# Lepton flavour and the matter-antimatter asymmetry of the Universe

Stéphane Lavignac (IPhT Saclay)

- Introduction
- lepton flavour effects in standard leptogenesis
- scalar triplet leptogenesis in the single flavour approximation
- flavour-dependent scalar triplet leptogenesis
- a predictive scheme for scalar triplet leptogenesis

based on SL and B. Schmauch, arXiv:1503.00629 + to appear

(and also Dev, Di Bari, Garbrecht, SL, Millington, Teresi, arXiv:1711.02861)

New physics paradigms after Higgs and gravitational wave discoveries
7th International Conference on New Frontiers in Physics (ICNFP2018)
Kolymbari, Crete, 10 July 2018

# 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

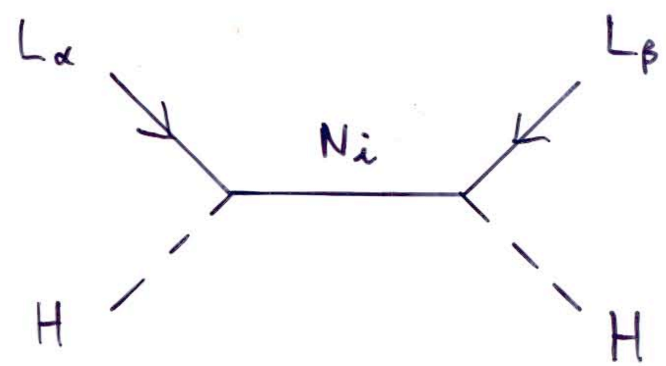
(1) B+L anomaly $\Rightarrow$ transitions between vacua with different (B+L) possible at $T \gtrsim M_{weak}$, where nonperturbative (B+L)-violating processes (electroweak sphalerons) are in equilibrium

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]




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

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

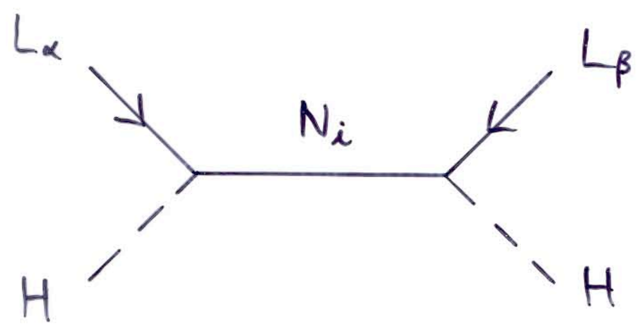
This mechanism contains all ingredients for baryogenesis (L violation due to heavy Majorana mass, CP violation due to complex heavy neutrino couplings)

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

# Review of standard leptogenesis

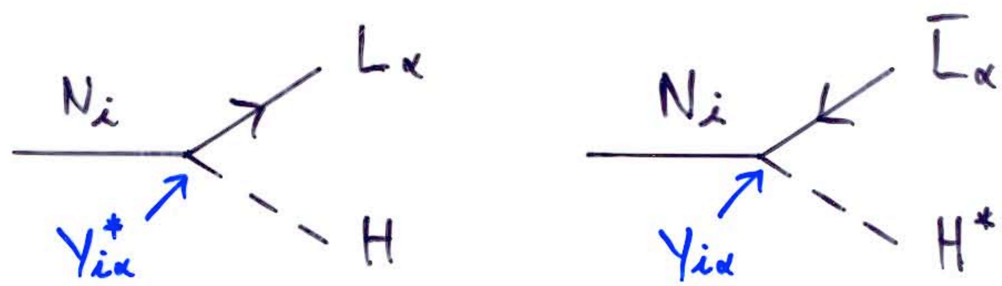
Generate a B-L asymmetry through the out-of-equilibrium decays of the heavy Majorana neutrinos responsible for neutrino mass [Fukugita, Yanagida '86]

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




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

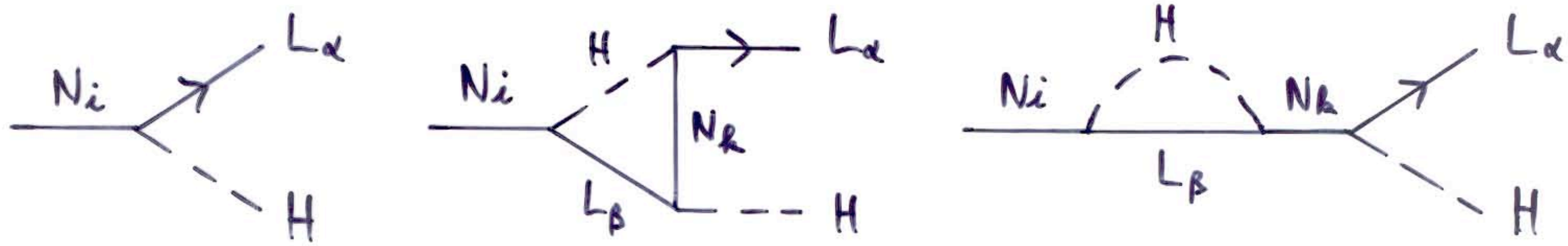
$N_i^c \equiv C \bar{N}_i^T = N_i$ (Majorana) ⇒ decays both into $l^+$ and $l^-$




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

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

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




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

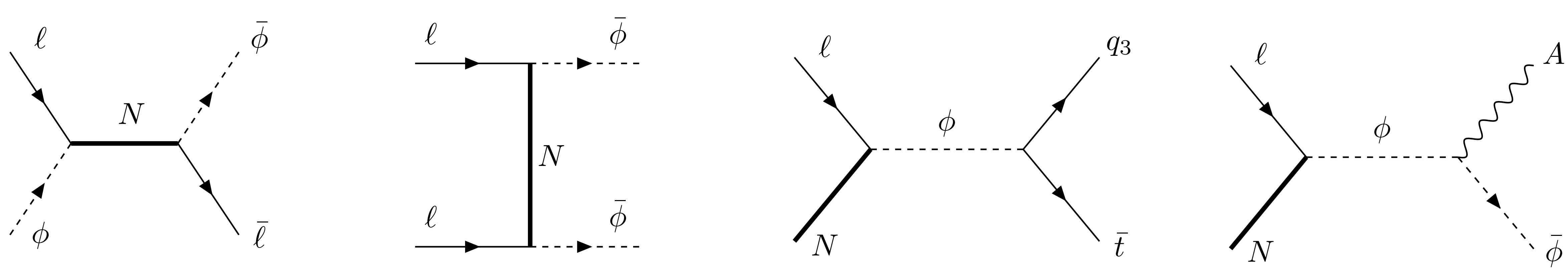
## CP asymmetry in N1 decays (hierarchical case $M_1 \ll M_2, M_3$ ):

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

Covi, Roulet, Vissani '96
Buchmüller, Plümacher '98

## 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

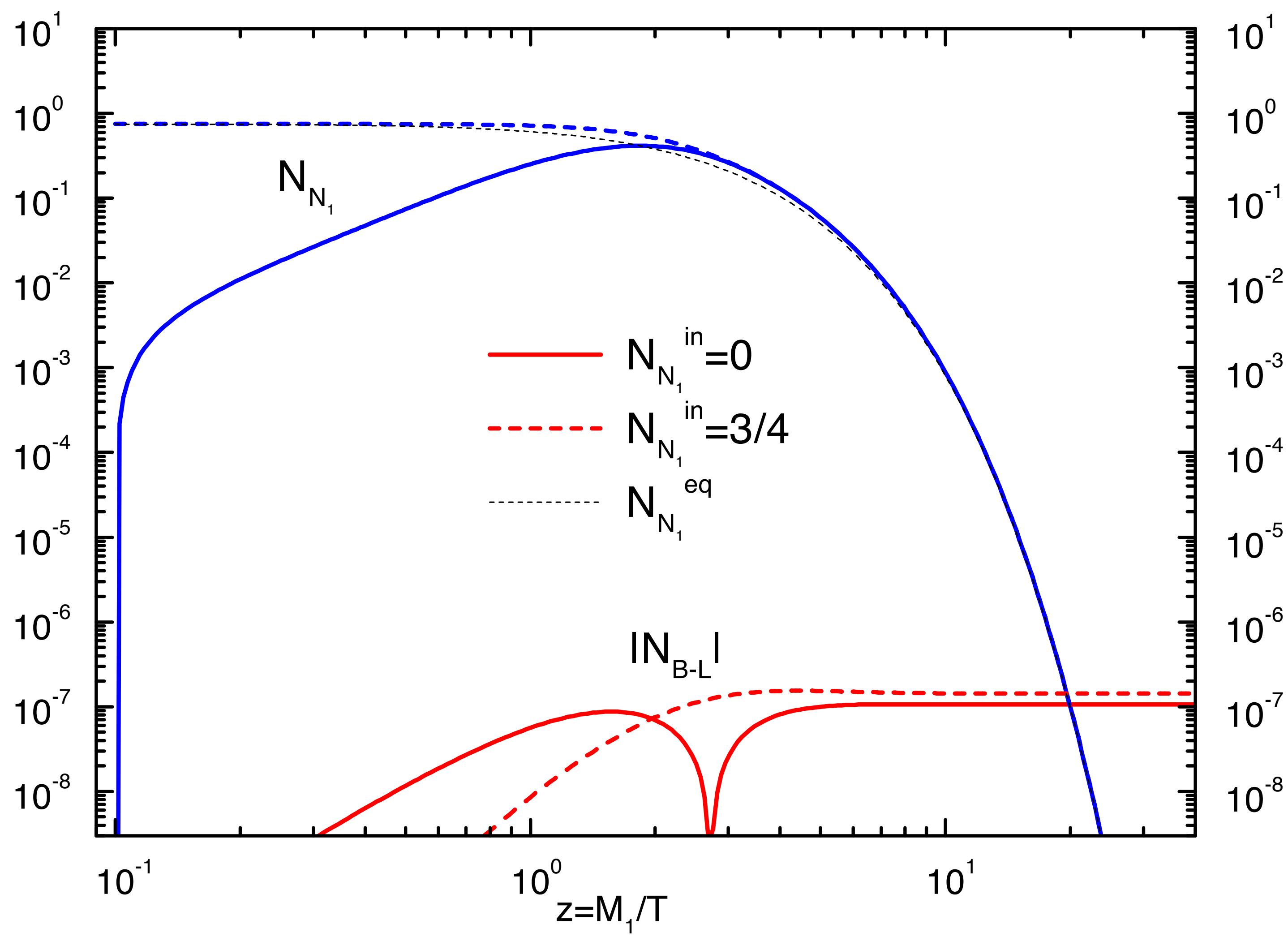


The evolution of the lepton asymmetry is described by the Boltzmann eq.

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

$$Y_X \equiv \frac{n_X}{s} \qquad Y_L \equiv Y_\ell - Y_{\bar\ell} \qquad z \equiv \frac{M_1}{T}$$

Typical evolution:




[Buchmüller, Di Bari, Plümacher ’02]

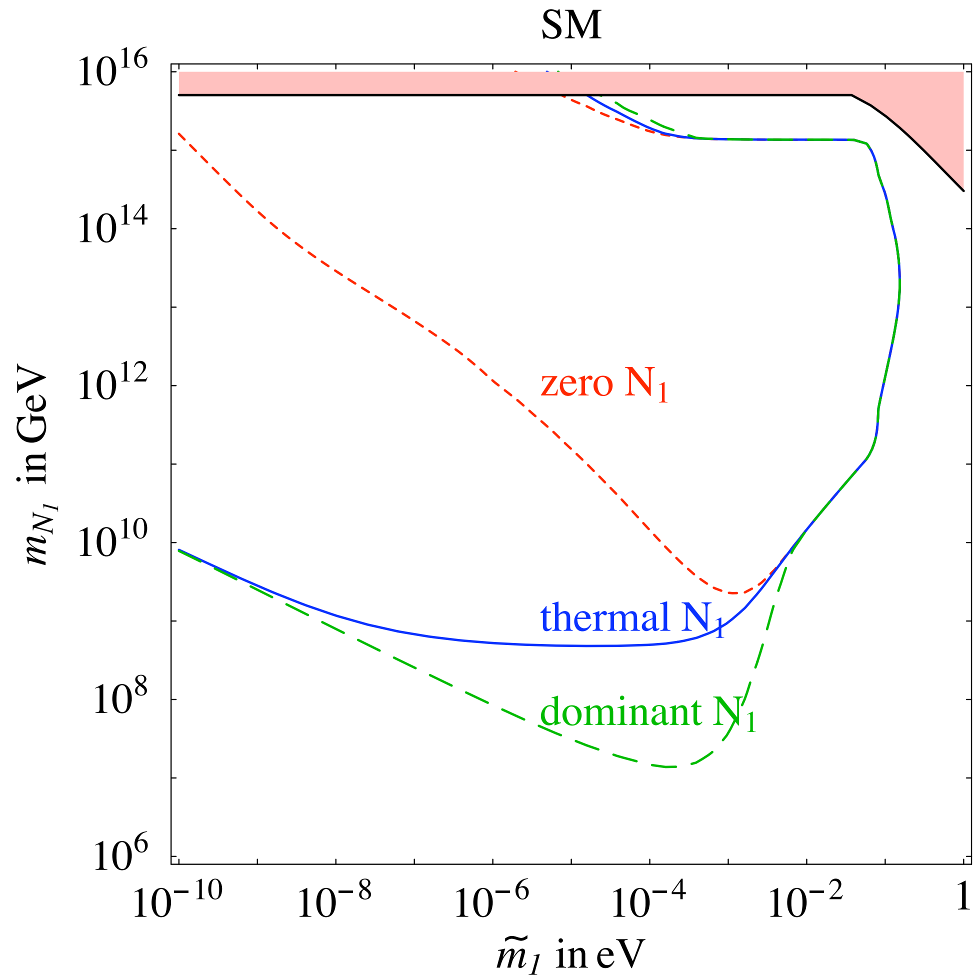
# Can leptogenesis explain the observed baryon asymmetry?

(assuming $M_1 \ll M_2, M_3$ )

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]

## 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 $\ell_{N_1}$ to which N1 couples

$$\sum_\alpha Y_{1\alpha}\, \bar{N}_1 \ell_\alpha H \;\equiv\; y_{N_1} \bar{N}_1 \ell_{N_1} H \qquad\qquad \ell_{N_1} \;\equiv\; \sum_\alpha Y_{1\alpha}\, \ell_\alpha / y_{N_1}$$

This is valid as long as the charged lepton Yukawas $\lambda_\alpha$ are out of equilibrium

At $T \lesssim 10^{12}\,\mathrm{GeV}$, $\lambda_\tau$ is in equilibrium and destroys the coherence of $\ell_{N_1}$
$\Rightarrow$ 2 relevant flavours: $\ell_\tau$ and a combination $\ell_a$ of $\ell_e$ and $\ell_\mu$

At $T \lesssim 10^9\,\mathrm{GeV}$, $\lambda_\tau$ and $\lambda_\mu$ are in equilibrium $\Rightarrow$ must distinguish $\ell_e$, $\ell_\mu$ and $\ell_\tau$

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

Flavour-dependent CP asymmetries and washout rates:

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

→ 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

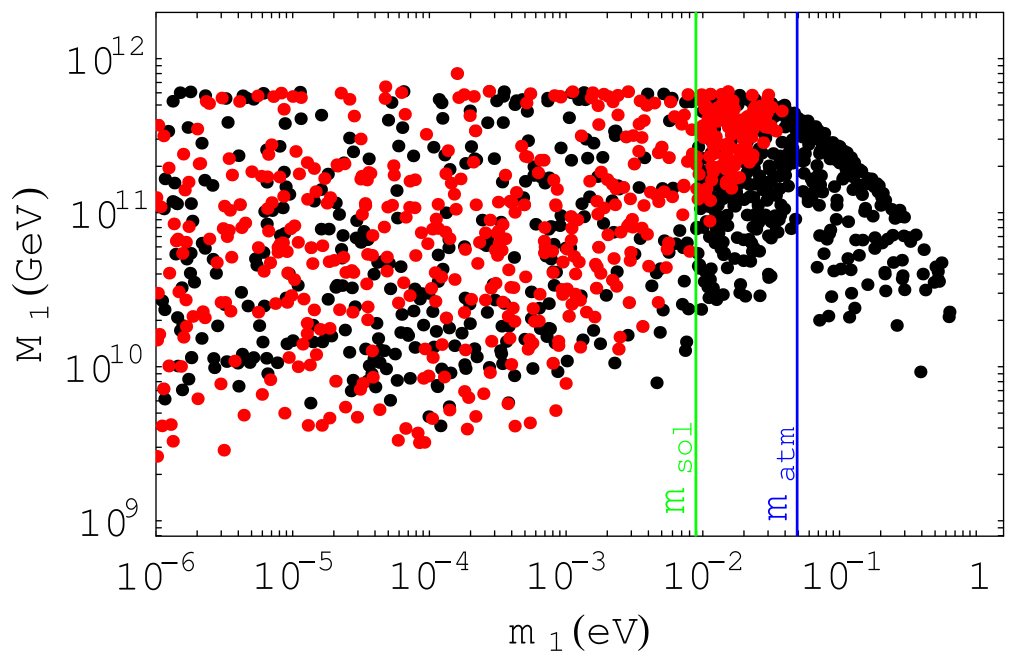
$$\ell \to U\ell \qquad\qquad \Delta_\ell \to U^* \Delta_l \, U^T$$

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 asymmetry in $\ell_{N_1}$ evolves independently of the other asymmetries

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

# Flavour effects lead to quantitatively different results from the 1FA

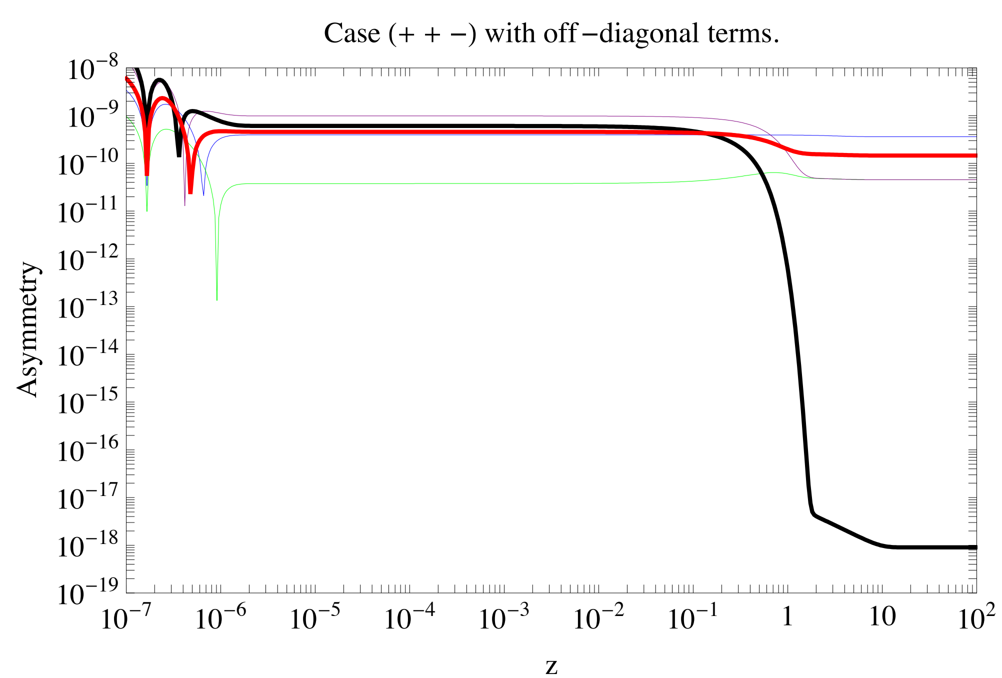



red: 1FA

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 - Di Bari, Riotto '08]




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

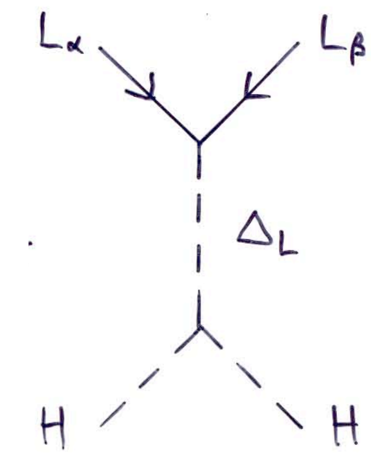
# Scalar triplet leptogenesis

Type II seesaw mechanism:

$$\mathcal{L} = -\frac{1}{2}\left(f_{\alpha\beta}\,\Delta\ell_\alpha\ell_\beta + \mu\,\Delta^\dagger HH + \mathrm{h.c.}\right) - M_\Delta^2\,\mathrm{Tr}(\Delta^\dagger\Delta)$$

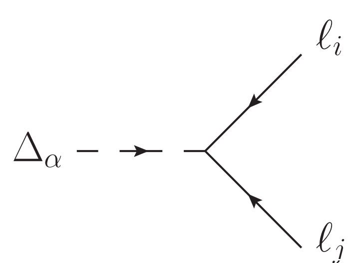
$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$ electroweak triplet

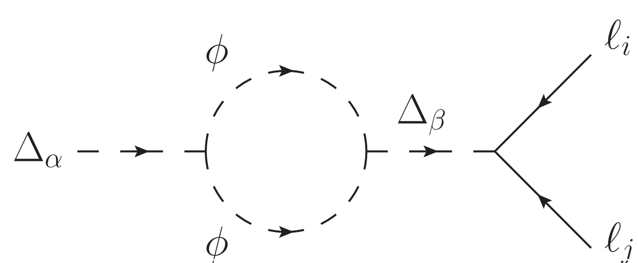
generates a neutrino mass matrix $(m_\nu)_{\alpha\beta} = \dfrac{\mu f_{\alpha\beta}}{2M_\Delta^2}\,v^2$



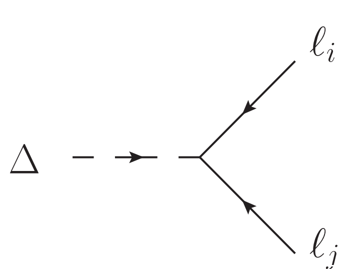

Also leads to leptogenesis provided another heavy state couples to lepton doublets $\Rightarrow$ generation of a CP asymmetry in triplet decays possible

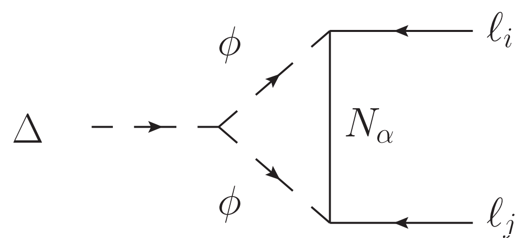
[Ma, Sarkar '98 - Hambye, Senjanovic '03]




additional triplets



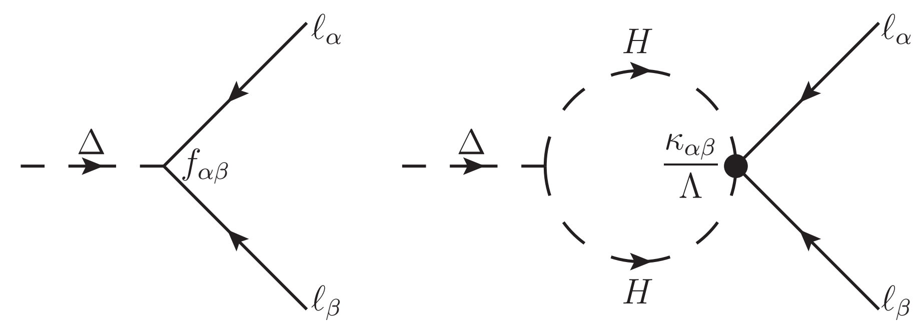

RH neutrinos

Can parametrize the effect of the heavier state(s) (assumed to be much heavier than the triplet) in a model-independent way:

$$\mathcal{L}_{\mathcal{H}} = -\frac{1}{4}\frac{\kappa_{\alpha\beta}}{\Lambda}\,\ell_\alpha \ell_\beta H H + \text{h.c.} \quad \Rightarrow \quad (m_{\mathcal{H}})_{\alpha\beta} = \frac{1}{2}\kappa_{\alpha\beta}\frac{v^2}{\Lambda}$$

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

The flavoured CP asymmetries are given by:




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

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

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

Main differences with standard leptogenesis (with RH neutrinos):

(i) the triplet has gauge interactions $\Rightarrow$ competition between annihilations $\Delta\bar{\Delta} \to X\bar{X}$ and decays $\Delta \to \bar{\ell}_\alpha \bar{\ell}_\beta$ , $\Delta \to HH$ (2 decay modes)

(ii) the heavy decaying state is not self-conjugate $\Rightarrow$ possibility of an asymmetry $\Delta_\Delta$

# single-flavour approximation [Hambye, Raidal, Strumia '05]

Boltzmann equations (neglecting the off-shell scatterings $\ell\ell \to \bar{H}\bar{H}$, $\ell H \to \bar{\ell}\bar{H}$)

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

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

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

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

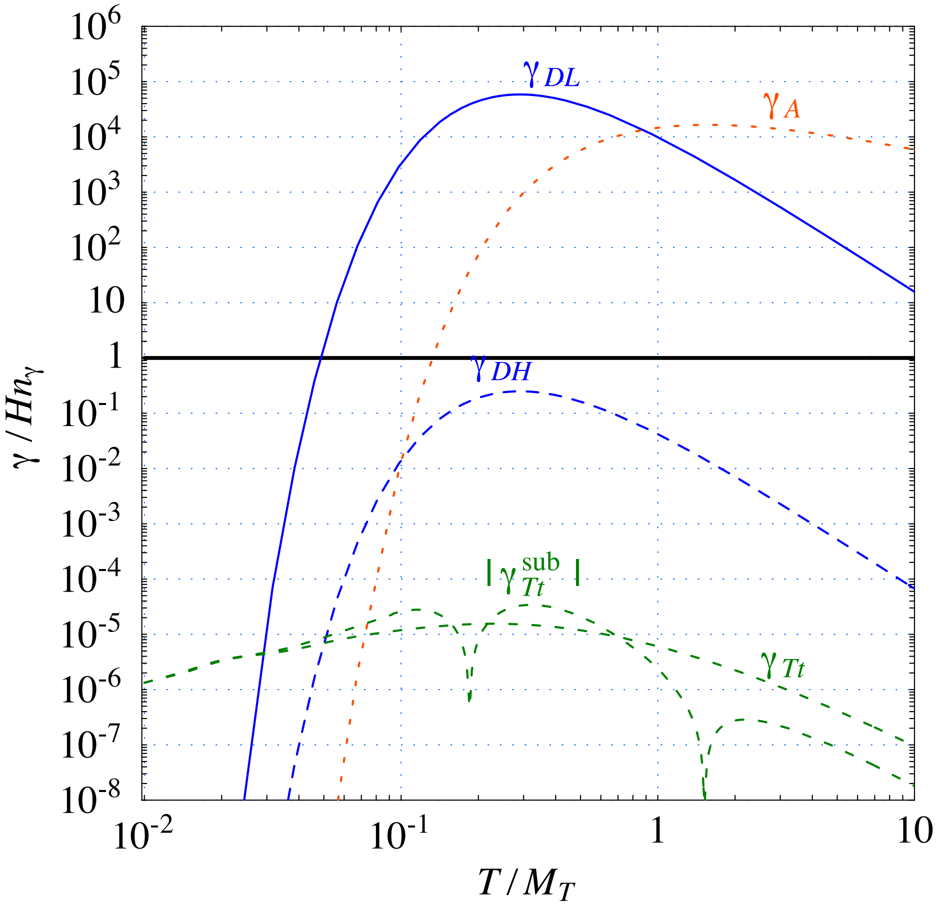
$$\Delta_\Delta \equiv Y_\Delta - Y_{\bar{\Delta}}$$

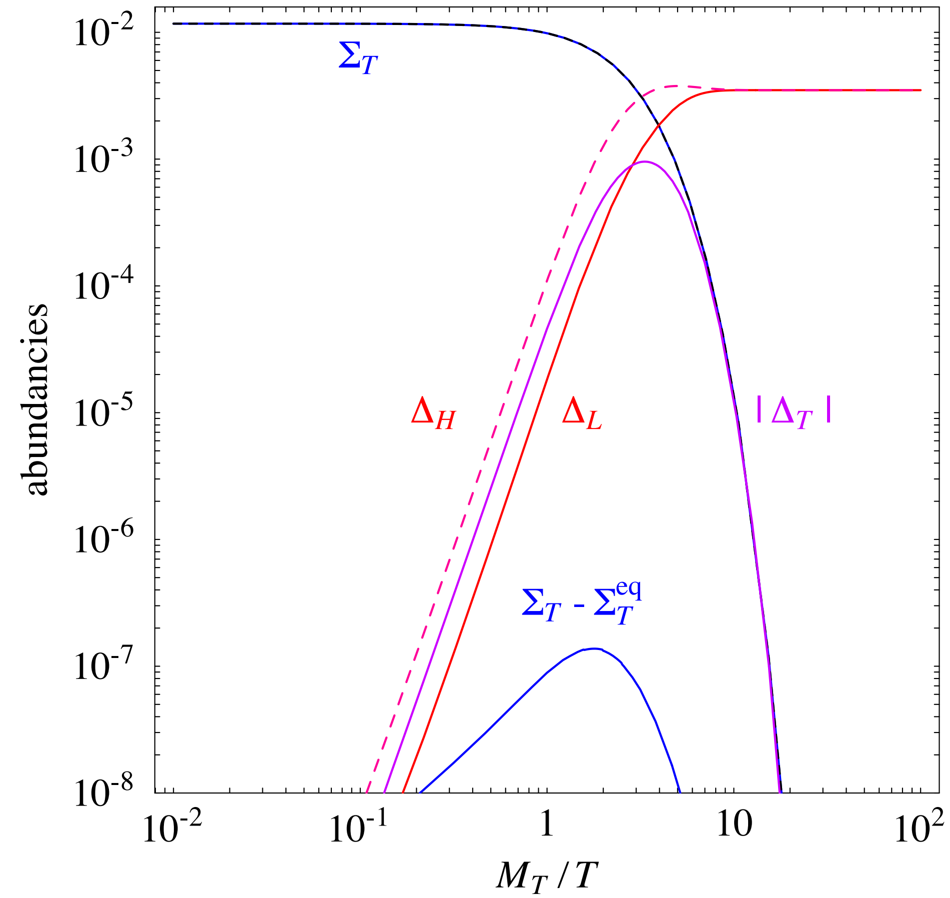
$$\epsilon_\Delta = \sum_{\alpha,\beta}\epsilon_{\alpha\beta}$$

[no BE for $\Delta_H$ since depends on the other asymmetries ( $\Delta_H = \Delta_\ell - 2\Delta_\Delta$ )]

$B_\ell\,(B_H)$ = scalar triplet branching ratios into leptons (Higgs)

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




$M_\Delta = 10^{10}\,\mathrm{GeV}$

$\bar{m}_\Delta = 0.05\,\mathrm{eV}$

[Hambye, Raidal, Strumia '05]

Case $B_H \ll B_\ell$ : even though triplet decays remain in thermal equilibrium, an asymmetry is generated because the decay mode $\Delta \to HH$ is out of equilibrium $\Rightarrow$ an asymmetry $\Delta_H$ develops, followed by $\Delta_\Delta$ and $\Delta_\ell$

The observed BAU can be reproduced for

$$M_\Delta \;>\; 2.8 \times 10^{10}\,\mathrm{GeV} \qquad (\bar{m}_\Delta = 0.001\,\mathrm{eV})$$

$$M_\Delta \;>\; 1.3 \times 10^{11}\,\mathrm{GeV} \qquad (\bar{m}_\Delta = 0.05\,\mathrm{eV})$$

$\bar{m}_\Delta$ = size of the triplet contribution to neutrino masses

# Flavour-dependent scalar triplet leptogenesis

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]

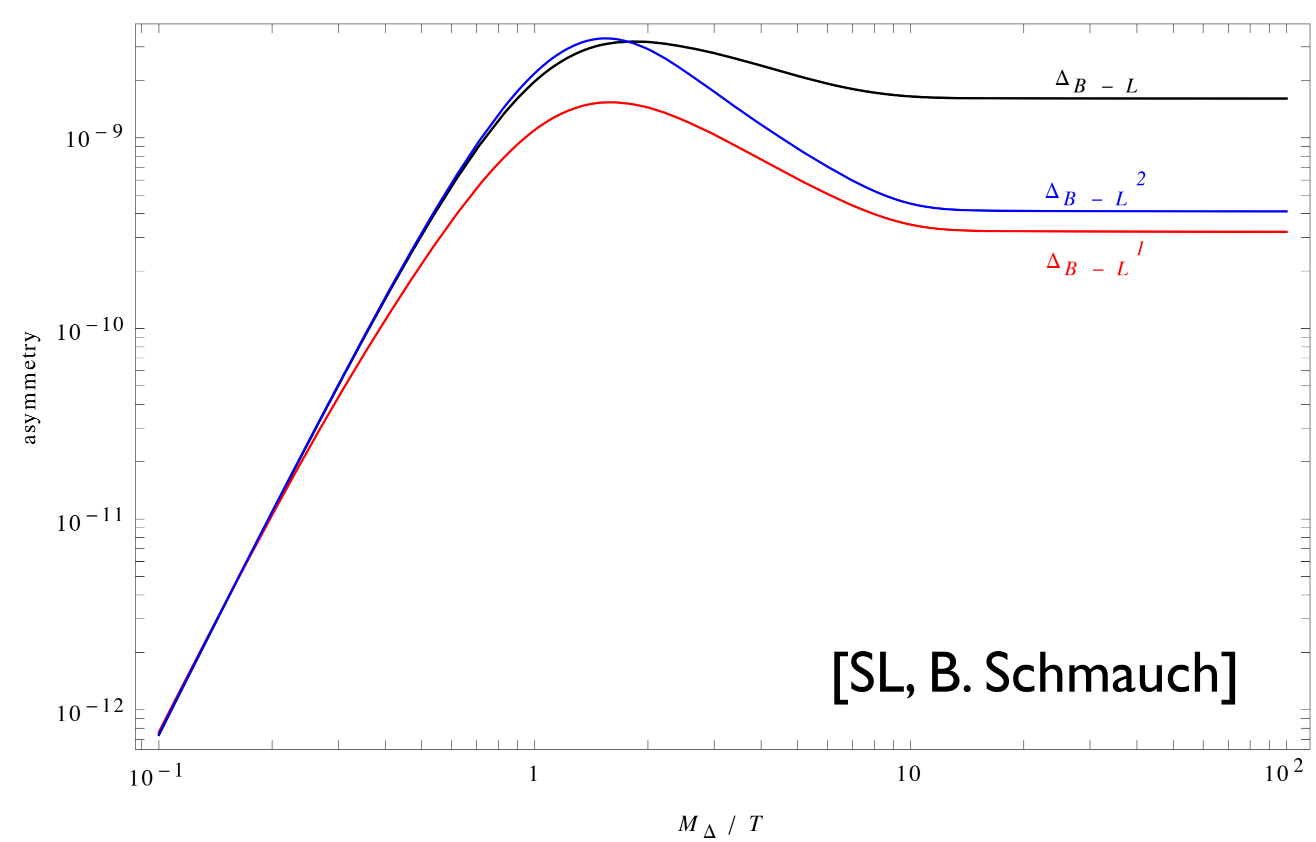
If write BE's for the individual flavour asymmetries in two different bases, will find a different result for the final baryon asymmetry

density matrix

neutrino mass eigenstate basis

charged lepton eigenstate basis

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



## Derivation of the flavour-covariant Boltzmann equations [SL, B. Schmauch]

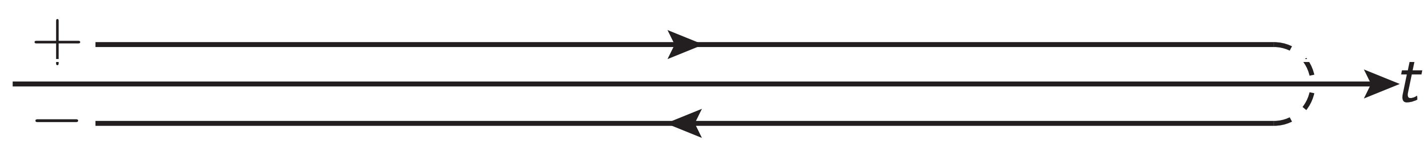
We use the closed-time path (CTP) formalism, which has already been used to derive quantum Boltzmann equations for standard leptogenesis

[Buchmuller, Fredenhagen '00 - De Simone, Riotto '07 - Garny et al. '09 - Cirigliano et al. '09 - Beneke et al. '10 ...]

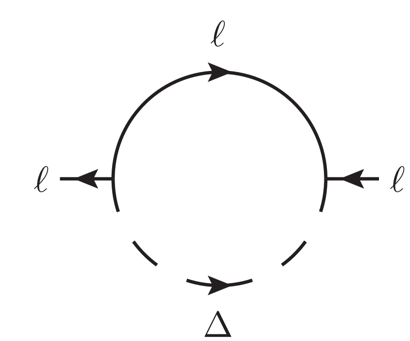
The Boltzmann equations are obtained from the Schwinger-Dyson equations:

$$sHz\frac{d(\Delta_\ell)_{\alpha\beta}}{dz} = -\int d^3w \int_0^t dt_w \; \mathrm{tr}\Big[\Sigma^{>}_{\beta\gamma}(x,w)G^{<}_{\gamma\alpha}(w,x) - \Sigma^{<}_{\beta\gamma}(x,w)G^{>}_{\gamma\alpha}(w,x) \\ -G^{>}_{\beta\gamma}(x,w)\Sigma^{<}_{\gamma\alpha}(w,x) + G^{<}_{\beta\gamma}(x,w)\Sigma^{>}_{\gamma\alpha}(w,x)\Big]$$

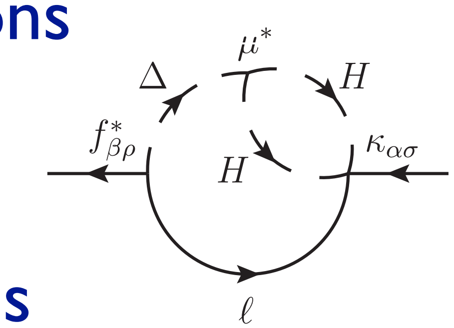
where the G's are Green's functions path-ordered along the closed time contour

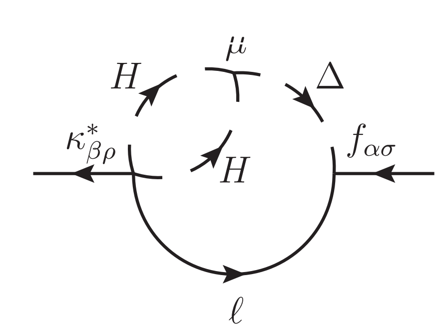



and the Σ's are lepton doublet self energies




The washout term due to inverse decays is obtained from the one-loop lepton doublet self-energy while the washout terms from 2-2 scatterings and the source term arise from 2-loop contributions to the lepton self-energy




At the end of the computation, we take the limit $t \to \infty$ to obtain the classical Boltzmann equations

# Boltzmann equations for the density matrix $(T > 10^{12}\,\mathrm{GeV})$ [SL, B. Schmauch]

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

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

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

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

inverse decays

$\ell_\alpha\ell_\beta \leftrightarrow \bar{\Delta}\,, \quad \bar{\ell}_\alpha\bar{\ell}_\beta \leftrightarrow \Delta$

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

4-lepton scatterings

$\ell_\alpha\ell_\beta \leftrightarrow \ell_\gamma\ell_\delta\,, \quad \ell_\alpha\bar{\ell}_\gamma \leftrightarrow \bar{\ell}_\beta\ell_\delta$

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

lepton-triplet scatterings

$\ell_\alpha\Delta \leftrightarrow \ell_\beta\Delta\,, \quad \ell_\alpha\bar{\Delta} \leftrightarrow \ell_\beta\bar{\Delta}\,, \quad \ell_\alpha\bar{\ell}_\beta \leftrightarrow \Delta\bar{\Delta}$

(4-lepton and lepton-triplet scatterings are purely flavoured washout processes)

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

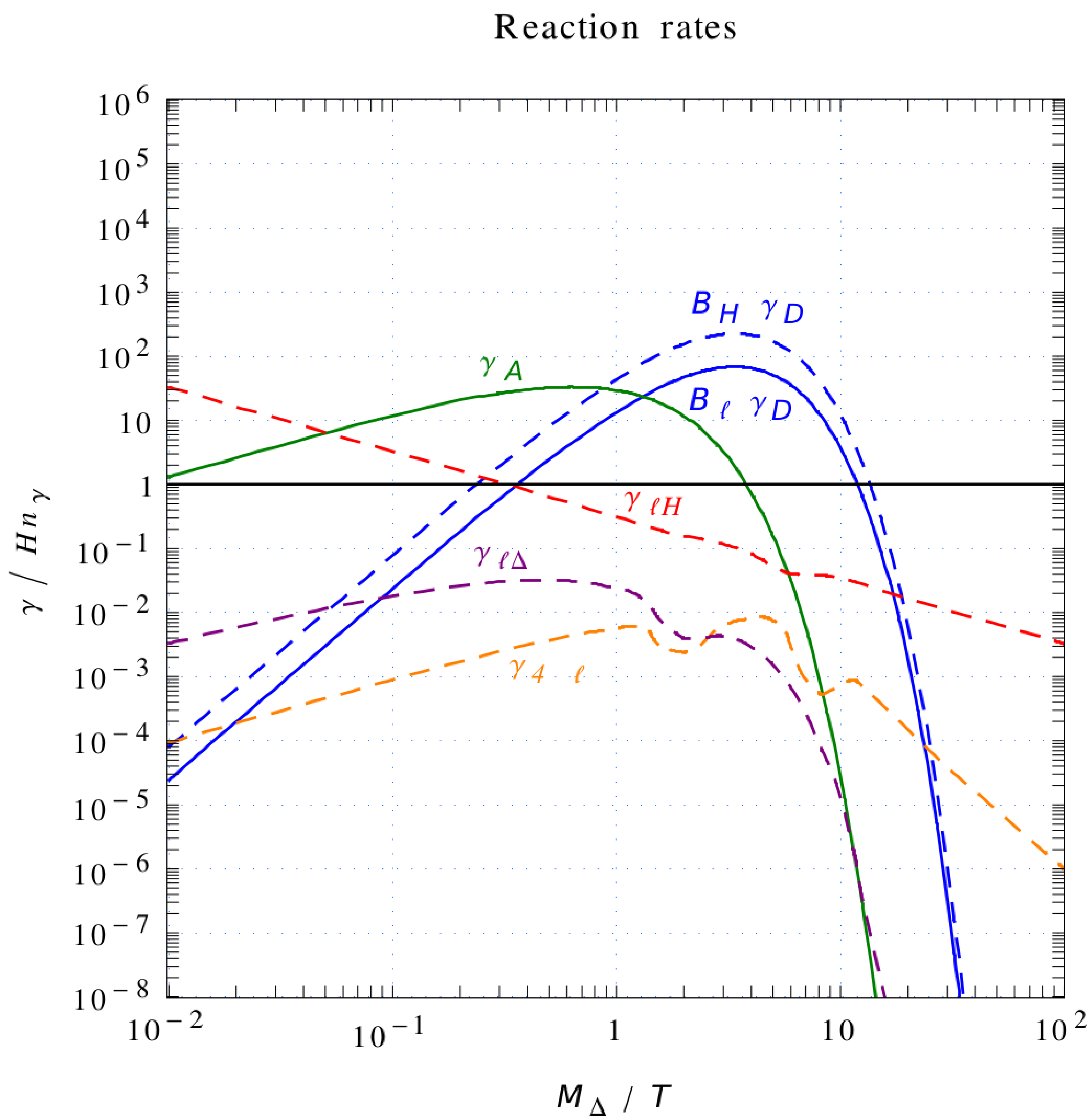
(scatterings involving leptons and Higgs bosons) $\ell_\alpha\ell_\beta \leftrightarrow \bar{H}\bar{H}\,, \quad \ell_\alpha H \leftrightarrow \bar{\ell}_\beta \bar{H}$

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

(flavour-covariant CP-asymmetry matrix)

All terms on the RHS of the Boltzmann equation for $\Delta_{\alpha\beta}$ transform covariantly under $\ell \to U\ell$ :

$$
\mathcal{M} \to U^*\mathcal{M}U^T \qquad \mathcal{M} = \{\mathcal{E}, \mathcal{W}^D, \mathcal{W}^{\ell H}, \mathcal{W}^{4\ell}, \mathcal{W}^{\ell\Delta}\}
$$




$$M_\Delta = 5 \times 10^{12}\,\text{GeV}\,,\ m_\Delta = i m_\nu\,,\ \lambda_H = 0.2$$

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

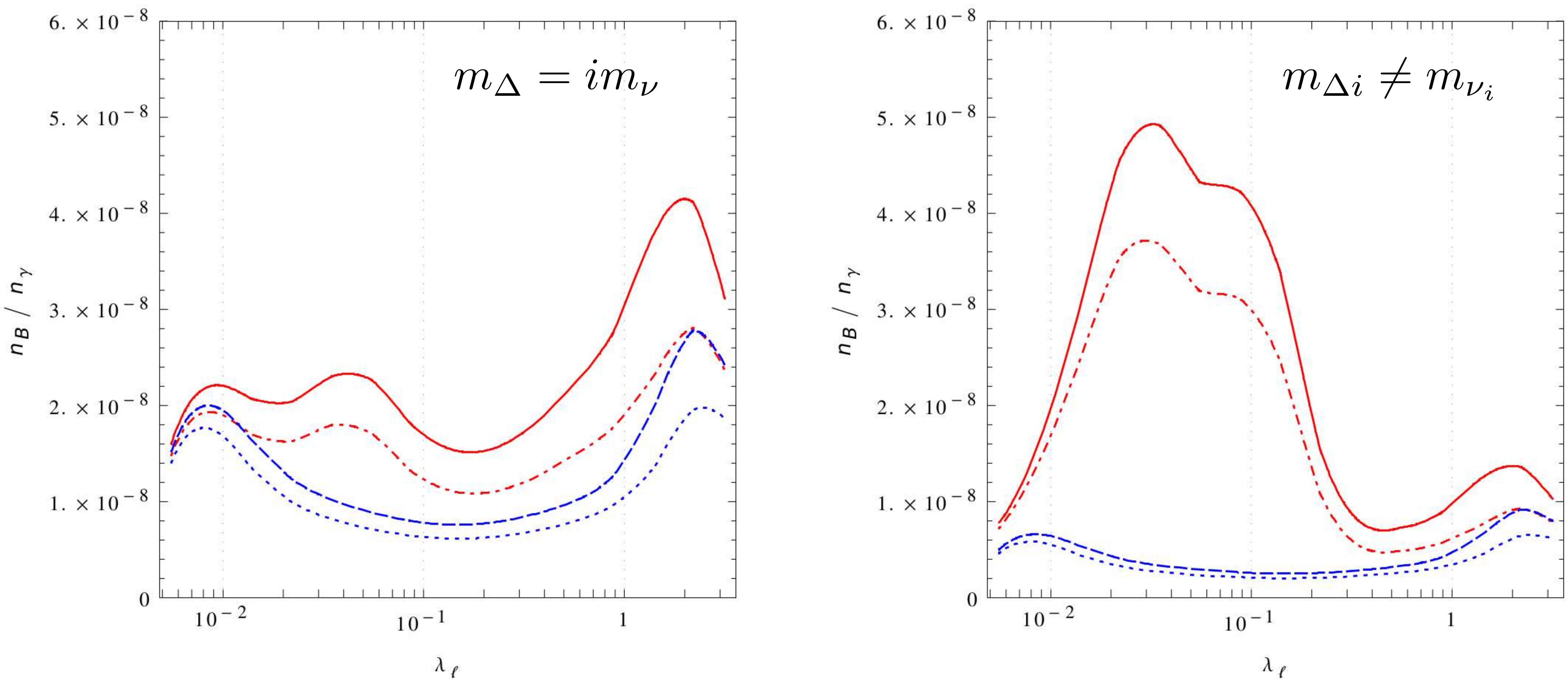



Figure 9: Baryon-to-photon ratio $n_B/n_\gamma$ as a function of $\lambda_\ell$ for $M_\Delta = 5 \times 10^{12}\,\mathrm{GeV}$, assuming Ansatz 1 (left panel) or Ansatz 2 with $(x, y) = (0.05, 0.95)$ (right panel). The red lines indicate the result of the flavour-covariant computation involving the $3 \times 3$ density matrix $\Delta_{\alpha\beta}$, with (solid red line) or without (dashed-dotted red line) spectator processes taken into account, whereas the blue lines indicate the result of the single flavour approximation, taking spectator processes into account (blue dashed line) or not (blue dotted line). The equality of branching ratios $B_\ell = B_H$ is realized for $\lambda_\ell \simeq 0.15$.

$m_\Delta = i m_\nu$ $\qquad$ $m_{\Delta i} \neq m_{\nu_i}$

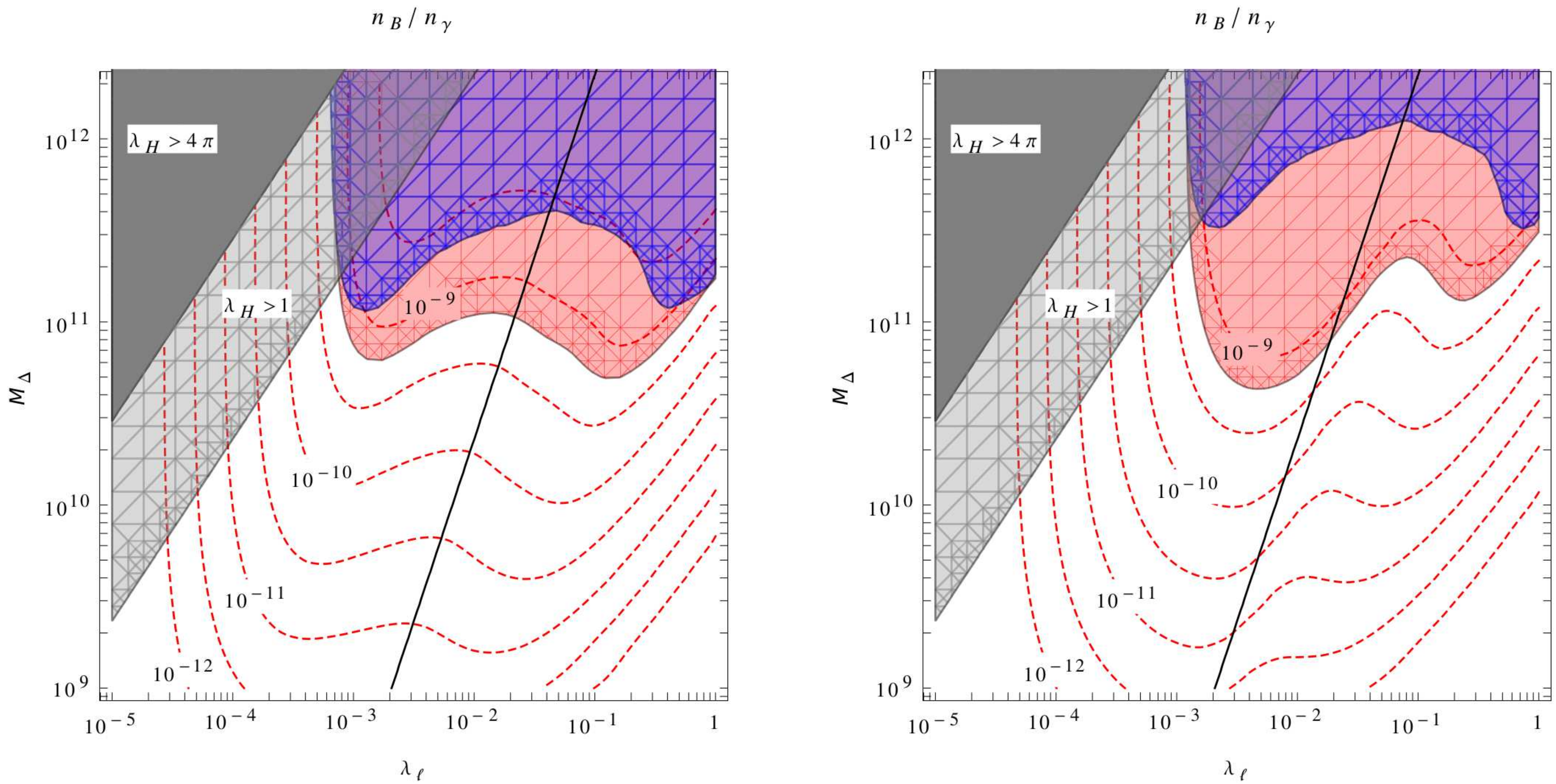


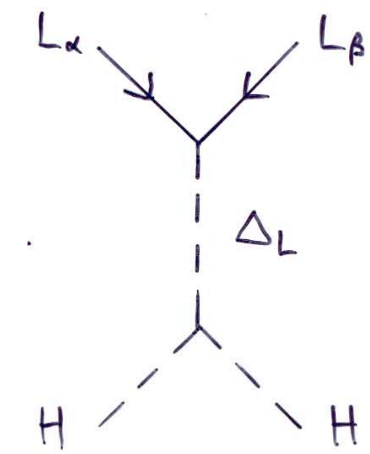

Figure 11: Isocurves of the baryon-to-photon ratio $n_B/n_\gamma$ in the $(\lambda_\ell, M_\Delta)$ plane obtained performing the full computation, assuming Ansatz 1 (left panel) or Ansatz 2 with $(x, y) = (0.05, 0.95)$ (right panel). The coloured regions indicate where the observed baryon asymmetry can be reproduced in the full computation (light red shading) or in the single flavour approximation with spectator processes neglected (dark blue shading). The solid black line corresponds to $B_\ell = B_H$. Also shown are the regions where $\lambda_H$ is greater than 1 or $4\pi$.

$M_\Delta > 4.4 \times 10^{10}\,\mathrm{GeV}$ $\qquad$ ($1.2 \times 10^{11}$ GeV without flavour effects)

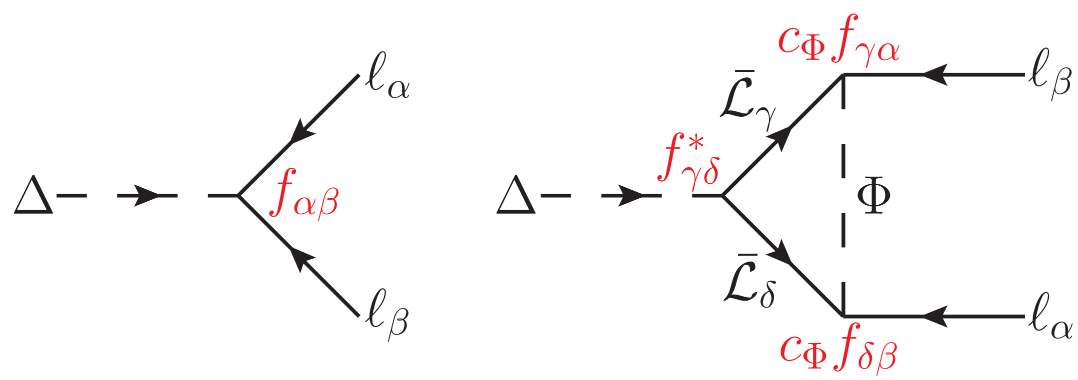
# A predictive scheme for scalar triplet leptogenesis

Non-standard SO(10) model that leads to pure type II seesaw mechanism $\Rightarrow$ neutrinos masses proportional to triplet couplings to leptons:

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




This model also contains heavy (non-standard) leptons that induce a CP asymmetry in the heavy triplet decays




$$\Phi = S, T \in 54$$

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]

# SO(10) models with type II seesaw mechanism

[Frigerio, Hosteins, SL, Romanino]

Avoiding the type I contribution is difficult: $N_R$'s 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

$$\begin{aligned} 16_i &= 10_i \oplus \ . \ \oplus 1_i \\ 10_i &= \ . \ \oplus \bar{5}_i^{10} \end{aligned}$$

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

$\Rightarrow$ contains heavy lepton doublets and quark singlets and their VL partners

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

<u>Neutrino masses</u>: no coupling of the $N_R$'s to the SM leptons at tree level
$\Rightarrow$ type II seesaw mechanism (in the presence of a 54 Higgs representation)

$$W_{II} = \frac{1}{2} f_{ij} 10_i 10_j 54 + \frac{1}{2} \sigma 10\, 10\, 54 + \frac{1}{2} M_{54} 54^2 \quad \Longrightarrow \quad M_\nu = \frac{\sigma (v_u^{10})^2}{2 M_\Delta} f$$

# Dependence on the light neutrino parameters

Assuming $M_1 \ll M_\Delta < M_1 + M_2$ , one obtains:

$$\epsilon_\Delta \; \propto \; \mathrm{Im}\left[f_{11}(f^* f f^*)_{11}\right] \; \propto \; \mathrm{Im}\left[(m_\nu)_{11}(m_\nu^* m_\nu m_\nu^*)_{11}\right]$$

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

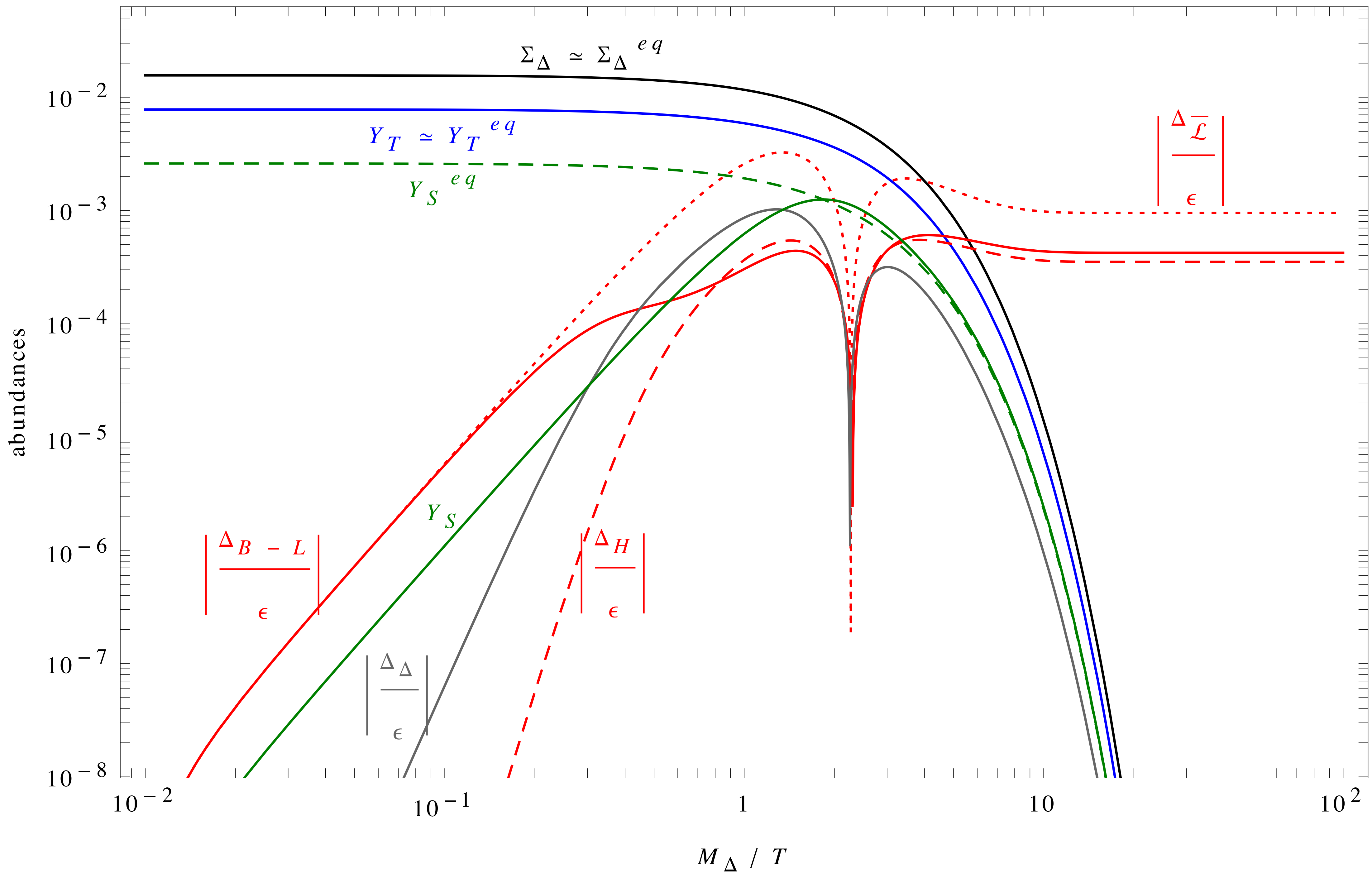
→ $\epsilon_\Delta$ depends on measurable neutrino parameters

→ 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 $\theta_{13}$ is large enough (prior to its measurement by the Daya Bay experiment) [Frigerio, Hosteins, SL, Romanino '08]

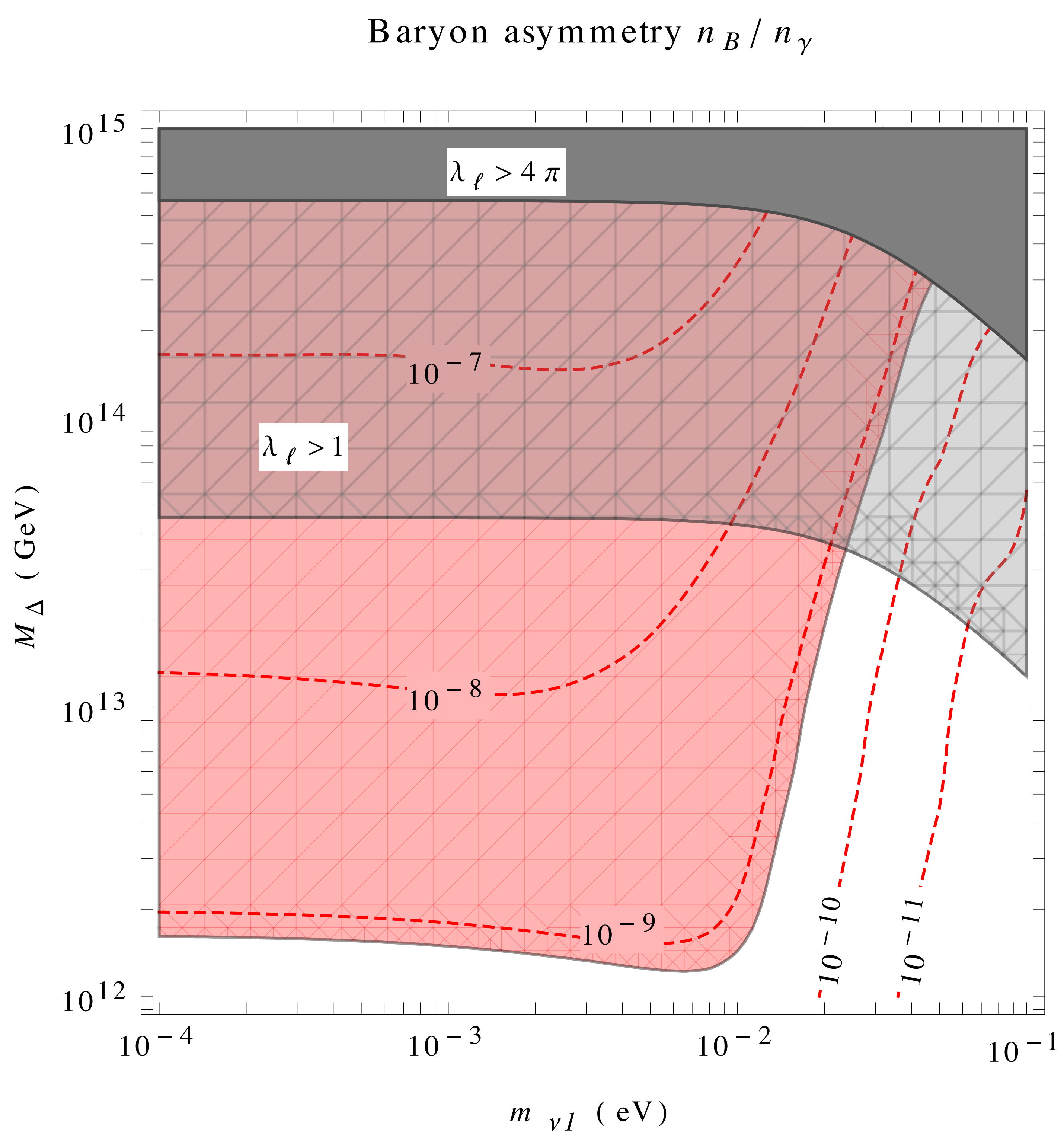
→ confirmed by the numerical resolution of the flavour-covariant Boltzmann equations [SL, B. Schmauch, to appear]

# Numerical results [SL, B. Schmauch, to appear]




$$M_\Delta = 10^{13}\,\text{GeV}\,,\;\; m_1 = 10^{-3}\,\text{eV}\,,\;\; \lambda_H = 0.2$$

# Parameter space allowed by successful leptogenesis: normal hierarchy

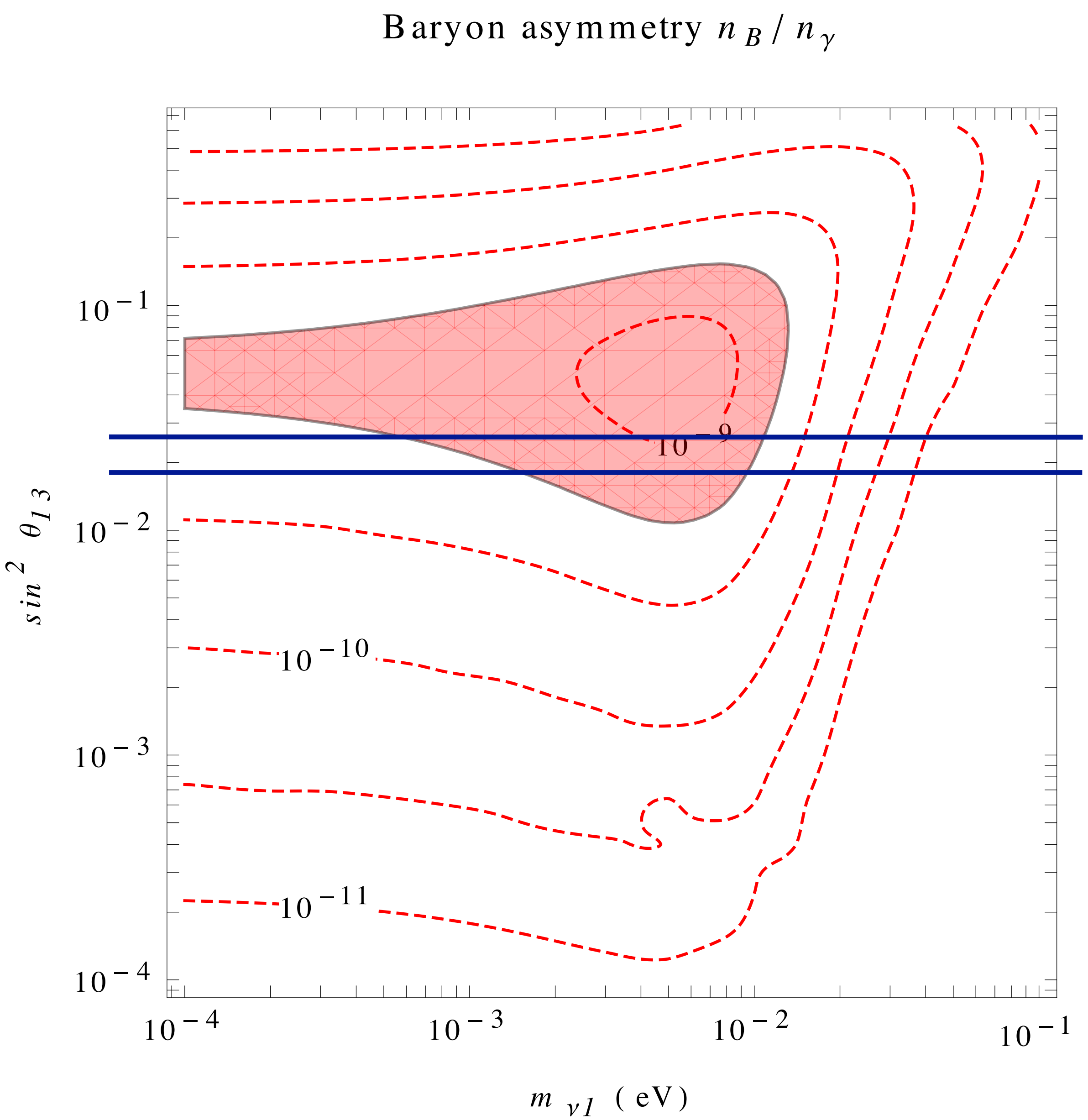



$\lambda_H = 0.2$

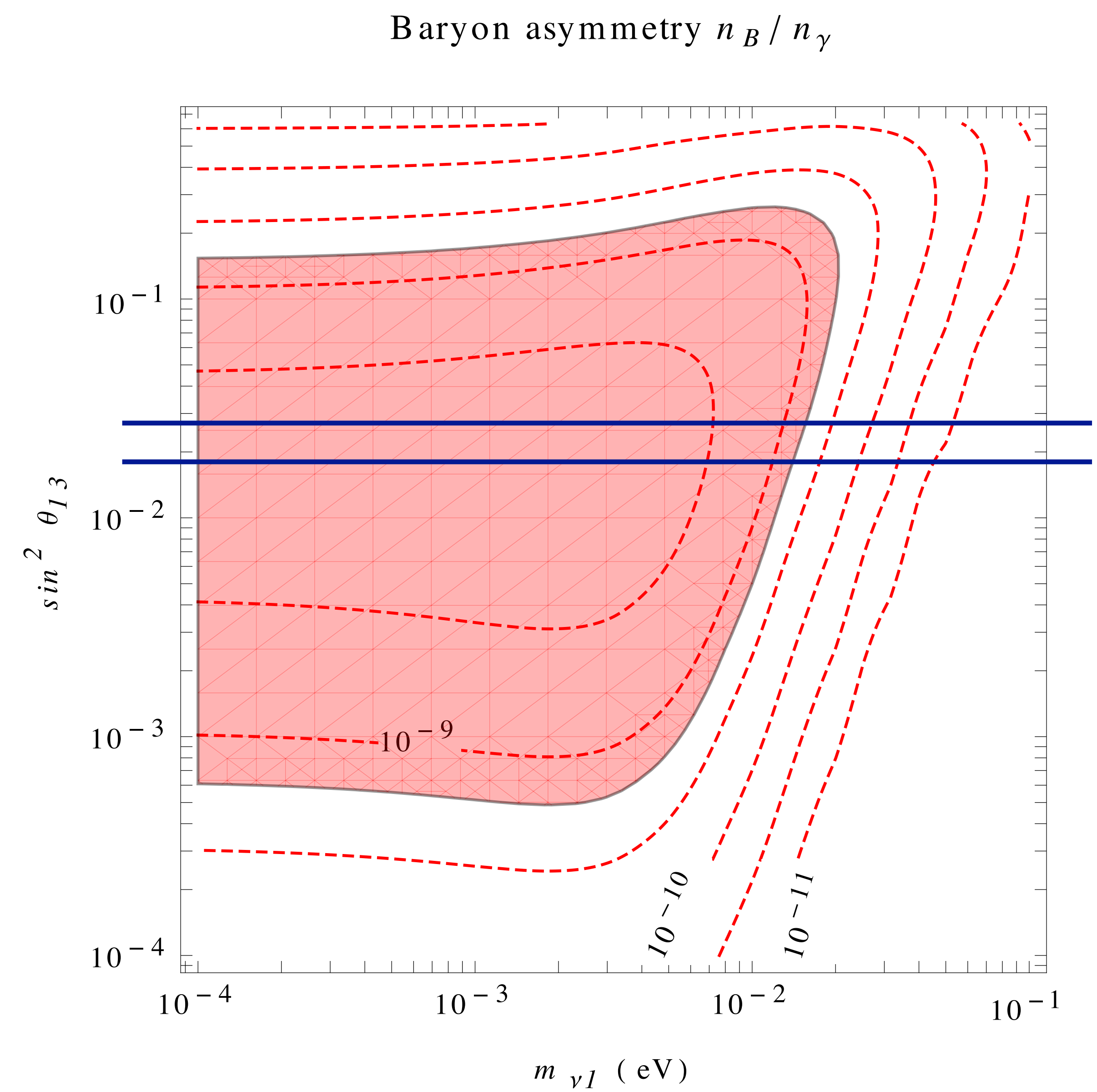
→ excludes a quasi-degenerate spectrum

# $\theta_{13}$ dependence

$M_\Delta = 1.5 \times 10^{12}\,\mathrm{GeV}$



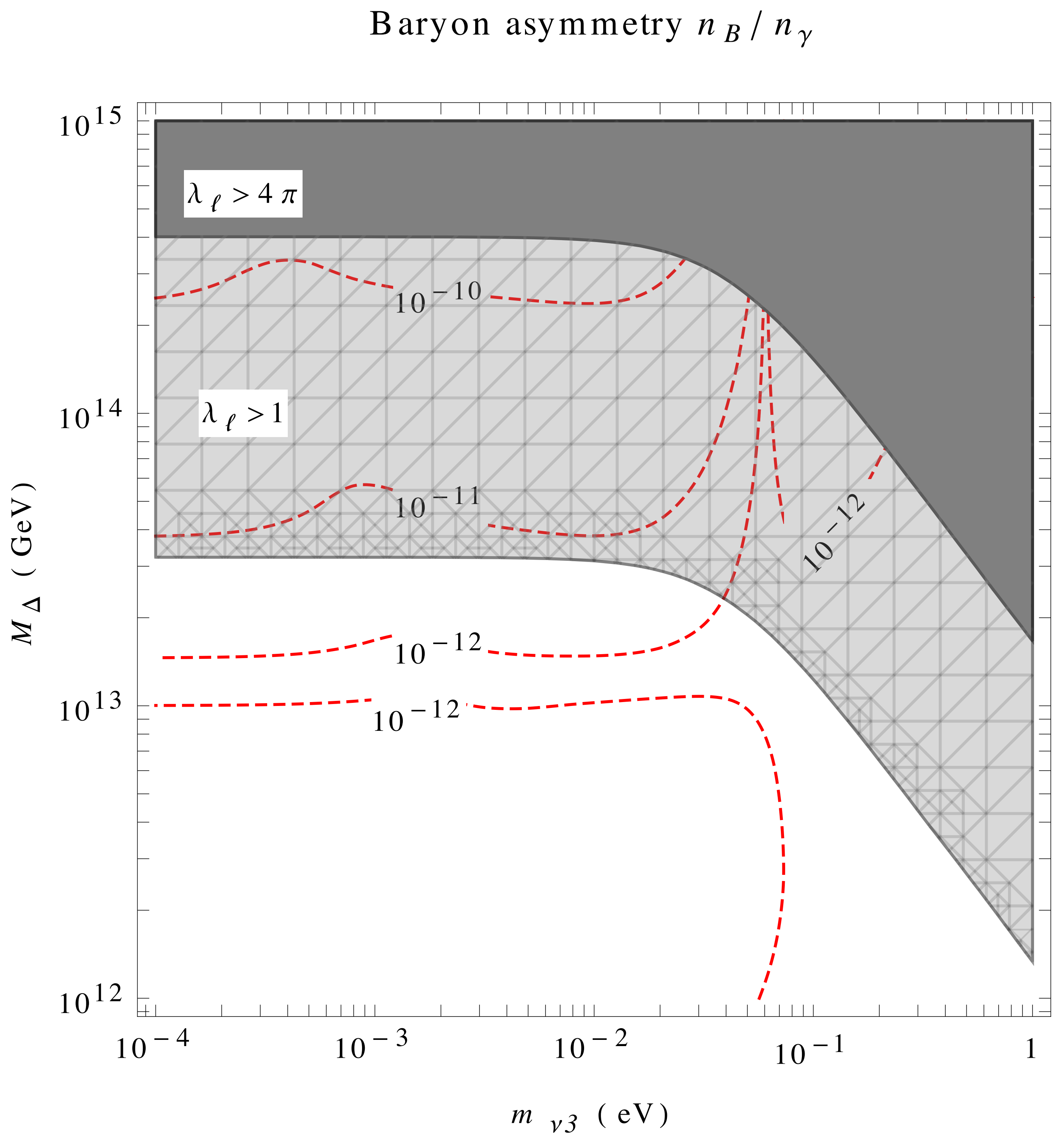

$M_\Delta = 5 \times 10^{12}\,\mathrm{GeV}$




(3σ range)

$\lambda_H = 0.2$

# Inverted hierarchy case




$\lambda_H = 0.2$

→ inverted hierarchy disfavoured

# Conclusions

Lepton flavour dynamics can never be neglected in scalar triplet leptogenesis, even when all charged lepton Yukawa couplings are out of equilibrium (at variance with standard leptogenesis with RHNs, for which the single flavour approximation is very good)

Except at $T < 10^9\,\mathrm{GeV}$, where all quantum correlations between the different lepton flavours are destroyed, it is not possible to describe accurately the flavour dynamics in terms of individual flavour asymmetries

$\rightarrow$ must use flavour-covariant Boltzmann equations

Flavour effects can significantly affect the generated baryon asymmetry (extreme case: purely flavoured scalar triplet leptogenesis)

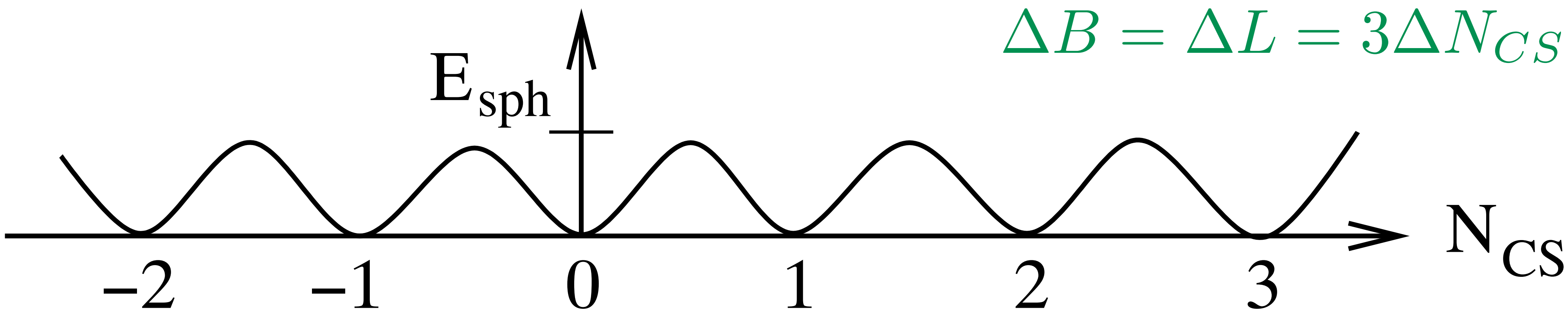
Non-standard embedding of the SM fermions in SO(10) representations provides a link between leptogenesis and low-energy neutrino parameters

# Backup slides

# Baryon number violation in the Standard Model

The baryon (B) and lepton (L) numbers are accidental global symmetries of the SM Lagrangian $\Rightarrow$ all perturbative processes preserve B and L

However, B+L is violated at the quantum level (anomaly) $\Rightarrow$ non-perturbative transitions between vacua of the electroweak theory characterized by different values of B+L [but B-L is conserved]




In equilibrium above the EWPT [ $T > T_{EW} \sim 100\,\mathrm{GeV}$ , $\langle\phi\rangle = 0$ ]:

$$\Gamma(T > T_{EW}) \sim \alpha_W^5 T^4 \qquad \alpha_W \equiv g^2/4\pi$$

[Kuzmin, Rubakov, Shaposhnikov]

Exponentially suppressed below the EWPT [ $0 < T < T_{EW}$ , $\langle\phi\rangle \neq 0$ ]:

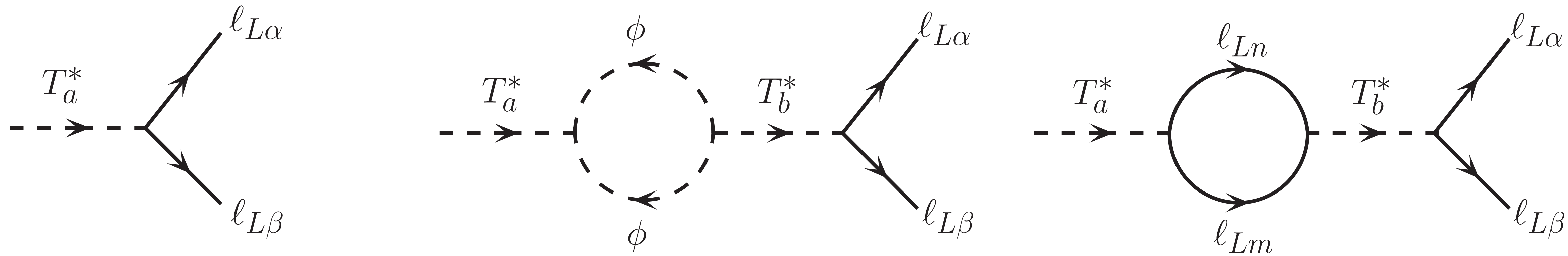
$$\Gamma(T < T_{EW}) \propto e^{-E_{sph}(T)/T}$$

[Arnold, McLerran-Khlebnikov, Shaposhnikov]

$E_{sph}(T)$ = energy of the gauge field configuration (“sphaleron”) that interpolates between two vacua

# Purely flavoured leptogenesis

New contribution to the CP asymmetry in the flavoured regime (models with several triplets) [González Felipe, Joaquim, Serôdio, 1301.0288]




(i) usual contribution: violates both L and L$\alpha$

$$\epsilon_{\alpha\beta}^{(i)} \propto \mathrm{Im}\left[\mu_a \mu_b^* (f_a)_{\alpha\beta} (f_b^*)_{\alpha\beta}\right] \qquad \epsilon^{(i)} = \sum_{\alpha,\beta} \epsilon_{\alpha\beta}^{(i)} \propto \mathrm{Im}\left[\mu_a \mu_b^* \mathrm{Tr}(f_a f_b^\dagger)\right]$$

(ii) new contribution: violates L$\alpha$ but not L

$$\epsilon_{\alpha\beta}^{(ii)} \propto \mathrm{Im}\left[\mathrm{Tr}(f_a f_b^\dagger)(f_a)_{\alpha\beta}(f_b^*)_{\alpha\beta}\right] \qquad \epsilon^{(ii)} = \sum_{\alpha,\beta} \epsilon_{\alpha\beta}^{(ii)} \propto \mathrm{Im}\left[\left|\mathrm{Tr}(f_a f_b^\dagger)\right|^2\right] = 0$$

If the triplets couple much more strongly to leptons than to Higgs bosons, then $|\epsilon_{\mathrm{total}}| = |\epsilon^{(i)}| \ll |\epsilon_{\alpha\beta}^{(ii)}|$ ➞ purely flavoured leptogenesis (PFL)

# Detailed study of PFL [Aristizabal Sierra, Dhen, Hambye, 1401.4347]

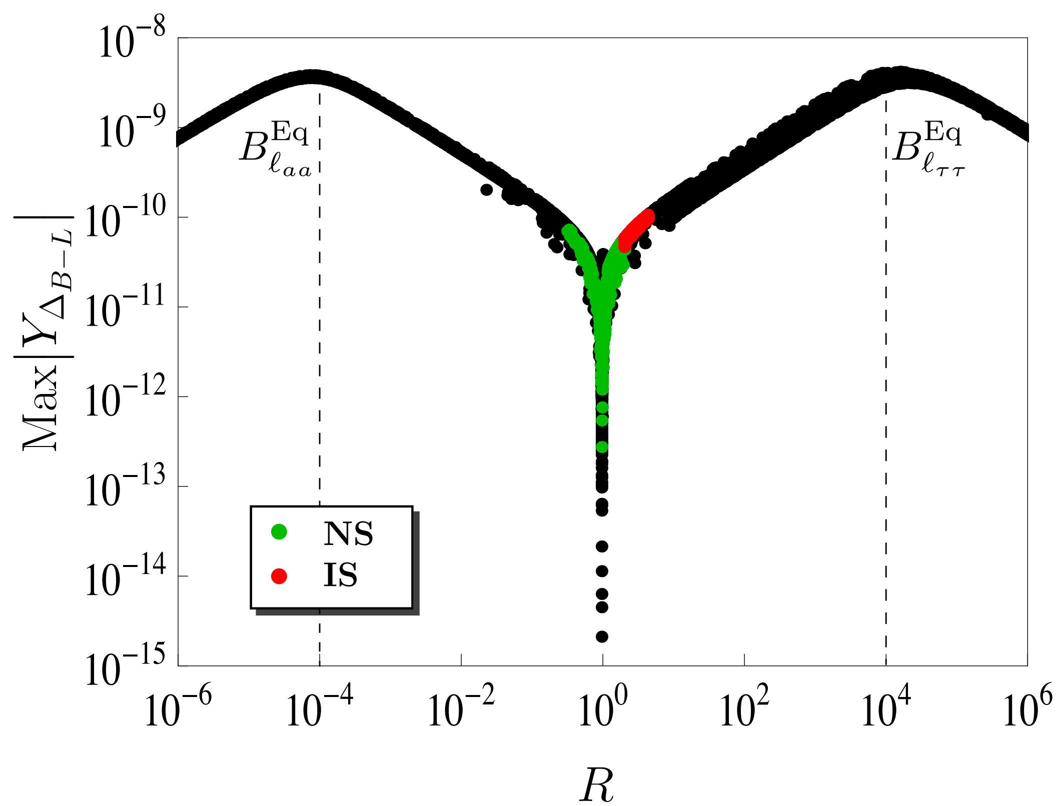
Assume $B_H \ll B_\ell, \; |\epsilon_{\rm total}| \simeq 0$

Triplet decays generate flavour asymmetries but no overall B-L asymmetry

Crucial role of the asymmetry $\Delta_\Delta$, which is generated through inverse decays thanks to the flavour structure in the $B_{\ell_\alpha}$ or $C^l_{\alpha\beta}$

$$sHz\frac{d\Delta_\Delta}{dz} \ni \sum_{\alpha,\beta} B_{\ell_\alpha} C^\ell_{\alpha\beta} \frac{\Delta_\beta}{Y_\ell^{\rm eq}} \gamma_D$$

$\Delta_\Delta$ is then converted into a B-L asymmetry through decays




$$R \equiv \frac{B_{\ell_a}}{B_{\ell_\tau}} = \frac{B_{\ell_{aa}} + B_{\ell_{a\tau}}}{B_{\ell_{\tau a}} + B_{\ell_{\tau\tau}}}$$

Figure 11: *Maximum attainable final $B-L$ asymmetry as a function of the $R$ parameter, for $B_\phi = 10^{-5}$, $m_\Delta = 10^{11}$ GeV and $\tilde{m}_\Delta = 0.05$ eV. Neutrino data constraints have been imposed as in Fig. (7).*

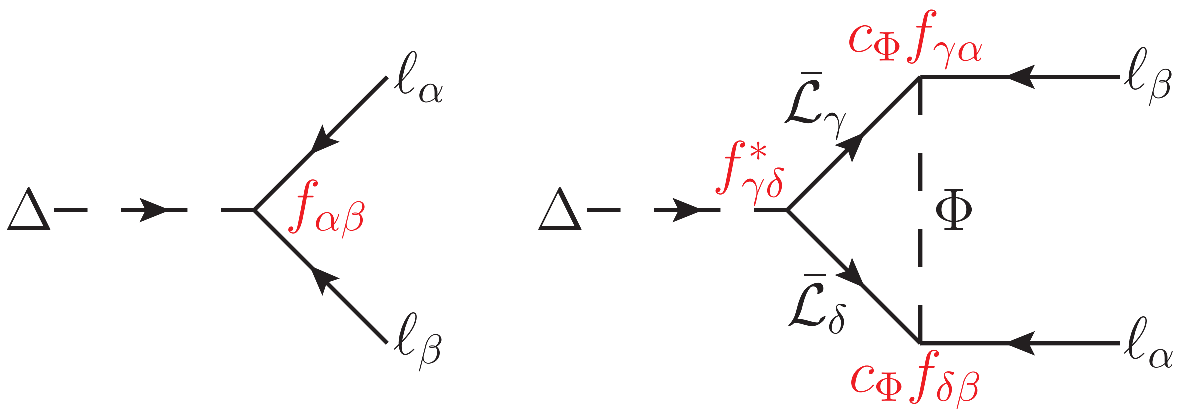
# Leptogenesis

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
$\Rightarrow$ no direct connection between leptogenesis and neutrino masses

In our scenario, the states in the loop are heavy and the trace is incomplete




$$\Phi = S, T \in 54$$

Assuming $M_1 \ll M_\Delta < M_1 + M_2$ , one obtains:

$$\epsilon_\Delta \propto \mathrm{Im}\left[f_{11}(f^* f f^*)_{11}\right] \propto \mathrm{Im}\left[(m_\nu)_{11}(m_\nu^* m_\nu m_\nu^*)_{11}\right]$$