Affleck-Dine Dirac Leptogenesis

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NDB and Chengcheng Han, arxiv: 2402.15245

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: Leptogenesis

Dirac Leptogenesis

Standard thermal Leptogenesis:

- Heavy RH neutrinos are thermally produced after inflation,
- Out-of-equilibrium $\mathcal{CP}$ violating RH neutrinos decays generate an L,
- Equilibrium sphaleron processes redistribute L into B.

Typically requires $m_{\rm RH} > 10^7$ GeV.

Dirac Leptogenesis:

- Does not require $B - L$ violation,
- Equal and opposite L in SM leptons and sequestered RH neutrinos,
- Equilibrium sphaleron processes redistribute L into B,
- Lighter neutrino masses and unique phenomenology.

Two Higgs Doublet Model

Particle content:

- SM-like Higgs $\Phi_1 = (\Phi_1^0,\ \Phi_1^-)$
- Neutrinophillic Higgs doublet $\Phi_2 = (\Phi_2^0,\ \Phi_2^-)$
- A RH neutrino ν_R

Consider the Φ_2 and ν_R as charged under a $U(1)_X$ with $+1$ and -1 ,

$$\mathcal{L}_{\rm Yuk} = y\bar{L}\Phi_2\nu_R \ + h.c. \ ,$$

The scalar potential includes $U(1)_X$ violating terms,

$$\mathcal{L}_{\not{L}} = \frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \mathrm{h.c.}$$

but global lepton number is conserved.

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_ϕ.

We want to identify ϕ with a Neutrinophillic Higgs doublet.

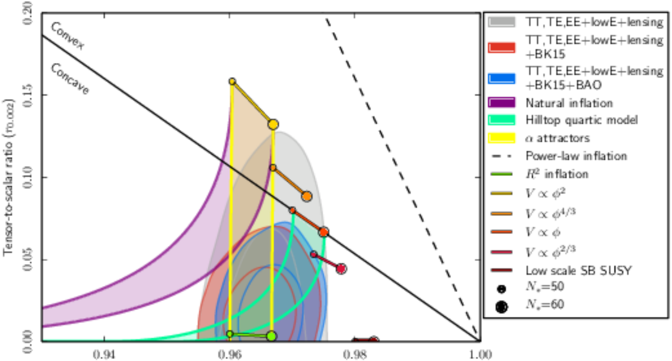
Higgs Inflation

Flattening by non-minimal couplings of higgs'

$$M_p^2\left(1+\frac{\xi_1|\Phi_1|^2}{M_p^2}+\frac{\xi_2|\Phi_2|^2}{M_p^2}\right)R$$

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 unknowns of Inflation, Baryogenesis, and the neutrinos.

A minimal renomalizable framework, to describe these phenomena through the addition of a Neutrinophillic Higgs and RH neutrino to the SM,

- Two-field inflation, with Starobinsky-like observables,
- X number density, n_X, induced during inflationary phase,
- X stored in Φ_2 sequestered into RH neutrinos, with opposing net lepton number produced in SM leptons,
- Baryon asymmetry via sphaleron redistribution of the SM leptons,
- Possible collider and cosmological signatures.

Model Framework

Lagrangian:

$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{1}{2}M_P^2 R - f(\Phi_1,\Phi_2)R - g^{\mu\nu}(D_\mu\Phi_1)^\dagger(D_\nu\Phi_1)$$
$$-g^{\mu\nu}(D_\mu\Phi_2)^\dagger(D_\nu\Phi_2) - V(\Phi_1,\Phi_2) + \mathcal{L}_{\rm Yukawa},$$

with the scalar potential,

$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 + \lambda_3\Phi_1^\dagger\Phi_1\Phi_2^\dagger\Phi_2 + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2$$
$$+\frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_4\Phi_1^\dagger\Phi_2\Phi_2^\dagger\Phi_1 + (\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + {\rm h.c.}) \ .$$

and

$$f(H,\Delta) = \xi_1|\Phi_1|^2 + \xi_2|\Phi_2|^2 = \frac{1}{2}\xi_1\rho_1^2 + \frac{1}{2}\xi_2\rho_2^2 \ ,$$

Reparametrised in polar coordinates $\Phi_1 \equiv (\frac{1}{\sqrt{2}}\rho_1 e^{i\eta}, 0)$, $\Phi_2 \equiv (\frac{1}{\sqrt{2}}\rho_2 e^{i\theta}, 0)$.

Inflationary Setting

Reparametrising,

$$\rho_1 = \varphi \sin\alpha,\ \ \rho_2 = \varphi \cos\alpha,\ \ \xi \equiv \xi_1 \sin^2\alpha + \xi_2 \cos^2\alpha\ .$$

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

$$V(\varphi,\theta) = \frac{m^2}{2}\varphi^2 + \frac{1}{4}\lambda\varphi^4 + 2\tilde{\lambda}_5\cos 2\theta\varphi^4\ ,$$

The inflationary trajectory is approximately fixed by,

$$\frac{\rho_1}{\rho_2} \equiv \tan\alpha = \sqrt{\frac{\lambda_2\xi_1 - (\lambda_3+\lambda_4)\xi_2}{\lambda_1\xi_2 - (\lambda_3+\lambda_4)\xi_1}}\ .$$

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

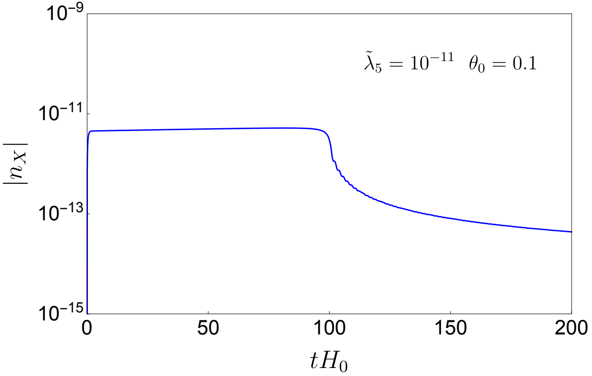
The inflaton is defined as χ with potential,

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

- Initial $\theta_0 \neq 0$, but $\dot{\theta}_0 = 0$,
- The mixing angle α is approximately constant,
- The $\tilde{\lambda}_5$ term has a negligible effect on the inflationary trajectory.

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

Numerical Solution



Motion of θ and X Number Density

Generated X asymmetry at the end of inflation may be estimated from the slow roll evolution,

$$\dot{\chi} \simeq -\frac{M_p U_{,\chi}}{\sqrt{3U}}, \quad \text{and} \quad \dot{\theta} \simeq -\frac{M_p U_{,\theta}}{f(\chi)\sqrt{3U}} \ .$$

from which we obtain,

$$n_X^{\rm inf} = Q_X f(\chi)\dot{\theta} \simeq \frac{8\tilde{\lambda}_5 \sin(2\theta)}{\sqrt{3\lambda}\xi} M_p^3.$$

The n_X exists in the form of Φ_2 which subsequently decays in SM leptons and RH neutrinos.

Sphaleron redistribution then gives,

$$\eta_B = \frac{28}{79}\frac{n_X}{s} \ .$$

where we require $n_X \sim 10^{-18} M_p^3 \Rightarrow$ small λ_5.

Washout Processes

RH neutrinos are solely sourced by decays of the Φ_2 and must besequestered from the SM until after the EWPT.

The Φ_2 must decay before EWPT, which for $m_{\Phi_2} > T_{\rm EWPT} \sim 100$ GeV,

$$y > 2 \cdot 10^{-8} \sqrt{\frac{1 \text{ TeV}}{m_{\Phi_2}}} \, ,$$

The $U(1)_X$ breaking term, λ_5, is out-of-equilibrium,

$$\lambda_5^2 \lesssim \frac{m_{\Phi_2}}{M_p} \, .$$

which is easily satisfied as we require small $\lambda_5 \sim \mathcal{O}(10^{-13})$.

If the RH neutrino have a Majorana mass, it is required that, $y < 10^{-3} \sqrt{\frac{1 \text{ GeV}}{m_{\nu_R}}}$, easily satisfied for $m_{\Phi_2} > m_{\nu_R}$.

Parameter Requirements

- Successful Leptogenesis - $\eta_B \simeq \eta_B^{\rm obs}$,
- Lepton number washout effects, $10^{-3}\sqrt{\frac{1\ \mathrm{GeV}}{m_{\nu_R}}} > y > 2\cdot 10^{-8}\sqrt{\frac{1\ \mathrm{TeV}}{m_{\Phi_2}}}$
- 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 $\tilde{\lambda}_5$ term, and $\lambda_5^2 \lesssim \frac{m_{\Phi_2}}{M_p}$.

Phenomenological Implications

- Successful explanation of the baryon asymmetry and inflation,
- Remnant RH neutrinos may increase the N_{eff}, and possible component of dark matter,
- Inflationary observables will be tested by LiteBIRD - possible non-gausssianities and gravitational waves from violent preheating,
- Embed into neutrino mass models - e.g. radiative neutrino mass models and a 2HDM,
- Possible unique lepton flavour violation signatures and non-standard neutrino interactions,
- Components from new Higgs doublet - a charged scalar H^+, a neutral scalar H_0 and a pseudoscalar A, with approx degenerate masses.

Conclusion

Simple and economical extension of the SM by an additional doublet and a RH neutrino, unifying multiple unknowns.

- Inflationary measurements consistent with observations,
- Successful Leptogenesis scenario,
- Unique cosmological signatures,
- May be embedded in neutrino mass mechanisms,
- Possible future collider signatures through new Higgs doublet components.