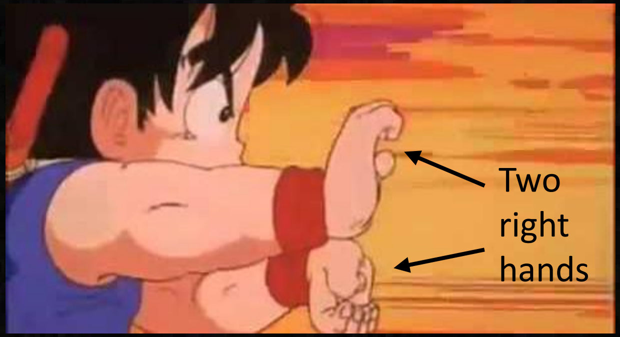
The parameter space of two right-handed neutrinos



EMFCSC
INTERNATIONAL SCHOOL OF SUBNUCLEAR PHYSICS 2024

Vaisakh Plakkot

3+2 type-I seesaw model

- Sterile mass matrix: $M_M = \begin{pmatrix} M_4 & 0 \\ 0 & M_5 \end{pmatrix}$
  - $\bar{M} = \frac{M_4+M_5}{2}; \quad \Delta M = M_5 - M_4; \quad \mu = \frac{\Delta M}{\bar{M}}$

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_M \end{pmatrix}$$

$$\sum_{i=1}^{5} m_i \mathcal{U}_{ei}^2 = (M_\nu)_{ee} = 0$$

- Light neutrino mixing angles: PMNS matrix $\begin{pmatrix} (U_\nu)_{3\times3} & \cdots \\ \cdots & \cdots \end{pmatrix}_{5\times5}$

- HNL mixing angles: $\Theta = m_D M_M^{-1}$ $\begin{pmatrix} \cdots & \Theta_{3\times2} \\ \cdots & \cdots \end{pmatrix}_{5\times5}$

- Five Majorana neutrinos; lightest neutrino massless

Neutrinoless double beta decay

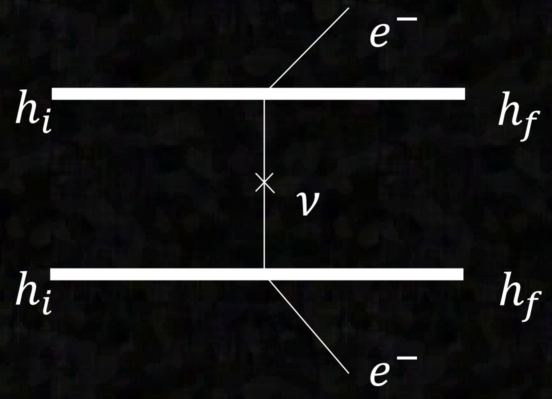
CKM element
~ 0.97

Phase space factor (nucleus-dependent)

$$\left(T_{1/2}^{0\nu}\right)^{-1} = g_A^4\, V_{ud}^2\, \frac{G_{01}}{m_e} \left|\sum_i \mathcal{U}_{ei}^2\, m_i\, A(m_i)\right|^2$$

Nuclear axial charge
~ 1.27

Electron mass
0.511 MeV

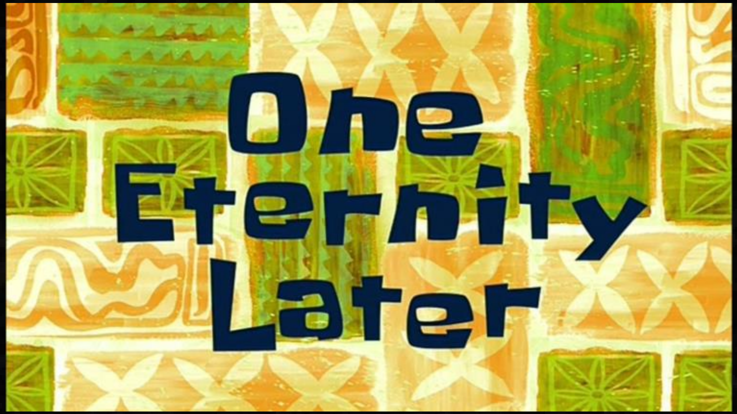


Small splitting approximation

$$\mathcal{A}_{eff} \equiv \sum_{i=1}^{5} \mathcal{U}_{ei}^2 m_i A(m_i)$$

$$\left(T_{1/2}^{0\nu}\right)^{-1} \propto \left|\mathcal{A}_{eff}\right|^2$$

$$\sum_{i=1}^{5} m_i \mathcal{U}_{ei}^2 = (M_\nu)_{ee} = 0$$



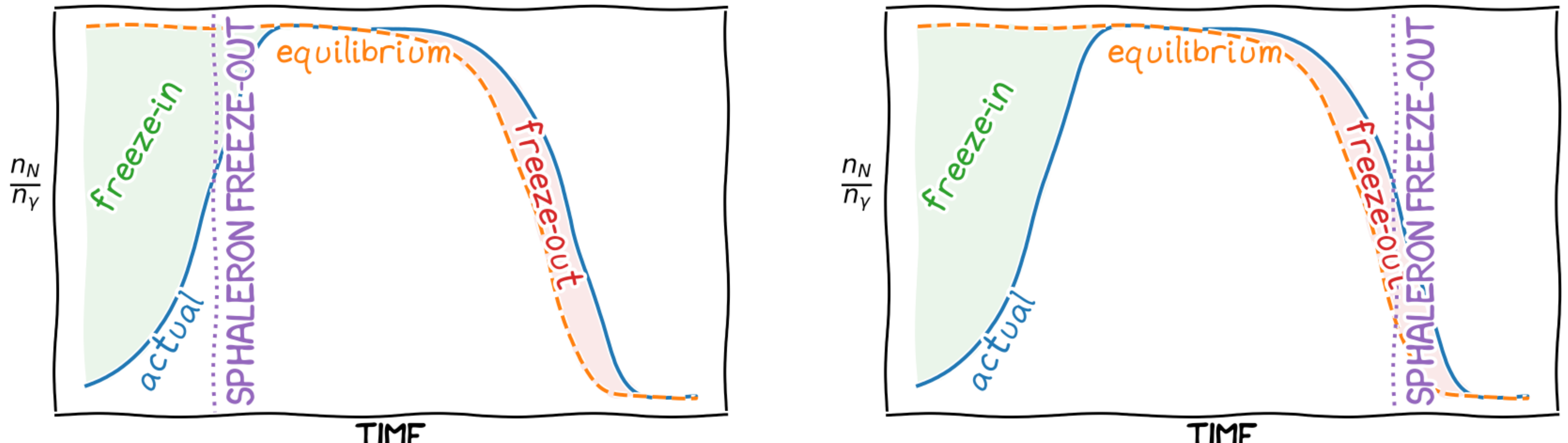
$$U_e^2 = \sum_I |\Theta_{eI}|^2$$

$$\mathcal{A}_{eff} \approx \sum_{i=1}^{3} m_i \mathcal{U}_{ei}^2 \left(A(0) - A(\bar{M})\right) + e^{i\lambda}\mu\, U_e^2 \frac{\bar{M}^2}{2} A'(\bar{M})$$

$$\lambda = f(\mathrm{Re}(\omega), \alpha_{ij}, \delta_{CP}, \dots)$$

Low-scale leptogenesis

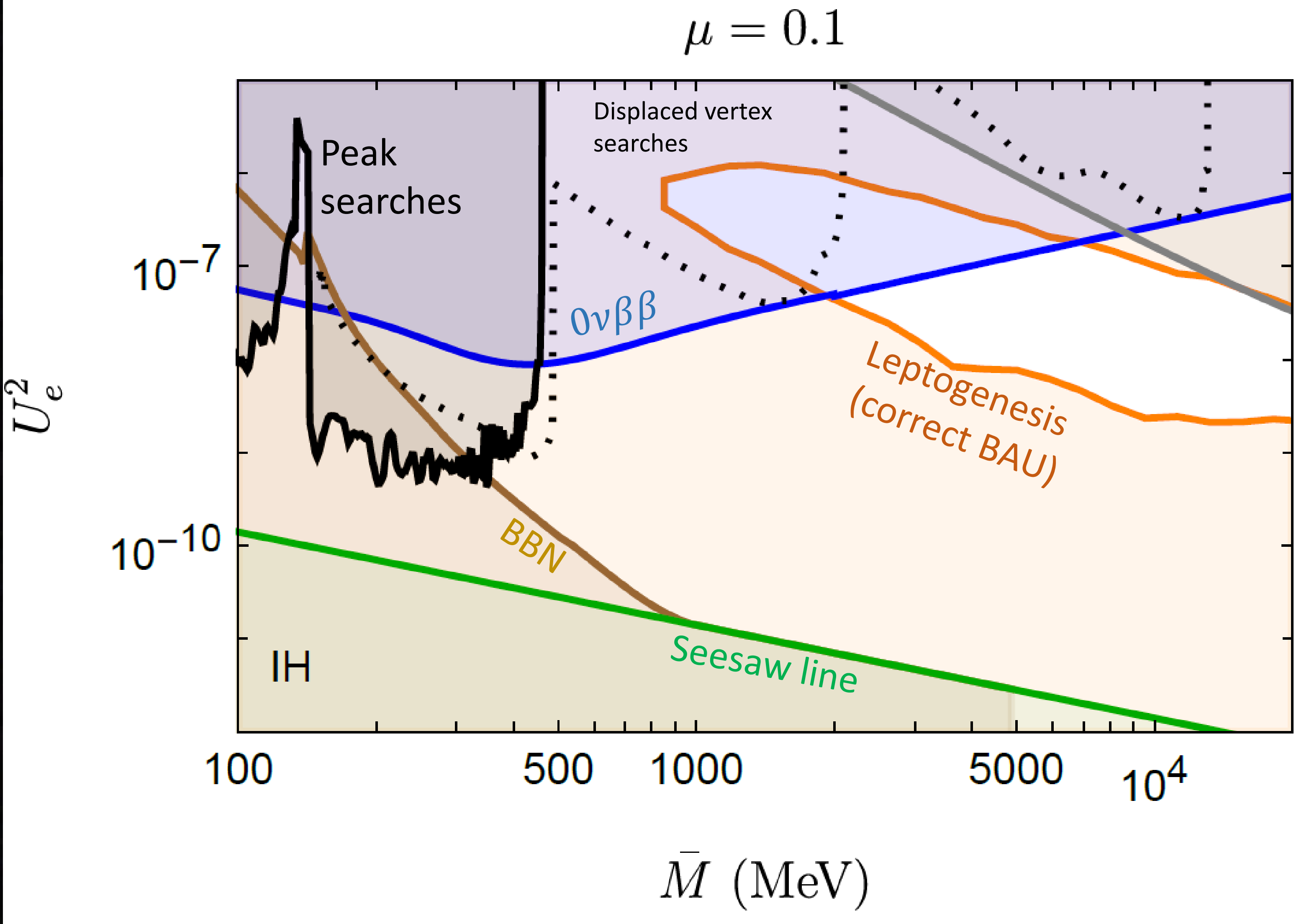
Leptogenesis: convert lepton asymmetry to baryon asymmetry



Klaric, Shaposhnikov, Timiryasov [2103.16545]

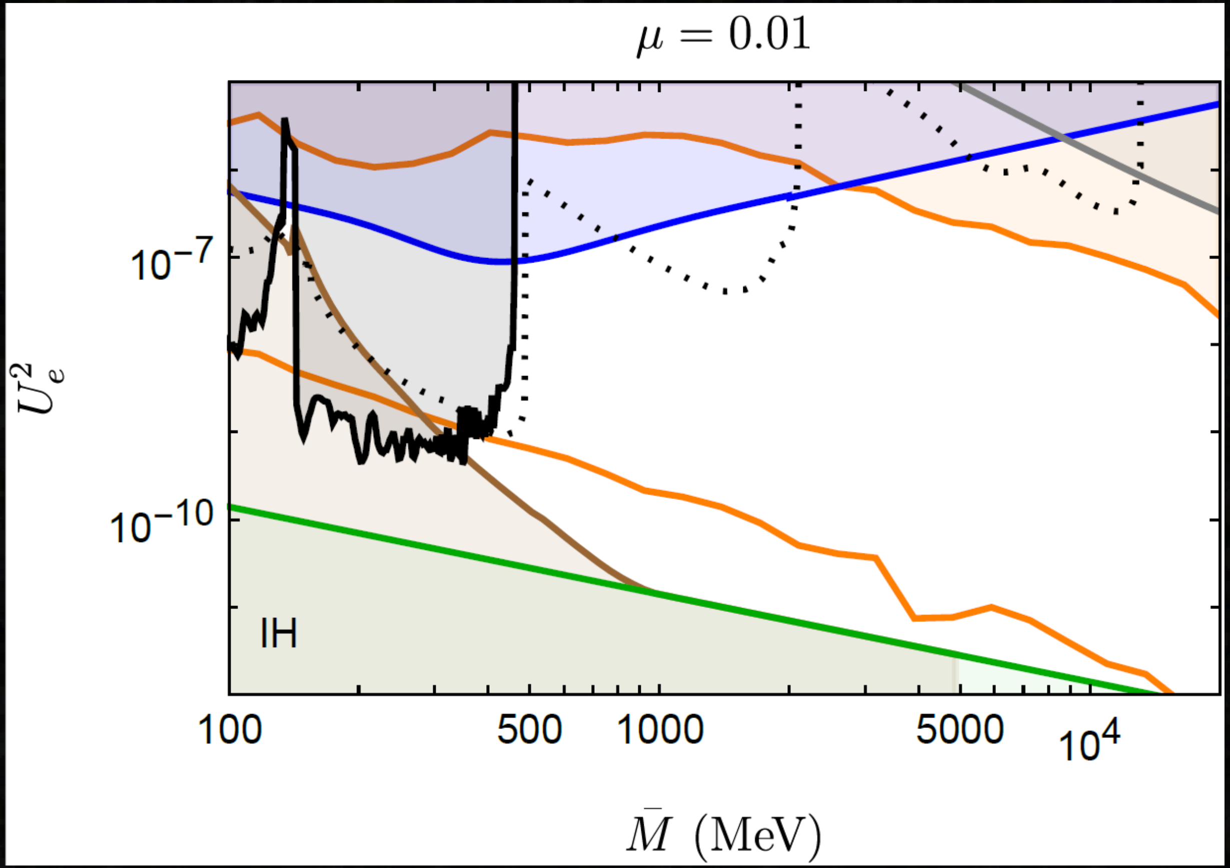
Map out regions where correct BAU ($\sim 10^{-10}$) is produced

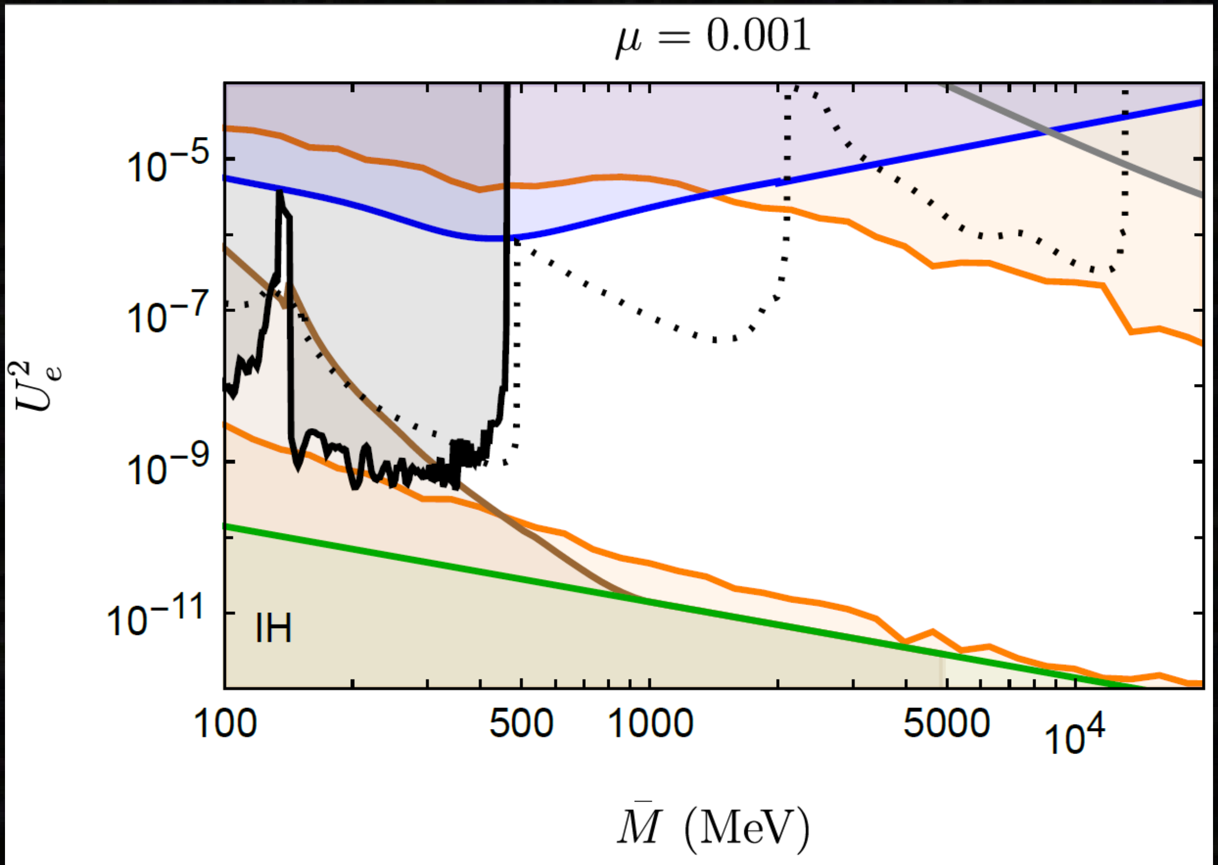
Exclusions galore



Work in progress:
with Jordy de Vries, Marco Drewes, Yannis Georis, Juraj Klaric

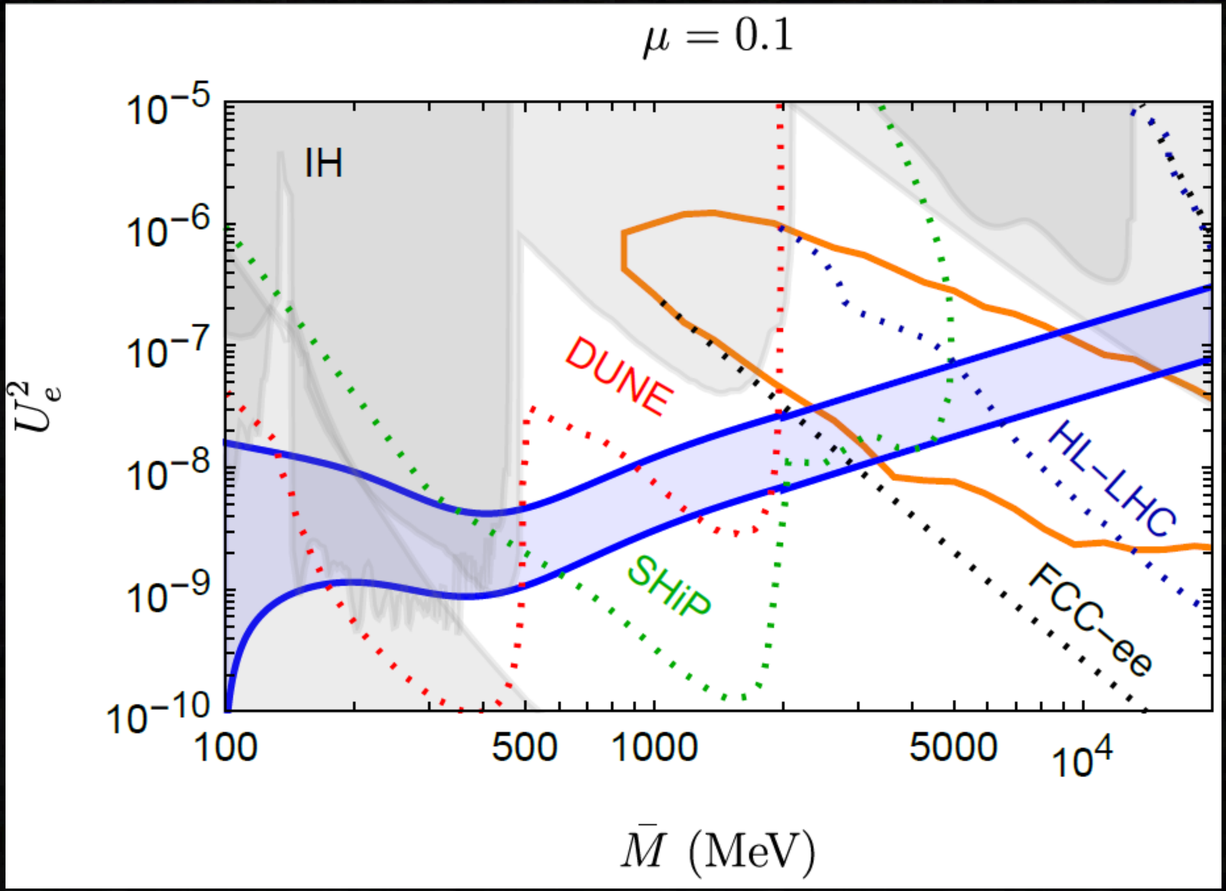
Exclusions galore part 2

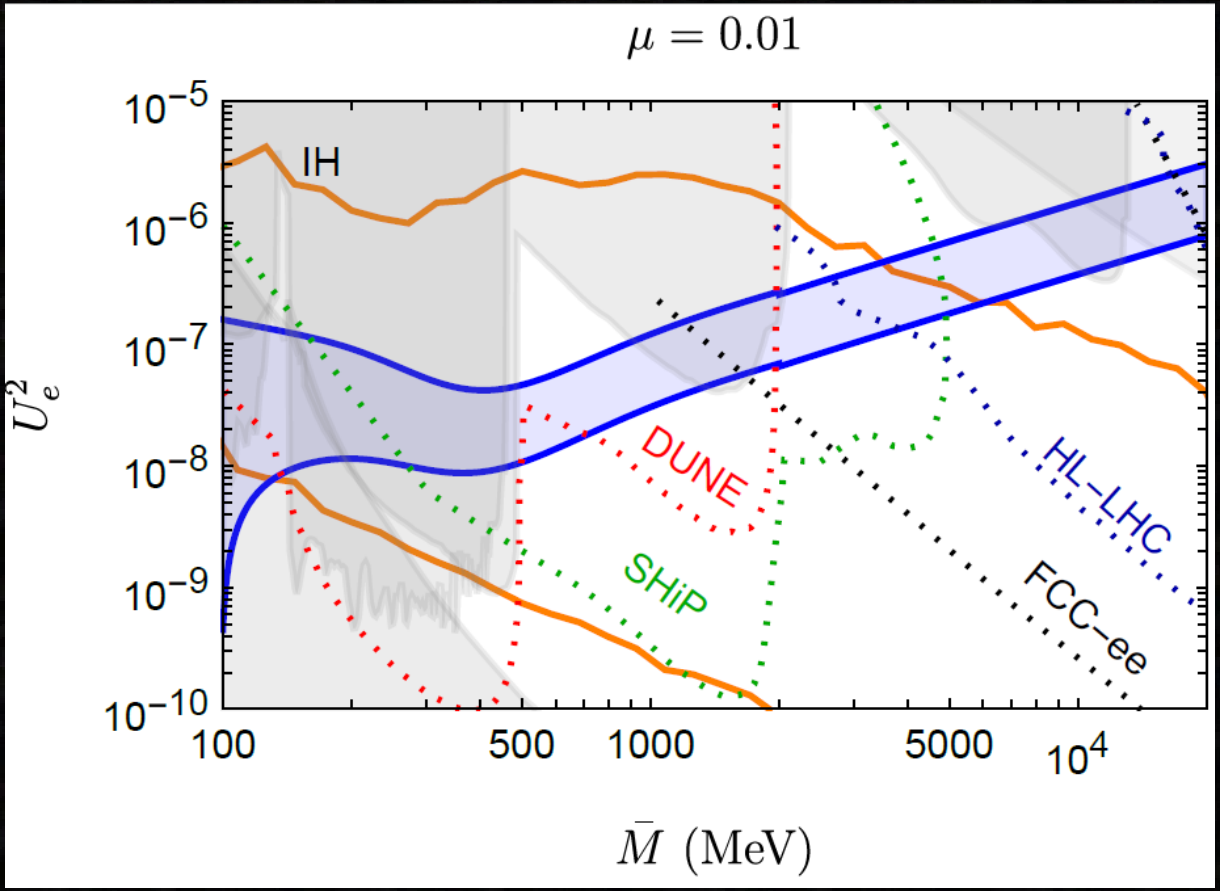




$$\mathcal{A}_{eff} \approx \sum_{i=1}^{3} m_i \mathcal{U}_{ei}^2 \left(A(0) - A(\bar{M})\right) + e^{i\lambda}\mu\, U_e^2 \frac{\bar{M}^2}{2} A'(\bar{M})$$

Future prospects





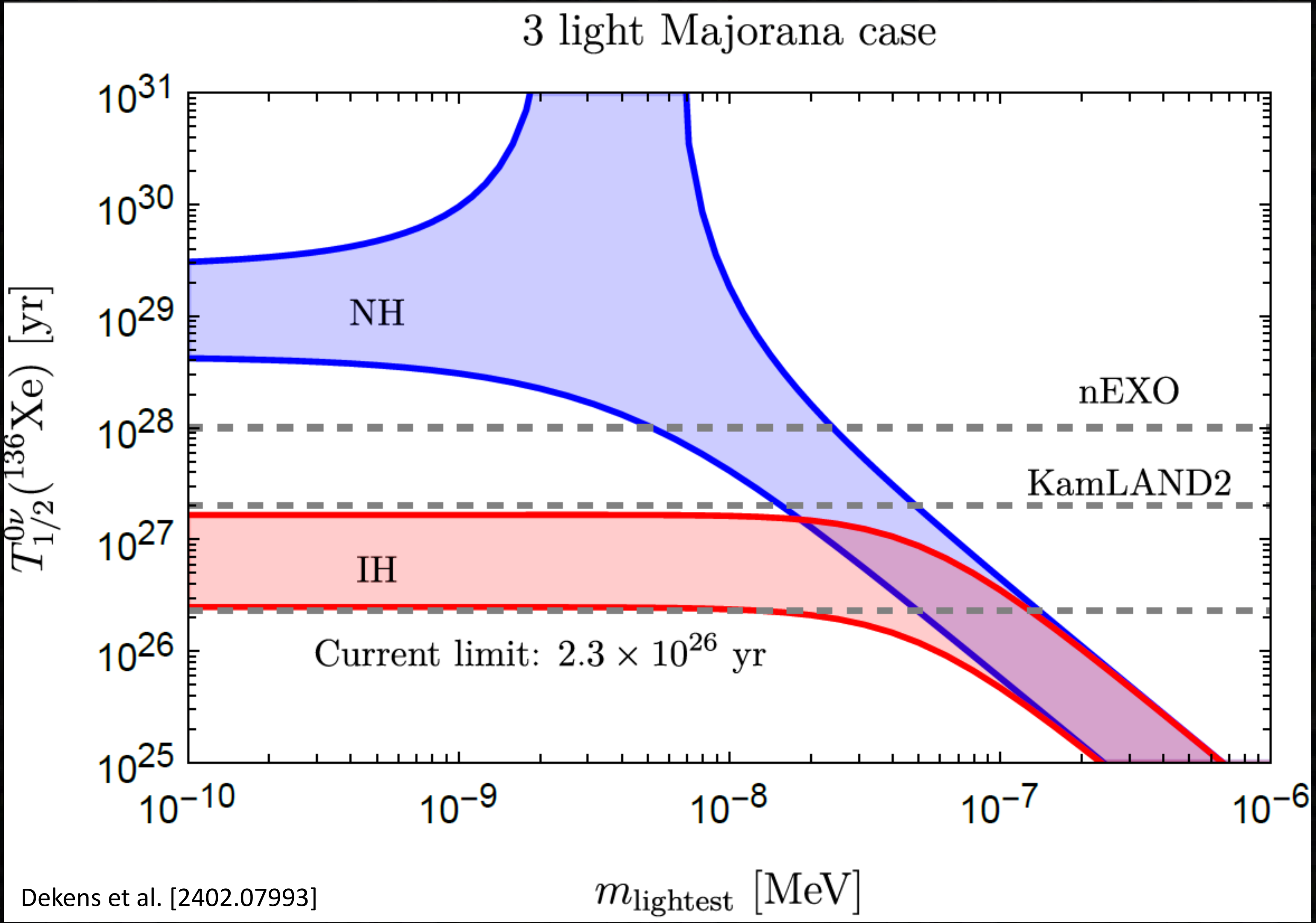
$$\mathcal{A}_{eff} \approx \sum_{i=1}^{3} m_i U_{ei}^2 \left(A(0) - A(\bar{M})\right) + e^{i\lambda}\mu\, U_e^2 \frac{\bar{M}^2}{2}\, A'(\bar{M})$$

Summary

- Right-handed neutrinos are useful, but a minimal model requires two of them
- Majorana nature of neutrinos → LNV effects → Leptogenesis, $0\nu\beta\beta$, …
- Requirement of correct BAU + $0\nu\beta\beta$ bounds complementary to other experimental searches and cosmological constraints
- No $0\nu\beta\beta$ detection in near future ⇒ small testable allowed parameter space left for such minimal 3+2 models

Backup

Standard 3+0 scenario

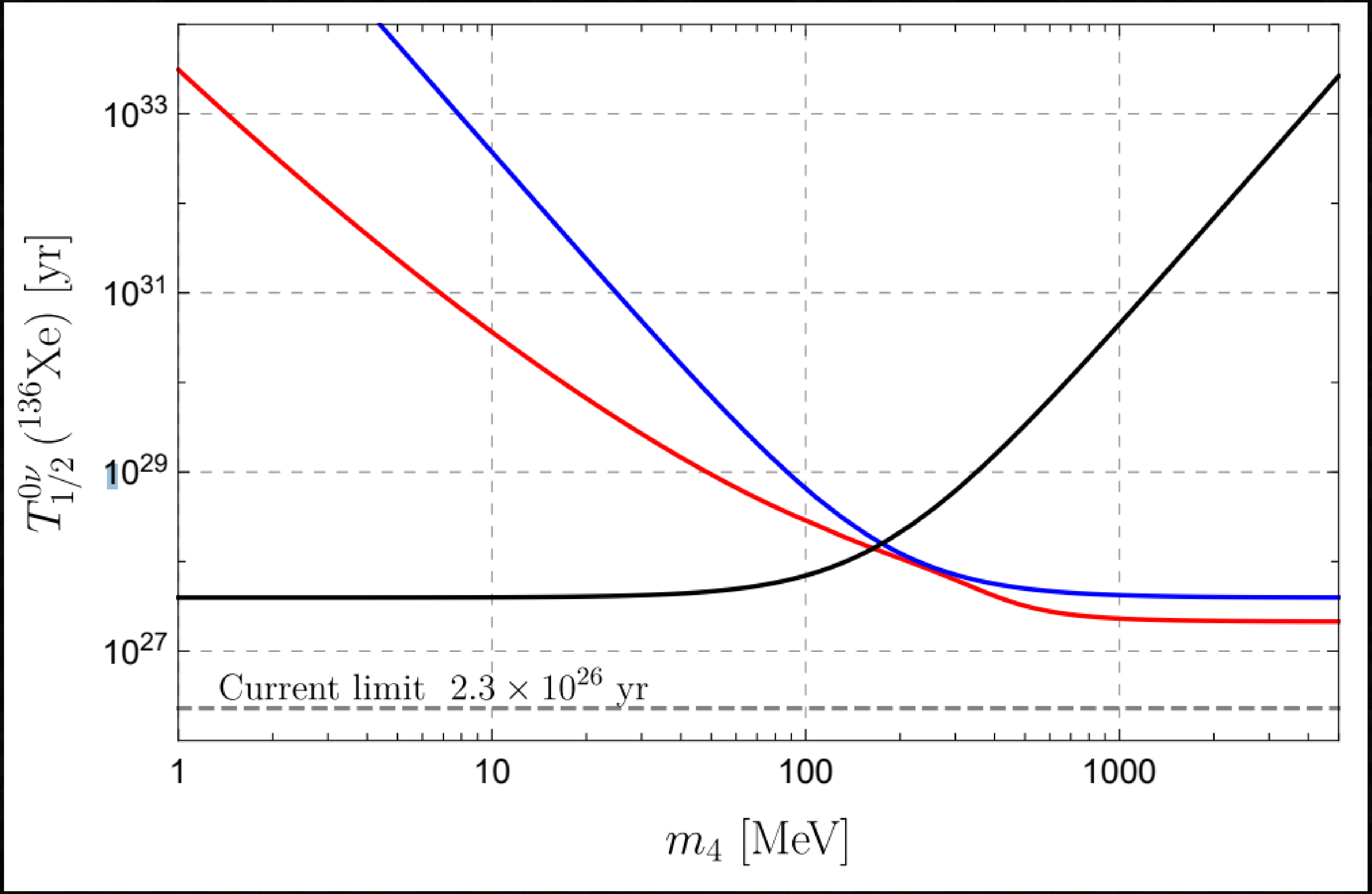


Dekens et al. [2402.07993]

Pieces of the puzzle

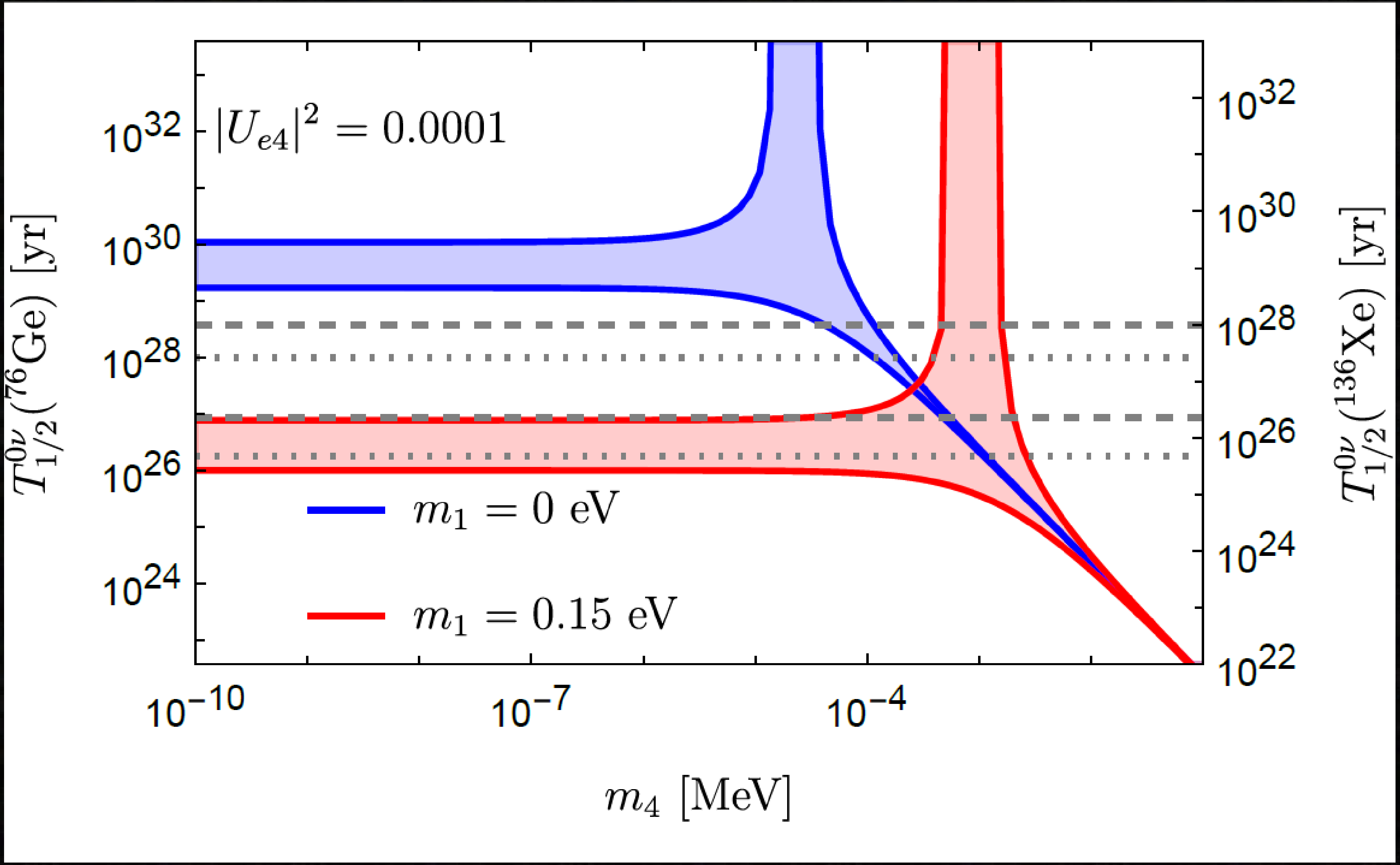
- $A_\nu^{(9)} = -2\,\eta\,\frac{m_\pi^2}{m_i^2}\left[\frac{5}{6} g_1^{\pi\pi}\left(M_{GT,sd}^{PP} + M_{T,sd}^{PP}\right) + g_1^{\pi N}\left(M_{GT,sd}^{AP} + M_{T,sd}^{AP}\right) - \frac{2}{g_A^2} g_1^{NN} M_{F,sd}\right]$
- $A_\nu^{(\text{usoft})} = 2\,\frac{\mathrm{R_A}}{\pi g_A^2} \sum_n \langle 0_f^+ | \mathcal{J}^\mu | 1_n^+ \rangle \langle 1_n^+ | \mathcal{J}_\mu | 0_i^+ \rangle \left(f(m_i, \Delta E_1) + f(m_i, \Delta E_2)\right)$
- $A_\nu^{(\text{pot})} = -\frac{M(0)}{1+\frac{m_i}{m_a}+\left(\frac{m_i}{m_b}\right)^2} = -M(m_i)$
- $A_\nu^{(\text{pot},<)} = -\left[M(m_i) - m_i \left(\frac{d}{dm_i} M(m_i) \right)\Big|_{m_i=0} \right]$
- $A_\nu^{(\text{hard})} = -\frac{2\, m_\pi^2 g_\nu^{NN}(m_i)}{g_A^2}\, M_{F,sd}$

$$g_\nu^{NN}(m_i) = \frac{g_\nu^{NN}(0)\left(1 \pm \left(\frac{m_i}{m_c}\right)^2\right)}{1 + \left(\frac{m_i}{m_c}\right)^2 \left(\frac{m_i}{|m_d|}\right)^2}$$



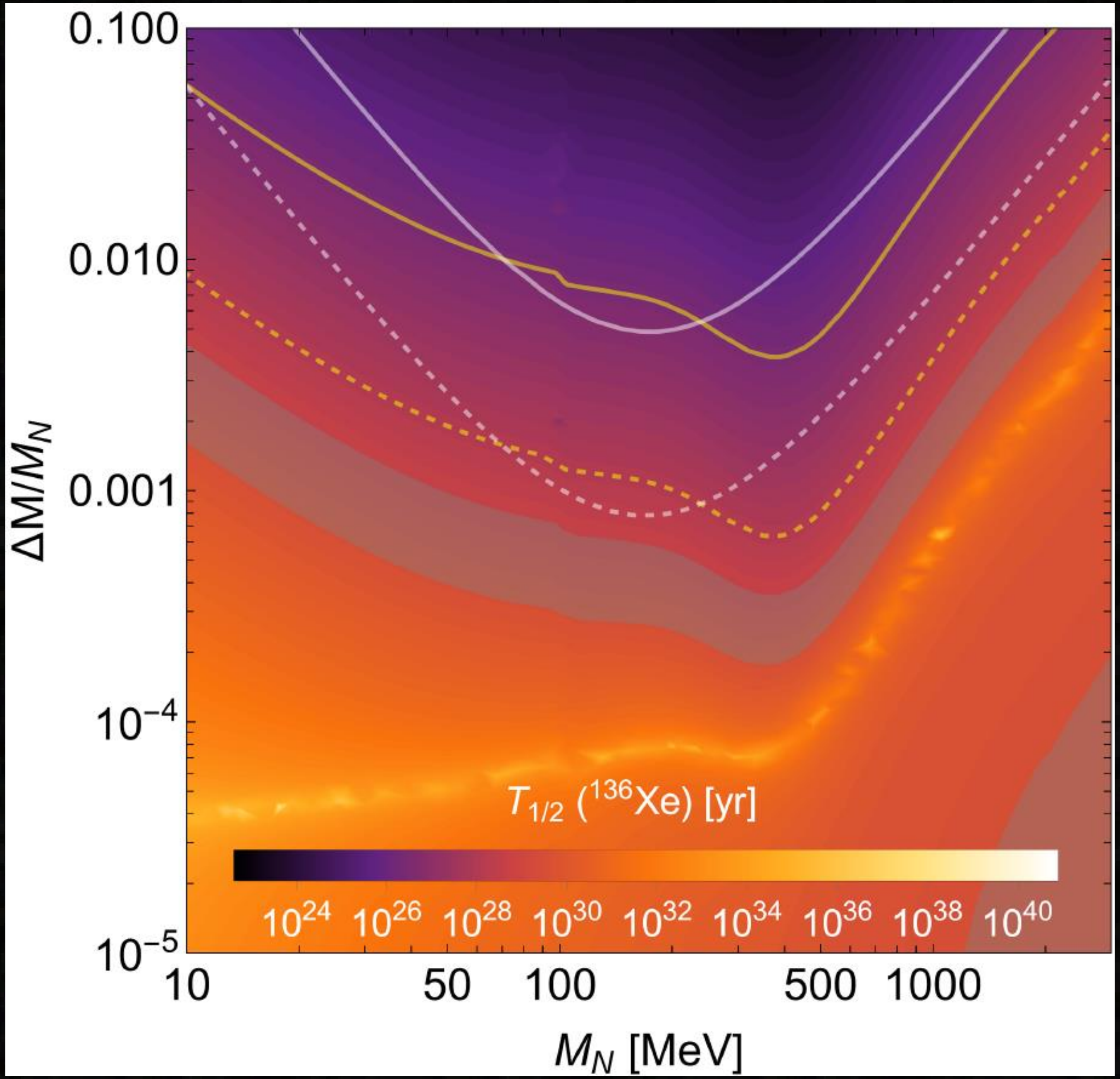
10^{33}
10^{31}
10^{29}
10^{27}
$T^{0\nu}_{1/2}\,(^{136}\mathrm{Xe})$ [yr]
Current limit 2.3×10^{26} yr
1
10
100
1000
m_4 [MeV]

Adding a sterile neutrino



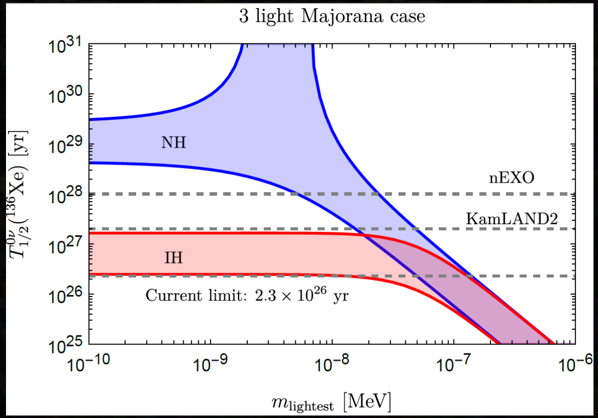
NH

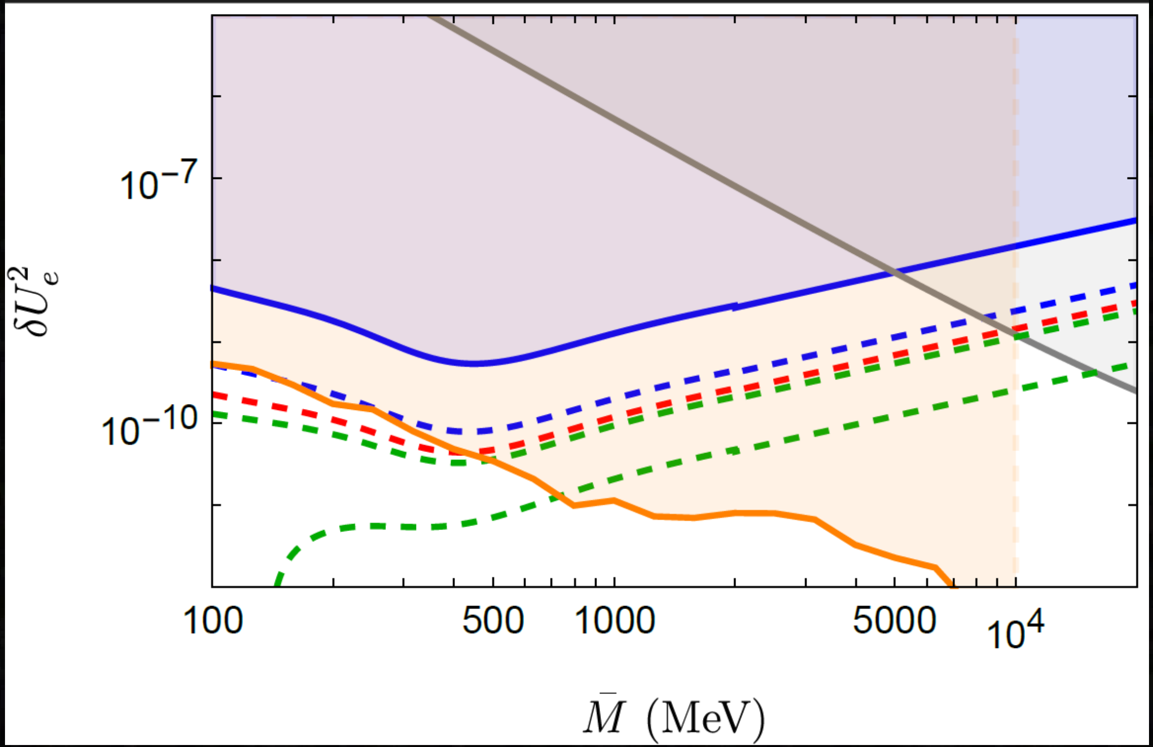
Cool contour plot



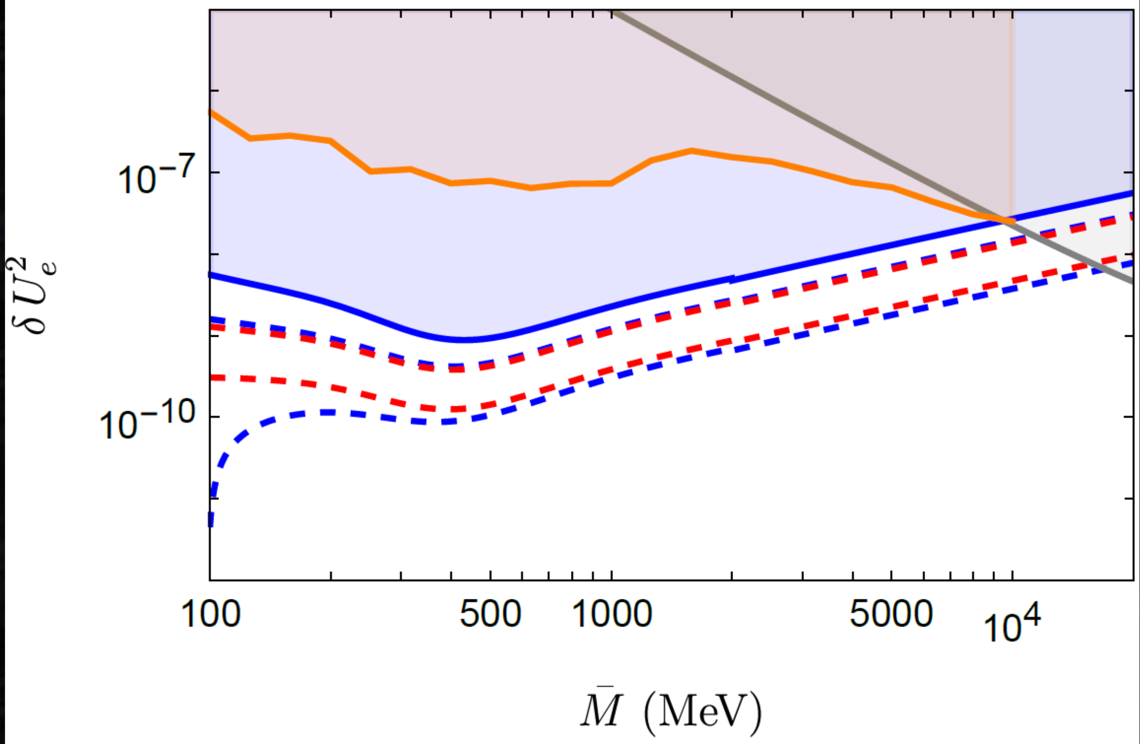
NH

Plots, plots, and more plots



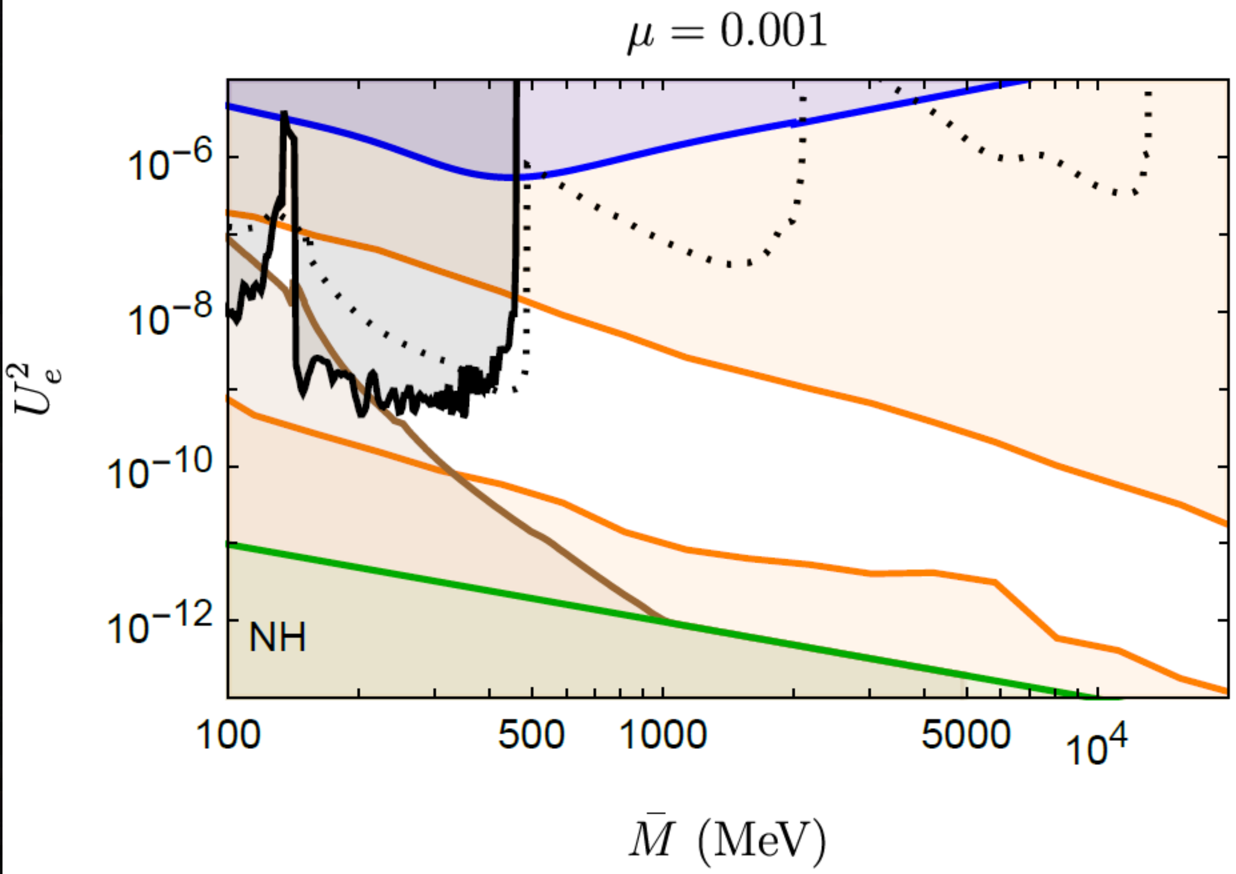


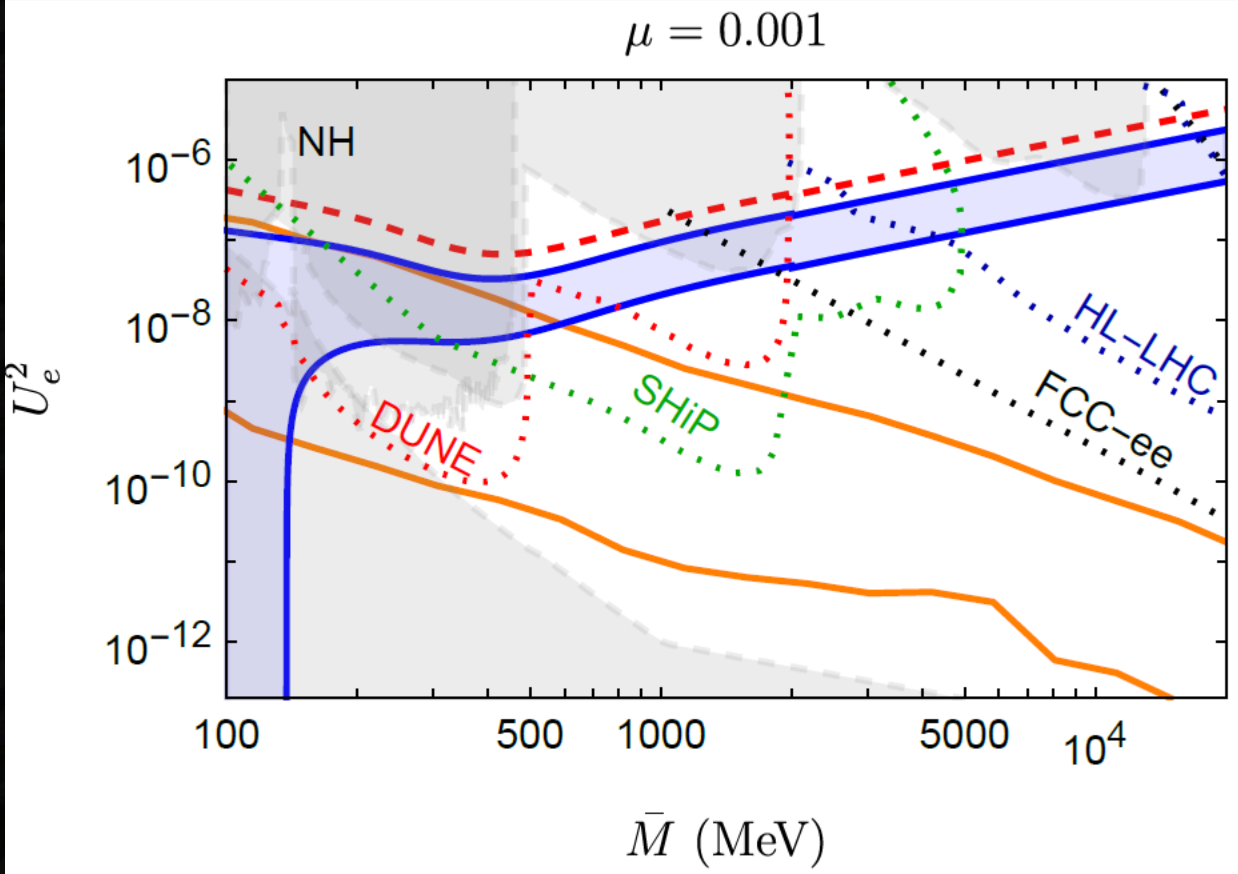
NH



IH

NH


$\mu = 0.001$
U_e^2
10^{-6}
10^{-8}
10^{-10}
10^{-12}
NH
100
500
1000
5000
10^4
$\bar{M}$ (MeV)


$\mu = 0.001$
U_e^2
NH
10^{-6}
10^{-8}
10^{-10}
10^{-12}
DUNE
SHiP
HL-LHC
FCC-ee
100
500
1000
5000
10^4
$\bar{M}$ (MeV)

Casas-Ibarra parametrisation

- $U_\nu = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} . \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\,\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\,\delta_{CP}} & 0 & c_{13} \end{pmatrix} . \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} . \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix}$

- Ensure neutrino oscillation data (masses) are automatically satisfied

  - $\Theta = i\, U_\nu \sqrt{m_\nu^d}\, \mathcal{R}\, \sqrt{M^d}^{-1}$

  - $\mathcal{R}_{NH} = \begin{pmatrix} 0 & 0 \\ \cos\omega & \sin\omega \\ -\sin\omega & \cos\omega \end{pmatrix}$; $\mathcal{R}_{IH} = \begin{pmatrix} \cos\omega & \sin\omega \\ -\sin\omega & \cos\omega \\ 0 & 0 \end{pmatrix}$

More constraints

- Missing energy and displaced vertex searches: upper bounds on U_e^2
- Big Bang Nucleosynthesis: lower bound on U_e^2
- Neutrino masses: seesaw relation $\Rightarrow$ lower bound on U_e^2
- Loop-induced corrections to neutrino masses: upper bound on U_e^2 *

*T&C apply: we have to fix μ for this