Flavored leptogenesis in Scotogenic models

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work in progress

Outline

- **Introduction / Scotogenic model**
- **Flavor effects**
- **Time evolution of B-L number**
- **Summary**

Motivation for BSM

Some issues suggesting BSM

- Baryon asymmetry
- Nonzero neutrino masses
- Dark matter

asymmetry between baryonic matter and anti-baryonic matter

baryon number density

$$Y_B = \frac{n_B - n_{\bar{B}}}{s} \simeq 8 \times 10^{-11}$$

s : entropy density

Sakharov conditions

1. Baryon number violation
2. C and CP-symmetry violation
3. Departure from the thermal equilibrium

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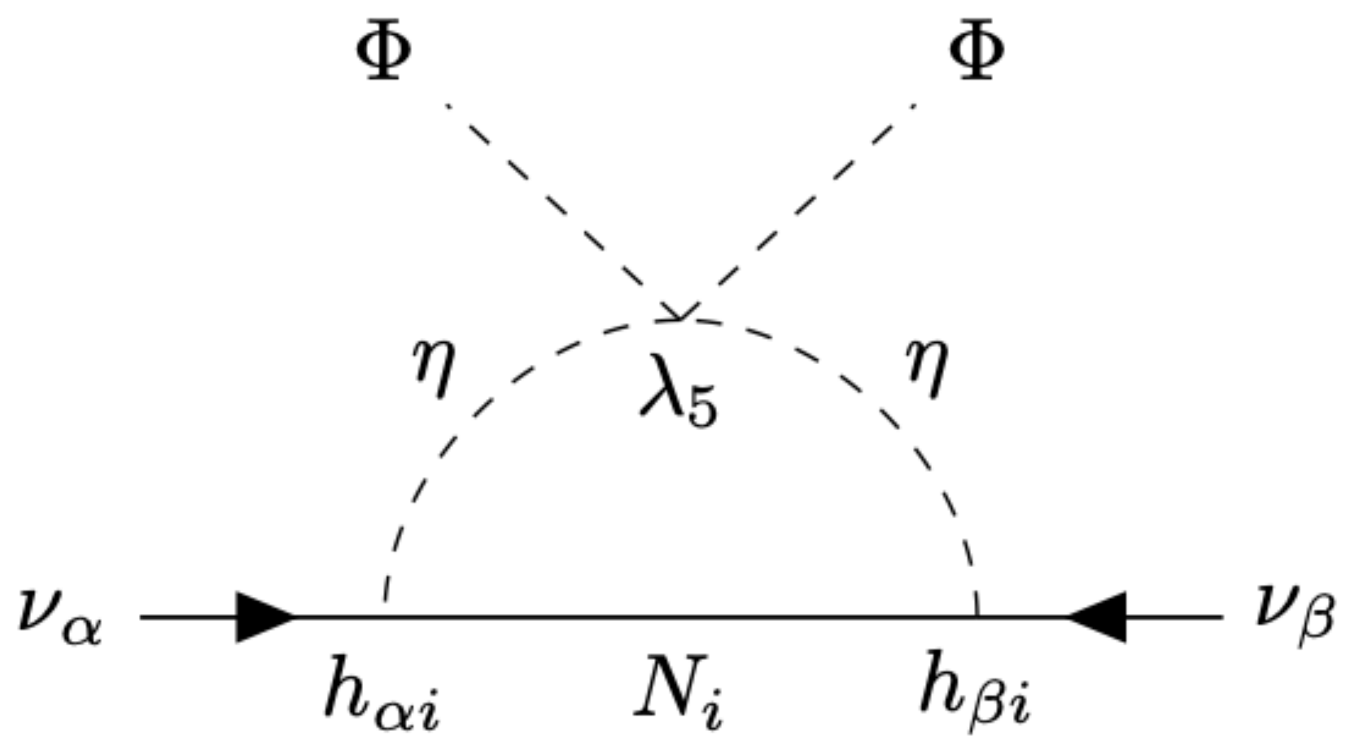
Sakharov conditions

1. Baryon number violation
2. C and CP-symmetry violation
3. Departure from the thermal equilibrium

Scotogenic model satisfies Sakharov conditions and accounts for these issues

Scotogenic model

small neutrino masses are generated via radiative corrections



SM (Z_2 even)

+

Right-handed neutrino (Z_2 odd) : N_i

$SU(2)_L$ doublet scalar (Z_2 odd) : $\eta = \begin{pmatrix} \eta^+ \\ \eta^0 \end{pmatrix}$

$$\mathcal{L} \supset \left(h_{\alpha i} \bar{L}_\alpha \tilde{\eta} N_i + \text{h.c.}\right) - \frac{1}{2} M_i N_i N_i - V$$

$$V = m_\eta^2 \eta^\dagger \eta + \frac{1}{2}\lambda_2 \left(\eta^\dagger \eta\right)^2 + \lambda_3 \left(\Phi^\dagger \Phi\right)\left(\eta^\dagger \eta\right) + \lambda_4 \left(\Phi^\dagger \eta\right)\left(\eta^\dagger \Phi\right) + \frac{1}{2}\lambda_5 \left[\left(\Phi^\dagger \eta\right)^2 + \text{h.c.}\right]$$

E. Ma, Phys.Rev.D 73 (2006) 077301

Z. Tao, Phys.Rev.D54:5693-5697,1996

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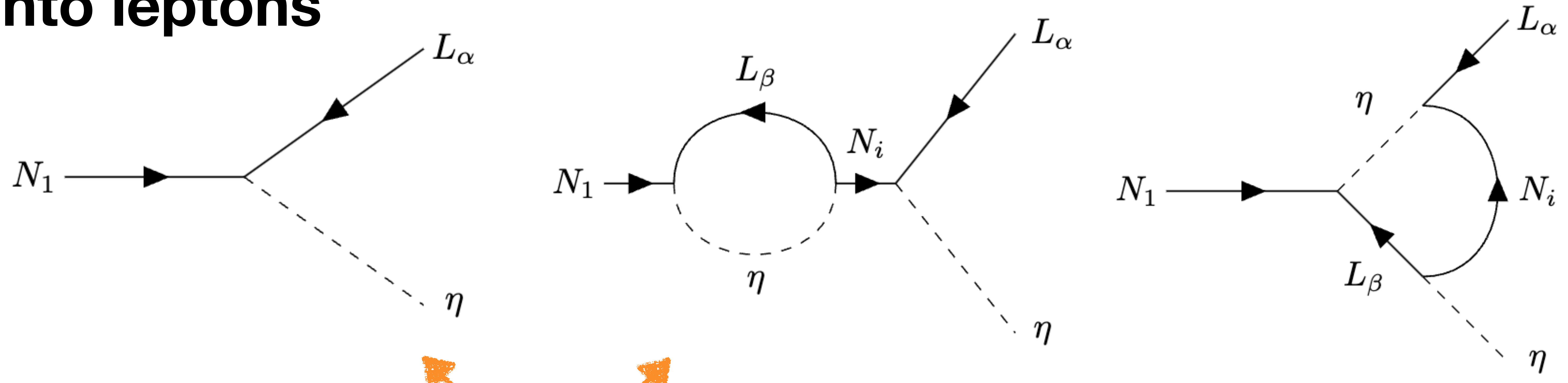
Leptogenesis in scotogenic model

N_i **are generated via inverse decay and depart from equilibrium**

N_i **decays into leptons**



CP asym. from interference of tree and 1-loop

$$\epsilon_i^\alpha = \frac{\Gamma\left(N_1 \to L_\alpha \eta\right) - \Gamma\left(N_1 \to \bar{L}_\alpha \eta^\dagger\right)}{\Gamma\left(N_1 \to L_\alpha \eta\right) + \Gamma\left(N_1 \to \bar{L}_\alpha \eta^\dagger\right)}$$

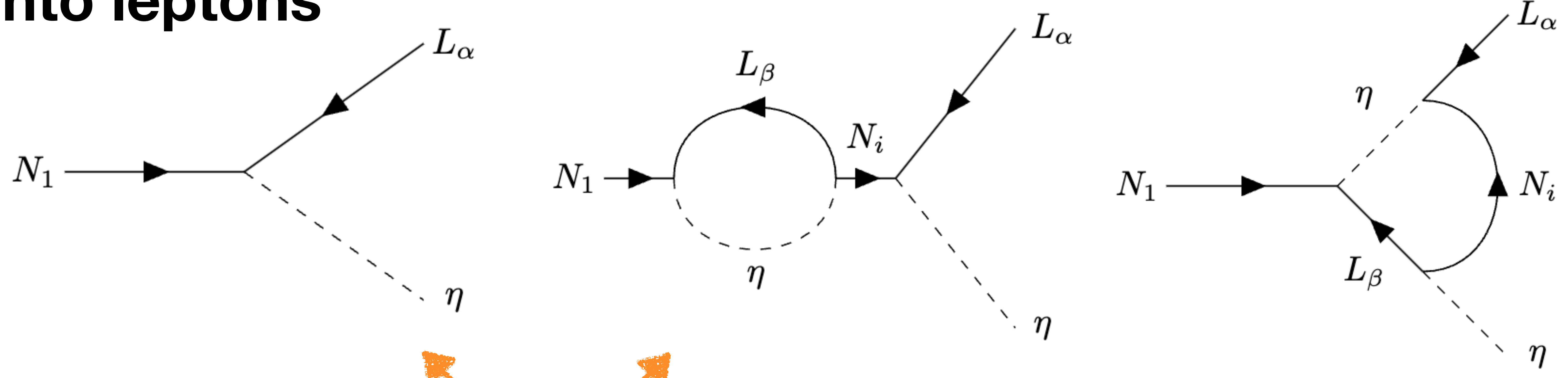
L is generated !

L is converted to B via spharelon process $B \simeq \frac{28}{79}(B-L)$

Leptogenesis in scotogenic model

N_i **are generated via inverse decay and depart from equilibrium**

⇨ N_i **decays into leptons**



CP asym. from interference of tree and 1-loop

$$\epsilon_i^\alpha = \frac{\Gamma\left(N_1 \to L_\alpha \eta\right) - \Gamma\left(N_1 \to \bar{L}_\alpha \eta^\dagger\right)}{\Gamma\left(N_1 \to L_\alpha \eta\right) + \dots}$$

The efficiency is determined by the decay parameter.

⇨ L is converted to B via sphaleron process $B \simeq \frac{28}{79}(B \dots$

Leptogenesis without flavor effect

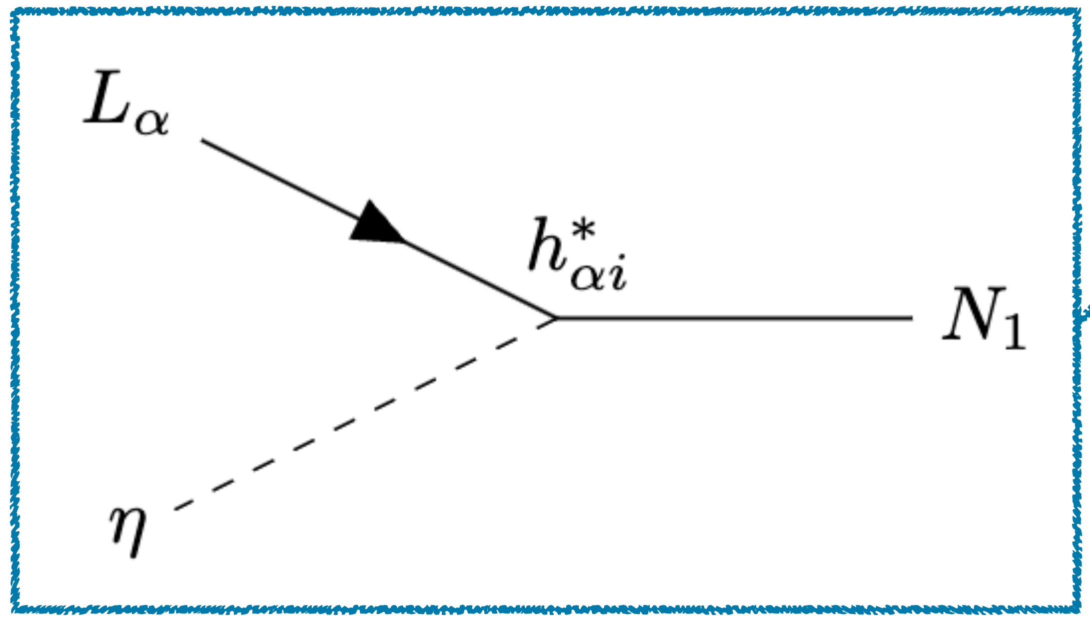
decay parameter controll L

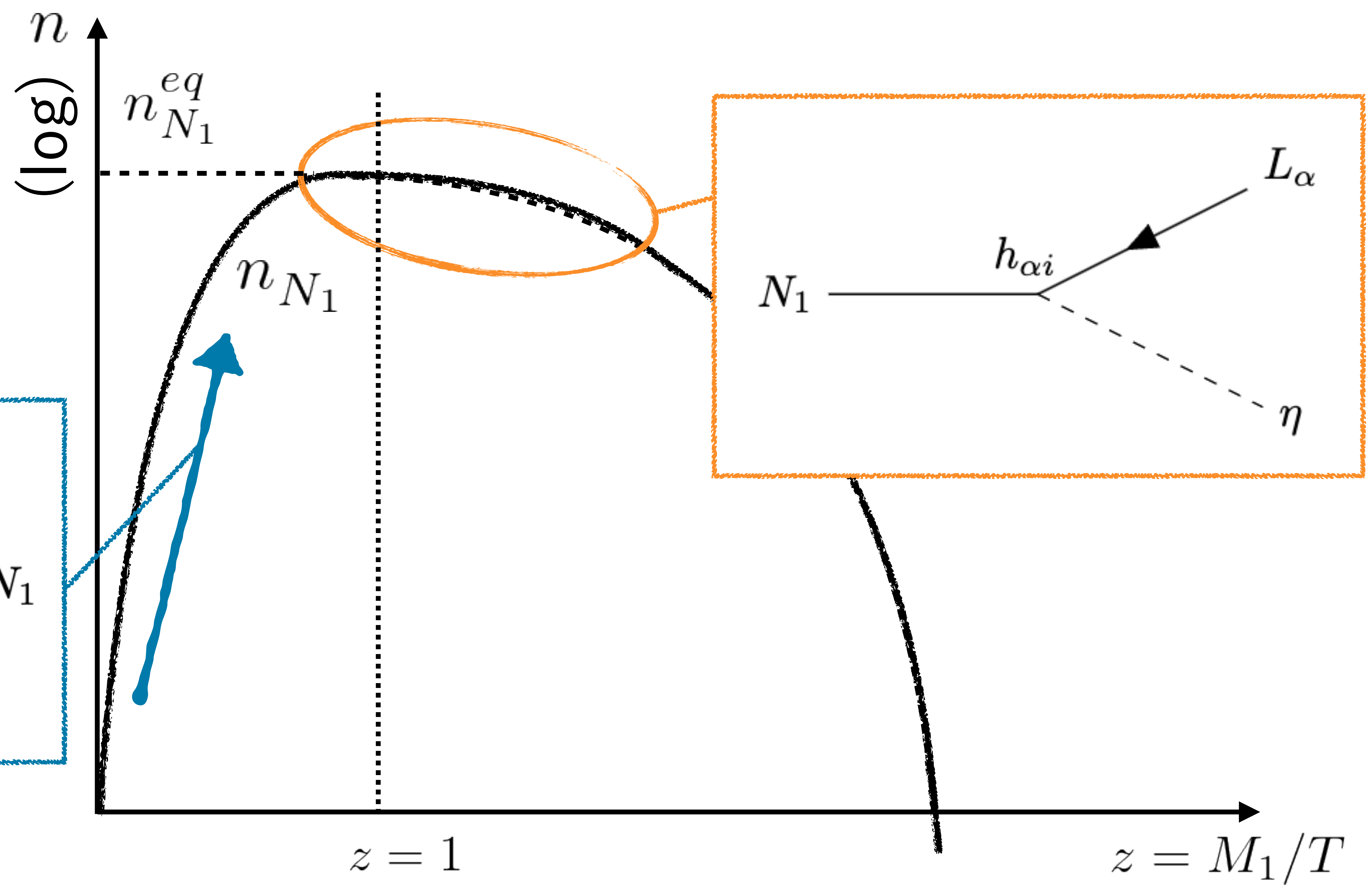
Decay parameter $K \equiv \dfrac{\Gamma(N_i \to \ell\,\eta)}{H(T = M_i)}$

$$H = \frac{\dot{R}}{R} = 1.66 g_*^{1/2} \frac{T^2}{m_{pl}}$$

Best efficient $K \sim \mathcal{O}(1)$

- If K is large, less departure, strong washout
- If K is small, N1 is NOT enough thermarize





… How about with flavor effcts?

Leptogenesis with flavor effect

✦ Baryon asymmetry can be enhanced by up to one order of magnitude with flavor effects at $T \lesssim 10^{12}\mathrm{GeV}$ E. Nardi et al. *JHEP 0601:164* (2006)

Decay parameters are defferent by flavor

$$K_e = \frac{\Gamma(N_i \to \ell_e \eta)}{H(T = M_i)} = K \cdot BR(N_i \to \ell_e \eta)$$

$$K_\mu = \frac{\Gamma(N_i \to \ell_\mu \eta)}{H(T = M_i)} = K \cdot BR(N_i \to \ell_\mu \eta)$$

$$K_\tau = \frac{\Gamma(N_i \to \ell_\tau \eta)}{H(T = M_i)} = K \cdot BR(N_i \to \ell_\tau \eta)$$

⇨ Each flavor has different washout factor

→ larger lepton number

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The $L_\alpha \to B/3 - L_\beta$ conversion rates

$L_\alpha \to B/3 - L_\beta$ **conversion rates depend on flavor**

In thermal equilibrium, Boson $n_+ - n_- \simeq \frac{gT^3}{3}\left(\frac{\mu}{T}\right)$ Fermion $n_+ - n_- \simeq \frac{gT^3}{6}\left(\frac{\mu}{T}\right)$

For $10^6\text{GeV} \lesssim T \lesssim 10^9\text{GeV}$

- processes in chemical eqilibrium

$$\mu_{W^-} = -\mu_{\eta^+} + \mu_{\eta^0} \qquad \mu_{\phi^0} = -\mu_{u_L} + \mu_{u_R}$$
$$\mu_{W^-} = -\mu_{\phi^+} + \mu_{\phi^0} \qquad \mu_{\phi^0} = \mu_{d_L} - \mu_{d_R}$$
$$\mu_{W^-} = -\mu_{uL} + \mu_{dL} \qquad \mu_{\phi^0} = \mu_{\ell_L} - \mu_{\ell_R} \ (\ell_L = \mu, \tau)$$
$$\mu_{W^-} = -\mu_\nu + \mu_{\ell_L}$$

- Before SU(2) symmetry breaking, weak isospin and U(1) charge is 0

- Electroweak Spharelon process

$$\sum_i (3\mu_{q_i} - \mu_{L_i}) = 0$$

$$\frac{1}{3}B - L_\alpha = \begin{pmatrix} -\frac{64}{27} & -\frac{10}{27} & -\frac{10}{27} \\ -\frac{56}{297} & -\frac{1813}{594} & -\frac{31}{594} \\ -\frac{56}{297} & -\frac{31}{594} & -\frac{1813}{594} \end{pmatrix} \begin{pmatrix} \frac{T^2}{6s}\mu_e \\ \frac{T^2}{6s}\mu_\mu \\ \frac{T^2}{6s}\mu_\tau \end{pmatrix}$$

Time evolution of B-L

Calculate B-L time evolution by solving Boltzmann eq.

Parameters

yukawa coupling with right-handed neutrinos

$$h_{\alpha i} = \begin{pmatrix} 3.12\times10^{-4} - 6.65\times10^{-7}i & 0.385e + 2.11\times10^{-7}i & -0.287 + 8.76\times10^{-2}i \\ 3.21\times10^{-4} + 1.20\times10^{-5}i & 0.426 + 1.28\times10^{-2}i & 1.51 + 4.43\times10^{-7}i \\ -3.02\times10^{-4} + 1.10\times10^{-5}i & -0.408 + 1.11\times10^{-2}i & 1.31 - 4.24\times10^{-7}i \end{pmatrix}$$

α: lepton flavor index

i : generation of right-handed neutrino

N_1 mass $M_1 = 10^7\text{GeV}$

η mass $m_\eta = 10^4\text{GeV}$

ν_L mass $m_1 = 10^{-20}\text{GeV}$

$\lambda_5 = 10^{-7}$

$M_2/M_1 = M_3/M_2 = 1.5$

Parameter of left-handed neutrino (NuFIT5.3)

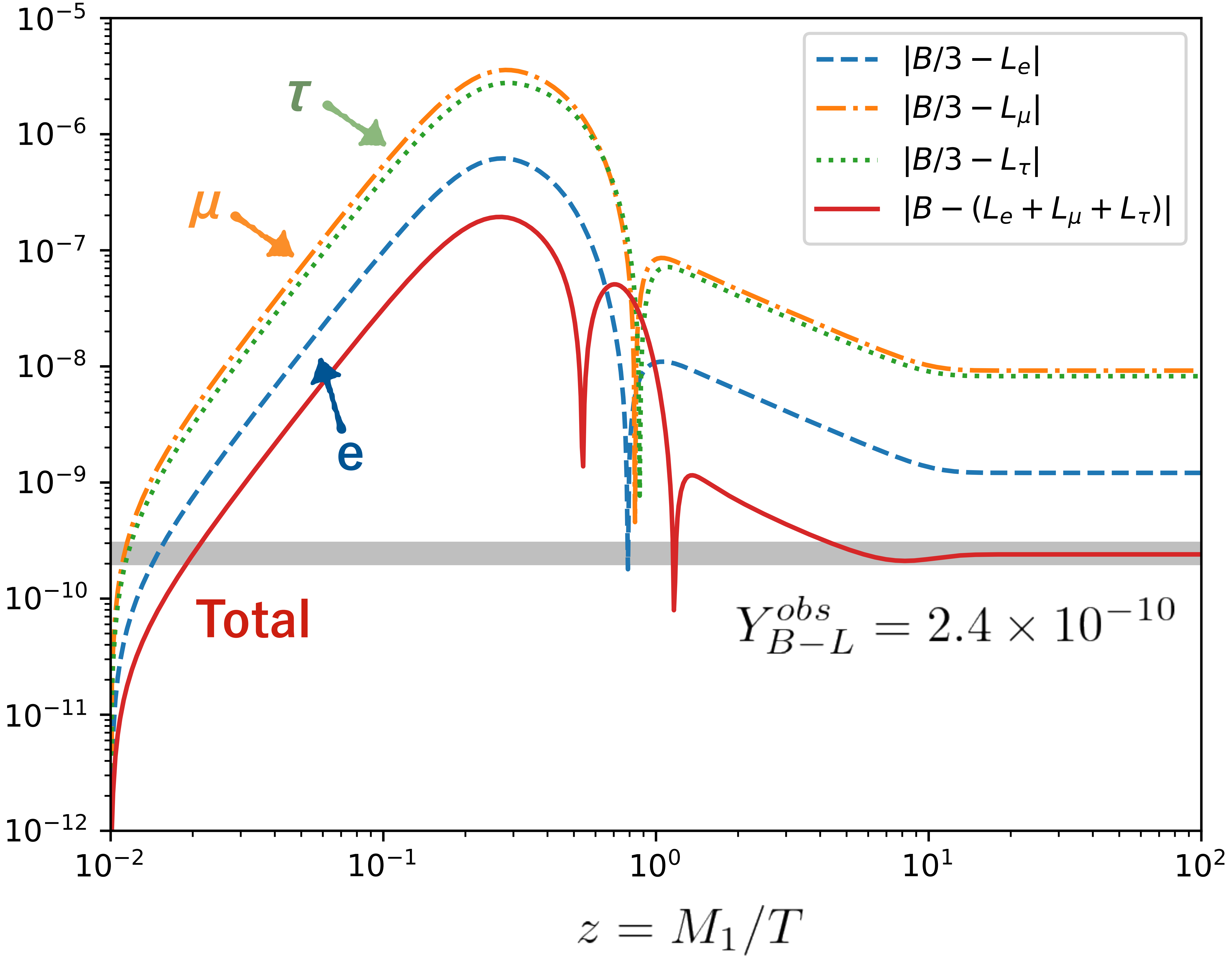
$\sin^2\theta_{12} = 0.307$ $\delta_{CP} = 197^\circ$

$\sin^2\theta_{23} = 0.572$ $\Delta m^2_{21} = 7.41\times10^{-5}\text{eV}^2$

$\sin^2\theta_{13} = 0.02203$ $\Delta m^2_{3\ell} = 2.511\times10^{-3}\text{eV}^2$

Time evolution of B-L

$|B/3 - L_\alpha|$ and $|B-L|$



- N_1 and L are generated via inverse decay
- N_1 depart from equilibrium, reverse sign L generated.
- $B/3 - L_\mu$ Have opposite sign of $B/3 - L_\tau$ and $B/3 - L_e$

B-L for observed baryon asymmetry!

Summery

- For precise baryon number calculation, flavor effects must be taken into account
- We found that there is a parameter set ($M_1, m_1, m_\eta, \lambda_5, h_{\alpha i}$) that accounts for $Y^{obs}_{B-L} = 2.4 \times 10^{-10}$ in scotogenic model considering flavor effects.

Future work

- research the contribution from N_2 and N_3 decay

backup

パラメータへの制限1

- ✦ 最も軽い右巻きニュートリノの質量 M_1 についての制限
  - $M_1 \gg m_\eta$ (計算の都合上)

- ✦ スカラー粒子 η の質量についての制限
  - $M_1 \gg m_\eta$ (計算の都合上)
  - 今回の計算では η の残存量と暗黒物質の観測値を比較してはいないが、それによって m_η のパラメータを絞ることができる
  - 加速器実験からの制限により $1\mathrm{TeV} < m_\eta$

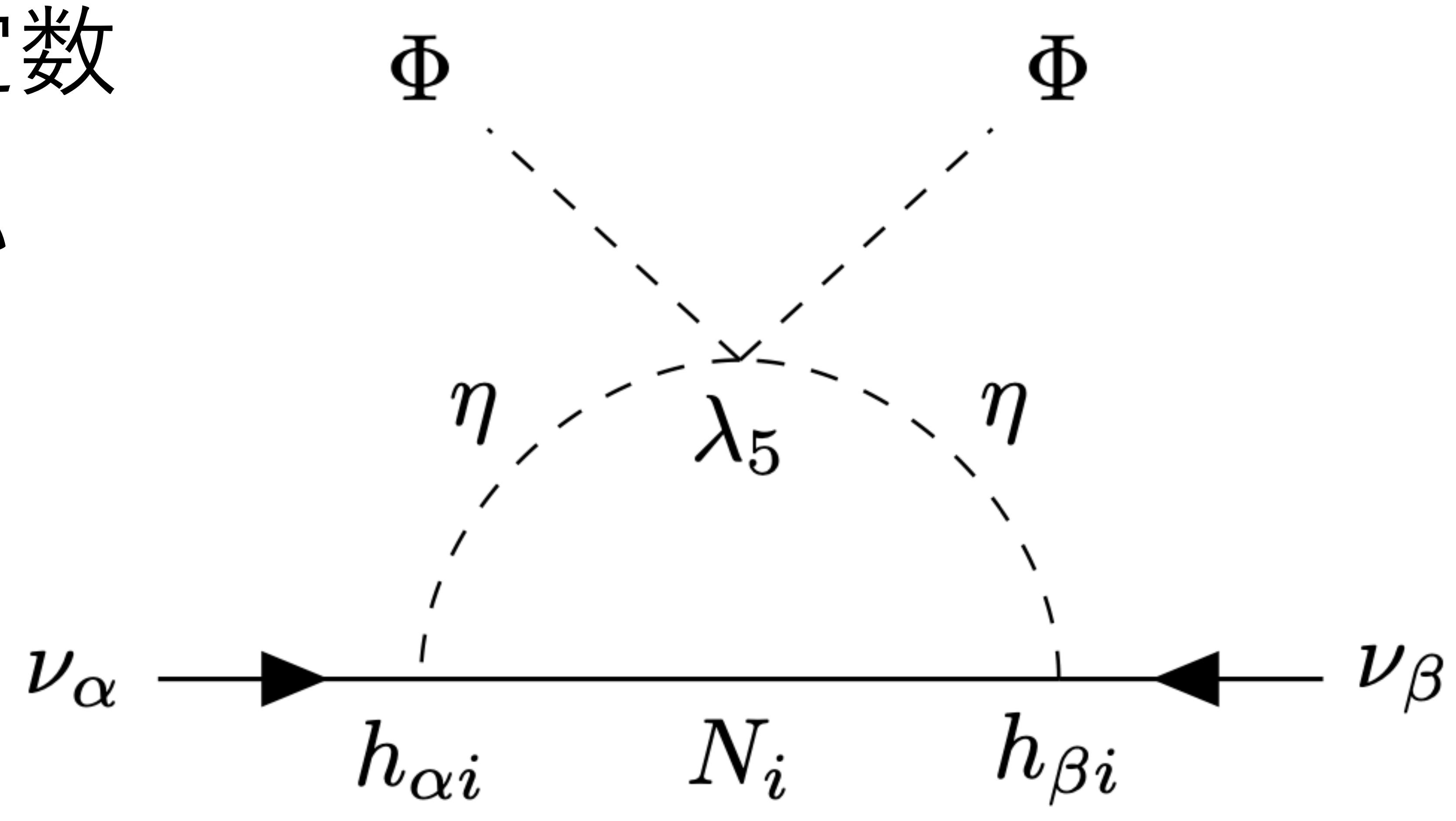
パラメータへの制限2

✦ 軽いニュートリノの質量への制限

- トリチウム^3Hのベータ崩壊実験より $m_\nu < 0.8\mathrm{eV}$

✦ 結合定数 λ_5 への制限

- 軽いニュートリノ質量の生成に関与する結合定数
- 小さすぎると軽いニュートリノ質量を作れない



パラメータへの制限3

✦ 右巻きニュートリノの質量の階層性への制限

- シーソー機構から、左巻きニュートリノの質量は (dirac mass)^2/Mi
  ⟶ 一番軽い右巻きニュートリノの質量が最も効く
- 左巻きニュートリノの質量行列はランクが最低でも 2、または 3
  ⟶ ランク2の行列を作るには最低 2 つの重い右巻きニュートリノが寄与
- 質量の階層性が大きすぎると、実質的に右巻きが 1 個しか寄与せず、ランクが 1 に落ちる
  ⟶ ニュートリノ振動を再現できず、質量の二乗差が出てこない。
- 階層性が小さすぎると、十分なレプトン数を作れなくなる。

フレーバーがない場合との比較1

バリオン数の大まかな評価 [3]

$$\eta_B = -0.01\epsilon_1\kappa_1$$

各フレーバーのAsymmetry parameter ε

$$\epsilon_1^\alpha = \frac{\Gamma\left(N_1 \to L_\alpha \eta\right) - \Gamma\left(N_1 \to \bar{L}_\alpha \eta^\dagger\right)}{\sum_\alpha \left[\Gamma\left(N_1 \to L_\alpha \eta\right) + \Gamma\left(N_1 \to \bar{L}_\alpha \eta^\dagger\right)\right]} = \frac{1}{8\pi}\frac{1}{\left(h^\dagger h\right)_{11}}\sum_{j\neq 1}\left(\mathrm{Im}\left[h_{\alpha j}h^*_{\alpha 1}\left(h^\dagger h\right)_{1j}\right]\frac{F\left(r_{j1},\eta_1\right)}{\sqrt{r_{j1}}}\right)$$

$$F\left(r_{ji},\eta_i\right) = \sqrt{r_{ji}}\left[f\left(r_{ji},\eta_i\right) - \frac{\sqrt{r_{ji}}}{r_{ji}-1}\left(1-\eta_i\right)^2\right]$$

$$f\left(r_{ji},\eta_i\right) = \sqrt{r_{ji}}\left[1 + \frac{\left(1-2\eta_i+r_{ji}\right)}{\left(1-\eta_i\right)^2}\ln\left(\frac{r_{ji}-\eta_i^2}{1-2\eta_i+r_{ji}}\right)\right]$$

$$\eta_i = m_\eta^2/M_i^2 \quad r_{ji} = M_j^2/M_i^2$$

結果

$$\epsilon_1^e = -7.809\times 10^{-5}$$

$$\epsilon_1^\mu = 3.375\times 10^{-4}$$

$$\epsilon_1^\tau = -3.201\times 10^{-4}$$

[3] W. Buchmüller et.al. Annals of Physics, Vol. 315, No. 2, pp. 305–351

フレーバーがない場合との比較2

バリオン数の大まかな評価 [3]

$$\eta_B = -0.01\epsilon_1\kappa_1$$

Efficiency parameter κ　　（Kは崩壊パラメータ、Hはハッブルパラメータ）

$$\kappa_1 = \frac{1}{1.2K_1[\mathrm{In}K_1]^{0.8}}$$

$$K_1 = \frac{\Gamma_1}{H(T=M_1)} \longrightarrow K_1^e = \frac{\Gamma(N_1 \to L_e\eta)}{H(T=M_1)} \quad K_1^\mu = \frac{\Gamma(N_1 \to L_\mu\eta)}{H(T=M_1)} \quad K_1^\tau = \frac{\Gamma(N_1 \to L_\tau\eta)}{H(T=M_1)}$$

$$\Gamma_1 = \frac{M_1}{8\pi}\left(h^\dagger h\right)_{11}\left(1-\eta_1\right)^2$$

結果

$$K_1^e = 275.5 \qquad \kappa_1^e = 7.603 \times 10^{-4}$$

$$K_1^\mu = 292.0 \qquad \kappa_1^\mu = 7.114 \times 10^{-4}$$

$$K_1^\tau = 258.5 \qquad \kappa_1^\tau = 8.178 \times 10^{-4}$$

フレーバーがない場合との比較3

(1) **フレーバーごとにCPの破れの大きさとwashoutが異なる近似計算**

$$\eta_B = -0.01\left(\epsilon_1^e \kappa_1^e + \epsilon_1^\mu \kappa_1^\mu + \epsilon_1^\tau \kappa_1^\tau\right) \simeq 8.112 \times 10^{-10}$$

(2) **フレーバーが考慮されていない近似計算**

$$\kappa_1 = \frac{1}{1.2K_1[\mathrm{In}K_1]^{0.8}}$$

$K_1 = K_e + K_\mu + K_\tau$ として washout factor κ_1 を求める

各フレーバーごとのCPの破れの度合いを足し上げて、バリオン数を見積もると

$$\eta_B = -0.01\kappa_1\left(\epsilon_1^e + \epsilon_1^\mu + \epsilon_1^\tau\right) \simeq 1.335 \times 10^{-10}$$

(3) **ボルツマン方程式を解くと**

$$\eta_B = Y_{B-L}^{obs} \times \frac{28}{79}$$

$$= 2.4 \times 10^{-10} \times \frac{28}{79} = 0.85 \times 10^{-10}$$

ニュートリノ質量はどのように生成される？

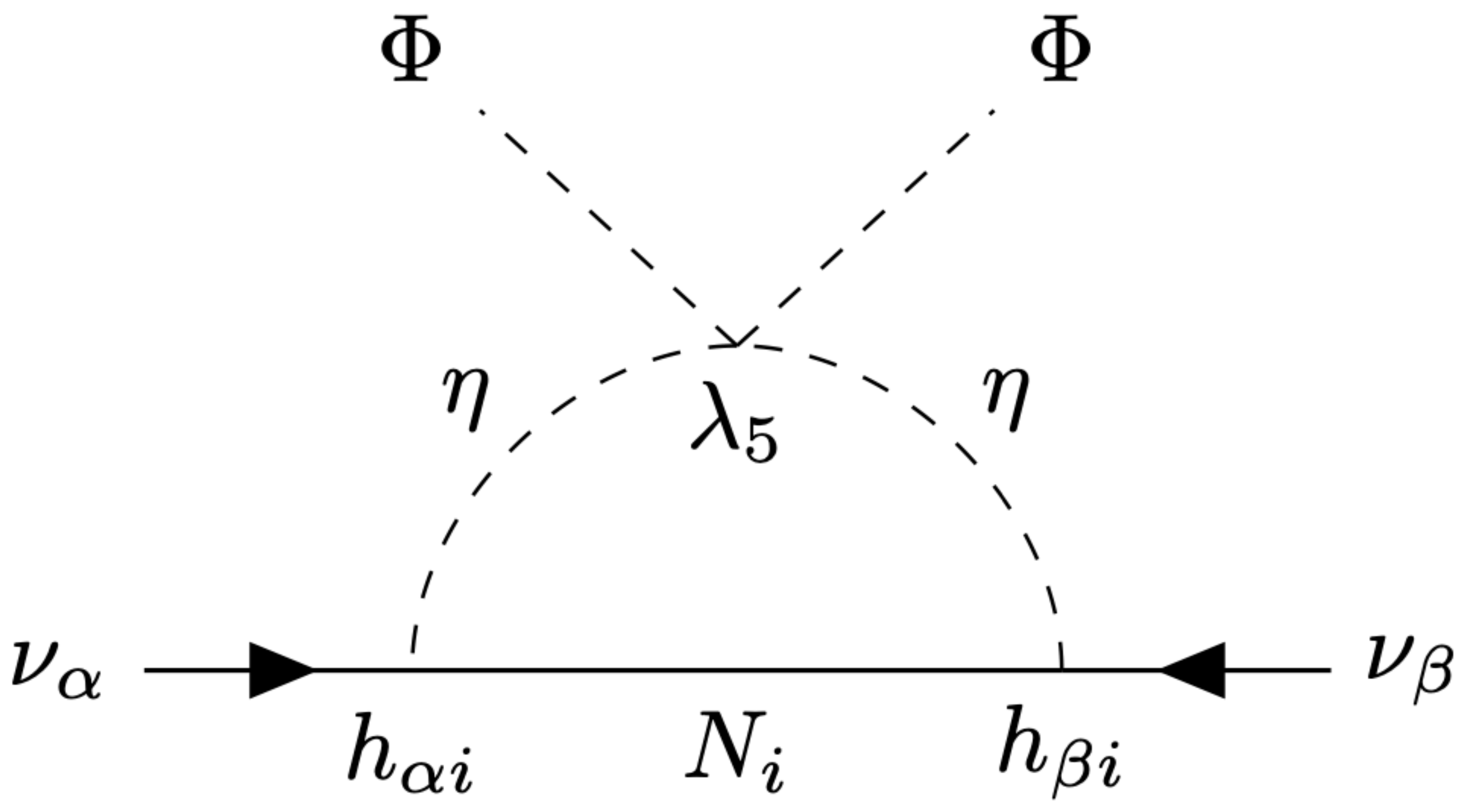
$$(\mathcal{M}_\nu)_{\alpha\beta} = \sum_i \frac{h_{\alpha i} h_{\beta i} M_i}{32\pi^2} \left[\frac{m_R^2}{m_R^2 - M_i^2} \log\left(\frac{m_R^2}{M_i^2}\right) - \frac{m_I^2}{m_I^2 - M_i^2} \log\left(\frac{m_I^2}{M_i^2}\right) \right]$$

✦ $m_{\eta_R}^2 - m_I^2 = 2\lambda_5 v^2$ が

$m_0^2 = (m_R^2 + m_I^2)/2$ よりも小さい

✦ $M_i^2 \gg m_0^2$ と近似

$$(\mathcal{M}_\nu)_{\alpha\beta} \simeq \frac{\lambda_5 v^2}{8\pi^2} \sum_i \frac{h_{\alpha i} h_{\beta i}}{M_i} \left[\log \frac{M_i^2}{m_0^2} - 1 \right]$$



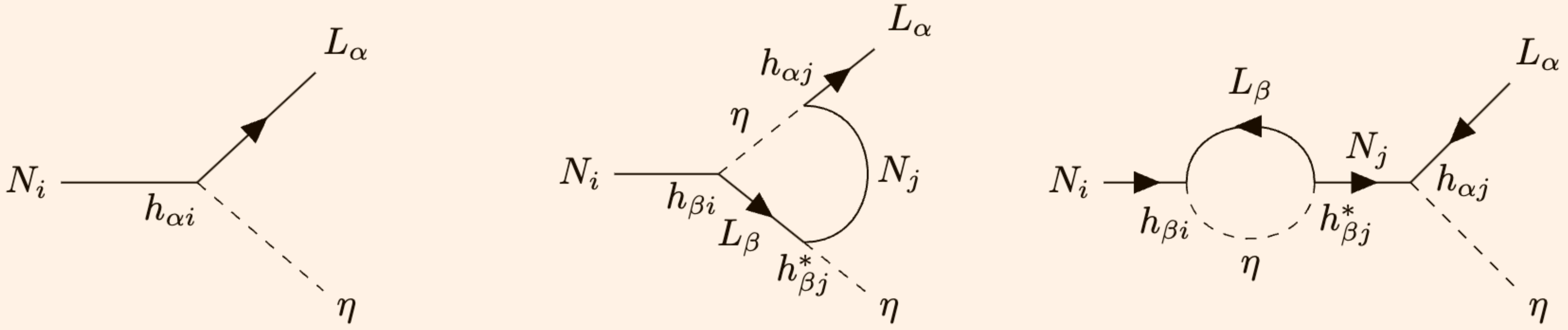
ニュートリノ質量を生成する
1-loopのファインマン図

干渉項からCP非対称の部分が現れるのはなぜ？

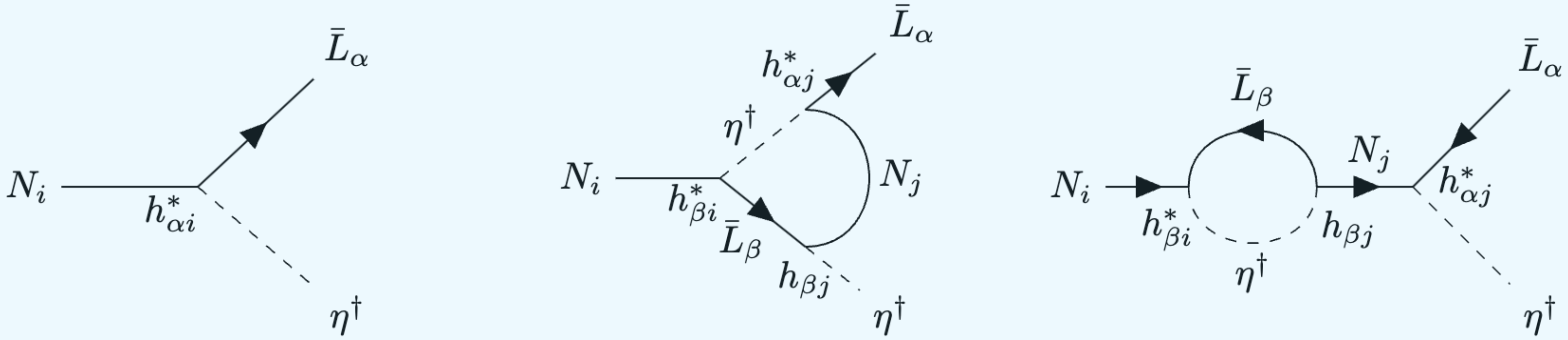
$$\mathcal{L} = -\, h_{\alpha i}\, \bar{N}_i\, \tilde{\eta}^\dagger L_\alpha + \text{h.c.}$$

$$\Gamma(N_1 \to L\eta) = \frac{1}{2M_1}\int \frac{d^3p_1}{(2\pi^3)}\frac{1}{2E_1}\frac{d^3p_2}{(2\pi^3)}\frac{1}{2E_2}|\mathcal{M}_{\text{lowest}} + \mathcal{M}_{\text{1-loop}}|^2(2\pi)^4\delta^4(p_N - p_1 - p_2)$$

$$= |h_{\alpha i}|^2 I_{\text{tree}} + h^*_{\alpha i}h_{\alpha j}h^*_{\beta j}h_{\beta i}I_{N_i N_j} + (h^*_{\alpha i}h_{\alpha j}h^*_{\beta j}h_{\beta i}I_{N_i N_j})^* + |h_{\alpha j}h^*_{\beta j}h_{\beta i}|^2 I_{\text{1-loop}}$$



$$\Gamma(N_1 \to \bar{L}\eta^\dagger) = |h_{\alpha i}|^2 I_{\text{tree}} + h_{\alpha i}h^*_{\alpha j}h_{\beta j}h^*_{\beta i}I_{N_i N_j} + (h_{\alpha i}h^*_{\alpha j}h_{\beta j}h^*_{\beta i}I_{N_i N_j})^* + |h^*_{\alpha j}h_{\beta j}h^*_{\beta i}|^2 I_{\text{1-loop}}$$



干渉項からCP非対称の部分が現れるのはなぜ？

CPの破れの大きさ $\epsilon_1^\alpha = \dfrac{\Gamma\left(N_1 \to L_\alpha \eta\right) - \Gamma\left(N_1 \to \bar{L}_\alpha \eta^\dagger\right)}{\sum_\alpha \left[\Gamma\left(N_1 \to L_\alpha \eta\right) + \Gamma\left(N_1 \to \bar{L}_\alpha \eta^\dagger\right)\right]}$

$$\begin{aligned}\Gamma(N_1 \to L\eta) - \Gamma(N_1 \to \bar{L}\eta^\dagger) &= 2i\, Im[h^*_{\alpha i} h_{\alpha j} h^*_{\beta j} h_{\beta i} I_{N_i N_j}] - 2i\, Im[h_{\alpha i} h^*_{\alpha j} h_{\beta j} h^*_{\beta i} I^*_{N_i N_j}] \\ &= 4\, Im[h^*_{\alpha i} h_{\alpha j} h^*_{\beta j} h_{\beta i}]\, Im[I_{N_i N_j}]\end{aligned}$$

- treeの振幅の二乗、1-loopの振幅の二乗は残らない
- 湯川結合定数が複素数であれば、干渉項からCPの破れの寄与が現れる

$10^{12}\mathrm{GeV}$ からフレーバー効果が効くのはなぜ？

反応率とハッブルパラメータとの比 $\Gamma/H(T)$

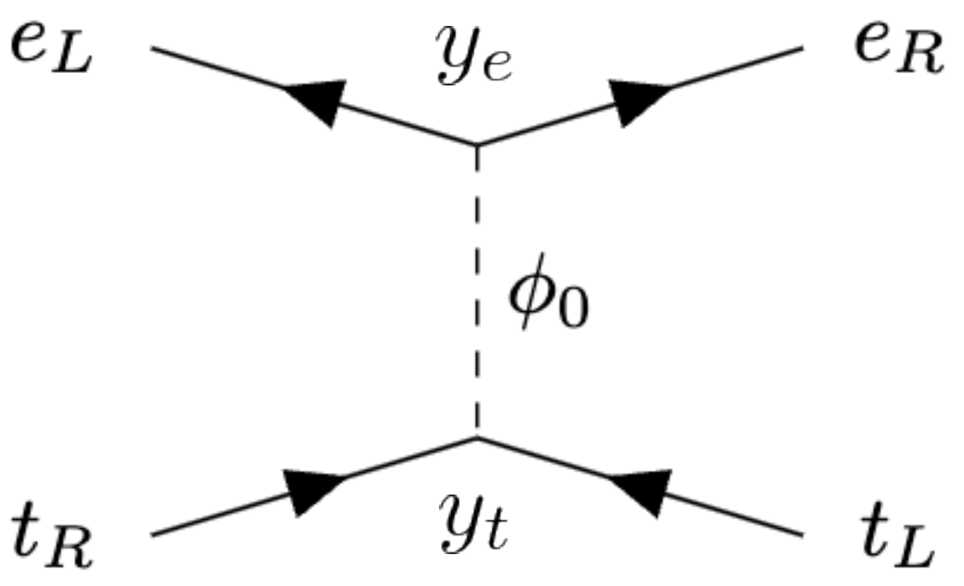
$\Gamma/H(T) < 1$ → 宇宙膨張の効果が反応率よりも大きく、反応は起きない

$\Gamma/H(T) > 1$ → 宇宙膨張の効果より反応率が大きく、反応が起こる

宇宙が温度Tのとき
ある反応が起こるか
どうかの指標

例. ヒッグスとレプトンの湯川相互作用の反応率

$$\frac{n_t \langle \sigma v \rangle}{H} \sim \frac{T^3 \cdot y_t^2\, y_e^2\, \frac{1}{T^2}}{1.66 g_*^{1/2} \frac{T^2}{m_{pl}}} \sim 0.49\, y_e^2\, \frac{10^{18} GeV}{T}$$



⇒

$$\frac{\Gamma_e}{H} \sim \frac{10^6 GeV}{T} \qquad (\ell = e)$$

$$\frac{\Gamma_\mu}{H} \sim \frac{10^9 GeV}{T} \qquad (\ell = \mu)$$

$$\frac{\Gamma_\tau}{H} \sim \frac{10^{12} GeV}{T} \qquad (\ell = \tau)$$