Thermal Baryogenesis at Low Energies

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Invisibles webinar

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Goal of the talk: Explain the problems and *some* solutions to achieve thermal baryogenesis at low temperatures ($T \lesssim 10^5$ TeV).

some = some or all known?

- Introduction
- Basics of thermal baryogenesis
- Problems for baryogenesis at low temperatures
- Solutions
- Conclusions

References and more details on [JR, JCAP 1403 (2014) 025]

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 $\longrightarrow \quad \frac{\overline{He}}{He} < 1 \times 10^{-7}$.
- 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.

$$Y_B \equiv \frac{n_B - n_{\bar{B}}}{s} = \frac{n_B}{s} \simeq 8{,}6 \times 10^{-11}$$

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:

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

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 $\rightarrow$ The Higgs is too heavy for the EW phase transition to be strongly first order.

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

Thermal Baryogenesis

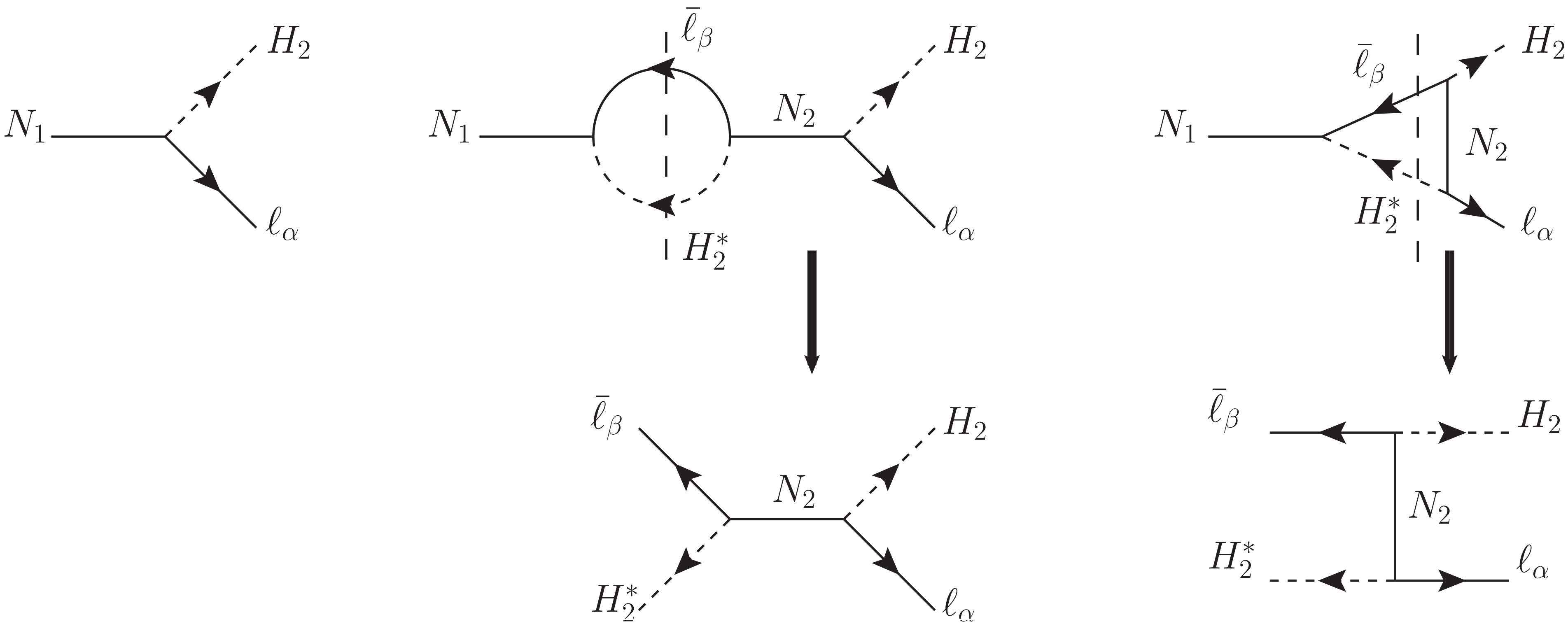
The baryon -or lepton- asymmetry is generated in the decay or scattering of heavy particles thermally produced.

To be more specific we start considering type I leptogenesis:
The singlet Majorana neutrinos of the type I seesaw can generate a lepton asymmetry when decaying in the primitive Universe.

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

- $\kappa = \frac{28}{79} Y_{N_1}^{eq}(T \gg M_1) \sim 10^{-3}$
- $\epsilon = \frac{\gamma(N_1 \to H\ell) - \gamma(N_1 \to \bar{H}\bar{\ell})}{\gamma(N_1 \to H\ell) + \gamma(N_1 \to \bar{H}\bar{\ell})}$
- $\eta = efficiency \;, \qquad 0 \leq |\eta| \leq 1.$

$\epsilon \quad \propto \quad$ CP odd phase $\quad \times \quad$ CP even phase



$\eta \quad \longrightarrow \quad$ from Boltzmann equations

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

$$\frac{\mathrm{d}Y_{\Delta L}}{\mathrm{d}z} = -\epsilon \frac{\mathrm{d}Y_N}{\mathrm{d}z} \;-\; \frac{1}{z}\left\{ Y_{\Delta L}\left[\frac{\gamma_D^{eq}}{n_\ell^{eq} H} + \frac{\gamma_{N_2}^{eq}}{n_\ell^{eq} H}\right] + Y_{\Delta h}\left[\frac{\gamma_D^{eq}}{n_h^{eq} H} + \frac{\gamma_{N_2}^{eq}}{n_h^{eq} H}\right]\right\}$$

$$= \textbf{source} \;-\; \textbf{w a s h o u t s}$$

with $\quad Y_x \equiv \dfrac{n_x}{s}\,, \qquad z \equiv \dfrac{M_1}{T}\,, \qquad N \equiv N_1\,.$

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

Washouts = asymmetries $(Y_{\Delta L},\; Y_{\Delta h})$ $\times$ rates (γ/Hn).

Two types of washouts

♣ $N \to \ell\, h,\ \overline{\ell h} \quad \Longrightarrow \quad \ell\, h,\ \overline{\ell h} \to N$

$$\gamma(\ell\, h \to N) = \int \mathrm{d}\pi\, f_\ell f_h \left|\mathcal{A}(N \to \ell\, h)\right|^2$$

Assume kinetic equilibrium: $f_x(E) \;=\; \dfrac{n_x}{n_x^{eq}}\, f_x^{eq}(E)$

$$\gamma(\ell\, h \to N) = \frac{n_\ell}{n_\ell^{eq}} \frac{n_h}{n_h^{eq}} \gamma_D^{eq}\,, \qquad \gamma(\bar\ell\, \bar h \to N) = \frac{n_{\bar\ell}}{n_\ell^{eq}} \frac{n_{\bar h}}{n_h^{eq}} \gamma_D^{eq}$$

$$\gamma(\ell\, h \to N) - \gamma(\bar\ell\, \bar h \to N) \quad = \quad n_{\Delta\ell}\, \frac{\gamma_D^{eq}}{n_\ell^{eq}} \quad + \quad n_{\Delta h}\, \frac{\gamma_D^{eq}}{n_h^{eq}}$$

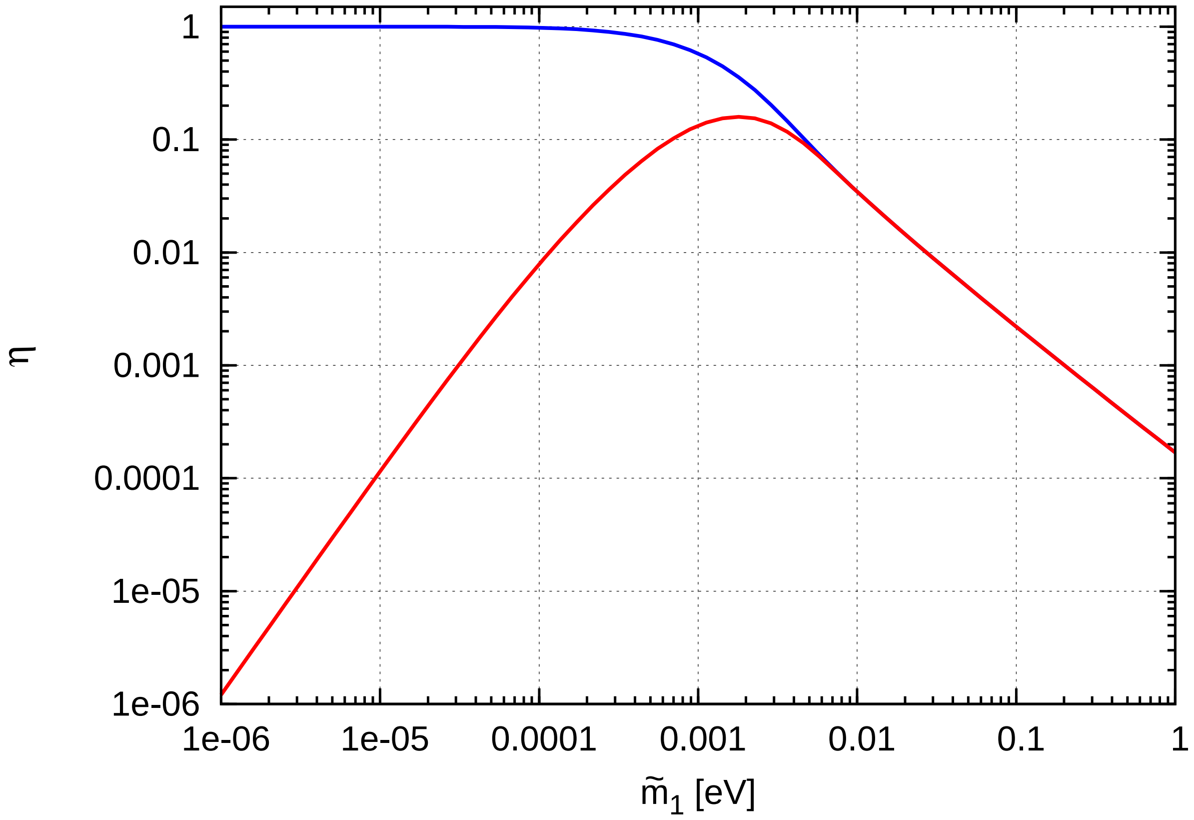
(at first order in the n-asymmetries and zeroth order in ϵ)

$$\gamma_D^{eq}(z) \; = \; n_N^{eq}(z) \, \frac{K_1(z)}{K_2(z)} \, \frac{1}{2} \, \Gamma_N$$

with $\quad \Gamma_N = \dfrac{(\lambda^\dagger \lambda)_{11} \; M}{8\pi} \quad$ and $\quad \mathcal{L} = \lambda_{\alpha i} \, \bar{\ell}_\alpha P_R N_i \tilde{h} + \ldots$

strength $\quad \longrightarrow \quad \dfrac{\Gamma_N}{H(T=M)} \simeq \dfrac{\sqrt{g_*}}{40} \; \dfrac{m_P \; (\lambda^\dagger \lambda)_{11}}{M}$

- If $M \searrow$, just decrease $(\lambda^\dagger \lambda)_{11}$ to keep $\frac{\Gamma_N}{H(T=M)}$ constant.
- ϵ is -basically- independent of $(\lambda^\dagger \lambda)_{11}$.
- $\gamma_D^{eq}(T) \; \propto \; e^{-M/T}$



— $Y_N^i = 0$ — $Y_N^i = Y_N^{eq}$

$$\frac{\Gamma_N}{H(T{=}M)} = \frac{\tilde{m}_1}{m_*}$$

$\tilde{m}_1 \equiv \frac{(\lambda^\dagger \lambda)_{11}\ v^2}{M_1} \ \rightarrow$ contribution of N_1 to $\sum_i m_{\nu_i}$.

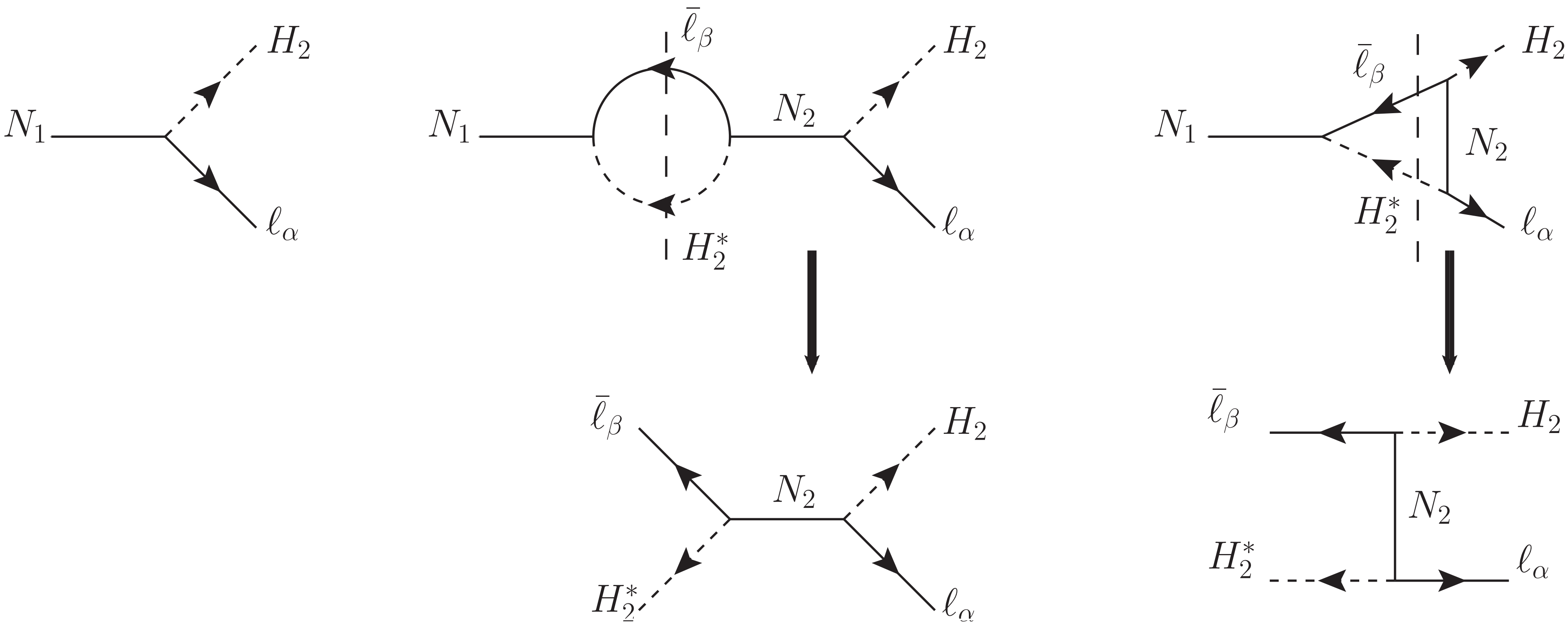
$m_* \equiv \frac{16}{3\sqrt{5}}\pi^{5/2}\sqrt{g_*}\frac{v^2}{m_P} \sim 10^{-3}$ eV

η is maximum for $\tilde{m}_1 \ \sim\ m_* \ \sim\ 10^{-3}$ eV !!

Two types of washouts (cont.)

♣ $\epsilon \quad \Longrightarrow \quad \ell\, h \leftrightarrow \overline{\ell h}$

$\epsilon \quad \propto \quad$ CP odd phase $\quad \times \quad$ CP even phase



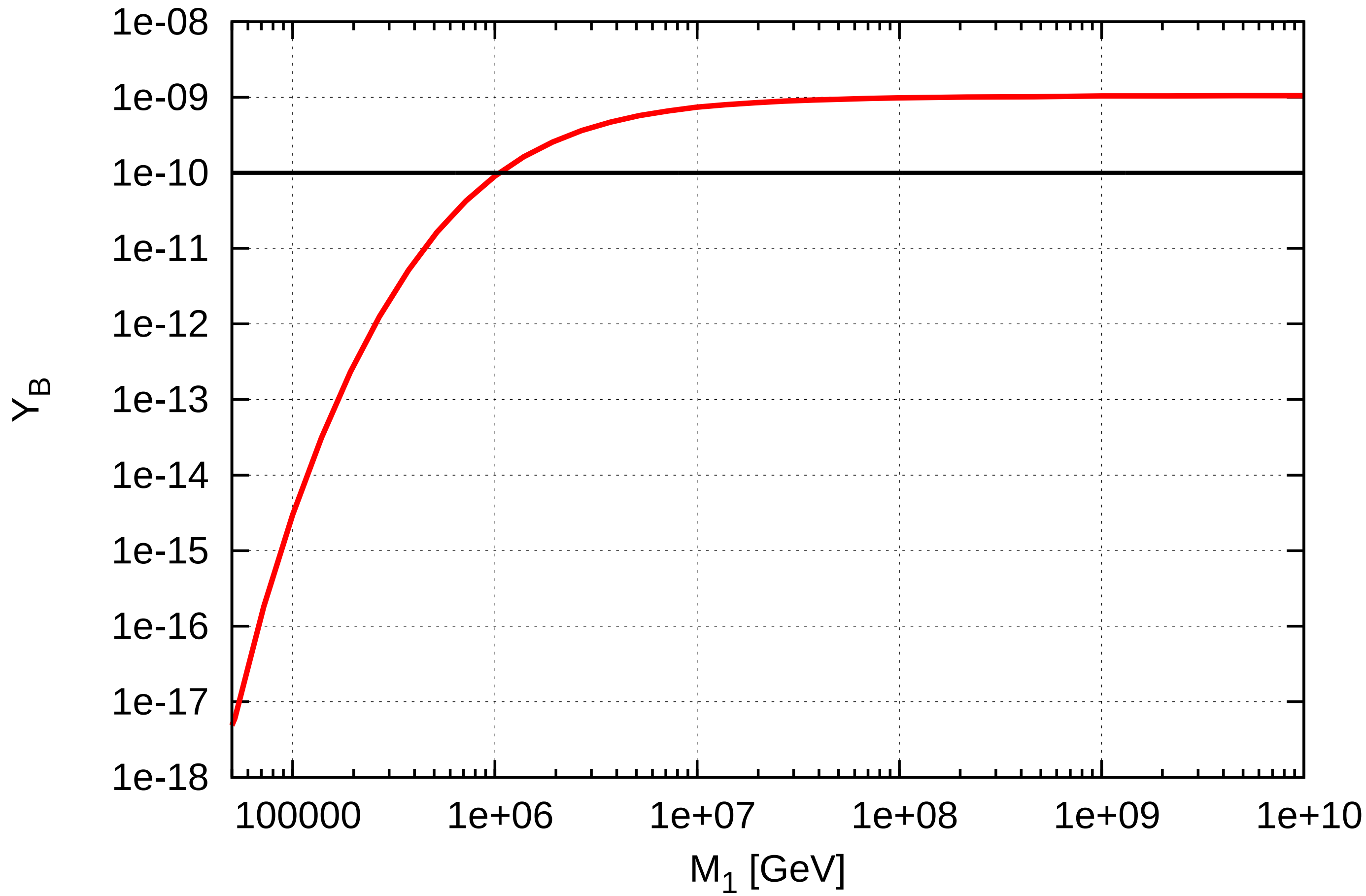
Two types of washouts (cont.)

♣ $\epsilon \quad \Longrightarrow \quad \ell\, h \leftrightarrow \overline{\ell h}$

strength $\quad \longrightarrow \quad \dfrac{\Gamma(\ell\, h \leftrightarrow \overline{\ell h})}{H(T=M)} \propto \left(\dfrac{M}{M_2}\right)^2 \dfrac{m_P\,(\lambda^\dagger\lambda)^2_{22}}{M}$

- $\epsilon \quad \longleftrightarrow \quad \ell\, h \leftrightarrow \overline{\ell h}$
- If M $\searrow$ and you decrease $(\lambda^\dagger\lambda)_{22}$ to keep $\frac{\Gamma}{H}$ const $\rightarrow$ ϵ $\searrow$

  If M $\searrow$ and you keep ϵ $=$ const. $\rightarrow$ $\frac{\Gamma(\ell\, h \leftrightarrow \overline{\ell h})}{H(T=M)}$ $\nearrow$
- $\dfrac{\gamma_{N_2}}{n_\ell^{eq} H} \propto \dfrac{T}{M} \quad \left(\text{or } \dfrac{T^3}{M^3}\right) \qquad \text{for } T \ll M$



$$\frac{\Gamma_N}{H(T{=}M)} = 1 \qquad \frac{M_2}{M_1} = 10 \qquad (\lambda^\dagger \lambda)_{22} = 2 \times 10^{-4}$$

$$(\implies \epsilon = \text{ const. })$$

Thermal baryogenesis at low energies

We keep exemplifying with leptogenesis from sterile neutrino decays.

If $(\lambda^\dagger\lambda)_{11} \sim (\lambda^\dagger\lambda)_{22}$, what would be the scale of leptogenesis?:

$$\begin{array}{ccccccc} Y_B^f & = & \kappa & \epsilon & & \eta & \\ 10^{-10} & \sim & 10^{-3} & 10^{-1}(\lambda^\dagger\lambda)_{22} & \dfrac{1}{(\lambda^\dagger\lambda)_{11}} & 10^{-17}\, M_1[\mathrm{GeV}] & (\eta \sim \frac{m_*}{\tilde{m}}) \end{array}$$

$\Longrightarrow \quad M_1 \sim 10^{11}\mathrm{GeV}$; actually $M_1 \gtrsim 10^{11}\mathrm{GeV}$

Two problems to lower the energy scale

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

- Connection with light neutrino masses:

  Type I seesaw: $\epsilon \quad \sim \quad \frac{3}{16\pi}\frac{m_i}{v^2} M_1 \qquad\qquad (\text{type I seesaw})$

  $$|\epsilon| \leq \epsilon^{\mathsf{DI}}_{\mathsf{max}} = \frac{3}{16\pi}\frac{M_1}{v^2}(m_3 - m_1) \implies M_1 \gtrsim 10^9\ \text{GeV} \qquad\qquad (\eta \leq 1)$$

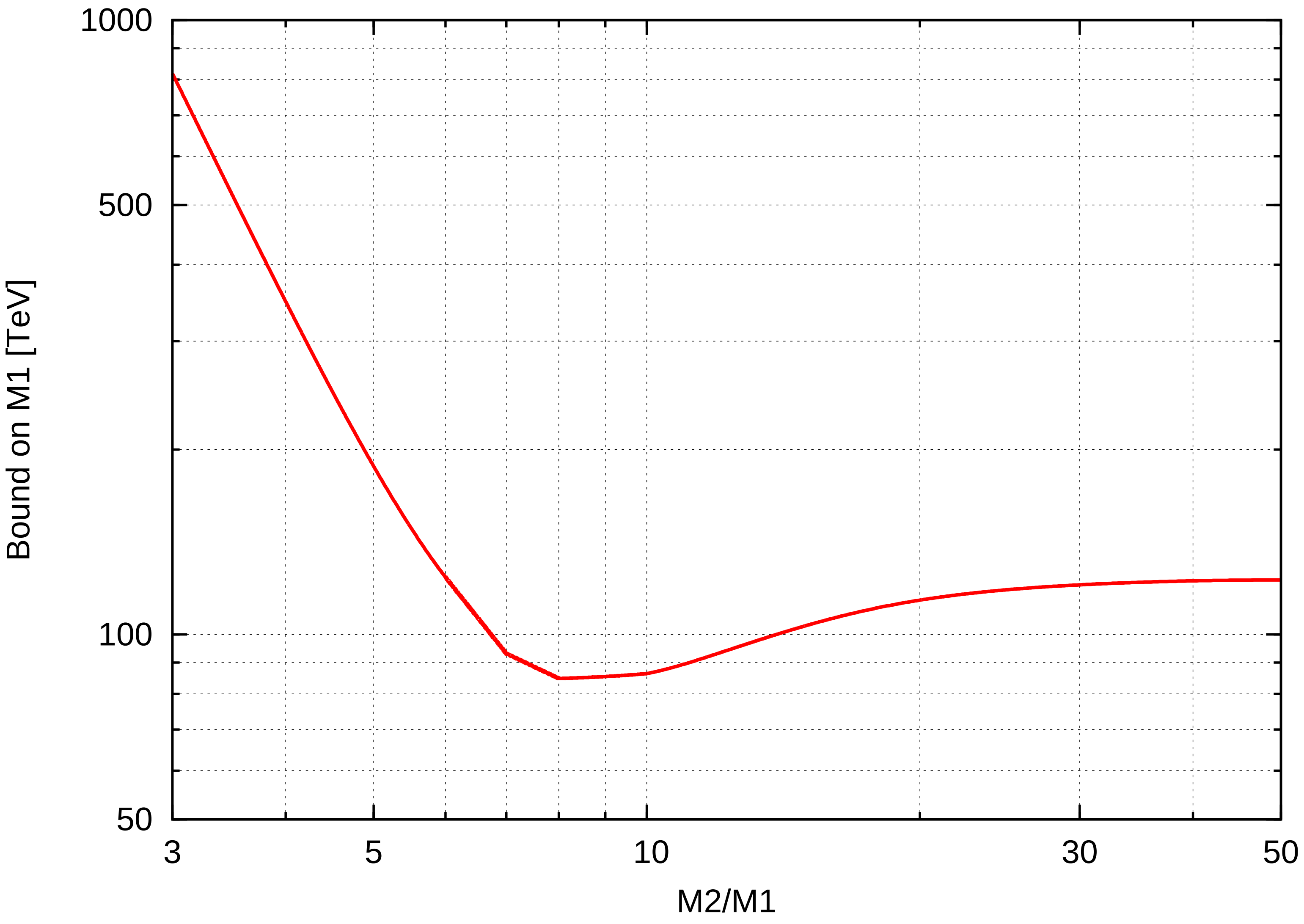
  Some alternatives: Inverse seesaw, radiative seesaws, ...

- Even with no connection to neutrino masses:

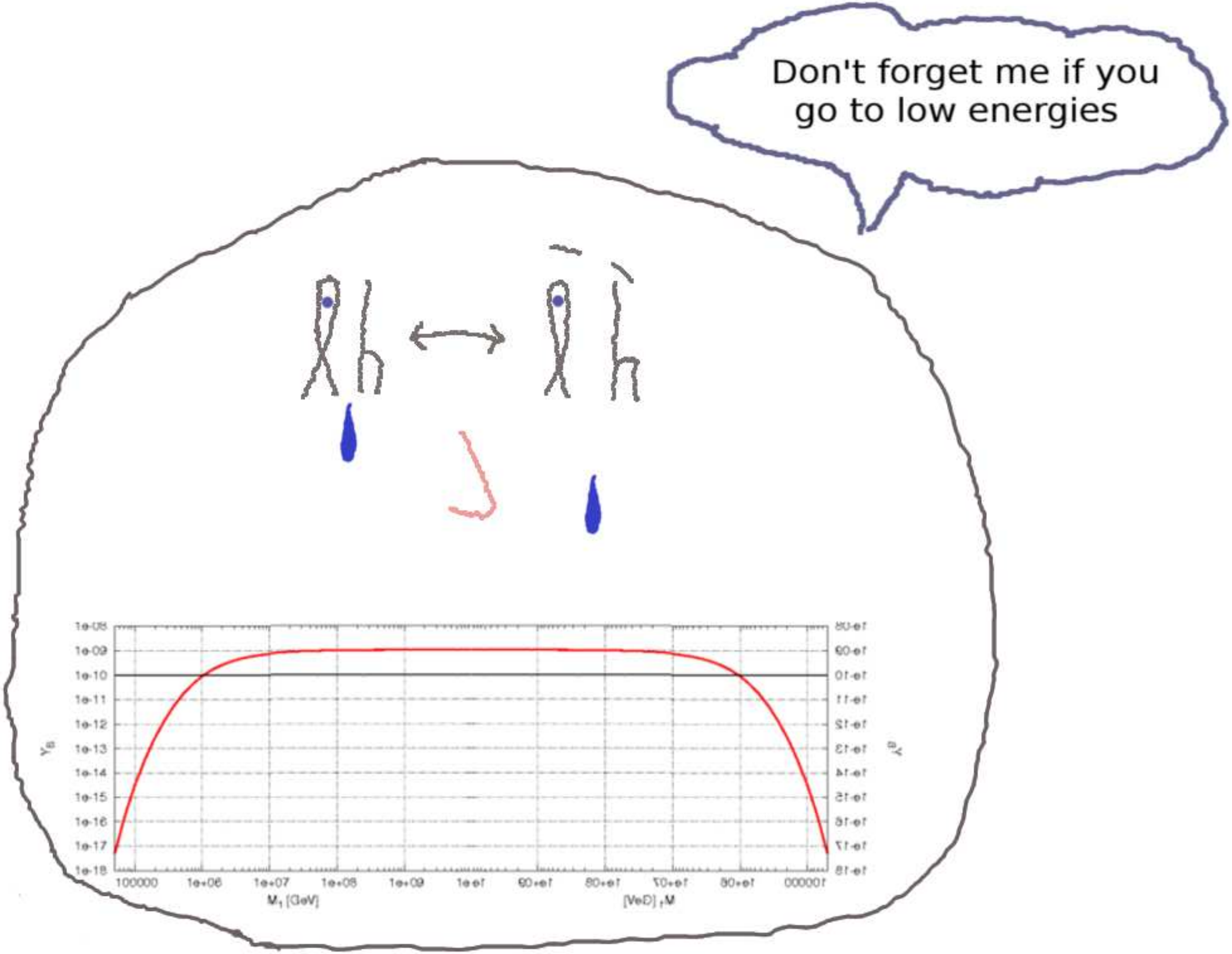
  Washout processes inherent to the existence of CP violation

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

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



[JR, JCAP 1403 (2014) 025]


Don't forget me if you go to low energies
1e-08
1e-09
1e-10
1e-11
1e-12
1e-13
1e-14
1e-15
1e-16
1e-17
1e-18
Y_B
100000
1e+06
1e+07
1e+08
1e+09
M_1 [GeV]

Motivations for baryogenesis at low energy scales

- Experimental accessibility
- Some supergravity models require $T_{rh} \lesssim 10^5 \ - \ 10^7$ GeV
- Many models of physics BSM incorporate particles with $M \sim O\left(1\right)$ TeV
- Baryogenesis at $T \gtrsim \mathrm{few\ TeV's}$ could become severely disfavored, e.g. if some lepton number violating processes are observed at the LHC

Ways for thermal Baryogenesis at low energies

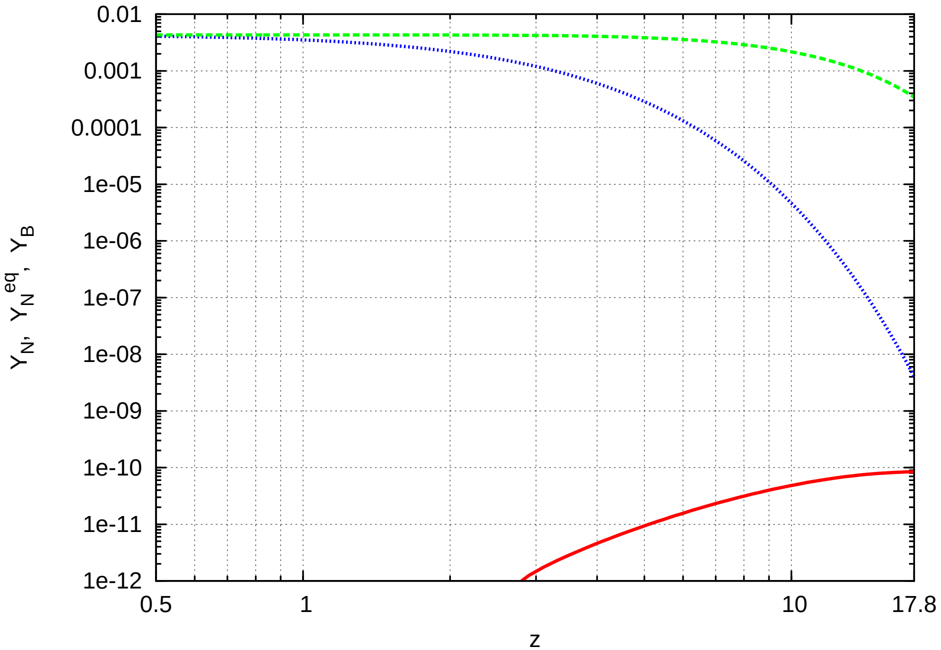
1) Initial thermal density $+$ late decay

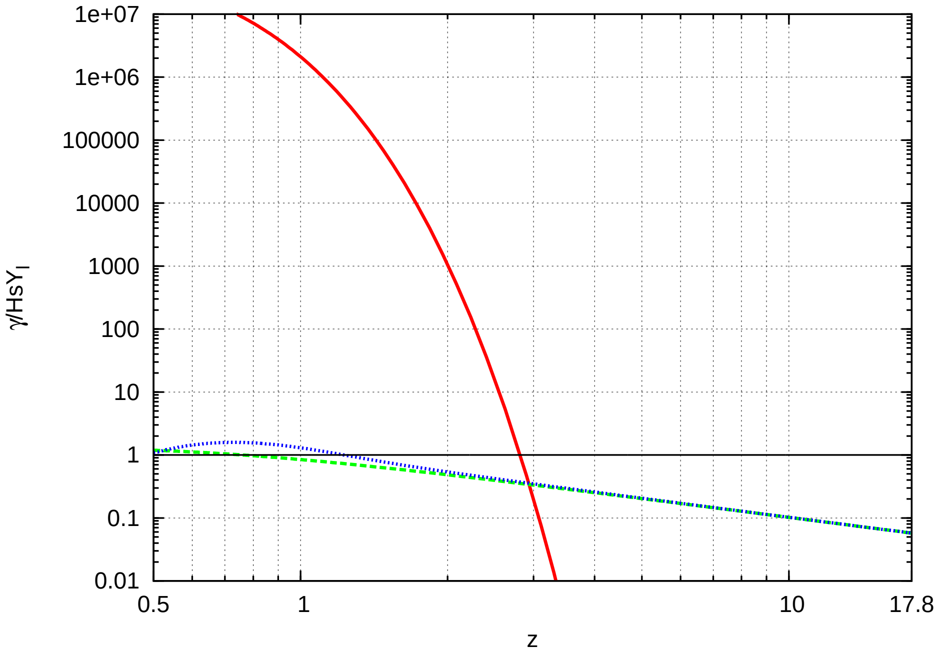
If the N_1 are produced at $T \gg M_1$ by a process different from the Yukawa interactions, then $\lambda_{\alpha 1}$ can be chosen small enough to have the N_1 decay at $T \ll M_2$.

$\Rightarrow$ 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.

- $M_{1\,\mathrm{min}} \sim 2500\ (2000)$ GeV for $T_{sfo} = 140\ (80)$ GeV $(\not{L})$.
- $M_{1\,\mathrm{min}} \gtrsim O\,(1)$ GeV $(\not{B})$

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





$$M_1 = 2{,}5\ \mathrm{TeV} \qquad M_2 = 10\, M_1 \qquad T_{sfo} = 140\ \mathrm{GeV}$$

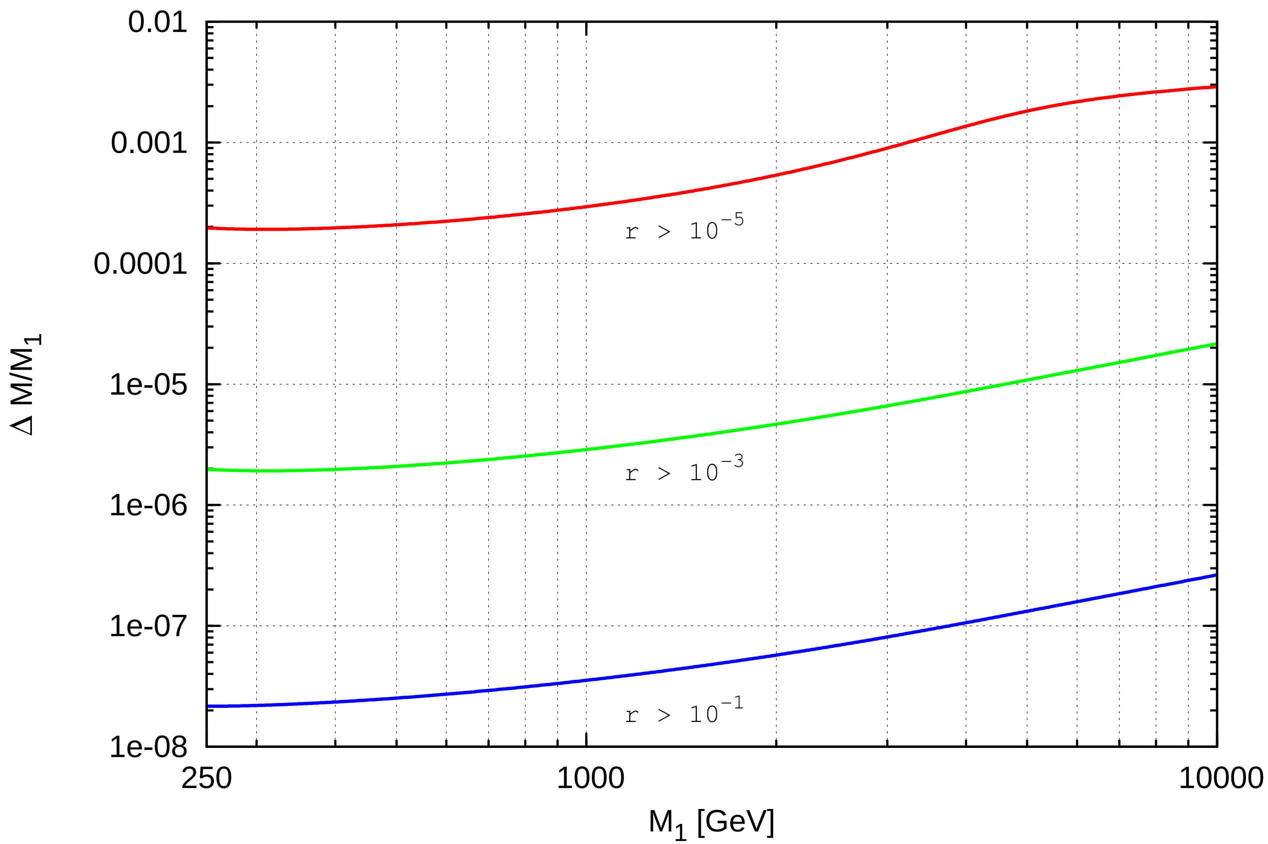
$$(\lambda^\dagger\lambda)_{11} = 2\times 10^{-15} \qquad (\lambda^\dagger\lambda)_{22} = 2\times 10^{-5}$$

2) Degenerate neutrinos

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

$$\Gamma_{N_1,N_2} \ll \Delta M \ll M_1 \qquad \Longrightarrow \qquad |\epsilon| \propto \frac{(\lambda^\dagger \lambda)_{22}}{\delta}$$

$$\delta \equiv \frac{\Delta M}{M_1} \qquad \qquad \Delta M \equiv M_2 - M_1$$



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

$$\delta \times r \lesssim 10^{-8} \qquad \text{for} \qquad M_1 \sim 4 \text{ TeV}$$

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

3) Massive decay products

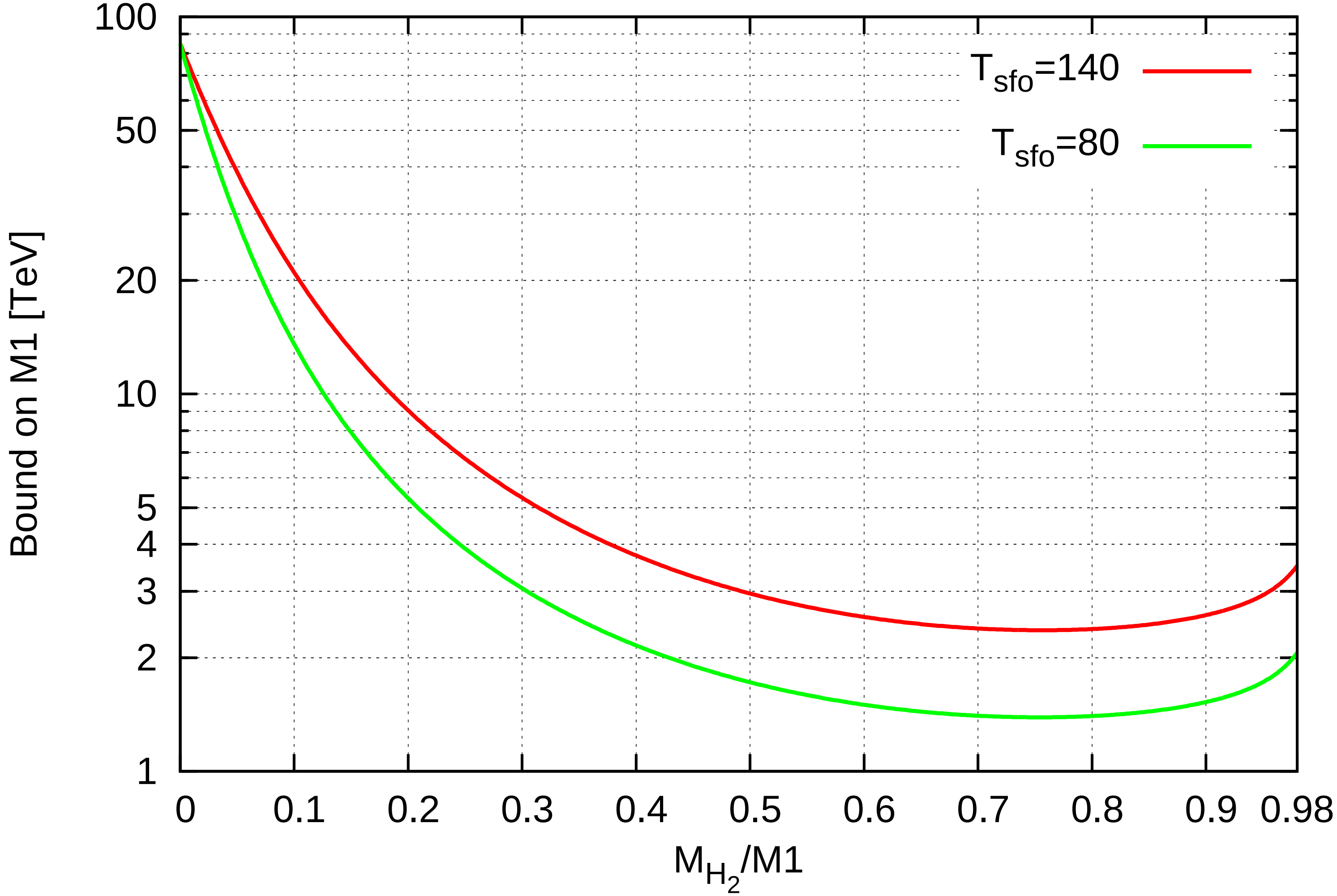
In baryogenesis from annihilations, $\chi\chi \to \psi u$, it is possible to take $m_\psi > m_\chi \implies$ Boltzmann suppression $\propto e^{-m_\psi/T}$ of the washouts without reducing the CP asymmetry.

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

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, JCAP 1403 (2014) 025]

There is a crucial point for this mechanism to work:

$$\frac{\mathrm{d}Y_{\Delta L}}{\mathrm{d}z} = -\frac{1}{z}\left\{Y_{\Delta L}\,\frac{\gamma_{N_2}^{eq}}{n_\ell^{eq} H} + Y_{\Delta H_2}\,\frac{\gamma_{N_2}^{eq}}{n_{H_2}^{eq} H}\right\} + \dots$$

The first term decouples exponentially, but what about the second?

$$\downarrow$$

relation among $Y_{\Delta H_2}$ and $Y_{\Delta L}$

$$\downarrow$$

If $Y_{\Delta H_2} = c\, Y_{\Delta L} \longrightarrow$ the mechanism does not work $\quad (c = \mathrm{const.})$

$Y_{\Delta H_2}$ must vanish exponentially without erasing -or canceling- $Y_{\Delta L}$

fast $H_2 a_1 \leftrightarrow a_2 a_3 \implies \mu_{H_2} = \sum_i \mu_i \implies Y_{\Delta H_2} \propto e^{-M_{H_2}/T} \; (m_i \ll M_{H_2})$

Alternatively, take a real scalar or Majorana fermion as the massive particle $(Y_\Delta = 0)$ [JR, Nuria Rius, in arXiv soon]

Model (in)dependence

$$\frac{\mathrm{d}Y_{N_1}}{\mathrm{d}z} = a\, C(z)\left(Y_{N_1} - b\, Y_{N_1}^{eq}\right)$$

$$\frac{\mathrm{d}Y_{B-L}}{\mathrm{d}z} = c\,\frac{\epsilon_1}{3} C(z)\left(Y_{N_1} - b\, Y_{N_1}^{eq}\right) - Y_{B-L}\left[a\, d\, W_{N_1}^{\Delta L=1}(z) + e\, W_{N_2}^{\Delta L=2}(z)\right]$$

$$C(z) \propto (\lambda^\dagger\lambda)_{11} \quad W_{N_1}^{\Delta L=1} \propto (\lambda^\dagger\lambda)_{11} \quad W_{N_2}^{\Delta L=2} \propto (\lambda^\dagger\lambda)_{22}^2 \quad \epsilon_1 \propto (\lambda^\dagger\lambda)_{22}$$

$$\boxed{Y_B^{\text{max}}(M_1) = \frac{c\, b}{a\sqrt{e}}\, Y_B^{\max\mathrm{IDM}}(M_1)}$$

- Without low scale mechanism: $Y_B^{\max\mathrm{IDM}}(M_1) \propto \sqrt{M_1}$
- Initial thermal density + Late decay: $Y_B^{\max\mathrm{IDM}}(M_1) \propto M_1^{0{,}9}$
- Massive decay product: $Y_B^{\max\mathrm{IDM}}(M_1) \propto M_1^p\,, \quad p \gtrsim 4$

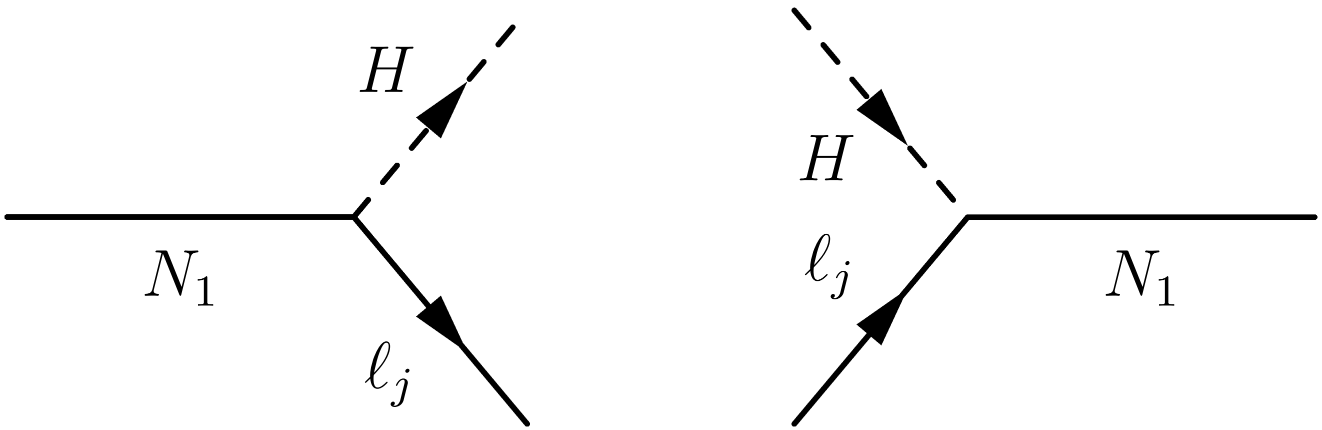
Take $Y_B^{\text{max}}(M_1) = 8{,}6 \times 10^{-11}$ and get $M_{1\,\min}$

Conclusions and outlook

- There are *nice* motivations to study thermal baryogenesis at low energies, but one should keep in mind that the “natural” scale seems to be very high $T \gg 100$ TeV and there are severe problems to have it at the TeV scale.
- Baryogenesis at the TeV scale -or lower- can be achieved by:
    - Initial thermal density $+$ late decay
    - Degenerate heavy particles
    - Massive decay -or annihilating- product “p” $+$ a way to $\cancel{Y_{\Delta p}}$
- For experimental accessibility, the coupling of the heavy particles with the SM sector is as important as the scale of baryogenesis.

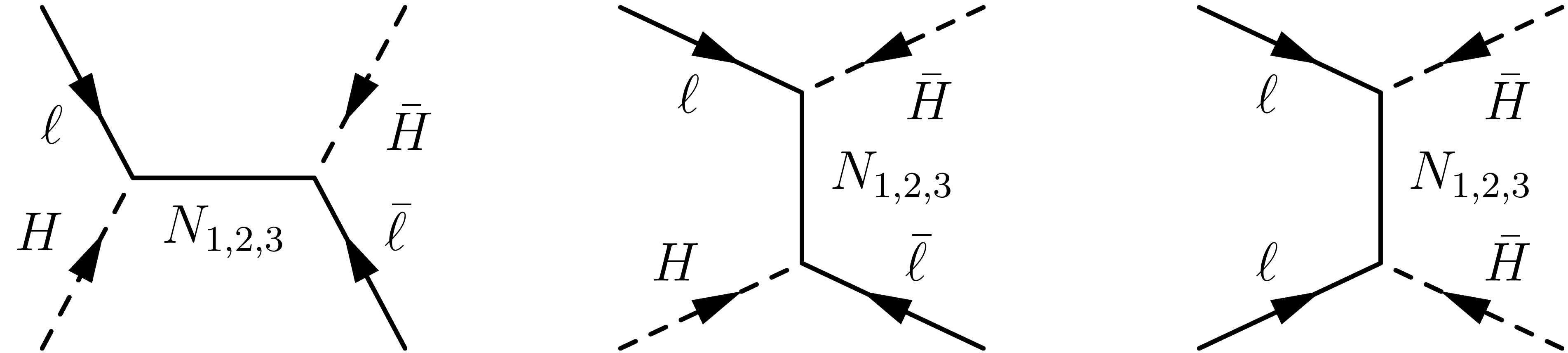
Additional slides ...

Relevant processes for N_1–Leptogenesis

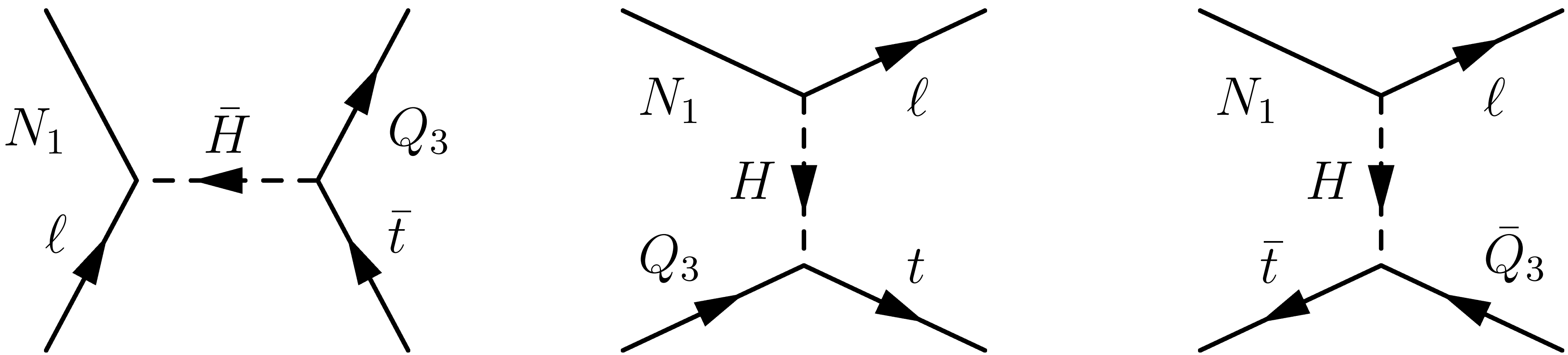


(c) Decay and inverse decay (production) of N_1.

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



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



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

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

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

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

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]

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

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

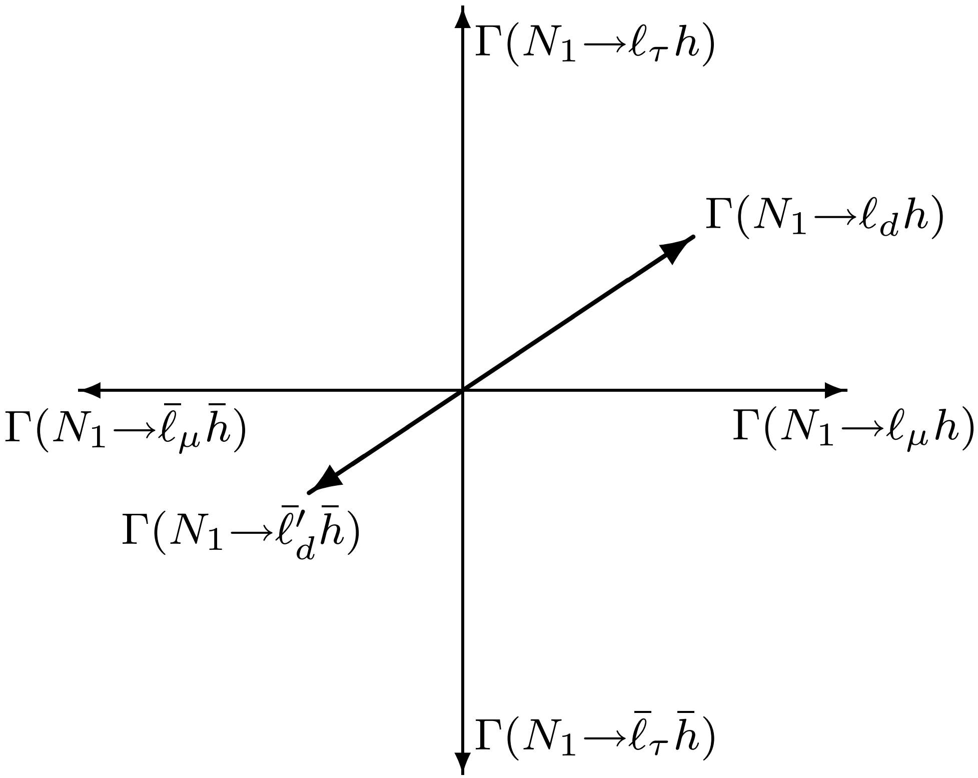
Define $Y_{\Delta_\alpha} \equiv \frac{1}{3}Y_B - Y_{L_\alpha}$ ($B/3 - L_\alpha$ is conserved by sphalerons)

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

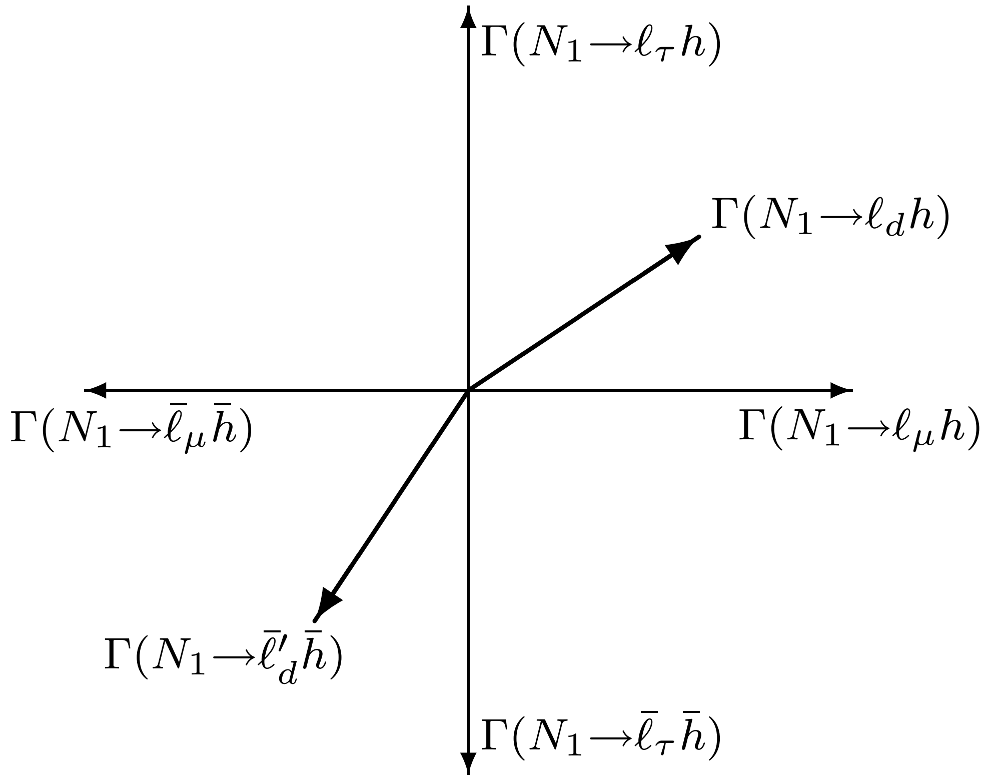
with $z \equiv M_1/T$, $\quad K_\alpha \equiv |\langle \ell_\alpha | \ell_d \rangle|^2$

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

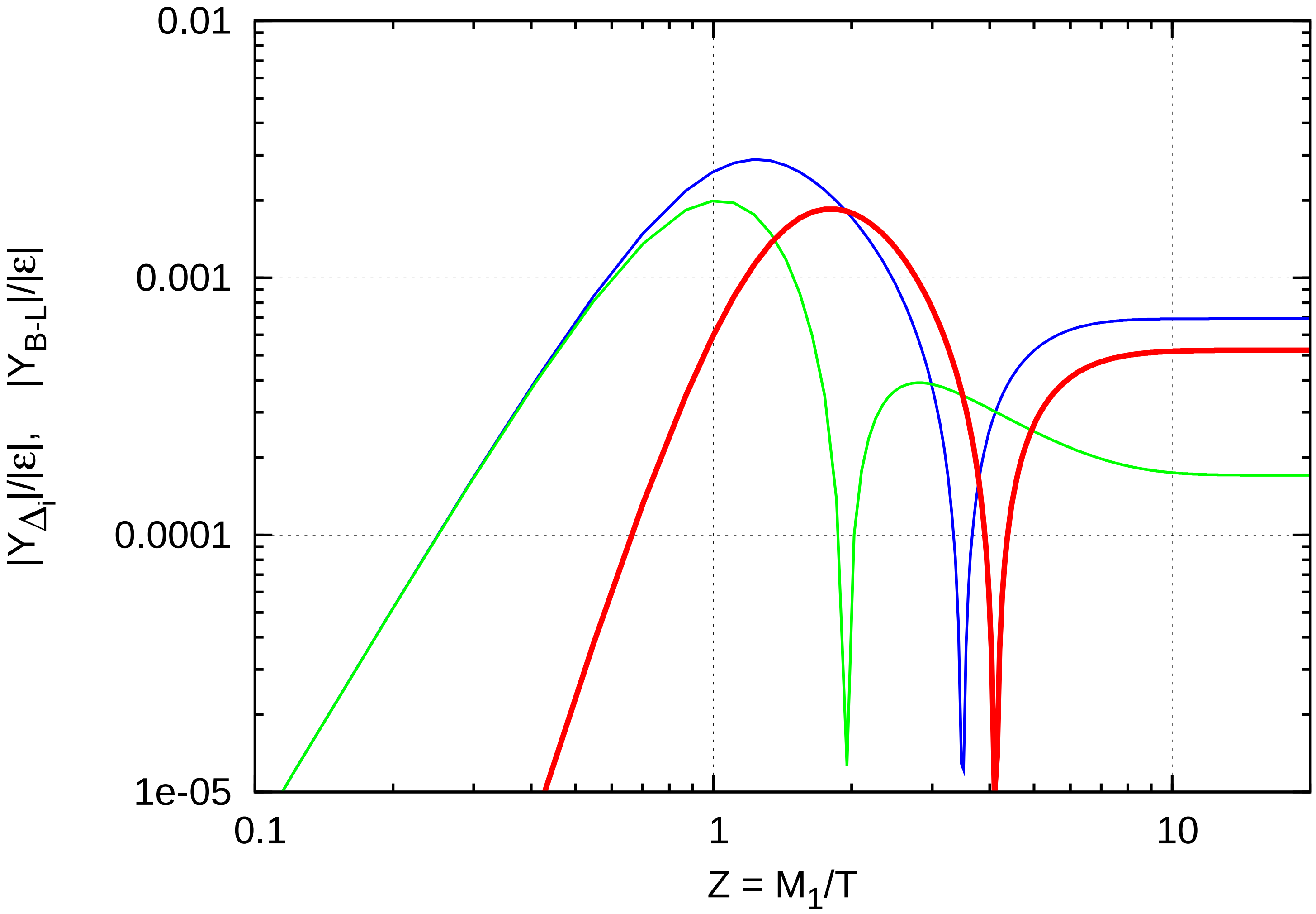
Two types of CP violation



(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

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

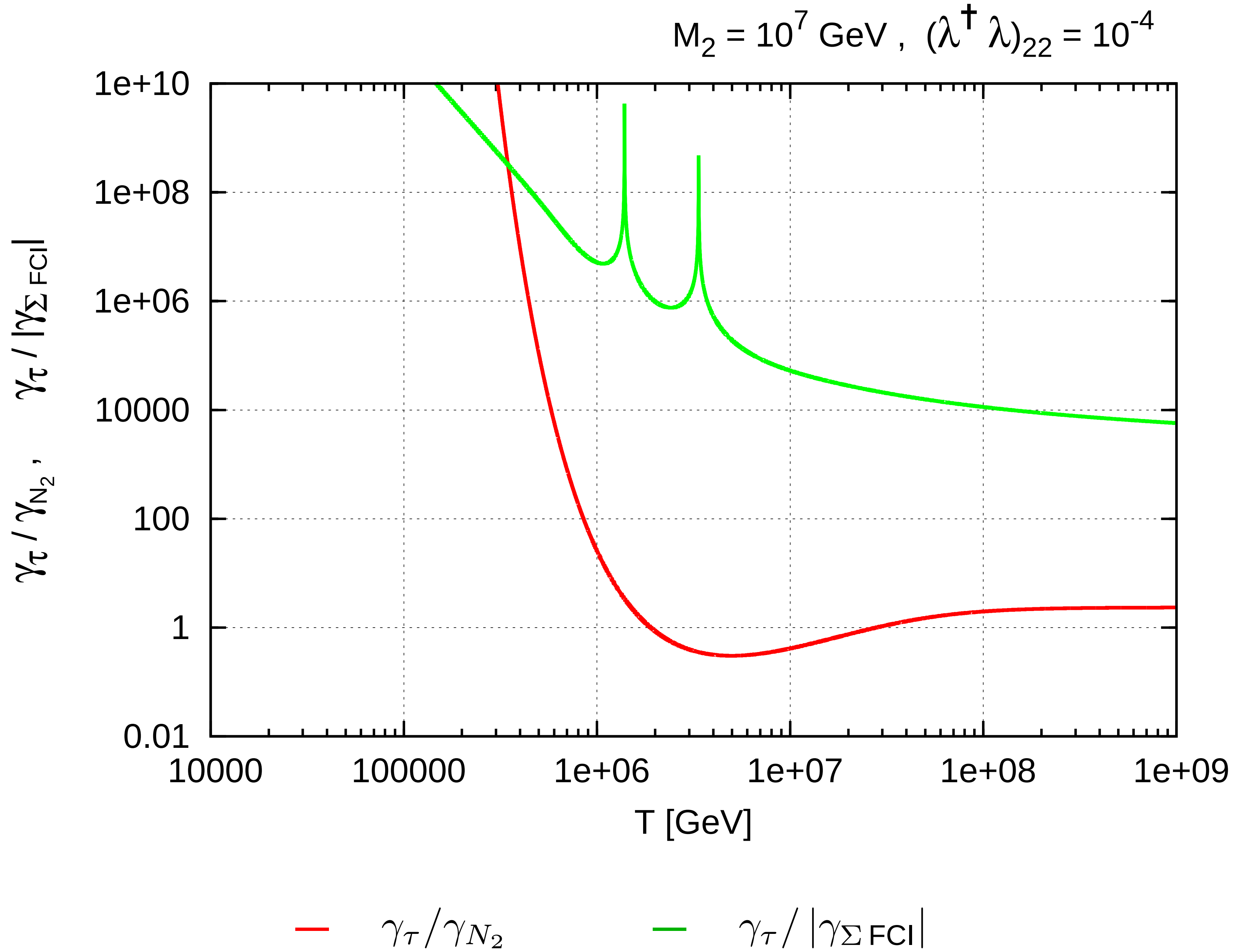
where $z \equiv M_1/T$, $Y_X \equiv n_X/s$, $y_X \equiv (Y_X - Y_{\bar{X}})/Y_X^{eq}$, and $Y_{\Delta_\alpha} \equiv Y_B/3 - Y_{L_\alpha}$.

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

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

$$\frac{\mathrm{d}Y_{N_2-\bar{N}_2}}{\mathrm{d}z} = \frac{-1}{sHz}\sum_\alpha \gamma_{\ell_\alpha h}^{N_2}\left[y_{N_2}-y_{\ell_\alpha}\right] \ ,$$

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



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

Light neutrino masses:

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

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

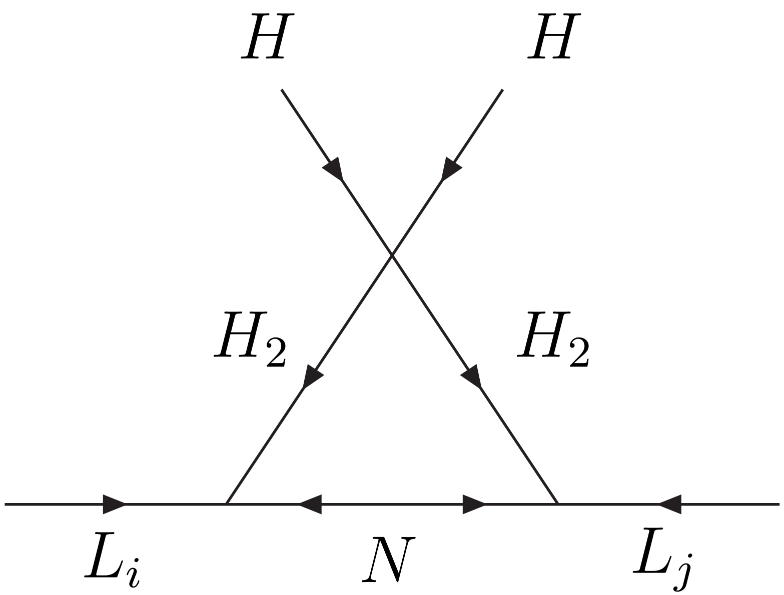
$$\lambda_{\alpha 1} \sim 10^{-5} - 10^{-4}, \quad \mu_2/M_2 \sim 10^{-8} - 10^{-6}, \quad \lambda'_{\alpha 2} \sim 10^{-8} - 10^{-7} \ .$$

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 $\mu_2 \gtrsim \Gamma_{N_2}$.

Radiative seesaw   E.g. Inert Doublet Model



Leptogenesis: Different ways for baryogenesis at the TeV scale

Or no seesaw: Dirac leptogenesis

$$
\begin{array}{ccc}
\text{L-asymmetry in } \psi_L & = & -\text{ L-asymmetry in } \psi_R \\
\downarrow \ (\text{sphal}) & & \downarrow \\
\text{B-asymmetry} & & \text{part stored in } N_R \text{ until } T \ll T_{sfo}
\end{array}
$$

Note: This works because neutrino masses are very tiny

Testability

Standard leptogenesis scenarios with hierarchical singlet neutrinos cannot be proved in foreseeable experiments ($M \gtrsim 10^9$ GeV). But ...

Experimental and observational inputs

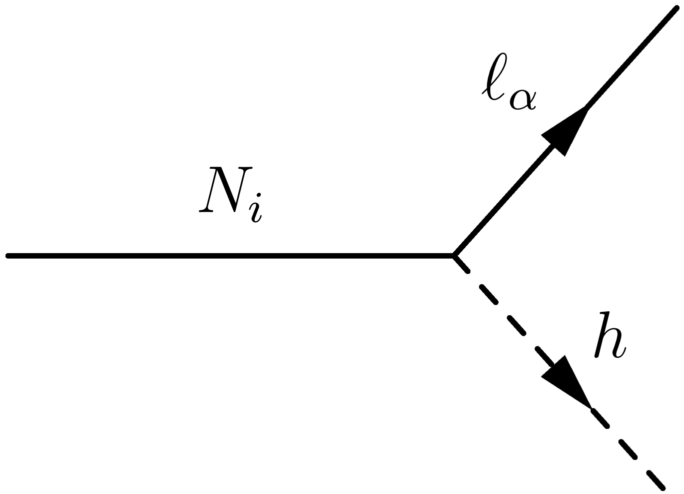
- Bound on $T_{\rm reheating} \lesssim 10^{16} GeV$ (but difficult to saturate the bound).
- Observation of QCD sphalerons in heavy ion collisions at the LHC (chiral magnetic effect). [Kharzeev,McLerran,Warringa, 2008]
- $0\nu\beta\beta$ and L violation at colliders.
- $\sum_i m_{\nu_i}$
- Leptonic CP violation.
- CLFV and EDMs (could favor or discard some models, e.g. in SUSY)
- SUSY
- Be open to surprises, e.g. CPT violation.

Falsifying Leptogenesis

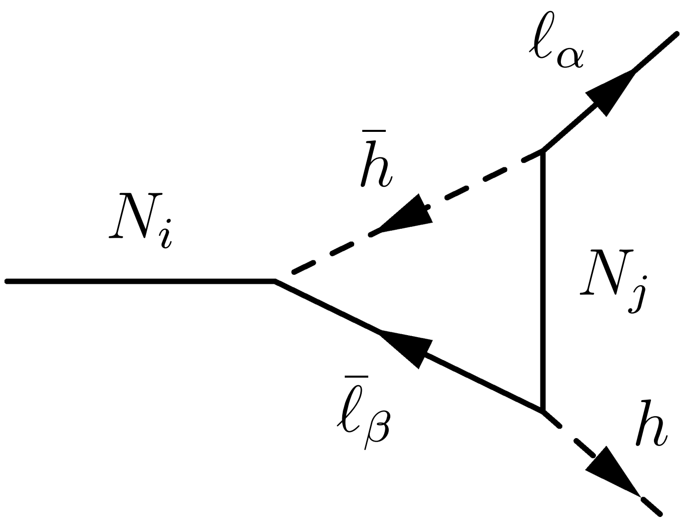
- Ruling out the seesaw mechanism
  - If neutrino masses are quasi-degenerate or inversely hierarchical, and $|m_{ee}| \lesssim 10$ meV
  - Other explanation to neutrino masses is found at the LHC (supersymmetric R-parity violating couplings or L-violating bilinear terms, leptoquarks, triplet Higgses, new scalar particles of Zee-Babu models, ...)
- Ruling out baryogenesis mechanisms above the electroweak scale, e.g. by finding at the LHC W_R + N, scalar or fermion triplets with non-negligible lepton number violating couplings (in all flavours).
- Discovery of a W_R coupled to a N (at the LHC) would rule out Type-I leptogenesis (for $m_{W_R} \lesssim 10$ TeV).

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

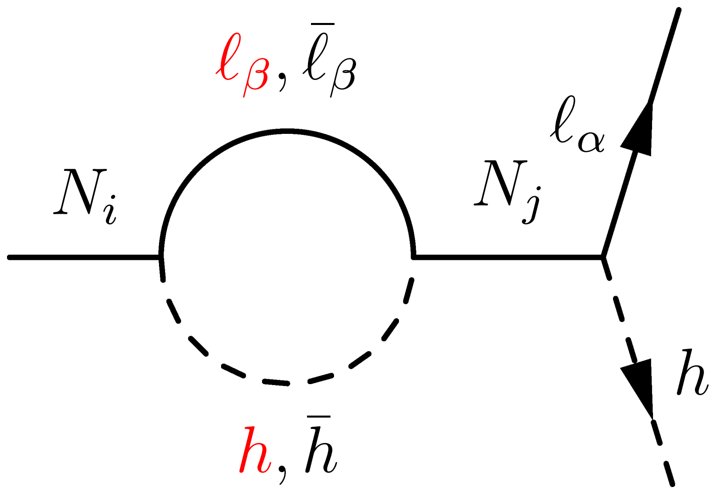
CP violation in decays



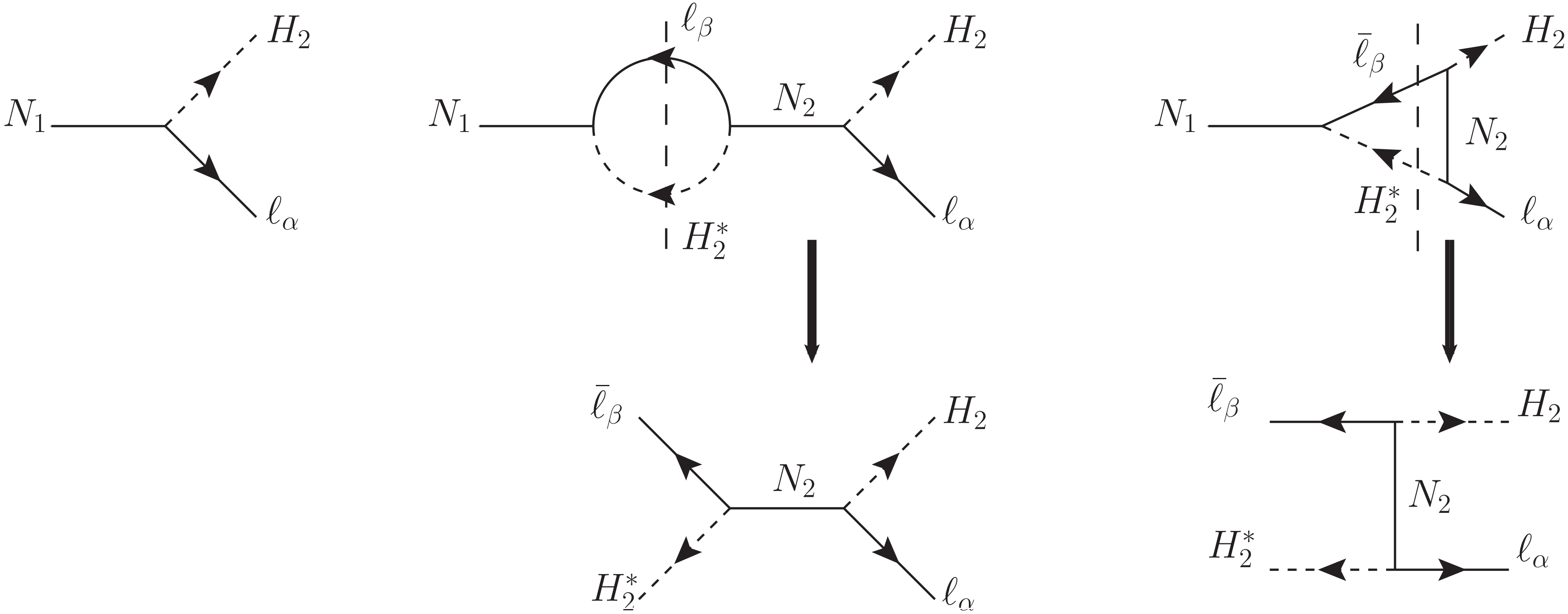
(c) Tree



(d) Vertex



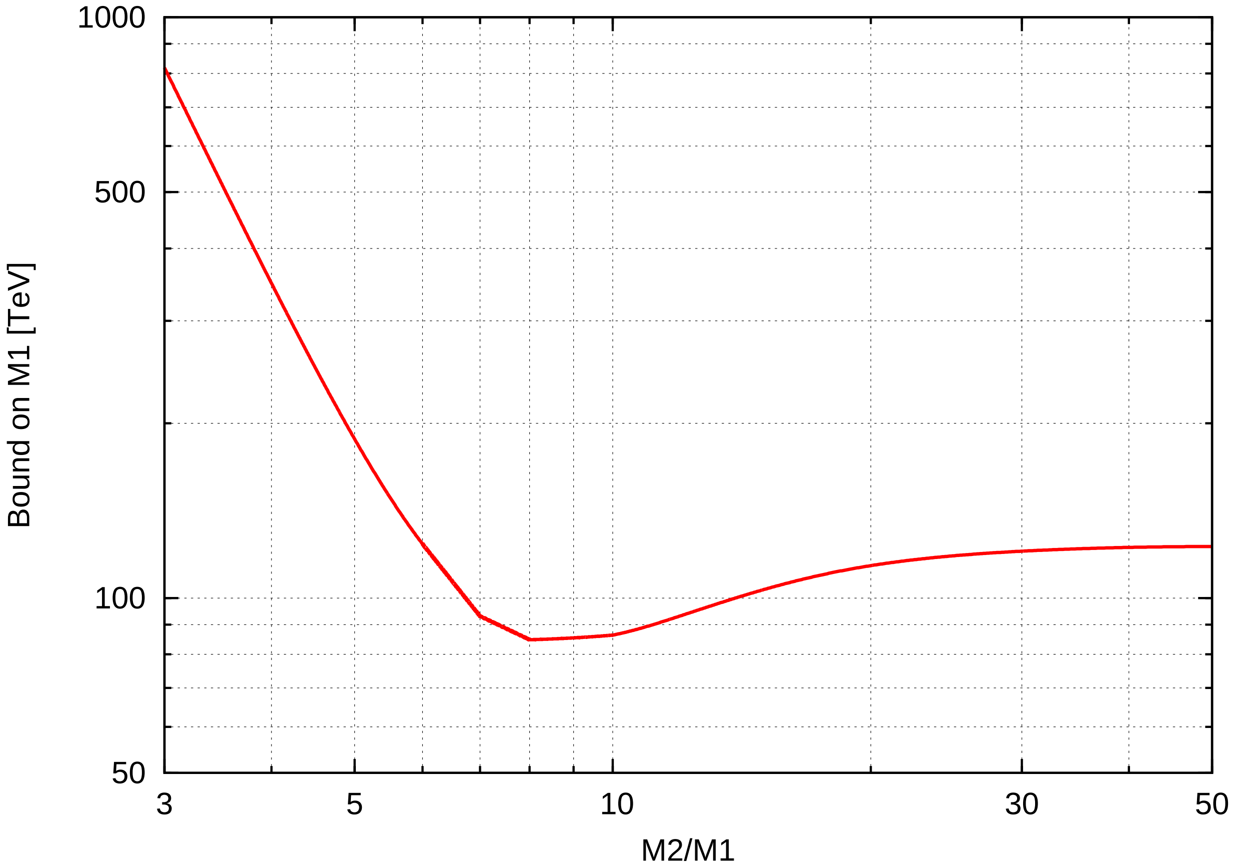
(e) Wave


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

Ways for thermal Baryogenesis at low energies

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, JCAP 1403 (2014) 025]

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).

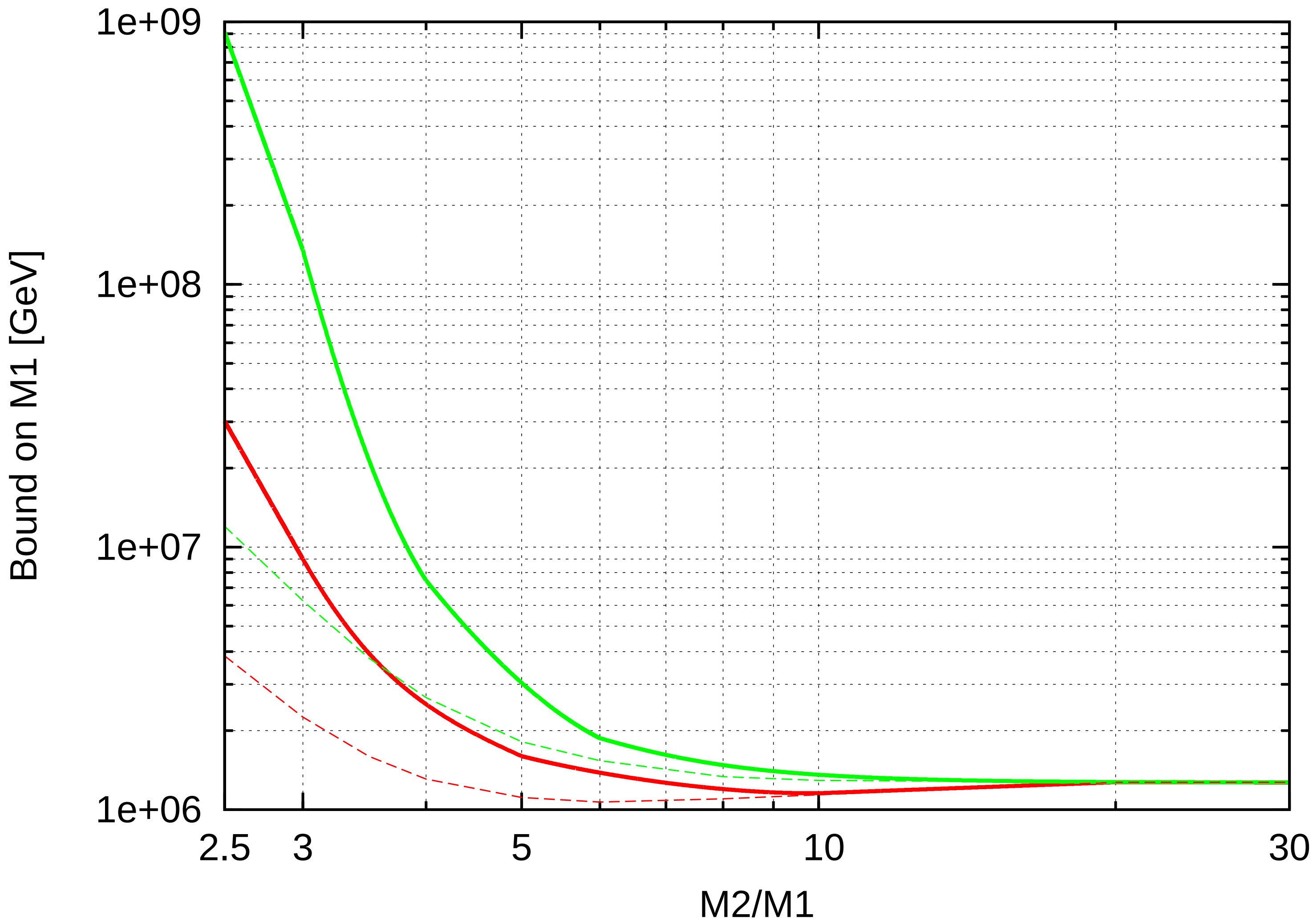
The mass matrix of the neutral sector in the basis ν_L, ν_R^c, s_L is

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

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

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

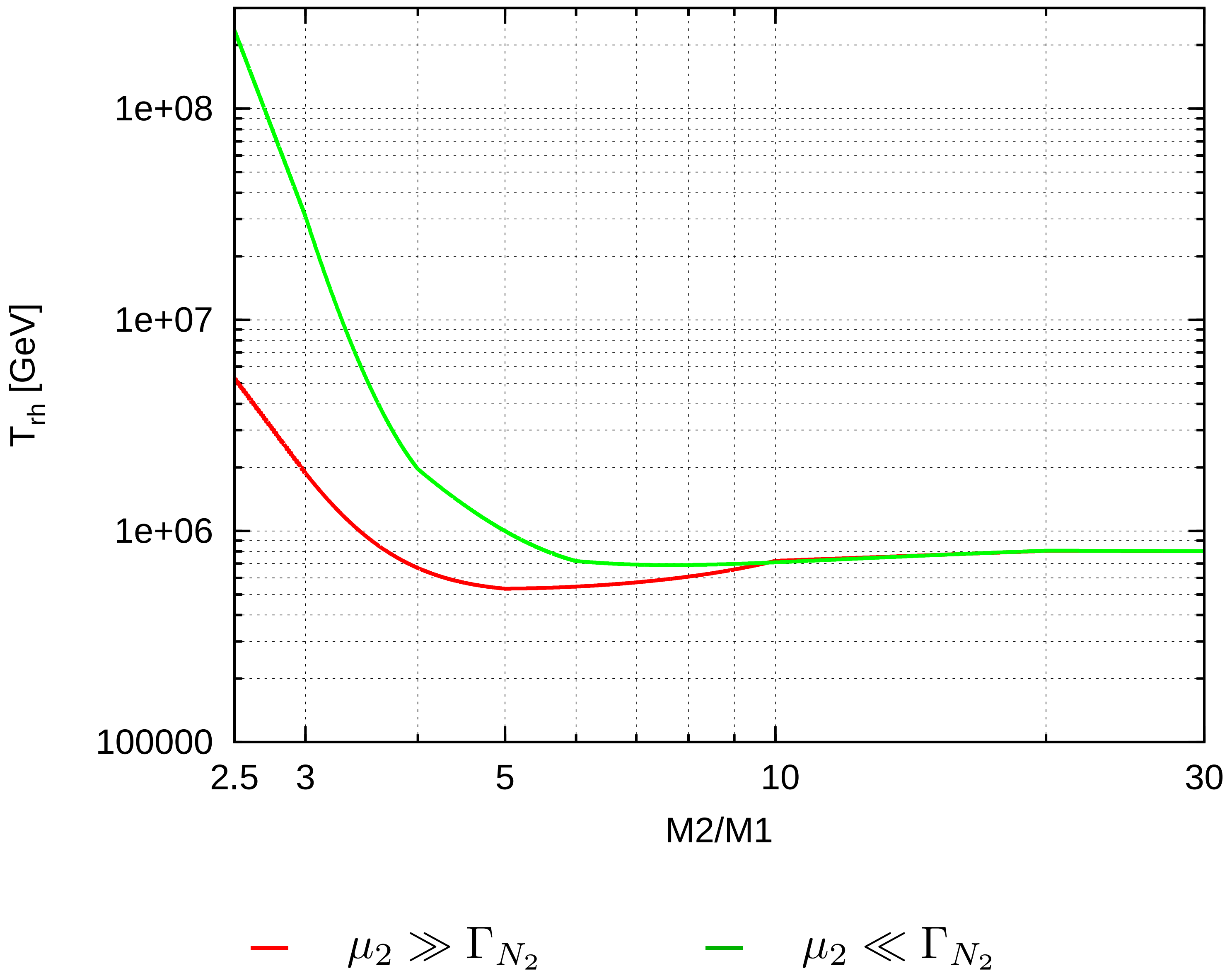
$$\text{mixing} \;\sim\; \frac{m_D}{M} \;\sim\; \sqrt{\frac{m_\nu}{\mu}}$$



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

[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.



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

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. [T. Hambye, 2002].

- 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.

- See also [Fong, Gonzalez-Garcia, Nardi, Peinado, 2013].

- Massive decay products provide an interesting way to lower the energy scale of baryogenesis.
- The inert doublet model can explain simultaneously neutrino masses, DM and the BAU at the TeV scale, without resorting to degenerate heavy neutrinos (for initial thermal abundance of N or with some fine tuning among phases).