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

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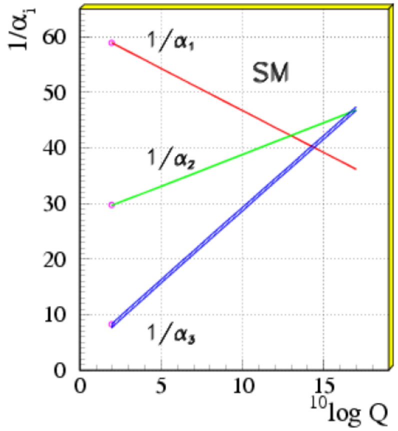
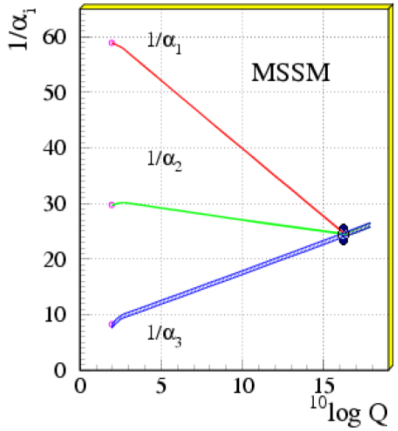
Attractive point and issue in $E_6 \times U(1)_A$ model

- ☑ SUSY GUT: framework for unifications of gauge and matters





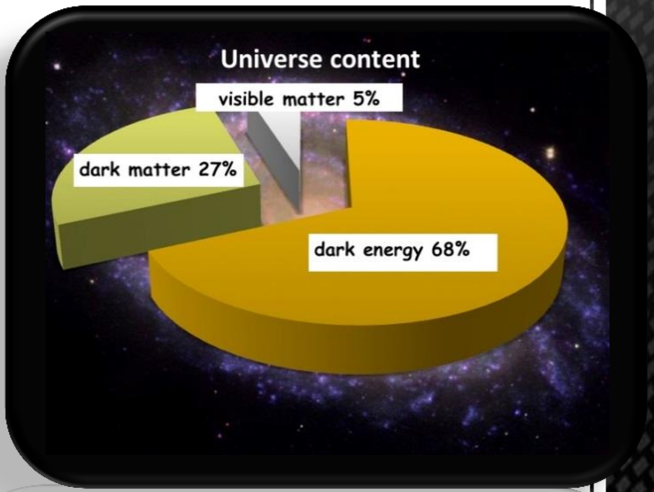
- ☑ $E_6 \times U(1)_A$ model, in addition to the unifications, derives mass matrices of quarks and leptons

  [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?

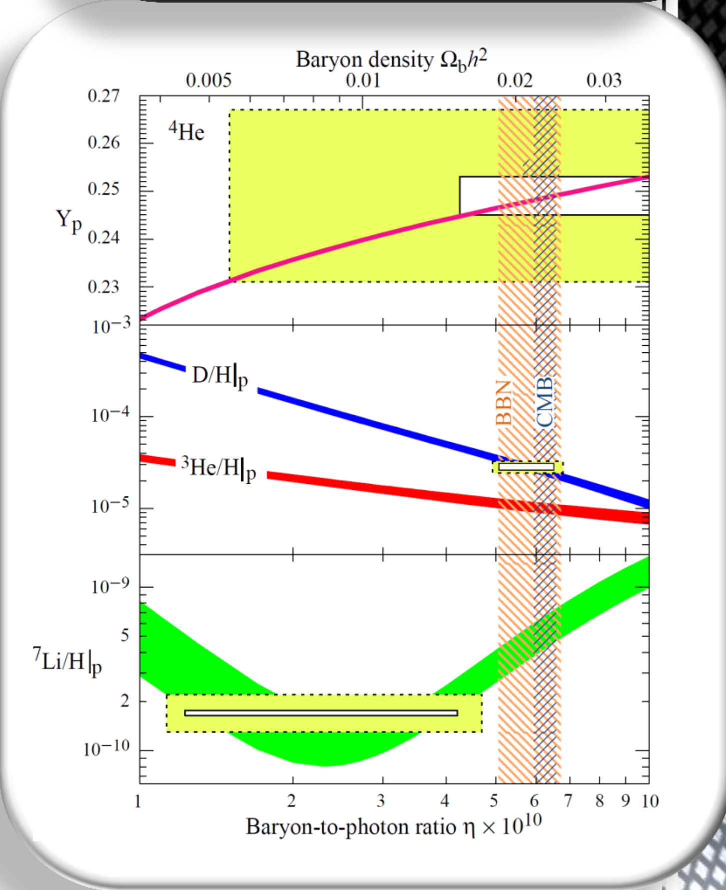
Baryon asymmetry



☑ Visible matter ≈ “matter”, not “anti-matter”

☑ Observed baryon asymmetry

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6.1 \times 10^{-10}$$



☑ A way to baryogenesis: Leptogenesis

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

Leptogenesis

- ☑ A requirement from ν oscillation:
  right-handed (RH) neutrino

- ☑ Seesaw mechanism: SM + gauge singlet Majorana fermion

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \lambda_{\alpha i}\bar{N}_\alpha l_i H + \frac{1}{2}M_\alpha \bar{N}_\alpha N_\alpha + {\rm h.c.}$$

[P. Minkowski, PLB67 (1977)]
[T. Yanagida, Proceedings of the workshop (1979)]

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

Leptogenesis

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

Leptogenesis

- ☑ Conditions for baryogenesis (Sakharov conditions) are satisfied

- ☑ Leptogenesis: promising scenario

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

Beyond the simplest leptogenesis

- ☑ Thermal corrections

  [e.g., G. F. Giudice, et al, NPB685 (2004)]

  - Thermal masses
  - CP asymmetries
  - etc.
- ☑ Heavier RH neutrino contribution
- ☑ Spectator process

  [W. Buchmuller and M. Plumacher, PLB511 (2001)]
- ☑ Flavor effect

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

  [E. Nardi, Y. Nir, E. Roulet and J. Racker, JHEP01 (2006)]

Judge the scenario from leptogenesis

- ☑ Applying leptogenesis to generate B asymmetry in this scenario
- ☑ $E_6 \times U(1)_A$ model predicts values 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

Outline

1. introduction
2. Leptogenesis
3. Flavored leptogenesis
4. Leptogenesis in $E_6 \times U(1)_A$ GUT
5. Summary

2. Leptogenesis

Setup in this talk

- ☑ Framework: Type-I seesaw

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \lambda_{\alpha i}\bar{N}_\alpha l_i H + \frac{1}{2}M_\alpha \bar{N}_\alpha N_\alpha + \text{h.c.}$$

N_α $(\alpha = 1,2,3)$: right-handed neutrino

l_i $(i = e, \mu, \tau)$: left-handed lepton

- ☑ Thermal leptogenesis with zero initial abundance of RH neutrino

- ☑ No finite temperature correction

[analysis in finite T theory -> see, e.g., G. F. Giudice, et al, NPB685 (2004)]

- ☑ Hierarchical in RH neutrino mass $M_1 \ll M_2, M_3$

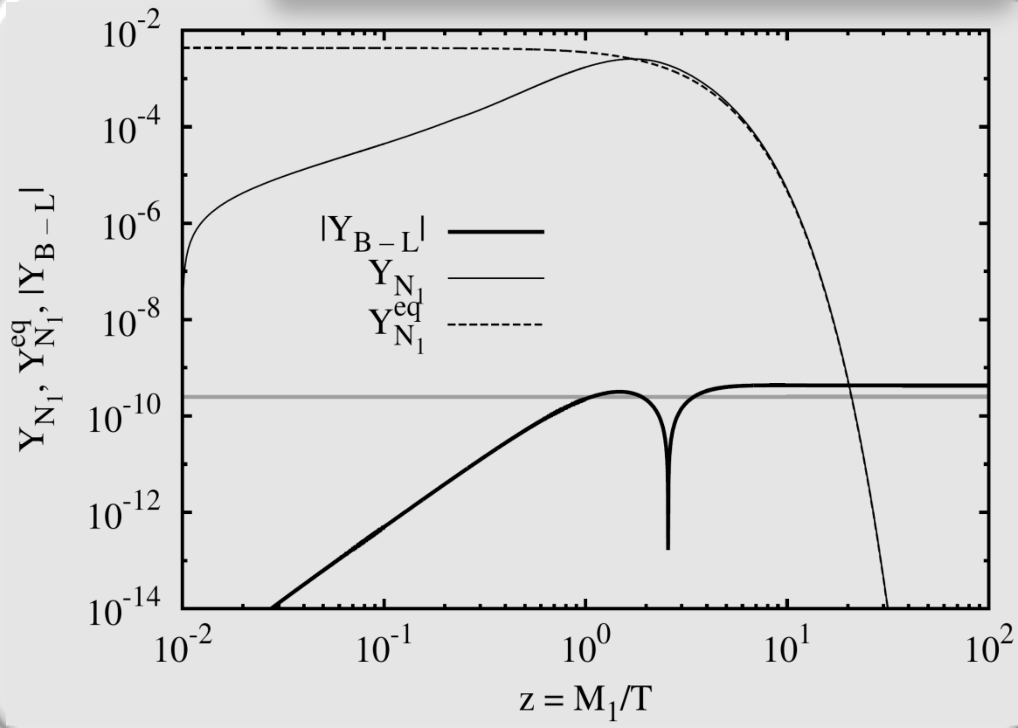
[resonant leptogenesis -> see, e.g., S. Iso, K. Shimada, M.Y., JHEP1404 (2014)]

Thermal leptogenesis

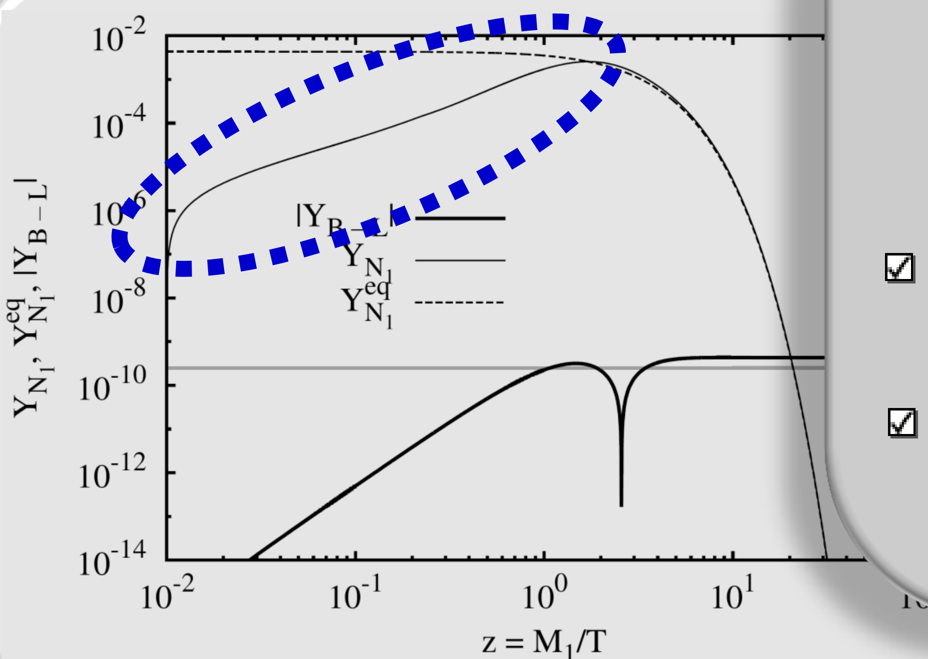
☑ Process of thermal leptogenesis

- Production of RH neutrino in thermal bath
- Decoupling from thermal equilibrium
- CP violating decay out of equilibrium
- Evolution of lepton asymmetry

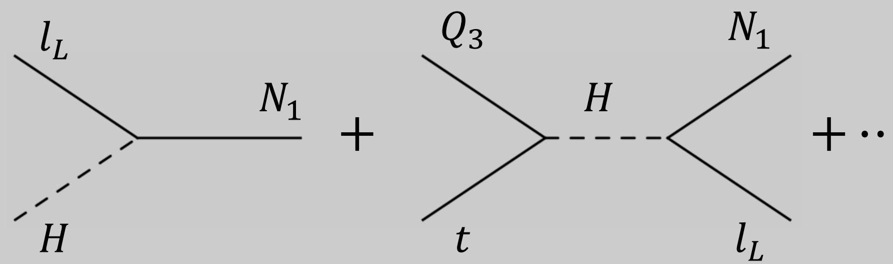
"Summary" of leptogenesis



Thermal leptogenesis



- ☑ Production of RH neutrino
- ☑ Production reactions

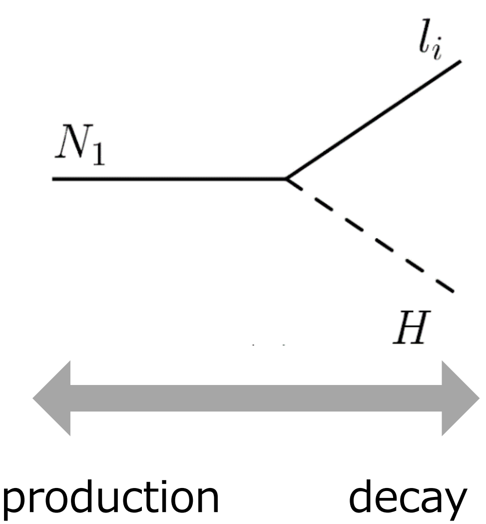


- ☑ All of reaction rates $\propto (\lambda\lambda^{\dagger})_{11}$
- ☑ Production rate is calculated by Boltzmann Eq.

Evolution of RH neutrino

☑ Boltzmann Eq. for RH neutrino

$$\frac{dn_{N_1}}{dt} + 3Hn_{N_1} = -\langle\Gamma_{N_1}\rangle\left(n_{N_1} - n_{N_1}^{eq}\right) - \sum_i \langle\sigma_{N_1 i} v\rangle\left(n_{N_1} n_i - n_{N_1}^{eq} n_i^{eq}\right)$$



☑ Controlled by decay parameter

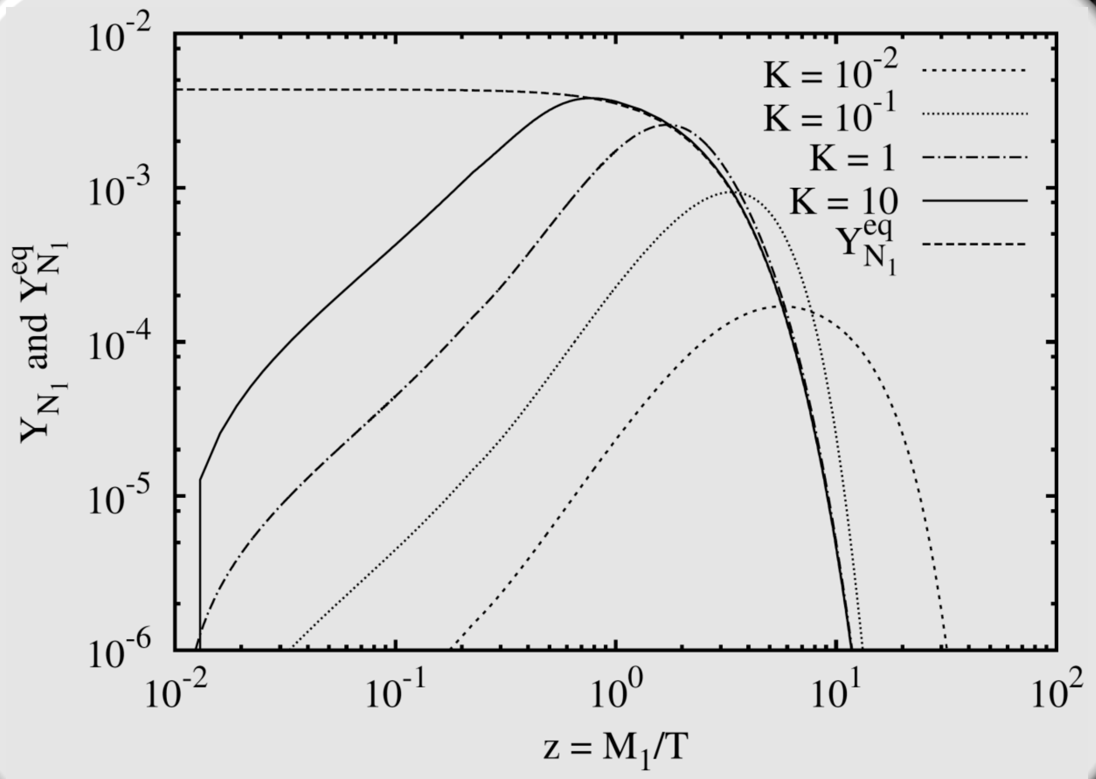
$$K \equiv \frac{\Gamma(N_1 \to l + H)}{H(T = M_1)}$$

Decay rate of N_1 at $T = 0$

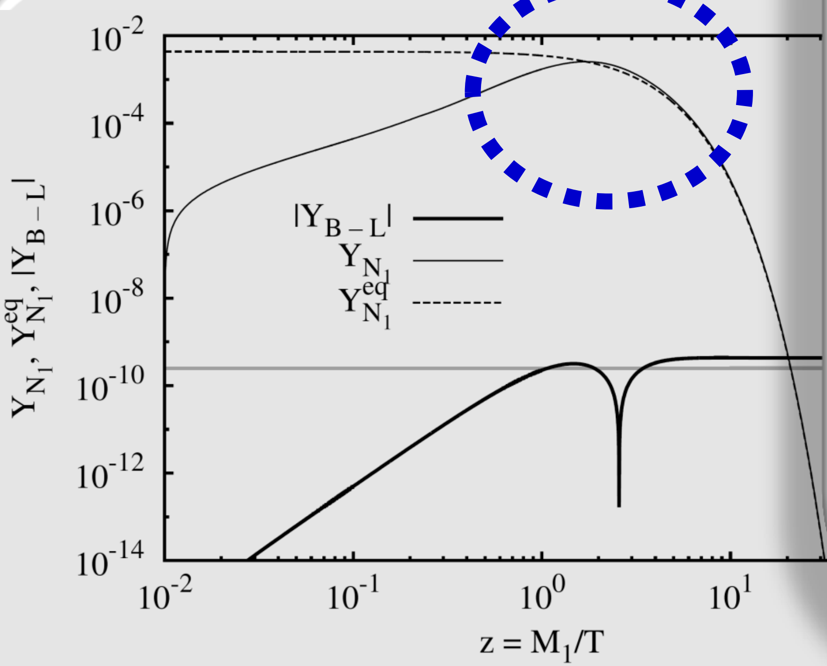
Hubble parameter at $T = M_1$

Evolution of RH neutrino

- ☑ Large K makes n_{N_1} to be in equilibrium
- ☑ Otherwise n_{N_1} can not reach thermal equilibrium
- ☑ Large K leads large production of RH neutrino
- ☑ Large K also leads large L asymmetry?
  → No, due to two reasons



Thermal leptogenesis



☑ Decoupling from thermal equilibrium

☑ When and why does it decouple?

- $T > M_1$

  Large scattering rate $\langle\sigma v\rangle n_i > H$

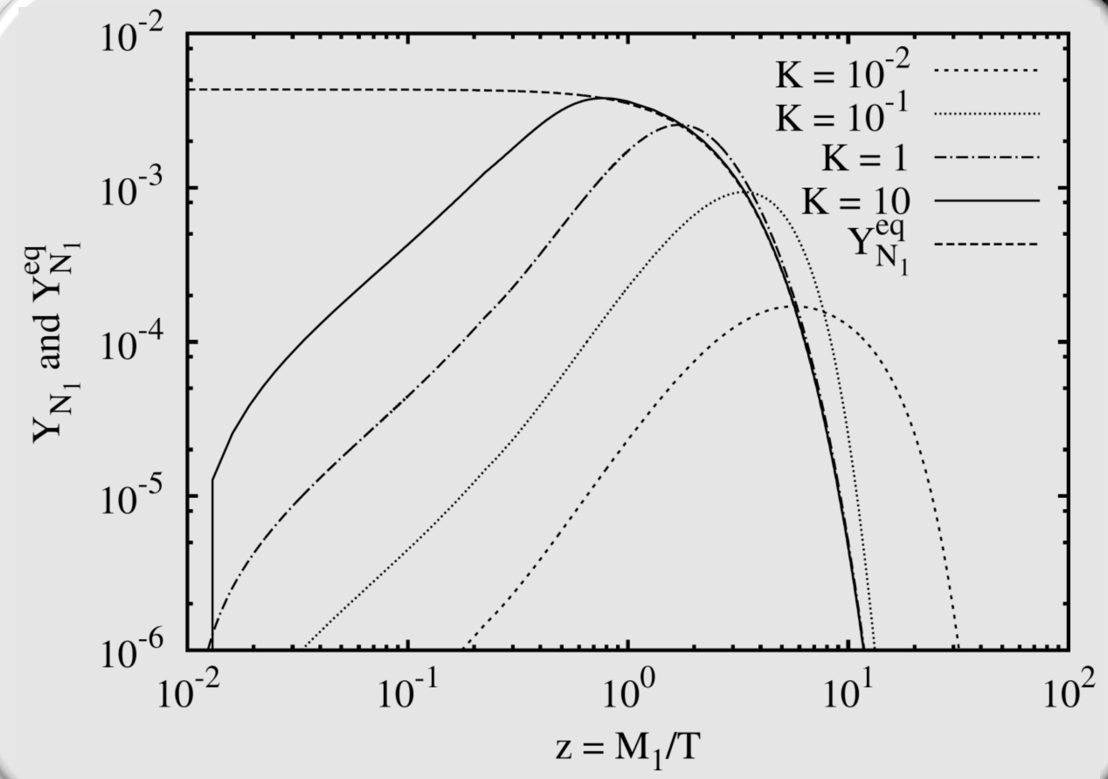
- $T \simeq M_1$

  $\langle\sigma v\rangle n_i \lesssim H$ and $\langle\Gamma_{N_1}\rangle \neq \langle\Gamma_{N_1}\rangle_{ID}$ due to delay factor in decay reaction

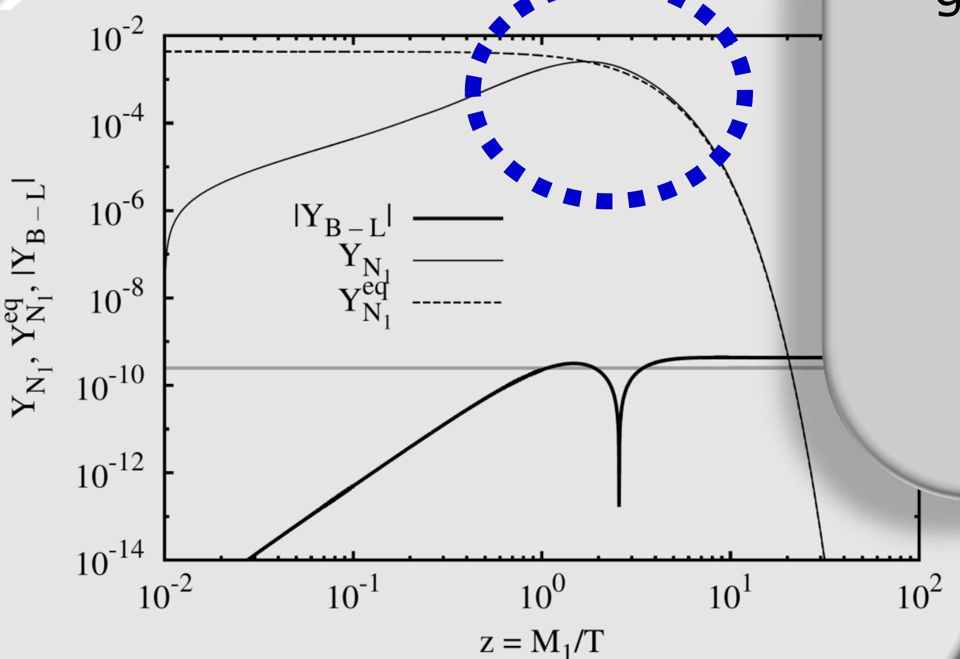
☑ Also controlled by decay parameter

Evolution of RH neutrino

- ☑ Large K keeps n_{N_1} to be equilibrium distribution
- ☑ Otherwise n_{N_1} largely deviates from $n_{N_1}^{eq}$
- ☑ Smaller K leads sufficient decoupling for baryogenesis
- ☑ Important: favored K is opposite from N_1 production



Thermal leptogenesis



- ☑ CP violating decay out of equilibrium

- ☑ Unequal rate of L violating decays generate L asymmetry

$$\Gamma(N_1 \to lH) \neq \Gamma(N_1 \to \bar{l}H^*)$$

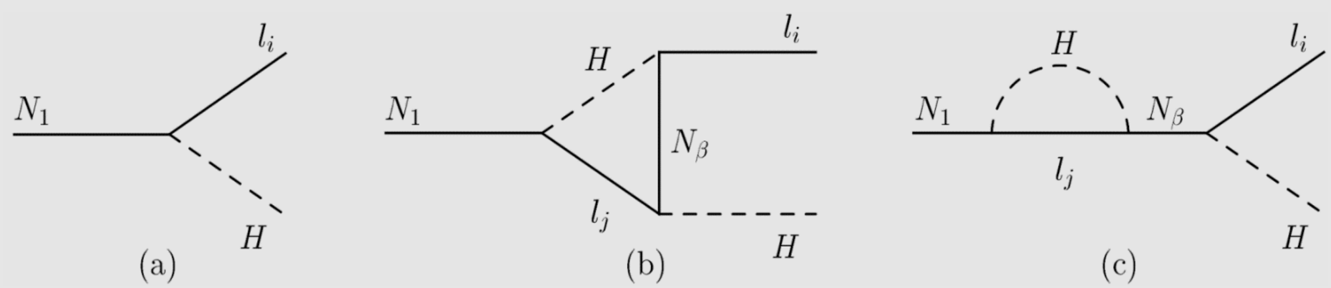
$$L \text{ number} \neq \bar{L} \text{ number}$$

CP asymmetry in N_1 decay

- ☑ CP asymmetry from interference between tree-level amplitude with 1-loop contributions

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

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



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Casas-Ibarra parametrization

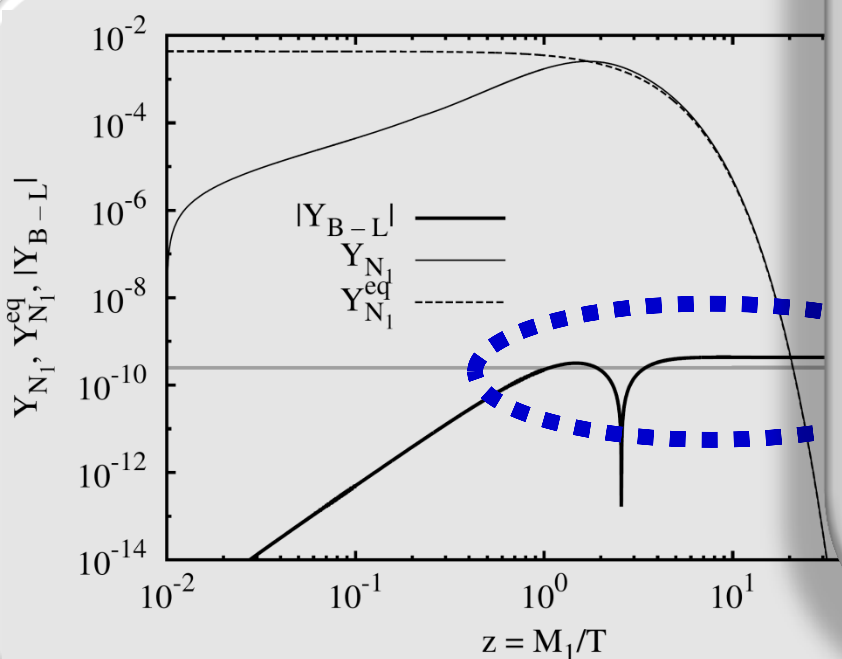
[J. A. Casas and A. Ibarra, NPB618 (2001)]

$$\lambda_{\alpha j} = v^{-1} \left[\sqrt{M} R \sqrt{m} U^\dagger\right]_{\alpha j}$$

$$(\lambda^\dagger \lambda)^2_{\beta 1} = \frac{M_1 M_\beta}{v^4} \left(\sum_i m_i R^*_{1i} R_{\beta i}\right)^2$$

- If the orthogonal matrix R is real, no CP violation arises
- This statement is not valid in flavored leptogenesis

Thermal leptogenesis



- ☑ Evolution of lepton asymmetry
- ☑ A part of L asymmetry converts to B asymmetry via $B + L$ violating sphaleron processes
- ☑ A part of L asymmetry is washed out by various reactions
- ☑ L asymmetry is calculated by coupled Boltzmann Eqs.

Evolution of L asymmetry

- ☑ Coupled Boltzmann Eqs. for L asymmetry

$$\frac{dn_{N_1}}{dt} + 3Hn_{N_1} = -\langle\Gamma_{N_1}\rangle \left(n_{N_1} - n_{N_1}^{eq}\right) - \sum_i \langle\sigma_{N_1 i} v\rangle \left(n_{N_1} n_i - n_{N_1}^{eq} n_i^{eq}\right)$$

$$\frac{dn_{B-L}}{dt} + 3Hn_{B-L} = \varepsilon_{N_1}\langle\Gamma_{N_1}\rangle \left(n_{N_1} - n_{N_1}^{eq}\right)$$
$$- \langle\sigma v(lN_1 \to Q_3 t)\rangle\, n_{B-L} n_{N_1} - \langle\sigma v(lQ_3 \to N_1 t)\rangle\, n_{B-L} n_{Q_3}^{eq}$$

[e.g., M. A. Luty, PRD45 (1992)]

Evolution of L asymmetry

☑ Coupled Boltzmann Eqs. for L asymmetry

$$\frac{dn_{N_1}}{dt} + 3Hn_{N_1} = -\langle \Gamma_{N_1} \rangle \left(n_{N_1} - n_{N_1}^{eq}\right) - \sum_i \langle \sigma_{N_1 i} v \rangle \left(n_{N_1} n_i - n_{N_1}^{eq} n_i^{eq}\right)$$

$$\frac{dn_{B-L}}{dt} + 3Hn_{B-L} = \varepsilon_{N_1} \langle \Gamma_{N_1} \rangle \left(n_{N_1} - n_{N_1}^{eq}\right) - \langle \sigma v(lN_1 \to Q_3 t) \rangle n_{B-L} n_{N_1} - \langle \sigma v(lQ_3 \to N_1 t) \rangle n_{B-L} n_{Q_3}^{eq}$$

Source term of L asymmetry $\propto \varepsilon K \ll K$

Washout term of L asymmetry $\propto K$

☑ Large K leads strong washout, and makes L asymmetry to be small

☑ Important: contrary to N_1 production, smaller K is favored

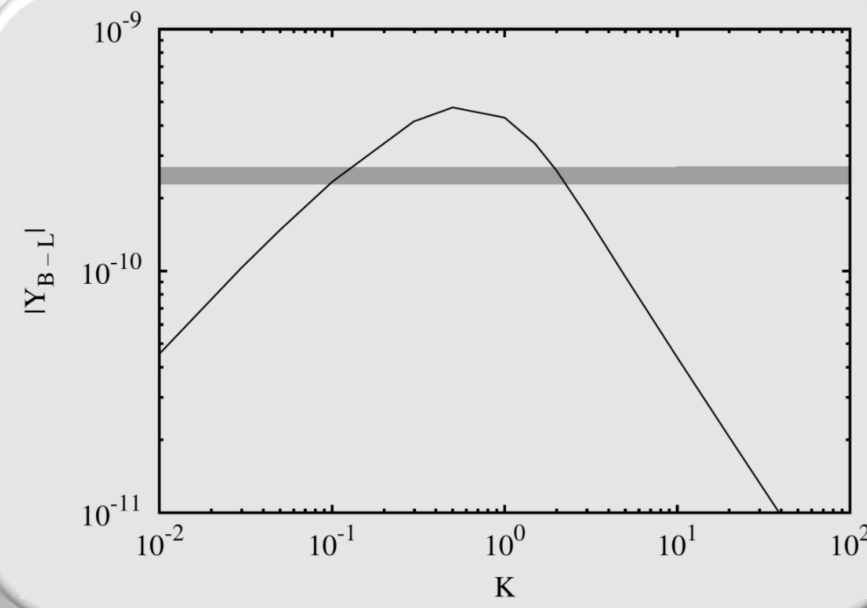
Summary of unflavored leptogenesis

- ☑ Final B asymmetry is controlled by
  - Decay parameter K
  - CP asymmetry ε_{N_1}
- ☑ (In general) CP asymmetry is given by Majorana parameter, and is not observable quantity
- ☑ Generated L asymmetry partially converts into B asymmetry
- ☑ The conversion rate is derived by equilibrium conditions of gauge interactions, top Yukawa interaction, and sphaleron processes

Summary of unflavored leptogenesis

☑ $K \sim 1$ is favored by

- N_1 thermal production
- departure from equilibrium
- washout 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

3. Leptogenesis with flavor effect

Outline of flavored leptogenesis

- A part of process depends on temperature regime, which leads $O(1)$ correction in final B asymmetry (flavor effect)

- Process of thermal leptogenesis
  - Production of RH neutrino in thermal bath
  - Decoupling from thermal equilibrium
  - CP violating decay out of equilibrium
  - Evolution of lepton asymmetry

- Same with non-flavored leptogenesis

- Flavor dependent CP asymmetry
- Additional CP violating source

- Flavor dependent washout
- (spectator effect)

When is flavor effect important?

- ☑ If leptogenesis occurs at $T < 10^{12}$ GeV, evaluation of lepton asymmetry must include flavor effects

- ☑ Why $T = 10^{12}$ GeV?

- ☑ Comparison of Hubble rate and charged Yukawa int. rate

$$\frac{\Gamma(H \to l\bar{l})}{H} = 0.93 \left(\frac{Y_l}{1.02 \times 10^{-2}}\right) \left(\frac{g_*}{106.75}\right)^{-1/2} \left(\frac{10^{12}\,\mathrm{GeV}}{T}\right)$$

When is flavor effect important?

$\Gamma/H < 1$ at $T \gtrsim 10^{12}$ GeV

- ☑ Universe does not "observe" lepton flavor
- ☑ Lepton produced in the RH neutrino decay is in a coherent state
- ☑ No lepton flavor effect on the leptogenesis

- ☑ Comparison of Hubble rate and charged Yukawa int. rate

$$\frac{\Gamma(H \to l\bar{l})}{H} = 0.93 \left(\frac{Y_l}{1.02 \times 10^{-2}} \right) \left(\frac{g_*}{106.75} \right)^{-1/2} \left(\frac{10^{12}\,\mathrm{GeV}}{T} \right)$$

When is flavor effect important?

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- ☑ Universe does not “observe” lepton flavor
- ☑ Lepton produced in the RH neutrino decay is in a coherent state
- ☑ No lepton flavor effect on the leptogenesis

$\Gamma/H > 1$ at $T \lesssim 10^{12}$ GeV

- ☑ Universe “observes” lepton flavor
- ☑ Lepton produced in the RH neutrino decay is no longer the interaction state, which is projected onto each flavor state
- ☑ CP asymmetry and washout effect become flavor dependent

What is difference in each temperature regime?

☑ What we should evaluate to show successful baryogenesis?

Unflavored leptogensis $(B-L)$ asymmetry n_{B-L}

Once interaction state is projected onto flavor state,
each flavored L asymmetry evolves separately

Flavored leptogensis flavored $(B-L)$ asymmetry n_{Δ_i}

$(\Delta_i = B/3 - L_i,\ n_{B-L} = n_{\Delta_e} + n_{\Delta_\mu} + n_{\Delta_\tau})$

☑ Important for the evaluation: which reactions are in equilibrium?

What is difference in each temperature regime?

☑ L asymmetry is partially converted into $(B-L)$ asymmetry

[J. A. Harvey and M. S. Turner, PRD42 (1990)]

How to determine conversion rate:

1. Express asymmetries of each particle species with chemical potential
2. Express total L and $(B-L)$ asymmetries with chemical potential
3. Relate these asymmetries each other with equilibrium conditions imposed by fast reactions, and find the relation of L and $(B-L)$

☑ Important for the evaluation: which reactions are in equilibrium?

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- ☑ The conversion rate of flavored L asymmetry is sensitive to
  - Which Yukawa interactions are in equilibrium
  - EW-spharelon is active or not

Specific regime and flavor structures

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	$u = Q_1 + H$ $d = Q_1 - H$ $e = l_e - H$

Chemical potentials are labeled with the fields, $i \equiv \mu_i$

Top Yukawa and gauge interactions are always in equilibrium

3.1 decay parameter

Decay parameter K → Flavored decay parameter K_e, K_μ, K_τ

Flavored decay parameter

- ☑ Once lepton interaction state is projected onto flavor state, each flavored L asymmetry evolves separately

- ☑ Flavored L asymmetry is controlled by flavored decay parameter

- ☑ Flavored decay parameter

$$K_e = \frac{\Gamma(N_1 \to l_e H)}{H(T = M_1)} = K \cdot \mathrm{BR}(N_1 \to l_e H)$$

$$K_\mu = \frac{\Gamma(N_1 \to l_\mu H)}{H(T = M_1)} = K \cdot \mathrm{BR}(N_1 \to l_\mu H)$$

$$K_\tau = \frac{\Gamma(N_1 \to l_\tau H)}{H(T = M_1)} = K \cdot \mathrm{BR}(N_1 \to l_\tau H)$$

Flavored decay parameter

☑ Large K ensures sufficient N_1 production

(All of flavors contribute to N_1 production)

☑ Small K_e and K_μ lead to weak washout of L asymmetry

For $K = 5$

☑ Flavored decay parameter

$$K_e = \frac{\Gamma(N_1 \to l_e H)}{H(T = M_1)} = K \cdot \mathrm{BR}(N_1 \to l_e H) = 0.1K$$

$$K_\mu = \frac{\Gamma(N_1 \to l_\mu H)}{H(T = M_1)} = K \cdot \mathrm{BR}(N_1 \to l_\mu H) = 0.2K$$

$$K_\tau = \frac{\Gamma(N_1 \to l_\tau H)}{H(T = M_1)} = K \cdot \mathrm{BR}(N_1 \to l_\tau H) = 0.7K$$

Reference value

Flavored decay parameter

☑ Large K ensures sufficient N_1 production

(All of flavors contribute to N_1 production)

☑ Small K_e and K_μ lead to weak washout of L asymmetry

☑ 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

3.2 CP asymmetry

- CP asymmetry ε_{N_1} ➡ Flavored CP asymmetry $\varepsilon_{N_1}^{e}, \varepsilon_{N_1}^{\mu}, \varepsilon_{N_1}^{\tau}$
- Additional CP violating source

Flavor dependent CP asymmetry

- ☑ CP asymmetry in unflavored leptogenesis

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

Including the sum over the final lepton flavor

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

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

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

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

Flavor dependent CP asymmetry

- ☑ In general, $\Gamma\left(N_1 \to l_j H\right) \neq \Gamma(N_1 \to \bar{l} H^\dagger)$, and hence $K_j \neq \bar{K}_j$
- ☑ Additional contribution to CP asymmetry

$$\varepsilon^i_{N_1} = \frac{\Gamma K_j - \bar{\Gamma}\bar{K}_j}{\Gamma + \bar{\Gamma}} \simeq \varepsilon_{N_1} K^0_j + \frac{\Delta K_j}{2} \qquad \left(K^0_j = \frac{\Gamma^0_j}{\Gamma^0}, \;\; \Delta K_j \equiv K_j - \bar{K}_j \right)$$

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

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$$\varepsilon_{N_1} \propto \Im\left(\lambda^\dagger \lambda\right)^2_{\beta 1} = \Im\left[\frac{M_1 M_\beta}{v^4}\left(\sum_i m_i R^*_{1i} R_{\beta i}\right)^2\right]$$

  - Total asymmetry vanishes for real orthogonal matrix R

Flavor dependent CP asymmetry

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- Additional contribution to CP asymmetry

$$\varepsilon^i_{N_1} = \frac{\Gamma K_j - \bar{\Gamma}\bar{K}_j}{\Gamma + \bar{\Gamma}} \simeq \varepsilon_{N_1} K^0_j + \frac{\Delta K_j}{2} \qquad \left(K^0_j = \frac{\Gamma^0_j}{\Gamma^0}, \ \ \Delta K_j \equiv K_j - \bar{K}_j \right)$$

$$\varepsilon^j_{N_1} \ni \Im\left[\left(\lambda_{\beta j}\lambda^*_{1j}\right)\left(\lambda\lambda^\dagger\right)_{\beta 1}\right] = \frac{M_1 M_\beta}{v^4} \Im\left[\left(\sum_i m_i R^*_{1i} R_{\beta i} \right) \left(\sum_{k,l} \sqrt{m_k m_l} R_{\beta l} R^*_{1k} U^*_{jl} U_{jk} \right) \right]$$

  - Flavored CP asymmetry exists even for real R
  - For a real R, $\varepsilon^j_{N_1} \propto \Im[U^*_{jl} U_{jk}]$, and hence leptogenesis could be checked in low energy experiments

3.3 Boltzmann Eq.

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}

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

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

  - $Y_i = n_i/s$ (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

- Conversion rate of flavored L asymmetry onto flavored $(B - L)$ asymmetry
- $Y_{L_i} = -(C^l_{ie} Y_{\Delta_e} + C^l_{i\mu} Y_{\Delta_\mu} + C^l_{i\tau} Y_{\Delta_\tau})$

$$\frac{dY_{\Delta_i}}{dz} = -\frac{z}{sH(z=1)}\left\{\left(\frac{Y_{N_1}}{Y^{eq}_{N_1}}-1\right)\epsilon_{1i}\gamma_D + K_i^0\sum_j\left[\frac{1}{2}\left(C^l_{ij}+C^H_j\right)\gamma_D + \left(\frac{Y_{N_1}}{Y^{eq}_{N_1}}-1\right)\left(C^l_{ij}\gamma_{S_s}+\frac{C^H_j}{2}\gamma_{S_t}\right) + \left(2C^l_{ij}+C^H_j\right)\left(\gamma_{S_t}+\frac{\gamma_{S_s}}{2}\right)\right]\frac{Y_{\Delta_i}}{Y^{eq}_l}\right\}$$

- Conversion rate of spectator contribution onto flavored $(B - L)$ asymmetry
- $Y_H - Y_{\bar{H}} = -(C^H_e Y_{\Delta_e} + C^H_\mu Y_{\Delta_\mu} + C^H_\tau Y_{\Delta_\tau})$

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	$u = Q_1 + H$ $d = Q_1 - H$ $e = l_e - H$

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

Evolution of flavored $(B-L)$ asymmetry

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

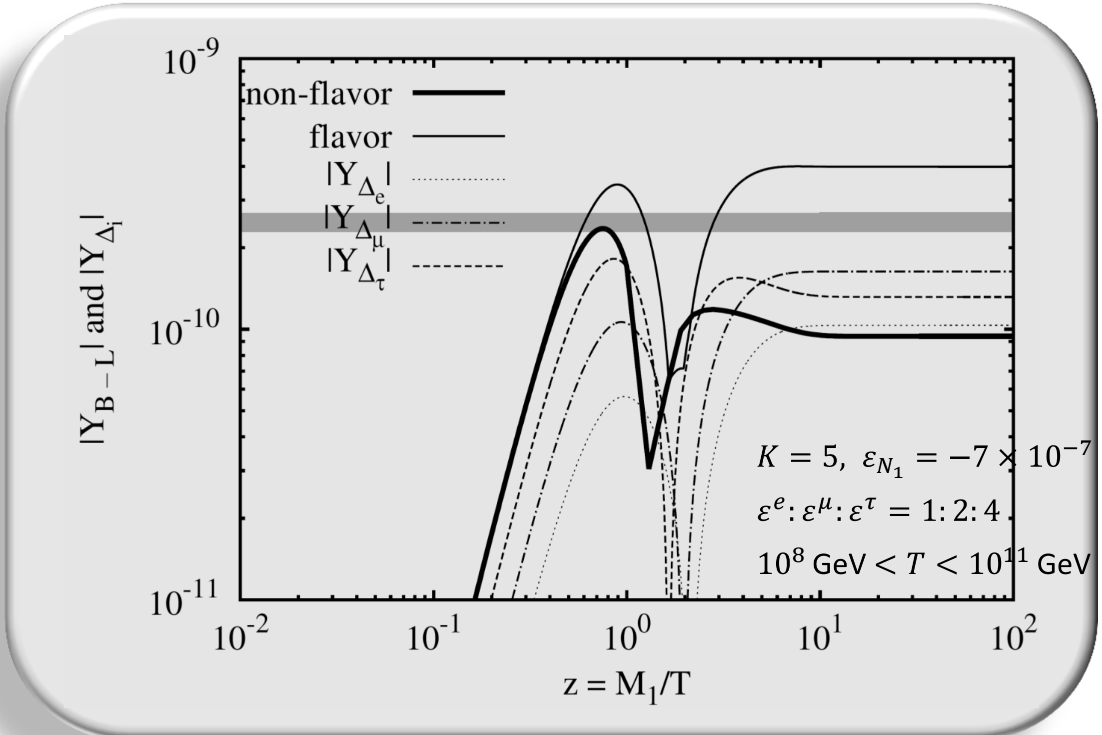
- Example 2:

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	$u = Q_1 + H$ $d = Q_1 - H$ $e = l_e - H$

$$C^l_{ij} = \frac{1}{711}\begin{pmatrix} 221 & -16 & -16 \\ -16 & 221 & -16 \\ -16 & -16 & 221 \end{pmatrix}, \quad C^H = \frac{8}{79}\begin{pmatrix} 1 & 1 & 1 \end{pmatrix}$$

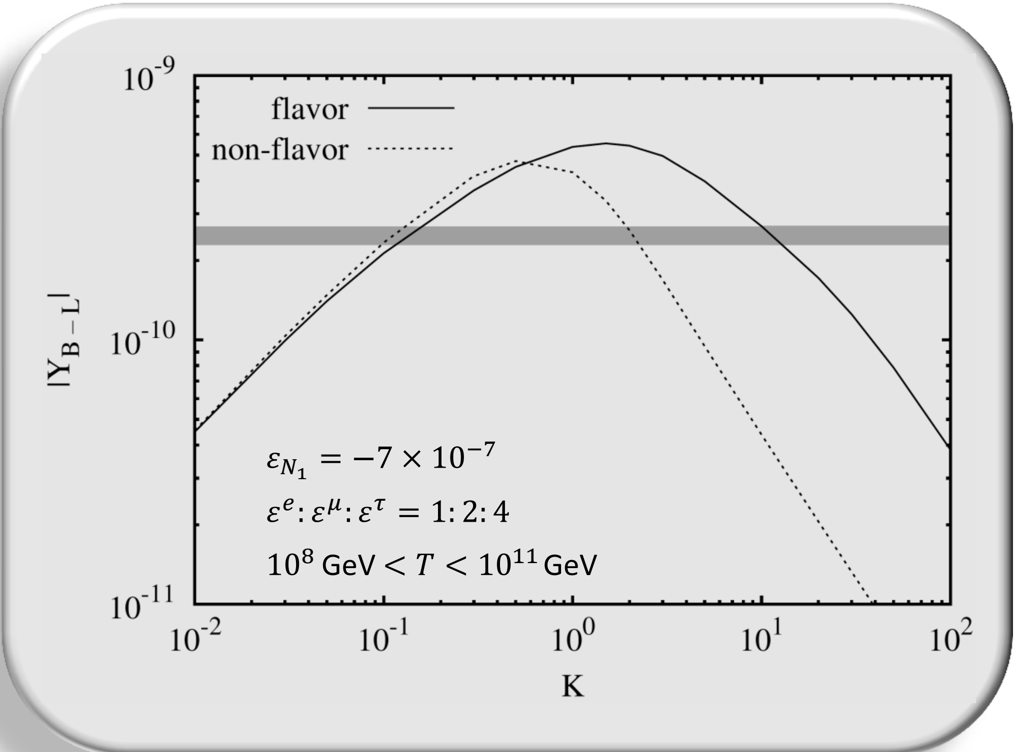
3.4 result and discussion

Impact of flavor effect



- ☑ Large enhancement with respect to unflavored case
- ☑ Nonetheless production rates of e and μ are lower than τ, they yield large contribution due to small washout
- ☑ Strongly depends on flavored decay parameter and CP asymmetry

Impact of flavor effect



- ☑ Importance of flavor effect becomes larger for larger K, because small K_i can keep large L_i asymmetry which is yielded by large K
- ☑ Similar K dependence also in other temperature regimes

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

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

☑ 2 SM singlets from matter representation **27** will be RH neutrinos

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

☑ Interaction of X, Y, Z are determined by $U(1)_A$ charges x, y, z

$$\lambda^{x+y+z} XYZ$$

$\lambda \simeq 0.22$: parameter to fit mass matrices

☑ RH neutrino masses and neutrino Yukawa couplings are predicted by the symmetry of E_6 and $U(1)_A$

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		

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 $\Theta_a\Theta_b \dots \Psi_i\Psi_i\overline{H}\overline{H}$

  Θ_x $(x = a, b, \dots)$: E_6 singlet scalar

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

Enhancement of RH neutrino mass

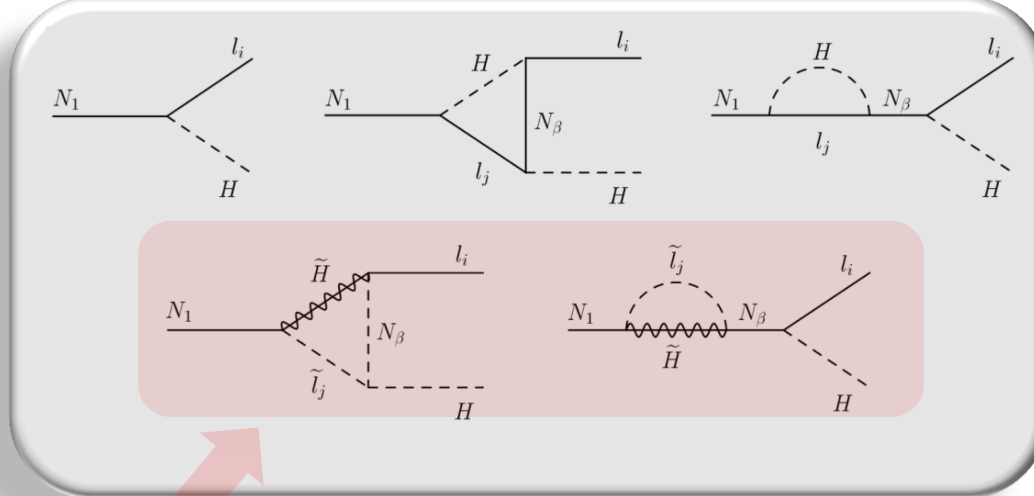
☑ Enhancement of physical mass of RH neutrino is reflected onto decrease of decay parameter

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

☑ 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

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

SUSY extension

- ☑ Corrections by SUSY extension
  - Relativistic degrees of freedom: $g_*^{SM} = 106.75 \to g_*^{SUSY} = 228.75$
  - 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

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

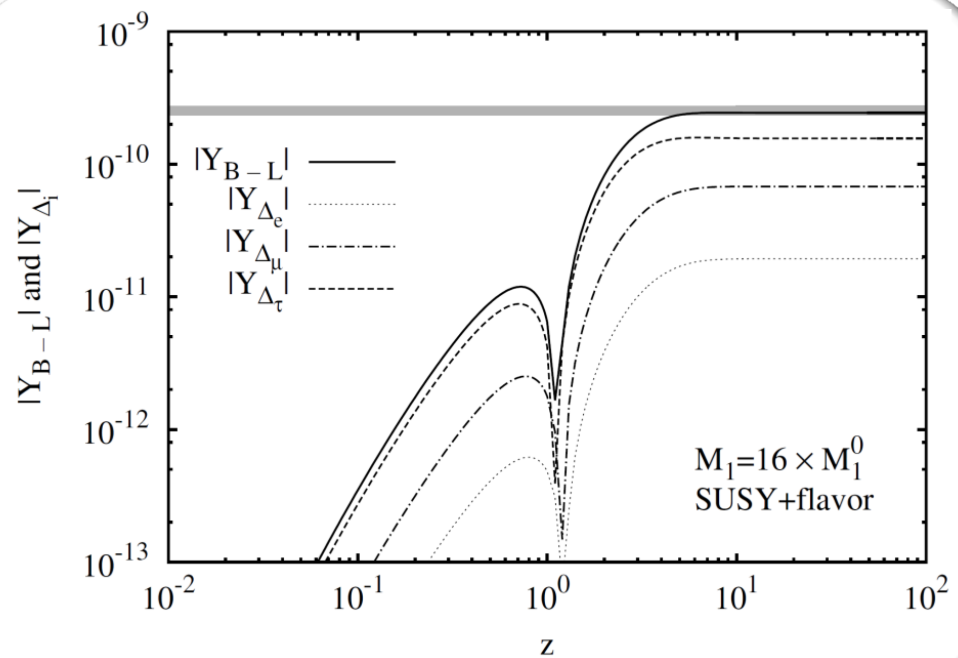
$$K_\mu^{\rm SM} = \frac{\Gamma^{\rm SM}(N_1 \to l_\mu H)}{H(T=M_1)} \simeq 6.4 \left(\frac{5.7\times 10^7\,{\rm GeV}}{M_1}\right)$$

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

Numerical result



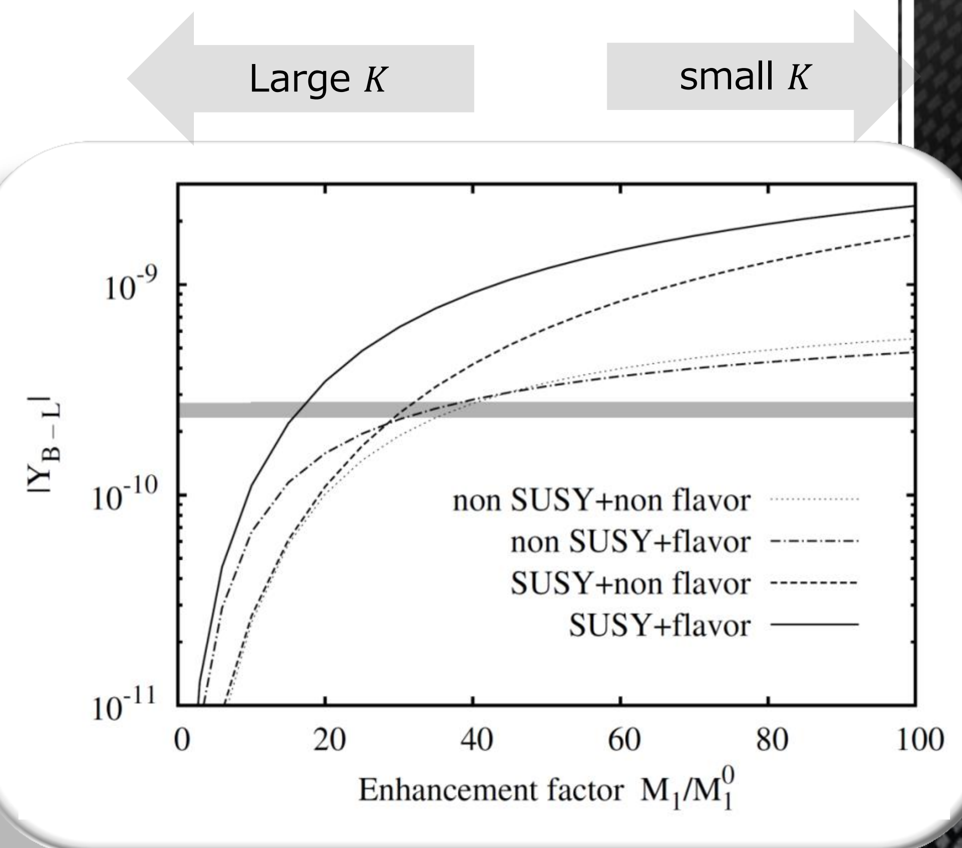
Evolutions of total $(B-L)$ asymmetry and each flavor $(B-L)$ asymmetries

- ☑ $E_6 \times U(1)_A$ 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

5. Summary

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

Hubble rate and charged Yukawa int. rate

$$H = 1.66 g_*^{1/2} \frac{T^2}{M_{\rm pl}} = 1.41 \times 10^6\,{\rm GeV} \left(\frac{g_*}{106.75}\right)^{1/2} \left(\frac{T}{10^{12}\,{\rm GeV}}\right)^2$$

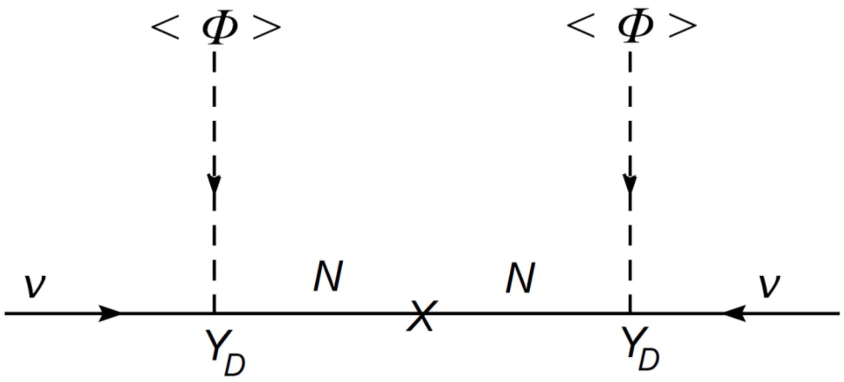
$$\Gamma(H \to l\bar{l}) = \frac{1}{8\pi}\frac{m_l^2}{v^2} m_H \left(1 - \frac{4m_l^2}{m_H^2}\right)^{3/2} = 1.31 \times 10^6\,{\rm GeV} \left(\frac{Y_l}{1.02 \times 10^{-2}}\right) \left(\frac{T}{10^{12}\,{\rm GeV}}\right)$$

$$m_H^2(T) = T^2 \left(1 - \frac{T_c^2}{T^2}\right) \frac{2m_W^2 + m_Z^2 + 2m_t^2 + m_H^2}{4v^2}$$

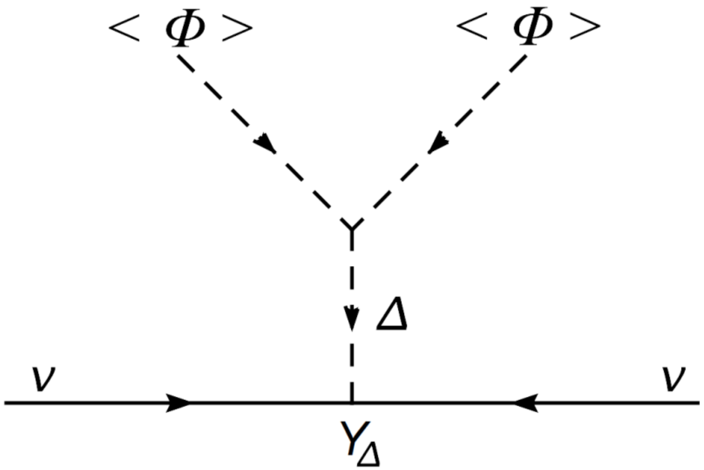
[e.g. *Thermal Field Theory*, Le Bellac]

Seesaw mechanism

☑ Type-I seesaw



☑ Type-II seesaw



CP asymmetry in N_1 decay

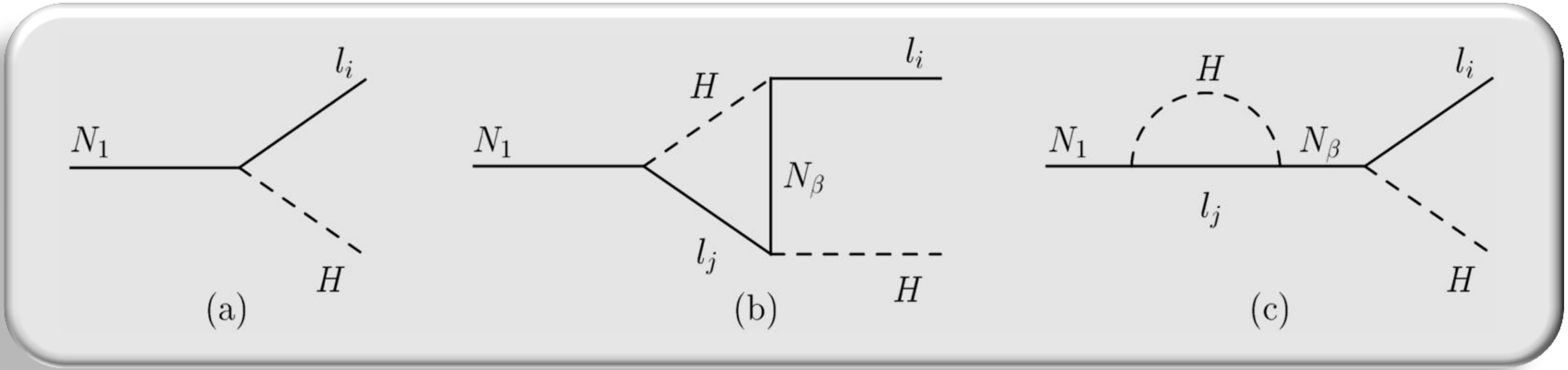
- ☑ Non-zero CP asymmetry comes from interference between tree-level amplitude with 1-loop contributions

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

$$= -\frac{1}{8\pi}\sum_{\beta\neq 1}\frac{\Im\left[\left(\lambda^\dagger\lambda\right)^2_{\beta 1}\right]}{(\lambda^\dagger\lambda)_{11}}\left\{\left[-\frac{M_\beta}{M_1}\left(1-\left(1+\frac{M_\beta^2}{M_1^2}\right)\right)\ln\left(1+\frac{M_1^2}{M_\beta^2}\right)\right]+\left[\frac{M_1/M_\beta}{1-(M_1^2/M_\beta^2)}\right]\right\}$$

$$\simeq -\frac{3}{16\pi}\sum_{\beta\neq 1}\frac{\Im\left[\left(\lambda^\dagger\lambda\right)^2_{\beta 1}\right]}{(\lambda^\dagger\lambda)_{11}}\frac{M_1}{M_\beta} \qquad (\text{For } M_1 \ll M_\beta)$$

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



Flavor dependent CP asymmetry

- ☑ Relation between flavored CP asymmetry and decay parameter

$$\varepsilon^i_{N_1} = \frac{\Gamma K_j - \bar{\Gamma}\bar{K}_j}{\Gamma + \bar{\Gamma}} \simeq \varepsilon_{N_1} K^0_j + \frac{\Delta K_j}{2}$$

- ☑ Derivation

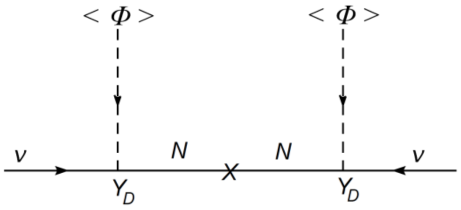
$$\begin{aligned}
\varepsilon^i_{N_1} &= \frac{\Gamma K_j - \bar{\Gamma}\bar{K}_j}{\Gamma + \bar{\Gamma}} \\
&= \frac{\Gamma K_j - \bar{\Gamma} K_j + \Gamma \bar{K}_j - \bar{\Gamma}\bar{K}_j}{2\left(\Gamma + \bar{\Gamma}\right)} + \frac{\Gamma K_j - \bar{\Gamma} K_j + \Gamma \bar{K}_j - \bar{\Gamma}\bar{K}_j}{2\left(\Gamma + \bar{\Gamma}\right)} \\
&= \frac{K_j + \bar{K}_j}{2}\frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} + \frac{K_j - \bar{K}_j}{2}\frac{\Gamma + \bar{\Gamma}}{\Gamma + \bar{\Gamma}} \\
&\simeq \varepsilon_{N_1} K^0_j + \frac{\Delta K_j}{2}
\end{aligned}$$

$$K^0_j = \frac{\Gamma^0_j}{\Gamma^0} \qquad \Delta K_j \equiv K_j - \bar{K}_j$$

Light neutrino mass by seesaw mechanism

☑ Framework: Type-I seesaw

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \lambda_{\alpha i}\bar{N}_\alpha l_i H + \frac{1}{2}M_\alpha \bar{N}_\alpha N_\alpha + \text{h.c.}$$



Integrating out RH neutrino

Naturally accounts for tiny neutrino mass by $O(1)$ Yukawa

$$m_\nu = v^2\frac{Y_\nu^T Y_\nu}{M_\alpha} = 0.061\,\text{eV}\left(\frac{Y_\nu^T Y_\nu}{1}\right)\left(\frac{10^{15}\,\text{GeV}}{M_\alpha}\right)$$

[P. Minkowski, PLB67 (1977)]
[T. Yanagida, Proceedings of the workshop (1979)]

c.f. $\Delta m^2_{\rm atm} = |m_3^2 - m_2^2| \simeq 2.4\times 10^{-3}\text{eV}^2$

Numerical result in flavored leptogenesis

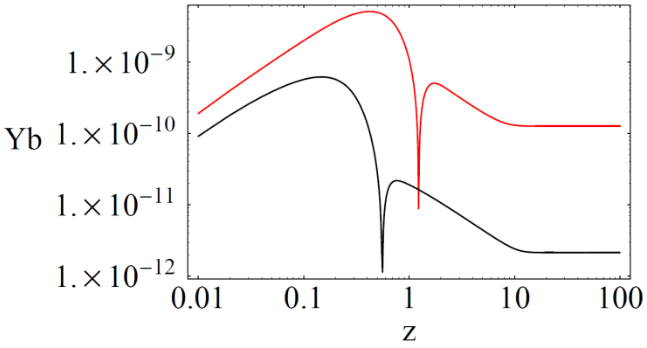


Figure 1: The total baryon asymmetry including flavours (upper) and within the one-flavour approximation (lower) as a function of z. The chosen parameters are $K_{ee} = 10$, $K_{\mu\mu} = 30$, $K_{\tau\tau} = 30$, $\epsilon_{ee} = 2.5 \times 10^{-6}$, $\epsilon_{\mu\mu} = -2 \times 10^{-6}$, $\epsilon_{\tau\tau} = 10^{-7}$ and $M_1 = 10^{10}$ GeV.

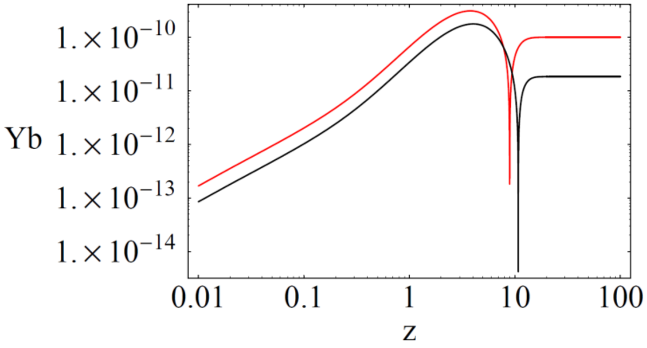


Figure 2: The total baryon asymmetry including flavours (upper) and within the one-flavour approximation (lower) as a function of z. The chosen parameters are $K_{ee} = 5 \times 10^{-2}$, $K_{\mu\mu} = 10^{-2}$, $K_{\tau\tau} = 10^{-3}$, $\epsilon_{ee} = 2.5 \times 10^{-6}$, $\epsilon_{\mu\mu} = -2 \times 10^{-6}$, $\epsilon_{\tau\tau} = 10^{-7}$ and $M_1 = 10^{10}$ GeV.

[A. Abada, et al, JHEP09(2006)010]

Corrections by flavor effect

☑ Process of thermal leptogenesis

- Production of RH neutrino in thermal bath
- Decoupling from thermal equilibrium
- CP violating decay out of equilibrium
- Evolution of lepton asymmetry

- No corrections

“No corrections” leads large correction

- Modification of CP asymmetry parameter

Leptogenesis and low energy observables can be connected

- Flavor dependent washout
- Additional source of L asymmetry

Correction to washout strength can yield large enhancement of L asymmetry