Flavour Mixing of Neutrinos and Baryon Asymmetry of the Universe

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1. νMSM [Asaka, Blanchet and Shaposhnikov(2005)], [Asaka and Shaposhnikov(2005)]

・Lagrangian (SM + three right-handed neutrinos : N_1, N_2, N_3)

$$\mathcal{L}_N = i\bar{N}_I \partial\!\!\!/ N_I - F_{\alpha I}\bar{\ell}_{L\alpha}\Phi N_I - \frac{M_I}{2}\bar{N}_I^C N_I + \text{h.c.}$$

・Key Assumption

$$|M_D| = F_{\alpha I}\langle\Phi\rangle \ll M_I \lesssim 100\text{GeV}$$

Small Yukawa couplings

➡ See-saw mechanism still works!!

・The roles of right-handed neutrinos

N_1 : Candidate of DM ⇨ $F_{\alpha 1} \simeq 0$

N_2, N_3 : Tiny neutrino masses by see-saw mechanism; Baryon asymmetry of the universe

Low energy *CP* violation in neutrino sector
and
Baryon asymmetry of the universe

2. Baryogenesis via sterile neutrino oscillation

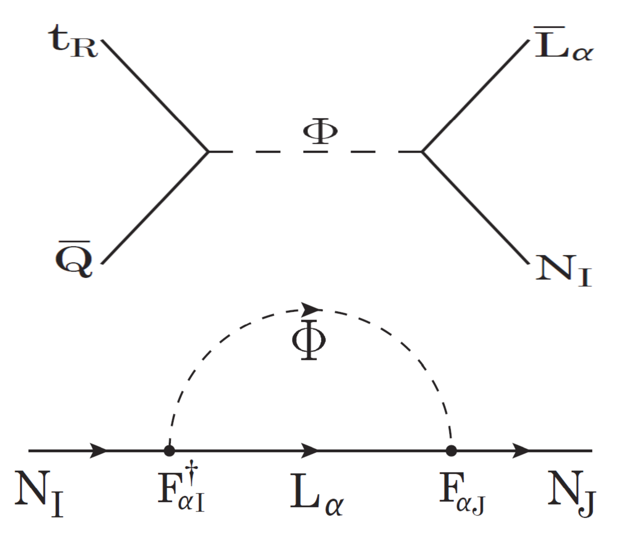
[Akhmedov, Rubakov and Smirnov(1998)], [Asaka and Shaposhnikov(2005)]

・Baryogenesis mechanism

Total lepton number is conserved ($T \gg \Lambda_{\rm EW}$) $\because M < \Lambda_{\rm EW}$

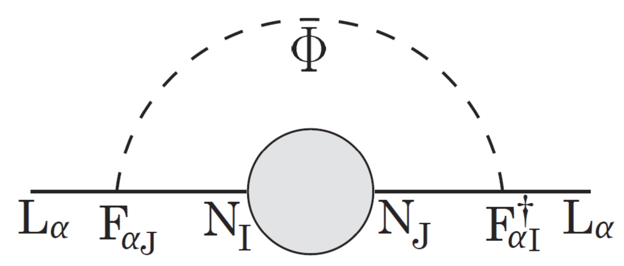
Generation mechanism of lepton asymmetry

$\mathcal{O}(F^2)$



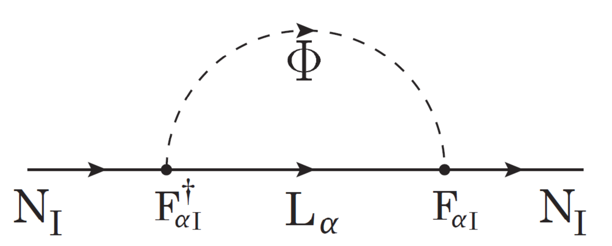
Production and oscillation of sterile neutrinos

$\mathcal{O}(F^4)$



$\Delta L_\alpha \neq 0$
But $\Sigma_\alpha \Delta L_\alpha = 0$ at $\mathcal{O}(F^4)$

$\mathcal{O}(F^6)$



Non-zero asymmetry arise at $\mathcal{O}(F^6)$

Separation of lepton asymmetry : $\Delta L_{\rm tot} = \Sigma_\alpha \Delta L_\alpha + \Sigma_I \Delta N_I = 0$

The created active lepton asymmetry
is partially converted to baryon number by Sphaleron effect

・The kinetic equation for density matrices

$$i\frac{d\rho_{NN}}{dt} = [H_0 + V_N(t), \rho_{NN}] - \frac{i}{2}\{\Gamma_N, \rho_{NN} - \rho_{NN}^{eq}\} + \frac{i\sin\phi}{8}TU^\dagger F_{\alpha I}^\dagger(\rho_{LL} - \rho_{LL}^{eq})F_{\alpha I}U$$

$$i\frac{d\rho_{LL}}{dt} = [H_0 + V_L(t), \rho_{LL}] - \frac{i}{2}\{\Gamma_L, \rho_{LL} - \rho_{LL}^{eq}\} + \frac{i\sin\phi}{4}TU^\dagger F_{\alpha I}(\rho_{NN} - \rho_{NN}^{eq})F_{\alpha I}^\dagger U$$

$$\Delta L_\alpha = (\rho_{LL} - \rho_{\bar{L}\bar{L}})_{\alpha\alpha} \qquad \Delta N_I = (\rho_{NN} - \rho_{\bar{N}\bar{N}})_{II}$$

$$V_N(t) = \frac{T}{8}(F^\dagger F)_{IJ} \quad V_L(t) = \frac{T}{16}(FF^\dagger)_{\alpha\beta} \qquad \Gamma_N = 0.02V_N(t) \quad \Gamma_L = 0.02V_L(t)$$

3. CP phases in neutrino Yukawa couplings

$$F = \frac{i}{\langle\Phi\rangle}U_{\rm MNS}D_\nu^{\frac{1}{2}}\Omega D_N^{\frac{1}{2}}$$ [Casas and Ibarra(2001)]

・$U_{MNS} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-s_{13}s_{23}c_{12}e^{i\delta} & c_{12}c_{23}-s_{12}s_{13}c_{23}e^{i\delta} & s_{13}c_{13} \\ s_{12}s_{23}-s_{13}c_{12}c_{23} & -s_{23}c_{12}-s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}\begin{pmatrix} 1 & & \\ & e^{i\eta} & \\ & & 1 \end{pmatrix}$

($s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$)

・$D_\nu^{\frac{1}{2}} = \text{diag}(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3})$ ・$D_N^{\frac{1}{2}} = \text{diag}(\sqrt{M_2}, \sqrt{M_3})$

・$\Omega_{\rm NH} = \begin{pmatrix} 0 & 0 \\ \cos\omega & -\sin\omega \\ \xi\sin\omega & \xi\cos\omega \end{pmatrix}$ ・$\Omega_{\rm IH} = \begin{pmatrix} \cos\omega & -\sin\omega \\ \xi\sin\omega & \xi\cos\omega \\ 0 & 0 \end{pmatrix}$

By taking ${\rm Im}\,\omega = 0$,
we can see how baryon asymmetry depend on δ and η

4. Results [Asaka and H.I.(2010)]

・Baryon asymmetry of the Universe

$$Y_B = 4.7\times 10^{-10}\left(\frac{10^2\text{GeV}}{T_W}\right)\left(\frac{M_N}{5\text{GeV}}\right)^{5/3}\left(\frac{10^{-8}}{\Delta M_{32}^2/M_N^2}\right)^{2/3}\times\delta_{CP},$$

$$\delta_{CP} = \xi\sin 2{\rm Re}\,\omega S_{m_\nu}\times\delta_\nu$$

δ_ν can be expanded by active neutrino mass ratio $r_m \equiv \frac{m_{\rm sol}}{m_{\rm atm}}$

Normal hierarchy case

$$S_{m_\nu} = 1,$$

$$\delta_\nu = \frac{1}{2}\sin\theta_{12}\sin 2\theta_{13}\left[\cos^2\theta_{13}(3+\cos 4\theta_{23}) - 4\sin^2\theta_{13}\right]\sin(\delta+\eta) + \cos\theta_{12}\sin 4\theta_{23}\cos^3\theta_{13}\sin\eta + \mathcal{O}(r_m).$$

・$\theta_{23} = \pi/4$ limit

$$\delta_\nu \to \sin\theta_{12}\sin 2\theta_{13}\left[\cos^2\theta_{13} - 2\sin^2\theta_{13}\right]\sin(\delta+\eta).$$

・$\theta_{13} = 0$ limit

$$\delta_\nu \to \cos\theta_{12}\sin 4\theta_{23}\sin\eta.$$

When $\theta_{23} = \pi/4$ and $\theta_{13} = 0$,
Y_B at $\mathcal{O}(F^6)$ vanishes !!

Inverted hierarchy case

$$S_{m_\nu} = \left(\frac{m_{\rm sol}}{m_{\rm atm}}\right)^{1/2} = 0.04,$$ ⇦ Suppression factor!!

$$\delta_\nu = \frac{1}{4}\sin 2\theta_{12}\cos^2\theta_{13}\left[-5 - 3\cos 4\theta_{23} + \cos 2\theta_{13}(7+\cos 4\theta_{23})\right]\sin\eta + \sin 4\theta_{23}\sin\theta_{13}\cos^2\theta_{13}(\sin\delta\cos\eta - \cos 2\theta_{12}\cos\delta\sin\eta) + \mathcal{O}(r_m^2).$$

・$\theta_{23} = \pi/4$ limit

$$\delta_\nu \to -\frac{1}{2}\sin 2\theta_{12}\cos^2\theta_{13}\left[3\cos 2\theta_{13} - 1\right]\sin\eta,$$

・$\theta_{13} = 0$ limit

$$\delta_\nu \to -\frac{1}{2}\sin 2\theta_{12}\left[1 + \cos 4\theta_{23}\right]\sin\eta,$$

When $\theta_{23} = \pi/4$ and $\theta_{13} = 0$,
Y_B does not vanish and IH case is required to explain the observed BAU!!

Mixing angles dependence on the Baryon Asymmetry