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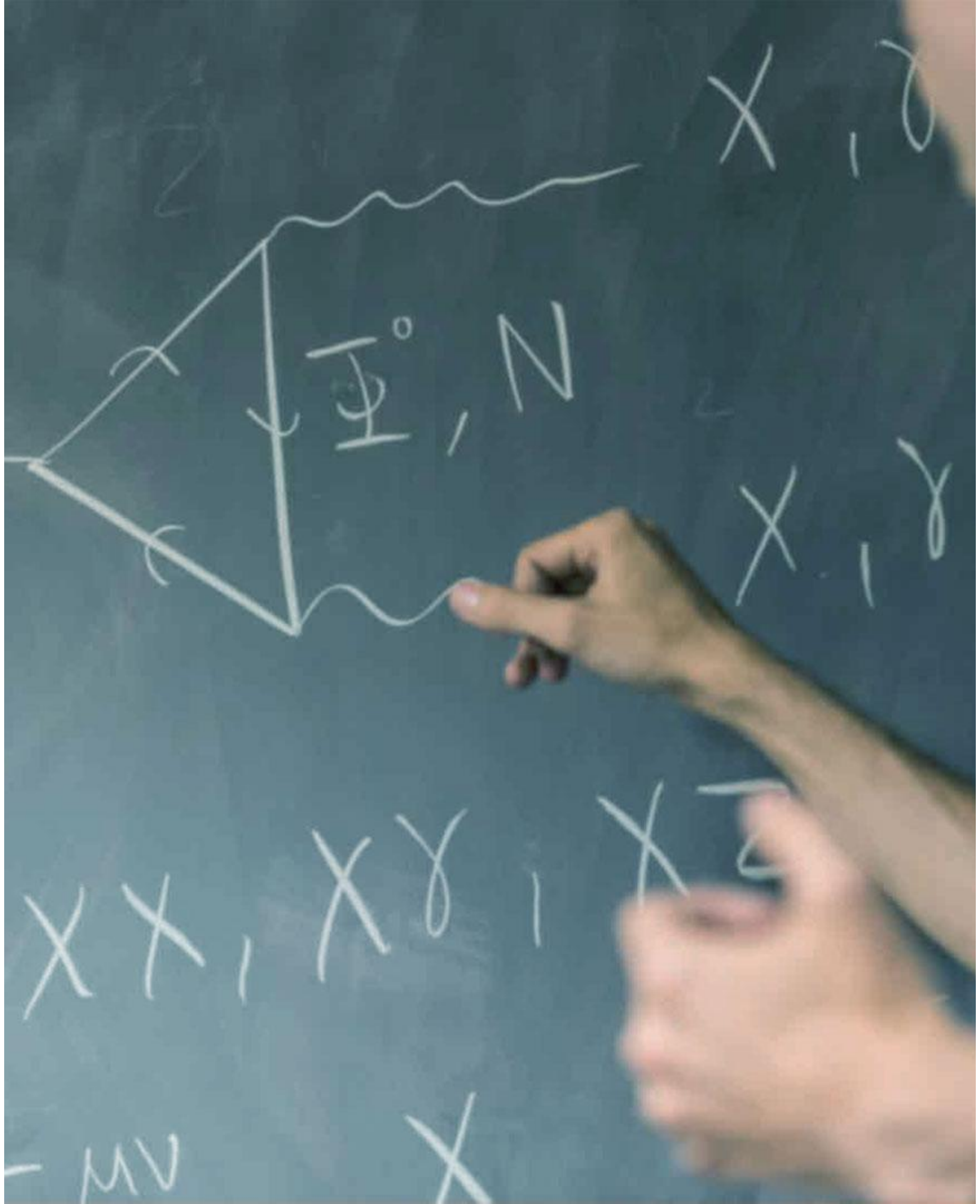
Sterile Neutrinos and 0νββ Decay from Nuclear Interactions



Taiki Shickele

Nuclear Hamiltonians for Advancing Nuclear Physics and Beyond

May 15th, 2026

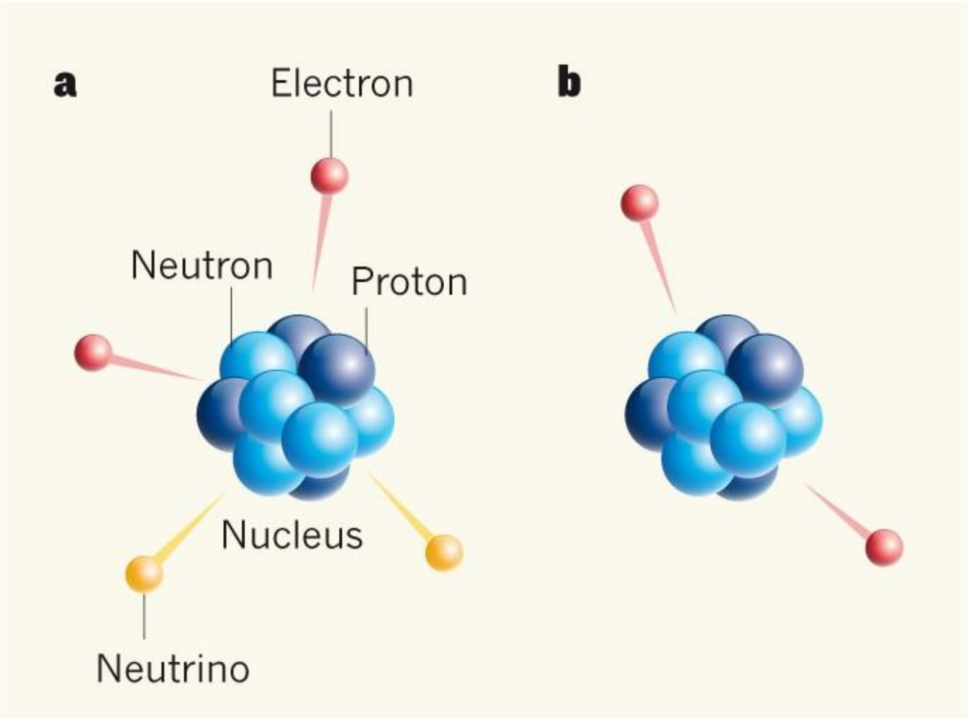
Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

Discovery, accelerated

Neutrinoless Double-Beta (0vββ) Decay

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

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



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

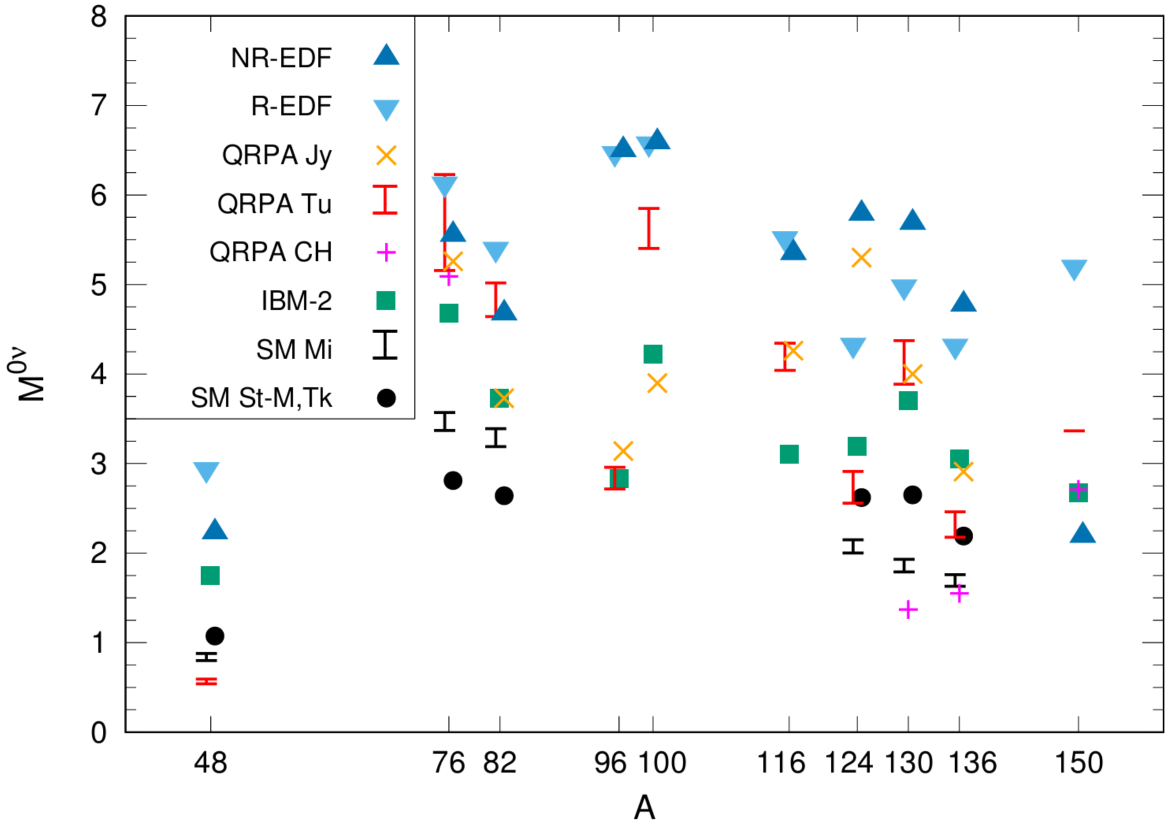
Gratta, G. Search for neutrinoless double-β decay. *Nature* **538**, 48–49 (2016)

Nuclear Matrix Elements (NMEs) for 0νββ Decay

- NME critical for an extraction of the underlying physics from experimental results

$$\left[T_{1/2}^{0\nu}\right]^{-1} = g_A^4 G^{0\nu} |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

- Phenomenological determinations show a large spread and face difficultly assigning uncertainties
- **Ab initio methods** rooted in chiral effective field theory (χEFT) offer a path forward

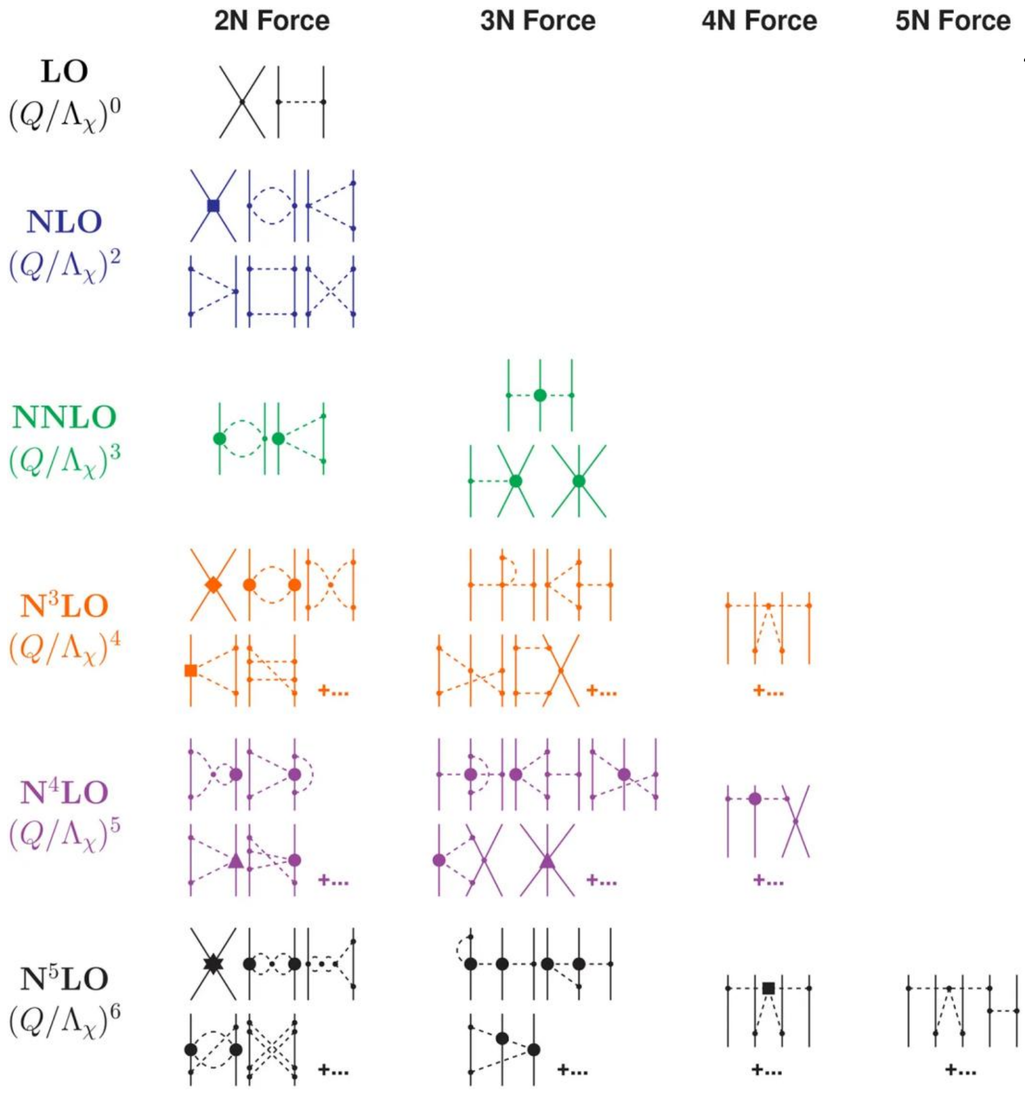


* Note this half-life equation is only valid in the case of light-neutrino exchange

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

Nuclear Hamiltonians from Chiral Effective Field Theory

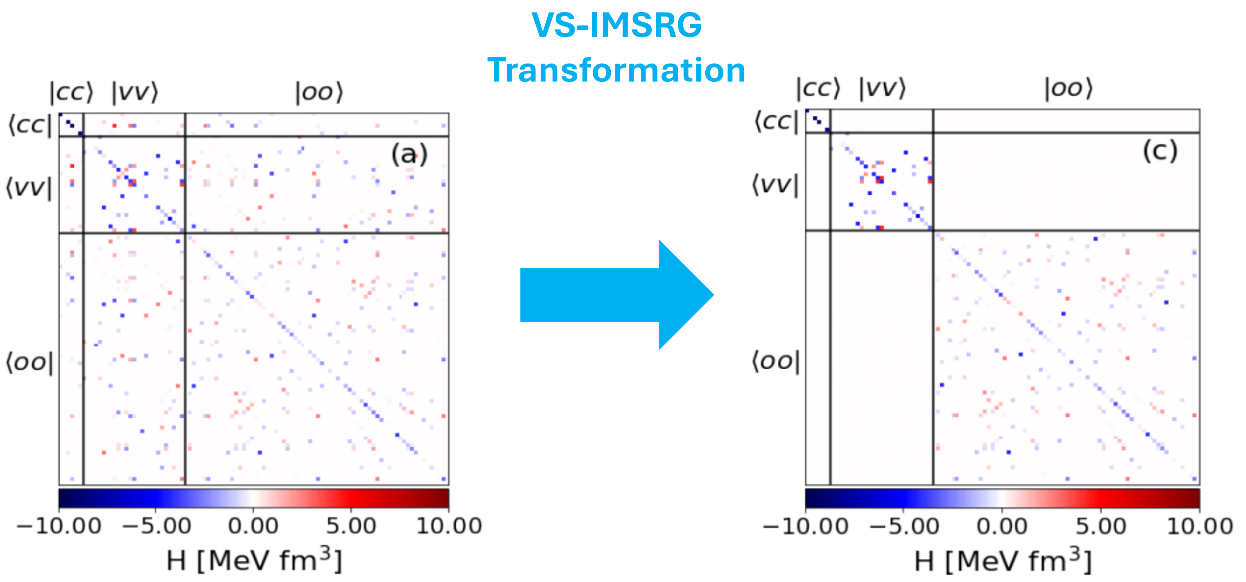
- Use a set of "practically optimized" chiral interactions:
  - EM(1.8/2.0)
  - N3LO-LNL
  - ΔNNLO-GO(394)
  - N3LO-Texas



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

The Valence Space IMSRG

- 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

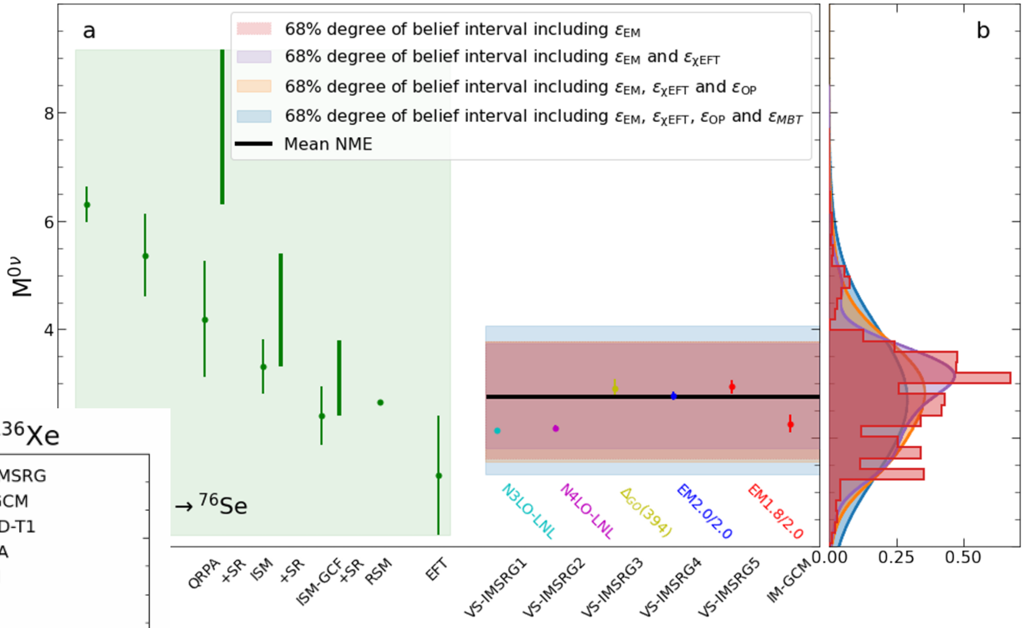


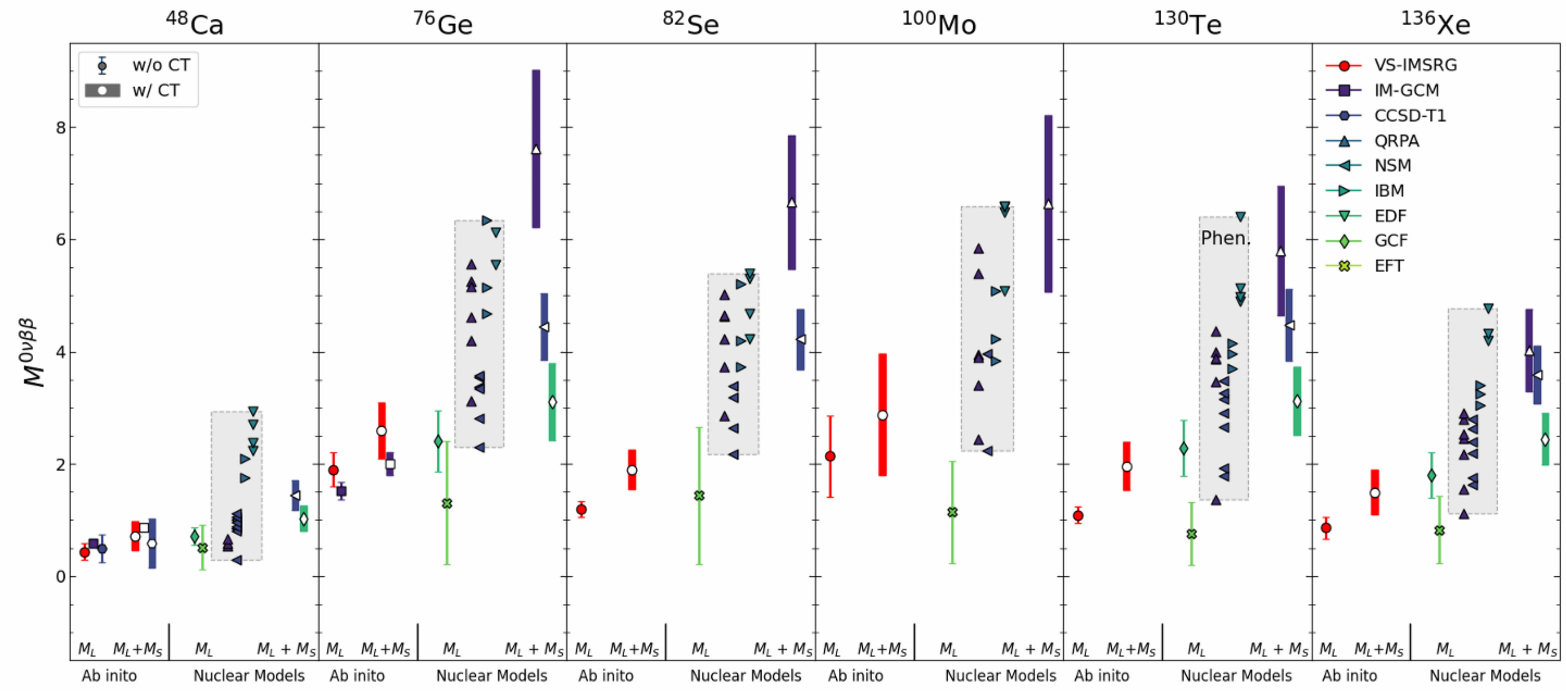
S. R. Stroberg, et al., Annu. Rev. Nucl. Part. Sci. 69, 307 (2019).

A. Belley, PhD. Thesis (2024)

VS-IMSRG for 0νββ Decay NMEs

- Belley 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



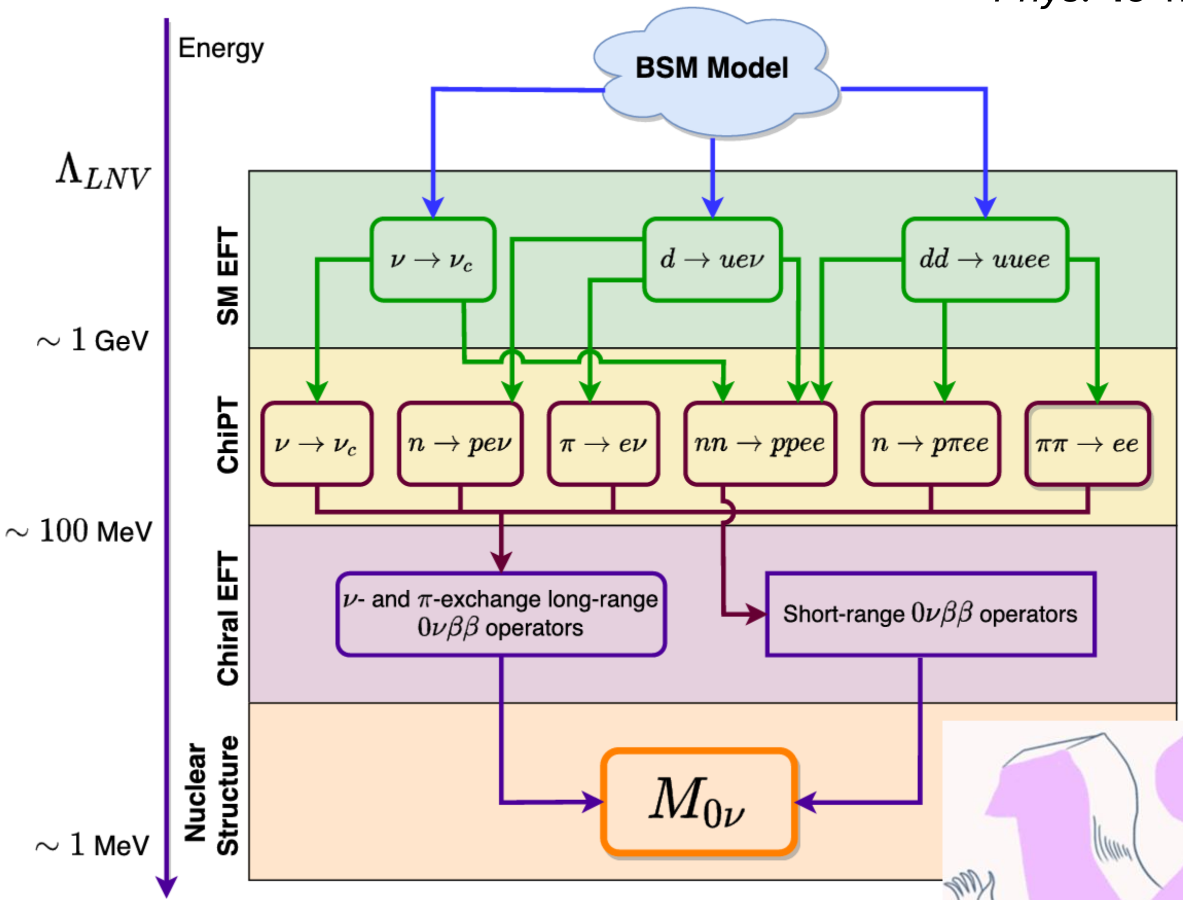


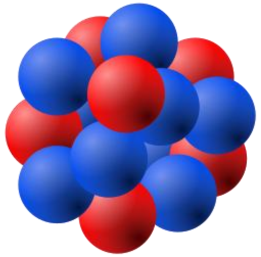
Figures courtesy of Antoine

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

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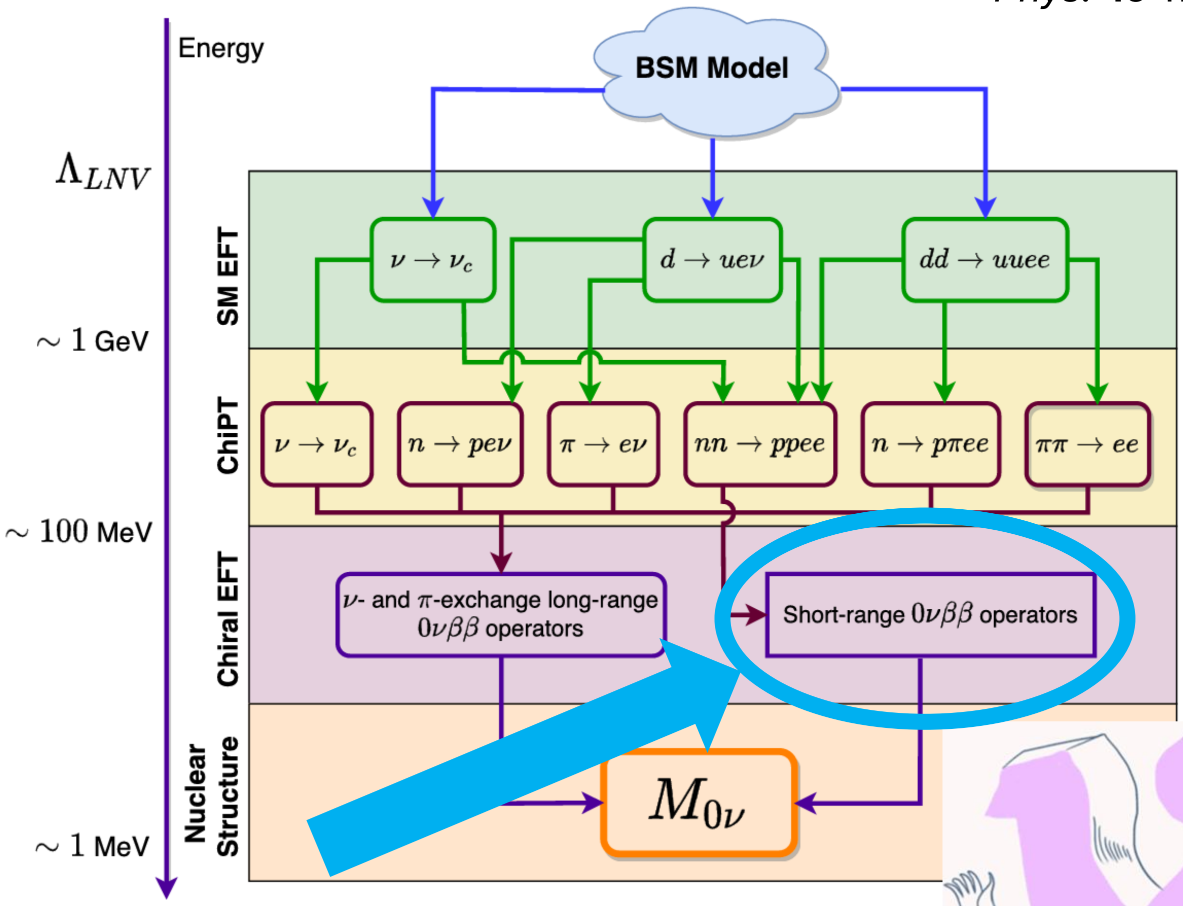
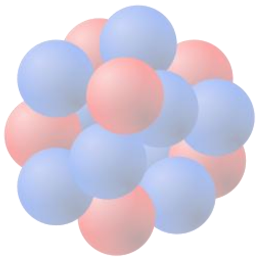
Heavy Sterile Neutrinos

- 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
  - Spearheaded by **Alex Todd**



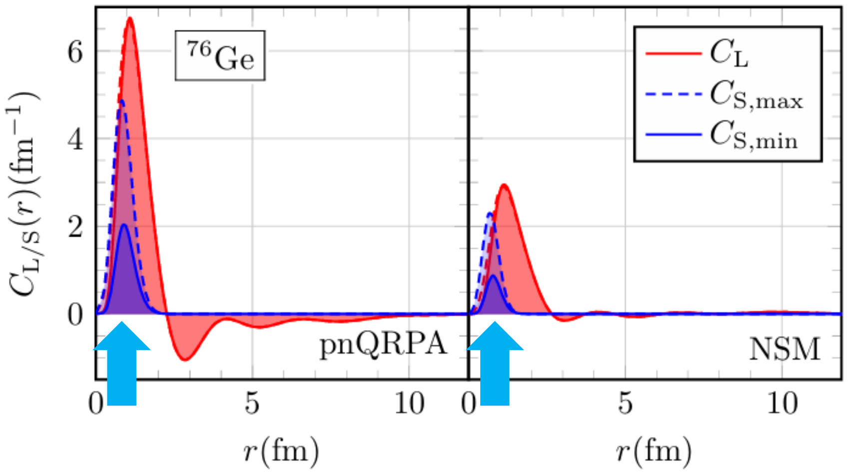


Λ_χ ~ GeV

Heavy Sterile Neutrinos

- 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)

Heavy Sterile Neutrinos

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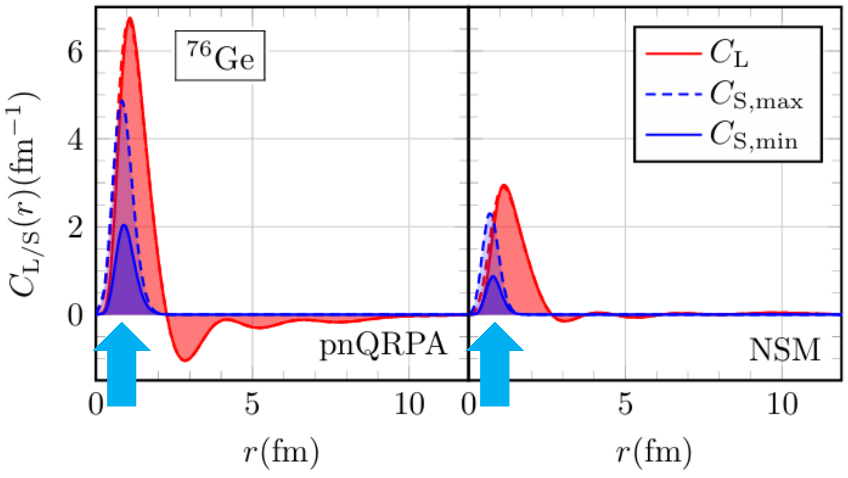


- Need **consistently SRG-evolve decay operator** alongside interaction – particularly **important for short-range operators!**
- Further need to regularize decay operator
  - We use a regulator consistent with the nuclear interaction* instead of the dipole regulator popular in literature

$$f_{\mathrm{dipole}}(\mathbf{q}) = \left(1 + \frac{\mathbf{q}^2}{\Lambda^2}\right)^{-2} \rightarrow f_{\mathrm{local}}^{\mathrm{NN}}(\mathbf{q}) = \exp\left[-\left(\frac{\mathbf{q}}{\Lambda}\right)^{2n}\right]$$

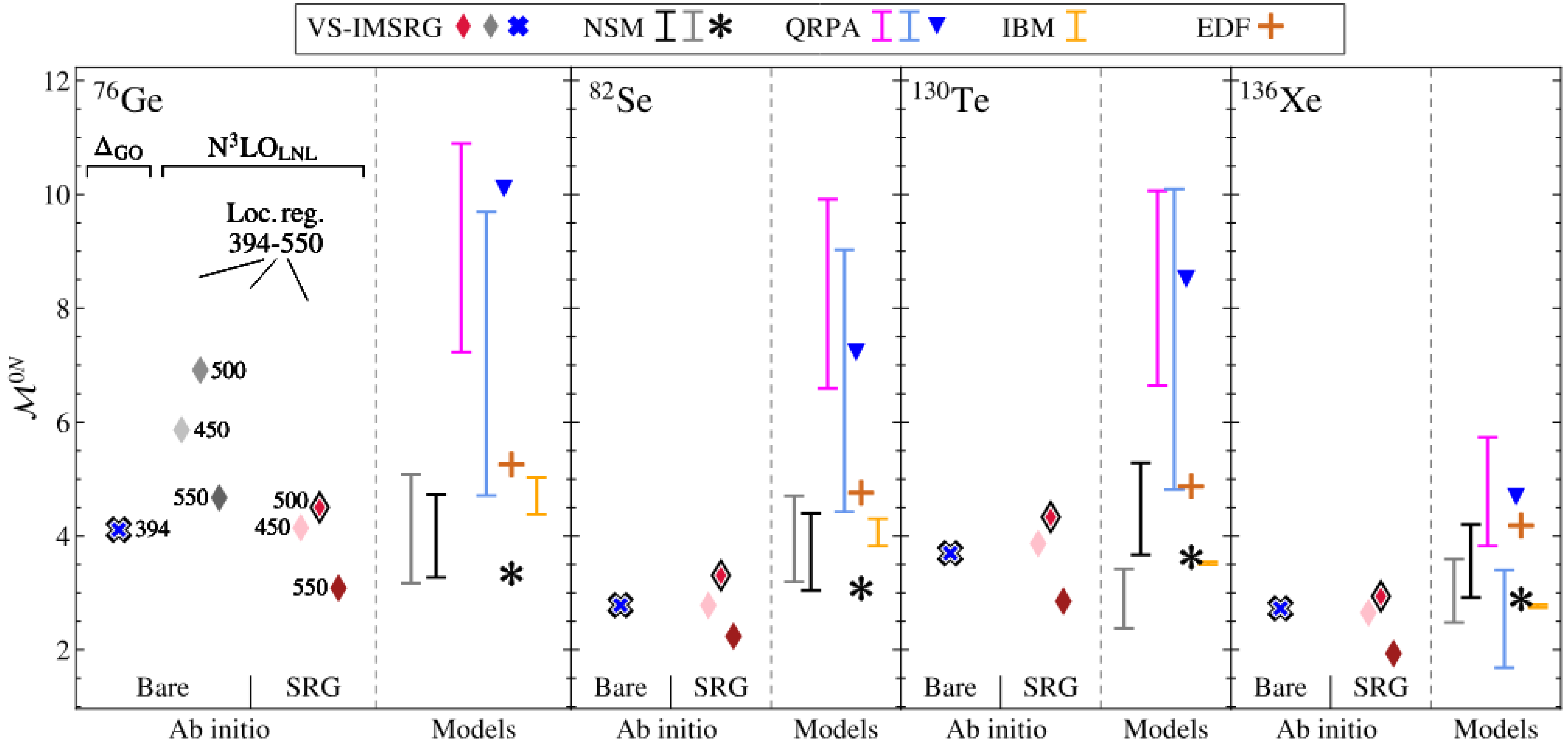
- Restrict to interactions consistently SRG evolved (or not) in both the NN and 3N sector

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

- 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

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

$$m_s \sim M_R^T$$

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

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

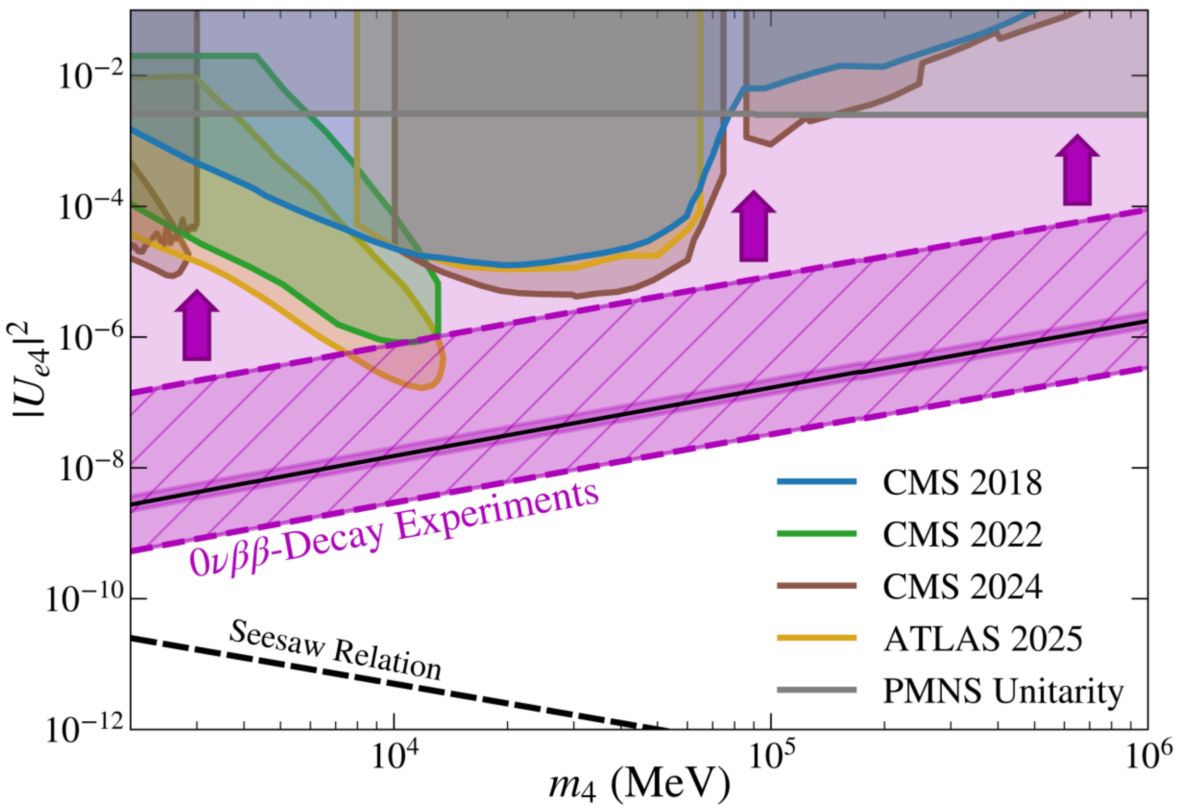
$$\left[T_{1/2}^{0\nu}\right]^{-1} = 4 g_A^4 G_{01} V_{ud}^4 \eta(\mu, m_4)^2 |U_{e4}|^4 \frac{m_\pi^4}{m_e^2 m_4^2} \times \left[\frac{5}{6} g_1^{\pi\pi} M_{\rm sd}^{\rm PP} + \frac{g_1^{\pi N}}{2} M_{\rm sd}^{\rm AP} + 2 g_1^{NN} M_{\rm F,sd}\right]^2$$

- 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 0vββ decay experiments leaves competitive constraints on $|U_{e4}|^2$
- Large uncertainty dominated by unknown LECs $g_1^{\pi\pi}$, $g_1^{\pi N}$ and g_1^{NN}
- Potential for LQCD to provide much needed LEC input ($g_1^{\pi\pi}$ already has some determinations)



$$\left[T_{1/2}^{0\nu}\right]^{-1} = 4g_A^4 G_{01} V_{ud}^4 \eta(\mu, m_4)^2 |U_{e4}|^4 \frac{m_\pi^4}{m_e^2 m_4^2}$$

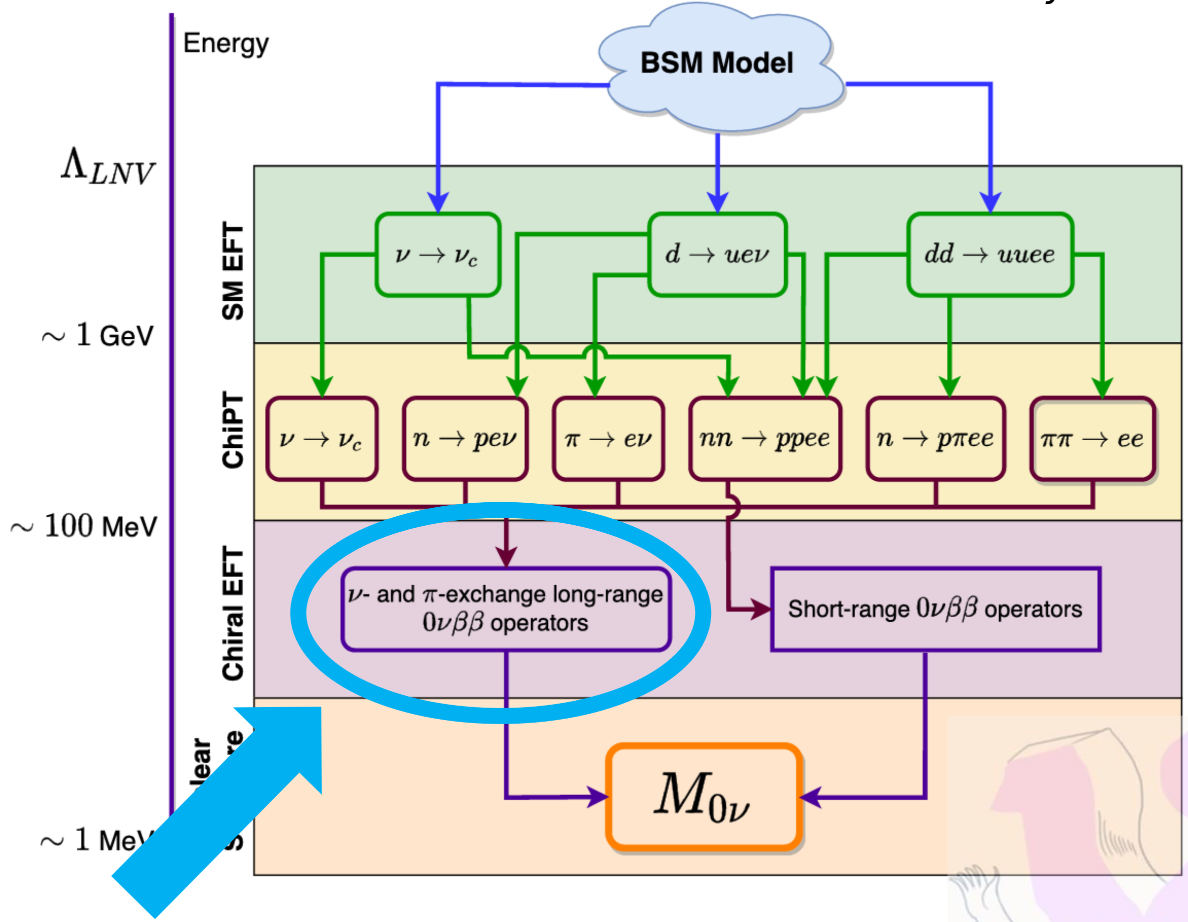
$$\times \left[\frac{5}{6} g_1^{\pi\pi} M_{\rm sd}^{\rm PP} + \frac{g_1^{\pi N}}{2} M_{\rm sd}^{\rm AP} + 2 g_1^{NN} M_{\rm F,sd}\right]^2$$

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

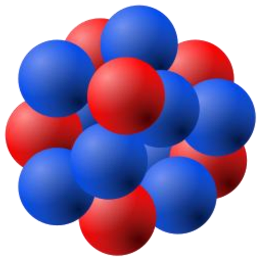
V Cirigliano *et al* 2022 *J. Phys. G: Nucl. Part. Phys.* **49** 120502

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

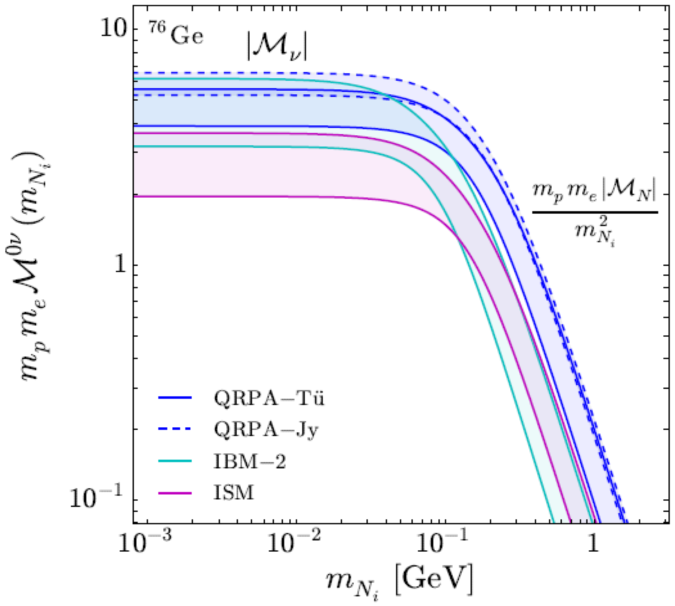


Light Sterile Neutrinos

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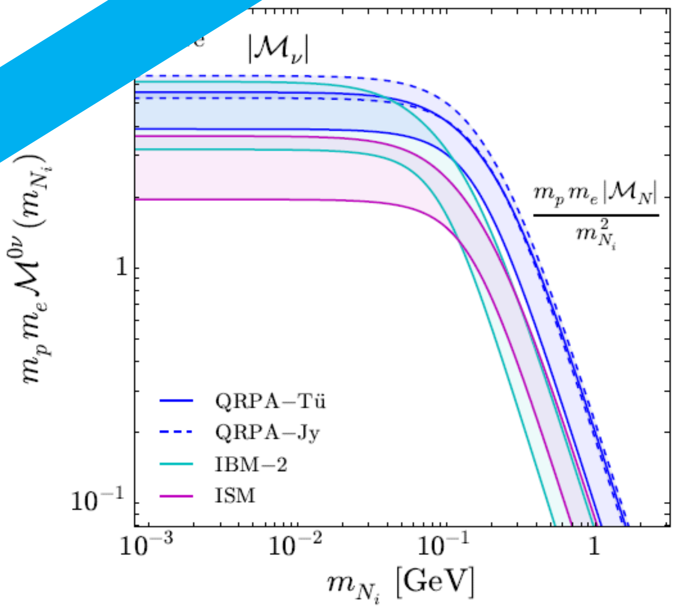
Bolton, P.D., Deppisch, F.F. & Dev, P.B., J. High Energ. Phys., 170 (2020)

- 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 also exist…

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

Light Sterile Neutrinos

- B
  a in
  st

- P
  in
  p
  t...

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

LO

N^2LO

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

m_{N_i} [GeV]

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

Light Sterile Neutrinos

- B… a… in st…
- P… in… p… t…

Interpolation formula only estimates this contribution

$$M^{0\nu}(m_s) = M^{0\nu}_{F}(m_s) + M^{0\nu}_{GT}(m_s) + M^{0\nu}_{T}(m_s) \quad \text{LO}$$

$$- 2g^{NN}_{\nu}(m_s)M^{0\nu}_{CT}$$

$$+ M^{0\nu}_{usoft}(m_s) \quad \text{N}^2\text{LO}$$

$$+ M^{0\nu}_{loop}(m_s)$$

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

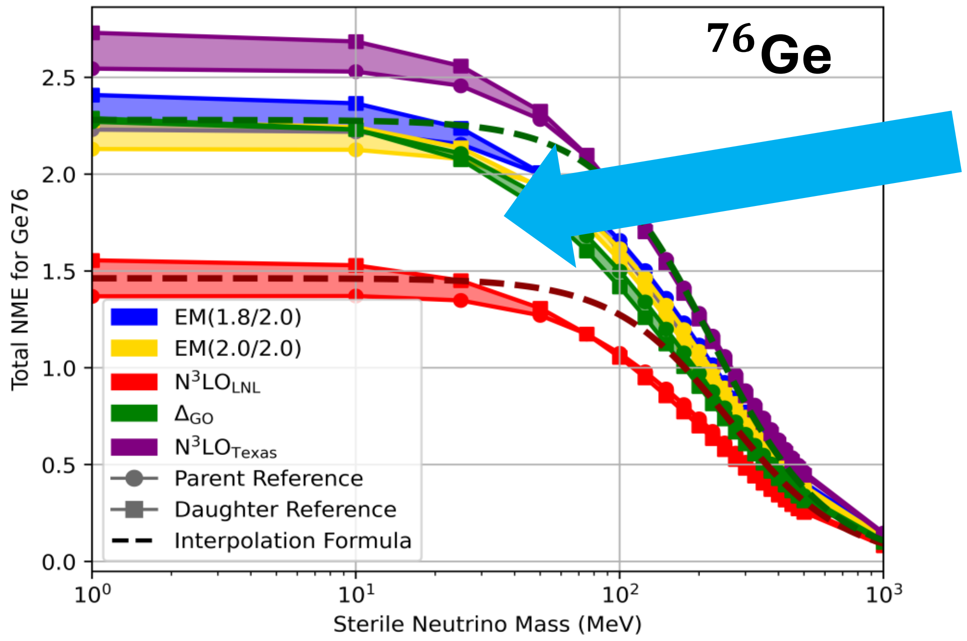
10^{-3} 10^{-2} 10^{-1} 1

m_{N_i} [GeV]

Leading Order Light Sterile Neutrino NMEs

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

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



w/o contact term

Large spread from a selection of a few optimized interactions!

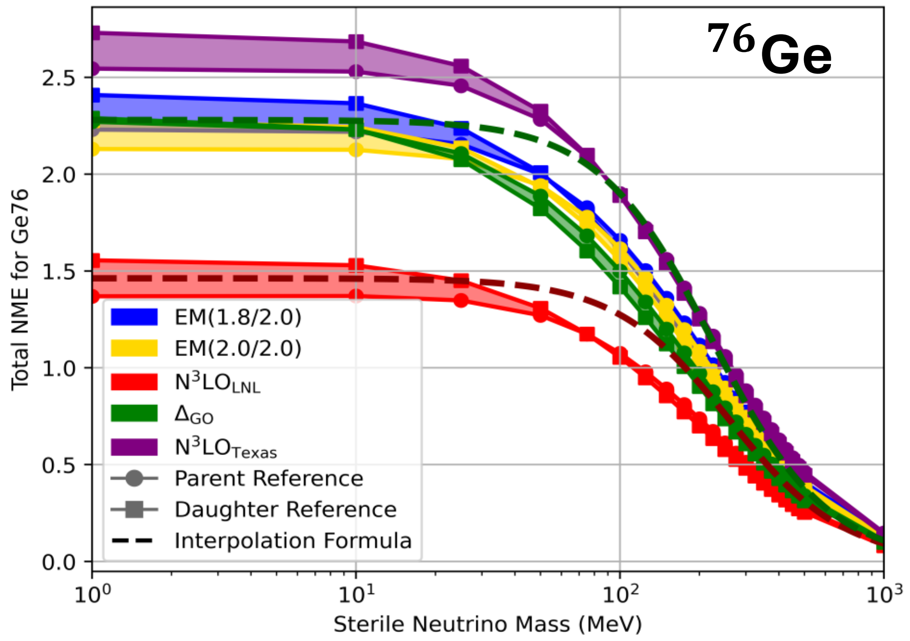
Cirigliano, V., Dekens, W. & Quiroga, S.U., J. High Energ. Phys. 2025, 181 (2025)

Leading Order Light Sterile Neutrino NMEs

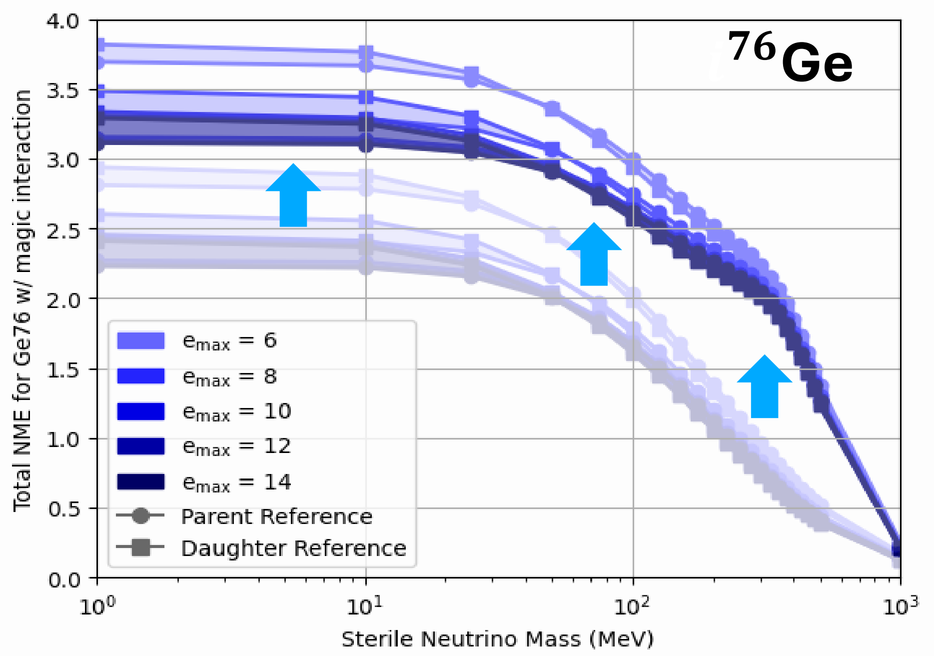
- NMEs for the standard long-range components explicitly depend on m_s

- Contact term has a m_s dependent LEC $g_\nu^{NN}(m_s)$
- Matching of LEC across schemes in progress

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



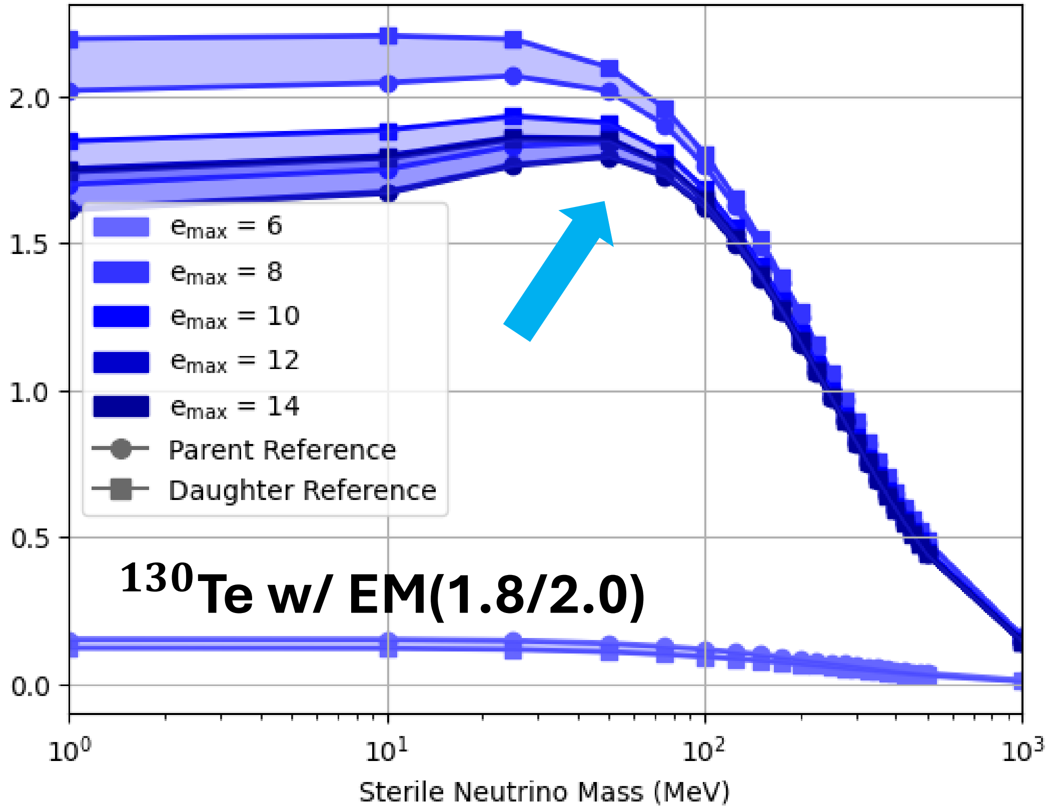
w/o contact term

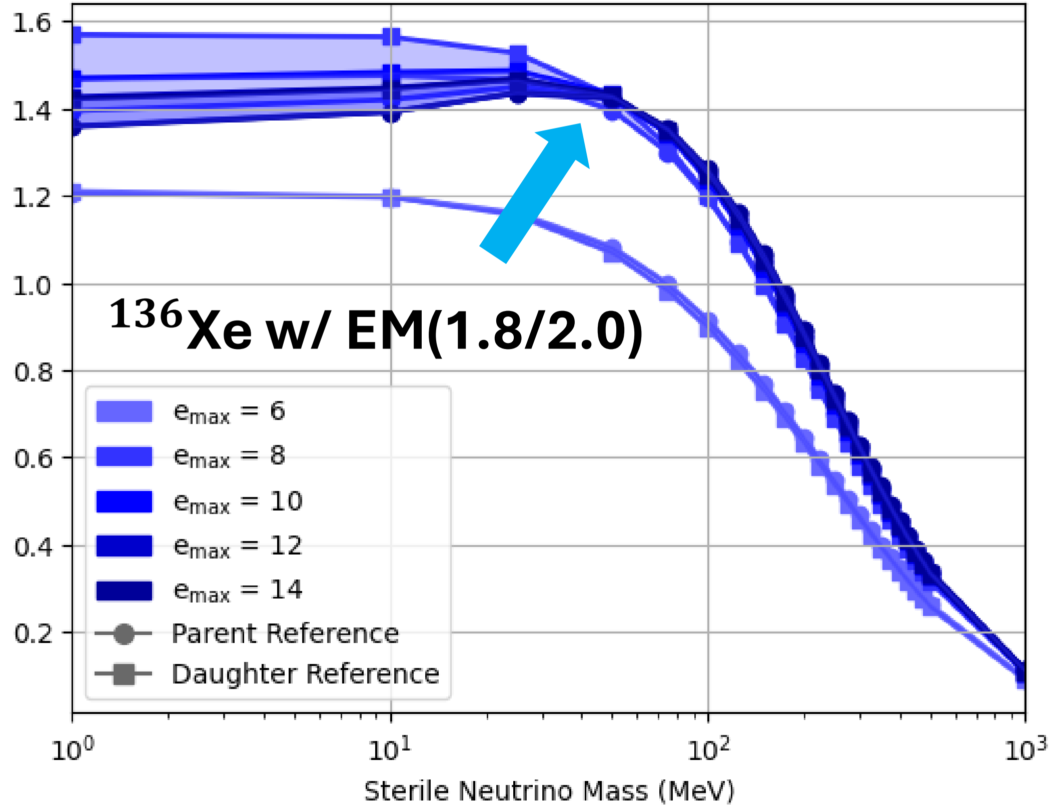


w/ contact term

Issues in Heavy Nuclei

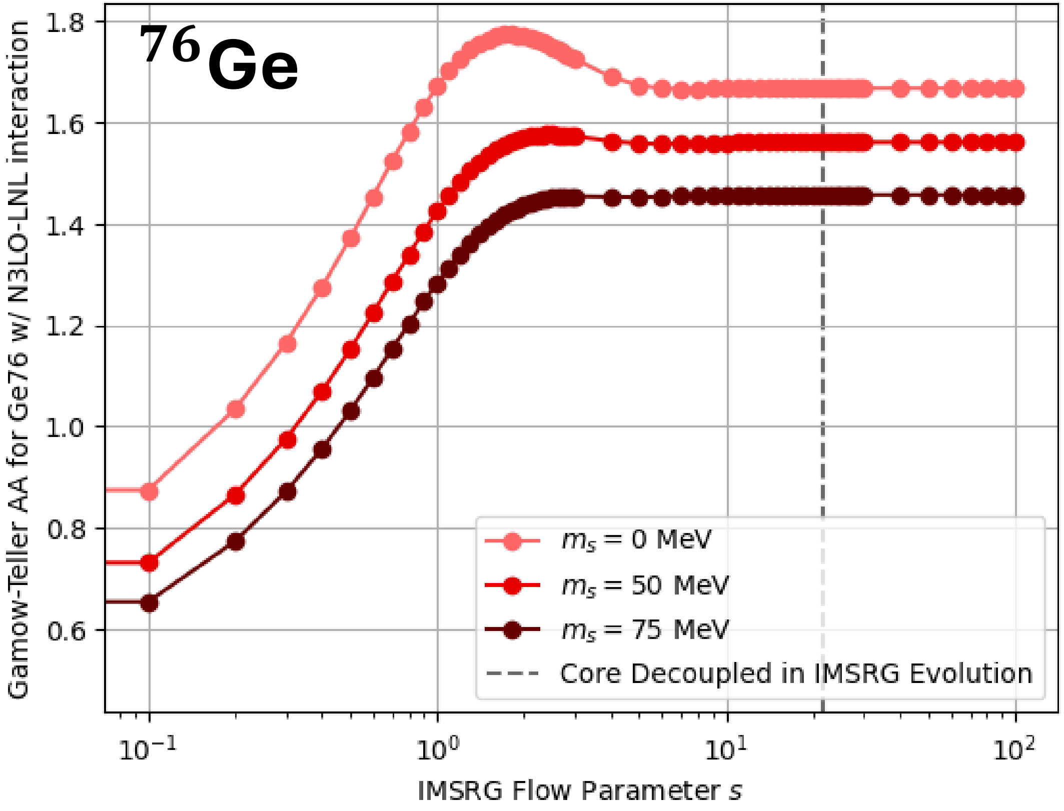
- Unphysical "bump" present in the NMEs for ^{130}Te and ^{136}Xe around 50 MeV
  - ➢ What could be the possible causes? Does not seem to be the interaction?

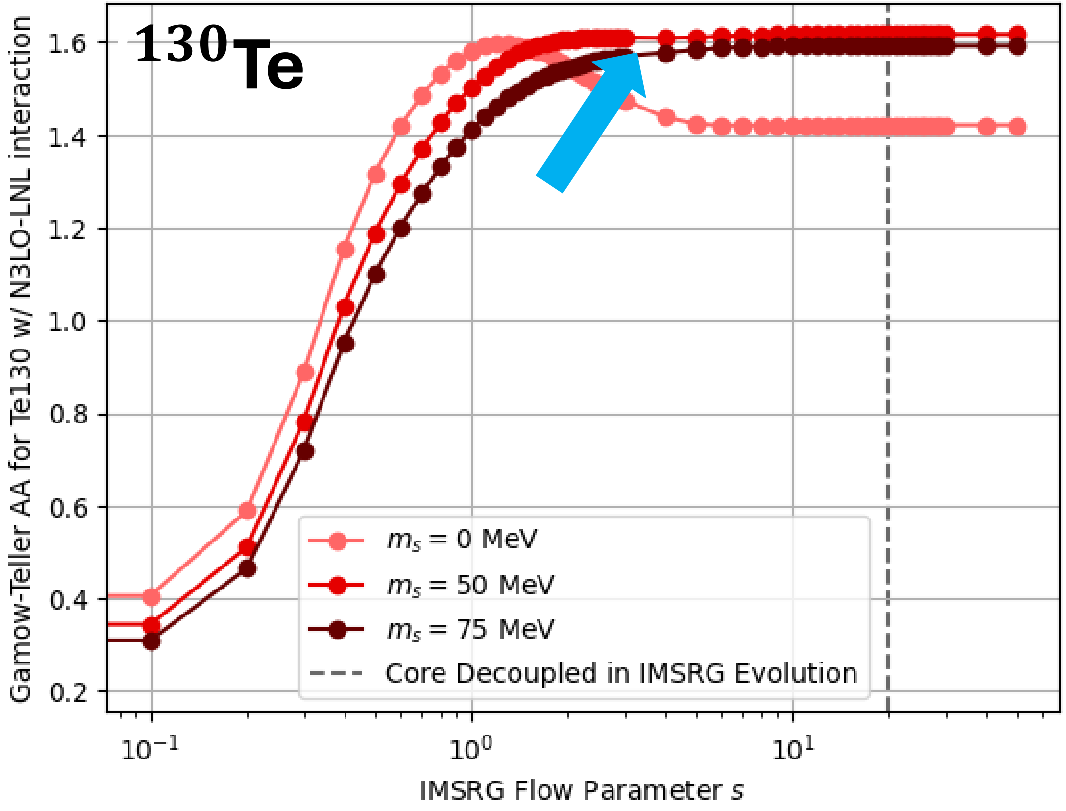




Culprit: Induced Higher-Body Operators

- 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 (not captured at 3f2 level)





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

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

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

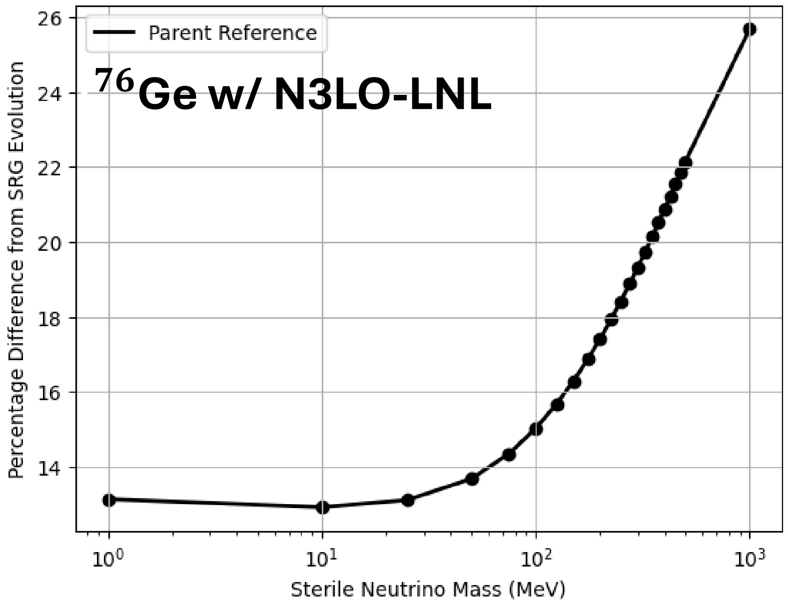
SRG Evolution of Light Sterile Neutrino NMEs

- 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

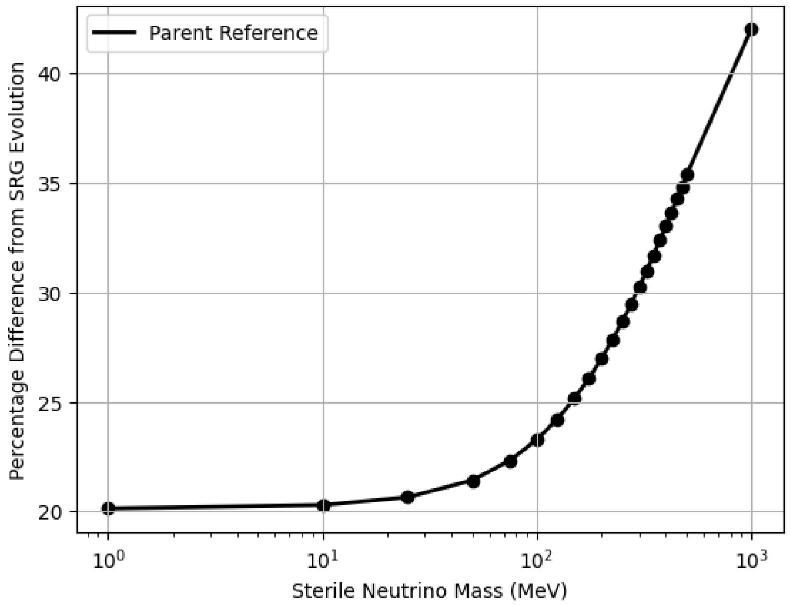
$$M^{0\nu}(m_s) = M_F^{0\nu}(m_s) + M_{GT}^{0\nu}(m_s) + M_T^{0\nu}(m_s)$$

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

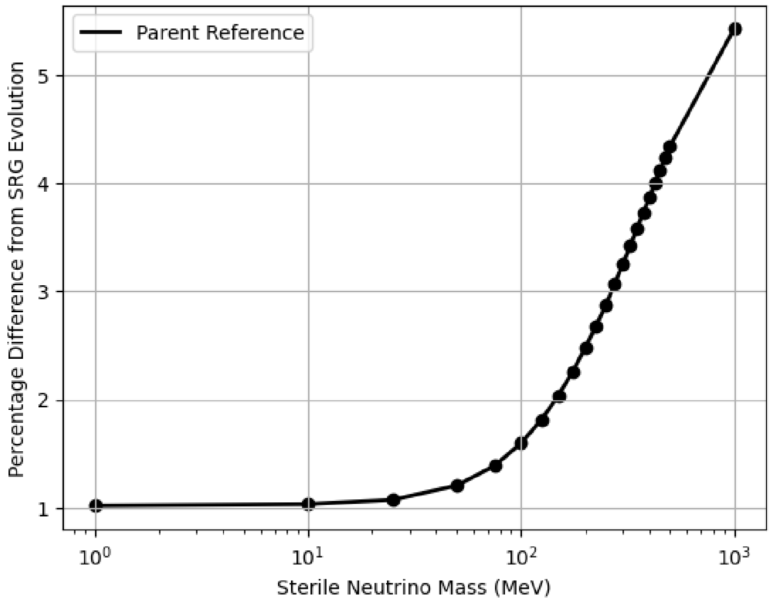
Fermi (10-30%)



Gamow-Teller (20-45%)



Tensor (1-5%)

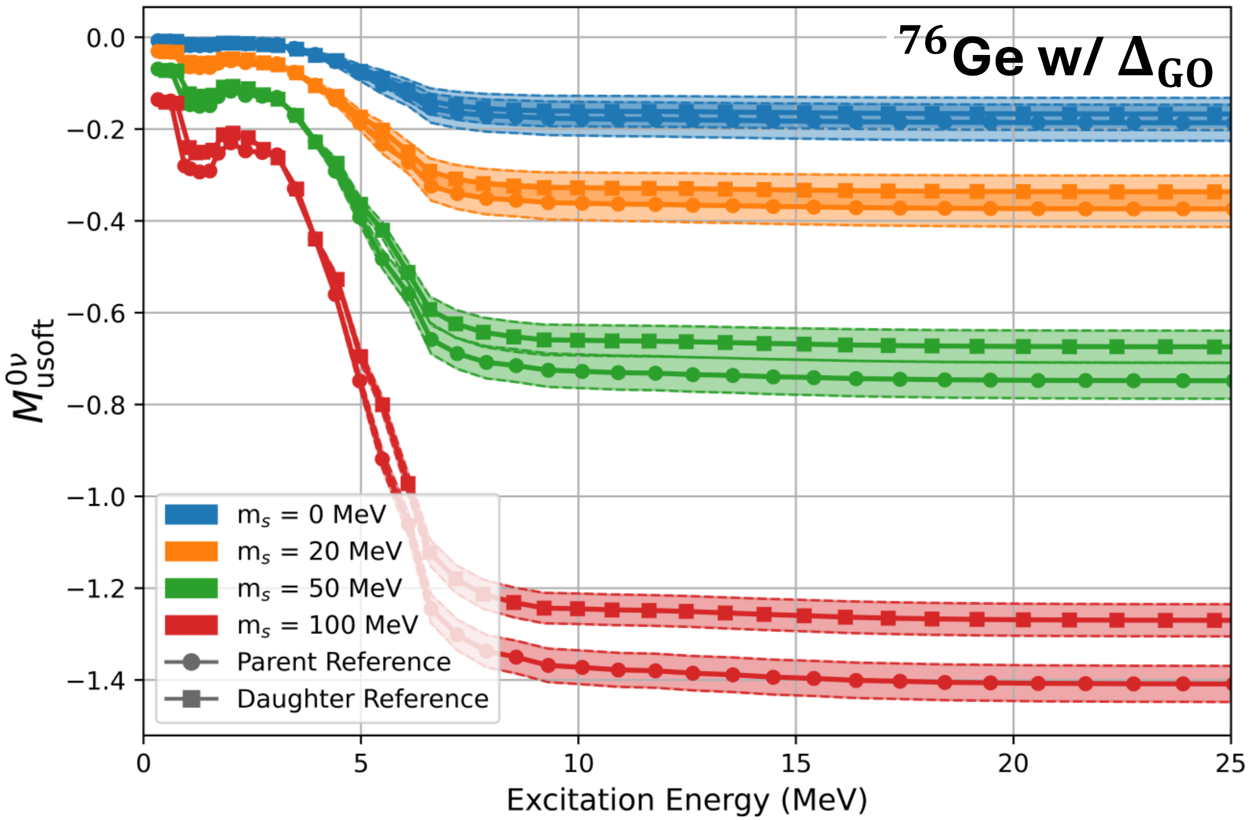


N^2LO Ultrasoft Contributions

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

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

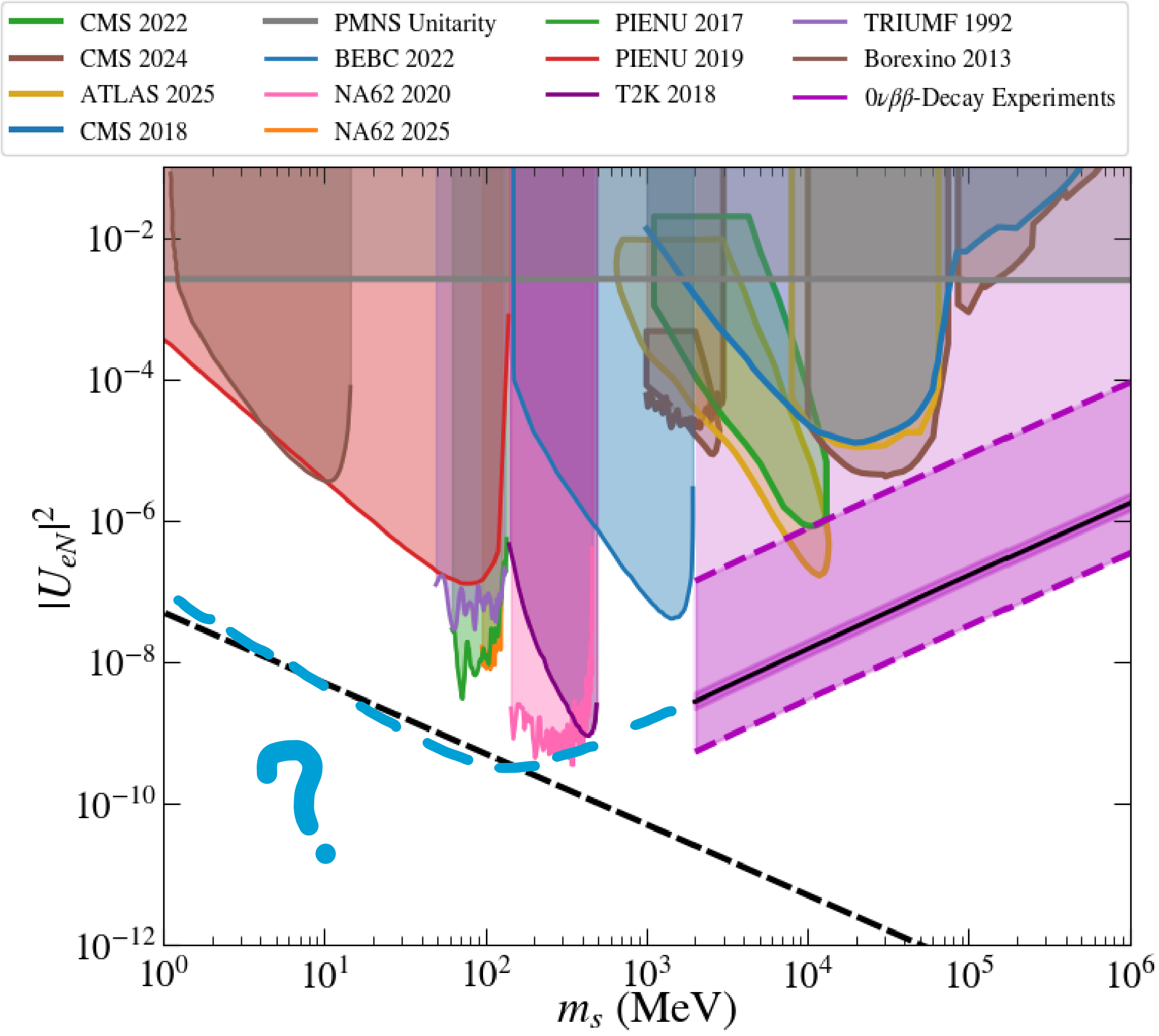
- Interaction dependence to be studied – difficult to quantify uncertainties



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

Next Steps

- Perform matching to account for scale and scheme dependence of leading-order contact LEC $g_\nu^{NN}(m_s)$
- Calculation N^{2}LO loop contributions
  - More LECs ($g_\nu^{\pi\pi}$ and $g_\nu^{\pi N}$) also enter
- Analyze IMSRG(3f2) results which incorporate effects of intermediate three-body operators during the IMSRG evolution



Thoughts on Open Challenges

- BSM observables exacerbate the need to quantify uncertainties from Hamiltonians
  - Interactions seen to perform "well" in certain observables – not guaranteed to do so here $\Rightarrow$ Bayesian UQ
  - Wishlist: A family of consistent NN + 3N forces and currents, order-by-order with different cutoffs?
- How can we better interface with the LQCD community to utilize lattice input on LECs for BSM searches?
  - $0\nu\beta\beta$ decay
  - Super-allowed beta decays
  - Symmetry violation
  - …

Special thanks to:

Alex Todd, Antoine Belley, Lotta Jokiniemi, Frank Deppisch, Wouter Dekens, Vincenzo Cirigliano and Jason Holt