Neutrinos and physics beyond the Standard Model

Stéphane Lavignac (IPhT Saclay)

- Dirac versus Majorana neutrinos
- neutrino masses as evidence for physics beyond the SM ?
- models of neutrino mass generation
- light sterile neutrinos
- heavy neutral leptons and their experimental signatures
- (low-scale) leptogenesis

Neutrino Frontiers training week
Galileo Galilei Institute, Florence, 25-28 June 2024

Neutrinos and physics beyond the Standard Model

Lecture 2

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Sterile neutrinos

Only 3 light neutrinos ($m_\nu < M_Z/2$) couple to the Z boson :

$$N_\nu \equiv \Gamma_Z^{\text{invisible}} / \Gamma(Z \to \nu\bar{\nu})_{\text{SM}} = 2.9840 \pm 0.0082 \qquad \text{[LEP]}$$

Still additional light neutrino species without electroweak interactions may exist. These "sterile neutrinos" would interact only through their mixing with the "active neutrinos" ν_e, ν_μ, ν_τ and affect their oscillations.

(eV-scale) sterile neutrinos have been invoked to explain experimental anomalies that cannot be accounted for within 3-flavour oscillations

Sterile neutrinos are present in models where the SM neutrino masses arise from their coupling to RH neutrinos with a Majorana mass. In the seesaw limit, the sterile neutrinos are very heavy and mix very weakly with the SM neutrinos. But in general, their masses may lie anywhere between the eV and the Grand Unification scale. Generic prediction : the lighter the sterile neutrinos, the stronger their mixing with active neutrinos

$$m_\nu \sim \frac{m_D^2}{M}\,, \quad m_s \sim M\,, \quad \sin\theta \sim \frac{m_D}{M} \quad \Rightarrow \quad \sin\theta \sim \sqrt{\frac{m_\nu}{m_s}}$$

Active-sterile neutrino mixing

Standard case (3 flavours)

3x3 lepton mixing matrix (PMNS)

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\, \nu_i$$

3 flavour eigenstates $(\alpha = e, \mu, \tau)$

3 mass eigenstates with masses mi $(i = 1, 2, 3)$

Add a sterile neutrino :

$$\nu_\alpha = \sum_{i=1}^{4} U_{\alpha i}\, \nu_i \qquad (\alpha = e, \mu, \tau, s)$$

ν_s flavour eigenstate

ν_4 mass eigenstate (m_4)

lepton mixing matrix U = 4x4 unitary matrix

Only ν_e, ν_μ, ν_τ couple to electroweak gauge bosons, but all four mass eigenstates are produced in a weak process like beta decay

e^-

$\nu_e = \sum_{i=1}^{4} U_{ei}\, \nu_i$

(if kinematically accessible, as assumed in the following)

New oscillation parameters : $\Delta m^2_{43}\,,\ \Delta m^2_{42}\,,\ \Delta m^2_{41}$

$\theta_{14}\,,\ \theta_{24}\,,\ \theta_{34}$ $\quad$ (or $U_{e4}, U_{\mu 4}, U_{\tau 4}$)

<u>Consider short baseline oscillations with</u> $\Delta m^2_{41} \gg \Delta m^2_{31}$

$$\frac{\Delta m^2_{41} L}{4E} \lesssim 1 \quad \Longrightarrow \quad \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \gg \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right),\ \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

→ approximate $\Delta m^2_{31} = \Delta m^2_{21} = 0\,,\quad \Delta m^2_{43} = \Delta m^2_{42} = \Delta m^2_{41} \equiv \Delta m^2_{\mathrm{SBL}}$

$$P_{\nu_\alpha \to \nu_\alpha} \simeq 1 - 4\left(|U_{\alpha 1}|^2 + |U_{\alpha 2}|^2 + |U_{\alpha 3}|^2\right)|U_{\alpha 4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\equiv 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

where $\sin^2 2\theta_{\alpha\alpha} \equiv 4\,(1 - |U_{\alpha 4}|^2)|U_{\alpha 4}|^2$

$$P_{\nu_\alpha \to \nu_\beta} \simeq -4\,\mathrm{Re}\left[\left(U_{\alpha 1} U^*_{\beta 1} + U_{\alpha 2} U^*_{\beta 2} + U_{\alpha 3} U^*_{\beta 3}\right) U^*_{\alpha 4} U_{\beta 4}\right] \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\equiv \sin^2 2\theta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

where $\sin^2 2\theta_{\alpha\beta} \equiv 4\,|U_{\alpha 4} U_{\beta 4}|^2$

Experimental status of oscillation anomalies

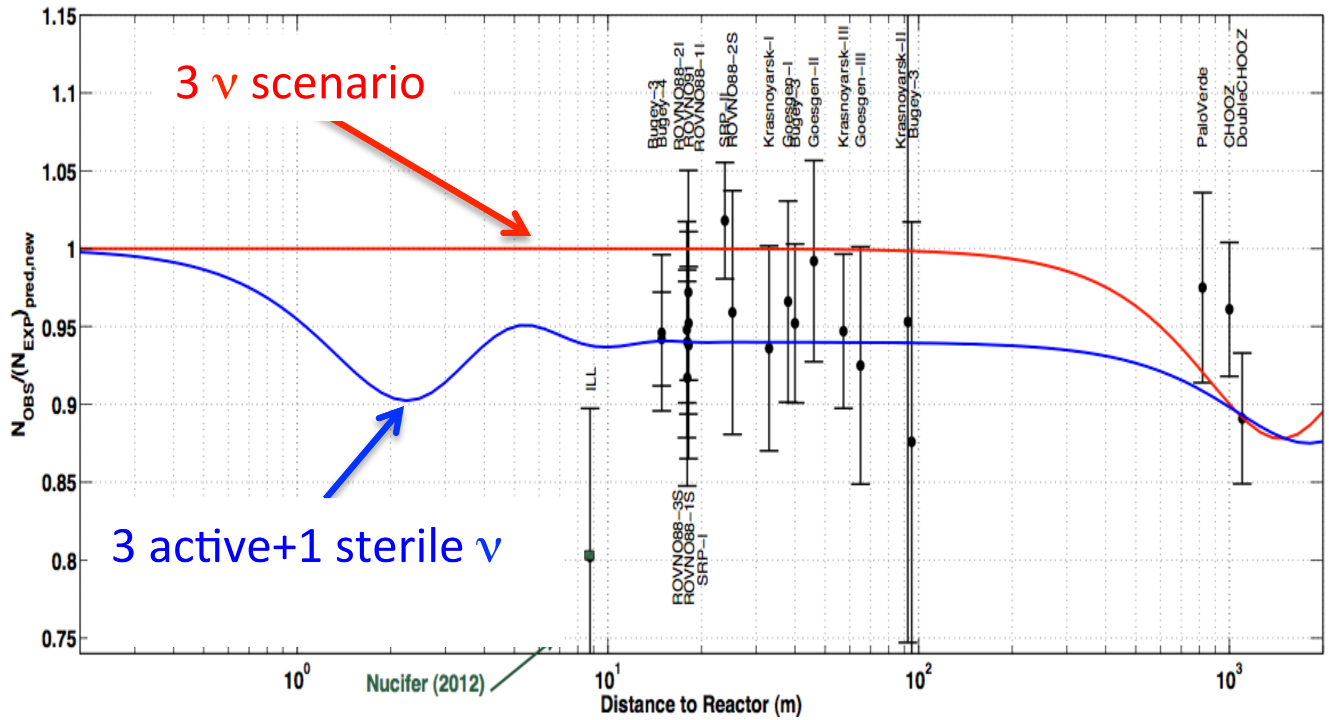
<u>Short-baseline $\nu_e(\bar{\nu}_e)$ disappearance experiments</u>

<u>The reactor antineutrino anomaly (RAA) [2011]</u>

New computation of the reactor $\bar{\nu}_e$ spectra [Th. Mueller et al., 2011 - P. Huber, 2011]
$\Rightarrow$ increase of the flux by about 3.5%
$\Rightarrow$ deficit of antineutrinos in SBL reactor experiments

Mean observed to predicted rate 0.943 ± 0.023 [G. Mention et al., arXiv:1101.2755]
(significance of 2.6 σ)

can be explained by $\bar{\nu}_e \to \bar{\nu}_s$ oscillations with $\Delta m^2_{41} \sim 1\,\mathrm{eV}^2$ and $\sin^2 2\theta_{ee} \sim 0.1$

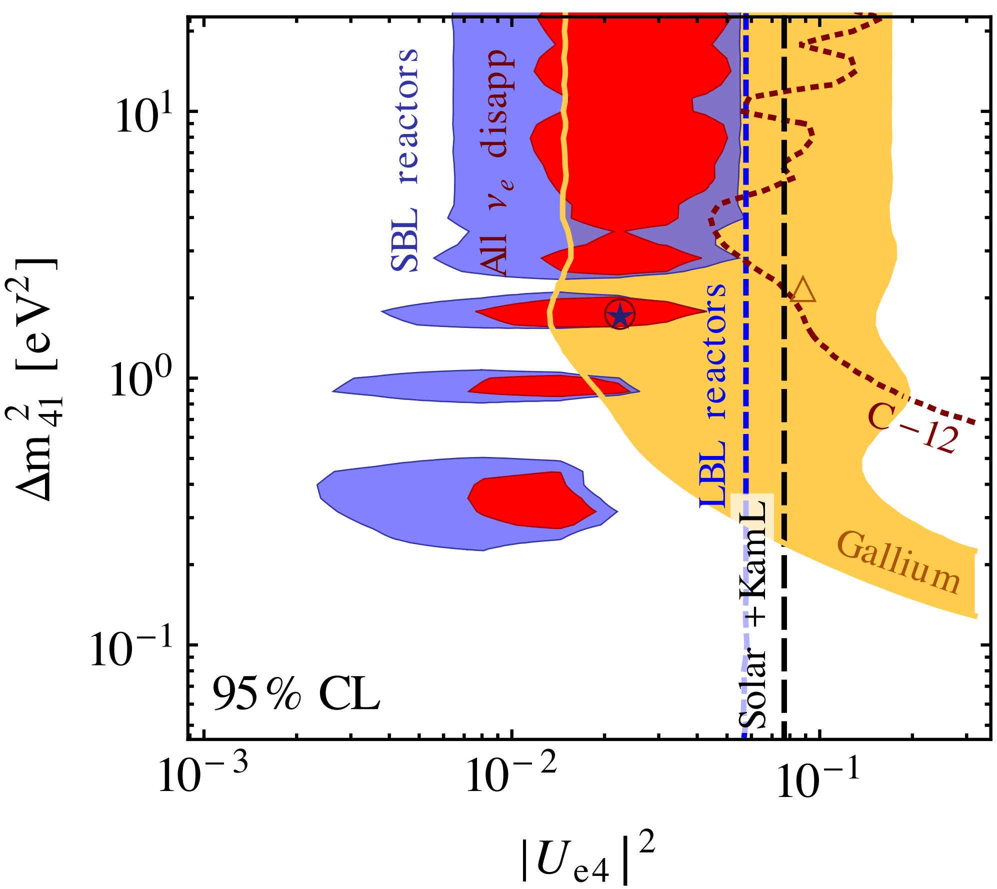


[D. Lhuillier, talk at IPA 2016]

The Gallium anomaly

Calibration of the Gallex and SAGE experiments with radioactive sources
$\Rightarrow$ observed 3σ deficit of ν_e with respect to predictions (R = 0.84 ± 0.05)

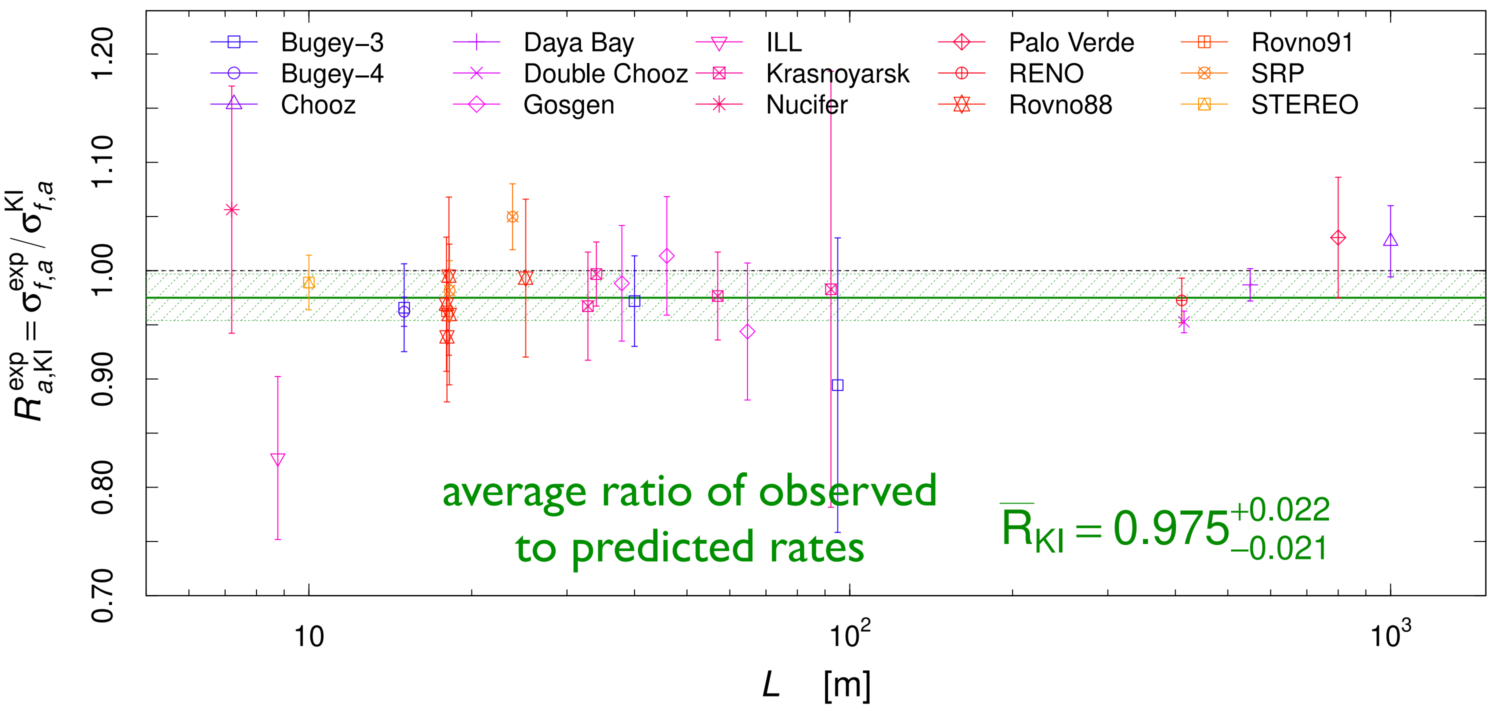
The reactor and gallium anomalies suggest oscillations into a sterile neutrino with $\Delta m^2_{41} \gtrsim 1\,\mathrm{eV}^2$ and $\sin^2 2\theta_{ee} \sim 0.1$ $\quad [\,\sin^2 2\theta_{ee} \equiv 4(1-|U_{e4}|^2)|U_{e4}|^2\,]$



[Kopp et al., arXiv:1303.3011]

Recent results on the reactor antineutrino anomaly

Kopeikin et al. (arXiv:2103.01684): new computation of the reactor $\bar{\nu}_e$ spectra using recent measurements at the Kurchatov Institute (KI). Find a smaller $^{235}\mathrm{U}$ antineutrino flux than Mueller and Huber, in agreement with the dependence of the antineutrino flux on the fuel composition (proportion of $^{235}\mathrm{U}$, $^{238}\mathrm{U}$, $^{239}\mathrm{Pu}$, $^{241}\mathrm{Pu}$) observed by the Daya Bay and RENO experiments, and confirmed by PROSPECT and STEREO.



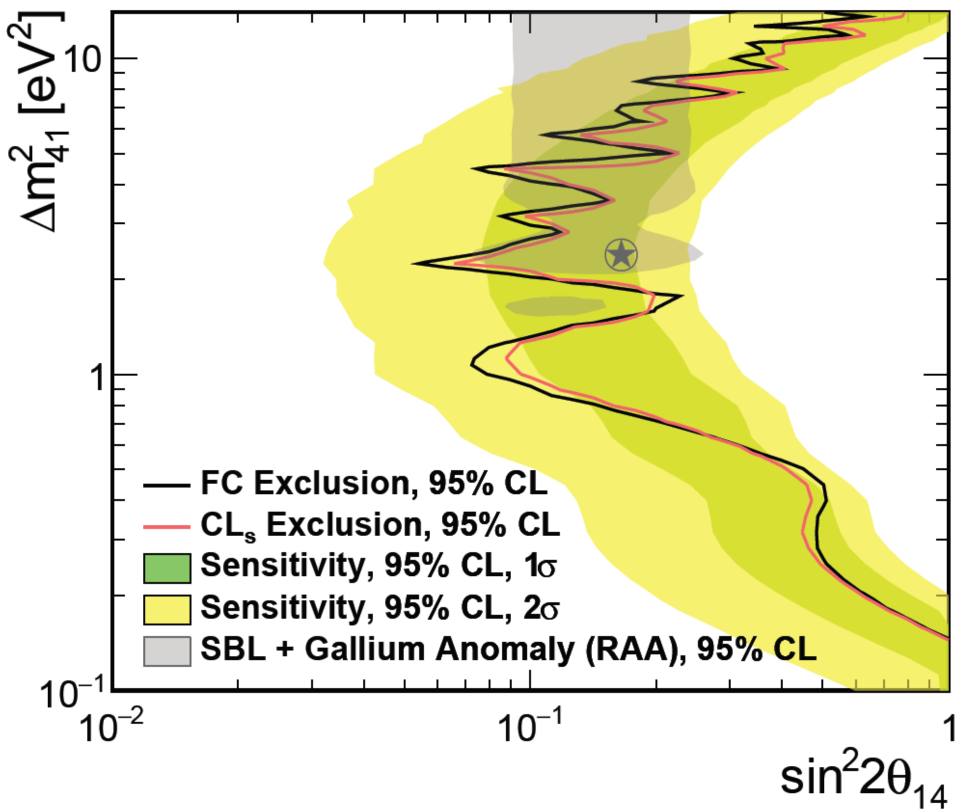
Giunti et al., arXiv:2110.06820

$\Rightarrow$ the significance of the RAA decreases to $1.1\ \sigma$ [similar conclusion with an independent flux computation by Estienne et al. (2019) using a different method]

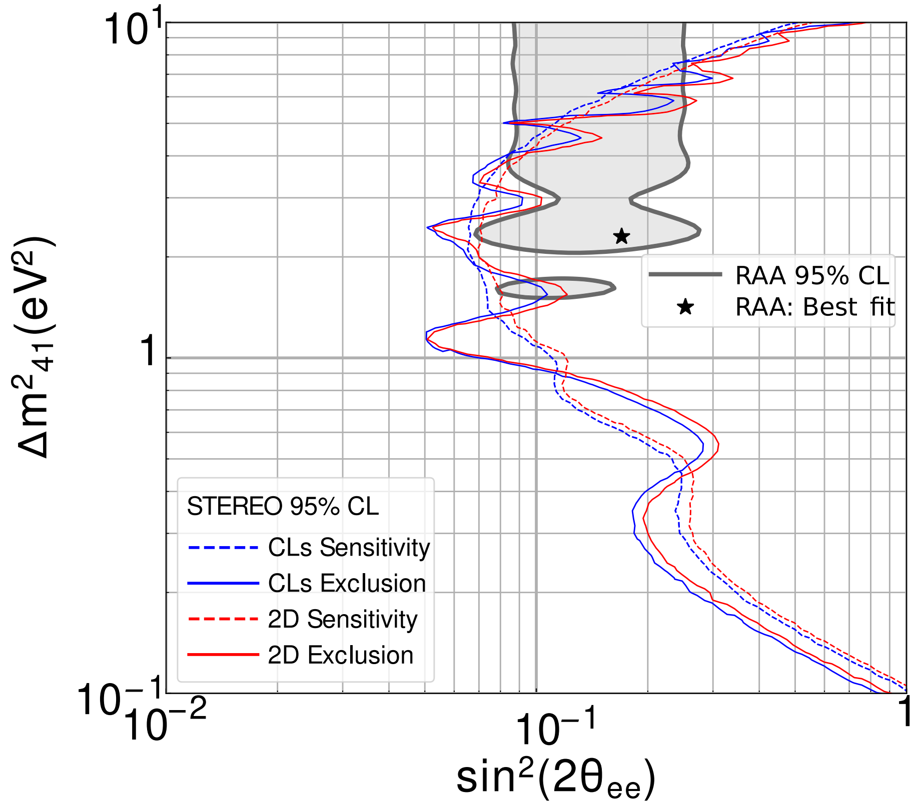
Searches for short-baseline $\bar{\nu}_e$ disappearance

NEOS, DANSS, STEREO and PROSPECT exclude a significant portion of the reactor antineutrino anomaly parameter space

[PROSPECT Collaboration, arXiv:2006.11210]



[STEREO Collaboration, arXiv:2210.07664]



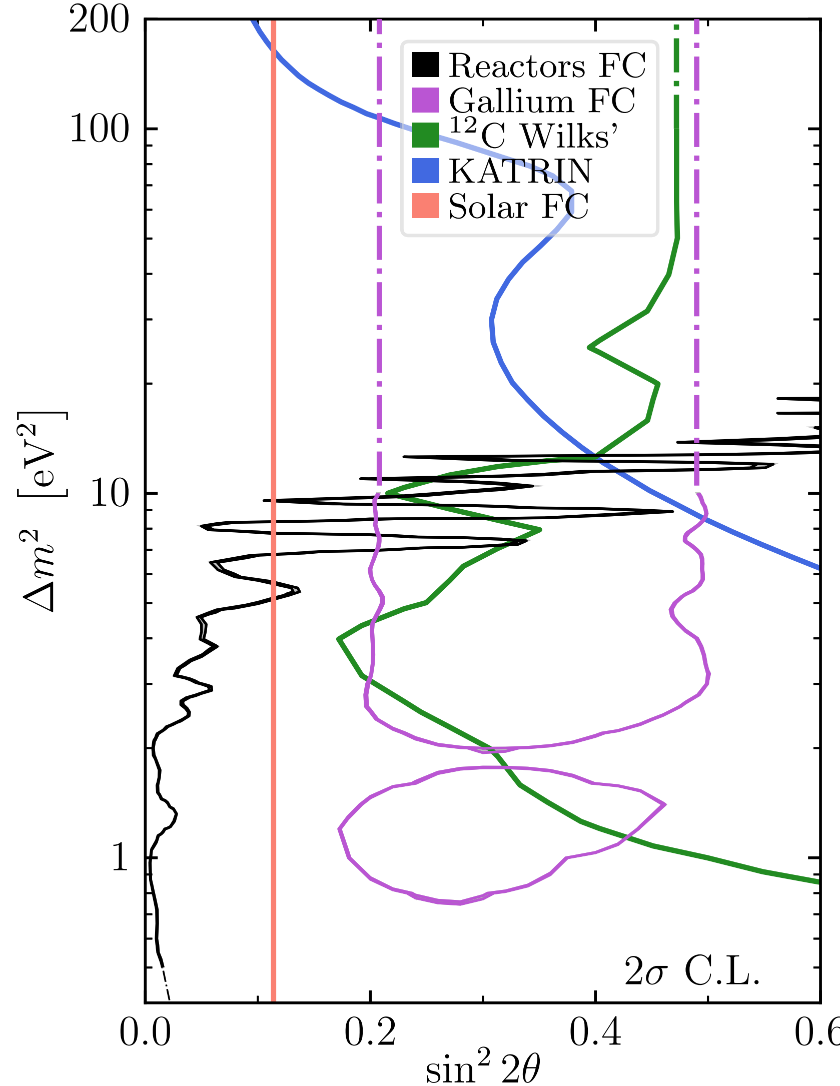
⇒ the reactor antineutrino anomaly is disfavored by SBL reactor experiments and no longer supported by reactor antineutrino flux computations

Update on the gallium anomaly

Recently confirmed by the BEST experiment (arXiv:2109.11482), with an increased statistical significance of 4σ

Oscillation explanation requires a large active-sterile mixing, $\sin^2 2\theta_{ee} \geq 0.2$, in conflict with reactor data for $\Delta m^2_{41} \lesssim 10\,\mathrm{eV}^2$ and with solar neutrino data, which excludes $\sin^2 2\theta_{ee} > 0.11$ at 2σ

⇒ very confusing situation



[J.M. Berryman et al., arXiv:2111.12530]

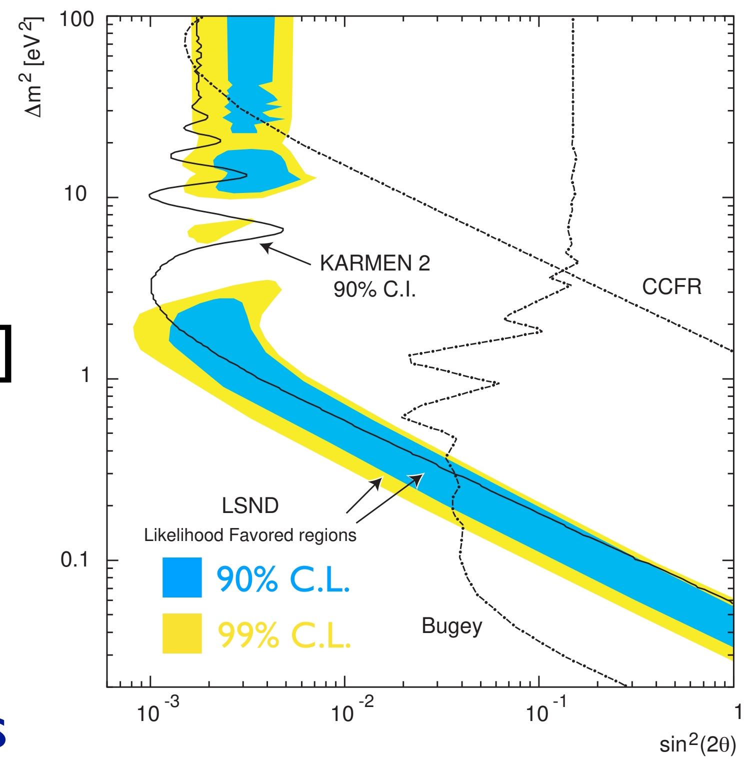
Short-baseline appearance experiments [$\nu_e(\bar{\nu}_e)$ appearance in a $\nu_\mu(\bar{\nu}_\mu)$ beam]

LSND (1993-1998) [$\bar{\nu}_\mu$ beam, $L \approx 35\,\mathrm{m}$]

Excess of $\bar{\nu}_e$ events over background at 3.8 σ interpreted by LSND as $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations

Not observed by KARMEN

[LSND allowed region in the $(\sin^2 2\theta, \Delta m^2)$ plane (2-neutrino fit) - hep-ex/0203021]



$$\sin^2 2\theta_{\mu e} \equiv 4|U_{e4}U_{\mu 4}|^2$$

MiniBooNE (2002-2017) [ν_μ and $\bar{\nu}_\mu, L = 541\,\mathrm{m}$]

Designed to test the LSND anomaly with a different L but a similar L/E

2002-2012 : inconclusive/contradictory results

Full 2002-2019 data : excess of $\nu_e(\bar{\nu}_e)$ CC events both in the ν and $\bar{\nu}$ modes (4.8 σ in total), mainly in the low-energy region, consistent with LSND

→ suggests $\nu_\mu \to \nu_e \;/\; \bar{\nu}_\mu \to \bar{\nu}_e$ oscillations

2002-2019 MiniBooNE results

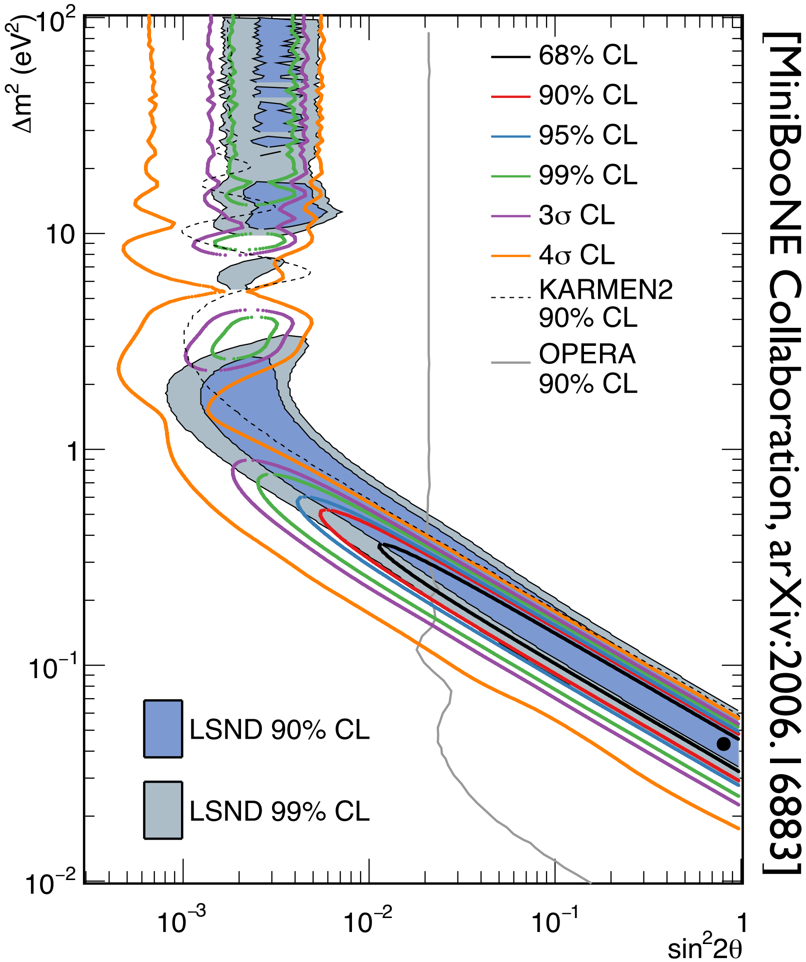


FIG. 20: MiniBooNE allowed regions for combined neutrino mode (18.75×10^{20} POT) and antineutrino mode (11.27×10^{20} POT) data sets for events with $200 < E_\nu^{QE} < 3000$ MeV within a two-neutrino oscillation model. The shaded areas show the 90% and 99% C.L. LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ allowed regions. The black point shows the MiniBooNE best fit point. Also shown are 90% C.L. limits from the KARMEN [26] and OPERA [27] experiments.

MiniBooNE + LSND excesses : 6.1 σ significance

Oscillation interpretation requires a 4th massive neutrino in the eV range

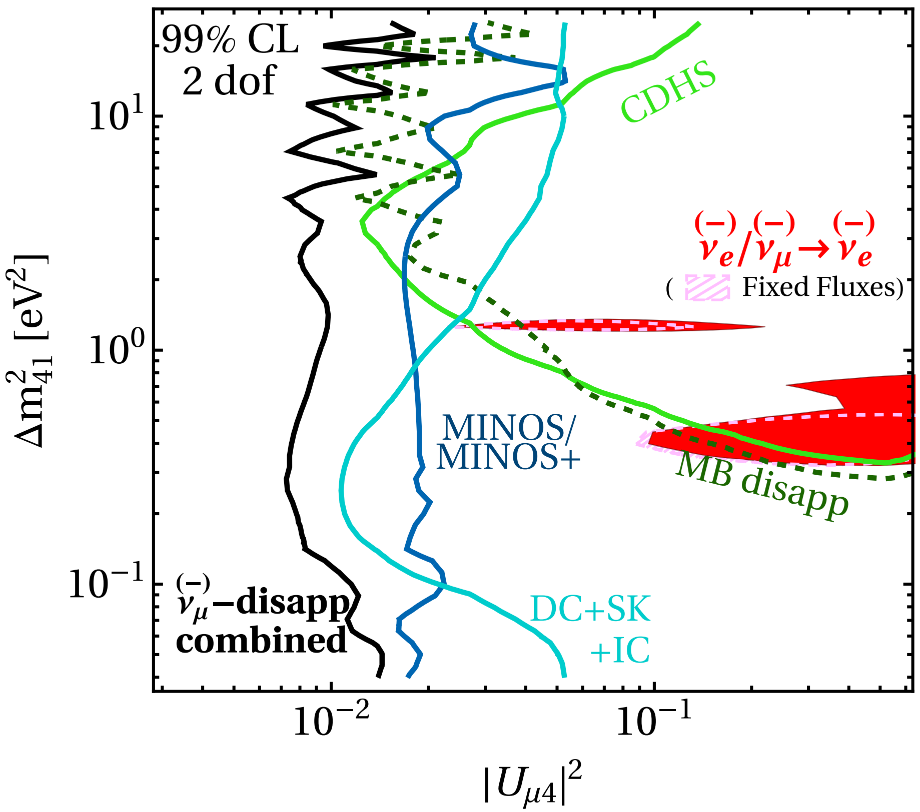
$$\Delta m^2_{41} \gtrsim 0.1\,\mathrm{eV}^2, \quad \sin^2 2\theta_{\mu e} \approx (10^{-3} - 10^{-2})$$

However, this interpretation is essentially excluded by $\nu_\mu(\bar{\nu}_\mu)$ disappearance data :

- MINOS/MINOS+ (long-baseline oscillation experiment)
- IceCube (neutrino telescope located under the Antarctic ice: atmospheric neutrino data)

MINOS/MINOS+ : long-baseline oscillation experiment (L_{near} = 1.04 km, L_{far}= 735 km). Has analyzed both charged current data ($\nu_\mu/\bar{\nu}_\mu$ disappearance) and neutral current data, which is sensitive to the total flux of active neutrinos, hence to $\nu_\mu \to \nu_s$ oscillations

IceCube : a sterile neutrino in the eV range would affect the survival probability of atmospheric $\bar{\nu}_\mu$ passing through the Earth (MSW resonance) $\Rightarrow$ sensitivity to Δm^2_{41} and $\sin^2 2\theta_{\mu\mu}$



strong conflict between appearance data (LSND + MiniBooNE, allowed regions in red) and disappearance data (exclusion curves from CDHS, MINOS/MINOS+, MiniBooNE disappearance data, SK + IceCube)

[M. Dentler et al., arXiV:1803.10661]

Origin of the conflict between appearance (LSND + MiniBooNE) and disappearance experiments (reactors, accelerators, IceCube…)

Reactors : $$P_{\bar{\nu}_e \to \bar{\nu}_e} \simeq 1 - \sin^2 2\theta_{ee} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

require relatively small $\sin^2 2\theta_{ee} \equiv 4\,(1 - |U_{e4}|^2)|U_{e4}|^2 \simeq 4\,|U_{e4}|^2$

($|U_{e4}|^2 \approx 1$ excluded by SNO)

MINOS, IceCube… : $\nu_\mu (\bar{\nu}_\mu)$ disappearance not observed

require relatively small $\sin^2 2\theta_{\mu\mu} \equiv 4\,(1 - |U_{\mu 4}|^2)|U_{\mu 4}|^2 \simeq 4\,|U_{\mu 4}|^2$

($|U_{\mu 4}|^2 \approx 1$ excluded by SK and LBL experiments)

Appearance experiments (LSND + MiniBooNE) :

$$P_{\bar{\nu}_\mu \to \bar{\nu}_e} \simeq \sin^2 2\theta_{\mu e} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

require relatively large $\sin^2 2\theta_{\mu e} \equiv 4\,|U_{e4} U_{\mu 4}|^2 \simeq \dfrac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$

Quantifying the tension between appearance and disappearance data

(M. Dentler et al., arXiV:1803.10661)

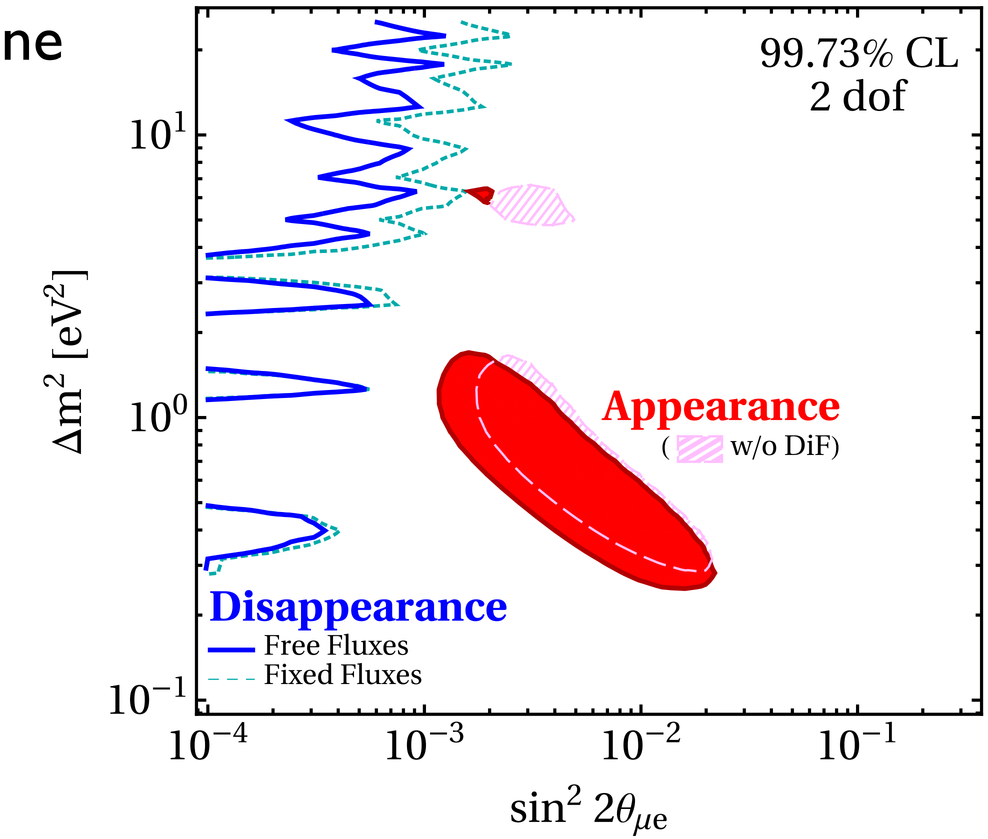
$\left(\sin^2 2\theta_{\mu e} \equiv 4|U_{e4}U_{\mu4}|^2,\, \Delta m_{41}^2\right)$ plane

red region is allowed at 3σ by appearance data

[pink hatched: without LSND DiF]

blue curve defines 3σ excluded region by disappearance data

[dashed = fixed reactor fluxes]



[M. Dentler et al., arXiV:1803.10661]

→ sterile neutrino interpretation of LSND and MiniBooNE data excluded at the 4.7 σ level

This tension persists for 2 sterile neutrinos [M. Maltoni at Neutrino 2018]

Cosmological constraints on sterile neutrinos

Cosmological measurements constrain the number of stable, relativistic degrees of freedom (other than photons) in the early Universe :

$$N_{\text{eff}} = 2.99^{+0.34}_{-0.33} \quad (95\,\%, \text{ TT,TE,EE+lowE+lensing +BAO}).$$

[Planck 2018]

A given species contributes to Neff proportionally to its contribution to the relativistic energy density (normalization : Neff = 1 for a neutrino)

The Standard Model value, due to neutrinos, is $N_{\text{eff}} = 3.044$

[not exactly 3, since neutrino decoupling is not fully completed when e+ and e- annihilate]

In the presence of a sterile neutrino, the cosmological constraint becomes :

$$\left.\begin{aligned} N_{\text{eff}} &< 3.29, \\ m^{\text{eff}}_{\nu,\,\text{sterile}} &< 0.65 \text{ eV}, \end{aligned}\right\} \quad 95\,\%, \textit{Planck} \text{ TT,TE,EE+lowE +lensing+BAO},$$

[Planck 2018]

A sterile neutrino with the mixing angles suggested by oscillation anomalies would be fully thermalized and contribute as $\Delta N_{\text{eff}} = 1$

→ strongly disfavored by standard cosmology [at 6σ according to Planck]

<u>Ways out :</u> non-standard cosmological model, sterile neutrino interactions that would prevent thermalization… however no compelling proposal so far

Conclusions on sterile neutrinos

- ν_e disappearance: the reactor antineutrino anomaly is fading away, but the gallium anomaly is reinforced by the BEST results, which are in tension with solar neutrino and reactor data

- ν_e appearance (LSND, MiniBooNE) is in strong conflict with disappearance experiments. Also, MicroBooNE has excluded the possibility that the low-energy excess of MiniBooNE be due to e+/e-. Might be due to an unidentified background process or to some new physics other than oscillations

- will be tested by the short baseline accelerator neutrino program at Fermilab (SBN), consisting of a near detector (SBND, 110 m), MicroBoone (470 m) and a far detector (ICARUS, 600 m)

- eV-scale sterile neutrino with significant mixing with active neutrinos are disfavored by cosmology

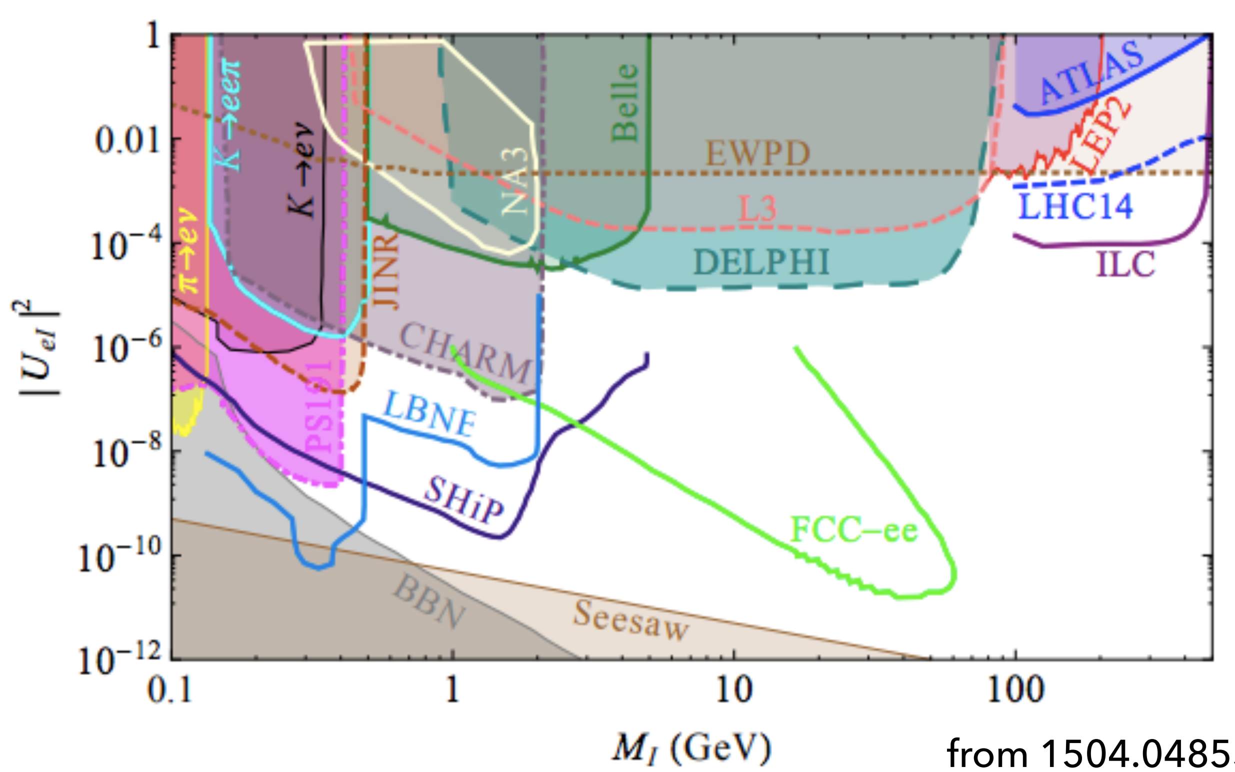
- heavier sterile neutrinos (keV, MeV, GeV, TeV and above) are a less constrained possibility and may play a role in the origin of SM neutrino masses, dark matter and the baryon asymmetry of the Universe

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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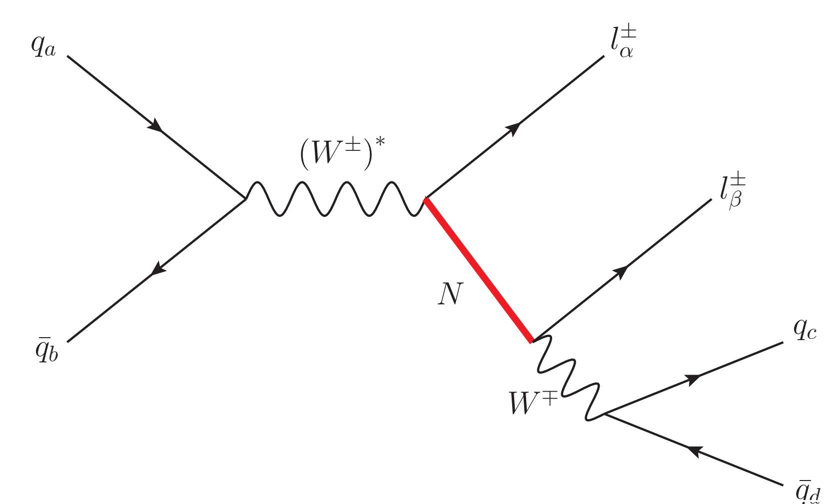


searches for SS dileptons at the LHC

Heavy neutral leptons

Heavy neutral leptons (HNLs) = sterile neutrinos with GeV-TeV scale masses, remnants of a low-scale neutrino mass generation mechanism (type-I or inverse seesaw), which could be produced at colliders

Sterile $\Rightarrow$ only interact through their mixing with active neutrinos, resulting in the effective couplings to the W and Z bosons

$$\mathcal{L}_N \,=\, -\frac{1}{2}\, M_N \bar{N} N + \left(\frac{g}{\sqrt{2}}\, U_{\alpha N}\, W^-_\mu \,\bar{\ell}_\alpha \gamma^\mu N + \frac{g}{2\cos\theta_W}\, U_{\alpha N}\, Z_\mu \bar{\nu}_\alpha \gamma^\mu N + \mathrm{h.c.} \right)$$

$U_{\alpha N}$ $(U_{\alpha 4})$ = active-sterile neutrino mixing $(\alpha = e, \mu, \tau)$

Thus N may be produced in W and Z decays (or via off-shell W or Z bosons), and their decays are also mediated by (on- or off-shell) W and Z bosons

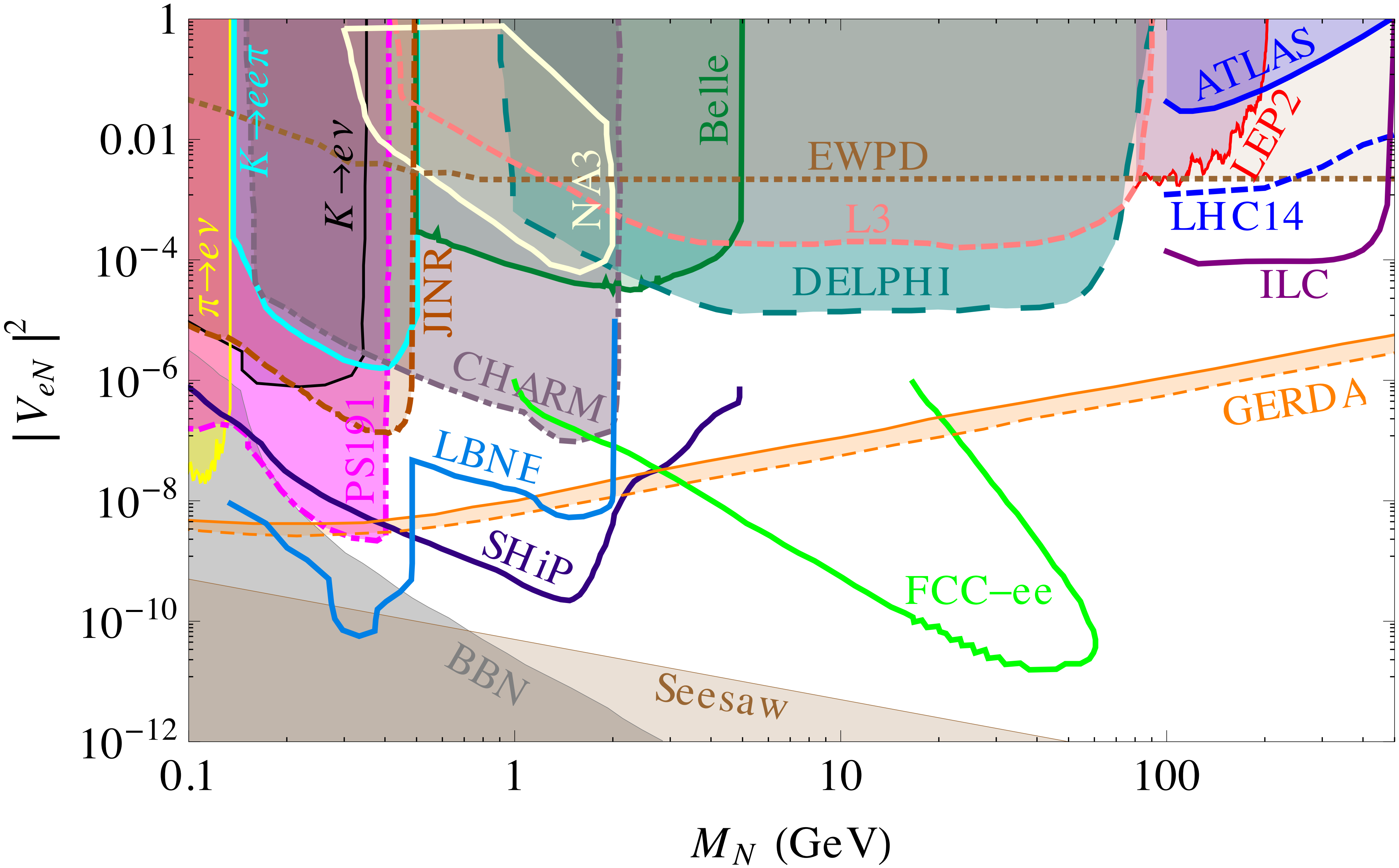
$$N \to l^\pm W^\mp \to l^\pm jj \quad \text{or} \quad l^\pm l'^\mp \nu_{l'}$$

$$N \to \nu Z \to \nu jj \quad \text{or} \quad l^\pm l^\mp \nu_{l'} \quad \text{or} \quad \nu \bar{\nu} \nu$$

$\Rightarrow$ both the N production cross section and decay rate are suppressed by $|U_{\alpha N}|^2$

Constraints on / sensitivity to heavy neutral leptons

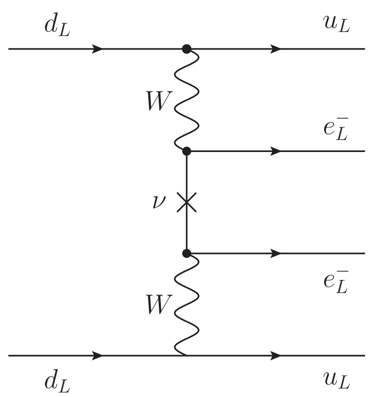
Deppisch, Dev, Pilaftsis, arXiv:1502.06541



Warning: LHC constraints not up to date / some future experiments missing,
LBNE = obsolete for DUNE (near detector)

[earlier derivations of current constraints: Atre et al. (arXiv:0901.3589), Mitra et al. (arXiv:1108.0004)]

<u>BBN constraint</u>: sterile neutrino decays will spoil the successful predictions from Big Bang Nucleosynthesis if their lifetime is < 1s or so



<u>bb0nu constraint</u>: the non-observation of neutrinoless double beta decay constrains U_{eN}

Heavy neutrino ($M_N \gg 100\,\mathrm{MeV}$) contribution to the bb0nu amplitude $\propto U_{eN}^2/M_N$ ($\propto \sum_i m_i U_{ei}^2$ for light = SM neutrinos)

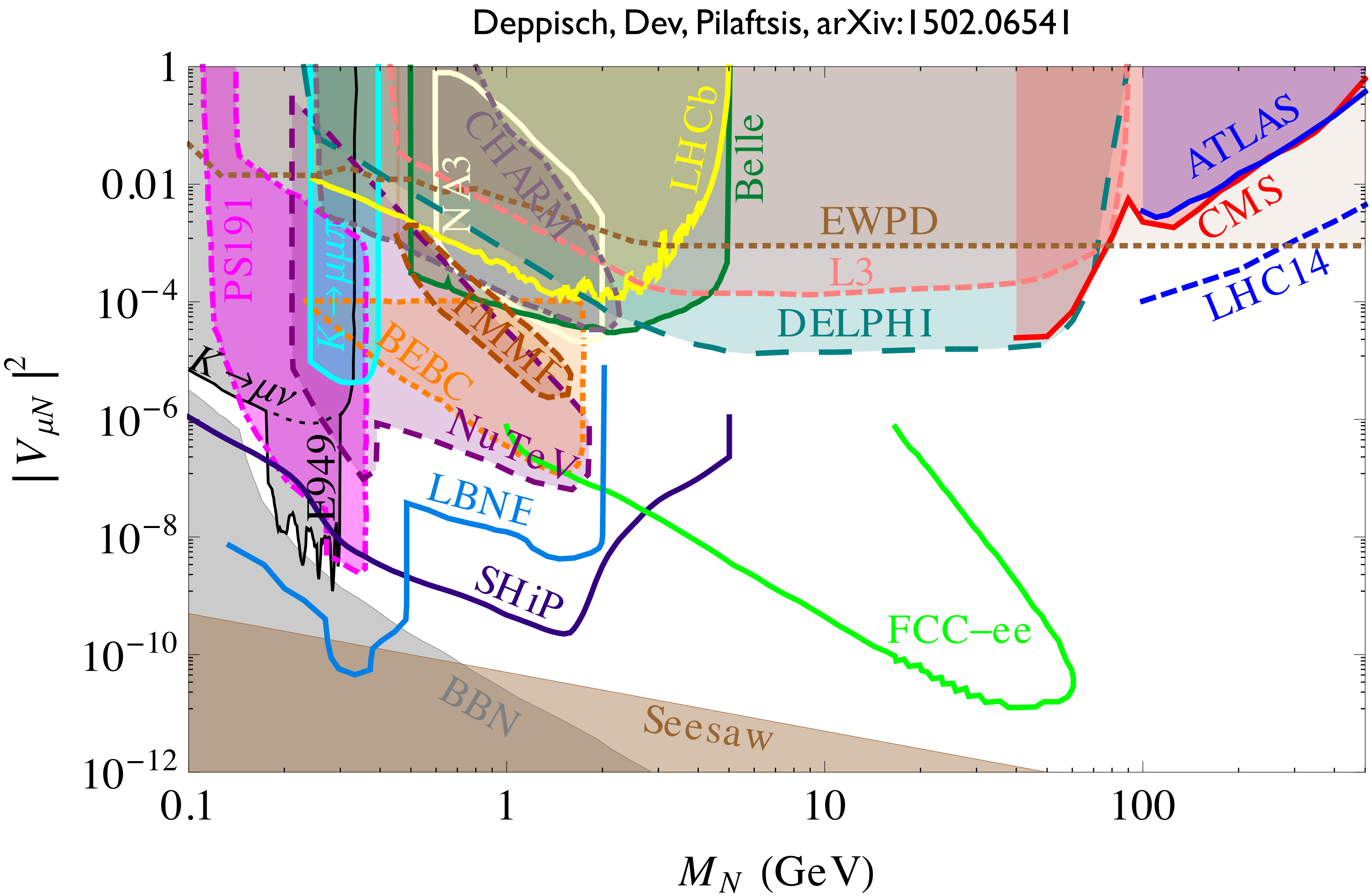
Cancellations (due to Majorana phases or to the neutrino mass mechanism itself) must be invoked in order to allow the HNL parameter space above

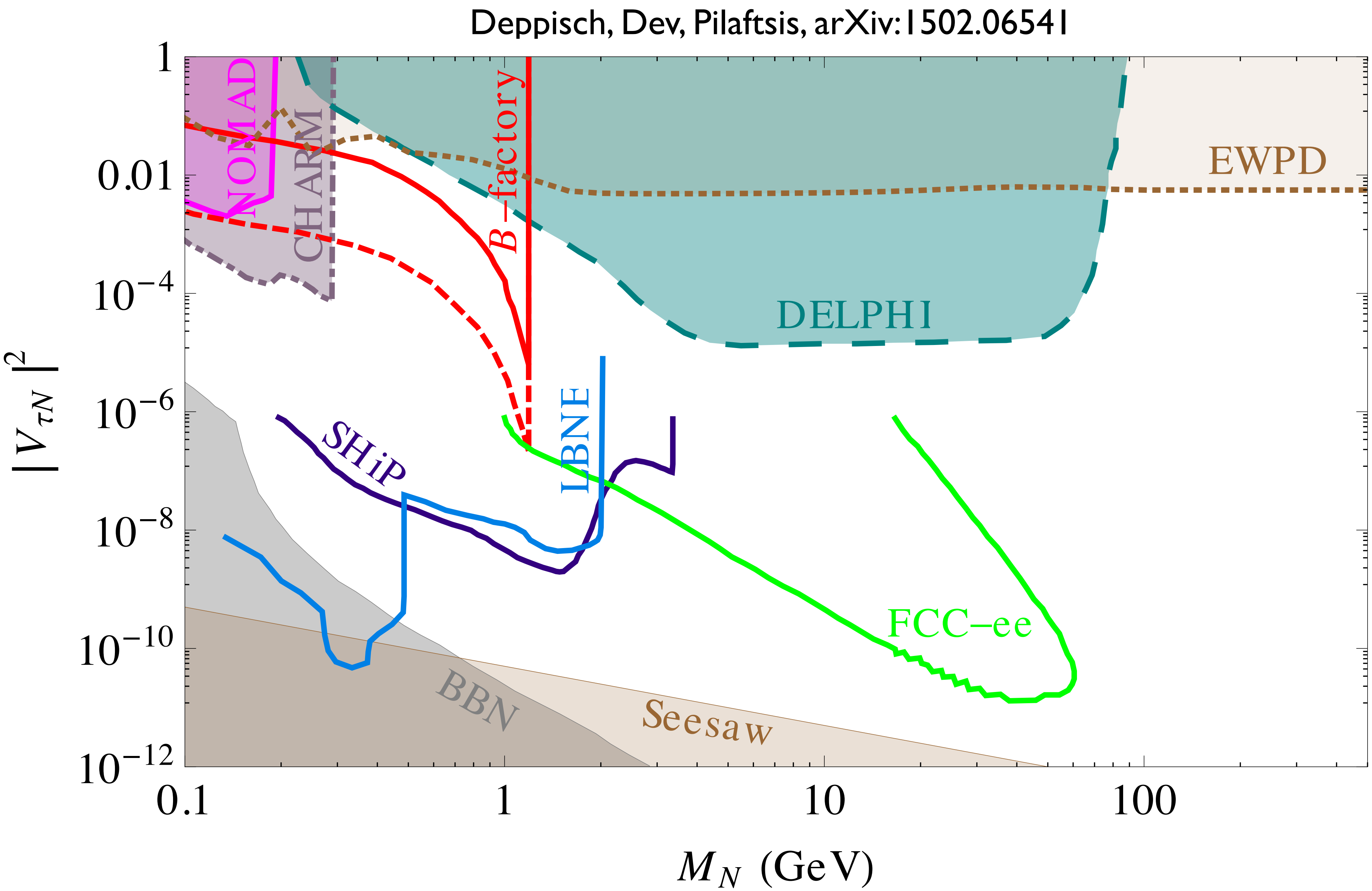
<u>Peak searches in leptonic meson decays</u>: e.g. $K^+ \to e^+ N$ suppressed relative to $K^+ \to e^+ \nu$ by $|U_{eN}|^2$, and the electron momentum is shifted due to M_N

Also constraints from semileptonic B decays (Belle), muon and tau decays (future expected limits from B factories)

<u>Beam dump experiments</u>: search for decay products of N's produced in semileptonic meson decays. Strong improvement expected from the planned SHiP experiment at CERN, and from the DUNE near detector

Also constraints from LNV meson decays (due to Majorana nature of N) at B factories (Belle, LHCb)


Deppisch, Dev, Pilaftsis, arXiv:1502.06541
1
0.01
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
$|V_{\mu N}|^2$
0.1
1
10
100
M_N (GeV)
PS191
$K\to\mu\nu$
E949
CHARM
NA3
LHCb
Belle
EWPD
L3
DELPHI
FMMF
BEBC
NuTeV
LBNE
SHiP
FCC−ee
ATLAS
CMS
LHC14
BBN
Seesaw



Deppisch, Dev, Pilaftsis, arXiv:1502.06541
NOMAD
CHARM
B−factory
EWPD
DELPHI
LBNE
SHiP
FCC−ee
BBN
Seesaw
$|V_{\tau N}|^2$
M_N (GeV)
1
0.01
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
0.1
1
10
100

Can we actually observe heavy neutral lepton ?

The naive type-I seesaw relation $|U_{\alpha N}|^2 \sim \frac{m_\nu}{M_N}$ seems to imply that most of the HNL parameter space accessible to experiments is excluded

However, variations of the type-I seesaw, such as the inverse seesaw mechanism, can allow for $|U_{\alpha N}|^2 \gg \frac{m_\nu}{M_N}$

Inverse seesaw mechanism: add 2 sterile neutrinos per generation with opposite chiralities (N_{Ri}, S_{Li})

Wyler, Wolfenstein - Mohapatra
Mohapatra, Valle

$$\mathcal{M}_{\nu N} = \overline{\begin{pmatrix} \nu_L & N^c & S \end{pmatrix}} \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M^T \\ 0 & M & \mu \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N \\ S^c \end{pmatrix} + \text{h.c.}$$

$\Rightarrow$ smallness of neutrino masses controlled by the LNV mass $\mu\, \overline{S^c} S$

$$m_\nu = m_D (M^{-1}) \mu (M^T)^{-1} m_D^T \qquad (\mu,\, m_D \ll M)$$

[small μ can be justified by approximate lepton number conservation]

$\Rightarrow$ can have "large" $|U_{\alpha N}|^2$ with HNLs in the GeV-TeV range if $\mu \ll M$
(S and N then form a pseudo-Dirac pair)

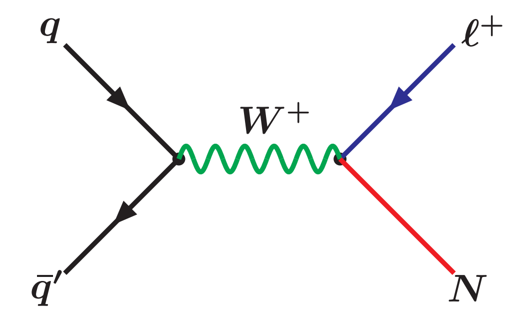
Heavy neutral lepton collider searches

LEP: HNL production from $e^+e^- \to Z \to N\bar{\nu}_i \,/\bar{N}\nu_i$ (off-shell Z at LEP2)
Best limit from DELPHI in the range $5\,\mathrm{GeV} \lesssim M_N \lesssim 60\,\mathrm{GeV}$

$$|U_{\alpha N}|^2 \lesssim 2\times 10^{-5} \quad (\alpha = e,\mu,\tau)$$

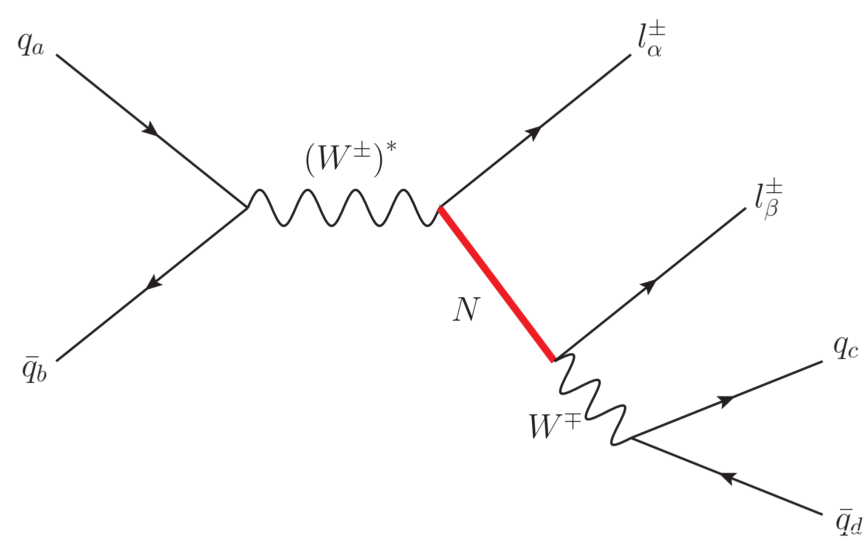
FCC-ee (future 90 km circular e+e- collider): will be a Z factory
$\Rightarrow$ strong improvement in the limits on $|U_{\alpha N}|^2$ expected

Hadron colliders (LHC): Drell-Yan production $pp \to W^{\pm(*)} \to N\ell^\pm$
followed by N decay (for M_N > 600 GeV, dominant production mode involves a photon in the t-channel, giving $pp \to N\ell^\pm + 2\ \mathrm{jets}$)

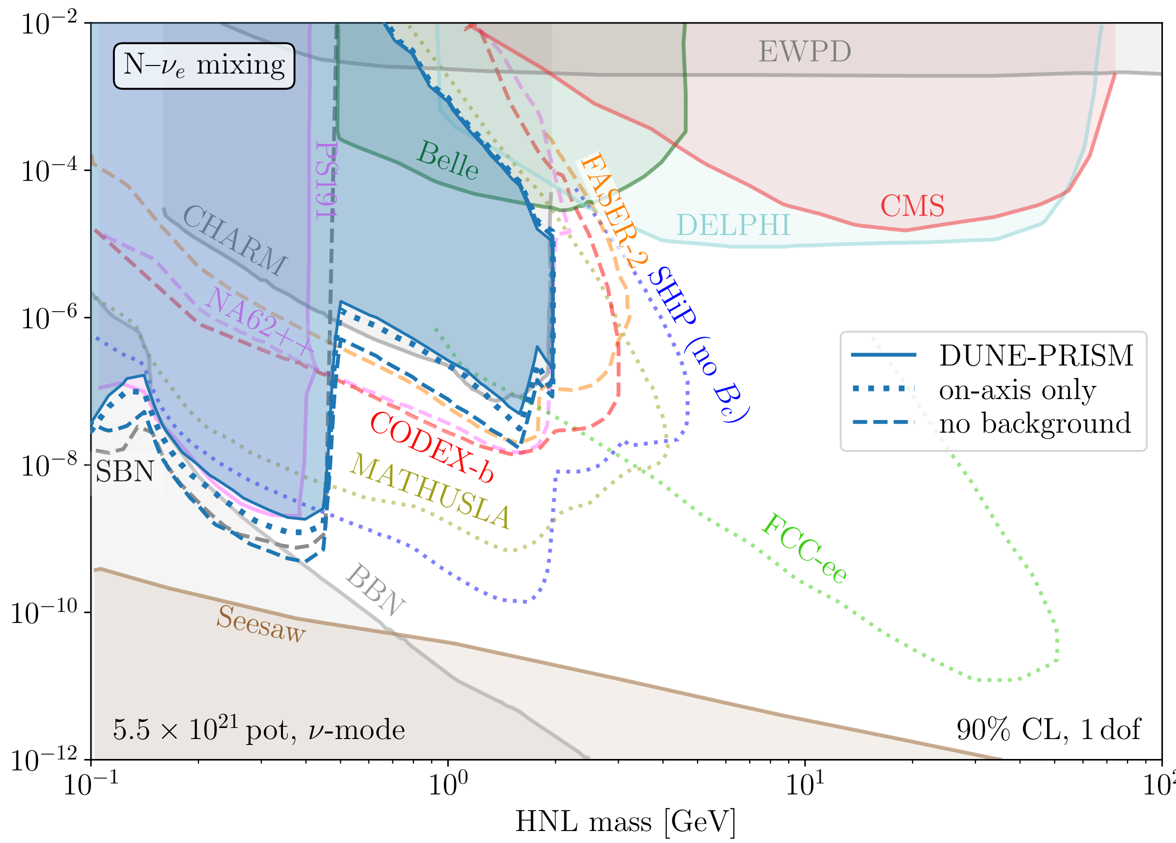


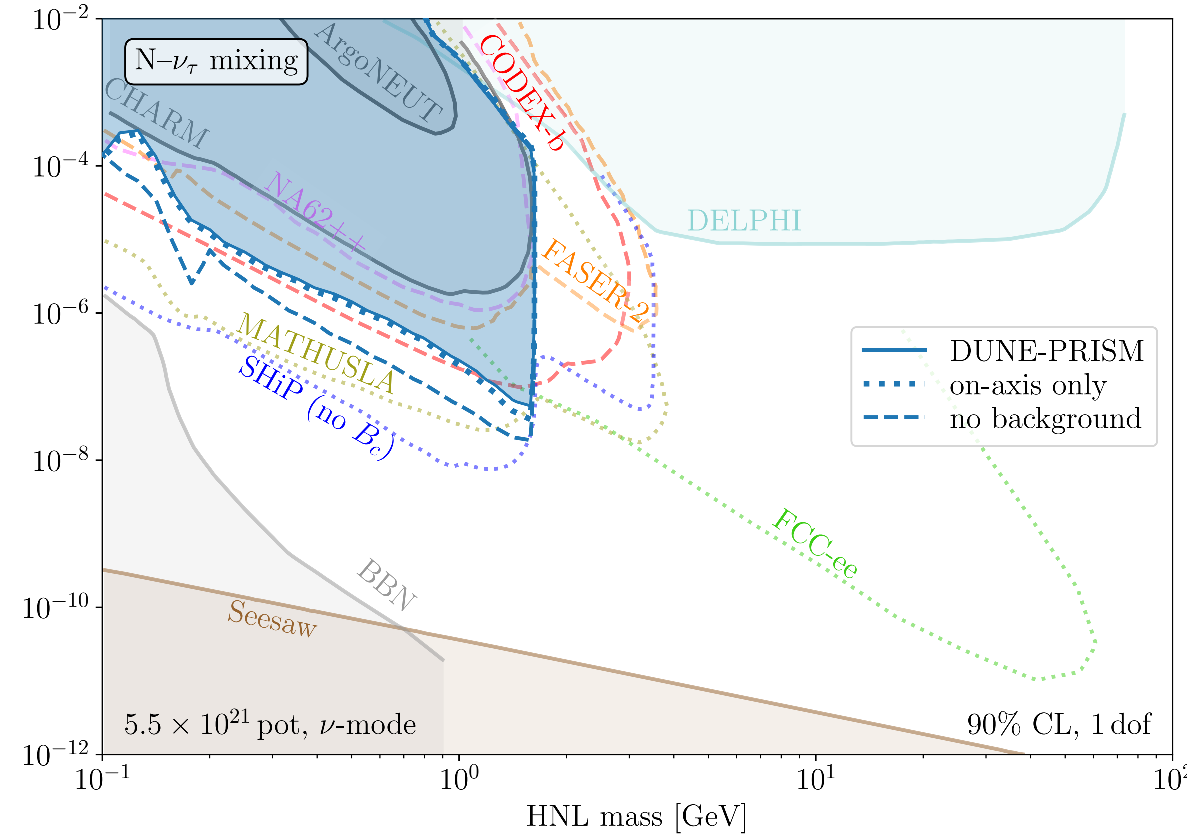
Sensitivity limited by $\sigma \propto |U_{\alpha N}|^2$

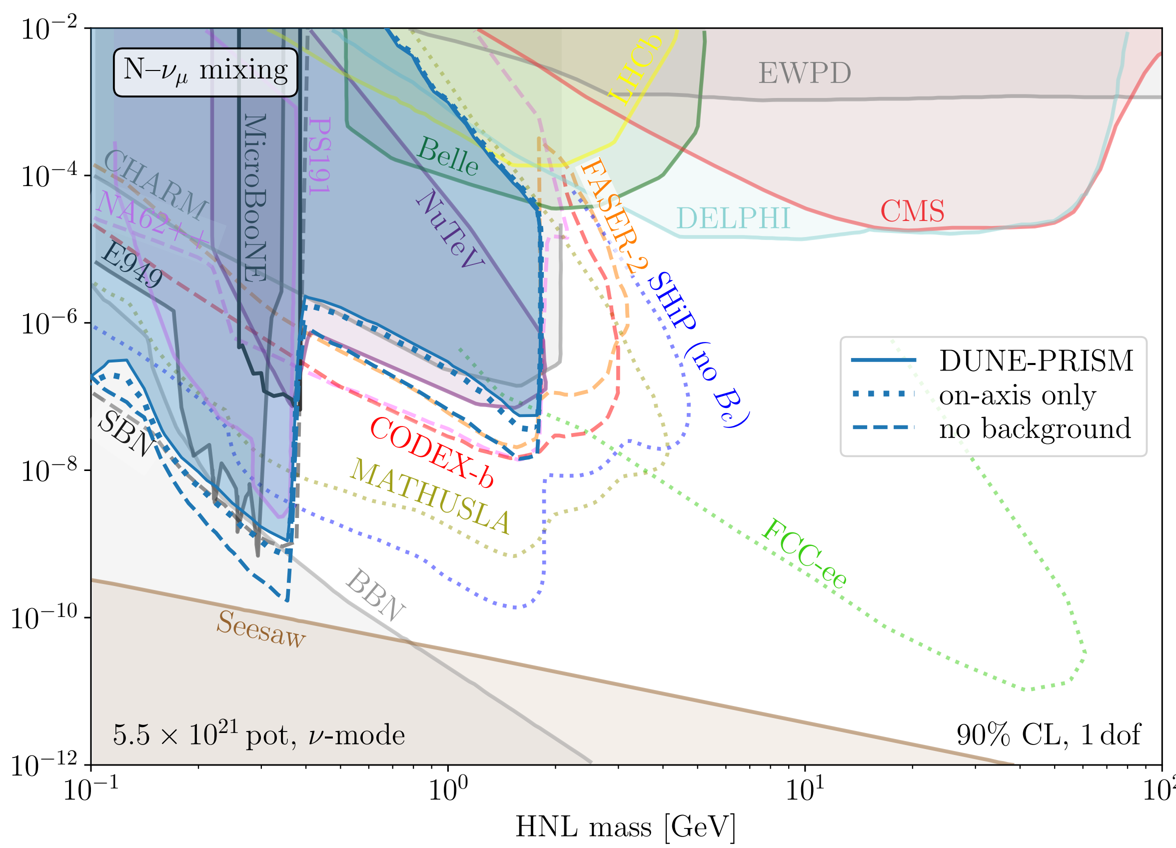
Smoking gun for a Majorana HLN:
same-sign dileptons + jets, not MET



Updated constraints on HNLs [M. Breitbach et al., arXiv:2102.03383]





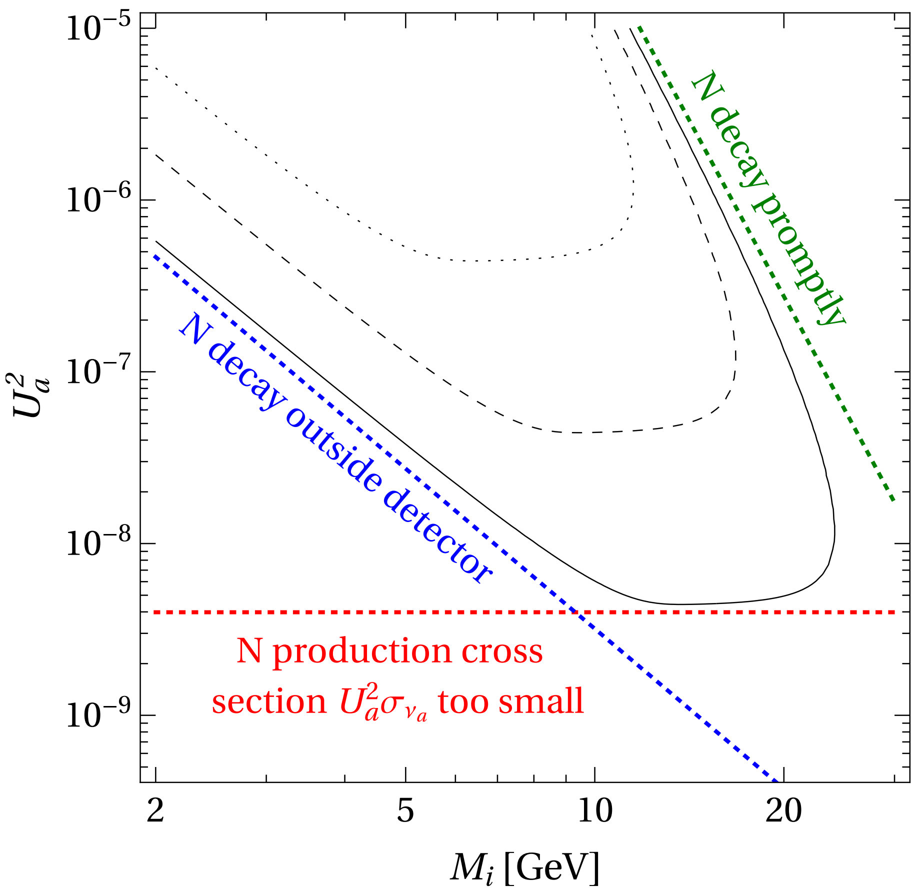


$\nu\mu^+\mu^-$, $\nu e^\pm\mu^\mp$, $\nu\pi^0$, $\pi^\pm e^\mp$, $\pi^\pm\mu^\mp$ are combined. As in fig. 10, solid blue curves show the sensitivity of DUNE-PRISM (5.5×10^{21} pot in neutrino mode, equally split between the on-axis position and six different off-axis locations). Dotted blue contours show results for on-axis running only, and thin dashed blue curves represent a hypothetical background-free analysis. The contours shown in the background correspond to existing limits (filled) and sensitivities of planned experiments (unfilled dashed and dotted).

FASER-2, CODEX-b, MATHUSLA
= planned foward or transverse physics
detectors at the LHC, located away
from the interaction point

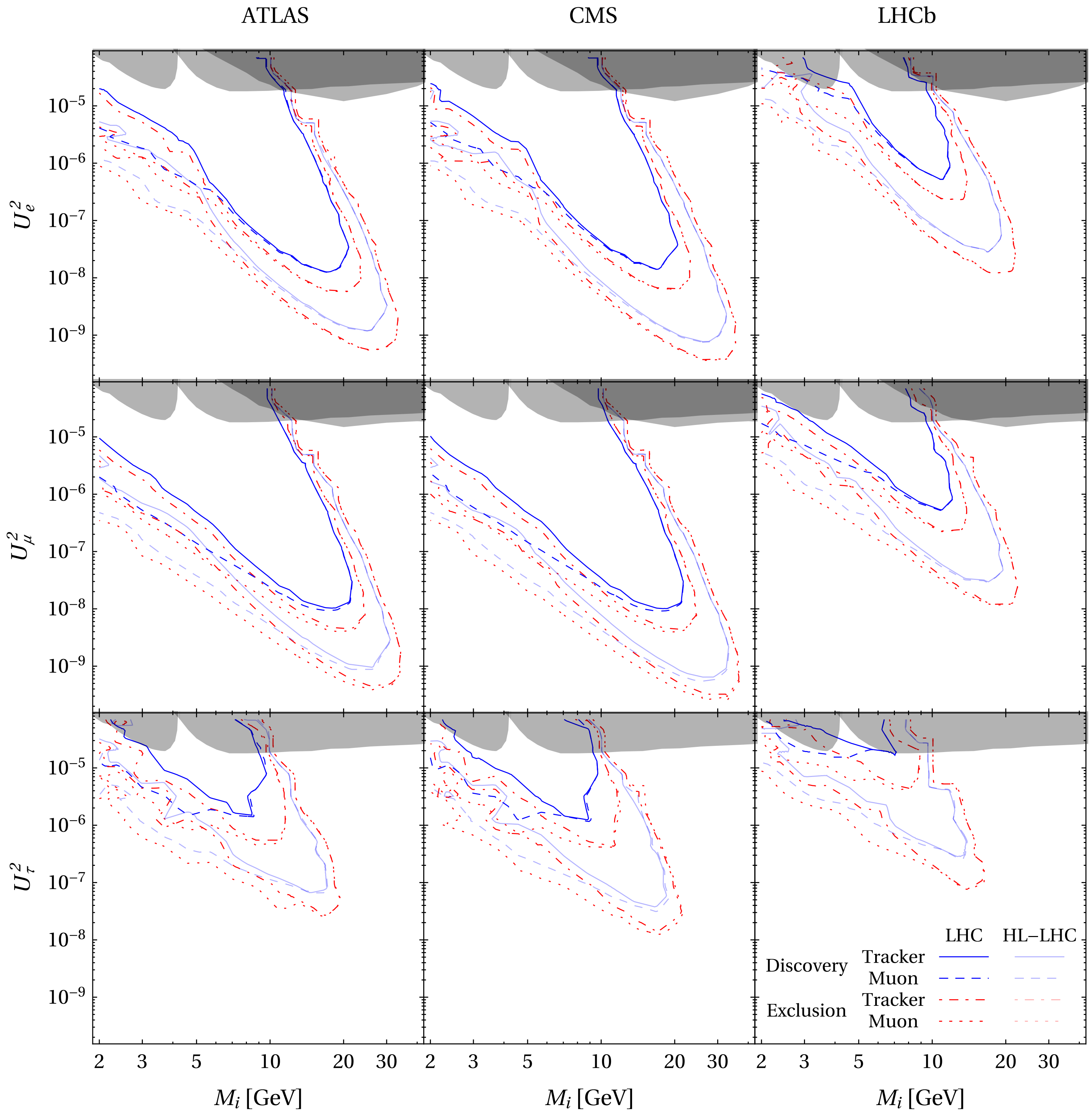
Displaced vertices can be used to improve the LHCsensitivity to small active-sterile mixing angles

Drewes & Hajer, arXiv:1903.06100



$$\Gamma_N \propto M_N^5 \sum_\alpha |U_{\alpha N}|^2$$

Small production cross section, but almost no SM background

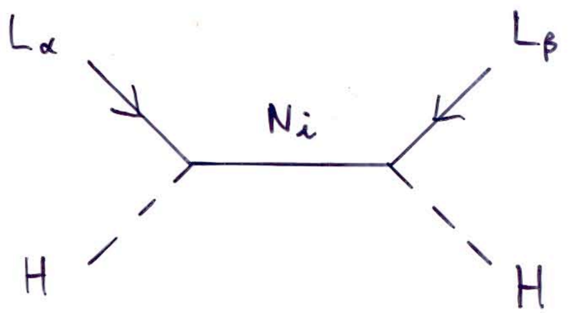


Drewes & Hajer, arXiv:1903.06100

Figure 6: Sensitivity reach of the 13 and 14 TeV LHC. The three columns show the results for ATLAS, CMS and LHCb. The luminosities assumed for CMS and ATLAS are 0.3 and 3 ab^{-1} and for LHCb are 30 and 380 fb^{-1}. The three rows constitute the three extreme cases of pure electron, muon and tau coupling, respectively. The blue (red) curves show the discovery (exclusion) potential, both of which are shown for searches using only the tracker and using the tracker together with the muon chamber. For the simulation of LHCb we require decays to happen before or within the first RICH (*cf.* also figure 8). The gray bands represent the exclusion bound from DELPHI [52] and CMS [50].

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

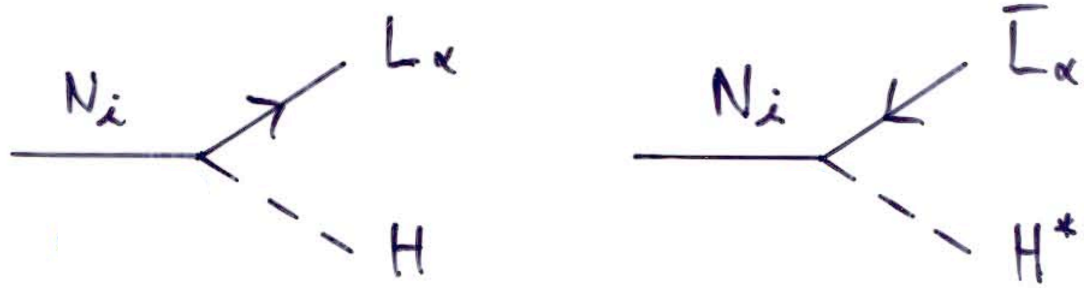
Interestingly, this mechanism contains all ingredients needed for baryogenesis [Sakharov conditions: B violation, C and CP violation, departure from thermal equilibrium]:

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

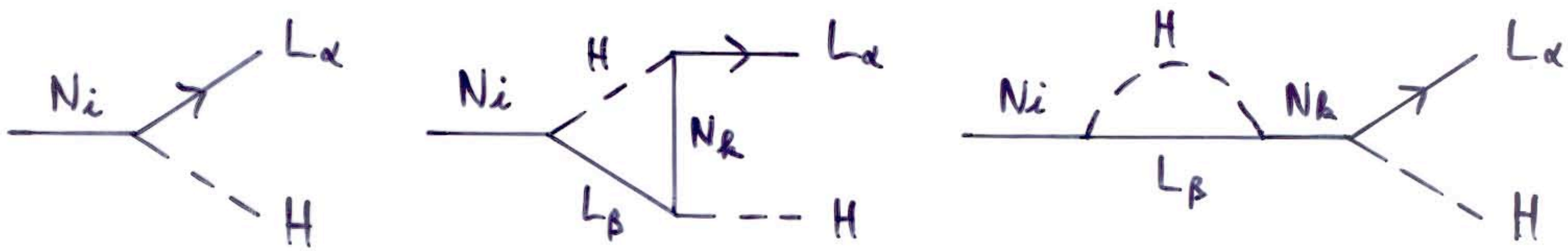
- part of the generated lepton asymmetry is converted into a baryon asymmetry by non-perturbative SM processes (sphalerons), which are in equilibrium in the early Universe and violate B and L, while preserving B-L

$\rightarrow$ leptogenesis   Fukugita, Yanagida '86

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



CP violation: 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

out-of-equilibrium condition: provided by the expansion of the Universe, as the temperature drops below the heavy Majorana neutrino masses

The generated lepton asymmetry is partly erased by washout processes

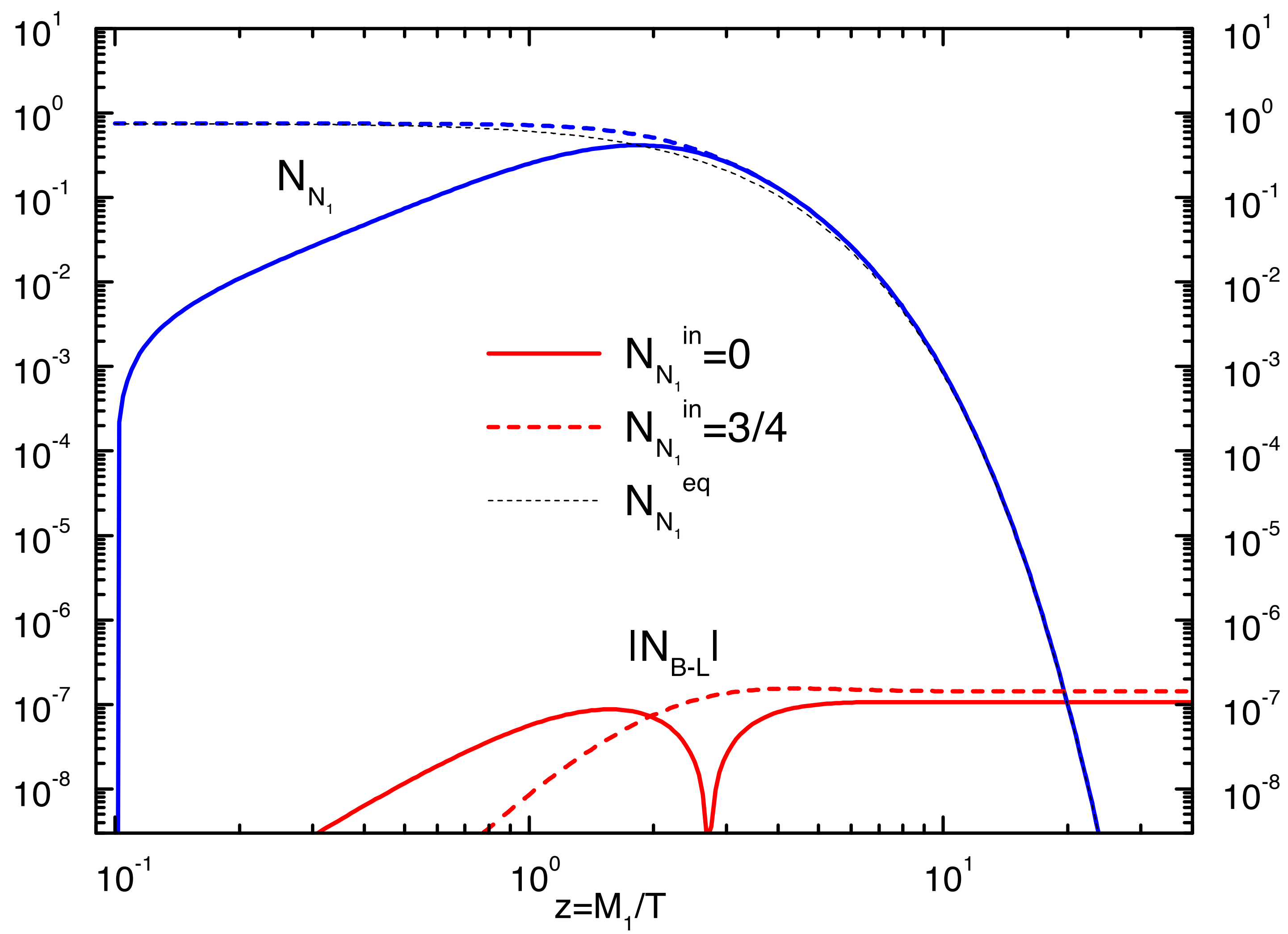
- inverse decays $LH \to N_1$
- ΔL=2 N-mediated scatterings $LH \to \bar{L}\bar{H}\,, \quad LL \to \bar{H}\bar{H}$
- ΔL=1 scatterings involving the top or gauge bosons

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:



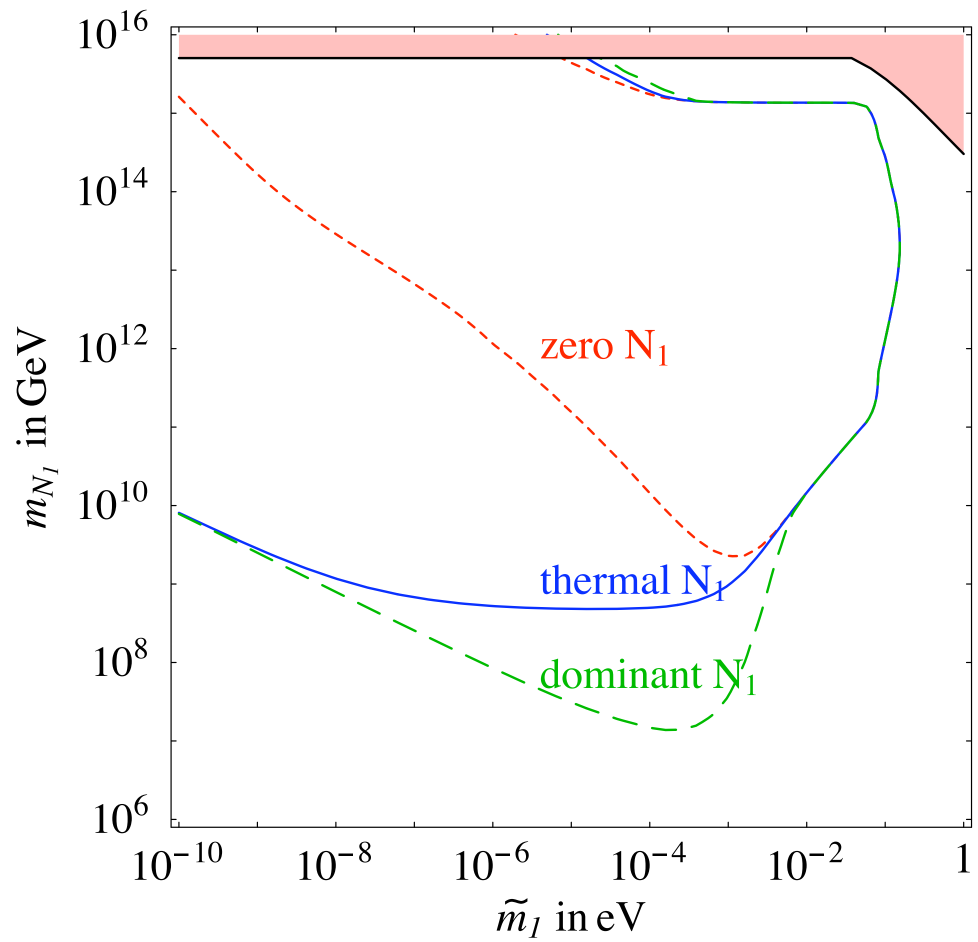
[Buchmüller, Di Bari, Plümacher '02]

Thermal leptogenesis can explain the observed baryon asymmetry

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

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]

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

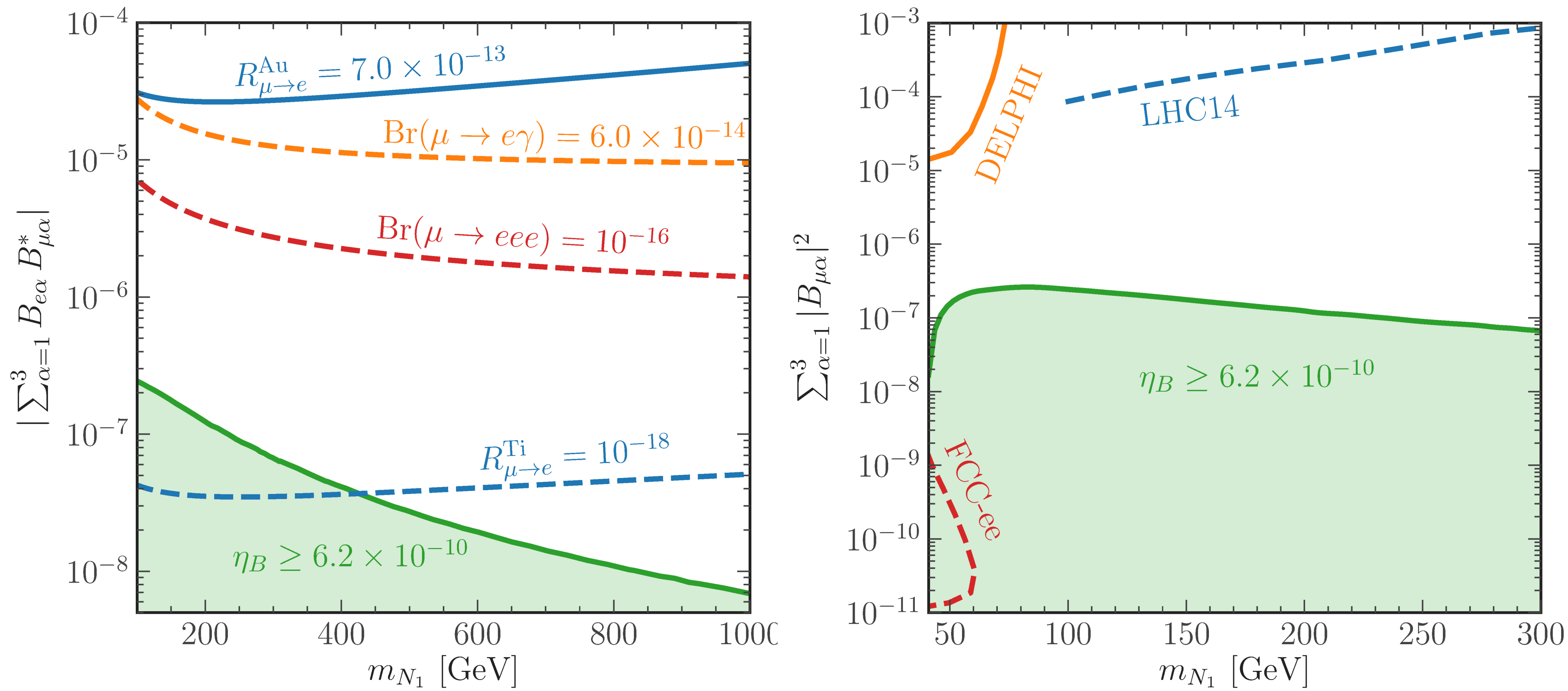
$\Rightarrow$ can be tested via direct production of heavy Majorana neutrinos at colliders + contributions to flavour violating processes in the charged lepton sector

[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 $m_\nu \sim y^2 v^2 / M$

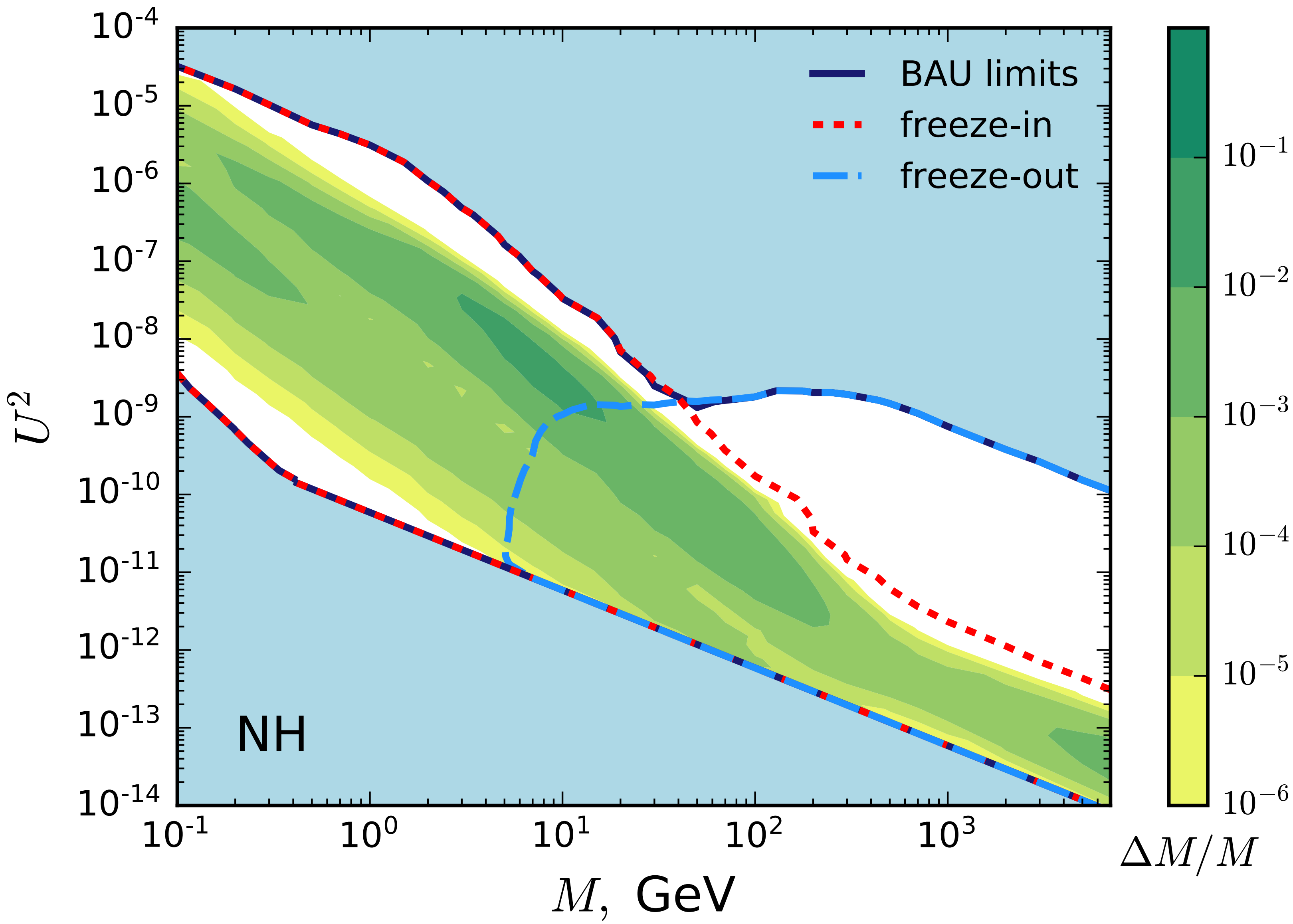
$$\Rightarrow \quad \frac{\Gamma(T)}{H(T)} \sim \left(\frac{m_\nu}{0.05\,\mathrm{eV}}\right)\left(\frac{M}{10\,\mathrm{GeV}}\right)\left(\frac{100\,\mathrm{GeV}}{T}\right)$$

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]

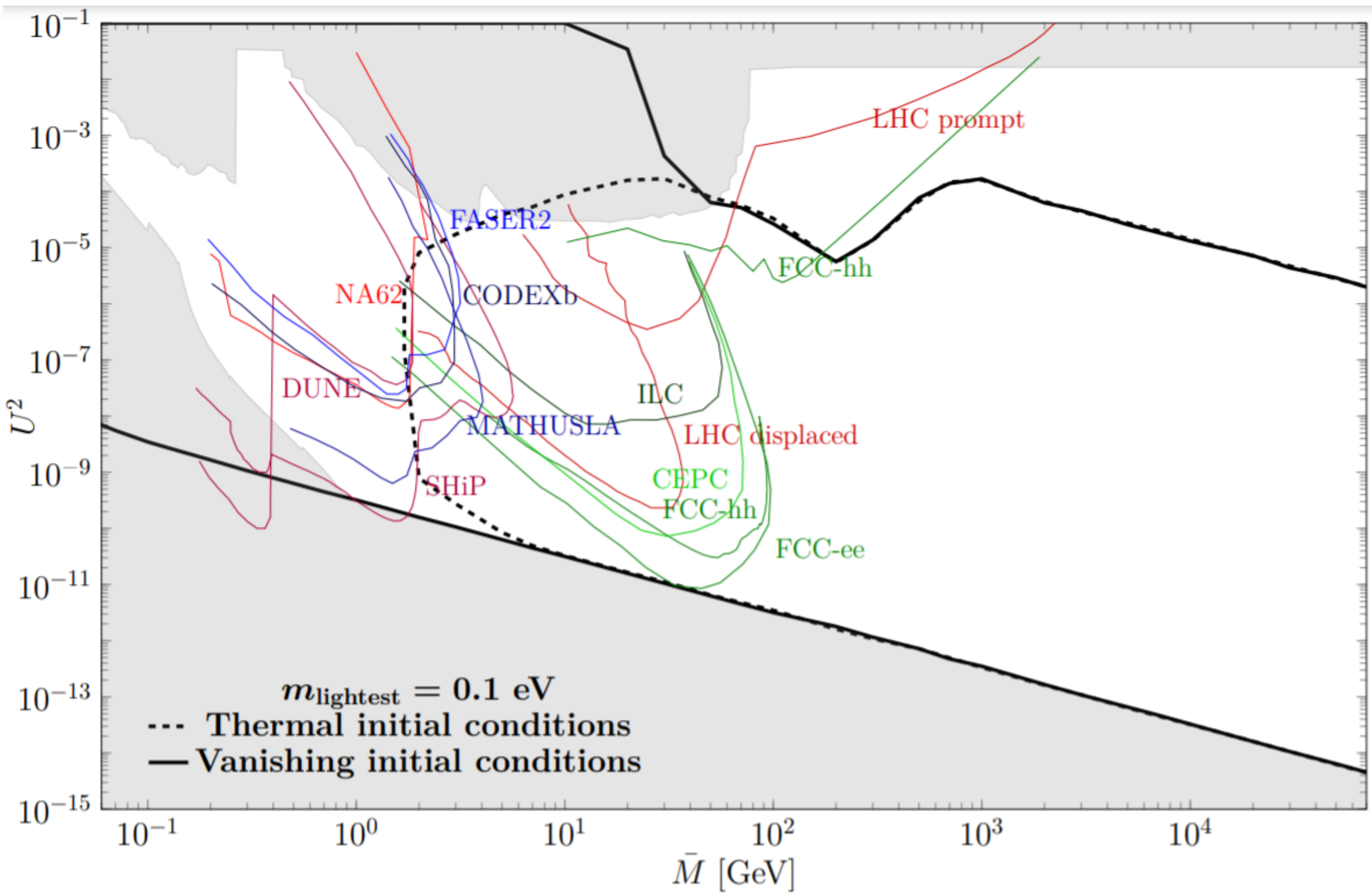


Large values of the active-sterile neutrino mixing U arise when some tuning is present in the sterile neutrino couplings (can be justified by symmetries)

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]



Conclusion on leptogenesis

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)