Leptogenesis in $E_6 \times U(1)_A$ SUSY GUT

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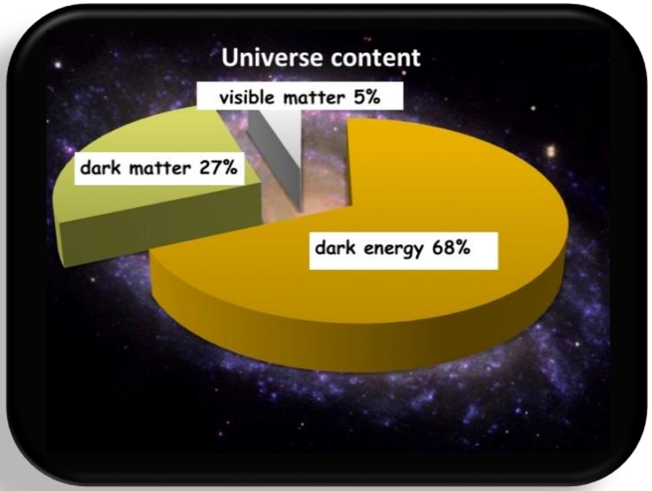
Attractive point and issue in $E_6 \times U(1)_A$ model

- ☑ SUSY GUT: framework for unifications of gauge and matters
- ☑ $E_6 \times U(1)_A$ model, in addition to the unifications, derives mass matrices of quarks and leptons

[M. Bando and N. Maekawa, PTP106 (2001)]

- ☑ $E_6 \times U(1)_A$ model must be consistent with the cosmology
- ☑ Is observed baryon asymmetry generated or not in this scenario?



Judge the scenario from leptogenesis

- ☑ Applying leptogenesis to generate B asymmetry in this scenario

  [M. Fukugita and T. Yanagida, PLB174 (1986)]

- ☑ $E_6 \times U(1)_A$ model derives quantities for leptogenesis, e.g., RH neutrino mass, neutrino Yukawa

  Possible to judge whether this scenario leads to matter dominant universe or not

- ☑ Need precise calculation of lepton asymmetry to correctly judge this issue

Key ingredients and aim of work

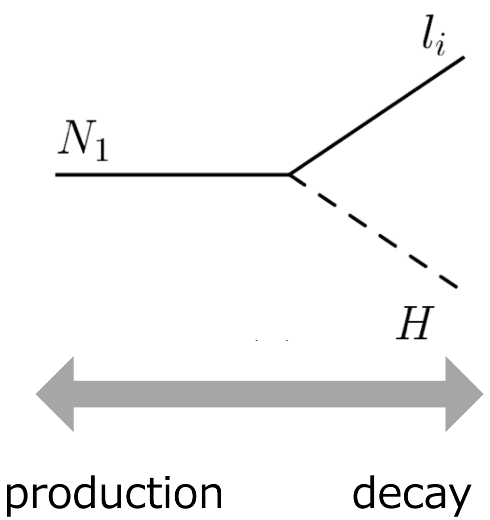
- ☑ key ingredients to precisely calculate L asymmetry
  - Enhancement of physical mass of RH neutrino
  - SUSY extension
  - Effect of final lepton flavor

- ☑ Aim of work
  - To judge whether this scenario leads to matter dominant universe or not
  - To show the leptogenesis can be a nice probe to $E_6 \times U(1)_A$ model

Leptogenesis

- ☑ RH neutrino decays to lepton or anti-lepton with different rate out of thermal equilibrium

- ☑ L asymmetry is converted to B asymmetry via EW sphaleron



- ☑ L asymmetry is controlled by decay parameter

Decay rate of N_1 at $T = 0$

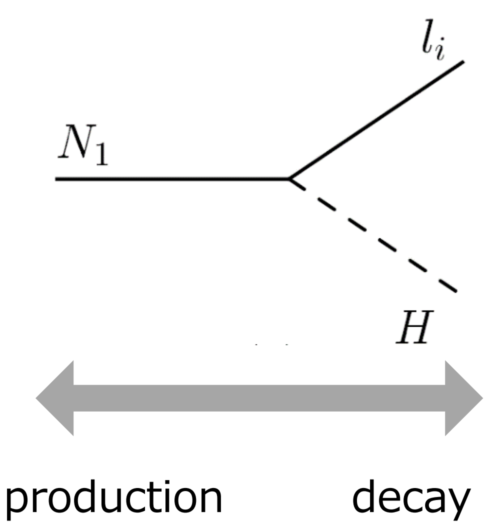
$$K \equiv \frac{\Gamma(N_1 \to l + H)}{H(T = M_1)}$$

Hubble parameter at $T = M_1$

Leptogenesis

☑ $K \sim 1$ is required in simplest framework

	$K > 1$	$K < 1$
advantage	sufficient N_1 production	large departure from equilibrium weak washout of L
disadvantage	small departure from equilibrium strong washout of L	insufficient N_1 production



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Enhancement of RH neutrino mass

- ☑ RH neutrino mass term $\Psi_i\Psi_i\overline{H}\overline{H}$ (original Majorana mass M_i^0)

  E_6 singlet, but not $U(1)_A$ singlet

	Ψ_1	Ψ_2	Ψ_3	H	$\bar{H}$	C	$\bar{C}$	A
E_6	**27**	**27**	**27**	**27**	$\overline{\mathbf{27}}$	**27**	$\overline{\mathbf{27}}$	**78**
$U(1)_A$	$\frac{9}{2}$	$\frac{7}{2}$	$\frac{3}{2}$	-3	1	-4	-1	-1

Field contents and charge assignment under $E_6 \times U(1)_A$

- ☑ Many $U(1)_A$ singlet higher dimensional interactions $\Theta_a\Theta_b \ldots \Psi_i\Psi_i\overline{H}\overline{H}$

- ☑ Additional Majorana masses of same order with M_1^0 after Θ_a acquire vev

Enhancement of RH neutrino mass

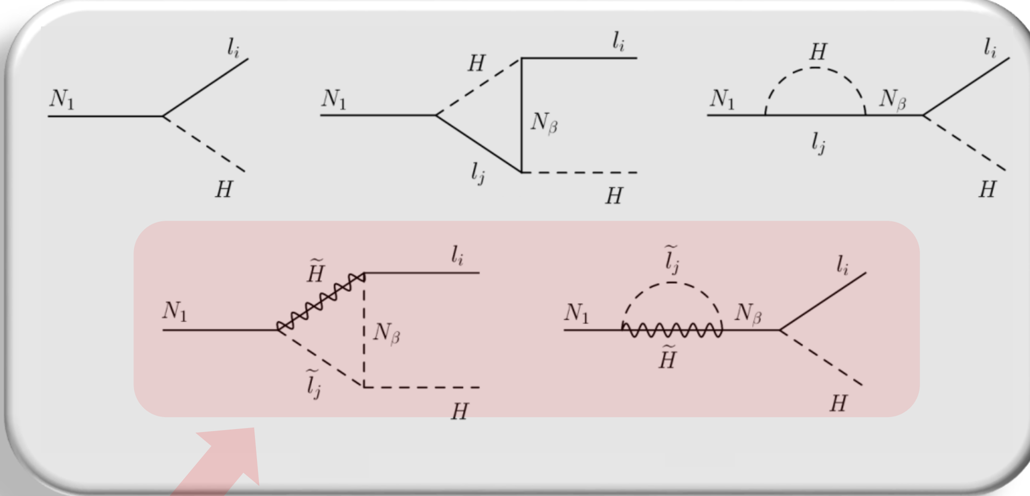
- ☑ Enhancement of physical mass of RH neutrino is reflected onto decrease of decay parameter

$$K_{E_6\times U(1)_A} \equiv \frac{\Gamma_{N_1}}{H\big|_{T=M_1}} = \frac{[Y^\dagger Y]_{11} M_1/8\pi}{1.66 g_*^{1/2} M_1^2/M_{\rm pl}} \simeq 37\left(\frac{5.7\times 10^7\,{\rm GeV}}{M_1}\right)$$

- ☑ With enhancement of M_1, strong washout → weak washout

- ☑ Additional Majorana masses of same order with M_1^0 after Θ_a acquire vev

SUSY extension



- ☑ Corrections by SUSY extension
  - Relativistic degrees of freedom: $g_*^{SM} = 106.75 \rightarrow g_*^{SUSY} = 228.75$
  - Additional contributions to CP asymmetry
  - Additional final states of RH neutrino decay

- ☑ CP asymmetry in RH neutrino decay

$$\varepsilon_{N_1} = \frac{\Gamma(N_1 \to lH) - \Gamma(N_1 \to \bar{l}H^\dagger) + \Gamma(N_1 \to \tilde{l}\tilde{H}) - \Gamma(N_1 \to \tilde{l}^*\bar{\tilde{H}})}{\Gamma(N_1 \to lH) + \Gamma(N_1 \to \bar{l}H^\dagger) + \Gamma(N_1 \to \tilde{l}\tilde{H}) + \Gamma(N_1 \to \tilde{l}^*\bar{\tilde{H}})}$$

SUSY extension

- Corrections by SUSY extension
  - Relativistic degrees of freedom: $g_*^{SM} = 106.75 \rightarrow g_*^{SUSY} = 228.75$
  - Additional contributions to CP asymmetry
  - Additional final states of RH neutrino decay

- SUSY extension leads to enhancement L asymmetry generation, in particular for the case of small K

Effect of final state lepton flavor

[R. Barbieri, P. Creminelli, A. Strumia and N. Tetradis, NPB575 (2000)]

- ☑ If $T < 10^{12}$ GeV, the lepton produced in the decay is no longer the interaction state, which is projected onto each flavor state

- ☑ L asymmetry must be calculated with flavor dependent CP asymmetry and washout effect

- ☑ Flavor dependent decay parameter in $E_6 \times U(1)_A$ model

$$K_e^{\rm SM} = \frac{\Gamma^{\rm SM}(N_1 \to l_e H)}{H(T=M_1)} \simeq 1.4 \left(\frac{5.7\times 10^7\,{\rm GeV}}{M_1}\right)$$

$$K_\mu^{\rm SM} = \frac{\Gamma^{\rm SM}(N_1 \to l_\mu H)}{H(T=M_1)} \simeq 6.4 \left(\frac{5.7\times 10^7\,{\rm GeV}}{M_1}\right)$$

Small K_e (K_μ) leads to weak washout of L

$$K_\tau^{\rm SM} = \frac{\Gamma^{\rm SM}(N_1 \to l_\tau H)}{H(T=M_1)} \simeq 29 \left(\frac{5.7\times 10^7\,{\rm GeV}}{M_1}\right)$$

Large K_τ ensures sufficient N_1 production

Effect of final state lepton flavor

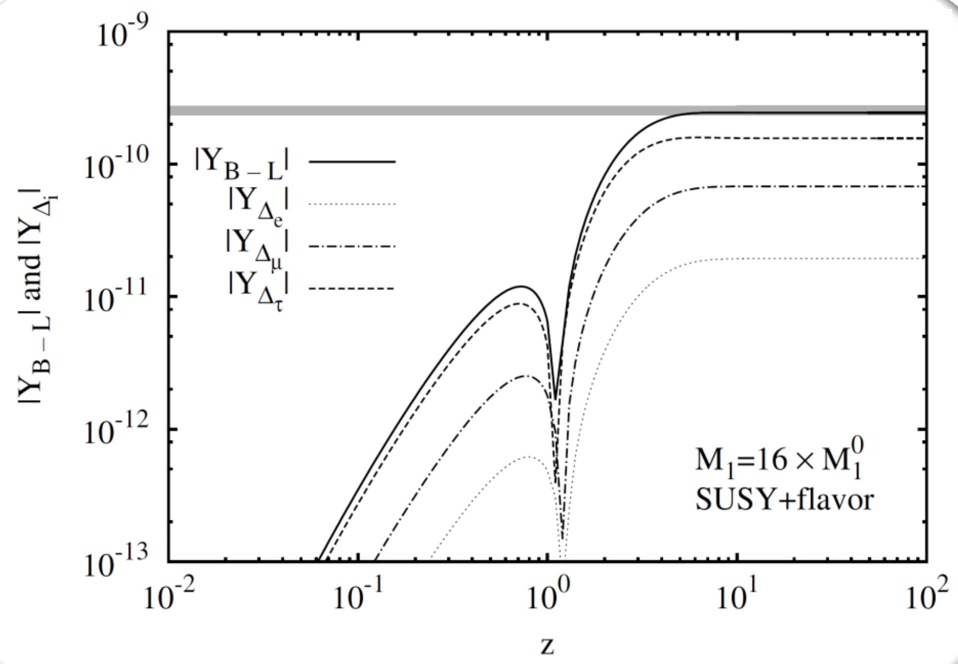
[R. Barbieri, P. Creminelli, A. Strumia and N. Tetradis, NPB575 (2000)]

☑ Picking the best of both, and enhancement of L asymmetry

	$K > 1$	$K < 1$
advantage	sufficient N_1 production	large departure from equilibrium weak washout of L
disadvantage	small departure from equilibrium strong washout of L	insufficient N_1 production

☑ Flavor effect leads to enhancement L asymmetry generation, in particular for the case of large K

Numerical result



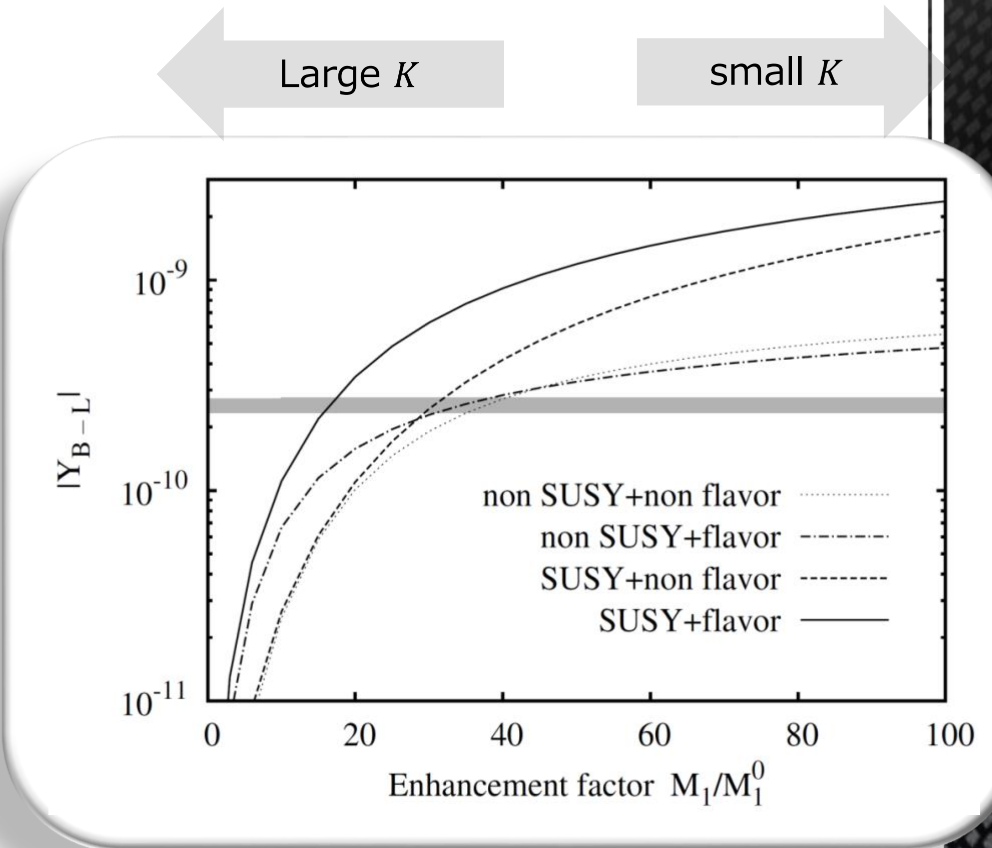
Evolutions of total $(B-L)$ asymmetry and each flavor $(B-L)$ asymmetries

☑ $E_6 \times U(1)_A$ GUT yields observed B asymmetry (grey band)

☑ Required physical mass of RH neutrino: $16 \leq M_1/M_1^0 \leq 17$

Important suggestion to the RH neutrino sector in this scenario from baryogenesis

Numerical result



- ☑ Enhancement by 3 ingredients with respect to simplest one
  - SUSY extension
  - Effect of final lepton flavor
  - Enhancement of physical mass of RH neutrino

- ☑ Important result explicitly shown for the first time:

  SUSY extension can lead to large enhancement even in the strong washout regime when flavor effect is taken into account

Summary

- ☑ $E_6 \times U(1)_A$ GUT is a promising model, which derives neutrino Yukawa, RH neutrino masses, and so on
- ☑ Aim: to judge whether $E_6 \times U(1)_A$ can yield observed Baryon asymmetry or not
- ☑ We applied leptogenesis mechanism, and calculated lepton asymmetry by taking into account 3 key ingredients
  - SUSY extension
  - Effect of final lepton flavor
  - Enhancement of physical mass of RH neutrino
- ☑ This scenario successfully accounts for matter dominant universe
- ☑ L asymmetry is a nice probe to RH neutrino sector in $E_6 \times U(1)_A$ GUT

Backup slides

Leptogenesis

☑ Conditions for baryogenesis (Sakharov conditions) are satisfied

L asymmetry → B asymmetry

☑ In early universe, RH neutrino decays to lepton or anti-lepton with different rate out of thermal equilibrium

C and CP violation

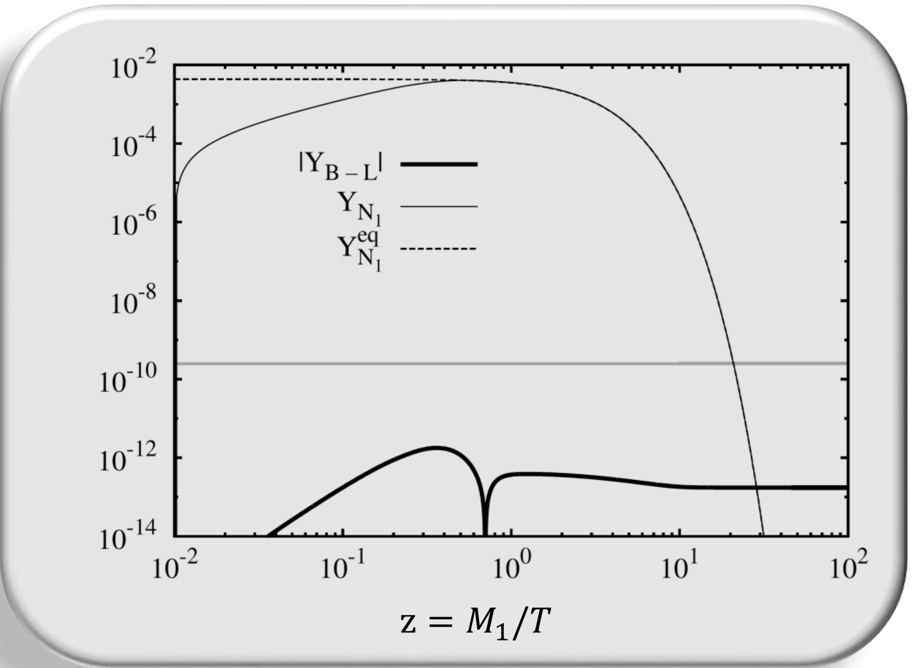
Interactions out of equilibrium

Key ingredients for successful leptogenesis

☑ Applying leptogenesis to generate B asymmetry in this scenario

[M. Fukugita and T. Yanagida, PLB174 (1986)]

☑ $E_6 \times U(1)_A$ model derives relevant quantities for leptogenesis, i.e., RH neutrino mass, neutrino Yukawa



☑ Estimation with the quantities shows insufficient L asymmetry

☑ Must take into account 3 key ingredients to correctly evaluate

Flavor dependent CP asymmetry

- ☑ CP asymmetry in unflavored leptogenesis

$$\varepsilon_{N_1} = \frac{\Gamma(N_1 \to lH) - \Gamma(N_1 \to \bar{l}H^\dagger)}{\Gamma(N_1 \to lH) + \Gamma(N_1 \to \bar{l}H^\dagger)} \simeq -\frac{3}{16\pi} \sum_{\beta \neq 1} \frac{\Im\left[\left(\lambda^\dagger \lambda\right)^2_{\beta 1}\right]}{\left(\lambda^\dagger \lambda\right)_{11}} \frac{M_1}{M_\beta} \quad (\text{For } M_1 \ll M_\beta)$$

Including the sum over the final lepton flavor

- ☑ CP asymmetry has to be calculated for each lepton flavor

$$\varepsilon^i_{N_1} = \frac{\Gamma(N_1 \to l_i H) - \Gamma(N_1 \to \bar{l}_i H^\dagger)}{\sum_i \left[\Gamma(N_1 \to l_i H) + \Gamma(N_1 \to \bar{l}_i H^\dagger)\right]}$$

$$\simeq -\frac{3}{8\pi \left(\lambda\lambda^\dagger\right)_{11}} \sum_{\beta \neq 1} \Im\left\{\lambda_{\beta j}\lambda^*_{1j}\left[\frac{3}{2}\left(\lambda\lambda^\dagger\right)_{\beta 1}\frac{M_1}{M_\beta} + \left(\lambda\lambda^\dagger\right)_{1\beta}\frac{M_1^2}{M_\beta^2}\right]\right\} \quad (\text{For } M_1 \ll M_\beta)$$

[L. Covi, E. Roulet and F. Vissani, PLB384 (1996)]

parameter

Parameter	value	comment
Λ_G	2.000×10^{16} GeV	GUT scale
$M_1 = \lambda^{13}\Lambda_G$	5.656×10^{7} GeV	1st RH neutrino mass
$M_2 = \lambda^{12}\Lambda_G$	2.571×10^{8} GeV	2nd RH neutrino mass
$M_3 = \lambda^{11}\Lambda_G$	1.169×10^{9} GeV	3rd RH neutrino mass
$M_4 = \lambda^{10}\Lambda_G$	5.312×10^{9} GeV	4th RH neutrino mass
$M_5 = \lambda^{7}\Lambda_G$	4.989×10^{11} GeV	5th RH neutrino mass
$M_6 = \lambda^{6}\Lambda_G$	2.268×10^{12} GeV	6th RH neutrino mass
$Y_{11} = \lambda^{6.5}$	5.318×10^{-5}	11 component of Y_ν
$Y_{12} = \lambda^{6.0}$	1.134×10^{-4}	12 component of Y_ν
$Y_{13} = \lambda^{5.5}$	2.417×10^{-4}	13 component of Y_ν
$Y_{21} = \lambda^{6.0}$	1.134×10^{-4}	21 component of Y_ν
$Y_{22} = \lambda^{5.5}$	2.417×10^{-4}	22 component of Y_ν
$Y_{23} = \lambda^{5.0}$	5.154×10^{-4}	23 component of Y_ν
などなど		

$E_6 \times U(1)_A$ GUTにおけるCP非対称

☑ 本模型におけるCP非対称

N_6の寄与

仮定2：$\Im\left[\left(Y^\dagger Y\right)_{61}^2\right] = \Re\left[\left(Y^\dagger Y\right)_{61}^2\right]$

SMの寄与+SUSYの寄与

$$\epsilon_{N_1} = 2 \times 2 \left(-\frac{3}{16\pi} \frac{\Im\left[\left(Y^\dagger Y\right)_{61}^2\right]}{\left(Y^\dagger Y\right)_{11}} \frac{M_1}{M_6} \right) = -1.77 \times 10^{-8} \left(\frac{M_1}{5.7 \times 10^7\,\mathrm{GeV}} \right)$$

仮定1：N_2~N_6の寄与の和はN_6の寄与の2倍

模型の構造により、N_2~N_5のそれぞれの寄与はN_6の寄与と同じ。

ただし、CP位相の符号が不定のため、各寄与の相対符号も不定。

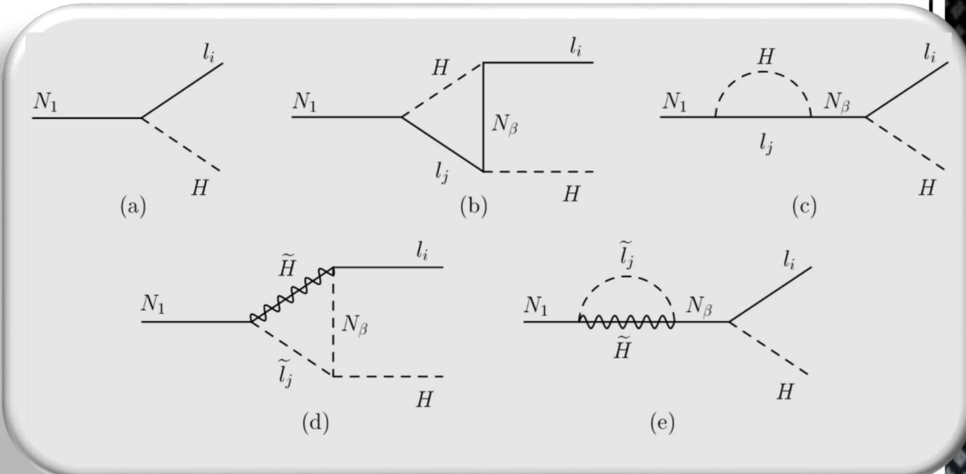
そこで、期待値として「2」を採用。

$E_6 \times U(1)_A$ GUTにおけるCP非対称

- ☑ レプトンと反レプトンへの崩壊率の差を用いてCP非対称を定義

$$\varepsilon_{N_1} = \frac{\Gamma(N_1 \to lH) - \Gamma(N_1 \to \bar{l}H^\dagger) + \Gamma(N_1 \to \tilde{l}\tilde{H}) - \Gamma(N_1 \to \tilde{l}^* \bar{\tilde{H}})}{\Gamma(N_1 \to lH) + \Gamma(N_1 \to \bar{l}H^\dagger) + \Gamma(N_1 \to \tilde{l}\tilde{H}) + \Gamma(N_1 \to \tilde{l}^* \bar{\tilde{H}})}$$

- ☑ Treeの崩壊と1-loopの崩壊の干渉項からε_{N_1}に有限の寄与



- ☑ 模型の特徴：右巻きニュートリノが６つ。全てが寄与する。

$$\mathbf{27} = \mathbf{16}_1[\mathbf{10}_1 + \bar{\mathbf{5}}_{-3} + \mathbf{1}_5] + \mathbf{10}_{-2}[\mathbf{5}_{-2} + \bar{\mathbf{5}}'_2] + \mathbf{1}_4[\mathbf{1}'_0]$$

Evolution of flavored $(B-L)$ asymmetry

- Flavored $(B-L)$ asymmetry is evaluated by coupled Boltzmann Eqs. for $Y_{N_1}, Y_{\Delta_e}, Y_{\Delta_\mu}$, and Y_{Δ_τ}

$$\frac{dY_{N_1}}{dz} = -\frac{z}{sH(z=1)}\left(\frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1\right)\left[\gamma_D + 2\gamma_{Ss} + 4\gamma_{St}\right]$$

$$\frac{dY_{\Delta_i}}{dz} = -\frac{z}{sH(z=1)}\left\{\left(\frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1\right)\epsilon_{1i}\gamma_D + K_i^0 \sum_j \left[\frac{1}{2}\left(C_{ij}^l + C_j^H\right)\gamma_D \right.\right.$$
$$\left.\left. + \left(\frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1\right)\left(C_{ij}^l \gamma_{S_s} + \frac{C_j^H}{2}\gamma_{S_t}\right) + \left(2C_{ij}^l + C_j^H\right)\left(\gamma_{S_t} + \frac{\gamma_{S_s}}{2}\right)\right]\frac{Y_{\Delta_i}}{Y_l^{eq}}\right\}$$

  - $Y_i = n_i/s$ (s: entropy density)
  - $z = M_1/T$
  - γ_D $(\gamma_{S_s},\ \gamma_{S_t})$: reduced thermal averaged decay rate (cross section)

Evolution of flavored $(B-L)$ asymmetry

- ☑ Each conversion rate is determined by various constraints with equilibrium conditions in each temperature regime

- ☑ Example 1:

T (GeV)	Equilibrium	Constraints
10^{12} - 10^{13}	$+\,h_b, h_\tau$ interactions	$b = Q_3 - H$ $\tau = l_\tau - H$
10^{11} - 10^{12}	+ EW-sphalerons	$\sum_i (3Q_i + l_i) = 0$
10^{8} - 10^{11}	$+\,h_c, h_s, h_\mu$ interactions	$c = Q_2 + H$ $s = Q_2 - H$ $\mu = l_\mu - H$
$\ll 10^{8}$	All Yukawa interactions	$u = Q_1 + H$ $d = Q_1 - H$ $e = l_e - H$

$$C^l_{ij} = \frac{1}{2148}\begin{pmatrix} 906 & -120 & -120 \\ -75 & 688 & -28 \\ -75 & -28 & 688 \end{pmatrix}, \quad C^H = \frac{1}{358}\begin{pmatrix} 37 & 52 & 52 \end{pmatrix}$$

右巻きニュートリノの世代数依存性