Higgs-dependent Leptogenesis

Yuji Kajiyama

(Nat. Inst. of Chemical Physics and Biophysics, ESTONIA)

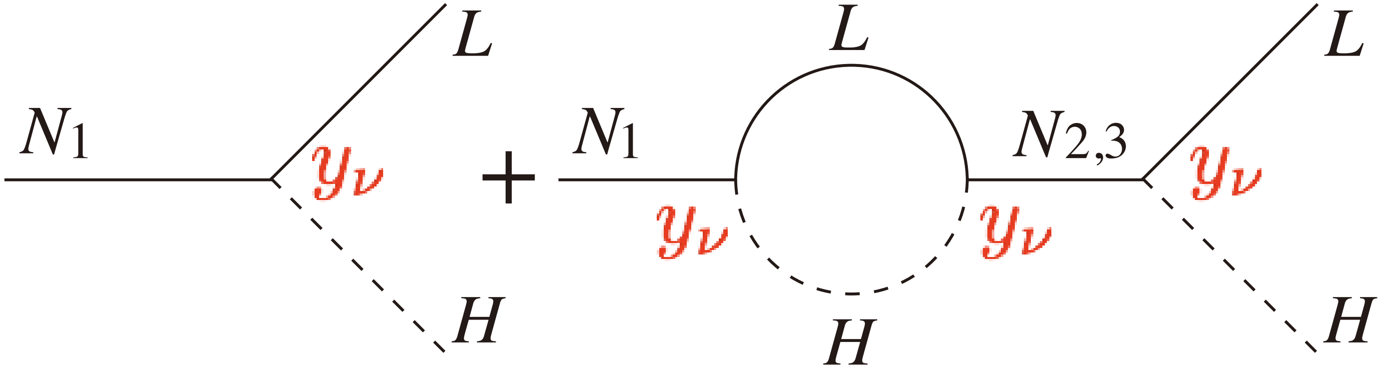
March 12. 2009, MORIOND

with M. Raidal
in preparation

1. Introduction

Baryon asymmetry $\eta_B^{\rm exp} = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.05 - 6.37) \times 10^{-10}$

- TeV-scale leptogenesis with $y_\nu \sim 10^{-6}$

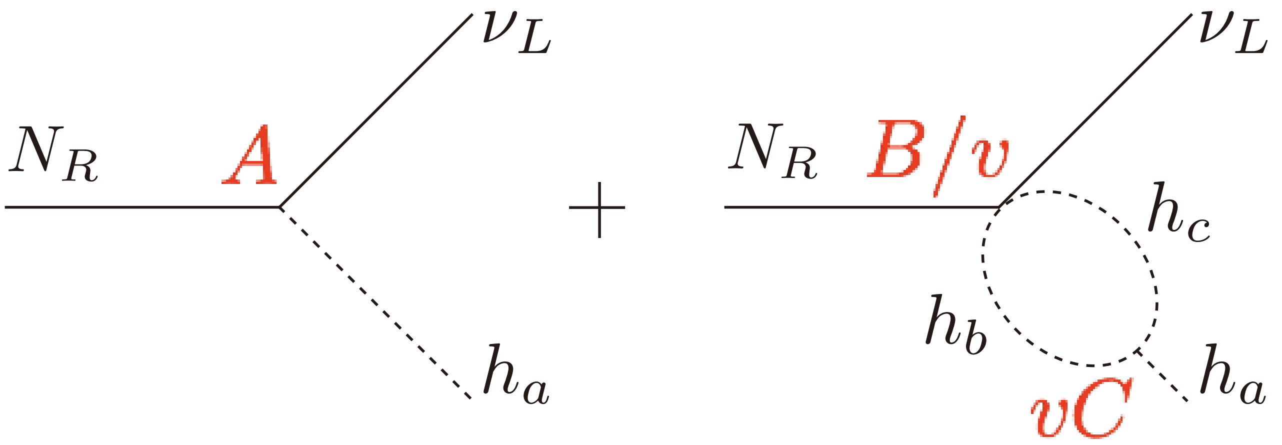


CP asymmetry: $\epsilon \equiv \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}$

$$\epsilon \sim \frac{1}{8\pi}\frac{{\rm Im} y_\nu^4}{y_\nu^2}\frac{M_1 M_2}{M_1^2 - M_2^2} \sim 10^{-13}\frac{M_1 M_2}{M_1^2 - M_2^2} \sim 10^{-6}$$

$\rightarrow \frac{M_2 - M_1}{M_1} \sim 10^{-7}$ Resonance condition

- In this talk, we consider leptogenesis by



$\epsilon \sim \frac{1}{16\pi}\frac{\mathrm{Im}[AB^*]C}{|A|^2}$ can be large if $A \sim B \sim 10^{-6}$.

We discuss:

(1) leptogenesis below EWSB scale $(T < T_c)$
without resonance condition,

(2) source of CPV is in the Higgs sector.

2. The Model

K.S.Babu and S.Nandi,
Phys.Rev.D62,033002(2000)

G.F.Giudice and O.Lebedev,
Phys.Lett.B665,79(2008)

- Consider a Froggatt-Nielsen type model by Higgs doublets with U(1) charge assignment

$$H_u : 0,\ \ H_d : 1,\ \ L_i : -3,\ \ N_{Ri} : 0$$

U(1) invariant Yukawa terms are given by

$$\mathcal{L}_\nu = y^\nu_{ij} \bar{N}_{Ri} L_{Lj} H_u \left(\frac{H_u H_d}{M^2}\right)^{n^\nu_{ij}} + \frac{1}{2} N_{Ri} M_{Nij} N_{Rj} + c.c.$$

where $(n^\nu_{ij}) = 3$. Mass hierarchy: $\left(\frac{v_u v_d}{M^2}\right)^{n_{ij}} \equiv \epsilon^{n_{ij}} = 10^{-2n_{ij}}$

$\boxed{y^\nu \sim \mathcal{O}(1) \text{ and real,}}\ M \sim 1\text{TeV}.$

No CPV in Yukawa

$\boxed{(M_N)_{ij} = M_N \text{diag}(0.5, 1.25, 1.5),}$ with $M_N = 1$ TeV

No Degeneracy

- Expanding the Higgs part $(\epsilon = v^2/M^2)$,

$$N\nu(v+h)\left(\frac{v+h}{M}\right)^{2n} = N\nu\left[\underset{\substack{\uparrow\\ \text{mass term}}}{v\epsilon^n} + \underset{\color{red}{A}}{(2n+1)\epsilon^n h} + \underset{\color{red}{B/v}}{n(2n+1)\frac{\epsilon^n}{v}h^2} + \cdots\right]$$

effective Yukawa interactions

- Higgs potential is given by

$$\begin{aligned} V &= m^2_{H_u}\left|H_u\right|^2 + m^2_{H_d}\left|H_d\right|^2 + \lambda_1\left|H_u\right|^4 + \lambda_2\left|H_d\right|^4 + \lambda_3\left|H_u\right|^2\left|H_d\right|^2 + \lambda_4\left|H_uH_d\right|^2 \\ &+ \boxed{\left[m^2H_uH_d + \lambda_5\left(H_uH_d\right)^2 + \lambda_6\left|H_u\right|^2H_uH_d + \lambda_7\left|H_d\right|^2H_uH_d + c.c.\right]} \end{aligned}$$

Source of CPV $(m^2, \lambda$ are complex.)

Mass matrix of neutral Higgs bosons M_0^2 are diagonalized by orthogonal matrix $O(\mathrm{Im}\lambda)$

$$\mathrm{O}^T M_0^2 O = \mathrm{diag}(m^2_{h1}, m^2_{h2}, m^2_{h3}, 0),\ \ h = O(\mathrm{Im}\lambda)^T H_0$$

- Effective Lagrangian in the mass eigenstate:

$$\mathcal{L}_\nu = \sum_{i,j=1}^{3}\sum_{a,b=1}^{3} \bar{N}_i P_L \left(U_{\nu L}\nu\right)_j \left(A_{ij}^a h_a + \frac{1}{v} B_{ij}^{ab} h_a h_b\right) + c.c.$$

$$\begin{aligned}
A_{ij}^a &= \frac{(-1)^{n_{ij}^\nu}}{\sqrt{2}} \underline{y_{ij}^\nu \epsilon^{n_{ij}^\nu}} \left[\left(1-n_{ij}^\nu\right)\left(O_{1a}+iO_{3a}\right) - n_{ij}^\nu \left(O_{2a}+iO_{4a}\right)\right] \\
B_{ij}^{ab} &= \frac{1}{2}\frac{(-1)^{n_{ij}^\nu}}{4} \underline{y_{ij}^\nu \epsilon^{n_{ij}^\nu}} \left[\frac{1}{s_\beta}\left(O_{1a}+iO_{3a}\right) + \frac{1}{c_\beta}\left(O_{2a}+iO_{4a}\right)\right] \times \\
&\quad \times \left[n_{ij}^\nu \left(n_{ij}^\nu - 3\right)\left(O_{1b}+iO_{3b}\right) + n_{ij}^\nu \left(n_{ij}^\nu - 1\right)\left(O_{2b}+iO_{4b}\right) c_\beta\right] + (a \leftrightarrow b)
\end{aligned}$$

- Three-point vertex: $V \sim \sum_{a,b,c=1}^{3} v\, C_{abc} h_a h_b h_c$

Effective Yukawa couplings A, B are complex because of $\mathrm{Im}\lambda$ from Higgs potential, which is the source of CPV.

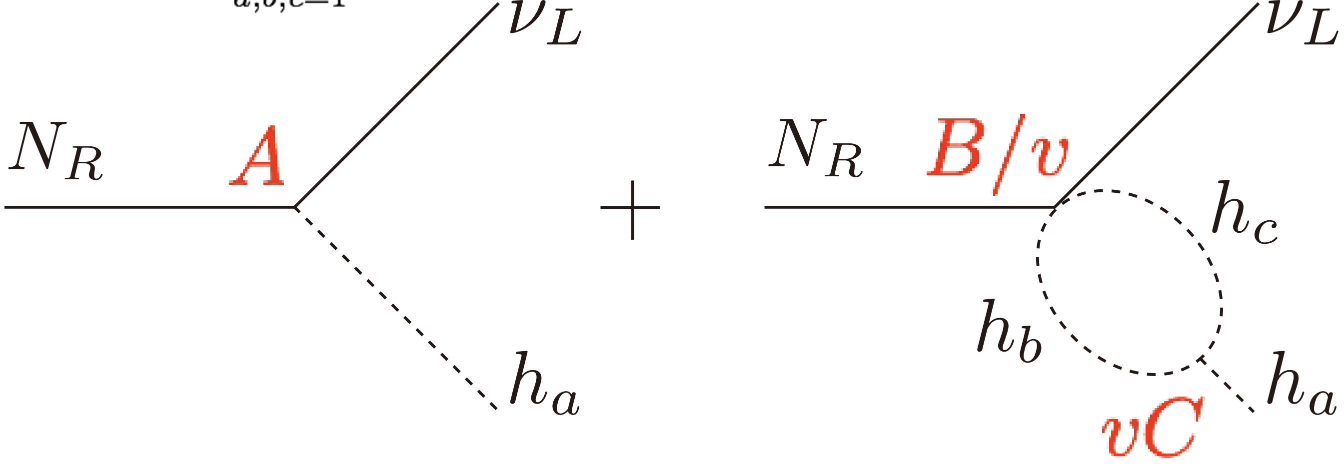
$$A \sim B \sim \epsilon^{n_{ij}^\nu} \sim 10^{-6}\ \left(n_{ij}^\nu = 3\right)$$

3. Leptogenesis

- We consider leptogenesis by the effective Yukawa couplings

$$\mathcal{L}_\nu = \sum_{i,j=1}^{3} \sum_{a,b=1}^{3} \bar{N}_i P_L \left(U_{\nu L} \nu\right)_j \left(A^a_{ij} h_a + \frac{1}{v} B^{ab}_{ij} h_a h_b \right) + c.c.$$

$$V \sim \sum_{a,b,c=1}^{3} v \, C_{abc} h_a h_b h_c$$



Interference between these diagrams generates CP asymmetry.

$\epsilon \sim \frac{1}{16\pi} \frac{\mathrm{Im}[AB^*]C}{|A|^2}$ can be large because $A \sim B \sim 10^{-6}$.

- We give a numerical example.

$$m_{\nu D} = v s_\beta \epsilon^3 \begin{pmatrix} 0.755 & 0.702 & -0.130 \\ * & 1.02 & 0.382 \\ * & * & 0.709 \end{pmatrix} \longrightarrow M_\nu = \frac{v^2 s_\beta^2}{M_N} \epsilon^6 \begin{pmatrix} 1.55 & 1.60 & -0.0427 \\ * & 1.92 & 0.310 \\ * & * & 0.485 \end{pmatrix}$$

$$\boxed{(M_N)_{ij} = M_N \mathrm{diag}(0.5, 1.25, 1.5),} \text{with } M_N = 1 \text{ TeV}$$

No Degeneracy

$$\begin{aligned} \lambda_1 &= 1.0,\ \lambda_2 = 0.5,\ \underline{\mathrm{Im}\lambda_5 \neq 0,}\ \mathrm{V} \sim \lambda_5 (H_u H_d)^2 + c.c. \\ m^2 &= (300\mathrm{GeV})^2 + 2iv^2 s_\beta c_\beta \mathrm{Im}\lambda_5,\ \text{others} = 0. \end{aligned}$$

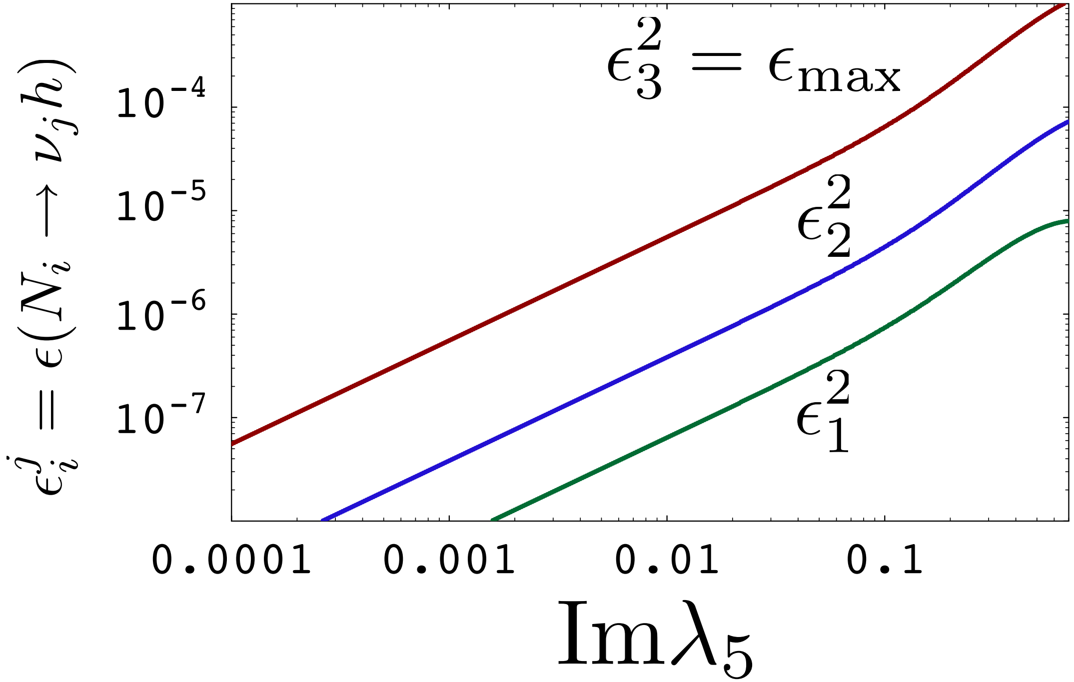
Higgs boson masses are given by

$$h_1 \sim 200\mathrm{GeV},\ h_2 \sim 480\mathrm{GeV},\ h_3 \sim 440\mathrm{GeV}.$$

$\mathrm{Im}\lambda_5$ is the only source of CPV.

⟶ CP asymmetry

- CP asymmetry $\epsilon_i^j = \epsilon(N_i \to \nu_j h)$



$\epsilon_{\rm max}$ is the maximal component of ϵ_i^j .

We can obtain large CP asymmetry

$$\boxed{0 < \epsilon < 10^{-3}}$$

by taking appropriate value of ${\rm Im}\lambda_5$.

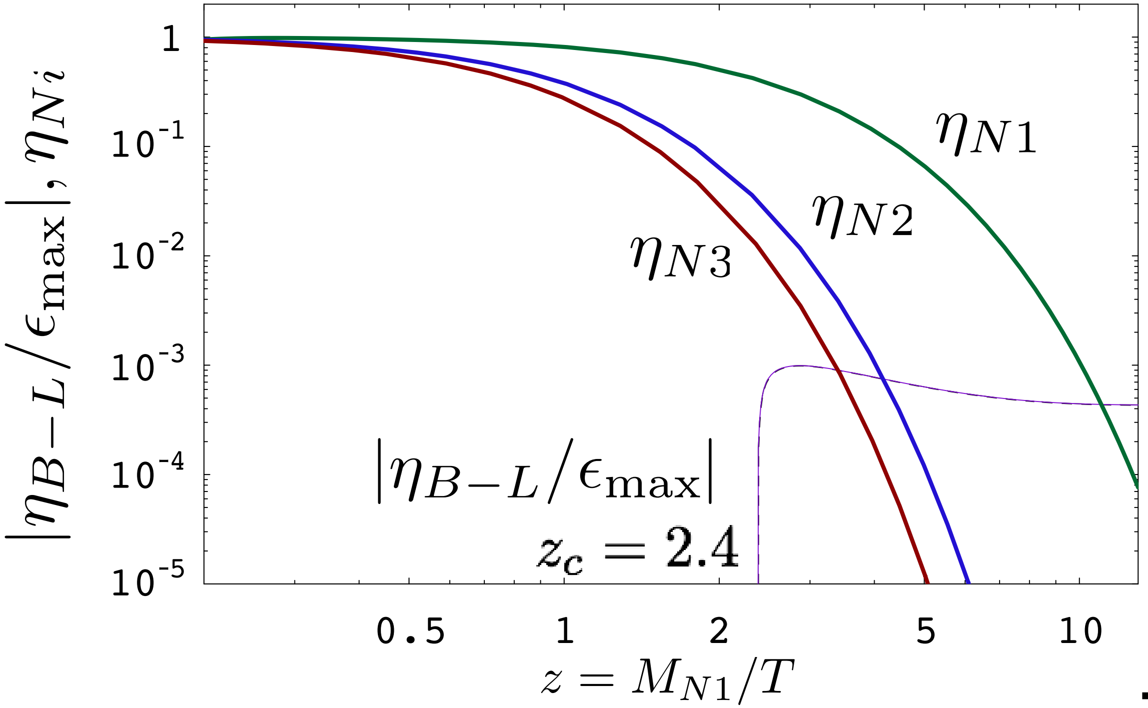
⟶ Boltzmann eqs.

- By solving the Boltzmann Eqs. for $N_i, \Delta_j (= B/3 - L_j)$

$$\frac{d\eta_{Ni}}{dz} = -\frac{z}{n_\gamma H(z=1)} \left(\frac{\eta_{Ni}}{\eta_{Ni}^{eq}} - 1 \right) \gamma_{Di},$$

$$\frac{d\eta_{\Delta j}}{dz} = -\frac{z}{n_\gamma H(z=1)} \sum_{i=1}^{3} \left[\left(\frac{\eta_{Ni}}{\eta_{Ni}^{eq}} - 1 \right) \epsilon_i^j \gamma_{Di}^{\nu} - \frac{\eta_{\Delta \nu j}}{2\eta_{\nu_j}^{eq}} \gamma_{Di}^{\nu j} - \frac{\eta_{\Delta e j}}{2\eta_{e_j}^{eq}} \gamma_{Di}^{ej} \right],$$

we obtain B-L asymmetry $(\eta_X = n_X / n_\gamma)$.



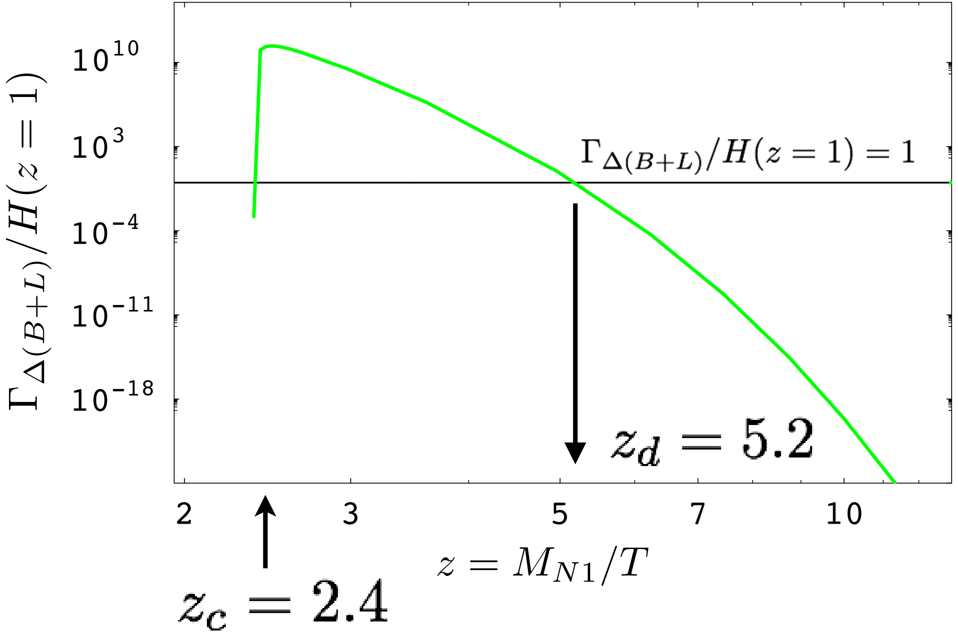
η_{B-L} is generated at $z = z_c$.

⟶ Sphaleron

•Sphaleron process for $T < T_c$:

$$\Gamma_{\Delta(B+L)} = \frac{(2208/\pi^2)T^2}{56T^2 + 38v(T)^2}\frac{\gamma_{\Delta(B+L)}}{n_\gamma},$$

$$\gamma_{\Delta(B+L)} = \frac{\omega_-}{2\pi}\mathcal{N}_{\rm tr}\left(\mathcal{N}V\right)_{\rm rot}\left(\frac{\alpha_W T}{4\pi}\right)^3 \alpha_3^{-6} e^{-E_{\rm sp}/T}.$$

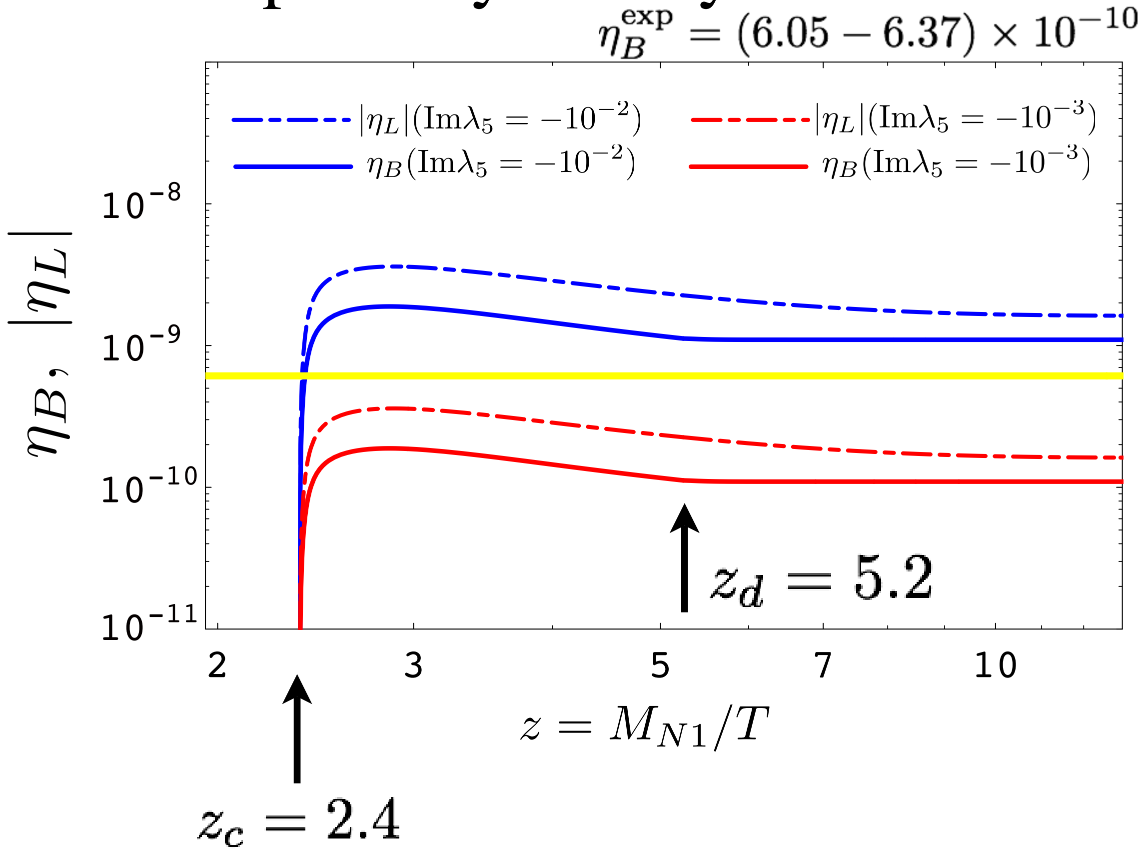


$$z_c < z < z_d: \quad \eta_B = \frac{16T^2 + 10v(T)^2}{46T^2 + 31v(T)^2}\eta_{B-L}$$

$$z > z_d: \quad \eta_B \sim const.$$

⟶ B and L

•Baryon and Lepton asymmetry:



$\eta_B^{\rm exp} = (6.05 - 6.37) \times 10^{-10}$

$z_d = 5.2$

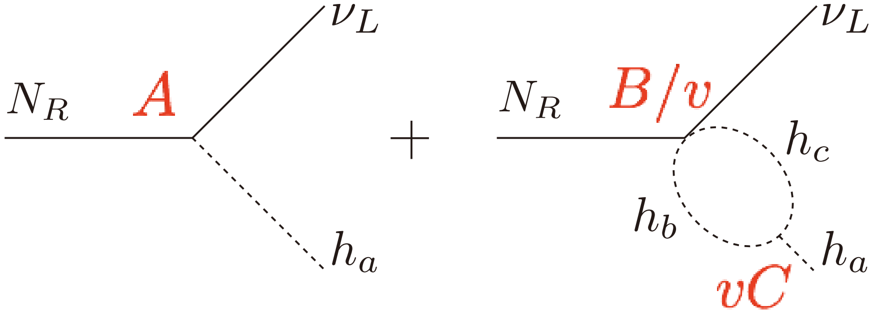
$z_c = 2.4$

- Lepton asymmetry is generated at $z = z_c$.
- Sphaleron converts $\eta_L \longrightarrow \eta_B$ in the region $z_c < z < z_d$.
- Sphaleron processes are switched off at $z = z_d$.

4. Conclusions

We have discussed Higgs-dependent Leptogenesis:

(1) leptogenesis occurs below EWSB scale $(T < T_c)$,



(2) source of CPV is in the Higgs sector,

(3) large CP asymmetry ($0 < \epsilon < 10^{-3}$) is generated without resonance condition,

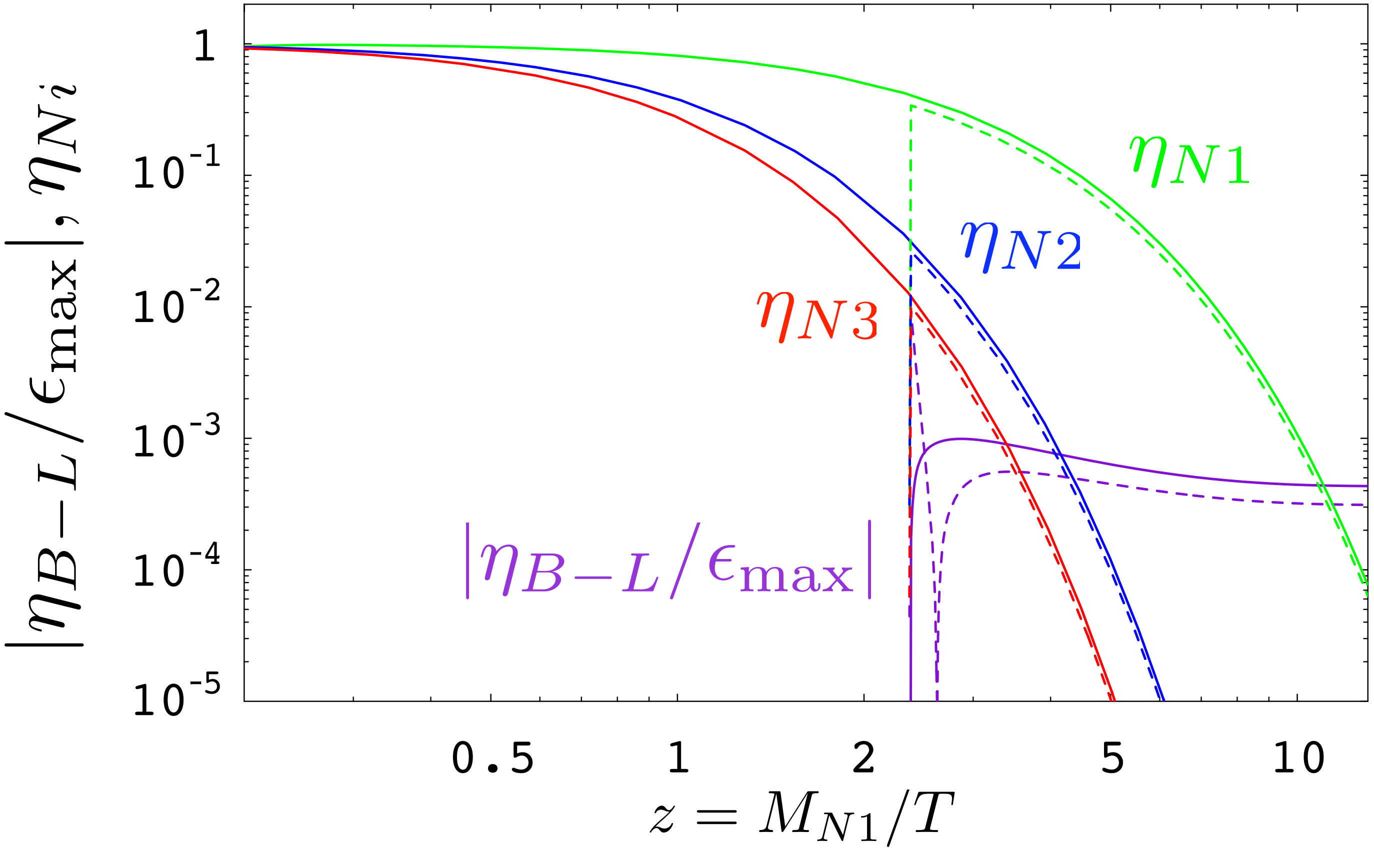
(4) sphaleron converts $\eta_L \longrightarrow \eta_B$ for $z_c < z < z_d$,

(5) and we can get baryon asymmetry.

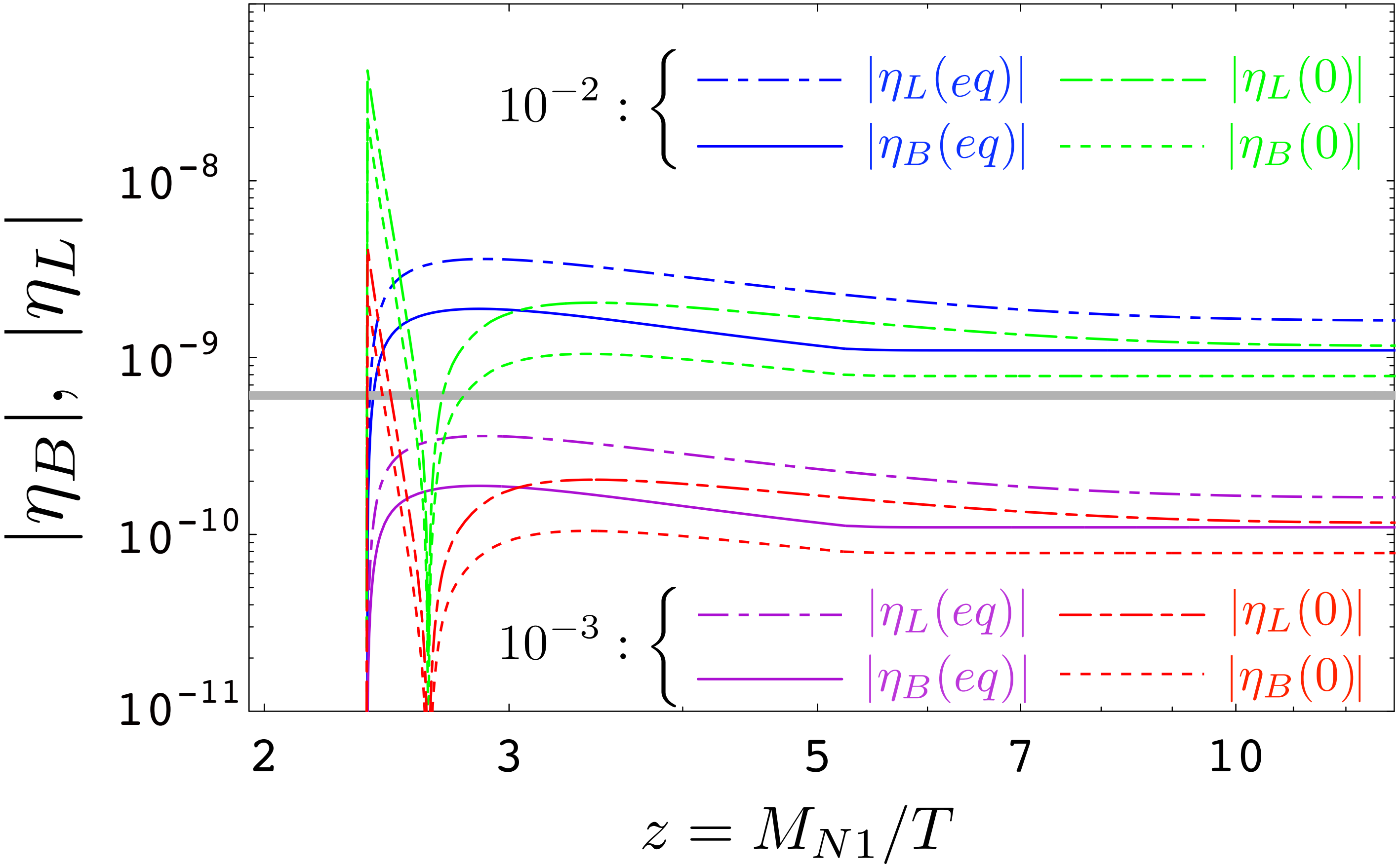
$$V \sim \sum_{a,b,c=1}^{3} v \; C_{abc} h_a h_b h_c$$

$$\begin{aligned}
C_{abc} &= \frac{1}{6}\Bigg[\sqrt{2}\lambda_1 s_\beta \mathrm{Re}\left[\alpha_{ab}\right] O_{1c} + \sqrt{2}\lambda_2 c_\beta \mathrm{Re}\left[\beta_{ab}\right] O_{2c} + \frac{1}{\sqrt{2}}\lambda_3 \left[c_\beta \mathrm{Re}\left[\alpha_{ab}\right] O_{2c} + s_\beta \mathrm{Re}\left[\beta_{ab}\right] O_{1c}\right] \\
&+ \frac{1}{\sqrt{2}}\lambda_4 \mathrm{Re}\left[\gamma_{ab}\delta_c^*\right] + \sqrt{2}\mathrm{Re}\left[\lambda_5 \gamma_{ab}\delta_c\right] \\
&- \frac{1}{\sqrt{2}}\mathrm{Re}\left[\alpha_{ab}\right]\mathrm{Re}\left[\lambda_6\delta_c\right] - \sqrt{2}s_\beta \mathrm{Re}\left[\lambda_6\gamma_{ab}\right] O_{1c} \\
&- \frac{1}{\sqrt{2}}\mathrm{Re}\left[\beta_{ab}\right]\mathrm{Re}\left[\lambda_7\delta_c\right] - \sqrt{2}c_\beta \mathrm{Re}\left[\lambda_7\gamma_{ab}\right] O_{2c} + (\text{all permutations of } a, b, c)\Bigg]
\end{aligned}$$

$$\begin{aligned}
\alpha_{ab} &= \left(O_{1a} + iO_{3a}\right)\left(O_{1b} - iO_{3b}\right) \\
\beta_{ab} &= \left(O_{2a} + iO_{4a}\right)\left(O_{2b} - iO_{4b}\right) \\
\gamma_{ab} &= \left(O_{1a} + iO_{3a}\right)\left(O_{2b} + iO_{4b}\right) \\
\delta_c &= s_\beta\left(O_{2c} + iO_{4c}\right) + c_\beta\left(O_{1c} + iO_{3c}\right)
\end{aligned}$$



$\left|\eta_{B-L}/\epsilon_{\max}\right|, \eta_{Ni}$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0.5
1
2
5
10
$z = M_{N1}/T$
η_{N1}
η_{N2}
η_{N3}
$\left|\eta_{B-L}/\epsilon_{\max}\right|$



10^{-2} :
$|\eta_L(eq)|$
$|\eta_B(eq)|$
$|\eta_L(0)|$
$|\eta_B(0)|$
10^{-3} :
$|\eta_L(eq)|$
$|\eta_B(eq)|$
$|\eta_L(0)|$
$|\eta_B(0)|$
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$|\eta_B|, \ |\eta_L|$
2
3
5
7
10
$z = M_{N1}/T$