CP violation for leptogenesis with seesaw

Pei-Hong Gu
Shanghai Jiao Tong University

PHG, 1612.04344; H. Zhou, PHG, 1612.06759.

4th International Workshop on

Dark Matter, Dark Energy and Matter-Antimatter Asymmetry

National Tsing Hua University, Hsinchu, December 29-31, 2016

Outline

1. Motivation
2. Seesaw
3. CP violation for leptogenesis
4. Non-thermal leptogenesis with minimal dark matter
5. Summary

Motivation

‡ 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.

$$\eta_B = \frac{n_B}{s} \sim 10^{-10} \,.$$

We need a dynamical baryogenesis mechanism!

Sakharov conditions

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.

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

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

Sphaleron processes

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'.),

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

We need a baryogenesis beyond the standard model!

In the standard model, the sphaleron processes, the CKM phase and the electroweak phase transition can fulfill all of the three Sakharov conditions to realize an electroweak baryogenesis scenario (e.g. Morrissey, Ramsey-Musolf, 12'.).

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 is much lower than 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 $\eta_B = \mathcal{O}(10^{-20})$.

Seesaw

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.

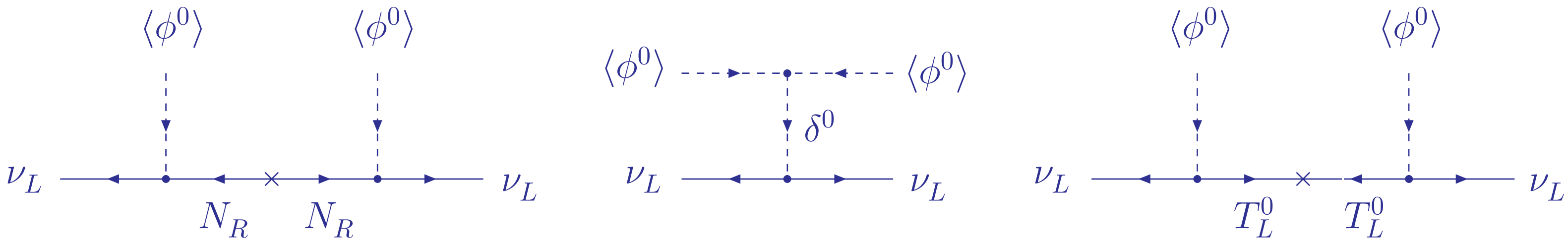
$$\mathcal{L}_{\mathrm{SM}} \supset \sum_{\alpha} \left[i\bar{l}_{L\alpha} \not{D} l_{L\alpha} + i\bar{e}_{R\alpha} \not{D} e_{R\alpha} - y_\alpha \left(\bar{l}_{L\alpha} \tilde{\phi} e_{R\alpha} + \mathrm{H.c.} \right) \right] ,$$

$$\phi(1,2,-\tfrac{1}{2}) = \begin{bmatrix} \phi^0 \\ \phi^- \end{bmatrix} , \quad l_{L\alpha}(1,2,-\tfrac{1}{2}) = \begin{bmatrix} \nu_{L\alpha} \\ e_{L\alpha} \end{bmatrix} , \quad e_{R\alpha}(1,1,-1) .$$

$$\mathcal{L}_{\mathrm{I}} \supset -\frac{1}{2} M_{N_i} \left(\bar{N}_{Ri} N^c_{Ri} + \mathrm{H.c.} \right) - \left(g_{\alpha i} \bar{l}_{L\alpha i} \phi N_{Ri} + \mathrm{H.c.} \right) \quad \text{with} \quad N_{Ri}(1,1,0) ,$$

$$\mathcal{L}_{\mathrm{II}} = -M^2_{\Delta_i} \mathrm{Tr} \left(\Delta_i^\dagger \Delta_i \right) - \frac{1}{2} \mu_i \left(\phi^\dagger \Delta_i i\tau_2 \phi^* + \mathrm{H.c.} \right) - \left(\frac{1}{2} f_{\alpha\beta i} \bar{l}_{L\alpha} \Delta_i i\tau_2 l^c_{L\beta} + \mathrm{H.c.} \right) \quad \text{with} \quad \Delta_i(1,3,-1) = \begin{bmatrix} \delta_i^-/\sqrt{2} & \delta_i^0 \\ \delta_i^{--} & -\delta_i^-/\sqrt{2} \end{bmatrix} ,$$

$$\mathcal{L}_{\mathrm{III}} = -\frac{1}{2} M_{T_i} \left[\mathrm{Tr} \left(\bar{T}^c_{Li} i\tau_2 T_{Li} i\tau_2 \right) + \mathrm{H.c.} \right] - \left(\sqrt{2}\, h_{\alpha i} \bar{l}_{L\alpha} i\tau_2 T^c_{Li} i\tau_2 \phi + \mathrm{H.c.} \right) \quad \text{with} \quad T_{Li}(1,3,0) = \begin{bmatrix} T^0_{Li}/\sqrt{2} & T^+_{Li} \\ T^-_{Li} & -T^0_{Li}/\sqrt{2} \end{bmatrix} .$$



$$\mathcal{L} \supset -\frac{1}{2}\bar{\nu}_L m_\nu \nu_L^c + \text{H.c.} \quad \text{with} \quad m_\nu = U\,\hat{m}\,U^T\,,$$

$$\left(m_\nu^{\rm I}\right)_{\alpha\beta} = -\sum_i g_{\alpha i} g_{\beta i}\frac{v^2}{M_{N_i}}\,, \quad \left(m_\nu^{\rm II}\right)_{\alpha\beta} = -\sum_i f_{\alpha\beta i}\frac{\mu_i v^2}{2M_{\Delta_i}^2}\,, \quad \left(m_\nu^{\rm III}\right)_{\alpha\beta} = -\sum_i h_{\alpha i} h_{\beta i}\frac{v^2}{M_{T_i}}\,.$$

$$m_\nu = U\,\hat{m}\,U^T \quad \text{with}$$

$$\hat{m} = \text{diag}\left\{m_1\,,\ m_2\,,\ m_3\right\}\,,$$

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \times \text{diag}\left\{e^{i\alpha_1/2}\,,\ e^{i\alpha_2/2}\,,\ 1\right\}\,.$$

Davidson-Ibarra parametrization (Davidson, Ibarra, 01')

$$m_\nu = -g\frac{v}{\sqrt{M_{N_i}}}\frac{v}{\sqrt{M_{N_i}}}g^T = U\sqrt{\hat{m}}OO^T\sqrt{\hat{m}}U^T \Rightarrow g_{\alpha i} = i\sum_j U_{\alpha j}\sqrt{m_j}O_{ji}\sqrt{M_{N_i}}/v$$

$$\text{or} \quad m_\nu = -h\frac{v}{\sqrt{M_{T_i}}}\frac{v}{\sqrt{M_{T_i}}}h^T = U\sqrt{\hat{m}}OO^T\sqrt{\hat{m}}U^T \Rightarrow h_{\alpha i} = i\sum_j U_{\alpha j}\sqrt{m_j}O_{ji}\sqrt{M_{T_i}}/v\,.$$

Here O being an arbitrary complex orthogonal matrix. Ones hence conclude that in the presence of the complex orthogonal matrix O, the Yukawa couplings g/h can be complex even if the PMNS matrix U does not contain any CP phases.

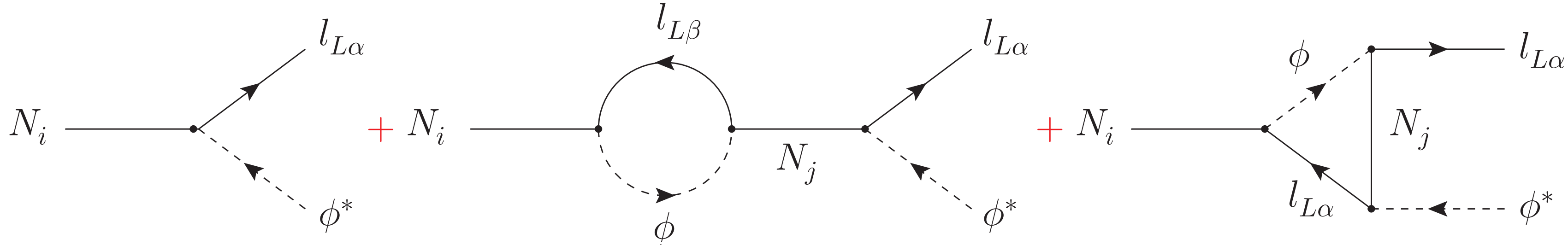
However, we should keep in mind that the Yukawa couplings g/h contain three unphysical phases which can be removed by redefining the SM lepton doublets. In such a physical basis, the complex orthogonal matrix O can be never arbitrary.

$$g_{\alpha 1} \equiv g^*_{\alpha 1} \quad \text{or} \quad h_{\alpha 1} \equiv h^*_{\alpha 1} \quad \Rightarrow \quad \sum_i \left(U_{\alpha i}\sqrt{m_i}O_{i1} + U^*_{\alpha i}\sqrt{m_i}O^*_{i1}\right) = 0\,.$$

CP violation for leptogenesis

$$\eta_B = c_{\rm sph} \frac{\sum_i \kappa_{N_i}\varepsilon_{N_i} + \sum_j \kappa_{\Delta_j}\varepsilon_{\Delta_j} r_{\Delta_j} + \sum_k \kappa_{T_k}\varepsilon_{T_k} r_{T_k}}{g_*}\,.$$

Here $c_{\rm sph} = -\frac{28}{79}$ is the sphaleron lepton-to-baryon coefficient, $g_* = 106.75$ is the relativistic degrees of freedom during the leptogenesis epoch, $\kappa_{N_i/\Delta_i/T_i} \lesssim 1$ denote the washout factors and their exact numbers are solved by the related Boltzmann equations, $r_{\Delta_i/T_i} = 3$ appear for the triplets, while $\varepsilon_{N_i/\Delta_i/T_i}$ are the CP asymmetries in the decays of the fermion singlet $N_i = N_{Ri} + (N_{Ri})^c = N_i^c$, the Higgs triplet pair $(\Delta_i,\ \Delta_i^*)$ and the fermion triplet $T_i = (T_i^-,\ T_i^0,\ T_i^+)$ with $T_i^0 = T_{Li}^0 + (T_{Li}^0)^c = (T_i^0)^c$ and $T_i^\pm = T_{Li}^\pm + (T_{Li}^\mp)^c = (T_i^\mp)^c$. The CP asymmetries $\varepsilon_{N_i/\Delta_i/T_i}$ well characterize the CP violation required by the leptogenesis and they are evaluated at one-loop level.



Basis: $\quad g_{\alpha 1} \equiv g_{\alpha 1}^* \quad$ or $\quad h_{\alpha 1} \equiv h_{\alpha 1}^*\,.$

- In the type-I seesaw,

$$\mathrm{Im}\left[(m_\nu)_{\alpha\beta}\right] = -\mathrm{Im}\left(\sum_{i\neq 1} g_{\alpha i} g_{\beta i} \frac{v^2}{M_{N_i}}\right) .$$

- In the type-III seesaw,

$$\mathrm{Im}\left[(m_\nu)_{\alpha\beta}\right] = -\mathrm{Im}\left(\sum_{i\neq 1} h_{\alpha i} h_{\beta i} \frac{v^2}{M_{T_i}}\right) .$$

- In the type-I+III seesaw,

$$\mathrm{Im}\left[(m_\nu)_{\alpha\beta}\right] = -\mathrm{Im}\left(\sum_{i\neq 1} g_{\alpha i} g_{\beta i} \frac{v^2}{M_{N_i}} + \sum_{j} h_{\alpha j} h_{\beta j} \frac{v^2}{M_{T_j}}\right) ,$$

$$\text{or} \quad \mathrm{Im}\left[(m_\nu)_{\alpha\beta}\right] = -\mathrm{Im}\left(\sum_{i} g_{\alpha i} g_{\beta i} \frac{v^2}{M_{N_i}} + \sum_{j\neq 1} h_{\alpha j} h_{\beta j} \frac{v^2}{M_{T_j}}\right) .$$

- In the type-I+II seesaw,

$$\mathrm{Im}\left[(m_\nu)_{\alpha\beta}\right] = -\mathrm{Im}\left(\sum_{i\neq 1} g_{\alpha i} g_{\beta i} \frac{v^2}{M_{N_i}} + \sum_{j} f_{\alpha\beta j} \frac{\mu_j v^2}{2 M_{\Delta_j}^2}\right) .$$

- In the type-III+II seesaw,

$$\mathrm{Im}\left[(m_\nu)_{\alpha\beta}\right] = -\mathrm{Im}\left(\sum_{i\neq 1} h_{\alpha i} h_{\beta i} \frac{v^2}{M_{T_i}} + \sum_{j} f_{\alpha\beta j} \frac{\mu_j v^2}{2 M_{\Delta_j}^2}\right) .$$

- In the type-I seesaw with two fermion singlets,

$$\varepsilon_{N_1} = \frac{1}{8\pi} \frac{\sum_{\alpha\beta} g_{\alpha 1} g_{\beta 1} \mathrm{Im}\left[(m_\nu)_{\alpha\beta}\right] M_{N_2} I_{N_1}^{N_2}}{v^2 \sum_\alpha g_{\alpha 1}^2}, \quad \varepsilon_{N_2} = -\frac{1}{8\pi} \frac{\sum_{\alpha\beta} g_{\alpha 1} g_{\beta 1} \mathrm{Im}\left[(m_\nu)_{\alpha\beta}\right] M_{N_1} I_{N_2}^{N_1}}{v^2 \sum_\alpha g_{\alpha 2}^* g_{\alpha 2}}.$$

- In the type-III seesaw with two fermion triplets,

$$\varepsilon_{T_1} = \frac{1}{8\pi} \frac{\sum_{\alpha\beta} h_{\alpha 1} h_{\beta 1} \mathrm{Im}\left[(m_\nu)_{\alpha\beta}\right]}{\sum_\alpha h_{\alpha 1}^2} \frac{M_{T_2} I_{T_1}^{T_2}}{v^2}, \quad \varepsilon_{T_2} = -\frac{1}{8\pi} \frac{\sum_{\alpha\beta} h_{\alpha 1} h_{\beta 1} \mathrm{Im}\left[(m_\nu)_{\alpha\beta}\right]}{\sum_\alpha h_{\alpha 2}^* h_{\alpha 2}} \frac{M_{T_1} I_{T_2}^{T_1}}{v^2}.$$

- In the type-I+III seesaw with one fermion singlet and one fermion triplet,

$$\varepsilon_{N_1} = \frac{1}{8\pi} \frac{\sum_{\alpha\beta} g_{\alpha 1} g_{\beta 1} \mathrm{Im}\left[(m_\nu)_{\alpha\beta}\right] M_{T_1} I_{N_1}^{T_1}}{v^2 \sum_\alpha g_{\alpha 1}^2}, \quad \varepsilon_{T_1} = -\frac{1}{8\pi} \frac{\sum_{\alpha\beta} g_{\alpha 1} g_{\beta 1} \mathrm{Im}\left[(m_\nu)_{\alpha\beta}\right] M_{N_1} I_{T_1}^{N_1}}{v^2 \sum_\alpha h_{\alpha 1}^* h_{\alpha 1}}.$$

- In the type-I+II seesaw with one fermion singlet and one Higgs triplet,

$$\varepsilon_{N_1} = \frac{1}{8\pi} \frac{\sum_{\alpha\beta} g_{\alpha 1} g_{\beta 1} \mathrm{Im}\left[(m_\nu)_{\alpha\beta}\right] M_{\Delta_1} I_{N_1}^{\Delta_1}}{v^2 \sum_\alpha g_{\alpha 1}^2}, \quad \varepsilon_{\Delta_1} = -\frac{1}{8\pi} \frac{\sum_{\alpha\beta} g_{\alpha 1} g_{\beta 1} \mathrm{Im}\left[(m_\nu)_{\alpha\beta}\right] M_{N_1} I_{\Delta_1}^{N_1}}{v^2 \left(\sum_{\alpha\beta} f_{\alpha\beta 1}^* f_{\alpha\beta 1} + \frac{\mu_1^2}{M_{\Delta_1}^2}\right)}.$$

- In the type-III+II seesaw with one fermion triplet and one Higgs triplet,

$$\varepsilon_{T_1} = \frac{1}{8\pi} \frac{\sum_{\alpha\beta} h_{\alpha 1} h_{\beta 1} \mathrm{Im}\left[(m_\nu)_{\alpha\beta}\right] M_{\Delta_1} I_{T_1}^{\Delta_1}}{v^2 \sum_\alpha h_{\alpha 1}^2}, \quad \varepsilon_{\Delta_1} = -\frac{1}{8\pi} \frac{\sum_{\alpha\beta} h_{\alpha 1} h_{\beta 1} \mathrm{Im}\left[(m_\nu)_{\alpha\beta}\right] M_{T_1} I_{\Delta_1}^{T_1}}{v^2 \left(\sum_{\alpha\beta} f_{\alpha\beta 1}^* f_{\alpha\beta 1} + \frac{\mu_1^2}{M_{\Delta_1}^2}\right)}.$$

- In the seesaw models with more fermion singlet(s)/triplet(s) and Higgs triplet(s), the leptogenesis can be realized by the decays of the lightest fermion singlet/triplet,

$$\varepsilon_{N_1} = \frac{3}{16\pi} \frac{\sum_{\alpha\beta} \left\{ g_{\alpha 1} g_{\beta 1} \mathrm{Im}\left[(m_\nu)_{\alpha\beta}\right]\right\} M_{N_1}}{v^2 \sum_\alpha g_{\alpha 1}^2} \quad \text{or} \quad \varepsilon_{T_1} = \frac{3}{16\pi} \frac{\sum_{\alpha\beta} \left\{ h_{\alpha 1} h_{\beta 1} \mathrm{Im}\left[(m_\nu)_{\alpha\beta}\right]\right\} M_{T_1}}{v^2 \sum_\alpha h_{\alpha 1}^2}.$$

Non-thermal leptogenesis with minimal dark matter

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm III} + \mathcal{L}_{\rm I/II} + \mathcal{L}_{\sigma} + \mathcal{L}_{\chi} + \mathcal{L}_{\sigma\chi T} \,.$$

$$\mathcal{L}_{\sigma} = \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}M_\sigma^2\sigma^2 - \frac{1}{4}\lambda_\sigma\sigma^4 \quad \text{with} \quad \sigma(1,1,0)\,,$$

$$\mathcal{L}_{\chi} = i\mathrm{Tr}\left(\bar{\chi}_L \not{D}\chi_L\right) - \frac{1}{2}M_\chi \mathrm{Tr}\left(\bar{\chi}_L^c i\tau_2\chi_L i\tau_2\right) + \mathrm{H.c.}$$

$$\text{with} \quad \chi_L(1,3,0) = \begin{bmatrix} \chi_L^0/\sqrt{2} & \chi_L^+ \\ \chi_L^- & -\chi_L^0/\sqrt{2} \end{bmatrix}\,, \quad D_\mu\chi_L = \partial_\mu\chi_L - ig\left[\frac{\tau_a}{2}W_\mu^a\,,\ \chi_L\right]\,.$$

$$\mathcal{L}_{\sigma\chi T} = -f_\sigma\sigma\mathrm{Tr}\left(\bar{T}_L i\tau_2\chi_L^c i\tau_2\right) + \mathrm{H.c.}\,.$$

$$(\mathrm{SM}\,,\,T_L\,,\,N_R/\Delta) \xrightarrow{Z_2} (\mathrm{SM}\,,\,T_L\,,\,N_R/\Delta)\,, \qquad (\sigma\,,\,\chi_L) \xrightarrow{Z_2} -(\sigma\,,\,\chi_L)\,.$$

$$
\begin{aligned}
\mathcal{L}_{\mathrm{I}} &= i\bar{N}_R \not{\partial} N_R - \frac{1}{2} M_N \bar{N}_R N_R^c - f_{N\alpha} \bar{l}_{L\alpha} \phi N_R + \mathrm{H.c.} \quad \text{with} \quad N_R(1,1,0)\,, \\
\mathcal{L}_{\mathrm{II}} &= \mathrm{Tr}\left[\left(D_\mu \Delta\right)^\dagger \left(D^\mu \Delta\right)\right] - M_\Delta^2 \mathrm{Tr}\left(\Delta^\dagger \Delta\right) - \frac{1}{2}\mu_\Delta \phi^\dagger \Delta i\tau_2 \phi^* - \frac{1}{2} f_{\Delta\alpha\beta} \bar{l}_{L\alpha} \Delta i\tau_2 l_{L\beta}^c + \mathrm{H.c.} \\
&\quad \text{with} \quad \Delta(1,3,-1) = \begin{bmatrix} \delta^-/\sqrt{2} & \delta^0 \\ \delta^{--} & -\delta^-/\sqrt{2} \end{bmatrix}, \quad D_\mu \Delta = \partial_\mu \Delta - ig\left[\frac{\tau_a}{2} W_\mu^a\,,\ \Delta\right] + ig' B_\mu \Delta\,, \\
\mathcal{L}_{\mathrm{III}} &= i\mathrm{Tr}\left(\bar{T}_L \not{D} T_L\right) - \frac{1}{2} M_T \mathrm{Tr}\left(\bar{T}_L^c i\tau_2 T_L i\tau_2\right) - \sqrt{2}\, f_{T\alpha} \bar{l}_{L\alpha} i\tau_2 T_L^c i\tau_2 \phi + \mathrm{H.c.} \\
&\quad \text{with} \quad T_L(1,3,0) = \begin{bmatrix} T_L^0/\sqrt{2} & T_L^+ \\ T_L^- & -T_L^0/\sqrt{2} \end{bmatrix}, \quad D_\mu T_L = \partial_\mu T_L - ig\left[\frac{\tau_a}{2} W_\mu^a\,,\ T_L\right].
\end{aligned}
$$

Basis: $M_\chi = M_\chi^*\,, \quad M_T = M_T^*\,, \quad f_{T\alpha} = f_{T\alpha}^*\,, \quad M_N = M_N^*\,, \quad \mu_\Delta = \mu_\Delta^*\,.$

$$
\begin{aligned}
\mathcal{L}_\chi &= \frac{i}{2}\overline{\chi^0}\partial\!\!\!/\chi^0 - \frac{1}{2}M_\chi\overline{\chi^0}\chi^0 + i\overline{\chi^-}\partial\!\!\!/\chi^- - M_\chi\overline{\chi^-}\chi^- - g\overline{\chi^-}\gamma^\mu\chi^- W_\mu^3 + g\left(\overline{\chi^-}\gamma^\mu\chi^0 W_\mu^- + \text{H.c.}\right) \\
&\quad \text{with} \quad \chi^0 = \chi_L^0 + (\chi_L^0)^c = (\chi^0)^c\,, \quad \chi^\pm = \chi_L^\pm + (\chi_L^\mp)^c = (\chi^\mp)^c\,, \\
\mathcal{L}_{\text{III}} &\supset \frac{i}{2}\overline{T^0}\partial\!\!\!/ T^0 - \frac{1}{2}M_T\overline{T^0}T^0 + i\overline{T^-}\partial\!\!\!/ T^- - M_T\overline{T^-}T^- \\
&\quad -f_{T\alpha}\left[\left(\bar{\nu}_{L\alpha}\phi^0 T^0 - \bar{e}_{L\alpha}\phi^- T^0 + \sqrt{2}\bar{\nu}_{L\alpha}\phi^- T^+ + \sqrt{2}\bar{e}_{L\alpha}\phi^0 T^-\right) + \text{H.c.}\right] \\
&\quad \text{with} \quad T^0 = T_L^0 + (T_L^0)^c = (T^0)^c\,, \quad T^\pm = T_L^\pm + (T_L^\mp)^c = (T^\mp)^c\,, \\
\mathcal{L}_{\text{I}} &= \frac{i}{2}\bar{N}\partial\!\!\!/ N - \frac{1}{2}M_N\bar{N}N - \left[f_{N\alpha}\left(\bar{\nu}_{L\alpha}\phi^0 + \bar{e}_{L\alpha}\phi^-\right)N + \text{H.c.}\right] \quad \text{with} \quad N = N_R + (N_R)^c = N^c\,, \\
\mathcal{L}_{\text{II}} &\supset -M_\Delta^2\left(\delta^{0*}\delta^0 + \delta^+\delta^- + \delta^{++}\delta^{--}\right) - \frac{1}{2}\mu_\Delta\left[\left(\phi^+\phi^+\delta^{--} + \sqrt{2}\phi^{0*}\phi^+\delta^- - \phi^{0*}\phi^{0*}\delta^0\right) + \text{H.c.}\right] \\
&\quad -\frac{1}{2}\left[f_{\Delta\alpha\beta}\left(\bar{e}_{L\alpha}e_{L\beta}^c\delta^{--} + \sqrt{2}\bar{\nu}_{L\alpha}e_{L\beta}^c\delta^- - \bar{\nu}_{L\alpha}\nu_{L\beta}^c\delta^0\right) + \text{H.c.}\right]\,, \\
\mathcal{L}_{\sigma\chi T} &= -f_\sigma\sigma\left(\overline{T^-}P_R\chi^- + \overline{T^0}P_R\chi^0 + \overline{T^+}P_R\chi^+\right) + \text{H.c.}\,.
\end{aligned}
$$

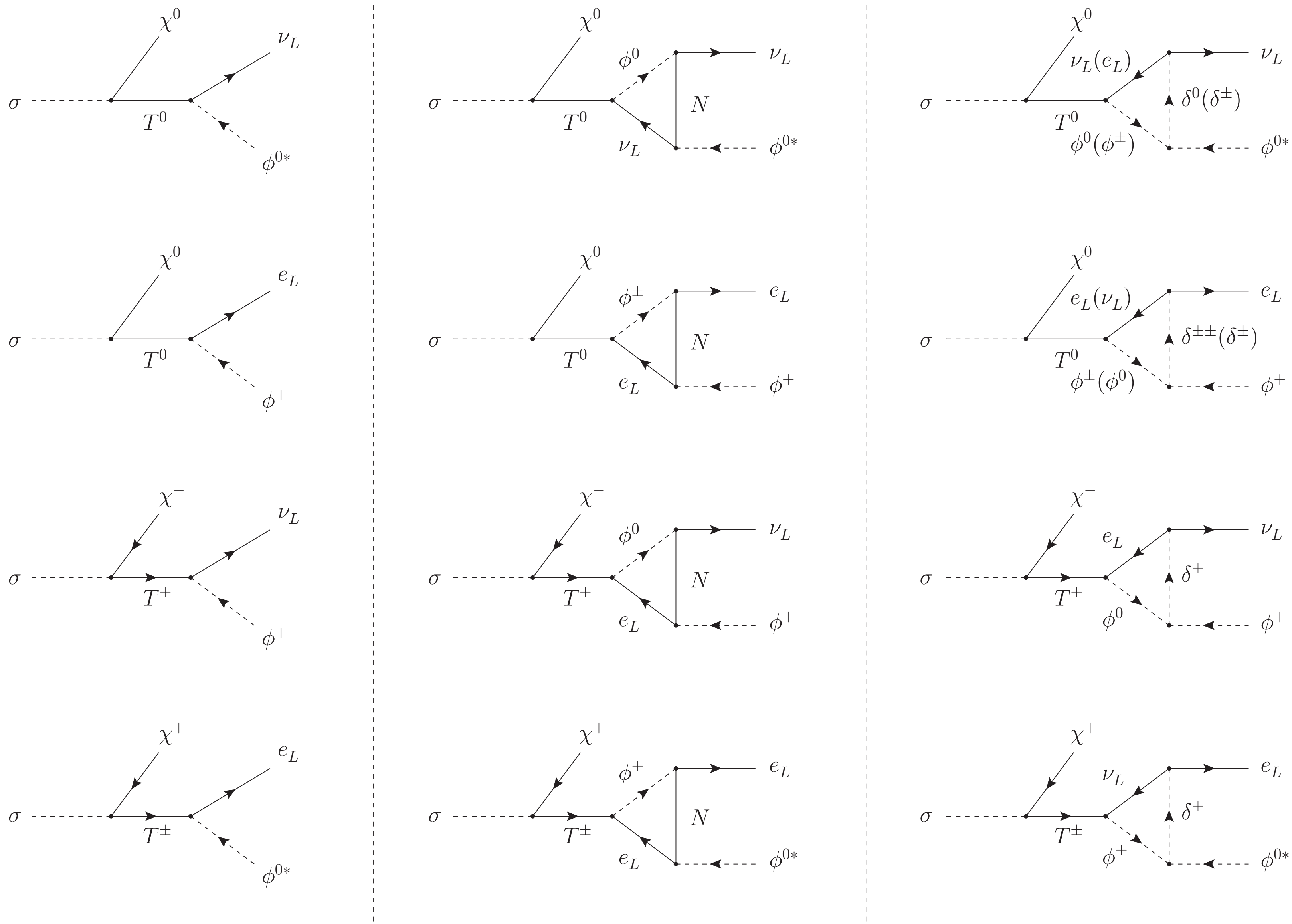
$$\mathcal{L} \supset -\frac{1}{2}\bar{\nu}_L m_\nu \nu_L^c + \text{H.c.} \quad \text{with} \quad m_\nu = m_\nu^{\text{III}} + m_\nu^{\text{I/II}}\,,$$

$$\left(m_\nu^{\text{III}}\right)_{\alpha\beta} = -f_{T\alpha} f_{T\beta} \frac{v^2}{M_T}\,, \quad \left(m_\nu^{\text{I}}\right)_{\alpha\beta} = -f_{N\alpha} f_{N\beta} \frac{v^2}{M_N}\,, \quad \left(m_\nu^{\text{II}}\right)_{\alpha\beta} = -f_{\Delta\alpha\beta} \frac{\mu_\Delta v^2}{2M_\Delta^2}\,.$$

$$\text{Im}\left(m_\nu^{\text{I/II}}\right) = \text{Im}\left(m_\nu\right) = \text{Im}\left(U\,\hat{m}\,U^T\right)\,.$$

Inflation: $M_\sigma = 1.5 \times 10^{13}\,\text{GeV}\,, \quad \lambda_\sigma = 0\,.$

R. Kallosh, A. Linde, and A. Westphal, Phys. Rev. D **90**, 023534 (2014).



σ
χ^0
χ^-
χ^+
T^0
$T^\pm$
ν_L
e_L
ϕ^{0*}
ϕ^+
ϕ^0
$\phi^\pm$
N
$\nu_L(e_L)$
$e_L(\nu_L)$
$\delta^0(\delta^\pm)$
$\delta^{\pm\pm}(\delta^\pm)$
$\delta^\pm$
$\phi^0(\phi^\pm)$
$\phi^\pm(\phi^0)$

(a) (b) (c)

$$
\begin{aligned}
\Gamma_\sigma &= \Gamma(\sigma \longrightarrow \nu_L + \chi^0 + \phi^{0*}) + \Gamma(\sigma \longrightarrow e_L + \chi^0 + \phi^+) \\
&\quad +\Gamma(\sigma \longrightarrow \nu_L + \chi^- + \phi^+) + \Gamma(\sigma \longrightarrow e_L + \chi^+ + \phi^{0*}) \\
&\quad +\Gamma(\sigma \longrightarrow \nu_L^c + \chi^0 + \phi^{0*}) + \Gamma(\sigma \longrightarrow e_L^c + \chi^0 + \phi^-) \\
&\quad +\Gamma(\sigma \longrightarrow \nu_L^c + \chi^+ + \phi^-) + \Gamma(\sigma \longrightarrow e_L^c + \chi^- + \phi^0) \\
&= \frac{|f_\sigma|^2 \sum_\alpha y_{T\alpha}^2}{2^8\pi^3}\frac{M_\sigma^3}{M_T^2} = \frac{|f_\sigma|^2\,\mathrm{Tr}\left(m_\nu^{\mathrm{III}}\right)}{2^8\pi^3}\frac{M_\sigma^3}{v^2 M_T}\,.
\end{aligned}
$$

$$
\Gamma_\sigma = H(T)\,\Big|_{T_{\mathrm{RH}}} \Rightarrow T_{\mathrm{RH}} = \left(\frac{90}{8\pi g_*}\right)^{\frac{1}{4}} \frac{|f_\sigma|}{16\pi^2}\frac{M_\sigma}{v}\left[\frac{\mathrm{Tr}\left(m_\nu^{\mathrm{III}}\right) M_\sigma M_{\mathrm{Pl}}}{M_T}\right]^{\frac{1}{2}}\,.
$$

$$
H = \left(\frac{8\pi^3 g_*}{90}\right)^{\frac{1}{2}} \frac{T^2}{M_{\mathrm{Pl}}}\,.
$$

$$\varepsilon_\sigma = \varepsilon_\sigma^{\nu_L\chi^0} + \varepsilon_\sigma^{e_L\chi^0} + \varepsilon_\sigma^{\nu_L\chi^-} + \varepsilon_\sigma^{e_L\chi^+} \neq 0 \quad \text{with}$$

$$\varepsilon_\sigma^{\nu_L\chi^0} = \frac{\Gamma(\sigma \longrightarrow \nu_L + \chi^0 + \phi^{0*}) - \Gamma(\sigma \longrightarrow \nu_L^c + \chi^0 + \phi^0)}{\Gamma_\sigma},$$

$$\varepsilon_\sigma^{e_L\chi^0} = \frac{\Gamma(\sigma \longrightarrow e_L + \chi^0 + \phi^+) - \Gamma(\sigma \longrightarrow e_L^c + \chi^0 + \phi^-)}{\Gamma_\sigma},$$

$$\varepsilon_\sigma^{\nu_L\chi^-} = \frac{\Gamma(\sigma \longrightarrow \nu_L + \chi^- + \phi^+) - \Gamma(\sigma \longrightarrow \nu_L^c + \chi^+ + \phi^-)}{\Gamma_\sigma},$$

$$\varepsilon_\sigma^{e_L\chi^+} = \frac{\Gamma(\sigma \longrightarrow e_L + \chi^+ + \phi^{0*}) - \Gamma(\sigma \longrightarrow e_L^c + \chi^- + \phi^0)}{\Gamma_\sigma}.$$

$$\varepsilon_\sigma = -\frac{1}{16\pi}\frac{\sum_{\alpha\beta}\left[y_{T\alpha}y_{T\beta}\mathrm{Im}\left(y_{N\alpha}y_{N\beta}\right)\right]}{\sum_\alpha y_{T\alpha}y_{T\alpha}}\frac{M_\sigma^2}{M_N M_T} \quad \text{or} \quad \varepsilon_\sigma = -\frac{1}{16\pi}\frac{\sum_{\alpha\beta}\left[y_{T\alpha}y_{T\beta}\mathrm{Im}\left(f_{\Delta\alpha\beta}\right)\right]}{\sum_\alpha y_{T\alpha}y_{T\alpha}}\frac{M_\sigma^2\mu_\Delta}{2M_\Delta^2 M_T}$$

$$\text{with} \quad 2\varepsilon_\sigma^{\nu_L\chi^0} = 2\varepsilon_\sigma^{e_L\chi^0} = \varepsilon_\sigma^{\nu_L\chi^-} = \varepsilon_\sigma^{e_L\chi^+} = \frac{1}{3}\varepsilon_\sigma\,.$$

$$\varepsilon_\sigma = \frac{1}{16\pi}\frac{\sum_{\alpha\beta}\left[y_{T\alpha}y_{T\beta}\mathrm{Im}\left(m_{\alpha\beta}\right)\right]}{\sum_\alpha y_{T\alpha}y_{T\alpha}}\frac{M_\sigma^2}{v^2 M_T}\,.$$

$$\left[\Gamma = \frac{1}{\pi^3}\frac{T^3}{v^4}\mathrm{Tr}\left(m_\nu^\dagger m_\nu\right) < H(T)\right]\Big|_{T=T_D>T_{\mathrm{RH}}} \quad \text{for} \quad M_T\,,\; M_{N/\Delta} > T_D\,.$$

$$T_D = 10^{12}\,\mathrm{GeV}\left[\frac{0.04\,\mathrm{eV}^2}{\mathrm{Tr}\left(m_\nu^\dagger m_\nu\right)}\right] \quad \text{for} \quad \mathrm{Tr}\left(m_\nu^\dagger m_\nu\right) = m_1^2 + m_2^2 + m_3^2\,.$$

$$\eta_B = \frac{n_B}{s} = c_{\mathrm{sph}}\frac{n_L}{s} = c_{\mathrm{sph}}\varepsilon_\sigma\frac{T_{\mathrm{RH}}}{M_\sigma} \quad \text{with} \quad c_{\mathrm{sph}} = -\frac{28}{79}\,.$$

$$M_\sigma = 1.5\times 10^{13}\,\mathrm{GeV}\,, \quad f_\sigma = 7.9\times 10^{-3}\,, \quad M_{N/\Delta}\sim M_T = 10^{14}\,\mathrm{GeV}\,, \quad f_{Te}\,,\; f_{T\mu} \ll f_{T\tau}\,.$$

$$T_{\mathrm{RH}} = 5.7\times 10^7\,\mathrm{GeV}\left(\frac{m_{\tau\tau}^{\mathrm{III}}}{0.01\,\mathrm{eV}}\right)^{\frac{1}{2}} < T_D\,, \quad \varepsilon_\sigma = \frac{1}{16\pi}\frac{M_\sigma^2\mathrm{Im}\left(m_{\tau\tau}\right)}{v^2 M_T} = -7.4\times 10^{-5}\left[\frac{\mathrm{Im}\left(m_{\tau\tau}\right)}{-0.05\,\mathrm{eV}}\right]\,.$$

$$\eta_B = 10^{-10}\left(\frac{\varepsilon_\sigma}{-7.4\times 10^{-5}}\right)\left(\frac{T_{\mathrm{RH}}}{5.7\times 10^7\,\mathrm{GeV}}\right)\,.$$

Summary

1. In the pure type-I/III seesaw models, or the combined type-I+III seesaw models, or the combined type-I/III+II seesaw models, the CP violation required by the leptogenesis should come from the imaginary part of the neutrino mass matrix.

2. In a combined type-III+I/II seesaws, a non-thermal leptogenesis can be realized through the inflaton decays into the standard model lepton and Higgs doublets with a dark matter fermion triplet.

Thank you！