Mass bounds for thermal baryogenesis from particle decays

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Outline of the talk:

- Brief Introduction
- Problems for having baryogenesis at low energy
- Some solutions and bounds

The matter-antimatter asymmetry of the Universe

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).

$\Longrightarrow$ 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]

(b) 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.

$$Y_B \equiv \frac{n_B - n_{\bar{B}}}{s} = \frac{n_B}{s} \simeq 8{,}5 \times 10^{-11}$$

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

Basic requirements to dynamically generate a baryon asymmetry:

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

In thermal baryogenesis from the decay of a particle with mass M:

$$\frac{H(T=M)}{\text{Interaction rates}} \quad \propto \quad f(M_i/M, \text{couplings}) \, \frac{M}{M_{\rm Pl}}$$

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.

Problems for thermal Baryogenesis at low energy

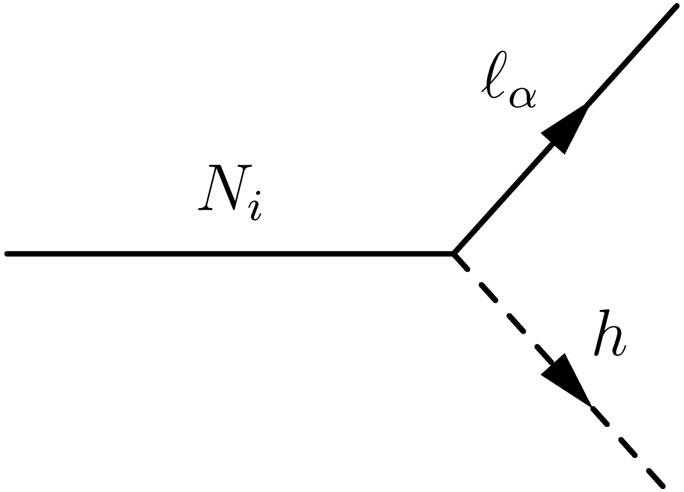
Example: Type I Leptogenesis

The singlet Majorana neutrinos of the type I seesaw can generate a lepton asymmetry when decaying in the primitive Universe.

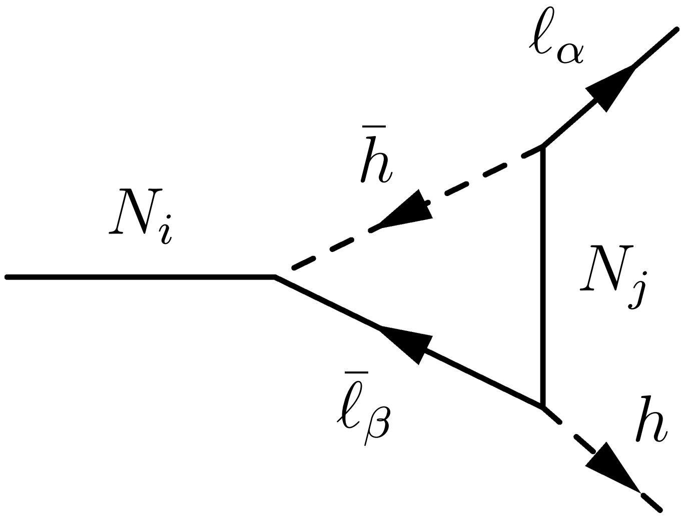
$$\boxed{Y_B^f = -\kappa \, \epsilon \, \eta} \qquad \big(\text{constant } \epsilon\big)$$

- $\kappa = \frac{28}{79} Y_N^{eq}(T \gg M_1) \sim 10^{-3}$
- $\epsilon = \sum_\alpha \epsilon_\alpha = \sum_\alpha \quad \frac{\gamma(N_1 \to H\ell_\alpha) - \gamma(N_1 \to \bar{H}\bar{\ell}_\alpha)}{\sum_\beta \gamma(N_1 \to H\ell_\beta) + \gamma(N_1 \to \bar{H}\bar{\ell}_\beta)}$
- $\eta = \mathit{efficiency} \sim \frac{1}{\text{strength of interactions}}$

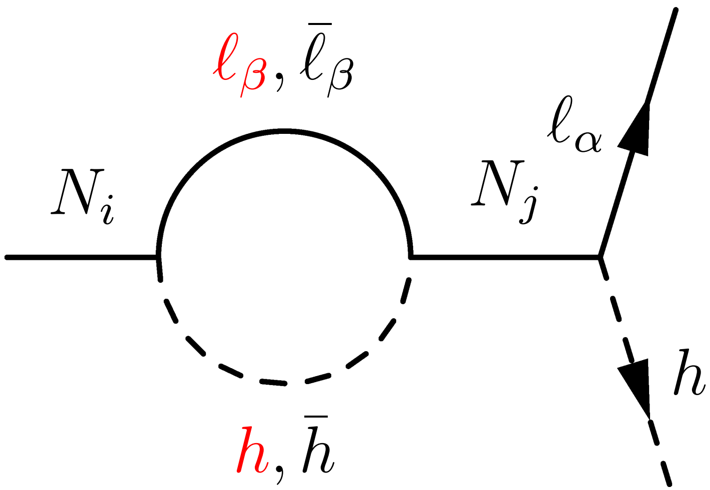
CP violation in decays



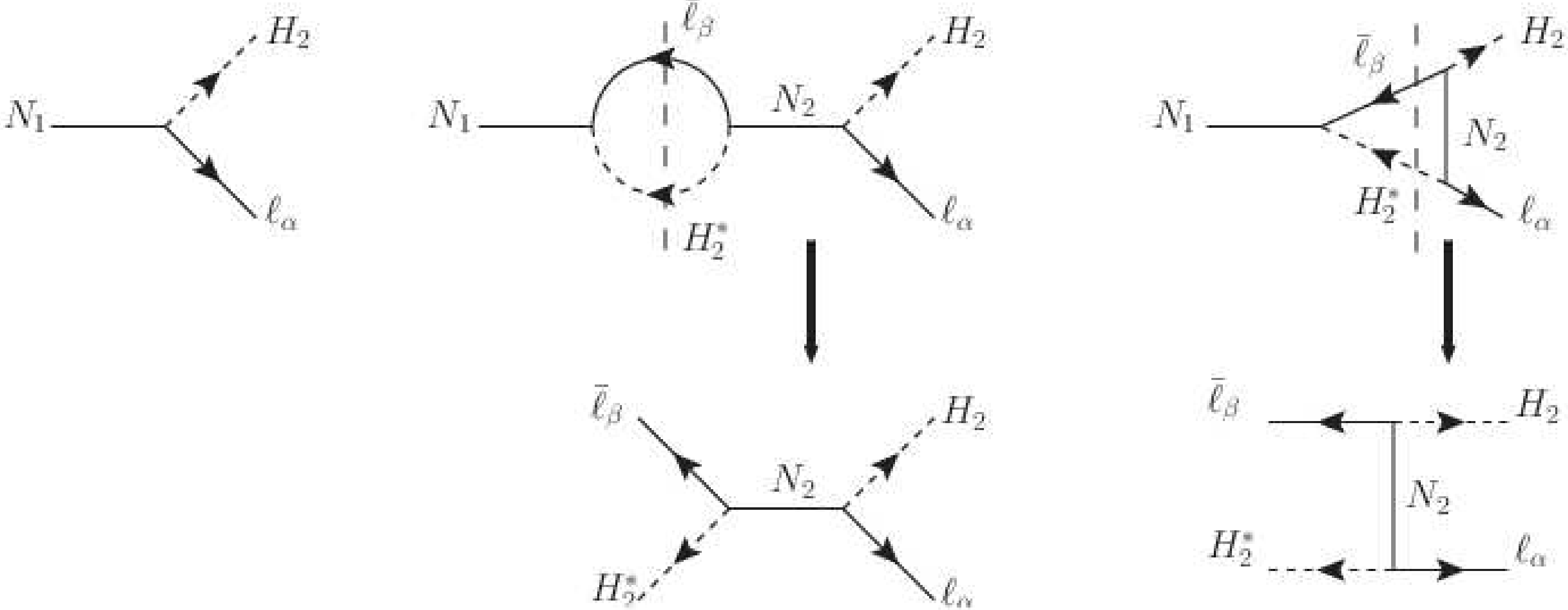
(a) Tree



(b) Vertex



(c) Wave


N_1
H_2
ℓ_α
N_1
$\bar{\ell}_\beta$
H_2^*
N_2
H_2
ℓ_α
N_1
$\bar{\ell}_\beta$
H_2^*
N_2
H_2
ℓ_α
$\bar{\ell}_\beta$
N_2
H_2
H_2^*
ℓ_α
$\bar{\ell}_\beta$
H_2
N_2
H_2^*
ℓ_α

Two problems to lower the energy scale

$$\epsilon \quad \sim \quad \frac{3}{16\pi}\frac{\lambda^2_{\alpha 2}}{M_2} M_1 \qquad \text{(hierarchical)}$$

- Connection with light neutrino masses:
  Type I seesaw: $\epsilon \quad \sim \quad \frac{3}{16\pi}\frac{m_i}{v^2} M_1 \qquad \text{(type I seesaw)}$
  $$|\epsilon| \leq \epsilon^{\text{DI}}_{\text{max}} = \frac{3}{16\pi}\frac{M_1}{v^2}(m_3 - m_1) \implies M_1 \gtrsim 10^9 \text{ GeV} \qquad (\eta \leq 1)$$
  Some alternatives: Inverse seesaw, radiative seesaws, ...
- Even with no connection to neutrino masses:
  Washout processes inherent to the existence of CP violation

$$\text{washouts} \quad \propto \quad \left(\frac{\lambda^2_{\alpha 2}}{M_2}\right)^2$$

large ϵ $\rightarrow$ large $\lambda_{\alpha 2}$ $\rightarrow$ too much washout at LE $\rightarrow$ How low?

Ways to have Baryogenesis at low energy scales

- Mass degeneracy:

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

Note: However in the type I seesaw the mixing between active and sterile neutrinos is:

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

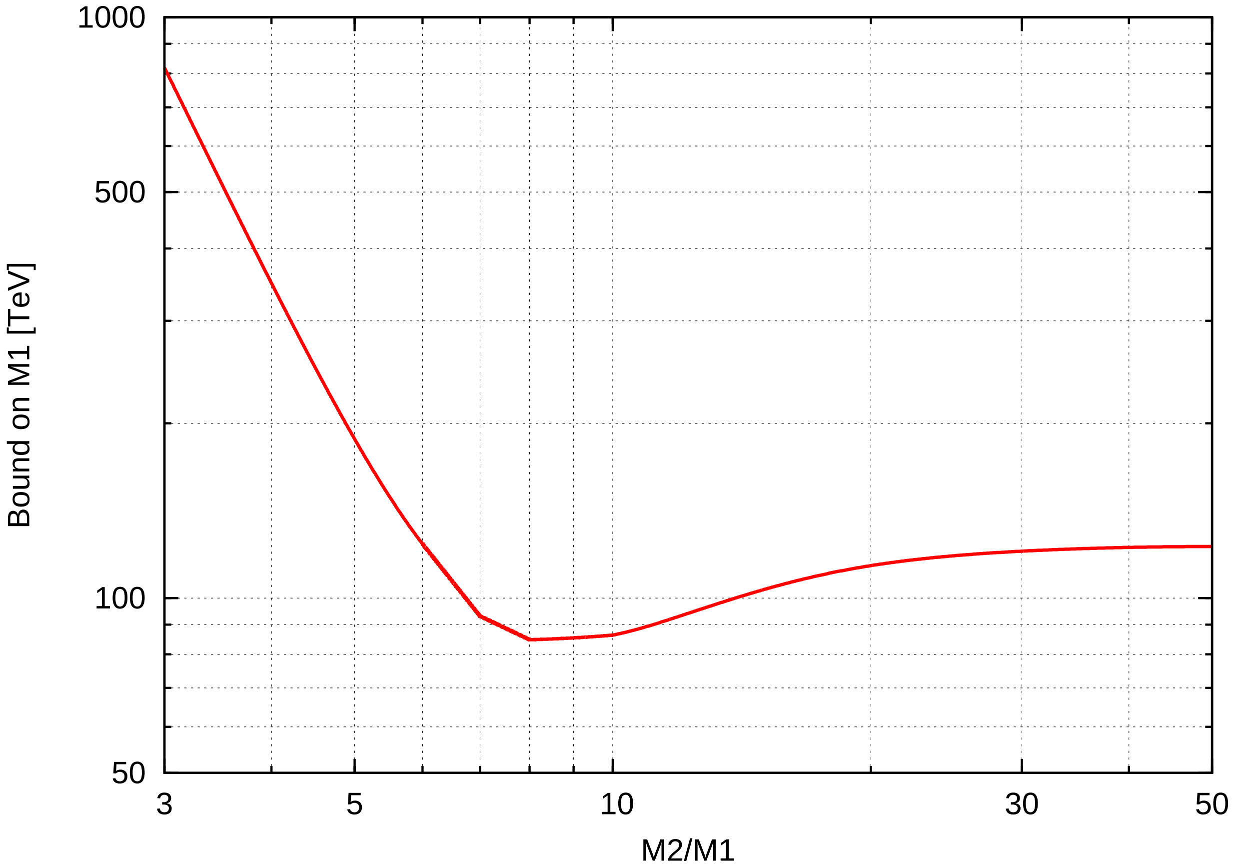
- Three body decays: It's more easy to satisfy the o.e.c.
- Hierarchy of couplings:
  - Take $\lambda_{\alpha 1}$ as small as necessary.
    E.g. $\lambda_{\alpha 1} \sim 10^{-7}$ to have $\Gamma \sim H(T = M_1)$ for $M_1 = 1$ TeV.
  - Take $\lambda_{\alpha 2}$ much larger to have enough CP violation.

[T. Hambye, 2002]

Other ways and bounds

L-violating CP asymmetry

$$\epsilon \;\propto\; \lambda_{\alpha 2}^2 \, \frac{M_1}{M_2}, \qquad \text{washouts} \;\propto\; \left[\lambda_{\alpha 2}^2 \, \frac{M_1}{M_2}\right]^2$$



[JR, arXiv:1308.1840]

L-conserving CP asymmetry

$\epsilon_\alpha \;\propto\; \lambda^2_{\beta 2} \left(\frac{M_1}{M_2}\right)^2$, washouts $\propto \left[\lambda^2_{\beta 2} \left(\frac{M_1}{M_2}\right)^2\right]^2$.

Inverse seesaw

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

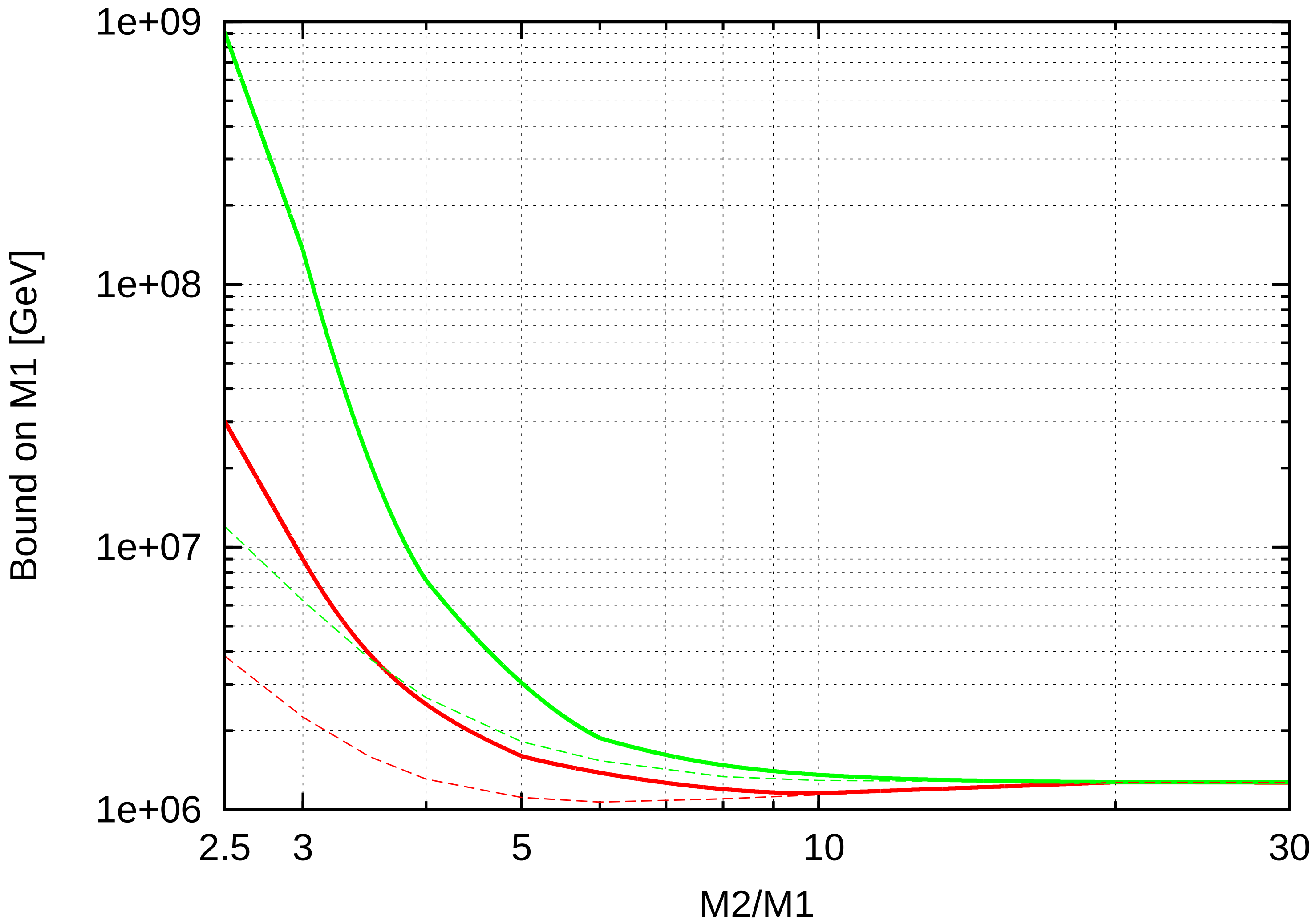
The mass matrix of the neutral sector in the basis ν_L, ν_R^c, s_L is

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

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

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

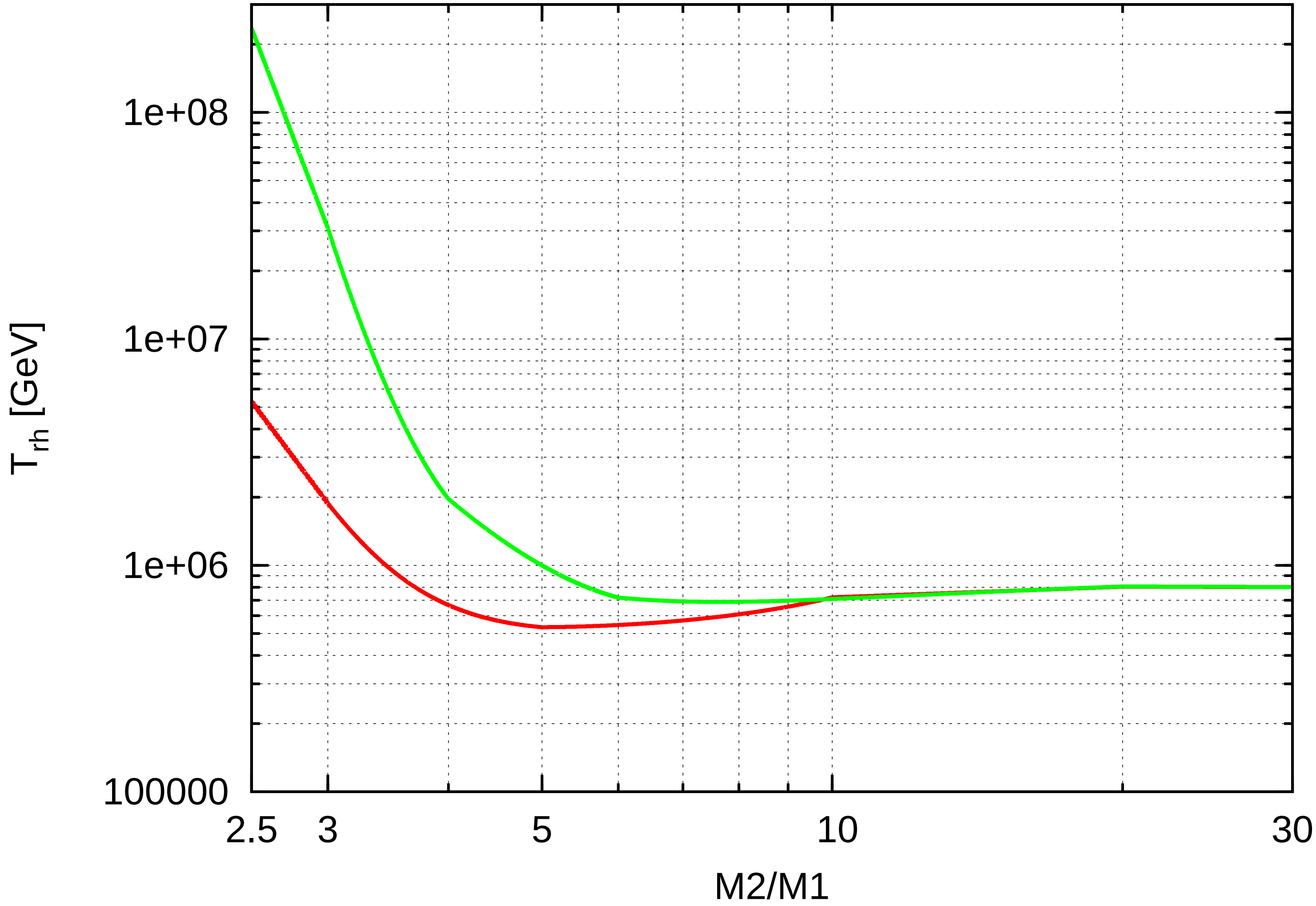
$$\text{mixing} \;\sim\; \frac{m_D}{M} \;\sim\; \sqrt{\frac{m_\nu}{\mu}}$$



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

[JR, M. Peña, N. Rius, 2012]

Note: This is for 2 flavors. The bound can be up to a factor ~ 4 smaller for 3 flavors.



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

Note: The Upper bound on T_{rh} from gravitino overproduction can be satisfied

Massive decay products

In baryogenesis from annihilations, $\chi\chi \to \psi u$, it is possible to take $m_\psi > m_\chi \implies$ Boltzmann suppression $\propto e^{-m_\psi/T}$ of the washouts without reducing the CP asymmetry.

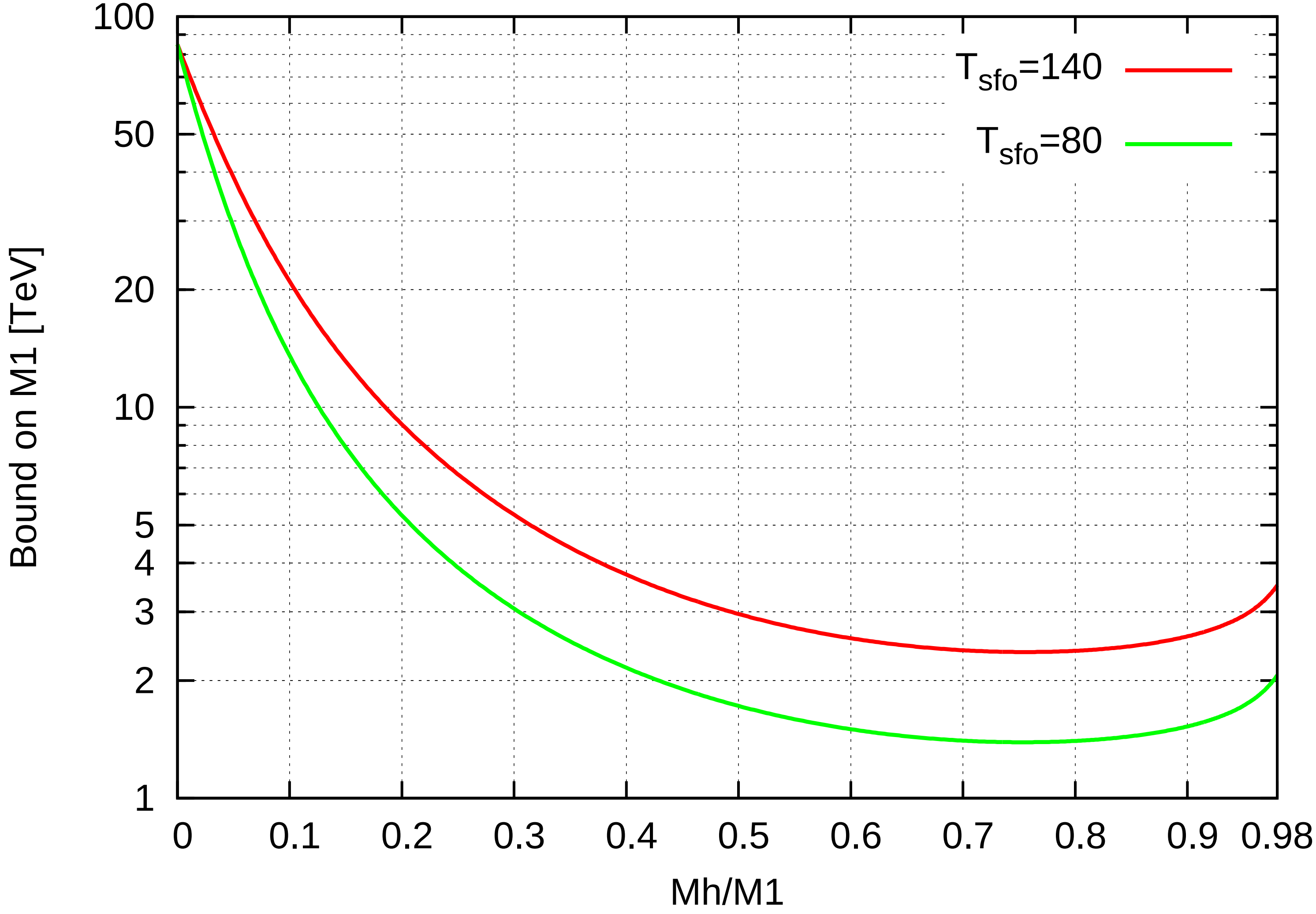
[Y. Cui, L. Randall, B. Shuve, 2012],

[N. Bernal, S. Colucci, F-X. Josse-Michaux, JR, L. Ubaldi, 2013]

In decays, e.g. taking a massive H_2 in $N_1 \to H_2 \ell$, like in the inert doublet model, there are two opposite effects:

- Boltzmann suppression of the washouts (but not as much as for annihilations, since $m_{H_2} < M_1$).
- Phase space suppression of the CP asymmetry

$\Downarrow$ SM + H_2 + N_i, with H_2 and N_i odd under a Z_2



[JR, arXiv:1308.1840]

Initial thermal density

If the N_1 are produced at $T \gg M_1$ by a process different from the Yukawa interactions, then $\lambda_{\alpha 1}$ can be chosen small enough to have the N_1 decay at $T \ll M_2$.

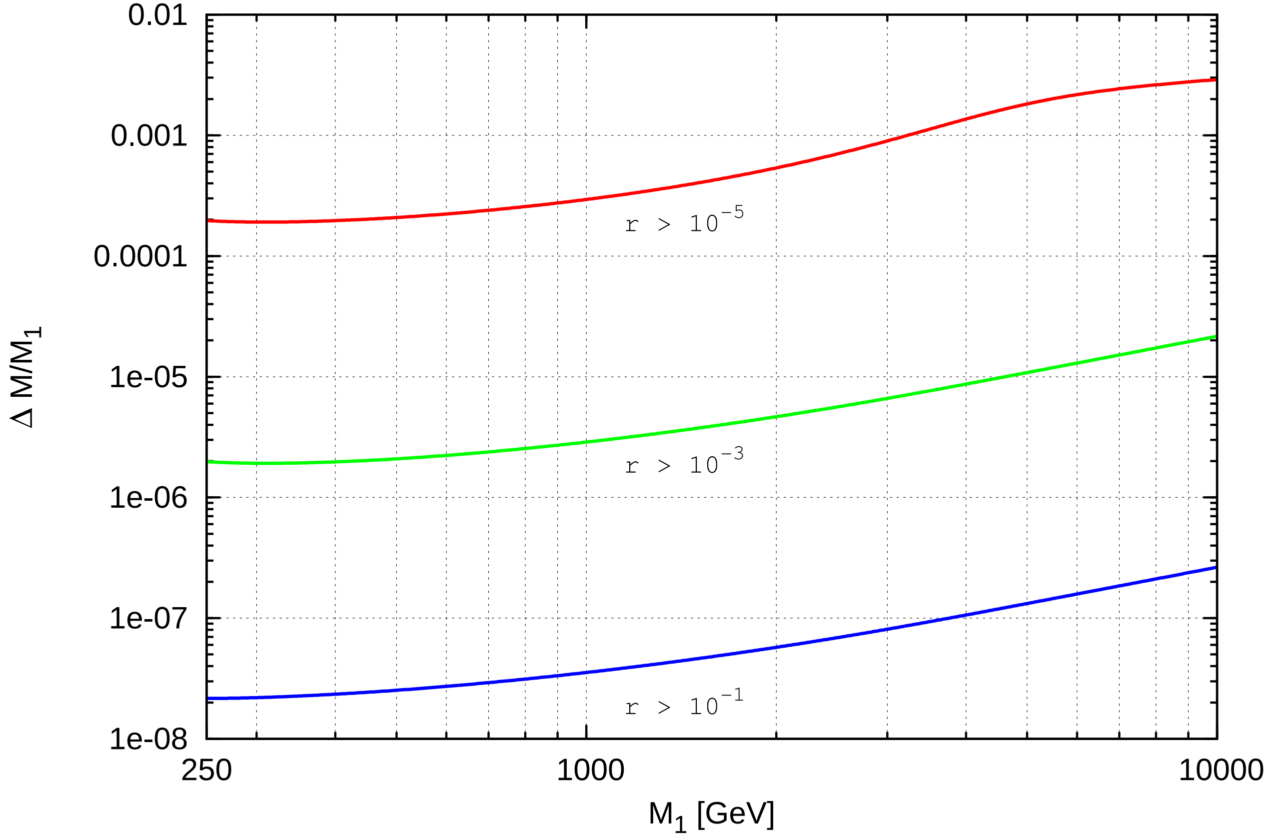
$\Rightarrow$ It is possible to have large $\lambda_{\alpha 2}$ and consequently a big ϵ, but at the same time small washouts at the moment the N_1 start to decay and produce the BAU.

$$M_{1\,\mathrm{min}} \sim 2500\ (2000)\ \text{GeV} \qquad \text{for} \qquad T_{sfo} = 140\ (80)\ \text{GeV}.$$

In this way the small neutrino masses, DM, and BAU can be simultaneously explained at the TeV scale in the inert doublet model, without degenerate heavy neutrinos or fine tuning among phases.

Note: The interaction that creates the N_1 must decouple before they decay.

Almost degenerate neutrinos



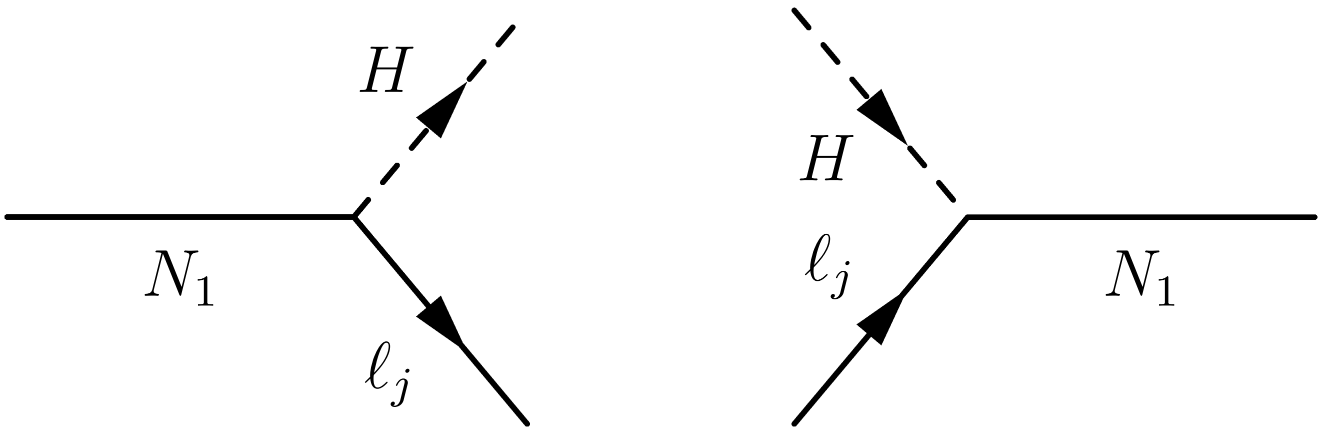
$$\delta \equiv \frac{M_2 - M_1}{M_1}\,, \qquad r = \frac{\text{smallest Yukawa coupling}}{\text{largest Yukawa coupling}}$$

$\delta \times r \lesssim 10^{-8}\,,$ for $250 \text{ GeV} \lesssim M_1 \lesssim 4 \text{ TeV}$ and

$\delta \times r \lesssim 3 \times 10^{-9}\,,$ for $250 \text{ GeV} \lesssim M_1 \lesssim 1 \text{ TeV}\,.$

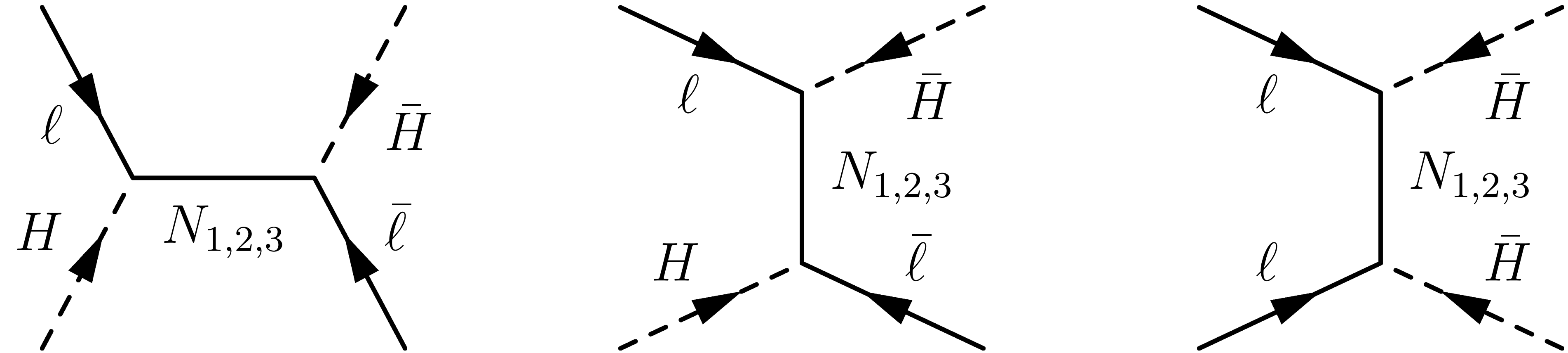
Additional slides ...

Relevant processes for N_1–Leptogenesis

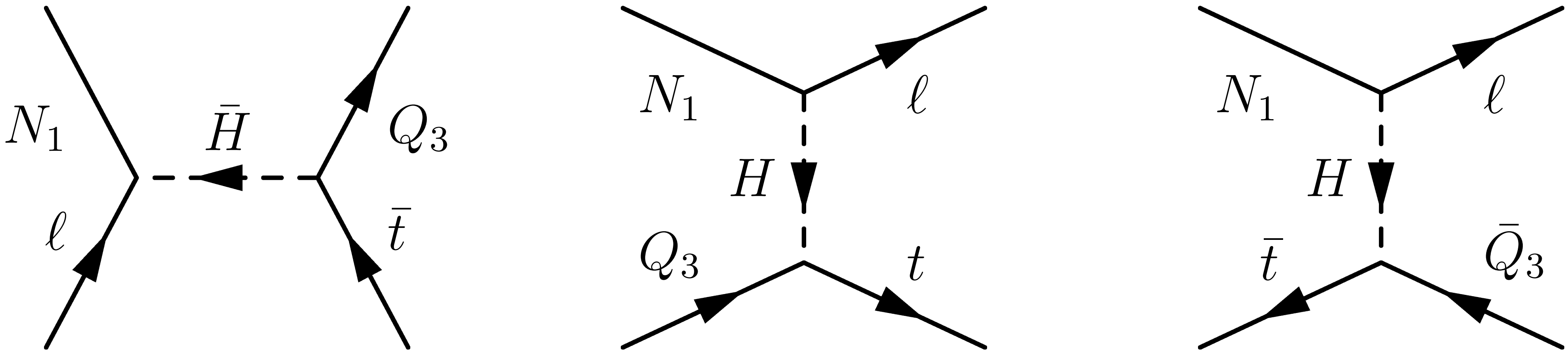


(a) Decay and inverse decay (production) of N_1.

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



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



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

$$\epsilon_{\ell_\alpha}^{N_i} = \epsilon_{\ell_\alpha}^{N_i}(\text{vertex}) + \epsilon_{\ell_\alpha}^{N_i}(\text{wave})$$

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

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

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:

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

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

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

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

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

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

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 $Y_N^i = 0 \ \rightarrow \ \eta \propto \tilde{m}_1^1 \ \tilde{m}_1^2$.

Is leptogenesis possible with $\epsilon = 0$?

Flavor effects

$N_1 \longrightarrow \ell_d \ H$

- $T \gtrsim 10^{12}$ 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 $N_1 \longrightarrow \bar{\ell}'_d \ \bar{H}$

Boltzmann equations

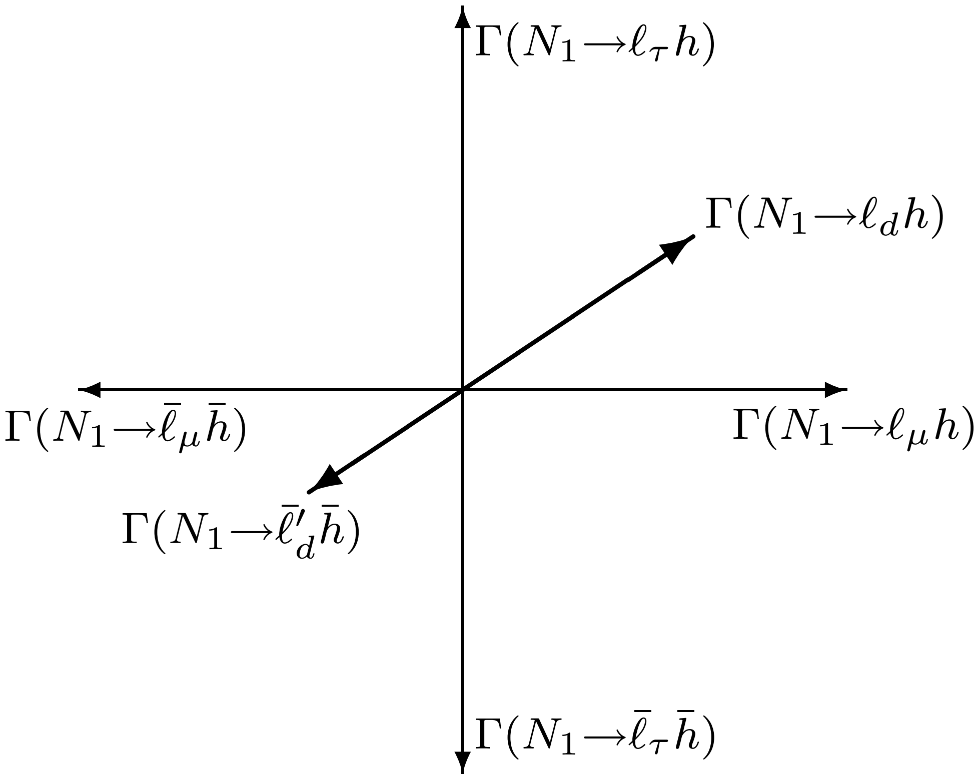
Define $Y_{\Delta_\alpha} \;\equiv\; \frac{1}{3}Y_B - Y_{L_\alpha}$ ($B/3 - L_\alpha$ is conserved by sphalerons)

$$\frac{\mathrm{d}Y_{\Delta_\alpha}}{\mathrm{d}z} \approx f(z)\epsilon_\alpha - Y_{\Delta_\alpha} K_\alpha w(z) \qquad\qquad (\alpha = e, \mu, \tau),$$

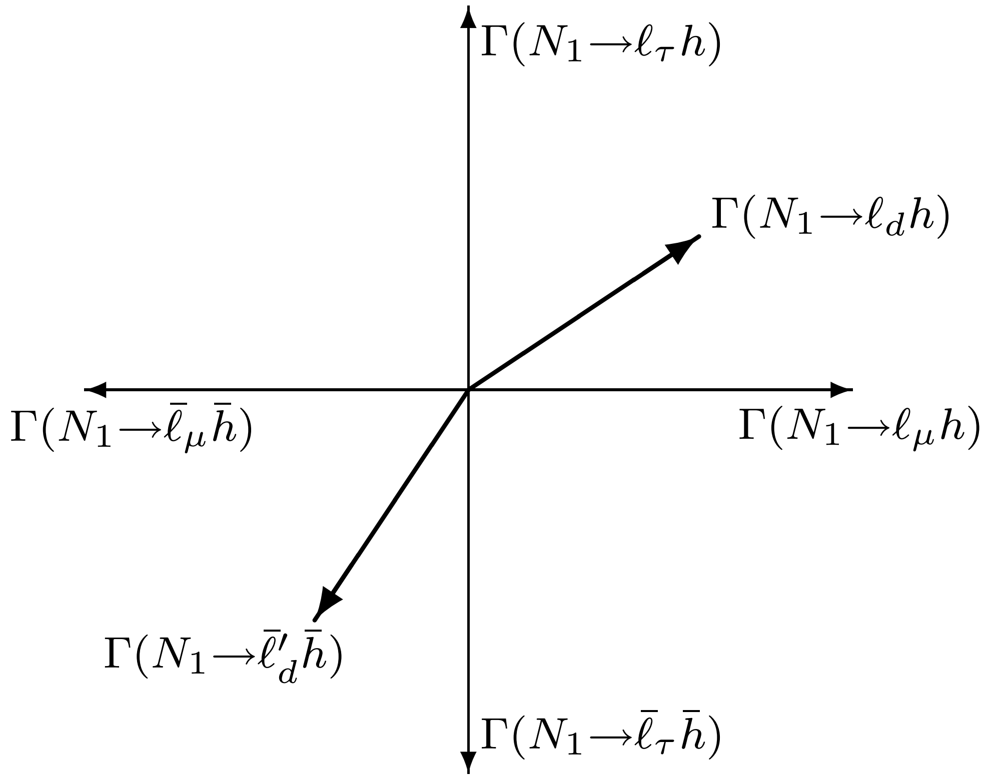
with $z \equiv M_1/T$, $\quad K_\alpha \equiv \left|\langle \ell_\alpha | \ell_d \rangle\right|^2$

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

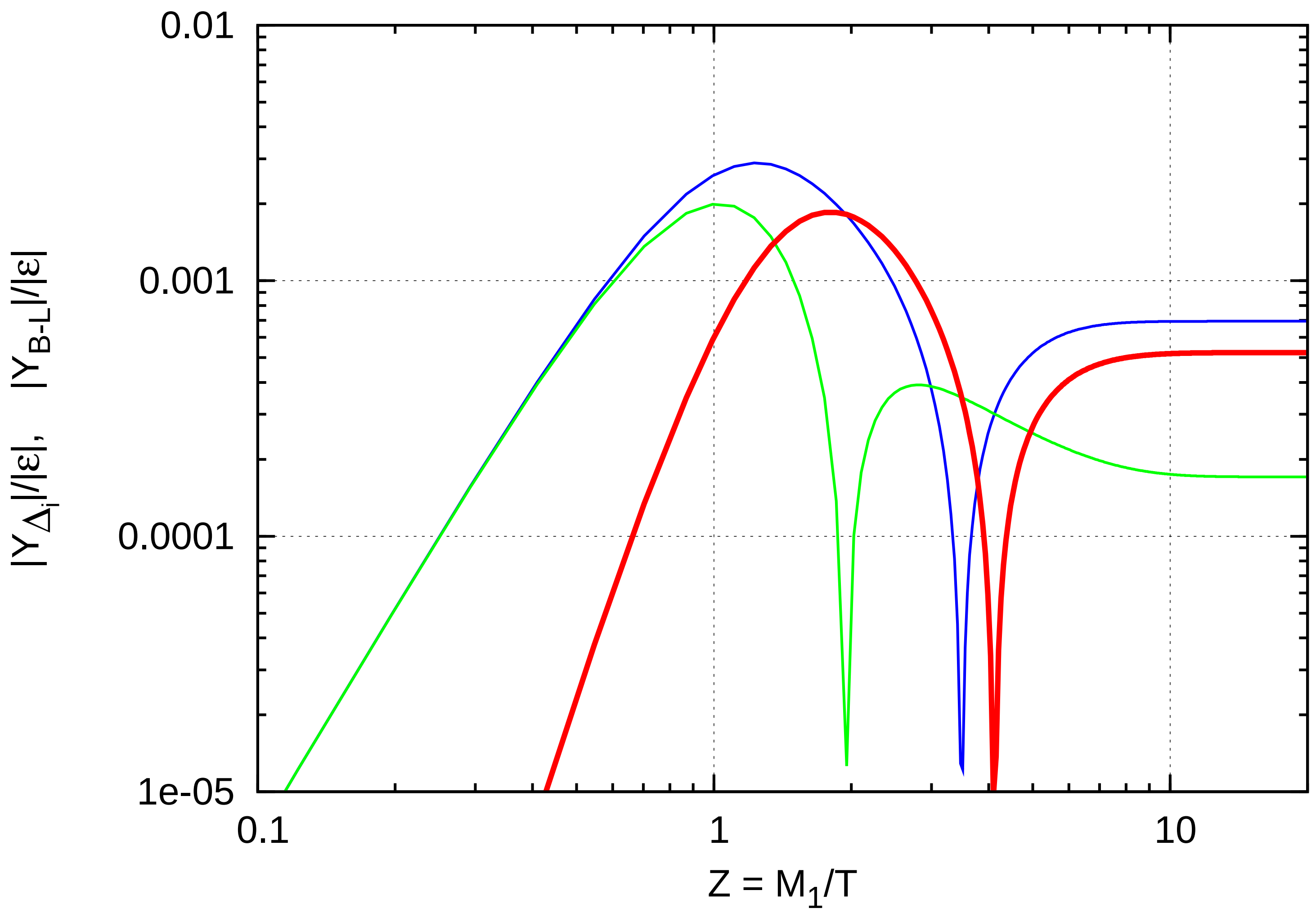
Two types of CP violation



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



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



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

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

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

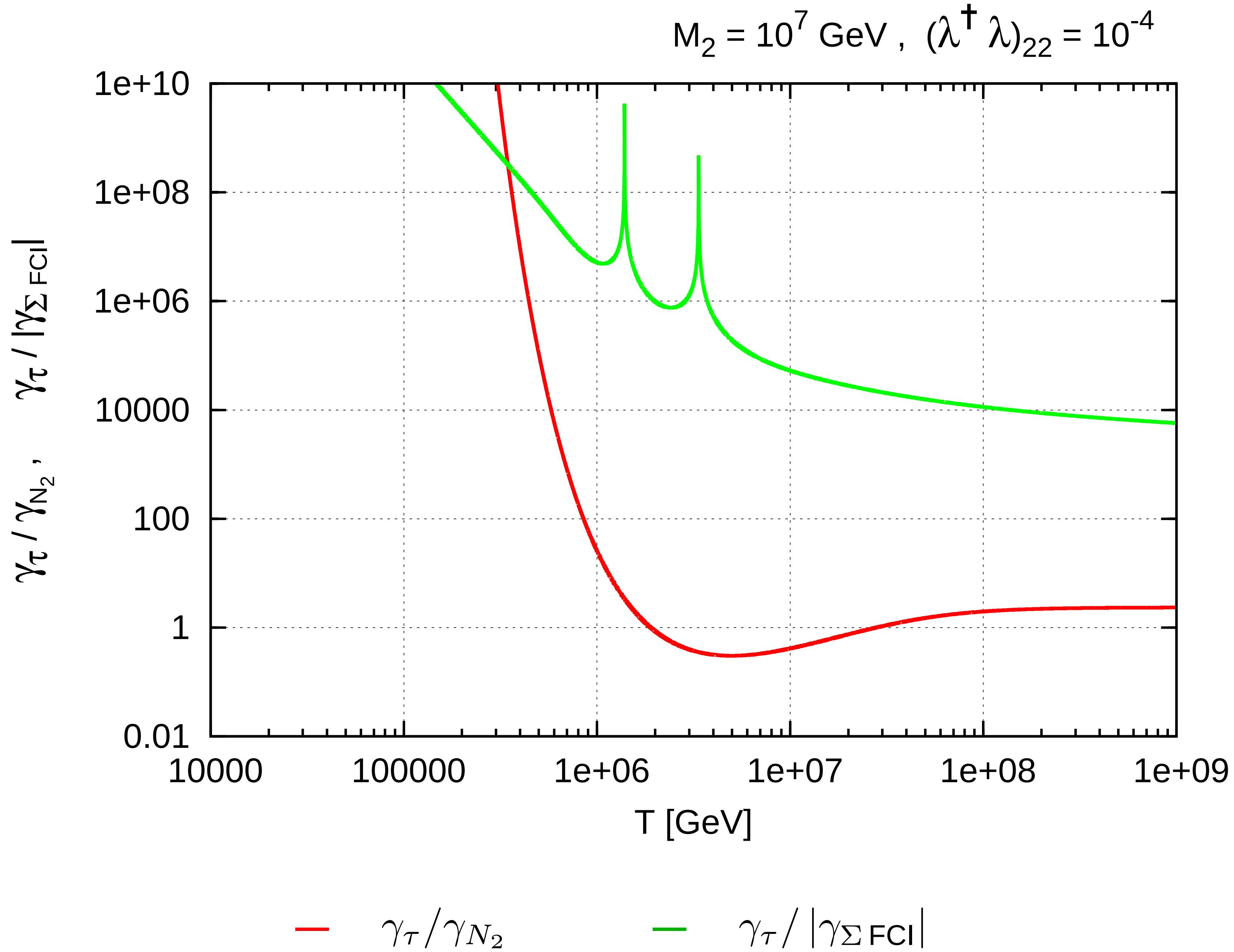
$$\frac{\mathrm{d}Y_{N_1}}{\mathrm{d}z} = \frac{-1}{sHz}\left(\frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1\right)\gamma_{D_1} \ ,$$

$$\frac{\mathrm{d}Y_{\Delta_\alpha}}{\mathrm{d}z} = \frac{-1}{sHz}\left\{\left(\frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1\right)\epsilon_{\alpha 1}\,\gamma_{D_1} - \sum_i \gamma^{N_i}_{\ell_\alpha h} y_{\ell_\alpha} - \sum_{\beta\neq\alpha}\left(\gamma^{\ell_\beta h}_{\ell_\alpha h}{}' + \gamma^{\ell_\beta \bar{h}}_{\ell_\alpha \bar{h}} + \gamma^{h\bar{h}}_{\ell_\alpha \bar{\ell}_\beta}\right)\left[y_{\ell_\alpha} - y_{\ell_\beta}\right]\right\} \ ,$$

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 $\mu_2 \ll \Gamma_{N_2}$

$$
\begin{aligned}
\frac{\mathrm{d}Y_{N_1}}{\mathrm{d}z} &= \frac{-1}{sHz}\left(\frac{Y_{N_1}}{Y^{eq}_{N_1}} - 1\right)\gamma_{D_1} \ , \\
\frac{\mathrm{d}Y_{N_2-\bar{N}_2}}{\mathrm{d}z} &= \frac{-1}{sHz}\sum_\alpha \gamma^{N_2}_{\ell_\alpha h}\left[y_{N_2} - y_{\ell_\alpha}\right] \ , \\
\frac{\mathrm{d}Y_{\Delta_\alpha}}{\mathrm{d}z} &= \frac{-1}{sHz}\left\{\left(\frac{Y_{N_1}}{Y^{eq}_{N_1}} - 1\right)\epsilon_{\alpha 1}\,\gamma_{D_1} - \gamma^{N_1}_{\ell_\alpha h} y_{\ell_\alpha} + \gamma^{N_2}_{\ell_\alpha h}\left[y_{N_2} - y_{\ell_\alpha}\right]\right. \\
&\left. - \sum_{\beta\neq\alpha}\left(\gamma^{\ell_\beta h\,\prime}_{\ell_\alpha h} + \gamma^{\ell_\beta \bar{h}}_{\ell_\alpha \bar{h}} + \gamma^{h\bar{h}}_{\ell_\alpha \bar{\ell}_\beta}\right)\left[y_{\ell_\alpha} - y_{\ell_\beta}\right]\right\} \ .
\end{aligned}
$$



$M_2 = 10^7$ 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]
$\gamma_\tau / \gamma_{N_2}$, $\gamma_\tau / |\gamma_{\Sigma \text{ FCI}}|$
$\gamma_\tau / \gamma_{N_2}$
$\gamma_\tau / |\gamma_{\Sigma \text{ FCI}}|$

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 $m_i \sim m_{atm} \sim 0{,}05$ 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 $\mu_2 \gtrsim \Gamma_{N_2}$.