Overview of leptogenesis

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- leptogenesis from out-of-equilibrium decays (thermal leptogenesis): heavy Majorana neutrinos / scalar electroweak triplet
- resonant leptogenesis
- leptogenesis from sterile neutrino oscillations (ARS leptogenesis)
- in passing: is there a link with CP violation at low energy ? how to probe these scenarios ?

International Workshop on the Origin of the Matter-Antimatter Asymmetry
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Introduction

The baryon asymmetry of the universe (BAU)

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq \frac{n_B}{n_\gamma} = (6.12 \pm 0.04) \times 10^{-10} \qquad \text{(Planck 2020)}$$

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

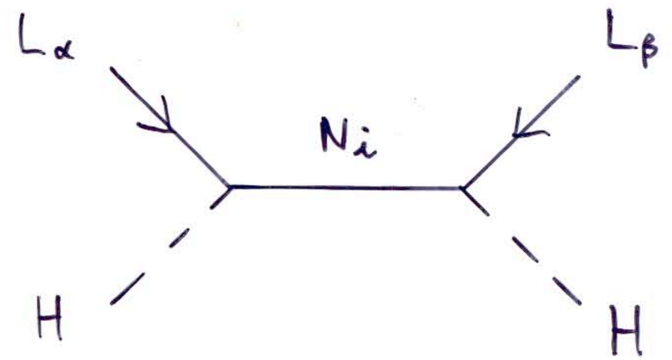
Electroweak baryogenesis fails in the SM because (3) is not satisfied [also CP violation is too weak] $\Rightarrow$ need either new physics at M_{weak} to modify the dynamics of the EWPT, or generate a (B-L) asymmetry at $T > T_{EW}$

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

Main motivation for leptogenesis: neutrino masses, which strongly suggest lepton number violation

Attractive mechanism since connects neutrino masses to the BAU :

the B-L asymmetry is generated in out-of-equilibrium decays and/or oscillations of heavy states involved in neutrino mass generation, such as the heavy Majorana neutrinos of the (type I) seesaw mechanism



$$\Longrightarrow \qquad m_\nu \sim \frac{Y^2 v^2}{M}$$

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

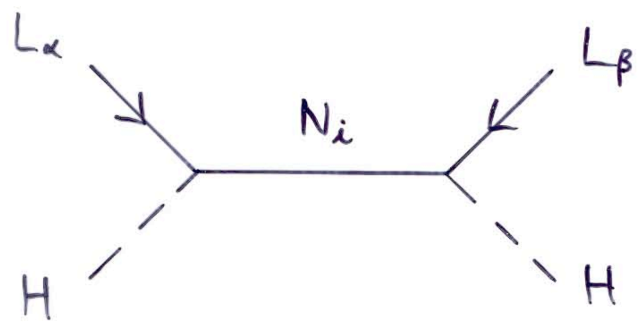
Leptogenesis is also possible with an EW scalar triplet (type II seesaw) or with EW fermion triplets (type III seesaw)

Thermal leptogenesis with heavy Majorana neutrinos

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

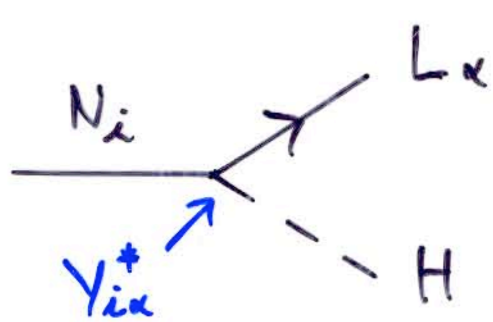
Seesaw mechanism:

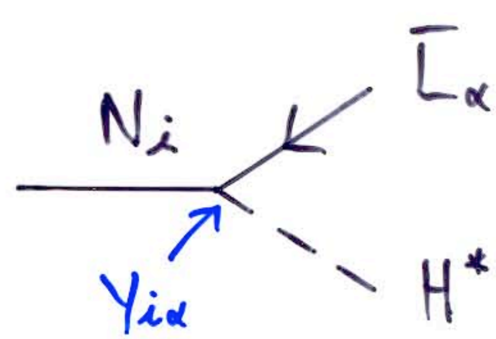
$$\mathcal{L}_{seesaw} = -\frac{1}{2} M_i \bar{N}_i N_i - \left(\bar{N}_i Y_{i\alpha} L_\alpha H + \text{h.c.} \right)$$



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

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

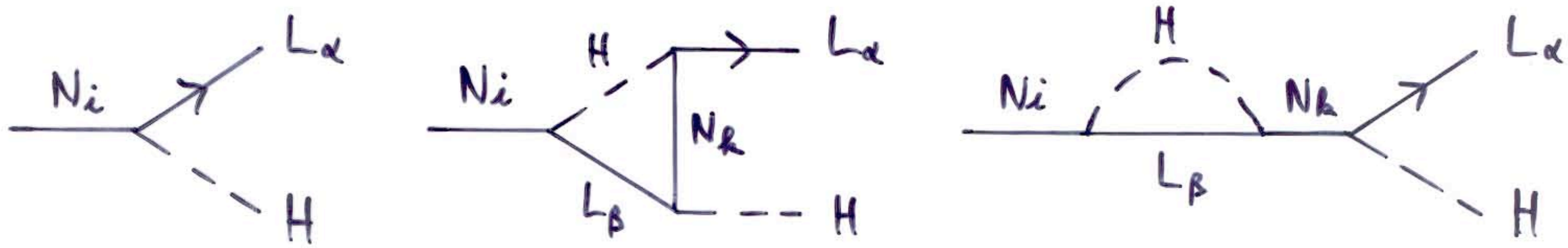




$N_i \longrightarrow L_\alpha H$ $\qquad$ $N_i \longrightarrow \bar{L}_\alpha H^*$

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

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



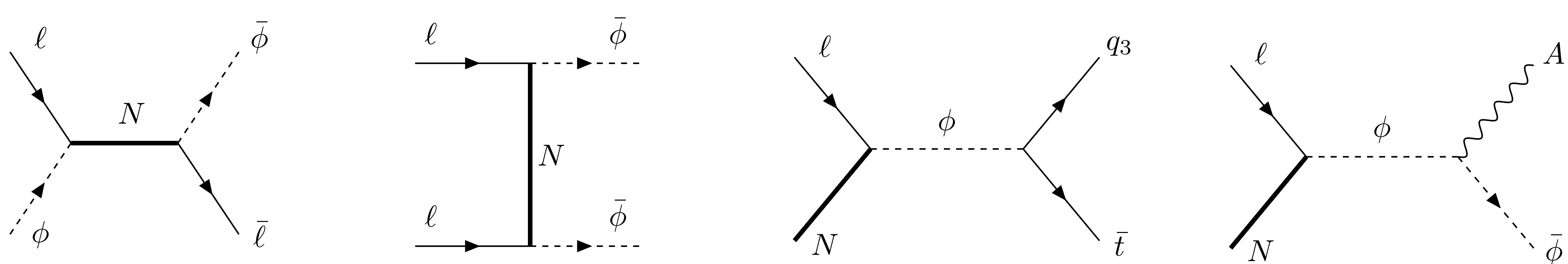
$$\Rightarrow \quad \Gamma(N_i \to LH) \neq \Gamma(N_i \to \bar{L}H^\star)$$

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

CP asymmetry in N1 decays (hierarchical case $M_1 \ll M_2, M_3$) $\Rightarrow$ generation of a lepton asymmetry proportional to $\epsilon_{N_1} \equiv \dfrac{\Gamma(N_1 \to LH) - \Gamma(N_1 \to \bar{L}H^\star)}{\Gamma(N_1 \to LH) + \Gamma(N_1 \to \bar{L}H^\star)}$

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

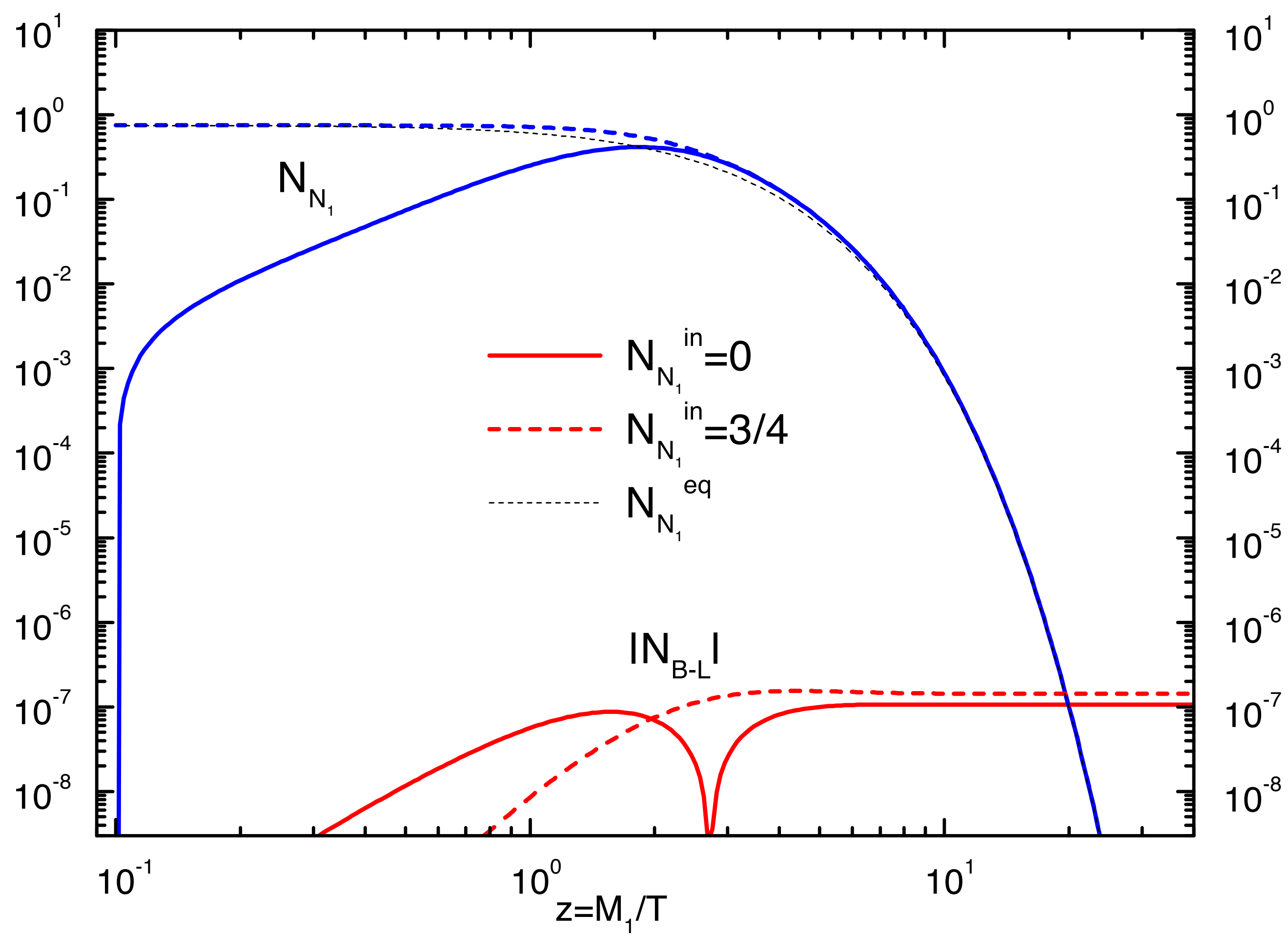


The generated asymmetry is partly washed out by L-violating processes. Its evolution is described by the Boltzmann equation

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

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

Typical evolution:



[Buchmüller, Di Bari, Plümacher ’02]

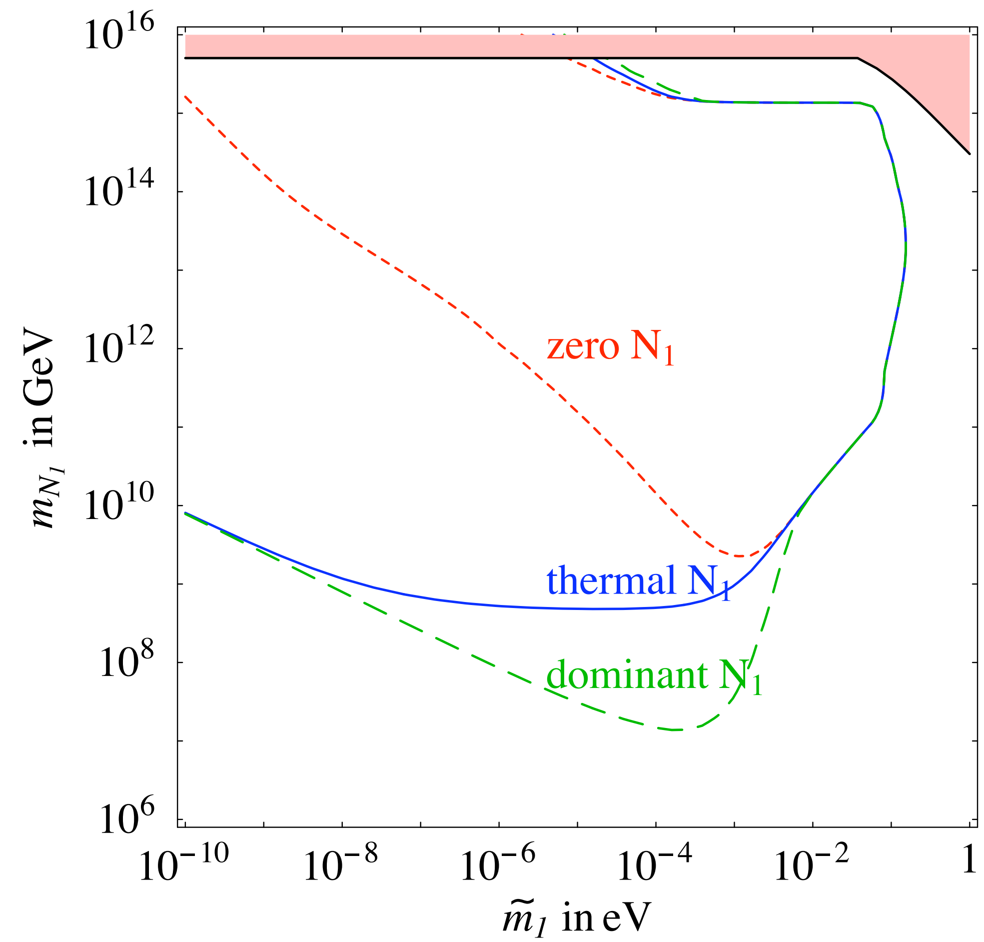
Thermal leptogenesis can explain the observed baryon asymmetry

(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]

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

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

This is valid as long as the charged lepton Yukawas λ_α are out of equilibrium

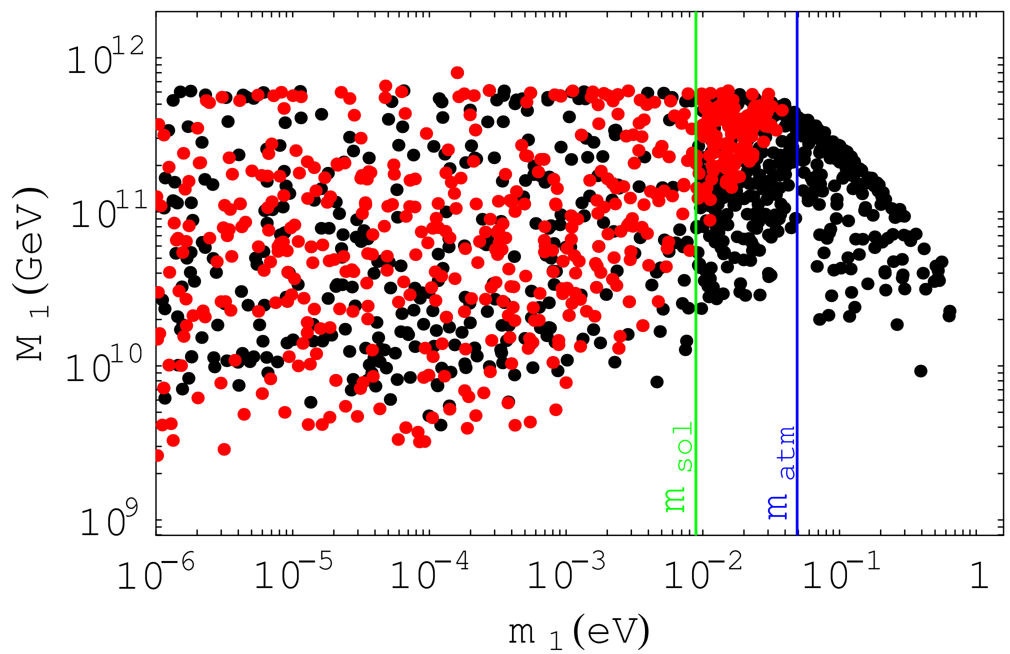
At $T \lesssim 10^{12}\,\mathrm{GeV}$, λ_τ is in equilibrium and destroys the coherence of ℓ_{N_1}
$\Rightarrow$ 2 relevant flavours: ℓ_τ and a combination ℓ_a of ℓ_e and ℓ_μ

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 temperature regime, must solve Boltzmann equations for 1, 2 or 3 lepton asymmetries ($Y_{L_e}, Y_{L_\mu}, Y_{L_\tau}$ in the 3-flavour regime, with $Y_L = Y_{L_e} + Y_{L_\mu} + Y_{L_\tau}$)

[a more rigorous treatment involves a 3x3 matrix in flavour space, the "density matrix", describing the flavour asymmetries and their quantum correlations]

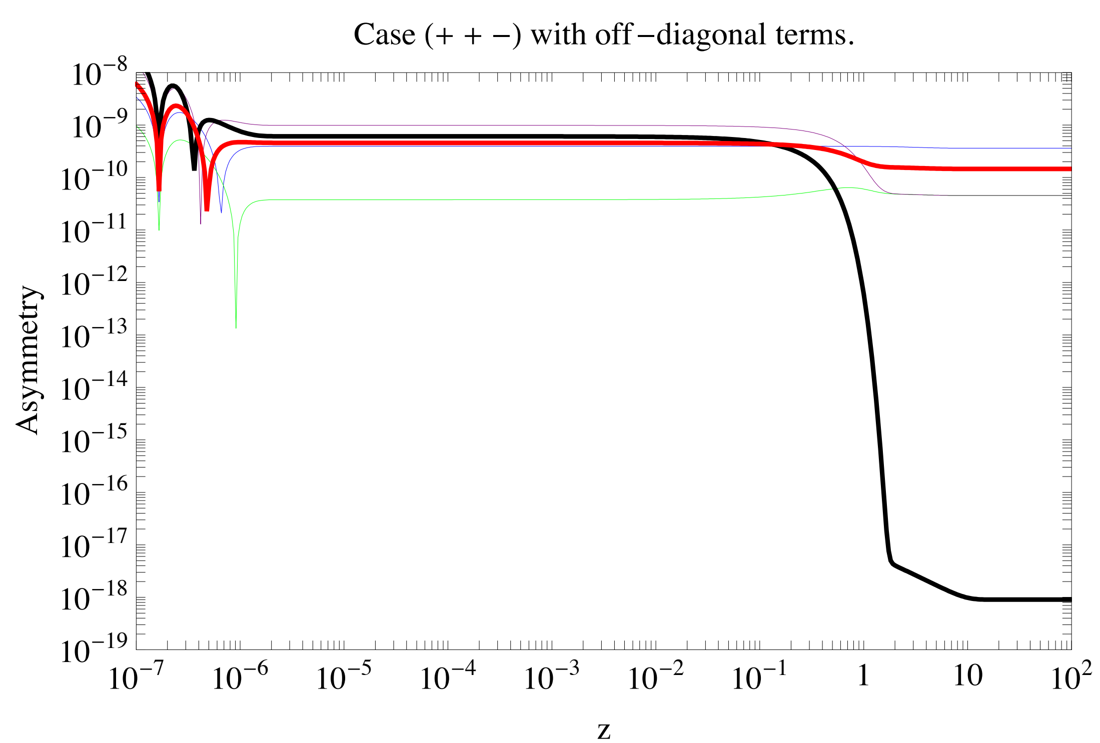
Flavour effects lead to quantitatively different results from the 1FA



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]



$$M_2 = 5 \times 10^{11}\ \mathrm{GeV}$$
$$M_1 = 8 \times 10^{4}\ \mathrm{GeV}$$

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

$$z = M_1/T$$

Is leptogenesis related to low-energy CP violation? (1FA argument)

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 U_{PMNS} $\begin{cases} \delta & \to \text{oscillations} \\ \phi_2, \phi_3 & \to \text{neutrinoless double beta} \end{cases}$

→ 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

$\Rightarrow$ unrelated to CP violation at low-energy, except in specific scenarios

[e.g. Frampton, Glashow, Yanagida '02]

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 (in R) vanish

leptogenesis from the PMNS phase δ (all other phases are assumed to vanish)

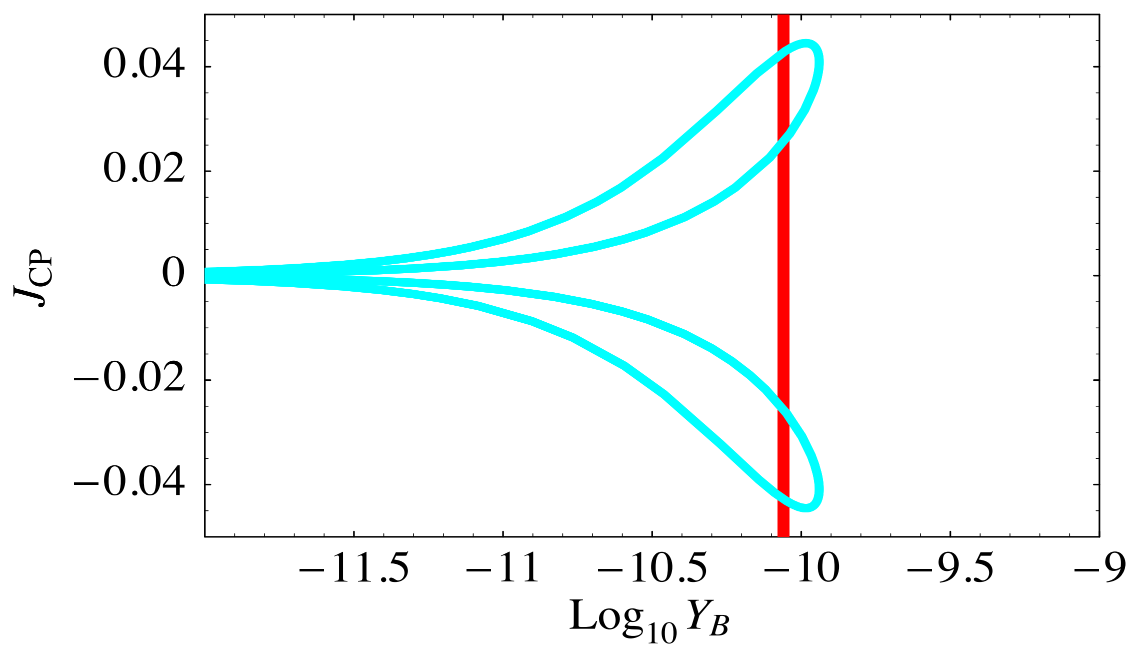


FIG. 1. The invariant J_{CP} versus the baryon asymmetry varying (in blue) $\delta = [0, 2\pi]$ in the case of hierarchical RH neutrinos and NH light neutrino mass spectrum for $s_{13} = 0.2$, $\alpha_{32} = 0$, $R_{12} = 0.86$, $R_{13} = 0.5$ and $M_1 = 5 \times 10^{11}$ GeV . The red region denotes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

[Pascoli, Petcov, Riotto '06]

Updated analysis in arXiv:1809.08251 (Moffat, Pascoli, Petcov, Turner): successful leptogenesis solely from Dirac (δ) or Majorana PMNS phases can be achieved without tuning in the whole range $10^9\,\mathrm{GeV} < M_1 < 10^{12}\,\mathrm{GeV}$

→ (it is fair to say that) the discovery of CP violation in neutrino oscillations would not test directly leptogenesis, but would give some support to it

Resonant leptogenesis

Covi, Roulet, Vissani '96 - Pilaftsis '97 - Pilaftsis, Underwood '04 '05 - Deppisch, Pilaftsis '10
Garny, Kartavtsev, Hohenegger '11 - Dev, Millington, Pilaftsis, Teresi '14

When $\Delta M \equiv M_2 - M_1 \ll M \equiv (M_1 + M_2)/2$, the CP asymmetries ε_{N_1} and ε_{N_2} are dominated by the self-energy diagram :

$$\epsilon_{N_i} \simeq -\frac{1}{8\pi} \frac{\mathrm{Im}[(YY^\dagger)^2_{21}]}{(YY^\dagger)_{ii}} \frac{M_1 M_2}{M_2^2 - M_1^2}$$

[must regulate this formula when $\Delta M \lesssim \Gamma_{N_i}$]

$\Rightarrow$ resonant enhancement of $\varepsilon_{N_{1,2}}$ allows to evade the Davidson-Ibarra bound, which relies on $|\epsilon_{N_1}| \lesssim 3 M_1 m_\nu / (16 \pi v^2)$, valid for $M_1 \ll M_2, M_3$

Successful resonant leptogenesis possible at the TeV scale at the price of a strong mass degeneracy, e.g. [Dev, Millington, Pilaftsis, Teresi '14]

$$M_1 = 400\,\mathrm{GeV}, \qquad (M_2 - M_1)/M_1 \simeq 3 \times 10^{-5}, \qquad (M_3 - M_2)/M_1 \simeq 1.2 \times 10^{-9}$$

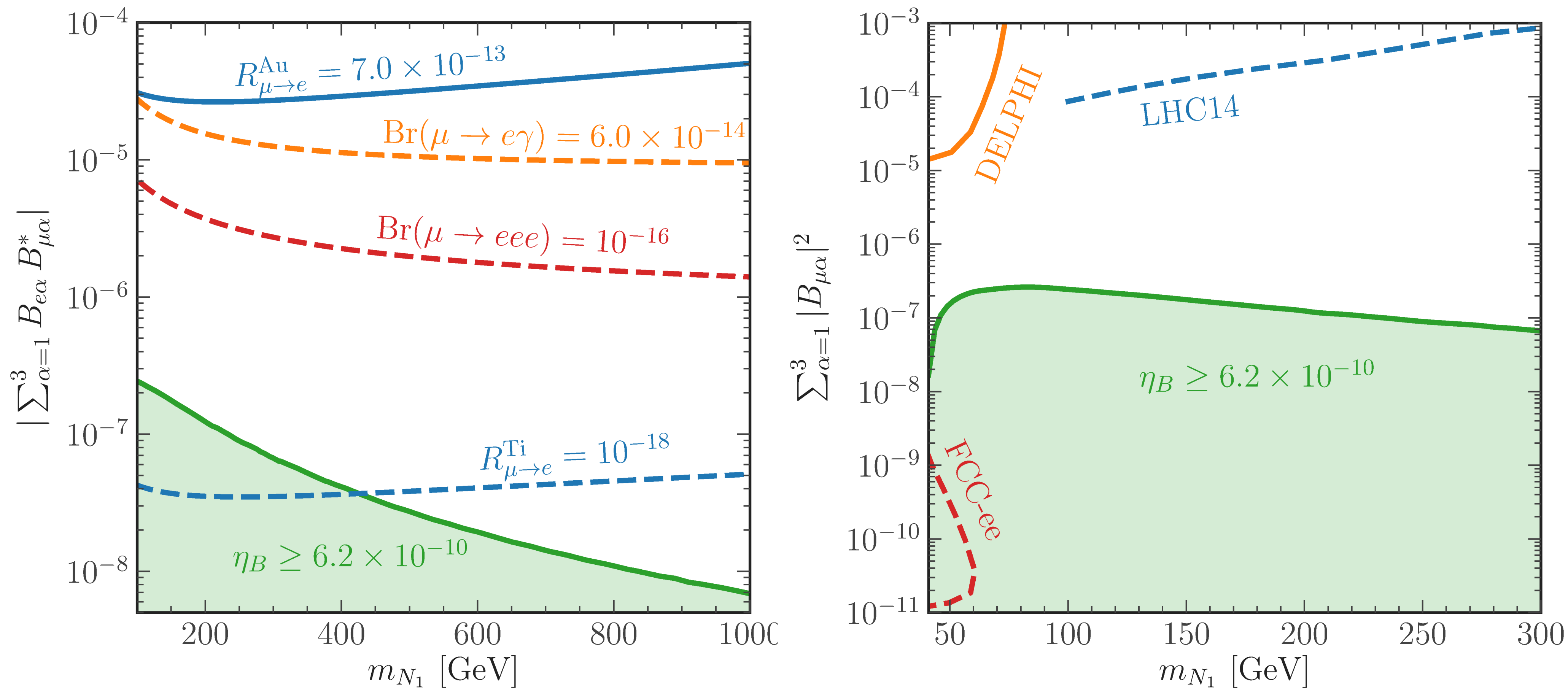
$\Rightarrow$ can be tested via direct production of heavy Majorana neutrinos at colliders + contributions to flavour violating processes in the charged lepton sector

[note : this assumes cancellations in the seesaw formula, such that the heavy neutrino couplings are larger than suggested by the SM neutrino masses, namely $Y_{i\alpha} \sim \mathrm{few}\, 10^{-3}$ rather than $Y_{i\alpha} \sim \sqrt{M_i m_\nu}/v \sim 10^{-6}$]

A recent study : "tri-resonant leptogenesis" [Candia da Silva, Karamitros, McKelvey, Pilaftsis '22]

Assumes three nearly degenerate heavy Majorana neutrinos with mass differences comparable to their widths (motivated by SO(3) and Z6 symmetries)

Results in the (M1, light-heavy mixing^2) plane :



Left plot (cLFV) : solid = current bound, dashed = future bounds

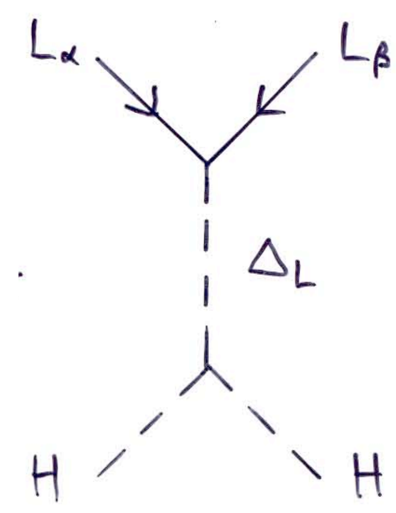
Right plot (colliders) : reach of LHC14 with $300\,\mathrm{fb}^{-1}$ $(W^\pm \to \mu^\pm N,\ N \to \ell^\pm jj)$ and of FCC-ee $(Z \to N\nu)$

Successful leptogenesis possible with M1 as light as 50 GeV

Scalar triplet leptogenesis

Type II seesaw mechanism:

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

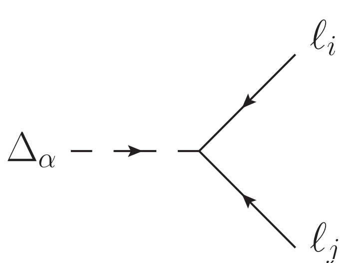


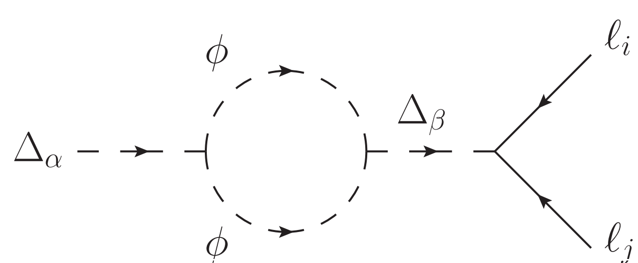
$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$ electroweak triplet

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

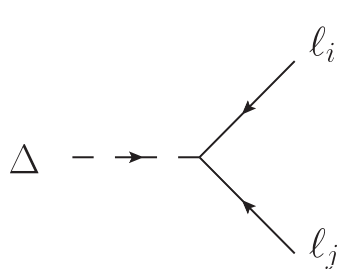
Also leads to leptogenesis provided another heavy state couples to lepton doublets ⇒ generation of a CP asymmetry in triplet decays possible

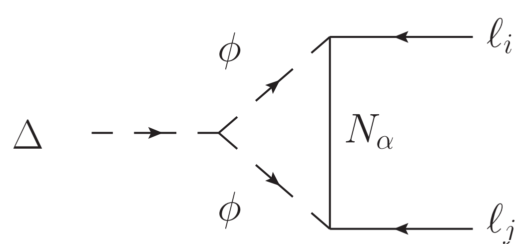
[Ma, Sarkar '98 - Hambye, Senjanovic '03]





additional triplets





RH neutrinos

Main differences with leptogenesis with heavy Majorana neutrinos:

(i) the heavy decaying state is not self-conjugate $\Rightarrow$ the lepton asymmetry arises from $\Gamma(\Delta \to \bar{\ell}\bar{\ell}) \neq \Gamma(\bar{\Delta} \to \ell\ell)$ (CP asymmetry)

(ii) 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)

The triplet must decay before annihilating, which requires one of the decay modes to be in equilibrium; however, the third Sakharov condition is still satisfied if the other decay mode is slow enough

First quantitive study of scalar triplet leptogenesis by Hambye, Raidal and Strumia '05 (without flavour effects)

Can reproduce the observed BAU 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

Inclusion of flavour effects in scalar triplet leptogenesis

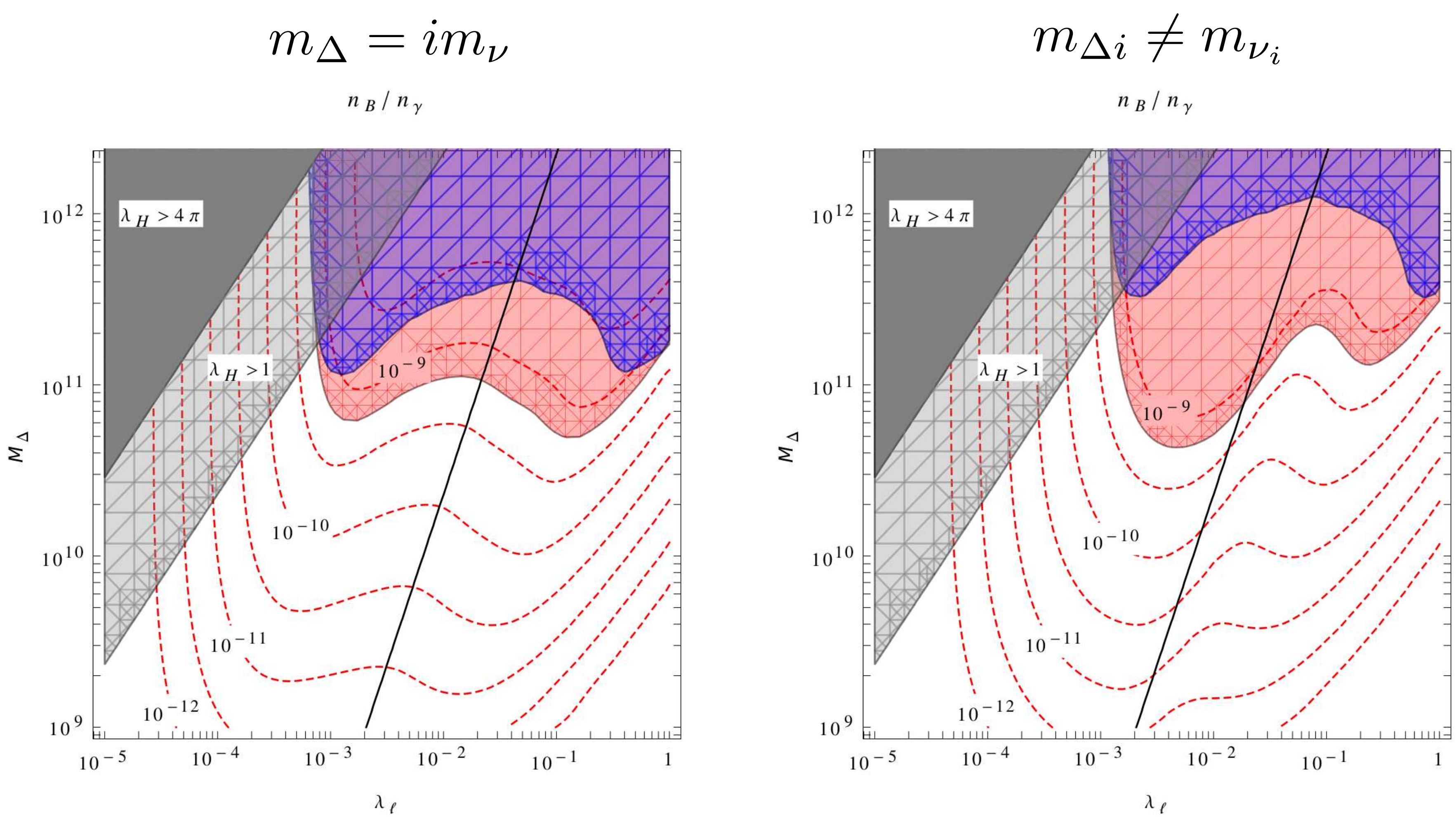


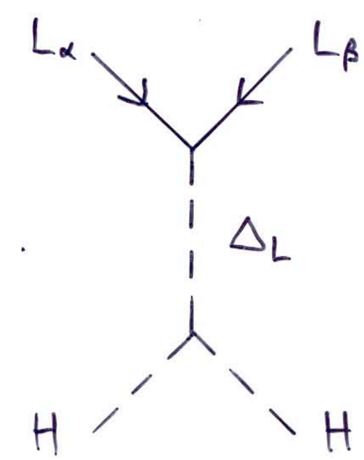
Figure 11: Isocurves of the baryon-to-photon ratio n_B/n_γ in the (λ_ℓ, M_Δ) plane obtained performing the full computation, assuming Ansatz 1 (left panel) or Ansatz 2 with $(x, y) = (0.05, 0.95)$ (right panel). The coloured regions indicate where the observed baryon asymmetry can be reproduced in the 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 λ_H is greater than 1 or 4π.

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

[SL, Schmauch '15]

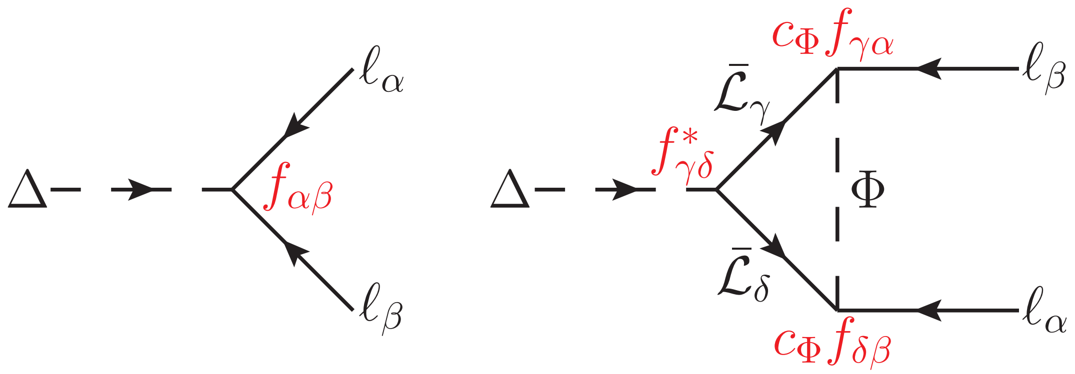
A predictive scheme for scalar triplet leptogenesis

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



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

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



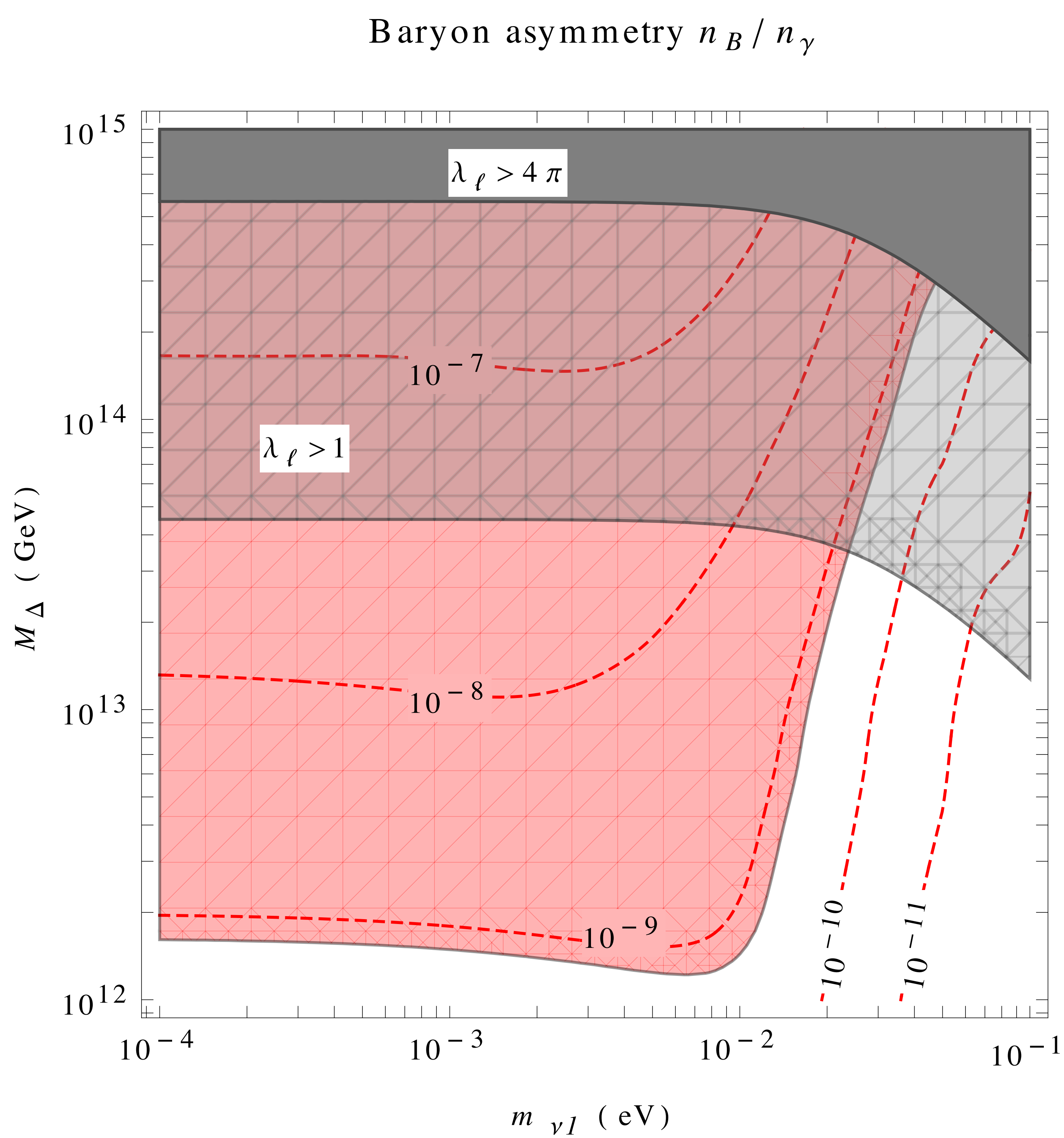
$$\Phi = S, T \in 54$$

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 neutrino parameters (masses, mixing angles, Majorana phases)

→ important difference with other triplet leptogenesis scenarios

[Frigerio, Hosteins, SL, Romanino ’08]

Parameter space allowed by successful leptogenesis: normal hierarchy



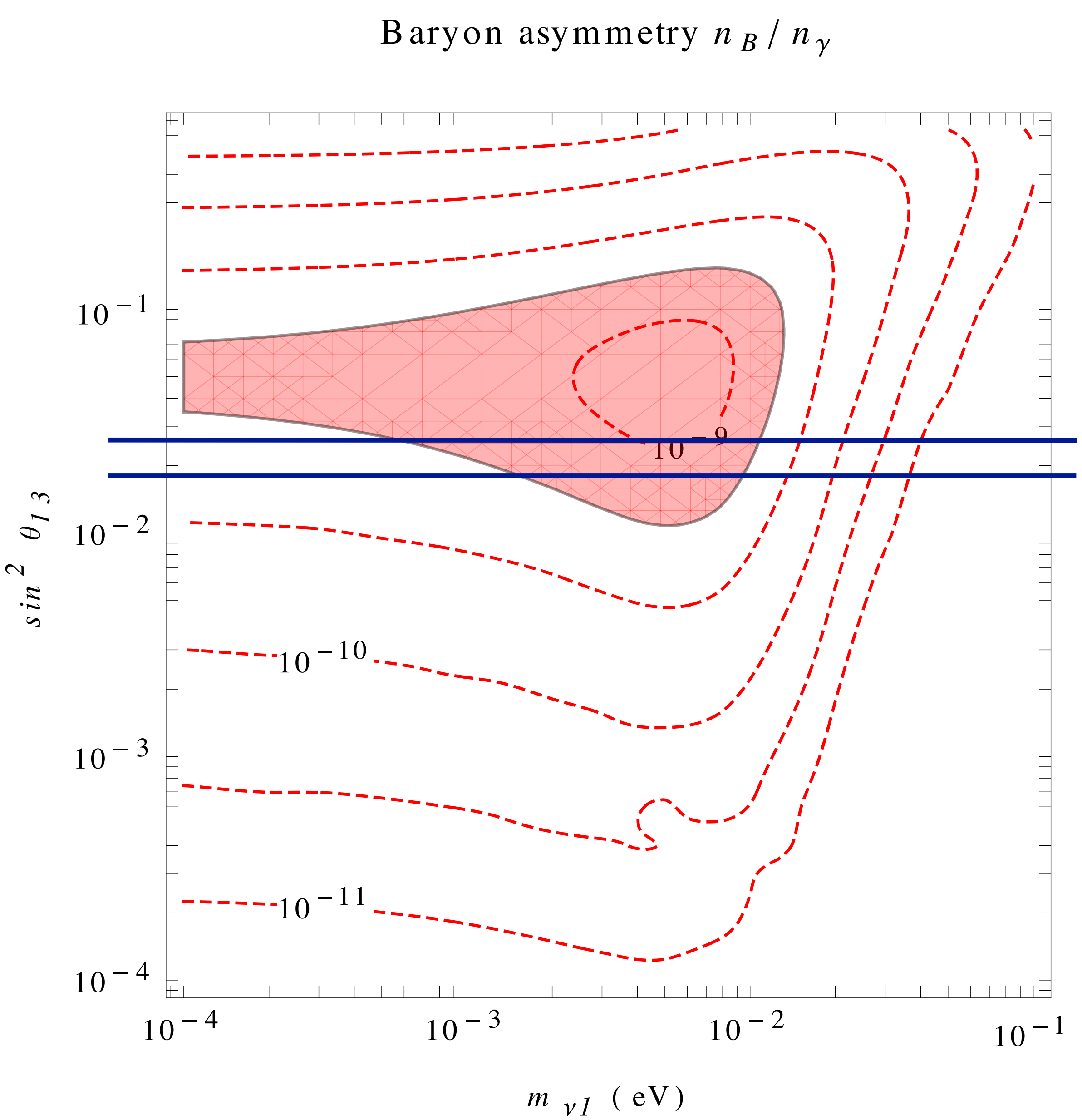
$\lambda_H = 0.2$

→ excludes a quasi-degenerate spectrum

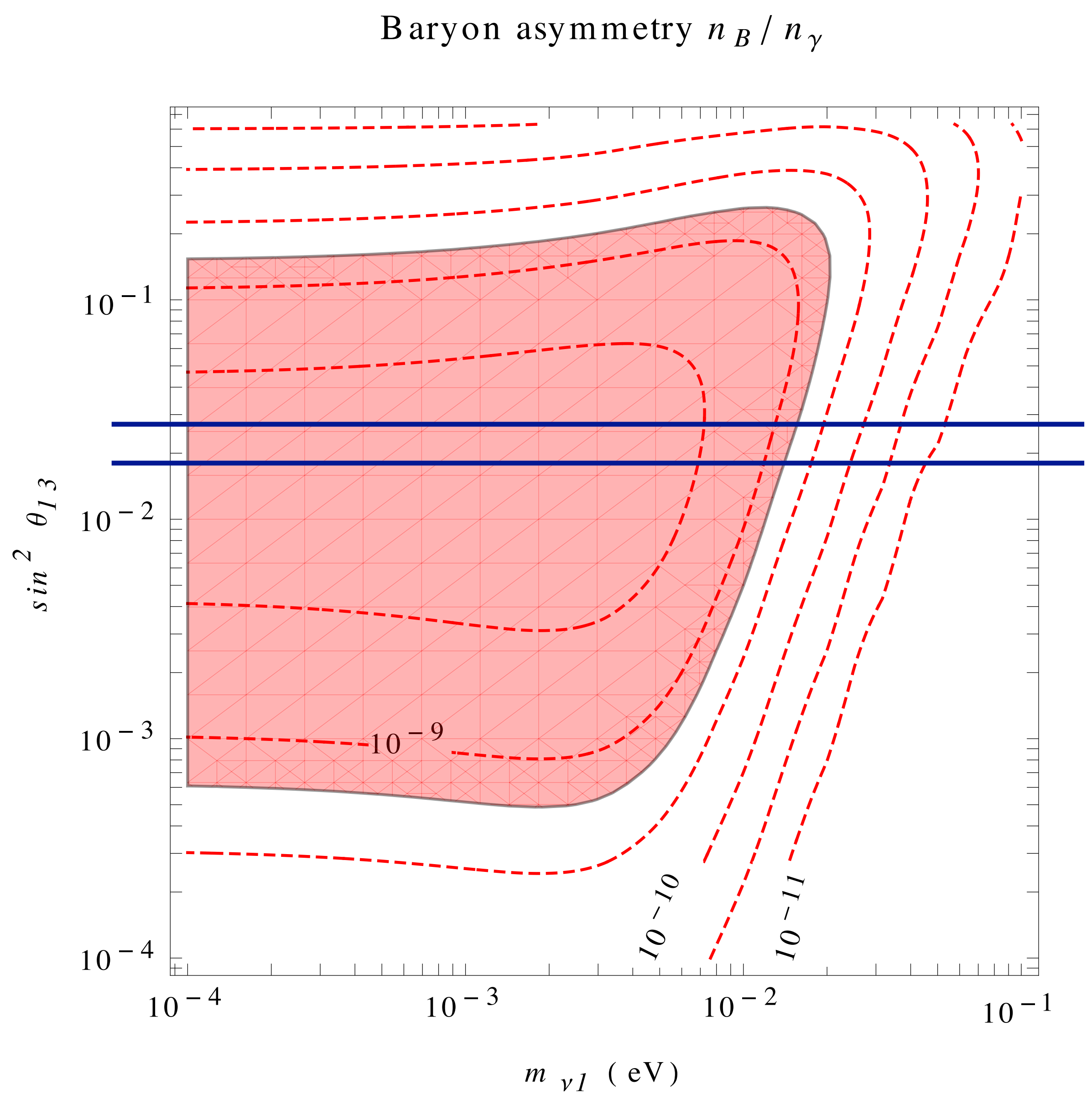
[SL, Schmauch]

θ13 dependence

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



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

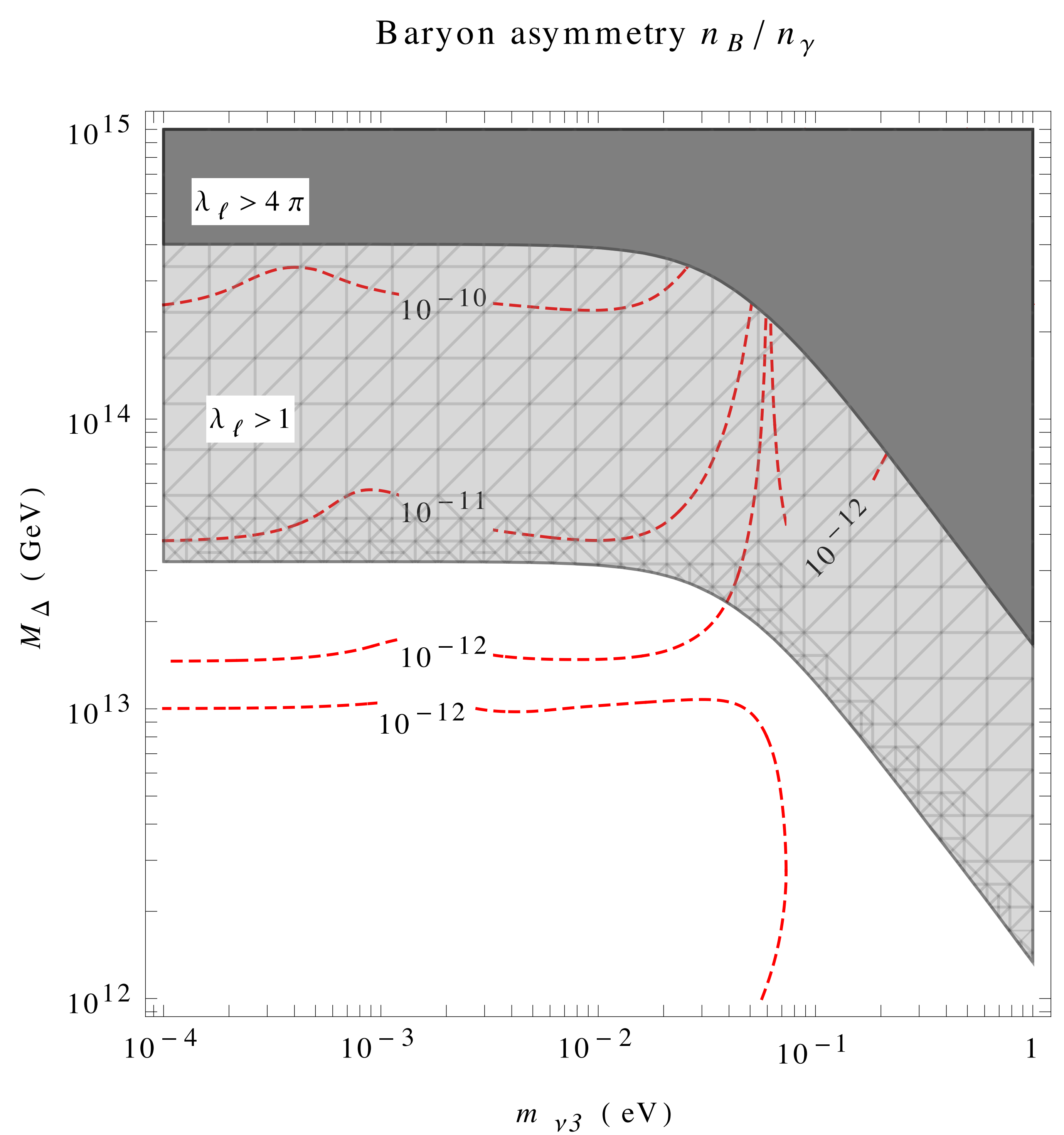


(3σ range)

$\lambda_H = 0.2$

[SL, Schmauch]

Inverted hierarchy case



$\lambda_H = 0.2$

→ inverted hierarchy disfavoured

[SL, Schmauch]

Leptogenesis from sterile neutrino oscillations

Thermal leptogenesis does not work for GeV-scale sterile neutrinos (they would decay after sphaleron freeze-out), but their CP-violating oscillations can produce a lepton asymmetry above the electroweak phase transition (ARS mechanism) [Akhmedov, Rubakov, Smirnov '98]

This is how the baryon asymmetry of the Universe is produced in the νMSM, where N_1 is a keV sterile neutrino that constitutes dark matter, while N_2 and N_3 have GeV-scale masses [Asaka, Shaposhnikov '05]

However, large lepton asymmetries are needed to resonantly produce N_1
Can be due to N_2 and N_3 decays after sphaleron freeze-out [Canetti et al. '12] , but requires extreme fine-tuning:

$$\frac{\Delta M}{M} = \frac{M_3 - M_2}{(M_2 + M_3)/2} \lesssim 10^{-11}$$

Canetti et al. '12
Ghiglieri, Laine '20

(other parameters must also be precisely tuned)

In addition, as a warm dark matter candidate, N_1 is strongly constrained by structure formation [Baur et al. '17]

Key points of the ARS mechanism

Out-of-equilibrium condition: due to their small couplings to the SM leptons, GeV-scale sterile neutrinos typically do not reach thermal equilibrium before sphaleron freeze-out ⇒ « freeze-in leptogenesis »

$\Gamma(T) \sim y^2 T$ sterile neutrino production rate, with $m_\nu \sim y^2 v^2 / M$

$$\Rightarrow \quad \frac{\Gamma(T)}{H(T)} \sim \left(\frac{m_\nu}{0.05\,\mathrm{eV}}\right)\left(\frac{M}{10\,\mathrm{GeV}}\right)\left(\frac{100\,\mathrm{GeV}}{T}\right)$$

The CP-violating oscillations of sterile neutrinos generate asymmetries in the different sterile neutrino flavours (neutrinos and antineutrinos oscillate with different probabilities), which are transferred to the active sector by the SM leptons / sterile neutrino interactions. Eventually net lepton asymmetries develop in the active and in the sterile sectors (which sum up to zero if lepton number violating processes are negligible)

Sphalerons convert part of the SM lepton asymmetry into a baryon asymmetry, which is frozen below the electroweak phase transition (even if the lepton asymmetry continues to evolve)

The price of minimality: fine-tuning in the νMSM [Ghiglieri, Laine '20]

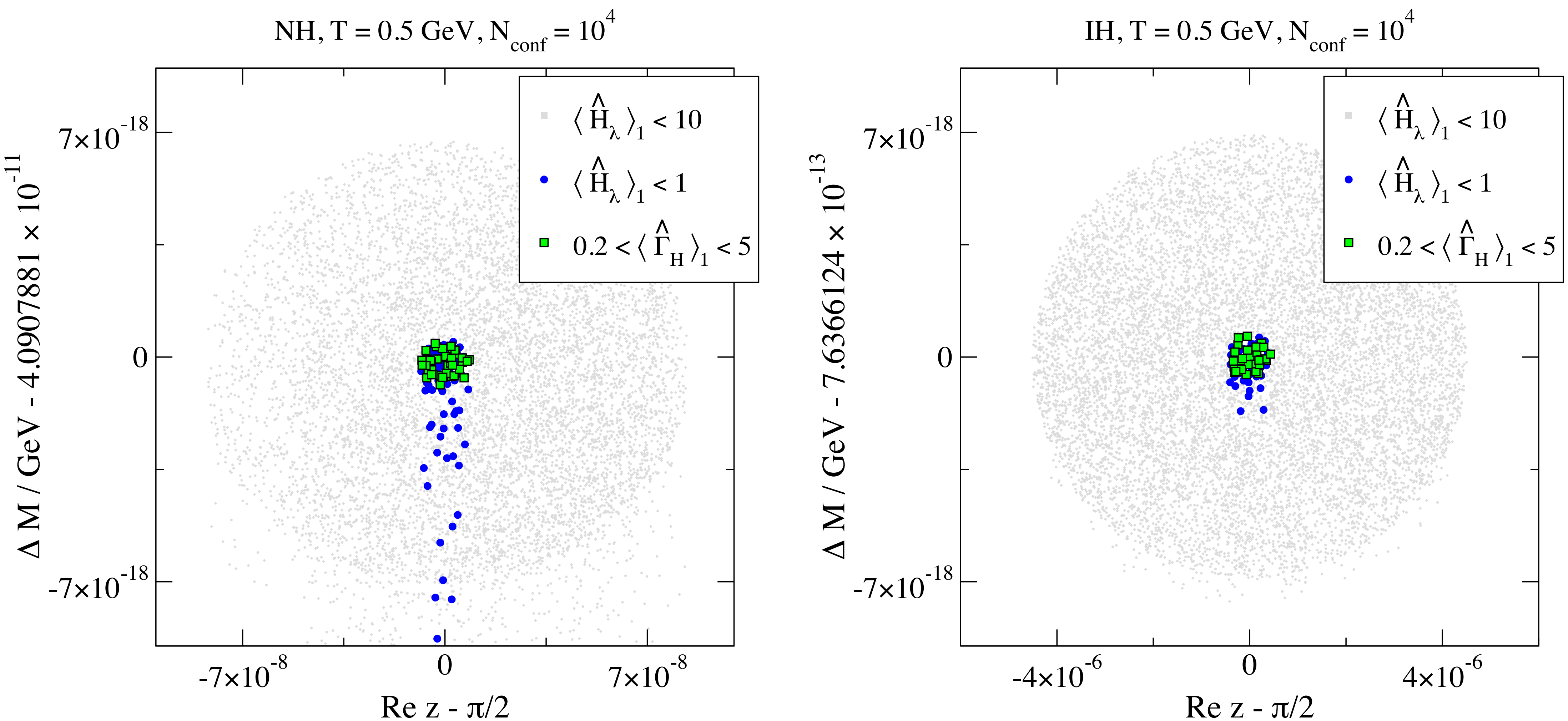
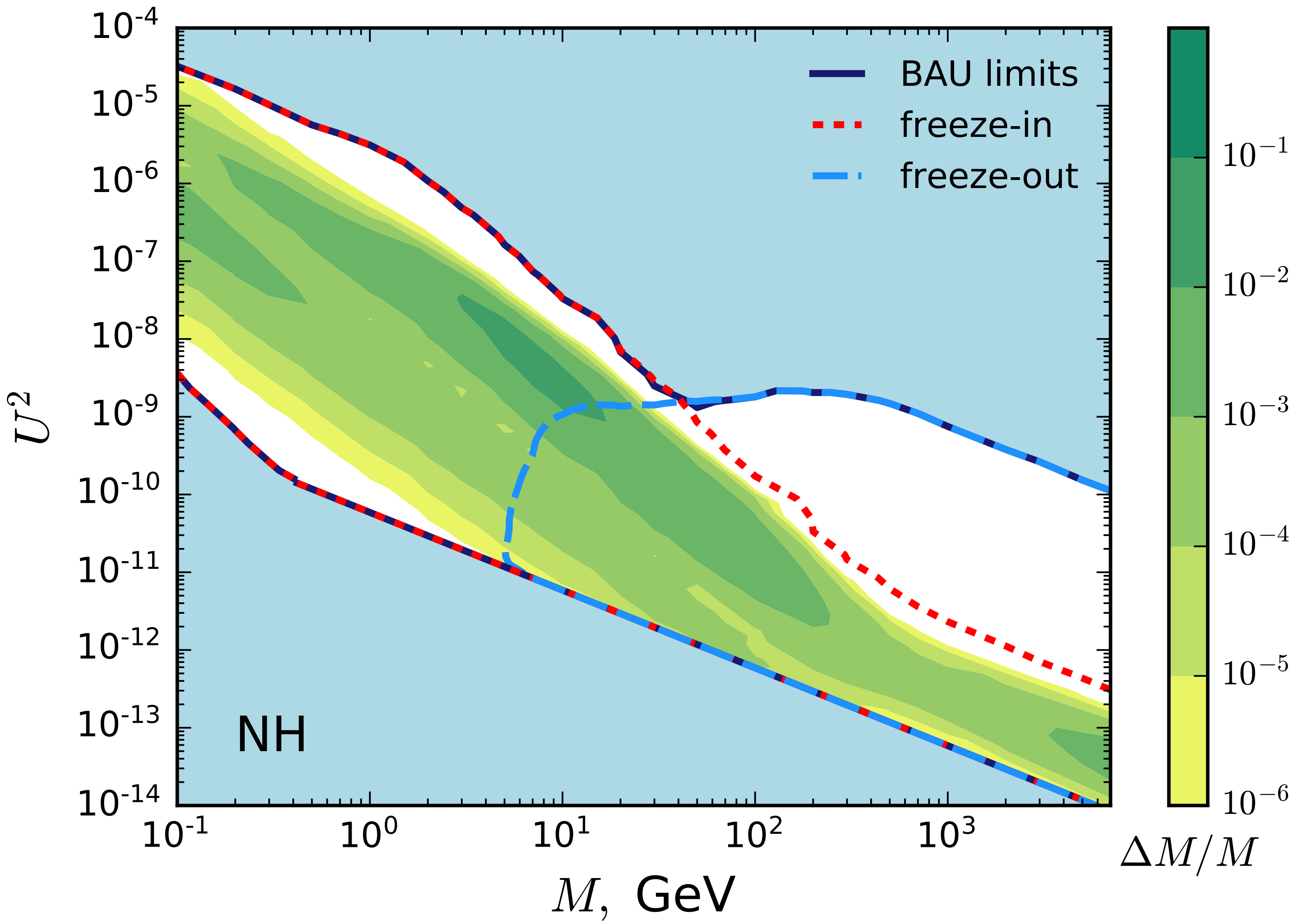


Figure 2: Points satisfying the increasingly stringent constraints indicated by the legend (cf. sec. 4.1), in the plane of $\mathrm{Re}\, z$ and ΔM (left: normal hierarchy, right: inverted hierarchy). The narrow axis ranges illustrate the extraordinary degree of fine-tuning that is needed for realizing the desired scenario.

Not only is $\Delta M/M$ very small, but its value (as well as the value of other parameters) must be adjusted with a precision of order 10^{-6}

If do not require N1 to constitute the dark matter, the strong fine-tuning of the νMSM is relaxed [Antusch et al. '17]

Under suitable conditions on the sterile neutrino couplings, ARS leptogenesis is even possible for M as large as 100 TeV [Klaric, Shaposhnikov, Timiryasov '21]

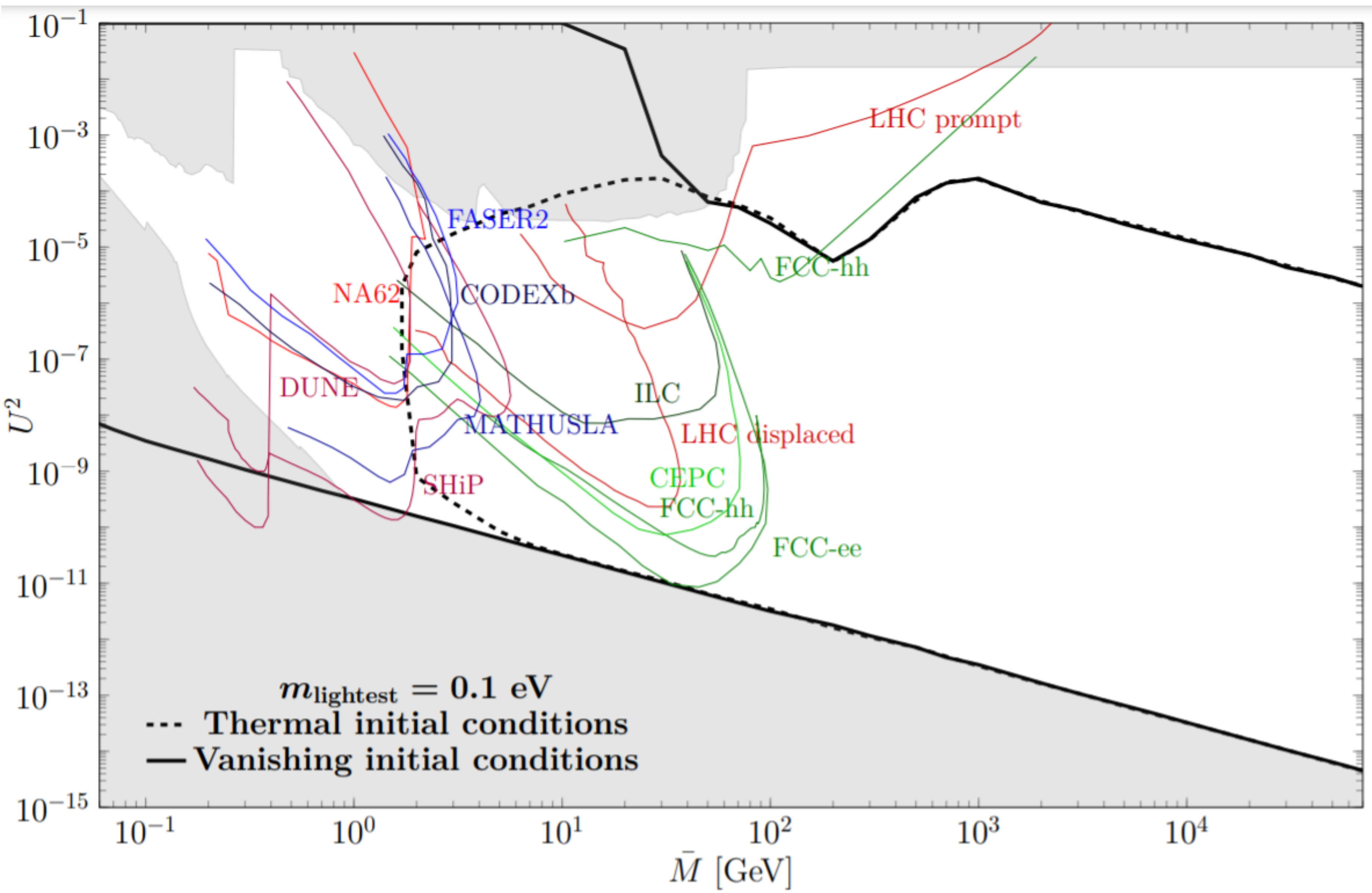


Large values of the active-sterile neutrino mixing U arise when some tuning is present in the sterile neutrino couplings (can be justified by symmetries)

If the 3 sterile neutrinos contribute to the baryon asymmetry of the Universe, only a mild tuning of their masses is required [Abada et al. '18]

Successful leptogenesis is possible for values of the sterile neutrino masses and of their mixing angles with the active neutrinos that can be probed in particle physics experiments

[Drewes, Georis, Klaric '21]



Conclusions

The observed baryon asymmetry of the Universe requires new physics beyond the Standard Model. Leptogenesis, which relates neutrino masses to the baryon asymmetry, is a very interesting possibility

Although difficult to test, leptogenesis would gain support from:

- observation of neutrinoless double beta decay: $(A,Z) \to (A,Z+2)\, e^- e^-$ [proof of the Majorana nature of neutrinos - necessary condition]
- observation of CP violation in the lepton sector, e.g. in neutrino oscillations [neither necessary nor sufficient]
- non-observation of other light scalars (which are present in many non-standard electroweak baryogenesis scenarios) than the Higgs boson at high-energy colliders; strong constraints on additional CP violation (e.g. on the electron EDM)

Scenarios involving sterile neutrinos in the 100 MeV - 1 TeV range (resonant and ARS leptogenesis) may be directly probed in particle physics experiments (at least part of their parameter space)