

Leptogenesis with small violation of B-L

Nuria Rius
IFIC, Universidad de Valencia-CSIC

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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:

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

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

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

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

Kawasaki et al. (2008)

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

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

$$\mathcal{L}_\mu = -\lambda'_{\alpha j} \tilde{h}^\dagger \overline{P_R N'_j} \ell_\alpha - \lambda'_{\alpha j} \tilde{h}^\dagger \overline{P_R N''_j} \ell_\alpha - \frac{1}{2} \mu_{ik} \overline{N_i^c} N_k - \frac{1}{2} \mu'_{jk} \overline{N'_j^c} N'_k + h.c.$$

$\lambda_{\alpha i}$ 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:

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

$L_{\ell_\alpha} = 1$ 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) \rightarrow resonant leptogenesis at $T \sim \mathcal{O}(1 \text{ TeV})$

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

Low energy effective Lagrangian:

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

where Λ_{FL} can be $\mathcal{O}(\text{TeV})$ 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:

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

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

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

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

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

→ Leptogenesis:

- Out of equilibrium decay of heavy Majorana neutrinos (L violation)
- CP asymmetry → 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 → heavy neutrino which generates the lepton asymmetry

N_2 → 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 :

$$\epsilon_{\alpha 1} \equiv \frac{\Gamma(N_1 \rightarrow \ell_\alpha h) - \Gamma(N_1 \rightarrow \bar{\ell}_\alpha \bar{h})}{\sum_{\alpha} \Gamma(N_1 \rightarrow \ell_\alpha h) + \Gamma(N_1 \rightarrow \bar{\ell}_\alpha \bar{h})} = \epsilon_{\alpha 1}^{\cancel{L}} + \epsilon_{\alpha 1}^L$$

with

$$\epsilon_{\alpha 1}^{\cancel{L}} = \sum_{j=2h,2l} f(a_j) \text{Im} \lambda_{\alpha j}^* \lambda_{\alpha 1} (\lambda^\dagger \lambda)_{j1} \quad \epsilon_{\alpha 1}^L = \sum_{j=2h,2l} g(a_j) \text{Im} \lambda_{\alpha j}^* \lambda_{\alpha 1} (\lambda^\dagger \lambda)_{1j}$$

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 $\mu_2 \rightarrow 0$:

$$\epsilon_{\alpha 1}^{\cancel{L}} \longrightarrow f(a_{2h}) \text{Im} \lambda_{\alpha 2h}^* \lambda_{\alpha 1} (\lambda^\dagger \lambda)_{2h 1} (1 + i^{*2}) = 0$$

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

$\epsilon_{\alpha 1}^L$ are related to the lepton number conserving d=6 operators \rightarrow 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 $\sum_{\alpha} \epsilon_{\alpha 1}^L = 0 \rightarrow$ 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); Anisimov 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)

Boltzmann 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

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

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):

$$\ell_\beta h \rightarrow \ell_\alpha h \quad \ell_\beta \bar{h} \rightarrow \ell_\alpha \bar{h} \quad \text{and} \quad h \bar{h} \rightarrow \ell_\alpha \bar{\ell}_\beta$$

- 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 :

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

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

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

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

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

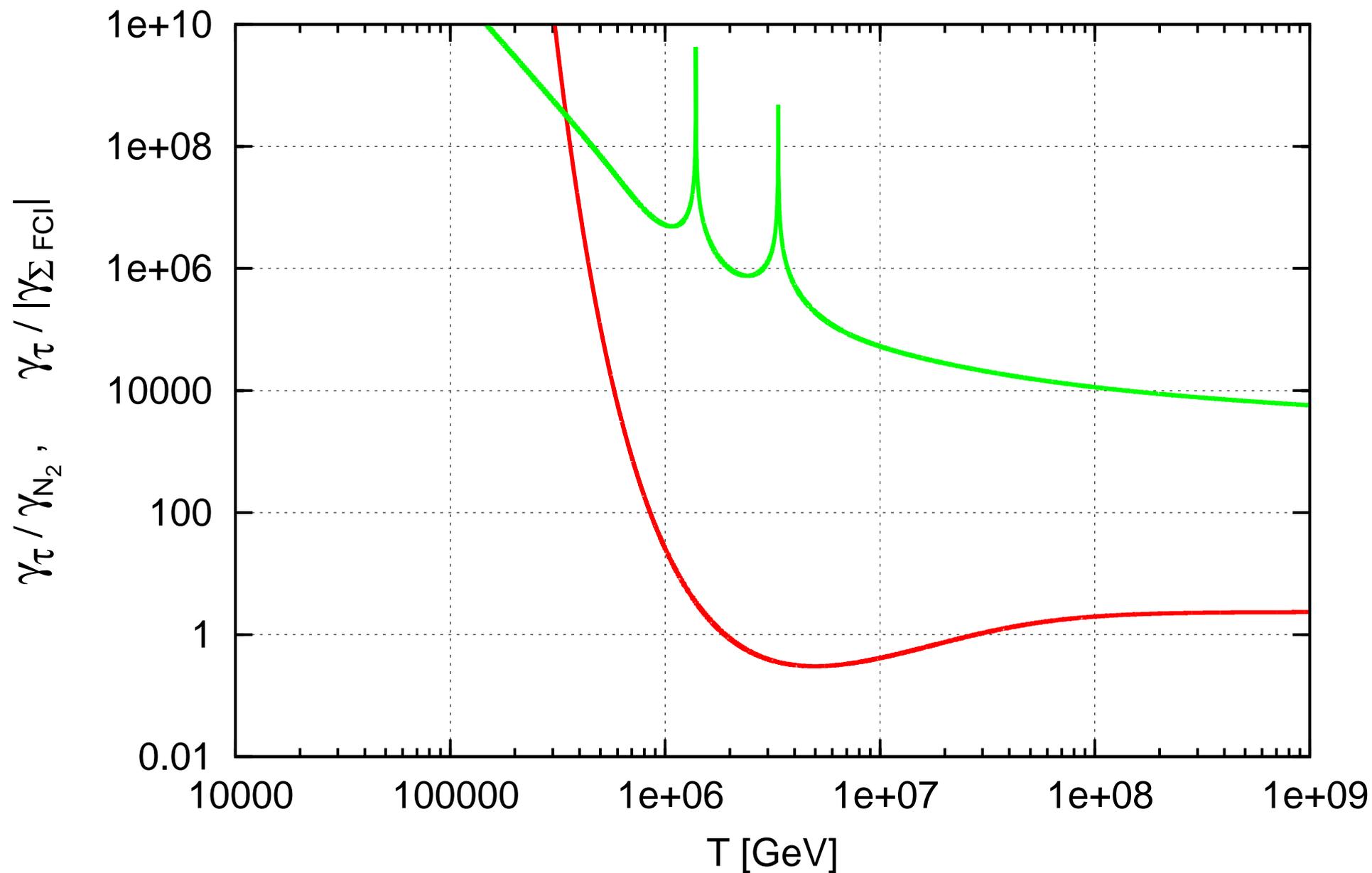
- $(\lambda^\dagger \lambda)_{22}$: $\epsilon_{\alpha 1} \propto (\lambda^\dagger \lambda)_{22}$, but

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

- N_2 interactions should be slower than τ Yukawa interactions

Blanchet et al. (2007)

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



- 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 $\rightarrow Y_B$ 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: $\gamma_{c,d,\dots}^{a,b,\dots} \equiv \gamma(a, b, \dots \rightarrow c, d, \dots)$

$$z \equiv M_1/T$$

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

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

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

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, \bar{N}_2 : $Y_{N_2-\bar{N}_2}$

González-García, Racker, NR (2009)

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

4. Results and conclusions

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

WMAP 7 year (2011)

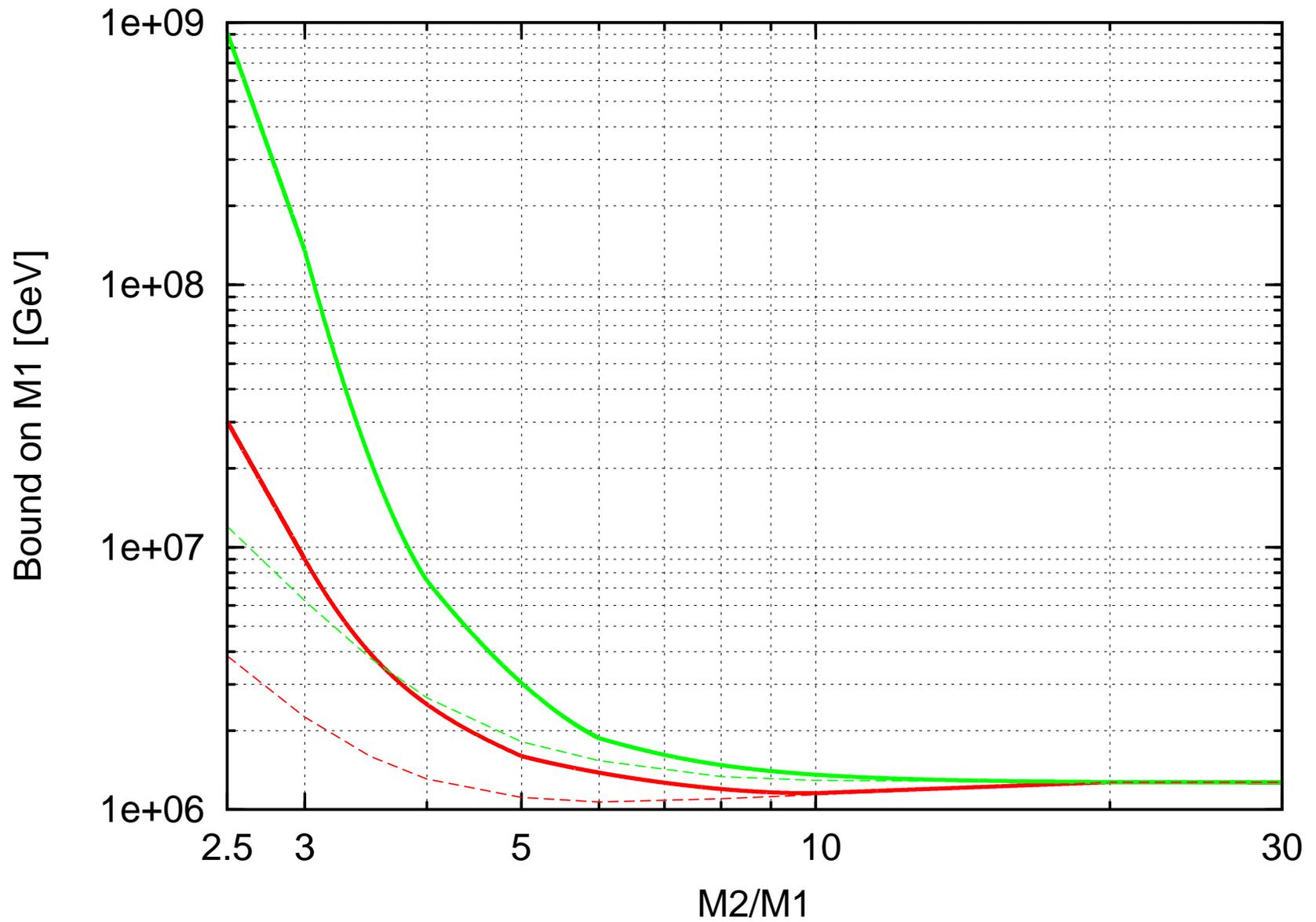
Minimum value of M_1 compatible with successful leptogenesis as a function of M_2/M_1 , maximizing Y_B over the remaining parameters.

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



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

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

Light neutrino masses?

- N_1 contribution:

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

- 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:

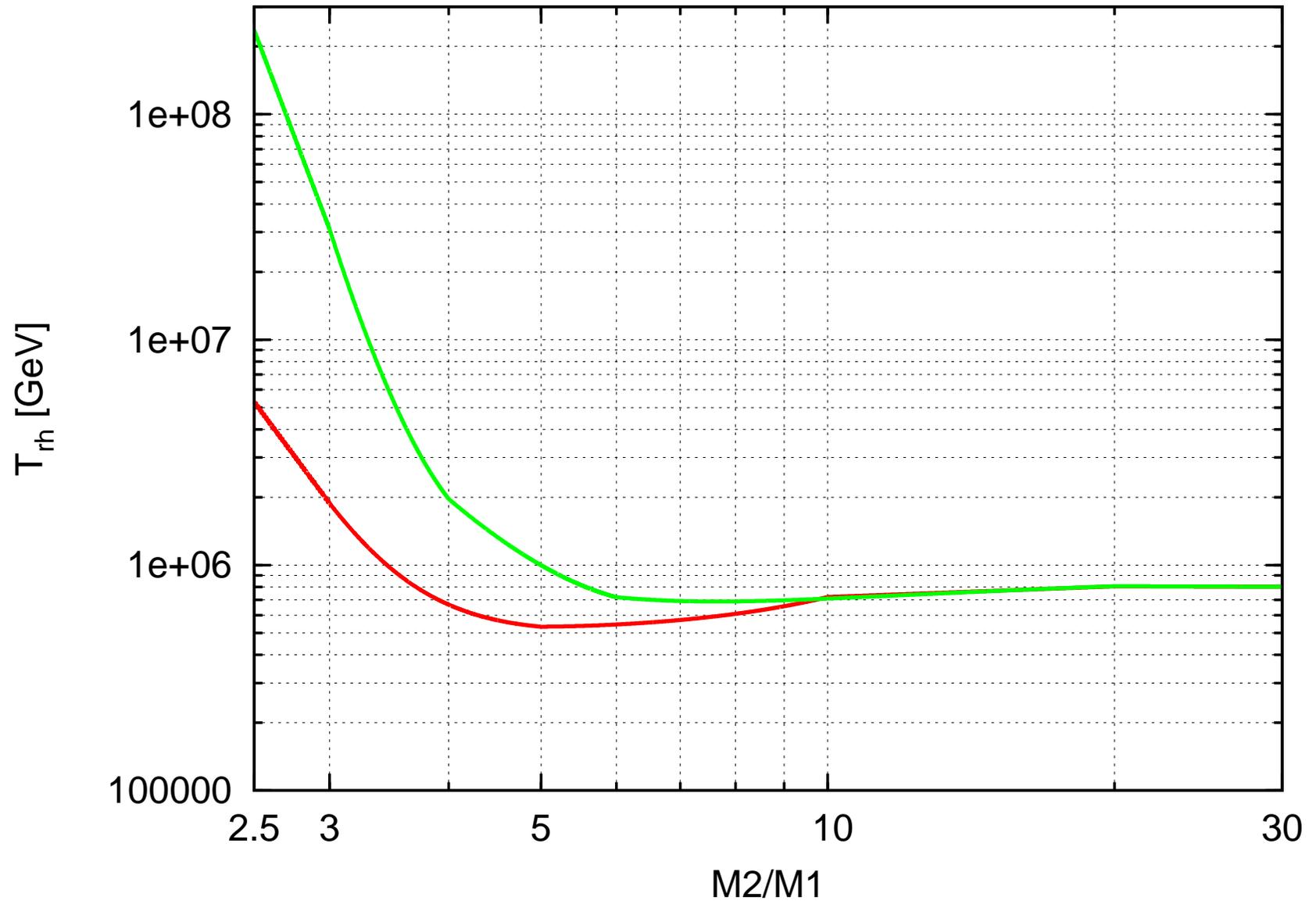
- for the parameters that minimize M_1 , $\mu_2/M_2 \sim 10^{-8} - 10^{-6}$ (independent of M_2/M_1) \rightarrow typically, $\mu_2 \ll \Gamma_{N_2}$

- 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}