Flavour dynamics of leptogenesis

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- introduction
- review of standard leptogenesis
- lepton flavour effects
- flavour-dependent scalar triplet leptogenesis
- a predictive scheme for scalar triplet leptogenesis
- conclusions

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Introduction

The baryon asymmetry of the universe (BAU)

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq \frac{n_B}{n_\gamma} = (6.04 \pm 0.08) \times 10^{-10} \qquad \text{(Planck)}$$

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

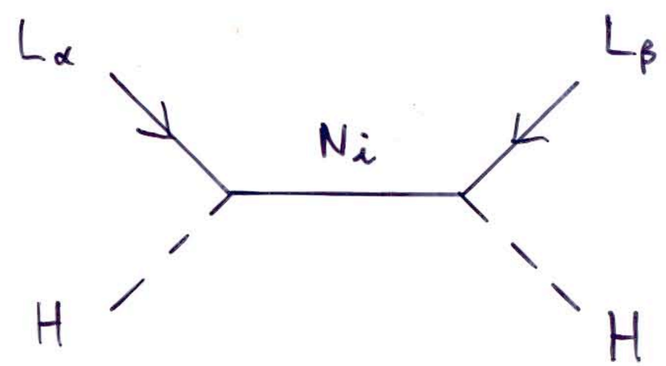
(1) B+L anomaly $\Rightarrow$ transitions between vacua with different (B+L) possible at $T \gtrsim M_{weak}$, where nonperturbative (B+L)-violating processes (electroweak sphalerons) are in equilibrium

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} to modify the dynamics of the EWPT, or generate a (B-L) asymmetry at $T > T_{EW}$

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

Attractive mechanism since connects neutrino masses to the BAU:

the B-L asymmetry is generated in out-of-equilibrium decays of heavy states involved in neutrino mass generation, such as the heavy Majorana neutrinos of the (type I) seesaw mechanism [Fukugita, Yanagida '86]



$$\Longrightarrow \quad m_\nu \sim \frac{y^2 v^2}{M_R}$$

Minkowski '77 - Gell-Mann, Ramond, Slansky '79
Yanagida '79 - Glashow '79 - Mohapatra, Senjanovic '80

This mechanism contains all ingredients for baryogenesis (L violation due to heavy Majorana mass, CP violation due to complex heavy neutrino couplings)

Other realizations are possible, e.g. with an EW scalar triplet (type II seesaw)

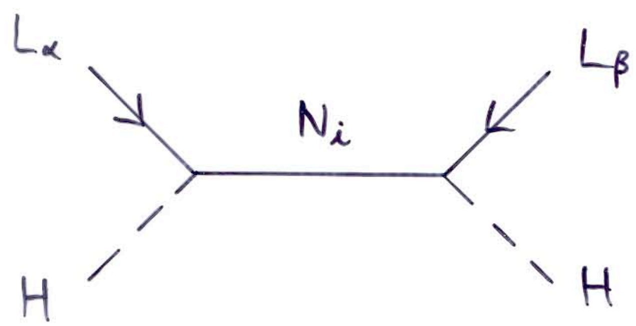
<u>This talk</u>: status of standard leptogenesis (with heavy Majorana neutrinos)
+ recent developments in scalar triplet leptogenesis

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 '86]

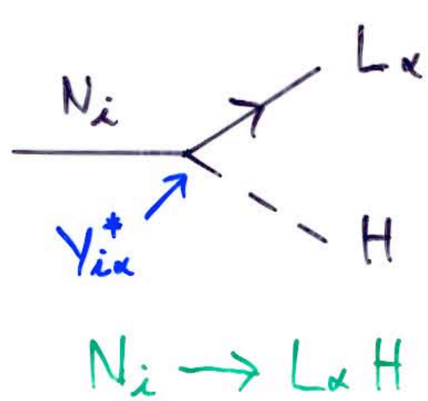
Seesaw mechanism:

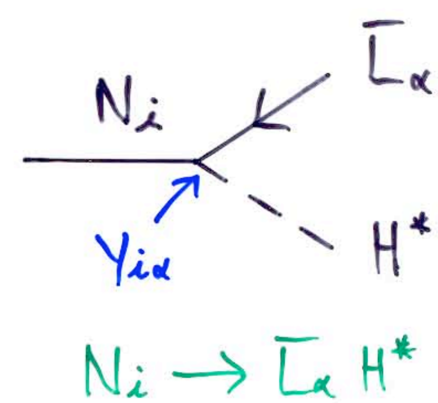
$$\mathcal{L}_{seesaw} = -\frac{1}{2} M_i \bar{N}_i N_i - \left(\bar{N}_i Y_{i\alpha} L_\alpha H + \text{h.c.} \right)$$



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

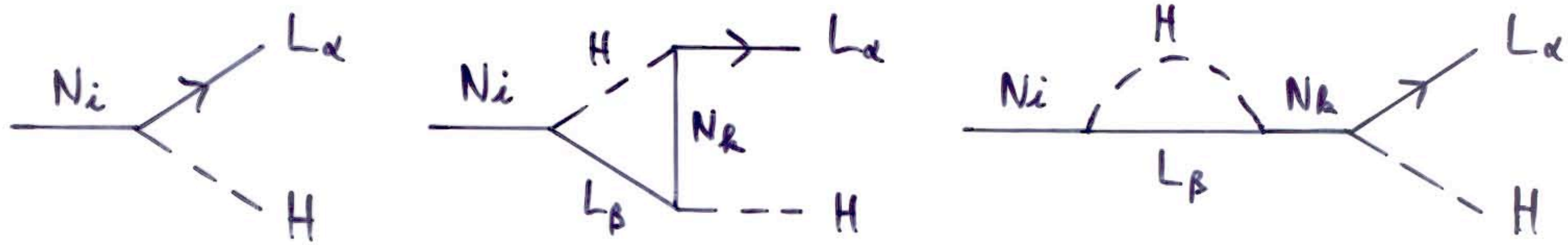
$N_i^c \equiv C \bar{N}_i^T = N_i$ (Majorana) $\Rightarrow$ decays both into l^+ and l^-





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

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



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

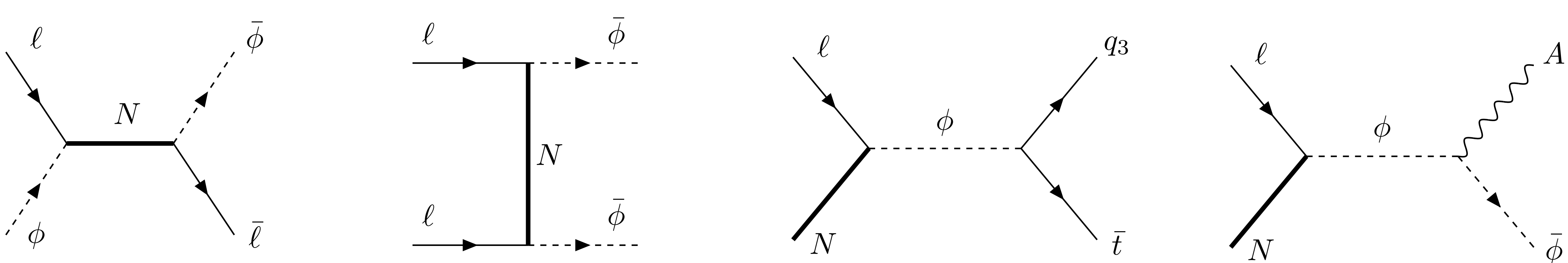
CP asymmetry in N1 decays (hierarchical case $M_1 \ll M_2, M_3$):

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

Covi, Roulet, Vissani '96
Buchmüller, Plümacher

The generated asymmetry is partly washed out by L-violating processes:

- inverse decays $LH \to N_1$
- ΔL=2 N-mediated scatterings $LH \to \bar{L}\bar{H}\,, \quad LL \to \bar{H}\bar{H}$
- ΔL=1 scatterings involving the top or gauge bosons

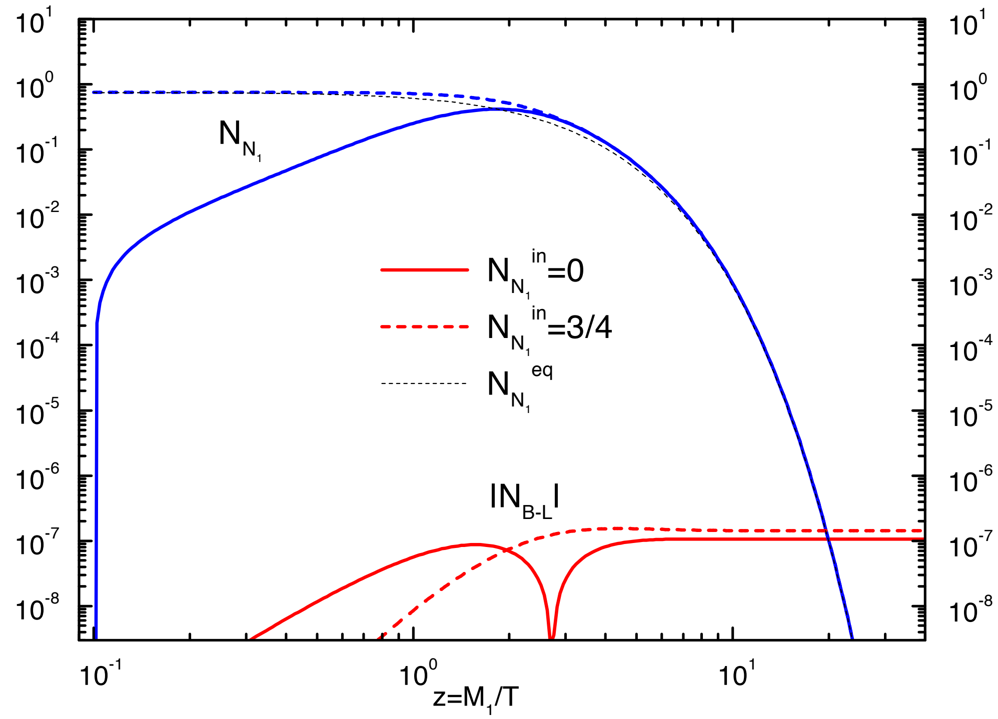


The evolution of the lepton asymmetry is described by the Boltzmann eq.

$$sHz\frac{dY_L}{dz} = \left(\frac{Y_{N_1}}{Y_{N_1}^{\mathrm{eq}}} - 1\right)\gamma_D\,\epsilon_{N_1} - \frac{Y_L}{Y_L^{\mathrm{eq}}}\left(\gamma_D + \gamma_{\Delta L=1} + \gamma_{\Delta L=2}\right)$$

$$Y_L \equiv (n_L - n_{\overline{L}})/s \qquad Y_{N_1} \equiv n_{N_1}/s \qquad z \equiv M_1/T$$

Typical evolution:



[Buchmüller, Di Bari, Plümacher]

Final baryon asymmetry: $$Y_B \equiv \frac{n_B - n_{\bar{B}}}{s} = -3.9\times 10^{-3}\,C\,\eta\,\epsilon_{N_1}$$

C = 28/79 conversion factor by sphalerons

η = efficiency factor

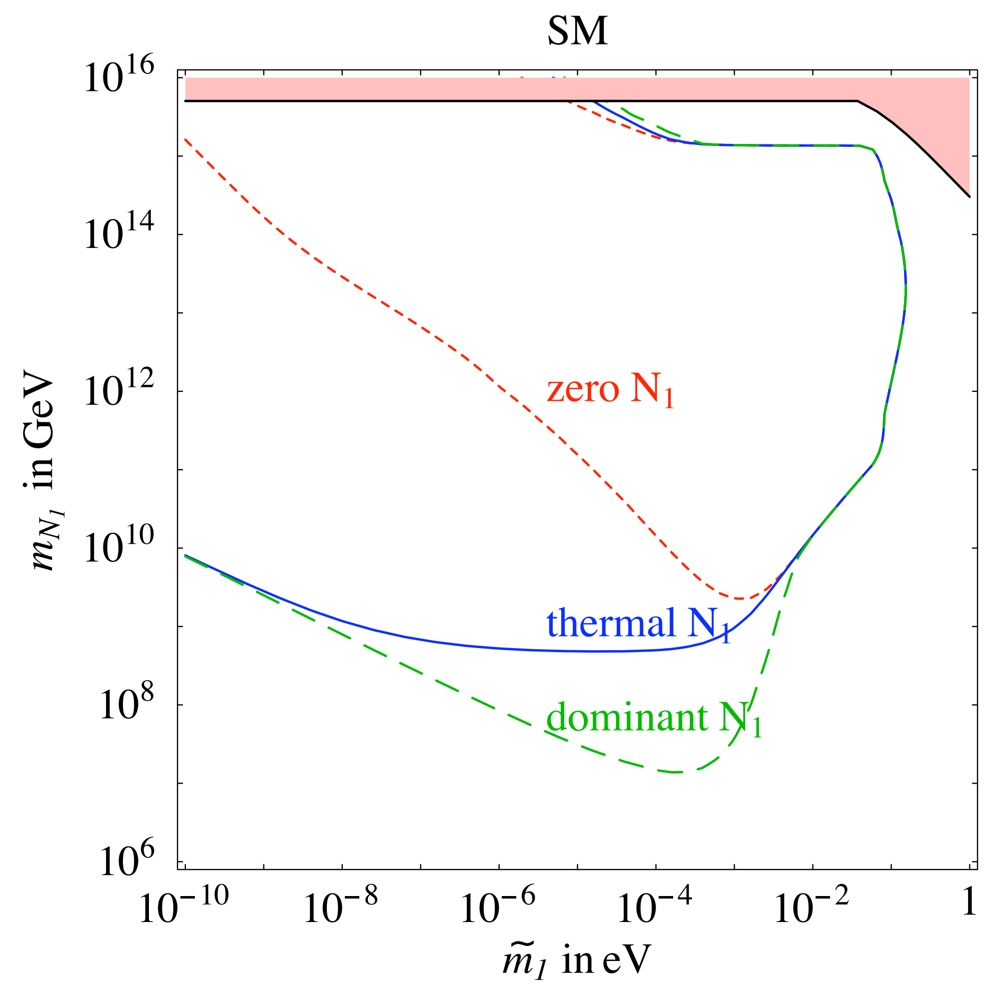
Can leptogenesis explain the observed baryon asymmetry?

Case $M_1 \ll M_2, M_3$

region of successful leptogenesis
in the $(\tilde{m}_1, M_1)$ plane

$$\tilde{m}_1 \equiv \frac{(YY^\dagger)_{11} v^2}{M_1}$$ controls washout

[Giudice, Notari, Raidal, Riotto, Strumia '03]



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

[Davidson, Ibarra '02]

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 '96
Pilaftsis '97

Flavour effects in leptogenesis

Barbieri, Creminelli, Strumia, Tetradis '99
Endoh et al. '03 - Nardi et al. '06 - Abada et al. '06
Blanchet, Di Bari, Raffelt '06 - Pascoli, Petcov, Riotto '06

"One-flavour approximation" (1FA): leptogenesis described in terms of a single direction in flavour space, the lepton ℓ_{N_1} to which N1 couples

$$\sum_\alpha \lambda_{1\alpha} \bar{N}_1 \ell_\alpha H \equiv \lambda_{N_1} \bar{N}_1 \ell_{N_1} H \qquad \ell_{N_1} \equiv \sum_\alpha \lambda_{1\alpha} \ell_\alpha / \lambda_{N_1}$$

This is 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 ℓ_{N_1}
$\Rightarrow$ 2 relevant flavours: ℓ_τ and a combination ℓ_a of ℓ_e and ℓ_μ

At $T \lesssim 10^{9}\,\mathrm{GeV}$, λ_τ and λ_μ are in equilibrium $\Rightarrow$ must distinguish ℓ_e, ℓ_μ and ℓ_τ

→ depending on the T regime, BE's for 1, 2 or 3 lepton flavours

Flavour-dependent CP asymmetries and washout rates:

$$\epsilon^\alpha_{N_1} = \frac{\Gamma(N_1 \to \ell_\alpha H) - \Gamma(N_1 \to \bar{\ell}_\alpha \bar{H})}{\Gamma(N_1 \to \ell_\alpha H) + \Gamma(N_1 \to \bar{\ell}_\alpha \bar{H})} \qquad \sum_\alpha \epsilon^\alpha_{N_1} = \epsilon_{N_1}$$

→ flavour-dependent Boltzmann equations

Proper description of flavour effects: density matrix

$(\Delta_\ell)_{\alpha\beta}$ → diagonal entries = flavour asymmetries $\Delta_{\ell_\alpha} \equiv Y_{\ell_\alpha} - Y_{\bar{\ell}_\alpha}$

$(\Delta_\ell)_{\alpha\beta}$ → off-diagonal entries = quantum correlations between flavours

explicitly flavour-covariant formalism: Boltzmann equations covariant under flavour rotations

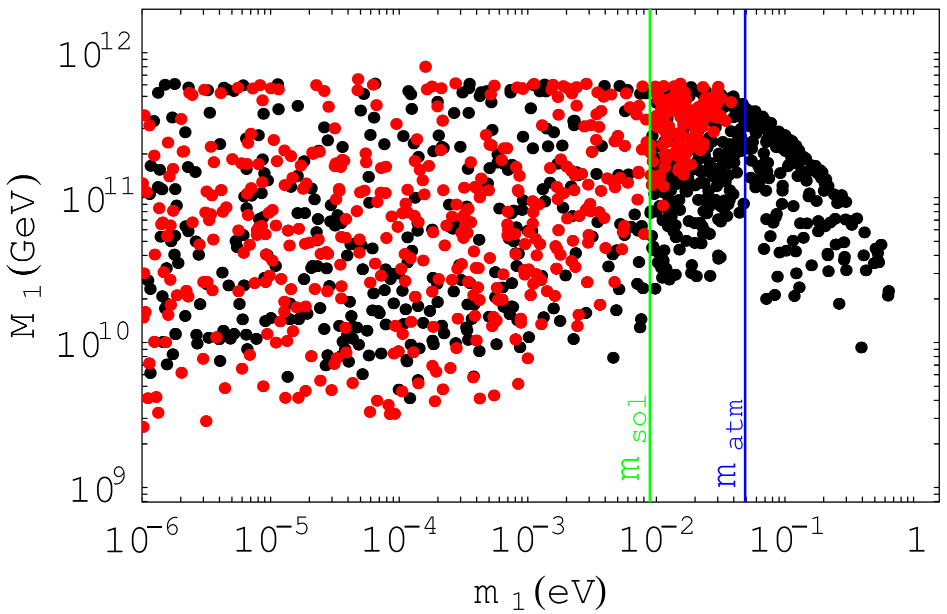
$$\ell \to U\ell \qquad \Delta_\ell \to U^* \Delta_l \, U^T$$

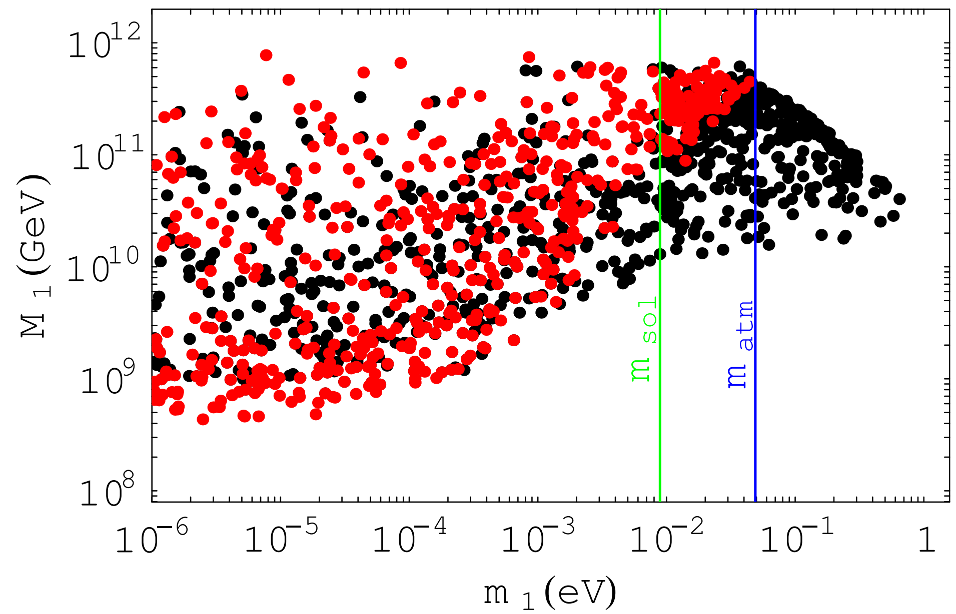
However, only really needed at the transition between 2 different flavour regimes; otherwise there is always a natural basis choice in which the BE's for the density matrix reduce to a set of BE's for flavour asymmetries

E.g. at $T > 10^{12}\,\mathrm{GeV}$ in the basis $(\ell_{N_1}, \ell_{\perp 1}, \ell_{\perp 2})$, the diagonal entry corresponding to ℓ_{N_1} is the only nonzero entry of Δ_ℓ

At $10^9\,\mathrm{GeV} < T < 10^{12}\,\mathrm{GeV}$, fast λ_τ-induced interactions such as $q_3\,\ell_\tau \to t_R\,\tau_R$ destroy the quantum coherence between ℓ_τ and the other lepton flavours

Flavour effects lead to quantitatively different results from the 1FA

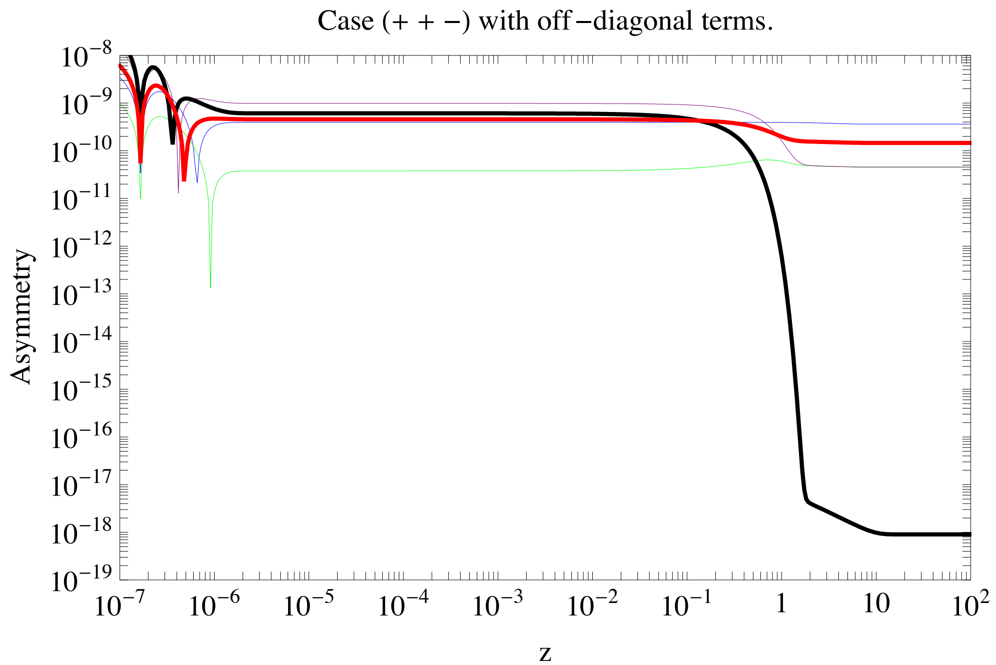




red: 1FA
black: flavoured case

[Abada, Josse-Michaux '07]

Spectacular enhancement of the final asymmetry in some cases, such as N2 leptogenesis (N2 generate an asymmetry in a flavour that is only mildly washed out by N1) [Vives '05 - Abada, Hosteins, Josse-Michaux, SL '08]



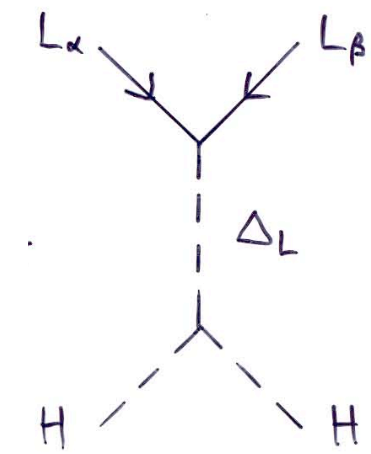
[Abada, Hosteins, Josse-Michaux, SL '08]

Scalar triplet leptogenesis

Type II seesaw mechanism:

$$\mathcal{L} = \left(-\frac{1}{2} f_{\alpha\beta}\, \ell_\alpha^T C i\sigma_2 \Delta\, \ell_\beta - \frac{\mu}{2} H^T i\sigma_2 \Delta^\dagger H + \text{h.c.} \right) - M_\Delta^2 \text{Tr}(\Delta^\dagger \Delta)$$

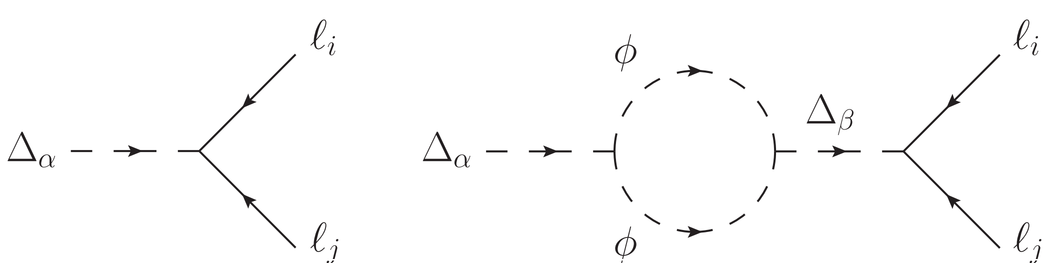
$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$ electroweak triplet



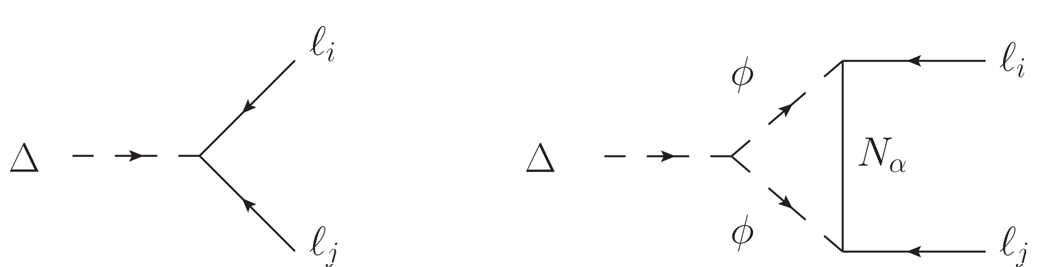
generates a neutrino mass matrix $(m_\nu)_{\alpha\beta} = \dfrac{\mu f_{\alpha\beta}}{2M_\Delta^2}\, v^2$

Also leads to leptogenesis provided another heavy state couples to lepton doublets $\Rightarrow$ generation of a CP asymmetry in triplet decays possible

[Ma, Sarkar '98 - Hambye, Senjanovic '03]



additional triplets



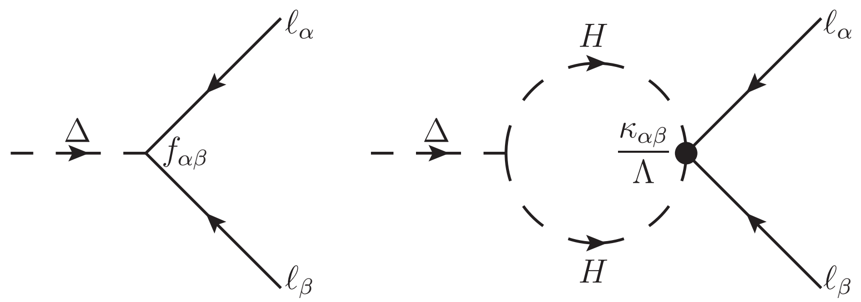
RH neutrinos

Can parametrize the effect of the heavier state(s) in a model-independent way by its (their) contribution(s) to neutrino masses:

$$\mathcal{L}_{\mathcal{H}} = -\frac{1}{4}\frac{\kappa_{\alpha\beta}}{\Lambda}(\ell_\alpha i\sigma_2 H)^T C(\ell_\beta i\sigma_2 H) \quad \Rightarrow \quad (m_{\mathcal{H}})_{\alpha\beta} = \frac{1}{2}\kappa_{\alpha\beta}\frac{v^2}{\Lambda}$$

$$m_\nu = m_\Delta + m_{\mathcal{H}} \qquad m_\Delta = \frac{\lambda_H f_{\alpha\beta}}{2M_\Delta}\, v^2 \qquad \lambda_H \equiv \mu/M_\Delta$$

The flavoured CP asymmetries are given by:



$$\epsilon_{\alpha\beta} = \frac{\Gamma(\bar{\Delta} \to \ell_\alpha \ell_\beta) - \Gamma(\Delta \to \bar{\ell}_\alpha \bar{\ell}_\beta)}{\Gamma_\Delta + \Gamma_{\bar{\Delta}}} (1 + \delta_{\alpha\beta})$$

$$= \frac{1}{4\pi}\frac{M_\Delta}{v^2}\sqrt{B_\ell B_H}\, \frac{\mathrm{Im}\left[(m_\Delta^\dagger)_{\alpha\beta}(m_{\mathcal{H}})_{\alpha\beta}\right]}{\bar{m}_\Delta}$$

$$\epsilon_\Delta = \sum_{\alpha,\beta} \epsilon_{\alpha\beta}$$

1-flavour case [Hambye, Raidal, Strumia '05]

Boltzmann equations (neglecting the off-shell scatterings $\ell\ell \to \bar{H}\bar{H}$, $\ell H \to \bar{\ell}\bar{H}$ and spectator processes such as top Yukawa interactions)

$$sHz\frac{d\Sigma_\Delta}{dz} = -\left(\frac{\Sigma_\Delta}{\Sigma_\Delta^{\rm eq}} - 1\right)\gamma_D - 2\left(\frac{\Sigma_\Delta^2}{\Sigma_\Delta^{\rm eq2}} - 1\right)\gamma_A,$$

$$sHz\frac{d\Delta_\ell}{dz} = \left(\frac{\Sigma_\Delta}{\Sigma_\Delta^{\rm eq}} - 1\right)\gamma_D\,\epsilon_\Delta - 2B_\ell\left(\frac{\Delta_\ell}{Y_\ell^{\rm eq}} + \frac{\Delta_\Delta}{\Sigma_\Delta^{\rm eq}}\right)\gamma_D$$

$$sHz\frac{d\Delta_\Delta}{dz} = -\left(\frac{\Delta_\Delta}{\Sigma_\Delta^{\rm eq}} + B_\ell\frac{\Delta_\ell}{Y_\ell^{\rm eq}} - B_H\frac{\Delta_H}{Y_H^{\rm eq}}\right)\gamma_D$$

$$\Sigma_\Delta \equiv Y_\Delta + Y_{\bar{\Delta}}$$

$$\Delta_\Delta \equiv Y_\Delta - Y_{\bar{\Delta}}$$

[no BE for Δ_H since depends on the other asymmetries]

The observed BAU can be reproduced for $M_\Delta \gtrsim 10^{10}\,\mathrm{GeV}$ (precise value depends on the size of the triplet contribution to neutrino masses)

First studies of lepton flavour effects by González-Felipe, Joaquim, Serôdio '13 and Aristizabal Sierra, Dehn Hambye '14, but flavour non-covariant formalism

Flavour-covariant Boltzmann equations

Contrarily to the type I seesaw case, in scalar triplet leptogenesis there is no preferred basis in which the BE's for the density matrix $(\Delta_\ell)_{\alpha\beta}$ reduce to BE's for flavour-diagonal asymmetries (except at $T < 10^9\,\mathrm{GeV}$, where all quantum correlations between lepton flavours are destroyed by Yukawa couplings)

In particular, no well-defined one-flavour approximation at $T > 10^{12}\,\mathrm{GeV}$ [basic reason: no basis in which the triplet couples to a single lepton flavour]

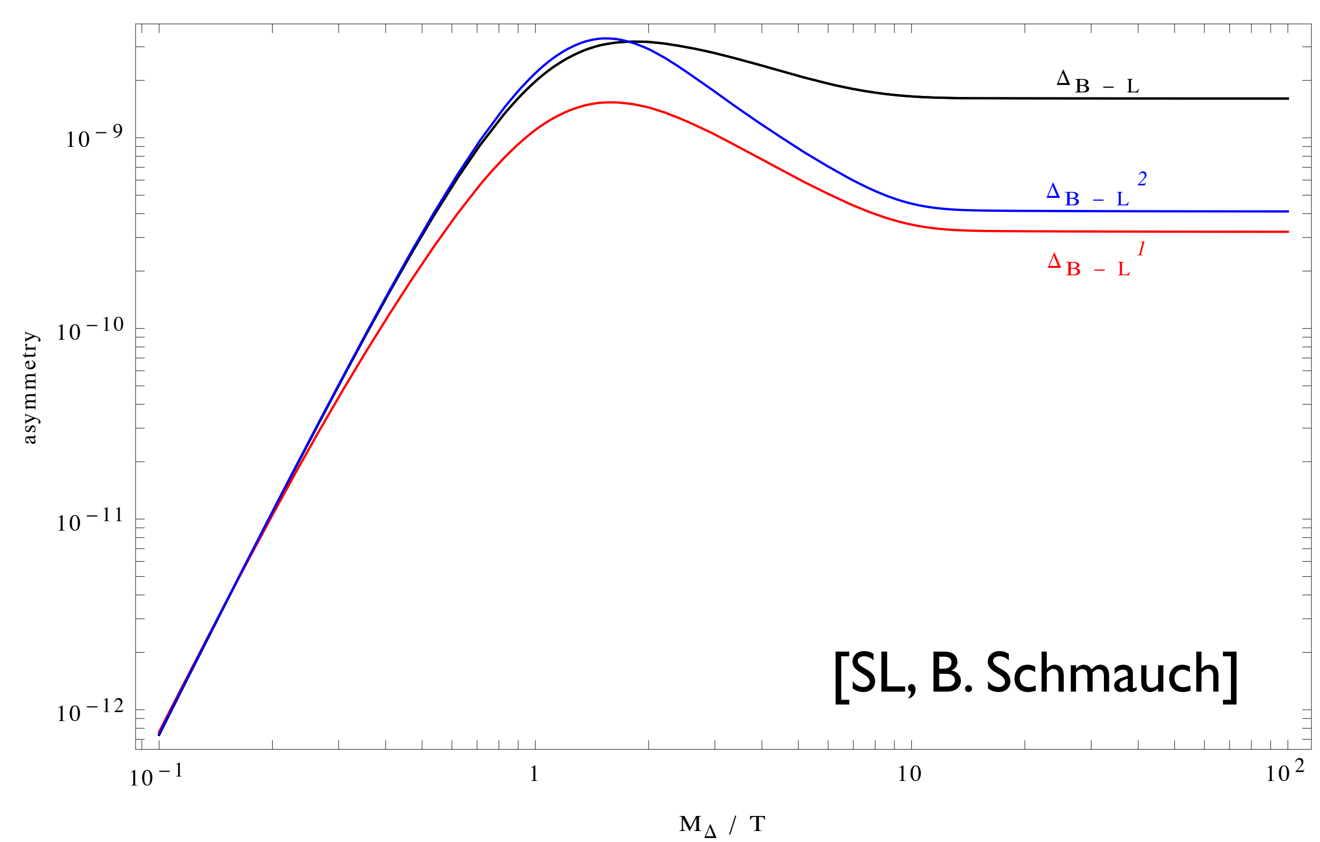
If write BE's for the individual flavour asymmetries in two different bases, will find a different result for the final baryon asymmetry

density matrix

neutrino mass eigenstate basis

charged lepton eigenstate basis

$(M_\Delta = 5 \times 10^{12}\,\mathrm{GeV})$



Boltzmann equations for the density matrix [SL, B. Schmauch, to appear]

At $T > 10^{12}$ GeV

$$sHz\frac{d\Sigma_\Delta}{dz} = -\left(\frac{\Sigma_\Delta}{\Sigma_\Delta^{\rm eq}} - 1\right)\gamma_D - 2\left(\frac{\Sigma_\Delta^2}{\Sigma_\Delta^{\rm eq2}} - 1\right)\gamma_A$$

$$sHz\frac{d\Delta_{\alpha\beta}}{dz} = -\mathcal{E}_{\alpha\beta}\left(\frac{\Sigma_\Delta}{\Sigma_\Delta^{\rm eq}} - 1\right)\gamma_D + \mathcal{W}^D_{\alpha\beta} + \mathcal{W}^{\ell H}_{\alpha\beta} + \mathcal{W}^{4\ell}_{\alpha\beta} + \mathcal{W}^{\ell\Delta}_{\alpha\beta},$$

$$sHz\frac{d\Delta_\Delta}{dz} = -\frac{1}{2}\left({\rm tr}(\mathcal{W}^D) - W^H\right), \qquad W^H = 2B_H\left(\frac{\Delta_H}{Y_H^{\rm eq}} - \frac{\Delta_\Delta}{\Sigma_\Delta^{\rm eq}}\right)\gamma_D$$

$$\mathcal{W}^D_{\alpha\beta} = \frac{2B_\ell}{\lambda_\ell^2}\left[(ff^\dagger)_{\alpha\beta}\frac{\Delta_\Delta}{\Sigma_\Delta^{\rm eq}} + \frac{1}{4Y_\ell^{\rm eq}}(2f\Delta_\ell^T f^\dagger + ff^\dagger\Delta_\ell + \Delta_\ell ff^\dagger)_{\alpha\beta}\right]\gamma_D$$ inverse decays

$$\mathcal{W}^{4\ell}_{\alpha\beta} = \frac{2}{[{\rm tr}(ff^\dagger)]^2}\left[{\rm tr}(ff^\dagger)\frac{\left(2f\Delta_\ell^T f^\dagger + ff^\dagger\Delta_\ell + \Delta_\ell ff^\dagger\right)_{\alpha\beta}}{4Y_\ell^{\rm eq}}\frac{{\rm Tr}(\Delta_\ell ff^\dagger)}{Y_\ell^{\rm eq}}(ff^\dagger)_{\alpha\beta}\right]\gamma_{4\ell}$$ 4-lepton scatterings

$$\mathcal{W}^{\ell\Delta}_{\alpha\beta} = \frac{1}{{\rm tr}(ff^\dagger ff^\dagger)}\left[\frac{1}{2Y_\ell^{\rm eq}}\left(ff^\dagger ff^\dagger\Delta_\ell - 2ff^\dagger\Delta_\ell ff^\dagger + \Delta_\ell ff^\dagger ff^\dagger\right)_{\alpha\beta}\right]\gamma_{\ell\Delta}$$ lepton-triplet scatterings

$$\mathcal{W}^{\ell H}_{\alpha\beta} = 2\left\{ \frac{1}{\mathrm{tr}(ff^\dagger)} \left[\frac{\left(2f\Delta_\ell^T f^\dagger + ff^\dagger\Delta_\ell + \Delta_\ell ff^\dagger\right)_{\alpha\beta}}{4Y_\ell^{\mathrm{eq}}} + \frac{\Delta_H}{Y_H^{\mathrm{eq}}}(ff^\dagger)_{\alpha\beta}\right]\gamma^{\Delta}_{\ell H} \right.$$
$$+ \frac{1}{\Re\left[\mathrm{tr}(f\kappa^\dagger)\right]} \left[\frac{\left(2f\Delta_\ell^T \kappa^\dagger + f\kappa^\dagger\Delta_\ell + \Delta_\ell f\kappa^\dagger\right)_{\alpha\beta}}{4Y_\ell^{\mathrm{eq}}} + \frac{\Delta_H}{Y_H^{\mathrm{eq}}}(f\kappa^\dagger)_{\alpha\beta}\right]\gamma^{\mathcal{I}}_{\ell H}$$
$$+ \frac{1}{\Re\left[\mathrm{tr}(f\kappa^\dagger)\right]} \left[\frac{\left(2\kappa\Delta_\ell^T f^\dagger + \kappa f^\dagger\Delta_\ell + \Delta_\ell \kappa f^\dagger\right)_{\alpha\beta}}{4Y_\ell^{\mathrm{eq}}} + \frac{\Delta_H}{Y_H^{\mathrm{eq}}}(\kappa f^\dagger)_{\alpha\beta}\right]\gamma^{\mathcal{I}}_{\ell H}$$
$$\left. + \frac{1}{\mathrm{tr}(\kappa\kappa^\dagger)} \left[\frac{\left(2\kappa\Delta_\ell^T \kappa^\dagger + \kappa\kappa^\dagger\Delta_\ell + \Delta_\ell \kappa\kappa^\dagger\right)_{\alpha\beta}}{4Y_\ell^{\mathrm{eq}}} + \frac{\Delta_H}{Y_H^{\mathrm{eq}}}(\kappa\kappa^\dagger)_{\alpha\beta}\right]\gamma^{\mathcal{H}}_{\ell H} \right\},$$

(scatterings involving leptons and Higgs bosons)

$$\mathcal{E}_{\alpha\beta} = \frac{1}{8\pi i}\frac{M_\Delta}{v^2}\sqrt{B_\ell B_H}\frac{(m_\Delta^\dagger m_{\mathcal{H}} - m_{\mathcal{H}}^\dagger m_\Delta)_{\alpha\beta}}{\bar{m}_\Delta}$$

$(M_\Delta = 5 \times 10^{12}\,\mathrm{GeV})$

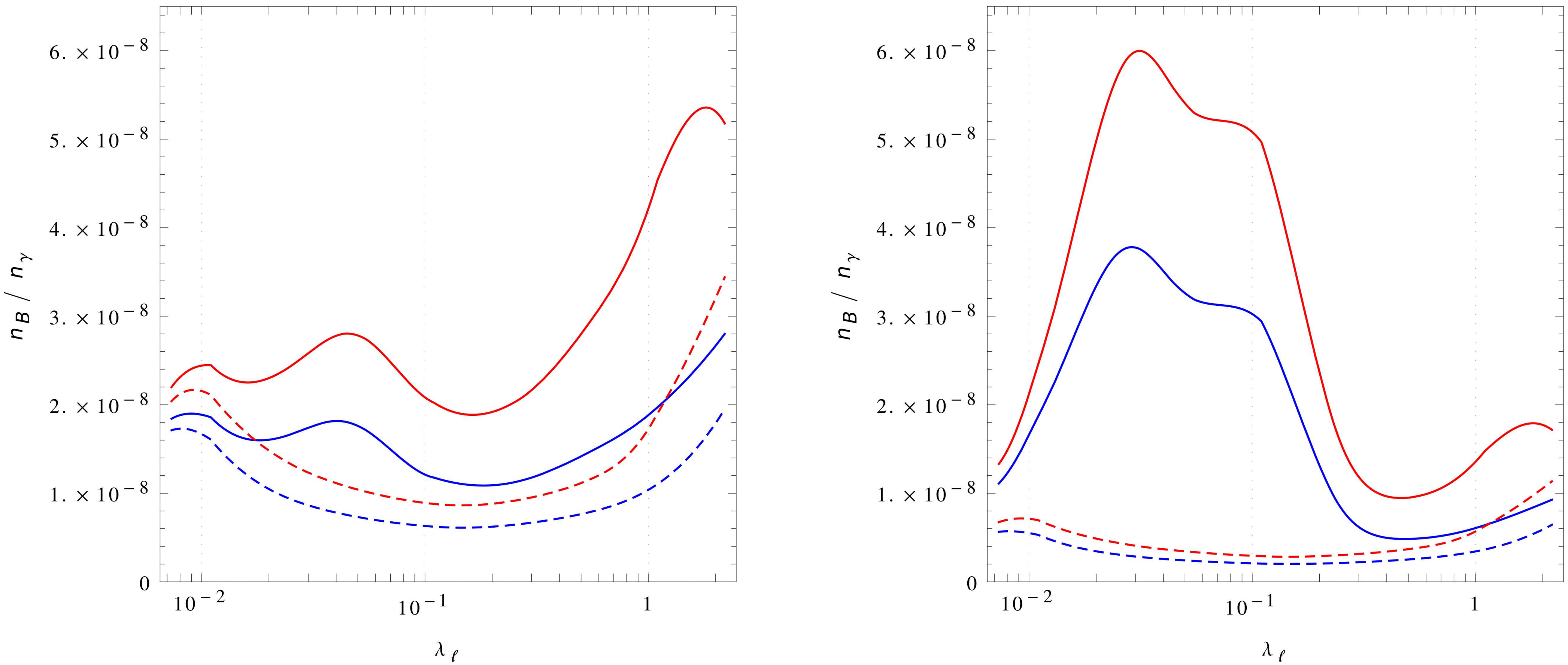


Figure 7: Baryon Asymmetry of the Universe as a function of λ_ℓ for $M_\Delta = 5 \times 10^{12}$ GeV, for $m_\Delta = i m_\nu$ (left) and $m_\Delta = i U^* \,\mathrm{diag}\,(\sqrt{1-x_\eta^2}\, y_\eta\, \bar{m}_\nu,\, x_\eta y_\eta\, \bar{m}_\nu,\, \sqrt{1-y_\eta^2}\, \bar{m}_\nu)\, U^\dagger$ (right). The continuous lines indicate the result of the computation involving a 3×3 density matrix, whereas the dotted lines indicate the result of the single flavour approximation, taking the spectator processes into account (red) or not (blue).

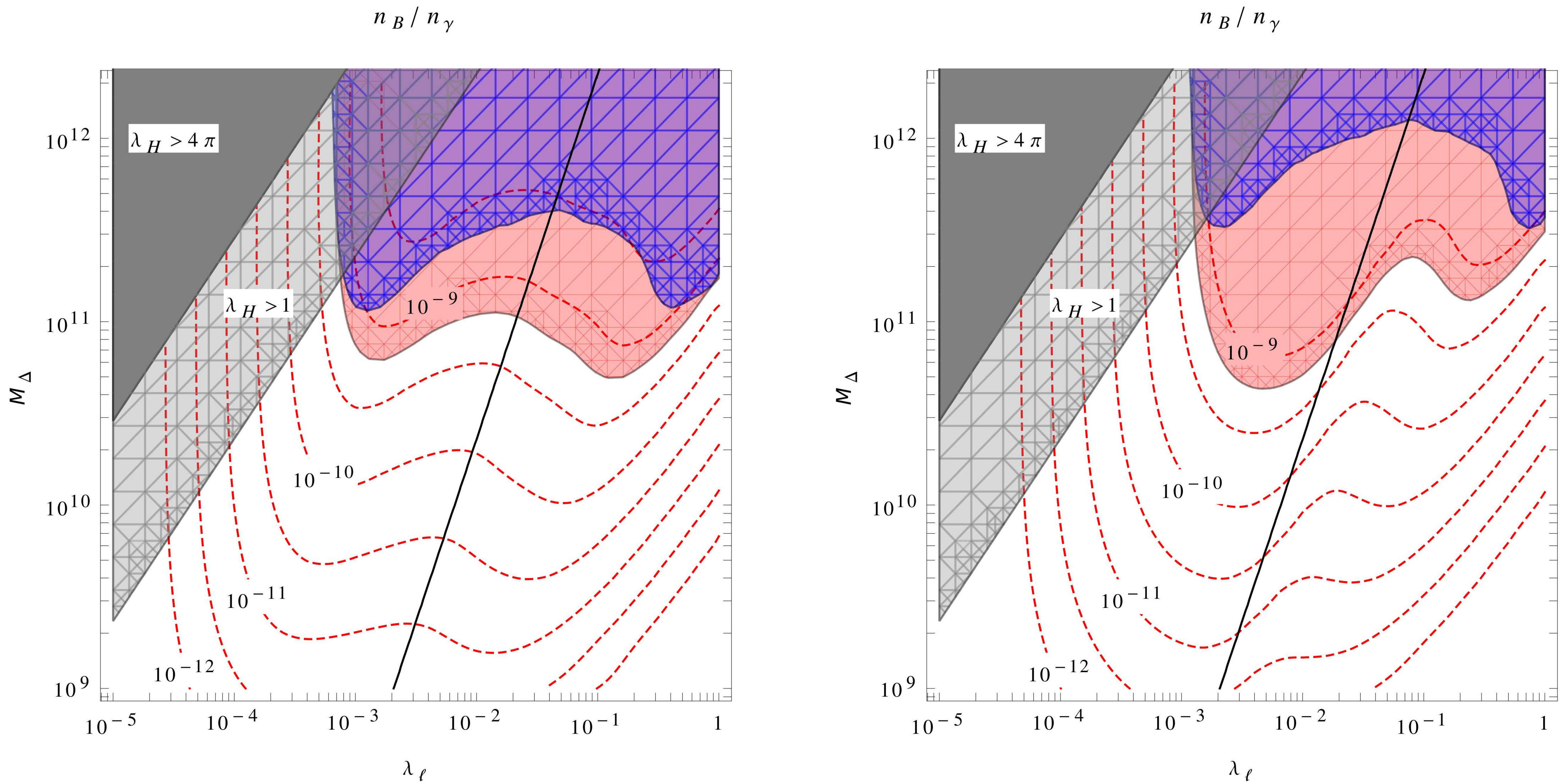
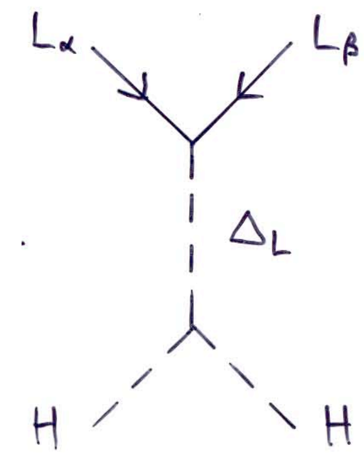


Figure 9: Isocurves of the final baryon asymmetry n_B/n_γ obtained performing the full computation, for $m_\Delta = im_\nu$ (left) and $m_\Delta = iU^*\mathrm{diag}(\sqrt{1-x_\eta^2}\,y\,\bar{m}_\nu,\, x_\eta y_\eta\,\bar{m}_\nu,\, \sqrt{1-y_\eta^2}\bar{m}_\nu)U^\dagger$ (right). The colored regions indicate where a large enough baryon asymmetry is created, for the full computation (red) or in the minimal single flavour approximation (blue).

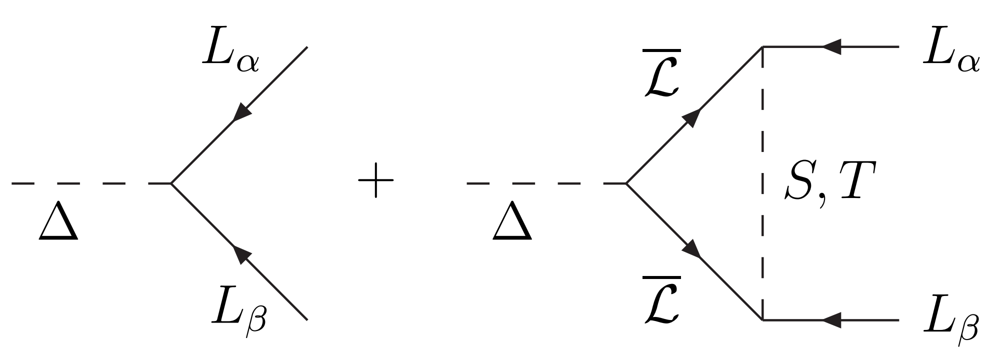
A predictive scheme for scalar triplet leptogenesis

Some non-standard SO(10) models lead to pure type II seesaw mechanism ⇒ neutrinos masses proportional to triplet couplings to leptons:

$$(M_\nu)_{\alpha\beta} = \frac{\lambda_H f_{\alpha\beta}}{2M_\Delta} v^2$$



These models also contain heavy (non-standard) leptons that induce a CP asymmetry in the heavy triplet decays



The SM and heavy lepton couplings are related by the SO(10) gauge symmetry, implying that the CP asymmetry in triplet decays can be expressed in terms of (measurable) neutrino parameters

→ important difference with other triplet leptogenesis scenarios

[Frigerio, Hosteins, SL, Romanino '08]

Dependence on the light neutrino parameters

$$\epsilon_\Delta \propto \frac{1}{(\sum_i m_i^2)^2} \Big\{ c_{13}^4 c_{12}^2 s_{12}^2 \sin(2\rho)\, m_1 m_2 \Delta m_{21}^2$$
$$+ c_{13}^2 s_{13}^2 c_{12}^2 \sin 2(\rho - \sigma)\, m_1 m_3 \Delta m_{31}^2 - c_{13}^2 s_{13}^2 s_{12}^2 \sin(2\sigma)\, m_2 m_3 \Delta m_{32}^2 \Big\}$$

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

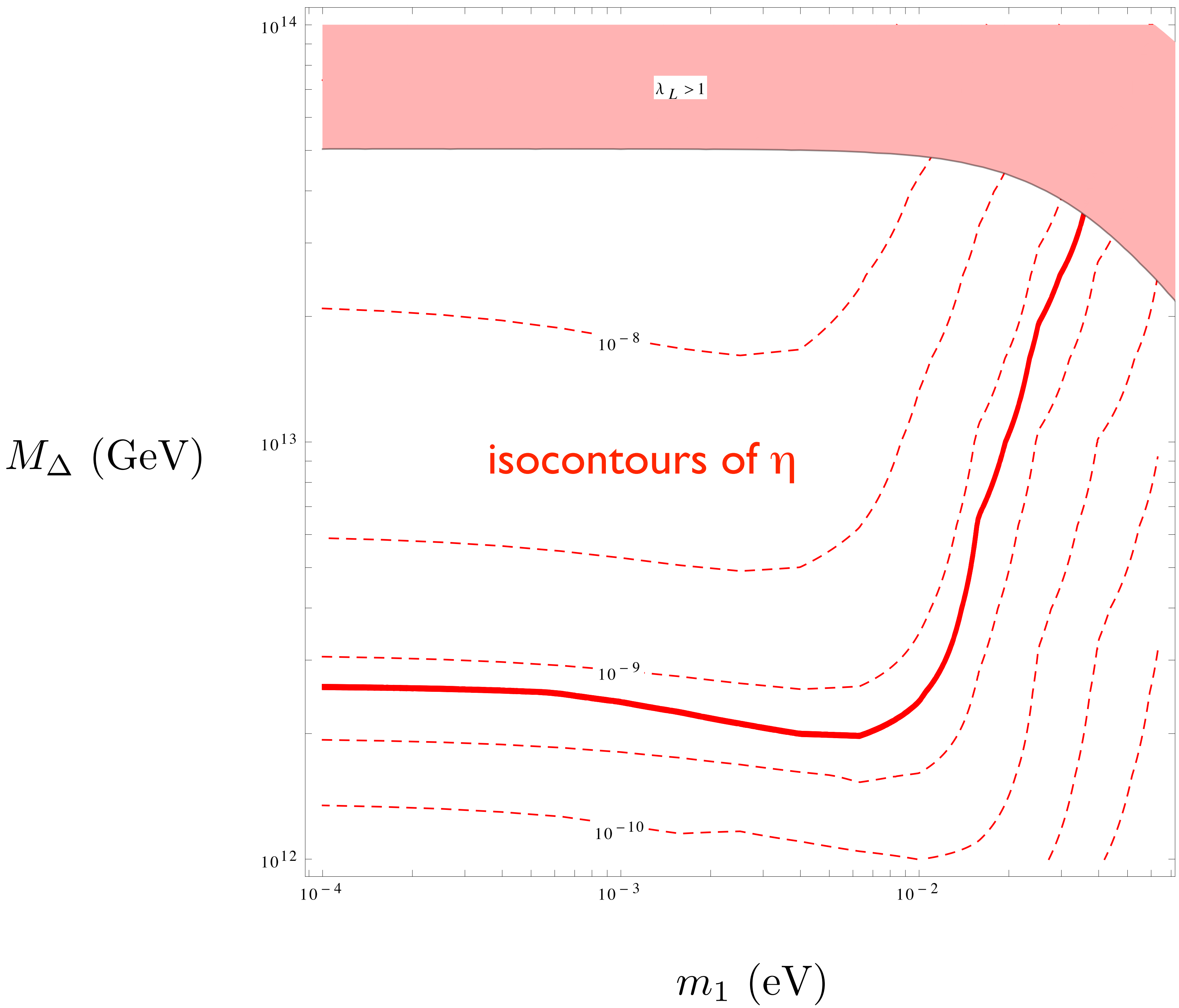
→ ϵ_Δ depends on measurable neutrino parameters

→ the CP violation needed for leptogenesis is provided by the CP-violating phases of the lepton mixing matrix (the Majorana phases to which neutrinoless double beta decay is sensitive)

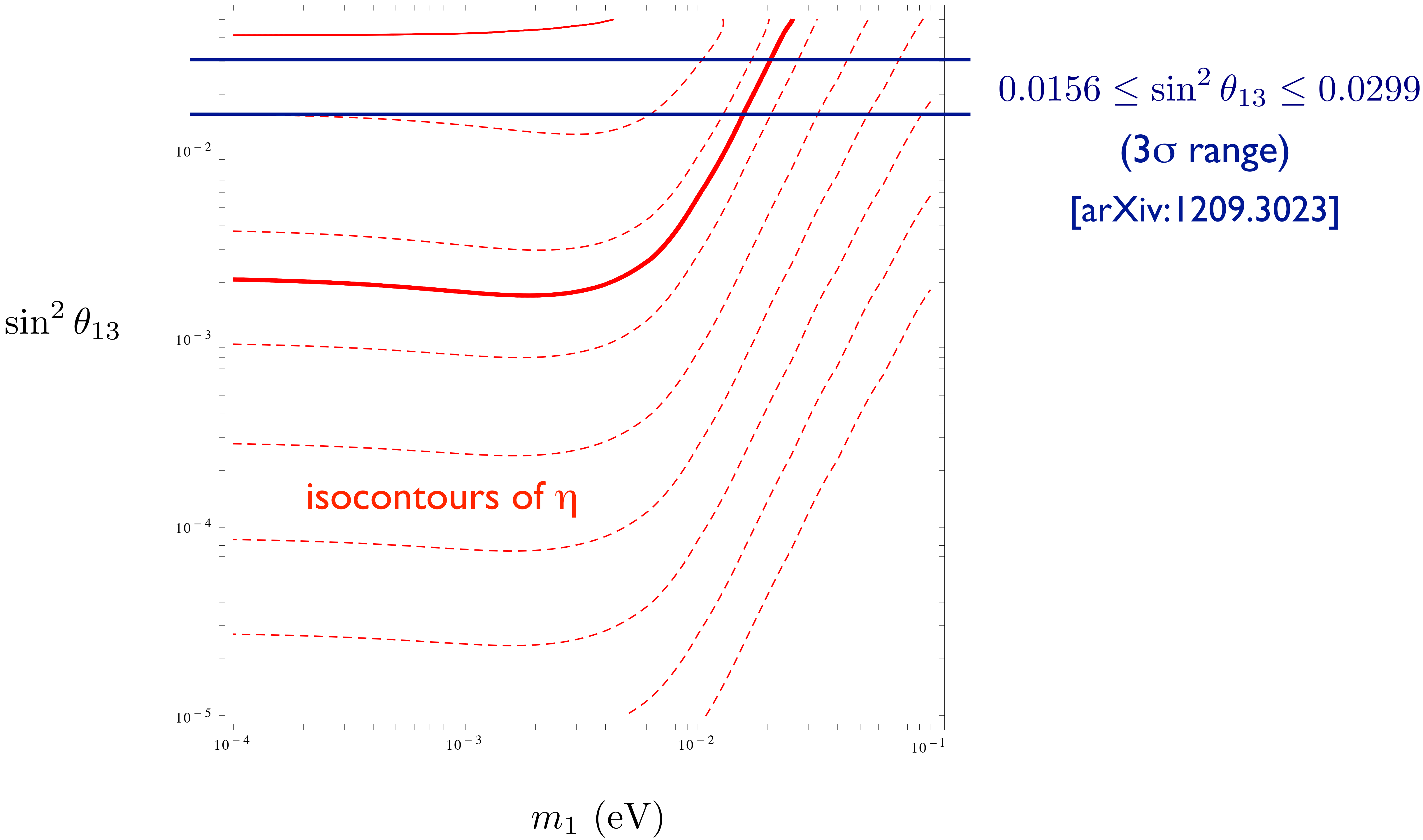
An approximate solution of the Boltzmann equations suggested that successful leptogenesis is possible if the "reactor" mixing angle θ_{13} is large enough (prior to its measurement by the Daya Bay experiment) [Frigerio, Hosteins, SL, Romanino '08]

→ confirmed by the numerical resolution of the flavour-covariant Boltzmann equations [SL, B. Schmauch, to appear]

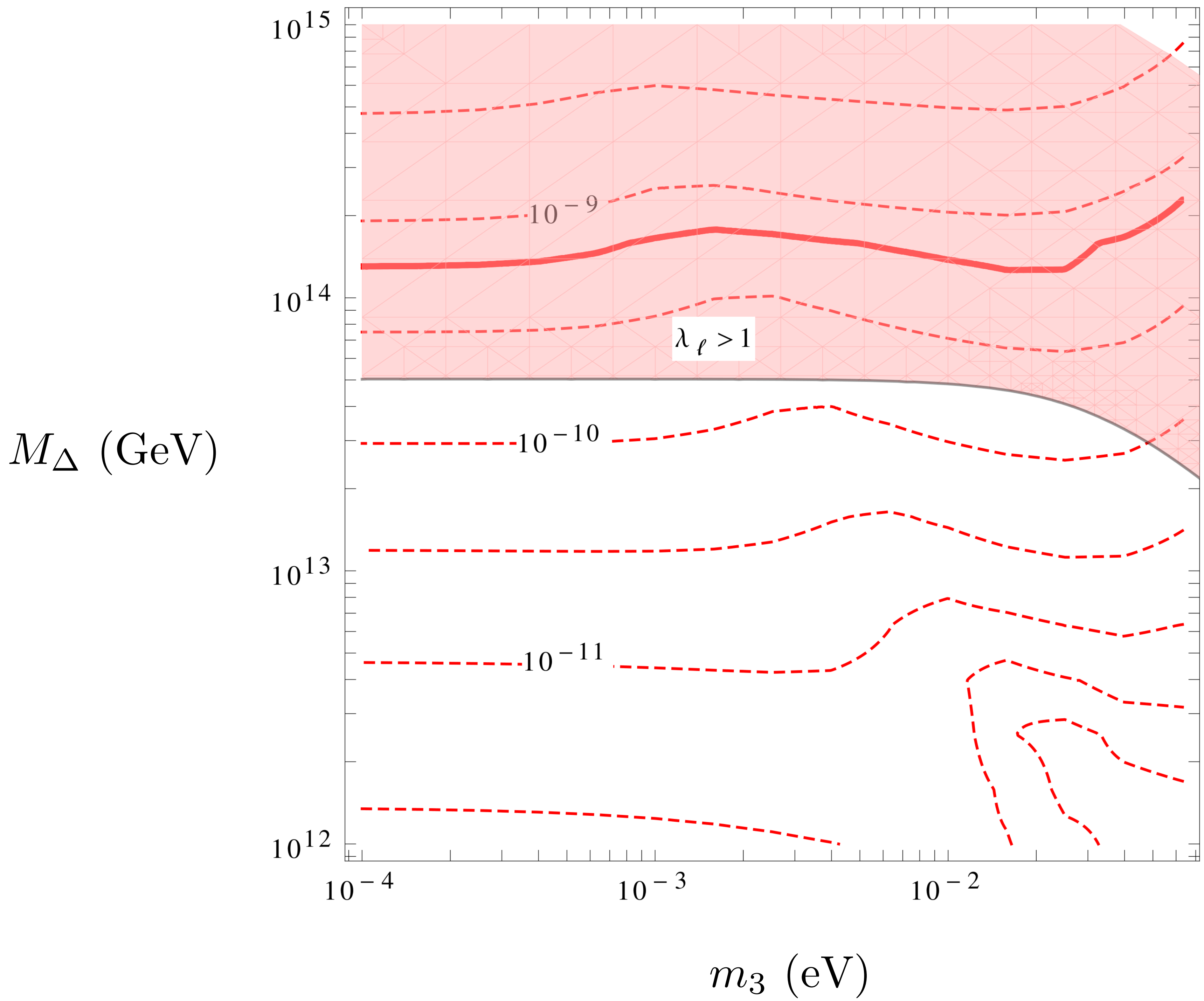
Parameter space allowed by successful leptogenesis



[SL, B. Schmauch]



[SL, B. Schmauch]



→ inverted hierarchy disfavoured

[SL, B. Schmauch]

Conclusions

Leptogenesis is an attractive mechanism for generating the baryon asymmetry of the Universe

In its minimal version with heavy Majorana neutrinos, the only required ingredients are the ones needed to generate small neutrino masses via the seesaw mechanism

Lepton flavour dynamics can significantly affect the baryon asymmetry generated by leptogenesis

Recent progress in scalar triplet leptogenesis: inclusion of flavour effects, flavour-covariant Boltzmann equations (density matrix formalism), application to a predictive model providing a link between leptogenesis and low-energy parameters

Back-up slides

Is leptogenesis related to low-energy (= PMNS) CP violation?

leptogenesis: $\epsilon_{N_1} \propto \sum_k \mathrm{Im}\,[(YY^\dagger)_{k1}]^2\, M_1/M_k$ depends on the phases of $YY^\dagger$

low-energy CP violation: phases of UPMNS $\begin{cases} \delta & \to \text{oscillations} \\ \phi_2, \phi_3 & \to \text{neutrinoless double beta} \end{cases}$

→ are they related?

$$Y = \begin{pmatrix} \sqrt{M_1} & 0 & 0 \\ 0 & \sqrt{M_2} & 0 \\ 0 & 0 & \sqrt{M_3} \end{pmatrix} R \begin{pmatrix} \sqrt{m_1} & 0 & 0 \\ 0 & \sqrt{m_2} & 0 \\ 0 & 0 & \sqrt{m_3} \end{pmatrix} U^\dagger$$

[Casa, Ibarra]

3 heavy Majorana masses Mi

9 low-energy parameters $(m_i, \theta_{ij}, \delta, \phi_i)$

complex 3x3 matrix satisfying $RR^T = 1 \;\Rightarrow$ 3 complex parameters

$$YY^\dagger = \begin{pmatrix} \sqrt{M_1} & 0 & 0 \\ 0 & \sqrt{M_2} & 0 \\ 0 & 0 & \sqrt{M_3} \end{pmatrix} R \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix} R^\dagger \begin{pmatrix} \sqrt{M_1} & 0 & 0 \\ 0 & \sqrt{M_2} & 0 \\ 0 & 0 & \sqrt{M_3} \end{pmatrix}$$

→ leptogenesis only depends on the phases of R = high-energy phases

⇒ unrelated to CP violation at low-energy, except in specific scenarios

However, if lepton flavour effects play an important role, the high-energy and low-energy phases both contribute to the CP asymmetry and cannot be disentangled. Leptogenesis possible even if all high-energy phases (R) vanish

Asymmetry in the flavour lα:

$$\epsilon_\alpha = -\frac{3M_1}{16\pi v^2} \frac{\mathrm{Im}\left(\sum_{\beta\rho} m_\beta^{1/2} m_\rho^{3/2} U^*_{\alpha\beta} U_{\alpha\rho} R_{1\beta} R_{1\rho}\right)}{\sum_\beta m_\beta \left|R_{1\beta}\right|^2}$$

leptogenesis from PMNS phase δ

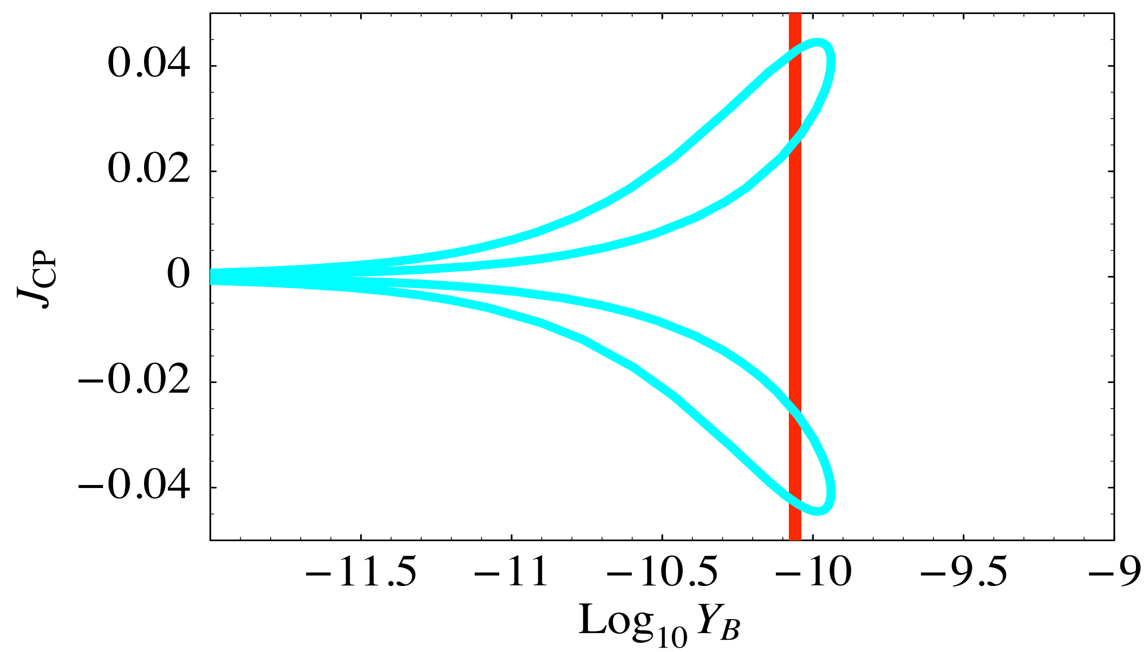


FIG. 1. The invariant J_{CP} versus the baryon asymmetry varying (in blue) $\delta = [0, 2\pi]$ in the case of hierarchical RH neutrinos and NH light neutrino mass spectrum for $s_{13} = 0.2$, $\alpha_{32} = 0$, $R_{12} = 0.86$, $R_{13} = 0.5$ and $M_1 = 5 \times 10^{11}$ GeV . The red region denotes the 2σ range for the baryon asymmetry.

[Pascoli, Petcov, Riotto]

Although difficult to test, leptogenesis would gain support from:

- observation of neutrinoless double beta decay: $(A,Z) \rightarrow (A,Z+2)\, e^- e^-$ [proof of the Majorana nature of neutrinos - necessary condition]

- observation of CP violation in the lepton sector, e.g. in neutrino oscillations [neither sufficient nor necessary condition (*)]

- experimental exclusion of non-standard electroweak baryogenesis scenarios [e.g. MSSM with a light stop, NMSSM, 2HDM, SM + Higgs singlet...]

(*) in general, leptogenesis depends both on high-energy and low-energy (i.e. PMNS) phases