Leptogenesis with small violation of B-L

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1. Introduction

• Neutrino masses and baryon asymmetry of the Universe (BAU) naturally explained by the seesaw mechanism

→ generically no testable

→ Davidson-Ibarra bound on M_1 for hierarchical heavy SM singlets:

$M_1 \gtrsim 10^9$ GeV (10^8 GeV if $M_2/M_1 \lesssim 10$).

→ tension between thermal leptogenesis and gravitino bound on the reheating temperature T_{RH} in SUSY seesaw scenarios with hierarchical RHN:

- Unstable gravitino → $T_{RH} \lesssim 10^5 - 10^7$ GeV ($10^9 - 10^{10}$ GeV) for $m_{3/2} \sim$ 100 GeV - 1 TeV ($\gtrsim$ 10 TeV)

- Gravitino is the LSP: bounds depend on the NLSP, but $T_{RH} \gtrsim 10^9$ GeV can be obtained for $m_{3/2} \gtrsim$ 10 GeV

Kawasaki et al. (2008)

• Global lepton number $U(1)_L$ slightly broken by small parameters μ, λ', protected from radiative corrections.

$$\mathcal{L}_L = -\lambda_{\alpha i}\,\widetilde{h}^\dagger\,\overline{P_R N_i}\ell_\alpha - \frac{1}{2}M_{ij}\overline{N_i^c}N'_j - \frac{1}{2}M_{ij}\overline{N_i''^c}N''_j + h.c.$$

$$\mathcal{L}_{\not L} = -\lambda'_{\alpha j}\,\widetilde{h}^\dagger\,\overline{P_R N'_j}\ell_\alpha - \lambda'_{\alpha j}\,\widetilde{h}^\dagger\,\overline{P_R N''_j}\ell_\alpha - \frac{1}{2}\mu_{ik}\overline{N_i^c}N_k - \frac{1}{2}\mu'_{jk}\overline{N_j'^c}N'_k + h.c.$$

$\lambda_{\alpha i}$ can be large, because they do not vanish in the $B-L$ conserved limit $\rightarrow$ in the absence of μ, μ' and $\lambda'_{\alpha i}$, a perturbatively conserved lepton number can be defined:

$$L_N = 1 \qquad L_{N'} = -1 \qquad L_{N''} = 0$$

$L_{\ell_\alpha} = 1$ for the SM leptons.

Example: Inverse seesaw $\rightarrow$ Only (N_i, N'_i) per generation, with $\mu_{ik} = \lambda'_{\alpha j} = 0$

Mohapatra, Valle (1986)

- Rich phenomenology:

- Large neutrino Yukawa couplings and heavy neutrino masses at the TeV scale

- Flavour and CP violating effects not suppressed by light neutrino masses

Bernabeu et al. (1987); NR, Valle (1990); González-García, Valle (1992);Gavela et al. (2009)

- Heavy neutrinos may be at LHC reach

Han, Zhang (2006); F. del Aguila et al. (2007); Kersten, Smirnov (2007)

- Two strongly degenerate RH neutrinos (quasi-Dirac fermion) $\longrightarrow$ resonant leptogenesis at $T \sim \mathcal{O}(1\ \text{TeV})$

Pilaftsis, Underwood (2005); Asaka, Blanchet (2008); Blanchet et al. (2010)

Low energy effective Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{c^{d=5}}{\Lambda_{LN}}\mathcal{O}^{d=5} + \sum_i \frac{c_i^{d=6}}{\Lambda_{FL}^2}\mathcal{O}_i^{d=6} + \dots \ ,$$

where Λ_{FL} can be $\mathcal{O}$(TeV) and $\Lambda_{LN} \gg \Lambda_{FL}$

If $B-L$ is approximately conserved:

i) N_i is a Majorana neutrino with small Yukawa couplings $\lambda'_{\alpha i}$,

$$\frac{(c_M^{d=5})_{\alpha\beta}}{\Lambda_{LN}} = \frac{\lambda'_{\alpha i}\lambda'_{\beta i}}{M_i} \ .$$

$$\frac{(c_M^{d=6})_{\alpha\beta}}{\Lambda_{FL}^2} = \frac{\lambda'_{\alpha i}\lambda'^{*}_{\beta i}}{M_i^2} \ .$$

ii) The N_i is a Dirac or quasi Dirac neutrino with four degrees of freedom $\rightarrow$ there are two Majorana neutrinos N_{ih} and N_{il} with masses $M_i + \mu_i$ and $M_i - \mu_i$ respectively.

If $B - L$ is conserved, $\mu_i = 0$ and $N_i = (N_{ih} + iN_{il})/\sqrt{2}$ is a Dirac fermion.

Yukawa interactions:

$$\mathcal{L}_{Y_{Ni}} = -\lambda_{\alpha i}\,\widetilde{h}^\dagger\,\overline{P_R\frac{N_{ih}+iN_{il}}{\sqrt{2}}}\ell_\alpha - \lambda'_{\alpha i}\,\widetilde{h}^\dagger\,\overline{P_R\frac{N_{ih}-iN_{il}}{\sqrt{2}}}\ell_\alpha + h.c.,$$

Contribution of a quasi Dirac heavy neutrino to the Weinberg operator at leading order:

$$\frac{(c^{d=5}_{QD})_{\alpha\beta}}{\Lambda_{LN}} = (\lambda'_{\alpha i} - \frac{\mu_i}{M_i}\lambda_{\alpha i})\frac{1}{M_i}\lambda_{\beta i} + \lambda_{\alpha i}\frac{1}{M_i}(\lambda'_{\beta i} - \frac{\mu_i}{M_i}\lambda_{\beta i}) + \ldots$$

$$\frac{(c^{d=6}_{QD})_{\alpha\beta}}{\Lambda^2_{FL}} = \frac{\lambda_{\alpha i}\lambda^*_{\beta i}}{M_i^2}\ .$$

2. Leptogenesis in models with small violation of B-L

Sakharov's conditions for generating the BAU are naturally satisfied in the seesaw framework for neutrino masses

$\longrightarrow$ Leptogenesis:

- Out of equilibrium decay of heavy Majorana neutrinos (L violation)

- CP asymmetry $\rightarrow$ lepton asymmetry Y_L

- $(B+L)$-violating non-perturbative sphaleron interactions partially convert Y_L into a baryon asymmetry Y_B.

What can be different regarding leptogenesis in different models with approximately conserved B-L ?

$N_1 \rightarrow$ heavy neutrino which generates the lepton asymmetry

$N_2 \rightarrow$ heavy neutrino which makes the most important (non resonant) contribution to asymmetry in N_1 decay.

I. Both N_1 and N_2 are type i) Majorana fermions $\rightarrow$ nothing different from the standard seesaw

II. N_1 is type i) and N_2 type ii) (quasi Dirac)

CP asymmetry produced in the decay of N_1 into leptons of flavour α:

$$\epsilon_{\alpha 1} \equiv \frac{\Gamma(N_1 \rightarrow \ell_\alpha h) - \Gamma(N_1 \rightarrow \bar{\ell}_\alpha \bar{h})}{\sum_\alpha \Gamma(N_1 \rightarrow \ell_\alpha h) + \Gamma(N_1 \rightarrow \bar{\ell}_\alpha \bar{h})} = \epsilon_{\alpha 1}^{\not L} + \epsilon_{\alpha 1}^{L}$$

with

$$\epsilon_{\alpha 1}^{\not L} = \sum_{j=2h,2l} f(a_j) \mathrm{Im} \lambda_{\alpha j}^* \lambda_{\alpha 1} (\lambda^\dagger \lambda)_{j1} \qquad \epsilon_{\alpha 1}^{L} = \sum_{j=2h,2l} g(a_j) \mathrm{Im} \lambda_{\alpha j}^* \lambda_{\alpha 1} (\lambda^\dagger \lambda)_{1j}$$

Covi et al. (1996)

- $a_j \equiv M_j^2 / M_1^2$
- to lowest order in μ_2, $f(a_{2h}) = f(a_{2l})$ and $g(a_{2h}) = g(a_{2l})$.

$\lambda_{\alpha 2l} = i\lambda_{\alpha 2h}$, therefore when $\mu_2 \to 0$:

$$\epsilon^{\not{L}}_{\alpha 1} \longrightarrow f(a_{2h})\mathrm{Im}\lambda^*_{\alpha\, 2h}\lambda_{\alpha 1}(\lambda^\dagger\lambda)_{2h\, 1}(1 + i^{*2}) = 0$$

$$\epsilon^{L}_{\alpha 1} \longrightarrow g(a_{2h})\mathrm{Im}\left[\lambda^*_{\alpha\, 2h}\lambda_{\alpha 1}(\lambda^\dagger\lambda)_{1\, 2h}\right](1+|i|^2) = 2g(a_{2h})\mathrm{Im}\left[\lambda^*_{\alpha\, 2h}\lambda_{\alpha 1}(\lambda^\dagger\lambda)_{1\, 2h}\right] \,.$$

$\epsilon^{L}_{\alpha 1}$ are related to the lepton number conserving d=6 operators $\to$ escape the DI bound because they are not linked to neutrino masses (LNV d=5 Weinberg operator)

Antusch et al. (2010)

However, $\epsilon_1 \equiv \sum_\alpha \epsilon_{\alpha 1} \propto \mu_2$ because $\sum_\alpha \epsilon^{L}_{\alpha 1} = 0 \to$ flavour effects mandatory for successful leptogenesis

Barbieri et al., (2000); Endoh et al. (2004); Abada et al. (2006); Nardi et al. (2006)

III. N_1 is quasi Dirac and N_2 type i): resonant enhancement of the CP asymmetry for degenerate neutrinos N_{1h}, N_{1l} when $\mu_1 \gtrsim \Gamma_{N_1}$, with

$$\Gamma_{N_{ih}} = \frac{M_i+\mu_i}{8\pi}\frac{(\lambda^\dagger\lambda)_{ii}}{2} \approx \frac{M_i-\mu_i}{8\pi}\frac{(\lambda^\dagger\lambda)_{ii}}{2} = \Gamma_{N_{il}} \equiv \Gamma_{N_i}$$

Covi and Roulet, (1997); Pilaftsis (2005); Anisinov et al. (2006)

Resonant contribution suppressed by $\frac{\lambda'_{\alpha 1}}{\sqrt{(\lambda^\dagger\lambda)_{11}}} \rightarrow$ the CP asymmetry can not reach the maximum value $1/2$.

Successful leptogenesis with $M = 10^6$ GeV (1 TeV), for $\epsilon \equiv \lambda'/\lambda \sim 10^{-3}$ and $\epsilon_M \equiv \mu_1/M_1 \sim 10^{-8}$ $(10^{-11}) \rightarrow$ no observable low energy effects

Asaka et al. (2008)

$\mu_1 \ll \Gamma_{N_1}$: observable $\mu \rightarrow e\gamma$

Blanchet et al. (2010)

Bolztmann picture breaks down

De Simone, Riotto (2007); Garny et al. (2010); Garbrecht, Herranen (2012); Garny et al. (2012)

IV. Both N_1 and N_2 are type ii) quasi Dirac neutrinos: $\rightarrow$ both, resonant contributions from $N_{1l,1h}$ and large contribution of N_2 to $\epsilon_{\alpha 1l}$ and $\epsilon_{\alpha 1h}$

This work:

- We do NOT consider resonant contributions, widely studied

- We focus on ϵ^L, not bounded by neutrino masses and large in models which approximately conserve B-L

- Exhaustive analysis of parameter space

4. Boltzmann equations

Scenario for leptogenesis involving three fermion singlets N_1, N_{2l}, N_{2h} with masses $M_1, M_2 - \mu_2, M_2 + \mu_2$ and Yukawa couplings given by the Lagrangian

$$\mathcal{L}_Y = -\lambda_{\alpha 1}\, \widetilde{h}^\dagger\, \overline{P_R N_1} \ell_\alpha - \lambda_{\alpha 2}\, \widetilde{h}^\dagger\, \overline{P_R \frac{N_{2h} + iN_{2l}}{\sqrt{2}}} \ell_\alpha + h.c. \; .$$

with $\lambda_{\alpha 1} \ll \lambda_{\alpha 2}$

- We neglect N_2 LNV Yukawa couplings, $\lambda'_{\alpha 2} \ll \lambda_{\alpha 2}$ (checked that they have negligible effects)

- We consider two flavours for simplicity (3 flavours discussed later)

- Include decays and inverse decays of N_1, N_2 and rapid L-conserving but L_α-violating flavour changing interaction (FCI):

$$\ell_\beta h \to \ell_\alpha h \qquad \ell_\beta \bar{h} \to \ell_\alpha \bar{h} \qquad \text{and} \qquad h\bar{h} \to \ell_\alpha \bar{\ell}_\beta$$

- Neglected spectator processes and $\Delta L = 1$ scatterings: few 10%

Relevant parameters:

• M_1: for fixed CP asymmetry, lower $M_1 \rightarrow$ stronger washout (slower Universe expansion rate)

• M_2/M_1:

$\epsilon_{\alpha 1} \propto (M_1/M_2)^2$ for $M_1 \ll M_2$

$\gamma_{FCI}(T) \propto (M_1/M_2)^4$ for $T \sim M_1 \ll M_2$

If $M_2/M_1 \lesssim 20 \rightarrow$ include real N_2 in BE

• $(\lambda^\dagger\lambda)_{11}$: Effective mass $\tilde{m}_1 \equiv (\lambda^\dagger\lambda)_{11} v^2/M_1 \gtrsim m_* \simeq 10^{-3}$ eV

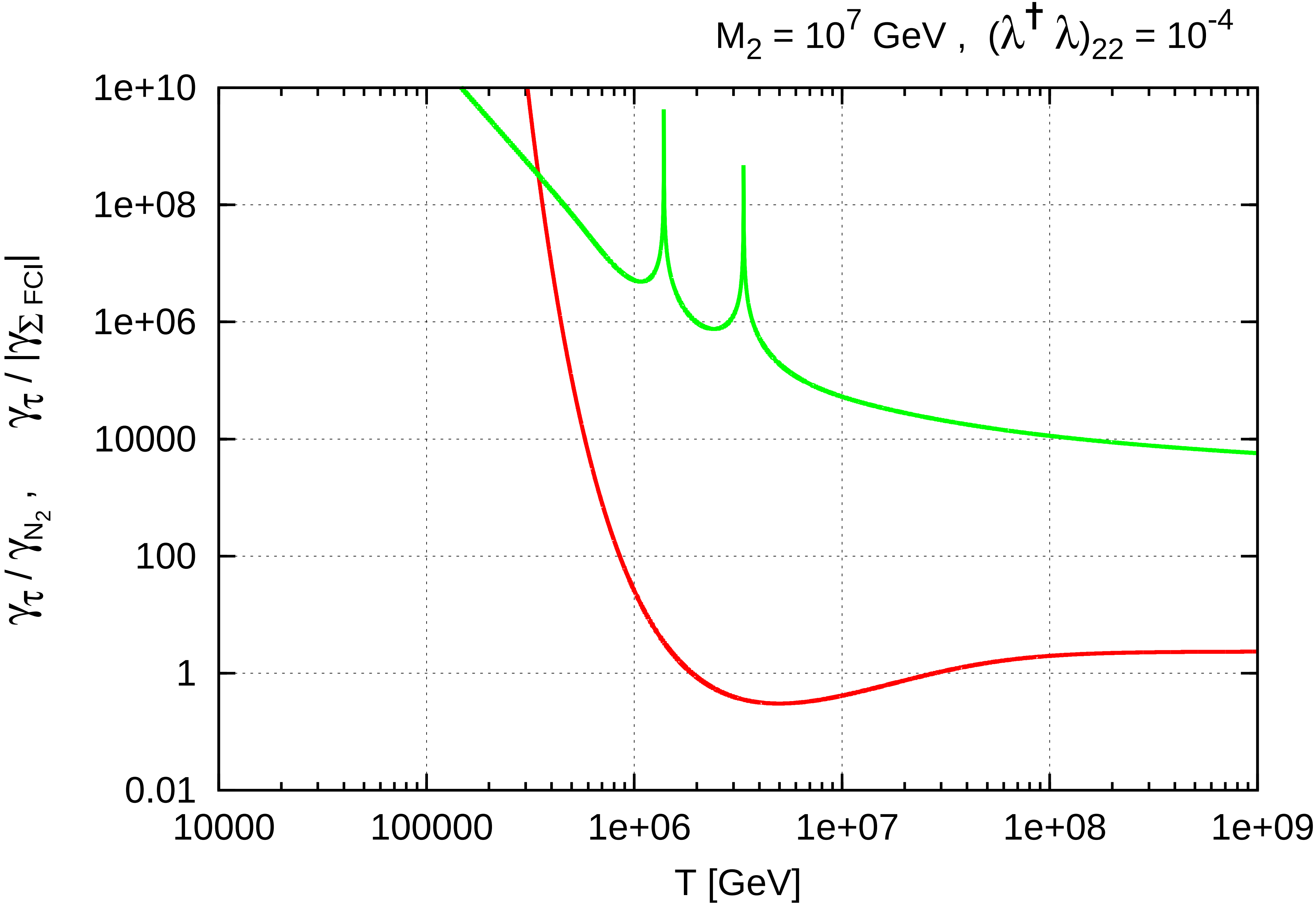
with m_* defined by $\frac{\Gamma_{N_1}}{H(T=M_1)} = \frac{\tilde{m}_1}{m_*}$

• $(\lambda^\dagger\lambda)_{22}$: $\epsilon_{\alpha 1} \propto (\lambda^\dagger\lambda)_{22}$, but

- FCI washout processes increase with $(\lambda^\dagger\lambda)_{22}$

- N_2 interactions should be slower than τ Yukawa interactions

Blanchet et al. (2007)



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

• Flavour projectors: $K_{\alpha i} \equiv \frac{\lambda_{\alpha i}\lambda^*_{\alpha i}}{(\lambda^\dagger\lambda)_{ii}}$

For two flavours, only two independent projectors, we take $K_{\mu 1}, K_{\mu 2}$

• μ_2: discrete parameter $\to$ Y_B takes different values for $\mu_2 \gg \Gamma_{N_2}$ and $\mu_2 \ll \Gamma_{N_2}$

Notation:

$Y_X \equiv n_X/s$

$y_X \equiv (Y_X - Y_{\bar{X}})/Y_X^{eq}$

Reaction densities: $\gamma^{a,b,\ldots}_{c,d,\ldots} \equiv \gamma(a, b, \ldots \to c, d, \ldots)$

$z \equiv M_1/T$

1. Case $\mu_2 \gg \Gamma_{N_{2l,2h}}$:

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

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

2. Case $\mu_2 \ll \Gamma_{N_{2l,2h}}$:

N_{2l} and N_{2h} combine to form a Dirac neutrino $N_2 \equiv (N_{2h} + iN_{2l})/\sqrt{2} \rightarrow$ there is an asymmetry generated among $N_2, \overline{N}_2$: $Y_{N_2 - \bar{N}_2}$

González-García, Racker, NR (2009)

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

4. Results and conclusions

Successful leptogenesis: $Y_B = 8.75 \times 10^{-11}$

WMAP 7 year (2011)

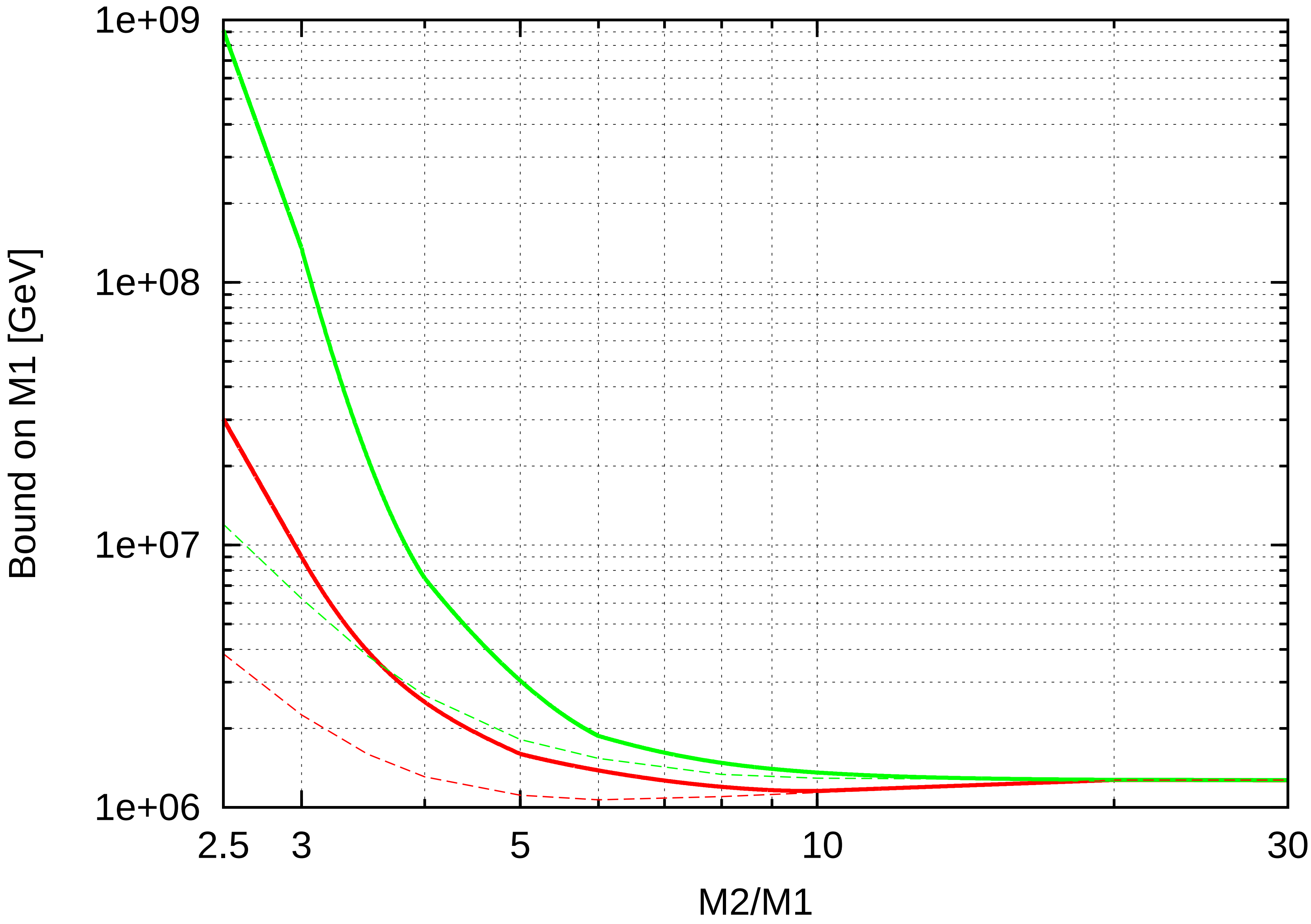
Minimum value of M_1 compatible with successful leptogenesis as a function of M_2/M_1, maximizing Y_B over the remaining parameters.

Maximum Y_B for $\tilde{m}_1 \sim 10^{-2}$ eV and $K_{\mu 1} \sim 0.1$

5×10^{-3} eV $\lesssim \tilde{m}_1 \lesssim 0.1$ eV allowed if weak washouts in one flavor, $K_{\mu 1}\tilde{m}_1 \lesssim m_*$ and strong washout in the other, $K_{\tau 1}\tilde{m}_1 \gtrsim (5-10)m_*$

$(\lambda^\dagger \lambda)_{22} \sim 0.01 - 1$

With three flavours, bound on $M_1 \sim 4$ times lower



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

$M_1 \sim 10^6$ GeV for $M_2/M_1 \gtrsim 5$ (DI bound: $M_1 \sim 10^9$ GeV)

Light neutrino masses?

- N_1 contribution:

$(m_\nu)_{\alpha\beta} \sim \lambda_{\alpha 1} \frac{v^2}{M_1} \lambda_{\beta 1} \sim 0.05$ eV $\rightarrow \lambda_{\alpha 1} \sim 10^{-5} - 10^{-4}$

- N_2 contributions:

$$(m_\nu)_{\alpha\beta} \sim (\lambda'_{\alpha 2} - \frac{\mu_2}{M_2}\lambda_{\alpha 2}) \frac{v^2}{M_2} \lambda_{\beta 2} + \lambda_{\alpha 2} \frac{v^2}{M_2} (\lambda'_{\beta 2} - \frac{\mu_2}{M_2}\lambda_{\beta 2})$$

At least one of the N_2 contributions should be of order 10^{-2} eV:

- for the parameters that minimize M_1, $\mu_2/M_2 \sim 10^{-8} - 10^{-6}$ (independent of M_2/M_1) $\rightarrow$ typically, $\mu_2 \ll \Gamma_{N_2}$

- for $M_1 \gtrsim 5 \times 10^6$ GeV, $\lambda_{\alpha 2}$ can be smaller and $\mu_2 \gtrsim \Gamma_{N_2}$

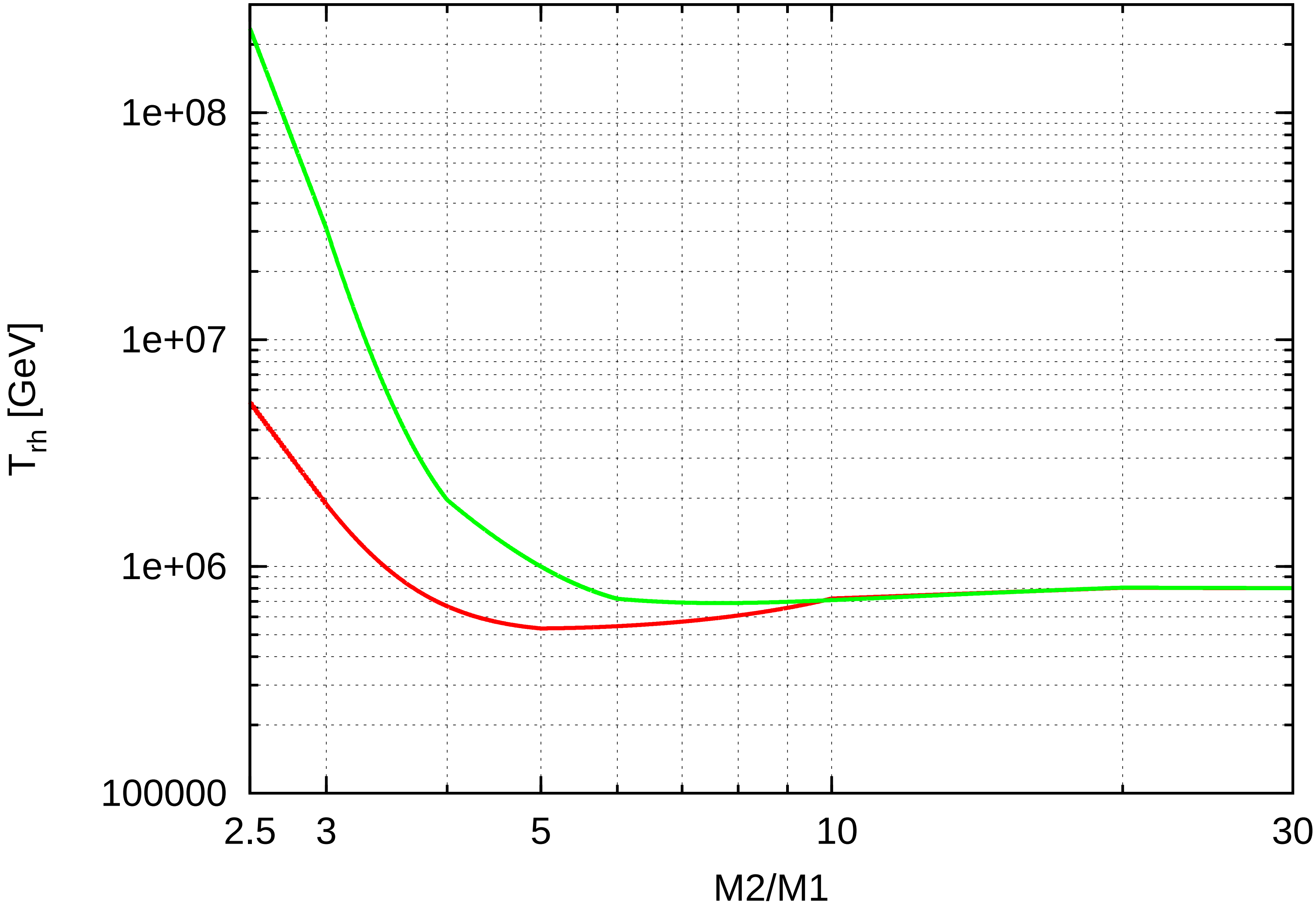
- $\lambda'_{\alpha 2} \sim 10^{-8} - 10^{-7} \rightarrow$ negligible contribution to leptogenesis

CONCLUSIONS

- Non-resonant, purely flavoured, successful leptogenesis for $M_1 \sim 10^6$ GeV in the framework of seesaw models with small violation of $B - L$

- Alleviates the conflict between the gravitino bound on T_{RH} and thermal leptogenesis in SUSY scenarios

- Far outside the reach of present and near future colliders, no observable LFV in non-SUSY seesaw.



Lower bound on T_{RH}