The neutrino mass and nature
Implications for physics beyond the Standard Model

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- the neutrino nature: Dirac versus Majorana
- neutrino masses and physics beyond the Standard Model
- potential signatures of low-scale neutrino mass generation
- the matter-antimatter asymmetry of the Universe as a byproduct of neutrino mass generation: leptogenesis
- low-scale leptogenesis mechanisms

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Introduction

Neutrino physics has made spectacular progress over the past 25 years, with the discovery of oscillations of atmospheric (Super-Kamiokande 1998), solar (SNO 2001) and reactor neutrinos (Daya Bay 2012)

→ evidence that neutrinos have (nondegenerate) masses and mix

$m_\nu \neq 0$ $\qquad$ $U_{\rm PMNS} \neq \mathbf{1}$ $\qquad$ [PMNS = Pontecorvo-Maki-Nakagawa-Sakata]

More and more precise measurement of oscillation parameters

$|\Delta m^2_{31}| = (2.507\,^{+0.026}_{-0.027}) \times 10^{-3}\,{\rm eV}^2$ $\qquad$ $\Delta m^2_{21} = (7.41\,^{+0.21}_{-0.20}) \times 10^{-5}\,{\rm eV}^2$

$\theta_{12}\,,\ \theta_{23}$ large ($\theta_{13} \simeq 8.6^\circ$ a bit smaller)

3σ uncertainties between 3-8% (except for θ_{23})

<u>But still many open questions…</u>

1) is CP violated in the lepton sector? [see Benjamin Quilain's talk]

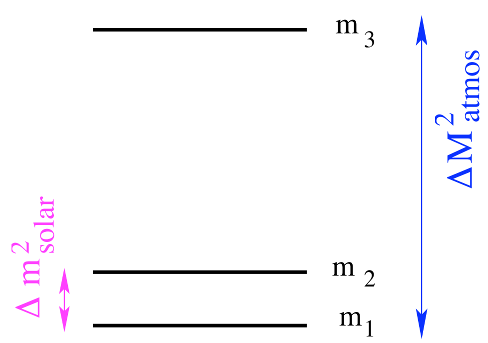
$\delta \neq 0, \pi$ would imply $P(\nu_\mu \to \nu_e) \neq P(\bar\nu_\mu \to \bar\nu_e)$

Hints (90% C.L.) from the T2K experiment

[no constraint on the Majorana phases of $U_{\rm PMNS}$ (relevant only for Majorana neutrinos)]

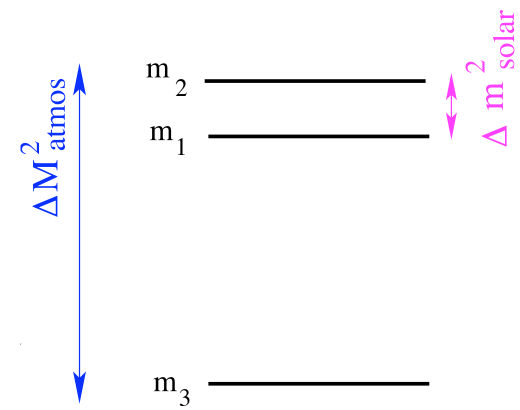
2) what are the absolute neutrino mass scale and the mass ordering?

[see Benjamin Quilain's talk]



Normal ordering

$$\Delta m^2_{31} > 0$$



Inverted ordering

$$\Delta m^2_{31} < 0$$

$m_{\rm heaviest} \geq \sqrt{\Delta m^2_{\rm atm}} \simeq 0.05\,{\rm eV}$ from oscillations

$m_\beta \equiv \sqrt{\sum_i m_i^2 |U_{ei}|^2} < 0.8\,{\rm eV}$ (95% C.L.) from beta decay endpoint [KATRIN]

$\sum_i m_i < 0.12\,{\rm eV}$ (95% C.L.) from cosmology [Planck 2018 + BAO]

[adding Lyman-a, Palanque-Delabrouille et al. obtain < 0.09 eV, 95% CL (JCAP04 (2020) 038)]

3) are neutrinos Dirac or Majorana fermions? ("neutrino nature")

$\overline{\nu} \neq \nu$ (Dirac) vs. $\overline{\nu} = \nu$ (Majorana) [see Claudia Nones' talk]

4) what is the origin of neutrino masses?

No answer within the Standard Model (predicts $m_\nu = 0$)

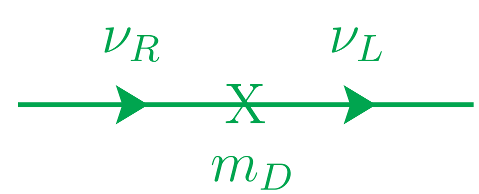
Fundamental question that is closely related to the one of the neutrino nature

Dirac versus Majorana neutrino

Neutrinos are the only SM fermions that do not carry electric charge
$\Rightarrow$ can be their own antiparticles (Majorana fermions)

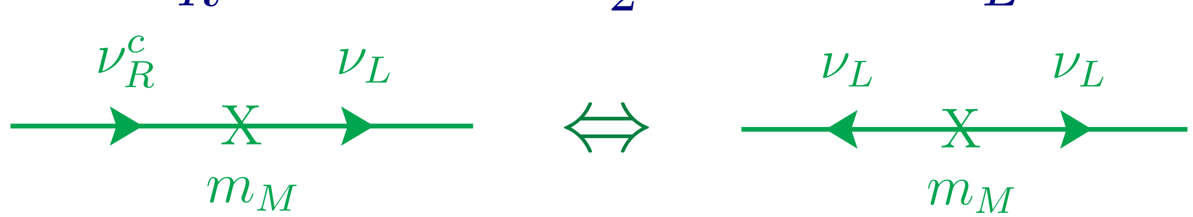
Experimentally, only ν_L (the "neutrino") and its CP conjugate ν_R^c (the "antineutrino") have been observed. We don't know if the neutrino also has a RH component ν_R (which would be a pure gauge singlet, unobservable)

A Dirac neutrino has two independent chiralities ν_L and ν_R, like the other SM fermions. Its mass term $-m_D\,\bar{\nu}_L \nu_R + \text{h.c.}$ <u>preserves lepton number</u>



$\Delta L = 0 \qquad \Delta T^3 = \frac{1}{2}$

Instead, the LH and RH components of a Majorana neutrino are related by the Majorana condition $\nu = \nu^c \equiv C\bar{\nu}^T$, namely $\nu_R = \nu_R^c \equiv C\bar{\nu}_L^T$. Its mass term $-\frac{1}{2}\,m_M\,\bar{\nu}_L \nu_R^c + \text{h.c.} = -\frac{1}{2}\,m_M\,\bar{\nu}_L C\,\bar{\nu}_L^T + \text{h.c.}$ <u>violates lepton number by 2 units</u>



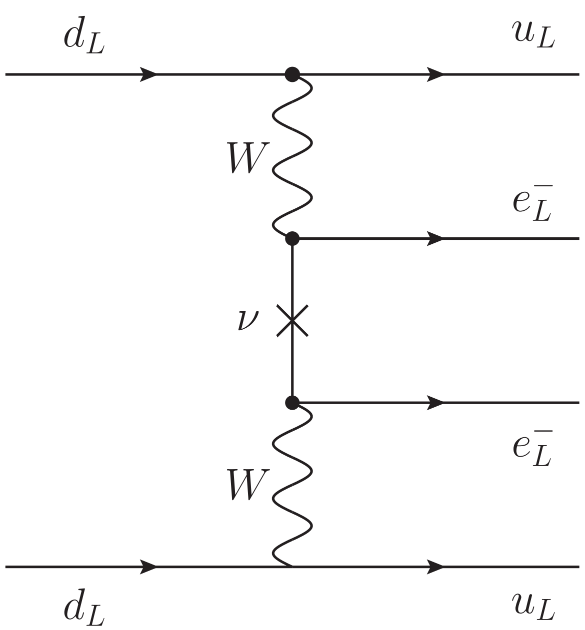
$\Delta L = 2 \qquad \Delta T^3 = 1$

Lepton number violation is the signature of Majorana neutrinos

How can we determine experimentally the neutrino nature?

Dirac and Majorana neutrinos have the same interactions, which are chiral (weak interactions) ⇒ can't be distinguished by their interactions or oscillations

The only practical way of establishing the Majorana nature of neutrinos (if they indeed are Majorana fermions) si to search for processes that violate lepton number by 2 units, such as neutrinoless double beta decay



<u>Neutrinoless double beta decay</u> [see Claudia's talk]

$$(A,Z) \;\to\; (A,Z+2) + e^- + e^-$$

Violates lepton number by 2 units
⇒ possible only for Majorana neutrinos

Half-life sensitive to the effective mass parameter

$$m_{\beta\beta} \;\equiv \sum_i m_i U_{ei}^2 \;=\; m_1 c_{13}^2 c_{12}^2 e^{2i\alpha_1} + m_2 c_{13}^2 s_{12}^2 e^{2i\alpha_2} + m_3 s_{13}^2$$

[α_1, α_2 = Majorana phases of the PMNS matrix]

Current best limit [KamLAND-Zen (2022)]:

$$|m_{\beta\beta}| < (36 - 156)\,\mathrm{meV} \quad (90\%\,\mathrm{C.L.})$$

[large uncertainties from nuclear matrix elements]

From a theoretical point of view, Dirac neutrinos are unnatural

To generate a Dirac mass for the neutrino, need to add a ν_R to the SM
But then must write a Majorana mass term for the RH neutrino, which is allowed by all (non-accidental) symmetries of the SM:

$$-\frac{1}{2}M\,\overline{\nu_L^c}\nu_R + \text{h.c.} = -\frac{1}{2}M\nu_R^T C\nu_R + \text{h.c.} \qquad \Delta L = 2 \qquad \Delta T^3 = 0$$

$\Rightarrow$ mixed Dirac-Majorana mass term $-m_D\,\bar{\nu}_L\nu_R - \frac{1}{2}M\nu_R^T C\nu_R + \text{h.c.}$
which yields two Majorana mass eigenstates per generation

Note: the limit $M \gg m_D$ corresponds to the so-called seesaw mechanism, which gives a light Majorana neutrino $\nu_{\text{light}} \simeq \nu_{\text{SM}}$ with mass $m_{\text{light}} \simeq m_D/M^2 \ll m_D$ and a heavy Majorana neutrino with mass $\simeq M$

Only way to avoid this conclusion: impose lepton number conservation (a global symmetry that is not preserved by quantum gravity), or gauge B-L

Majorana neutrinos are more natural… but what generates their masses?

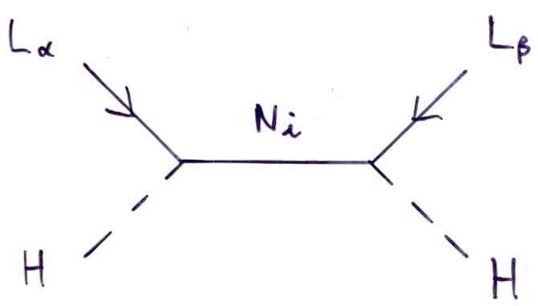
If light RH neutrinos do not exist, the low-energy effective theory is the SM
⇒ neutrino masses must be generated by new physics, which is parametrized by higher-dimensional operators in the SMEFT Lagrangian

Lowest D>4 SMEFT operator: $\frac{c}{\Lambda} LLHH$ (Weinberg operator)

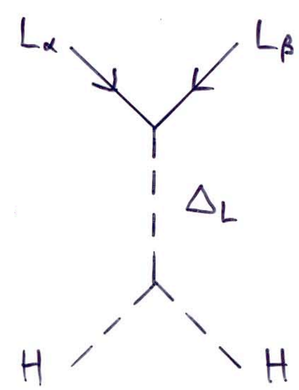
generates Majorana neutrino masses $m_\nu = c\,\frac{v^2}{\Lambda}$

⇒ suggests a high new physics scale $(\Lambda \sim 10^{15}\,\mathrm{GeV}\ \text{for}\ c = 1)$

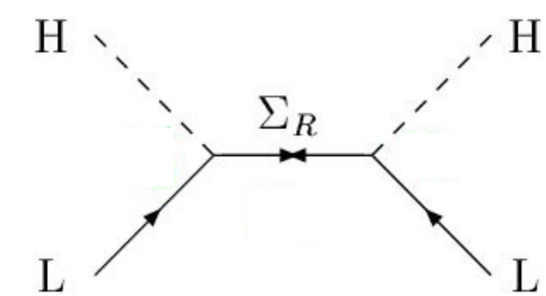
Many different kinds of new physics can generate the Weinberg operator :



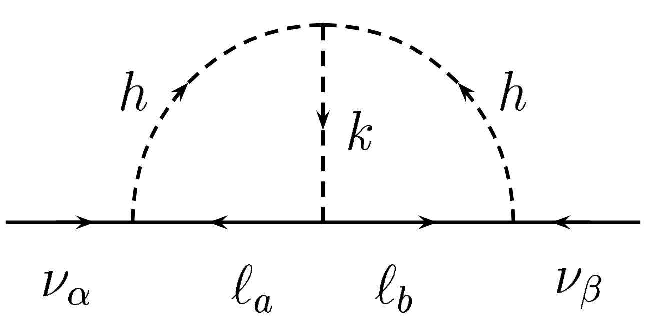
heavy RH neutrino exchange
(type-I seesaw)



heavy scalar triplet exchange
(type-II seesaw)



heavy fermion triplet exchange
(type-III seesaw)



Zee-Babu model

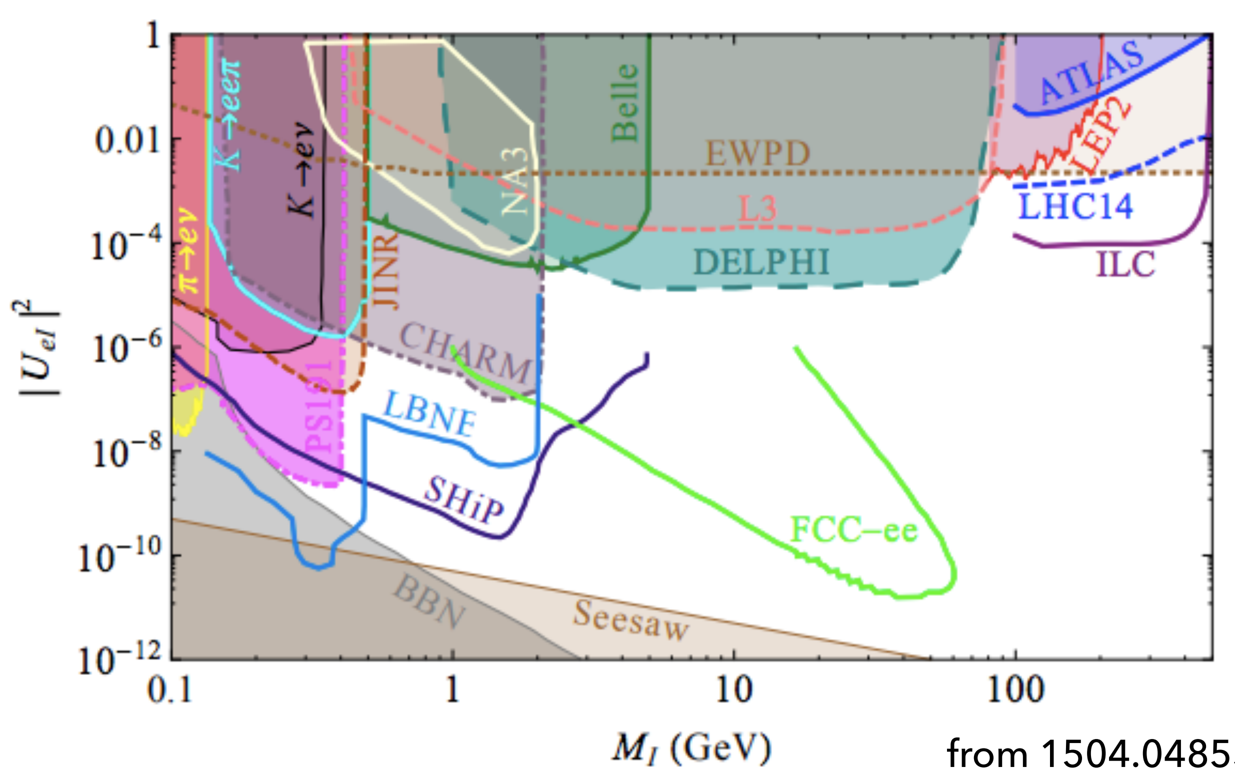
(example of a 2-loop radiative model involving 2 charged SU(2) singlet scalars)

Potential signatures of low-scale neutrino mass generation

The new physics responsible for neutrino masses may be light if the new particles couplings to leptons (and/or to the Higgs) are small

Type-I seesaw: no model-independent prediction for the RH neutrino masses Can lie anywhere between the GeV scale and 10^{15} GeV, or even below (same for the scalar triplet of the type-II seesaw mechanism)

If around the electroweak/TeV scale, can be produced at colliders through their mixing with the SM neutrinos (GeV-scale RH/sterile neutrinos can also be produced in beam-dump experiments like SHiP)



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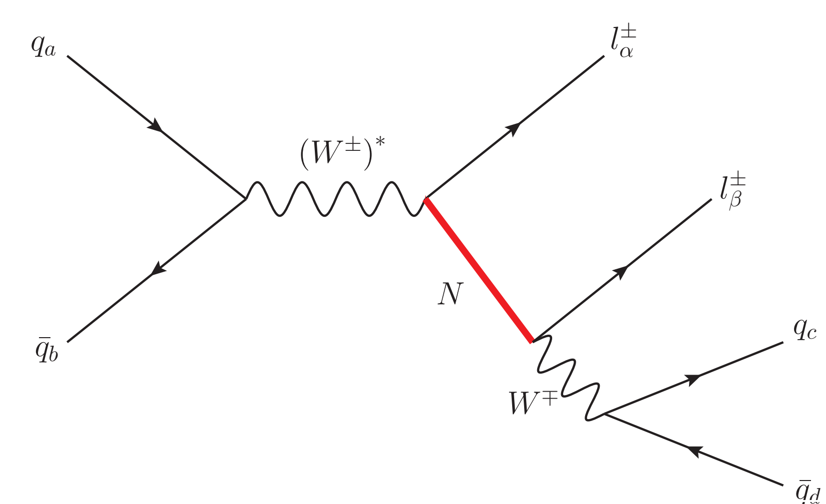
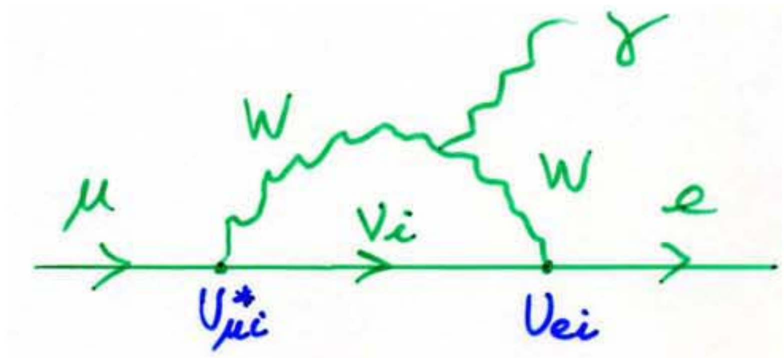


searches for SS dileptons at the LHC

TeV-scale states involved in neutrino mass generation may also induce processes violating the charged lepton flavour, which are extremely suppressed in the SM

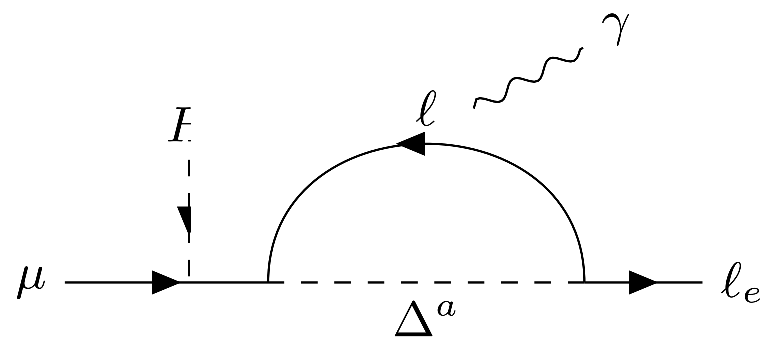
E.g. $\mu \to e\,\gamma$:

SM :



$$\mathrm{BR}\,(\mu \to e\gamma) \;\propto\; \left(\frac{m_\nu}{M_W}\right)^4 \lesssim 10^{-54}$$

Type-II seesaw :



$\mathrm{BR}\,(\mu \to e\gamma)$ may be sizable if the triplet couplings to leptons are large

Neutrino masses may also be connected to one of the big questions of cosmology: the origin of the matter-antimatter asymmetry of the Universe

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq \frac{n_B}{n_\gamma} = (6.13 \pm 0.08) \times 10^{-10} \quad (95\%\,\mathrm{C.L.})$$

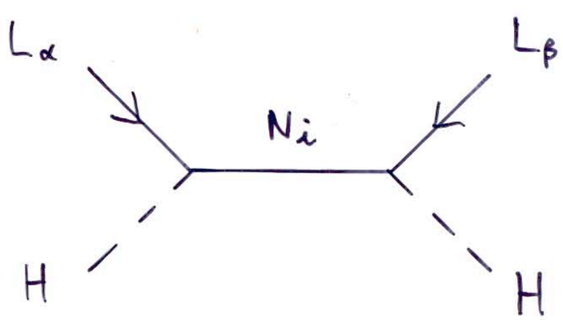
[Planck 2018]

Many neutrino mass generation mechanisms contain all the ingredients to generate the baryon asymmetry of the Universe (BAU) via leptogenesis

→ concentrate on leptogenesis (mainly with heavy right-handed neutrinos) in the following

A link between neutrino masses and the BAU: baryogenesis via leptogenesis

In the (type-I) seesaw mechanism, the SM neutrinos get Majorana masses through their couplings to heavy Majorana neutrinos



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

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

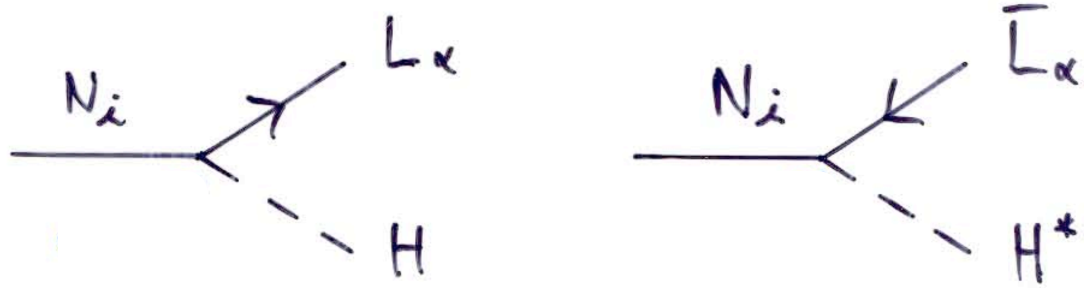
Interestingly, this mechanism contains all ingredients needed for baryogenesis [Sakharov conditions: B violation, C and CP violation, departure from thermal equilibrium]:

- out-of-equilibrium decays of the heavy Majorana neutrinos can generate a lepton asymmetry if their couplings to SM leptons violate CP

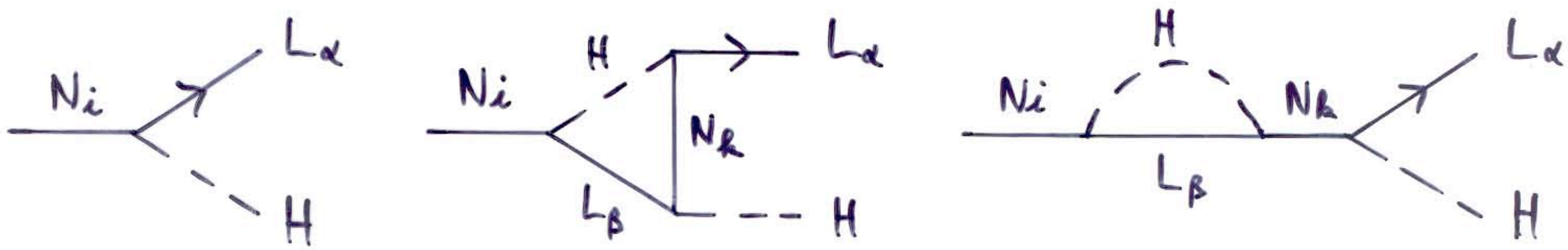
- part of the generated lepton asymmetry is converted into a baryon asymmetry by non-perturbative SM processes (sphalerons), which are in equilibrium in the early Universe and violate B and L, while preserving B-L

→ leptogenesis   Fukugita, Yanagida '86

<u>Lepton number violation</u>: being Majorana fermions, the heavy neutrinos can decay both into leptons and into antileptons



<u>CP violation</u>: the decay rates into leptons and antileptons differ due to quantum corrections induced by the CP-violating heavy neutrino couplings



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

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

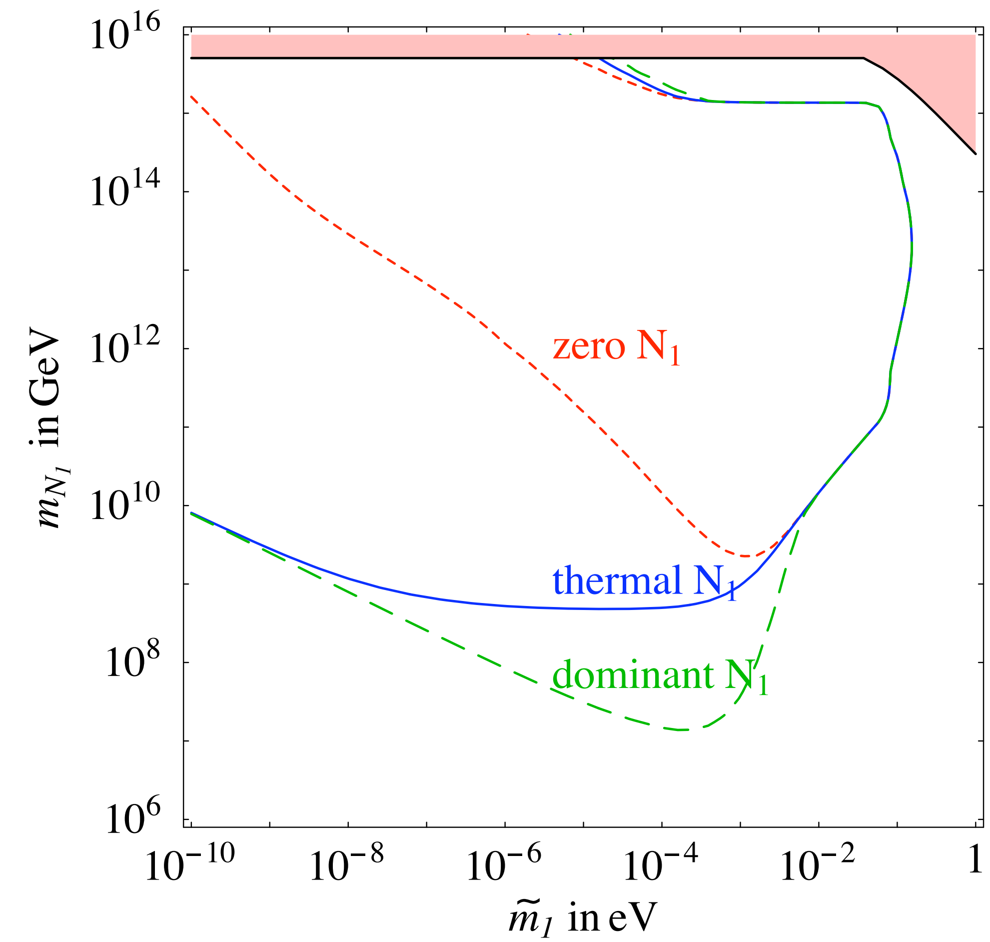
<u>out-of-equilibrium condition</u>: provided by the expansion of the Universe

Thermal leptogenesis can explain the observed baryon asymmetry

region of successful leptogenesis in the $(\tilde{m}_1, M_1)$ plane ($M_1 \ll M_2, M_3$)

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

[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]

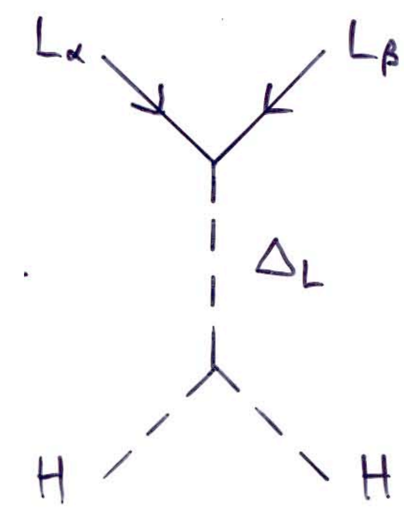
Case $M_1 \approx M_2$: if $|M_1 - M_2| \sim \Gamma_2$, the generated lepton asymmetry is resonantly enhanced, and $M_1 \ll 10^9\,\mathrm{GeV}$ becomes compatible with successful leptogenesis ("resonant leptogenesis")

Covi, Roulet, Vissani '96
Pilaftsis '97

Leptogenesis from other heavy decaying states

Leptogenesis is also possible in other neutrino mass generation mechanisms, such as the type-II seesaw mechanism

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$ scalar 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 (needed to induce different decay rates into leptons and antileptons)

→ scalar triplet leptogenesis [Ma, Sarkar '98 - Hambye, Senjanovic '03]

Can reproduce the observed baryon asymmetry for

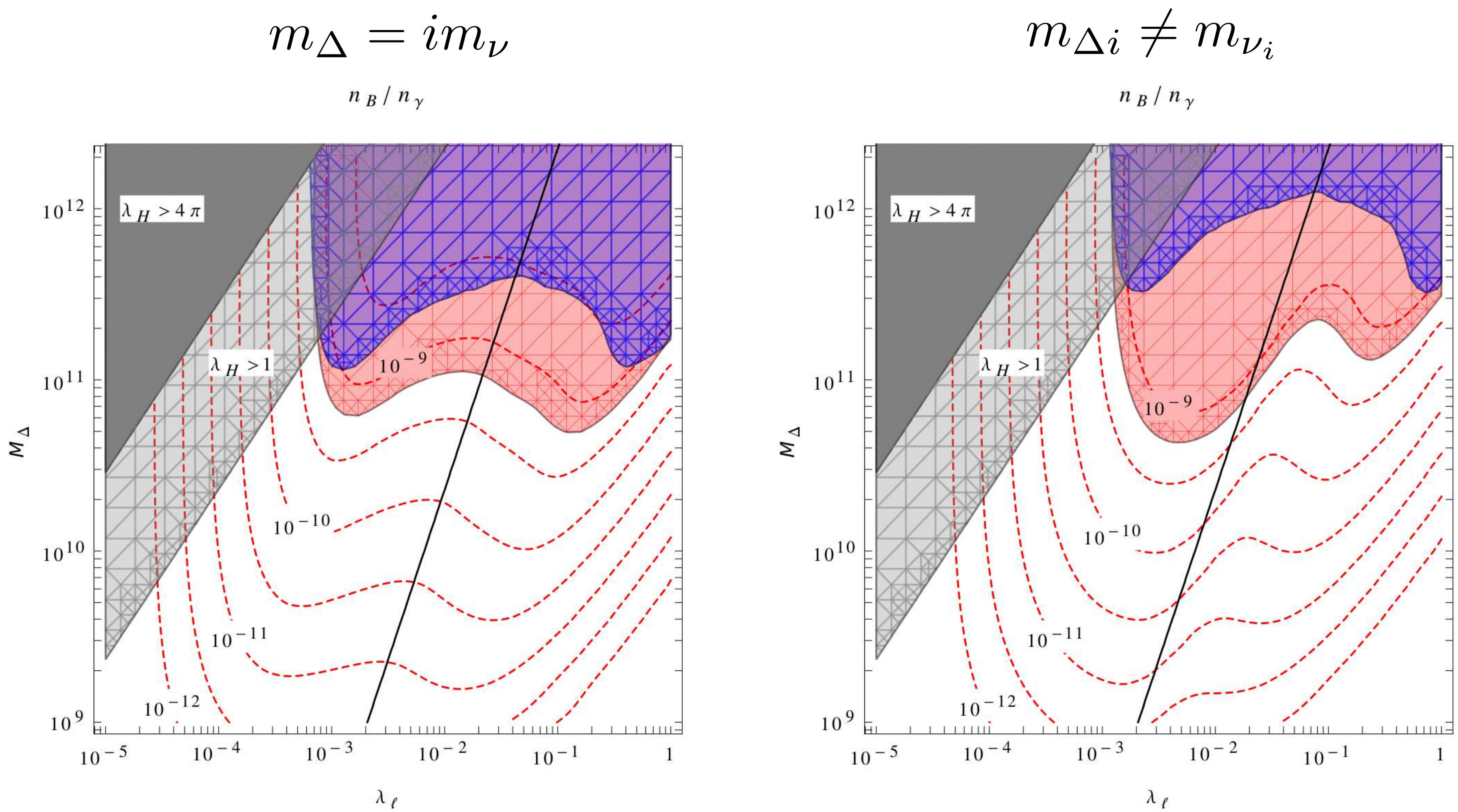
$$M_\Delta > 2.8 \times 10^{10}\,\mathrm{GeV} \qquad (\bar{m}_\Delta = 0.001\,\mathrm{eV})$$
$$M_\Delta > 1.3 \times 10^{11}\,\mathrm{GeV} \qquad (\bar{m}_\Delta = 0.05\,\mathrm{eV})$$

Hambye, Raidal, Strumia '05

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

The parameter space of scalar triplet leptogenesis

[SL, Schmauch '15]



without lepton flavour effects

with lepton flavour effects

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.

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

Leptogenesis can generate the observed baryon asymmetry of the Universe but hard to test directly. Can one find correlations between leptogenesis and low-energy CP violation?

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

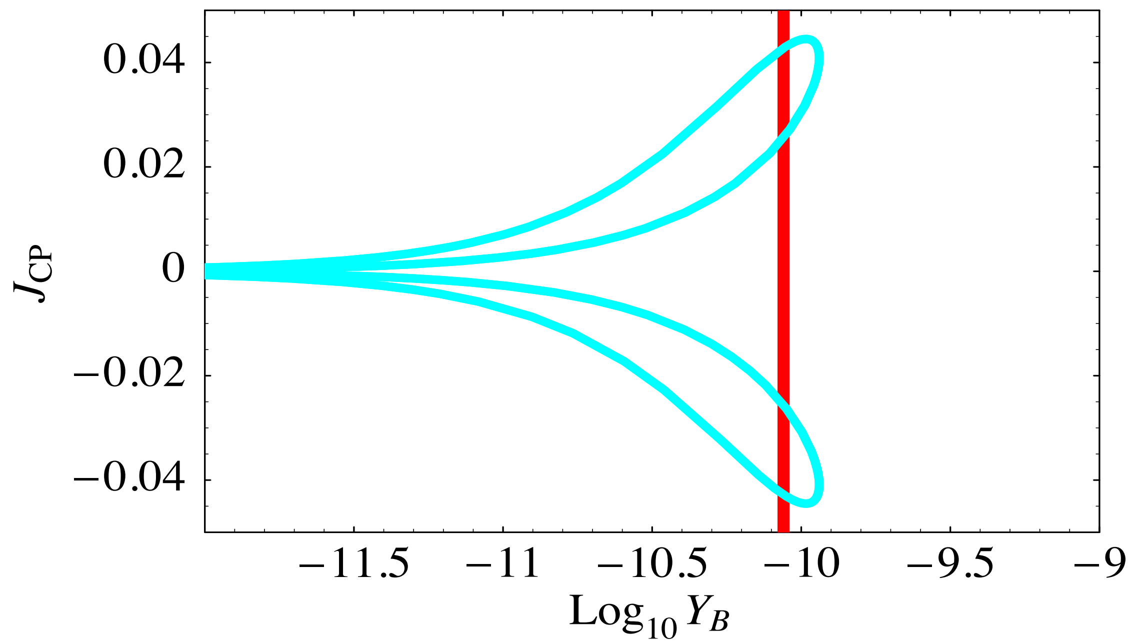


FIG. 1. The invariant J_{CP} versus the baryon asymmetry varying (in blue) $\delta = [0, 2\pi]$ in the case of hierarchical RH neutrinos and NH light neutrino mass spectrum for $s_{13} = 0.2$, $\alpha_{32} = 0$, $R_{12} = 0.86$, $R_{13} = 0.5$ and $M_1 = 5 \times 10^{11}$ GeV . The red region denotes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

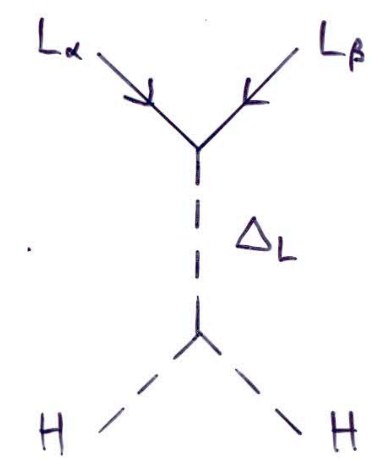
[Pascoli, Petcov, Riotto '06]

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

→ however, no direct link in general between leptogenesis (which depends on 6 phases in the type-I seesaw case) and low-energy CP phases / parameters. Only in specific models

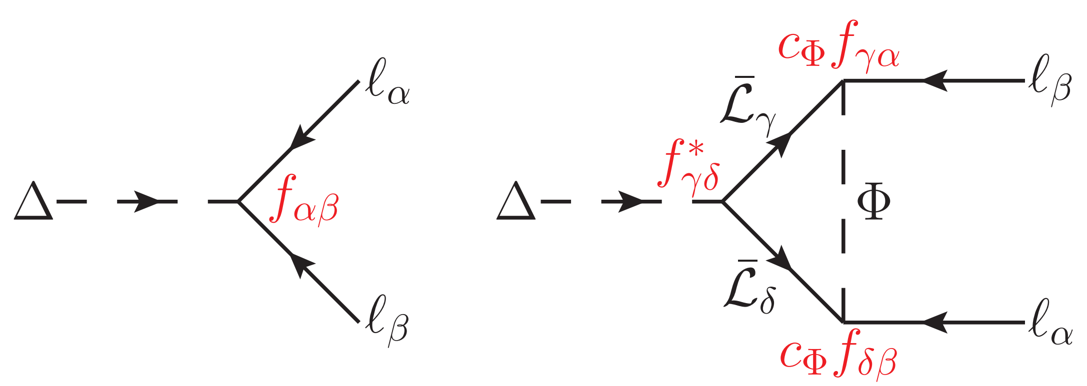
Example of a predictive (scalar triplet) leptogenesis model

Non-standard SO(10) model with a 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 different rates for (anti-)triplet decays into leptons and antileptons

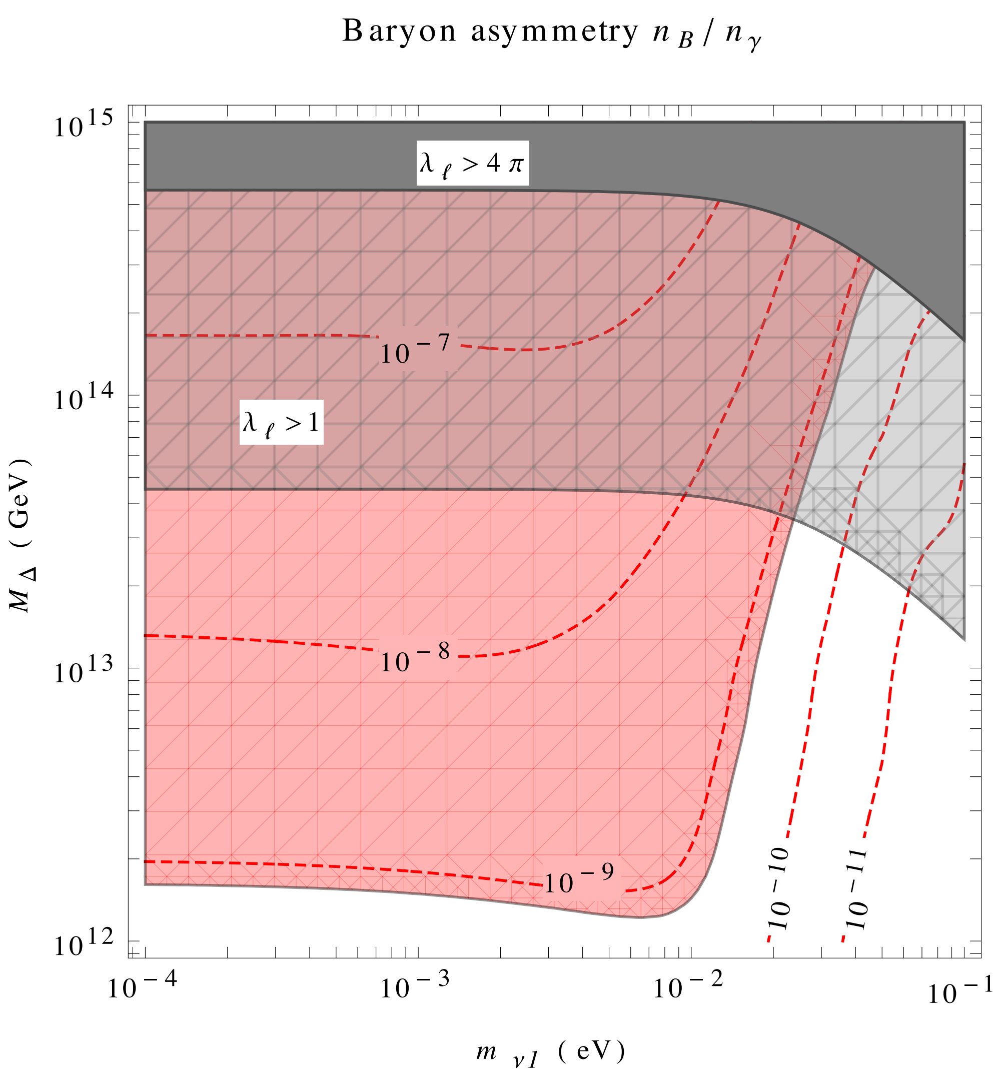


The SM and heavy lepton couplings are related by the SO(10) gauge symmetry ⇒ the asymmetry in triplet decays can be expressed in terms of neutrino parameters (masses, mixing angles, Majorana phases)

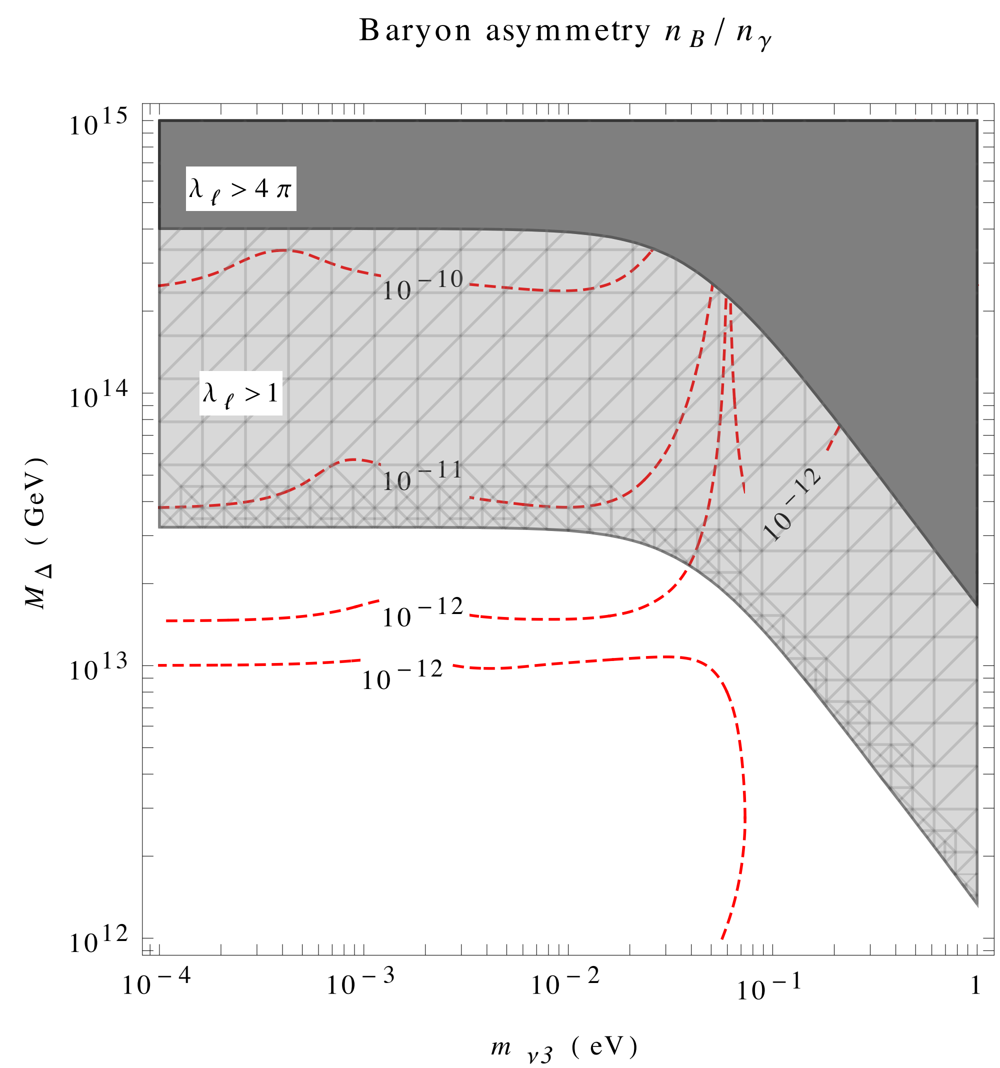
[Frigerio, Hosteins, SL, Romanino '08]

Parameter space allowed by successful leptogenesis

normal ordering



inverted ordering



$\lambda_H = 0.2$

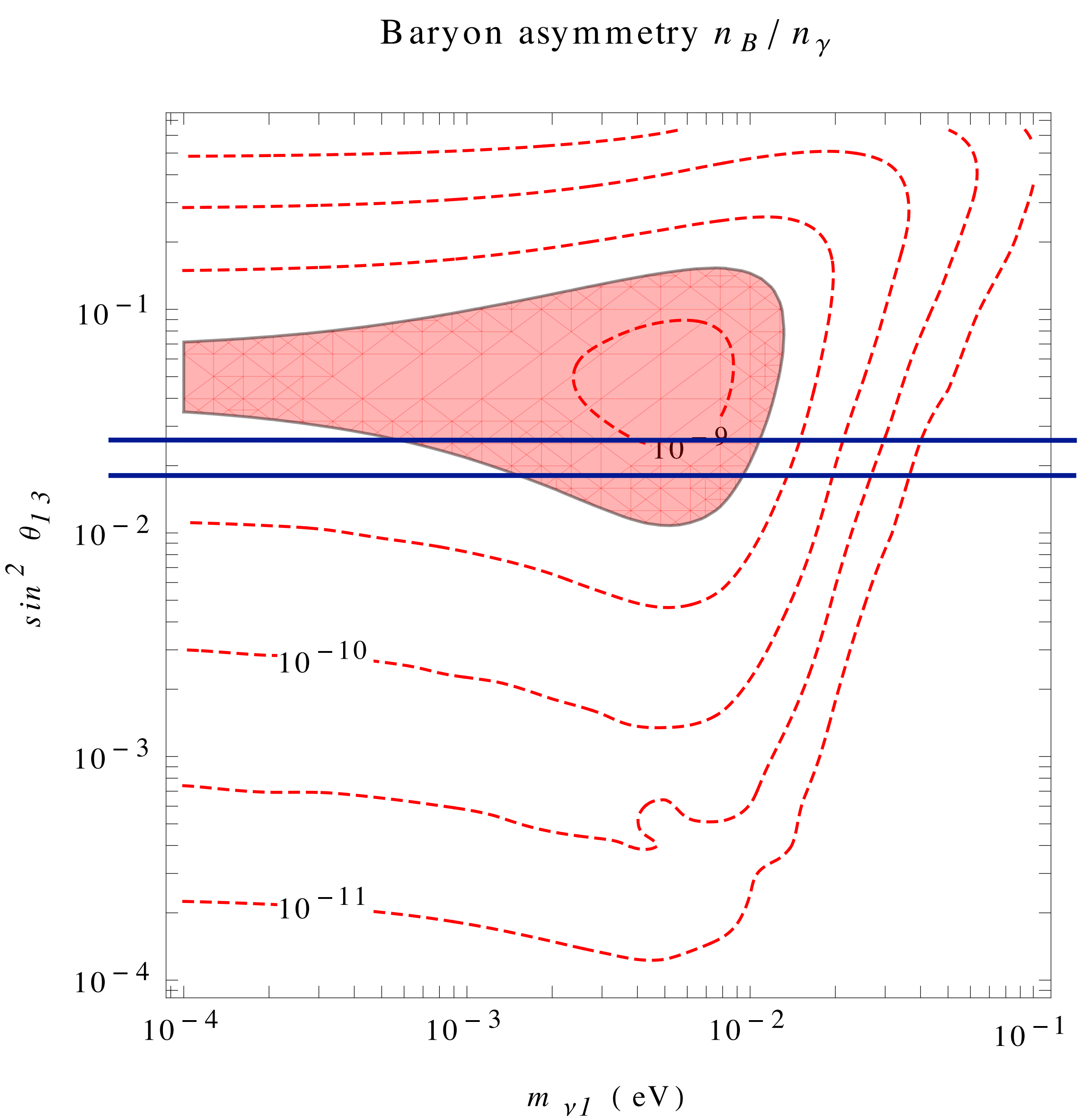
→ quasi-degenerate spectrum excluded for normal ordering

→ inverted ordering disfavored

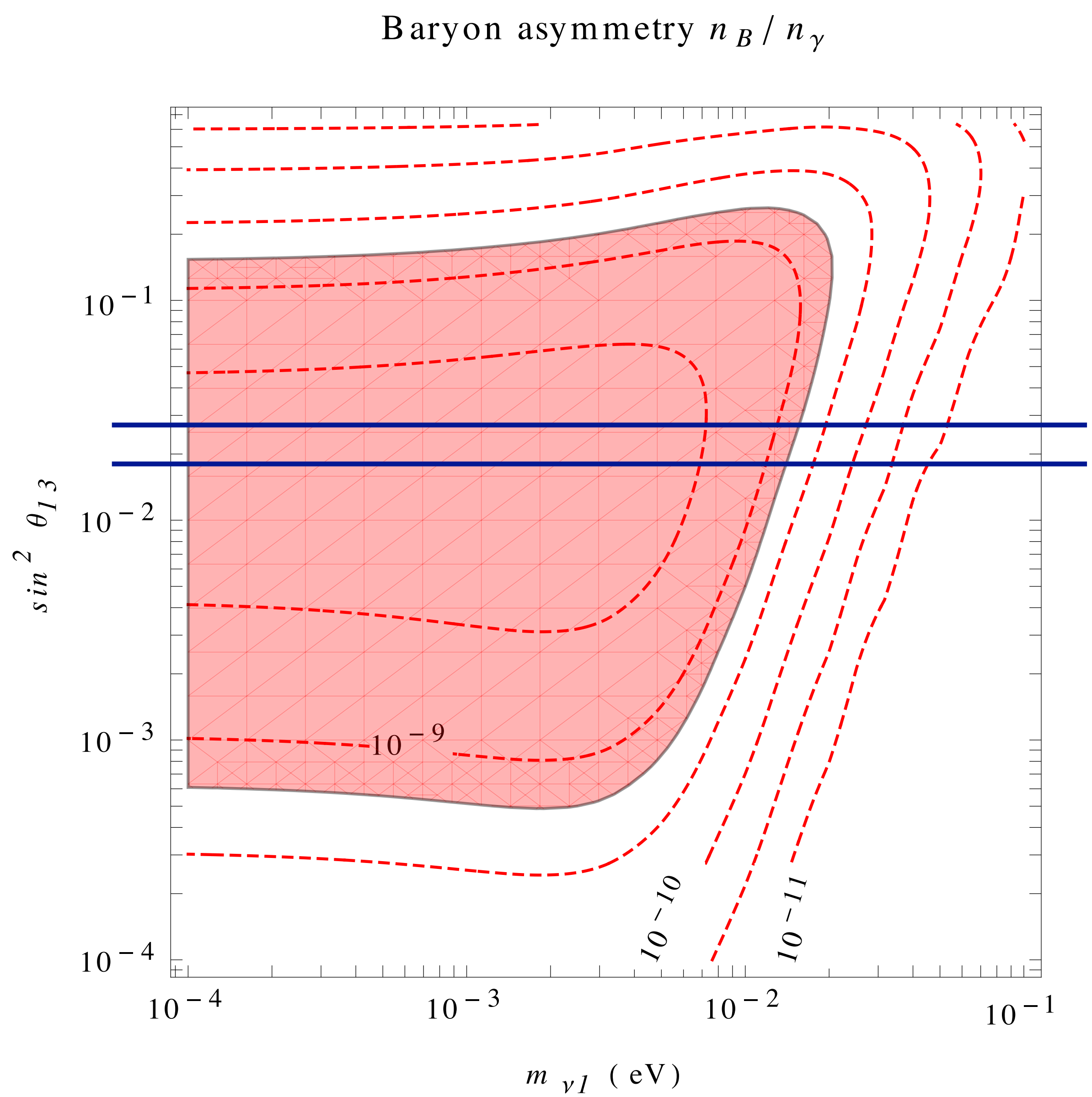
[SL, Schmauch]

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]

Low-scale leptogenesis

Even within the type-I seesaw model, leptogenesis possible with right-handed neutrinos in the TeV range (resonant leptogenesis) or in the GeV range, through a completely different mechanism (leptogenesis from sterile neutrino oscillations, aka ARS leptogenesis)

Resonant leptogenesis

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

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

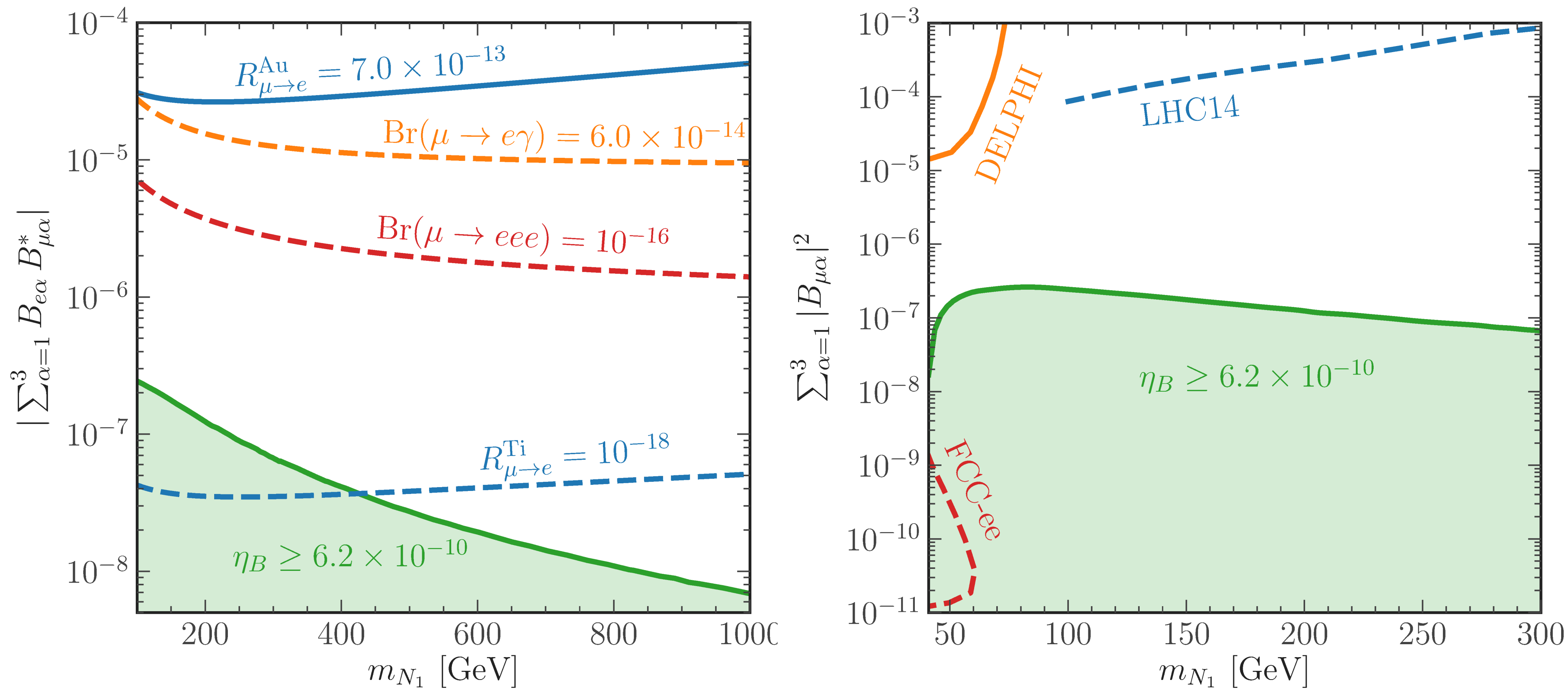
$\Rightarrow$ can be tested via direct production of heavy Majorana neutrinos at colliders + contributions to flavour violating processes in the charged lepton sector

[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

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

(also, the value of $\Delta M/M$ and of other parameters must be very 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 $m_\nu \sim y^2 v^2 / M$

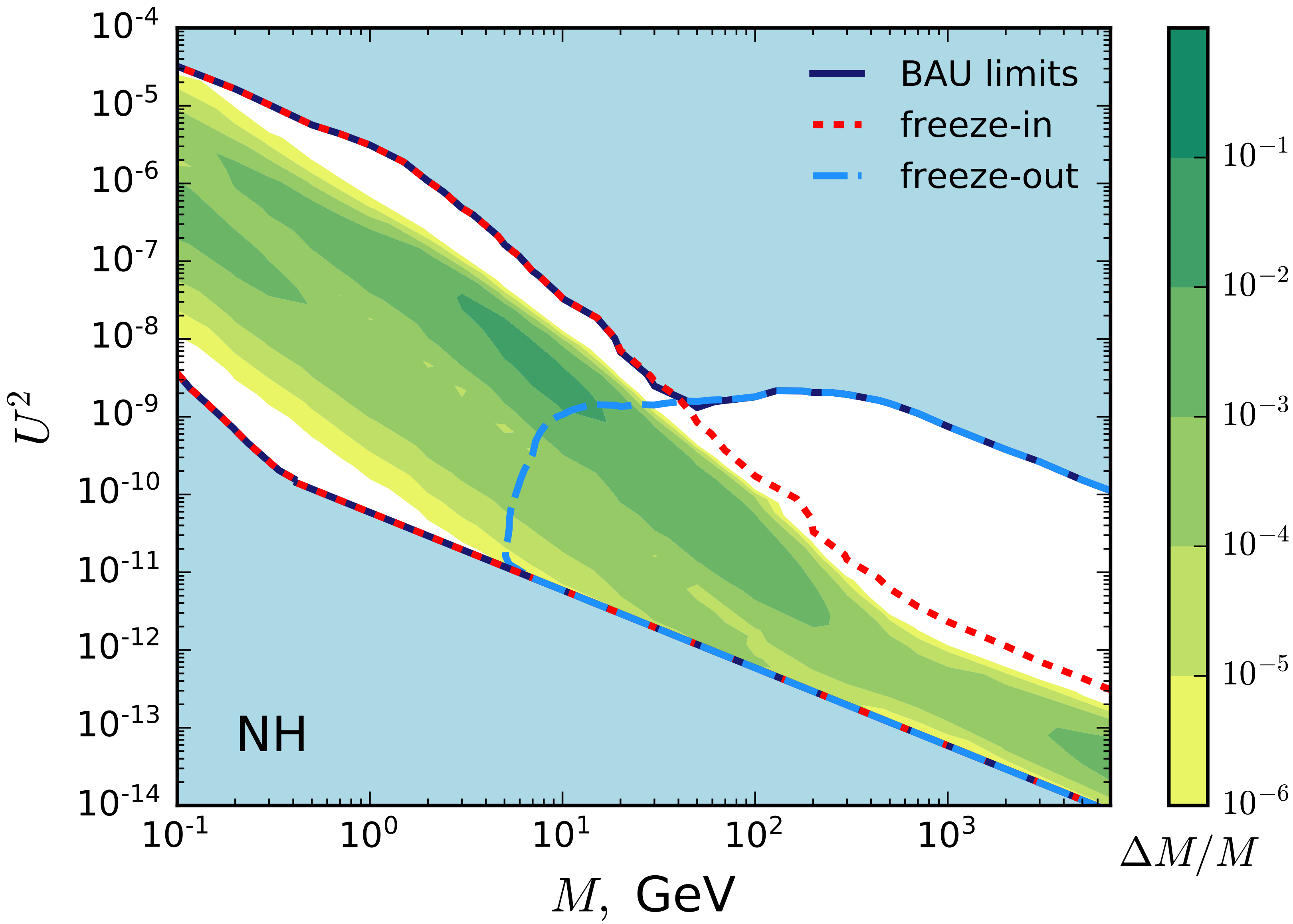
$$\Rightarrow \quad \frac{\Gamma(T)}{H(T)} \sim \left(\frac{m_\nu}{0.05\,\mathrm{eV}}\right)\left(\frac{M}{10\,\mathrm{GeV}}\right)\left(\frac{100\,\mathrm{GeV}}{T}\right)$$

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)

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]

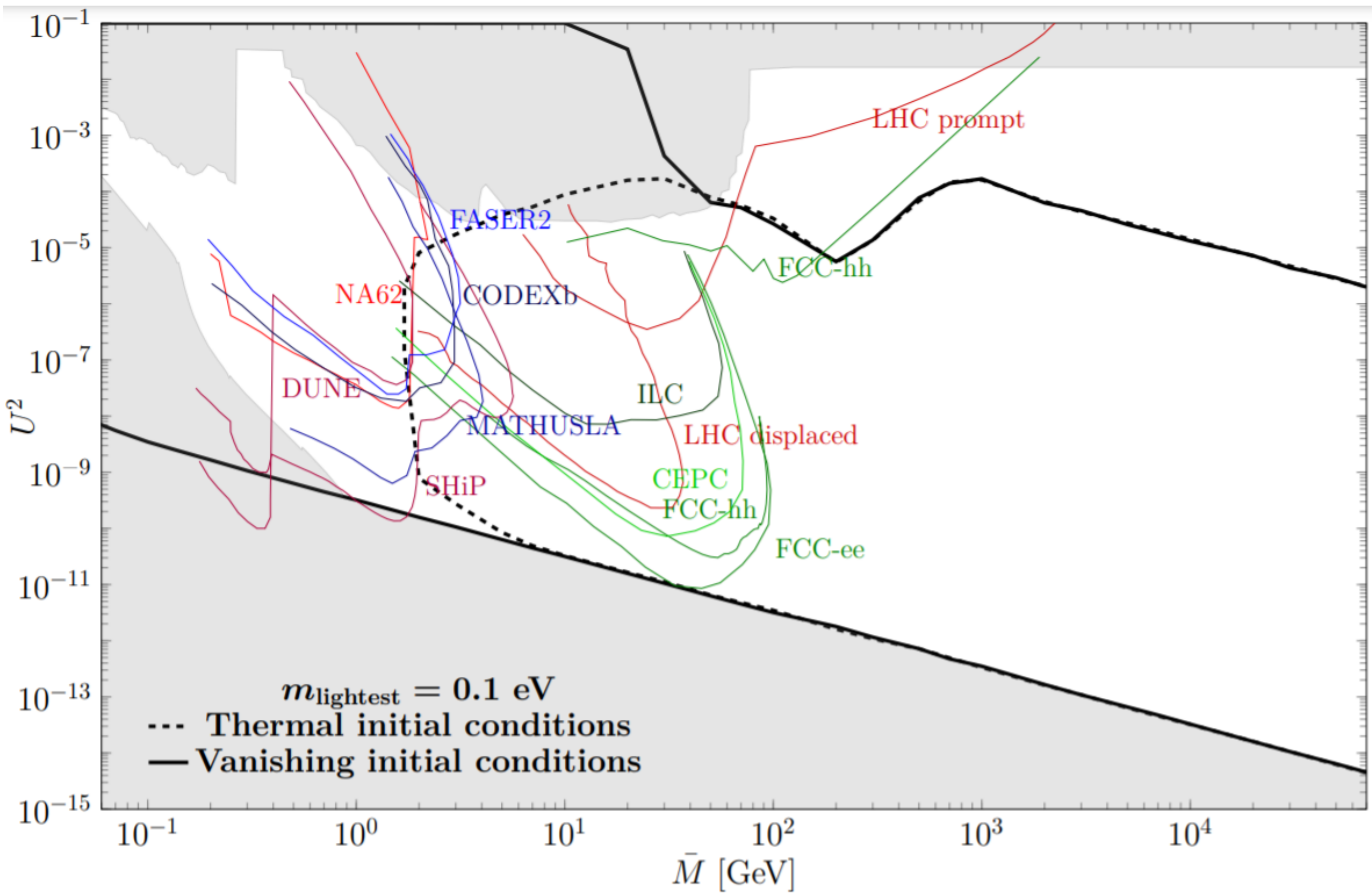


Large values of the active-sterile neutrino mixing U arise when some tuning is present in the sterile neutrino couplings (can be justified by symmetries)

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

In spite of enormous progress in neutrino physics over the past 25 years, the origin of neutrino masses remains a mystery

Theoretical arguments strongly suggests that neutrinos should be Majorana fermions, but an experimental observation of neutrinoless double beta decay is mandatory to validate them

If the new physics at the origin of neutrino masses is light (TeV-scale or less), it may yield observable signatures: production of new particles coupling to leptons at colliders (possibly with lepton number violating signatures), charged lepton flavour violation, non-standard contributions to neutrinoless double beta decay…

If the new physics at the origin of neutrino masses is heavy, leptogenesis might be its only observable consequence (beyond neutrino masses)