Leptogenesis and Grand Unification

Stéphane Lavignac (IPhT Saclay)

- introduction
- a quick review of leptogenesis
- successful leptogenesis in SO(10) unification
- a predictive SO(10) leptogenesis scenario

<u>based on:</u>

- P. Hosteins, S. L. and C. Savoy, hep-ph/0606078
- A. Abada, P. Hosteins, F.-X. Josse-Michaux and S. L., 0808.2058 [hep-ph]
- M. Frigerio, P. Hosteins, S. L. and A. Romanino, 0804.0801 [hep-ph]

Particle Physics and Cosmology : The Interface
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Introduction

The baryon asymmetry of the universe (BAU)

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq \frac{n_B}{n_\gamma} = (6.21 \pm 0.16) \times 10^{-10} \qquad \text{(WMAP 5y)}$$

must be explained by some dynamical mechanism $\Rightarrow$ baryogenesis

Sakharov's conditions:

(1) B violation
(2) C and CP violation
(3) departure from thermal equilibrium

(1) and (2) are present in the SM – B+L anomaly $\Rightarrow$ transitions between vacua with different (B+L) possible at $T \gtrsim M_{weak}$, where nonperturbative (B+L)-violating processes (sphalerons) are in equilibrium

Electroweak baryogenesis fails in the SM because (3) is not satisfied [also CP violation is too weak] $\Rightarrow$ need either new physics at M_{weak}, or generate a (B-L) asymmetry at $T > T_{EW}$

Leptogenesis (generation of a L asymmetry above T_{EW}, which is then converted into a B asymmetry by sphalerons) belongs to the second class

Attractive mechanism since (in its simplest versions) connects neutrino masses to the BAU

A lot of work has been done in the past decade:

- refinement of the calculation of the generated baryon asymmetry (finite T effects, spectator processes, lepton flavour effects...)

- alternative scenarios to the standard one, including low-scale scenarios

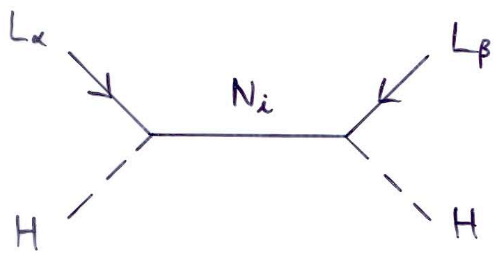
- attempts to relate leptogenesis to measurable parameters, in particular to low-energy CP violation (no direct connection in general)

<u>This talk</u>: possibility of realizing successful (and possibly predictive) lepogenesis in SO(10) GUTs

A quick review of (standard) leptogenesis

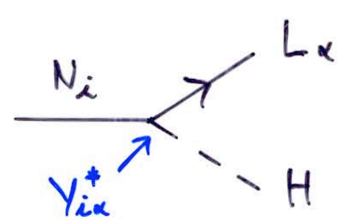
Generate a B-L asymmetry through the out-of-equilibrium decays of the heavy Majorana neutrinos responsible for neutrino mass (Fukugita, Yanagida)

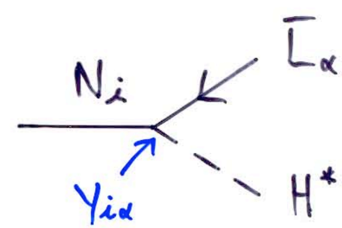
Seesaw mechanism: $\mathcal{L}_{seesaw} \; = \; -\frac{1}{2} M_i \bar{N}_i N_i - \left(\bar{N}_i Y_{i\alpha} L_\alpha H + \mathrm{h.c.} \right)$



$\Longrightarrow$ $(M_\nu)_{\alpha\beta} \; = \; - \sum_i \frac{Y_{i\alpha} Y_{i\beta}}{M_i} \, v^2 \quad (v = \langle H \rangle)$

$N_i^c \; \equiv \; C \bar{N}_i^T = N_i$ (Majorana) $\Rightarrow$ decays both into l^+ and l^-

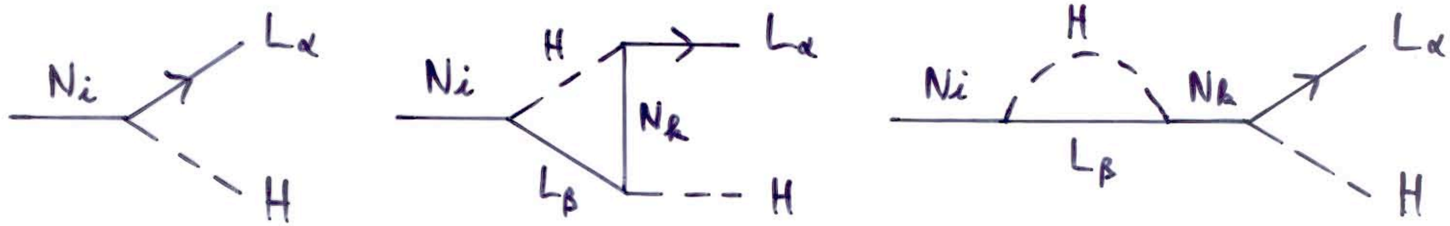




$N_i \rightarrow L_\alpha H$ $\qquad$ $N_i \rightarrow \bar{L}_\alpha H^*$

$$\Gamma_{tree}(N_i \rightarrow LH) \; = \; \Gamma_{tree}(N_i \rightarrow \bar{L} H^\star) \; = \; \frac{M_i}{16\pi} (Y Y^\dagger)_{ii}$$

CP asymmetry due to interference between tree and 1-loop diagrams:



$$\Rightarrow \quad \Gamma(N_i \to LH) \;\neq\; \Gamma(N_i \to \bar{L}H^\star)$$

When $M_1 << M_2, M_3$, L-violating processes involving N_1 tend to erase the asymmetry generated from N_2 and N_3 decays, and it is often assumed that the final baryon asymmetry is dominated by the CP asymmetry in N_1 decays:

$$\epsilon_{N_1} \;\equiv\; \frac{\Gamma(N_1 \to LH) - \Gamma(N_1 \to \bar{L}H^\star)}{\Gamma(N_1 \to LH) + \Gamma(N_1 \to \bar{L}H^\star)} \;\simeq\; \frac{3}{16\pi} \sum_k \frac{\mathrm{Im}[(YY^\dagger)^2_{k1}]}{(YY^\dagger)_{11}} \, \frac{M_k}{M_1}$$

Covi, Roulet, Vissani
Buchmüller, Plümacher

Generated lepton asymmetry: $\quad Y_L \;\equiv\; \dfrac{n_L - n_{\bar{L}}}{s} \;=\; 0.42 \, \dfrac{\eta\, \epsilon_{N_1}}{g_\star}$

g_* = total number of relativistic d.o.f. (g_* = 106.75 in the SM)

η = efficiency factor that takes into account the initial population of N_1, the out-of-equilibrium condition for their decays, and the dilution of the lepton asymmetry by L-violating processes ($LH \to N_1,\ LH \leftrightharpoons \bar{L}H^\star \cdots$)

Conversion into a baryon asymmetry: at $T > M_{weak}$, the sphalerons (which violate B+L, but preserve B-L) are in thermal equilibrium

$\Rightarrow Y_L$ partially converted into Y_B:

$$< Y_B >_T \, = \, C < Y_{B-L} >_T \qquad C \, = \, \frac{8N_f + 4N_H}{22N_f + 13N_H} \, = \, \frac{28}{79} \; \text{(SM)}$$

hence $Y_B \, = \, -0.42\, C\, \dfrac{\eta\, \epsilon_{N_1}}{g_\star} \, = \, -1.4 \times 10^{-3}\, \eta\, \epsilon_{N_1} \;\; \text{(SM)}$

Can leptogenesis explain the observed baryon asymmetry?

$\Rightarrow$ must compare Y_B computed from leptogenesis with observed value

- η essentially depends on M_1 and on $\tilde{m}_1 \, \equiv \, (YY^\dagger)_{11} v^2 / M_1$, which controls the out-of-equ. decay condition / strength of washout processes:

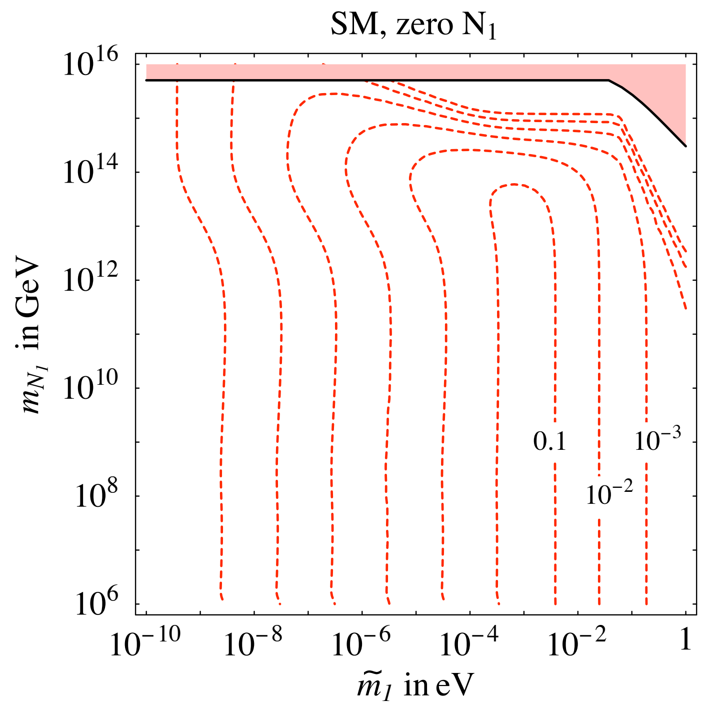
$$\Gamma_{N_1} < H(T = M_1) \quad \Longleftrightarrow \quad \tilde{m}_1 \, < \, \tilde{m}_1^\star = 2.2 \times 10^{-3}\, \text{eV}$$

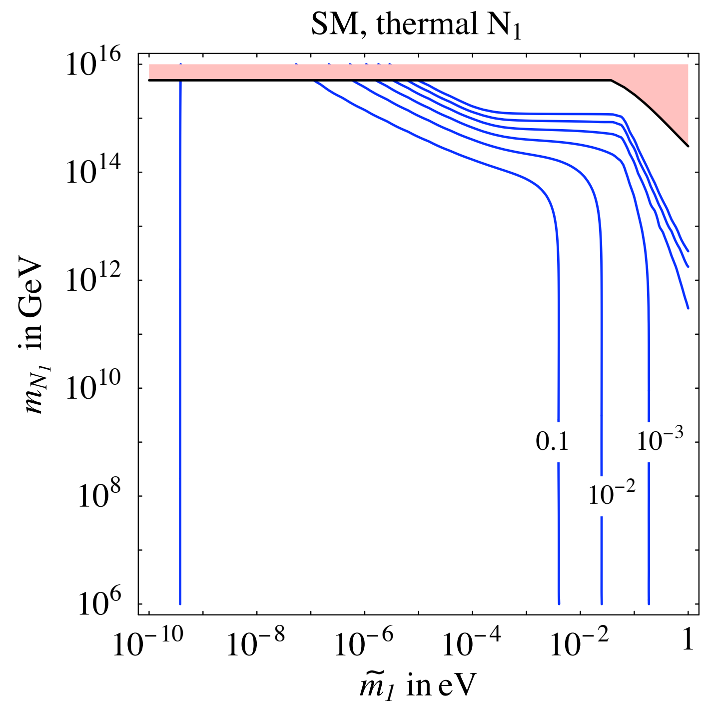
- ε_{N_1} depends on the N_i masses and couplings, but is bounded by a simple function of M_1, m_1 and $\tilde{m}_1$ [case $M_1 \ll M_2, M_3$]:

$$|\epsilon_{N_1}| \, \leq \, \frac{3}{16\pi} \frac{M_1 (m_3 - m_1)}{v^2} \, f\left(\frac{m_1}{\tilde{m}_1} \right) \qquad 0 \leq f\left(\frac{m_1}{\tilde{m}_1} \right) \leq 1$$

Davidson, Ibarra
Hambye et al.

Isocontours of η in the $(\tilde{m}_1, M_1)$ plane:





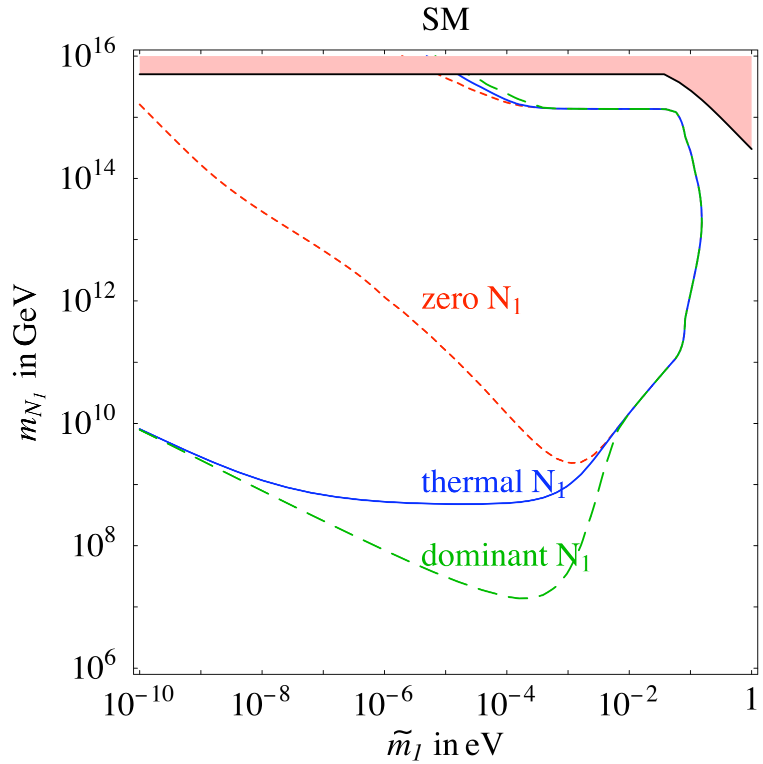
(Giudice et al.)

weak washout regime: $\tilde{m}_1 \ll \tilde{m}_1^\star \quad \Rightarrow \quad \eta \sim \tilde{m}_1 / \tilde{m}_1^\star$

strong washout regime: $\tilde{m}_1 \gg \tilde{m}_1^\star \quad \Rightarrow \quad \eta \sim (\tilde{m}_1^\star / \tilde{m}_1)^{1.16}$

(for $M_1 \ll 10^{14}\,\mathrm{GeV}$ and zero initial Ni abundance)

Region in the $(\tilde{m}_1, M_1)$ plane where leptogenesis can reproduce the observed baryon asymmetry:



Case $M_1 \ll M_2, M_3$

(Giudice et al.)

$\Rightarrow M_1 \geq (0.5 - 2.5) \times 10^9 \, \mathrm{GeV}$ depending on the initial conditions

Case $M_1 \approx M_2$: if $|M_1 - M_2| \sim \Gamma_2$, the self-energy part of ε_{N_1} has a resonant behaviour, and $M_1 \ll 10^9 \, \mathrm{GeV}$ is compatible with successful leptogenesis ("resonant leptogenesis")

Covi, Roulet, Vissani
Pilaftsis

Flavour effects in leptogenesis

Barbieri, Creminelli, Strumia, Tetradis
Endoh et al. - Nardi et al. - Abada et al.
Blanchet, Di Bari, Raffelt - Pascoli, Petcov, Riotto - ...

"one-flavour approximation": leptogenesis described in terms of a single direction in flavour space, the lepton $\mathcal{L}_1 \propto \sum_\alpha Y_{1\alpha} L_\alpha$ to which N_1 couples
$\Rightarrow$ valid as long as the charged lepton Yukawas λ_α are out of equilibrium

At $T \lesssim 10^{12}\,\mathrm{GeV}$, λ_τ is in equilibrium and destroys the coherence of $\mathcal{L}_1$
$\Rightarrow$ 2 relevant flavours: L_τ and a combination of L_e and L_μ

At $T \lesssim 10^{9}\,\mathrm{GeV}$, λ_τ and λ_μ are in equilibrium $\Rightarrow$ must distinguish between L_e , L_μ and L_τ

Relevant parameters for the discussion of flavour effects:

$$\epsilon^\alpha_{N_1} \equiv \frac{\Gamma(N_1 \to L_\alpha H) - \Gamma(N_1 \to \bar{L}_\alpha H^\star)}{\Gamma(N_1 \to L_\alpha H) + \Gamma(N_1 \to \bar{L}_\alpha H^\star)} \qquad \tilde{m}^\alpha_1 \equiv \frac{|Y_{1\alpha}|^2 v^2}{M_1}$$

qualitatively $Y_B \approx \sum_\alpha \epsilon^\alpha_{N_1} \eta(\tilde{m}^\alpha_1)$ $\Rightarrow$ can deviate from the one-flavour approximation if e.g. $\epsilon^\tau_{N_1} \gg \epsilon^e_{N_1}, \epsilon^\mu_{N_1}$ and $\tilde{m}^\tau_1 \ll \tilde{m}^e_1, \tilde{m}^\mu_1$

Leptogenesis in SO(10) models

Right-handed neutrinos are suggestive of SO(10) unification:

(i) $\mathbf{16} \; = \; (Q, \bar{u}, \bar{d}, L, \bar{e}) \oplus \bar{N}$

(ii) B-L is a generator of SO(10) $\Rightarrow$ the mass scale of the N_R is associated with the breaking of the gauge group $\Rightarrow$ $M_R >> M_{weak}$ natural

However, successful leptogenesis is not so easy to achieve in SO(10) models with a type I seesaw mechanism:

$M_D \propto M_u \Rightarrow$ very hierarchical right-handed neutrino masses

$\Rightarrow M_1 << 10^8$ GeV , below the Davidson-Ibarra bound

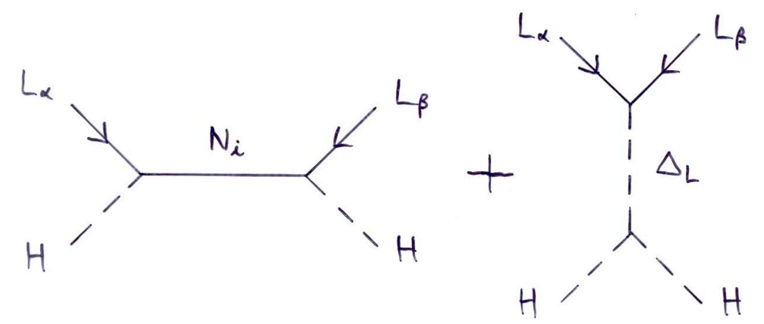
<u>Ways out:</u>

- flavour-dependent N_2 leptogenesis [Vives]: N_2 decays generate an asymmetry in a lepton flavour that is only mildly washed out by N_1
- large corrections to $M_D = M_u$
- other versions of the seesaw mechanism: type II (heavy scalar $SU(2)_L$ triplet exchange), type I + II (left-right symmetric seesaw mechanism)

SO(10) models with a left-right symmetric seesaw

Type I+II seesaw mechanism:

Δ_L = SU(2)$_L$ triplet with couplings f_{Lij} to lepton doublets



$$M_\nu \;=\; f_L v_L - \frac{v^2}{v_R} Y^T f_R^{-1} Y \;\equiv\; M_\nu^{II} + M_\nu^{I}$$

Right-handed neutrino mass matrix: $M_R \;=\; f_R v_R$

$v_R \equiv \langle \Delta_R \rangle$ scale of B-L breaking

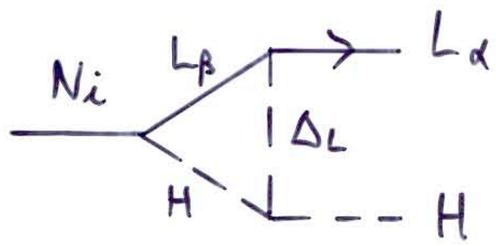
Δ_R = SU(2)$_R$ triplet with couplings f_{Rij} to right-handed neutrinos

v_L is small since it is an induced vev: $v_L \;\equiv\; \langle \Delta_L \rangle \sim\; v^2 v_R / M^2_{\Delta_L}$

In a broad class of theories with underlying left-right symmetry (such as SO(10) with a $\overline{126}_H$), one has $Y = Y^T$ and $f_L = f_R \equiv f$

→ left-right symmetric seesaw mechanism

The SU(2)$_L$ triplet also contributes to leptogenesis. If M_1 << $M_{\Delta L}$, it mainly affects leptogenesis by contributing to the CP asymmetry in N_1 decays:



$$\epsilon_{N_1}^{II} \;\simeq\; \frac{3}{8\pi} \sum_{k,l} \frac{\mathrm{Im}\left[\, Y_{1k} Y_{1l}\, f_{kl}^{\star}\, v_L \,\right]}{(YY^\dagger)_{11}\, v^2}\; M_1$$

Hambye, Senjanovic – Antusch, King

The total CP asymmetry is (for $M_1 \ll M_2, M_3, M_{\Delta_L}$):

$$\epsilon_{N_1} \;=\; \epsilon_{N_1}^{I} + \epsilon_{N_1}^{II} \;\simeq\; \frac{3}{8\pi}\, \frac{\sum_{k,l} \mathrm{Im}\left[Y_{1k} Y_{1l}\, (M_\nu)_{kl}^{\star}\right]}{(YY^\dagger)_{11}}\; \frac{M_1}{v^2}$$

Since the triplet is heavy, the dilution of the generated lepton asymmetry is mainly due to N_1-related processes and depends on the effective mass parameter $\tilde{m}_1 \;\equiv\; (YY^\dagger)_{11} v^2 / M_1$ as in the type I case

In order to study leptogenesis, need to reconstruct the fij (which determine both the triplet couplings and the RHN mass matrix) as a function of the Yij (predicted by the theory) and of the light neutrino parameters (in principe accessible to experiment)

Reconstruction of the f_{ij} couplings

Assuming that Y is known in the basis of charged lepton mass eigenstates, the LR symmetric seesaw formula

$$M_\nu \;=\; f_L v_L - \frac{v^2}{v_R} Y f_R^{-1} Y$$

admits $2^3 = 8$ solutions for f (for 3 generations) [Akhmedov, Frigerio]

→ new possibilities for leptogenesis with respect to the type I case

One can obtain useful analytical expressions from a reconstruction procedure using complex orthogonal matrices [Hosteins, S.L., Savoy]

<u>Application</u>: SO(10) models with two 10's and a $\overline{126}$ in the Higgs sector

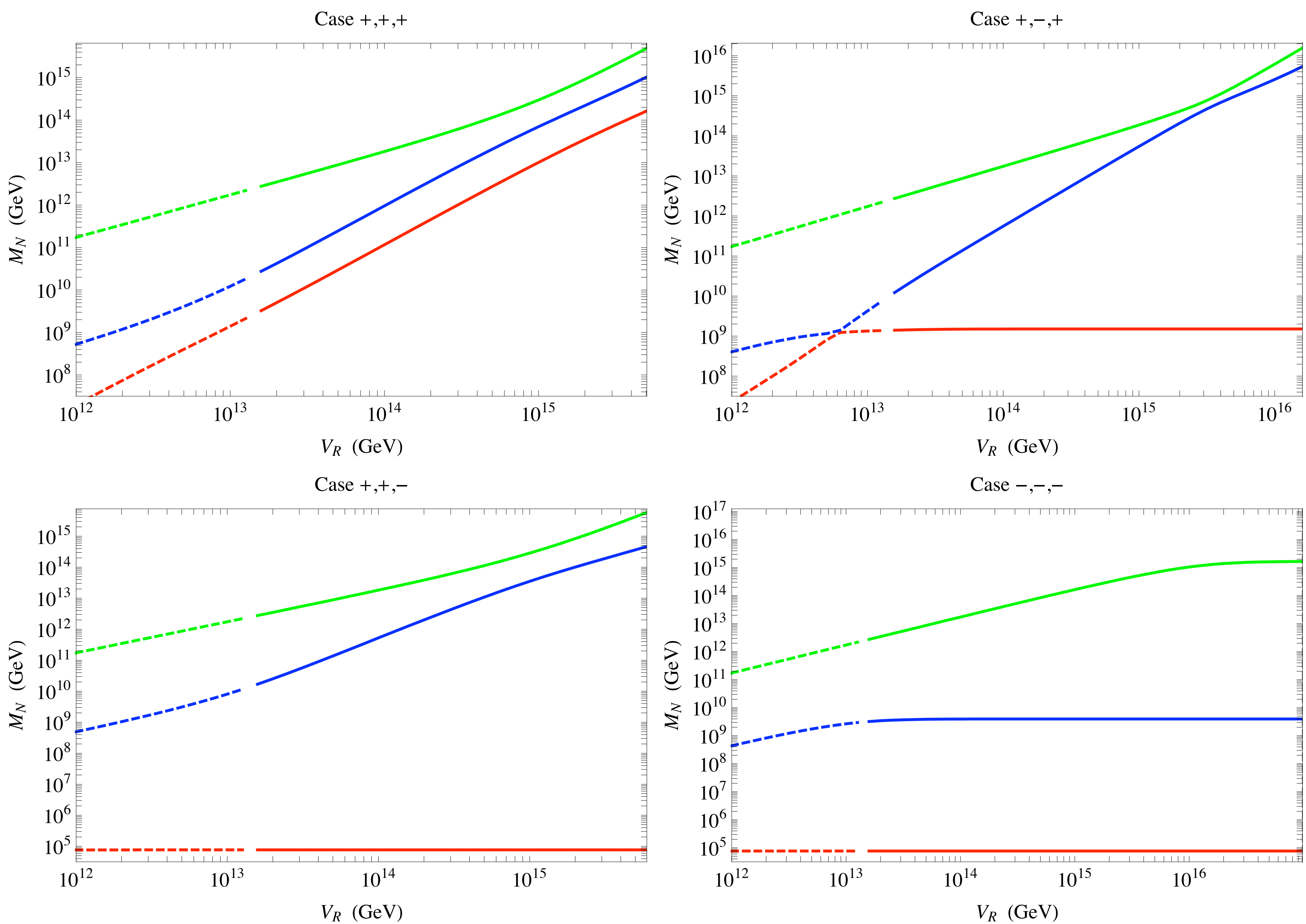
$$W \;\ni\; Y^{(1)}_{ij}\, 16_i 16_j 10_1 + Y^{(2)}_{ij}\, 16_i 16_j 10_2 + f_{ij}\, 16_i 16_j \overline{126}$$

$Y^{(1)}, Y^{(2)}$ symmetric $\qquad\qquad$ $\overline{126} \ni \Delta_L, \Delta_R$ with $f_L = f_R = f$

If the doublets in the $\overline{126}$ do not get vevs, this leads to:

$$Y v_u \equiv M_D = M_u \qquad\qquad\qquad M_d = M_e$$

(in general, Y and M_ν contain physical high-energy phases)



<u>Inputs</u>: normal hierarchy with $m_1 = 10^{-3}$ eV, $\theta_{13} = 0$, all PMNS and high-energy phases vanish – $v^2 = 0.1\, v_L\, v_R$

Among the 8 solutions, 3 different patterns emerge for leptogenesis:

- 2 solutions with a rising $M_1 \Rightarrow$ large ε_{N_1} for large v_R
- 2 solutions with $M_1 \sim \text{few}\,10^9\,\text{GeV}$
- 4 solutions with $M_1 \sim 10^5\,\text{GeV} \Rightarrow \varepsilon_{N_1}$ too small, but $M_2 \sim \text{few}\,10^9\,\text{GeV}$ or rises with $v_R \Rightarrow$ the observed baryon asymmetry could be generated from N_2 decays (relevance of flavour effects)

In all cases, the washout tends to be important and a numerical resolution of the Boltzmann equations is required to tell whether some of these solutions lead to successful leptogenesis

Relevant ingredients:

- contribution of N_2
- lepton flavour effects (independent evolution of the asymmetries in the e, μ and τ flavours)
- corrections to $M_d = M_e$ from appropriate SO(10) operators (affects the reconstruted RHN spectra)

Computation of the baryon asymmetry

Solve the Boltzmann equations with flavour effects and decays of N_1 and N_2

Relevant quantities:

- flavour-dependent CP asymmetries:

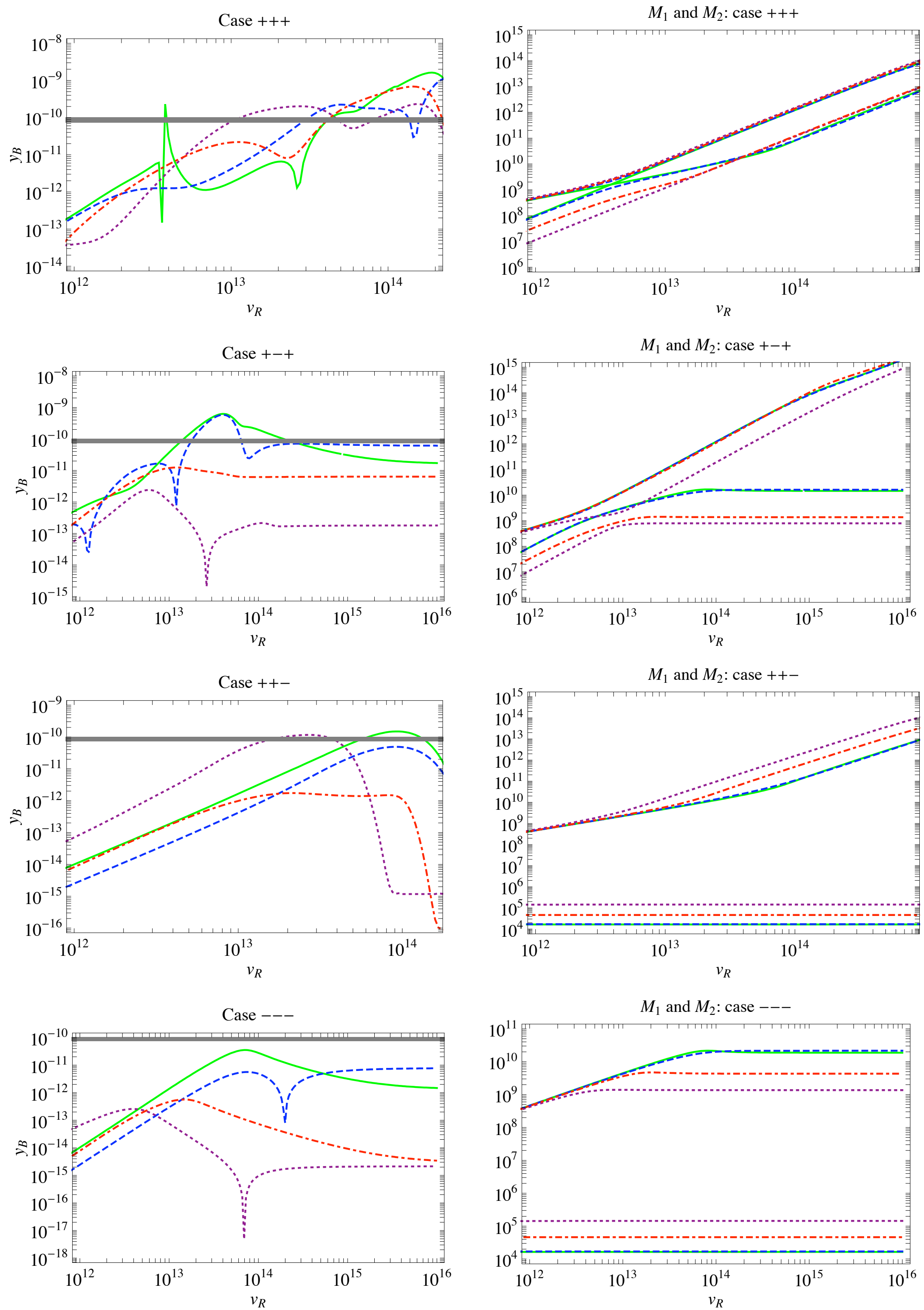
$$\epsilon_{N_i}^{\alpha} \equiv \frac{\Gamma(N_i \to L_\alpha H) - \Gamma(N_i \to \bar{L}_\alpha H^\star)}{\Gamma(N_i \to L_\alpha H) + \Gamma(N_i \to \bar{L}_\alpha H^\star)}$$

- wash-out processes: ΔL and N_3 very heavy $\Rightarrow$ associated wash-out processes suppressed. Furthermore, we neglect $\Delta L=2$ processes since we deal with masses M_1 and $M_2 < 10^{12}$ GeV

$\Rightarrow$ only inverse decays and $\Delta L=1$ scatterings associated with N_1 and N_2 enter the Boltzmann equations. The relevant washout parameters are:

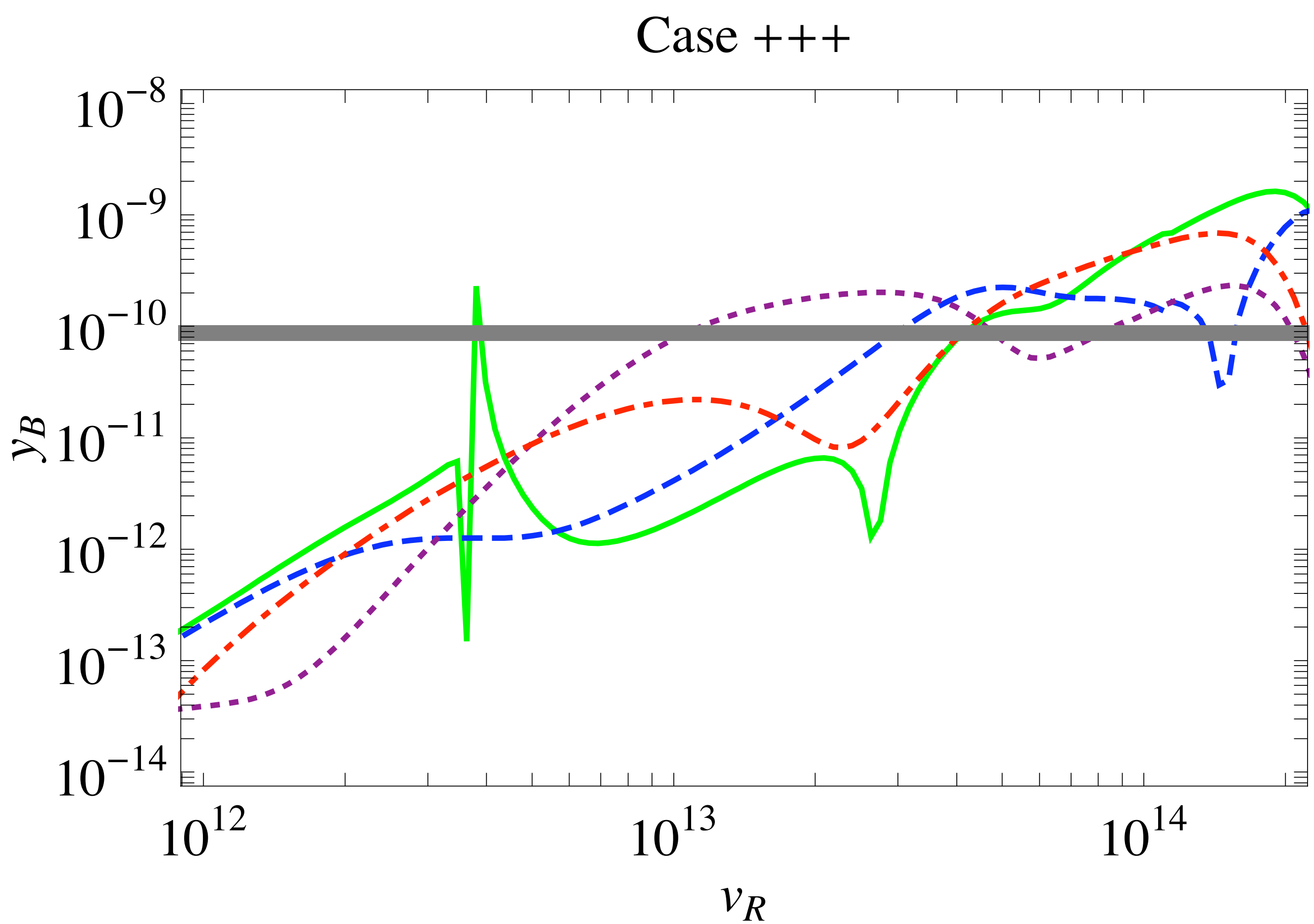
$$\tilde{m}_i^{\alpha} \equiv \frac{|Y_{i\alpha}|^2 v^2}{M_i}$$

Both the $\epsilon_{N_i}^{\alpha}$ and the $\tilde{m}_i^{\alpha}$ depend on the M_i and on the $Y_{i\alpha}$, hence on the reconstructed f_{ij} couplings

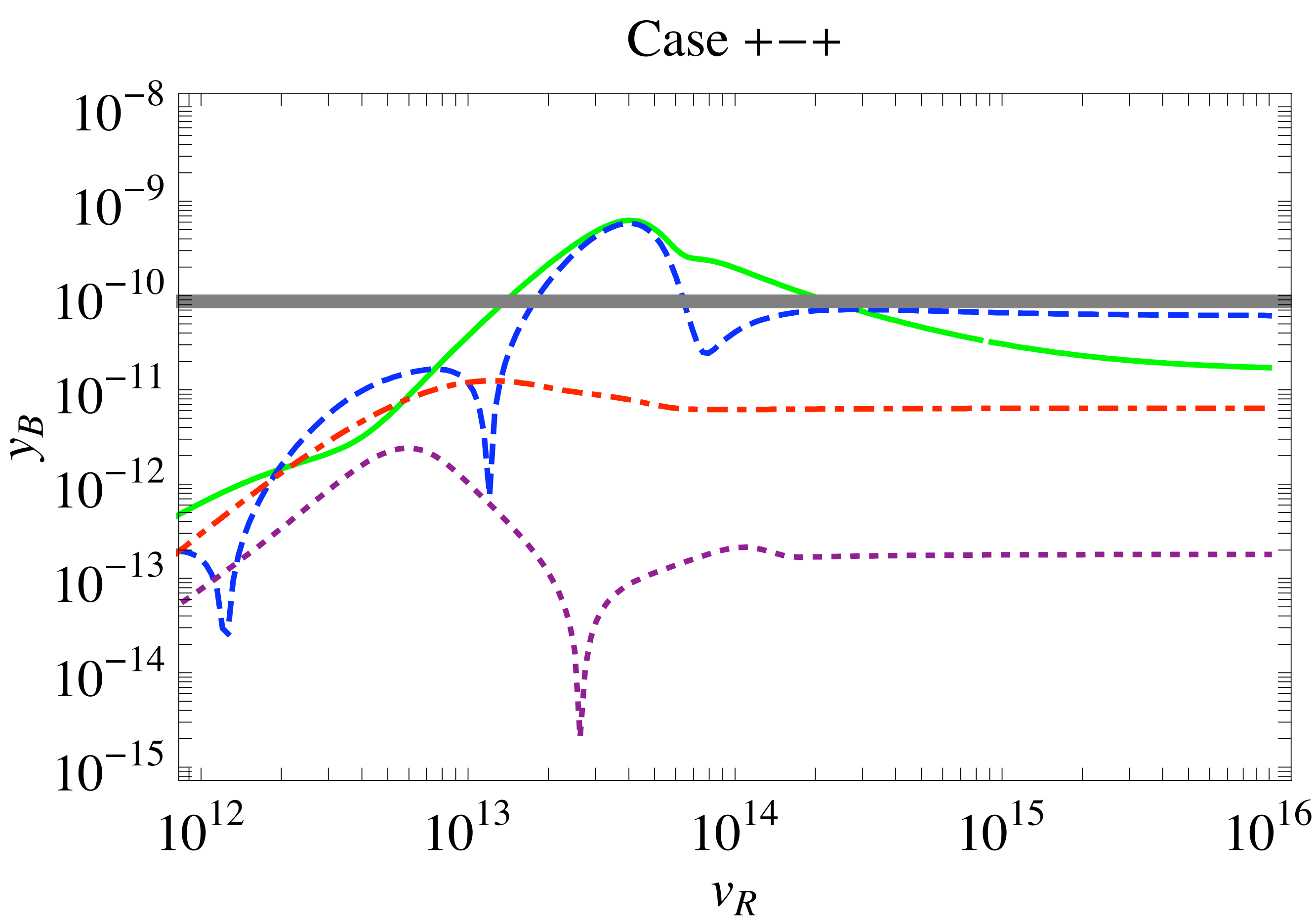


Case +++
y_B
v_R
M_1 and M_2: case +++
v_R
Case +−+
y_B
v_R
M_1 and M_2: case +−+
v_R
Case ++−
y_B
v_R
M_1 and M_2: case ++−
v_R
Case −−−
y_B
v_R
M_1 and M_2: case −−−
v_R

Inputs: normal hierarchy with $m_1 = 10^{-3}$ eV, $\theta_{13} = 0$, $\delta = 0$, different choices of Majorana and high-energy phases – $v^2 = 0.1\ v_L\ v_R$ – $T_{in} = 10^{11}$ GeV

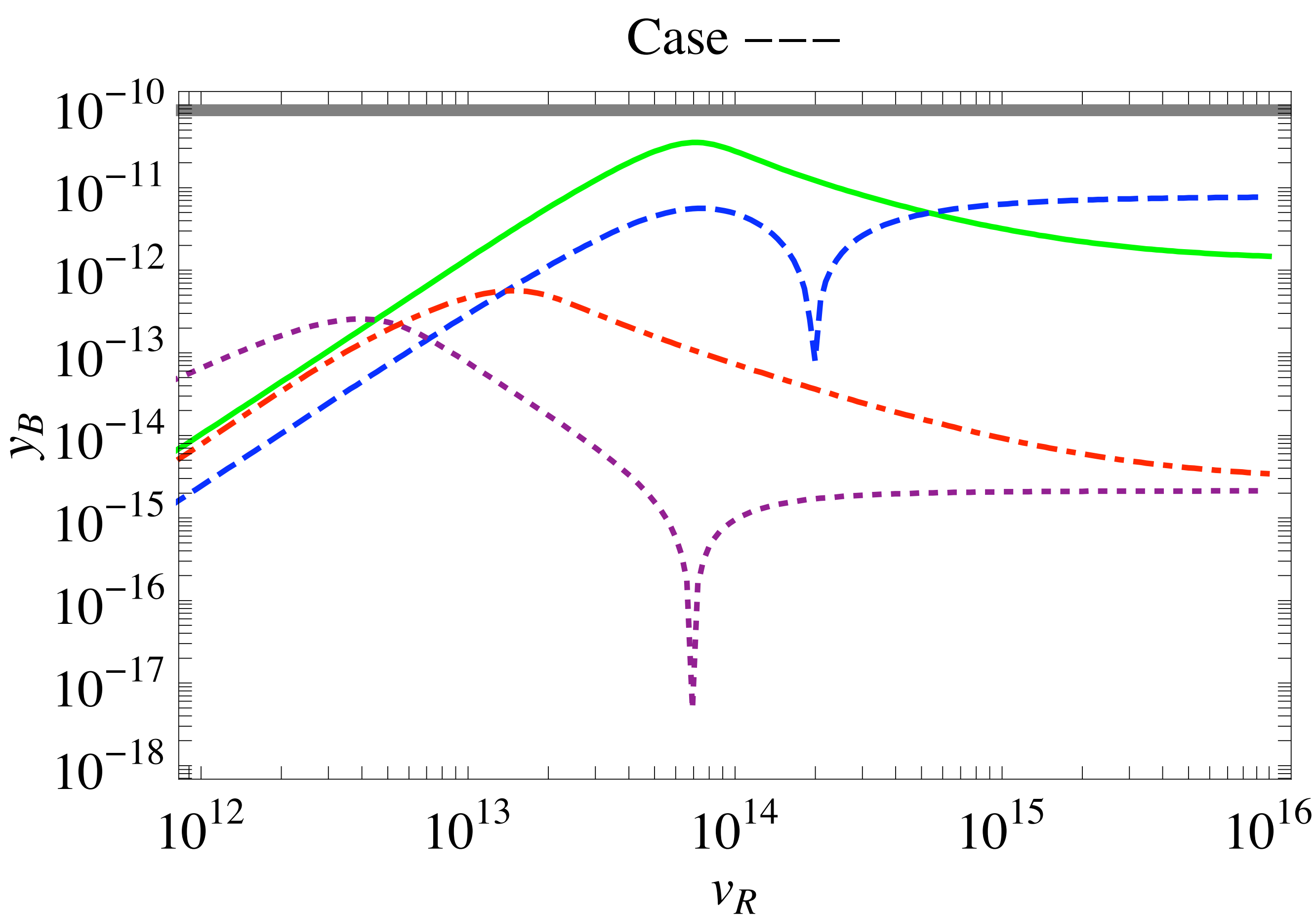


Successful leptogenesis possible for $v_R \gtrsim 10^{13}\,\mathrm{GeV}$



Successful leptogenesis possible for $v_R \sim (10^{13} - 10^{14})\,\mathrm{GeV}$

The corrections to $M_d = M_e$ play a crucial role here (not enough baryon asymmetry produced for $M_d = M_e$).



In spite of a huge enhancement by flavour effects, the baryon asymmetry generated from N_2 decays fails to reproduce the observed value (we did not find successful parameters – confirmed by Di Bari, Riotto in the type I case). Case $++-$ marginally successful, however not for $T_{RH} < 10^{10}$ GeV

Impact of flavour effects (case $M_d = M_e$)

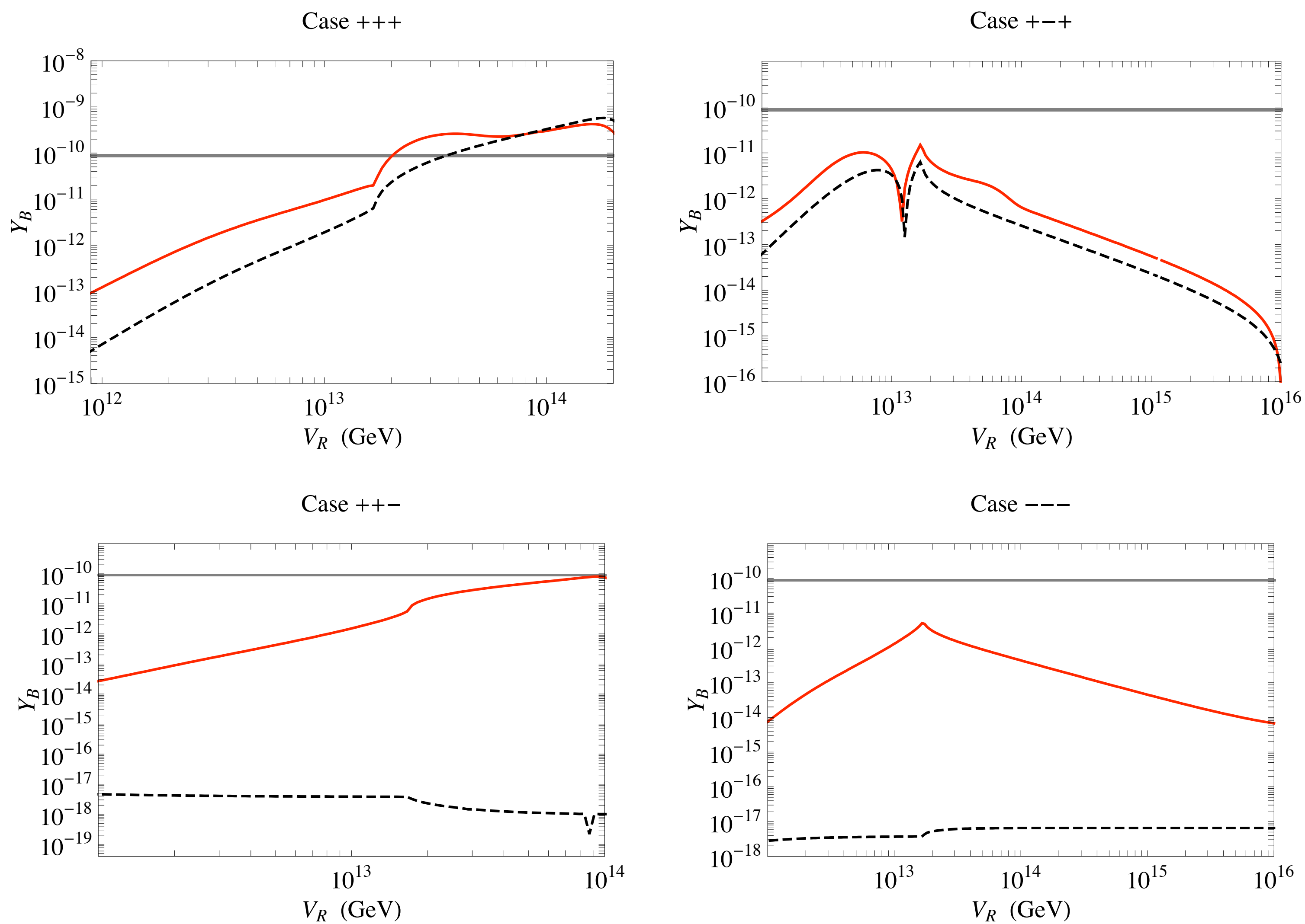


Figure 2: The final baryon asymmetry as a function of v_R for the four reference solutions, in the one-flavour approximation (dashed black line) and with flavour effects taken into account (solid red line). The GUT-scale mass relation $M_d = M_e$ is assumed. Inputs: hierarchical light neutrino masses with $m_1 = 10^{-3}$ eV, $\theta_{13} = 0$ and no CP violation in the PMNS mixing matrix; $\Phi_2^u = \pi/4$ and all other high-energy phases are set to zero; $\beta/\alpha = 0.1$. The Boltzmann equations are evolved starting from $T_{in} = 10^{11}$ GeV. The thick horizontal line corresponds to the WMAP constraint.

Flavour-dependent N2 leptogenesis

At $T \ll M_2$, the evolution of the flavour asymmetries Y_{Δ_α} $(\Delta_\alpha \equiv B/3 - L_\alpha)$ generated in N2 decays is governed by the Boltzmann equation:

$$\frac{dY_{\Delta_\alpha}}{dz} \simeq -2\,|A_{\alpha\alpha}|\,\kappa_{1\alpha}\,W_1(z)\,Y_{\Delta_\alpha}(z)$$

where $z \equiv M_1/T$, $\quad \kappa_{1\alpha} \equiv \tilde{m}_1^\alpha/\tilde{m}_1^\star$, $\quad |A_{\alpha\alpha}| \approx 1$

and W1(z) = rate of N1 inverse decays (main washout processes)

$$\begin{aligned}(Y_{\Delta_\alpha})_{\rm final} &\simeq (Y_{\Delta_\alpha})_{N_2}\, e^{-2|A_{\alpha\alpha}|\kappa_{1\alpha}\int_{z_{in}}^{\infty} dz\ W_1(z)} \\ &\simeq (Y_{\Delta_\alpha})_{N_2}\, e^{-\frac{3\pi}{4}|A_{\alpha\alpha}|\kappa_{1\alpha}}\end{aligned}$$

(using $\int_0^\infty dz\ W_1(z) = 3\pi/8$). If e.g. $\kappa_{1e} \ll 1 \ll \kappa_{1\mu}, \kappa_{1\tau}$, the asymmetry in the electron flavour is almost unaffected, while the asymmetries in the muon and tau flavours are exponentially diluted. This results in a large final B-L asymmetry. By contrast, in the one-flavour approximation, the asymmetry generated in N2 decays is completely washed out:

$$Y_{B-L} \simeq e^{-\frac{3\pi}{4}\sum_\alpha \kappa_{1\alpha}}\,(Y_{B-L})_{N_2} \lll (Y_{B-L})_{N_2}$$

Supersymmetric thermal leptogenesis ⇒ gravitino problem

If impose $T_{RH} < 10^{10}$ GeV, only 4 solutions survive (generically)

No successful realization of "N2 leptogenesis"

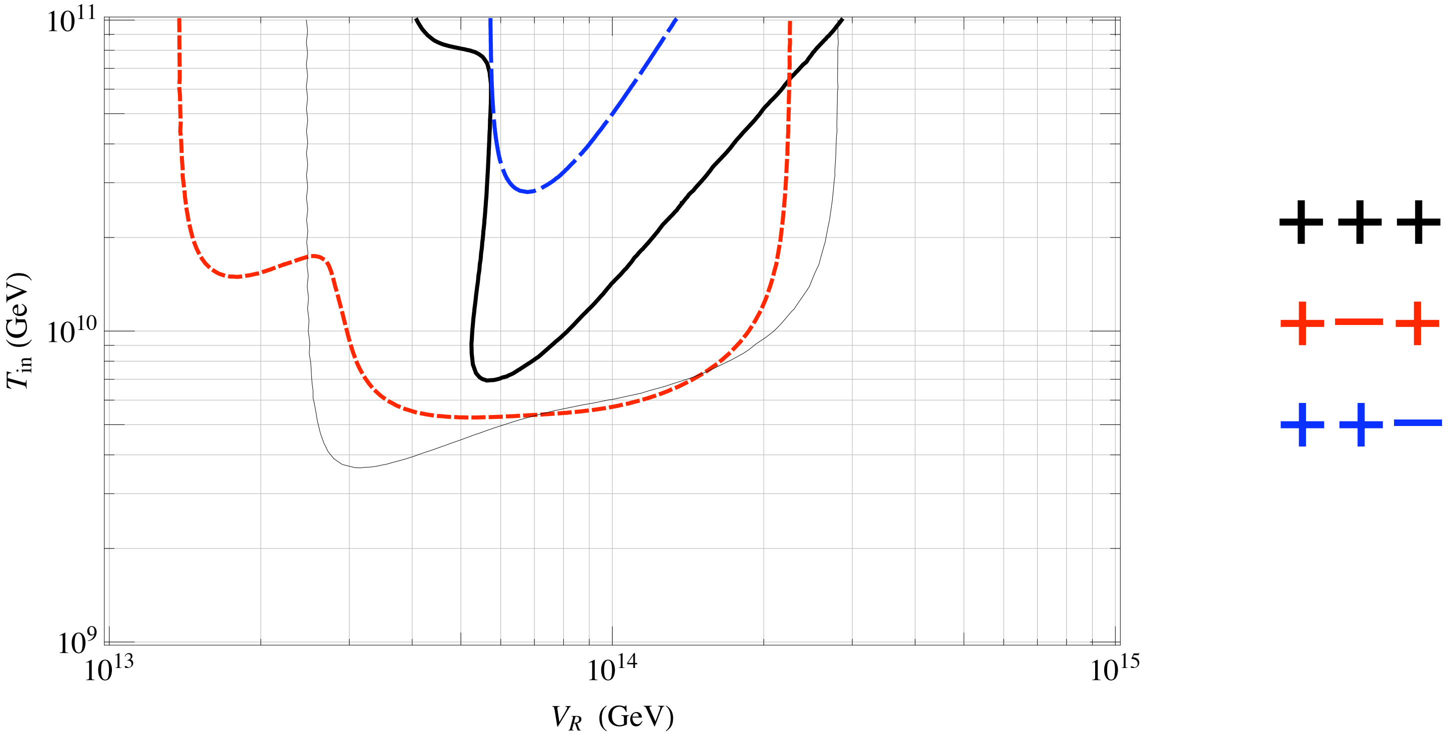


Figure 10: Regions of the (v_R, T_{in}) parameter space where $|Y_B| > Y_B^{WMAP}$ for solutions $(+,+,+)$, $(+,-,+)$ and $(+,+,-)$, and where $|Y_B| > 0.1\, Y_B^{WMAP}$ for solution $(-,-,-)$. These regions are delimited by the thick black contour in the $(+,+,+)$ case, the dashed red contour for $(+,-,+)$, the long-dashed blue contour for $(+,+,-)$, and the thin black contour for $(-,-,-)$. Inputs: set 1 of the Appendix for U_m and the high-energy phases; other input parameters as in Fig. 2.

Impact of corrections to MD = Mu

plots: $m_{D_2} = (0.1 - 10)\, m_c(M_{GUT})$

- successful flavour-dependent N2 leptogenesis (however, solution $---$ fails if impose $T_{RH} < 10^{10}$ GeV)

- solution $+-+$ successful for vR as large as MGUT

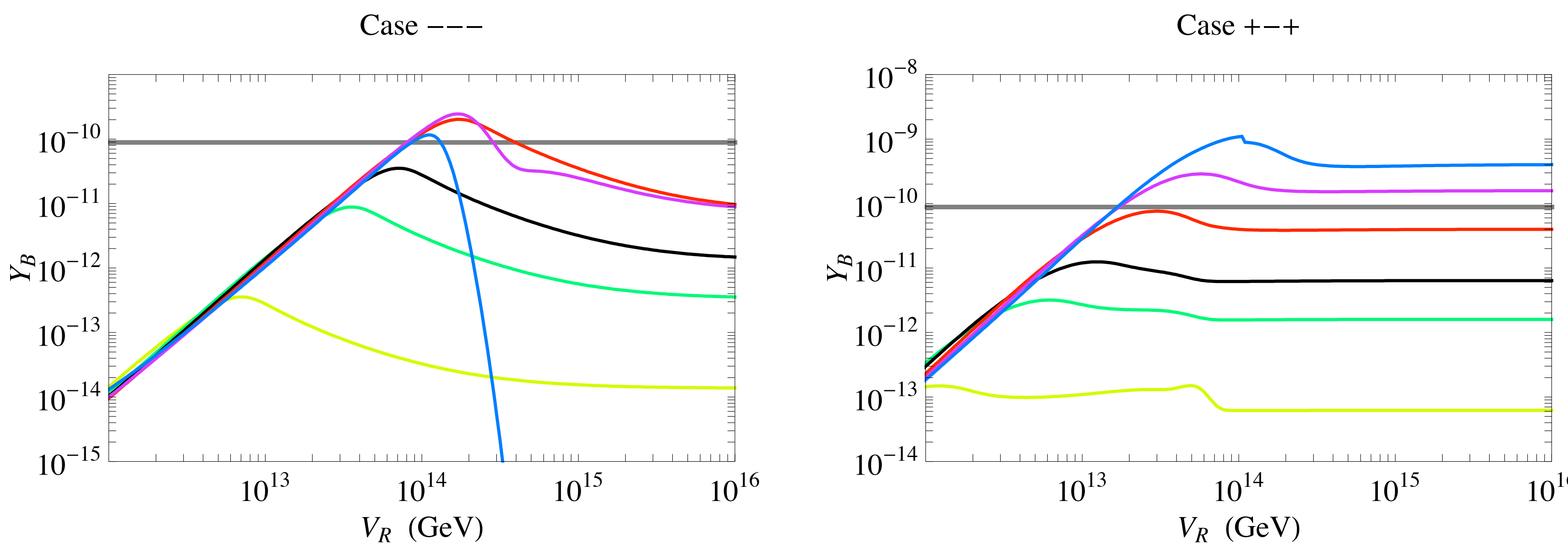


Figure 9: The final baryon asymmetry as a function of v_R for different values of y_2, from $y_2/y_c(M_{GUT}) = 0.1$ (yellow/light grey) to $y_2/y_c(M_{GUT}) = 10$ (blue/dark grey). The reference case $y_2 = y_c$ is plotted in black. Left panel: solution $(-,-,-)$, set 1 for U_m and the high-energy phases; right panel: solution $(+,-,+)$, set 4 for U_m and the high-energy phases. The other input parameters are as in Fig. 2.

SO(10) models with type II seesaw mechanism

Much more difficult: RHNs belong to the matter representation (16), hence are always around and couple to lepton doublets

<u>Way out</u>: "non-standard" embedding of the SM fermions into SO(10) representations

$$16_i \;=\; 10_i \;\oplus\; . \;\oplus\; 1_i$$
$$10_i \;=\; . \;\oplus\; \bar{5}_i^{10}$$

$(5_i^{10}, \bar{5}_i^{16})$ form a vector-like pair of matter fields

Motivation: E6? $\quad 27_i = 16_i \oplus 10_i \oplus 1_i$

<u>How to achieve this?</u> $\quad W \;=\; \frac{1}{2}\, y_{ij} 16_i 16_j 10 + h_{ij} 16_i 10_j 16$

SU(5) singlet in the 16: $v_1^{16} \neq 0$ ⇒ GUT-scale masses for $(5_i^{10}, \bar{5}_i^{16})$

$5_i^{10} \equiv (L_i^c, D_i)$ heavy anti-lepton doublets and quark singlets

SM matter fields: $\quad 10_i^{16} = (Q_i, u_i^c, e_i^c), \quad \bar{5}_i^{10} = (L_i, d_i^c), \quad 1_i^{16} = \nu_i^c$

$$W = \frac{1}{2}\, y_{ij} 16_i 16_j 10 + h_{ij} 16_i 10_j 16$$

Quark and lepton masses: $M_u = y\, v_u^{10}$ $\quad M_d = M_e^T = h\, v_d^{16}$

No neutrino Dirac couplings at tree level: RHNs couple to heavy leptons

The heavy leptons (quarks) have hierarchical masses proportional to down-type fermion masses: $M_i = h_i v_1^{16} = m_{e_i} v_1^{16} / v_d^{16}$

Neutrino masses: $W_{II} = \frac{1}{2}\, f_{ij} 10_i 10_j 54 + \frac{1}{2}\, \sigma 10\, 10\, 54 + \frac{1}{2}\, M_{54} 54^2$

$\Rightarrow \quad \frac{1}{2}\, f_{ij} L_i L_j \Delta + \frac{1}{2}\, \sigma H_u^{10} H_u^{10} \bar{\Delta} + M_\Delta \Delta \bar{\Delta} + \ldots$

where $54 = 15 \oplus \overline{15} \oplus 24\,, \quad 15 = (\Delta, Z, \Sigma)\,, \quad \Delta = (1,3)_{+2}$

$\Rightarrow$ type II seesaw: $M_\nu = \dfrac{\sigma (v_u^{10})^2}{2 M_\Delta}\, f$

Assumed:
- matter parity
- no mass term $10_i\ 10_j$, no 54 vev $\Rightarrow$ no mixing $\bar{5}_i^{10} / \bar{5}_i^{16}$

Leptogenesis

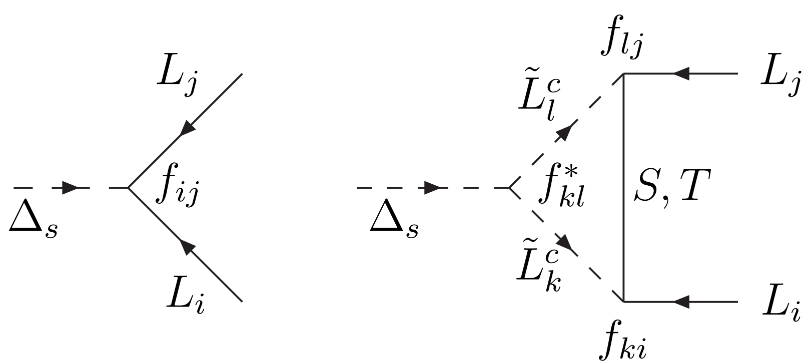
Requires a CP asymmetry in triplet decays. In standard triplet leptogenesis, the f_{ij} 's are not enough: need a second set of (flavour) couplings, otherwise

$$\epsilon_\Delta \propto \mathrm{Im}[\mathrm{Tr}(f f^* f f^*)] = 0$$

$\Rightarrow$ introduce e.g. a second triplet with couplings f'_{ij} to leptons

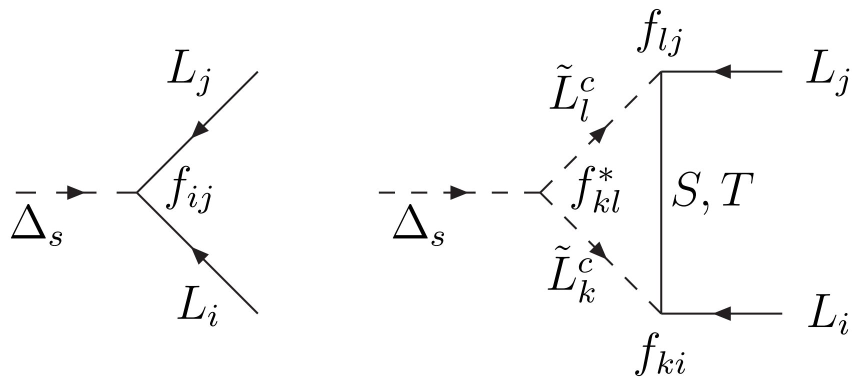
$\Rightarrow$ loose predictivity: no direct connection between leptogenesis and neutrino masses (usual problem of leptogenesis: see e.g. Davidson et al, Petcov et al.)

However, in our scenario the states in the loop are heavy:



$S, T \in 24$

(the self-energy diagram does not contribute to the asymmetry)



$$\epsilon_\Delta \;\propto\; \sum_{kl} c_{kl}\,\theta(M_\Delta - M_k - M_l)\,\mathrm{Im}[f_{kl}(f^* f f^*)_{kl}]$$

The $\tilde{L}_i^c$ are heavy with hierarchical masses:

$$(M_1,\, M_2,\, M_3) \;\sim\; (2\times 10^{11},\, 4\times 10^{13},\, 7\times 10^{14})\ \mathrm{GeV}\,\left(\frac{\tan\beta}{10}\right)\left(\frac{v_1^{16}}{10^{16}\,\mathrm{GeV}}\right)$$

If e.g. $M_3 > M_\Delta$, the trace is incomplete and $\epsilon_\Delta \neq 0$

Assuming $M_1 \ll M_\Delta < M_1 + M_2$ and $M_S = M_T = M_{24} \gg M_\Delta$, one obtains:

$$\epsilon_\Delta \;\simeq\; \frac{1}{10\pi}\,\frac{M_\Delta}{M_{24}}\,\frac{\lambda_L^4}{\lambda_L^2 + \lambda_{L_1^c}^2 + \lambda_{H_u}^2 + \lambda_{H_d}^2}\,\frac{\mathrm{Im}[M_{11}(M^* M M^*)_{11}]}{(\sum_i m_i^2)^2}$$

where $\lambda_L^2 \;\equiv\; \sum_{i,j=1}^{3} |f_{ij}|^2\,, \quad \lambda_{L_1^c}^2 \;\equiv\; |f_{11}|^2\,, \quad \lambda_{H_{u,d}}^2 \;\equiv\; |\sigma\,\alpha_{u,d}^2|^2$

$\Delta_s \to \tilde{L}_1^c \tilde{L}_1^c$: opposite CP asymmetry $(-\epsilon_\Delta)$ / $\Delta_s \to \overline{\tilde{H}}_d \overline{\tilde{H}}_d,\, H_u H_u$: no CP asymmetry

Dependence on the light neutrino parameters

$$\frac{\mathrm{Im}[M_{11}(M^* M M^*)_{11}]}{\overline{m}^4} = -\frac{1}{\overline{m}^4}\Big\{ c_{13}^4 c_{12}^2 s_{12}^2 \sin(2\rho)\, m_1 m_2 \Delta m_{21}^2$$

$$+ c_{13}^2 s_{13}^2 c_{12}^2 \sin 2(\rho - \sigma)\, m_1 m_3 \Delta m_{31}^2 - c_{13}^2 s_{13}^2 s_{12}^2 \sin(2\sigma)\, m_2 m_3 \Delta m_{32}^2 \Big\}$$

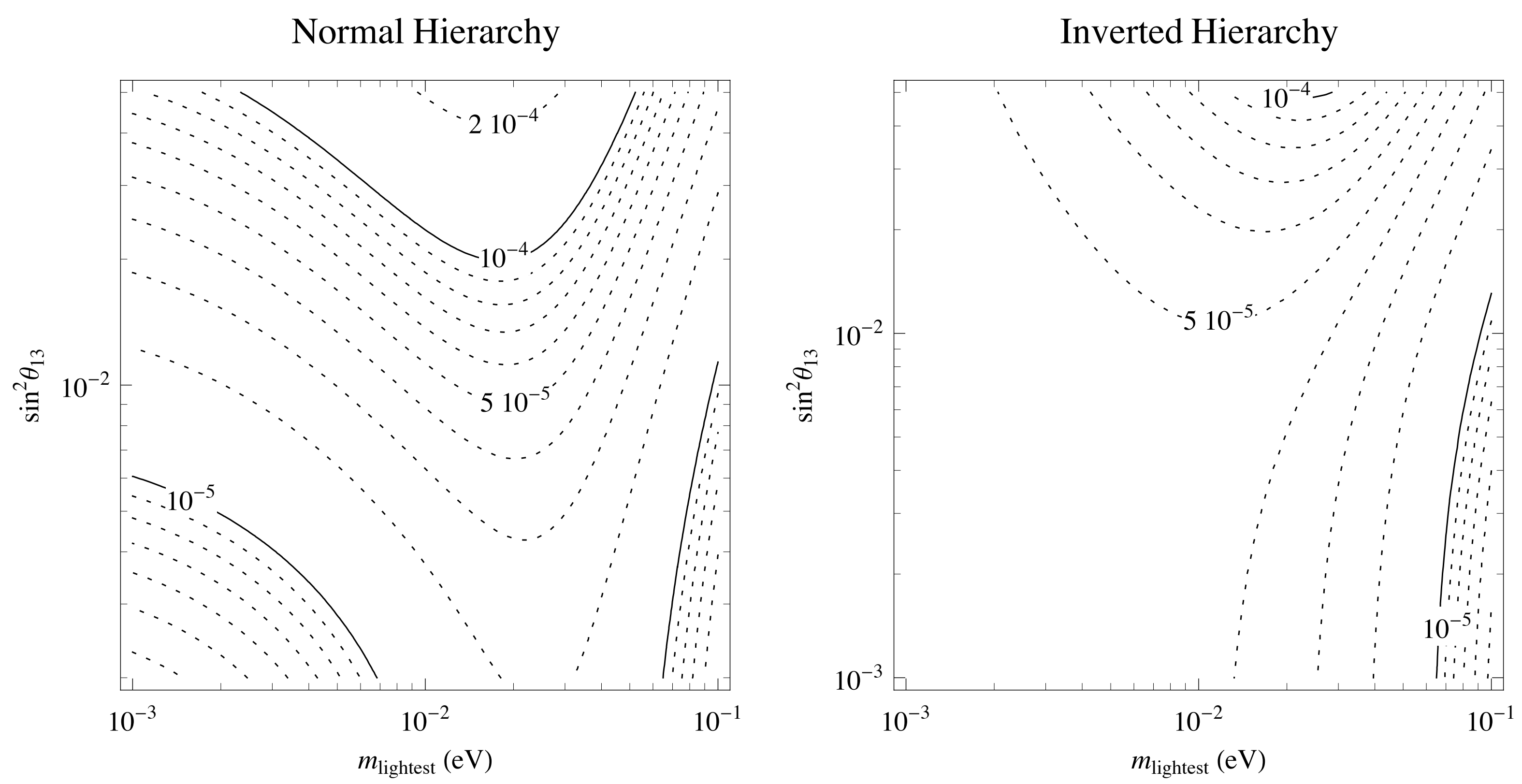
$$U_{ei} = (c_{13} c_{12} e^{i\rho}, c_{13} s_{12}, s_{13} e^{i\sigma})$$

→ ϵ_Δ does not depend on high-scale flavour parameters - only on the light neutrino parameters and on $\lambda_L, \lambda_{H_u}, \lambda_{H_d}, M_\Delta / M_{24}$

→ the CP violation needed for leptogenesis is provided by the CP-violating phases of the PMNS matrix (the Majorana phases to which neutrinoless double beta decay is sensitive in the case $M_1 < M_\Delta < M_1 + M_2$)

→ ϵ_Δ can be large (λ_L^2 is bounded by perturbativity):

$$\begin{aligned} \epsilon_\Delta^{\max} &\simeq 2.2 \times 10^{-4}\, \lambda_L^2 \qquad (\text{maximum}\, \theta_{13})\ , \\ &\simeq 3.4 \times 10^{-5}\, \lambda_L^2 \qquad (\text{vanishing}\, \theta_{13})\ , \end{aligned}$$



Isocontours of the CP asymmetry in units of λ_L^2 in the $(\sin^2\theta_{13}, m_{\rm lightest})$ plane, maximized with respect to the CP-violating phases and to M_Δ/M_{24}

$\frac{n_B}{s} = 7.62 \times 10^{-3}\,\eta\,\epsilon_\Delta$ agrees with the WMAP value $(8.82 \pm 0.23) \times 10^{-11}$

if $\eta\,\epsilon_\Delta \approx 10^{-8}$ $\Rightarrow$ the efficiency factor can be as small as $10^{-5} - 10^{-4}$ in the region where the CP asymmetry is maximal

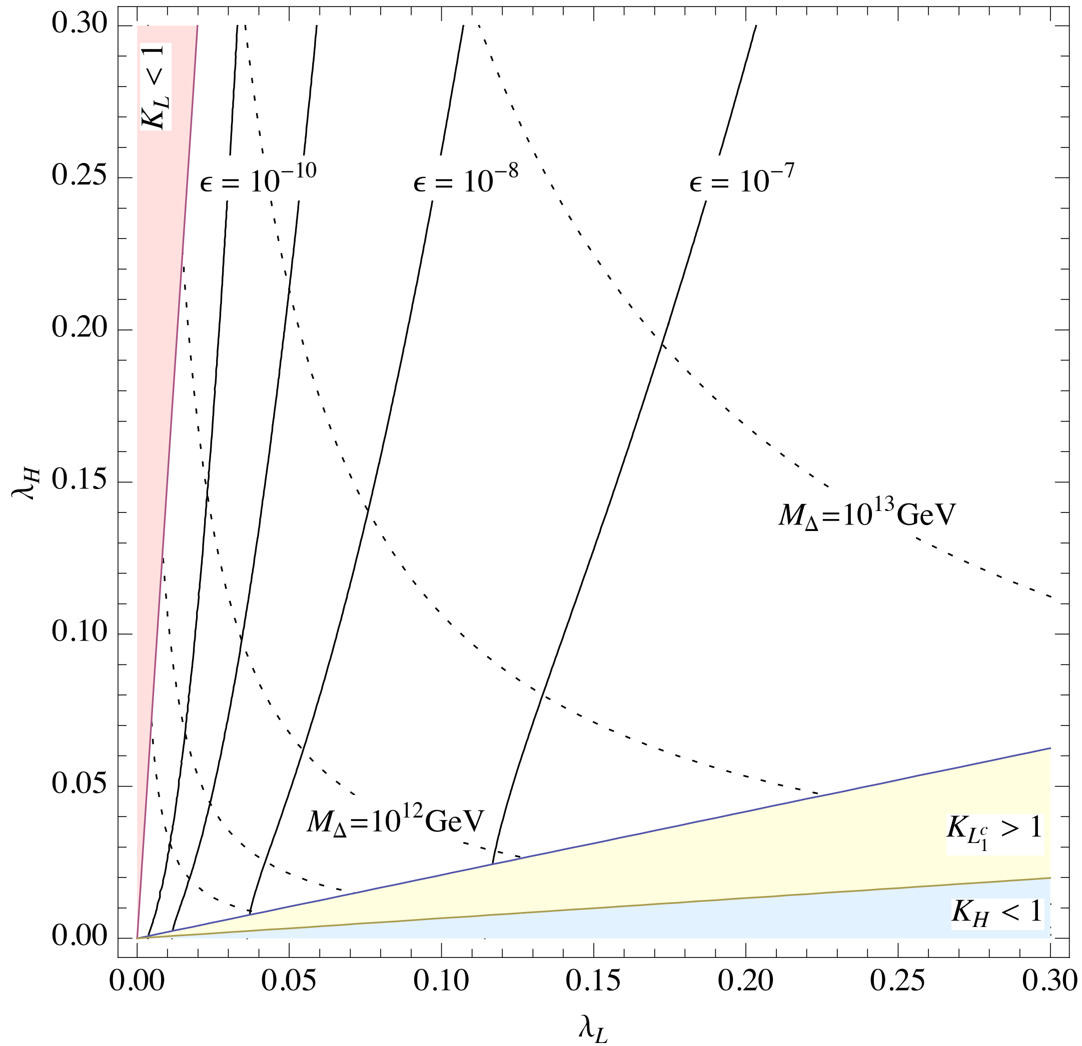
This regime must be studied numerically. There is also a large efficiency regime that can be discussed analytically, namely the regime where

$$K_{L_1^c} \ll 1\ , \quad K_L, K_{H_u} \gtrsim 1 \quad \text{and} \quad M_{24} \gg M_\Delta$$

with $K_a \equiv \Gamma(\Delta_s \to aa)/H(M_\Delta) \quad (a = \tilde{L}_1^c, \bar{L}, H_u)$

Even though triplet decays are in equilibrium, a lepton asymmetry is generated thanks to $K_{L_1^c} \ll 1$ [Hambye, Raidal, Strumia]

Unfortunately, the condition $K_{L_1^c} \ll 1$ corresponds to a suppressed neutrinoless double beta decay rate, hence to a suppressed CP asymmetry



Normal hierarchy with $m_1 \ll m_2,\ \sin^2\theta_{13} = 0.05$ and $\sin 2\sigma = 1$
$\tan\beta = 10,\ \lambda_{H_d} = 0$ and $M_\Delta/M_{24} = 0.1$

We find that successful leptogenesis is possible for $M_\Delta \gtrsim 10^{12}\,\mathrm{GeV}$

This scale is problematic in view of the gravitino problem, which requires $T_{RH} \lesssim (10^9 - 10^{10})\,\mathrm{GeV}$ in the most favourable cases (unstable gravitino with $m_{3/2} \gtrsim 10\,\mathrm{TeV}$ or gravitino LSP with harmless NLSP for BBN)

Ways out:

- very light gravitino (< 16 eV required by WMAP)
- very heavy gravitino (>> 100 TeV)
- non-thermal production of the triplets ($T_{RH} \ll M_\Delta$)
- non-supersymmetric scenario with a real 54

Conclusions

- Ways to realize successful leptogenesis in GUTs:
  - SO(10) models with a left-right symmetric seesaw mechanism: successful leptogenesis even with $M_D = M_u$
  - SO(10) models with SM fermions split among 16 and 10 matter multiplets and type II seesaw ⇒ predictive leptogenesis

- Work in progress [L. Calibbi, M. Frigerio, S.L., A. Romanino]
  - build complete SO(10) models with SM fermions in 16 and 10 matter multiplets
  - study flavour violating effects in these models

Back-up slides

Reconstruction of the heavy neutrino mass spectrum

The starting point is the left-right symmetric seesaw formula:

$$M_\nu \;=\; f v_L - \frac{v^2}{v_R} Y f^{-1} Y$$

with f, Y complex and symmetric. The goal is to reconstruct f assuming that Y is known in the basis of charged lepton mass eigenstates

Akhmedov and Frigerio (hep-ph/0509299) showed that there are 2^n solutions for n generations, connected 2 by 2 by a "seesaw duality":

$$f \;\longrightarrow\; \hat{f} \;\equiv\; \frac{M_\nu}{v_L} - f$$

and provided explicit expressions for the fij up to n=3

In hep-ph/0606078, we proposed an alternative reconstruction procedure which employs complex orthogonal matrices

First rewrite the LR symmetric seesaw formula $M_\nu = \alpha f - \beta Y f^{-1} Y$ as

$$Z \;=\; \alpha X - \beta X^{-1}$$

with $\alpha \;\equiv\; v_L\,,\;\; \beta \;\equiv\; v^2/v_R$ and

$$Z \;\equiv\; N_Y^{-1} M_\nu (N_Y^{-1})^T \qquad\qquad X \;\equiv\; N_Y^{-1} f (N_Y^{-1})^T$$

where N_Y is such that $Y = N_Y N_Y^T$ (Y invertible)

Z complex symmetric ⇒ can be diagonalized by a complex orthogonal matrix O_Z if its eigenvalues z_i are all distinct:

$$Z \;=\; O_Z \mathrm{Diag}\,(z_1, z_2, z_3) O_Z^T\;, \qquad O_Z O_Z^T \;=\; \mathbf{1}$$

Then X can be diagonalized by the same orthogonal matrix as Z, and its eigenvalues are the solutions of:

$$z_i \;=\; \alpha x_i - \beta x_i^{-1} \quad (i = 1, 2, 3)$$

2 solutions $x_i^+,\, x_i^-$ for each i ⇒ $2^3 = 8$ solutions for X, hence for f:

$$f \;=\; N_Y O_Z \begin{pmatrix} x_1 & 0 & 0 \\ 0 & x_2 & 0 \\ 0 & 0 & x_3 \end{pmatrix} O_Z^T N_Y^T\;, \qquad x_i = x_i^\pm$$

The corresponding right-handed neutrino masses $M_i = f_i v_R$ are obtained by diagonalizing f with a unitary matrix:

$$f \;=\; U_f \begin{pmatrix} f_1 & 0 & 0 \\ 0 & f_2 & 0 \\ 0 & 0 & f_3 \end{pmatrix} U_f^T \; , \qquad U_f U_f^\dagger \;=\; \mathbf{1}$$

and the couplings of the N_R mass eigenstates are $U_f^\dagger Y$

Note: diagonalization of a complex symmetric matrix by a complex orthogonal matrix

1) the eigenvalues of Z are the roots of $\mathrm{Det}\,(Z - z\mathbf{1}) = 0$

2) the eigenvectors associated with z_i are the solutions of $Z.\vec{v} = z_i\vec{v}$

It is always possible to find solutions of the latter equation, but in case of multiple solutions, it is not always possible to find an orthonormal basis of the eigenspace. The problem arises when one non-trivial solution has a zero norm in the SO(3, C) sense, i.e. $\vec{v}.\vec{v} = 0$; then Z cannot be diagonalized.

If all eigenvalues of Z are distinct, the eigenvectors automatically satisfy $\vec{v}.\vec{v} \neq 0$, hence Z is diagonalizable (it can be written as $O_Z \mathrm{Diag}\,(z_1, z_2, z_3) O_Z^T$)

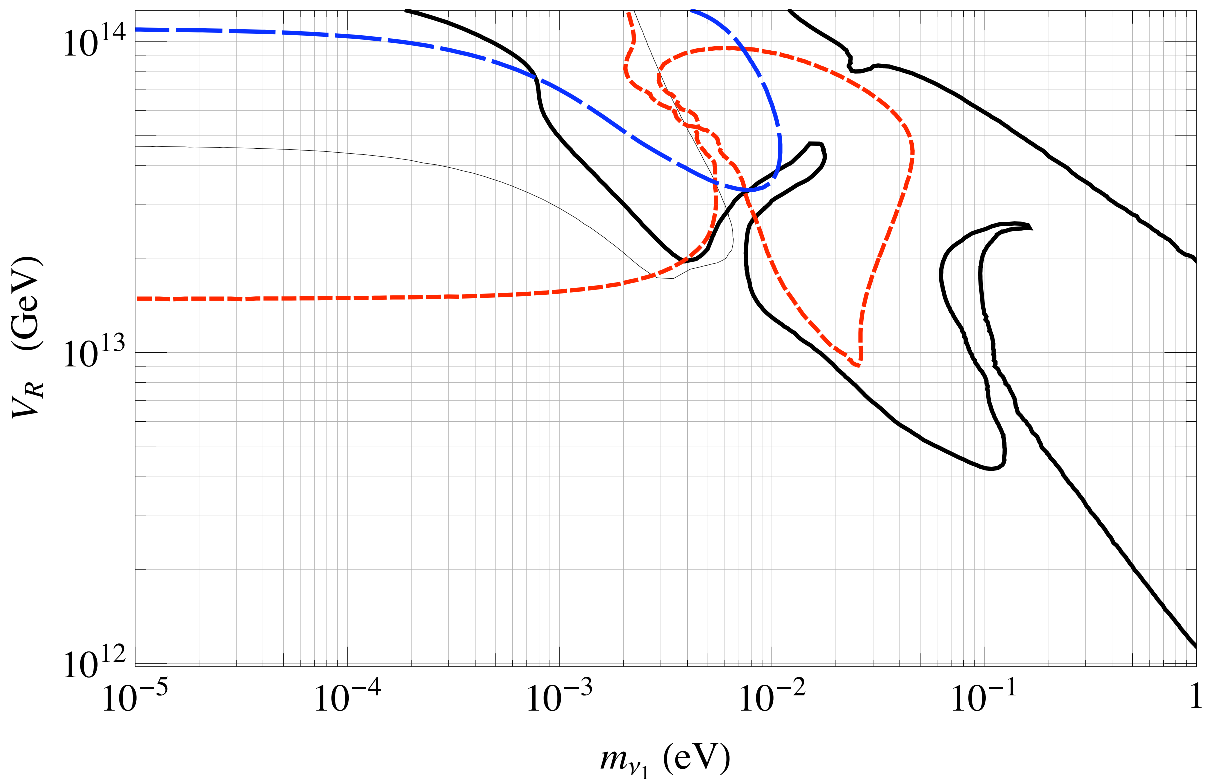


Figure 5: Regions of the $(m_1,\, v_R)$ parameter space where $|Y_B| > Y_B^{WMAP}$ for solutions $(+,+,+)$, $(+,-,+)$ and $(+,+,-)$, and where $|Y_B| > 0.1\, Y_B^{WMAP}$ for solution $(-,-,-)$. These regions are delimited by the thick black contour in the $(+,+,+)$ case, the dashed red contour for $(+,-,+)$, the long-dashed blue contour for $(+,+,-)$, and the thin black contour for $(-,-,-)$. Inputs: set 1 of the Appendix for U_m and the high-energy phases; other input parameters as in Fig. 2.

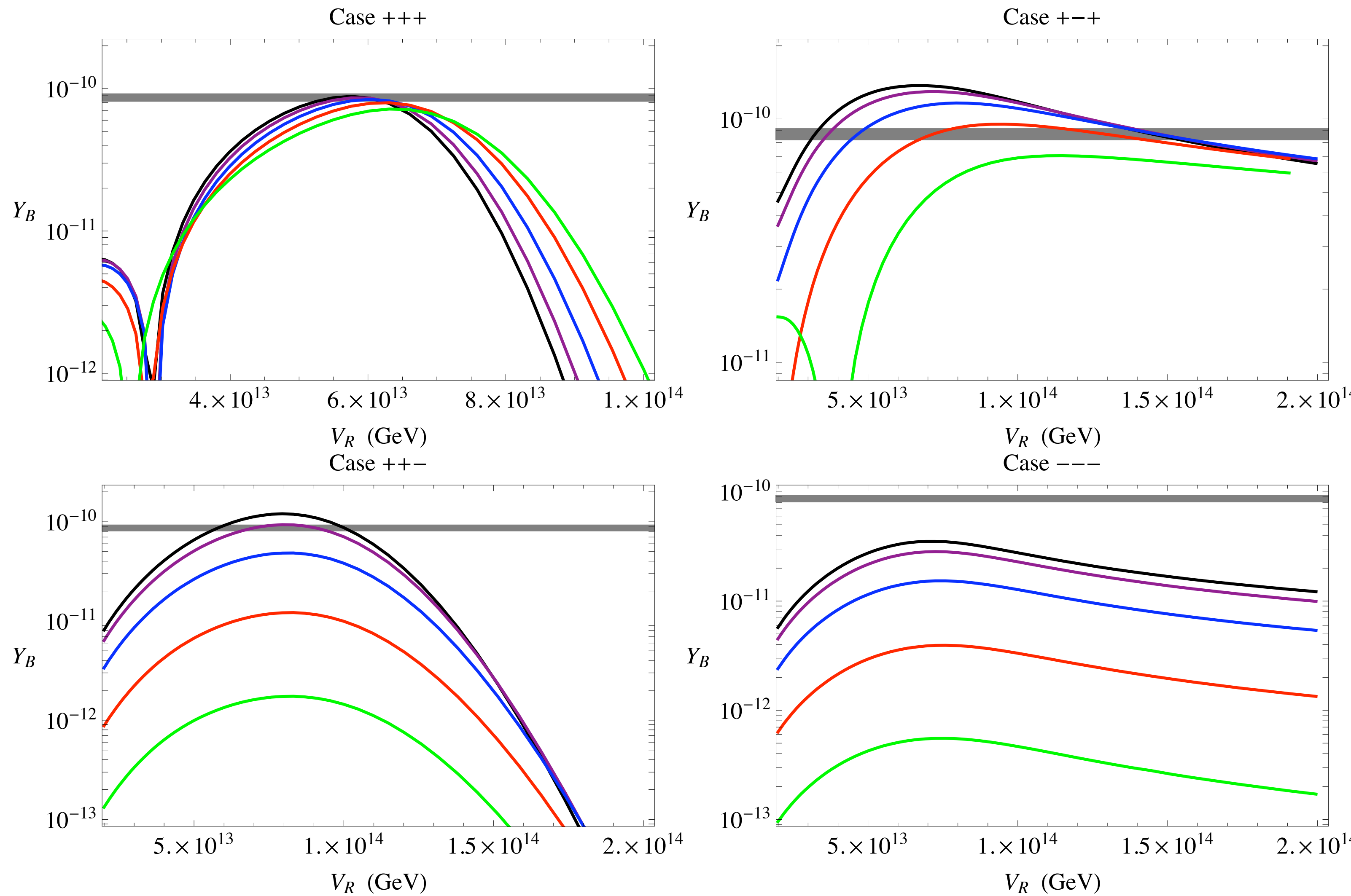


Figure 6: The final baryon asymmetry as a function of v_R in the four reference solutions, for $\delta_{PMNS} = 0$ and different values of θ_{13}: $\theta_{13} = 0°$ (black), $2°$ (purple), $5°$ (blue), $9°$ (red) and $13°$ (green / light grey). Inputs: set 1 of the Appendix for U_m and the high-energy phases; $T_{in} = 7 \times 10^9$ GeV for $(+,+,+)$ and $(+,-,+)$, while $T_{in} = 5 \times 10^{10}$ GeV for $(+,+,-)$ and $(-,-,-)$; other input parameters as in Fig. 2.

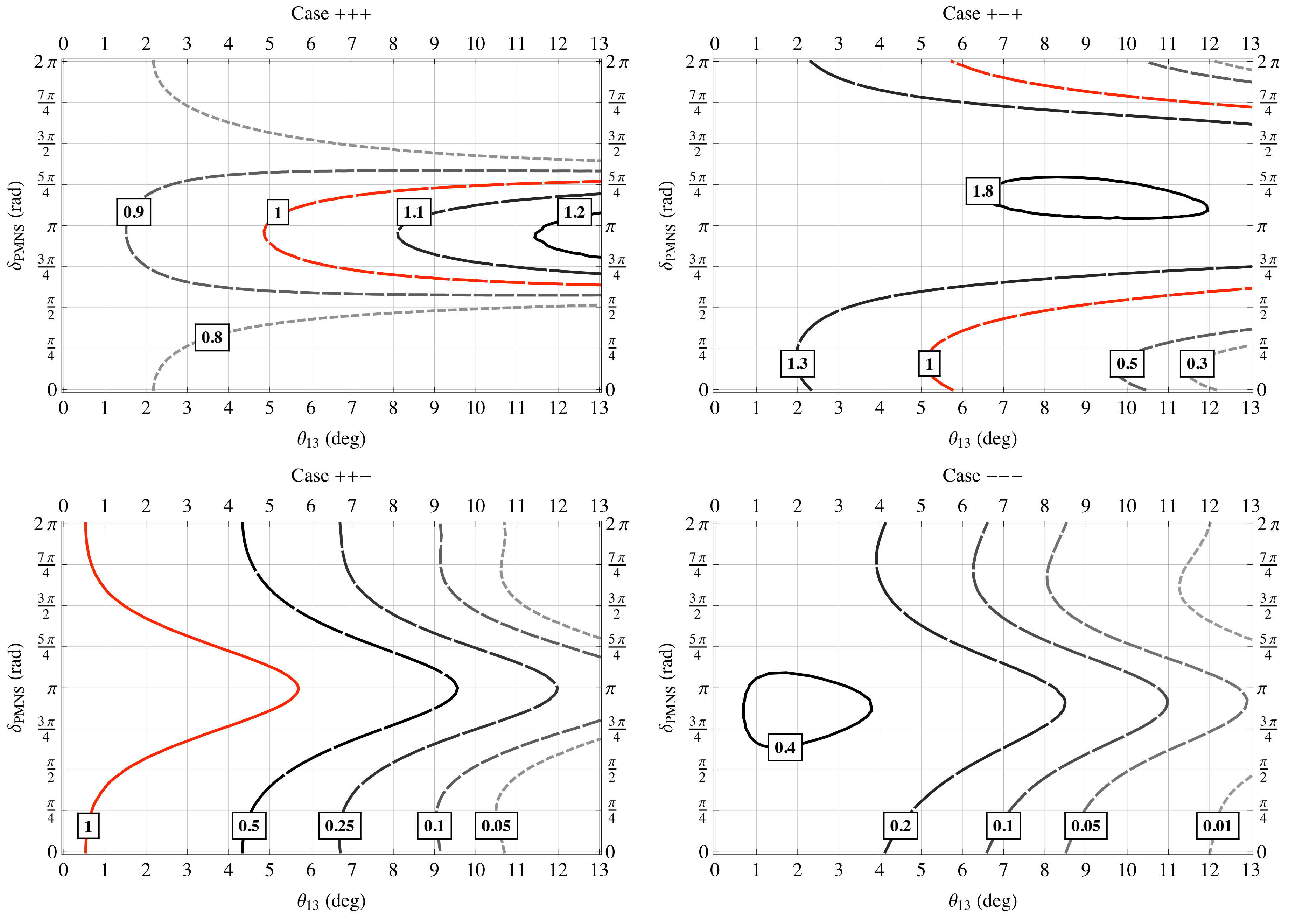


Figure 7: Contour lines of the ratio $|Y_B|/Y_B^{WMAP}$ in the four reference solutions, as a function of θ_{13} and δ_{PMNS}. The input parameters are the same as in Fig. 6, and the $B-L$ breaking scale has been fixed at $v_R = 5 \times 10^{13}$ GeV for $(+,+,+)$ and $(+,-,+)$, and at $v_R = 6 \times 10^{13}$ GeV for $(+,+,-)$ and $(-,-,-)$.