Parametrizing Baryon Asymmetry by Neutrino Mass Matrix

Pei-Hong Gu

Shanghai Jiao Tong University

PHG, 1705.05189, 1706.07706, 1711.xxxxx.

University of Science and Technology of China, Hefei, 09.11.2017

Outline

1. Electroweak Baryogenesis and Conventional Leptogenesis
2. Leptogenesis from Mirror Charged Current Interactions
3. Cosmic Matter from Dark Electroweak Phase Transition
4. Baryon Asymmetry from Left-Right Phase Transition
5. Summary

Electroweak Baryogenesis and Conventional Leptogenesis

‡ All particles should come in particle-antiparticle pairs.

‡ No primordial antimatter significantly exists in the present universe.

‡ An initial matter-antimatter asymmetry cannot survive after inflation.

The matter-antimatter asymmetry is as same as a baryon asymmetry, which has been precisely measured by the cosmological observations (e.g. PDG 2016.),

$$\Omega_B h^2 = \frac{\rho_B}{\rho_c} h^2 = 0.02226 \pm 0.00023 \,, \quad \rho_B = n_B m_p \,,$$

$$\eta_B = \frac{n_B}{n_\gamma} \simeq 2.68 \times 10^{-8} (\Omega_B h^2) = (5.97 \pm 0.06) \times 10^{-10} \,.$$

We need a dynamical baryogenesis mechanism!

If CPT (C – charge conjugation, P – parity, T – time reversal.) is invariant, any successful baryogenesis mechanisms should satisfy the Sakharov conditions (Sakharov 67'):

‡ baryon number nonconservation,

‡ C and CP violation,

‡ departure from equilibrium.

$$\left.\begin{array}{l} B \xrightarrow{C} -B \ \text{ for } \ q_{L(R)} \xrightarrow{C} q^c_{L(R)} \\ B \xrightarrow{CP} -B \ \text{ for } \ q_{L(R)} \xrightarrow{CP} q^c_{R(L)} \end{array}\right\} \Longrightarrow n_B \equiv n_b - n_{\bar{b}} = \frac{1}{3}(n_{q_L} - n_{\bar{q}_L} + n_{q_R} - n_{\bar{q}_R}) \xrightarrow{\quad C,CP \quad} 0\,.$$

$$\langle B\rangle = \text{Tr}(e^{-\frac{H}{T}}B) = \text{Tr}[e^{-\frac{H}{T}}(CPT)^{-1}B(CPT)] = \text{Tr}[e^{-\frac{H}{T}}(-B)] = -\langle B\rangle \Rightarrow \langle B\rangle = 0\,.$$

The standard model fulfils all of the three Sakharov conditions.

Both of the baryon (B) and lepton (L) numbers are violated by quantum effects in the standard model ('t Hooft, 76'.). The transition of the baryon and lepton numbers from one vacuum to the next vacuum is

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = N_f \frac{g_2^2}{32\pi^2} \epsilon_{\mu\nu\rho\sigma} \mathrm{Tr}\,(W^{\mu\nu} W^{\rho\sigma}) \Rightarrow \Delta B = \Delta L = N_f = 3\,, \;\; \Delta(B-L) = 0\,.$$

At zero temperature, the baryon and lepton number violating processes via a tunneling between the different vacua are highly suppressed and hence are unimportant today. However, such processes can have a sphaleron solution during the temperatures near and above the electroweak phase transition (Kuzmin, Rubakov, Shaposhnikov, 85'.),

$$100\,\mathrm{GeV} < T < 10^{12}\,\mathrm{GeV}\,.$$

At the crucial temperature T_c, the electroweak symmetry is spontaneously broken. During this electroweak phase transition, the sphaleron interaction rates Γ_{sph} are

$$\Gamma_{\text{sph}} \propto T_c^4 \exp\left(-\kappa\frac{v_c}{T_c}\right) \quad \text{(in the electroweak-symmetry broken phase)},$$

$$\Gamma_{\text{sph}} \propto T_c^4 \quad \text{(in the electroweak-symmetry unbroken phase)}.$$

The out-of-equilibrium condition is

$$\frac{v_c}{T_c} > 1 \quad \Longrightarrow \quad \text{strongly first order phase transition.}$$

In the quark sector, the CKM matrix contains a CP phase to violate the CP,

$$\mathcal{L}_{\mathrm{SM}} \supset -\bar{u}_L \widehat{m}_u u_R - \bar{d}_L \widehat{m}_d d_R + \frac{g}{\sqrt{2}} \bar{u}_L \gamma^\mu V_{\mathrm{CKM}} d_L W^+_{L\mu} + \mathrm{H.c.} \ \text{with}$$

$$V_{\mathrm{CKM}} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}.$$

In conclusion, the standard model fulfils all of the three Sakharov conditions so that it can accommodate an electroweak baryogenesis mechanism.

During the electroweak phase transition, the bubbles of the true ground state of the Higgs scalar will nucleate and expand until they fill the universe. The electroweak symmetry is broken inside the bubbles while is unbroken outside the bubbles. The $SU(2)_L$ sphaleron reactions can keep very fast outside the bubbles though they are highly suppressed inside the bubbles.

As a Higgs bubble expands, the quarks from the unbroken phase will be reflected off the bubble wall back into the unbroken phase. If the CP is not conserved, we can expect a difference between the reflection probabilities for the quarks and antiquarks with a given chirality.

$$\begin{aligned} \text{CP-violation} \quad &\Longrightarrow \quad \Delta n_{q_L} = n_{q_L} - n_{\bar{q}_L} \neq 0\,, \quad \Delta n_{q_R} = n_{q_R} - n_{\bar{q}_R} \neq 0\,, \\ \text{CPT-conservation} + \text{unitary-invariance} \quad &\Longrightarrow \quad \Delta n_{q_L} + \Delta n_{q_R} = 0\,. \end{aligned}$$

The reflected quarks can diffuse before the bubble wall catches up.

The reflected left- and right-handed quarks have different interactions so that they can have different thermal masses and hence different momenta perpendicular to the advancing bubble wall. Accordingly, the reflected left- and right-handed quarks have different distributions outside the bubbles.

At the time the bubble wall catches up the reflected quarks, we can obtain a net baryon number inside the bubble, e.g. a nonzero sum between a positive baryon number stored in the left-handed quarks and a negative baryon number stored in the right-handed quarks, and an opposite baryon number outside the bubble.

At the time the bubble wall catches up the reflected quarks, the $SU(2)_L$ sphaleron reactions have partially transferred a net baryon number inside the bubbles, other than an opposite baryon number outside the bubbles, to a lepton number. The final baryon number thus should be a sum of the unaffected baryon number outside the bubbles and the survival baryon number inside the bubbles.

The final baryon number is equal to the final lepton number.

Unfortunately, the baryon asymmetry induced by the electroweak baryogenesis in the standard model is too small to explain the observed value.

‡ The electroweak phase transition should be strongly first-order to avoid the washout of the induced baryon asymmetry. This requires the Higgs boson lighter than about $m_H < 40$ GeV, which has been excluded by the experimental value $m_H = 125$ GeV.

‡ Even if the electroweak phase transition is strongly first-order, the induced baryon asymmetry can only arrive at the order of $\eta_B < \mathcal{O}(10^{-20})$.

We need a baryogenesis beyond the standard model!

Based on the standard model $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge groups, the leptogenesis (Fukugita, Yanagida, 86'.) mechanism within the so-called type-I, II and III seesaw models (Minkowski, 77'; Yanagida, 79'; Gell-Mann, Ramond, Slansky, 79'; Glashow, 80'; Mohapatra, Senjanović, 80'; Magg, Wetterich, 80'; Schechter, Valle, 80'; Cheng, Li, 80'; Lazarides, Shafi, Wetterich, 81'; Mohapatra, Senjanović, 81'; Foot, Lew, He, 89'.) or their combinations can simultaneously explain the observed baryon asymmetry and the small neutrino masses.

$$\text{Type-I}: \quad \mathcal{L} \supset -y_N \bar{l}_L \phi N_R - \frac{1}{2} M_N \bar{N}_R^c N_R + \text{H.c.}\,. \qquad N_R(1,1,0)$$

$$\text{Type-II}: \quad \mathcal{L} \supset -\frac{1}{2} f_\Delta \bar{l}_L^c i\tau_2 \Delta l_L - \mu \phi^T i\tau_2 \Delta \phi + \text{H.c.} - M_\Delta^2 \text{Tr}(\Delta^\dagger \Delta)\,. \qquad \Delta(1,3,1) = \begin{bmatrix} \frac{1}{\sqrt{2}}\delta^+ & \delta^{++} \\ \delta^0 & -\frac{1}{\sqrt{2}}\delta^+ \end{bmatrix}$$

$$\text{Type-III}: \quad \mathcal{L} \supset -y_T \bar{l}_L^c i\tau_2 T_L \tilde{\phi} - \frac{1}{2} M_T \text{Tr}(i\tau_2 \bar{T}_L^c i\tau_2 T_L) + \text{H.c.}\,. \qquad T_L(1,3,0) = \begin{bmatrix} \frac{1}{\sqrt{2}}T_L^0 & T_L^+ \\ T_L^- & -\frac{1}{\sqrt{2}}T_L^0 \end{bmatrix}$$

$$l_L(1,2,-\tfrac{1}{2}) = \begin{bmatrix} \nu_L \\ e_L \end{bmatrix} \qquad \phi(1,2,-\tfrac{1}{2}) = \begin{bmatrix} \phi^0 \\ \phi^- \end{bmatrix}$$

In the most popular type-I seesaw model, the neutrino masses are

$$\mathcal{L} \supset -m_\nu \bar{\nu}_L \nu_L^c + \text{H.c.} \text{ with } m_\nu \simeq -y_N \frac{\langle\phi\rangle^2}{M_N} y_N^T = U^* \widehat{m}_\nu U^\dagger \,.$$

We can take the Majorana mass term of the right-handed neutrinos N_R diagonal and real to define the heavy Majorana neutrinos, i.e.

$$M_N = \text{diag}\{M_{N_1}, M_{N_2}, M_{N_3}\}\,, \qquad N_i = N_{Ri} + N_{Ri}^c = N_i^c\,.$$

As long as the CP is not conserved, the out-of-equilibrium decays of the heavy Majorana neutrinos N_i can generate a lepton asymmetry η_L between the standard model leptons l_L and the antileptons l_L^c at loop level,

$$\eta_L \propto \varepsilon_{N_i} = \frac{\Gamma(N_i \to l_L \phi^*) - \Gamma(N_i \to l_L^c \phi)}{\Gamma(N_i \to l_L \phi^*) + \Gamma(N_i \to l_L^c \phi)}\,.$$

Due to the sphaleron processes, the produced lepton asymmetry η_L can be partially converted to a baryon asymmetry η_B,

$$\eta_B = C\eta_{B-L} = -C\eta_L\,.$$

The CP asymmetry ε_{N_i} can arrive at a nonzero value if and only if the Yukawa couplings y_N are complex. However, the CP phases in the Yukawa couplings y_N may be irrelevant to the CP phases in the neutrino mass matrix,

$$y_N = iU^* \sqrt{\hat{m}_\nu} O \frac{\sqrt{M_N}}{\langle \phi \rangle} \text{ with } OO^T = O^T O = 1 \,.$$

The orthogonal matrix O is arbitrary and its CP phases can provide the required CP violation even if the neutrino mass matrix does not contain any CP phases (Davidson, Ibarra, 01'.).

It has been proved that in the type-I/III+II seesaw models, the CP phases in the neutrino mass matrix can be irrelevant to the CP violation required by the leptogenesis (PHG, 1612.04344.).

No distinct correlation between the baryon asymmetry and the neutrino mass matrix!

The dark matter particle may play an essential role in the generation of the neutrino masses and the baryon asymmetry. For example, we can consider the radiative seesaw models (Ma, 06'.),

$$\mathcal{L} \supset -y_N \bar{l}_L \eta N_R - \frac{1}{2} M_N \bar{N}_R^c N_R - \lambda \left(\eta^\dagger \phi\right)^2 + \text{H.c.}\,.$$

$$\text{SM}(+) \qquad N_R(1,1,0)(-) \qquad \eta(1,2,-\tfrac{1}{2})(-) = \begin{bmatrix} \frac{1}{\sqrt{2}}\left(\eta_R^0 + i\eta_I^0\right) \\ \eta^- \end{bmatrix}$$

Dark matter: $m_{\eta_R^0}^2 - m_{\eta_I^0}^2 = \lambda \langle\phi\rangle^2\,.$

$$m_\nu \simeq -\frac{\lambda}{16\pi^2} y_N \frac{\langle\phi\rangle^2}{M_N} y_N^T = U^* \widehat{m}_\nu U^\dagger\,.$$

$$\varepsilon_{N_i} = \frac{\Gamma(N_i \to l_L \eta^*) - \Gamma(N_i \to l_L^c \eta)}{\Gamma(N_i \to l_L \eta^*) + \Gamma(N_i \to l_L^c \eta)}\,.$$

No distinct correlation between the baryon asymmetry and the neutrino mass matrix!

Leptogenesis from Mirror Charged Current Interactions

$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)$ (Pati, Salam, 74'; Mohapatra, Pati, 75'; Mohapatra, Senjanović, 75'.)

$$q_L(3,2,1,+\tfrac{1}{3}) \qquad q'_R(3,1,2,+\tfrac{1}{3})$$

$$d_R(3,1,1,-\tfrac{2}{3}) \qquad d'_L(3,1,1,-\tfrac{2}{3})$$

$$u_R(3,1,1,+\tfrac{4}{3}) \qquad u'_L(3,1,1,+\tfrac{4}{3})$$

$$l_L(1,2,1,-1) \qquad l'_R(1,1,2,-1)$$

$$e_R(1,1,1,-2) \qquad e'_L(1,1,1,-2)$$

We can forbid the mixing between the ordinary and mirror fermions by a proper discrete symmetry, but allow the mirror fermions to decay into the ordinary fermions with the dark matter scalar(s) (PHG, 1201.3551, 1410.5753.),

$$\mathcal{L} \supset -f_d \chi_d \bar{d}_R d'_L - f_u \chi_u \bar{u}_R u'_L - f_e \chi_e \bar{e}_R e'_L + \text{H.c.}\,.$$

The dark matter scalar can obtain a right relic density through the Higgs portal interaction (Silveira, Zee ,85'.) which allows a resonantly enhanced annihilation (Ibe, Murayama, Yanagida, 08'.).

The charged current interactions can be given in the basis of mass eigenstates,

$$\begin{aligned}\mathcal{L}_{CC} &= \frac{g_2}{\sqrt{2}}\bar{u}_L\gamma^\mu V_{CKM} d_L W^+_{L\mu} + \frac{g_2}{\sqrt{2}}\bar{e}_L\gamma^\mu U^*_{PMNS}\nu_L W^-_{L\mu} \\ &\quad + \frac{g'_2}{\sqrt{2}}\bar{u}'_R\gamma^\mu V'_{CKM} d'_R W^+_{R\mu} + \frac{g'_2}{\sqrt{2}}\bar{e}'_R\gamma^\mu U'^*_{PMNS}\nu'_R W^-_{R\mu} + \text{H.c.}\,.\end{aligned}$$

For a proper arrangement of the Higgs fields, the mirror fermions can have the following spectrum,

$$M_{\mu'} + M_{d'} + M_{u'} \ll M_{\nu'_i} < M_{\tau'} + M_{d'} + M_{u'}\,,\ M_{W_R} + M_{e'}\,.$$

$$\text{Majorana neutrinos:}\left\{\begin{array}{lccc} \nu'_i = \nu'_{Ri} + \nu'^c_{Ri}\,, & \nu'_i & \rightarrow & e'_R(\mu'_R) + u'_R + d'^c_R \\ \nu_i = \nu_{Li} + \nu^c_{Li}\,, & \nu'_i & \rightarrow & e'^c_R(\mu'^c_R) + u'^c_R + d'_R \end{array}\right\} \Longrightarrow L_{e'} + L_{\mu'} \neq 0\,.$$

$$\text{Dirac neutrinos:}\left\{\begin{array}{lccc} \nu'_i = \nu'_{Ri} + \nu'_{Li}\,, & \nu'_i & \rightarrow & e'_R(\mu'_R) + u'_R + d'^c_R \\ \nu_i = \nu_{Li} + \nu_{Ri}\,, & \nu'^c_i & \rightarrow & e'^c_R(\mu'^c_R) + u'^c_R + d'_R \end{array}\right\} \Longrightarrow L_{e'} + L_{\mu'} = 0\,.$$

All or part of the mirror electron and muon asymmetries can be transferred to an ordinary lepton asymmetry through the decays of the mirror charged leptons into the ordinary charged leptons with the dark matter scalar(s) (PHG, 1201.3551, 1410.5753.).

The existence of the mirror quarks can provide a solution to the strong CP problem if a discrete parity symmetry is imposed (Mohapatra, Senjanović, 78'; Beg, Tsao, 78'; Georgi, 78'; Babu, Mohapatra, 89'; Barr, Chang, Senjanović, 91'.).

$$\mathcal{L} \supset -\left[\bar{d}_L \;\; \bar{d}'_L\right] M_d \begin{bmatrix} d_R \\ d'_R \end{bmatrix} - \left[\bar{u}_L \;\; \bar{u}'_L\right] M_u \begin{bmatrix} u_R \\ u'_R \end{bmatrix} + \text{H.c.}$$

$$\text{with } M_d = \begin{bmatrix} m_d & 0 \\ 0 & M^\dagger_{d'} \end{bmatrix}, \; m_d \propto M_{d'}; \; M_u = \begin{bmatrix} m_u & 0 \\ 0 & M^\dagger_{u'} \end{bmatrix}, \; m_u \propto M_{u'}.$$

$$\mathcal{L} \supset -\bar{\theta}\frac{g_3^2}{32\pi^2}G\tilde{G} \quad \text{with} \quad \bar{\theta} = \theta - \text{ArgDet}(M_u M_d).$$

While the θ-term is removed as a result of the parity invariance, the real determinants $\text{Det}(M_d)$ and $\text{Det}(M_u)$ will lead to a zero $\text{ArgDet}(M_u M_d)$. We hence can obtain a vanishing strong CP phase $\bar{\theta}$ at tree level (Mohapatra, Senjanović, 78'; Beg, Tsao, 78'; Georgi, 78'; Babu, Mohapatra, 89'; Barr, Chang, Senjanović, 91'.) and a calculable one at loop level (Ellis, Gaillard, 79').

With the parity symmetry, we can know

$$g_2' = g_2 = g\,;$$

$$\frac{M_{d'}}{m_d} = \frac{M_{s'}}{m_s} = \frac{M_{b'}}{m_b} = \text{constant}\,, \quad \frac{M_{u'}}{m_u} = \frac{M_{c'}}{m_c} = \frac{M_{t'}}{m_t} = \text{constant}\,, \quad V'_{CKM} = V_{CKM} = V\,;$$

$$\frac{M_{e'}}{m_e} = \frac{M_{\mu'}}{m_\mu} = \frac{M_{\tau'}}{m_\tau} = \text{constant}\,, \quad \frac{M_{\nu'_1}}{m_{\nu_1}} = \frac{M_{\nu'_2}}{m_{\nu_2}} = \frac{M_{\nu'_3}}{m_{\nu_3}} = \text{constant}\,, \quad U'_{PMNS} = U_{PMNS} = U\,.$$

We hence can fully determine the expected mirror neutrino decays by the ordinary neutrino mass matrix as long as we input one of the three mirror neutrino masses such as $M_{\nu'_1}$, and the $W_R^\pm$ gauge boson mass $M_{W_R^\pm}$ (PHG, 1201.3551, 1410.5753.).

A realistic model with Majorana neutrinos

$$
\begin{aligned}
q_L(-1)(-,+) &\overset{P}{\longleftrightarrow} & q'_R(-1)(+,-)\,,\\
d_R(+1)(-,+) &\overset{P}{\longleftrightarrow} & d'_L(+1)(+,-)\,,\\
u_R(+1)(-,+) &\overset{P}{\longleftrightarrow} & u'_L(+1)(+,-)\,,\\
l_L(-1)(-,+) &\overset{P}{\longleftrightarrow} & l'_R(-1)(+,-)\,,\\
e_R(+1)(-,+) &\overset{P}{\longleftrightarrow} & e'_L(+1)(+,-)\,,\\
N_R(+1)(-,+) &\overset{P}{\longleftrightarrow} & N'_L(+1)(+,-)\,,\\
\phi_1(-2)(+,+) &\overset{P}{\longleftrightarrow} & \phi'_1(-2)(+,+)\,,\\
\phi_2(+2)(+,+) &\overset{P}{\longleftrightarrow} & \phi'_2(+2)(+,+)\,,\\
\chi(0)(-,-) &\overset{P}{\longleftrightarrow} & \chi(0)(-,-)\,.
\end{aligned}
$$

Here the first and second brackets following the fields describe the transformations under a softly broken $U(1)_G$ global symmetry and an exactly conserved $Z_2\times Z_2$ discrete symmetry, respectively.

The spontaneous gauge symmetry breaking can automatically break the discrete parity symmetry (PHG, 1706.07706.), i.e.

$$\langle\phi_1'\rangle > \langle\phi_2'\rangle > \langle\phi_2\rangle > \langle\phi_1\rangle\,.$$

The Yukawa couplings and Majorana masses respect the parity and $Z_2 \times Z_2$ symmetries,

$$\begin{aligned}
\mathcal{L}_{Y+M} = & -y_d(\bar{q}_L\tilde{\phi}_1 d_R + \bar{q}'_R\tilde{\phi}'_1 d'_L) - f_d\chi\bar{d}_R d'_L \\
& -y_u(\bar{q}_L\phi_2 u_R + \bar{q}'_R\phi'_2 u'_L) - f_u\chi\bar{u}_R u'_L \\
& -y_e(\bar{l}_L\tilde{\phi}_1 e_R + \bar{l}'_R\tilde{\phi}'_1 e'_L) - f_e\chi\bar{e}_R e'_L \\
& -y_N(\bar{l}_L\phi_2 N_R + \bar{l}'_R\phi'_2 N'_L) - \frac{1}{2}M_N(\bar{N}^c_R N_R + \bar{N}'^c_L N'_L) - f_N\chi\bar{N}_R N'_L + \text{H.c.} \\
& \text{with } M_N = M_N^T\,,\ \ f_{d,u,e,N} = f^\dagger_{d,u,e,N}\,.
\end{aligned}$$

$$m_d = y_d\langle\phi_1\rangle \propto M_{d'} = y_d\langle\phi'_1\rangle\,,\quad m_u = y_u\langle\phi_2\rangle \propto M_{u'} = y_u\langle\phi'_2\rangle\,;$$

$$m_e = y_e\langle\phi_1\rangle \propto M_{e'} = y_e\langle\phi'_1\rangle\,,\quad m_\nu = -y_N\frac{\langle\phi_2\rangle^2}{M_N}y_N^T \propto M_{\nu'} = -y_N\frac{\langle\phi'_2\rangle^2}{M_N}y_N^T\,.$$

$$\Gamma_{\nu_i'} = \sum_{\alpha=e,\mu}\left[\Gamma(\nu_i' \to e_\alpha' + u' + d'^c) + \Gamma(\nu_i' \to e_\alpha'^c + u'^c + d')\right]$$

$$\simeq \frac{g^4}{2^{10}\pi^3}\left(\left|U_{ei}\right|^2 + \left|U_{\mu i}\right|^2\right)\frac{M_{\nu_i'}^5}{M_{W_R}^4}\,.$$

$$\varepsilon_{\nu_i'} = \frac{\left[\Gamma(\nu_i' \to e' + u' + d'^c) - \Gamma(\nu_i' \to e'^c + u'^c + d')\right]}{\Gamma_i}$$

$$= \frac{g^4}{2^{10}\pi^3}\frac{\mathrm{Im}\left[\sum_{\alpha,\beta=e,\mu}\left(U_{\alpha j}^* U_{\beta j}^* U_{\beta i} U_{\alpha i}\right)\right]}{\left|U_{ei}\right|^2 + \left|U_{\mu i}\right|^2}\left[S\left(M_{\nu_i'}, M_{\nu_j'}, M_{W_R}\right) + V\left(M_{\nu_i'}, M_{\nu_j'}, M_{W_R}\right)\right]\,.$$

$$S \simeq \frac{M_{\nu_i'}}{M_{\nu_j'}}\frac{M_{\nu_i'}^4}{M_{W_R}^4} = \frac{m_{\nu_i}}{m_{\nu_j}}\frac{m_{\nu_i}^4}{m_{\nu_1}^4}\frac{M_{\nu_1'}^4}{M_{W_R}^4} \simeq \frac{3}{5}V \qquad \text{for} \qquad M_{\nu_i'}^2 \ll M_{\nu_j'}^2\,,\ M_{W_R}^2\,,$$

$$S \simeq \frac{M_{\nu_i'}M_{\nu_j'}}{M_{\nu_j'}^2 - M_{\nu_i'}^2}\frac{M_{\nu_i'}^4}{M_{W_R}^4} = \frac{m_{\nu_i}m_{\nu_j}}{m_{\nu_j}^2 - m_{\nu_i}^2}\frac{m_{\nu_i}^4}{m_{\nu_1}^4}\frac{M_{\nu_1'}^4}{M_{W_R}^4} \gg V \qquad \text{for} \qquad M_{\nu_i'}^2 \simeq M_{\nu_j'}^2 \ll M_{W_R}^2\,.$$

Note the lepton-number-violating interactions for generating the Majorana masses of the ordinary and mirror neutrinos should go out of equilibrium at a higher temperature T_F before the mirror neutrinos begin to decay at a lower temperature T_D.

$$\left[\Gamma_{\Delta L=2} = \frac{1}{4\pi^3}\frac{T^3\sum_i m_{\nu_i}^2}{\langle\phi_2\rangle^4} < H(T)\right]\Big|_{T_F} \Longrightarrow T_F \simeq 10^{12}\,\text{GeV}\left[\frac{0.04\,\text{eV}^2}{\sum_i m_{\nu_i}^2}\right]\left[\frac{\langle\phi_2\rangle}{\langle\phi\rangle}\right]^4 .$$

$$\left[\Gamma_{\nu_i'+\nu_i'\to f_1+f_2} = \frac{32\sqrt{2}\left(2-5\tan^2\theta_W+\frac{22}{3}\tan^4\theta_W\right)}{\pi^{5/2}}\frac{M_{W_L}^4}{M_{W_R}^4}G_F^2\left(M_{\nu_i'}T\right)^{\frac{5}{2}}e^{-\frac{M_{\nu_i'}}{T}} < H(T)\right]\Big|_{T_D} .$$

$$\frac{n_L}{s} \simeq \sum_i \varepsilon_{\nu_i'}\left(\frac{n_{\nu_i'}^{\text{eq}}}{s}\right)\Big|_{T_D} \quad \text{for quasi-degenerate neutrino spectrum,}$$

$$\frac{n_L}{s} \simeq \varepsilon_{\nu_{1(3)}'}\left(\frac{n_{\nu_{1(3)}'}^{\text{eq}}}{s}\right)\Big|_{T_D} \quad \text{for hierarchical neutrino spectrum.}$$

As an example, we take

$$m_{\nu_1} \simeq m_{\nu_2} \simeq m_{\nu_3} \simeq 0.2\,\mathrm{eV}\,, \quad M_{W_R} = 3.3\, m_{\nu'_i} = 10^{12}\,\mathrm{GeV}\,, \quad \alpha_1 = \alpha_2 = \frac{\pi}{2}\,,$$

and obtain

$$T_D \simeq 0.2\, M_{\nu'_i}\,, \quad \left(\frac{n^{\mathrm{eq}}_{\nu'_i}}{s}\right)\Big|_{T_D} \simeq 2\times 10^{-4}\,;$$

$$\varepsilon_{\nu'_1} \simeq \frac{g^4}{2^9\pi^3}\frac{s_{12}c_{12}s_{23}c_{23}c_{13}^2 s_{13}\sin\delta}{c_{12}^2 c_{13}^2 + s_{12}^2 c_{23}^2}\frac{m_{\nu_1}m_{\nu_2}}{m_{\nu_2}^2 - m_{\nu_1}^2}\frac{M^4_{\nu'_1}}{M^4_{W_R}}\,,$$

$$\varepsilon_{\nu'_2} \simeq \frac{g^4}{2^9\pi^3}\frac{s_{12}c_{12}s_{23}c_{23}c_{13}^2 s_{13}\sin\delta}{s_{12}^2 c_{13}^2 + c_{12}^2 c_{23}^2}\frac{m_{\nu_1}m_{\nu_2}}{m_{\nu_2}^2 - m_{\nu_1}^2}\frac{M^4_{\nu'_2}}{M^4_{W_R}}\,,$$

$$\varepsilon_{\nu'_3} \ll \varepsilon_{\nu'_{1,2}}\,.$$

The final baryon asymmetry then should be

$$\frac{n_B}{s} \simeq -\frac{28}{79}\left[\varepsilon_{\nu'_1}\left(\frac{n^{\mathrm{eq}}_{\nu'_1}}{s}\right)\Big|_{T_D} + \varepsilon_{\nu'_2}\left(\frac{n^{\mathrm{eq}}_{\nu'_2}}{s}\right)\Big|_{T_D}\right] \simeq 10^{-10}\left(\frac{\sin\delta}{-0.27}\right)\,.$$

Cosmic Matter from Dark Electroweak Phase Transition

It is very intriguing the dark and baryonic matter contribute comparable energy densities in our universe although their properties are so different.

$$\Omega_{\mathrm{b}} h^2 = 0.02226\,,$$

$$\Omega_{\mathrm{dm}} h^2 = 0.1186\,.$$

This coincidence can be elegantly explained if the dark matter relic is due to a dark matter asymmetry (Kaplan, 92'.) and is related to the generation of the baryon asymmetry (Kitano, Low, 05'; Agashe, Servant, 05'; Cosme, Lopez Honorez, Tytgat, 05'; Kaplan, Luty, Zurek, 09'; PHG, Sarkar, Zhang, 09'; PHG, Sarkar, 09; An, Chen, Mohapatra, Zhang, 09'; PHG, Lindner, Sarkar, Zhang, 10'; PHG, Mohapatra, 17';...). The dark matter asymmetry, the baryon asymmetry and the neutrino mass even can have a common origin (PHG, 12'.).

The $SU(3)_c \times SU(2)_L \times U(1)_Y$ ordinary sector :

$\phi_d(+1)\,,\ \phi_u(-1)\,,\ \phi_e(+3)\,,\ \phi_\nu(-3)\,,\ q_L(0)\,,\ d_R(+1)\,,\ u_R(+1)\,,\ l_L(0)\,,\ e_R(+3)\,;$

The $SU(3)'_c \times SU(2)'_R \times U(1)'_Y$ dark sector :

$\phi'_d(-1)\,,\ \phi'_u(+1)\,,\ \phi'_e(-3)\,,\ \phi'_\nu(+3)\,,\ q'_R(0)\,,\ d'_L(-1)\,,\ u'_L(-1)\,,\ l'_R(0)\,,\ e'_L(-3)\,;$

The messenger sector : $\Sigma(0)\,,\ \chi(+2)\,,\ \nu'_L(-3)\,.$

$$\begin{aligned}\mathcal{L} \supset & -\left(\mu_1\phi_d^\dagger\phi_u + \mu_2\phi_e^\dagger\phi_d + \mu_3\phi_\nu^\dagger\phi_u\right)\chi - \left(\mu'_1\phi_d'^\dagger\phi'_u + \mu'_2\phi_e'^\dagger\phi'_d + \mu'_3\phi_\nu'^\dagger\phi'_u\right)\chi^* \\ & -\left(\bar{y}_d\bar{q}_L\tilde{\phi}_d d_R + \bar{y}_u\bar{q}_L\phi_u u_R + \bar{y}_e\bar{l}_L\tilde{\phi}_e e_R + \bar{y}_\nu\bar{l}_L\phi_\nu\nu_L'^c\right) - \left(\bar{y}'_d\bar{q}'_R\tilde{\phi}'_d d'_L + \bar{y}'_u\bar{q}'_R\phi'_u u'_L + \bar{y}'_e\bar{l}'_R\tilde{\phi}'_e e'_L + \bar{y}'_\nu\bar{l}'_R\phi'_\nu\nu'_L\right) \\ & -f\bar{l}_L\Sigma l'_R - \left(\rho_1\phi_d^\dagger\Sigma\phi'_u + \rho_2\phi_u^\dagger\Sigma\phi'_d + \rho_3\phi_e^\dagger\Sigma\phi'_\nu + \rho_4\phi_\nu^\dagger\Sigma\phi'_e\right) + \text{H.c.}\,.\end{aligned}$$

Mirror symmetry: $f'_{R(L)} \stackrel{CP}{\longleftrightarrow} f^c_{L(R)}\,,\cdots \implies g'_{1,2,3} = g_{1,2,3}\,,\ \bar{y}'_{d,u,e,\nu} = \bar{y}^*_{d,u,e,\nu}\,,\ f = f^T\,.$

After the Higgs singlet χ develops its vacuum expectation value, we can define the dark and ordinary Higgs doublets,

$$\phi' = \frac{\sum_{i=d,u,e,\nu}\langle\phi'_i\rangle\phi'_i}{\sqrt{\sum_{i=d,u,e,\nu}\langle\phi'_i\rangle^2}}\,, \qquad \phi = \frac{\sum_{i=d,u,e,\nu}\langle\phi_i\rangle\phi_i}{\sqrt{\sum_{i=d,u,e,\nu}\langle\phi_i\rangle^2}}\,,$$

and then get the terms for the fermion mass generation,

$$\begin{aligned}\mathcal{L} \supset\; & -\left(y_d\bar{q}_L\tilde{\phi}d_R + y_u\bar{q}_L\phi u_R + y_e\bar{l}_L\tilde{\phi}e_R + y_\nu\bar{l}_L\phi\nu'^c_L\right) - \left(y'_d\bar{q}'_R\tilde{\phi}'d'_L + y'_u\bar{q}'_R\phi' u'_L + y'_e\bar{l}'_R\tilde{\phi}'e'_L + y'_\nu\bar{l}'_R\phi'\nu'_L\right)\\ & - f\bar{l}_L\Sigma l'_R - \rho\phi^\dagger\Sigma\phi' + \text{H.c.}\;\; \text{with}\;\; y_i = r_i\bar{y}_i\,,\; y'_i = r'_i\bar{y}'_i\,,\; \rho = \sum_{i,j,k} r_i r'_j\rho_k\,,\; r_i = \frac{\langle\phi_i\rangle}{\langle\phi\rangle}\,,\; r'_i = \frac{\langle\phi'_i\rangle}{\langle\phi'\rangle}\,.\end{aligned}$$

The standard model Higgs doublet can be defined as

$$\begin{aligned}\Sigma &= [\sigma_1\;\; \sigma_2] \quad \text{with} \quad \langle\sigma_1\rangle = 0\,,\;\; \langle\sigma_2\rangle = \langle\Sigma\rangle\,,\\ H &= \phi\cos\beta + \sigma_2\sin\beta \quad \text{with} \quad \tan\beta = \frac{\langle\Sigma\rangle}{\langle\phi\rangle}\,,\;\; \langle H\rangle = \sqrt{\langle\phi\rangle^2 + \langle\Sigma\rangle^2} \simeq 174\,\text{GeV}\,.\end{aligned}$$

The masses of the ordinary neutrinos can be given by the seesaw mechanism,

$$\begin{aligned}\mathcal{L} &\supset -\frac{1}{2}\left[\bar{\nu}_L\ \ \bar{\nu}'^c_R\ \ \bar{\nu}'_L\right]\left[\begin{array}{ccc}0 & f\langle\Sigma\rangle & y_\nu\langle\phi\rangle\\ f^T\langle\Sigma\rangle & 0 & y'^*_\nu\langle\phi'\rangle\\ y^T_\nu\langle\phi\rangle & y'^\dagger_\nu\langle\phi'\rangle & 0\end{array}\right]\left[\begin{array}{c}\nu^c_L\\ \nu'_R\\ \nu'^c_L\end{array}\right]+\text{H.c.}\\ &\simeq -\frac{1}{2}\bar{\nu}_L m_\nu \nu^c_L - \bar{\nu}'_R M'_\nu \nu'_L + \text{H.c. with}\end{aligned}$$

$$M_{\nu'} = y'_\nu\langle\phi'\rangle \gg m_\nu = \left[f\frac{1}{y'^\dagger_\nu}y^T_\nu + y_\nu\frac{1}{y'^*_\nu}f^T\right]\frac{\langle H\rangle^2\sin 2\beta}{2\langle\phi'\rangle}\,.$$

If the mirror CP symmetry is imposed, the neutrino mass matrix can have a form of linear seesaw (Barr, 04'.),

$$m_\nu = -f\frac{\langle H\rangle^2\sin 2\beta}{\langle\phi'\rangle}\frac{r_\nu}{r'_\nu} = U^*\widehat{m}_\nu\text{diag}\{e^{-i\alpha_1}, e^{-i\alpha_2}, 1\}U^\dagger \propto f\,.$$

Two assumptions: (i) The dark electroweak symmetry breaking is before the ordinary electroweak symmetry breaking; (ii) The phase transition during the dark electroweak symmetry breaking is strongly first order.

During such a dark electroweak phase transition, a dark baryon asymmetry and an equal dark lepton asymmetry can be simultaneously induced by the CP-violating reflection of the dark fermions off the expanding dark Higgs bubbles.

The Yukawa couplings for the neutrino mass generation can transfer the dark lepton asymmetry to an ordinary lepton asymmetry.

The ordinary sphaleron processes can partially convert the ordinary lepton asymmetry to an ordinary baryon asymmetry.

The dark matter relic is the dark baryon asymmetry and hence is tightly connected to the ordinary baryon asymmetry.

By taking into account of the neutrality of the dark electric charge, we expect the dark neutron to be the dark matter particle, accordingly, the dark lepton asymmetry is stored in the dark neutrinos.

The conversion between the dark and ordinary lepton asymmetries depends on the following terms,

$$\mathcal{L} \supset -y_\nu \bar{l}_L \phi \nu_L'^c - f \bar{l}_L \sigma_2 \nu_R' - M_\nu' \bar{\nu}_R' \nu_L' - \rho \langle \phi' \rangle \phi^\dagger \sigma_2 + \text{H.c.}.$$

The above two Yukawa terms will wash out the lepton asymmetry if they are both strong enough. We hence require one of them to keep departure from equilibrium before the ordinary sphalerons stop working. For this purpose, we can simply take $y_\nu < \mathcal{O}(10^{-7}) \ll f < \mathcal{O}(1)$ or $f < \mathcal{O}(10^{-7}) \ll y_\nu < \mathcal{O}(1)$.

The final baryon asymmetry and then the dark matter mass should be

$$B_f = \begin{cases} -\frac{28}{79+22N_{\nu'}} B_{n'} & \text{for} \quad f \gg y_\nu \,, \\ -\frac{28}{79-22N_{\nu'}} B_{n'} & \text{for} \quad f \ll y_\nu \,. \end{cases} \qquad m_{n'} = m_p \frac{B_f}{B_{n'}} \frac{\Omega_{\text{dm}} h^2}{\Omega_{\text{b}} h^2} \simeq \frac{149}{|79 \pm 22 N_{\nu'}|} m_p \,.$$

$$N_{\nu'} = (0,1,2,3) \Longrightarrow m_{n'} = \begin{cases} (1.89, 1.48, 1.21, 1.03) m_p & \text{for} \quad f \gg y_\nu \,, \\ (1.89, 2.61, 4.26, 11.5) m_p & \text{for} \quad f \ll y_\nu \,. \end{cases}$$

Consider the lepton number from the reflection of the dark leptons and antileptons off the dark Higgs bubbles (Huet, Sather, 95'.),

$$n_L^r \simeq \int \frac{d\omega}{2\pi} n_0(\omega)\left[1 - n_0(\omega)\right] \frac{\Delta k \cdot v_W}{T} \Delta(\omega) + \mathcal{O}(v_W^2)\,.$$

ω :	energy.
$n_0(\omega) = \dfrac{1}{e^{\omega/T}+1}$:	Fermi-Dirac distribution.
Δk :	difference between the right and left-handed dark lepton momenta perpendicular to the bubble wall.
$\Delta(\omega)$:	reflection asymmetry between the dark leptons and antileptons.
v_W :	advancing wall velocity.

The reflected leptons and antileptons can diffuse before the bubble wall catches up. The typical distance from the advancing bubble wall to the reflected dark leptons and antileptons is $\sqrt{D_L t} - v_W t$ with D_L being a diffusion constant (Joyce, Prokopec, Turok, 96'.).

Within the time $t_D \sim D_L/v_W^2$, the dark sphalerons can partially convert the lepton number n_L^r to a baryon number n_B. The baryon and lepton numbers inside the expanded bubbles should be (Farrar, Shaposhnikov, 93',94'.),

$$\frac{n_L}{s} = \frac{n_B}{s} \sim -\frac{9\Gamma_{\text{sph}}}{T^3}\frac{D_L}{v_W^2}\frac{n_L^r}{s} = -\frac{3^3 g_2'^8 \kappa c_L}{2^7\pi^4 v_W^2}\frac{n_L^r}{s}\,.$$

$$\Gamma_{\text{sph}} = 6\kappa\left(\frac{g_2'^2}{4\pi}\right)^5 T^4 : \qquad \text{dark sphaleron rate per volume} \quad (\kappa \simeq 20)\,.$$

$$s = \frac{2\pi^2 g_* T}{45} : \qquad \text{one-dimensional entropy density} \quad (g_* \simeq 250.75)\,.$$

Thermal masses (Weldon, 82; D'Olivo, Nieves, 95'; Joyce, Prokopec, Turok, 96'.):

$$\Sigma = \Omega - \gamma^0(2i\gamma) \text{ with}$$

$$\Omega^2_{l'_R} = \frac{T^2}{8}\left(\frac{3}{4}g_2^2 + \frac{1}{4}g_1^2 + U\widehat{f}^2U^\dagger + \frac{1}{2}\widehat{\bar{y}}_e^2 + \frac{1}{2}\bar{y}_\nu^*\bar{y}_\nu^T\right),$$

$$\Omega^2_{e'_L} = \frac{T^2}{8}\left(g_1^2 + \widehat{\bar{y}}_e^2\right),$$

$$\Omega^2_{\nu'_L} = \frac{T^2}{8}\bar{y}_\nu^T\bar{y}_\nu^*,$$

$$\gamma_{l'_R} \sim \frac{T}{32\pi}\left[9g_2^2 + 6g_1^2 + U\widehat{f}^2U^\dagger + \frac{1}{2}\left(\widehat{\bar{y}}_e^2 + \bar{y}_\nu^*\bar{y}_\nu^T\right)\right],$$

$$\gamma_{e'_L} \sim \frac{T}{32\pi}\left(12g_1^2 + \widehat{\bar{y}}_e^2\right),$$

$$\gamma^2_{\nu'_L} \sim \frac{T}{32\pi}\left(\bar{y}_\nu^T\bar{y}_\nu^*\right).$$

Simplifications: $y_\nu \ll f\,,\ \bar{y}_e\,;\ \ \delta\widehat{f}^2 = \widehat{f}^2 - \widehat{f}_3^2 \ll \widehat{f}^2_{1,2,3}\,;\ \ \frac{3}{4}g_2^2 + \frac{1}{4}g_1^2 + \widehat{f}_3^2 > \frac{1}{2}\widehat{\bar{y}}_e^2\,.$

$$
\begin{aligned}
\Omega_{l'_R} &\simeq \Omega^{(0)}_{l'_R} + \Omega^{(1)}_{l'_R}\,,\\
\Omega^{(0)}_{l'_R} &\simeq \frac{T}{2\sqrt{2}}\sqrt{\frac{3}{4}g_2^2 + \frac{1}{4}g_1^2 + \widehat{f}_3^2}\,,\\
\Omega^{(1)}_{l'_R} &\simeq \frac{T}{4\sqrt{2}}\frac{\left(U\delta\widehat{f}^2U^\dagger + \frac{1}{2}\widehat{\bar{y}}_e^2\right)}{\sqrt{\frac{3}{4}g_2^2 + \frac{1}{4}g_1^2 + \widehat{f}_3^2}}\,,\\
\Omega_{e'_L} &= \frac{T}{2\sqrt{2}}\sqrt{g_1^2 + \widehat{\bar{y}}_e^2}\,,\\
\Omega_0 &= \frac{\Omega^{(0)}_{l'_R} + \Omega_{e'_L}}{2}\,,\\
\delta p &= -3\Omega^{(1)}_{l'_R}\,,\\
\Delta k &= 3\left(\Omega^{(0)}_{l'_R} - \Omega_{e'_L}\right)\,,\\
\bar{\gamma} &= \frac{\gamma_{l'_R} + \gamma_{e'_L}}{2} \sim \frac{T}{64\pi}\left(9g_2^2 + 18g_1^2 + \widehat{f}_3^2\right)\,.
\end{aligned}
$$

Under the perturbation condition $2\Omega_{l'_R,e'_L} > r'_e\hat{\bar{y}}_e\langle\phi'\rangle$, the reflection asymmetry $\Delta(\omega)$ can be analytically solved (Huet, Sather, 95'.), i.e.

$$\Delta(\omega) = -i\frac{\mathrm{Tr}\left[\left(r'_e\hat{\bar{y}}_e\langle\phi'\rangle\right)^2, \delta p\right]^3}{2^7\cdot 3^{10}\bar{\gamma}^9}\left[1+\left(\frac{\omega-\Omega_0}{\bar{\gamma}}\right)^2\right]^{-6}$$

$$= -\frac{2^{\frac{69}{2}}\pi^9 r_e'^6\hat{\bar{y}}_\tau^6\hat{f}_3^6\left[1+\left(\frac{\omega-\Omega_0}{\bar{\gamma}}\right)^2\right]^{-6}}{\left(\frac{3}{4}g_2^2+\frac{1}{4}g_1^2+\hat{f}_3^2\right)^{\frac{3}{2}}\left(9g_2^2+18g_1^2+\hat{f}_3^2\right)^9}\left(\frac{\langle\phi'\rangle}{T}\right)^6\prod_{\substack{i>j\\ e,\mu,\tau}}\left(\frac{m_i^2-m_j^2}{m_\tau^2}\right)\prod_{\substack{i>j\\ 1,2,3}}\left(\frac{m_{\nu_i}^2-m_{\nu_j}^2}{m_{\nu_3}^2}\right)J_{CP}\,.$$

$$J_{CP} = s_{12}c_{12}s_{23}c_{23}s_{13}c_{13}^2\sin\delta\,.$$

For $\hat{f}_3=\sqrt{4\pi}$, $\hat{\bar{y}}_\tau=\sqrt{4\pi}$, $r'_e=\frac{1}{\sqrt{2}}$, we can estimate an upper bound of the dark baryon and lepton numbers,

$$\frac{n_L}{s} = \frac{n_B}{s}\sim 2.75\times10^{-8}\times\left(\frac{\kappa}{20}\right)\left(\frac{c_L}{1}\right)\left(\frac{0.1}{v_W}\right)\left(\frac{\langle\phi'\rangle}{T}\right)^6\left(\frac{0.1\,\mathrm{eV}}{m_{\nu_3}}\right)^6\left(\frac{\sin\delta_{CP}}{1}\right).$$

Besides the predictive dark matter mass, our model have other implications:

The massless dark photon γ', which decouples at the temperature $T_{\gamma'} \sim m_{n'}/30$, can contribute to the additional neutrino number, $\Delta N_\nu = \frac{8}{7}\left[10.75/g_*\left(T_{\gamma'}\right)\right]^{\frac{4}{3}}$. This dark photon may be probed by more precise measurements in the future. For example, we have $T_{\gamma'} \sim 60\,\mathrm{MeV}$, $g_*\,(60\,\mathrm{MeV}) \simeq 60$ and hence $\Delta N_\nu = 0.11$ for $m_{n'} = 1.89\,m_p$.

The messenger Higgs bidoublet Σ can result in a mass mixing between the ordinary Z boson and the dark Z' boson. Without the mirror symmetry, the dark electroweak symmetry can be spontaneously broken near the electroweak scale. In this case, the dark Z' boson may be found at the colliders. Through the Z' exchange, the scattering of the dark neutrons off the ordinary nucleons can leave a distinct signal in the DM direct detection experiments since the dark neutron has a determined mass.

In the presence of the mirror symmetry, the Dirac CP phase $-\sin\delta_{CP} > 0.01$ in the Majorana neutrino mass matrix can be the unique source for the CP violation required by the baryogenesis. Moreover, the messenger Higgs bidoublet Σ may help to test the linear seesaw at the colliders as it is allowed a TeV mass and a sizeable vacuum expectation value.

Baryon Asymmetry from Left-Right Phase Transition

Introduce a mirror copy of the standard model fermions to construct the left-right symmetric framework.

Assume a strongly first order phase transition of the left-right symmetry breaking.

Apply the basic mechanism of electroweak baryogenesis in the mirror sector to generate a mirror baryon asymmetry and an equal lepton asymmetry.

Transfer the produced mirror baryon asymmetry, or the mirror lepton asymmetry, or their combination to the ordinary quark sector before the BBN.

If the mirror baryon and lepton asymmetries were both converted to the ordinary sector before the electroweak phase transition, no $B-L$ number would participate in the $SU(2)_L$ sphalerons.

Find some proper decays of the mirror fermions into their ordinary partners with a dark matter scalar.

$$
\begin{aligned}
q_L(-,+) &\stackrel{P}{\longleftrightarrow} q'_R(+,-)\,,\\
d_R(-,+) &\stackrel{P}{\longleftrightarrow} d'_L(+,-)\,,\\
u_R(-,+) &\stackrel{P}{\longleftrightarrow} u'_L(+,-)\,,\\
l_L(-,+) &\stackrel{P}{\longleftrightarrow} l'_R(+,-)\,,\\
e_R(-,+) &\stackrel{P}{\longleftrightarrow} e'_L(+,-)\,;\\
\phi_1(+,+) &\stackrel{P}{\longleftrightarrow} \phi'_1(+,+)\,,\\
\phi_2(+,+) &\stackrel{P}{\longleftrightarrow} \phi'_2(+,+)\,,\\
\Delta(+,+) &\stackrel{P}{\longleftrightarrow} \Delta'(+,+)\,,\\
\sigma(+,+) &\stackrel{P}{\longleftrightarrow} \sigma(+,+)\,;\\
\xi(-,-) &\stackrel{P}{\longleftrightarrow} \xi(-,-)\,,\\
\chi(+i,+i) &\stackrel{P}{\longleftrightarrow} \chi(+i,+i)\,.
\end{aligned}
$$

$$\begin{aligned}
\mathcal{L}_Y \;=\;& -y_d(\bar{q}_L\tilde{\phi}_1 d_R + \bar{q}_R\tilde{\phi}'_1 d'_L) - f_d\xi\bar{d}_R d'_L \\
& -y_u(\bar{q}_L\phi_2 u_R + \bar{q}'_R\phi'_2 u'_L) - f_u\xi\bar{u}_R u'_L \\
& -y_e(\bar{l}_L\tilde{\phi}_1 e_R + \bar{l}_R\tilde{\phi}'_1 e'_L) - f_e\xi\bar{e}_R e'_L \\
& -\frac{1}{2}y_\nu(\bar{l}^c_L i\tau_2\Delta l_L + \bar{l}'^c_R i\tau_2\Delta' l'_R) + \text{H.c.}
\end{aligned}$$

with $f_{d,u,e} = f^\dagger_{d,u,e}\,,\;\; y_\nu = y^T_\nu\,.$

$$V \supset \mu\xi\chi^2 + \lambda\sigma(\phi^T_2 i\tau_2\Delta\phi_2 + \phi'^T_2 i\tau_2\Delta'\phi'_2) + \text{H.c.}\,.$$

$$W^\pm_R: \quad f'^1_R \longrightarrow f'^2_R + f'^3_R + f'^4_R\,,$$

$$\xi: \quad f'_L \longrightarrow f_R + \chi + \chi\,.$$

- If neither the mirror baryon asymmetry nor the mirror lepton asymmetry participates in the $SU(2)_L$ sphalerons, the ordinary baryon asymmetry should be

$$B_q = B_{q'} \,.$$

- If only the mirror baryon asymmetry participates in the $SU(2)_L$ sphalerons, the ordinary baryon asymmetry should be

$$B_q = \frac{28}{79} B_{q'} \,.$$

- If only the mirror lepton asymmetry participates in the $SU(2)_L$ sphalerons, the ordinary baryon asymmetry should be

$$B_q = B_{q'} - \frac{28}{79} L_{l'} = \frac{51}{79} B_{q'} \,.$$

Summary

- In the mirror left-right symmetric models with the parity symmetry motivated to solve the strong CP problem, the right-handed charged current interactions of the mirror fermions can realize a successful leptogenesis where the baryon asymmetry is determined by the neutrino mass matrix up to an overall factor.

  In this leptogenesis scenario, the dark matter scalar is essential for converting the mirror lepton asymmetry to the ordinary lepton asymmetry.

- In the presence of a dark copy of the ordinary fields, the CP-violating reflection of the dark fermions off the expanding dark Higgs bubbles can simultaneously generate the ordinary and dark matter and hence explain the dark and baryonic matter coincidence. The dark neutron can have a determined mass to serve as the dark matter particle.

  By further imposing a mirror CP symmetry, the cosmic matter can be described by the ordinary lepton mass matrices up to an overall factor, while the Dirac CP phase in the Majorana neutrino mass matrix can provide a unique source for the required CP violation.

- In the mirror left-right symmetric models with the parity symmetry motivated to solve the strong CP problem, the CP-violating reflection of the mirror fermions off the expanding mirror Higgs bubbles can simultaneously generate a mirror baryon asymmetry and an equal lepton asymmetry.

  The mirror fermions can efficiently decay into their ordinary partners with a dark matter scalar before the BBN epoch. A proper combination between the ordinary baryon and lepton asymmetries can be available to explain the cosmic baryon asymmetry in association with the ordinary sphaleron processes.

  The cosmic baryon asymmetry can be described by the ordinary lepton mass matrices up to an overall factor. In this scenario, the Dirac CP phase in the Majorana neutrino mass matrix provides a unique source for the required CP violation.

  The Higgs triplets for type-II seesaw and the first generation of mirror fermions are allowed at the TeV scale.

Thank you very much!