2}m^2\varphi^2 + \frac{\lambda}{4}\varphi^4 + 2\varphi^3\left(\tilde{\mu} + \frac{\tilde{\lambda}_5}{M_P}\varphi^2\right)\cos\theta\ .$$

The inflationary trajectory is approximately fixed by,

$$\frac{\rho_H}{\rho_\Delta} \equiv \tan\alpha \simeq \sqrt{\frac{2\lambda_\Delta\xi_H - \lambda_{H\Delta}\xi_\Delta}{2\lambda_H\xi_\Delta - \lambda_{H\Delta}\xi_H}}\ .$$

Starobinsky-like Inflationary Setting

The Einstein frame field,

$$\frac{\chi}{M_p} \approx \begin{cases} \dfrac{\varphi}{M_p} & \text{for } \dfrac{\varphi}{M_p} \ll \dfrac{1}{\xi} \qquad \text{(after reheating)} \\ \sqrt{\dfrac{3}{2}}\,\xi \left(\dfrac{\varphi}{M_p}\right)^2 & \text{for } \dfrac{1}{\xi} \ll \dfrac{\varphi}{M_p} \ll \dfrac{1}{\sqrt{\xi}} \qquad \text{(reheating)} \\ \sqrt{\dfrac{3}{2}} \ln \Omega^2 = \sqrt{\dfrac{3}{2}} \ln \left[1 + \xi \left(\dfrac{\varphi}{M_p}\right)^2\right] & \text{for } \dfrac{1}{\sqrt{\xi}} \ll \dfrac{\varphi}{M_p} \qquad \text{(inflation)} \end{cases}$$

The Einstein frame potential,

$$U(\chi) \approx \begin{cases} \dfrac{1}{4}\lambda\chi^4 & \text{for } \dfrac{\chi}{M_p} \ll \dfrac{1}{\xi} \qquad \text{(after reheating)} \\ \dfrac{1}{2} m_S^2 \chi^2 & \text{for } \dfrac{1}{\xi} \ll \dfrac{\chi}{M_p} \ll 1 \qquad \text{(reheating)} \\ \dfrac{3}{4} m_S^2 M_p^2 \left(1 - e^{-\sqrt{\frac{2}{3}}(\chi/M_p)}\right)^2 & \text{for } 1 \ll \dfrac{\chi}{M_p} \qquad \text{(inflation)} \end{cases}$$

Assumptions

The inflaton is defined as χ with potential,

$$U(\chi) = \frac{3}{4} m_S^2 M_p^2 \left(1 - e^{-\sqrt{\frac{2}{3}}(\chi/M_p)}\right)^2 \ .$$

- Cubic term is suppressed relative to the Dim-5 term throughout inflation and reheating,
- Initial $\theta_0 \neq 0$, but $\dot{\theta}_0 = 0$,
- The mixing angle α is approximately constant,
- The Dim-5 term has a negligible effect on the inflationary trajectory.

Solve numerically and analytically to determine the generated $\dot{\theta}$.

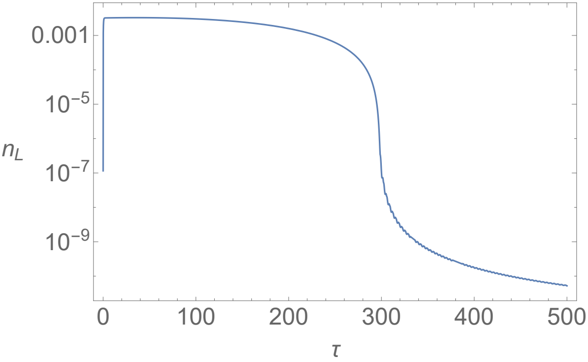
Motion of θ and Lepton Number Density

The lepton number density,

$$n_L = Q_L \varphi^2 \dot{\theta} \cos^2 \alpha \ .$$

Equation of motion for θ,

$$\ddot{\theta} + \left(3H + \frac{2\dot{\varphi}}{\varphi} \right) \dot{\theta} + \frac{2\tilde{\lambda}_5}{M_p} \frac{\varphi^3}{(1 + \xi\varphi^2/M_p^2)\cos^2 \alpha} \sin\theta = 0 \ ,$$



Lepton Number Density and Baryon Asymmetry

An analytical approximation is given by,

$$n_L^{\mathrm{reh}} \approx Q_L \frac{15\tilde{\lambda}_5 \sin\theta_0}{\lambda^{\frac{5}{4}}} (M_p H_{\mathrm{reh}})^{\frac{3}{2}} \ .$$

Assuming sphaleron redistribution and instantaneous reheating,

$$\frac{\eta_B}{\eta_B^{\mathrm{obs}}} \simeq 1.7 \cdot 10^{10} \frac{\tilde{\lambda}_5 \sin\theta_0}{\lambda^{\frac{5}{4}}} \ , \simeq 7 \cdot 10^{21} \frac{\tilde{\lambda}_5 \sin\theta_0}{\xi^{\frac{5}{2}}} \ .$$

Dim-5 term importance dependent upon Δ^0 or h domination.

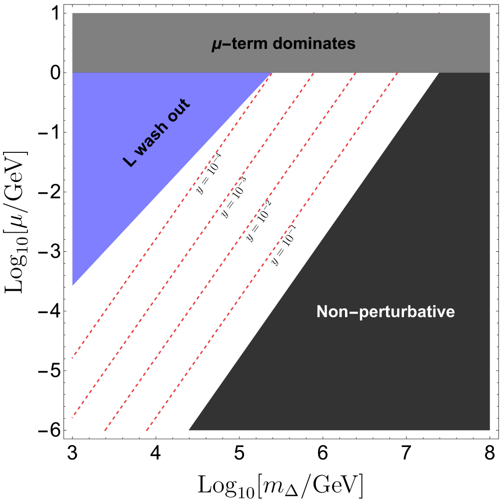
Upper bound from the Dim-5 term not altering inflation trajectory,

$$\frac{\eta_B}{\eta_B^{\mathrm{obs}}} \ll 5 \cdot 10^{10} \sin\theta_0 \ .$$

Parameter Requirements

- Successful Leptogenesis - $\eta_B \simeq \eta_B^{\rm obs}$,
- Lepton number washout effects - $\Gamma(HH \leftrightarrow \Delta)|_{T=m_\Delta} < H|_{T=m_\Delta}$,
- Inflationary observables - n_s, r, N_e, $\frac{\lambda}{\xi^2} \simeq 5 \cdot 10^{-10}$,
- Preheating - $\lambda\xi^2 < 300$,
- Isocurvature perturbations - $\theta_0 > \frac{2}{N_e \ln(4N_e/3)}$,
- Sub-dominance of μ and $\tilde{\lambda}_5$ terms - $\frac{\tilde{\mu}}{M_p} \ll \frac{\tilde{\lambda}_5}{\xi^2} \ll 6 \cdot 10^{-11} \sqrt{\xi} e^{-\frac{\chi_0}{\sqrt{6}M_p}}$,
- Neutrino masses - At least one satisfying $m_\nu \simeq y \frac{\mu v^2}{2m_\Delta^2} \gtrsim 0.05$ eV ,
- Perturbative neutrino yukawa coupling - $y \lesssim 1$.

Allowed Parameter Space



Example: $\lambda_H \simeq 0.1$, $\lambda_\Delta \simeq 4.5 \cdot 10^{-5}$, $\xi_H \sim \xi_\Delta \simeq 300$, $\alpha \sim 0.022$, $\theta_0 \sim 0.1$ and $\lambda_5' \sim 2.8 \cdot 10^{-11}$

Conclusion

Simple extension of the SM by a triplet Higgs, unifying multiple unknowns.

- Inflationary measurements consistent with observations,
- Successful Leptogenesis scenario,
- Generate the measured neutrino masses,
- Possible future collider signatures.