Leptogenesis

- the necessity of a dynamical generation mechanism for the baryon asymmetry of the Universe
- the failure of baryogenesis in the Standard Model
- a link with neutrino masses: baryogenesis via leptogenesis
- leptogenesis from out-of-equilibrium decays of heavy neutrinos
- leptogenesis from heavy neutrino oscillations (ARS leptogenesis)

The observational evidence

The matter-antimatter asymmetry of the Universe is measured by the baryon-to-photon ratio:

$$\eta \equiv \frac{n_B}{n_\gamma} \simeq \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

2 independent determinations:

(i) light element abundances

(ii) anisotropies of the cosmic microwave background (CMB)

⇒ remarkable agreement between the two:

$$\eta = (5.8 - 6.6) \times 10^{-10} \qquad \text{(BBN)}$$

$$\eta = (6.13 \pm 0.08) \times 10^{-10} \qquad \text{(Planck 2018)}$$

Although this number might seem small, it is actually very large:

in a baryon-antibaryon symmetric Universe, annihilations would leave a relic abundance $n_B/n_\gamma = n_{\bar{B}}/n_\gamma \approx 5 \times 10^{-19}$

The necessity of a dynamical generation

In a baryon-antibaryon symmetric Universe, annihilations would leave a relic abundance $n_B/n_\gamma = n_{\bar{B}}/n_\gamma \approx 5 \times 10^{-19}$

Since at high temperatures $n_q \sim n_{\bar{q}} \sim n_\gamma$, one would need to fine-tune the initial conditions in order to obtain the observed baryon asymmetry as a result of a small primordial excess of quarks over antiquarks:

$$\frac{n_q - n_{\bar{q}}}{n_q} \approx 3 \times 10^{-8}$$

Furthermore, there is convincing evidence that our Universe underwent a phase of inflation, which exponentially diluted the initial conditions

$\Rightarrow$ need a mechanism to dynamically generate the baryon asymmetry

Baryogenesis!

Conditions for baryogenesis

Sakharov's conditions [1967]:

(i) baryon number (B) violation

(ii) C and CP violation

(iii) departure from thermal equilibrium

Quite remarkably, the Standard Model (SM) of particle physics satisfies all three Sakharov's conditions:

(i) B is violated by non-perturbative processes known as sphalerons

(ii) C and CP are violated by SM interactions (CP violation due to quark mixing: phase of the Cabibbo-Kobayashi-Maskawa matrix, responsible for CP violation in kaon decays)

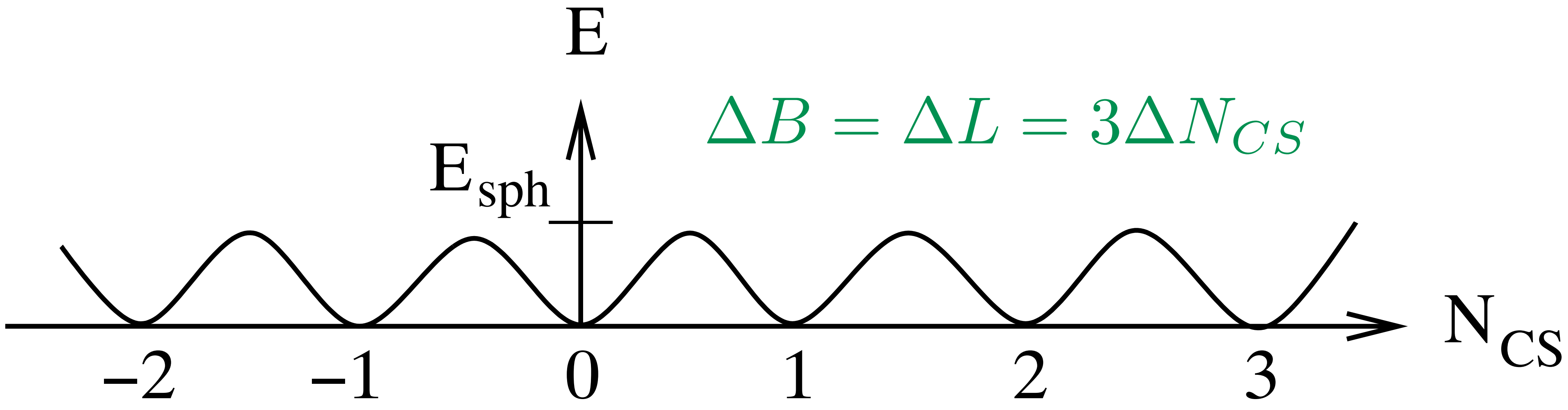
(iii) departure from thermal equilibrium can occur during the electroweak phase transition, during which particles acquire their masses

→ ingredients of electroweak baryogenesis

Baryon number violation in the Standard Model

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

However, B+L is violated at the quantum level ⇒ non-perturbative processes (sphalerons) change the values of B and L [but preserve B-L]



$$\Delta B = \Delta L = 3\Delta N_{CS}$$

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

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

[Kuzmin, Rubakov, Shaposhnikov]

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

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

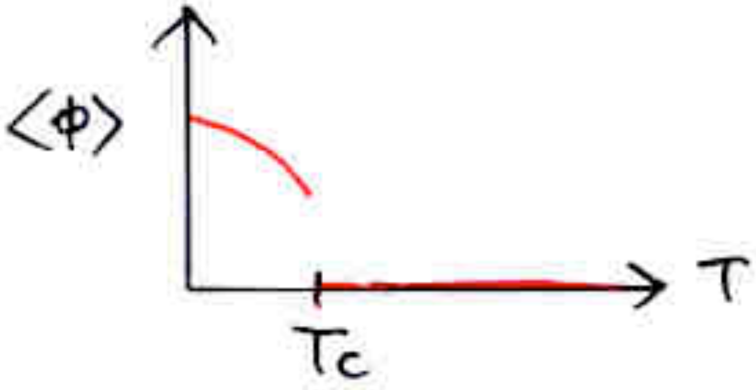
[Arnold, McLerran – Khlebnikov, Shaposhnikov]

Baryogenesis in the Standard Model: rise and fall of electroweak baryogenesis

The order parameter of the electroweak phase transition is the Higgs vev:

- $T > T_{EW}, \langle \phi \rangle = 0$ unbroken phase
- $T < T_{EW}, \langle \phi \rangle \neq 0$ broken phase

If the phase transition is first order, the two phases coexist at $T = T_c$ and the phase transition proceeds via bubble nucleation



[Cohen, Kaplan, Nelson]

Sphalerons are in equilibrium outside the bubbles, and out of equilibrium inside the bubbles (rate exponentially suppressed by $E_{sph}(T) / T$)

CP-violating interactions in the wall together with unsuppressed sphalerons outside the bubble generate a B asymmetry which diffuses into the bubble

For the mechanism to work, it is crucial that sphalerons are suppressed inside the bubbles (otherwise will erase the generated B+L asymmetry)

$$\Gamma(T < T_{EW}) \ \propto \ e^{-E_{sph}(T)/T} \quad \text{with} \quad E_{sph}(T) \ \approx \ (8\pi/g)\,\langle\phi(T)\rangle$$

The out-of-equilibrium condition is

$$\frac{\langle\phi(T_c)\rangle}{T_c} \gtrsim 1$$

⇒ strongly first order phase transition required

To determine whether this is indeed the case, need to study the 1-loop effective potential at finite temperature. The out-of-equilibrium condition $\Phi(T_c)/T_c > 1$ then translates into:

$m_H \lesssim 40\,\mathrm{GeV}$ condition for a strong first order transition

⇒ <u>excluded by LEP</u>

also not enough CP violation [small Jarlskog invariant] [Gavela, Hernandez, Orloff, Pene]

→ standard electroweak baryogenesis fails: the observed baryon asymmetry requires new physics beyond the Standard Model

The observed baryon asymmetry requires new physics beyond the SM

⇒ 2 approaches:

1) modify the dynamics of the electroweak phase transition [+ new source of CP violation needed] by adding new scalar fields coupling to the Higgs (2 Higgs doublet model, additional Higgs singlet…)

2) generate a B-L asymmetry at $T > T_{EW}$ (sphaleron processes violate baryon [B] and lepton [L] numbers, but preserve the combination B-L)

Leptogenesis (the generation of a lepton asymmetry in out-of-equilibrium decays or oscillations of heavy states, which is partially converted into a B asymmetry by sphaleron processes) belongs to the second class

Intestingly, the existence of such heavy states is also suggested by neutrino oscillations, which require neutrinos to be massive

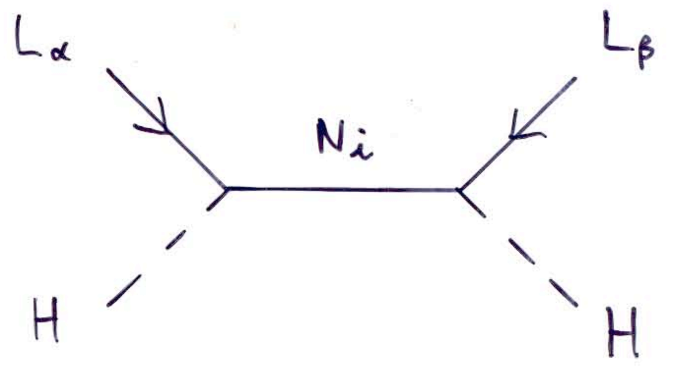
A link with neutrino masses: Baryogenesis via leptogenesis

The observation of neutrino oscillations from different sources (solar, atmospheric and accelerator/reactor neutrinos) has led to a well-established picture in which neutrinos have tiny masses and there is flavour mixing in the lepton sector (PMNS matrix), as in the quark sector

The tiny neutrino masses can be interpreted in terms of a high scale:

$$m_\nu = \frac{v_{EW}^2}{M} \qquad M \sim 10^{14}\,\mathrm{GeV}$$

Several mechanisms can realize this mass suppression. The most popular one (type I seesaw mechanism) involves heavy Majorana neutrinos:

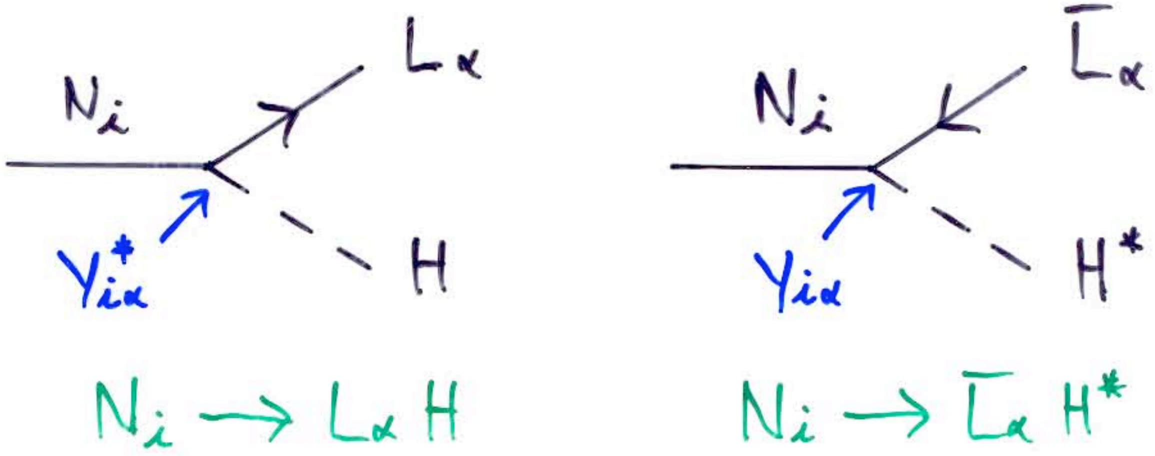


$$\Longrightarrow \qquad m_\nu \sim \frac{y^2 v^2}{M_R}$$

Minkowski - Gell-Mann, Ramond, Slansky
Yanagida - Mohapatra, Senjanovic

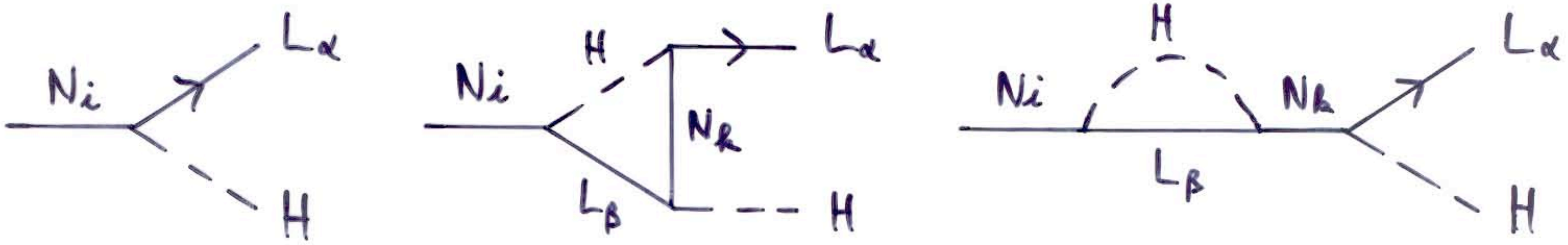
Interestingly, this mechanism contains all required ingredient for baryogenesis: out-of-equilibrium decays of the heavy Majorana neutrinos can generate a lepton asymmetry (L violation replaces B violation and is due to the Majorana neutrinos) if their couplings to SM leptons violate CP

CP violation: being Majorana, the heavy neutrinos are CP-conjugated and can decay both into l^+ and into l^-



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

The decay rates into l^+ and into l^- differ due to quantum corrections



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

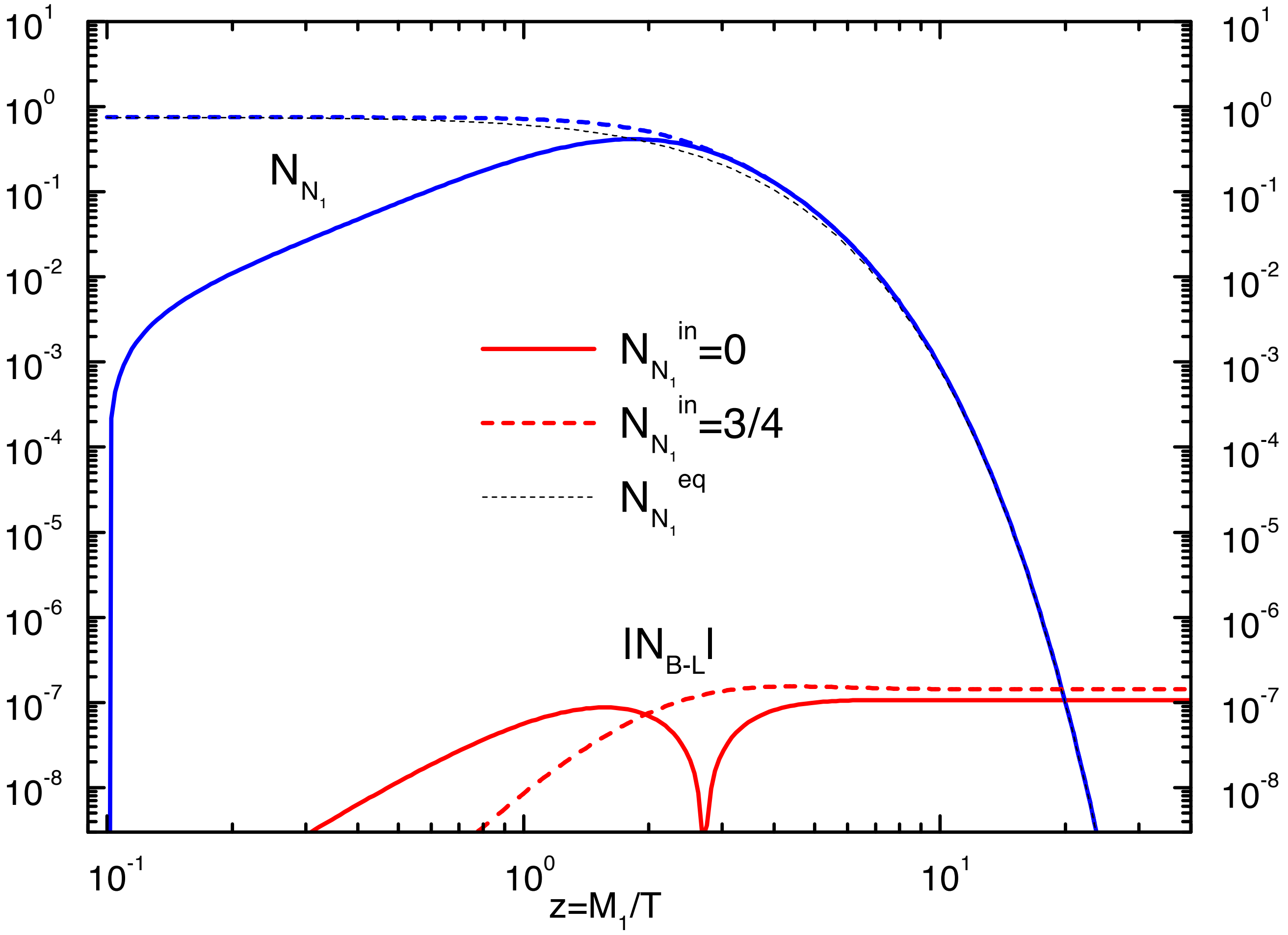
Covi, Roulet, Vissani '96
Buchmüller, Plümacher '98

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:



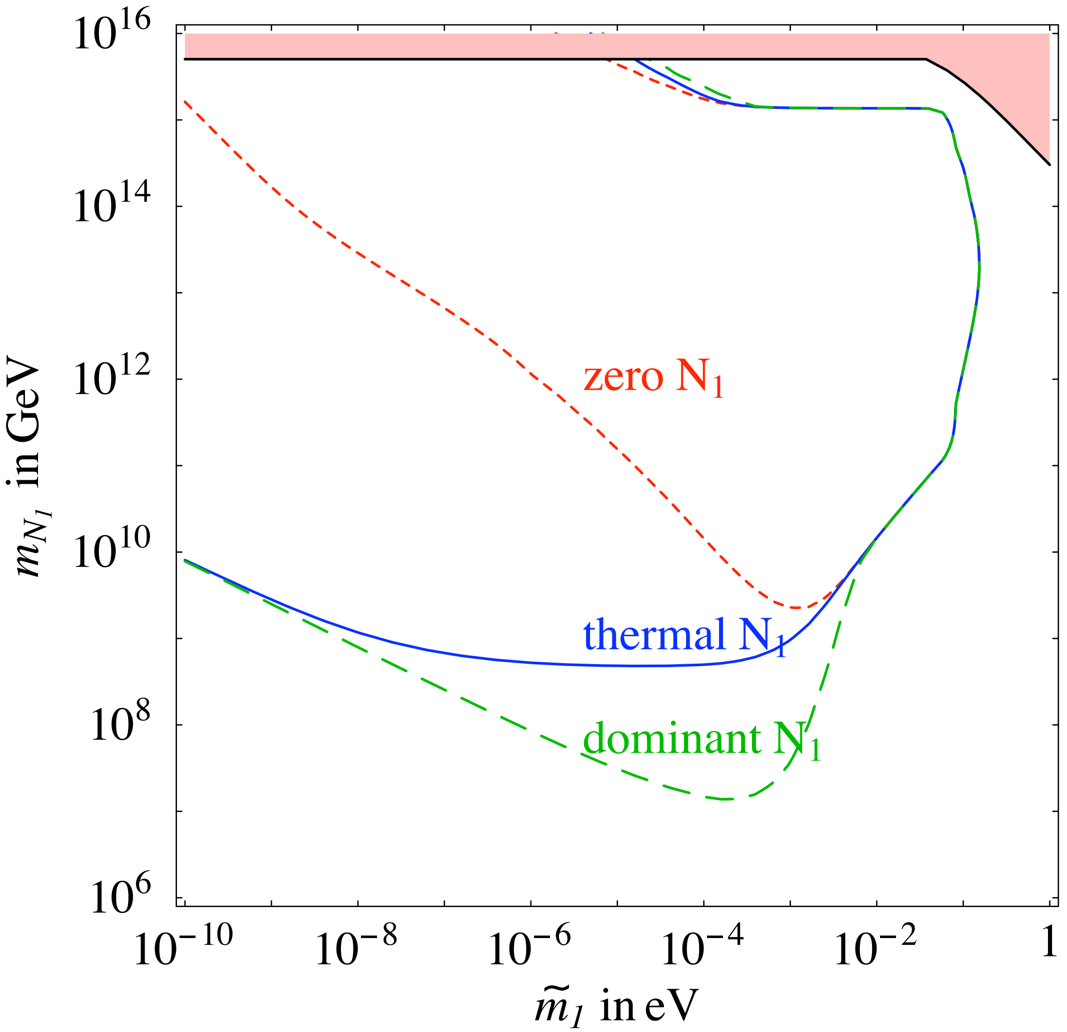
[Buchmüller, Di Bari, Plümacher ’02]

Thermal leptogenesis can explain the observed baryon asymmetry

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]

$M_1 \ll 10^9\,\mathrm{GeV}$ possible for $M_1 \simeq M_2$ (“resonant leptogenesis”)

[Covi, Roulet, Vissani - Pilaftsis]

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

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

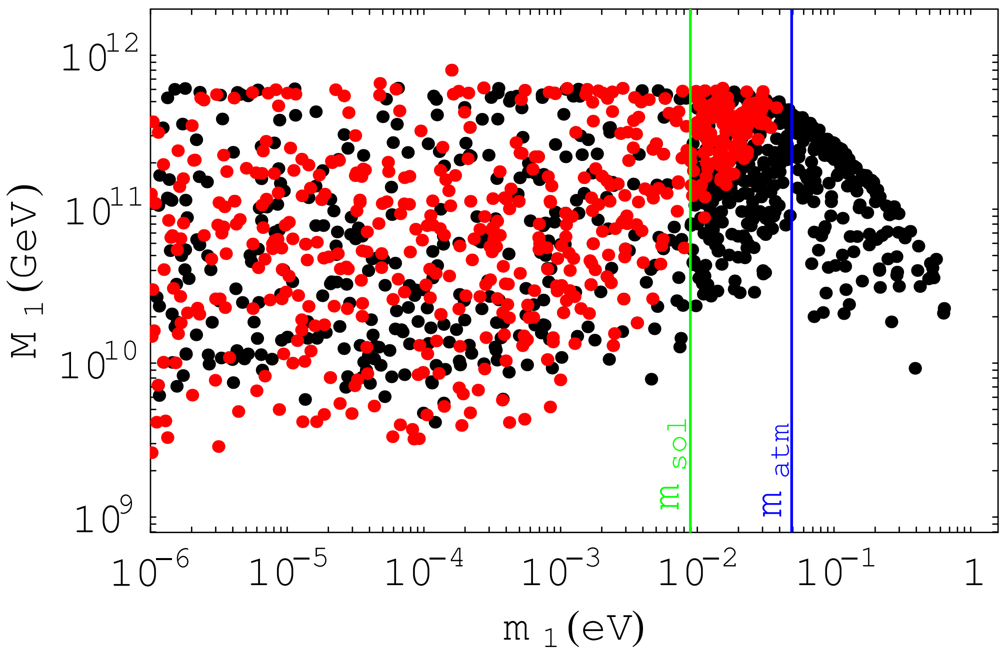
This is valid as long as the charged lepton Yukawas λα are out of equilibrium

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

At $T \lesssim 10^{9}\,\mathrm{GeV}$, λτ and λμ are in equilibrium ⇒ must distinguish ℓ_e, ℓ_μ and ℓ_τ

→ depending on the temperature regime, must solve Boltzmann equations for 1, 2 or 3 lepton flavours

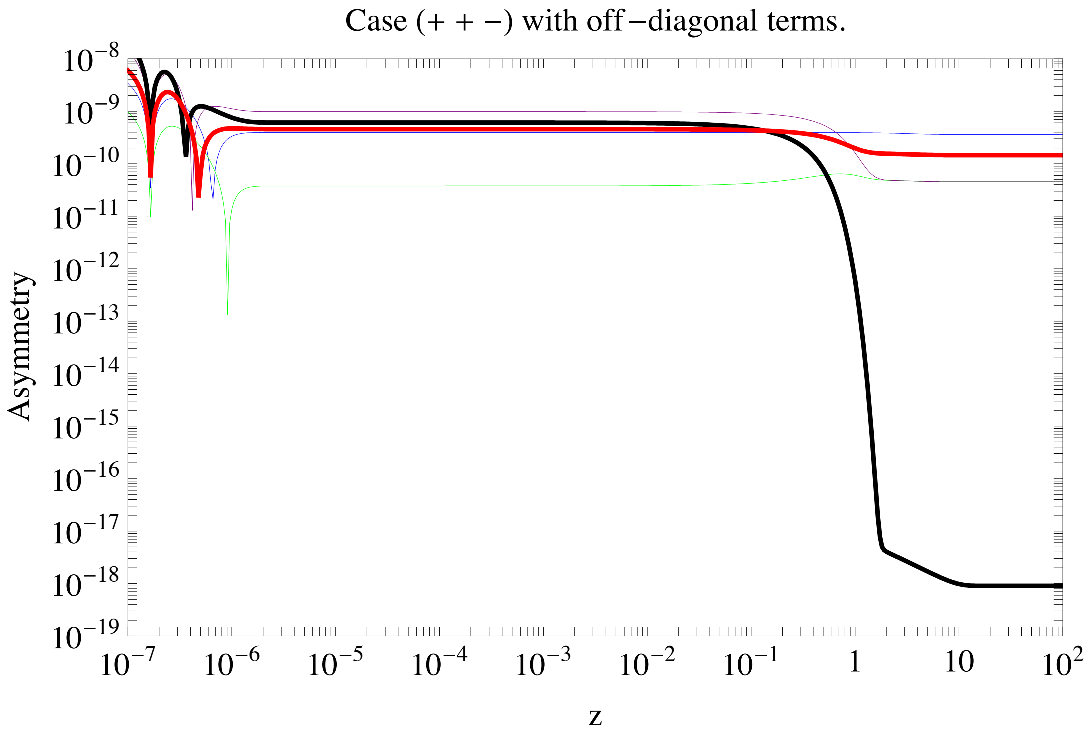
Flavour effects lead to quantitatively different results from the 1FA



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]



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

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

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

$$z = M_1/T$$

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

leptogenesis in the 1FA : $\epsilon_{N_1} \propto \sum_k \mathrm{Im}\,[(YY^\dagger)_{k1}]^2\, M_1/M_k$ depends on the phases of $YY^\dagger$

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

→ 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

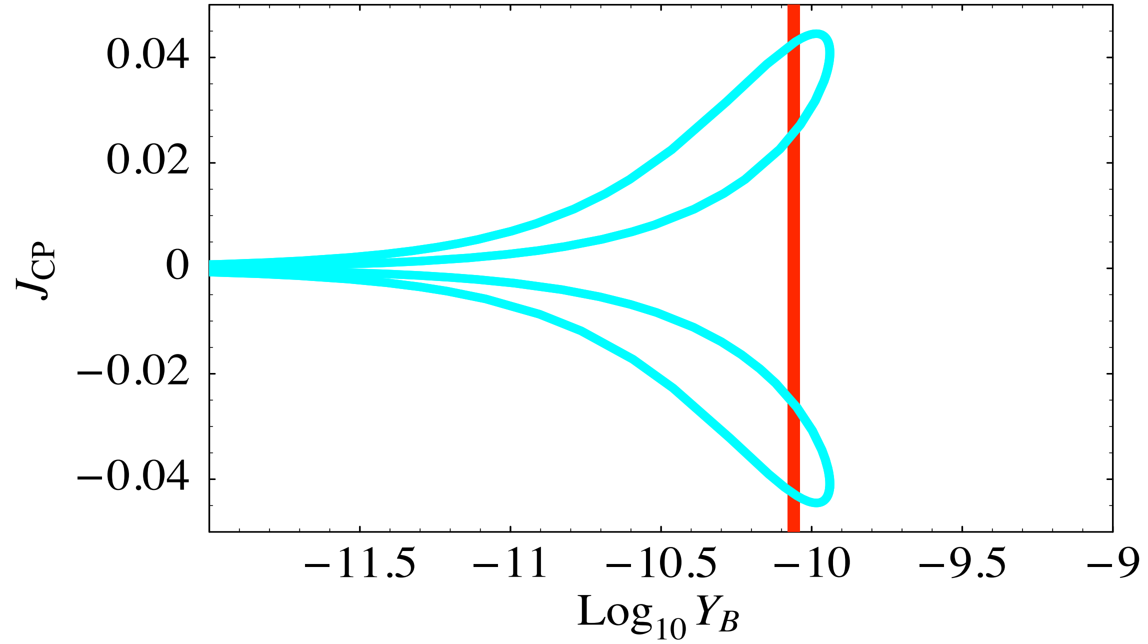
$$YY^\dagger = \begin{pmatrix} \sqrt{M_1} & 0 & 0 \\ 0 & \sqrt{M_2} & 0 \\ 0 & 0 & \sqrt{M_3} \end{pmatrix} R \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix} R^\dagger \begin{pmatrix} \sqrt{M_1} & 0 & 0 \\ 0 & \sqrt{M_2} & 0 \\ 0 & 0 & \sqrt{M_3} \end{pmatrix}$$

→ leptogenesis in the 1FA only depends on the phases of R = high-energy phases

$\Rightarrow$ 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

leptogenesis from the PMNS phase δ



[Pascoli, Petcov, Riotto '06]

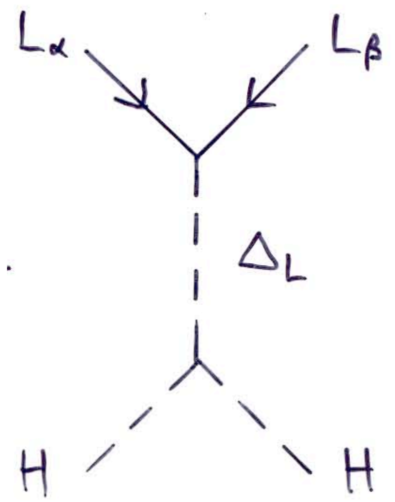
FIG. 1. The invariant $J_{\rm CP}$ versus the baryon asymmetry varying (in blue) $\delta = [0, 2\pi]$ in the case of hierarchical RH neutrinos and NH light neutrino mass spectrum for $s_{13} = 0.2$, $\alpha_{32} = 0$, $R_{12} = 0.86$, $R_{13} = 0.5$ and $M_1 = 5 \times 10^{11}$ GeV . The red region denotes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

→ the discovery of CP violation in oscillations would not test directly leptogenesis, but would give some support to it

→ similarly, the observation of neutrinoless double beta decay would prove that lepton number is violated, another necessary condition for leptogenesis

Scalar triplet leptogenesis

Alternative to heavy Majorana neutrinos: the SM neutrino masses may be generated by a heavy scalar (electroweak) triplet

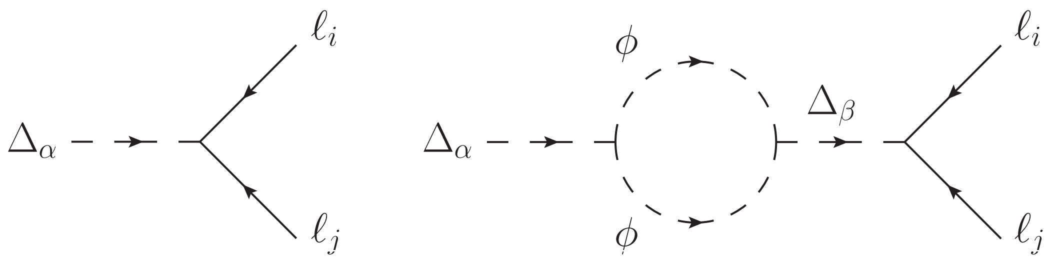


$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$ electroweak triplet

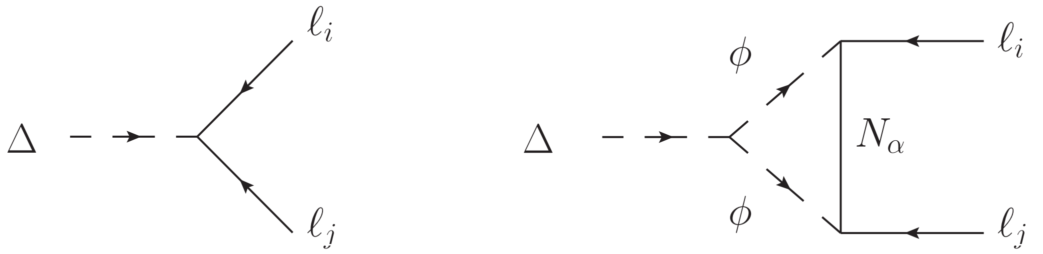
generates a neutrino mass $$m_\nu = \frac{\mu \lambda_\ell}{2 M_\Delta^2} v^2$$

Also leads to leptogenesis if another heavy state couples to leptons

$\Rightarrow$ CP asymmetry in triplet decays [Ma, Sarkar '98 - Hambye, Senjanovic '03]



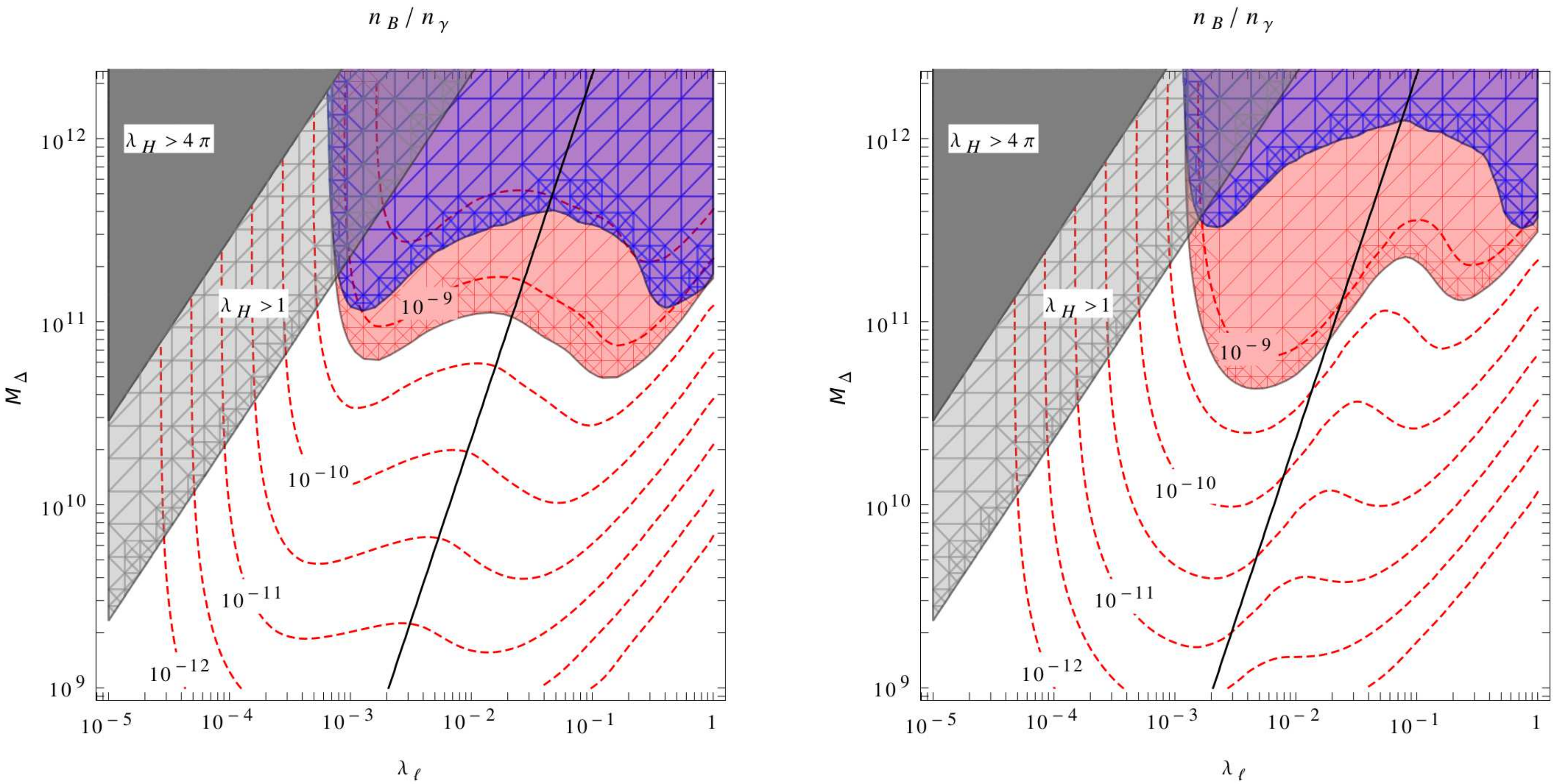
additional triplets



RH neutrinos

First quantitative study by Hambye, Raidal, Strumia '05 (without flavour effects)

Inclusion of flavour effects in scalar triplet leptogenesis


$m_\Delta = i m_\nu$

$m_{\Delta i} \neq m_{\nu_i}$

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.

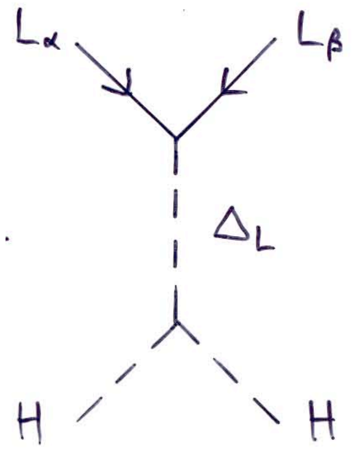
$$M_\Delta > 4.4 \times 10^{10}\,\mathrm{GeV} \qquad (1.2 \times 10^{11}\,\mathrm{GeV\ without\ flavour\ effects})$$

[SL, Schmauch ’15]

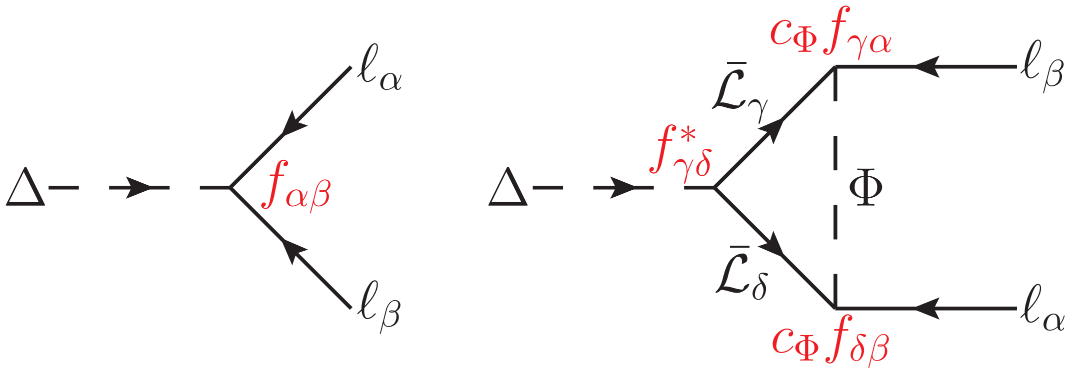
A predictive scheme for scalar triplet leptogenesis

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 (measurable) neutrino parameters

→ important difference with most leptogenesis scenarios

[Frigerio, Hosteins, SL, Romanino ’08]

Dependence on the light neutrino parameters

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

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

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

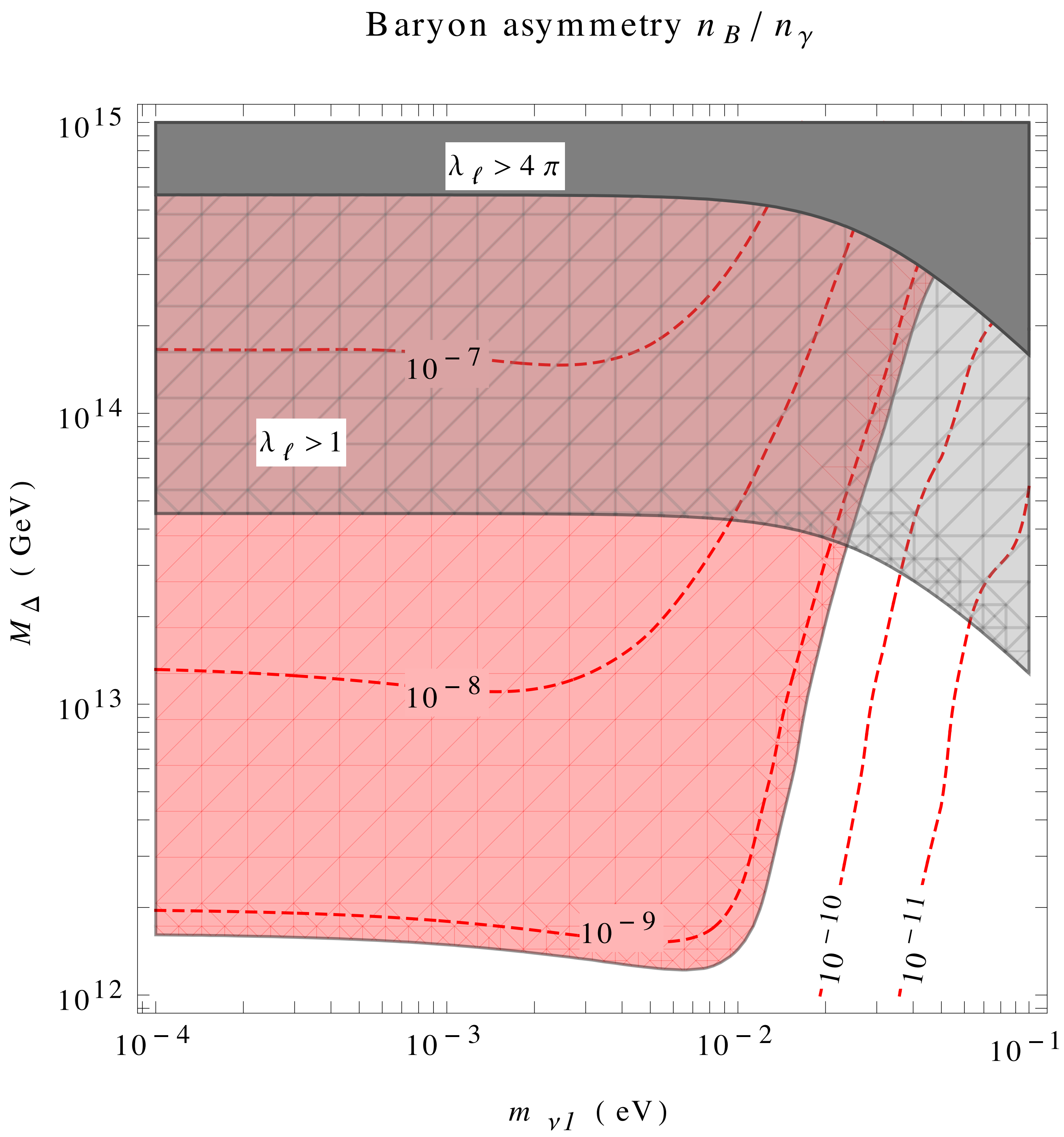
→ ϵ_Δ depends on measurable neutrino parameters

→ 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: normal hierarchy



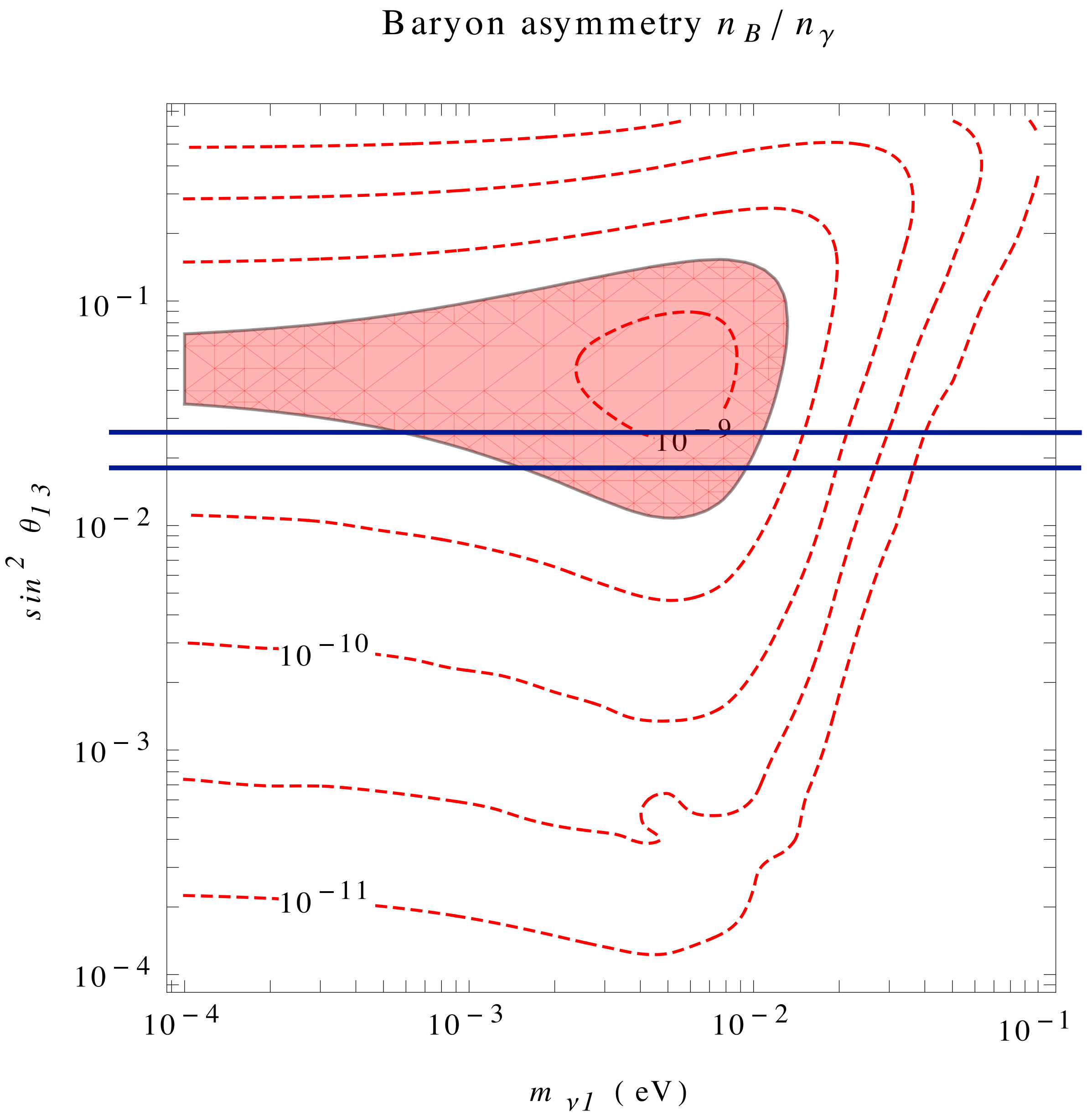
$\lambda_H = 0.2$

→ excludes a quasi-degenerate spectrum

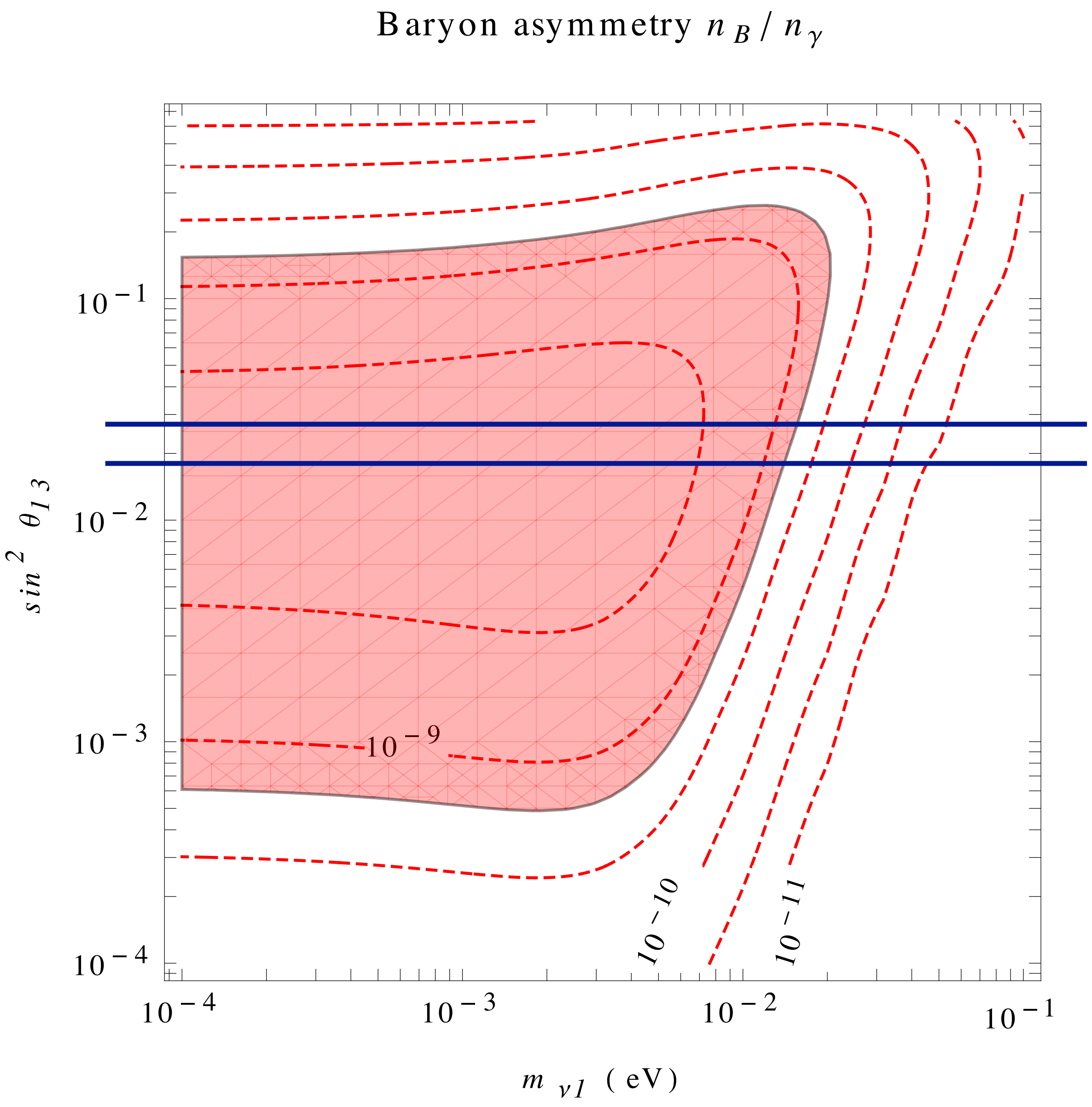
[SL, Schmauch]

θ_{13} dependence

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



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

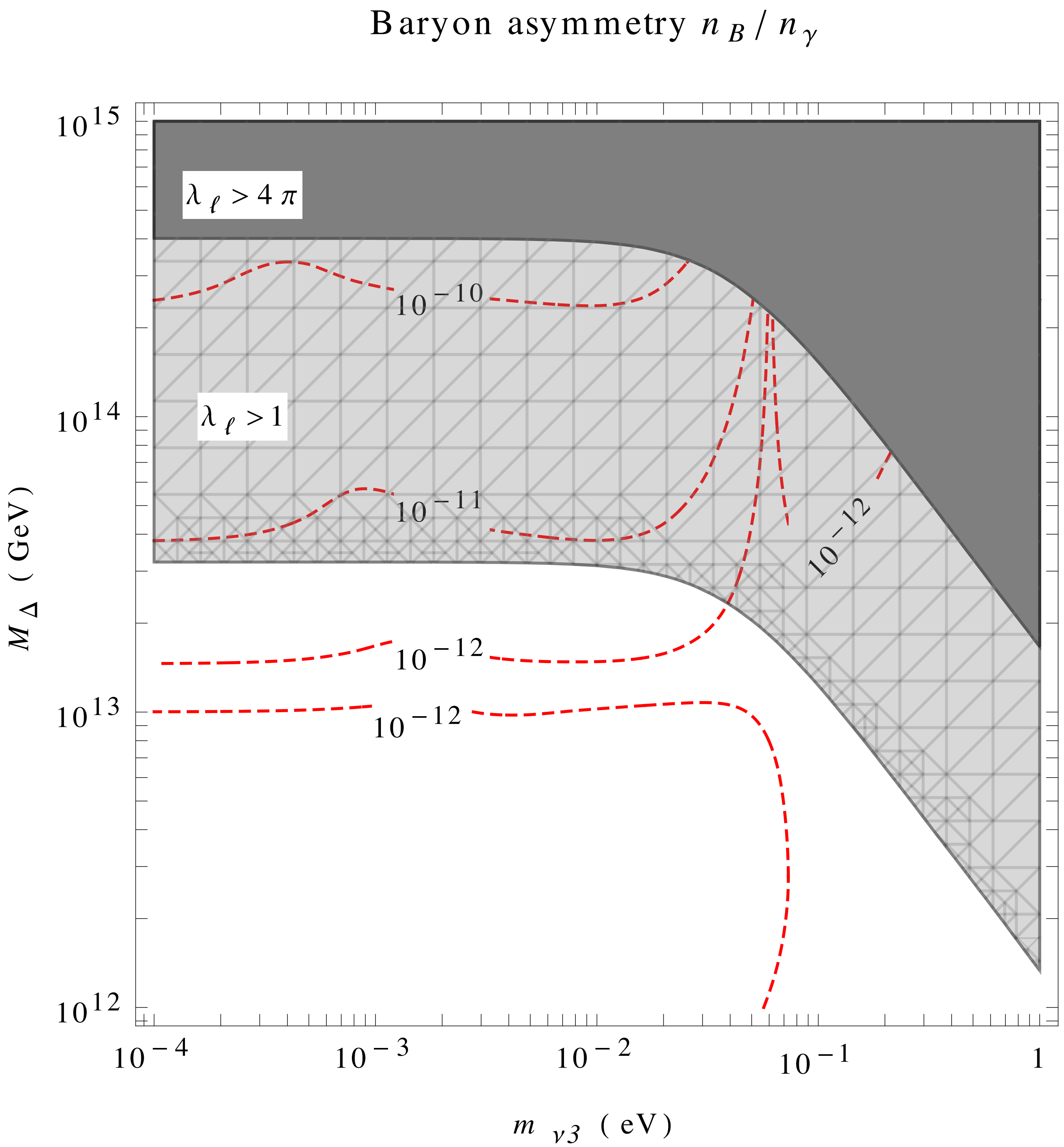


(3σ range)

$\lambda_H = 0.2$

[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 arise from 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]

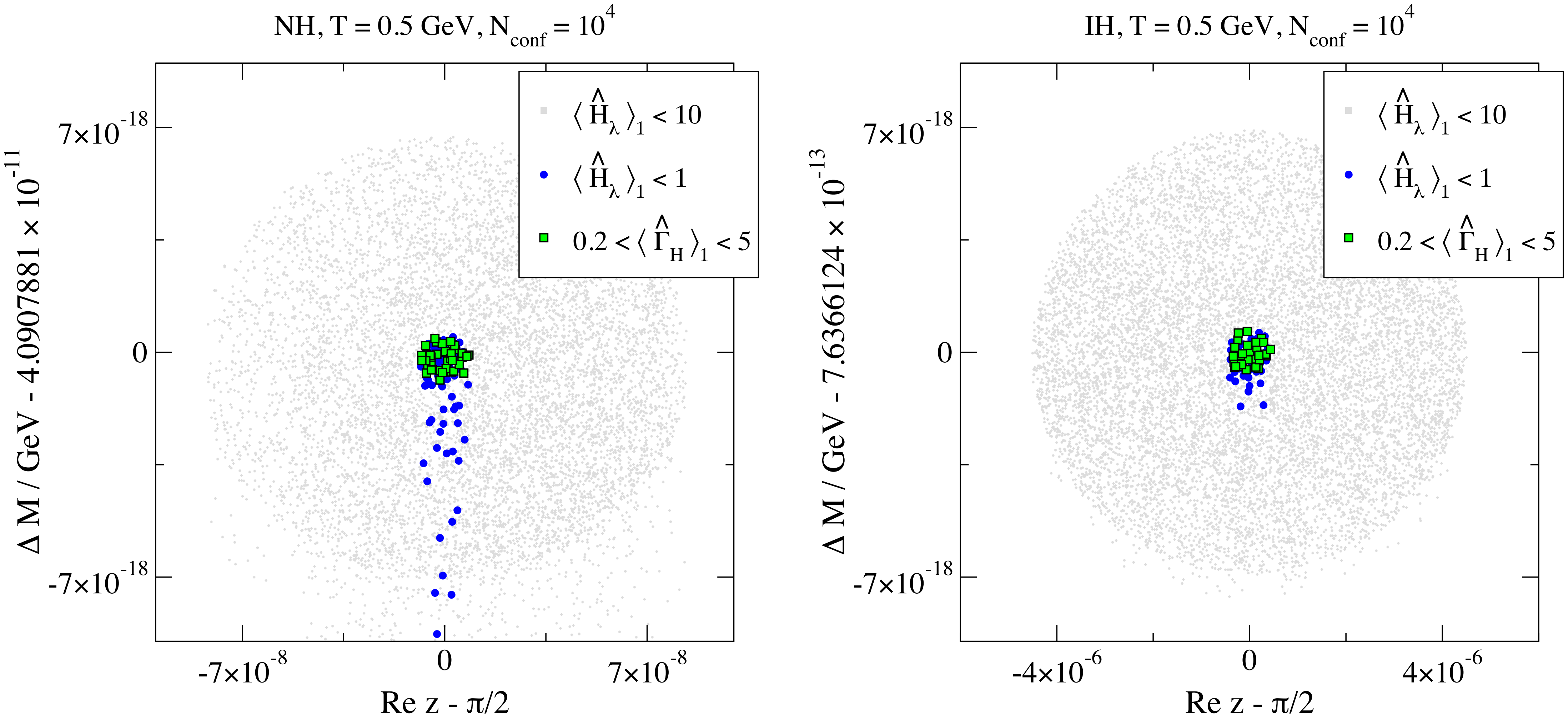
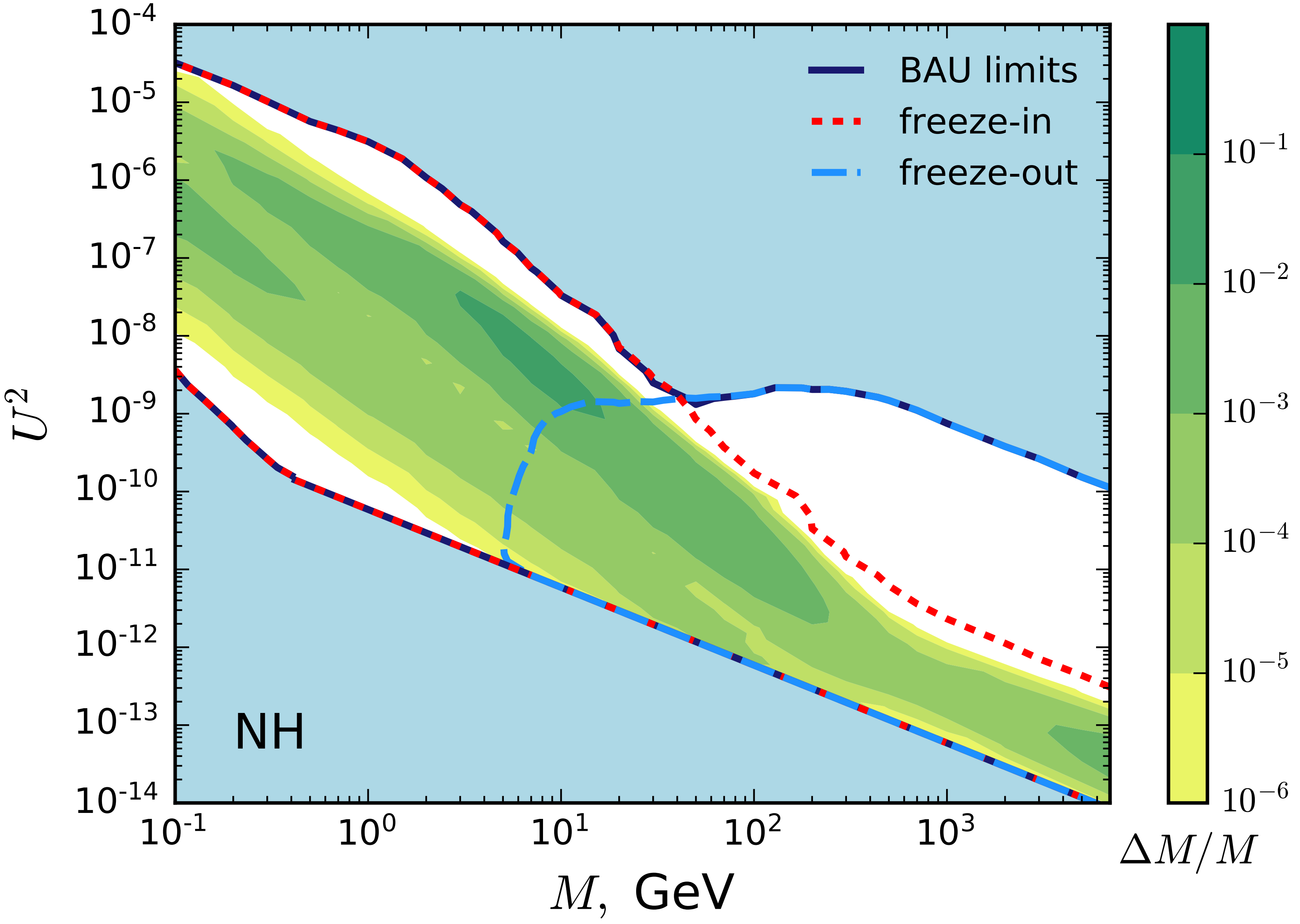


Figure 2: Points satisfying the increasingly stringent constraints indicated by the legend (cf. sec. 4.1), in the plane of Re z and ΔM (left: normal hierarchy, right: inverted hierarchy). The narrow axis ranges illustrate the extraordinary degree of fine-tuning that is needed for realizing the desired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

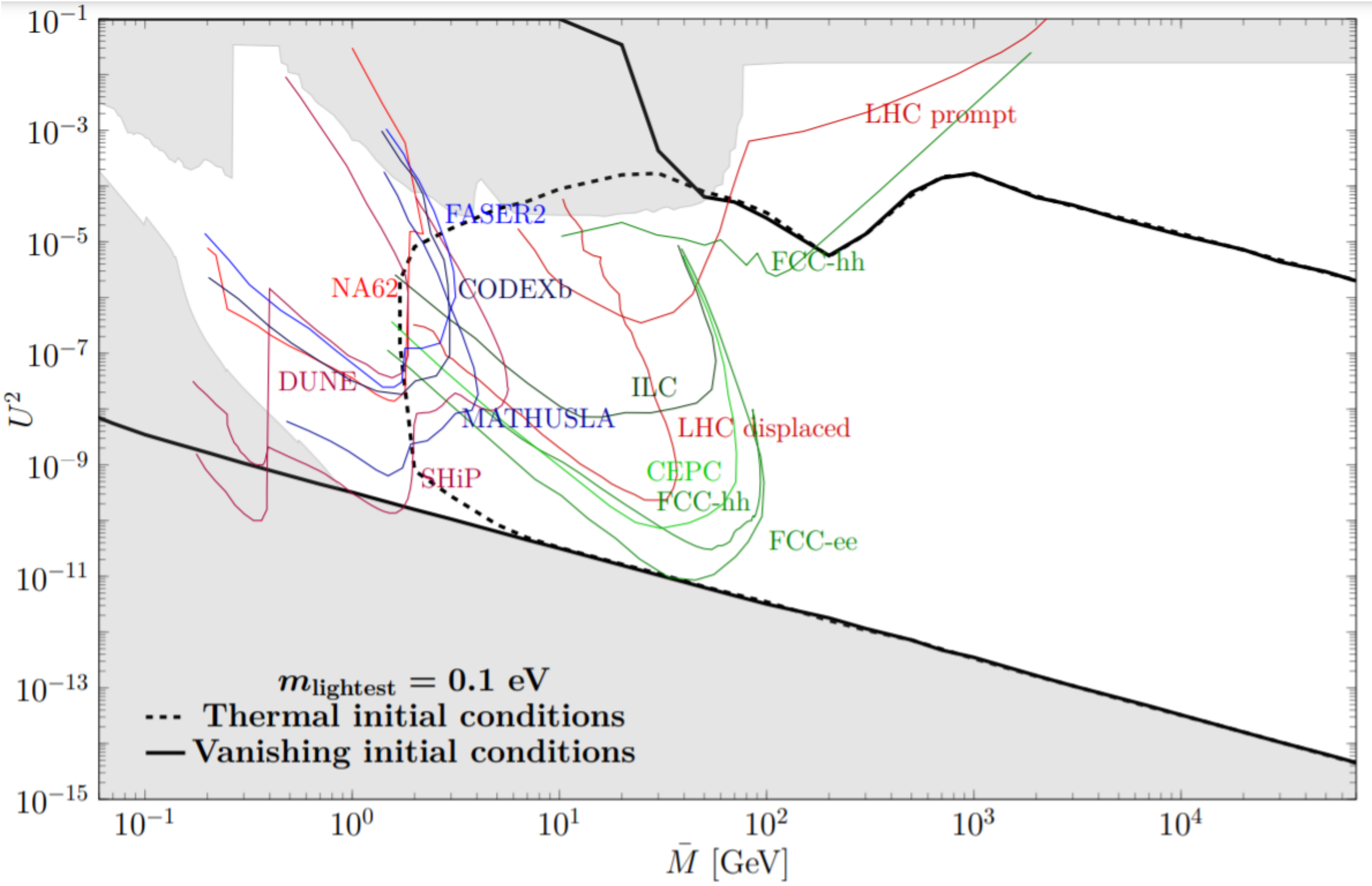


Large values of the active-sterile neutrino mixing U arise when some tuning is present in the sterile neutrino couplings (can be justified by symmetries)

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) → (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 the parameter space]