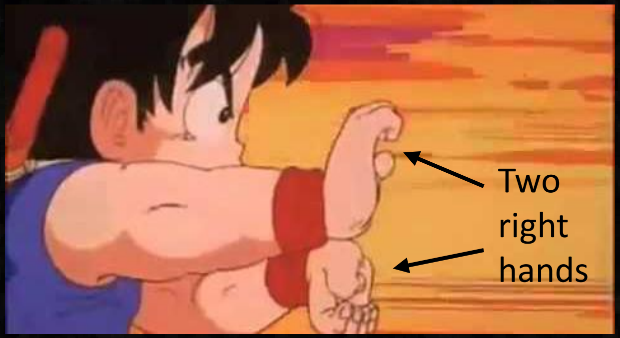


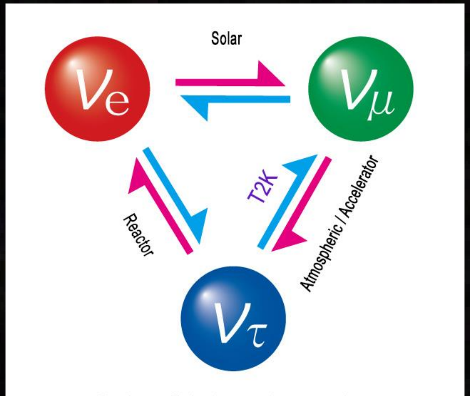
Hunting for two right-handed neutrinos at low scales

[2402.07993] with W. Dekens, J. de Vries, D. Castillo, J. Menéndez, E. Mereghetti, P. Soriano, G. Zhou
[2407.10560] with J. de Vries, M. Drewes, Y. Georis, J. Klarić

BLV 2024
Karlsruhe, Germany

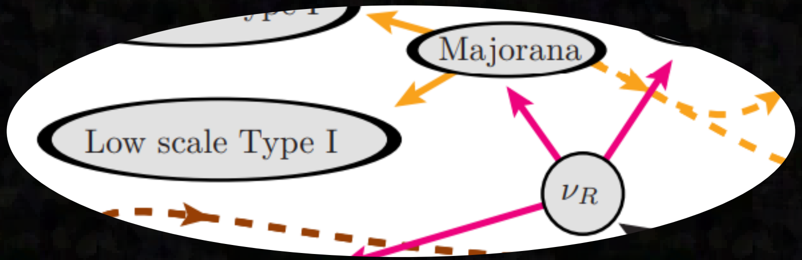
Vaisakh Plakkot

Pesky neutrino masses



Neutrino oscillation between three generations

- Gauge singlet RH neutrinos for light neutrino masses
  - Majorana mass term allowed (LNV)
- Rotate into mass basis
  - Light and heavy Majorana neutrinos



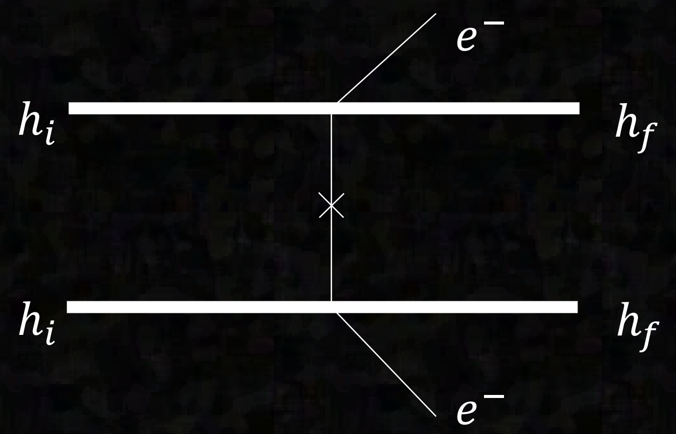
[From the talk by Richard Ruiz]

Type-I seesaw: $m_\nu \sim y^2 \frac{v^2}{M_R}$

Higgs vev

Sterile neutrino (Majorana) mass(es)

The "standard" prescription



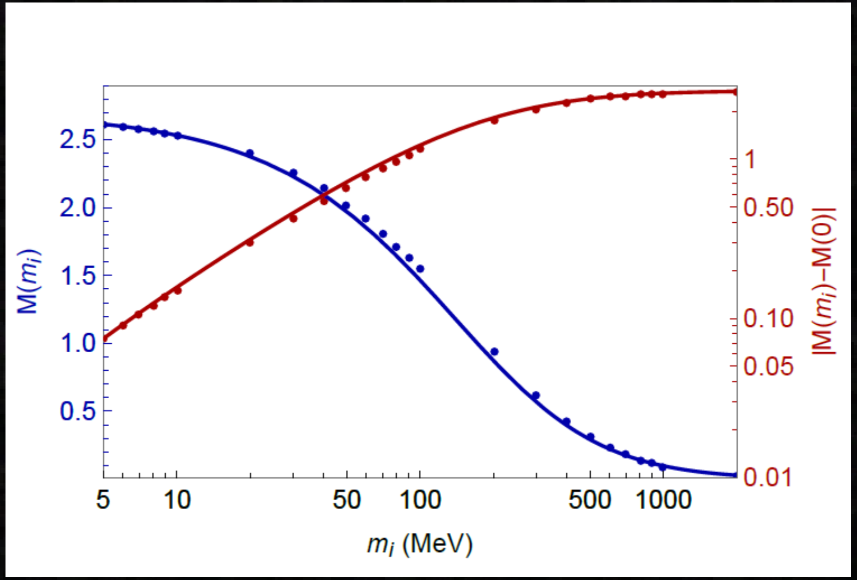
- Modify neutrino propagator

$$\sum_1^3 \frac{1}{k^2} \to \sum_1^{3+n_s} \frac{1}{k^2 - m_i^2}$$

- Amplitude takes the form

$$M(m_i) \simeq M(0)\frac{\langle p^2\rangle}{\langle p^2\rangle + m_i^2}$$

- $\langle p^2\rangle$ fit from calculated NMEs



All neutrinos are equal, but some are more equal than the others

- Hard neutrinos: $k_0 \sim |\vec{k}| \sim \Lambda_\chi$ (~ GeV)
- Soft neutrinos: $k_0 \sim |\vec{k}| \sim m_\pi$
- Potential neutrinos: $k_0 \sim \left|\vec{k}\right|^2 / m_N \sim m_\pi^2 / m_N$
- Ultrasoft neutrinos: $k_0 \sim |\vec{k}| \sim m_\pi^2 / m_N$

Divide and conquer

- $m_i \geq 2\ \mathrm{GeV}$: $A_\nu^{(9)}(m_i)$ from $u^2 d^2 e^2$ operator ($\sim G_F^2/m_i$)
  - Contains a bunch of LECs requiring LQCD
- $100\ \mathrm{MeV} \leq m_i < 2\ \mathrm{GeV}$: $A_\nu^{(\mathrm{pot})}(m_i) + A_\nu^{(\mathrm{hard})}(m_i)$
  - Contains NMEs and interpolations formulae
- $m_i < 100\ \mathrm{MeV}$: $A_\nu^{(\mathrm{pot},<)}(m_i) + A_\nu^{(\mathrm{hard})}(m_i) + A_\nu^{(\mathrm{usoft})}(m_i)$
  - Contains transition NMEs and correction in potential term to avoid double counting

Standard 3+0 scenario

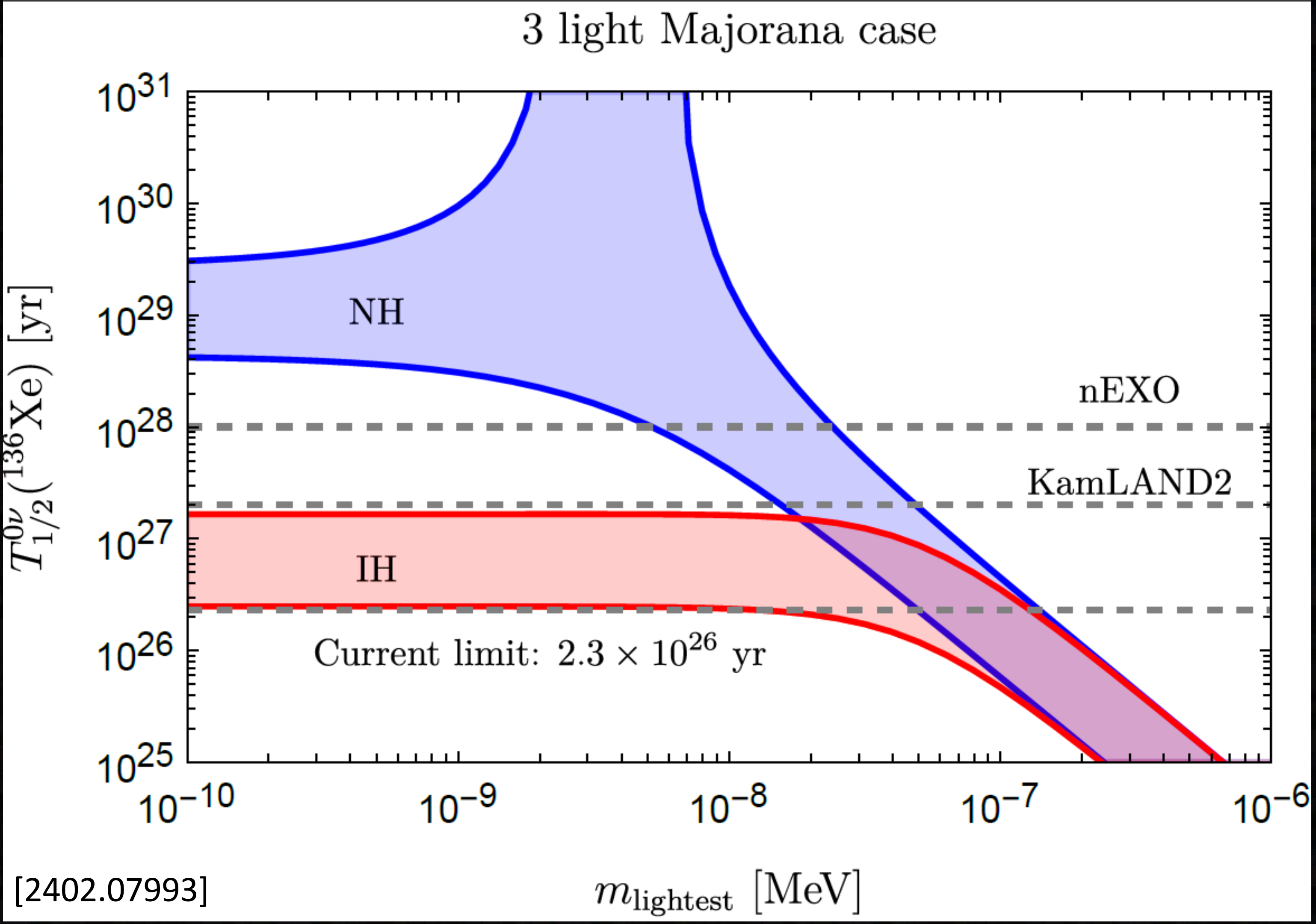
Phase space factor (nucleus-dependent)

CKM element
~ 0.97

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

Electron mass
0.511 MeV

Nuclear axial charge
~ 1.27



[2402.07993]

A toy 3+1 model

Phase space factor (nucleus-dependent)

CKM element
~ 0.97

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

Electron mass
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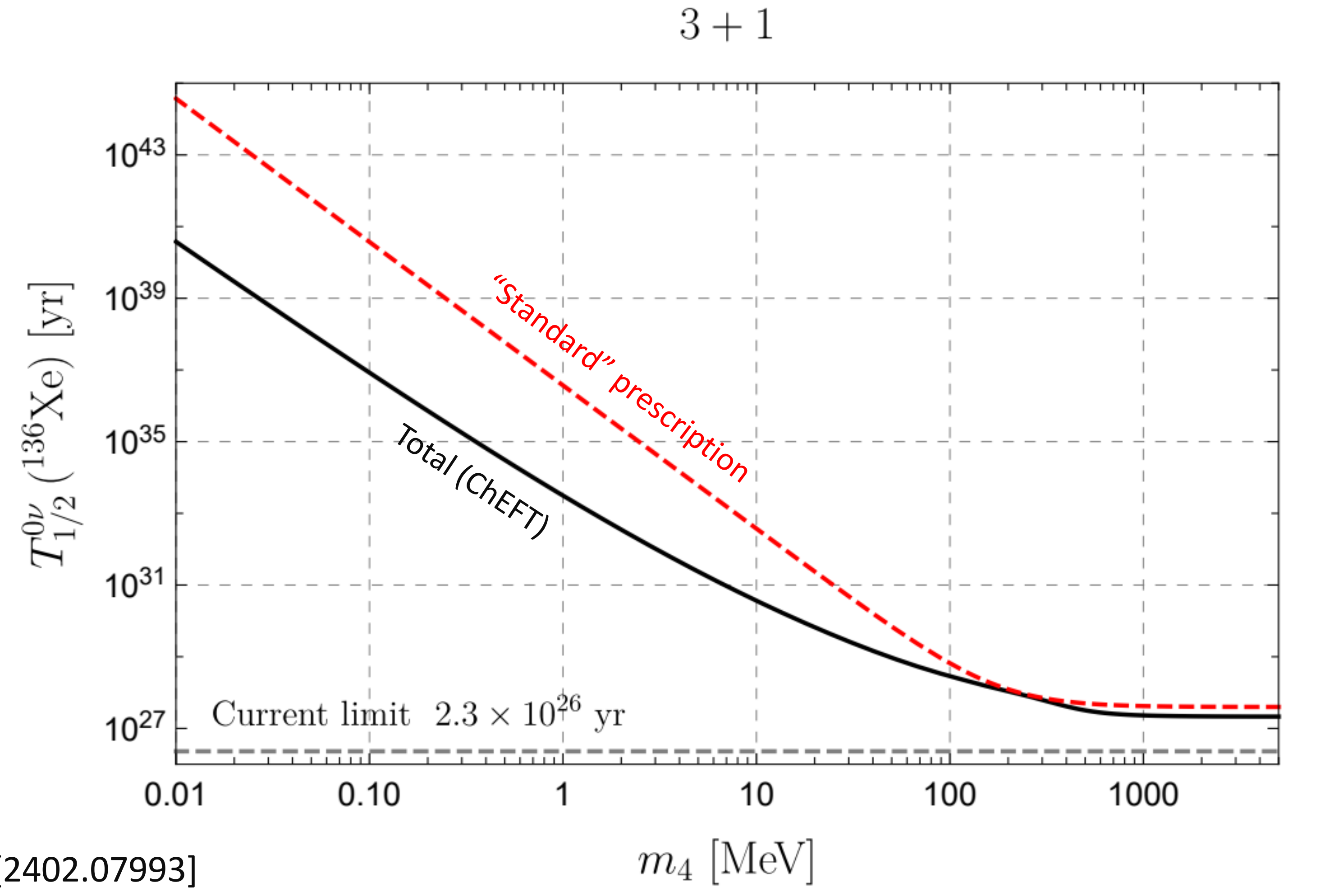


[2402.07993]

3+2 type-I seesaw model

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

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

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

- 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

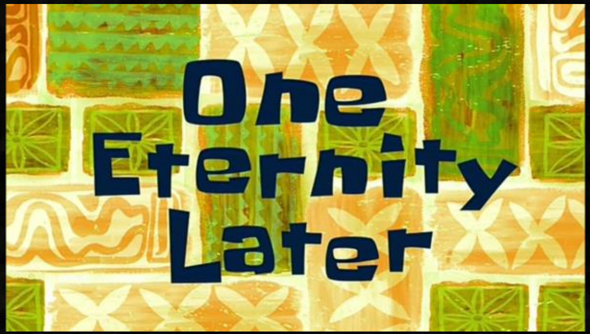
Small splitting approximation

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

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

…

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



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

…

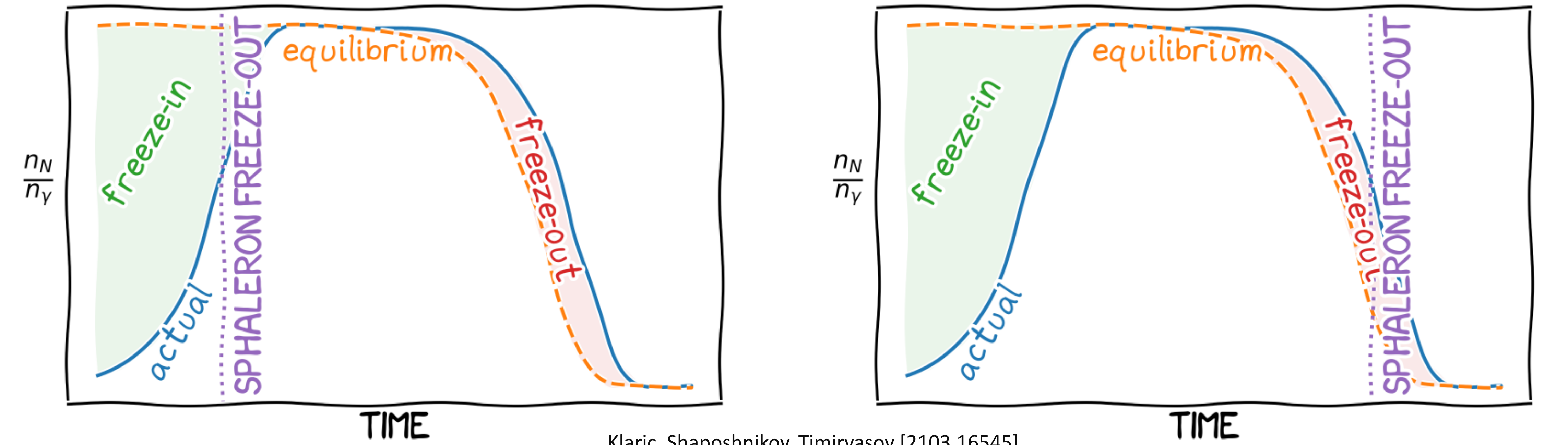
$$\mathcal{A}_{eff} \approx \sum_{i=1}^{3} m_i \mathcal{U}_{ei}^2 \left(A_\nu(0) - A_\nu(\bar{M})\right) + e^{i\lambda} \mu\, U_e^2 \frac{\bar{M}^2}{2} A_\nu'(\bar{M})$$

Limits from experiments and cosmology

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

Low-scale leptogenesis

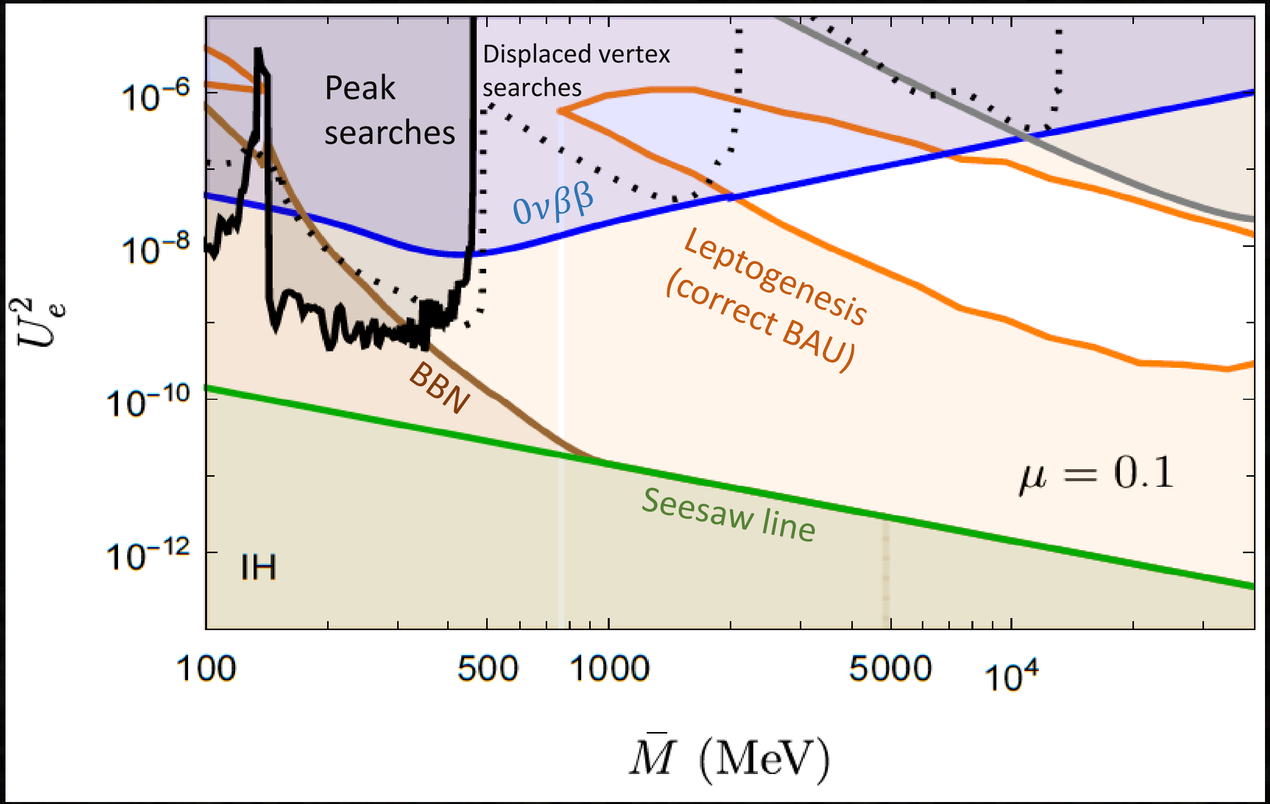
Leptogenesis: convert lepton asymmetry to baryon asymmetry

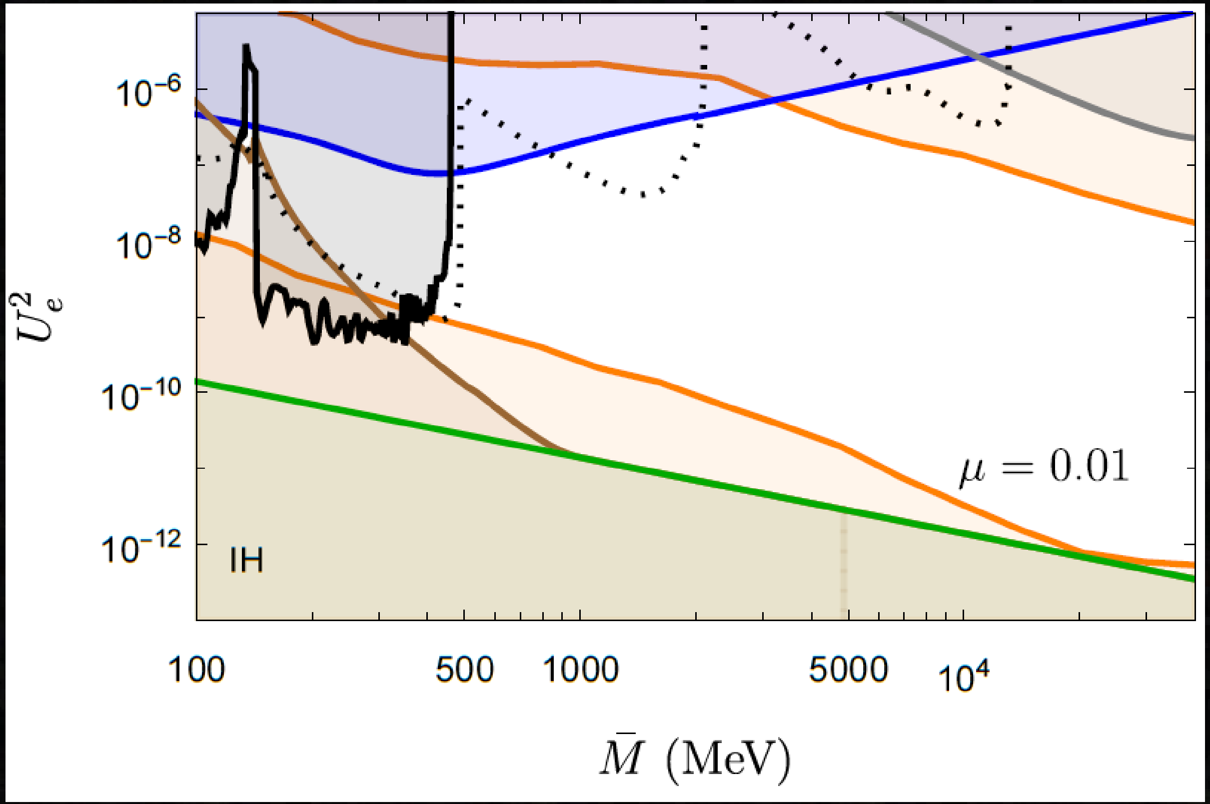


Klaric, Shaposhnikov, Timiryasov [2103.16545]

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

Exclusions galore

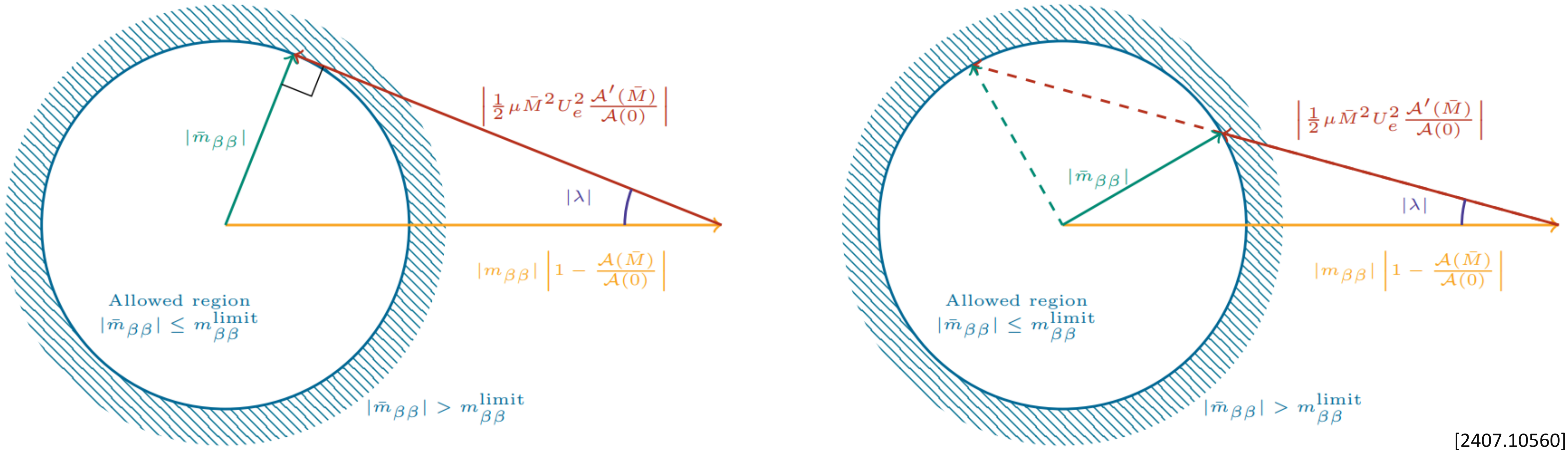




[2407.10560]

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

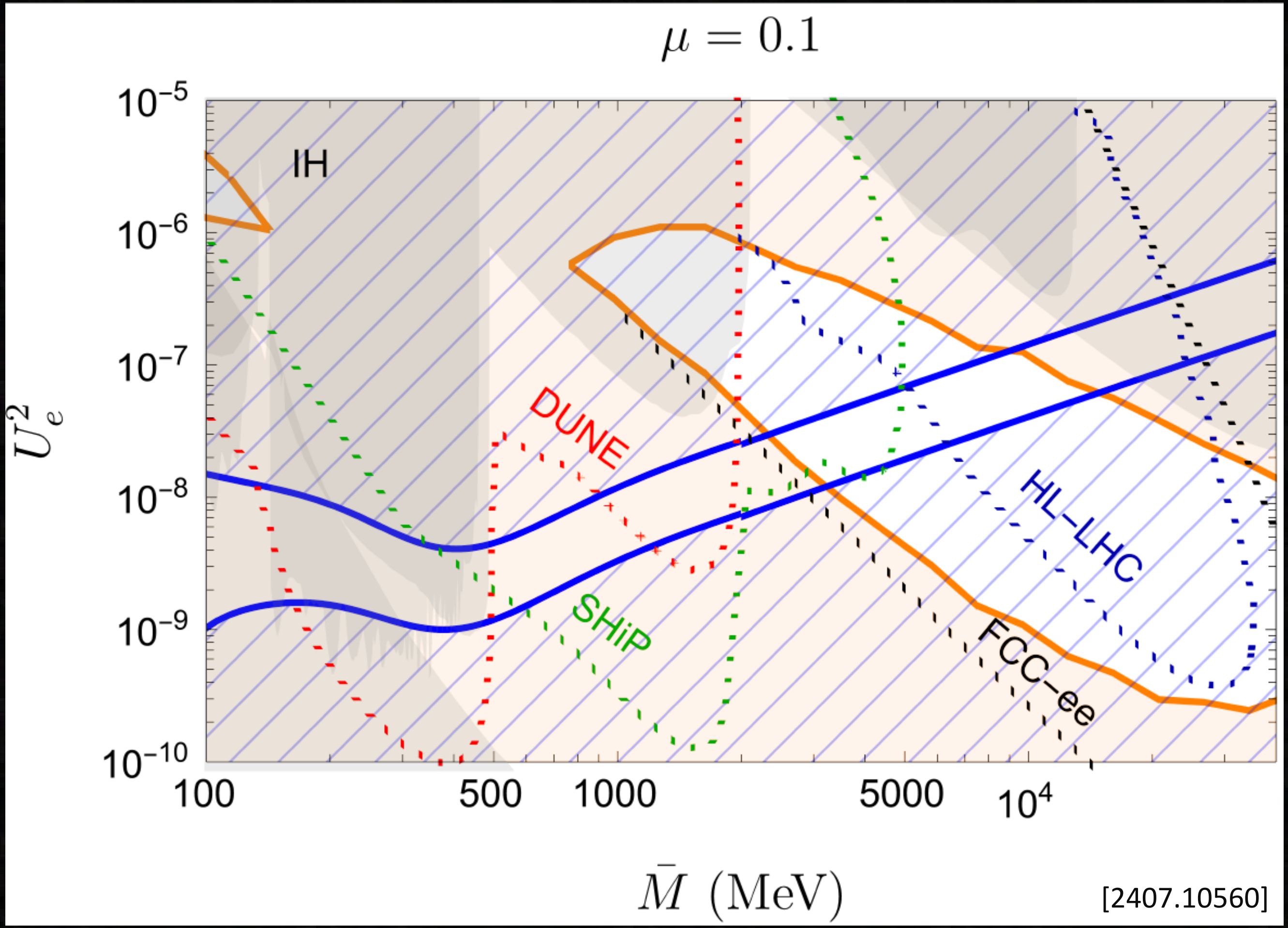
Mutual assured destruction



[2407.10560]

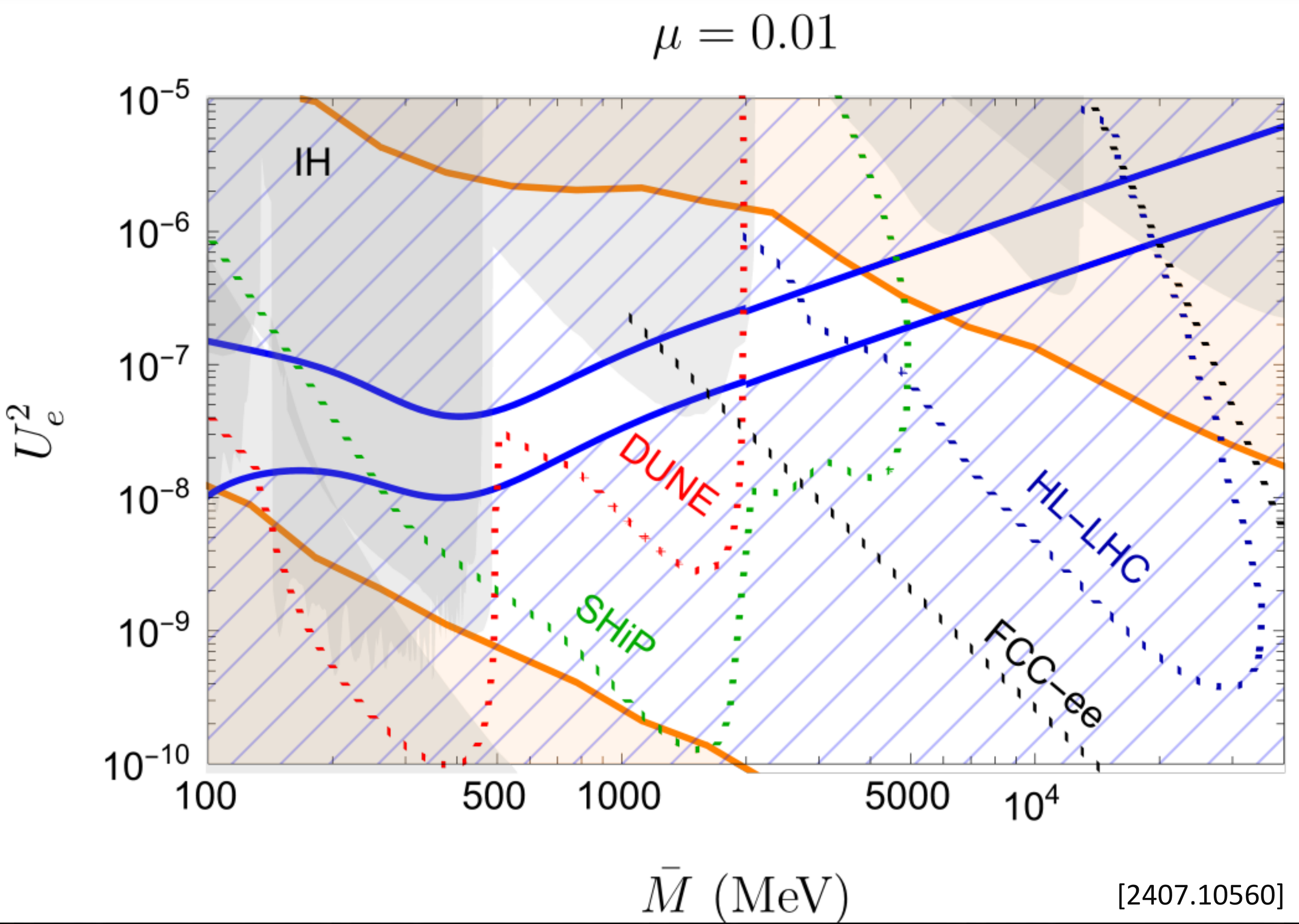
$$\mathcal{A}_{eff} \approx \sum_{i=1}^{3} m_i \mathcal{U}_{ei}^2 \left(A_\nu(0) - A_\nu(\bar{M})\right) + e^{i\lambda}\mu\, U_e^2 \frac{\bar{M}^2}{2} A'_\nu(\bar{M})$$

Future prospects



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

Future prospects



[2407.10560]

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

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 in the inverted neutrino mass ordering; normal ordering requires even better limits

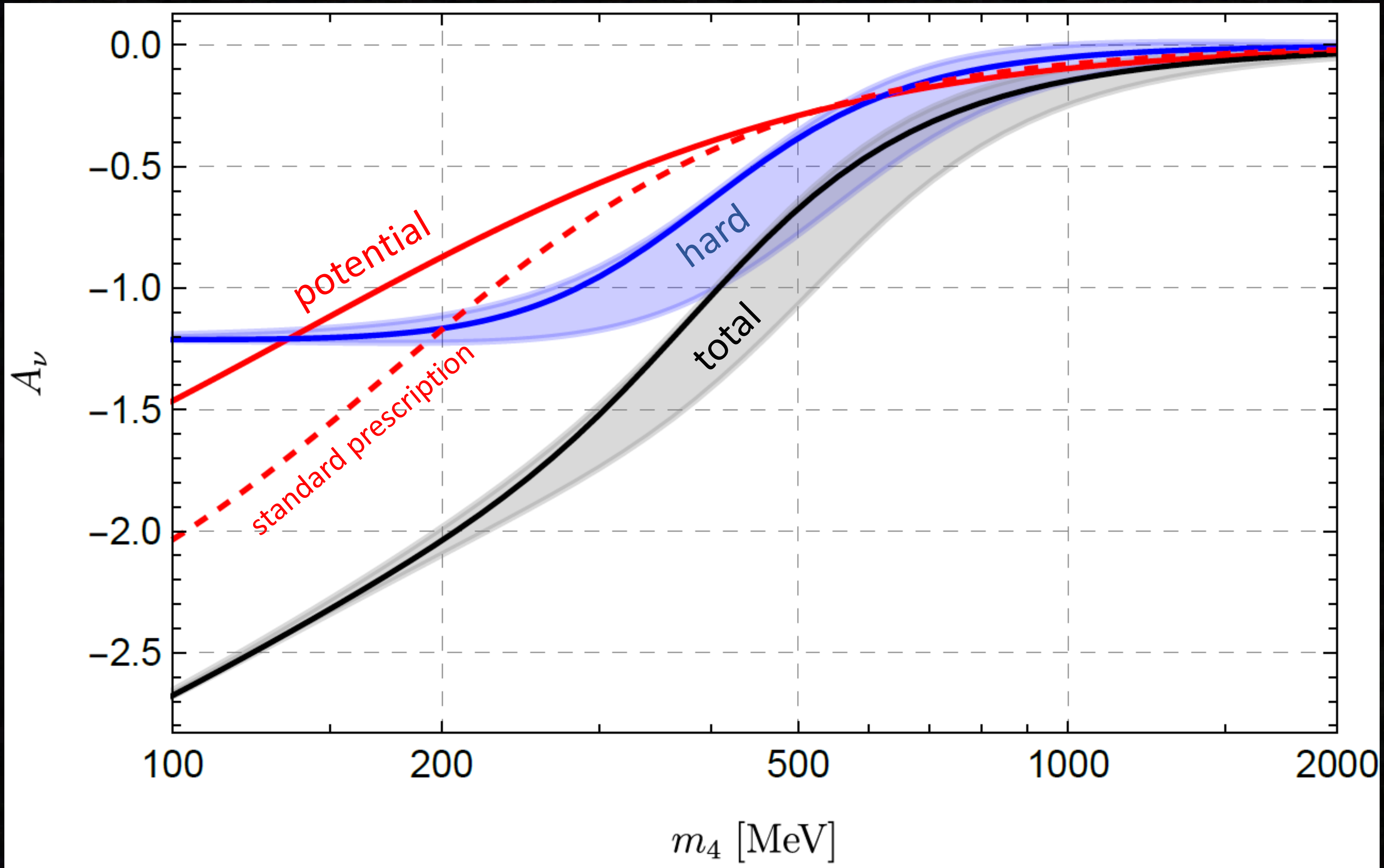
Backup

Pieces of the puzzle

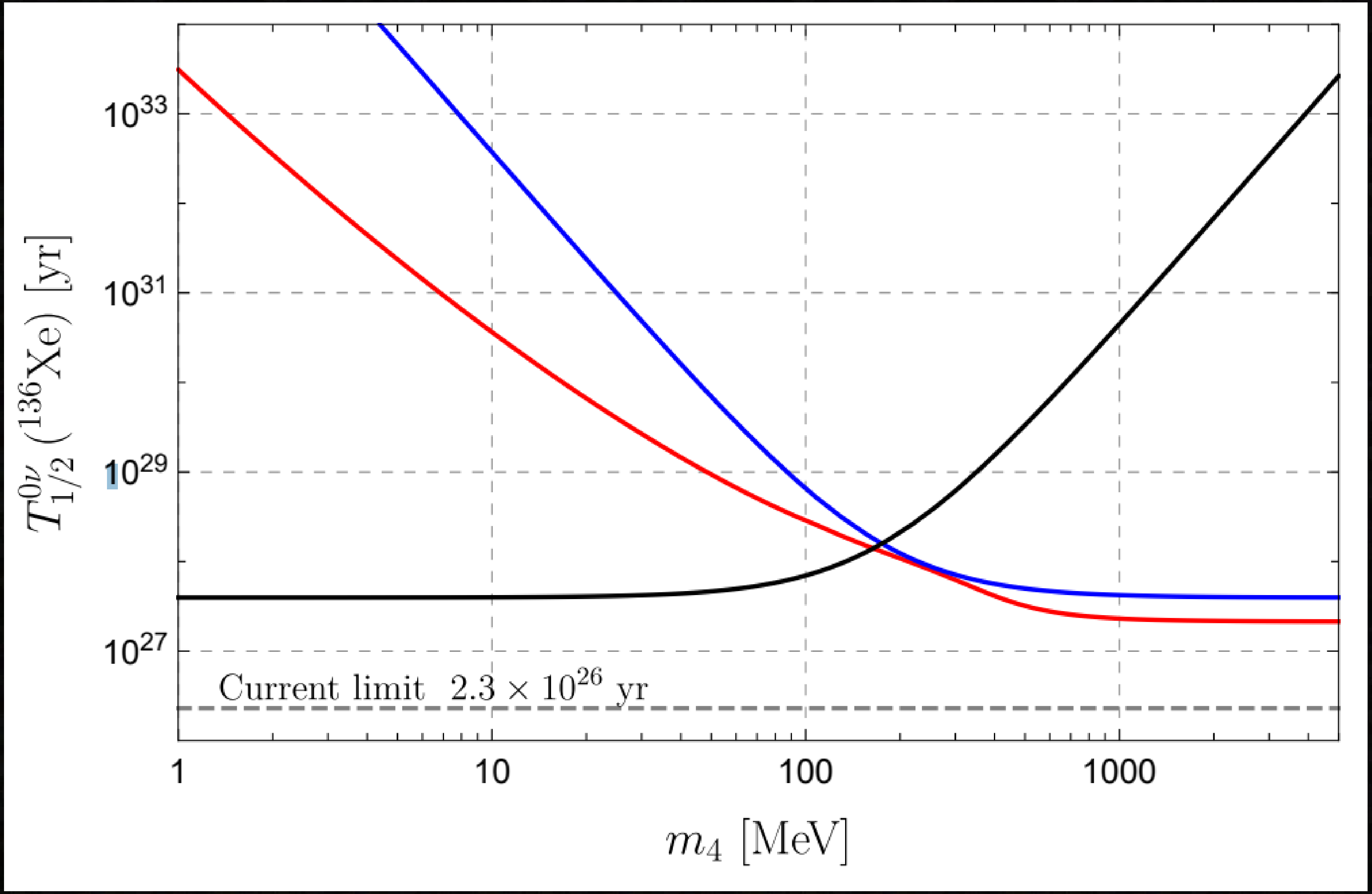
- $A_\nu^{(9)} = -2\,\eta \frac{m_\pi^2}{m_i^2}\left[\frac{5}{6} g_1^{\pi\pi}\left(M_{GT,sd}^{PP} + M_{T,sd}^{PP}\right) + g_1^{\pi N}\left(M_{GT,sd}^{AP} + M_{T,sd}^{AP}\right) - \frac{2}{g_A^2} g_1^{NN} M_{F,sd}\right]$
- $A_\nu^{(\text{usoft})} = 2\frac{\mathrm{R_A}}{\pi g_A^2} \sum_n \langle 0_f^+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

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

A comparison of amplitudes

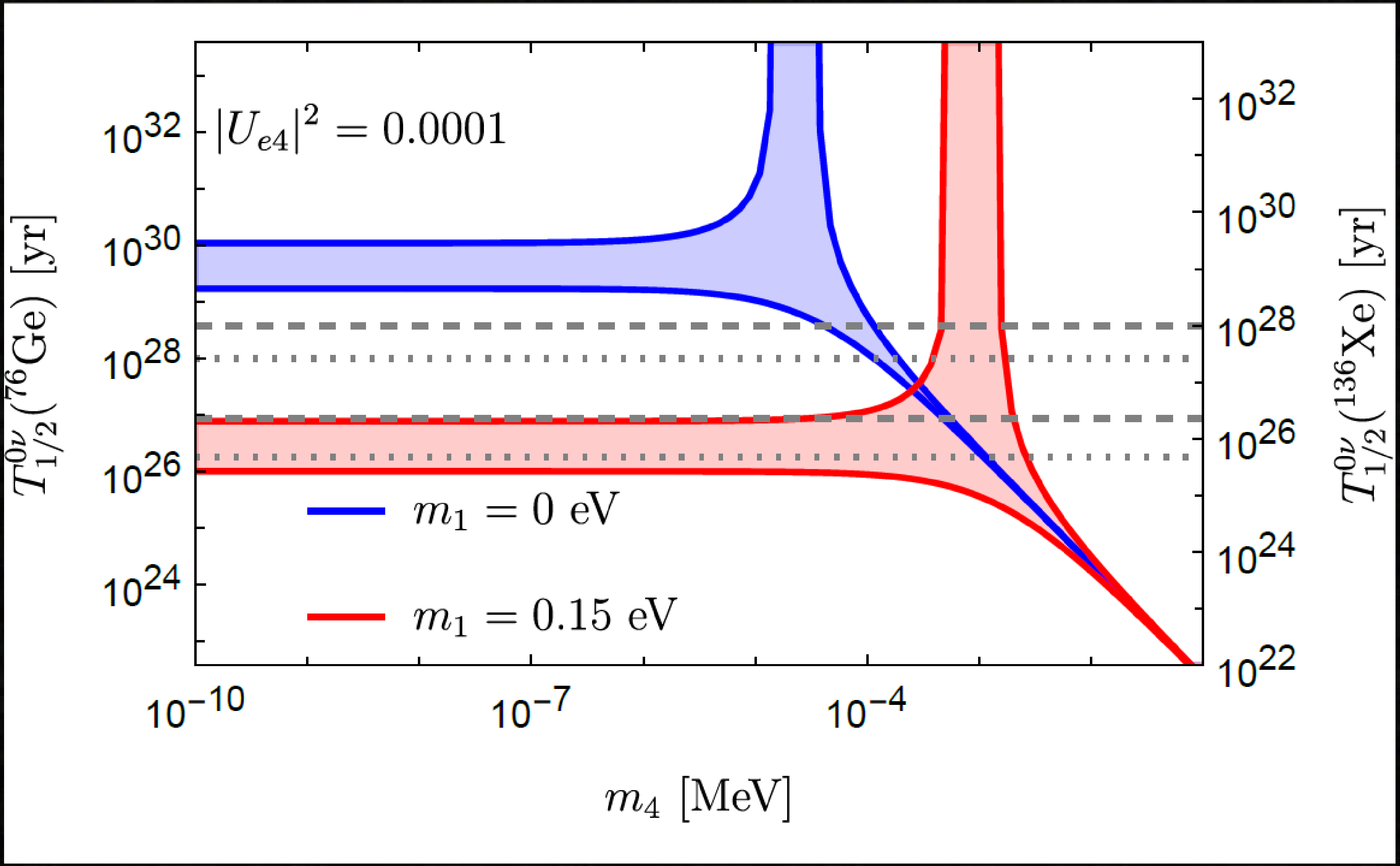


[2402.07993]



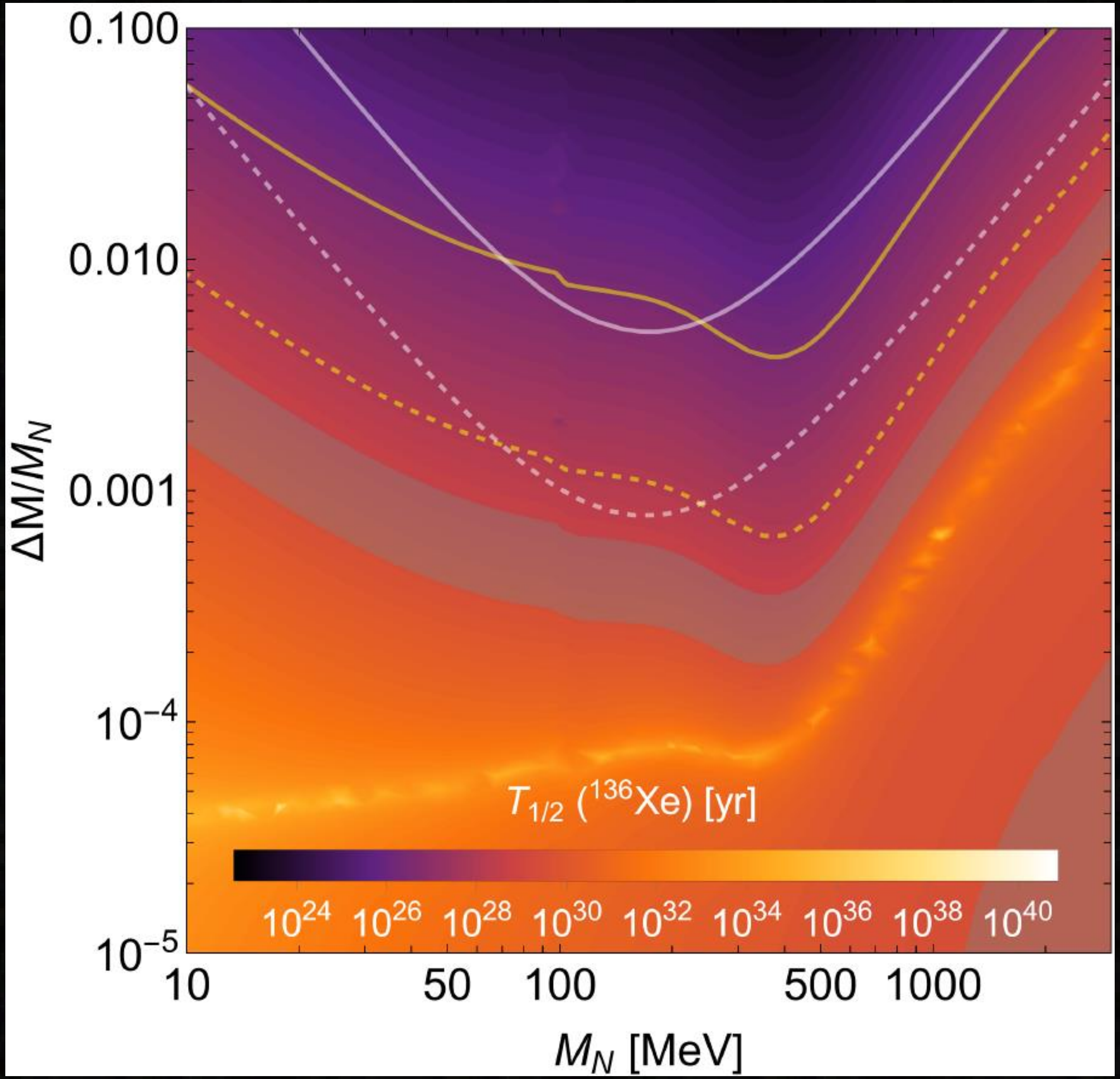
$T^{0\nu}_{1/2}\,(^{136}\mathrm{Xe})$ [yr]
10^{33}
10^{31}
10^{29}
10^{27}
Current limit 2.3×10^{26} yr
1
10
100
1000
m_4 [MeV]

Adding a sterile neutrino



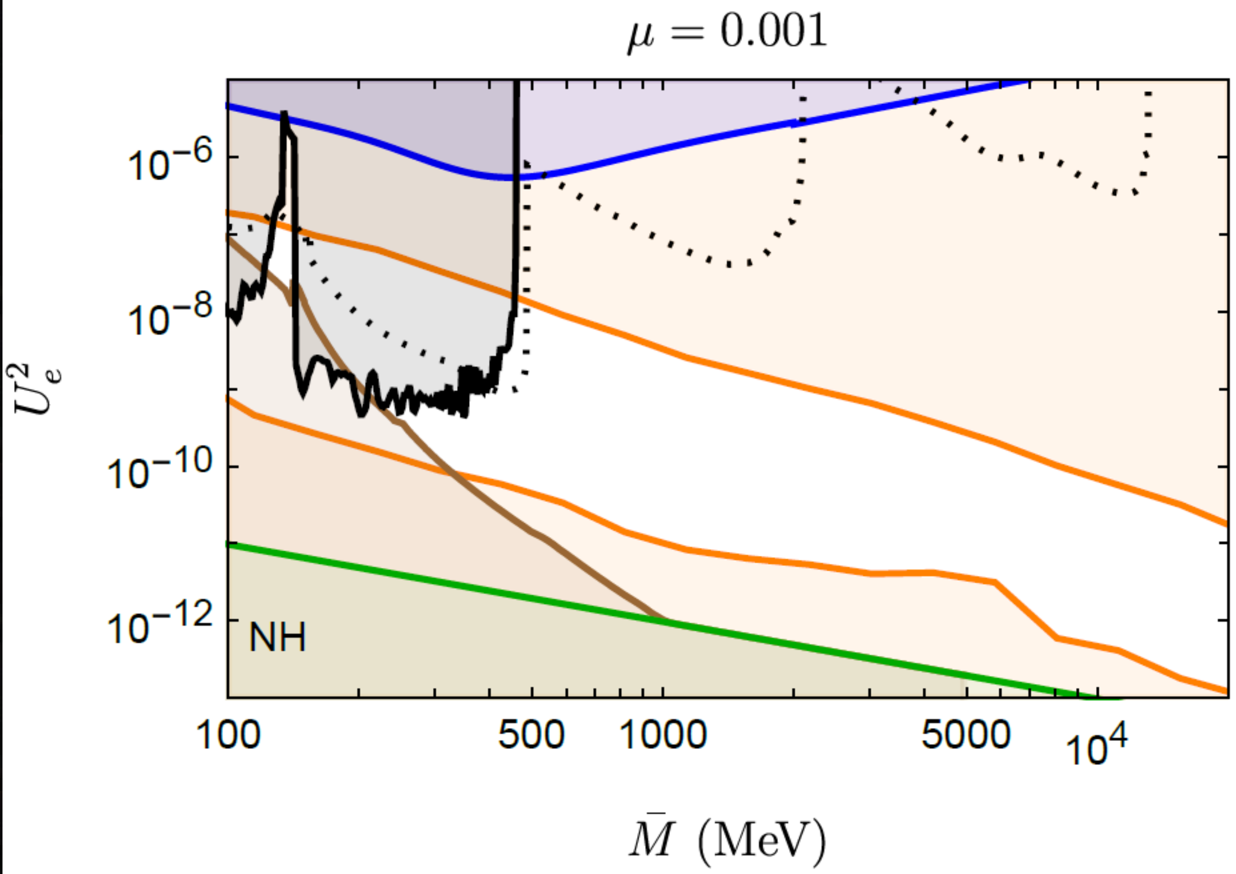
NH

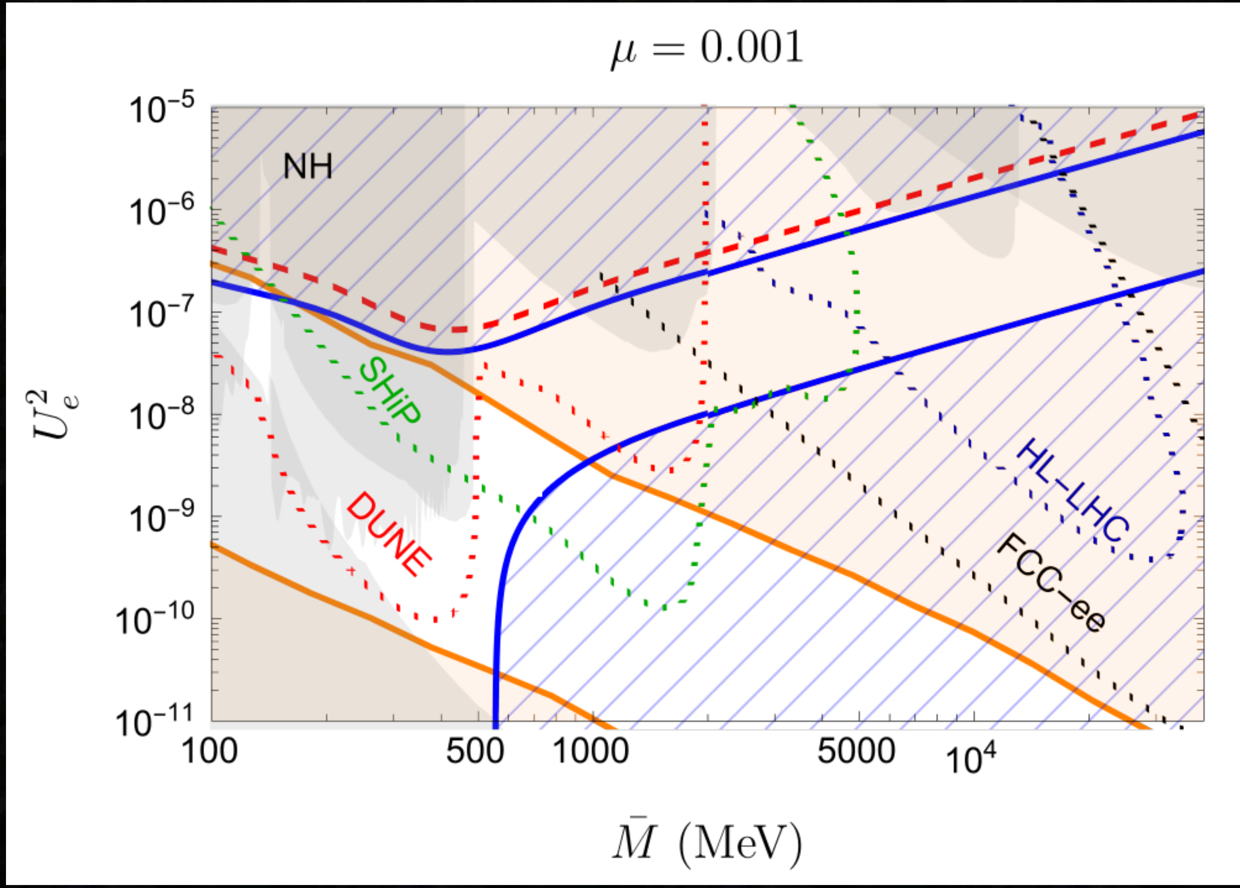
Cool contour plot



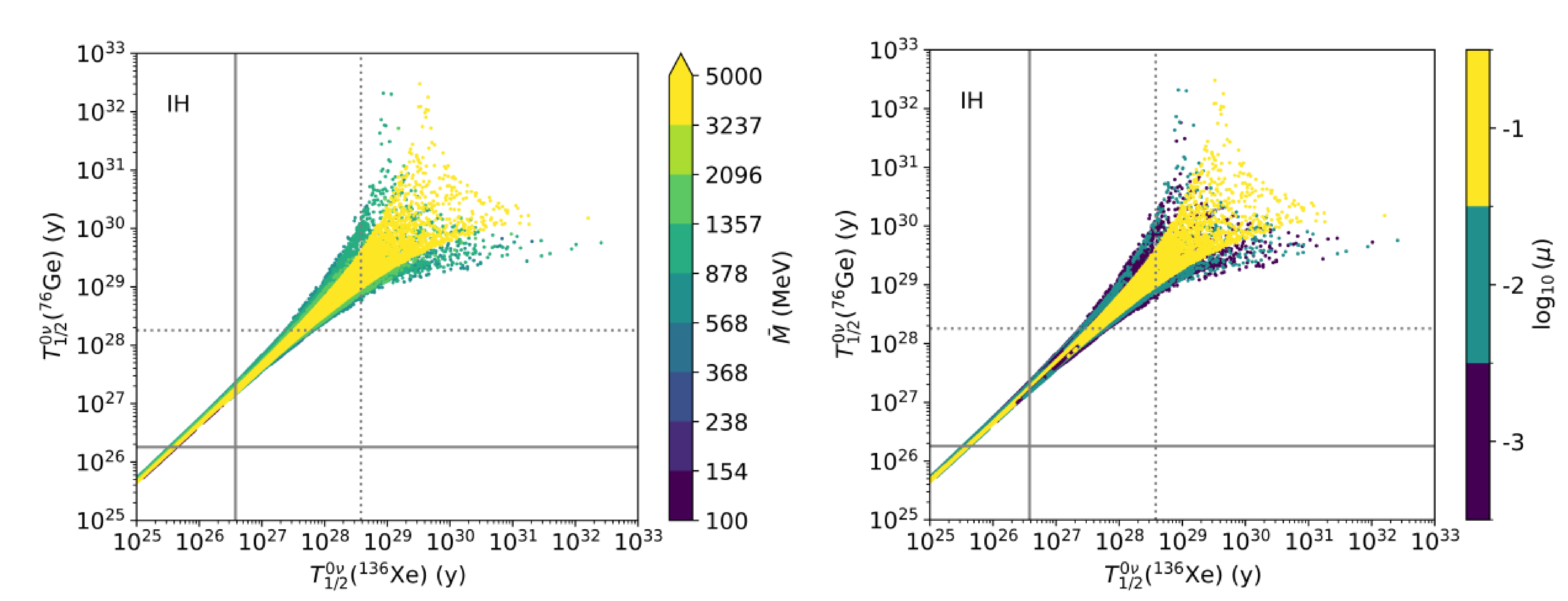
NH

NH


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


$\mu = 0.001$
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
NH
SHiP
DUNE
HL-LHC
FCC-ee
U_e^2
100
500
1000
5000
10^4
$\bar{M}$ (MeV)

Comparison between isotopes



Casas-Ibarra parametrisation

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

- Ensure neutrino oscillation data (masses) are automatically satisfied

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

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