Neutrinos, CP violation and the matter-antimatter asymmetry of the Universe

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- the matter-antimatter asymmetry of the Universe and the necessity of a dynamical generation mechanism
- the failure of baryogenesis in the Standard Model
- a link with neutrino masses: baryogenesis via leptogenesis
- is leptogenesis related to CP violation at low energy?
- other leptogenesis scenarios : scalar triplet leptogenesis, leptogenesis from sterile neutrino oscillations (ARS)

Institut de Physique des 2 Infinis de Lyon – 11 mai 2023

Introduction

The origin of the matter-antimatter asymmetry of the Universe is one of the big mysteries of particle physics and cosmology

There are very solid reasons to believe that it should be generated by some dynamical mechanism (baryogenesis). While the Standard Model of particle physics contains all the ingredients of baryogenesis, it fails to generate the observed asymmetry

An attractive possibility, known as leptogenesis, is that neutrino masses and the matter-antimatter asymmetry of the Universe share a common origin

Leptogenesis requires CP violation: is it related to the CP violation searched for in long-baseline neutrino oscillation experiments?

More generally, can one probe/support leptogenesis with neutrino/particle physics experiments?

The observational evidence

How do we know that there is (almost) no antimatter in the Universe?

Mere observation: the structures we observe in the Universe are made of matter (p, n, e-). No significant presence of antimatter (anti-p, anti-n, e+):

* solar system: no presence of antimatter

* milky way: $\bar{p}/p \approx 10^{-4}$ in cosmic rays - fully understood in terms of

$$p\,(\mathrm{primary\,CR}) + p\,(\mathrm{interstellar\,gas}) \to 3p + \bar{p}$$

* clusters of galaxies: would observe strong γ-ray emission from matter-antimatter annihilations, such as $p + \bar{p} \to \pi^0 + X \to \gamma\gamma + X$

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

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

Since the photon density is not preserved in the early Universe, one also considers:

$$Y_B \equiv \frac{n_B - n_{\bar{B}}}{s}$$

s = entropy density = 7.04 n_γ today

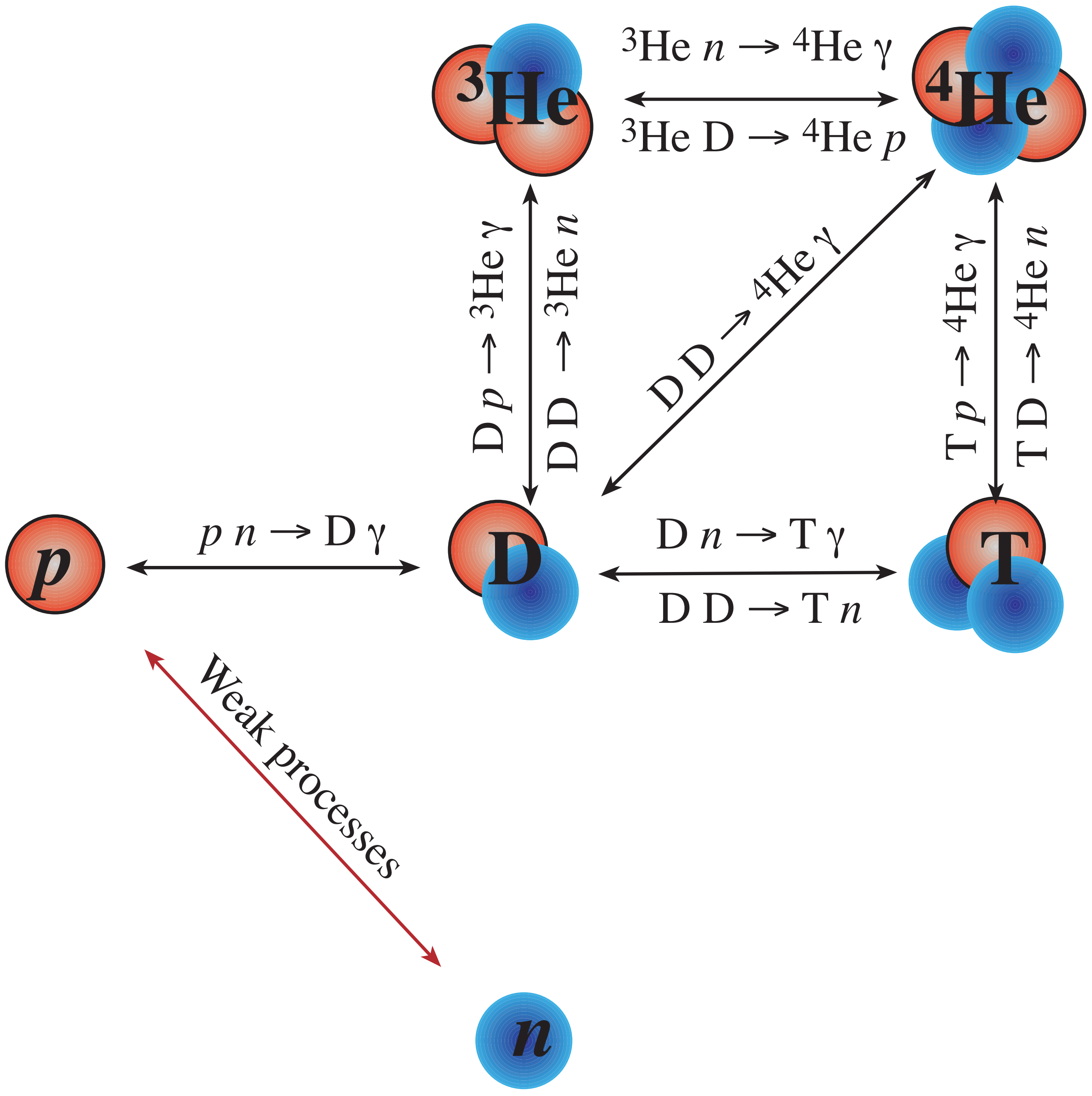
2 independent determinations of η:

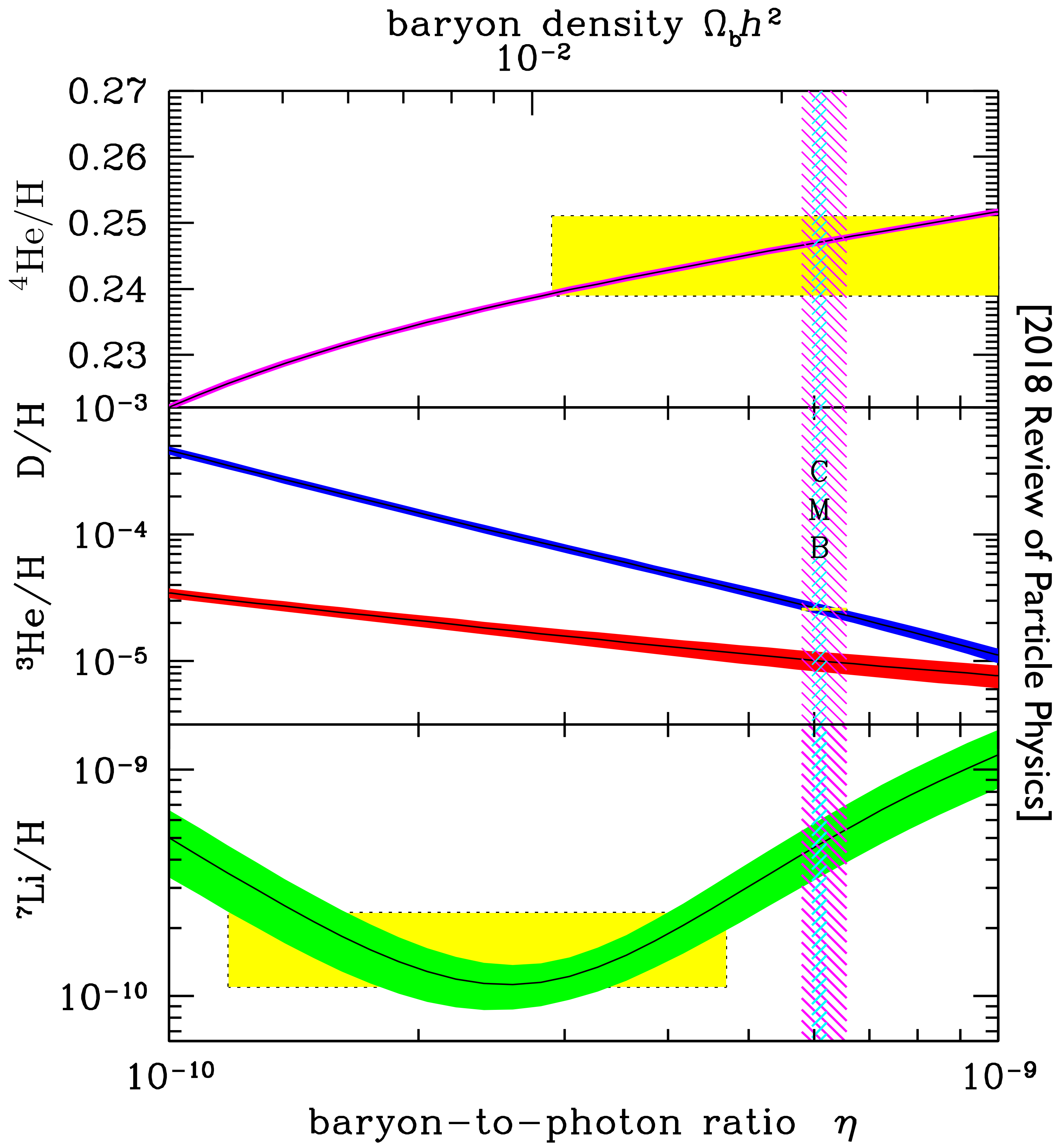
(i) light element abundances

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

Big Bang nucleosynthesis (BBN) predicts the abundances of the light elements (D, ^{3}He, ^{4}He and ^{7}Li) as a function of η:

The abundances of D and ^{3}He are very sensitive to η, since a larger η accelerates the synthesis of D and ^{3}He, which are themselves needed for the synthesis of ^{4}He, resulting in final lower abundances for D and ^{3}He



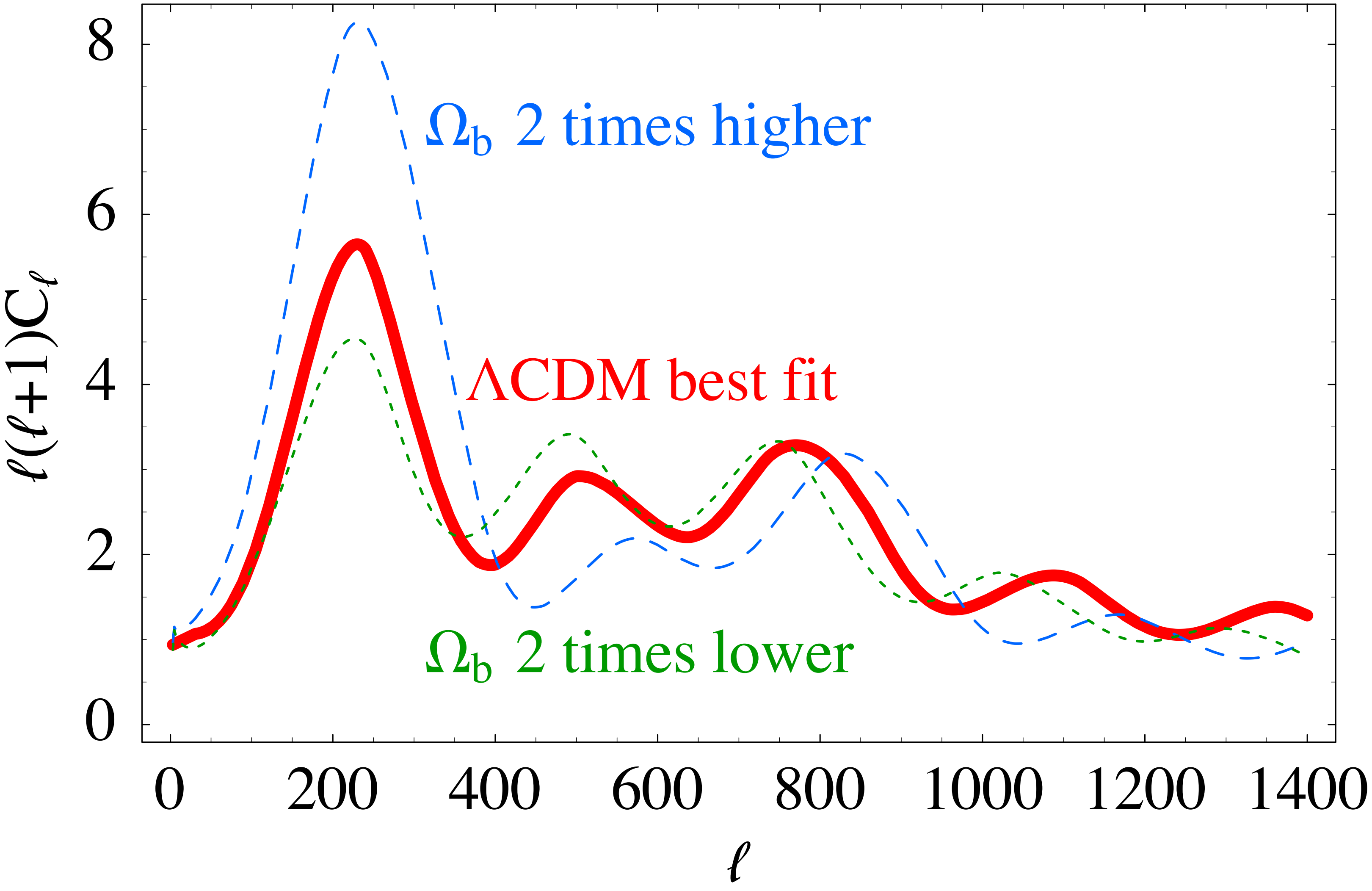


[2018 Review of Particle Physics]

There is a range of values for η consistent with all observed abundances ("concordance", up to a factor of 2 for Li)
→ major success of Big Bang cosmology

$$\eta = (5.8 - 6.6) \times 10^{-10}$$
$$\text{(95\% C.L.)}$$

- curves = BBN prediction (95% C.L.)
- boxes = observed abundances



A. Strumia, hep-ph/0608347

Information on the cosmological parameters can be extracted from the temperature anisotropies of the CMB

In particular, the anisotropies are affected by the oscillations of the baryon-photon plasma before recombination, which depend on η (or $\Omega_b h^2$)

$\Rightarrow \quad \eta = (6.13 \pm 0.08) \times 10^{-10}$ (Planck 2018, 95% C.L.)

$\Rightarrow$ remarkable agreement between the CMB and BBN determinations of the baryon asymmetry: another success of Big Bang cosmology

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

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

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

(i) is obvious

(ii) C and CP violation

C (charge conjugation) exchanges a particle with its antiparticle. If it were conserved, any processes creating n baryons would occur at the same rate as the C-conjugated process creating n antibaryons, resulting in a vanishing net baryon asymmetry

CP [C combined with a parity transformation, $(t, \vec{x}) \rightarrow (t, -\vec{x})$] also reverses the impulsion of the particle. If it were conserved, even with C violated, processes creating baryons and antibaryons would balance each other once integrated over phase space

(iii) departure from thermal equilibrium

At thermal equilibrium, any process creating baryons occurs at the same rate than the inverse process which destroys baryons, resulting in a vanishing net baryon asymmetry

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 and B meson decays)

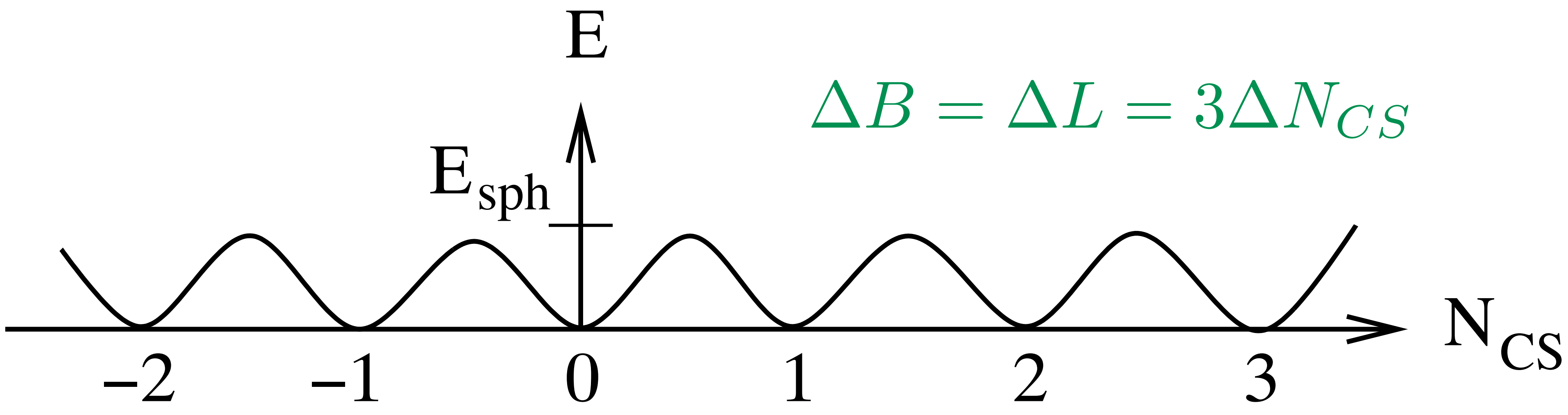
(iii) departure from thermal equilibrium can occur during the electroweak phase transition, during which particles acquire their masses

→ 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 $\Rightarrow$ all perturbative processes preserve B and L

However, B+L is anomalous $\Rightarrow$ non-perturbative transitions (“sphalerons”) between vacua of the electroweak theory characterized by different values of B+L (but B-L is conserved)



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

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

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

[Kuzmin, Rubakov, Shaposhnikov]

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

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

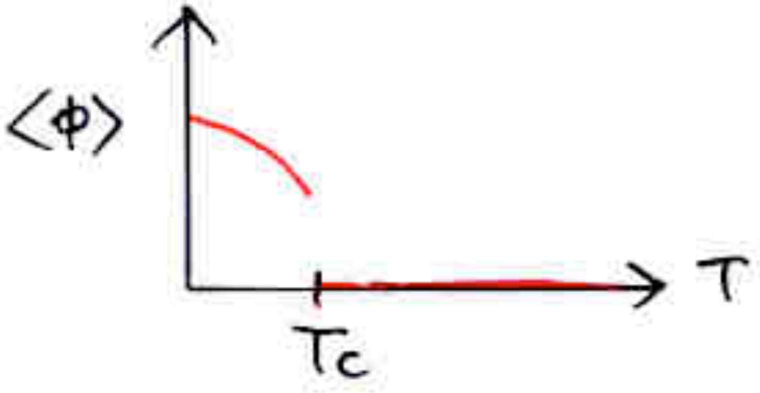
[Arnold, McLerran – Khlebnikov, Shaposhnikov]

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

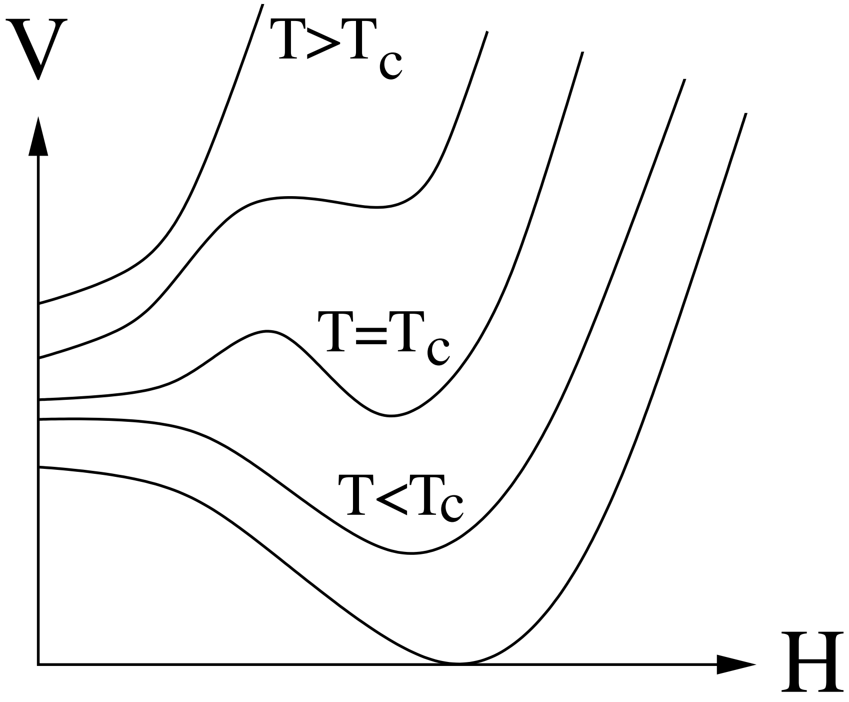
For the mechanism to work, it is crucial that sphalerons are suppressed inside the bubbles (otherwise will erase the generated B asymmetry)

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

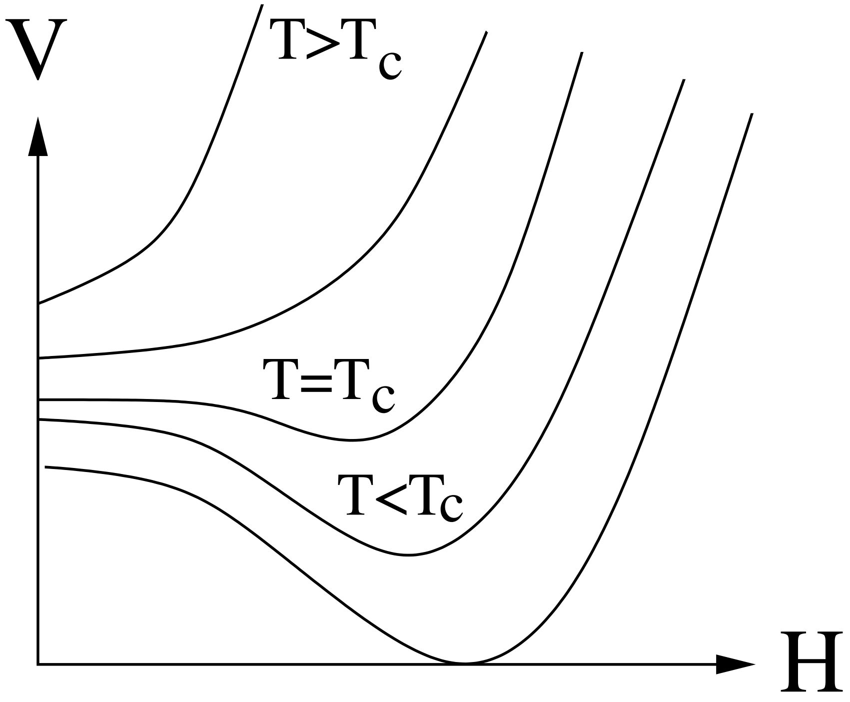
The out-of-equilibrium condition is $\dfrac{\langle\phi(T_c)\rangle}{T_c} \gtrsim 1$

$\Rightarrow$ 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



first order



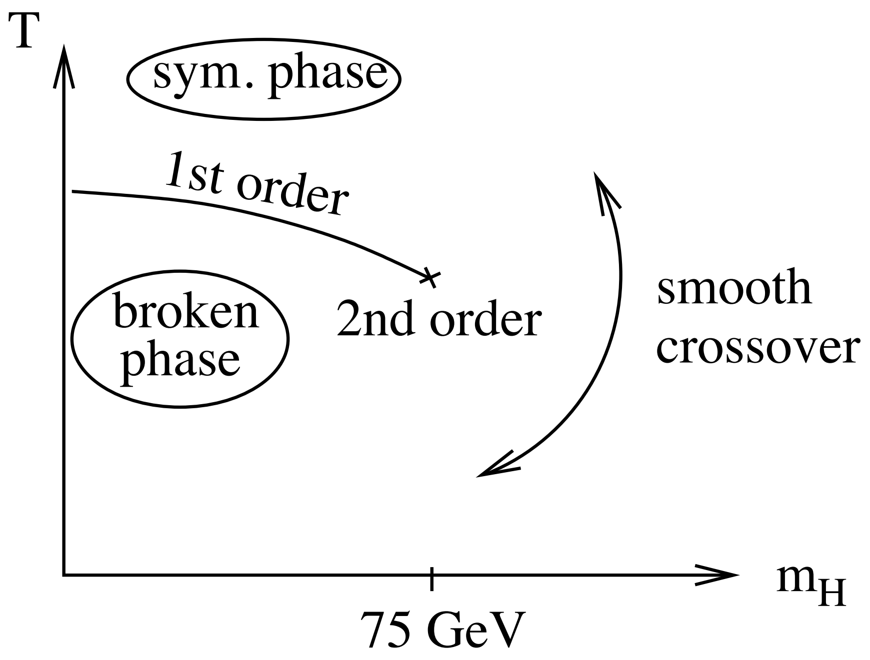
second order

One obtains $\phi(T_c) \propto v^2 T_c / m_H^2$

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 in the SM

⇒ excluded by LEP ! Actually for $m_H \gtrsim 75\,\mathrm{GeV}$ there is no phase transition but a smooth crossover [Arnold]



[Kajantie et al., hep-ph/9605228)]

It is also generally admitted that CP-violating effects are too small in the SM for successful electroweak baryogenesis [Gavela, Hernandez, Orloff, Pène]

⇒ 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 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

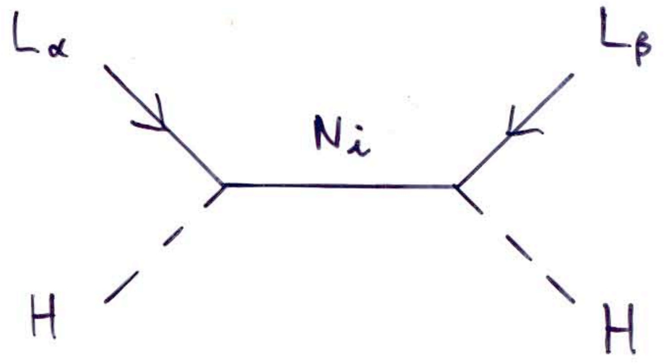
A link with neutrino masses: Baryogenesis via leptogenesis

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 sub-eV 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 new physics scale:

[Weinberg] $$\frac{1}{\Lambda} LLHH \quad \Rightarrow \quad m_\nu = \frac{v^2}{\Lambda} \qquad\qquad \Lambda \sim 10^{14}\,\mathrm{GeV}$$

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



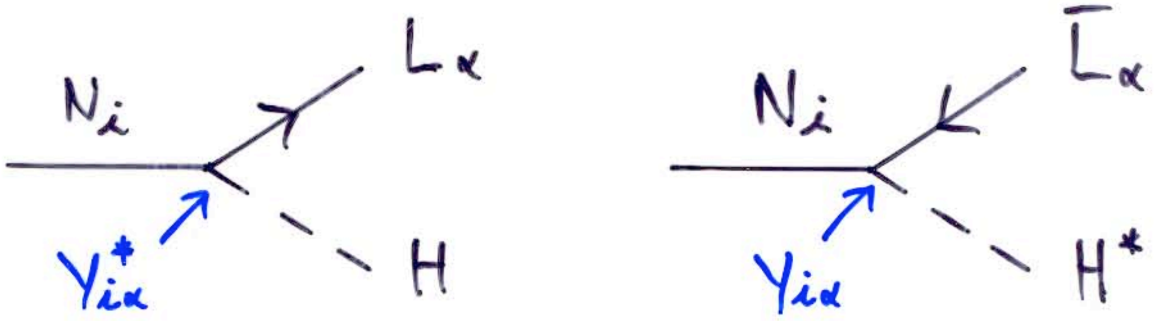
$$\Longrightarrow \qquad (M_\nu)_{\alpha\beta} \; = \; -\sum_i \frac{Y_{i\alpha} Y_{i\beta}}{M_i}\, v^2$$

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

Interestingly, this mechanism contains all ingredient for baryogenesis: out-of-equilibrium decays of the heavy Majorana neutrinos can generate a lepton asymmetry if their couplings to SM leptons violate CP

Fukugita, Yanagida ’86

Being Majorana, the heavy neutrinos can decay both into leptons and into antileptons (⇒ lepton number violation)

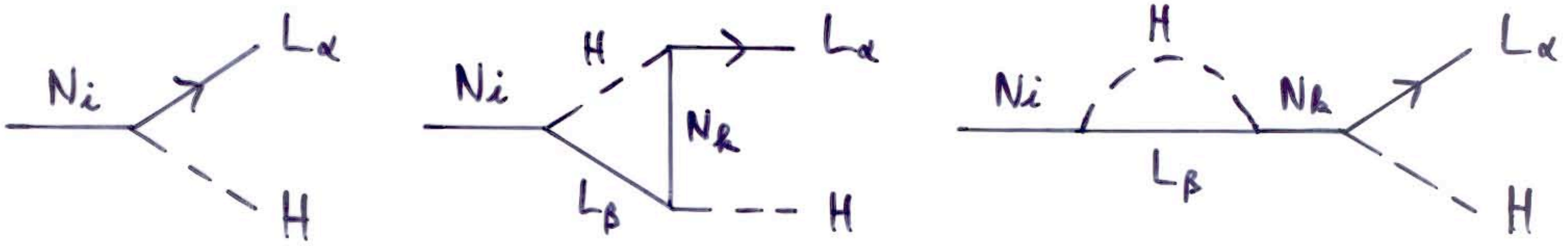


$N_i \to L_\alpha H$ $\qquad$ $N_i \to \bar{L}_\alpha H^*$

The decay rates into leptons and antileptons differ due to quantum corrections induced by the CP-violating heavy neutrino couplings
⇒ generation of a lepton asymmetry

The generated lepton asymmetry is partially converted into a baryon asymmetry by sphaleron processes, which are in equilibrium at $T > T_{EW}$

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



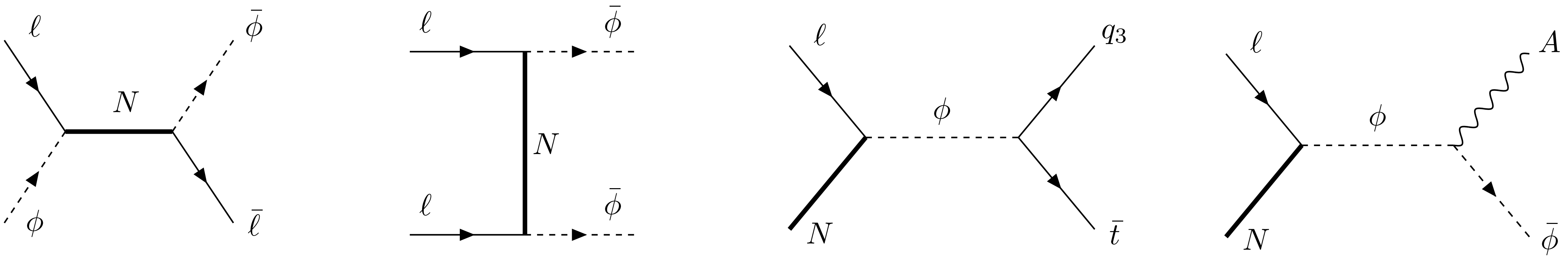
$$\Longrightarrow \quad \Gamma(N_i \to LH) \neq \Gamma(N_i \to \bar{L}H^\star)$$

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

CP asymmetry in N$_1$ decays (hierarchical case $M_1 \ll M_2, M_3$) ⇒ 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

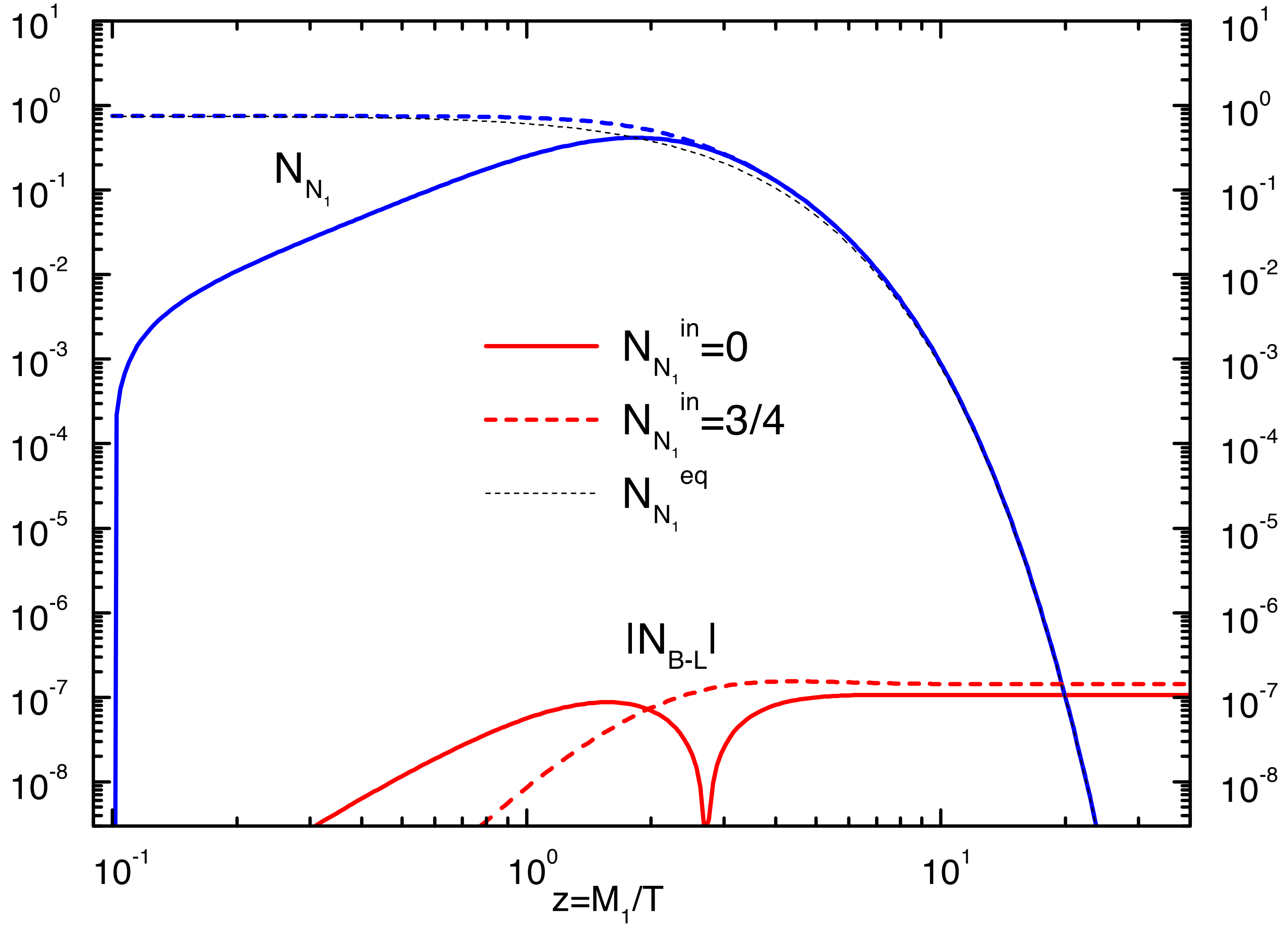


The evolution of the lepton asymmetry is described by the Boltzmann equation

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

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

Typical evolution:



[Buchmüller, Di Bari, Plümacher ’02]

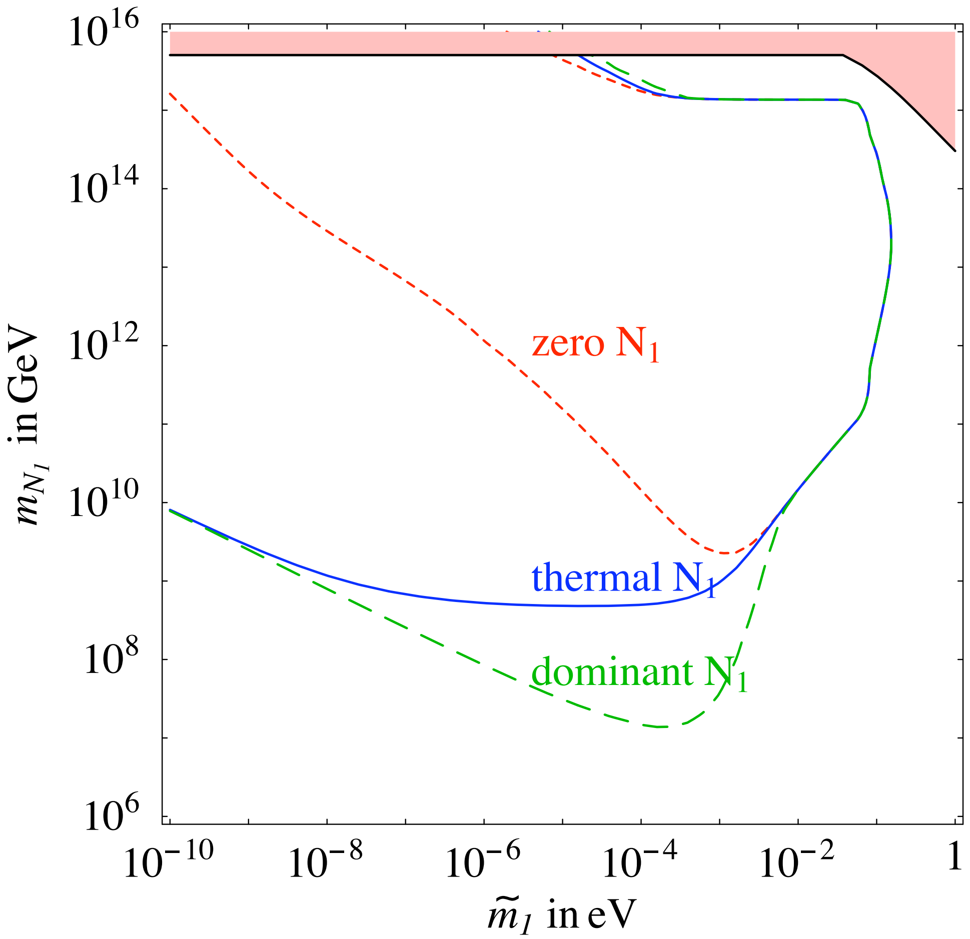
Thermal leptogenesis can explain the observed baryon asymmetry

(assuming $M_1 \ll M_2, M_3$)

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

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

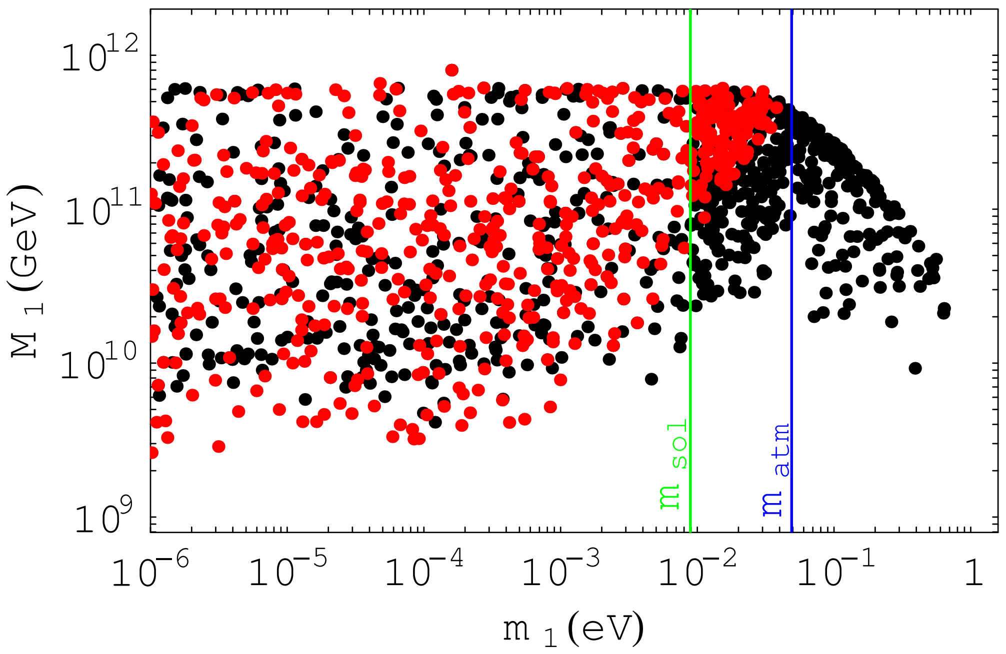
At $T \lesssim 10^{12}\,\mathrm{GeV}$, λ_τ is in equilibrium and destroys the coherence of ℓ_{N_1}
$\Rightarrow$ 2 relevant flavours: ℓ_τ and a combination ℓ_a of ℓ_e and ℓ_μ

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

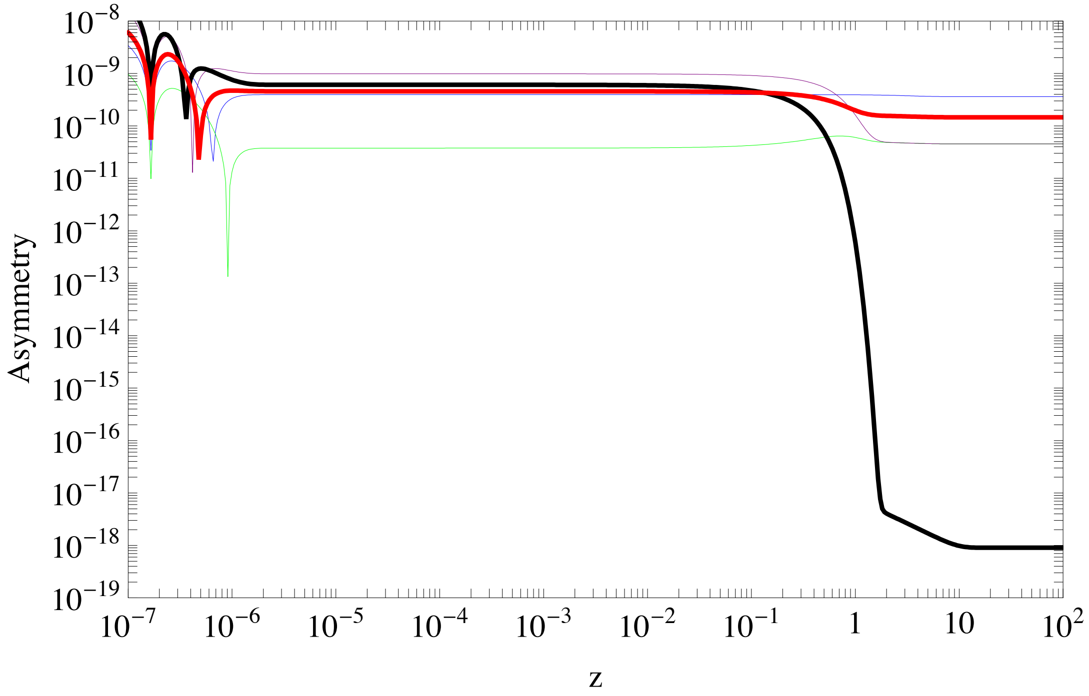


red: 1FA
black: flavoured case

[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]

Case (+ + −) with off−diagonal terms.



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

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

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

$$z = M_1/T$$

Is leptogenesis related to low-energy CP violation?

All existing oscillation data is well described in terms of 3-flavour oscillations

2 independent Δm^2: Δm^2_{32} (« atmospheric ») and Δm^2_{21} (« solar »)

3 mixing angles $\theta_{12}, \theta_{23}, \theta_{13}$ and one phase δ [+2 if Majorana] in the PMNS matrix

$$U \equiv U_{23}U_{13}U_{12} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

[the « Majorana » phases are relevant only for processes that violate lepton number, such as neutrinoless double beta decay, and have no effect on oscillations]

→ oscillation probability = ∑ oscillating terms with different « frequencies » $\Delta m^2_{ji} \equiv m^2_j - m^2_i$ and amplitudes (which depend on the θ_{ij} and δ)

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i<j} \mathrm{Re}\left[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{ji}L}{4E}\right)$$

$$+ 2\sum_{i<j} \mathrm{Im}\left[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}\right] \sin\left(\frac{\Delta m^2_{ji}L}{2E}\right)$$

For antineutrinos, U → U* (δ → - δ) and the last term changes sign

$\Rightarrow P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq P(\nu_\alpha \to \nu_\beta)$ (if $\delta \neq 0, \pi$) → CP violation

CP violation in neutrino oscillations

$\Delta P_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$ at leading order in Δm^2_{21} :

$$\Delta P_{\alpha\beta} = \pm 8\, J \left(\frac{\Delta m^2_{21} L}{2E}\right) \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right), \qquad J \equiv \mathrm{Im}\left[U_{e1} U^*_{\mu 1} U^*_{e2} U_{\mu 2}\right]$$

Jarlskog invariant $\quad J = \dfrac{1}{8} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \sin\delta$

→ condition for CP violation : $\quad \delta \neq 0, \pi$

→ for CP violation to be observable, sub-dominant oscillations governed by Δm^2_{21} must develop ⇒ long baseline oscillation experiments (> 100 km), also sensitive to matter effects (which can mimic a CP asymmetry)

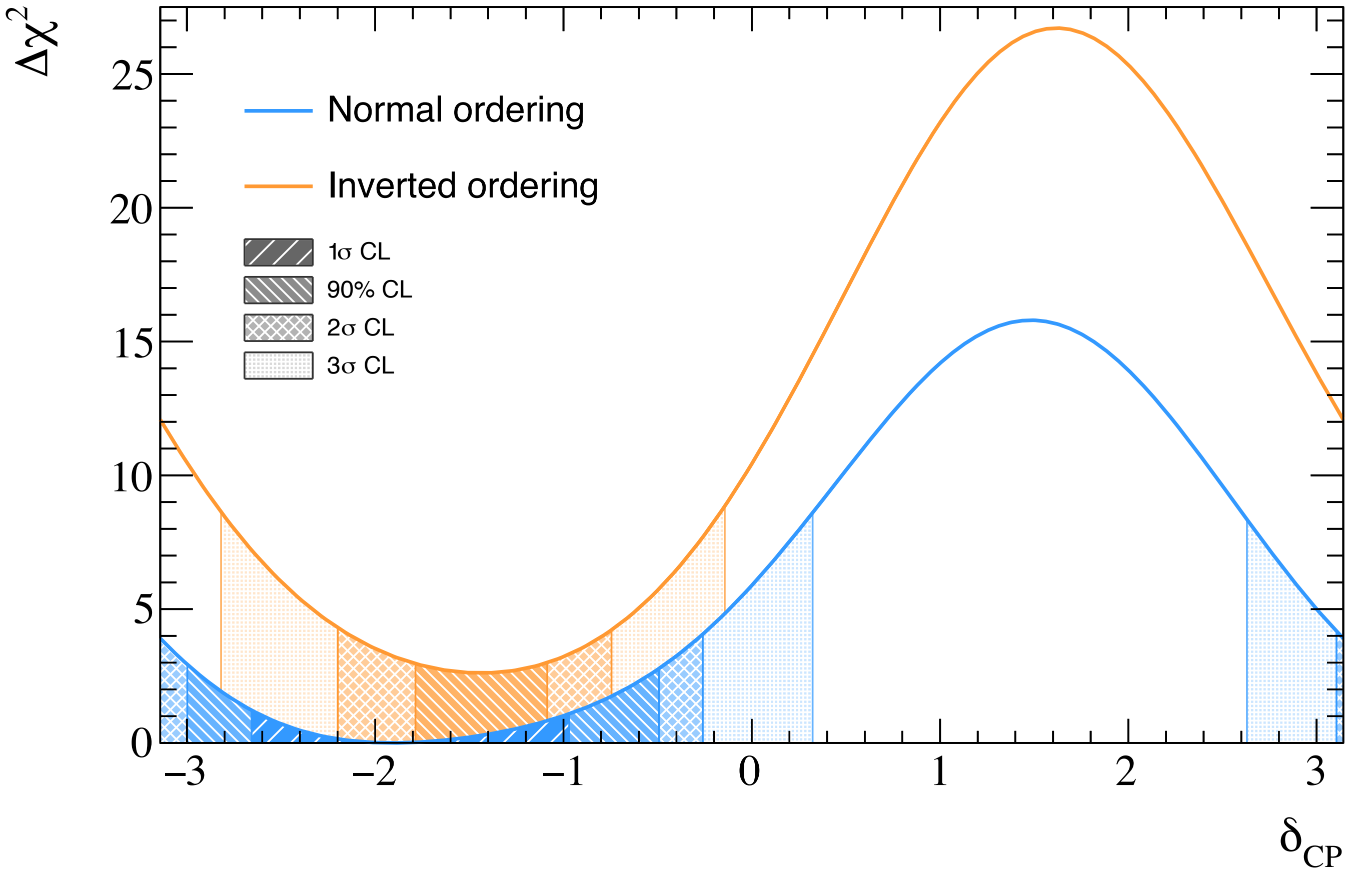
CP violation is only possible in <u>appearance experiments</u> $(\alpha \neq \beta)$
e.g. electron (anti-)neutrino appearance in a muon (anti-)neutrino beam
$(\nu_\mu \to \nu_e, \, \bar{\nu}_\mu \to \bar{\nu}_e)$

Disappearance experiments, e.g. at reactors, have no sensitivity to δ

First hints of CP violation at T2K

Long baseline accelerator experiment in Japan (295 km)

Observes more events in the neutrino mode $(\nu_\mu \to \nu_e)$ and less events in the antineutrino mode $(\bar{\nu}_\mu \to \bar{\nu}_e)$ than expected $\Rightarrow$ suggests CP violation (CP conservation excluded at more than 90% C.L.)



[talk at Neutrino 2020]

The upcoming experiments DUNE and Hyper-Kamiokande should be able to tell whether CP is violated or not in the lepton sector

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} $\left\{ \begin{array}{ll} \delta & \rightarrow \text{oscillations} \\ \phi_2, \phi_3 & \rightarrow \text{neutrinoless double beta} \end{array} \right.$

→ 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)

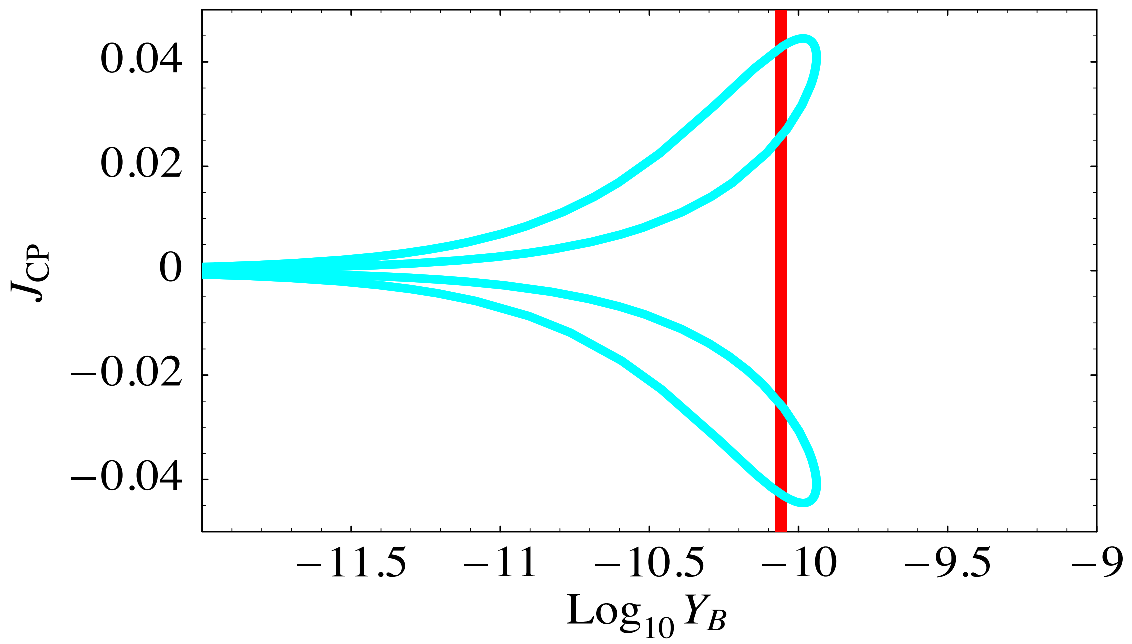


FIG. 1. The invariant $J_{\rm CP}$ versus the baryon asymmetry varying (in blue) $\delta = [0, 2\pi]$ in the case of hierarchical RH neutrinos and NH light neutrino mass spectrum for $s_{13} = 0.2$, $\alpha_{32} = 0$, $R_{12} = 0.86$, $R_{13} = 0.5$ and $M_1 = 5 \times 10^{11}$ GeV . The red region denotes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

[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 $10^9 \,\text{GeV} < M_1 < 10^{12} \,\text{GeV}$

→ (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]

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

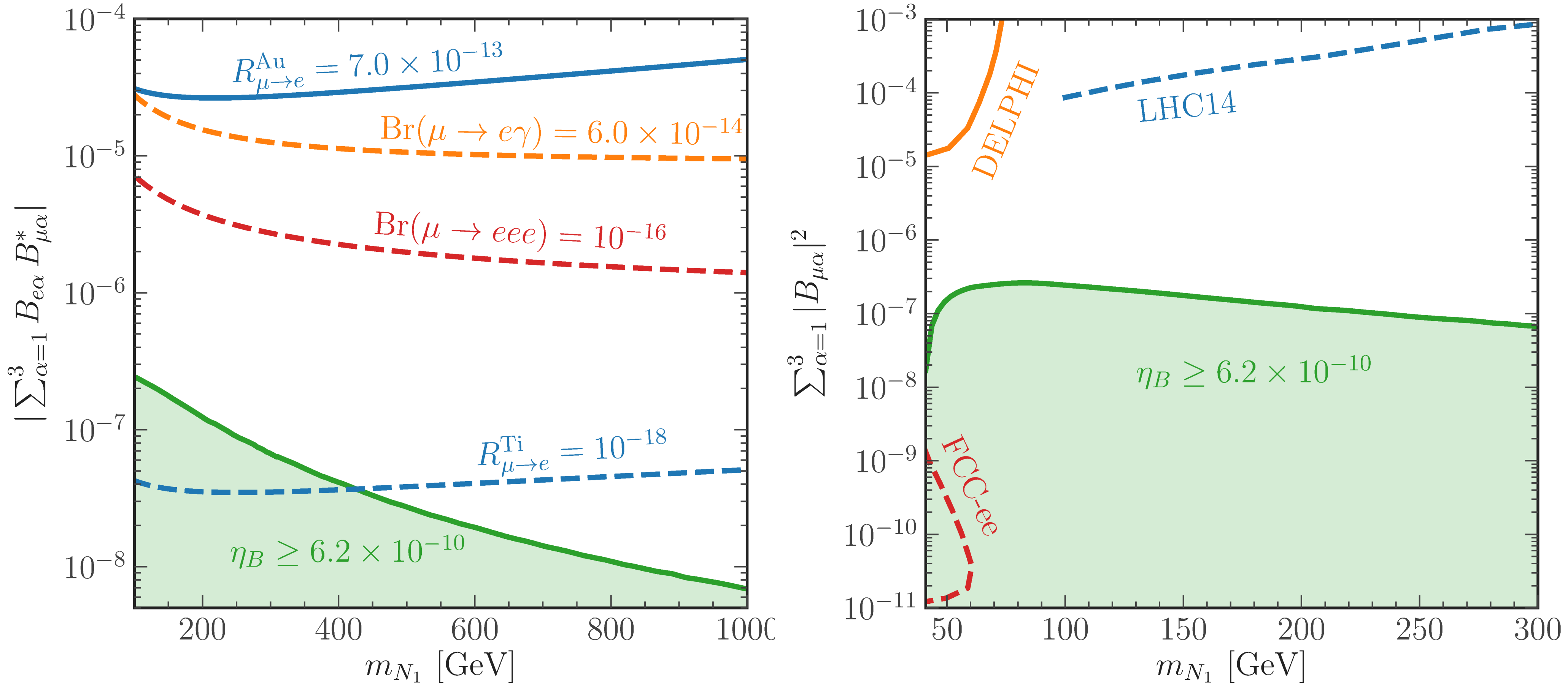
$\Rightarrow$ can be tested via direct production of heavy Majorana neutrinos at colliders + contributions to flavour violating processes in the charged lepton sector

[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 :



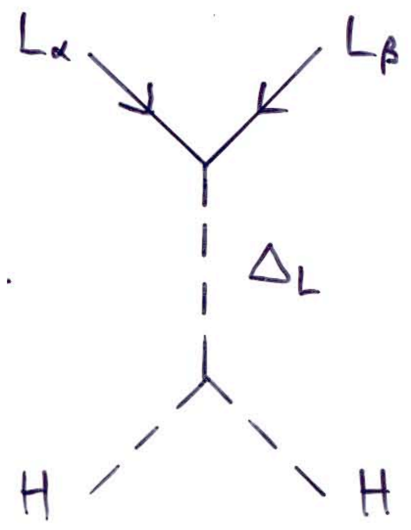
Left plot (cLFV) : solid = current bound, dashed = future bounds

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

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

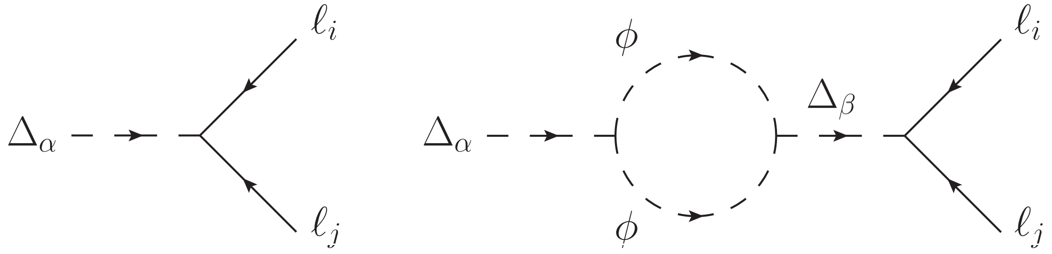


$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$ electroweak triplet

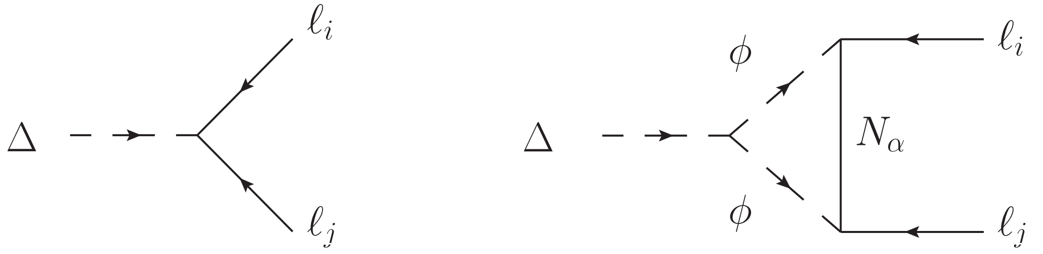
generates a neutrino mass $m_\nu = \dfrac{\mu \lambda_\ell}{2M_\Delta^2} v^2$

Also leads to leptogenesis if another heavy state couples to leptons

⇒ CP asymmetry in triplet decays [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 ⇒ 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 ⇒ 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

Including flavour effects in scalar triplet leptogenesis

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

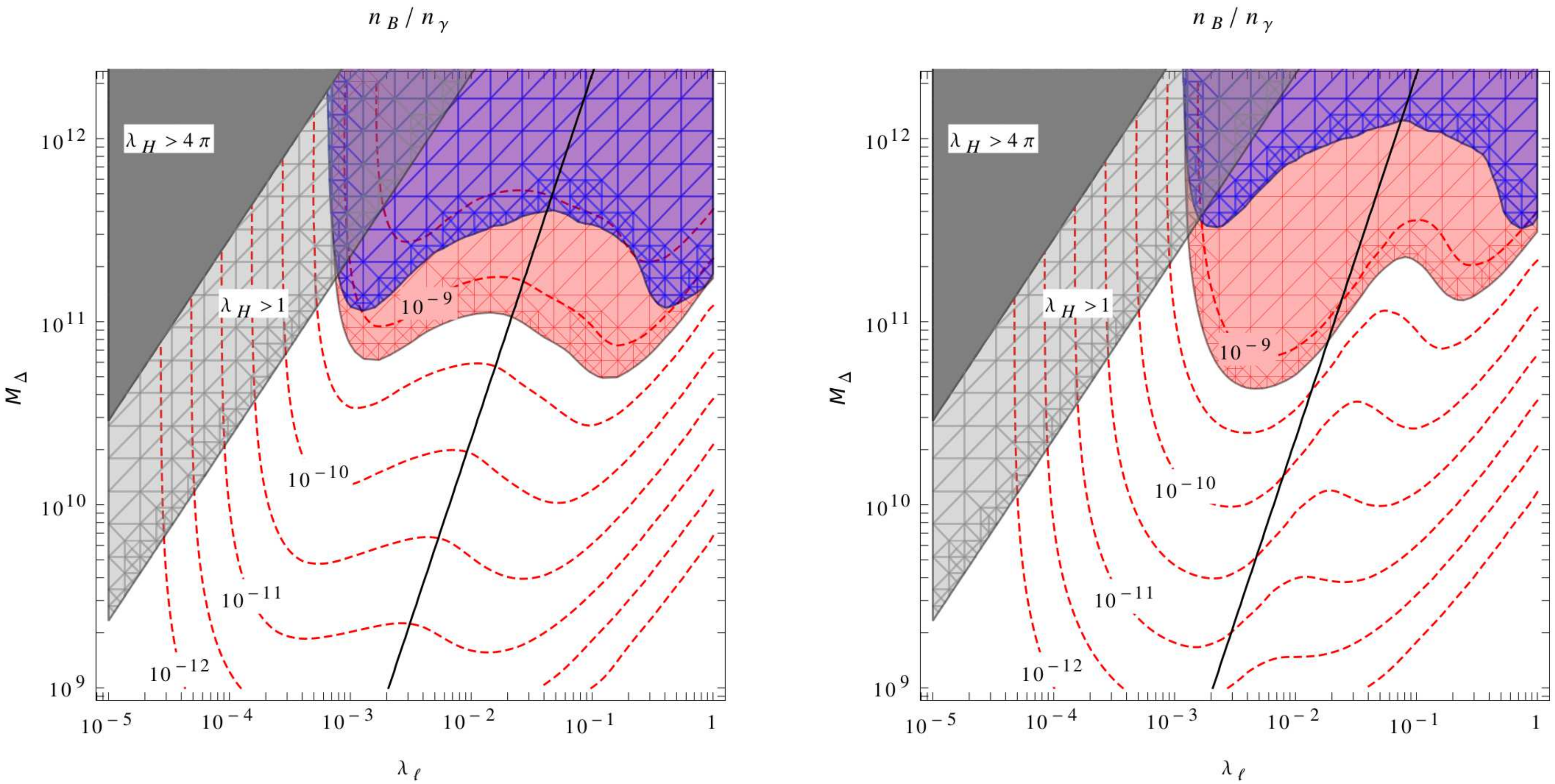


Figure 11: Isocurves of the baryon-to-photon ratio n_B/n_γ in the (λ_ℓ, M_Δ) plane obtained performing the full computation, assuming Ansatz 1 (left panel) or Ansatz 2 with $(x, y) = (0.05, 0.95)$ (right panel). The coloured regions indicate where the observed baryon asymmetry can be reproduced in the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

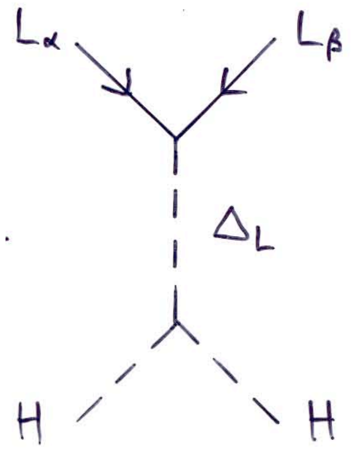
$$M_\Delta \; > \; 4.4 \times 10^{10}\,\text{GeV} \qquad (1.2 \times 10^{11}\,\text{GeV without flavour effects})$$

[SL, Schmauch '15]

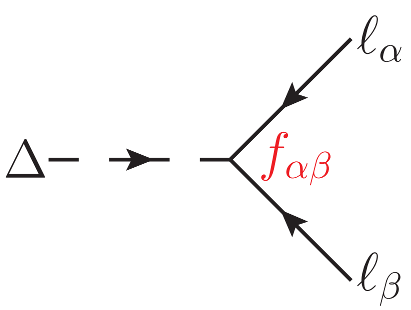
A predictive scheme for scalar triplet leptogenesis

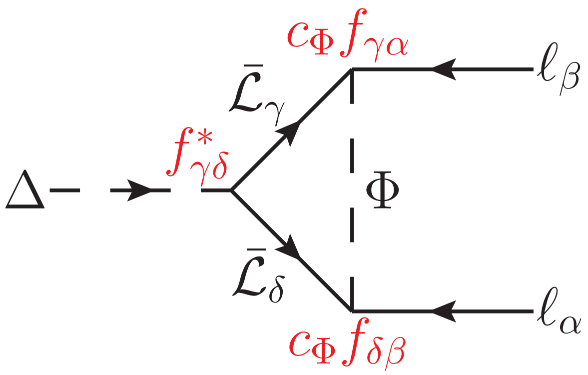
Non-standard SO(10) model that leads to pure type II seesaw mechanism ⇒ neutrinos masses proportional to triplet couplings to leptons:

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



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





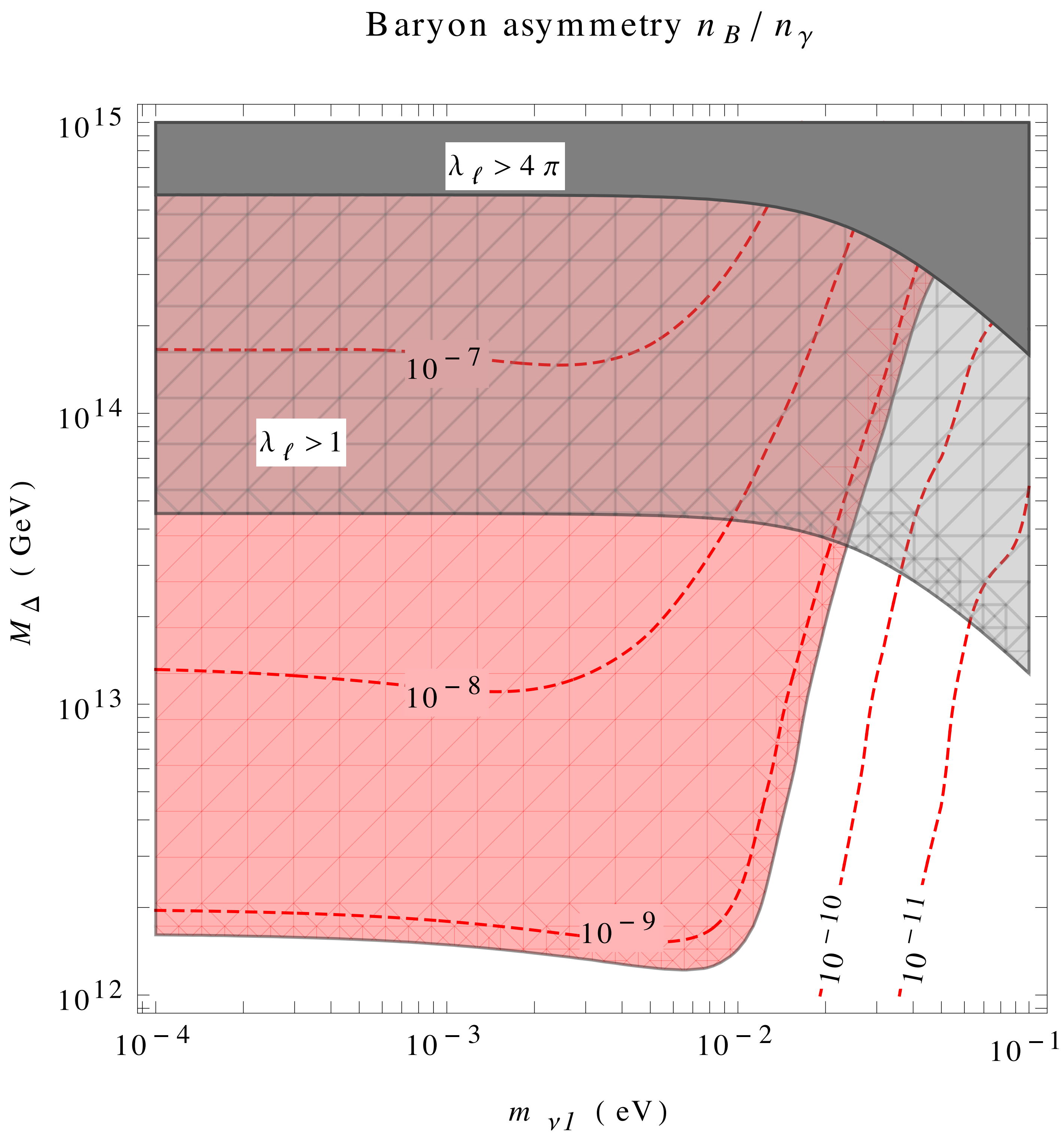
$$\Phi = S, T \in 54$$

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



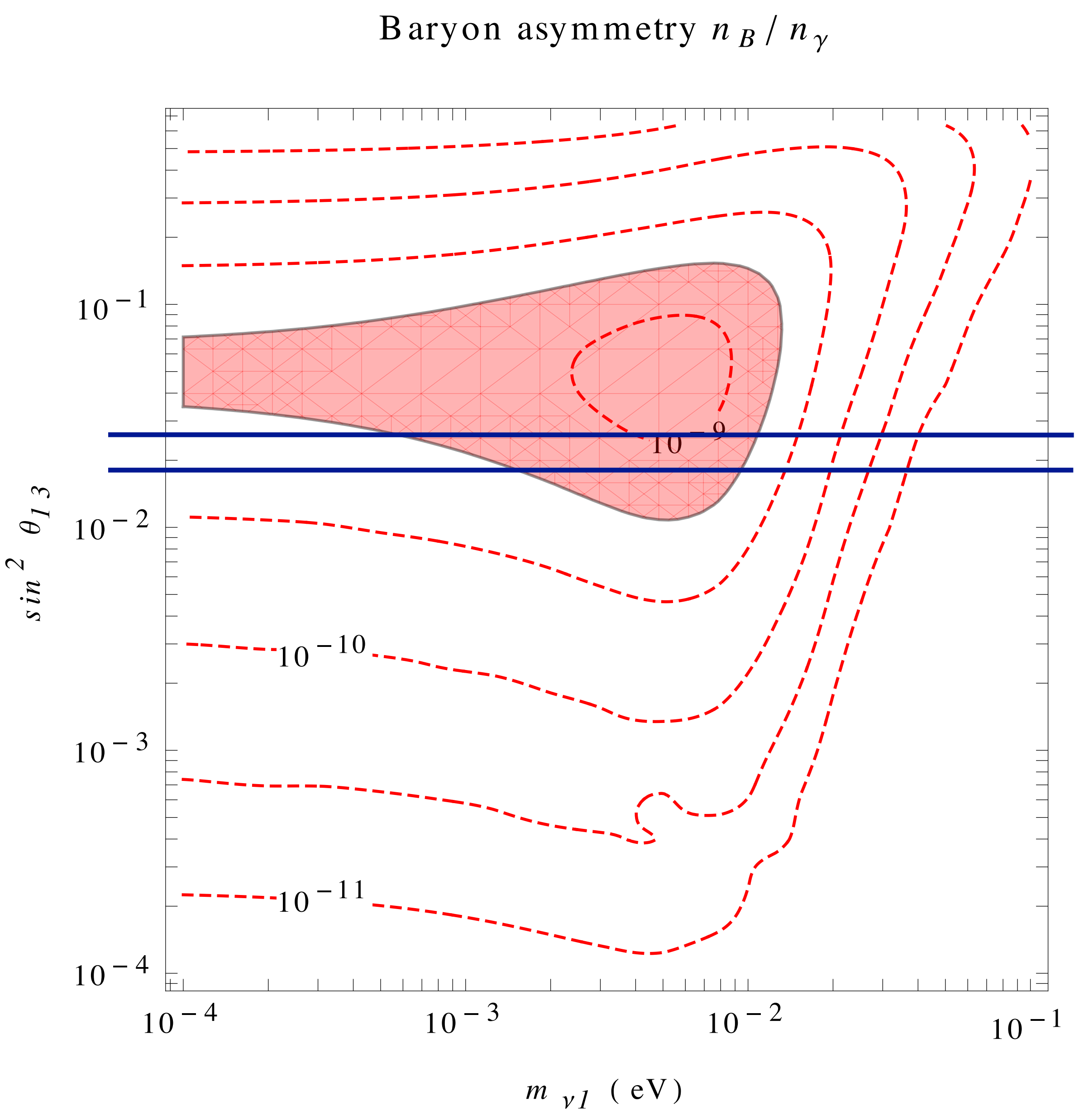
$\lambda_H = 0.2$

→ excludes a quasi-degenerate spectrum

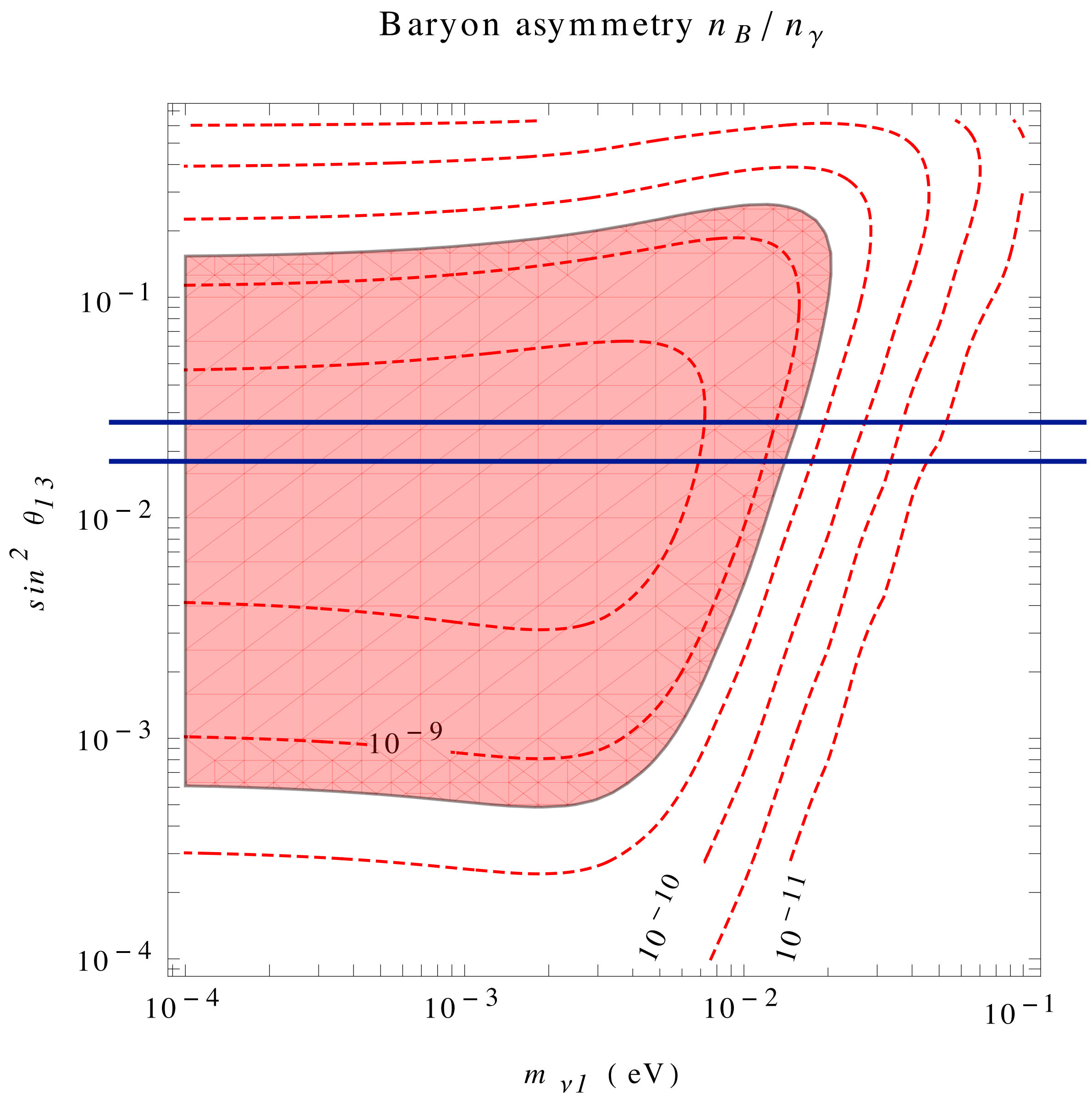
[SL, Schmauch]

θ13 dependence

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



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

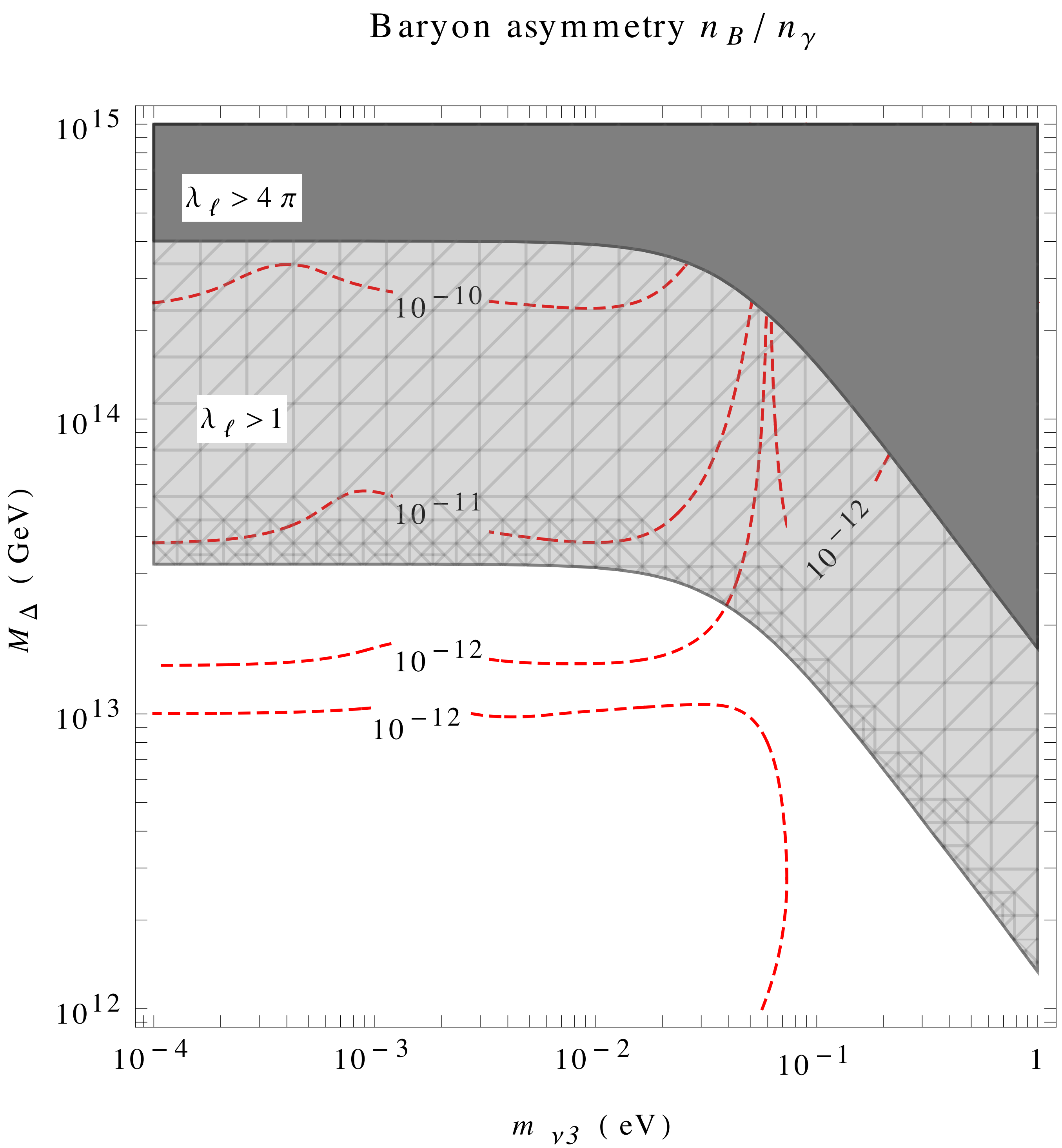


(3σ range)

$\lambda_H = 0.2$

[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]

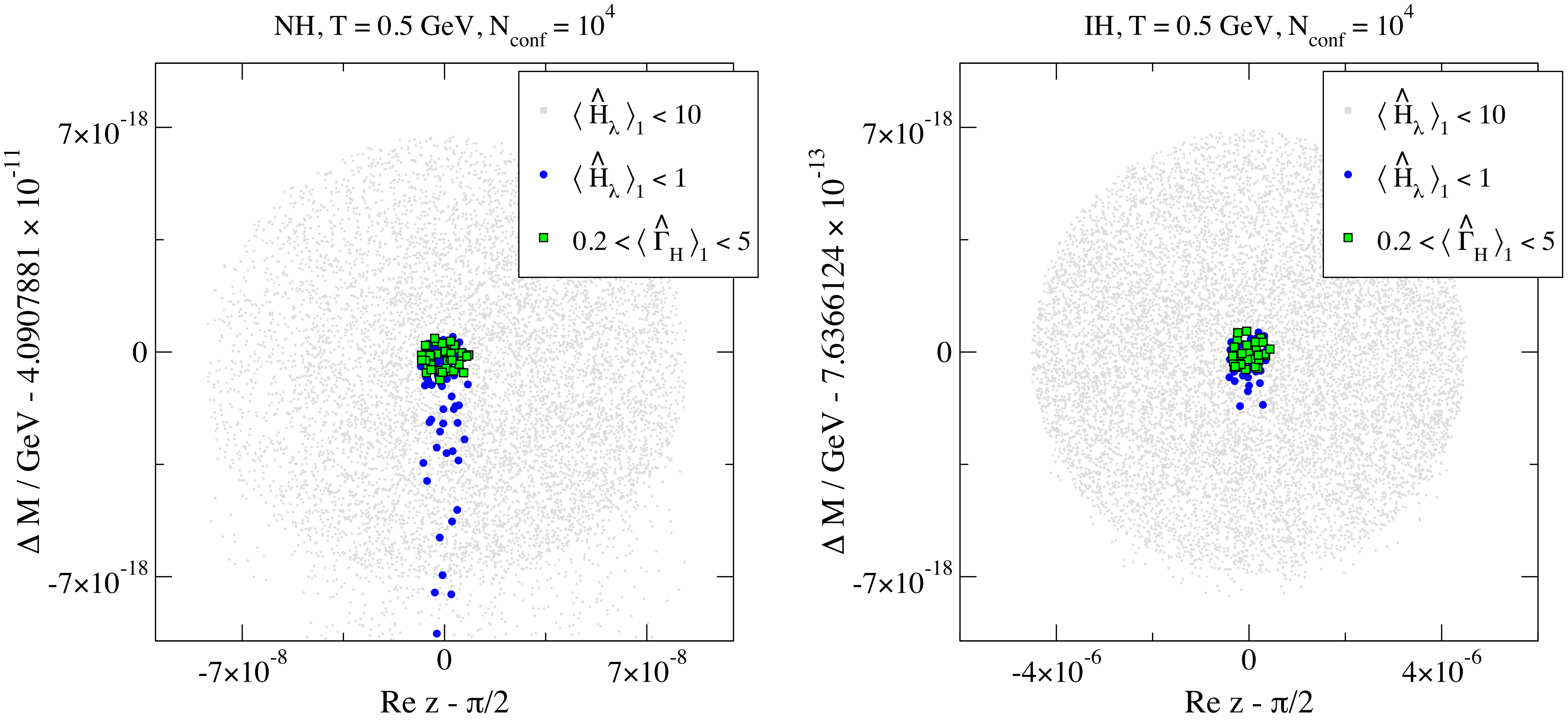
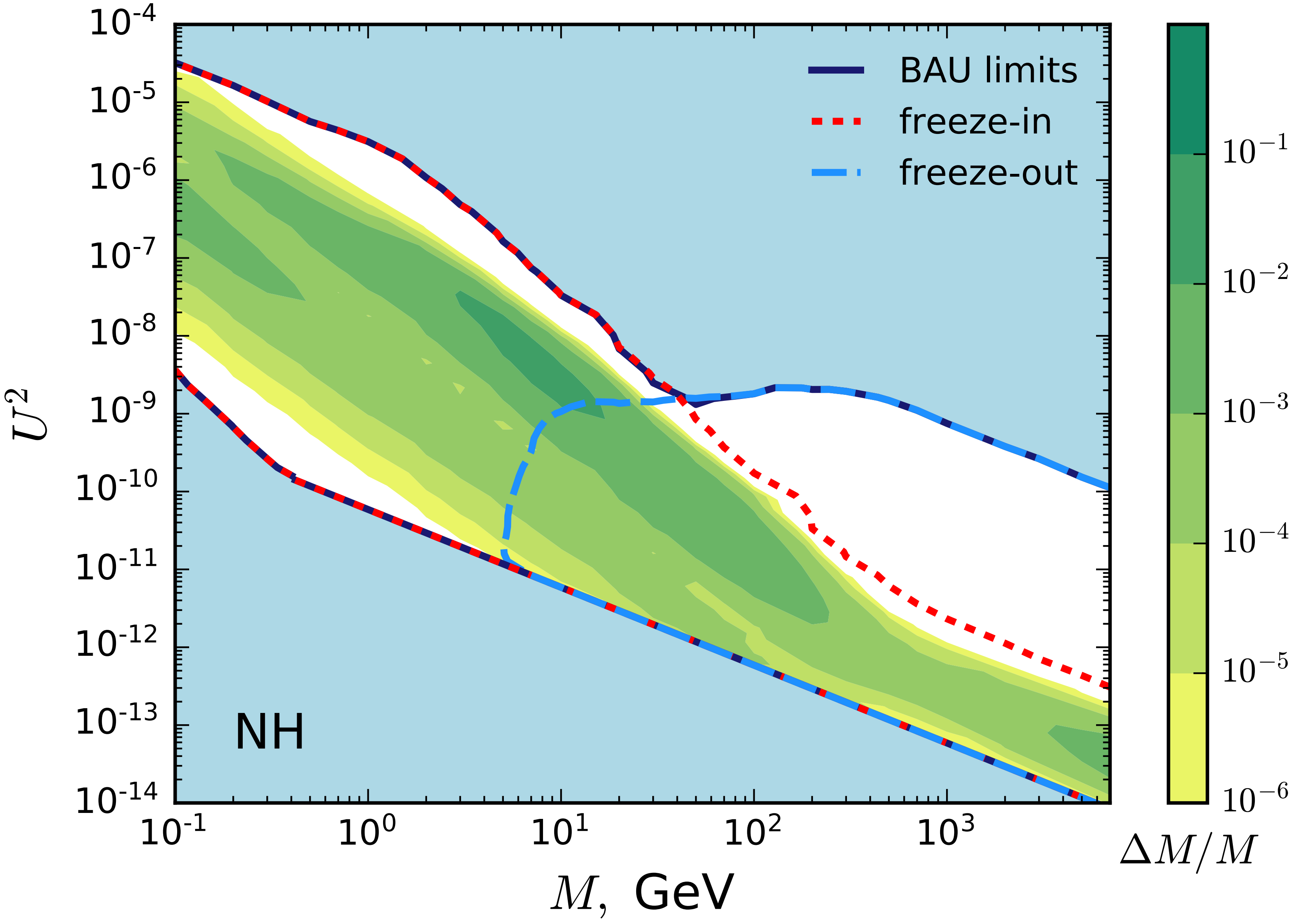


Figure 2: Points satisfying the increasingly stringent constraints indicated by the legend (cf. sec. 4.1), in the plane of Re z and ΔM (left: normal hierarchy, right: inverted hierarchy). The narrow axis ranges illustrate the extraordinary degree of fine-tuning that is needed for realizing the desired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

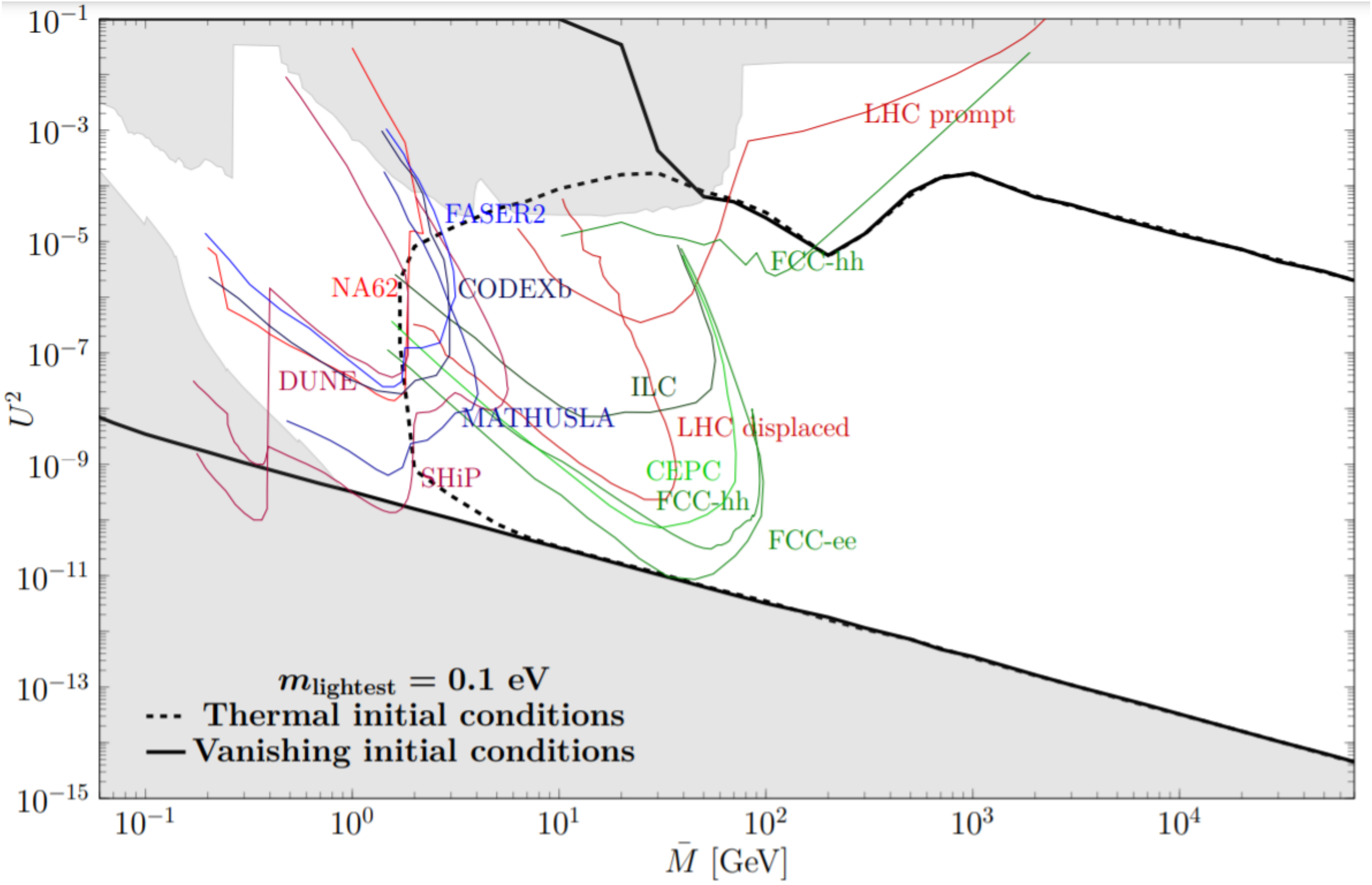


Large values of the active-sterile neutrino mixing U arise when some tuning is present in the sterile neutrino couplings (can be justified by symmetries)

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

- observation of CP violation in the lepton sector, e.g. in neutrino oscillations [neither 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)