Constraints from neutrinoless double beta decay

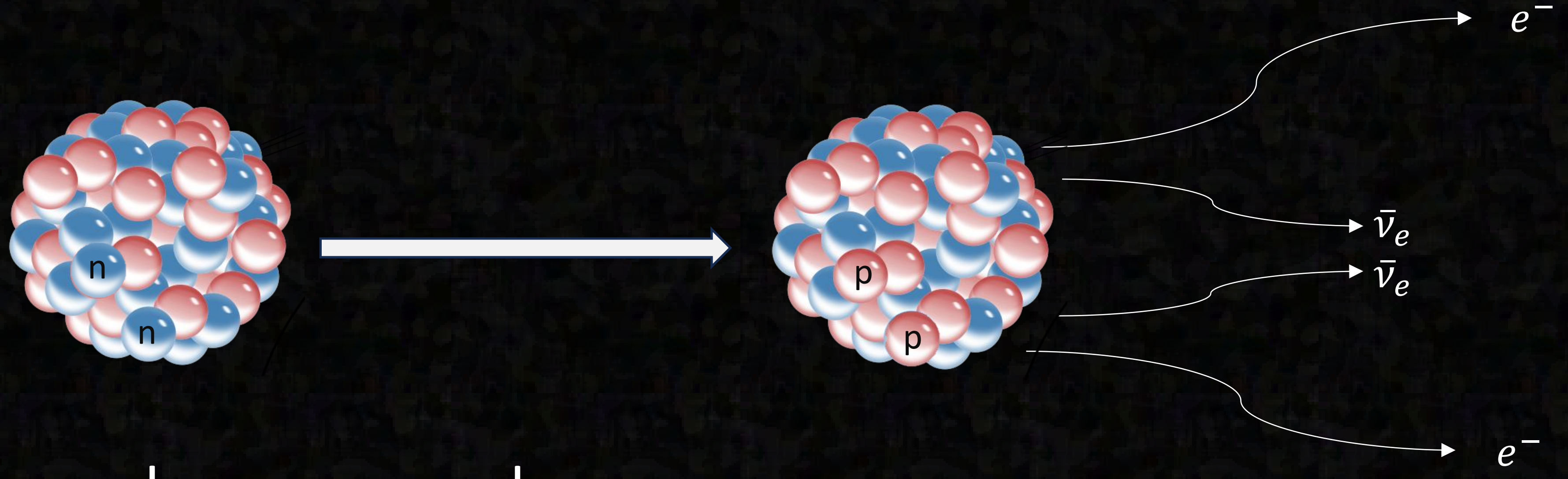
[2402.07993] with W. Dekens, J. de Vries, D. Castillo, J. Menéndez, E. Mereghetti, P. Soriano, G. Zhou
[2407.10560] with J. de Vries, M. Drewes, Y. Georis, J. Klarić

New-ν Physics: From Colliders to Cosmology
IPPP Durham

Vaisakh Plakkot

Double beta decay

- $(n \rightarrow p + e^{-} + \bar{\nu}_e) \times 2$

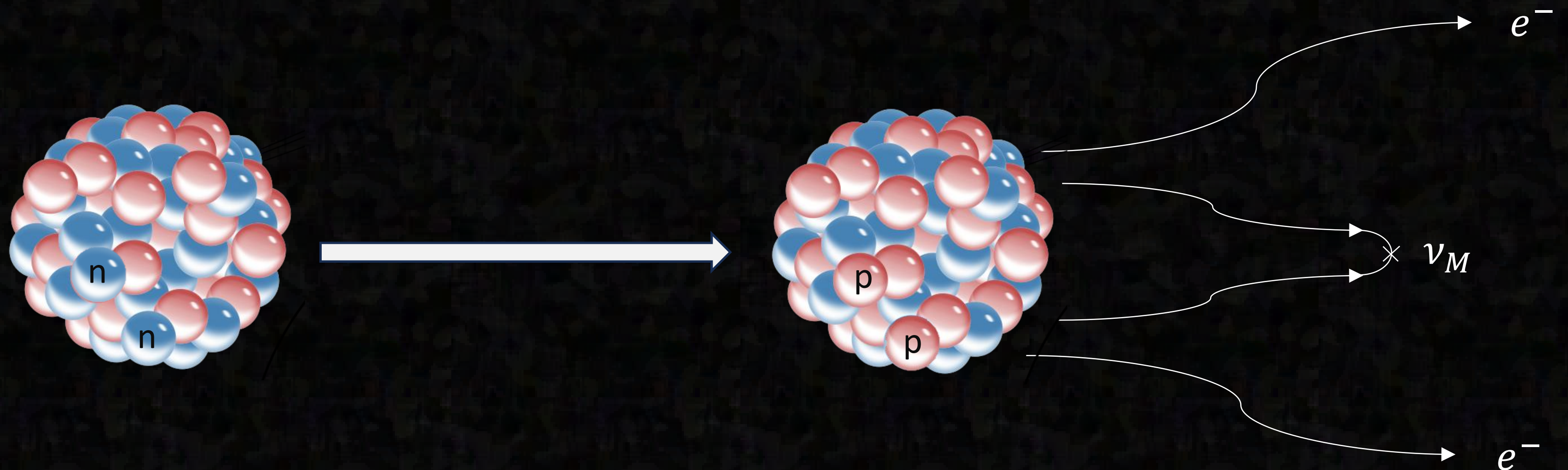


- Lepton number conserved

- Rare process: $T_{1/2}^{2\nu}(^{136}\text{Xe}) \approx 2.2 \cdot 10^{21}$ years

$\not\nu$ double beta decay $(0\nu\beta\beta)$

- $(n \rightarrow p + e^{-} + \bar{\nu}_e) \times 2$

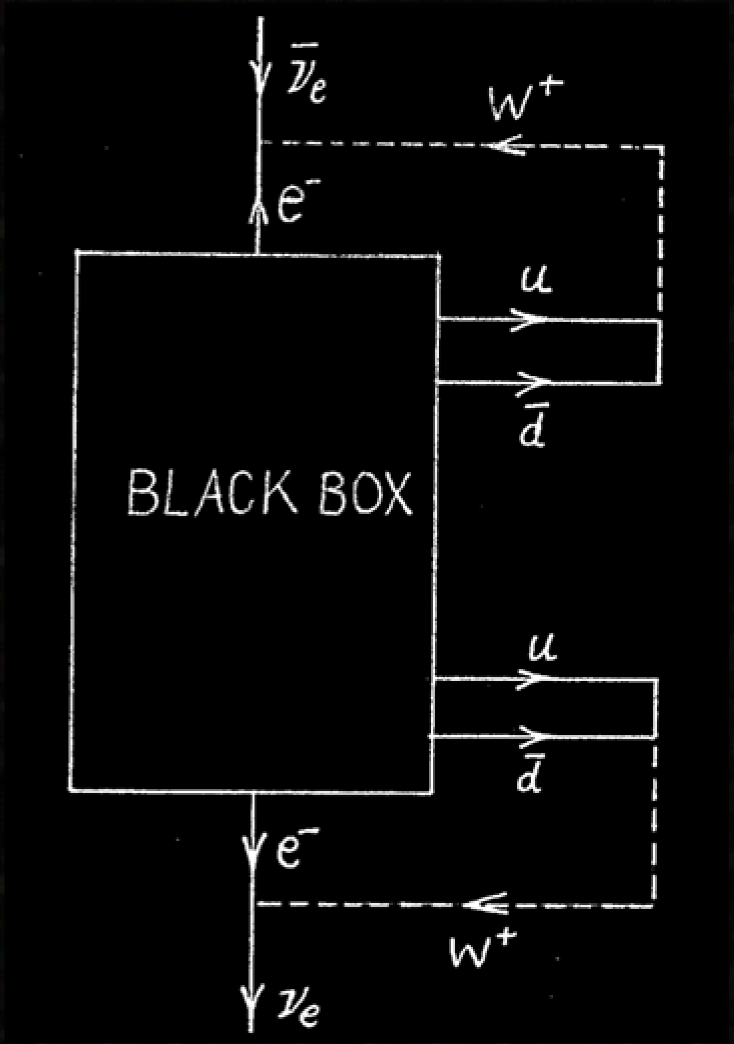


- Lepton number violated: $L_i = 0, L_f = 2$
- Yet unseen process: $T_{1/2}^{0\nu}(^{136}\mathrm{Xe}) > 3.8 \cdot 10^{26}$ years [KamLAND-Zen 2406.11438]

The Schechter-Valle theorem

- $0\nu\beta\beta \Rightarrow$ Majorana neutrinos [Schechter, Valle '81]

- Majorana neutrinos $\Rightarrow 0\nu\beta\beta$?



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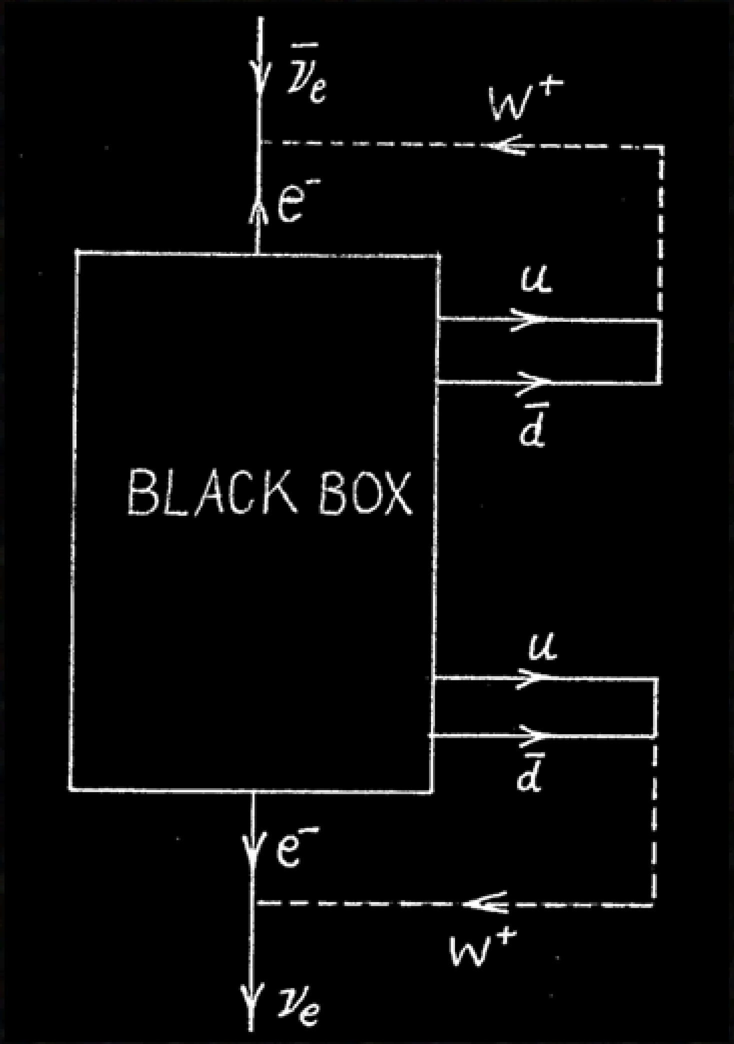
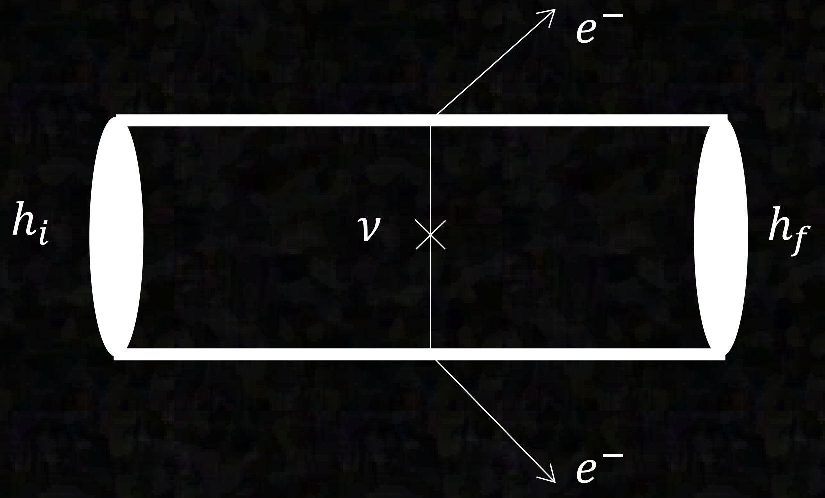


Prediction of a lifetime



$$\left(T_{1/2}^{0\nu}\right)^{-1} = \left|m_{\beta\beta}\right|^2 |\mathcal{M}|^2 G_{01}$$

New νs

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

$$m_{\beta\beta} = \sum_{i=1}^{3} \mathcal{U}_{ei}^2 m_i$$

How do you deal with the NMEs for arbitrary neutrino masses?

The “standard” prescription

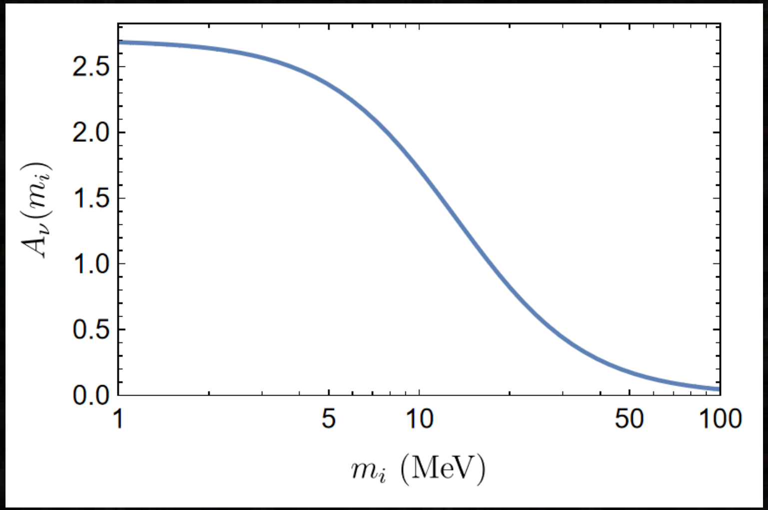
➢ Amplitude takes the functional form

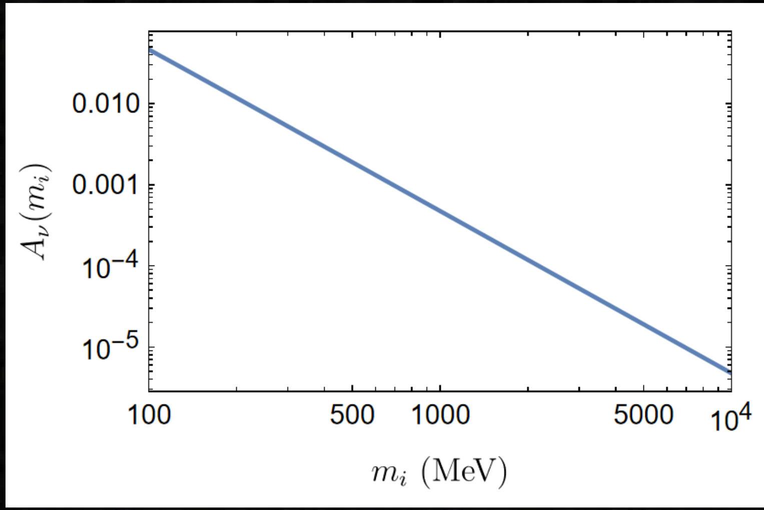
$$A_\nu(m_i) \simeq A_\nu(0)\frac{\langle p^2\rangle}{\langle p^2\rangle + m_i^2}$$

→ $\langle p^2\rangle \sim m_\pi^2$, nucleus-dependent

→ Approximately mass-independent for $m_i \to 0$

→ $\propto m_i^{-2}$ for large masses





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

- Hard neutrinos: $k_0 \sim \left|\vec{k}\right| \sim \Lambda_\chi \sim$ 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: $k_0 \sim |\vec{k}| \sim m_\pi^2 / m_N$

Important particularly for lower masses
where the rate can go to zero at leading order

Divide and conquer

- $m_i \geq 2$ 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

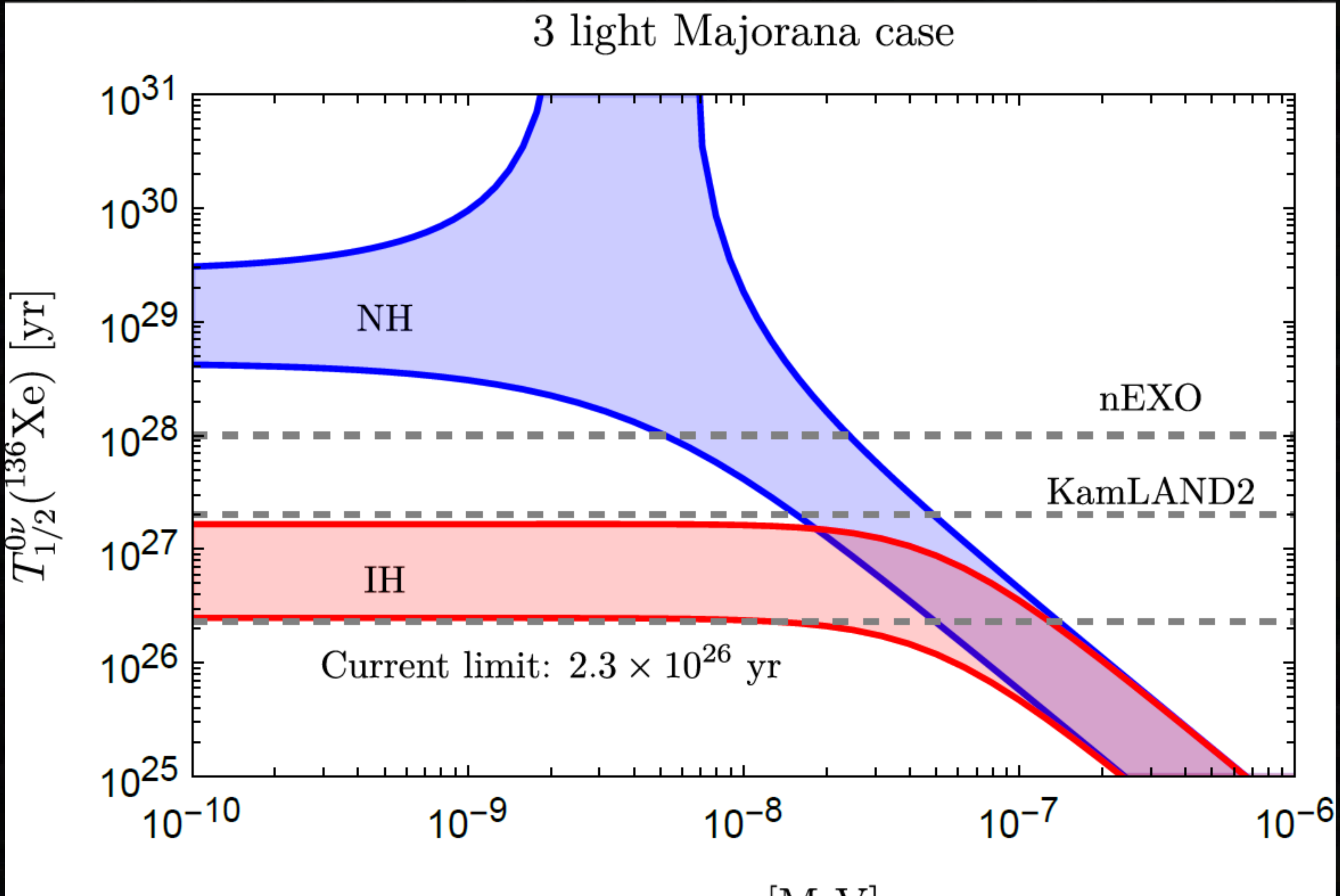
- 100 MeV $\leq m_i < 2$ GeV: $A_\nu^{(\mathrm{pot})}(m_i) + A_\nu^{(\mathrm{hard})}(m_i)$
  → Contains NMEs and interpolations formulae

- $m_i < 100$ 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

[Dekens et al. 2303.04168]

Standard 3+0 scenario

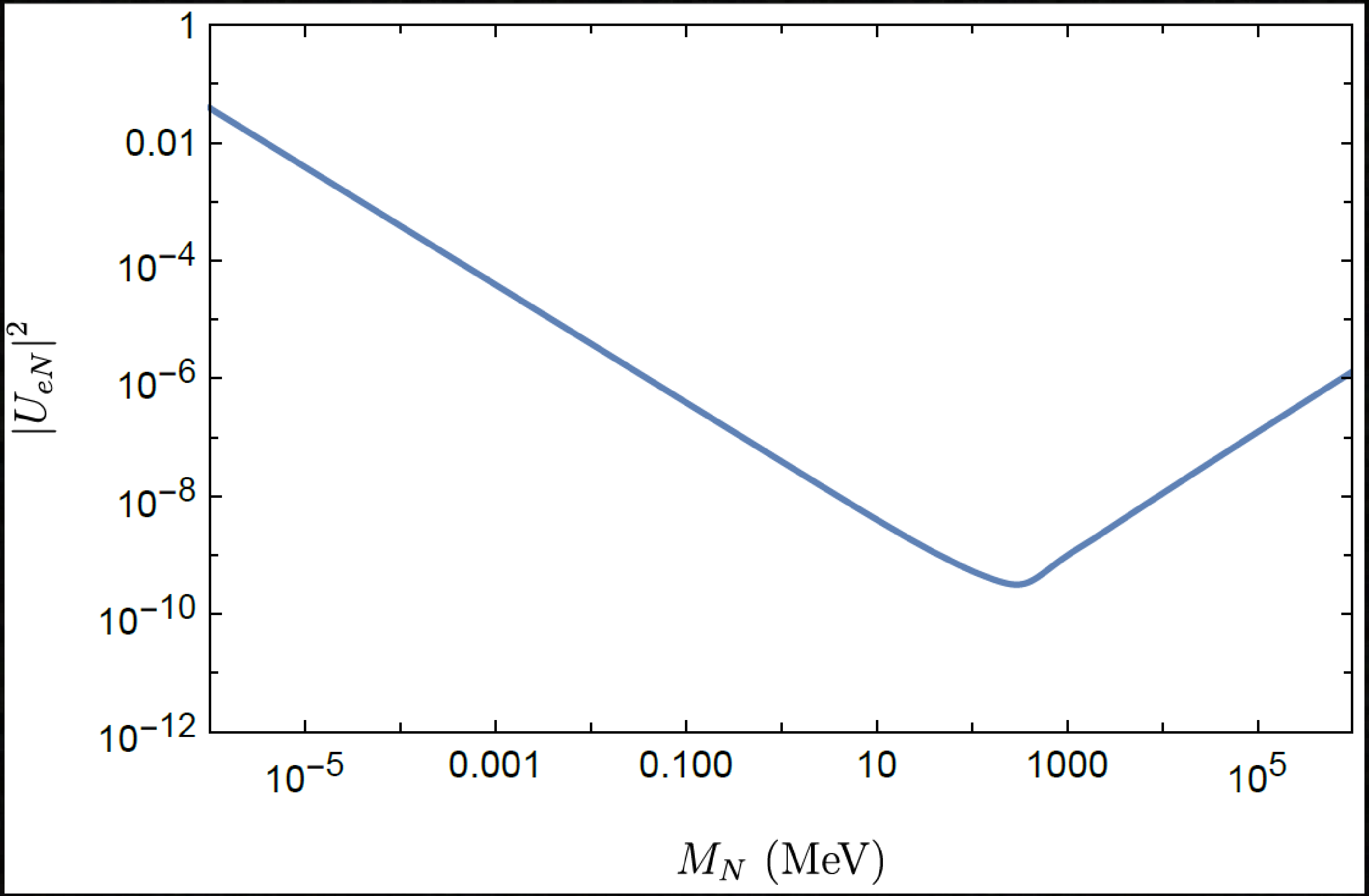
$$\left(T_{1/2}^{0\nu}\right)^{-1} = g_A^4\, V_{ud}^2\, G_{01} \left|\sum_i \mathcal{U}_{ei}^2 \frac{m_i}{m_e} A_\nu(m_i)\right|^2$$



[2402.07993]

Limits on heavy neutrinos

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



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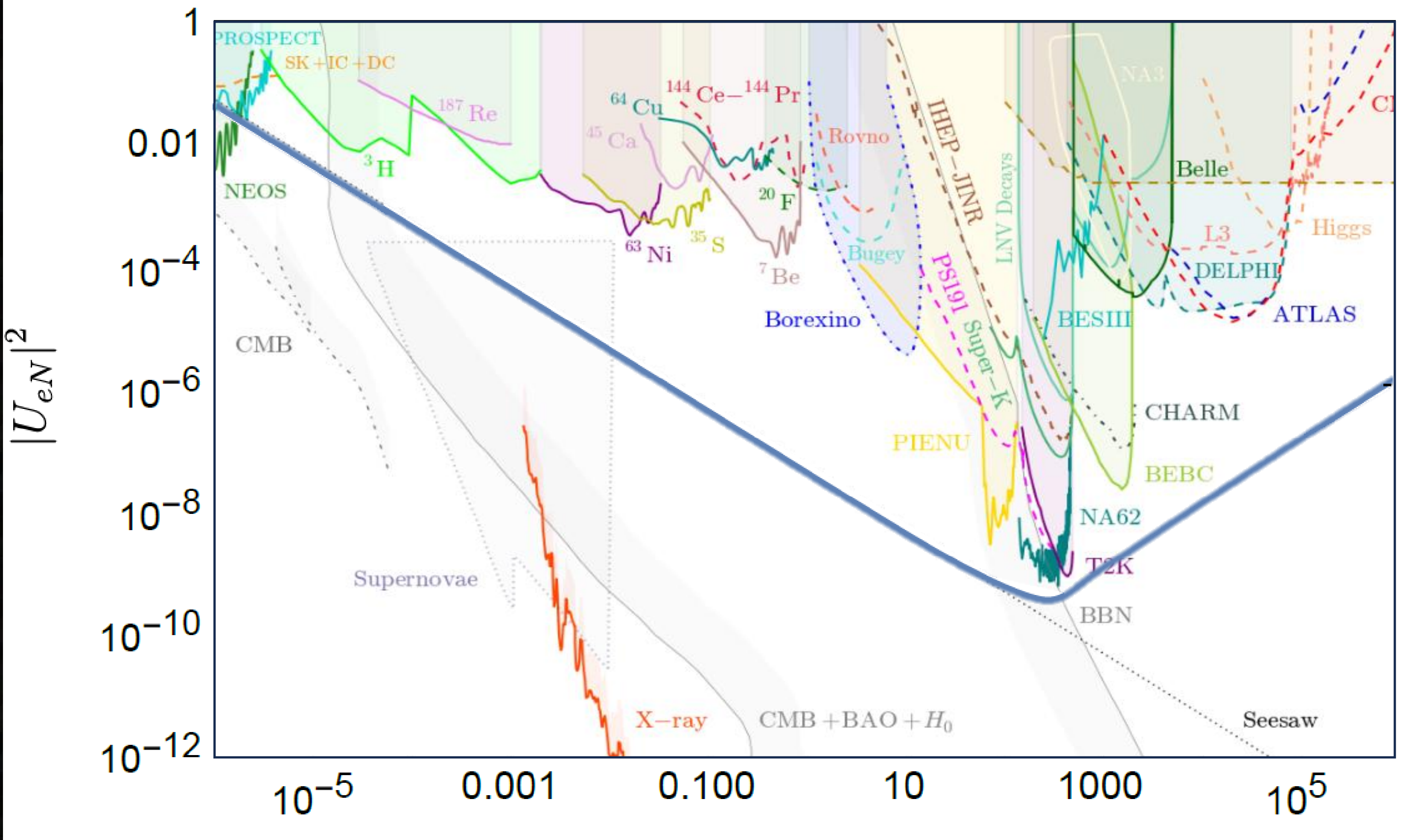


[Bolton, Deppisch, Dev 1912.03058]

https://www.hep.ucl.ac.uk/~pbolton/

The "minimal" 3+2 type-I seesaw model

- Sterile mass matrix: $M_M = \begin{pmatrix} \bar{M}\left(1 - \frac{\mu}{2}\right) & 0 \\ 0 & \bar{M}\left(1 + \frac{\mu}{2}\right) \end{pmatrix}$

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

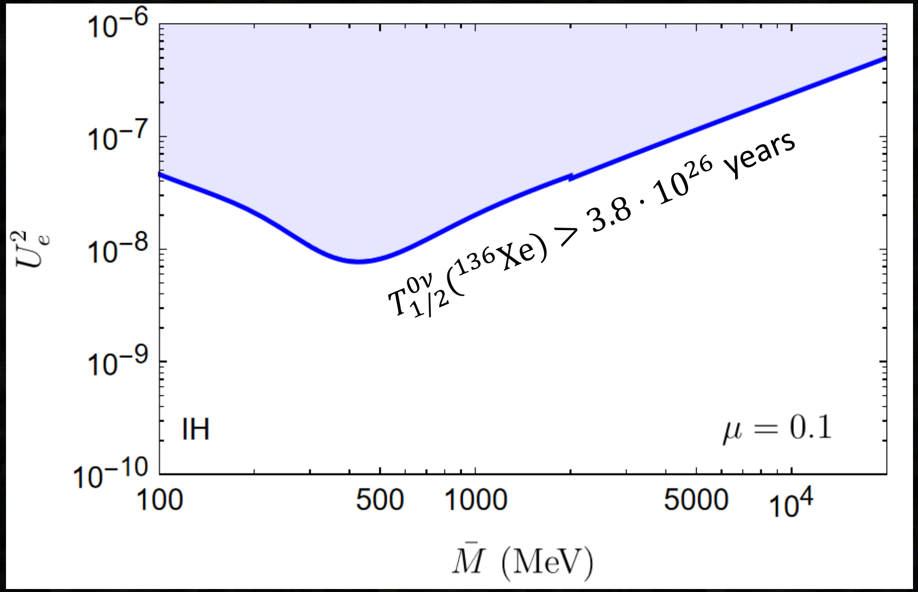
- Five Majorana neutrinos; lightest neutrino massless

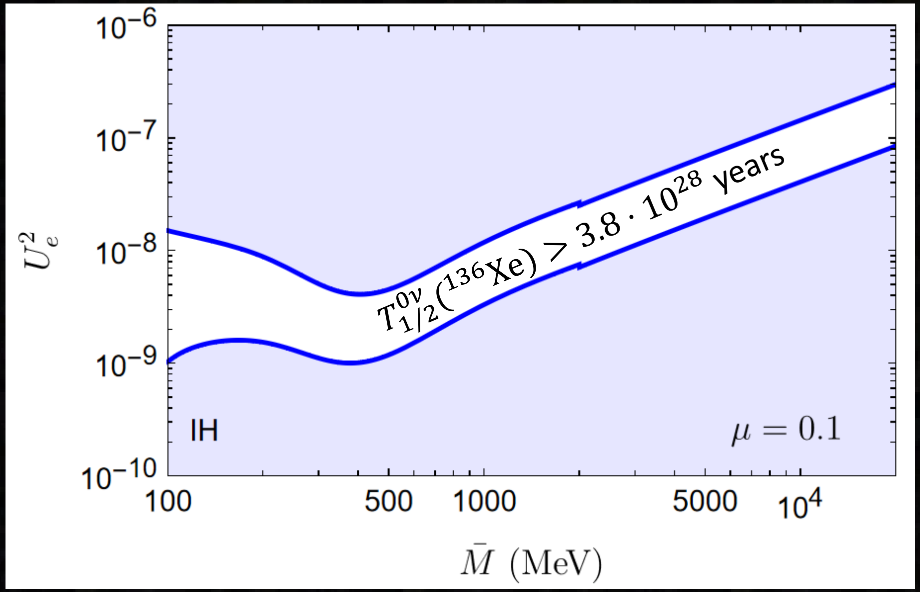
- 5×5 mixing matrix: $\begin{pmatrix} \mathcal{U}_{e1} & \mathcal{U}_{e2} & \dots & \dots & \mathcal{U}_{e5} \\ \mathcal{U}_{\mu 1} & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots \\ \mathcal{U}_{R_2 1} & \dots & \dots & \dots & \mathcal{U}_{R_2 5} \end{pmatrix}_{5\times 5}$ ← Relevant for $0\nu\beta\beta$

Probing the inverted mass ordering

- Next-gen experiments probe the IO band for 3 active neutrinos
  - → No signal ⇒ some sort of cancellation between the SM and BSM neutrino contributions
  - → Lower bound on $U_e^2 \equiv \sum_{I=4,5} |\mathcal{U}_{eI}|^2$

$$\left(T_{1/2}^{0\nu}\right)^{-1} \propto \left| A_\nu(0) \sum_{i=1,2,3} \mathcal{U}_{ei}^2 m_i + \sum_{I=4,5} \mathcal{U}_{eI}^2 M_I A_\nu(M_I) \right|^2$$





Other points of attack

- Leptogenesis: Convert lepton asymmetry to baryon asymmetry
  → Impose that correct matter-antimatter asymmetry must be produced

See Jacobo's talk

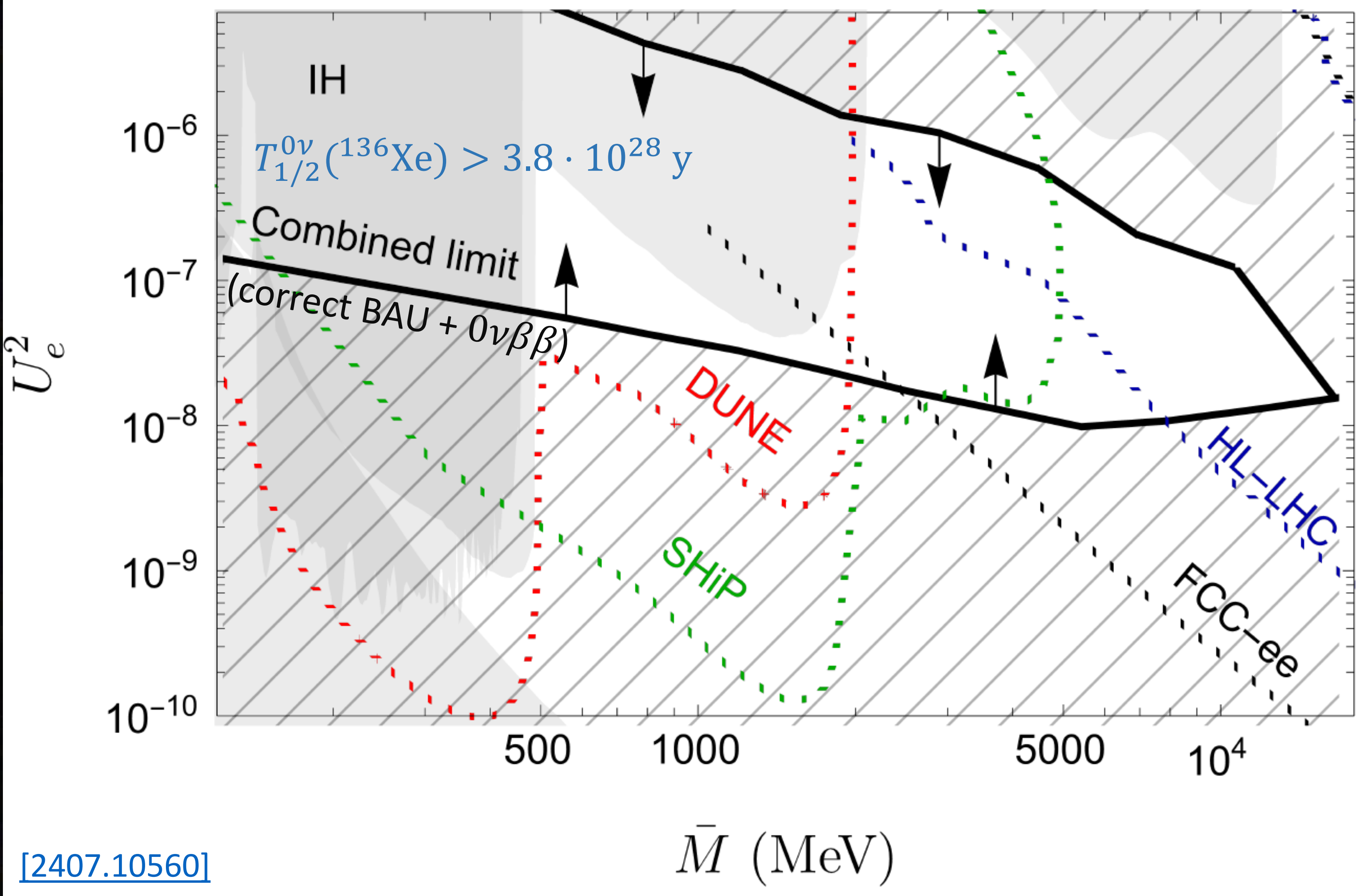
- Cosmology: Compatibility with Big Bang Nucleosynthesis

See William's talk

- Other searches: Upper limits on interaction strength from, e.g., displaced vertex searches

Discussed in other talks today

The hunt is on



[2407.10560]

$U_e^2 = |\mathcal{U}_{e4}|^2 + |\mathcal{U}_{e5}|^2$

Summary

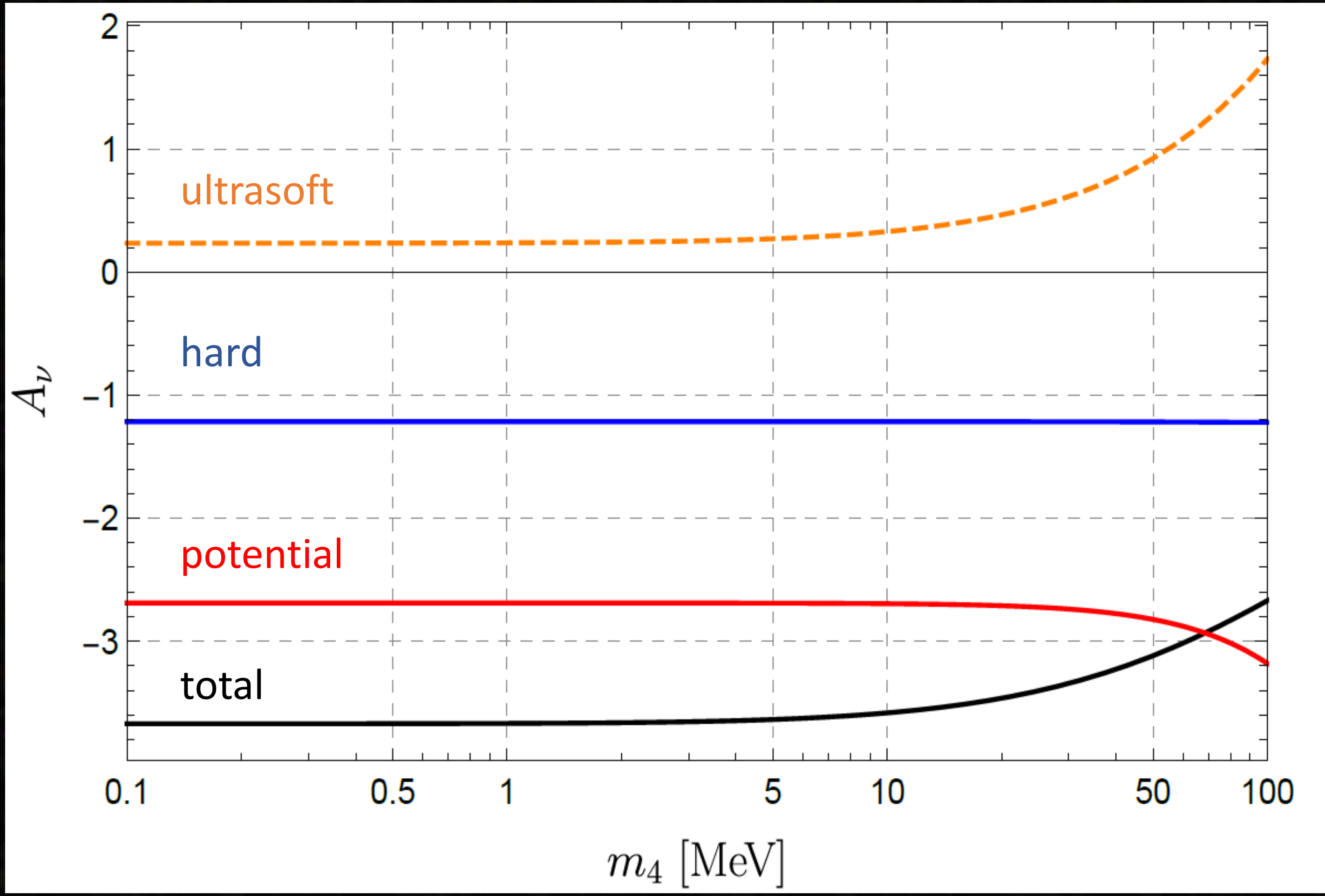
- $0\nu\beta\beta$ potentially a definitive probe of nature of neutrinos
- The constraining power of $0\nu\beta\beta$ almost unmatched for new (heavy) neutrino degrees of freedom
- Requirement of correct BAU + $0\nu\beta\beta$ bounds complementary to other experimental searches and cosmological constraints
- No $0\nu\beta\beta$ detection in the near future $\Rightarrow$ small testable allowed parameter space left for minimal 3+2 models (in the inverted mass ordering)

Backup

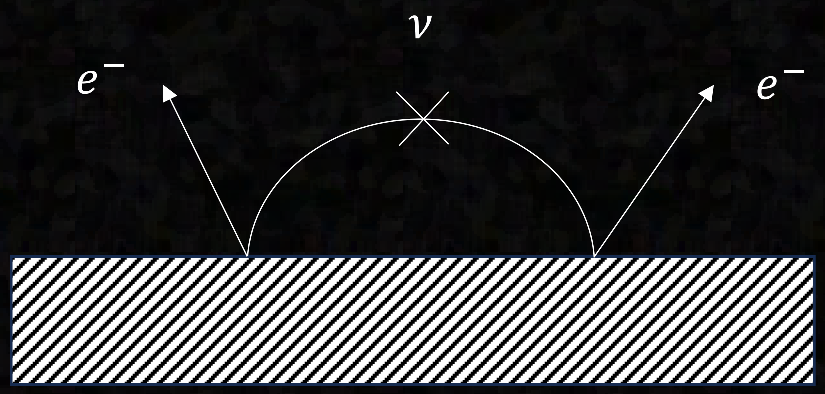
Pieces of the puzzle

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

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

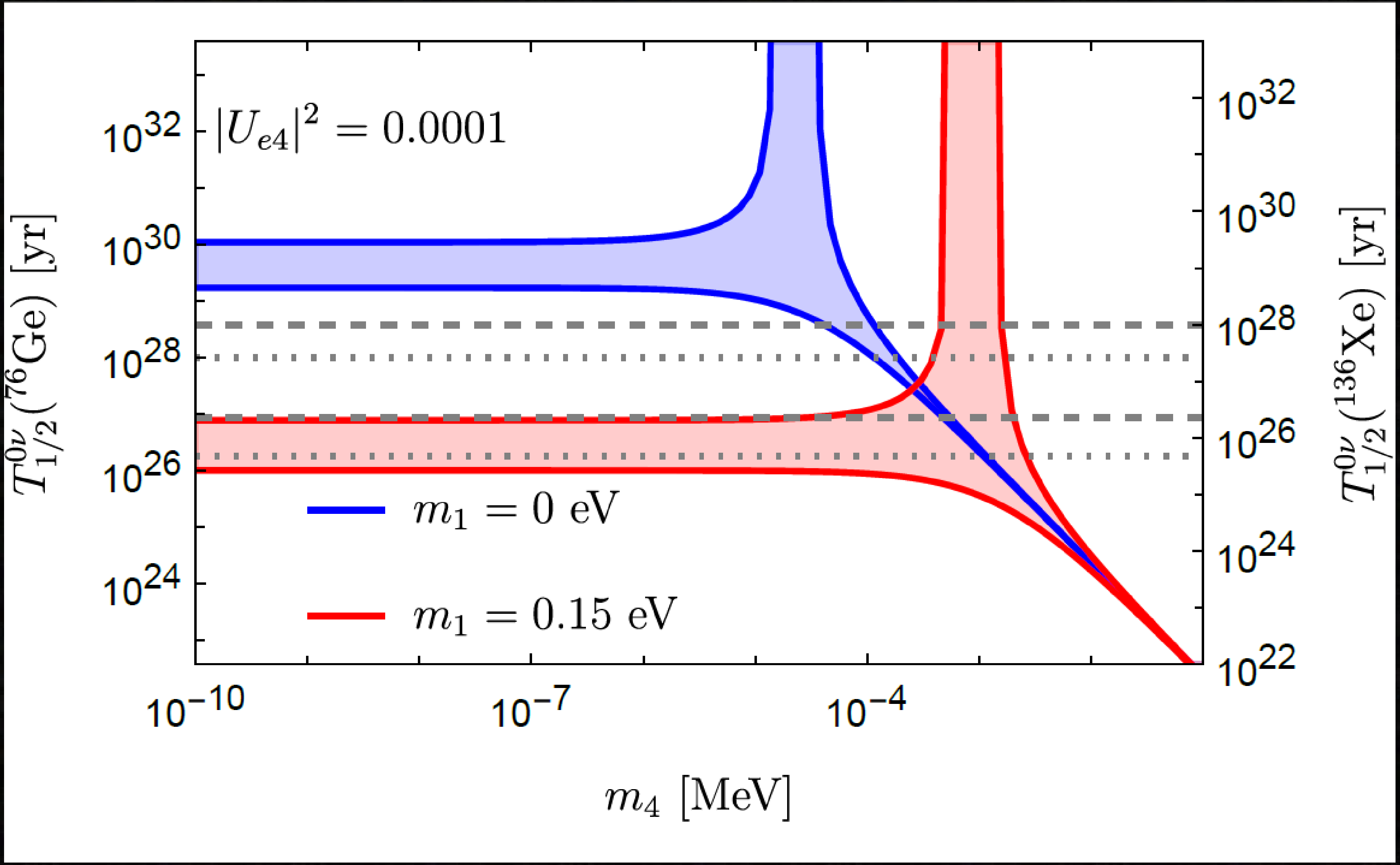

ultrasoft
hard
potential
total
A_ν
2
1
0
−1
−2
−3
0.1
0.5
1
5
10
50
100
m_4 [MeV]

Ultrasoft contributions



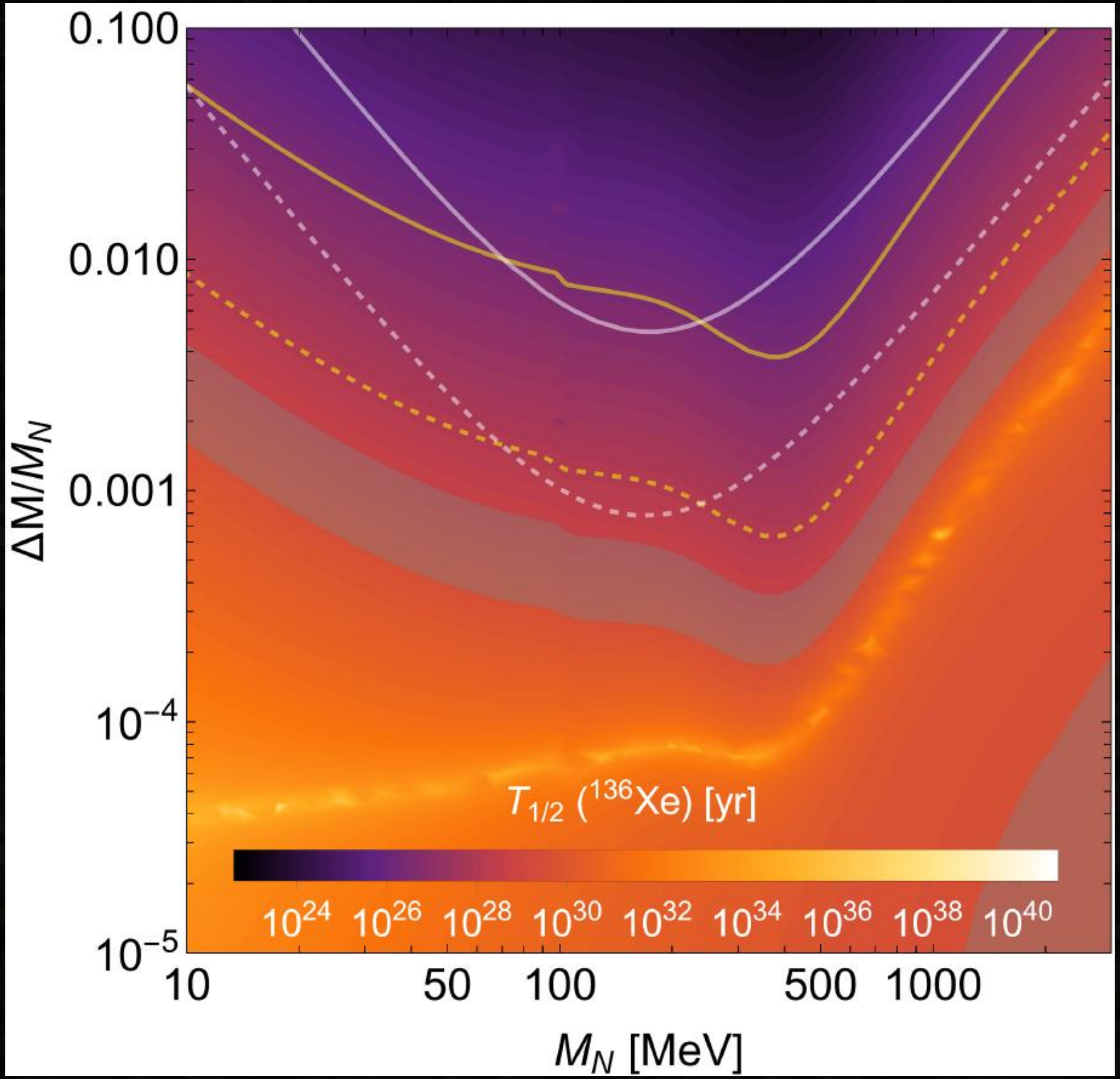
$$A_\nu^{(\text{usoft})} = 2\frac{\mathrm{R_A}}{\pi g_A^2}\sum_n \langle 0_f^+|\mathcal{J}^\mu|1_n^+\rangle\langle 1_n^+|\mathcal{J}_\mu|0_i^+\rangle\left(f(m_i,\Delta E_1)+f(m_i,\Delta E_2)\right)$$

Adding a sterile neutrino



NH

Cool contour plot



NH

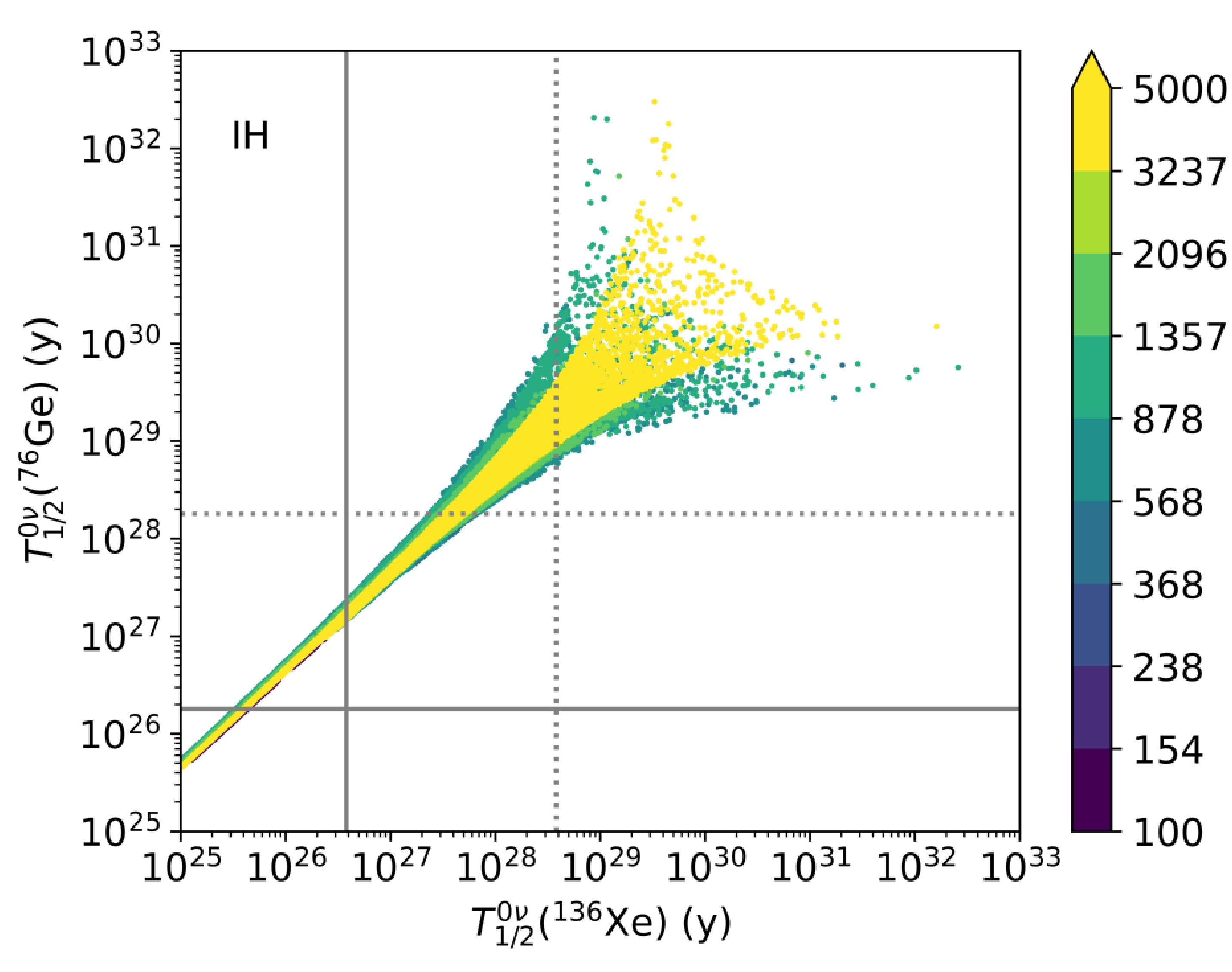
Casas-Ibarra parametrisation

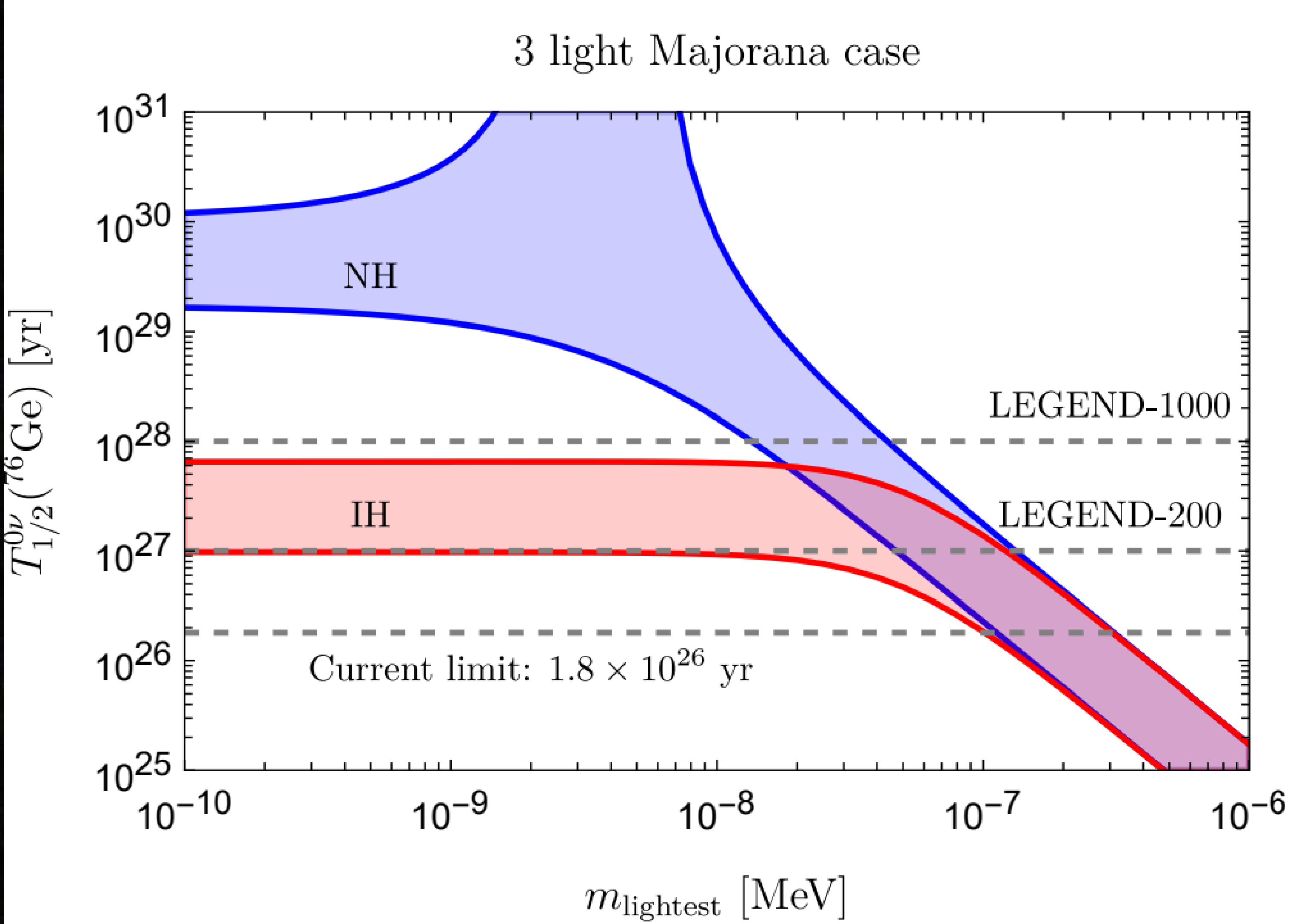
- $U_\nu = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\,\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\,\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 &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

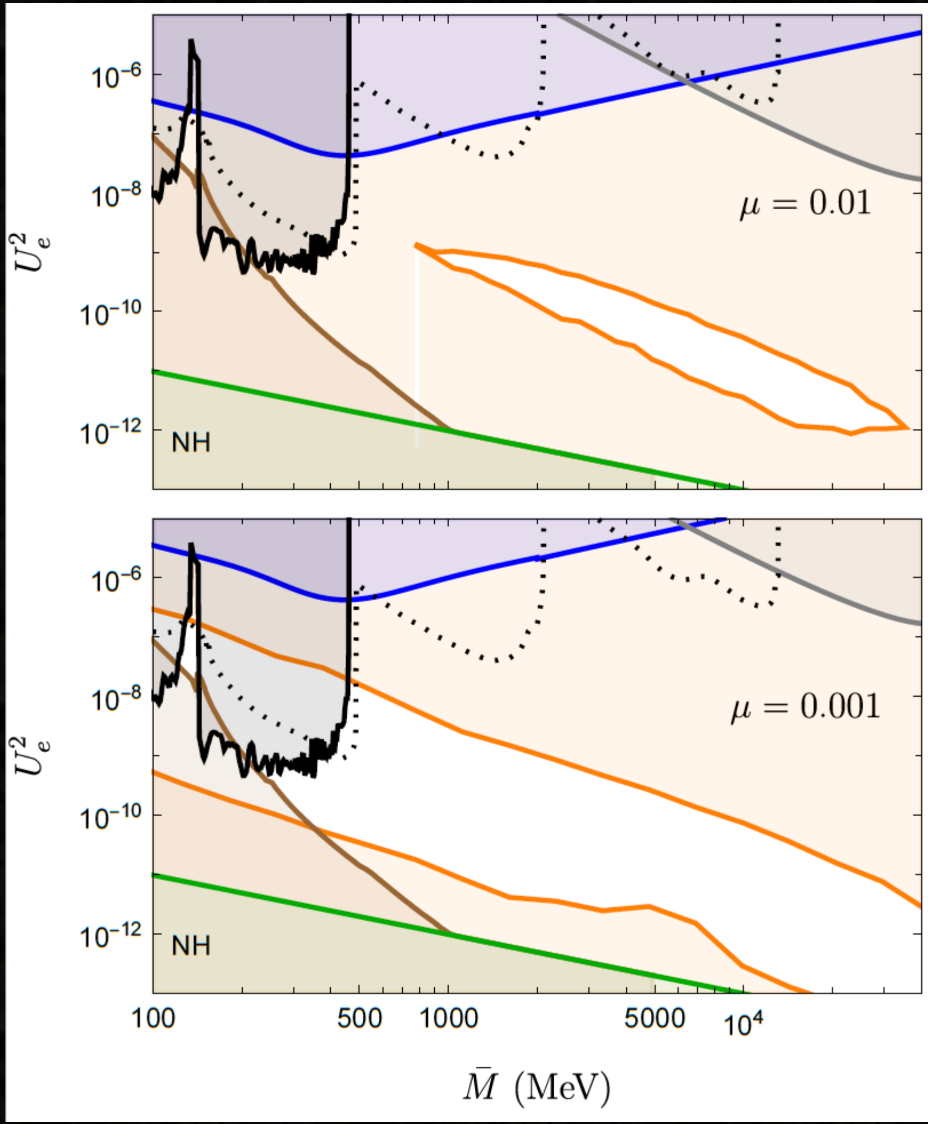
- Ensure neutrino oscillation data (masses) are automatically satisfied

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

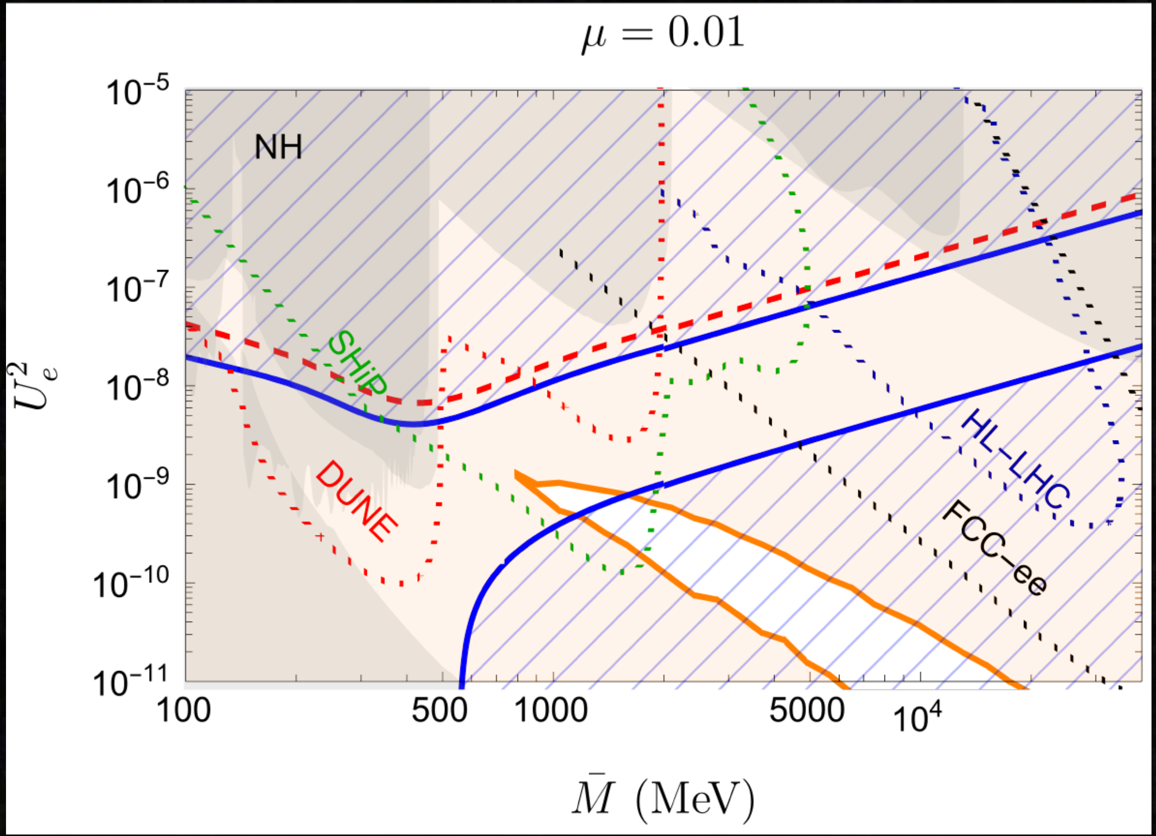
  - $\mathcal{R}_{NH} = \begin{pmatrix} 0 & 0 \\ \cos\omega & \sin\omega \\ -\sin\omega & \cos\omega \end{pmatrix}$; $\mathcal{R}_{IH} = \begin{pmatrix} \cos\omega & \sin\omega \\ -\sin\omega & \cos\omega \\ 0 & 0 \end{pmatrix}$


IH
$T^{0\nu}_{1/2}(^{76}\mathrm{Ge})$ (y)
$T^{0\nu}_{1/2}(^{136}\mathrm{Xe})$ (y)
10^{25}
10^{26}
10^{27}
10^{28}
10^{29}
10^{30}
10^{31}
10^{32}
10^{33}
5000
3237
2096
1357
878
568
368
238
154
100


3 light Majorana case
10^{31}
10^{30}
10^{29}
10^{28}
10^{27}
10^{26}
10^{25}
$T_{1/2}^{0\nu}(^{76}\mathrm{Ge})$ [yr]
NH
IH
LEGEND-1000
LEGEND-200
Current limit: 1.8×10^{26} yr
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
m_{lightest} [MeV]

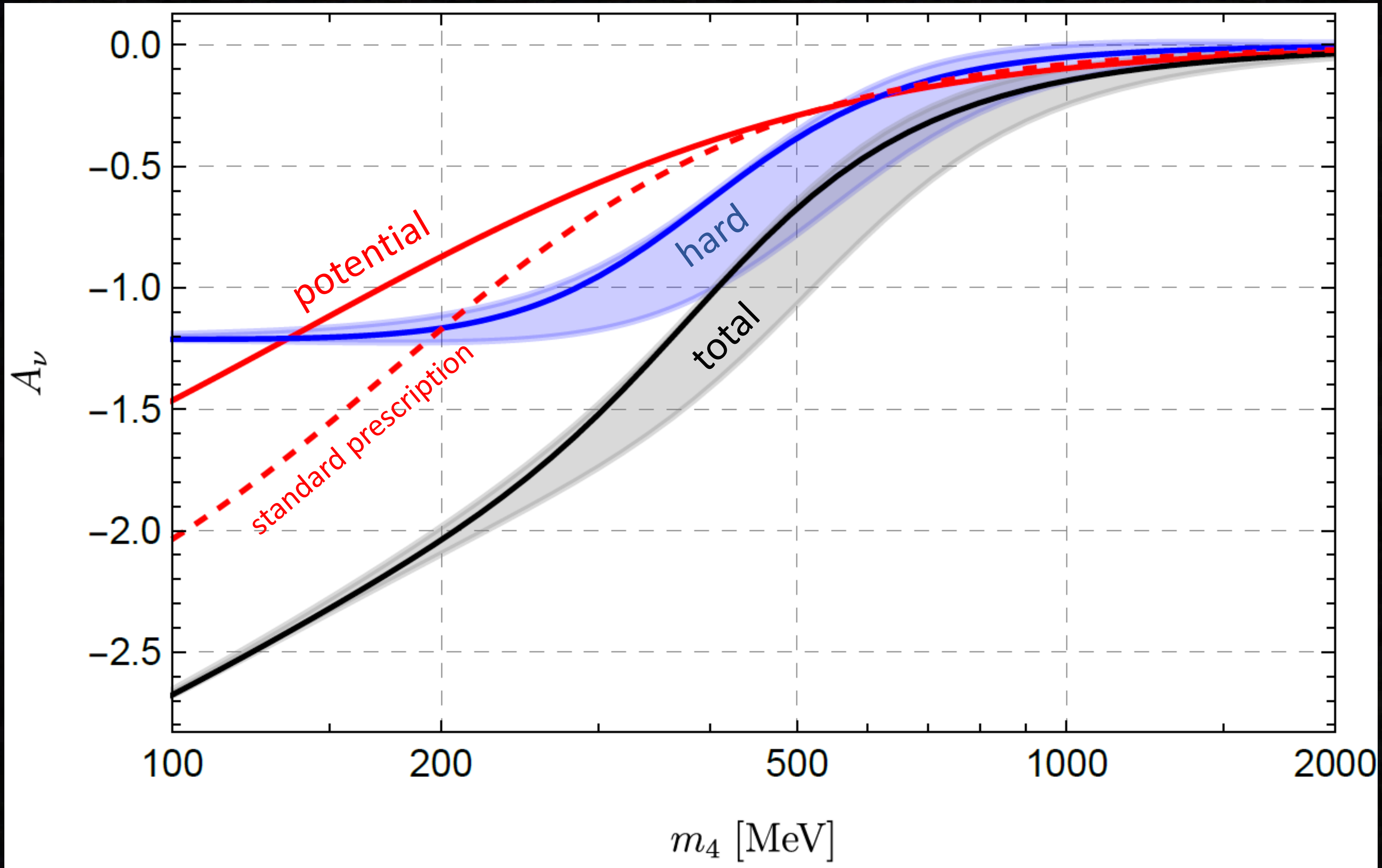


$\mu = 0.01$
$\mu = 0.001$
NH
NH
U_e^2
$\bar{M}$ (MeV)
100
500
1000
5000
10^4



$\mu = 0.01$
NH
SHiP
DUNE
HL-LHC
FCC-ee
U_e^2
$\bar{M}$ (MeV)
100
500
1000
5000
10^4

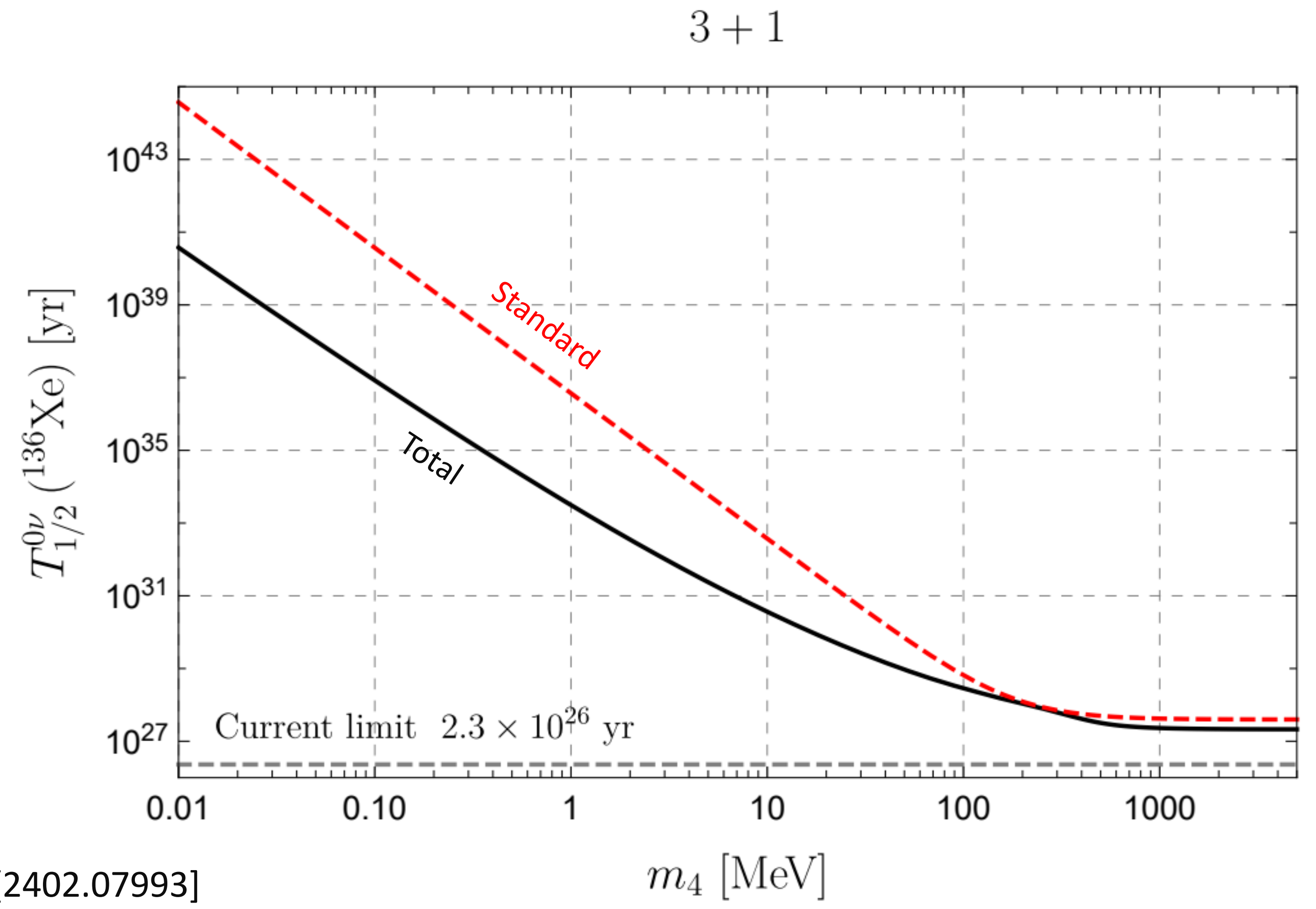
A comparison of amplitudes



[2402.07993]

A toy 3+1 model

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



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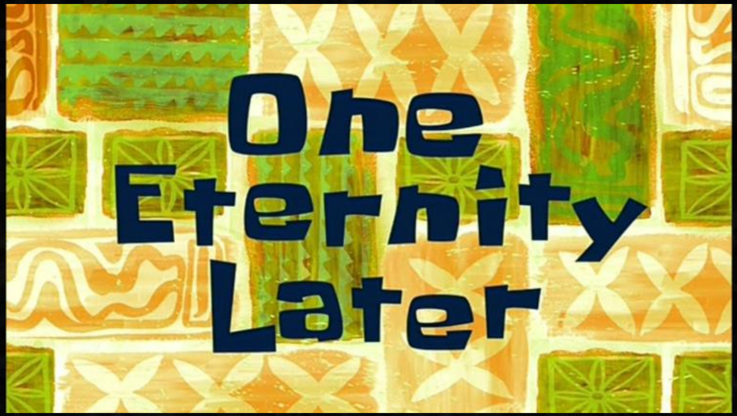
Small splitting approximation

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

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

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



$$U_e^2 = \sum_{I=4,5} |\mathcal{U}_{eI}|^2$$

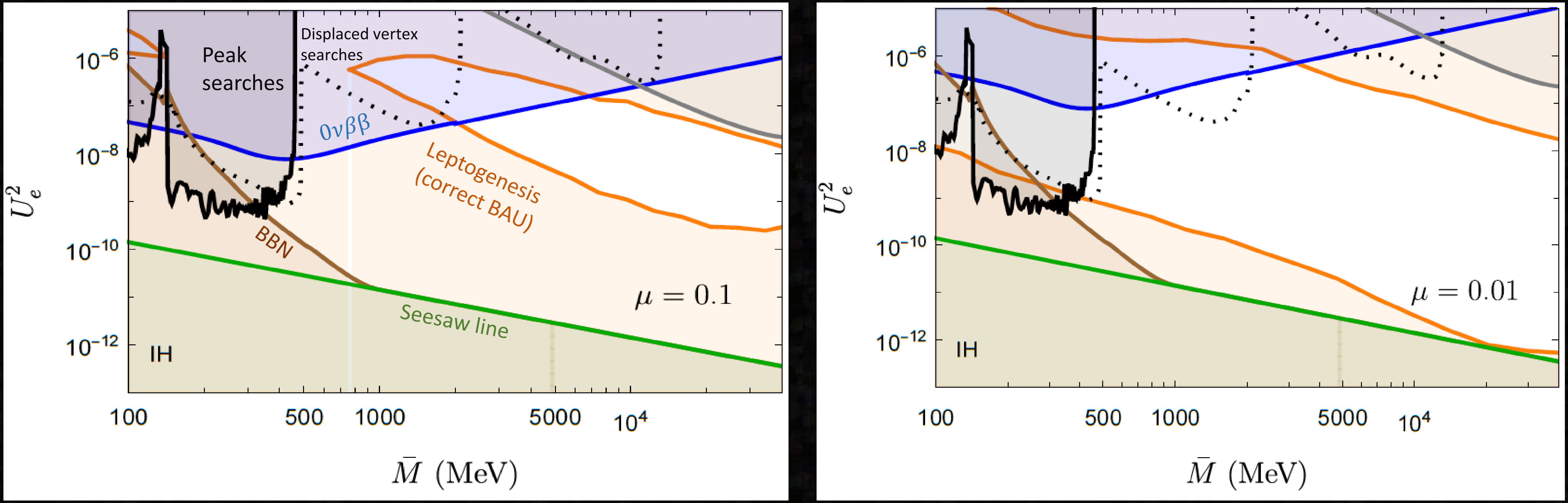
$$\mathcal{A}_{eff} \approx \sum_{i=1}^{3} m_i \mathcal{U}_{ei}^2 \left(A_\nu(0) - A_\nu(\bar{M})\right) + e^{i\lambda} \mu \, U_e^2 \frac{\bar{M}^2}{2} A'_\nu(\bar{M})$$

Unconstrained

Limits from experiments and cosmology

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

Exclusions galore



[2407.10560]

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