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.
- Neil Armstrong survived his "one small step".
- Planetary probes have also survived.
- Galactic cosmic rays.
- Absence of strong $\gamma-$ray flux from nucleon-antinucleon annihilations in clusters of Galaxies (like Virgo cluster).

$\Longrightarrow$ Matter and antimatter domains should be larger than 20 Mpc. [Steigman 1976]

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

... However these bounds are valid if antimatter makes the same type of objects as the observed matter, compact objects made of antimatter may be abundant even in our galaxy.

[Dolgov et al. 2009]

BESS experiment $\longrightarrow$ $\frac{\overline{He}}{He} < 2{,}7 \times 10^{-7}$.

(b) Local Baryon density

- Big Bang Nucleosynthesis.
  The abundances of the light elements D, ^{3}He, ^{4}He, and ^{7}Li depend mainly on one parameter, n_B/n_γ.
- CMB anisotropies.

$$\left.\frac{n_B - n_{\bar{B}}}{s}\right|_0 = \left.\frac{n_B}{s}\right|_0 = (8{,}82 \pm 0{,}23) \times 10^{-11}$$

The annihilation catastrophe

Nucleons and antinucleons remain in chemical equilibrium until $\Gamma_{ann} < H$, which occurs at

$$T_{fo} \sim 22 \text{ M}eV$$

If the Universe was locally-baryon-symmetric, then

$$Y_{B\,fo} \sim 7 \times 10^{-20} \quad !!!$$

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

Origin?

$\downarrow$

~~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 $\rightarrow$ $m_H > 114 GeV$ 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.

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:

$$\Delta m^2_{21} \equiv m^2_{\text{sol}} = (7{,}9 \pm 0{,}3) \times 10^{-5}\ \text{eV}^2\ ,$$

$$\left|\Delta m^2_{32}\right| \equiv m^2_{\text{atm}} = (2{,}6 \pm 0{,}2) \times 10^{-3}\ \text{eV}^2\ ,$$

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

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

Why are neutrino masses so tiny?

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

$$\mathcal{L} = \mathcal{L}_{\text{ME}} + i\overline{N}_\alpha \partial\!\!\!/ N_\alpha - \frac{1}{2} M_\alpha \overline{N}_\alpha N_\alpha - h_{i\alpha}\, \widetilde{H}^\dagger\, \overline{N}_\alpha \ell_i - h^*_{i\alpha} \overline{\ell}_i N_\alpha \widetilde{H}\ ,$$

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

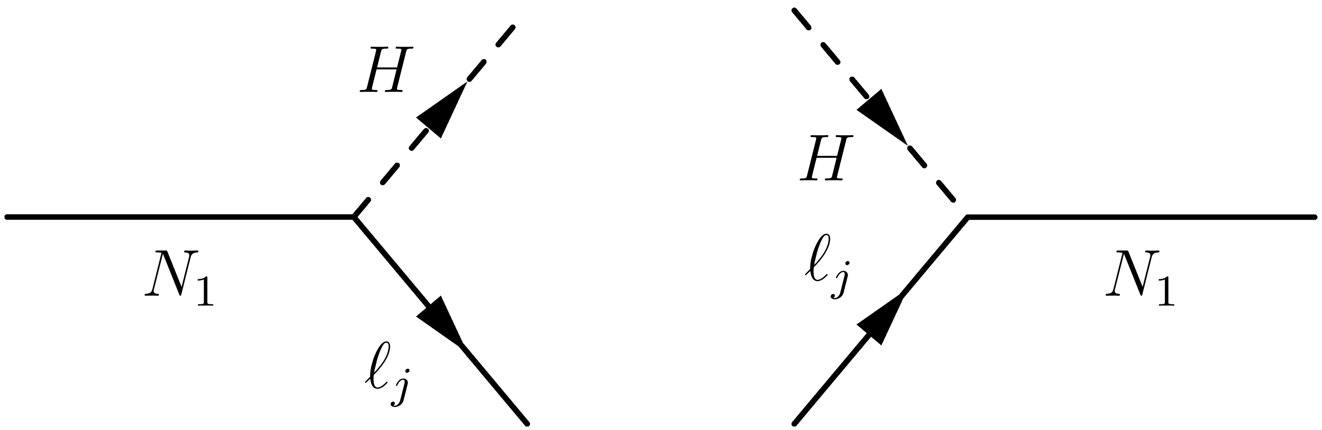
Some heavy Majorana singlet neutrinos N_α are added to the particle content of the SM. The Lagrangian is that of the SM minimally extended to include the (type I) seesaw mechanism.

Baryogenesis through Leptogenesis:

- $\not B$: Sphalerons + L violation due to the Majorana nature of the heavy neutrinos.
- $\not C$ and $\not C\not P$: The relevant CP violation comes from the complex Yukawa couplings $h_{i\alpha}$.
- Departure from thermal equilibrium: The source of the equilibrium departure is the expansion of the Universe.
  The N_1 decay out of equilibrium when

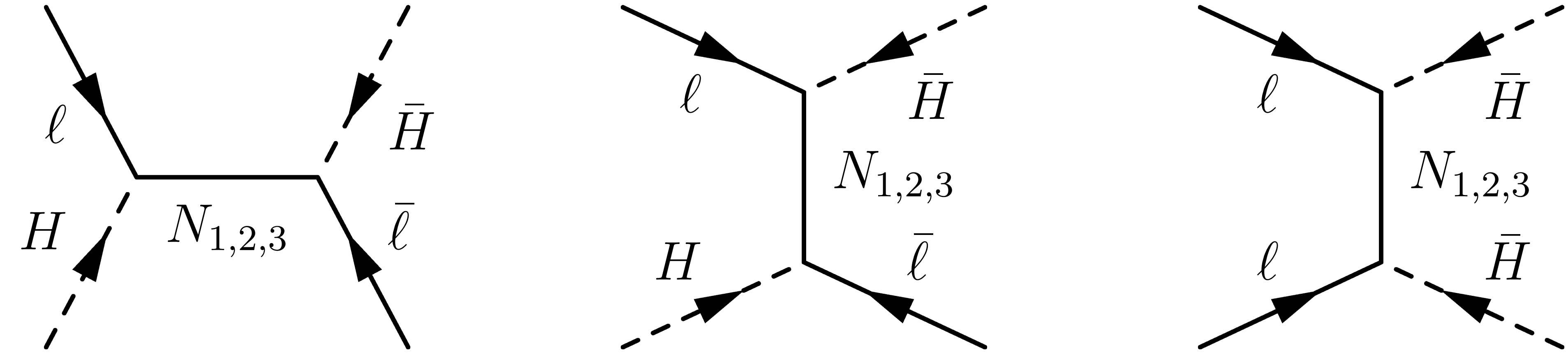
$$\Gamma_{N_1} \lesssim H(T = M_1) ,$$

Relevant processes for N_1–Leptogenesis

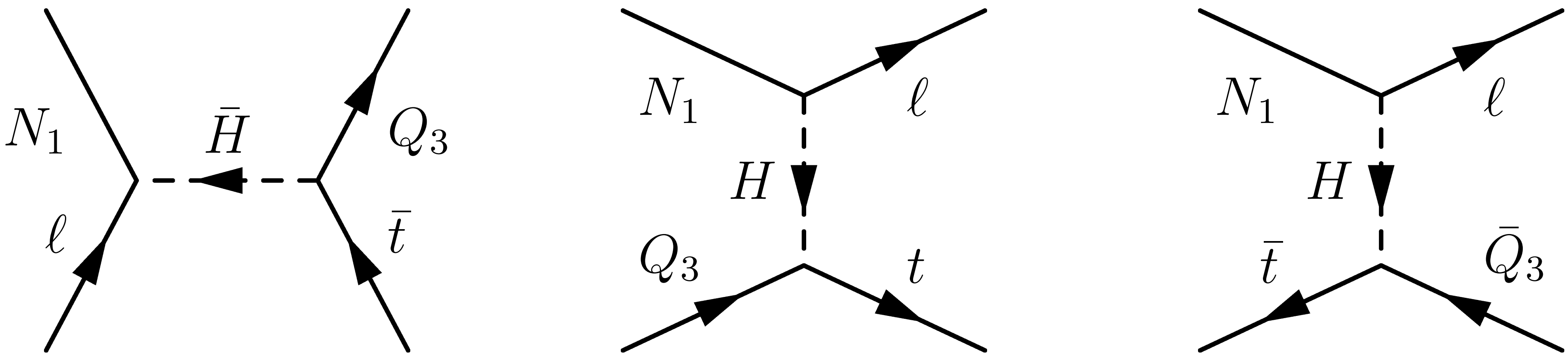


(a) Decay and inverse decay (production) of N_1.

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



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



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

The main parameters

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

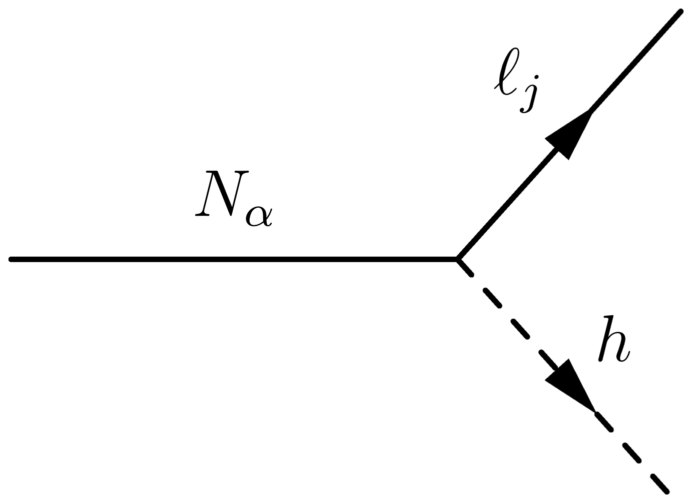
$$\epsilon_f^i \equiv \frac{\gamma(i \to f) - \gamma(\bar{i} \to \bar{f})}{\gamma(i \to f) + \gamma(\bar{i} \to \bar{f})} \quad \xrightarrow{\text{for decays}}$$

$$\epsilon = \sum_j \epsilon_j = \sum_j \frac{\gamma(N_1 \to H\ell_j) - \gamma(N_1 \to \bar{H}\bar{\ell}_j)}{\sum_k \gamma(N_1 \to H\ell_k) + \gamma(N_1 \to \bar{H}\bar{\ell}_k)}$$

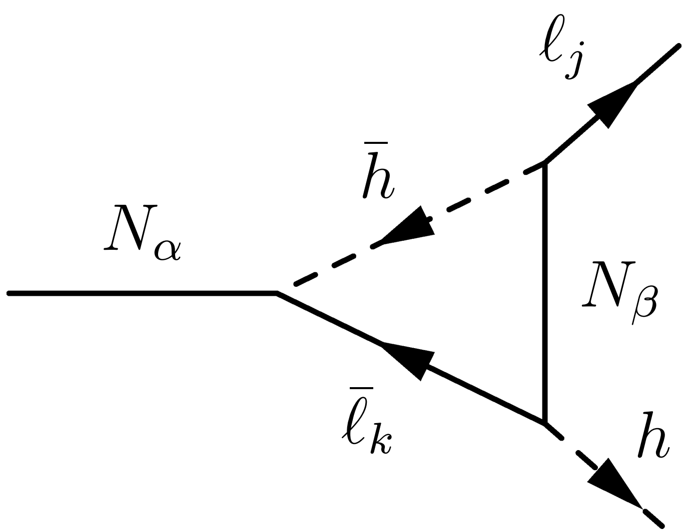
- $\tilde{m}_1$ (effective mass) $\;\longrightarrow\;$ Departure from equilibrium.

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

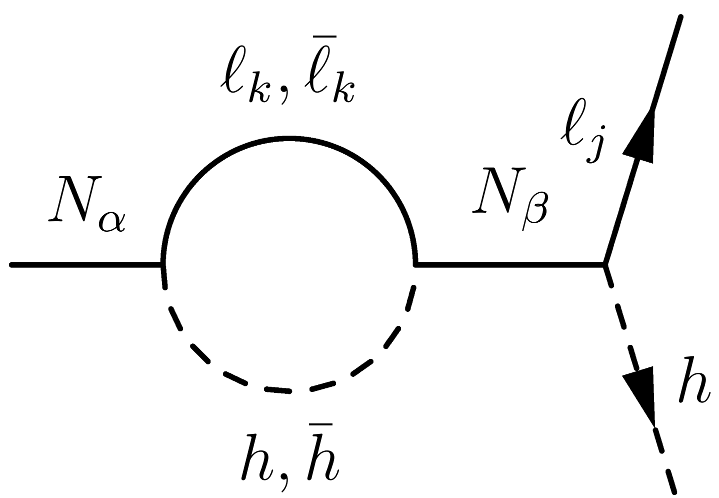
CP violation in decays



(a) Tree



(b) Vertex



(c) Wave

$$\epsilon_{\ell_j}^{N_\alpha} = \epsilon_{\ell_j}^{N_\alpha}(\text{vertex}) + \epsilon_{\ell_j}^{N_\alpha}(\text{wave})$$

$$\epsilon_{\ell_j}^{N_\alpha}(\text{vertex}) = \frac{1}{8\pi}\sum_{\beta} f(y_\beta)\frac{\text{Im}\left[h_{j\beta}^* h_{j\alpha}(h^\dagger h)_{\beta\alpha}\right]}{(h^\dagger h)_{\alpha\alpha}}$$

$$\epsilon_{\ell_j}^{N_\alpha}(\text{wave}) = -\frac{1}{8\pi}\sum_{\beta\neq\alpha}\frac{M_\alpha}{M_\beta^2 - M_\alpha^2}\frac{\text{Im}\left[\left(M_\beta(h^\dagger h)_{\beta\alpha} + M_\alpha(h^\dagger h)_{\alpha\beta}\right) h_{j\beta}^* h_{j\alpha}\right]}{(h^\dagger h)_{\alpha\alpha}}$$

with $y_\beta \equiv M_\beta^2/M_\alpha^2$ and $f(x) = \sqrt{x}(1-(1+x)\ln[(1+x)/x])$.

[Covi, Roulet, Vissani 1996]

Boltzmann equations

Simple unflavored version:

$$\frac{\mathrm{d}Y_N}{\mathrm{d}z} = -\frac{1}{zHs}\left(\frac{Y_N}{Y_N^{eq}} - 1\right)\gamma_D$$

$$\frac{\mathrm{d}Y_L}{\mathrm{d}z} = \frac{1}{zHs}\left\{\epsilon\left(\frac{Y_N}{Y_N^{eq}} - 1\right)\gamma_D - \frac{Y_L}{Y_L^{eq}}\frac{\gamma_D}{2}\right\}$$

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

- $\dfrac{\mathrm{d}Y_N}{\mathrm{d}z} = -\dfrac{K(z)}{z}(Y_N - Y_N^{eq})$ with $K(z) \sim \dfrac{\text{rates}}{H}$.
- $\dfrac{\mathrm{d}Y_L}{\mathrm{d}z}$ = source - washouts

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

Washouts = asymmetries (Y_L) $\times$ rates (γ).

$$\boxed{Y_B^f = -\kappa\,\epsilon\,\eta}$$

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

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

The role of $\tilde{m}_1$

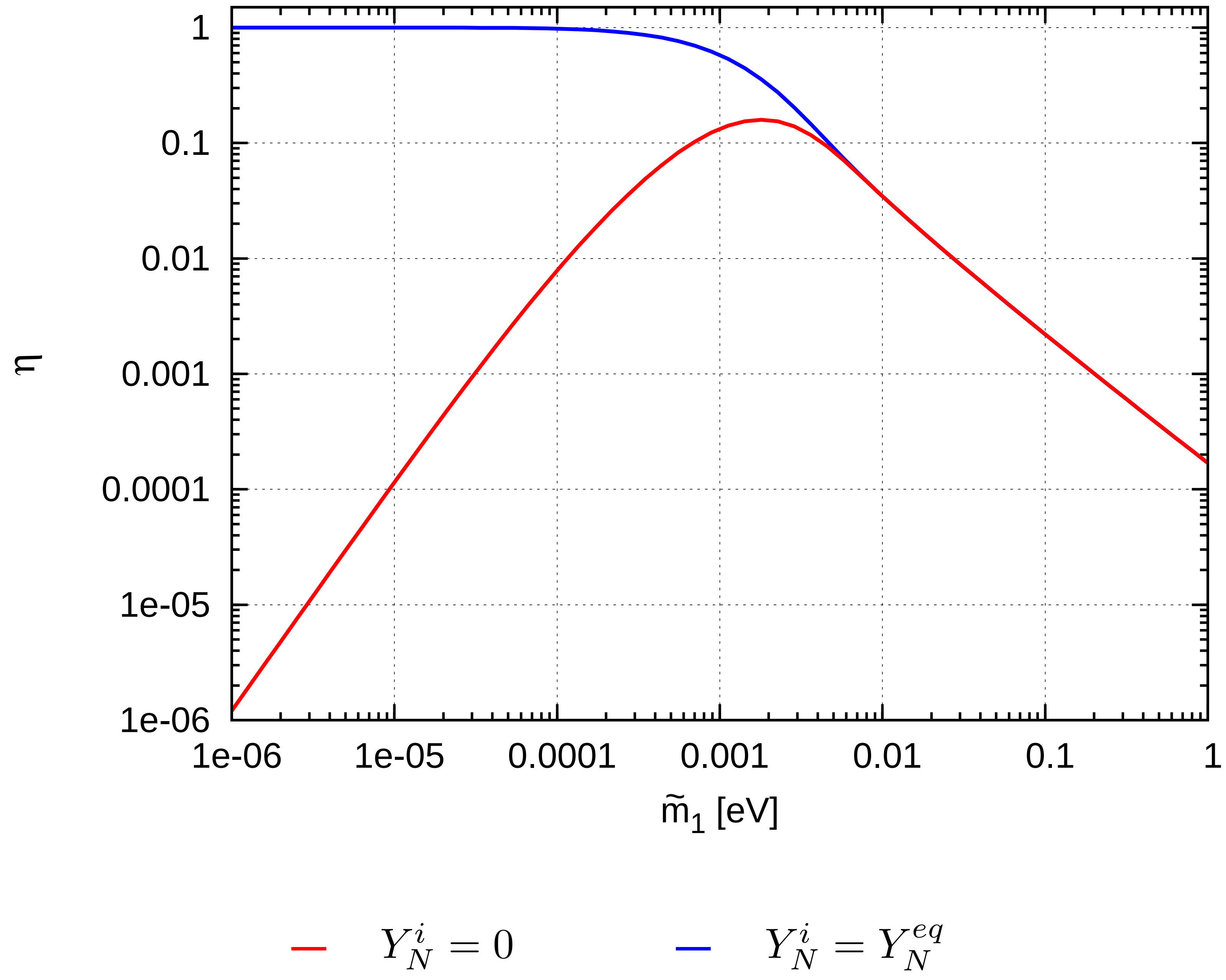
It determines the amount of departure from eq. and the intensity of the washouts.

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

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

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

- $\tilde{m}_1 \gg m_* \;\rightarrow$ *strong washout* regime:
  - Independence from initial conditions.
  - $\eta \propto \tilde{m}_1^{-1}$ $\quad (Y_L \sim$ source/wo $\sim (\,\epsilon\, \mathrm{d}Y_N^{eq}/\mathrm{d}z)/$wo $)$.
- $\tilde{m}_1 \ll m_* \;\rightarrow$ *weak washout* regime:
  - Very dependent on initial conditions.
  - If $Y_N^i = 0 \;\rightarrow\; \eta \propto \cancel{\tilde{m}_1^1}\;\; \tilde{m}_1^2$.


1
0.1
0.01
0.001
0.0001
1e-05
1e-06
η
1e-06
1e-05
0.0001
0.001
0.01
0.1
1
m̃1 [eV]
$Y_N^i = 0$
$Y_N^i = Y_N^{eq}$

Connection with low energy observables

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

- $|\epsilon| \le \epsilon_{\text{max}}^{\text{DI}} = \frac{3}{16\pi}\frac{M_1}{v^2}(m_3 - m_1)$ (also [Hambye, Notari, et al. 2003])
  $\eta \le 1 \implies M_1 \gtrsim 10^9$ GeV (gravitino problem $\to T_{rh} \lesssim 10^7$ TeV)
- $\tilde{m}_1 \ge m_1,$ neglecting phases $\tilde{m}_1 \sim \sum_i m_i,$
  note that $\sqrt{m_{\text{atm}}^2} \simeq 0{,}05$ eV $\sim m_*!$
- $m_1 \lesssim 0{,}15\ \text{eV}$ (open issue)

The simplest model will be very difficult to test. Current research on:

- Falsifying Leptogenesis at LHC
  [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,

$$\text{when} \quad M_2 - M_1 \sim \frac{\Gamma_{N_1}}{2}, \qquad |\epsilon| \sim \frac{1}{2} \frac{\mathrm{Im}\left[(h^\dagger h)^2_{21}\right]}{(h^\dagger h)_{11}(h^\dagger h)_{22}} \leq \frac{1}{2}$$

This allows to lower the energy scale of leptogenesis even until the TeV scale.

Even so ...

Type I Seesaw

The mass matrix of the neutral sector in the basis ν_L, N_R^c is

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

with $m_D = vh$.

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 light and heavy 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 + ν_{R_i}, s_{L_i} (singlet two-component fermions).

The mass matrix of the neutral sector in the basis ν_L, ν_R^c, s_L is

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

If $m_D, \mu \ll M$, the effective mass matrix for the light neutrinos is

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

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

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

(i) N_α is a Majorana neutrino with $h_{i\alpha} \ll 1$.

(ii) The N_α is a Dirac or quasi Dirac neutrino, $h_{i\alpha}$ can be large. This means that there are two Majorana neutrinos N_{iH} and N_{iL} with masses $M_i + \mu$ and $M_i - \mu$, such that the Yukawa couplings are given by

$$\mathcal{L}_{Y_{Ni}} = - h_{i\alpha} \widetilde{H}^\dagger \overline{P_R \frac{N_{iH} + i N_{iL}}{\sqrt{2}}} \ell_\alpha + h.c.$$

$$-h'_{i\alpha} \widetilde{H}^\dagger \overline{P_R \left(\frac{N_{iH} + i N_{iL}}{\sqrt{2}} \right)^C} \ell_\alpha + h.c. \quad \text{with} \quad h'_{i\alpha} \ll 1$$

Leptogenesis with small violation of $B - L$

Define:

- N_1: The heavy neutrino that is more responsible for the generation of the lepton asymmetry.
- N_2: The one that makes the most important virtual contribution to the CP asymmetry in the N_1 decays.

$$\epsilon \sim f(M1/M2){h^2}_2$$

Most interesting case for Leptogenesis (see also [T. Asaka, S. Blanchet 2008]):
$N1$ satisfies (i) [or (ii)] and $N2$ satisfies (ii). But ...

$$\epsilon_i = \epsilon_i^{\not L} + \epsilon_i^{L} = O\left(\mu\right) + \epsilon_i^{L} \ ,$$

hence $\epsilon = \sum_i \epsilon_i = O\left(\mu\right)$.

Is leptogenesis possible with $\epsilon = 0$?

Flavor effects

$N \longrightarrow \ell_d \, H$

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

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

Boltzmann equations

$$\ell_d = K_e \ell_e + K_\mu \ell_\mu + K_\tau \ell_\tau$$

$$\bar{\ell}'_d = \bar{K}_e \bar{\ell}_e + \bar{K}_\mu \bar{\ell}_\mu + \bar{K}_\tau \bar{\ell}_\tau$$

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

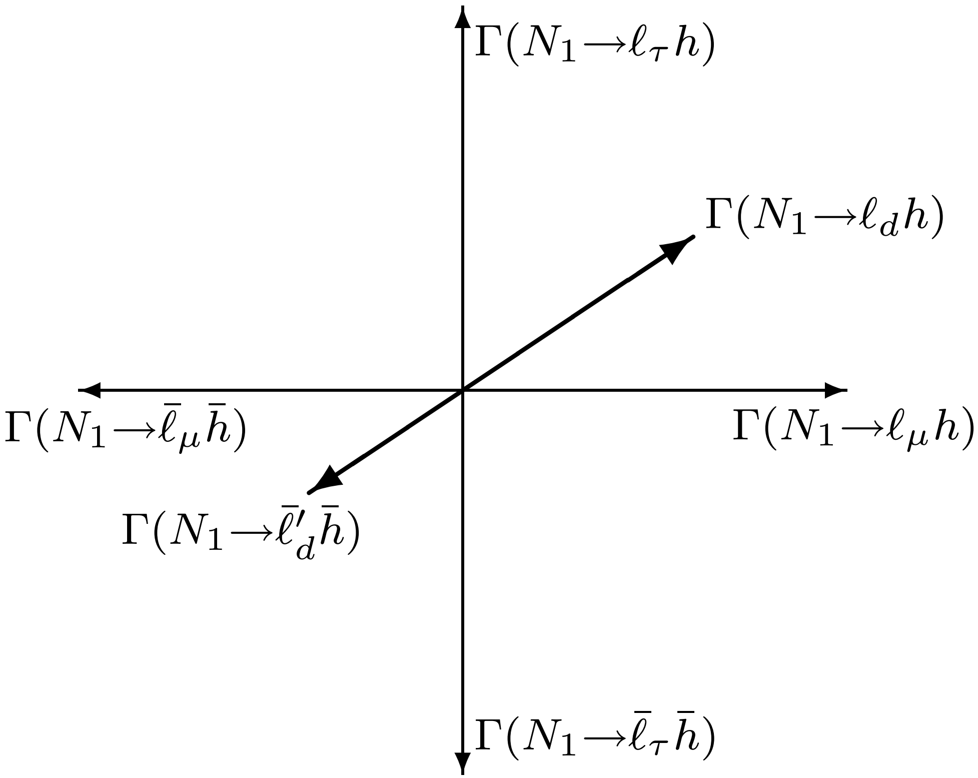
$$\frac{\mathrm{d}Y_{\Delta_i}}{\mathrm{d}z} \approx f(z)\epsilon_i - Y_{\Delta_i} K_i w(z) \qquad (i = e, \mu, \tau)$$

The asymmetries Y_{Δ_i} evolve (approximately) independently.

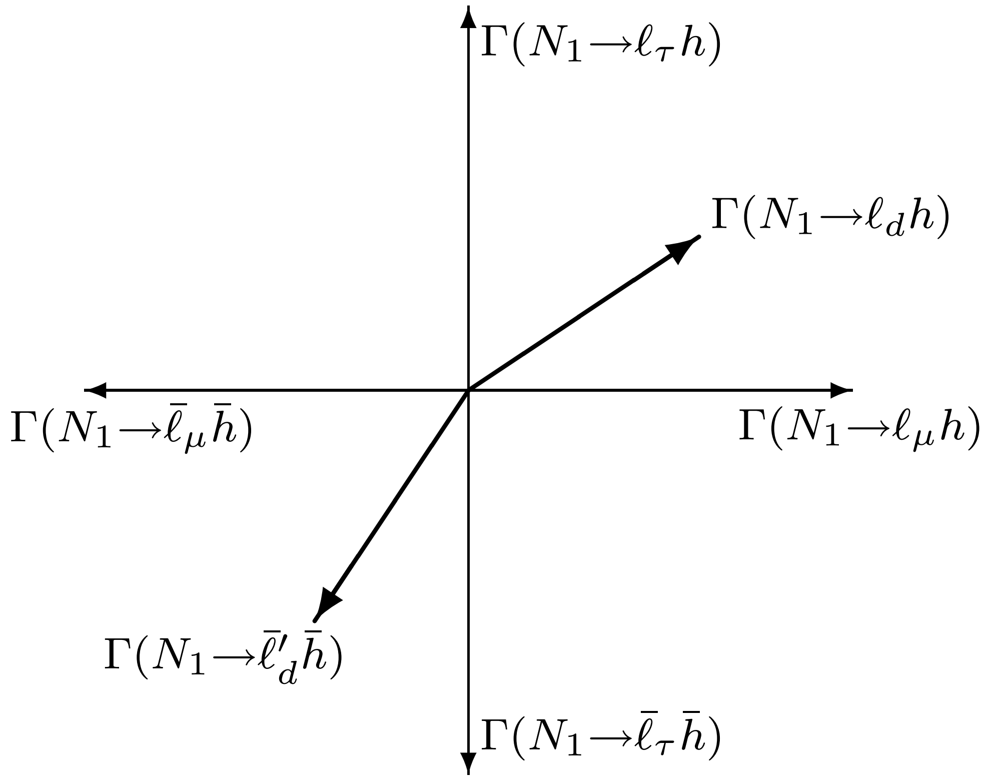
Compare with cases without decoherence

$$\frac{\mathrm{d}Y_{\Delta_i}}{\mathrm{d}z} = f(z)\epsilon_i - Y_{B-L} K_i w(z) \tag{1}$$

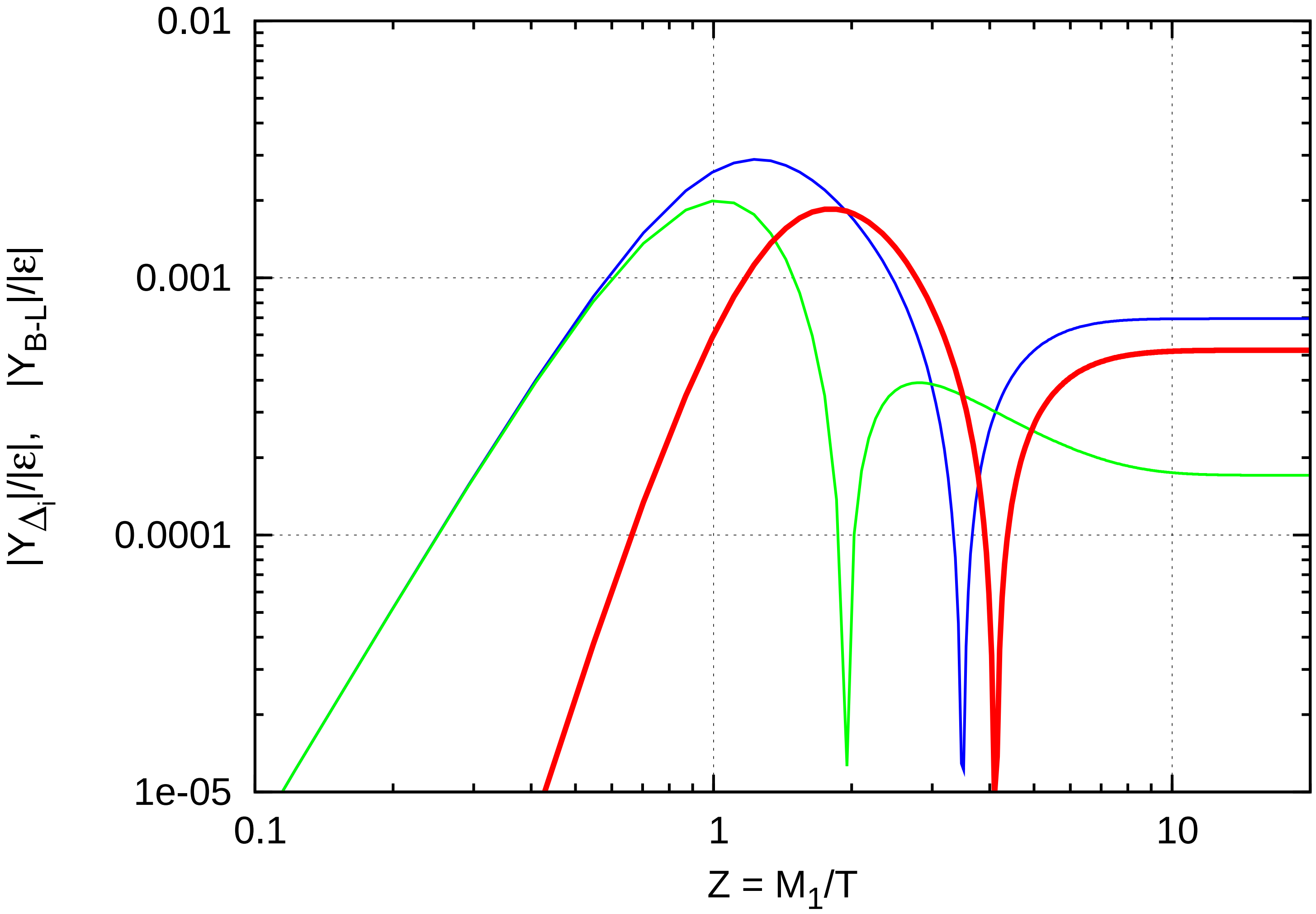
Two types of CP violation



(a) $\ell'_d = \ell_d, \epsilon \neq 0$

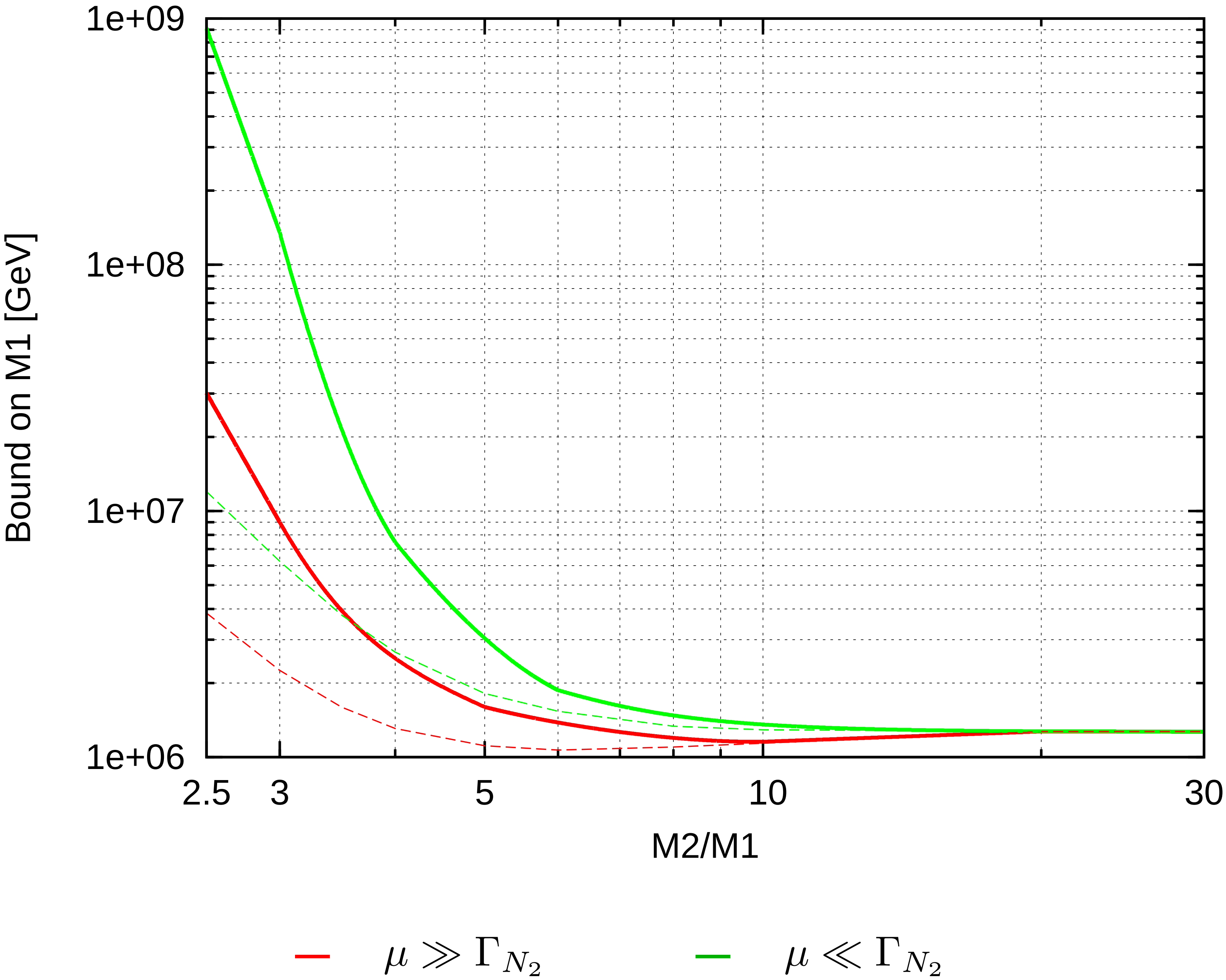


(b) $\epsilon = 0, \ell'_d \neq \ell_d, \epsilon_i \neq 0$

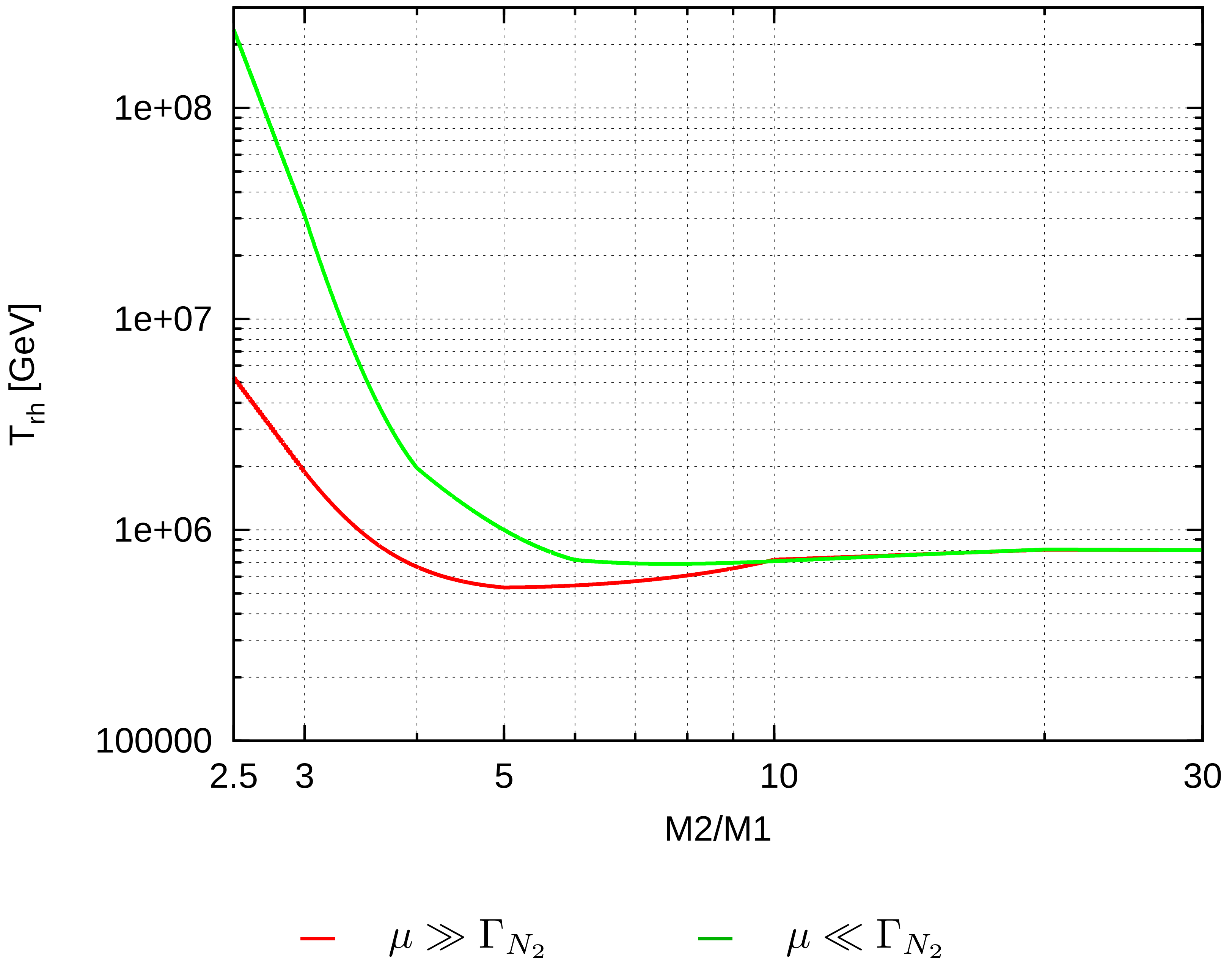


$|Y_{\Delta_\tau}/\epsilon_\tau|$ $\quad$ $\left|Y_{\Delta_\mu}/\epsilon_\mu\right|$ $\quad$ $|Y_{B-L}/\epsilon_\mu|$

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



1e+09
1e+08
1e+07
1e+06
Bound on M1 [GeV]
2.5
3
5
10
30
M2/M1
$\mu \gg \Gamma_{N_2}$
$\mu \ll \Gamma_{N_2}$


1e+08
1e+07
1e+06
100000
T_{rh} [GeV]
2.5
3
5
10
30
M2/M1
$\mu \gg \Gamma_{N_2}$
$\mu \ll \Gamma_{N_2}$

Light neutrino masses:

$$m_{\nu_i} \sim \frac{(\lambda^\dagger\lambda)_{11} v^2}{M_1} + \mu \frac{(\lambda^\dagger\lambda)_{22} v^2}{M_2^2} + \lambda'_{\alpha 2}\lambda_{\beta 2} v^2/M_2 \ .$$

Taking $m_{\nu_i} \sim m_{atm} \sim 0{,}05$ 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 $M_1 \gtrsim 5 \times 10^6$ 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 light-heavy neutrino mixing.
- Generate the baryon asymmetry at $T \sim 10^6$ GeV without a resonant enhancement of ϵ_i and independently of the initial conditions (Y_N, Y_{Δ_i}).
- . . . But not both!

Some mechanisms

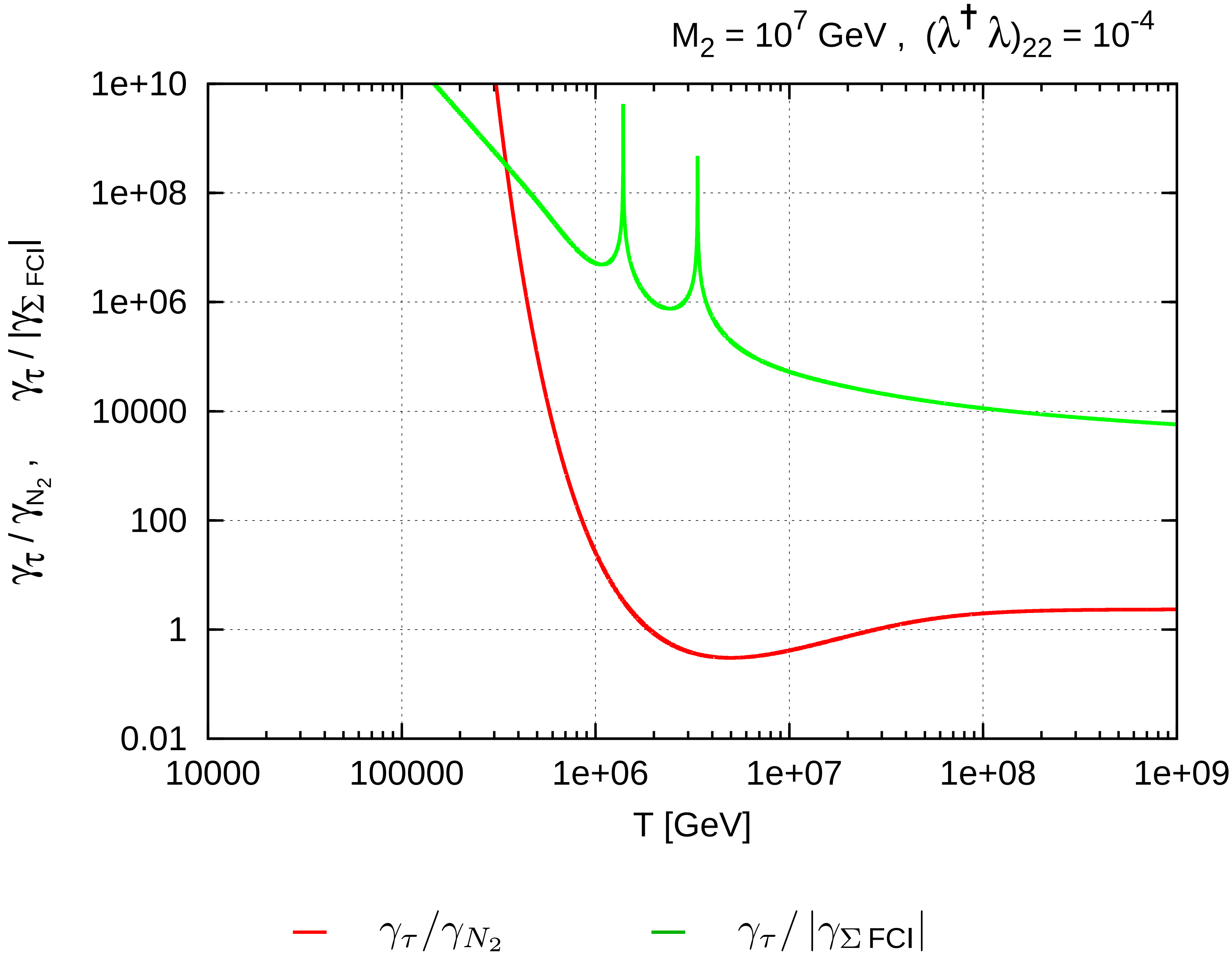
- GUT Baryogenesis: The asymmetry is generated in the out of equilibrium decays of heavy gauge bosons. But:

  $$\tau_p \gtrsim 5 \times 10^{33} yr \;\rightarrow\; T_{rh} \gtrsim M \gtrsim 10^{14}\ \text{GeV}\ ,$$

  is too high for simple inflation models and there can be problems with unwanted relics.

- Electroweak Baryogenesis: The departure from equilibrium is provided by the electroweak phase transition. It needs extensions of the SM, like MSSM and 2HDM, that modify the scalar potential and add new sources of $\not{C}\not{P}$.

- Leptogenesis



$M_2 = 10^7$ GeV , $(\lambda^\dagger \lambda)_{22} = 10^{-4}$
1e+10
1e+08
1e+06
10000
100
1
0.01
10000
100000
1e+06
1e+07
1e+08
1e+09
T [GeV]
$\gamma_\tau / \gamma_{N_2}$, $\gamma_\tau / |\gamma_{\Sigma\ \mathrm{FCI}}|$
$\gamma_\tau / \gamma_{N_2}$
$\gamma_\tau / |\gamma_{\Sigma\ \mathrm{FCI}}|$