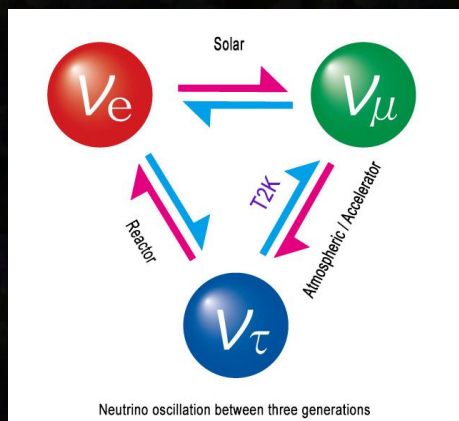


Neutrinoless double beta decay rates and the 3 + 2 scenario

[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

Pesky neutrino masses



- Neutrinos oscillate $\Rightarrow$ at least two of them are massive
- SM can't provide neutrino masses
- Right-handed (sterile) neutrinos to the rescue!
 - Bonus: Baryon asymmetry explained?

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

Higgs vev $\nearrow$

$\searrow$ Sterile neutrino (Majorana) mass(es)



The “standard” prescription

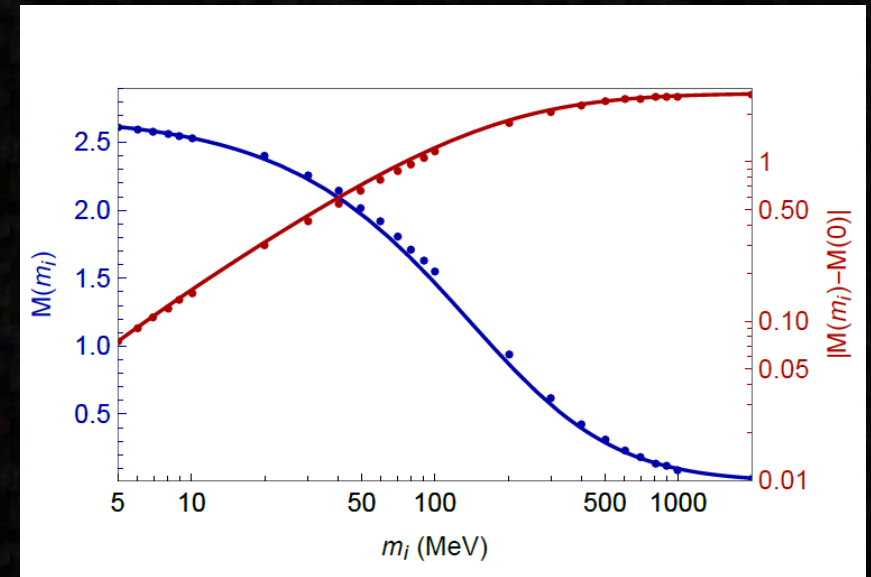
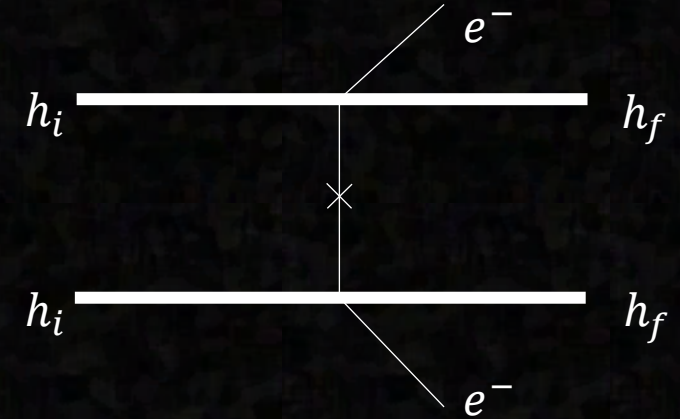
- Modify neutrino propagator

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

- 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



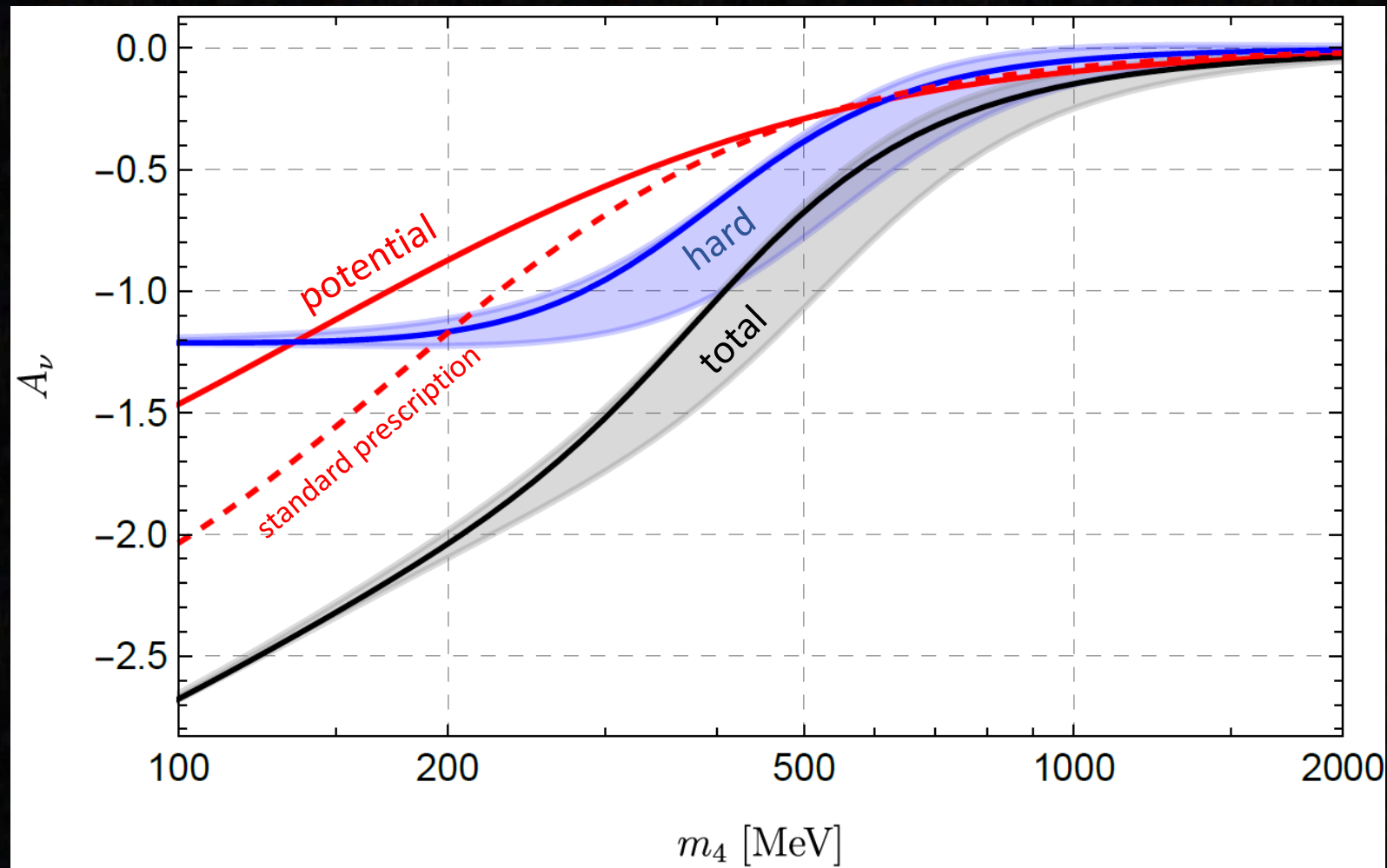
All neutrinos are equal, but some are more equal than the others

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

Divide and conquer

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

A comparison of amplitudes



Standard 3+0 scenario

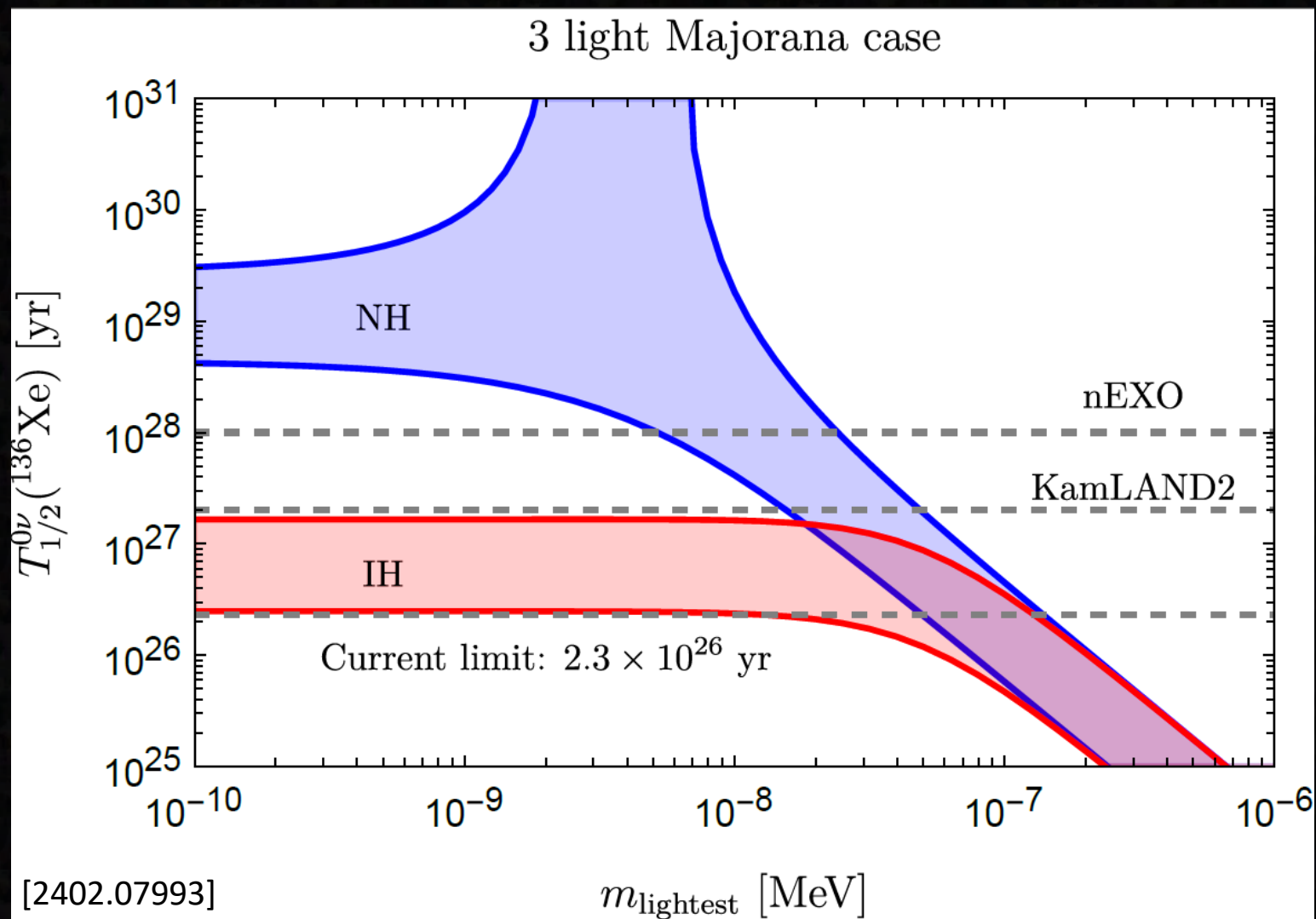
Phase space factor (nucleus-dependent)

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

CKM element
~ 0.97

Electron mass
0.511 MeV

Nuclear axial charge
~ 1.27



A toy 3+1 model

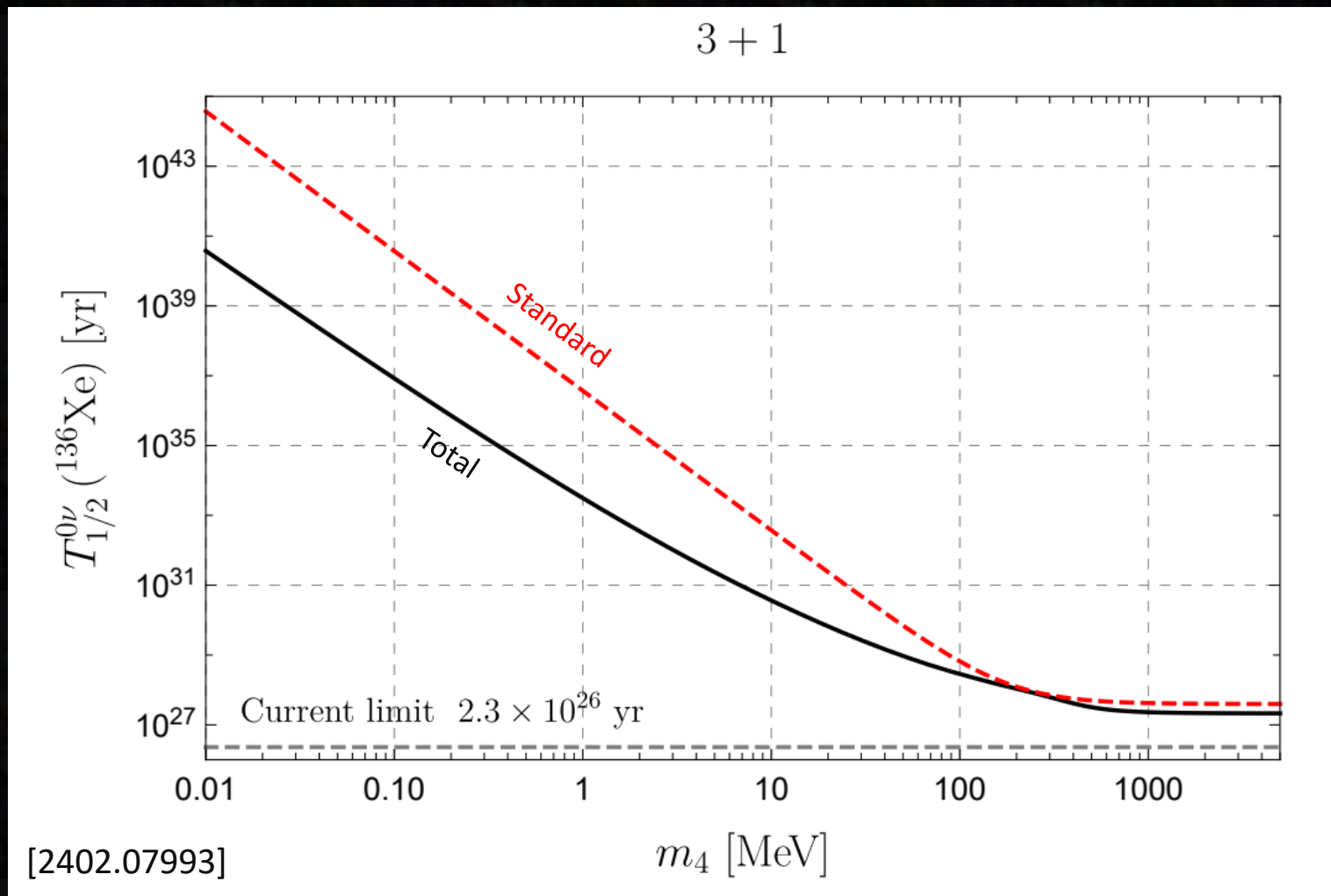
Phase space factor (nucleus-dependent)

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

CKM element ~ 0.97

Electron mass 0.511 MeV

Nuclear axial charge ~ 1.27



3+2 type-I seesaw model

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

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

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

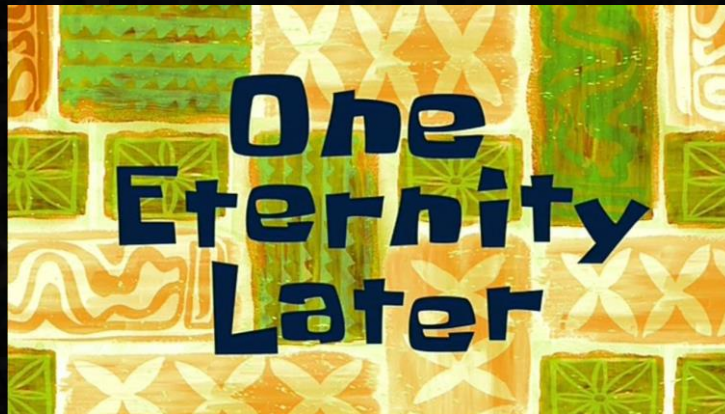
- Light neutrino mixing angles: PMNS matrix $\begin{pmatrix} (U_\nu)_{3 \times 3} & \cdots \\ \cdots & \cdots \end{pmatrix}_{5 \times 5}$
- Heavy-SM neutrino mixing angles: $\Theta = m_D M_R^{-1} \begin{pmatrix} \cdots & \Theta_{3 \times 2} \\ \cdots & \cdots \end{pmatrix}_{5 \times 5}$
- Five Majorana neutrinos; lightest neutrino massless

Small splitting approximation

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

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

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

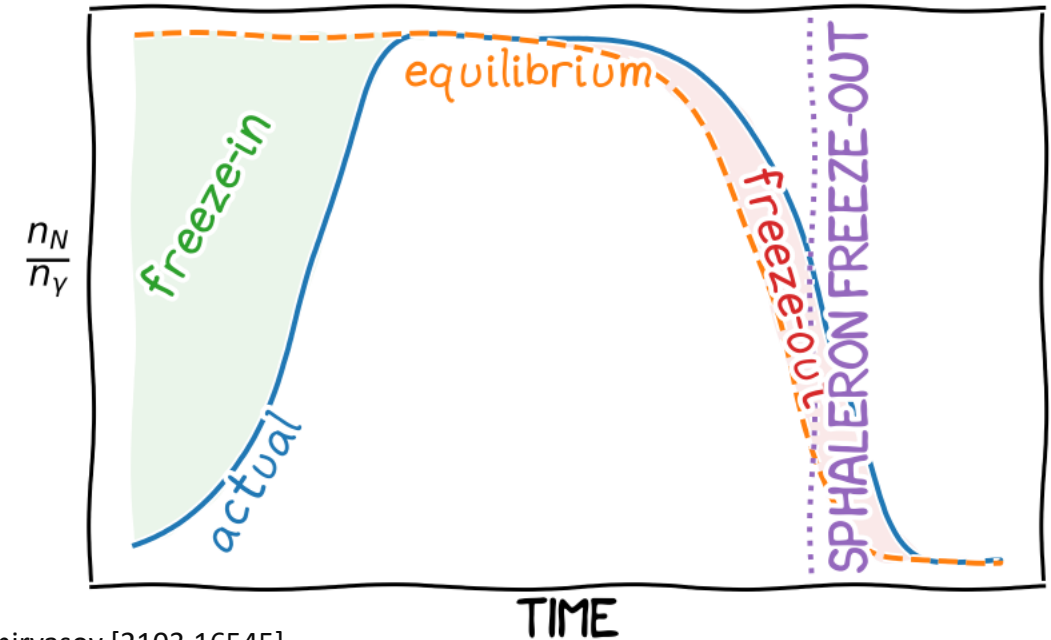
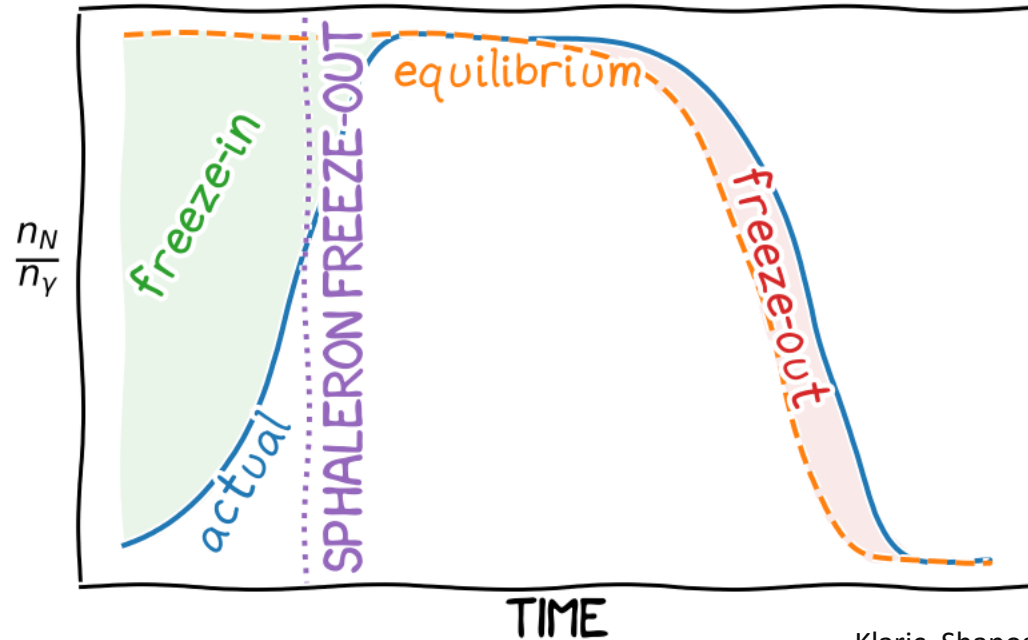


$$U_e^2 = \sum_I |\Theta_{eI}|^2$$

$$\mathcal{A}_{eff} \approx \sum_{i=1}^3 m_i \mathcal{U}_{ei}^2 (A_\nu(0) - A_\nu(\bar{M})) + e^{i\lambda} \mu \underbrace{U_e^2}_{\substack{\text{Limits from experiments and cosmology} \\ \lambda = f(\text{Re}(\omega), \alpha_{ij}, \delta_{CP}, \dots)}} \frac{\bar{M}^2}{2} A'_\nu(\bar{M})$$

Low-scale leptogenesis

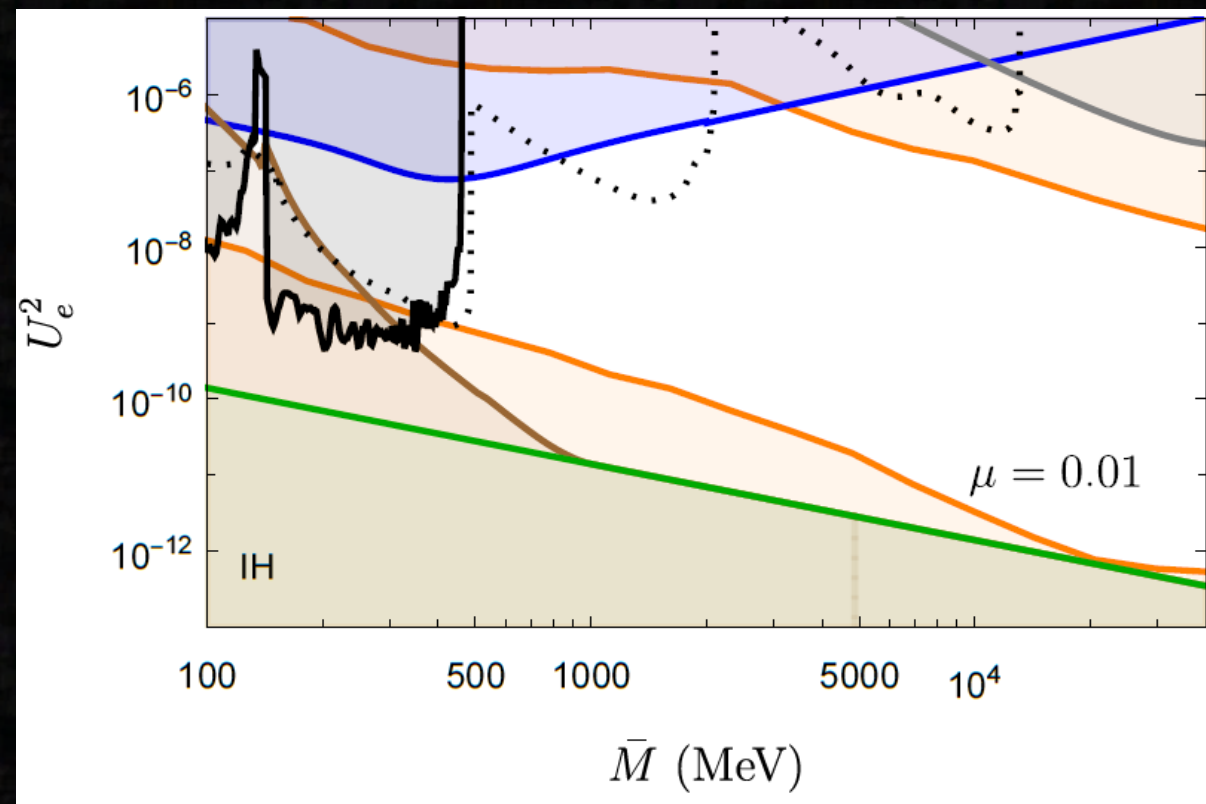
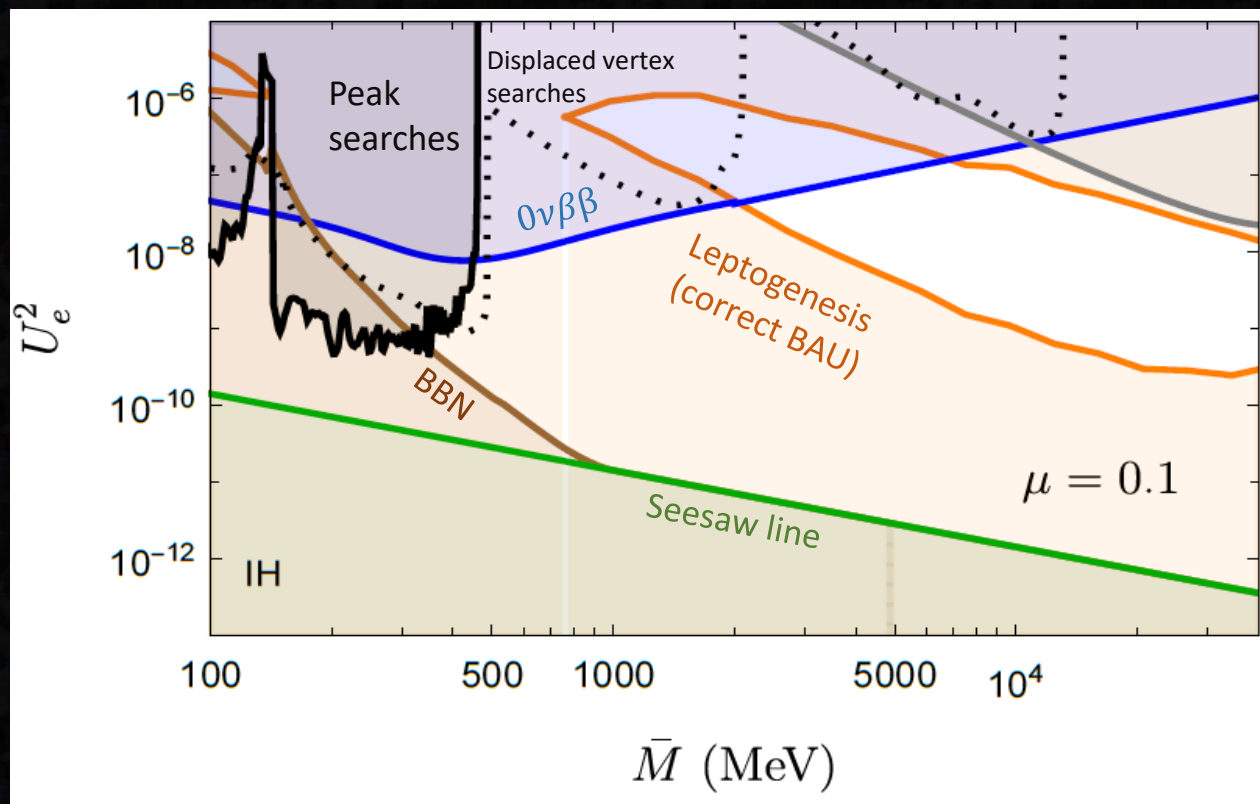
Leptogenesis: convert lepton asymmetry to baryon asymmetry



Klaric, Shaposhnikov, Timiryasov [2103.16545]

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

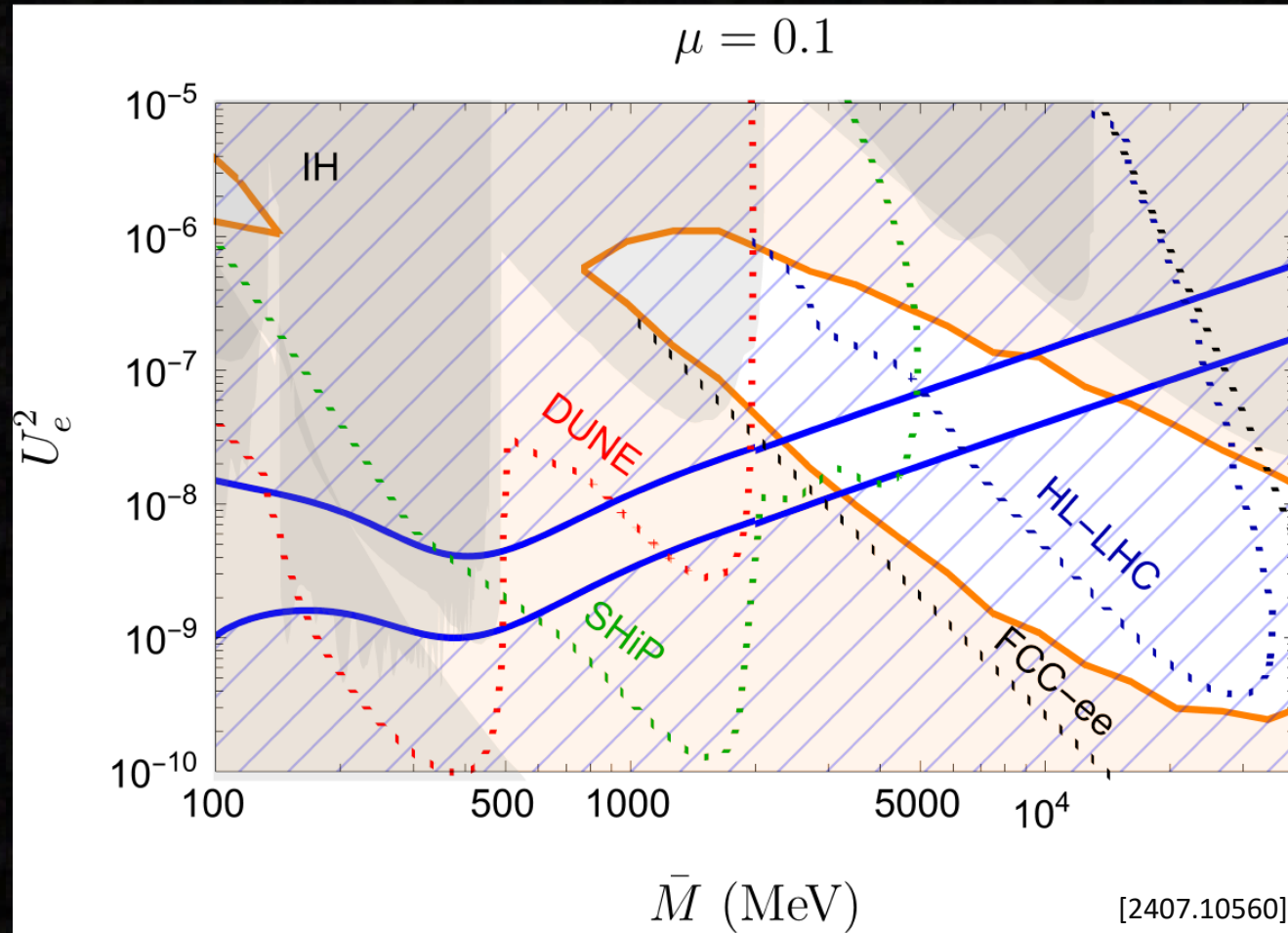
Exclusions galore



[2407.10560]

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

Future prospects



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

Summary

- Reconsider $0\nu\beta\beta$ calculations – standard methods might miss important effects!
- Right-handed neutrinos are useful, but a minimal model requires two of them
- 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 such minimal 3+2 models (in the inverted mass ordering)

Backup

Pieces of the puzzle

- $A_{\nu}^{(9)} = -2 \eta \frac{m_{\pi}^2}{m_i^2} \left[\frac{5}{6} g_1^{\pi\pi} (M_{GT,sd}^{PP} + M_{T,sd}^{PP}) + g_1^{\pi N} (M_{GT,sd}^{AP} + M_{T,sd}^{AP}) - \frac{2}{g_A^2} g_1^{NN} M_{F,sd} \right]$

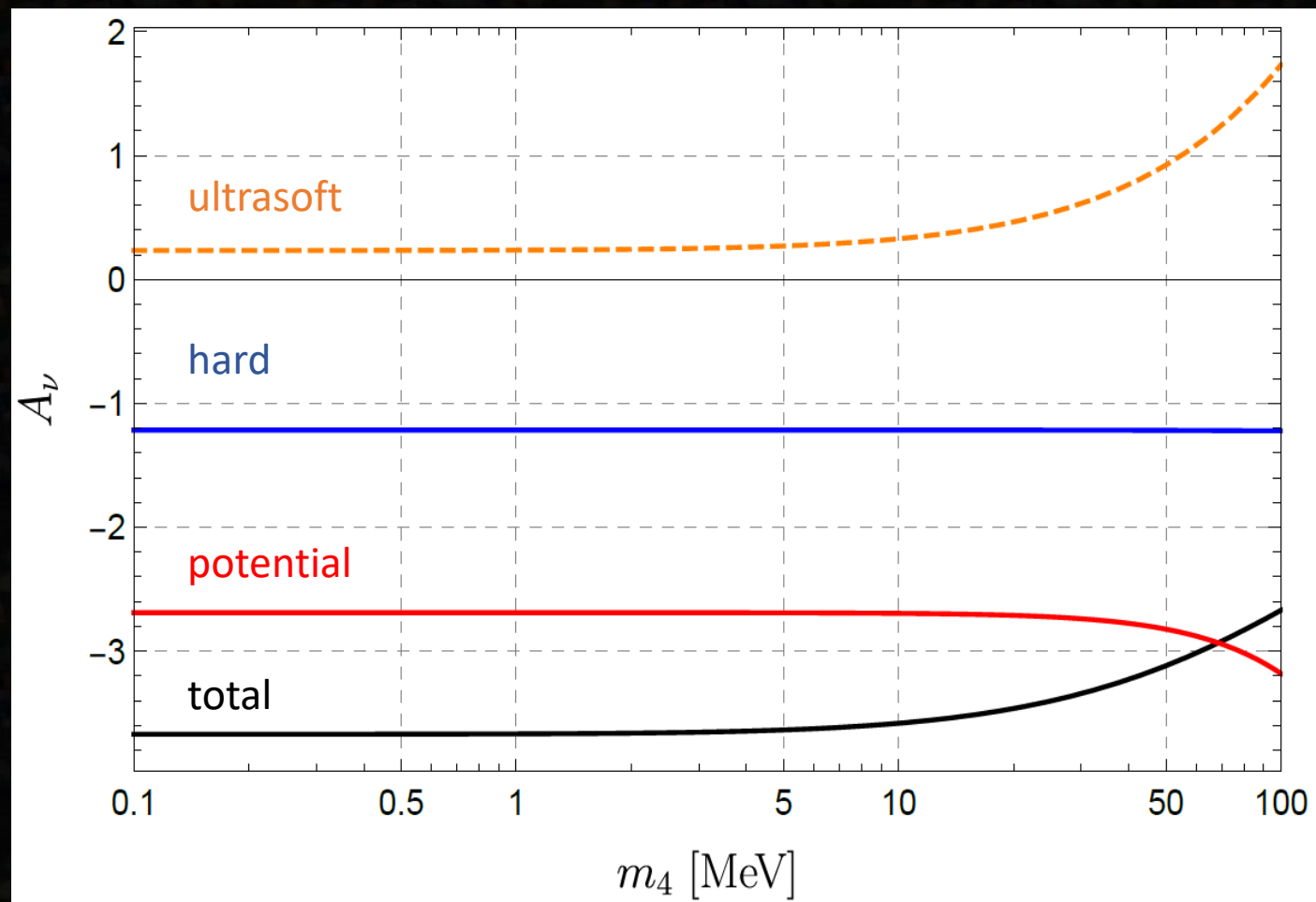
- $A_{\nu}^{(\text{usoft})} = 2 \frac{R_A}{\pi g_A^2} \sum_n \langle 0_f^+ | \mathcal{J}^{\mu} | 1_n^+ \rangle \langle 1_n^+ | \mathcal{J}_{\mu} | 0_i^+ \rangle (f(m_i, \Delta E_1) + f(m_i, \Delta E_2))$

- $A_{\nu}^{(\text{pot})} = - \frac{M(0)}{1 + \frac{m_i}{m_a} + \left(\frac{m_i}{m_b}\right)^2} = -M(m_i)$

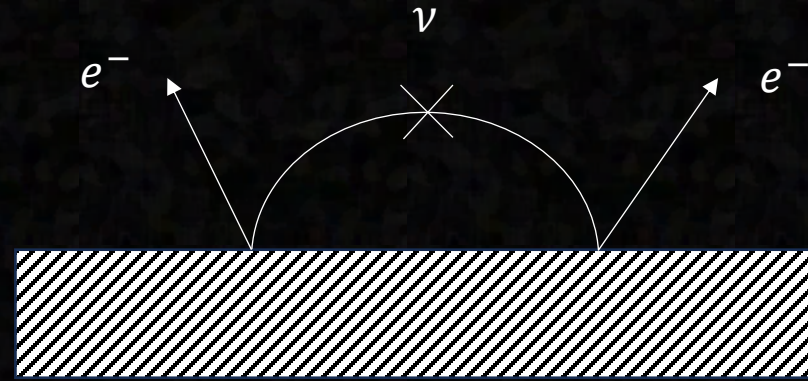
- $A_{\nu}^{(\text{pot}, <)} = - \left[M(m_i) - m_i \left(\frac{d}{dm_i} M(m_i) \right) \right]_{m_i=0}$

- $A_{\nu}^{(\text{hard})} = - \frac{2 m_{\pi}^2 g_{\nu}^{NN}(m_i)}{g_A^2} M_{F,sd}$

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

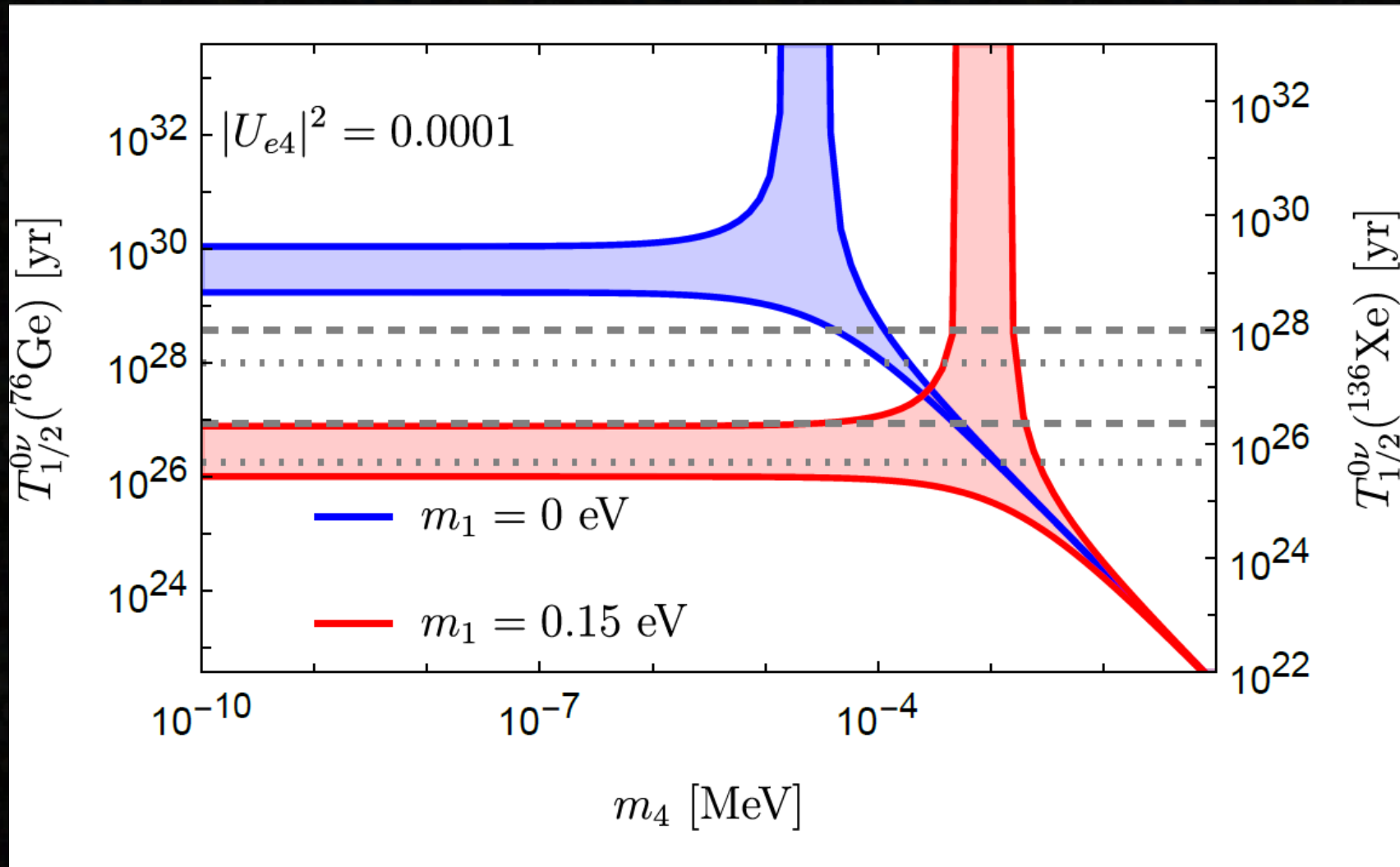


Ultrasoft contributions

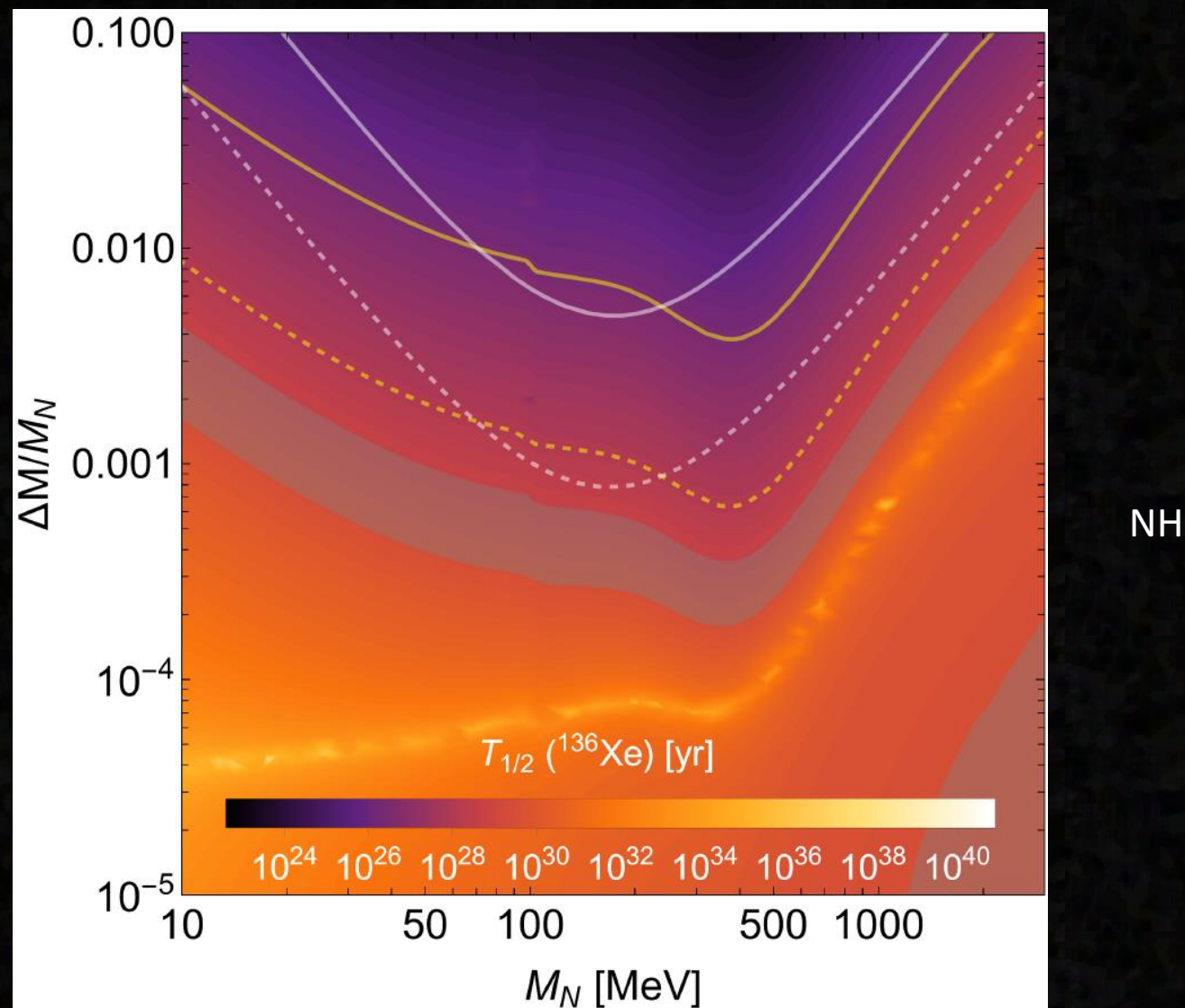


$$A_{\nu}^{(\text{usoft})} = 2 \frac{R_A}{\pi g_A^2} \sum_n \langle 0_f^+ | \mathcal{J}^\mu | 1_n^+ \rangle \langle 1_n^+ | \mathcal{J}_\mu | 0_i^+ \rangle (f(m_i, \Delta E_1) + f(m_i, \Delta E_2))$$

Adding a sterile neutrino



Cool contour plot



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

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

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

