

# Leptogenesis with small violation of $B - L$

Juan Diego Racker

In collaboration with Manuel Peña and Nuria Rius

IFIC - Universidad de Valencia

# Outline of the talk:

- Introduction to leptogenesis.
- Motivation for models with small violation of  $L$ .
- Leptogenesis with small violation of  $L$ .
- Conclusions.

# The mystery of the matter-antimatter asymmetry

Observations:

(a) **The Universe is globally asymmetric**: the amount of antimatter is negligible with respect to the amount of matter.

◆ Cosmic rays from the sun.

◆ Planetary probes.

◆ Galactic cosmic rays.

◆ BESS-Polar experiment  $\longrightarrow \frac{\overline{He}}{He} < 1 \times 10^{-7}$ .

◆ Absence of strong  $\gamma$ -ray flux from nucleon-antinucleon annihilations in clusters of Galaxies (like Virgo cluster).

$\implies$  Matter and antimatter domains should be larger than 20 Mpc.

[Steigman 1976]

Actually they must be larger than  $\sim$  the visible Universe ( **cosmic diffuse  $\gamma$ -ray background** ) . [Cohen, De Rújula, Glashow 1998]

(b) **Baryon density**

◆ Big Bang Nucleosynthesis.

The abundances of the light elements D,  $^3\text{He}$ ,  $^4\text{He}$ , and  $^7\text{Li}$  depend mainly on one parameter,  $n_B/n_\gamma$ .

◆ CMB anisotropies.

$$Y_B \equiv \frac{n_B - n_{\bar{B}}}{s} = \frac{n_B}{s} \simeq 9 \times 10^{-11}$$

## The annihilation catastrophe

Nucleons and antinucleons remain in chemical equilibrium until

$\Gamma_{ann} < H$ , which occurs at

$$T_{fo} \sim 22 \text{ MeV}$$

If the Universe was locally-baryon-symmetric, then

$$Y_{Bfo} \sim 7 \times 10^{-20} \quad !!!$$

Conclusion: There was a baryon asymmetry at  $T \sim O(10^2) \text{ MeV}$ .

Origin?



~~initial conditions~~ or dynamic generation

## Sakharov's conditions

In 1967 Sakharov showed which are the basic conditions to dynamically generate a baryon asymmetry:

- **Baryonic number ( $B$ ) violation**
- **$C$  and  $CP$  Violation**
- **Departure from thermal equilibrium**

## Is baryogenesis possible in the SM?

- **$B$  violation:** Yes  $\rightarrow$  *sphalerons* (violate  $B + L$  but conserve  $B - L$ ).
- **$C$  violation:** Yes
- **$CP$  Violation:** Not enough  $\rightarrow J_{CP}/T_c^{12} \sim 10^{-18}$
- **Departure from thermal equilibrium:** No  $\rightarrow m_H > 114\text{GeV}$   
implies that the EW phase transition is not strongly first order.

Conclusion: physics beyond the SM is needed to explain the origin of the cosmic asymmetry.

# Leptogenesis

## The connection between two mysteries

- Why is there more matter than antimatter?
- Neutrino masses: In the SM neutrinos don't have mass but observations indicate that:

$$\Delta m_{21}^2 \equiv m_{\text{sol}}^2 \simeq 8 \times 10^{-5} \text{ eV}^2 ,$$

$$|\Delta m_{32}^2| \equiv m_{\text{atm}}^2 \simeq 2,5 \times 10^{-3} \text{ eV}^2 ,$$

$$m_i \lesssim 2 \text{ eV (tritium decay) ,}$$

$$m_i \lesssim 0,5 - 1 \text{ eV (cosmology) .}$$

Why are neutrino masses so tiny?



There's a simple and natural extension of the SM that can solve both mysteries:

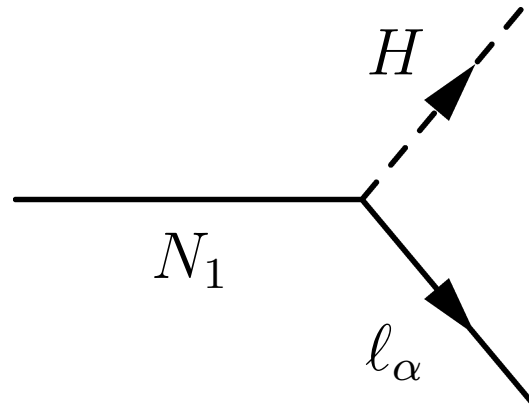
$$\mathcal{L} = \mathcal{L}_{\text{ME}} + i\bar{N}_i \not{\partial} N_i - \frac{1}{2} M_i \bar{N}_i N_i - \lambda_{\alpha i} \tilde{H}^\dagger \bar{N}_i \ell_\alpha - \lambda_{\alpha i}^* \bar{\ell}_\alpha N_i \tilde{H} ,$$

with  $H = (H^+, H^0)^T$  and  $\tilde{H} = i\tau_2 H^*$  .

Some heavy Majorana singlet neutrinos  $N_i$  are added to the particle content of the SM. The Lagrangian is that of the SM minimally extended to include the (type I) **seesaw** mechanism.

# Baryogenesis through Leptogenesis:

- $B$ : Sphalerons +  $L$  violation due to the Majorana nature of the heavy neutrinos.
- $\mathcal{C}$  and  $\mathcal{CP}$ : The relevant  $CP$  violation comes from the complex Yukawa couplings  $\lambda_{\alpha i}$ .
- **Departure from thermal equilibrium:** The source of the equilibrium departure is the expansion of the Universe.



$$\Gamma_{N_1} = \frac{1}{8\pi} (\lambda^\dagger \lambda)_{11} M_1$$

The  $N_1$  decay out of equilibrium when  $\Gamma_{N_1} \lesssim H(T = M_1)$ .

# The main parameters

- $M_1$  → Determines the leptogenesis epoch ( $T \sim M_1$ ).
- $\epsilon$  → CP violation.

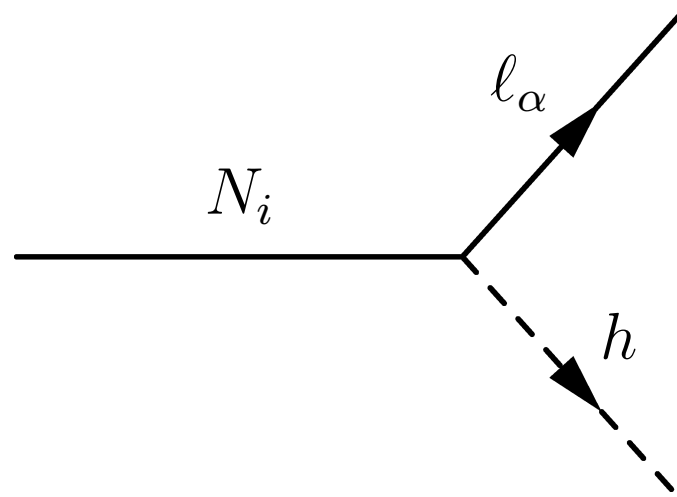
$$\epsilon_f^i \equiv \frac{\gamma(i \rightarrow f) - \gamma(\bar{i} \rightarrow \bar{f})}{\gamma(i \rightarrow f) + \gamma(\bar{i} \rightarrow \bar{f})} \quad \xrightarrow{\text{for decays}}$$

$$\epsilon = \sum_{\alpha} \epsilon_{\alpha} = \sum_{\alpha} \frac{\gamma(N_1 \rightarrow H\ell_{\alpha}) - \gamma(N_1 \rightarrow \bar{H}\bar{\ell}_{\alpha})}{\sum_{\beta} \gamma(N_1 \rightarrow H\ell_{\beta}) + \gamma(N_1 \rightarrow \bar{H}\bar{\ell}_{\beta})}$$

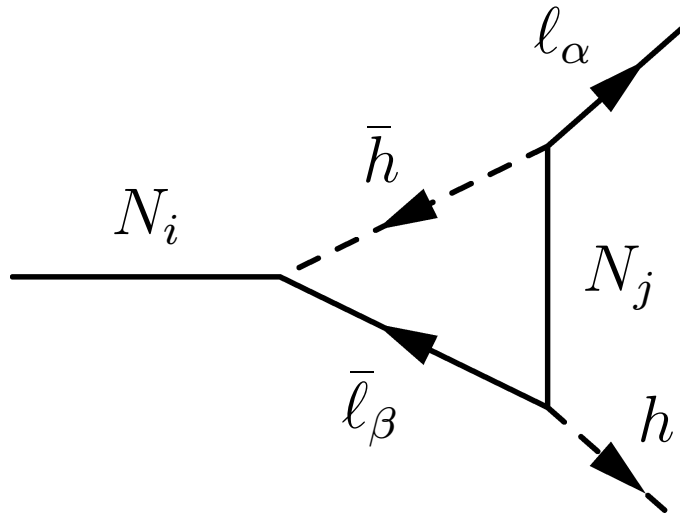
- $\tilde{m}_1$  (**effective mass**) → Departure from equilibrium.

It is the decay width conveniently normalized:  $\tilde{m}_1 \equiv \frac{(\lambda^{\dagger}\lambda)_{11}v^2}{M_1}$ .

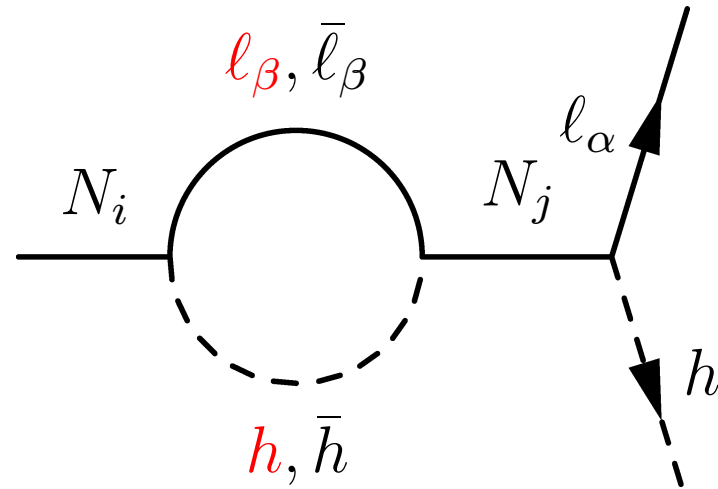
# CP violation in decays



(a) Tree



(b) Vertex



(c) Wave

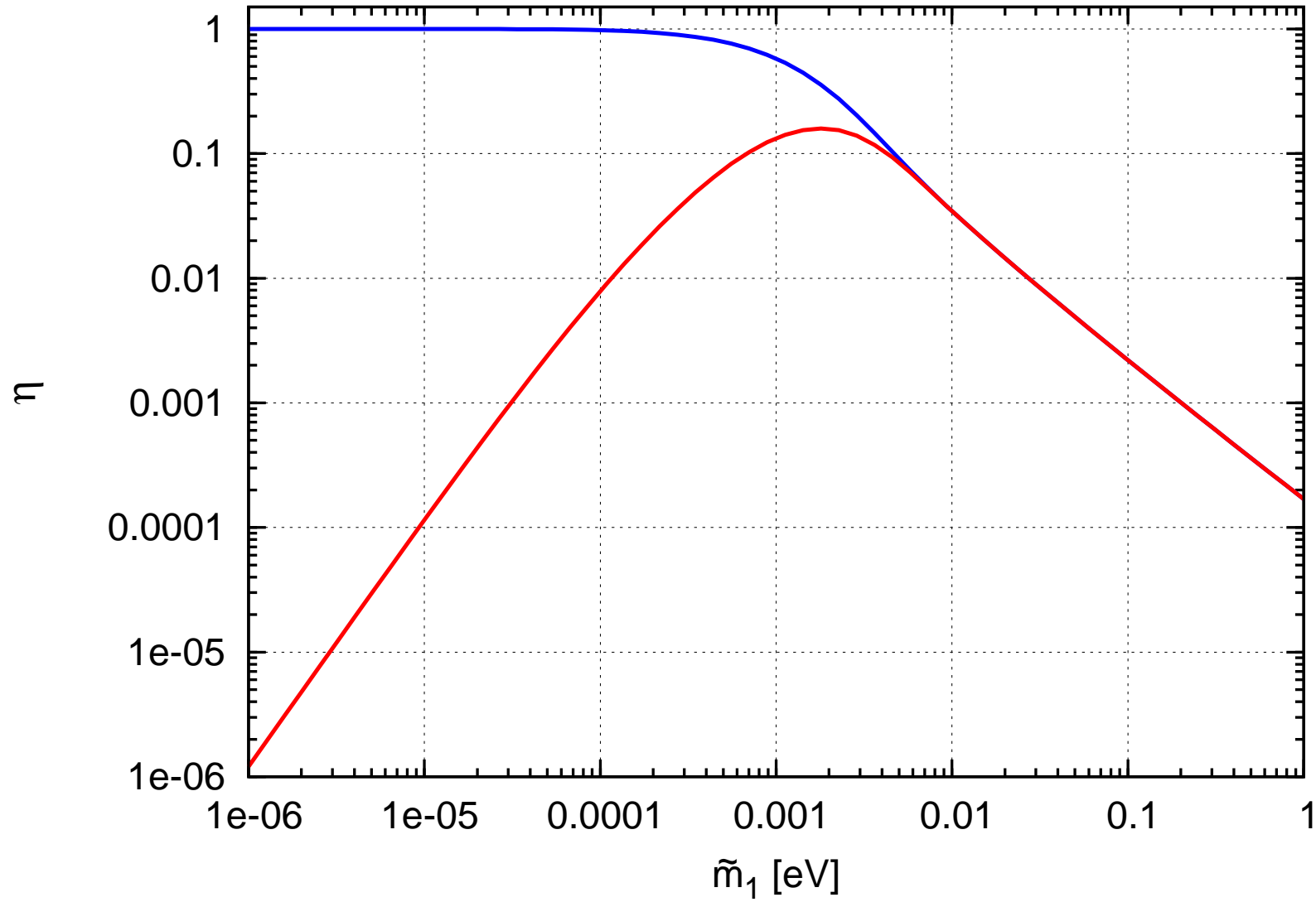
The evolution of  $Y_B$  can be obtained with an appropriate set of Boltzmann equations.

For a constant  $\epsilon$  (usually a good approximation),

$$Y_B^f = -\kappa \epsilon \eta$$

with  $\eta = \textit{efficiency}$ ,  $\kappa = \frac{28}{79} Y_N^{eq}(T \gg M_1) \sim 10^{-3}$ .

$\eta$  is mainly a function of  $\tilde{m}_1$ .



—  $Y_N^i = 0$

—  $Y_N^i = Y_N^{eq}$

# Connection with low energy observables

$$Y_B^f = -\kappa \epsilon \eta, \quad \text{main parameters } M_1, \epsilon, \tilde{m}_1$$

$$\epsilon \underset{\sim}{\overset{\text{(hierarchical)}}{}} \frac{3}{16\pi} \lambda_{\square 2}^2 M_1 / M_2 \quad \underset{\sim}{\overset{\text{(type I seesaw)}}{}} \frac{3}{16\pi} m_i M_1 / v^2$$

$$|\epsilon| \leq \epsilon_{\text{max}}^{\text{DI}} = \frac{3}{16\pi} \frac{M_1}{v^2} (m_3 - m_1)$$

(see also [T. Hambye, Y. Lin, A. Notari, M. Papucci, A. Strumia 2003])

$$\eta \leq 1 \implies M_1 \gtrsim 10^9 \text{ GeV} \quad (\text{gravitino problem} \rightarrow T_{rh} \lesssim 10^7 \text{ TeV})$$

$$\tilde{m}_1 \geq m_1,$$

$$\text{neglecting phases } \tilde{m}_1 \sim \sum_i m_i \gtrsim \sqrt{m_{\text{atm}}^2} \simeq 0,05 \text{ eV} \sim m_*!$$

$$m_1 \lesssim \text{few eV} \quad (0,15 \text{ eV}) \quad \text{flavored (unflavored)}$$

The simplest models will be very difficult to test.

Current research on:

- Falsifying Leptogenesis

[J. M. Frère, T. Hambye, G. Vertongen 2008]

[D. Aristizabal Sierra, J. F. Kamenik, M. Nemevsek 2010]

[A. Ibarra, C. Simonetto 2009]

- Low energy leptogenesis

If there is a pair of very **degenerate neutrinos** the CP asymmetry is resonantly enhanced,

$$\text{when } M_2 - M_1 \sim \frac{\Gamma_{N_2}}{2}, \quad |\epsilon| \sim \frac{1}{2} \frac{\text{Im} [(\lambda^\dagger \lambda)_{21}^2]}{(\lambda^\dagger \lambda)_{11} (\lambda^\dagger \lambda)_{22}} \leq \frac{1}{2}$$

The energy scale can be lowered up to the TeV range.

Even so ...



## Type I Seesaw

The mass matrix of the neutral sector in the basis  $\nu_L, N_R^c$  is

$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix},$$

with  $m_D = v\lambda$ .

The mass matrix for the light neutrinos is

$$m_\nu = m_D M^{-1} m_D^T \sim m_D \left( \frac{m_D}{M} \right)$$

and the mixing between active and sterile neutrinos is

$$\text{mixing} \sim \frac{m_D}{M} \sim \sqrt{\frac{m_\nu}{M}} \ll 1$$

# Models with small violation of $B - L$

Models with  $\approx L$  conservation are an interesting alternative.

## Inverse seesaw

Particle content: SM +  $\nu_{R_i}, s_{L_i}$  (singlet fermions).

The mass matrix of the neutral sector in the basis  $\nu_L, \nu_R^c, s_L$  is

$$\mathcal{M} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

$$m_\nu = m_D M^{T-1} \mu M^{-1} m_D^T \sim m_D \left( \frac{\mu}{M} \right) \left( \frac{m_D}{M} \right) \quad (m_D, \mu \ll M)$$

$\nu_{R_i}, s_{L_i}$  combine to form quasi-Dirac fermions with mass  $\sim M$ .

$$\text{mixing} \sim \frac{m_D}{M} \sim \sqrt{\frac{m_\nu}{\mu}}$$

More generally, if  $B - L$  is only slightly violated, then each singlet  $N_i$  satisfies (i) or (ii):

(i)  $N_i$  is a **Majorana** neutrino with  $\lambda_{\alpha i} \ll 1$ .

(ii) The  $N_i$  is a **Dirac** or **quasi Dirac** neutrino,  $\lambda_{\alpha i}$  can be **large**.

This means that there are two Majorana neutrinos  $N_{ih}$  and  $N_{il}$  with masses  $M_i + \mu_i$  and  $M_i - \mu_i$ , such that the Yukawa couplings are given by

$$\mathcal{L}_{Y_{N_i}} = -\lambda_{\alpha i} \tilde{H}^\dagger P_R \frac{N_{ih} + iN_{il}}{\sqrt{2}} \ell_\alpha + h.c.$$

$$- \lambda'_{\alpha i} \tilde{H}^\dagger P_R \frac{N_{ih} - iN_{il}}{\sqrt{2}} \ell_\alpha + h.c. \quad \text{with} \quad \lambda'_{\alpha i} \ll 1$$

# Leptogenesis with small violation of $B - L$

$N_1 \equiv$  The one that generates the largest lepton asymmetry.

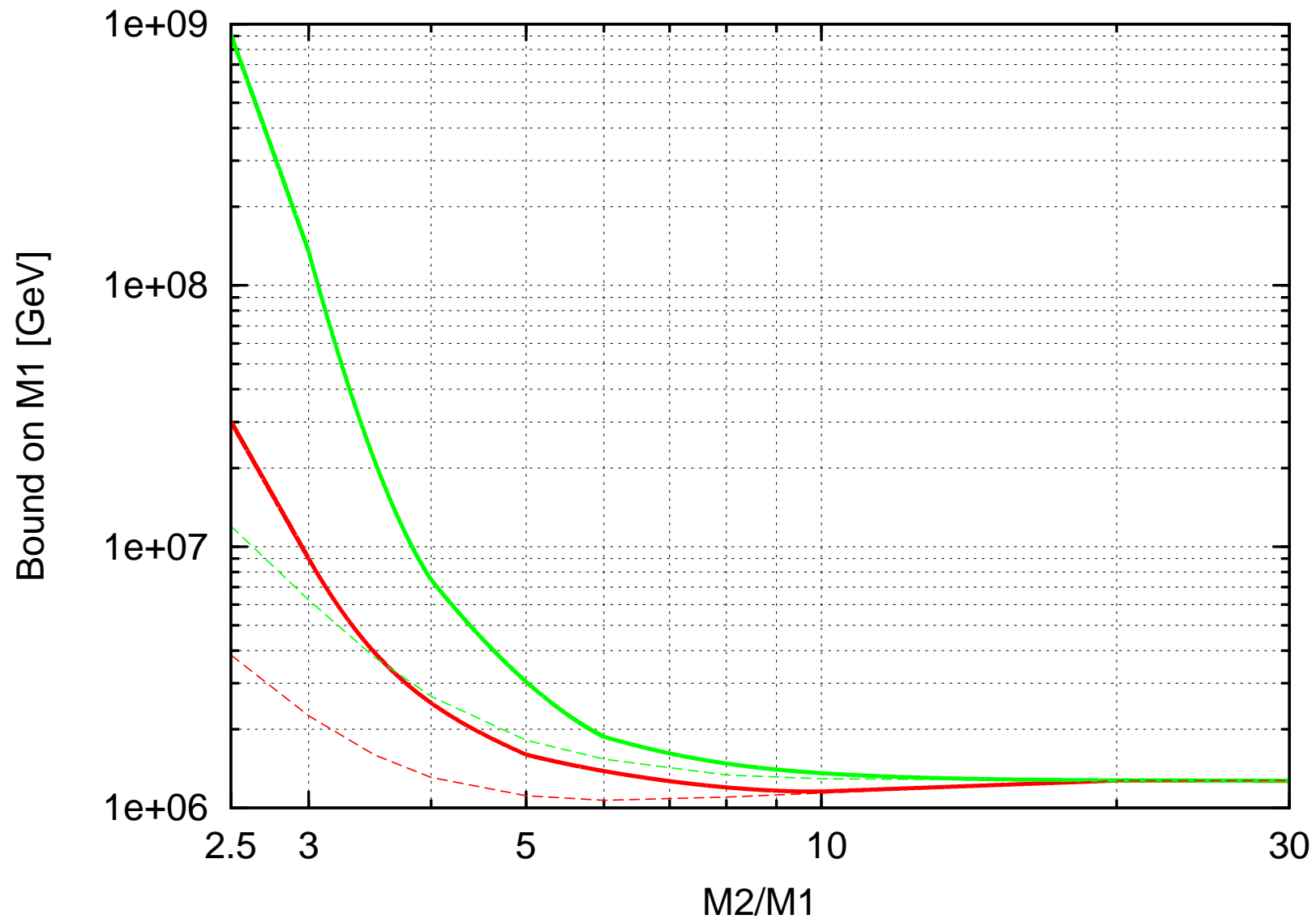
$N_2 \equiv$  The one that makes the most important contribution to  $\epsilon_\alpha$ .

Our analysis includes:

- Different combinations of possibilities, (i) or (ii), for  $N_1$  and  $N_2$ .
- Full scan of the parameter space, with 2 cases for quasi Dirac  $N_i$ :
  - ◆  $\mu_i \ll \Gamma_{N_i}$  (Dirac limit),
  - ◆  $\mu_i \gg \Gamma_{N_i}$  (Majorana limit).
- $\epsilon_\alpha = \epsilon_\alpha^{\cancel{L}} + \epsilon_\alpha^L = O(\mu_2) + \epsilon_\alpha^L \implies \epsilon = \sum_\alpha \epsilon_\alpha = O(\mu_2)$ . However,  $Y_B$  is generally not suppressed by  $\mu_2$  (flavor effects). It's crucial to:
  - ◆ Take into account flavor changing interactions.
  - ◆ Find the regions of param. space for 2 and 3-flavor regimes.

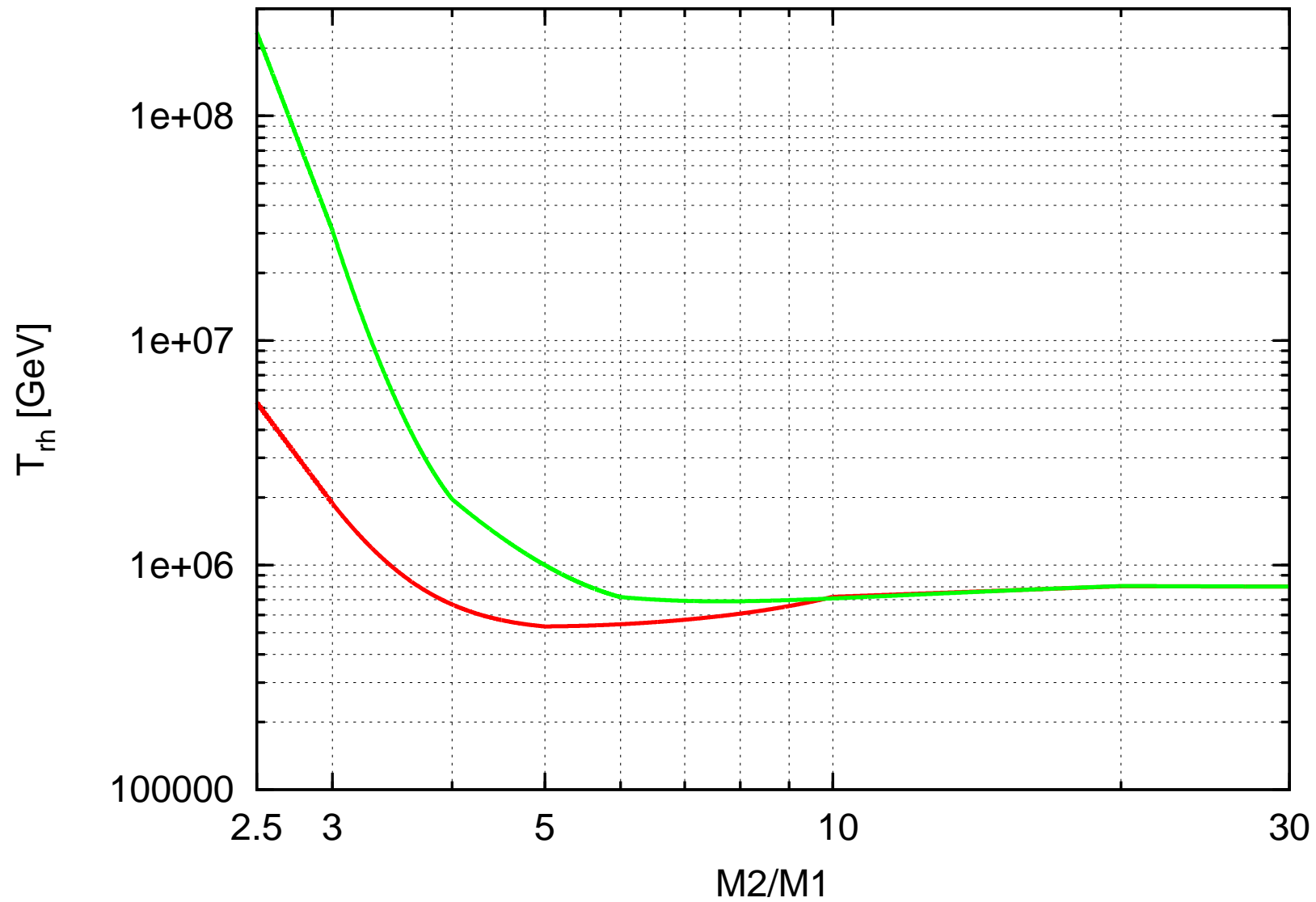
Also [T. Asaka, S. Blanchet 2008],[S. Antusch, S. Blanchet, M. Blennow, E. Fernandez-Martinez 2009],

[M. C. Gonzalez-Garcia, J. R., N. Rius 2009],[S. Blanchet, T. Hambye, and F.-X. Josse-Michaux 2009].



—  $\mu_2 \gg \Gamma_{N_2}$

—  $\mu_2 \ll \Gamma_{N_2}$



—  $\mu_2 \gg \Gamma_{N_2}$       —  $\mu_2 \ll \Gamma_{N_2}$

## Light neutrino masses:

$$m_i \sim \frac{\lambda_{\square 1}^2 v^2}{M_1} + \mu_2 \frac{\lambda_{\square 2}^2 v^2}{M_2^2} + \lambda'_{\square 2} \lambda_{\square 2} v^2 / M_2 .$$

Taking  $m_i \sim m_{atm} \sim 0,05 \text{ eV}$ , we get

$$\lambda_{\alpha 1} \sim 10^{-5} - 10^{-4}, \quad \mu_2 / M_2 \sim 10^{-8} - 10^{-6}, \quad \lambda'_{\alpha 2} \sim 10^{-8} - 10^{-7} .$$

Moreover,

$$\Gamma_{N_2} / M_2 \sim 5 \times (10^{-4} - 10^{-2}) \quad \Rightarrow \quad (\text{typically}) \quad \mu_2 \ll \Gamma_{N_2}$$

**Note:** For  $M_1 \gtrsim 5 \times 10^6 \text{ GeV}$ , and still not considering large fine tunings related to phase cancellations, it is also possible to have  $\mu_2 \gtrsim \Gamma_{N_2}$ .

# Conclusions

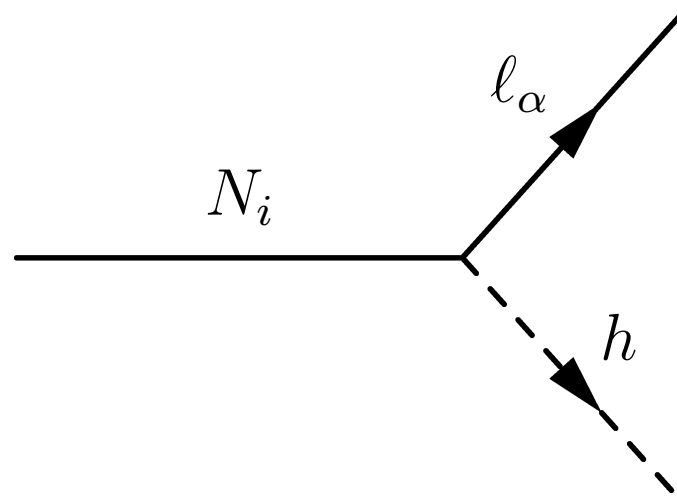
Models with small violation of  $B - L$  can:

- Explain naturally the smallness of neutrino masses without a big suppression of the active-sterile neutrino mixing.
- Generate the baryon asymmetry at  $T \sim 10^6$  GeV without a resonant enhancement of  $\epsilon_\alpha$  and independently of the initial conditions  $(Y_N, Y_{\Delta_\alpha})$ .
- . . . But not both!

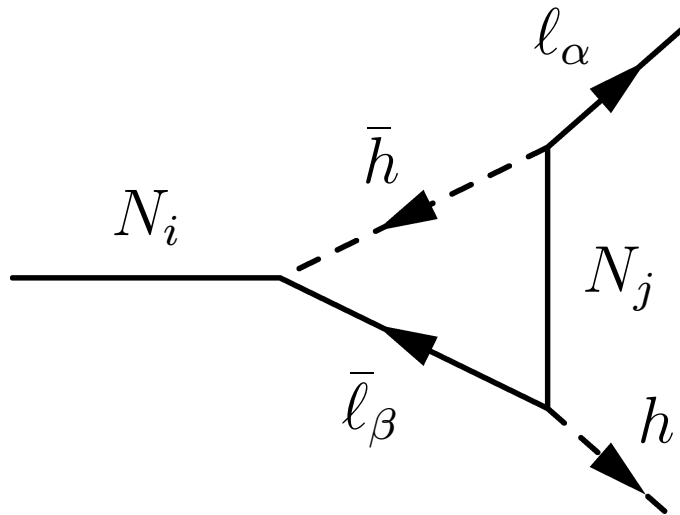




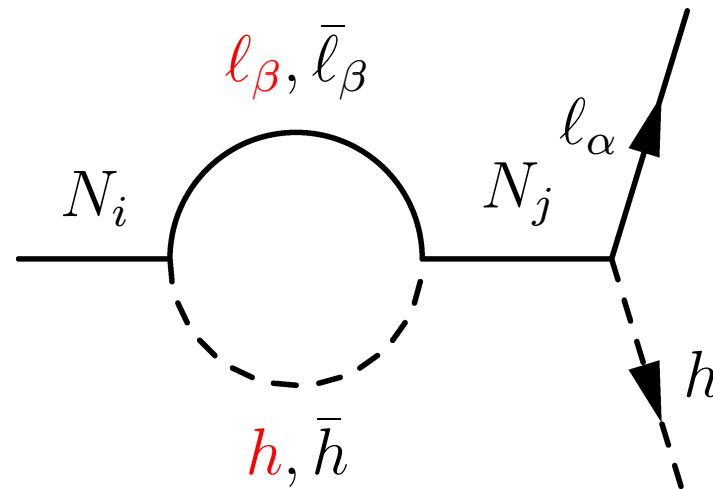
# CP violation in decays



(a) Tree



(b) Vertex



(c) Wave

$$\epsilon_{l_\alpha}^{N_i} = \epsilon_{l_\alpha}^{N_i}(\mathbf{vertex}) + \epsilon_{l_\alpha}^{N_i}(\mathbf{wave})$$

$$\epsilon_{l_\alpha}^{N_i}(\mathbf{vertex}) = \frac{1}{8\pi} \sum_j f(y_j) \frac{\text{Im} [\lambda_{\alpha j}^* \lambda_{\alpha i} (\lambda^\dagger \lambda)_{ji}]}{(\lambda^\dagger \lambda)_{ii}}$$

$$\epsilon_{l_\alpha}^{N_i}(\mathbf{wave}) = -\frac{1}{8\pi} \sum_{j \neq i} \frac{M_i}{M_j^2 - M_i^2} \frac{\text{Im} [(M_j (\lambda^\dagger \lambda)_{ji} + M_i (\lambda^\dagger \lambda)_{ij}) \lambda_{\alpha j}^* \lambda_{\alpha i}]}{(\lambda^\dagger \lambda)_{ii}}$$

with  $y_j \equiv M_j^2 / M_i^2$  and  $f(x) = \sqrt{x}(1 - (1 + x) \ln[(1 + x)/x])$ .

[Covi, Roulet, Vissani 1996]

# Boltzmann equations

Simple unflavored version:

$$\frac{dY_N}{dz} = -\frac{1}{zHs} \left( \frac{Y_N}{Y_N^{eq}} - 1 \right) \gamma_D$$
$$\frac{dY_L}{dz} = \frac{1}{zHs} \left\{ \epsilon \left( \frac{Y_N}{Y_N^{eq}} - 1 \right) \gamma_D - \frac{Y_L}{Y_L^{eq}} \frac{\gamma_D}{2} \right\}$$

with  $Y_x \equiv \frac{n_x}{s}$  and  $z \equiv \frac{M_1}{T}$ .

■  $\frac{dY_N}{dz} = -\frac{K(z)}{z} (Y_N - Y_N^{eq})$  with  $K(z) \sim \frac{\text{rates}}{H}$ .

■  $\frac{dY_L}{dz} = \text{source} - \text{washouts}$

**Source** = CP violation  $\times$  L violation  $\times$  departure from eq.

**Washouts** = asymmetries ( $Y_L$ )  $\times$  rates ( $\gamma$ ).

## The role of $\tilde{m}_1$

It determines the amount of departure from eq. and the intensity of the washouts.

Reference value given by the *equilibrium mass*  $m_*$  :

$$\frac{\Gamma_{N1}}{H(T = M_1)} = \frac{\tilde{m}_1}{m_*} ,$$

with  $m_* \simeq 1,08 \times 10^{-3} \text{ eV}$  .

■  $\tilde{m}_1 \gg m_*$   $\rightarrow$  *strong washout* regime:

- Independence from initial conditions.
- $\eta \propto \tilde{m}_1^{-1}$  ( $Y_L \sim \text{source/wo} \sim (\epsilon dY_N^{eq}/dz)/\text{wo}$ ) .

■  $\tilde{m}_1 \ll m_*$   $\rightarrow$  *weak washout* regime:

- Very dependent on initial conditions.
- If  $Y_N^i = 0 \rightarrow \eta \propto \cancel{\tilde{m}_1^1} \tilde{m}_1^2$  .

Is leptogenesis possible with  $\epsilon = 0$ ?

## Flavor effects

$$N_1 \rightarrow \ell_d H$$

- $T \gtrsim 10^{12}$  GeV: The Yukawa interactions of the charged leptons are out of equilibrium  
→  $\ell_d$  is the only relevant “direction” in flavor space.
- $T \lesssim 10^{12}$  GeV: The Yukawa interactions of the  $\tau$  (and eventually the  $\mu$ ) are in equilibrium  
→ they project  $\ell_d$  into the flavor eigenstates  $(\ell_\tau, \ell_\mu, \ell_e)$  → *decoherence*

Note: similarly for the antileptons, with  $N_1 \rightarrow \bar{\ell}'_d \bar{H}$

# Boltzmann equations

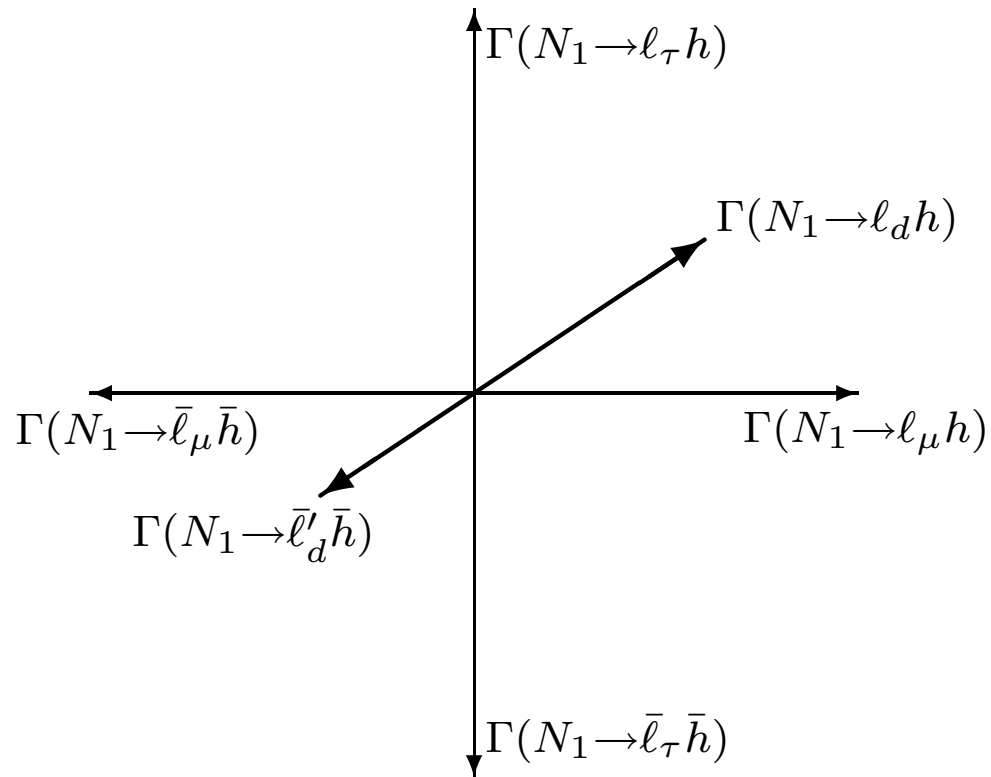
Define  $Y_{\Delta_\alpha} \equiv \frac{1}{3}Y_B - Y_{L_\alpha}$  ( $B/3 - L_\alpha$  is conserved by sphalerons)

$$\frac{dY_{\Delta_\alpha}}{dz} \approx f(z)\epsilon_\alpha - Y_{\Delta_\alpha}K_\alpha w(z) \quad (\alpha = e, \mu, \tau),$$

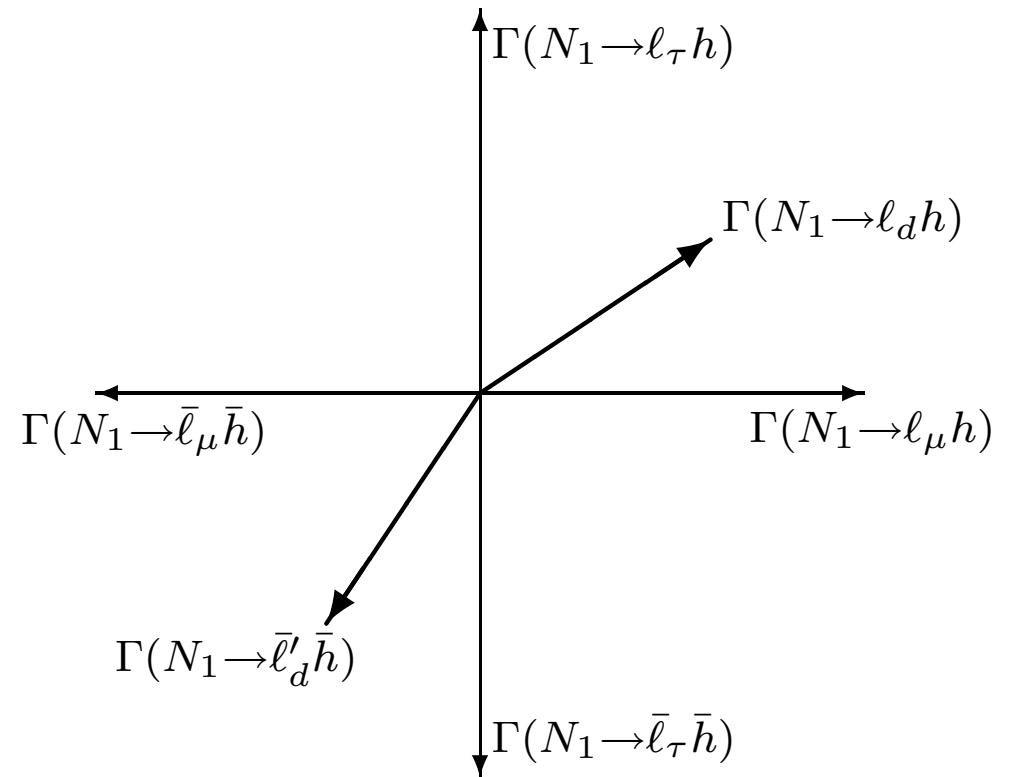
with  $z \equiv M_1/T$ ,  $K_\alpha \equiv |\langle \ell_\alpha | \ell_d \rangle|^2$

The asymmetries  $Y_{\Delta_\alpha}$  evolve (approximately) independently.

## Two types of CP violation

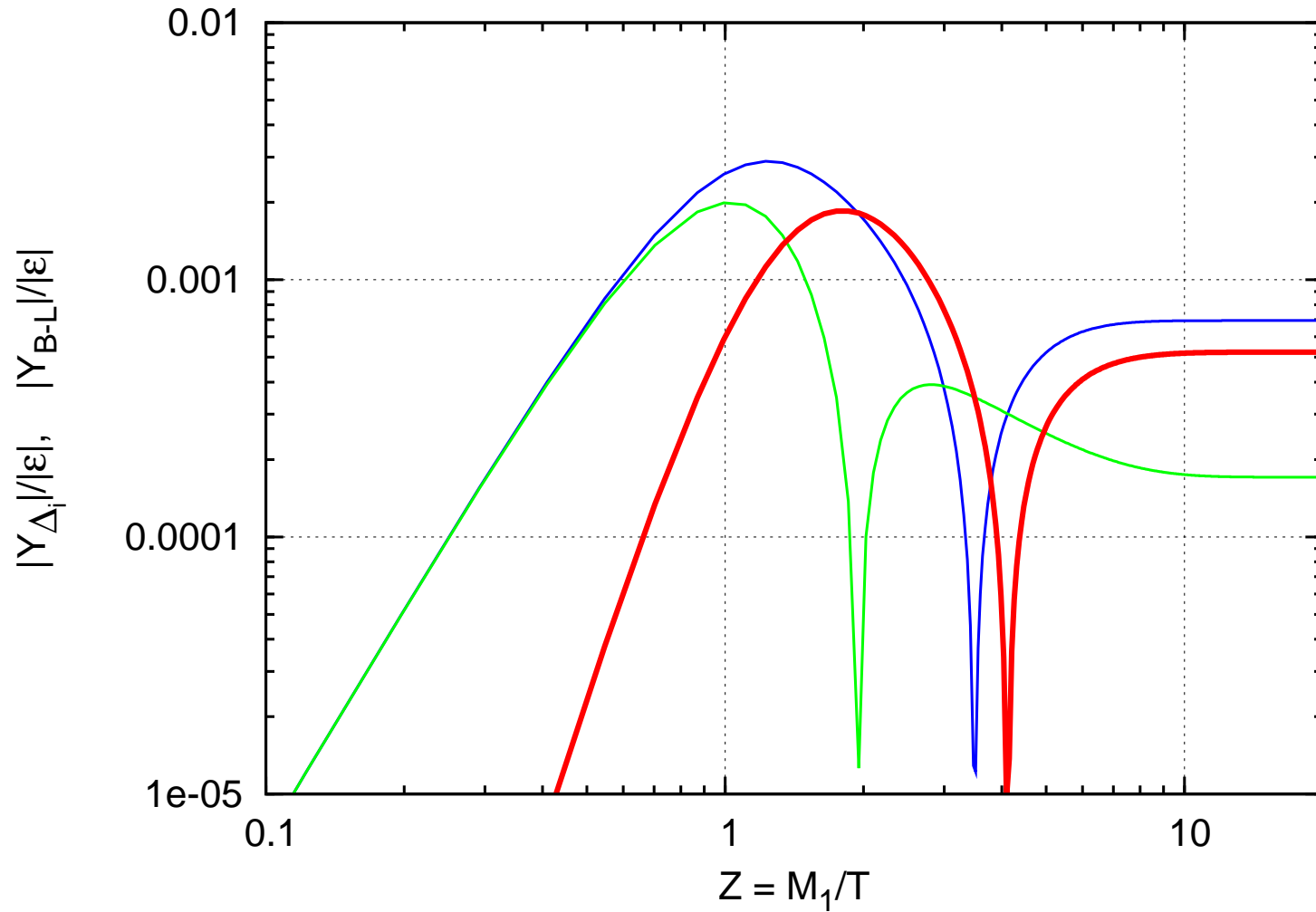


(a)  $l'_d = l_d, \epsilon \neq 0$



(b)  $\epsilon = 0, l'_d \neq l_d, \epsilon_\alpha \neq 0$





—  $|Y_{\Delta_\tau}/\epsilon_\tau|$     
—  $|Y_{\Delta_\mu}/\epsilon_\mu|$     
—  $|Y_{B-L}/\epsilon_\mu|$

$\epsilon_\tau = -\epsilon_\mu$      $K_\tau = 0,1$      $K_\mu = 0,9$      $\tilde{m}_1 = 0,01 \text{ eV}$

The relevant set of BE for the case  $\mu_2 \gg \Gamma_{N_2}$  is

$$\frac{dY_{N_1}}{dz} = \frac{-1}{sHz} \left( \frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1 \right) \gamma_{D_1} ,$$

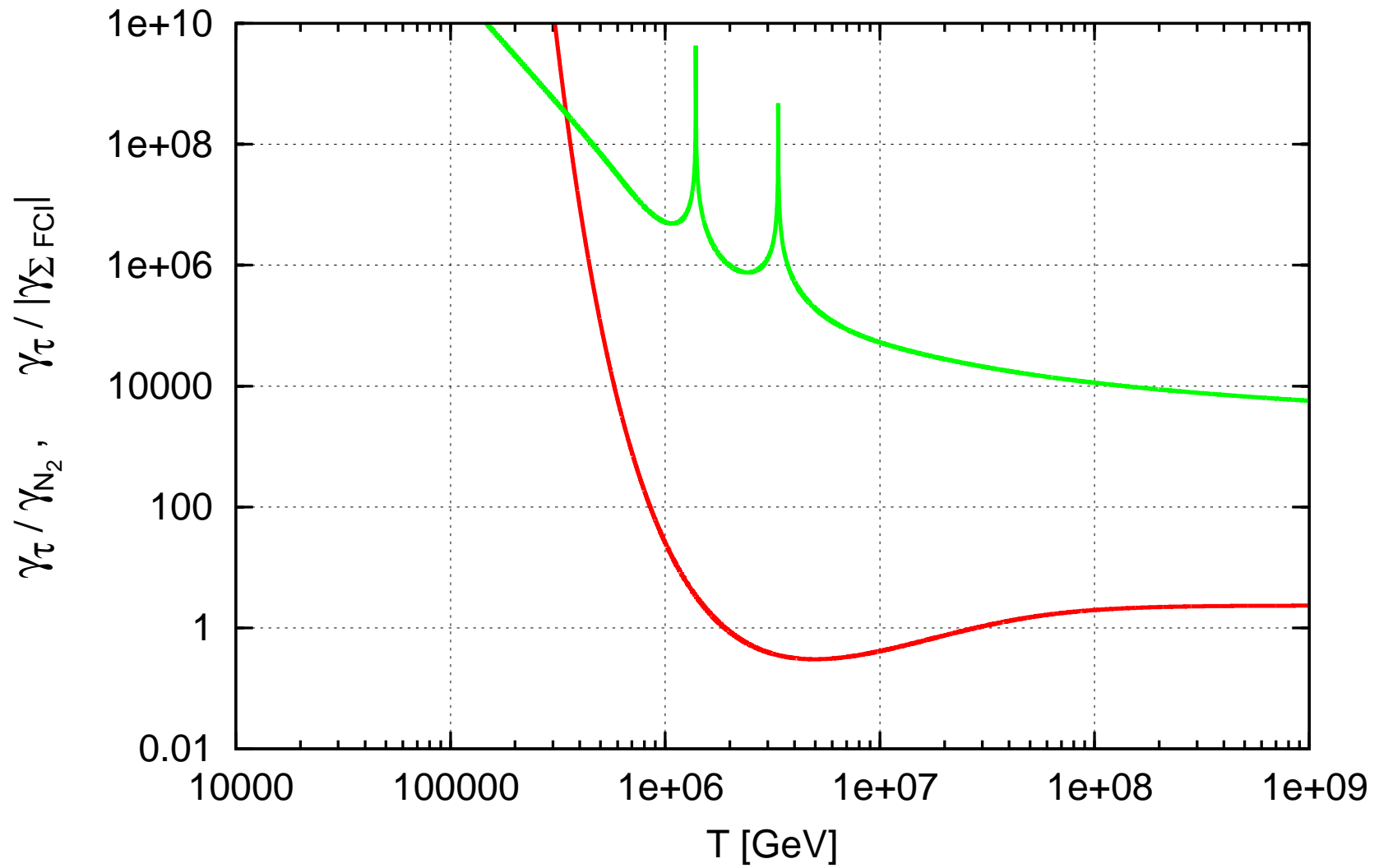
$$\frac{dY_{\Delta_\alpha}}{dz} = \frac{-1}{sHz} \left\{ \left( \frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1 \right) \epsilon_{\alpha 1} \gamma_{D_1} - \sum_i \gamma_{l_\alpha h}^{N_i} y_{l_\alpha} \right. \\ \left. - \sum_{\beta \neq \alpha} \left( \gamma_{l_\alpha h}^{l_\beta h'} + \gamma_{l_\alpha \bar{h}}^{l_\beta \bar{h}} + \gamma_{l_\alpha \bar{l}_\beta}^{h \bar{h}} \right) [y_{l_\alpha} - y_{l_\beta}] \right\} ,$$

where  $z \equiv M_1/T$ ,  $Y_X \equiv n_X/s$ ,  $y_X \equiv (Y_X - Y_{\bar{X}})/Y_X^{eq}$ , and  $Y_{\Delta_\alpha} \equiv Y_B/3 - Y_{L_\alpha}$ .

Instead, for  $\mu_2 \ll \Gamma_{N_2}$

$$\begin{aligned} \frac{dY_{N_1}}{dz} &= \frac{-1}{sHz} \left( \frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1 \right) \gamma_{D_1} , \\ \frac{dY_{N_2 - \bar{N}_2}}{dz} &= \frac{-1}{sHz} \sum_{\alpha} \gamma_{l_{\alpha} h}^{N_2} [y_{N_2} - y_{l_{\alpha}}] , \\ \frac{dY_{\Delta_{\alpha}}}{dz} &= \frac{-1}{sHz} \left\{ \left( \frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1 \right) \epsilon_{\alpha 1} \gamma_{D_1} - \gamma_{l_{\alpha} h}^{N_1} y_{l_{\alpha}} + \gamma_{l_{\alpha} h}^{N_2} [y_{N_2} - y_{l_{\alpha}}] \right. \\ &\quad \left. - \sum_{\beta \neq \alpha} \left( \gamma_{l_{\alpha} h}^{l_{\beta} h'} + \gamma_{l_{\alpha} \bar{h}}^{l_{\beta} \bar{h}} + \gamma_{l_{\alpha} \bar{l}_{\beta}}^{h \bar{h}} \right) [y_{l_{\alpha}} - y_{l_{\beta}}] \right\} . \end{aligned}$$

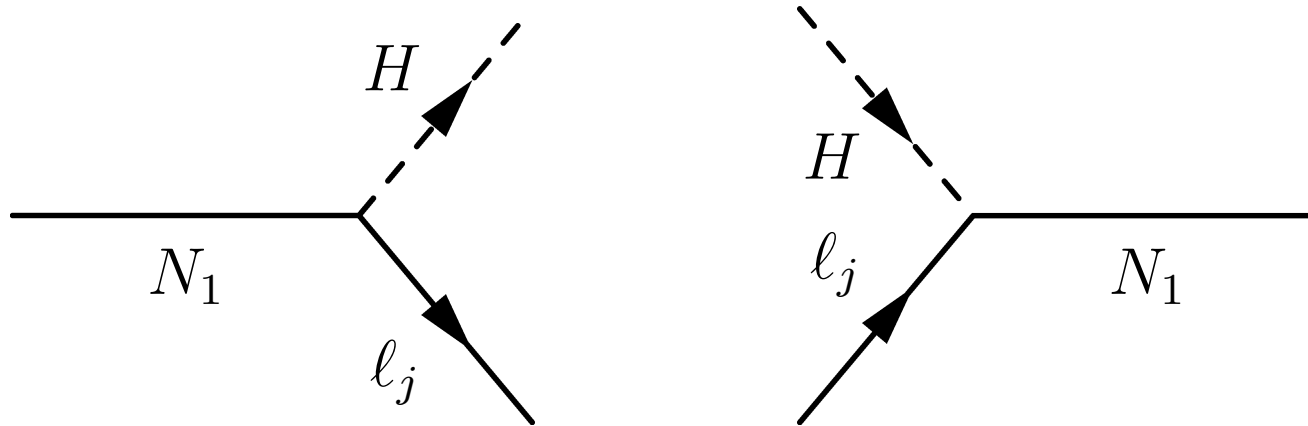
$$M_2 = 10^7 \text{ GeV}, (\lambda^\dagger \lambda)_{22} = 10^{-4}$$



—  $\gamma_\tau / \gamma_{N_2}$

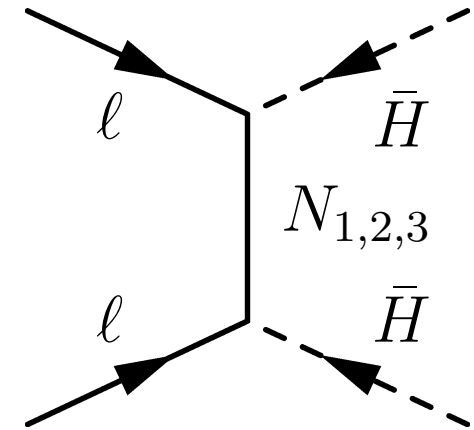
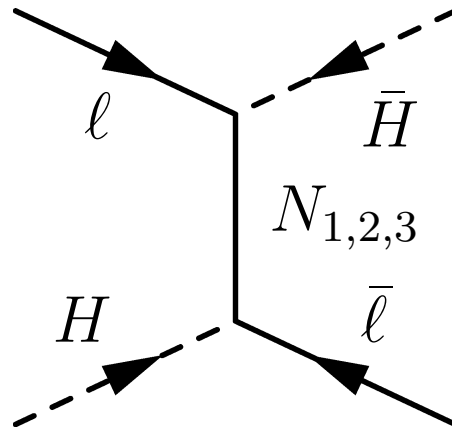
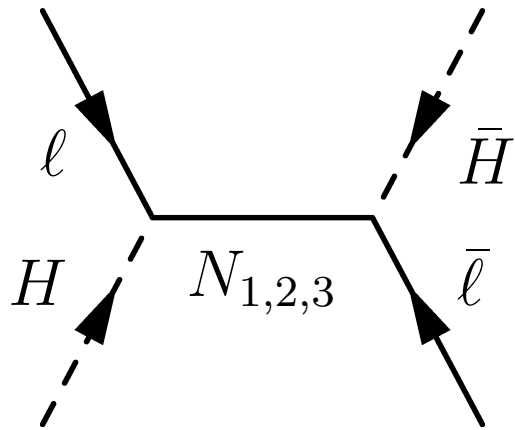
—  $\gamma_\tau / |\gamma_{\Sigma \text{FCI}}|$

## Relevant processes for $N_1$ -Leptogenesis

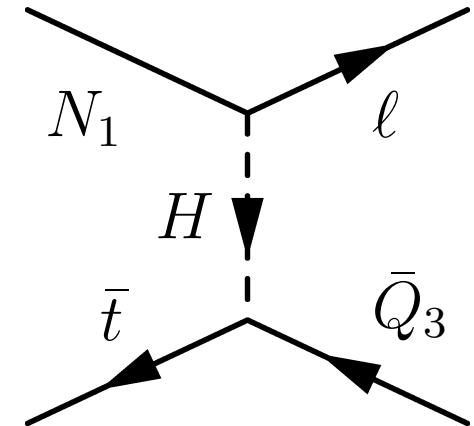
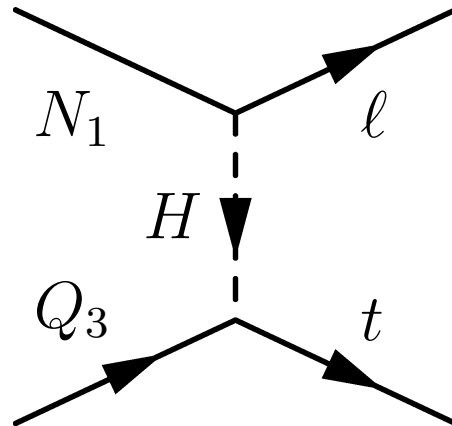
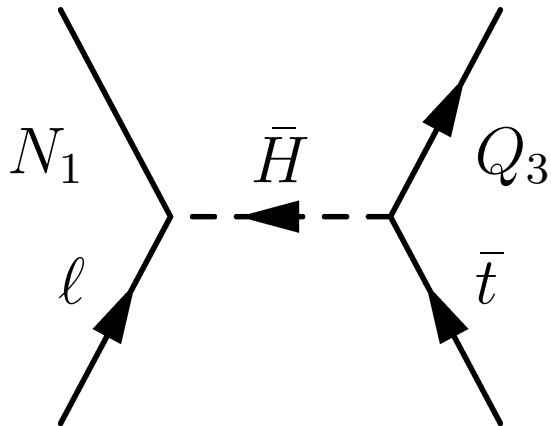


(c) Decay and inverse decay (production) of  $N_1$ .

$$\Gamma_{N_1} = \frac{1}{8\pi} (h^\dagger h)_{11} M_1 .$$



(d)  $\Delta L = 2$  scatterings mediated by  $N_{1,2,3}$ .



(e)  $\Delta L = 1$  scatterings mediated by the Higgs.