

# Sterile Neutrino Contributions to Neutrinoless Double- beta Decay

Taiki Shickele

Collaborators:

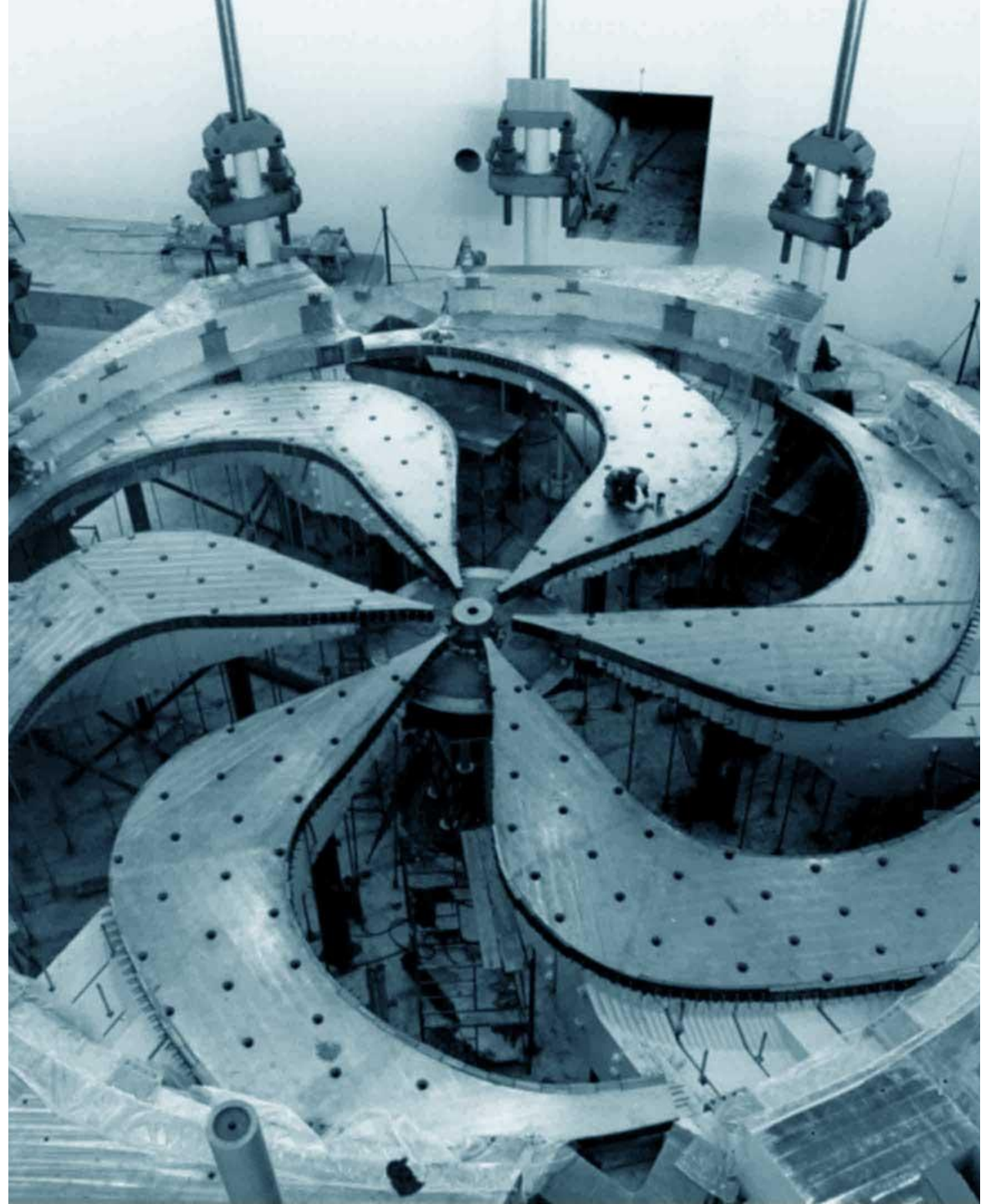
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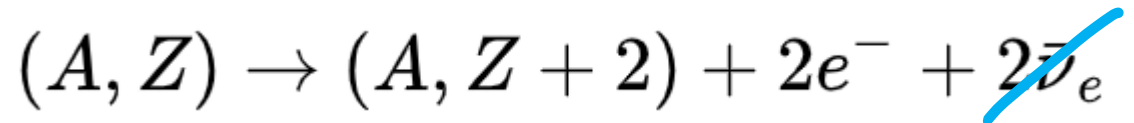
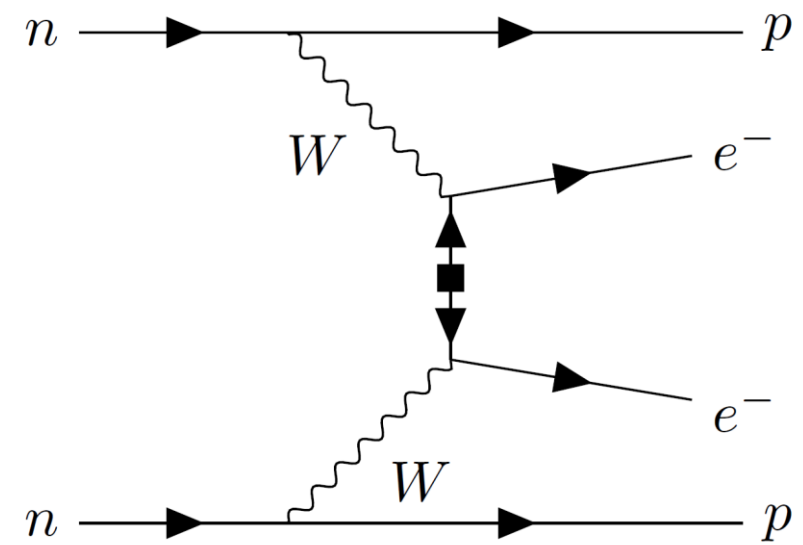
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# Neutrinoless Double-beta ( $0\nu\beta\beta$ ) Decay

- Requires the neutrino to be Majorana
- Lepton-number violating
  - Baryon asymmetry of the universe
- Half-life for light neutrino exchange:

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

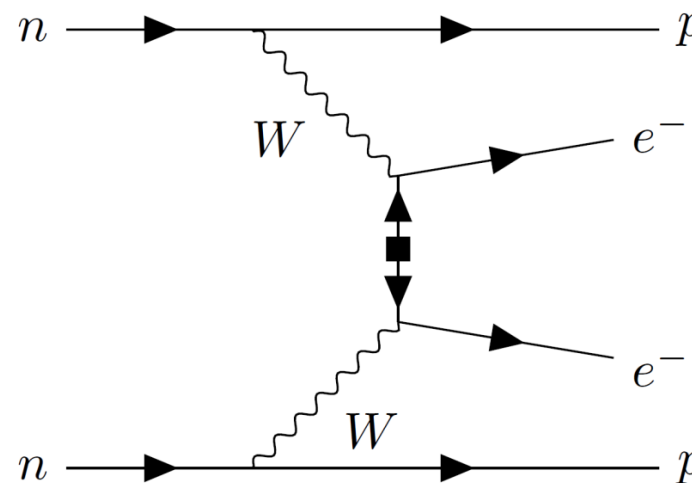
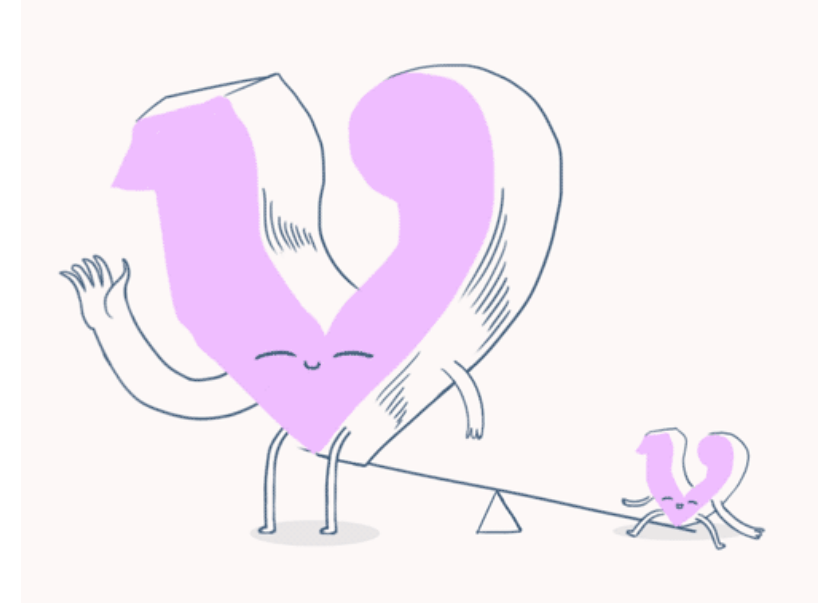


# Sterile Neutrinos in $0\nu\beta\beta$ Decay

- Seesaw mechanisms can explain Majorana neutrinos w/ sterile neutrinos
- Possible non-negligible contribution to  $0\nu\beta\beta$  from light sterile neutrinos

$$T_{1/2}^{-1} \propto \left| \sum_{i=1}^3 U_{ei}^2 m_i M^{0\nu} + \sum_{i=1}^{n_s} V_{esi}^2 m_{s_i} M^{0\nu}(m_{s_i}) \right|^2$$

- Typically, only standard mechanism ( $m_s \rightarrow 0$ ) and heavy sterile neutrino ( $m_s \gg 1 \text{ GeV}$ ) contributions considered

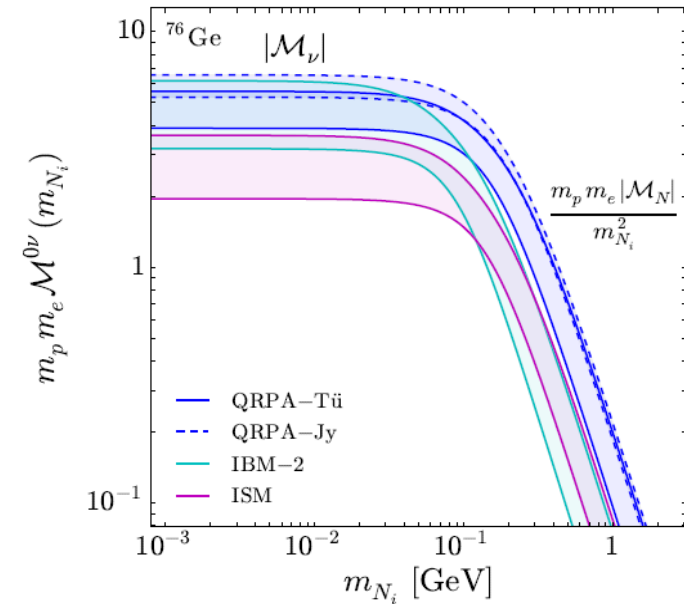


Mitra et al. Nucl Phys B **856**  
(2012)  
Sandbox Studio, Chicago with  
Ana Kova, Symmetry  
Magazine (2016)

# Nuclear Matrix Elements (NMEs) for Sterile Neutrino Contributions

- New matrix elements depend on sterile neutrino mass  $m_s$
- Mass dependence previously **estimated** w/ interpolation formula using phenomenological light and heavy NMEs

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



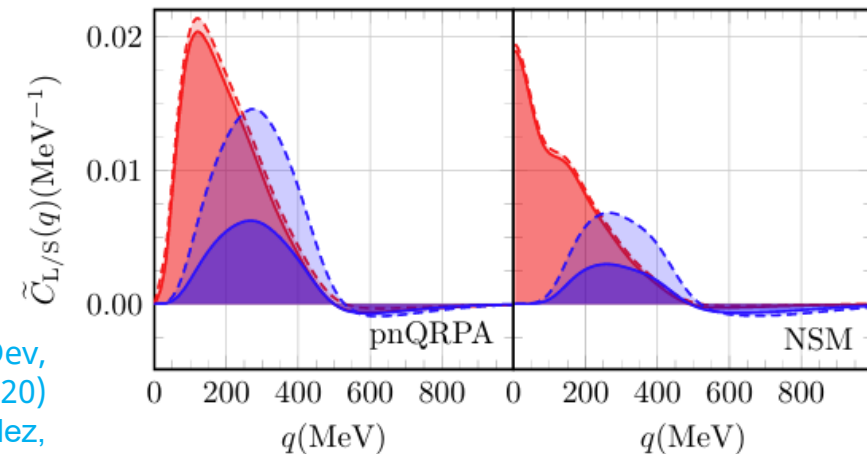
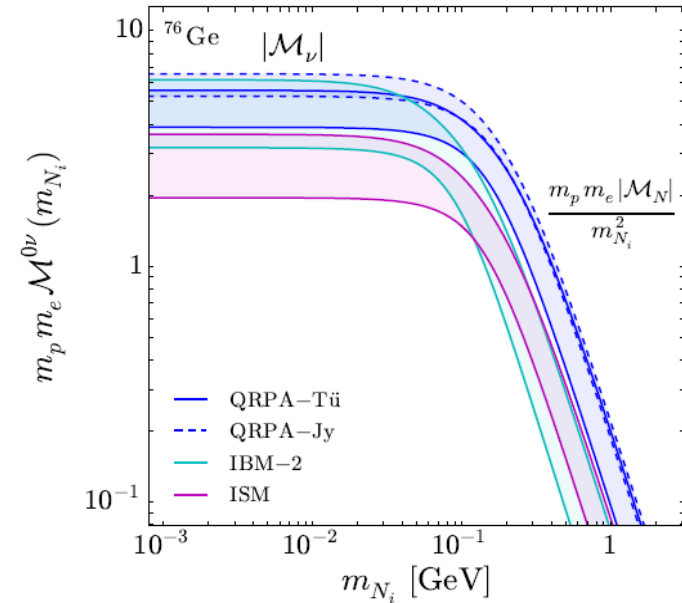
# Nuclear Matrix Elements (NMEs) for Sterile Neutrino Contributions

- New matrix elements depend on sterile neutrino mass  $m_s$
- Mass dependence previously **estimated** w/ interpolation formula using phenomenological light and heavy NMEs

$$M^{0\nu}(m_s) \approx \frac{M_H^{0\nu}}{m_p m_e \frac{M_H^{0\nu}}{M_L^{0\nu}} + m_s^2} \quad \longrightarrow \quad V_\alpha(q) = \frac{2R_A}{\pi} \frac{h_\alpha(q^2)}{q^2 + E_c \sqrt{q^2 + m_s^2} + m_s^2}$$

- Intermediate region  $\sim 100$  MeV consists of most of the NME contribution
- Overlooks contact and higher-order contributions from  $\chi$ EFT

Bolton, P.D., Deppisch, F.F. & Dev, P.B., J. High Energy. Phys., 170 (2020)  
 Jokiniemi, L., Soriano, P., Menendez, J., PLB 823 10 (2021)



Interpolation formula only  
 “captures” this contribution

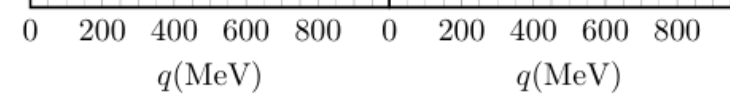
$$M^{0\nu}(m_s) = \underbrace{M_F^{0\nu}(m_s) + M_{GT}^{0\nu}(m_s) + M_T^{0\nu}(m_s)}_{\text{LO}} - 2g_\nu^{NN}(m_s)M_{CT}^{0\nu} \\
 + M_{usoft}^{0\nu}(m_s) \quad \text{N}^2\text{LO} \\
 + M_{loop}^{0\nu}(m_s)$$

$M^{0\nu}$

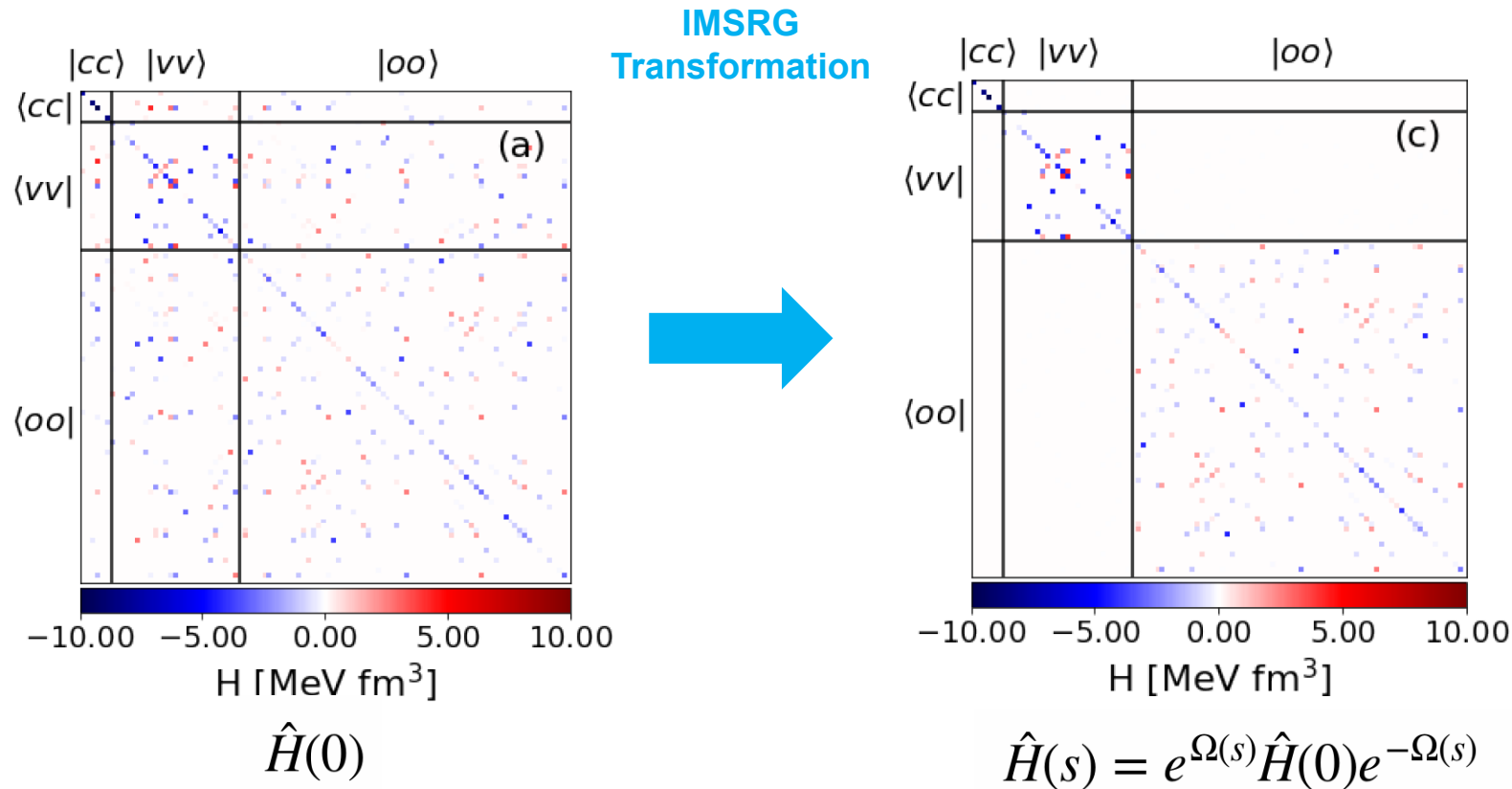


CONTRIBUTIONS FROM  $\chi$ EFT

Botton, P.B., Deppisch, M. & DeV, P.B., J. High Energy. Phys., 170 (2020)  
 Jokiniemi, L., Soriano, P., Menendez, J., PLB 823 10 (2021)



# The VS-IMSRG

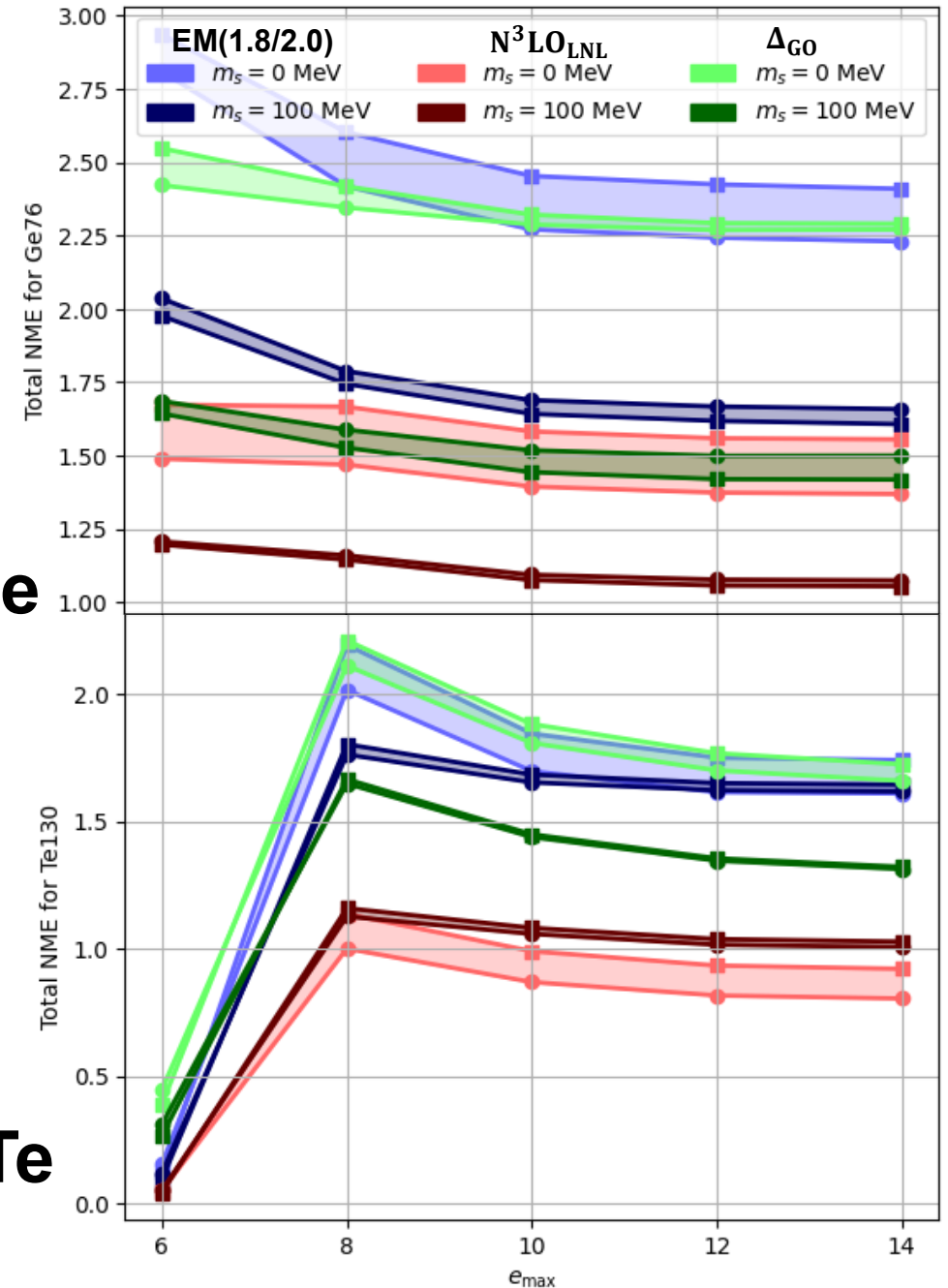


- Normal-order w/ respect to initial/final nuclear state
- Apply the IMSRG transformation to decouple the core, valence and excluded space
- Calculations w/ IMSRG(2) (talk to me at the poster and see Alex's talk about IMSRG(3f2))

# $e_{\max}$ Convergence

- NMEs calculated for  $^{76}\text{Ge}$ ,  $^{130}\text{Te}$ , and  $^{136}\text{Xe}$  using the EM(1.8/2.0),  $N^3\text{LO}_{\text{LNL}}$  and  $\Delta_{\text{GO}}$  interactions
- Convergence in  $e_{\max}$  reached for all  $m_s$  values at  $E_{3\max} = 24$
- Bands represent uncertainty from choice of reference state

$^{76}\text{Ge}$

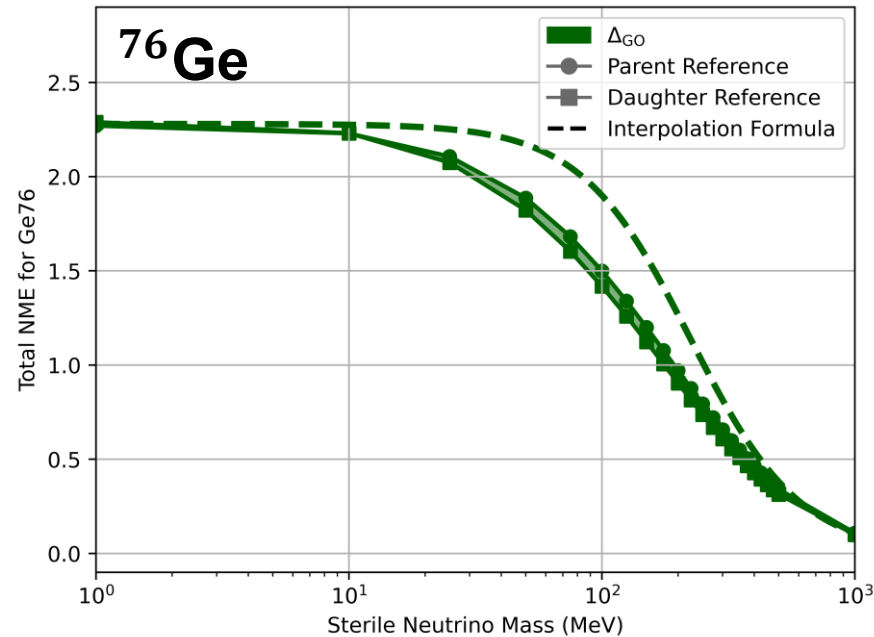


$^{130}\text{Te}$

# Leading Order NMEs

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

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

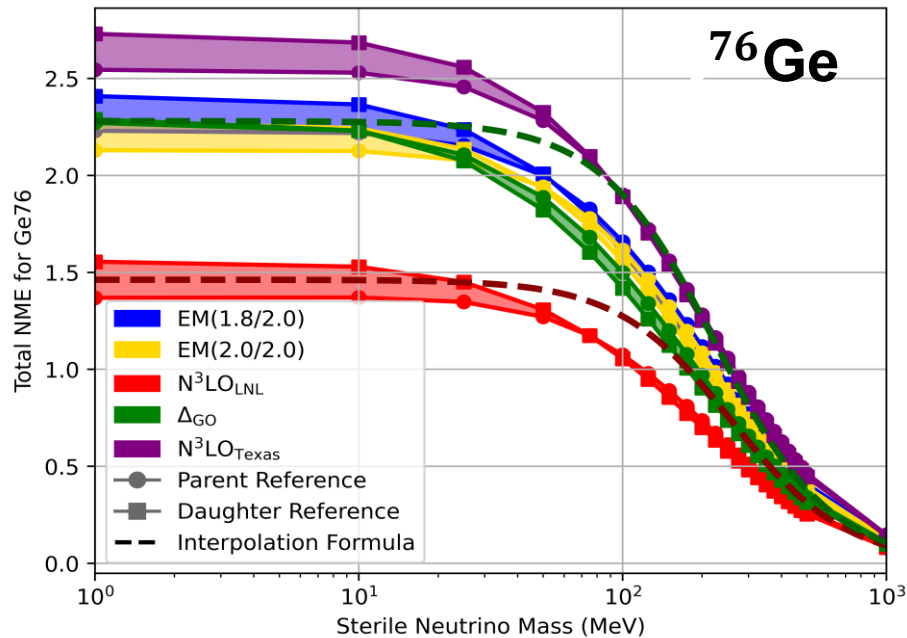


w/o contact term

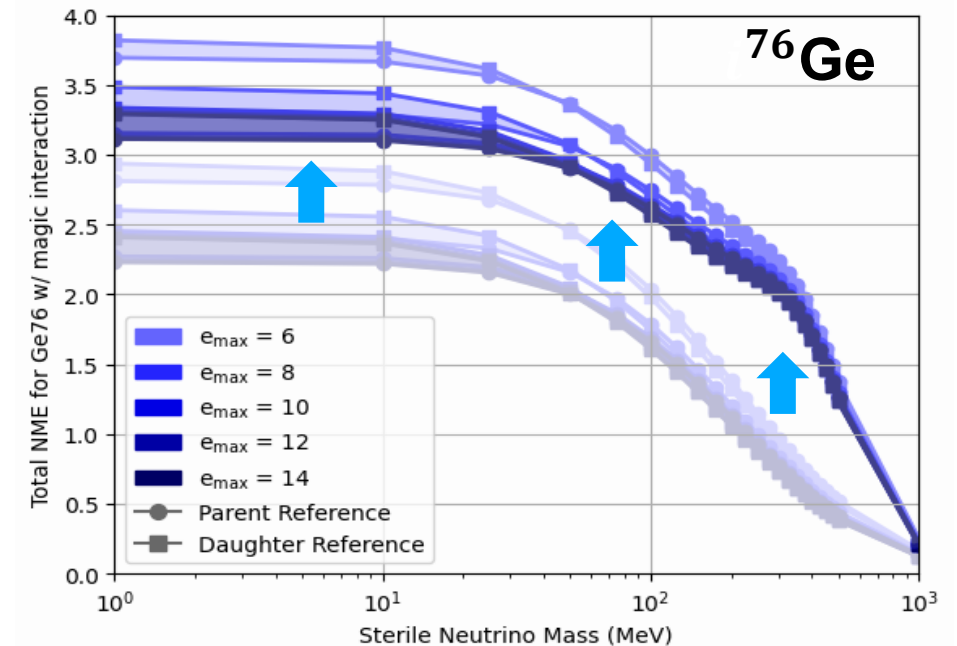
# Leading Order NMEs

- NMEs for the standard long-range components explicitly depend on  $m_s$
- Contact term has a  $m_s$  dependent LEC  $g_\nu^{NN}(m_s)$  (see Cirigliano et al. 2025)

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



w/o contact term



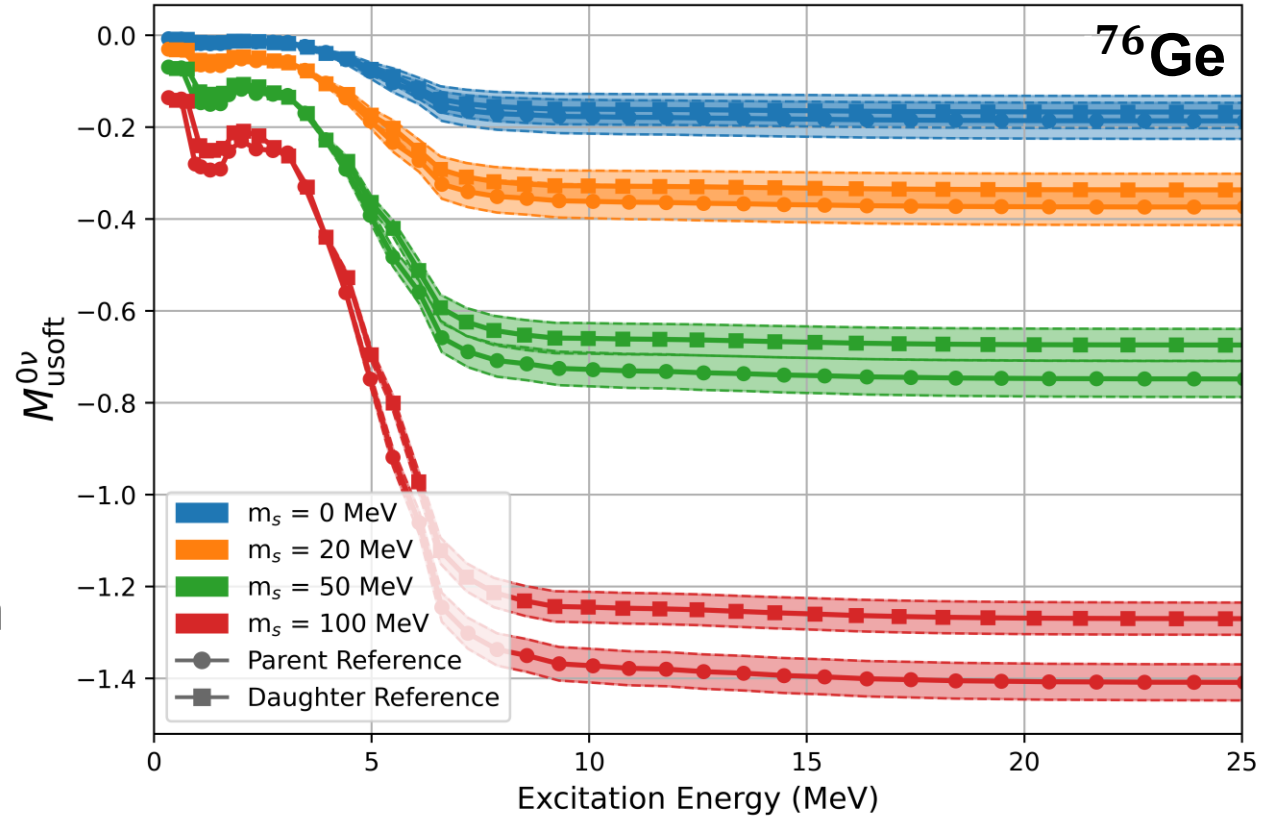
w/ contact term

# N<sup>2</sup>LO Ultrasoft Contributions

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

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

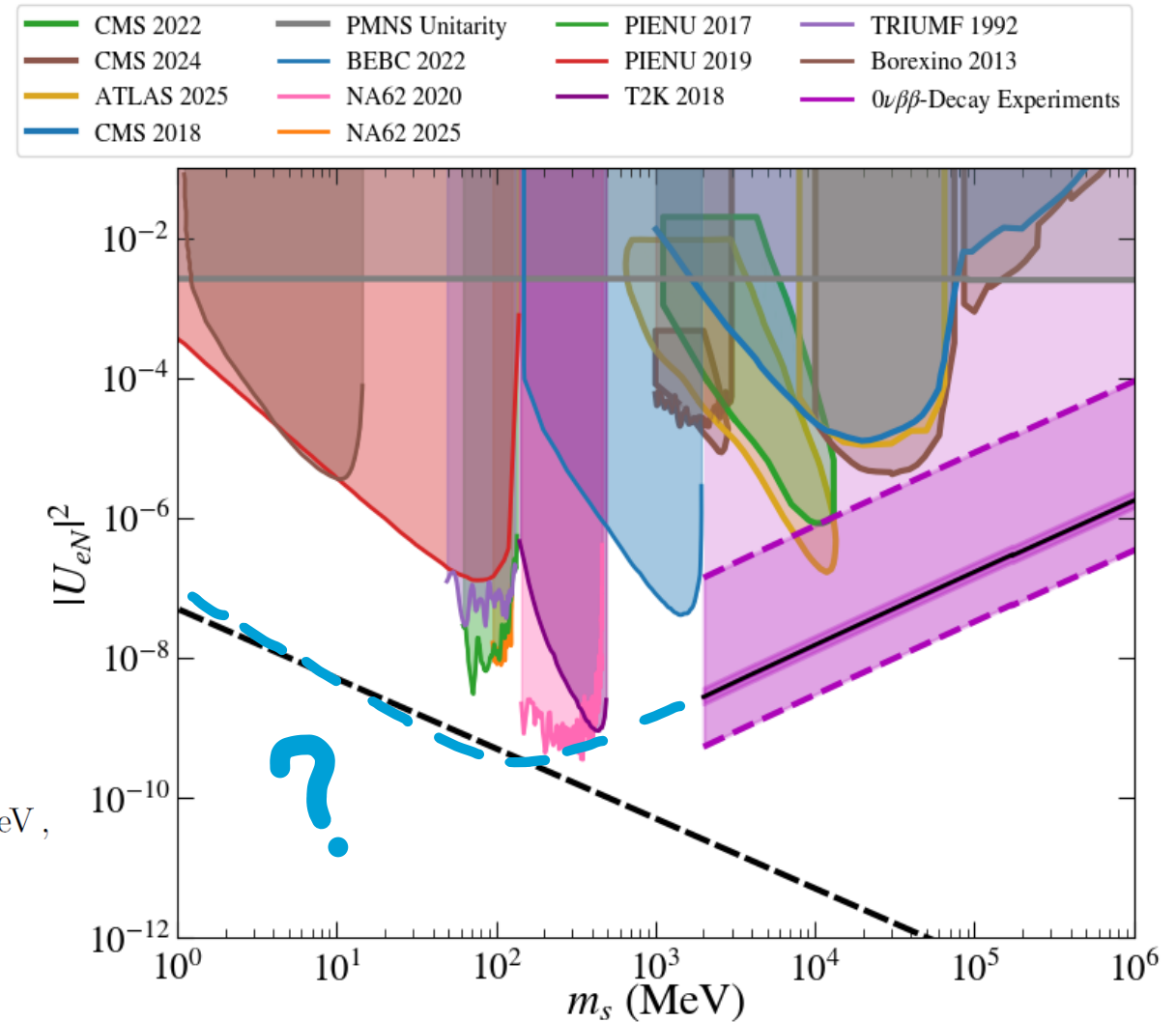
- Roughly linear dependence of  $M_{\text{usoft}}^{0\nu}$  on  $m_s$  in contrast to leading order case



# Next Steps

- Limits on the sterile neutrino mixing can be derived from  $0\nu\beta\beta$ -decay experimental limits
- Extension of constraints to  $m_s \leq 2$  GeV using the NMEs calculated in progress

$$A_\nu(m_i) = \begin{cases} A_\nu^{(\text{pot}, <)}(m_i) + A_\nu^{(\text{hard})}(m_i) + A_\nu^{(\text{usoft})}(m_i), & m_i < 100 \text{ MeV}, \\ A_\nu^{(\text{pot})}(m_i) + A_\nu^{(\text{hard})}(m_i), & 100 \text{ MeV} \leq m_i < 2 \text{ GeV}, \\ A_\nu^{(9)}(m_i), & 2 \text{ GeV} \leq m_i. \end{cases}$$



# Thank you!

## Conclusions

- 0νββ decay can have a significant contribution arising from sterile neutrinos
- Calculations of  $m_s$ -dependence suggest deviation from interpolation formula

## Outlook

- Implementation of N<sup>2</sup>LO soft neutrino contribution
- Limits on sterile neutrino mixing parameter space for the light mass regime
- Inclusion of IMSRG(3f2) and SRG-evolved operator results into final NMEs

## Collaborators:

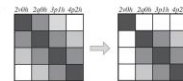
Lotta Jokiniemi, Antoine Belley, Frank Deppisch and Jason Holt

### Sterile Neutrino Contributions to Neutrinoless Double Beta Decay from Ab Initio Nuclear Theory

T. Shickel<sup>1,2</sup>, L. Jokiniemi<sup>2,4</sup>, A. Belley<sup>5</sup>, J.D. Holt<sup>1,6</sup>  
<sup>1</sup>TRIUMF, <sup>2</sup>University of British Columbia, <sup>3</sup>Technische Universität Darmstadt, <sup>4</sup>ExtreMe Matter Institute EMMI, GSI  
<sup>5</sup>Helmholtzzentrum für Schwerionenforschung GmbH, <sup>6</sup>Massachusetts Institute of Technology, <sup>6</sup>McGill University

#### Background

- Neutrinoless double-beta (0νββ) decay is a hypothetical decay involving the conversion of two neutrons into two protons and two electrons in the nucleus that probes:
  - The Majorana/Dirac nature of neutrinos
  - The observed baryon asymmetry of the universe through lepton number violation
- Typically, only light Majorana neutrino exchange is considered in the standard decay mechanism
- However, contributions from sterile neutrinos may be non-negligible and affect the decay rate
- Sterile neutrinos can also simultaneously explain the neutrino mass generation mechanism
- In this work, we study this within an *ab initio* (first principles) framework for the first time



#### The Nuclear Matrix Element

- We start with nuclear interactions and 0νββ decay operators derived within chiral effective field theory
- The valence space in-medium similarity renormalization group (VS-IMSRG) is used to solve the many-body problem by decoupling the Hamiltonian into a core and valence space through the continuous unitary transformation  $H = e^{iS} H_0 e^{-iS}$
- Diagonalizing the Hamiltonian leads to a NME consisting of Fermi (F), Gamow-Teller (GT) and Tensor (T) parts and a contact term (CT)

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

Previous studies relied on a simple interpolation formula instead of explicitly determining the dependence on the sterile neutrino mass

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

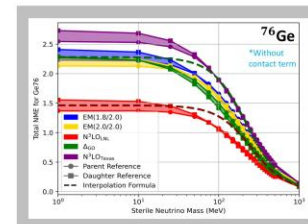
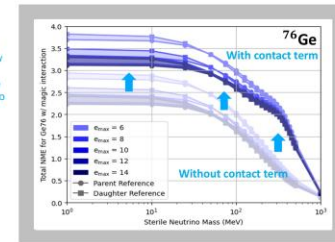


Fig. 1 Mass dependence of the sterile neutrino NME for <sup>76</sup>Ge. Results are shown in comparison to an interpolation formula (dashed lines) for several of the nuclear interactions, shown in different colours.

Fig. 2 Effect of contact NME  $M_{CT}^{0\nu}$  and associated low energy constant  $g_{NN}^{0\nu}(m_s)$  [4] on the total sterile neutrino NME.



#### Results

- Calculations for <sup>76</sup>Ge, <sup>130</sup>Te and <sup>136</sup>Xe NMEs show sharp drop after  $m_s \sim 50$  MeV
- Results show a slight plateau for  $m_s \sim 300$  MeV and overall  $\sim 30 - 40\%$  increase in the total NME.

#### N<sup>2</sup>LO Contributions

- At N<sup>2</sup>LO new contributions from so-called "ultrasoft" neutrinos enter when  $m_s < 100$  MeV

$$M_{N^2LO}^{0\nu} \propto \sum_n \langle 0_f | \sum_k \tau_k^i \sigma_k^j | 1_f \rangle \langle 1_f | \sum_k \tau_k^i \sigma_k^j | 0_i \rangle f(m_n, \Delta E_n)$$

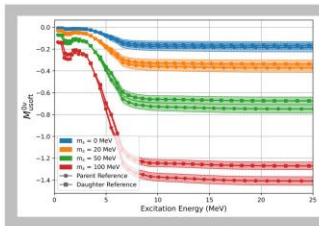


Fig. 3 Running sum of the ultrasoft NME for <sup>76</sup>Ge using the  $\Delta_{00}$  chiral interaction. Results are shown for a variety of sterile neutrino masses, with uncertainties due to the choice of many-body reference state and ultrasoft scale  $\mu_{ul}$ .

#### References

- [1] Dekens, W., de Vries, J., Casallo, D. et al. J. High Energy Phys. 2024, 201 (2024).
- [2] Cirigliano, V., Dekens, W., de Vries, J. et al. J. High Energy Phys. 2018, 97 (2018).
- [3] Bolton, P.D., Deppisch, F.F. & Dew, P.B. J. High Energy Phys. 2020, 170 (2020).
- [4] Cirigliano, V., Dekens, W. & Guadagnoli, S. U. J. High Energy Phys. 2025, 181 (2025).
- [5] Todd A. Shickel, T. Belley, A. Jokiniemi, L. & Holt, J. D. (in review)

#### Sterile Neutrino Mixing Constraints

- A complementary set of short-range NMEs contribute for  $m_s > 2$  GeV (see [5])
- Global 0νββ decay constraints on the sterile neutrino mixing assuming a type-1 seesaw mechanism competitive with collider experiments

$$(T_{1/2}^{0\nu})^{-1} = g_A^4 C^{0\nu} |V_{ud}|^4 |U_{eN}|^4 \frac{m^4}{m_s^2 m_2^2} M_{\text{decay}}^{0\nu} \mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & m_S \end{pmatrix}$$

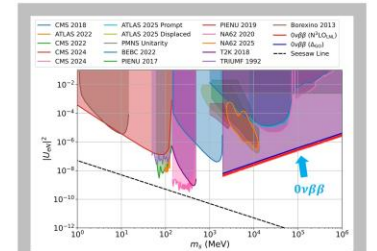


Fig. 4 Constraints on the sterile-electron neutrino mixing  $|U_{eN}|^2$  as a function of the sterile neutrino mass  $m_s$ . Limits from a combined global analysis of 0νββ decay experiments are shown for  $m_s > 2$  GeV. Results for the  $N^2LO_{EFT}$  and  $\Delta_{00}$  nuclear interactions are given in red and blue, respectively.

#### Conclusions

- Calculation of the sterile neutrino contributions to 0νββ decay for the first time using an *ab initio* method
- First *ab initio* calculation of N<sup>2</sup>LO ultrasoft corrections for both the standard and sterile neutrino-mediated 0νββ decay mechanisms

#### Outlook

- Implementation of additional "soft" neutrino contributions at N<sup>2</sup>LO underway
- Uncertainties from the many-body truncation, nuclear interaction and operator truncation yet to be fully quantified
- Constraints on sterile neutrino mixings for  $m_s \leq 2$  GeV in progress