Mirror Dirac leptogenesis

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Motivations

- The existence of a mirror world $(\psi_{\rm SM} \leftrightarrow \psi'_{\rm mir})$ has been widely discussed in the literature (Twin Higgs, asymmetric DM, ...)
- Leptogenesis [*Fukugita, Yanagida 1986*] provides a simple and elegant explanation of the baryon asymmetry and connection to neutrino properties
- An interesting model based on mirror world, that provides a unified picture of Dirac neutrino masses, leptogenesis and dark matter has been proposed in [*P.-H. Gu 1209.4579*]
- We study the leptogenesis mechanism of this model by allowing for different branching ratios of heavy singlets into SM and mirror leptons (unflavored case) and the possibility of having the asymmetry stored in leptons and mirror leptons of different flavor (flavored case)

The model

- SM + Mirror + Dirac neutrino portal lagrangian

$$\begin{aligned} \mathcal{L} &= i\bar{N}_{Ri}\partial\!\!\!/ N_{Ri} + i\bar{N}'_{Ri}\partial\!\!\!/ N'_{Ri} - M_i\bar{N}_{Ri}N'^{c}_{Ri} + \text{h.c.} \\ & -y_{\alpha j}\bar{l}_{L\alpha}\tilde{\Phi}N_{Rj} - y'_{\alpha j}\bar{l}'_{L\alpha}\tilde{\Phi}'N'_{Rj} + \text{h.c.} \end{aligned}$$

- N_{Ri} and N'_{Ri} heavy singlets under both EW and EW' group
- Total lepton number $L_{\text{tot}} = L - L'$ is a global $U(1)$ symmetry

$$L_{\text{tot}}(l_{L\alpha}) = L_{\text{tot}}(N_{Ri}) = -L_{\text{tot}}(l'_{L\alpha}) = -L_{\text{tot}}(N'_{Ri})$$

- SM and twin right-handed neutrinos form heavy Dirac states

$$N = N_R + (N'_R)^c$$

Properties

- Lagrangian

$$\mathcal{L} \;=\; i\bar{N}_i \partial\!\!\!/ N_i - M_i \bar{N}_i N_i - y_{\alpha j} \bar{l}_\alpha \tilde{\Phi} P_R N_j - y'_{\alpha j} \bar{l'}_\alpha \tilde{\Phi}' P_R N_j^c + \text{h.c.}$$

- Z_2 symmetry implies

$$y = y'$$

- Complete model has five $U(1)$ symmetries

$$U(1)_B \qquad U(1)_{B'} \qquad U(1)_{L_{\rm tot}} \qquad U(1)_Y \qquad U(1)_{Y'}$$

- Anomaly free combination

$$U(1)_{B-B'-L_{\rm tot}}$$

General picture

Total Baryon and Lepton number

$$B_{\rm tot} - L_{\rm tot} = (B - B') - (L - L')$$

i) initial condition (zero asymmetry)

$$B = 0 \qquad B' = 0 \qquad L = 0 \qquad L' = 0$$

ii) CPV decay of heavy Dirac N_i generates asymmetry in L and L'

$$B = 0 \qquad B' = 0 \qquad L = w \qquad L' = w$$

iii) sphalerons redistribute the asymmetry in $B - L$ and $B' - L'$

$$B = a \qquad B' = a' \qquad L = w + a \qquad L' = w + a'$$

iv) the two sectors decouple and sphaleron freeze out (B, B', L, L' seprately conserved)

Heavy N decay and CP violation

- For generic y and y' we can have CP violation in the decays of the N_i to lepton of flavor α

$$\epsilon_{i\alpha} \equiv \frac{\Gamma(N_i \to l_\alpha \Phi) - \Gamma(\bar{N}_i \to \bar{l}_\alpha \bar{\Phi})}{2\Gamma_{N_i}} \neq 0$$

$$\epsilon'_{i\alpha} \equiv \frac{\Gamma(\bar{N}_i \to l'_\alpha \Phi') - \Gamma(N_i \to \bar{l}'_\alpha \bar{\Phi}')}{2\Gamma_{N_i}} \neq 0$$

- CPT conservation implies that

$$\Gamma(N_i) = \Gamma(\bar{N}_i) \equiv \Gamma_{N_i} \qquad \Gamma_{N_i} = \frac{M_i}{16\pi}[(y^\dagger y)_{ii} + (y'^\dagger y')_{ii}]$$

and

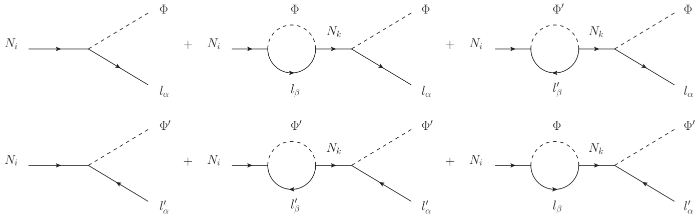
$$\epsilon_i \equiv \sum_\alpha \epsilon_{i\alpha} \quad = \quad \epsilon'_i \equiv \sum_\alpha \epsilon'_{i\alpha}$$

CP parameters

- Flavor specific CP parameters (in SM relevant for $T < 10^9$ GeV)

$$\epsilon_{i\alpha} = \frac{1/8\pi}{(y^2)_{ii} + (y'^2)_{ii}} \sum_k \left[\frac{1}{1-x_k} \mathrm{Im}[(y^\dagger y)_{ki} y_{\alpha k} y^*_{\alpha i}] + \frac{\sqrt{x_k}}{1-x_k} \mathrm{Im}[(y'^\dagger y')_{ik} y_{\alpha k} y^*_{\alpha i}] \right]$$

$$\epsilon'_{i\alpha} = \frac{1/8\pi}{(y^2)_{ii} + (y'^2)_{ii}} \sum_k \left[\frac{1}{1-x_k} \mathrm{Im}[(y'^\dagger y')_{ki} y'_{\alpha k} y'^*_{\alpha i}] + \frac{\sqrt{x_k}}{1-x_k} \mathrm{Im}[(y^\dagger y)_{ik} y'_{\alpha k} y'^*_{\alpha i}] \right]$$



- Flavor blind CP parameters (in SM relevant for $T > 10^{11}$ GeV)

$$\epsilon_i = \epsilon'_i = \frac{1}{8\pi} \frac{1}{(y^\dagger y)_{ii} + (y'^\dagger y')_{ii}} \sum_k \frac{\sqrt{x_k}}{1-x_k} \mathrm{Im}[(y'^\dagger y')_{ik} (y^\dagger y)_{ik}]$$

Assumptions

- 3 generations of N_i and 3 generations of mirror leptons l'_α

- Hierarchical spectrum

$$M_1 \ll M_2, M_3$$

leptogenesis proceeds through decay of lightest singlets N_1 and $\bar{N}_1$

- Zero initial asymmetry

$$B = 0 \qquad B' = 0 \qquad L = 0 \qquad L' = 0$$

Neutrino masses

- Integrating out the heavy N_i we get

$$\mathcal{L}_{\rm eff} = (yM^{-1}y'^T)_{\alpha\beta}\bar{l}_{L\alpha}\tilde{\Phi}\tilde{\Phi}'^T(l'_{L\beta})^c + \text{h.c.}$$

- after EWSB in both sectors $\qquad \nu_R = (\nu'_L)^c$

$$\mathcal{L}_{mass} = (\mathcal{M}_\nu)_{ij}\,\bar{\nu}_{Li}\nu_{Rj} + \text{h.c.}$$

where (f is the Φ' vev)

$$\mathcal{M}_\nu = v f\, y M^{-1} y'^T$$

- bound on CP parameter (equivalent to DI bound)

$$|\epsilon_1| \leq \frac{M_1(m_3 - m_1)}{16\pi}\frac{1}{vf} = \frac{M_1|\Delta m^2_{\rm atm}|}{16\pi(m_3+m_1)}\frac{1}{vf} \equiv \epsilon_1^{\rm max}$$

Unflavored case

- normalized charge asymmetries ($Y \sim \frac{n_{x-\bar{x}}}{s} \qquad s = \frac{2\pi^2}{45} g_\star T^3$)

$$Y_{\Delta_\alpha} \qquad Y_{\Delta'_\alpha} \qquad Y_{\Delta N_i}$$

  where

$$\Delta_\alpha = B/3 - L_\alpha \qquad \Delta'_\alpha = B'/3 - L'_\alpha \qquad \Delta N_i = N_i - \bar{N}_i$$

- conservation of $B - B' - L_{\text{tot}}$ implies

$$\sum_\alpha Y_{\Delta_\alpha} - \sum_\alpha Y_{\Delta'_\alpha} - \sum_i Y_{\Delta N_i} = \text{const} = 0$$

- after all N_1, $\bar{N}_1$ decay

$$Y_\Delta \equiv \sum_\alpha Y_{\Delta_\alpha} \qquad = \qquad Y_{\Delta'} \equiv \sum_\alpha Y_{\Delta'_\alpha}$$

  (enforced by the global symmetry)

BEs and final asymmetry

- Solve BEs for the asymmetries by varying $P_1 = BR(N_1 \to l\Phi)$
- Final asymmetry parametrized as (η efficiency)

$$Y_\Delta = Y_{\Delta'} = -2\epsilon_1 \, \eta \, Y_{N_1}^{\rm eq}(z=0)$$

- final baryon and mirror baryon asymmetry Y_B and $Y_{B'}$ (model dependent)

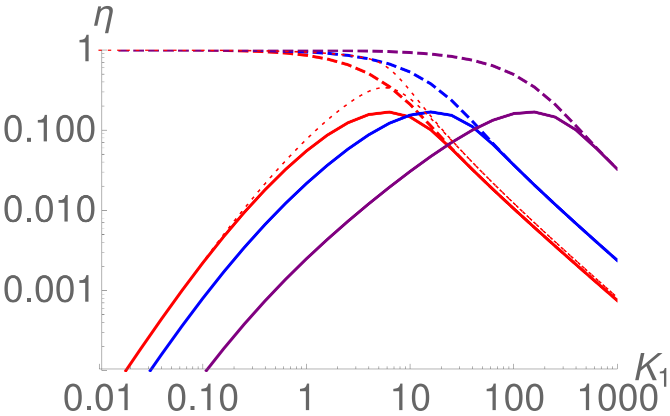
$$Y_B = \kappa \, Y_\Delta, \qquad Y_{B'} = \kappa' \, Y_{\Delta'}$$

- combining Y_B with the bound on $|\epsilon_1|$ we have that

$$M_1 \geq 2.3 \times 10^{10}\,{\rm GeV} \left(\frac{f}{500\,{\rm GeV}}\right) \left(\frac{1}{\eta}\right) \left(\frac{30/97}{\kappa}\right) \times \left(\frac{Y_B^{\rm obs}}{8.7 \times 10^{-10}}\right) \left(\frac{m_3 + m_1}{0.1\,{\rm eV}}\right) \left(\frac{2.5 \times 10^{-3}{\rm eV}^2}{|\Delta m^2_{\rm atm}|}\right)$$

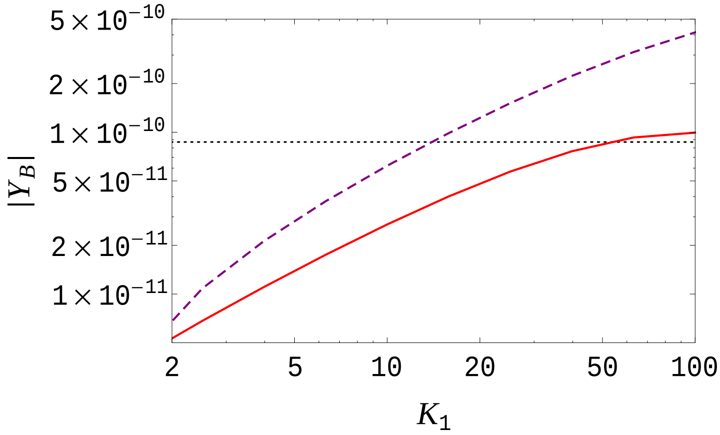
Efficiency plot

- η depends on $K_1 \equiv \frac{\Gamma_{N_1}}{H(T=M_1)}$ $(P_1 \neq 0.5 \to Z_2$ breaking)



Solid (dashed) lines = zero (thermal) initial $N_1, \bar{N}_1$ abundances.
Red is $P_1 = 0.5$, blue is $P_1 = 0.9$, purple is $P_1 = 0.99$.

Flavored case



$M_1 = 8 \times 10^8$ GeV, $f = 500$ GeV, $m_3 + m_1 = 0.1$ eV (the leptogenesis scale con be lowered by few orders of magnitude)

Conclusions

- the model assumes the existence of a mirror world with a global lepton number symmetry
- a Dirac seesaw mechanism generates small Dirac masses for the SM neutrinos which implies the absence of $0\nu\beta\beta$ decay
- after leptogenesis has occurred, the symmetries of the theory enforce the $Y_\Delta = Y_{\Delta'}$
- the final baryon Y_B and mirror baryon $Y_{B'}$ asymmetries are related by an order one coefficient, which depends on the details of the model
- if mirror baryons are the (A)DM, the model provides an elegant explanation of why DM has similar energy density with the SM baryons
- Z_2 breaking and flavor effects allow us to achieve enhanced production of asymmetry by a few orders of magnitude compared to the Z_2 symmetric and unflavored scenarios

Thank you

BACK UP

Leptogenesis

Part E

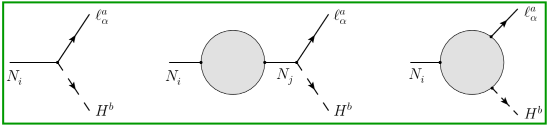
Thermal Leptogenesis

◆ **add heavy right-handed Majorana neutrinos into the SM and keep its SU(2)×U(1) gauge symmetry:**

$$-\mathcal{L}_{\rm lepton} = \overline{\ell_{\rm L}} Y_l H E_{\rm R} + \overline{\ell_{\rm L}} Y_\nu \tilde{H} N_{\rm R} + \frac{1}{2}\overline{N^{\rm c}_{\rm R}} M_{\rm R} N_{\rm R} + {\rm h.c.}$$

Fukugita, Yanagida 86

◆ **lepton-number-violating and CP-violating decays of heavy neutrinos:**



$$\varepsilon_i \equiv \frac{\sum_\alpha \left[\Gamma(N_i \to \ell_\alpha + H) - \Gamma(N_i \to \overline{\ell}_\alpha + \overline{H})\right]}{\sum_\alpha \left[\Gamma(N_i \to \ell_\alpha + H) + \Gamma(N_i \to \overline{\ell}_\alpha + \overline{H})\right]}$$

$$\approx \frac{1}{8\pi (Y_\nu^\dagger Y_\nu)_{ii}} \sum_j {\rm Im}\left[(Y_\nu^\dagger Y_\nu)_{ij}\right]^2 \left[f_{\rm V}\left(\frac{M_j^2}{M_i^2}\right) + f_{\rm S}\left(\frac{M_j^2}{M_i^2}\right)\right]$$

$$f_{\rm V}(x) = \begin{cases} \sqrt{x}\left[1 - (1+x)\ln\dfrac{1+x}{x}\right] & ({\rm SM}), \\ -\sqrt{x}\ln\dfrac{1+x}{x} & ({\rm SUSY}); \end{cases}$$

$$f_{\rm S}(x) = \begin{cases} \dfrac{\sqrt{x}}{1-x} & ({\rm SM}), \\ \dfrac{2\sqrt{x}}{1-x} & ({\rm SUSY}). \end{cases}$$

(Xing's slides)

Dirac leptogenesis or "neutrinogenesis" [*Dick et al. 9907562*]

Baryon and Lepton number

$$B - L_{\rm tot} = B - (L_{\rm L} + L_{\rm R})$$

i) initial condition

$$B = 0 \qquad L_{\rm L} = 0 \qquad L_{\rm R} = 0$$

ii) decay of heavy scalar doublets ϕ, ψ

$$B = 0 \qquad L_{\rm L} = L_{\nu_{\rm L}} = x \qquad L_R = L_{\nu_{\rm R}} = -x$$

iii) sphaleron

$$B = a \qquad L_{\nu_{\rm L}} = x + a \qquad L_{\nu_{\rm R}} = -x$$

iv) ν Yukawa equilibration after EWPT

$$B = a \qquad L_{\nu_{\rm L}} = a \qquad L_{\nu_{\rm R}} = 0$$

Boltzmann equation unflavored case

- Define normalized charge asymmetry

$$Y_q = \sum_x x_q Y_{\Delta x} = \sum_x x_q (Y_x - Y_{\bar{x}})$$

where $Y_x = \frac{n_x}{s}$ and $s = \frac{2\pi^2}{45} g_\star T^3$

- BEs for the charge asymmetries

$$\begin{aligned}
sHz\frac{dY_{\Sigma N_1}}{dz} &= -\gamma_{N_1}\left(\frac{Y_{\Sigma N_1}}{Y^{\mathrm{eq}}_{N_1}} - 2\right) \\
sHz\frac{dY_{\Delta}}{dz} &= -\epsilon_1\gamma_{N_1}\left(\frac{Y_{\Sigma N_1}}{Y^{\mathrm{eq}}_{N_1}} - 2\right) + P_1\gamma_{N_1}\left(c\frac{Y_\Delta}{Y^{\mathrm{nor}}} - \frac{Y_\Delta - Y_{\Delta'}}{Y^{\mathrm{eq}}_{N_1}}\right) \\
sHz\frac{dY_{\Delta'}}{dz} &= -\epsilon_1\gamma_{N_1}\left(\frac{Y_{\Sigma N_1}}{Y^{\mathrm{eq}}_{N_1}} - 2\right) + (1 - P_1)\,\gamma_{N_1}\left(c^{'}\frac{Y^{'}_\Delta}{Y^{\mathrm{nor}}} + \frac{Y_\Delta - Y_{\Delta'}}{Y^{\mathrm{eq}}_{N_1}}\right)
\end{aligned}$$

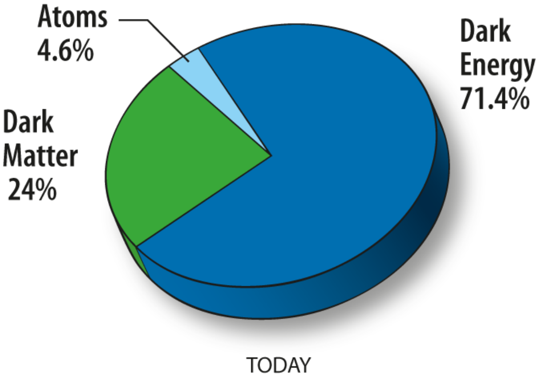
where $\gamma_{N_1} = sY^{\mathrm{eq}}_{N_1}\Gamma_{N_1}\frac{\mathcal{K}_1(z)}{\mathcal{K}_2(z)}$ and $P_1 = \mathrm{BR}(N_1 \to l\Phi)$

Dark matter

Given the observed ratio of DM and baryon energy densities $r \approx 5.4$ and assuming all the DM to be the mirror baryons, we have

$$m'_n = 5.4 \left(\frac{r}{5.4}\right)\left(\frac{\kappa}{\kappa'}\right) m_n$$

where $m_n \approx 1\,\mathrm{GeV}$ is the nucleon mass



General heavy neutrino lagrangian

Lagrangian

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{kin} - \frac{1}{2}(m_n)_{ij}n_i n_j - \frac{1}{2}(m'_n)_{ij}n'_i n'_j - (m_D)_{ij}n'_i n_j + \text{h.c.} \\ &\quad -y_{\alpha i}(l\Phi)_\alpha n_i - y'_{\alpha i}(l'\Phi')_\alpha n'_i + \text{h.c.} \\ &\quad -\tilde{y}_{\alpha i}(l\Phi)_\alpha n'_i - \tilde{y}'_{\alpha i}(l'\Phi')_\alpha n_i + \text{h.c.}\end{aligned}$$

Integrating out the heavy n, n' fields

$$\begin{aligned}\mathcal{L}_{eff} &= \left[\frac{-y^2 m'_n - \tilde{y}^2 m_n + 2y\tilde{y}m_D}{2(m_D^2 - m_n m'_n)}\right](l\Phi)^2 \\ &\quad + \left[\frac{-y'^2 m_n - \tilde{y}'^2 m_{n'} + 2y'\tilde{y}'m_D}{2(m_D^2 - m_n m'_n)}\right](l'\Phi')^2 \\ &\quad + \left[\frac{-y\tilde{y}'m'_n - y'\tilde{y}m_n + (yy' + \tilde{y}\tilde{y}')m_D}{(m_D^2 - m_n m'_n)}\right](l\Phi)(l'\Phi')\end{aligned}$$

DI bound parametrization

- parametrize the Yukawa matrices as

$$
\begin{aligned}
y &= \frac{1}{\sqrt{v f}} U^* D_{\sqrt{m}} X D_{\sqrt{M}} \\
y' &= \frac{1}{\sqrt{v f}} V^* D_{\sqrt{m}} (X^{-1})^T D_{\sqrt{M}}
\end{aligned}
$$

- for $M_1 \ll M_2, M_3$ we can write

$$
\epsilon_1 = -\frac{M_1}{8\pi} \frac{1}{v f} \frac{\sum_j m_j^2 \mathrm{Im}[(X^\dagger)_{1j} (X^{-1})^\dagger_{j1}]}{\sum_j m_j (|X_{j1}|^2 + |X^{-1}_{1j}|^2)}
$$

Flavored case example

- Assuming that $|y'| \gg |y|$ we have

$$\begin{aligned} \epsilon_{i\alpha} &\sim a(y^4/y'^2) + b(y^2) \\ \epsilon'_{i\alpha} &\sim a(y'^2) + b(y^2) \end{aligned}$$

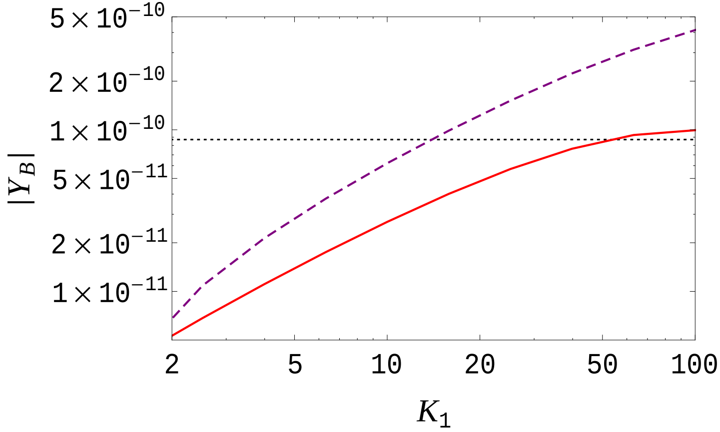
- purely flavored term a in the ϵ' parameter is enhanced by a factor of

$$\sim y'^2/y^2 \sim P^{-1}$$

- concrete example

$$\begin{aligned} (P_{1e}, P_{1\mu}, P_{1\tau}) &= 10^{-3}(1/3, 1/3, 1/3) \\ (P'_{1e}, P'_{1\mu}, P'_{1\tau}) &= 0.999(8 \times 10^{-3}, 2 \times 10^{-3}, 0.99) \\ (\epsilon_{1e}, \epsilon_{1\mu}, \epsilon_{1\tau}) &= -(1/3, 1/3, 1/3)\epsilon_1^{\max} \\ (\epsilon'_{1e}, \epsilon'_{1\mu}, \epsilon'_{1\tau}) &= (1000, 990, -1991)\epsilon_1^{\max} \end{aligned}$$

Flavored case plot



$M_1 = 8\times10^8$ GeV, $f = 500$ GeV, $m_3 + m_1 = 0.1$ eV

Flavored case comments

- The flavor effects are impotent in the weak washout, a sufficient baryon asymmetry can be generated for $K_1 \gtrsim 15$ and $K_1 \gtrsim 55$ respectively for thermal and zero initial N_1 abundance
- For the zero initial N_1 abundance, the largest asymmetry is induced in the flavor α for which $P'_{1\alpha} K_1 \sim \mathcal{O}(1)$ in order to have a significant washout of the initial "wrong" sign baryon asymmetry generated during N_1 production (τ sector)
- For thermal initial N_1 abundance, the largest asymmetry is induced in the flavor α for which $P'_{1\alpha} K_1$ is the smallest, i.e. the washout is the smallest (μ sector)
- Since the model is symmetric under the exchange of $y \leftrightarrow y'$, we can also achieve the same enhancement by having $|y| \gg |y'|$