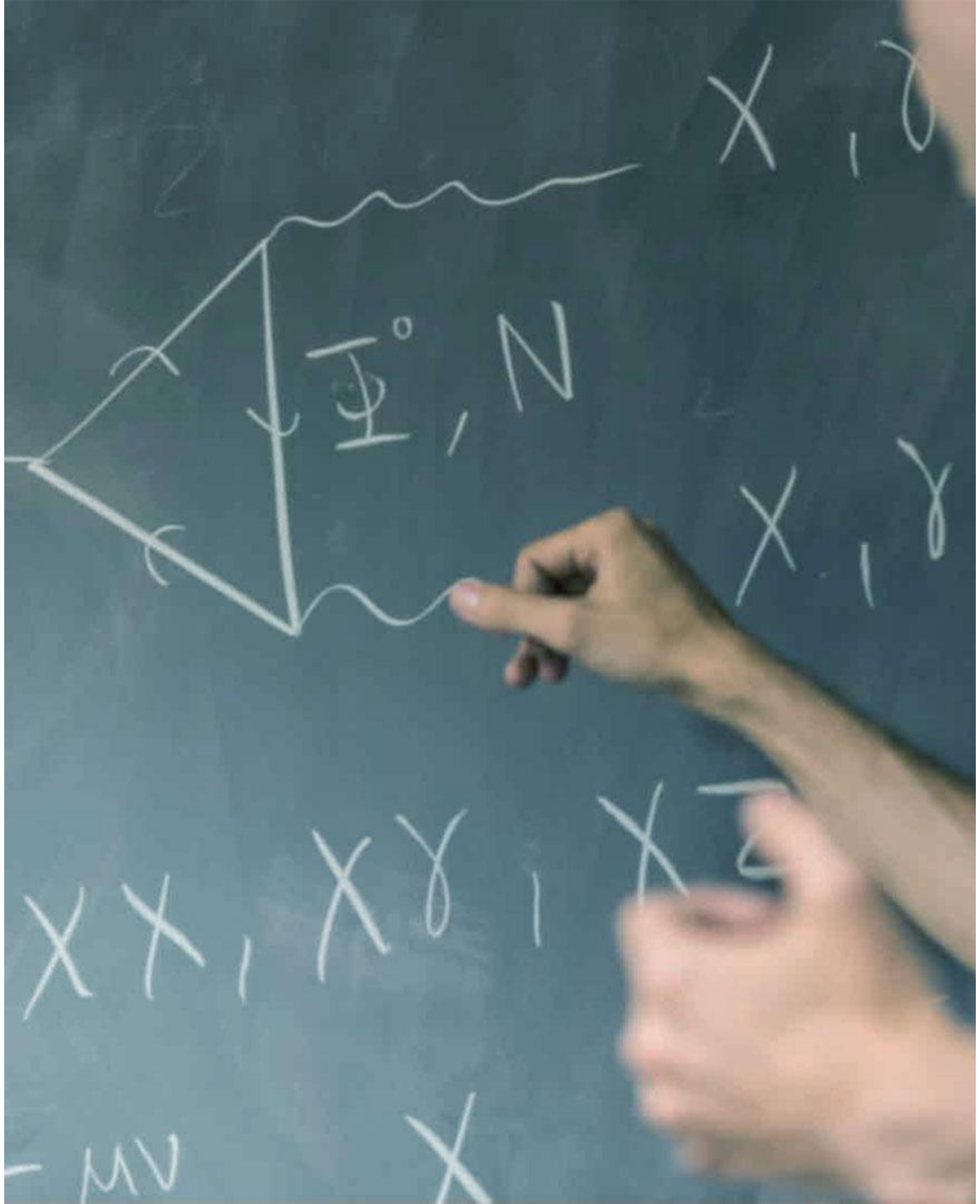
TRIUMF

THE UNIVERSITY OF BRITISH COLUMBIA

Sterile Neutrinos and 0νββ Decay



Taiki Shickele

Recommended Values for
Neutrinoless Double-Beta Decay
Nuclear Matrix Elements

July 17th, 2026

2026-07-17

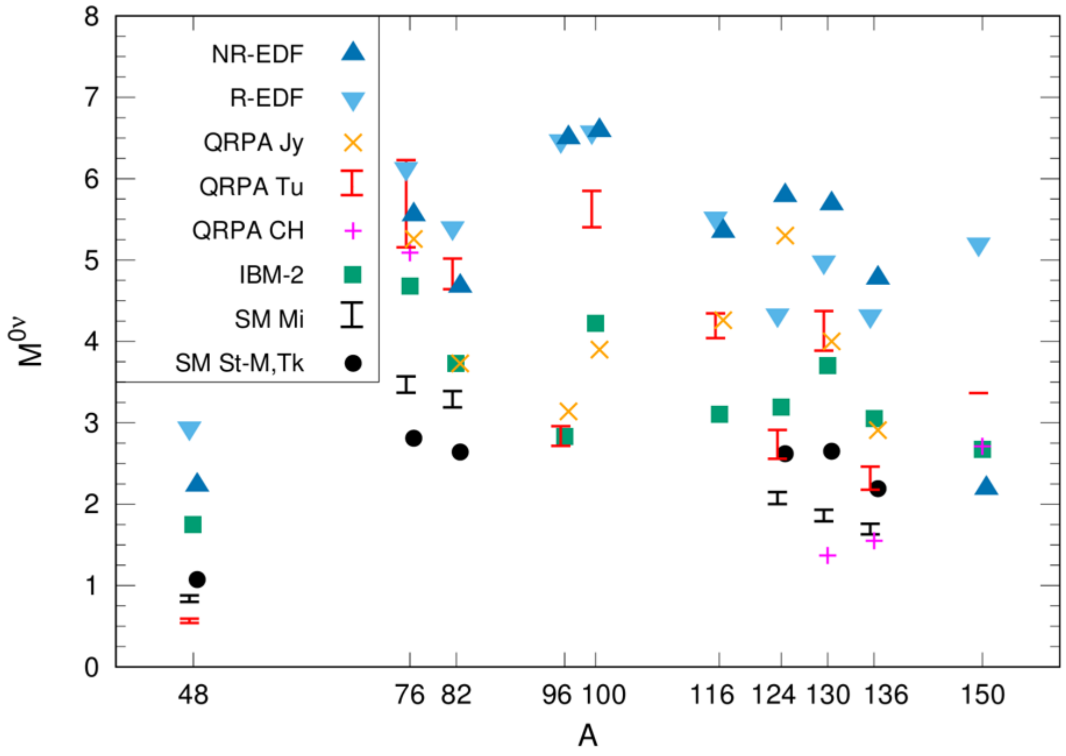
Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

Discovery, accelerated

Neutrinoless Double-Beta (0vββ) Decay

- New physics potential:
  1) **Majorana neutrinos** thru the Schechter-Valle Black Box Theorem
  2) **Lepton-number violating** $\Delta L = 2$
     - Observed baryon asymmetry of the universe?
  3) **Absolute neutrino mass scale** (not always)

- Requires knowledge of the **nuclear matrix element ⇒ nuclear theory**



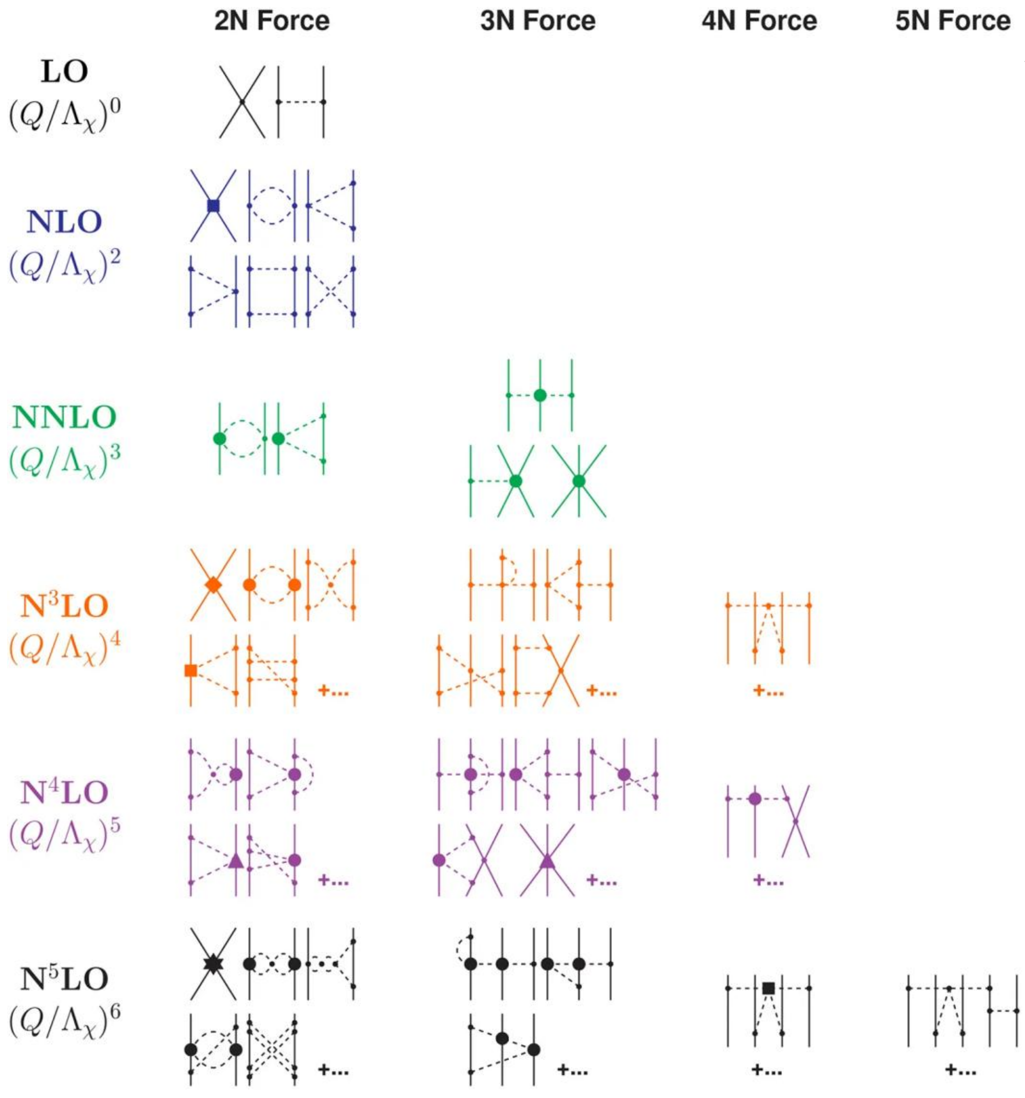
$$(A,Z) \rightarrow (A,Z+2) + 2e^{-} + \cancel{2\bar{\nu}_e}$$

J. Engel and J. Menéndez 2017 Rep. Prog. Phys. 80 046301

Chiral Effective Field Theory

- NN + 3N nuclear interactions following chiral effective field theory with LECs calibrated few-body observables

- Interactions presented here:
  - ➢ EM(1.8/2.0)
  - ➢ N3LO-LNL
  - ➢ ΔNNLO-GO(394)
  - ➢ N3LO-Texas



Rodriguez Entem D., Machleidt R. and Nosyk Y., Front. Phys. 8:57 (2020).

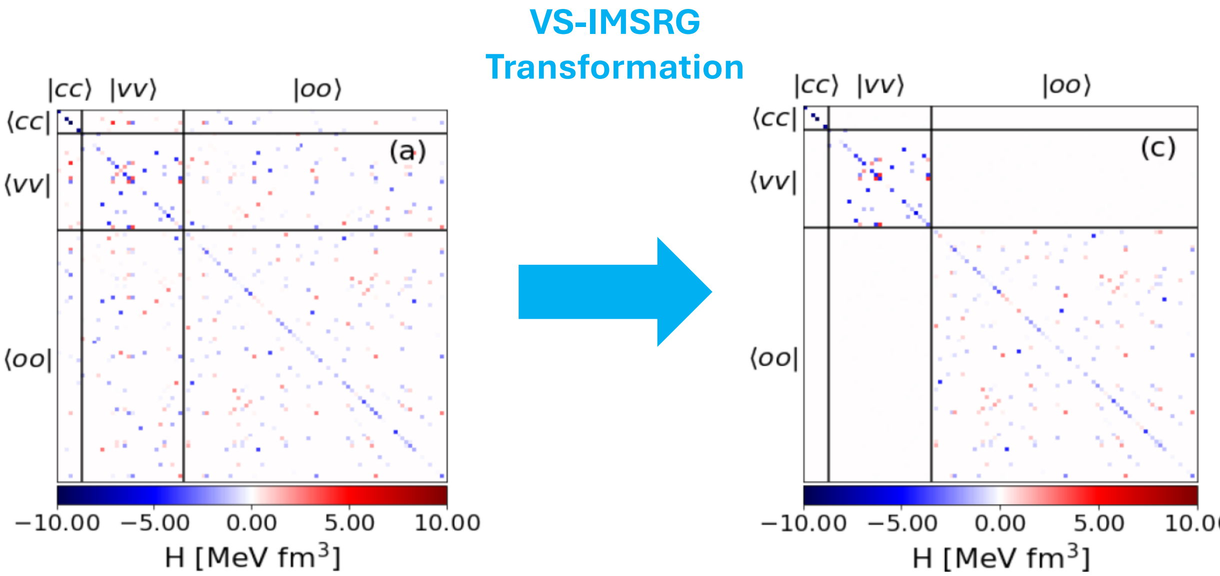
The Valence Space IMSRG

Also see talks from: Alex, Amelia, Ragnar, Bingcheng, Heiko, Lotta and Antoine

- Use the Valence Space In-Medium Similarity Renormalization Group (VS-IMSRG) to decouple inert core and valence space

- Use traditional shell model codes to diagonalize the resulting effective valence-space Hamiltonians

- Access to medium-heavy mass open-shell nuclei using an ab initio framework

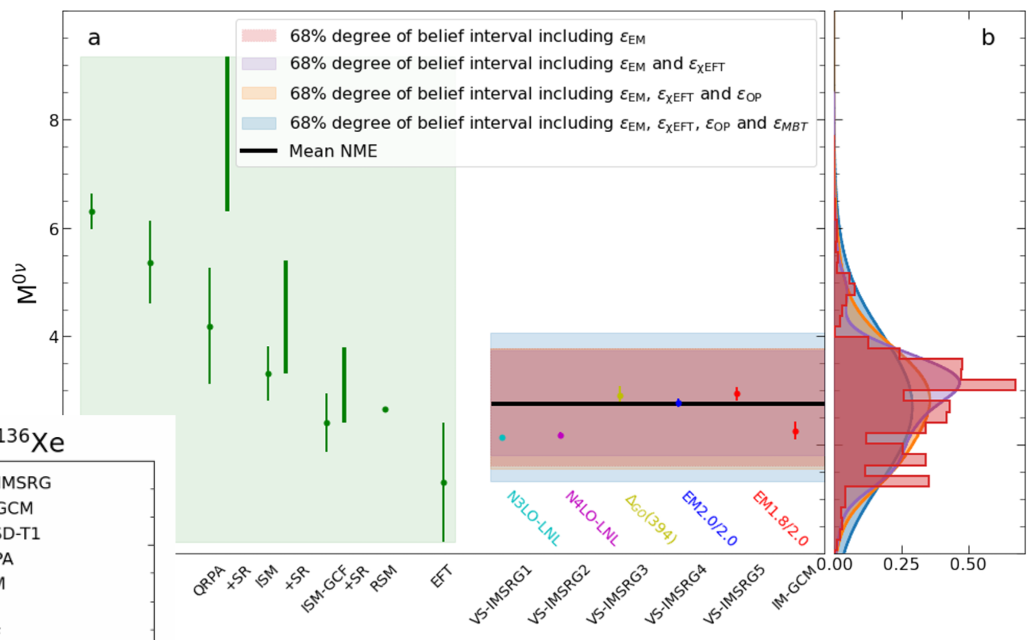


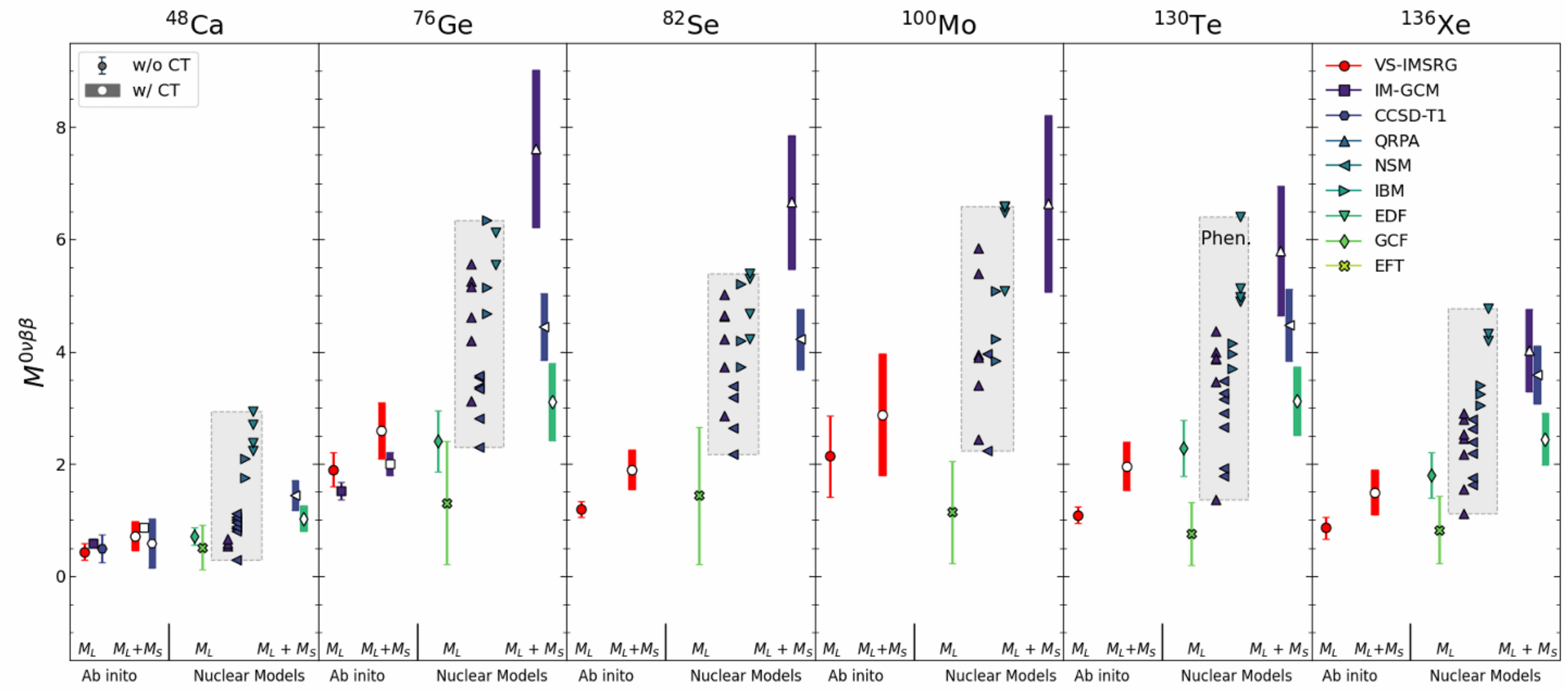
S. R. Stroberg, et al., Annu. Rev. Nucl. Part. Sci. 69, 307 (2019).

A. Belley, PhD. Thesis (2024)

VS-IMSRG for 0νββ Decay NMEs

- Antoine et al. calculated the 0νββ decay NMEs for the standard 0νββ decay mechanism
- Tend to be smaller and with more controlled uncertainties compared to phenomenological methods



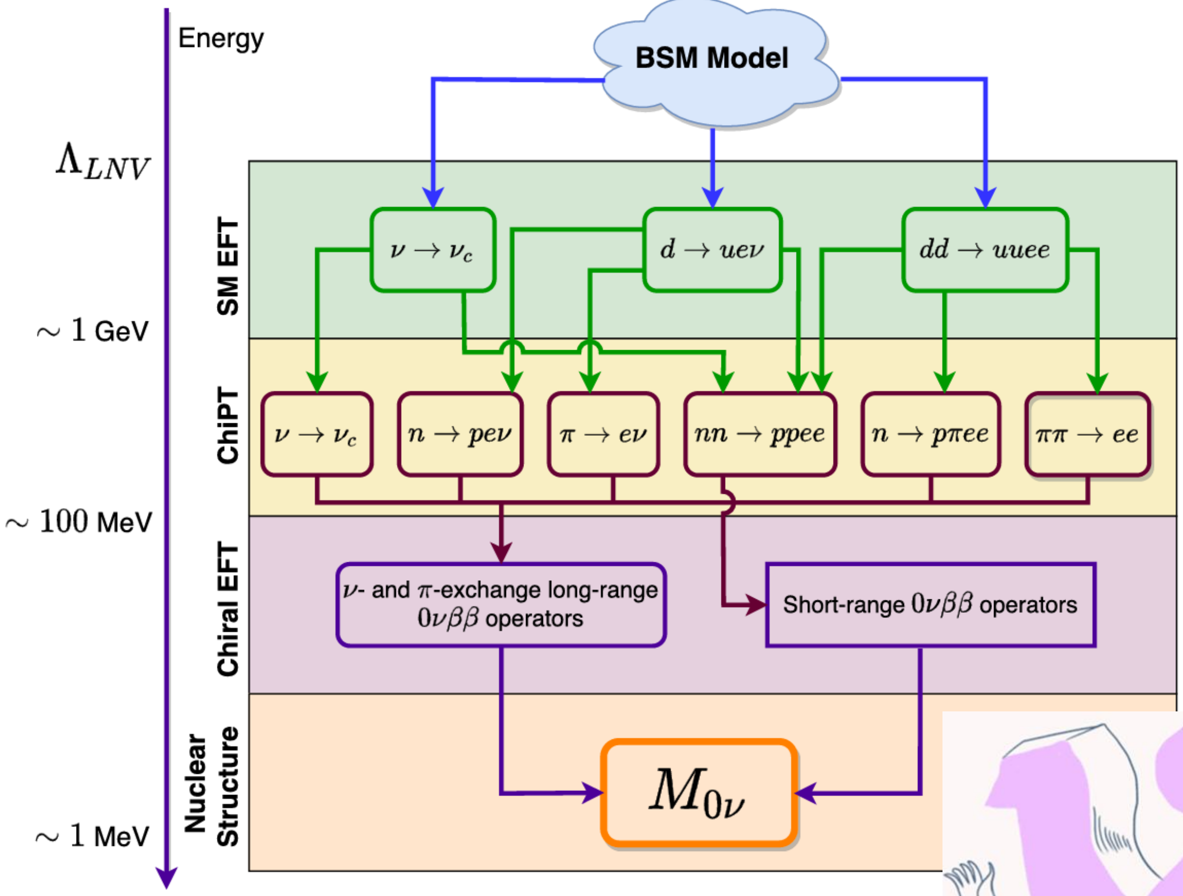


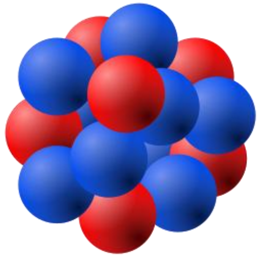
Figures courtesy of Antoine

V Cirigliano *et al* 2022 *J. Phys. G: Nucl. Part. Phys.* **49** 120502

Sterile Neutrinos in 0νββ Decay

- A hierarchy of scales to consider:
  - **Heavy sterile neutrinos**
  - **Light sterile neutrinos**
  - Nuclear scale ~ MeV
  - Seesaw scale ~ 10^{15} GeV



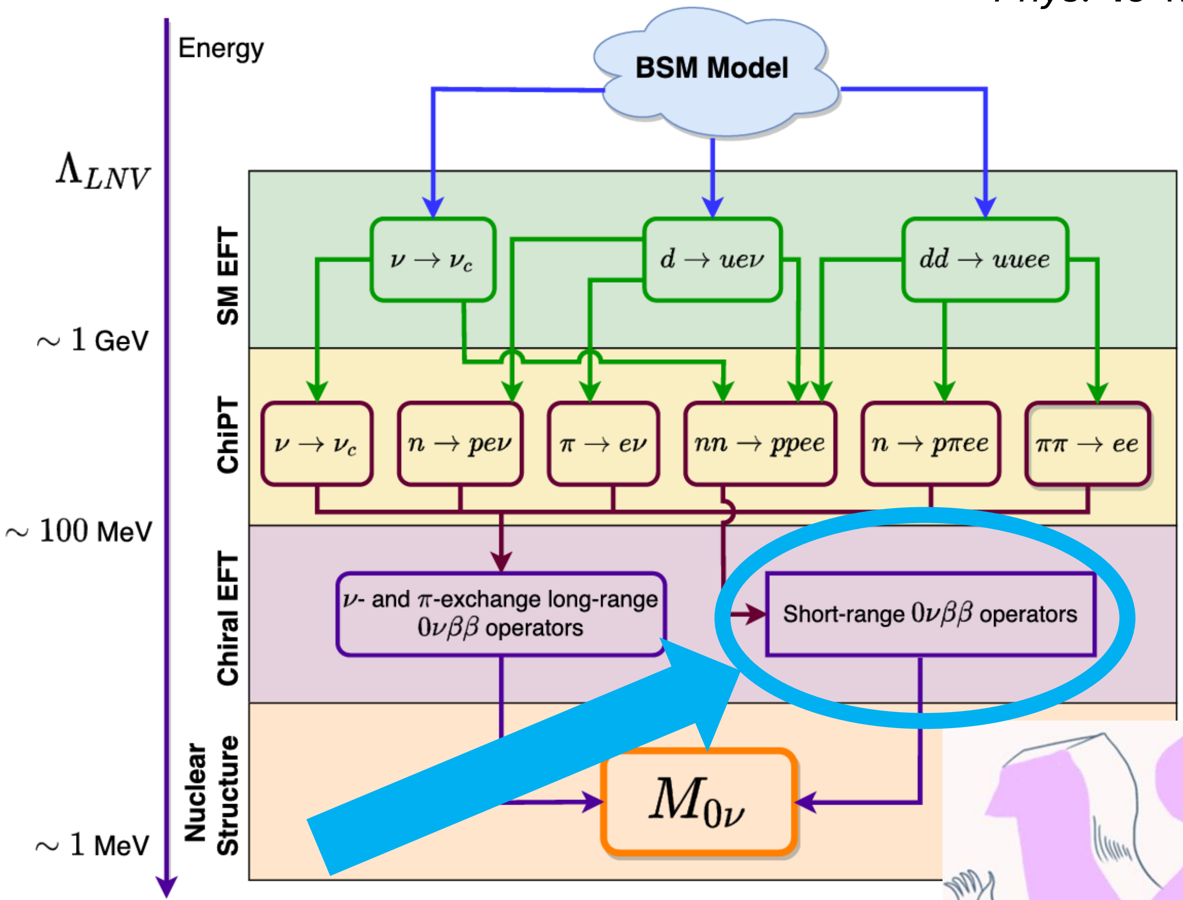


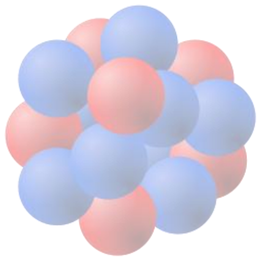
Λ_χ ~ GeV

V Cirigliano *et al* 2022 *J. Phys. G: Nucl. Part. Phys.* **49** 120502

Heavy Sterile Neutrinos

- For $m_s \gtrsim$ **GeV** sterile neutrinos integrated out at quark level
  - Generate 8 short-range $0\nu\beta\beta$ decay operators
- Use ab initio methods to compute matrix elements
  - See talk by Alex Todd (week 1)



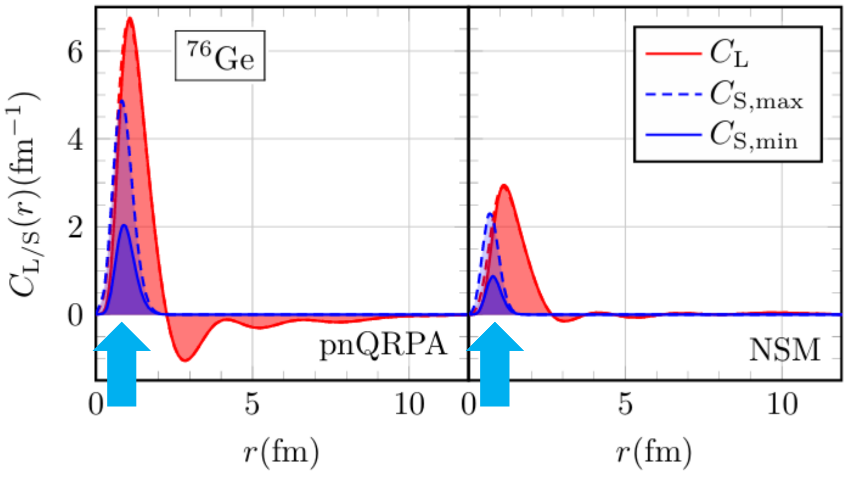


Λ_χ ~ GeV

Short-Range NMEs

- Short-range 0νββ decay operators have the form:

$$O_\alpha^{mn}(\mathbf{q}) = \tau_m^+ \tau_n^+ \frac{R}{2\pi m_\pi^2} h_\alpha(\mathbf{q}^2) S_\alpha(\mathbf{q})$$



L. Jokiniemi, et al., Phys.Lett.B 823 136720 (2021)

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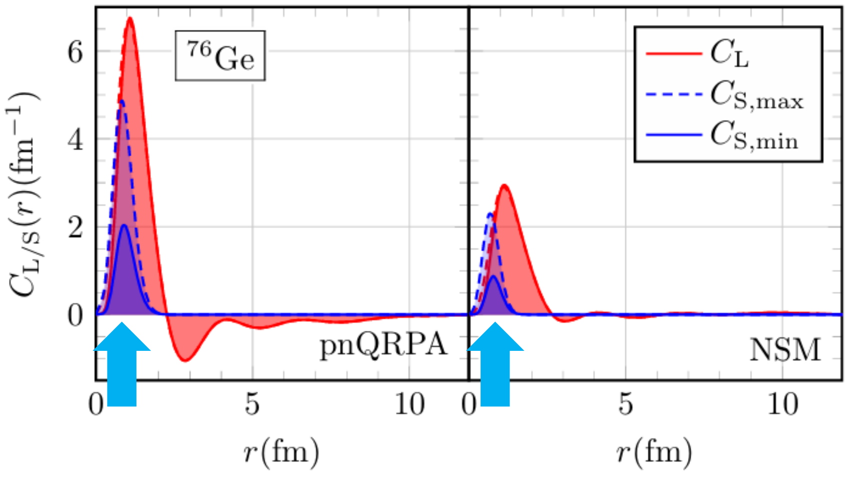


- Need **consistently SRG-evolve decay operator** alongside interaction – particularly **important for short-range operators!**
- Further need to regularize decay operator
  - ➢ We use a regulator consistent with the nuclear interaction*

$$f_{\mathrm{local}}^{\mathrm{NN}}(\mathbf{q}) = \exp\left[-\left(\frac{\mathbf{q}}{\Lambda}\right)^{2n}\right]$$

$$f_{\mathrm{dipole}}(\mathbf{q}) = \left(1 + \frac{\mathbf{q}^2}{\Lambda^2}\right)^{-2}$$

- Restrict to interactions consistently SRG evolved (or not) in both the NN and 3N sector

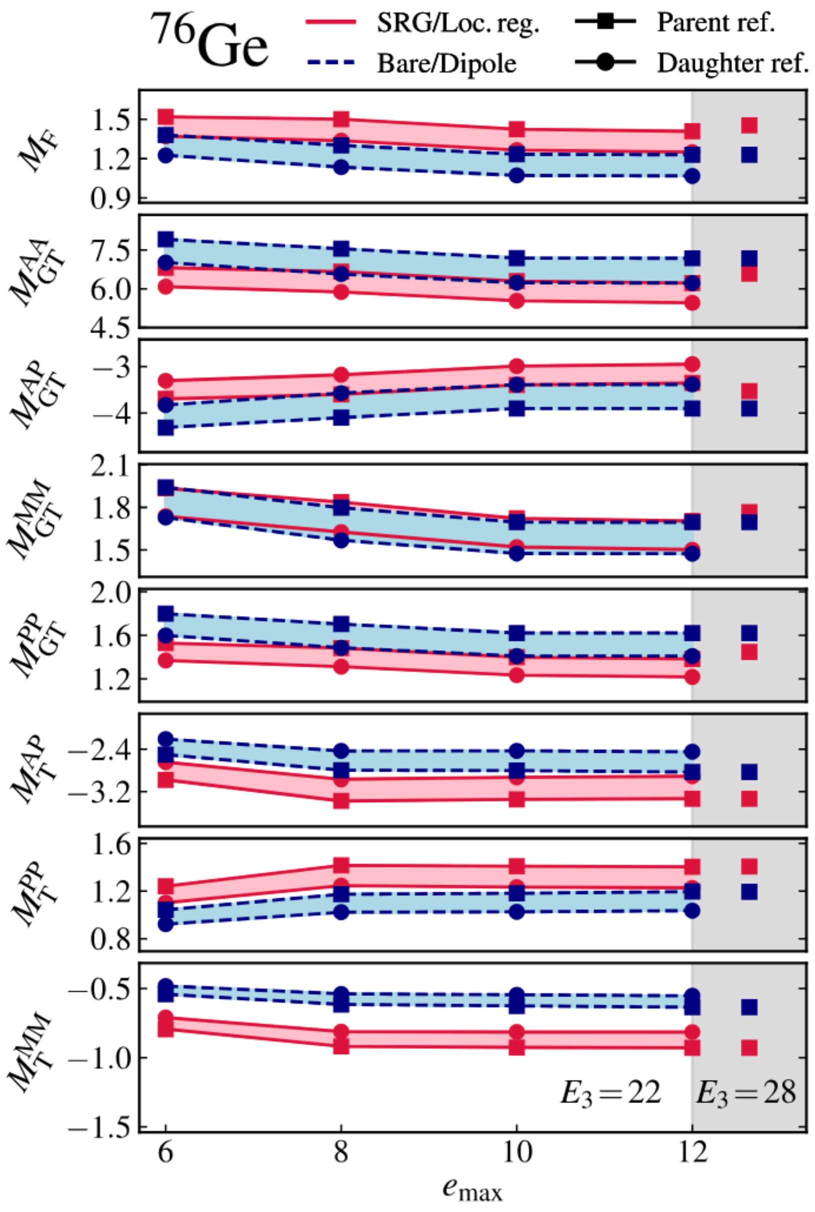
L. Jokiniemi, et al., Phys.Lett.B 823 136720 (2021)

*Regulator consistent w/ the NN sector in cases where the 3N regulator differs

Short-Range NMEs

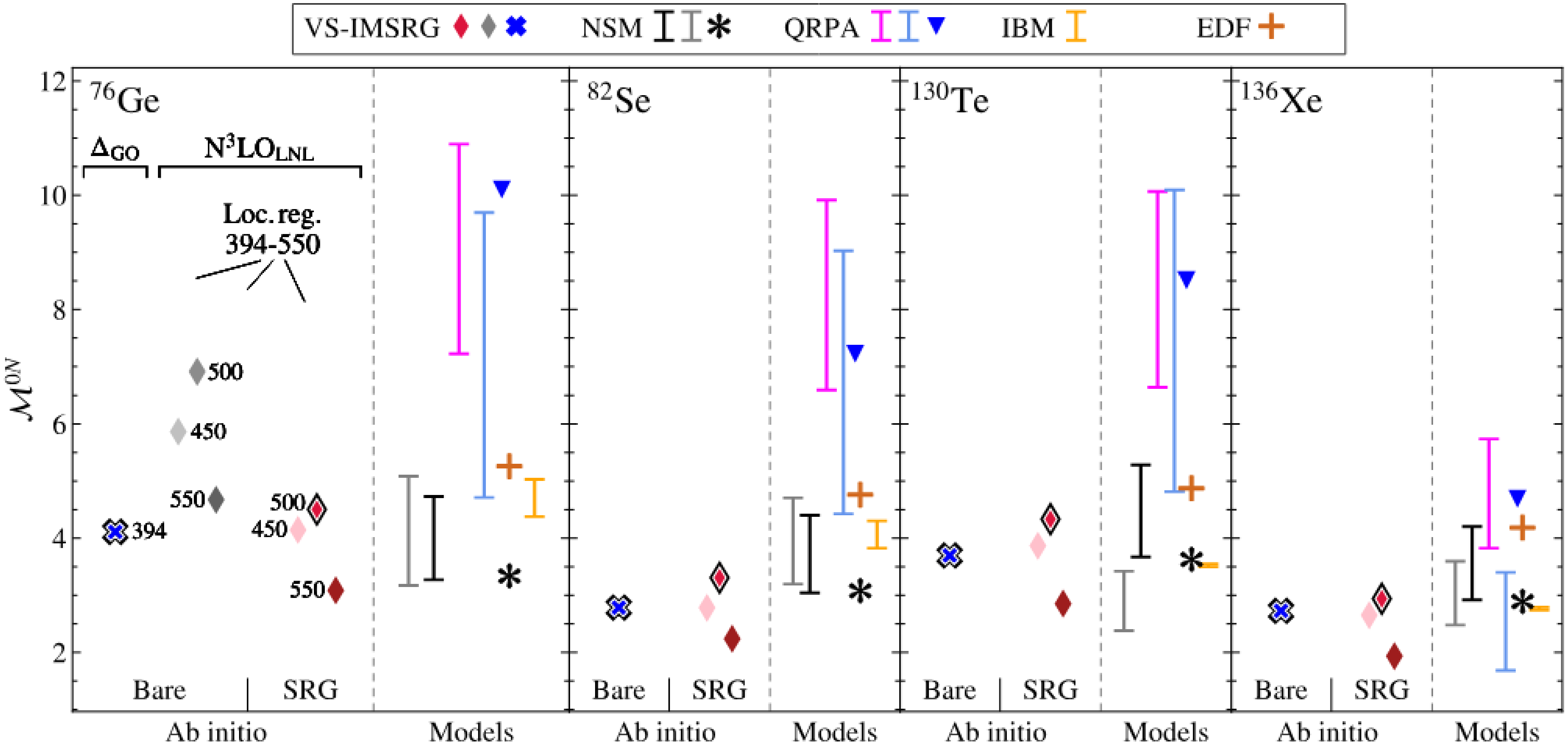
- Convergence of the NME in both e_{max} and E_{3max} using the $\mathrm{N^3LO_{LNL}}$ interaction

- Reference state dependence (square/circle markers) appears from many-body truncation at the level of IMSRG(2)
  - Keep only 2-body operators during the IMSRG flow (See Ragnar and Bingcheng's talks week 1 for improvements w/ the IMSRG(3f2))



Short-Range NMEs

- Include results for the Δ_{GO} and N^3LO_{LNL} interactions with varying cutoffs for the regulator on the transition operator



Limits on $|U_{e4}|^2$

- Assume a type-1 seesaw mechanism with the addition of one sterile neutrino*

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

- Diagonalizing and assuming $M_R \gg M_D$ gives

$$m_\nu \sim -M_D {M_R^T}^{-1} M_D^T$$

$$m_s \sim M_R^T$$

$$|U_{e4}|^2 \sim \frac{m_\nu}{m_s}$$

*At least 2 sterile neutrinos are required to reproduce ν-oscillation data. However, a 3+1 still offers a useful toy model

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$$|U_{e4}|^2 \sim \frac{m_\nu}{m_s}$$

- Assuming a saturating contribution from heavy sterile neutrinos, we get a half-life:

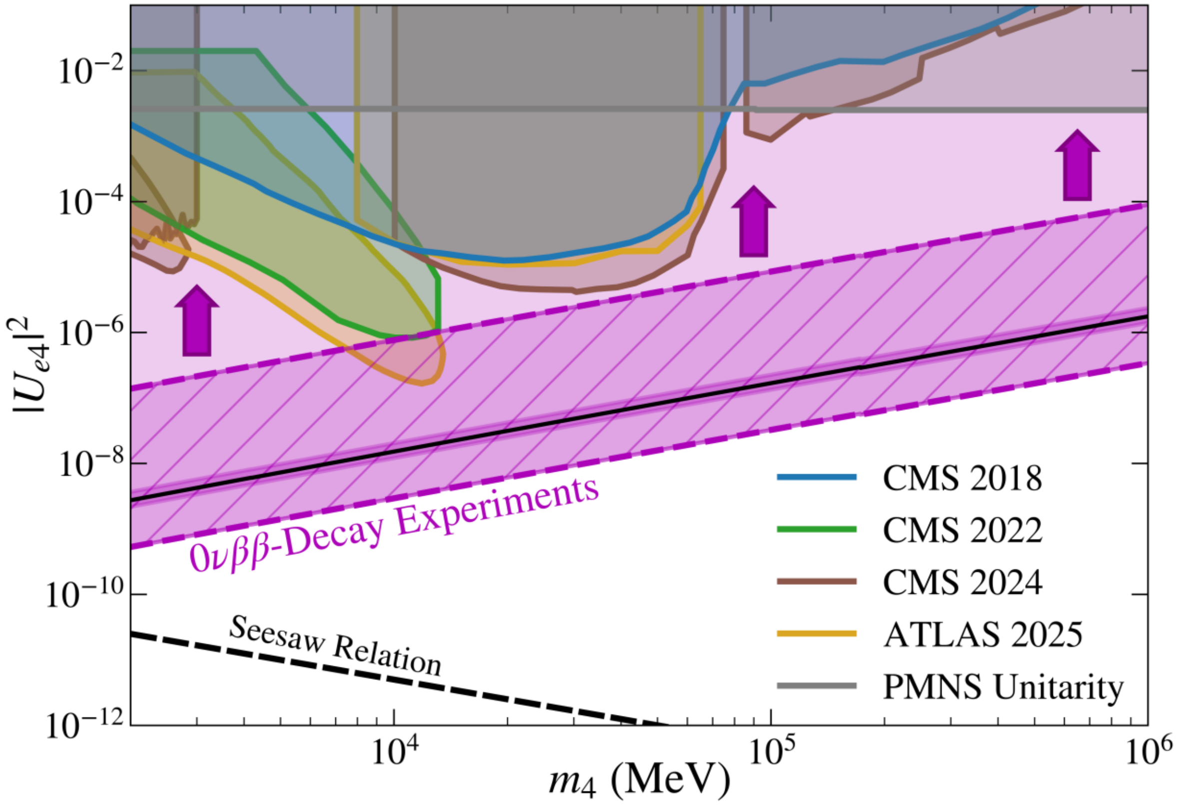
$$\left[T_{1/2}^{0\nu}\right]^{-1} = 4 g_A^4 G_{01} V_{ud}^4 \eta(\mu, m_4)^2 |U_{e4}|^4 \frac{m_\pi^4}{m_e^2 m_4^2} \times \left[\frac{5}{6} g_1^{\pi\pi} M_{\mathrm{sd}}^{\mathrm{PP}} + \frac{g_1^{\pi N}}{2} M_{\mathrm{sd}}^{\mathrm{AP}} + 2 g_1^{NN} M_{\mathrm{F,sd}}\right]^2$$

- Requires the short-range NMEs we calculated!

*At least 2 sterile neutrinos are required to reproduce ν-oscillation data. However, a 3+1 still offers a useful toy model

Limits on $|U_{e4}|^2$

- Combining the reach of several current-gen 0νββ decay experiments leaves competitive constraints on $|U_{e4}|^2$
- Large uncertainty dominated by unknown LECs $g_1^{\pi N}$ **and** g_1^{NN}
- Potential for LQCD to provide much needed LEC input



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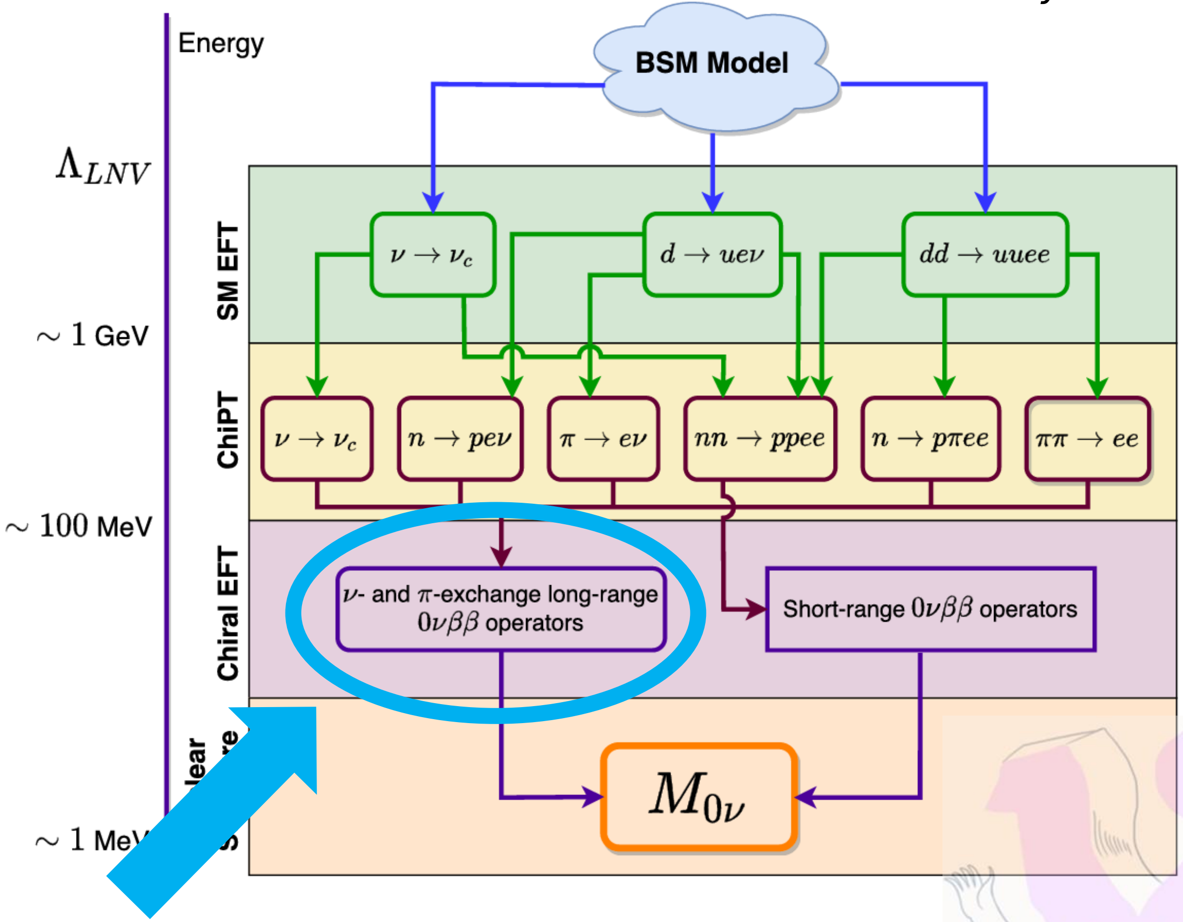
Nicholson et al. PRL 121, 172501 (2018)
W. Detmold et al. PRD 107, 094501 (2023)

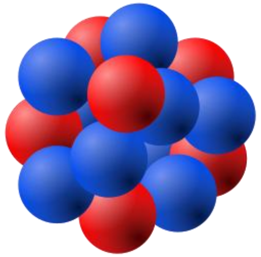
V Cirigliano *et al* 2022 *J. Phys. G: Nucl. Part. Phys.* **49** 120502

Light Sterile Neutrinos

- For $m_s \lesssim$ **GeV** sterile neutrinos remain active degrees of freedom
  - 8 long-range operators, and a short-range contact operator at leading order



Λ_χ ~ GeV

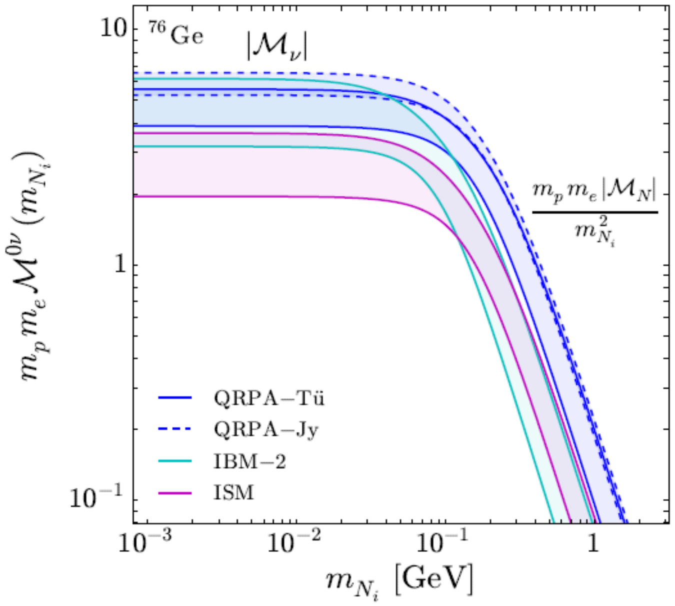


Light Sterile Neutrinos

- Matrix elements obtain an explicit dependence on the mass of the sterile neutrino

- Previously estimated using an interpolation formula and phenomenological NMEs

$$M^{0\nu}(m_s) \approx \frac{M_H^{0\nu}}{m_p m_e \frac{M_H^{0\nu}}{M_L^{0\nu}} + m_s^2}$$



Bolton, P.D., Deppisch, F.F. & Dev, P.B., J. High Energ. Phys., 170 (2020)

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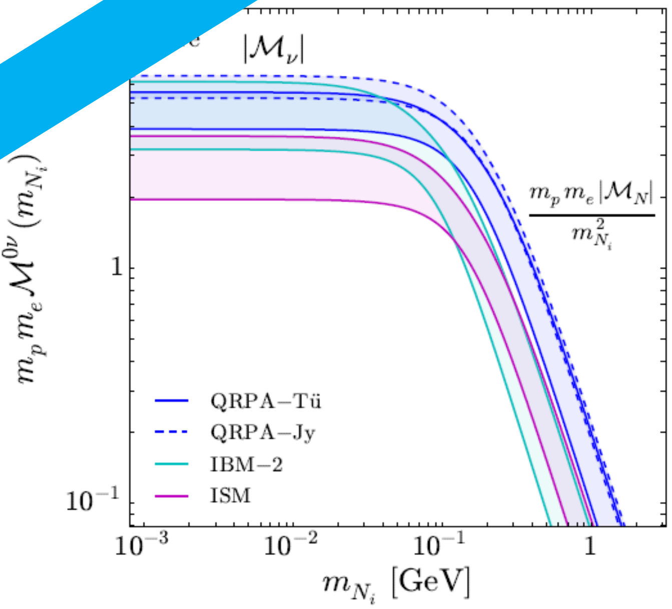
Bolton, P.D., Deppisch, F.F. & Dev, P.B., J. High Energ. Phys., 170 (2020)

- An explicit calculation involves the inclusion of sterile neutrino mass terms in the transition operator:

$$V_\alpha(q) = \frac{2R_A}{\pi} \frac{h_\alpha(q^2)}{q^2 + E_c\sqrt{q^2 + m_s^2} + m_s^2}$$



- EFT tells us additional contributions should exist…

Dekens, W., de Vries, J., Castillo, D. et al., J. High Energ. Phys. 2024, 201 (2024)

Light Sterile Neutrinos

- B
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$$
\begin{aligned}
M^{0\nu}(m_s) = \;& M_F^{0\nu}(m_s) + M_{GT}^{0\nu}(m_s) + M_T^{0\nu}(m_s) && \text{LO} \\
& - 2g_\nu^{NN}(m_s) M_{CT}^{0\nu} \\
& + M_{usoft}^{0\nu}(m_s) && \text{N}^2\text{LO} \\
& + M_{loop}^{0\nu}(m_s)
\end{aligned}
$$

10^{-3} 10^{-2} 10^{-1} 1

m_{N_i} [GeV]

Bolton, P.D.
Energ. Phys., 170 (2020)

Light Sterile Neutrinos

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Interpolation formula only
estimates this contribution

$$M^{0\nu}(m_s) = \boxed{M_F^{0\nu}(m_s) + M_{GT}^{0\nu}(m_s) + M_T^{0\nu}(m_s)} \quad \text{LO}$$

$$- 2g_\nu^{NN}(m_s)M_{CT}^{0\nu}$$

$$+ M_{usoft}^{0\nu}(m_s)$$

$$+ M_{loop}^{0\nu}(m_s) \quad \text{N}^2\text{LO}$$

10^{-3} 10^{-2} 10^{-1} 1

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Bolton, P.D.
Energ. Phys., 170 (2020)

Light Sterile Neutrino NMEs

- NMEs for the standard long-range components explicitly depend on m_s

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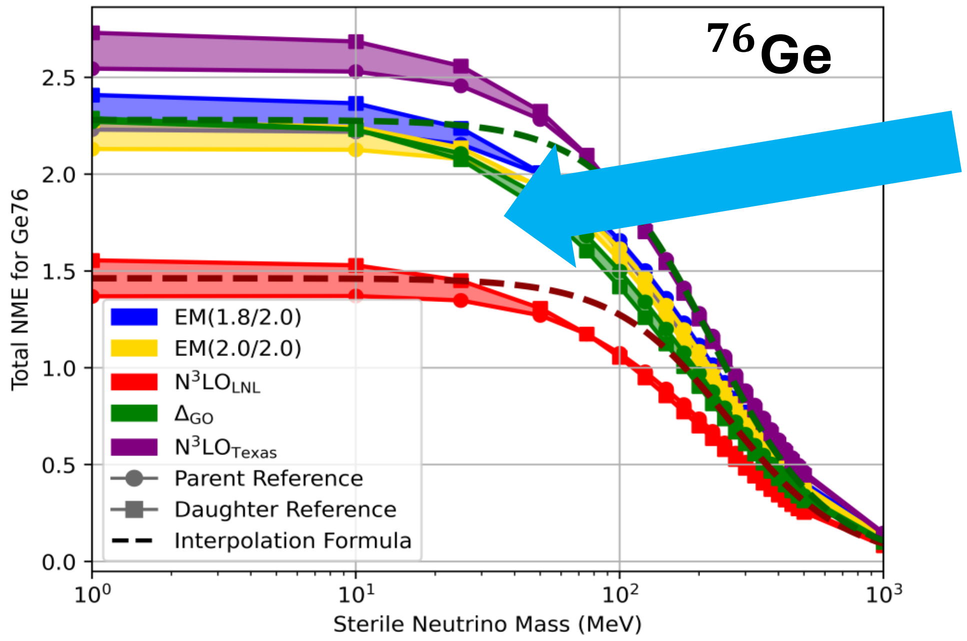


w/o contact term

Large spread from choice of chiral interaction

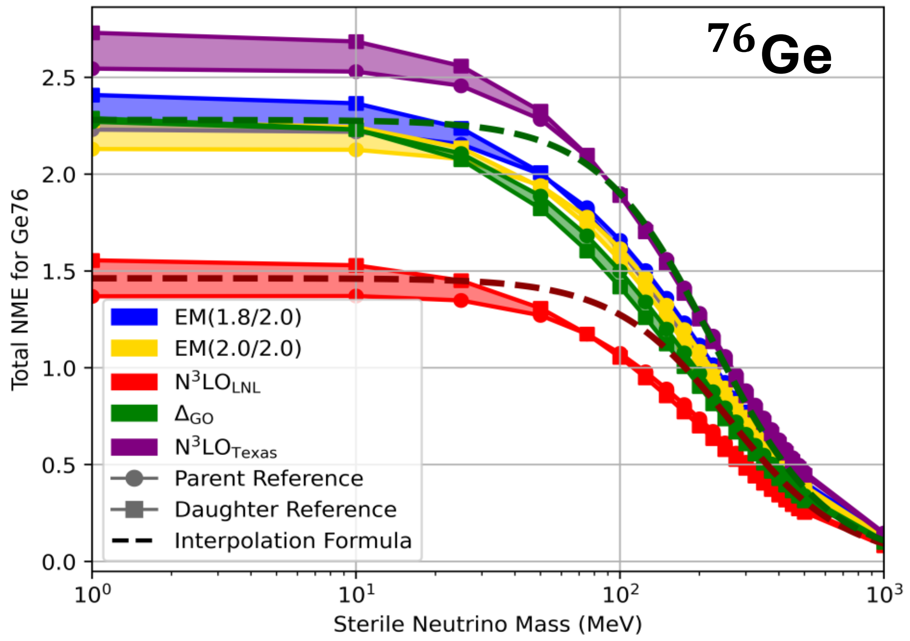
Cirigliano, V., Dekens, W. & Quiroga, S.U., J. High Energ. Phys. 2025, 181 (2025)

Light Sterile Neutrino NMEs

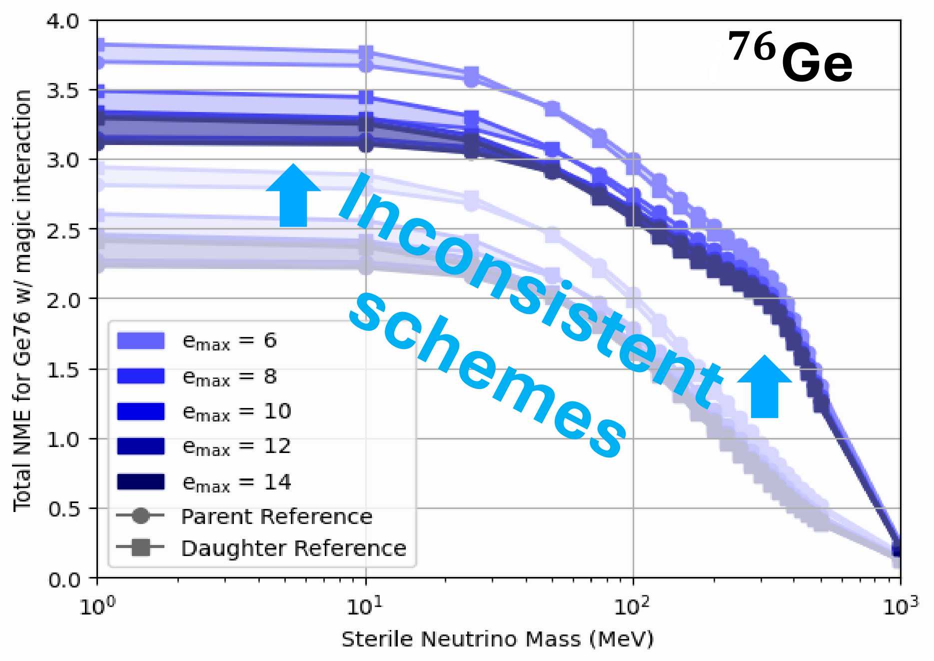
- NMEs for the standard long-range components explicitly depend on m_s

- Contact term has a m_s dependent LEC $g_\nu^{NN}(m_s)$
- Need to match LEC across schemes

$$M^{0\nu}(m_s) = M_F^{0\nu}(m_s) + M_{GT}^{0\nu}(m_s) + M_T^{0\nu}(m_s) - 2g_\nu^{NN}(m_s)M_{CT}^{0\nu}$$



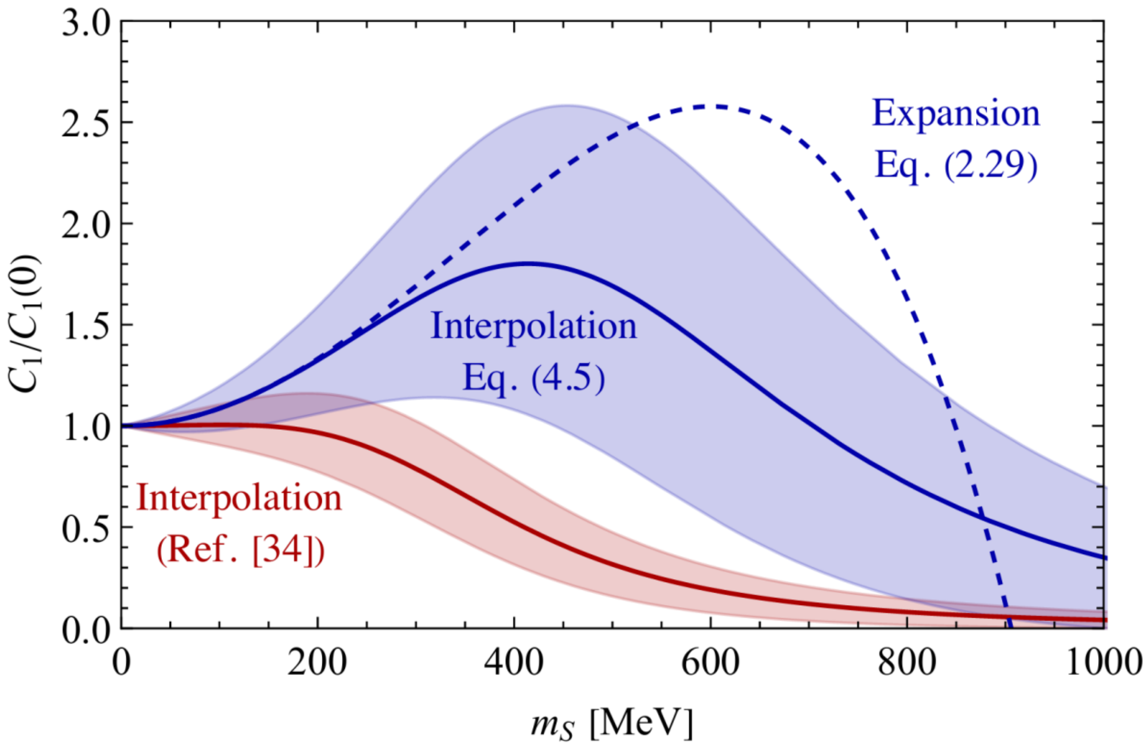
w/o contact term

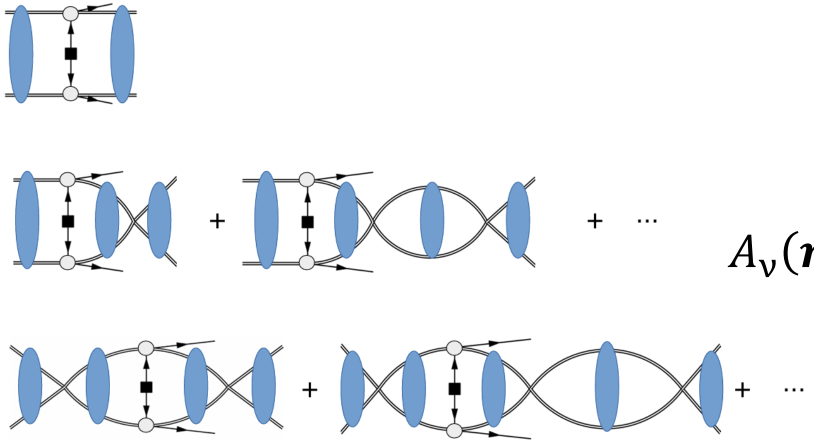


Synthetic Data for $nn \to ppe^-e^-$ w/ Sterile Neutrinos

- Contact term $g_\nu^{NN}(m_s)$ varies w/ sterile neutrino mass in the region $m_s \lesssim 1$ GeV

- $g_\nu^{NN}(m_s)$ scheme dependent
  - Compute an amplitude for the $nn \to ppe^-e^-$ process in the 1S0 channel to match across schemes



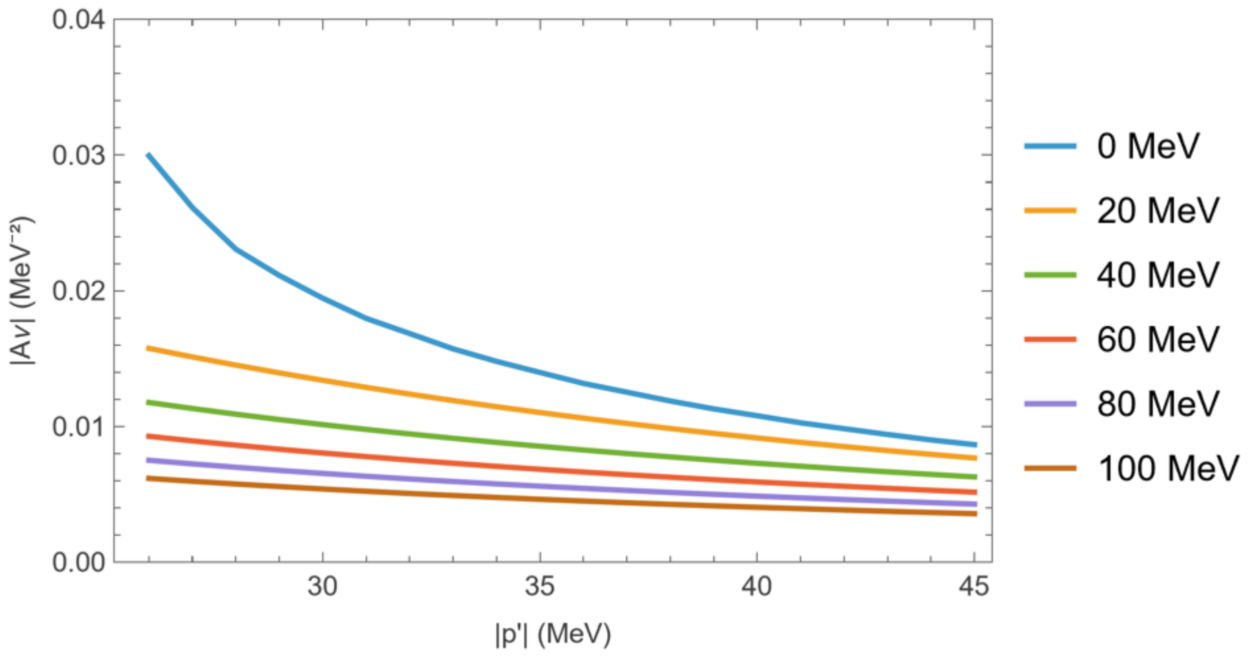


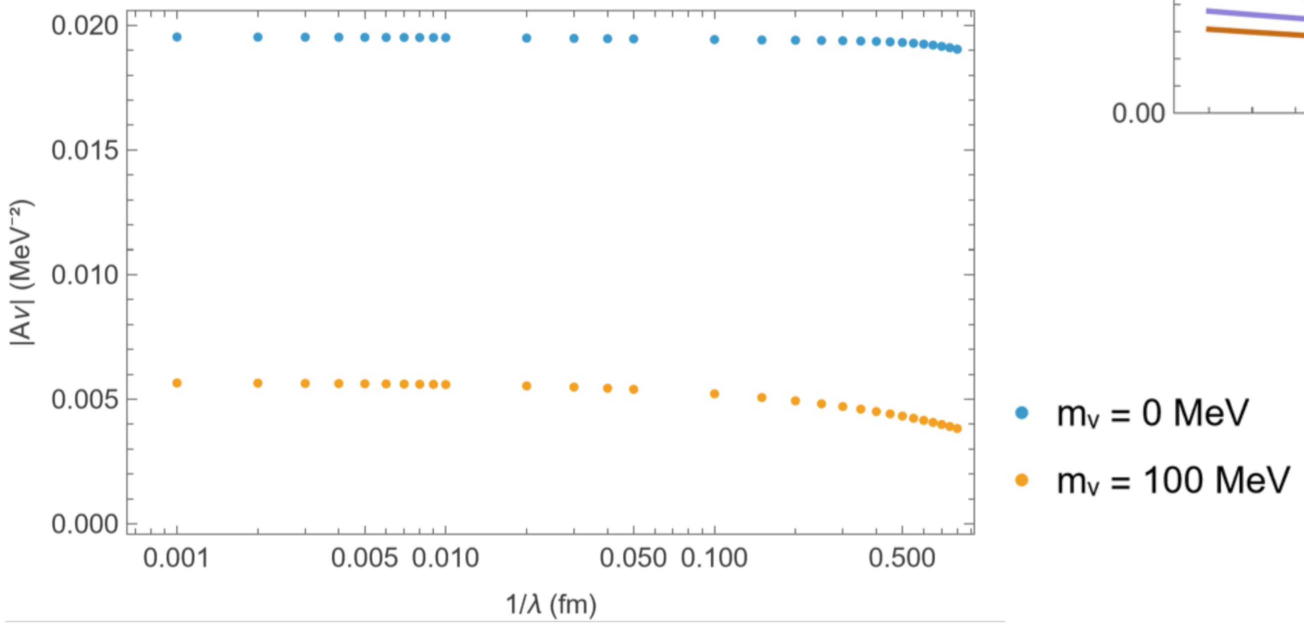
$$A_\nu(\boldsymbol{m_s}, \boldsymbol{p}, \boldsymbol{p'}) = \langle ppe^-e^- | V_{LR}(m_s) + g_\nu^{NN}(m_s) V_{SR}(m_s) | nn \rangle$$

Cirigliano, V., Dekens, W. & Quiroga, S.U.
J. High Energ. Phys. 2025, 181 (2025)

Synthetic Data for $nn \to ppe^- e^-$ w/ Sterile Neutrinos

- Computed A_ν for various sterile neutrino masses in λ scheme (see KSW ‘96)
- Scale dependence cured by g_ν^{NN} even for larger m_s





- Matching to cutoff regularization w/ χEFT interactions in progress

Kaplan D., Savage M. & Wise M., 1996

Cirigliano, V., Dekens, W. & Quiroga, S.U., J. High Energ. Phys. 2025, 181 (2025)

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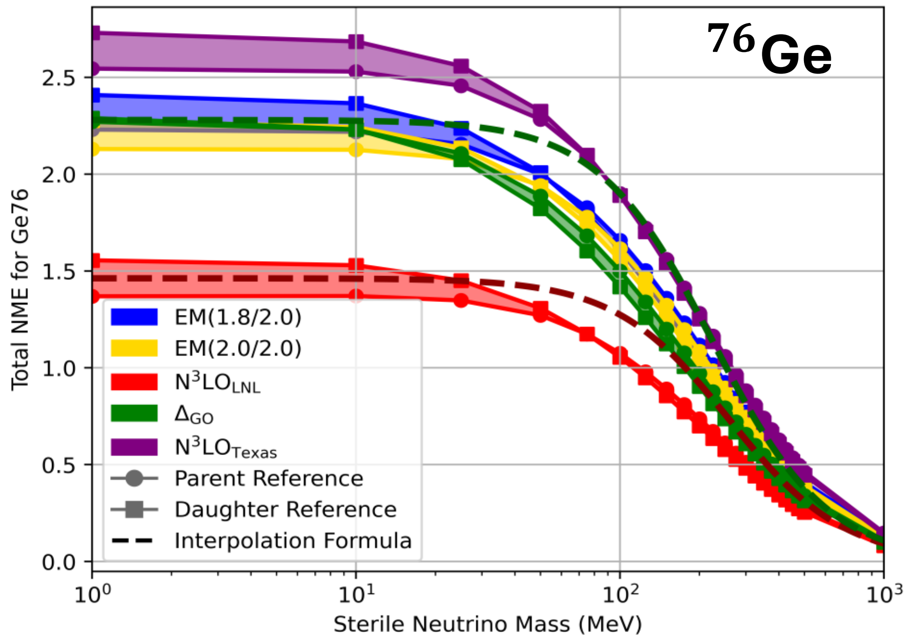
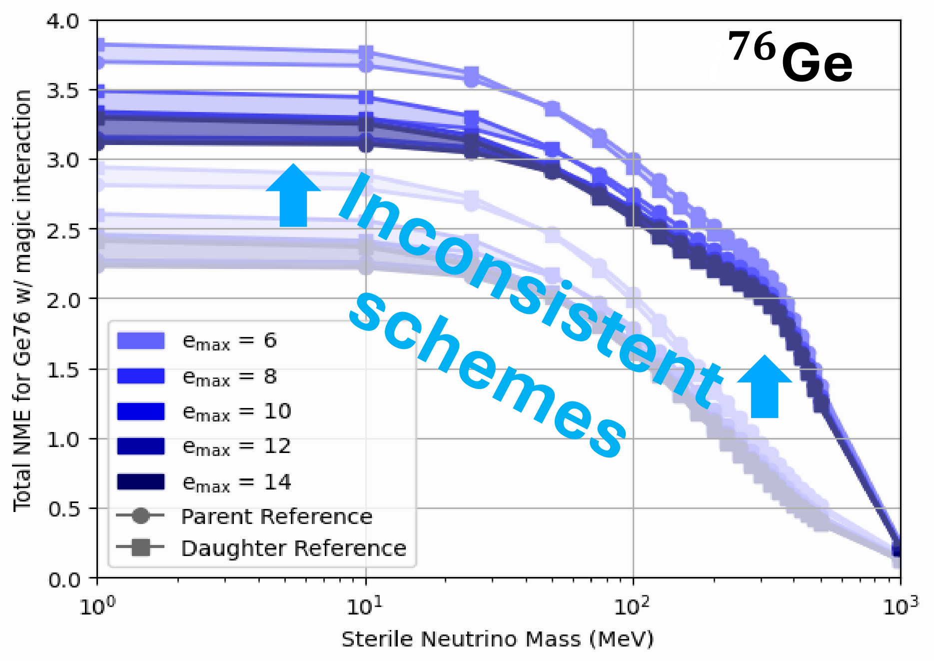
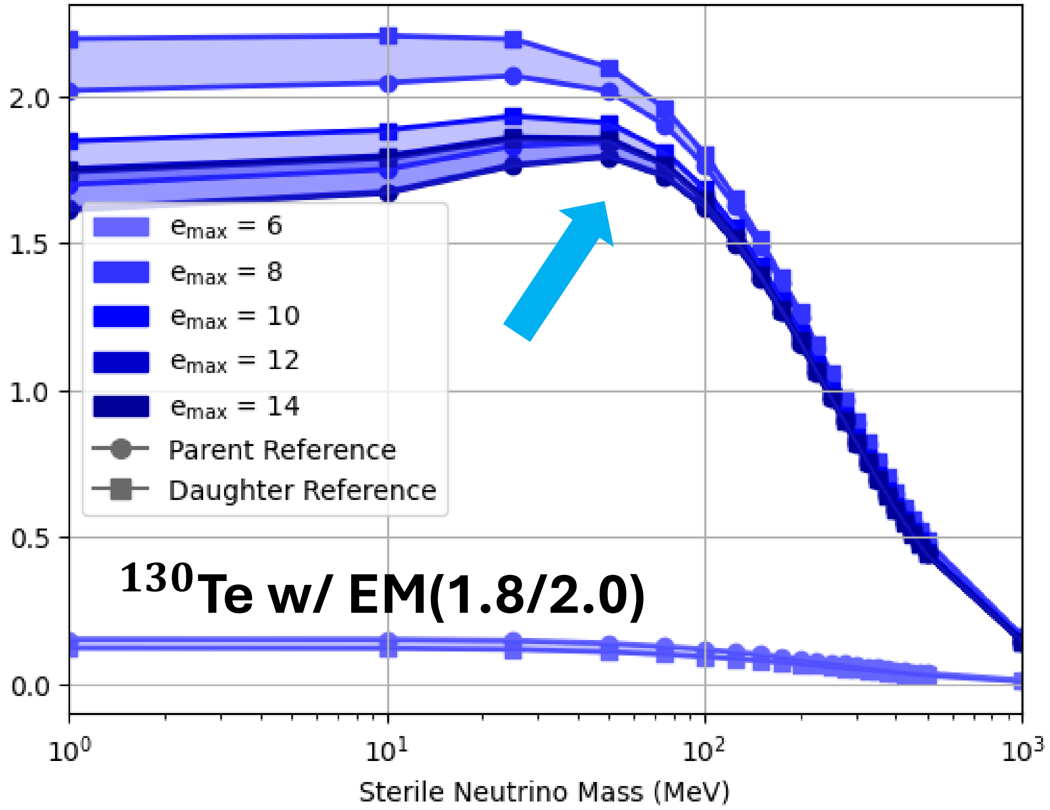


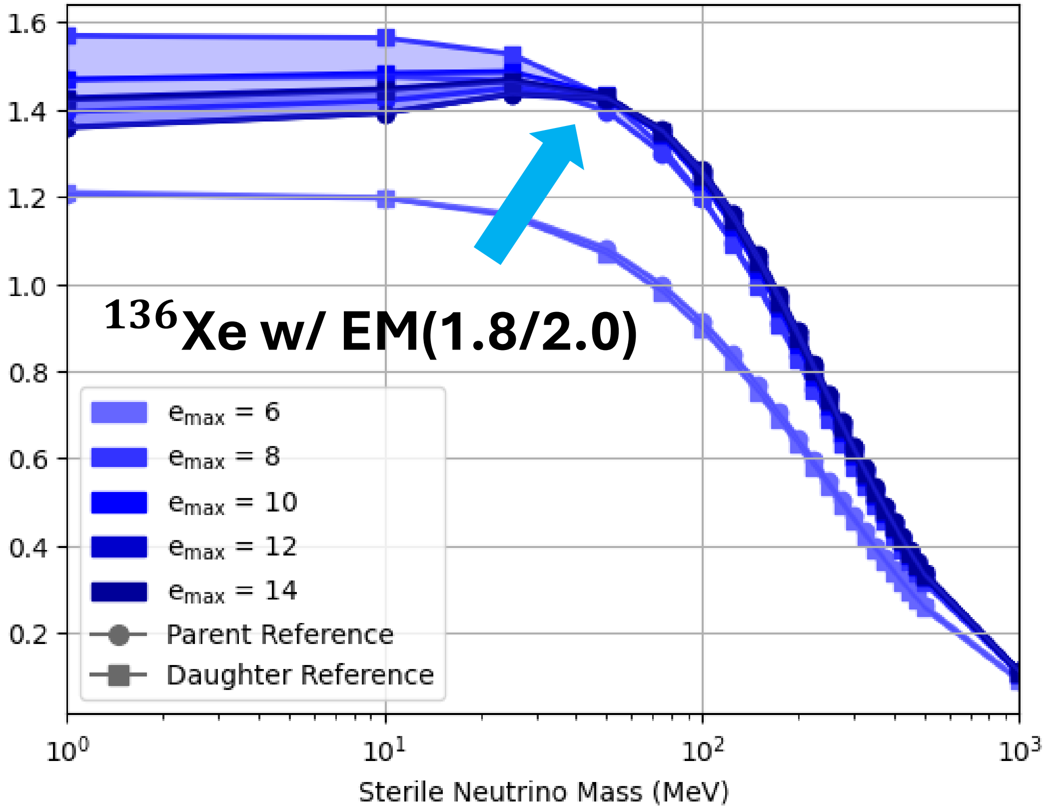
w/o contact term



Issues in Heavy Nuclei

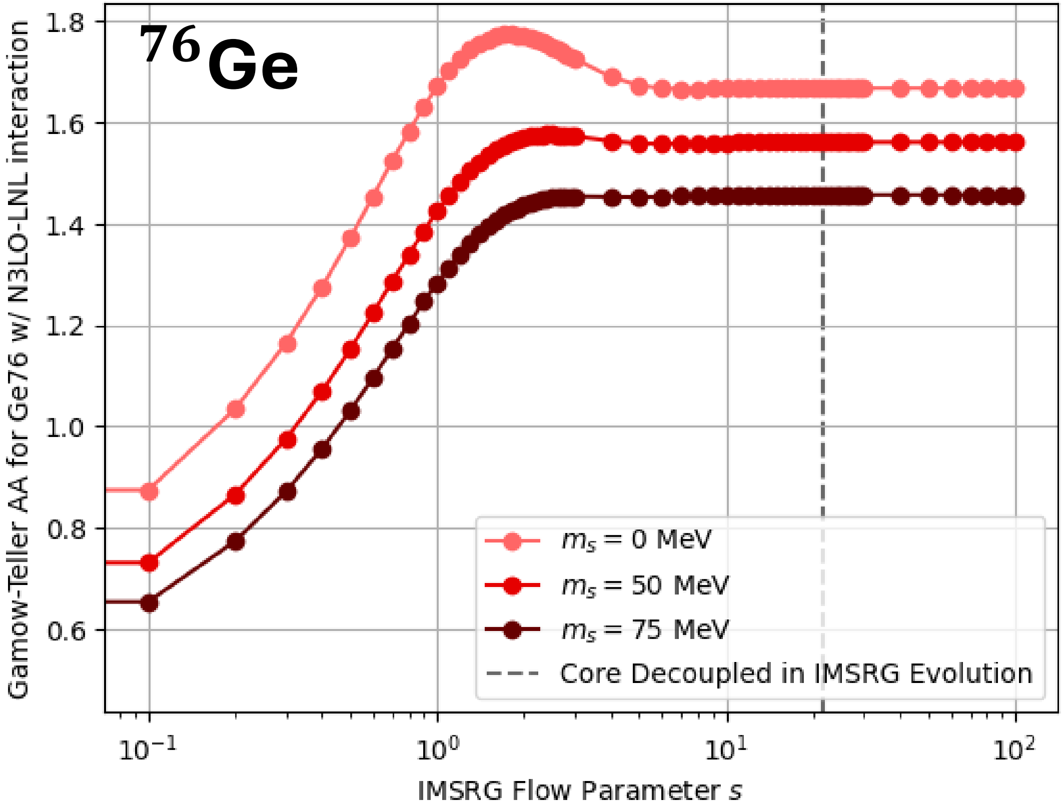
- Unphysical "bump" present in the NMEs for ^{130}Te and ^{136}Xe around 50 MeV
  - ➢ What could be the possible causes? Does not seem to be the interaction?

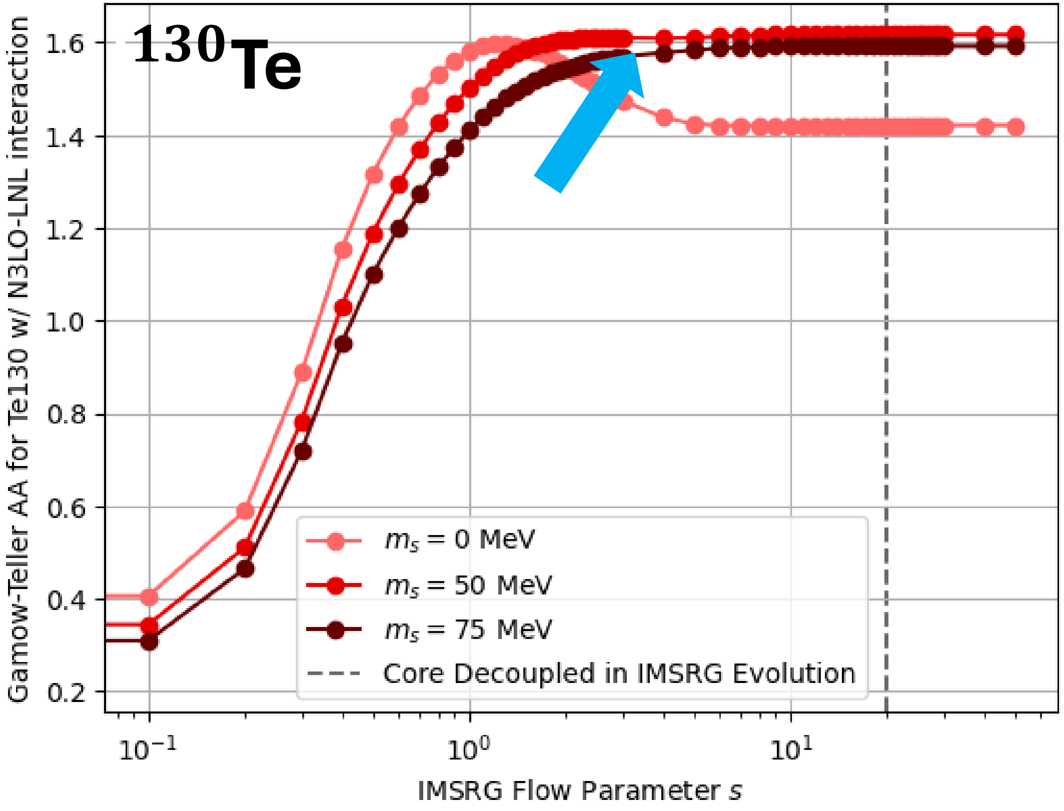




Culprit: Induced Higher-Body Operators

- IMSRG flow of the NMEs at $m_s = 0, 50, 75$ MeV in ^{76}Ge (left) and ^{130}Te (right) show contrasting behaviour for $s \geq 1$
- Likely due to higher-body operators induced during the IMSRG flow





Culprit: Induced Higher-Body Operators

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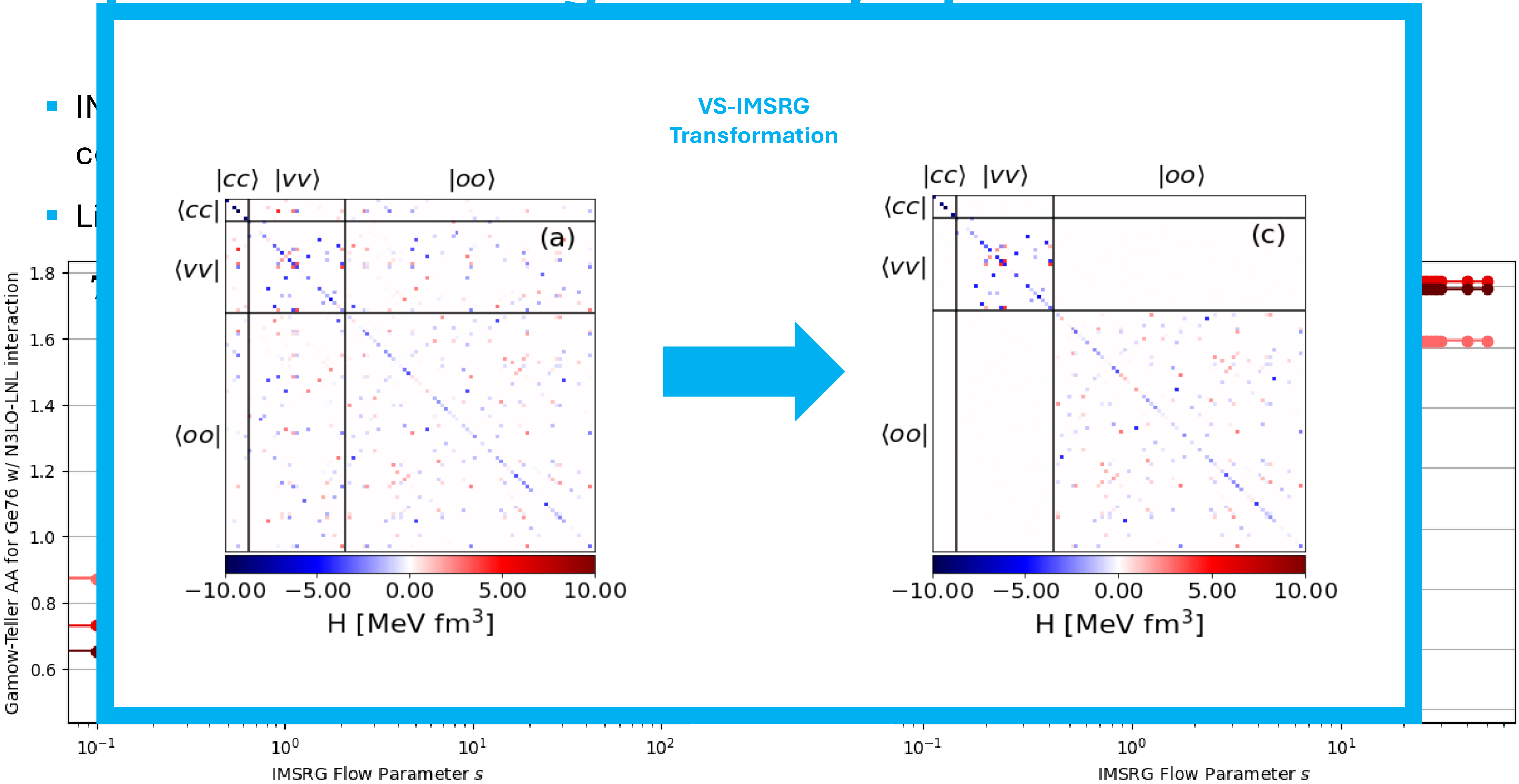

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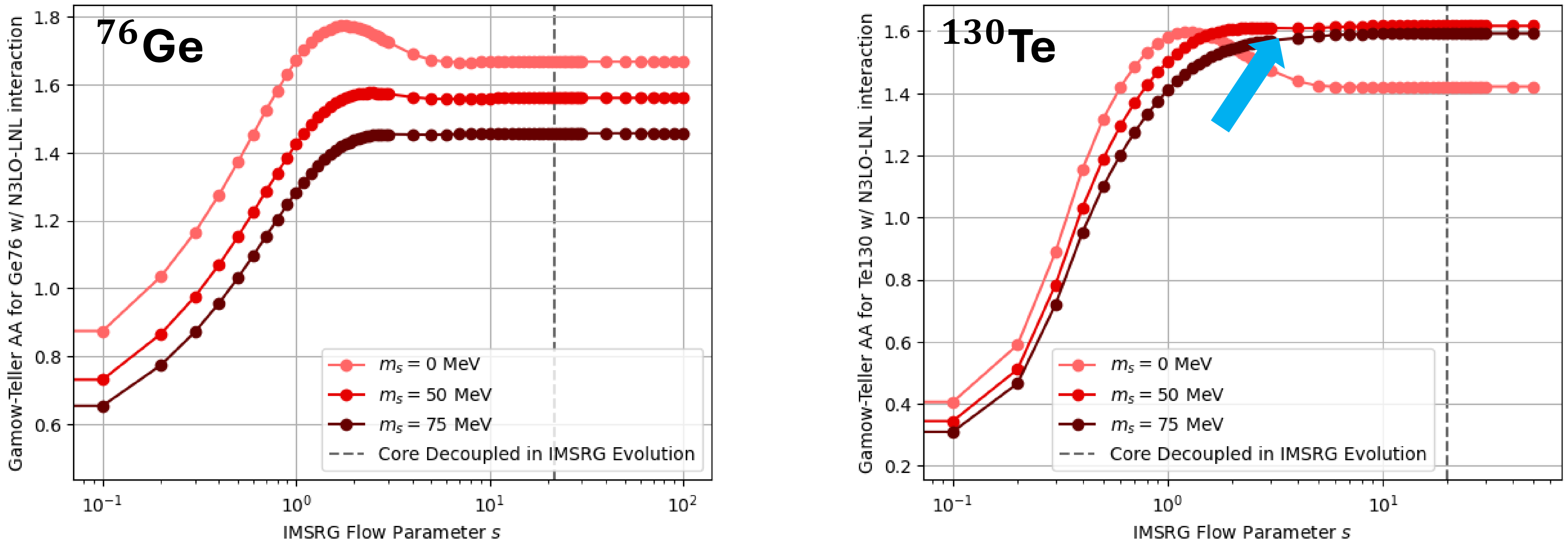

SRG Evolution of Light Sterile Neutrino NMEs

- Consistent free-space SRG evolution of operators expected to be a sub-leading correction for long-range operators

$$M^{0\nu}(m_s) = M_F^{0\nu}(m_s) + M_{GT}^{0\nu}(m_s) + M_T^{0\nu}(m_s)$$

$$V_\alpha(q) = \frac{2R_A}{\pi} \frac{h_\alpha(q^2)}{q^2 + E_c\sqrt{q^2 + m_s^2} + m_s^2}$$

SRG Evolution of Light Sterile Neutrino NMEs

- Consistent free-space SRG evolution of operators expected to be a sub-leading correction for long-range operators
  - ➢ **Larger effect than expected** in long-range operators

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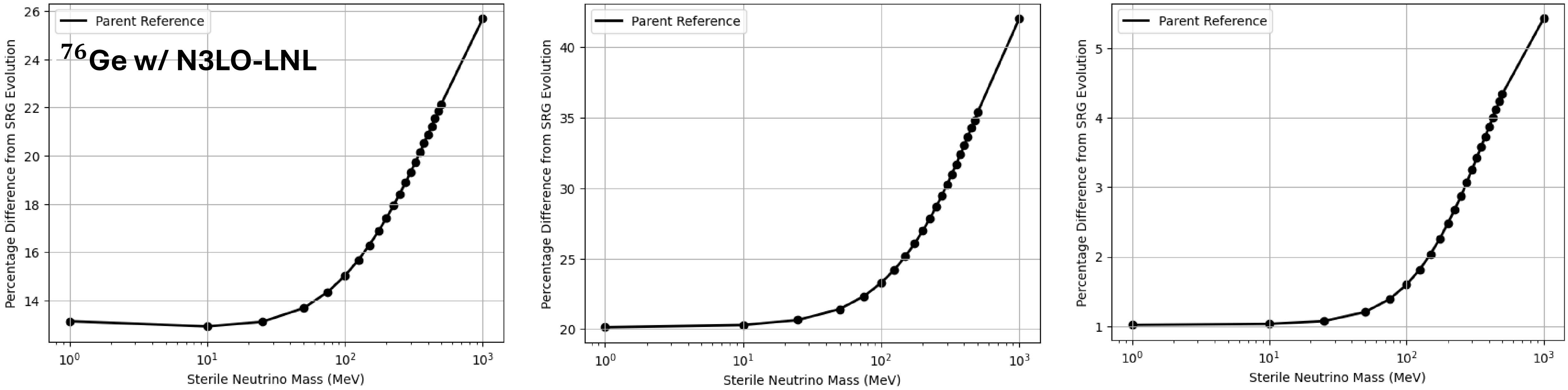
Fermi (10-30%) **Gamow-Teller (20-45%)** **Tensor (1-5%)**

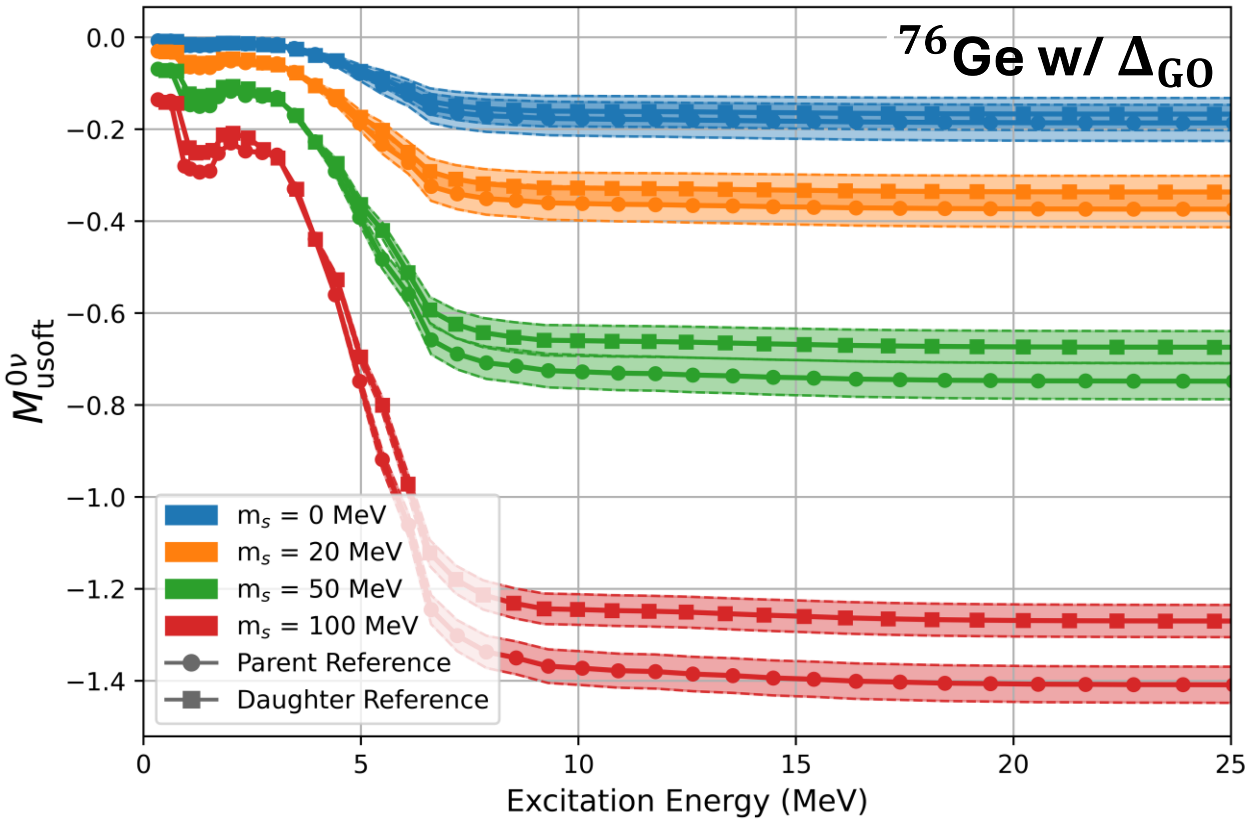


N^2LO Ultrasoft Contributions

- At N^2LO, contributions from ultrasoft neutrinos w/ $q < 100$ MeV
- LO for small m_s
- Dependence on intermediate 1^+ states and excitation energies

$$M^{0\nu}_{\text{usoft}}(m_s) = \frac{2R_A}{\pi g_A^2} \sum_n \langle 0_f^+ | \sum_k \tau_k^+ \boldsymbol{\sigma}_k | 1_n^+ \rangle \langle 1_n^+ | \sum_k \tau_k^+ \boldsymbol{\sigma}_k | 0_i^+ \rangle \times [f(m_s, \Delta E_1) + f(m_s, \Delta E_2)]$$

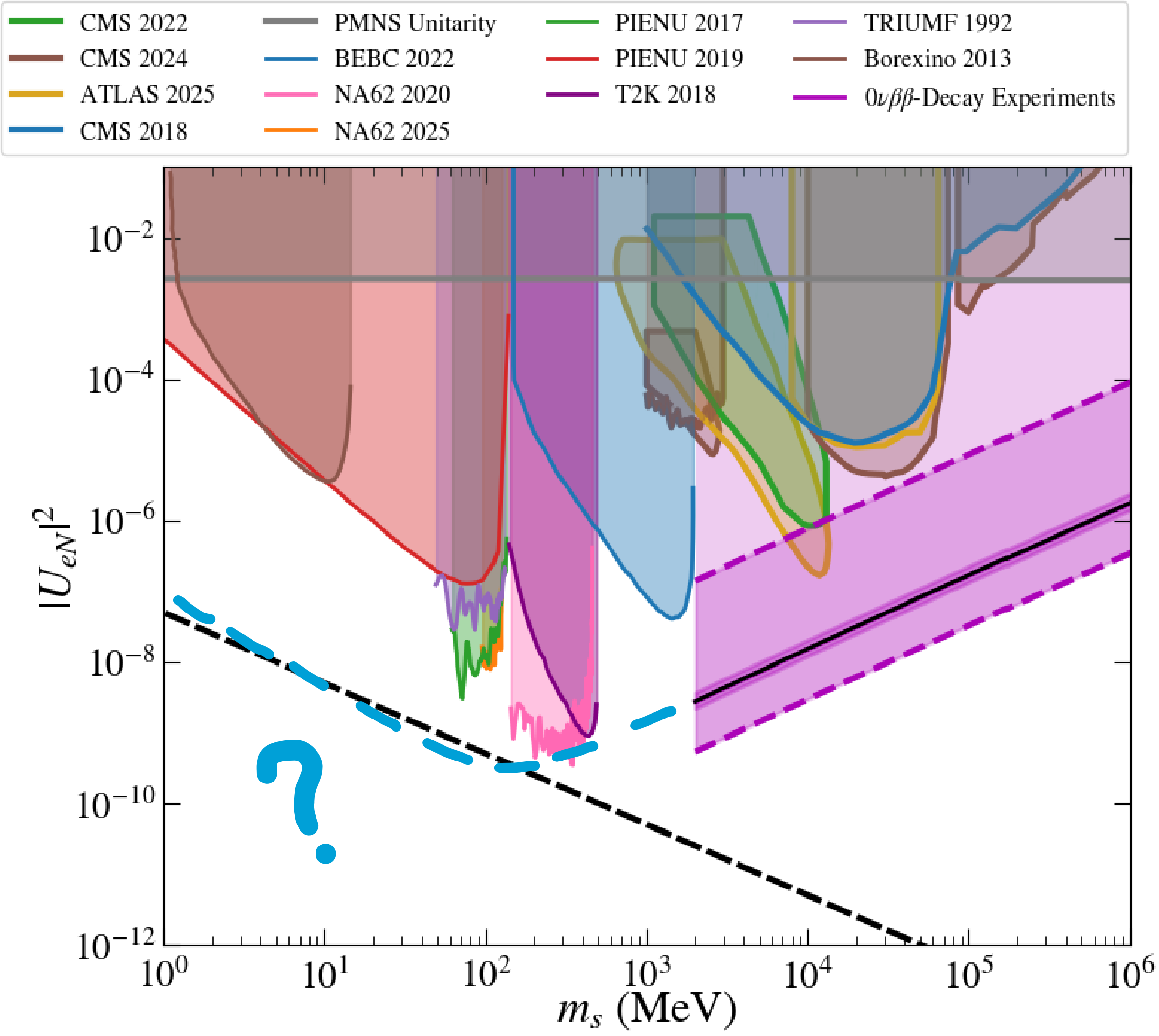
- Similar difficulties as to accurate description of 2νββ decay



Dekens, W., de Vries, J., Castillo, D. et al., J. High Energ. Phys. 2024, 201 (2024)

Next Steps

- Calculation of N^{2}LO loop contributions
  - More LECs ($g_\nu^{\pi\pi}$ and $g_\nu^{\pi N}$) enter here
- Potential large effect from VS-IMSRG(3f2) correction to investigate – see Ragnar's talk week 1
- Large effect of valence space choice in Ca48, will this affect results in heavy isotopes? – see Lotta's talk week 3



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Discovery, accelerated