# Ab Initio Nuclear Theory for Neutrinoless ββ Decay

Short-range Operators and Exotic Mechanisms

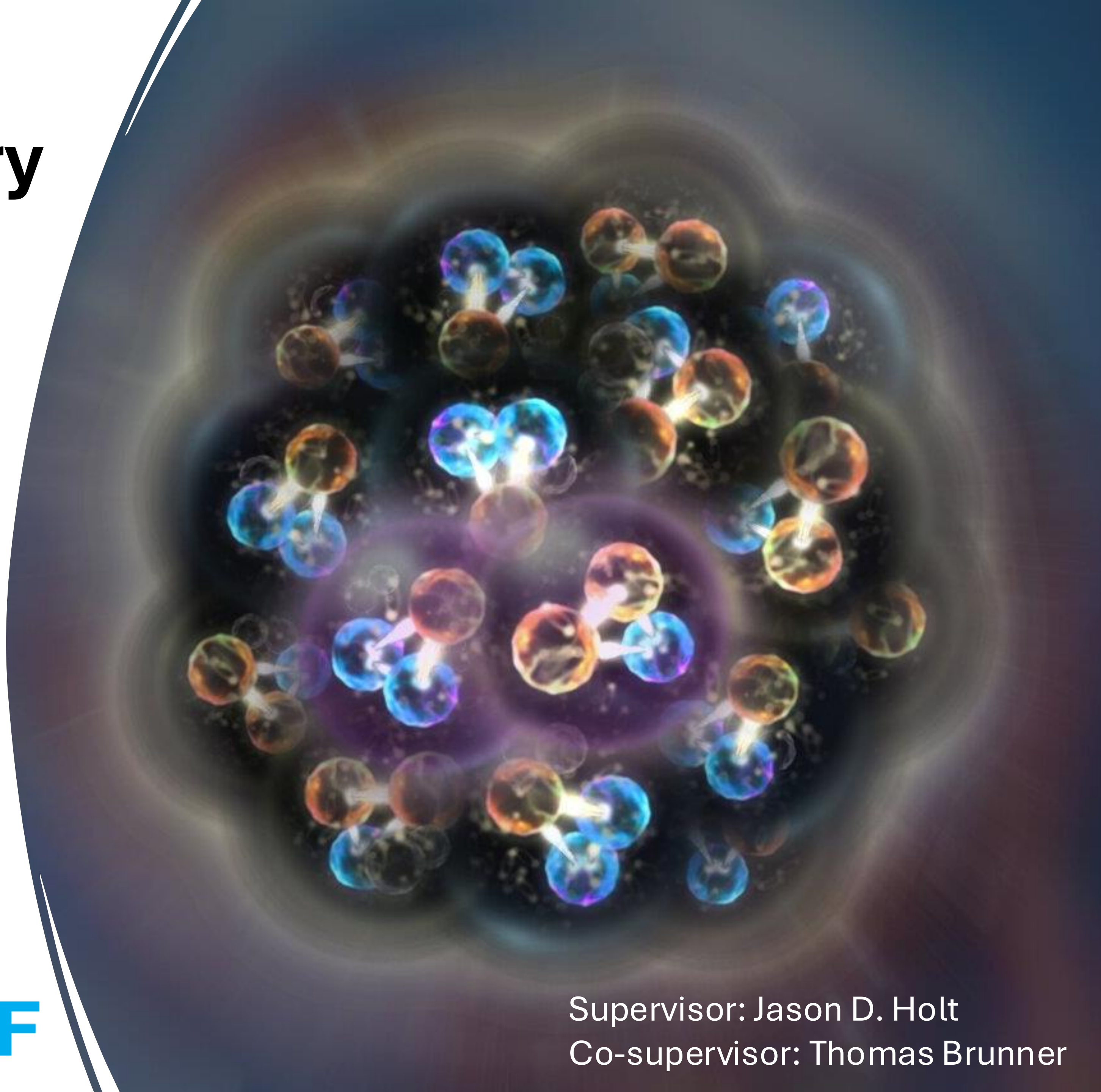
**Alex Todd** (McGill University)

CAP Congress 2026

McGill

Arthur B. McDonald Canadian Astroparticle Physics Research Institute

TRIUMF



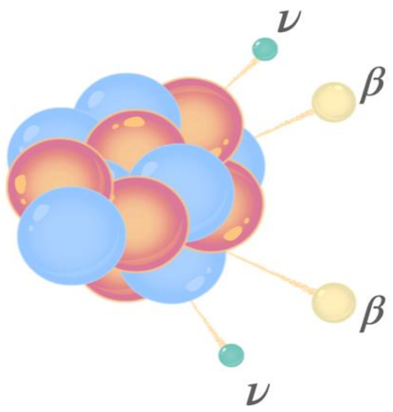
Supervisor: Jason D. Holt
Co-supervisor: Thomas Brunner

# What is neutrinoless ββ decay?

**0vββ probes:**

- Majorana/Dirac nature of neutrinos
- Lepton-number violation
  - ➢ Baryon asymmetry of universe
- Absolute neutrino mass scale
- Exotic BSM mechanisms
  - ➢ Heavy neutrinos? Seesaw mechanisms? Sterile neutrinos?

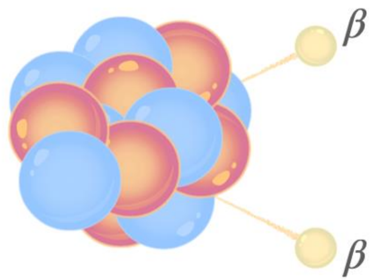
**2vββ**




**(Observed)**

**vs**

**0vββ**




**(Hypothetical)**

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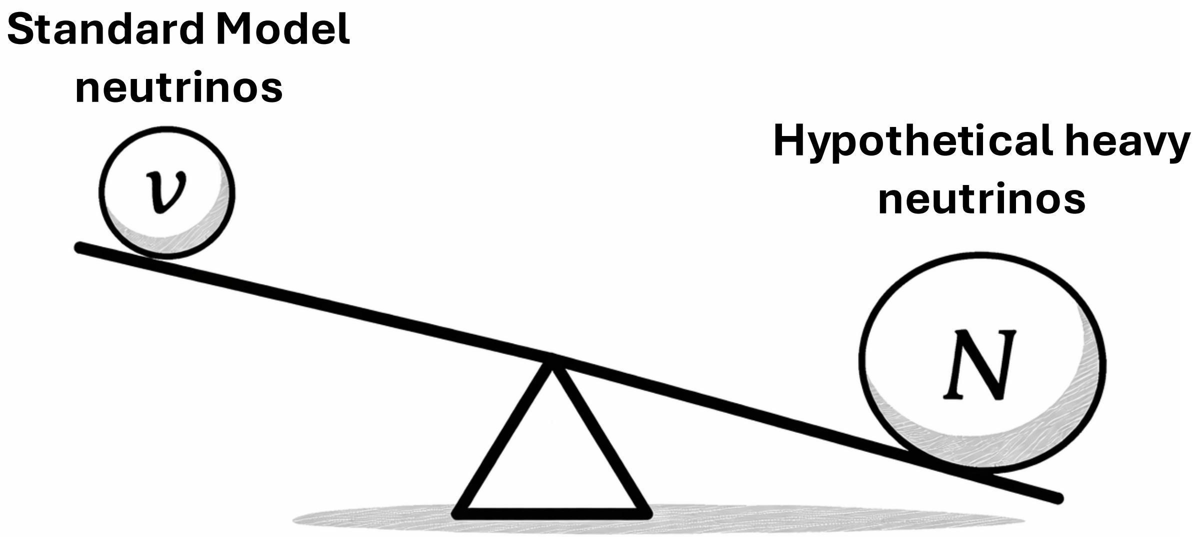

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**An observation of 0νββ would immediately confirm these**

**Interpretations rely on nuclear theory**

# Decay rate

$$\left[T_{1/2}^{0\nu}\right]_{\text{light}}^{-1} = g_A^4 G^{0\nu} \left|M^{0\nu}\right|^2 \left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$$

# Decay rate

$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^{3} U_{ei} m_i \right|$$

Effective neutrino mass

Phase space factor

Coupling constant

$$\left[ T_{1/2}^{0\nu} \right]_{\text{light}}^{-1} = g_A^4 G^{0\nu} \left| M^{0\nu} \right|^2 \left| \frac{\langle m_{\beta\beta} \rangle}{m_e} \right|^2$$

Half-life (what is measured)

Nuclear matrix element (NME)

# Nuclear Matrix Element

Initial and final states

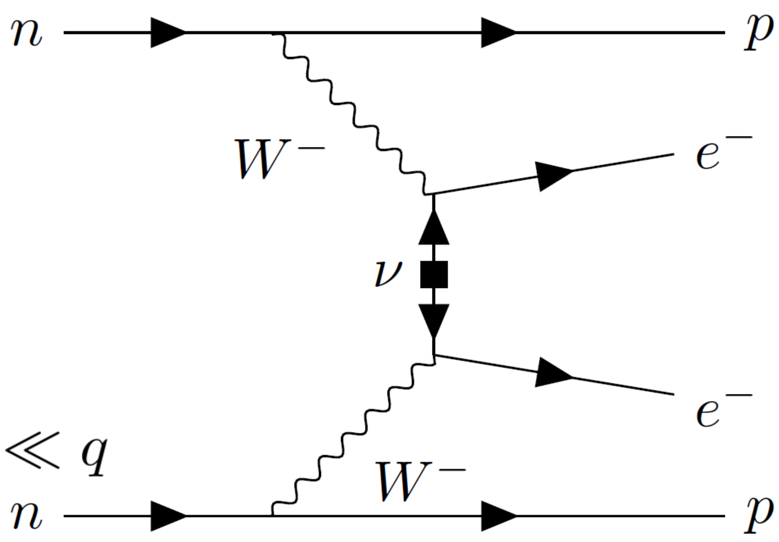
$$\mathcal{M}^{0\nu} = \langle f | \mathcal{O}^{0\nu} | i \rangle$$

Decay operator encodes specific mechanisms

# Decay Mechanism Example

## Light neutrino exchange (long-range)

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



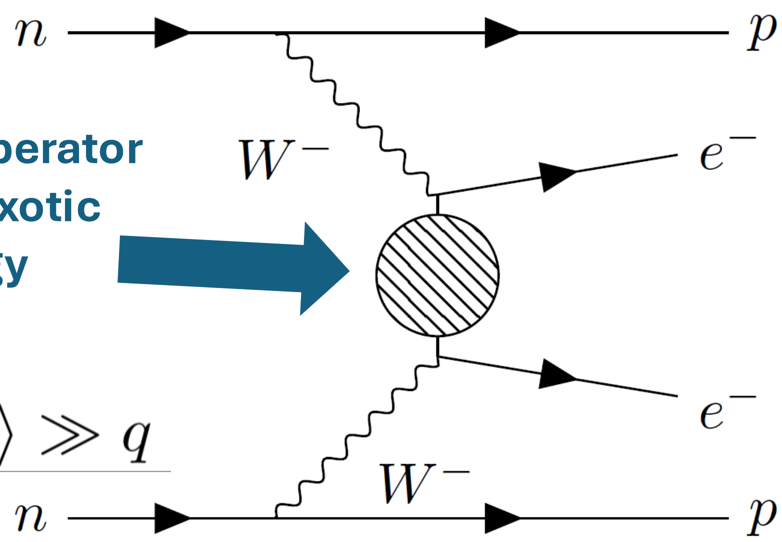

$\langle m_N \rangle \ll q$

## Heavy neutrino exchange (short-range)

$$\left[T_{1/2}^{0\nu}\right]^{-1}_{\text{heavy}} =$$ More complicated expressions

**Contact operator encodes exotic high-energy physics**

$\langle m_N \rangle \gg q$

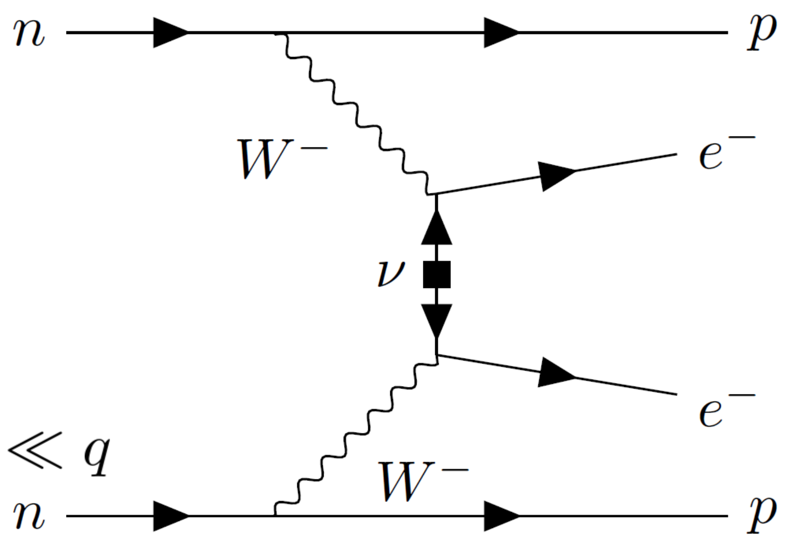


# Decay Mechanism Example

**Relatively unexplored in nuclear theory**

## Light neutrino exchange (long-range)

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

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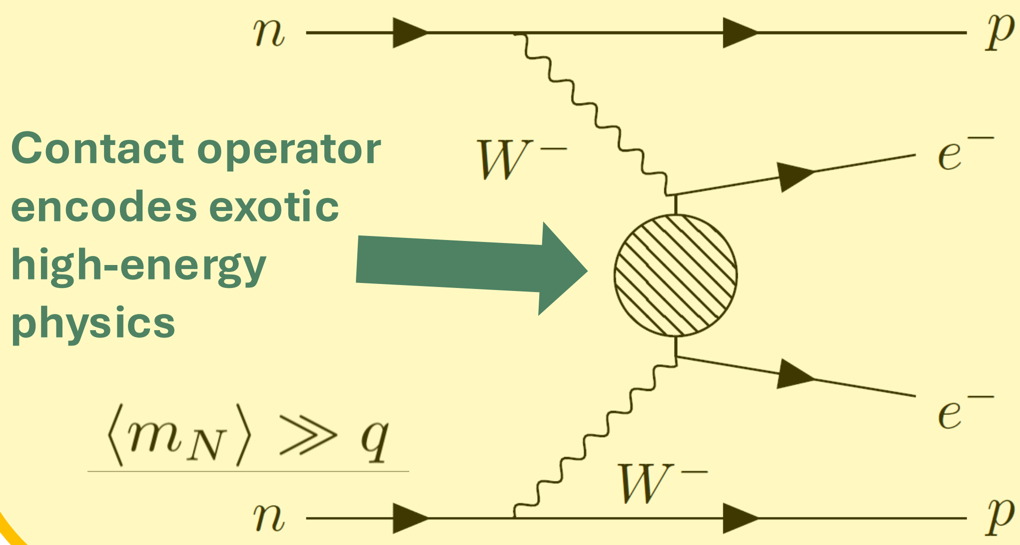
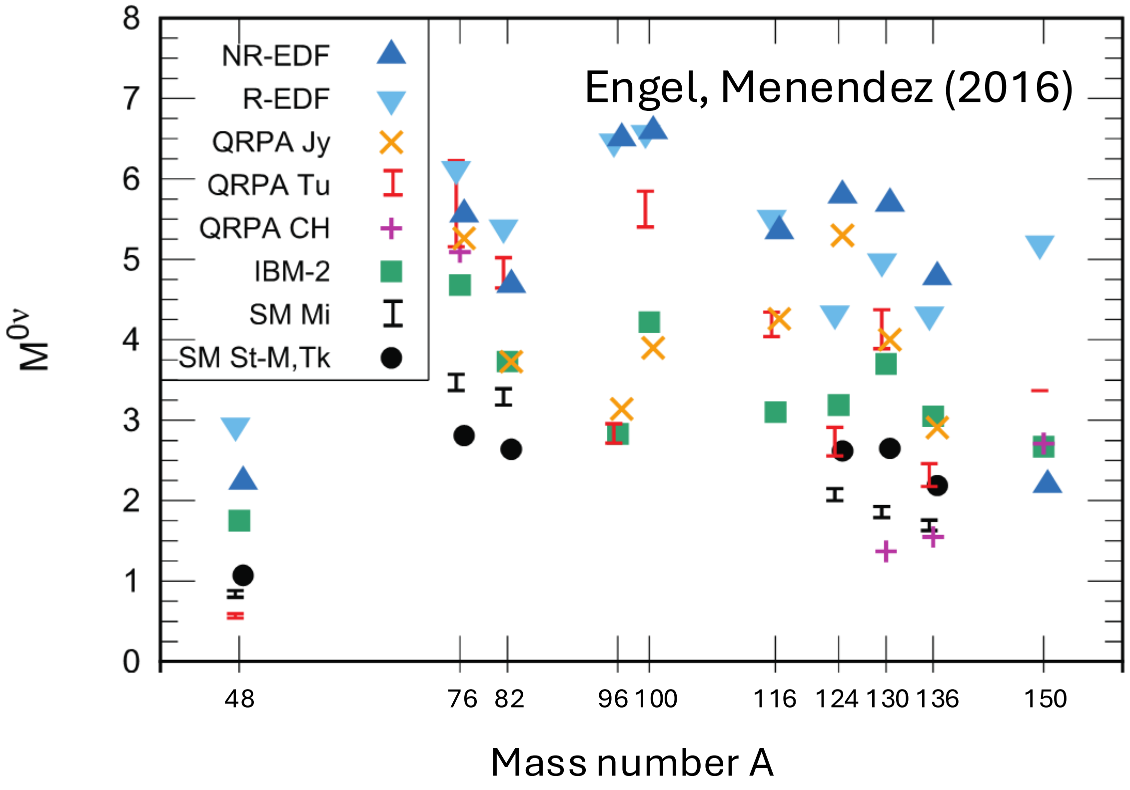



$\langle m_N \rangle \gg q$

# NME uncertainty

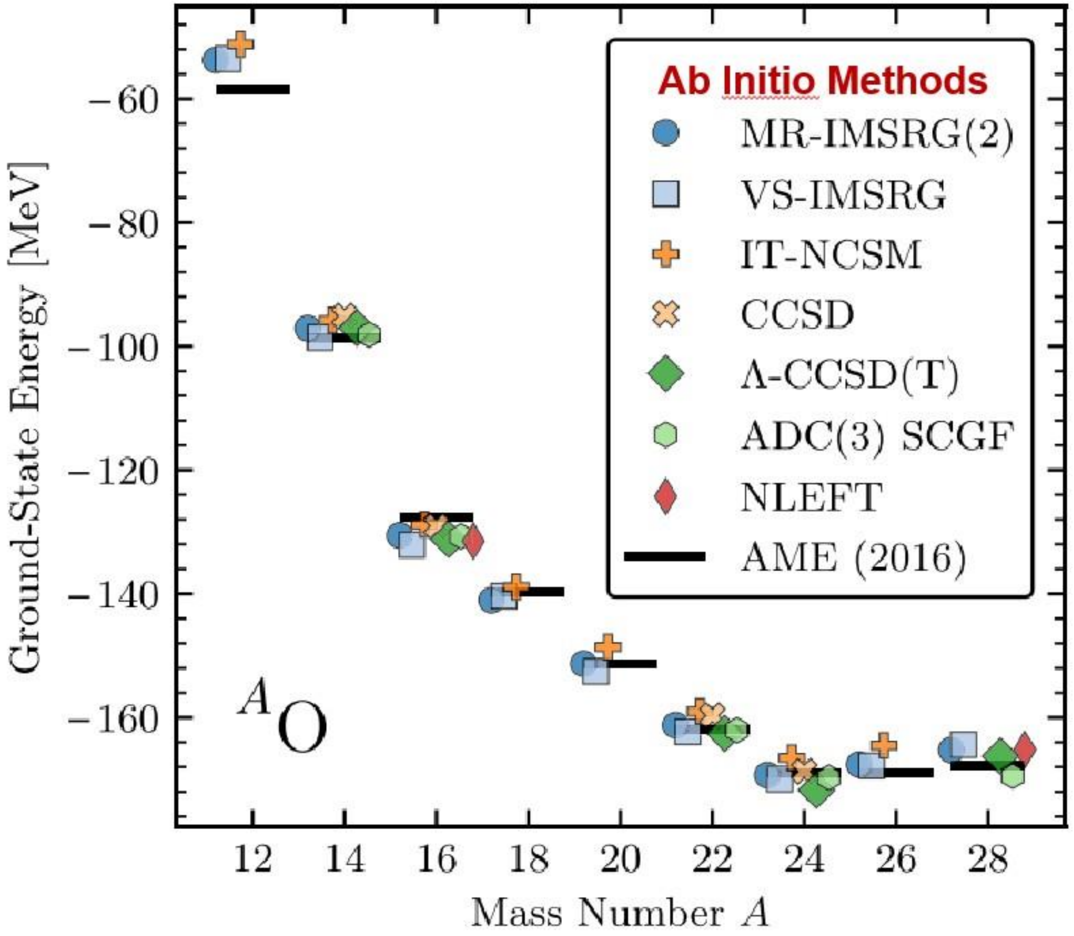
## Phenomenological Methods
## (fit to data)




Large NME uncertainty is not good for interpreting BSM physics

# NME uncertainty

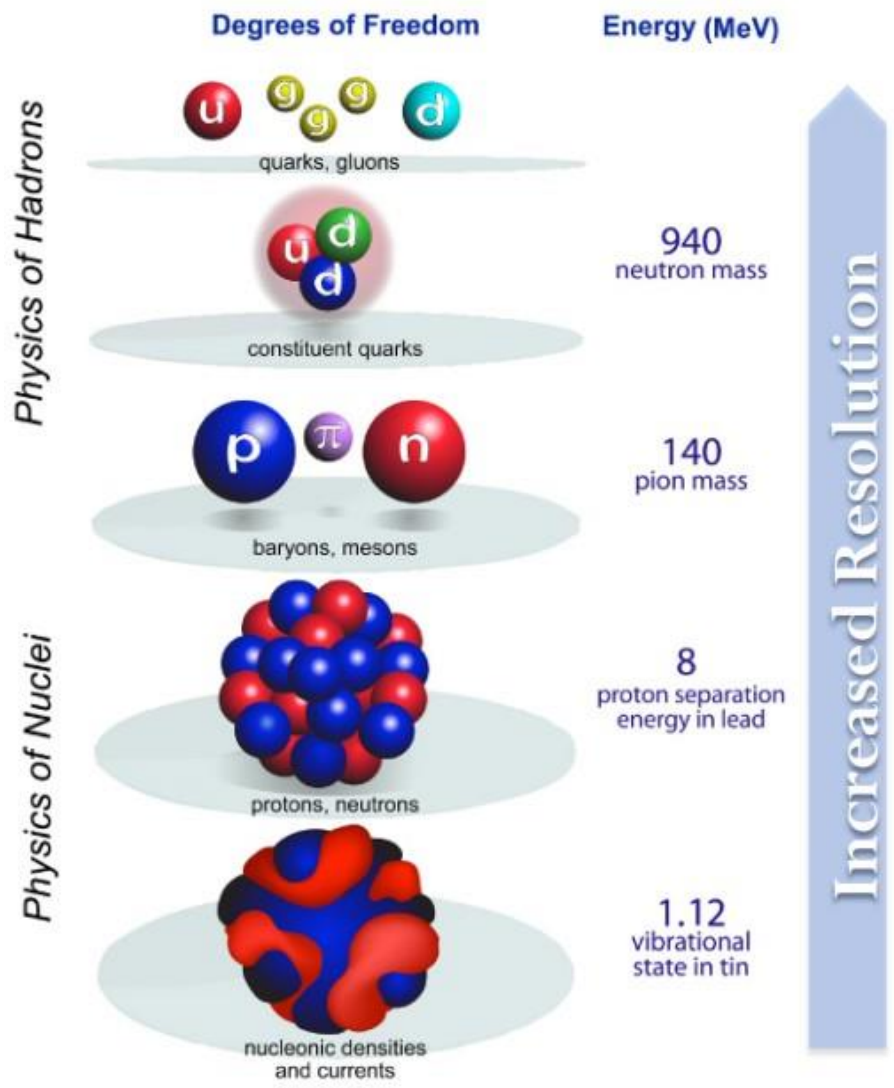
## *Ab initio* Nuclear Theory
## (from first-principles)



# Nuclear Matrix Element

**Why are the NMEs so hard to calculate?**

# The nucleus is complicated



# Phenomenological nuclear models

**Fit** Hamiltonian to data,
then predict

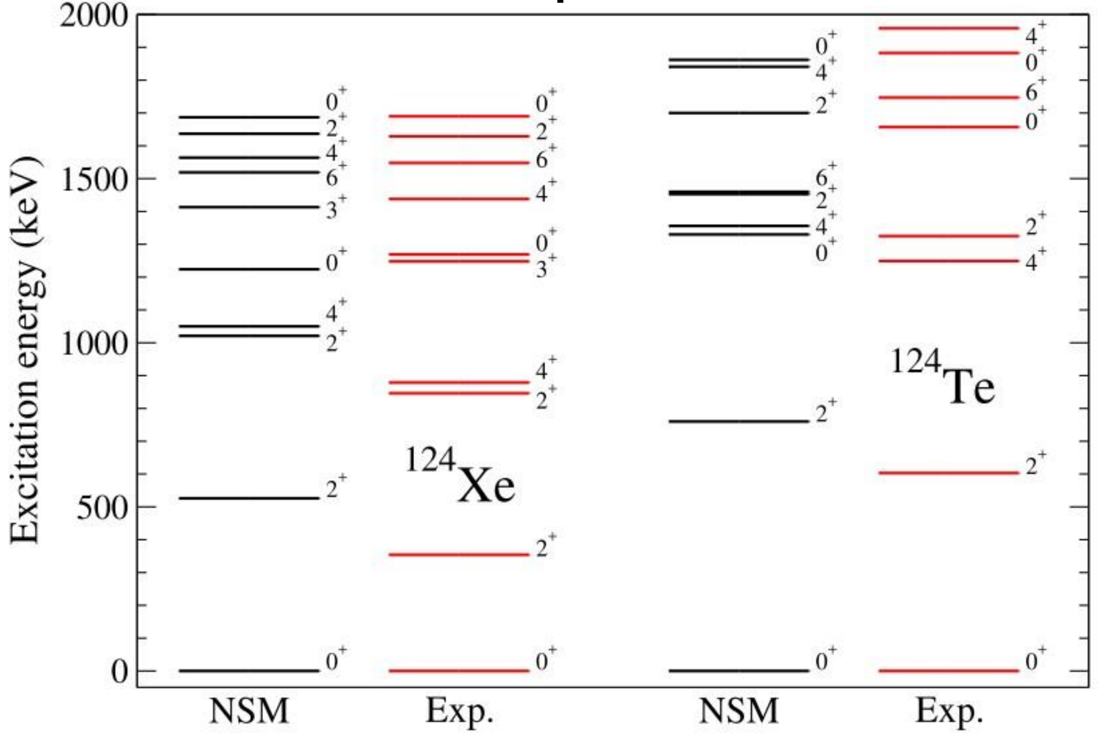
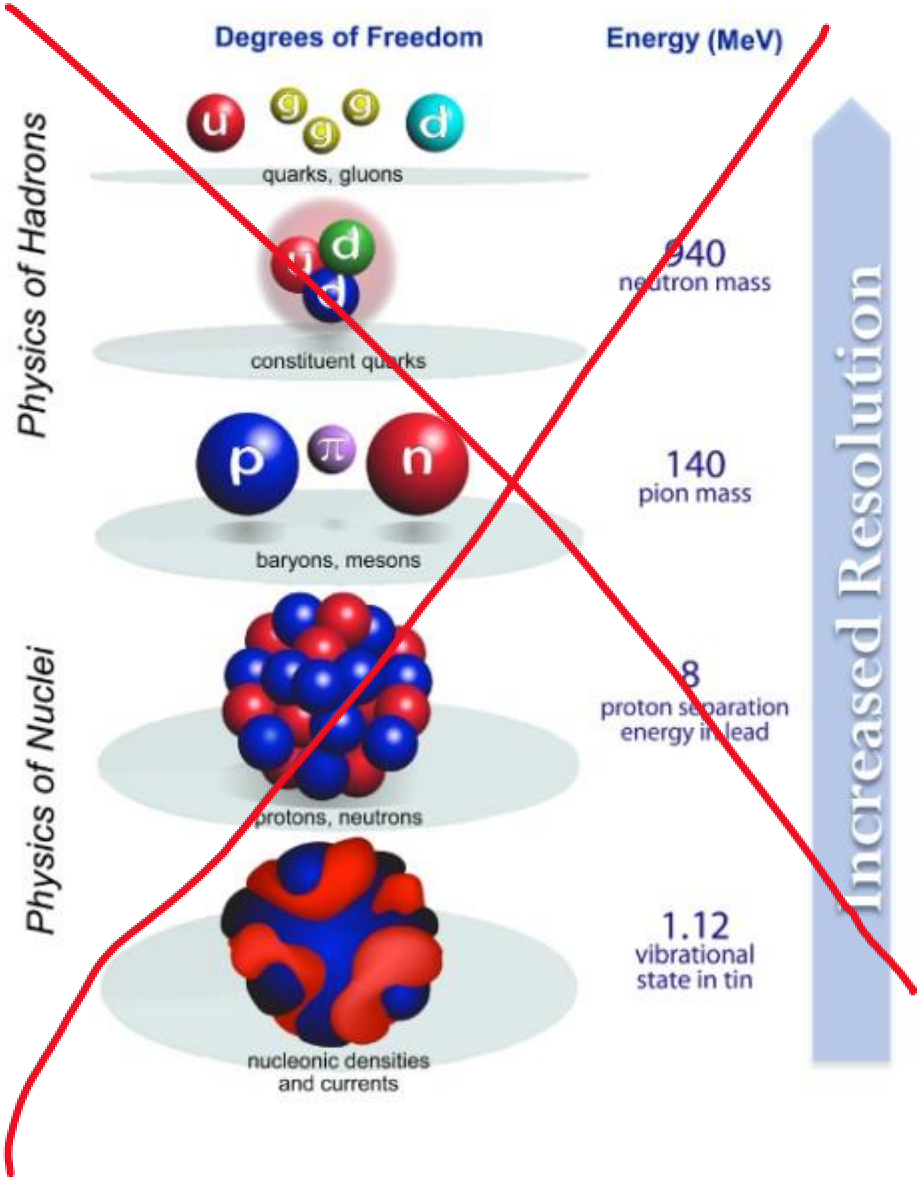



**Fig. 1.** $^{124}$Xe and $^{124}$Te excitation spectra obtained by the nuclear shell model (NSM) compared to experiment [74].

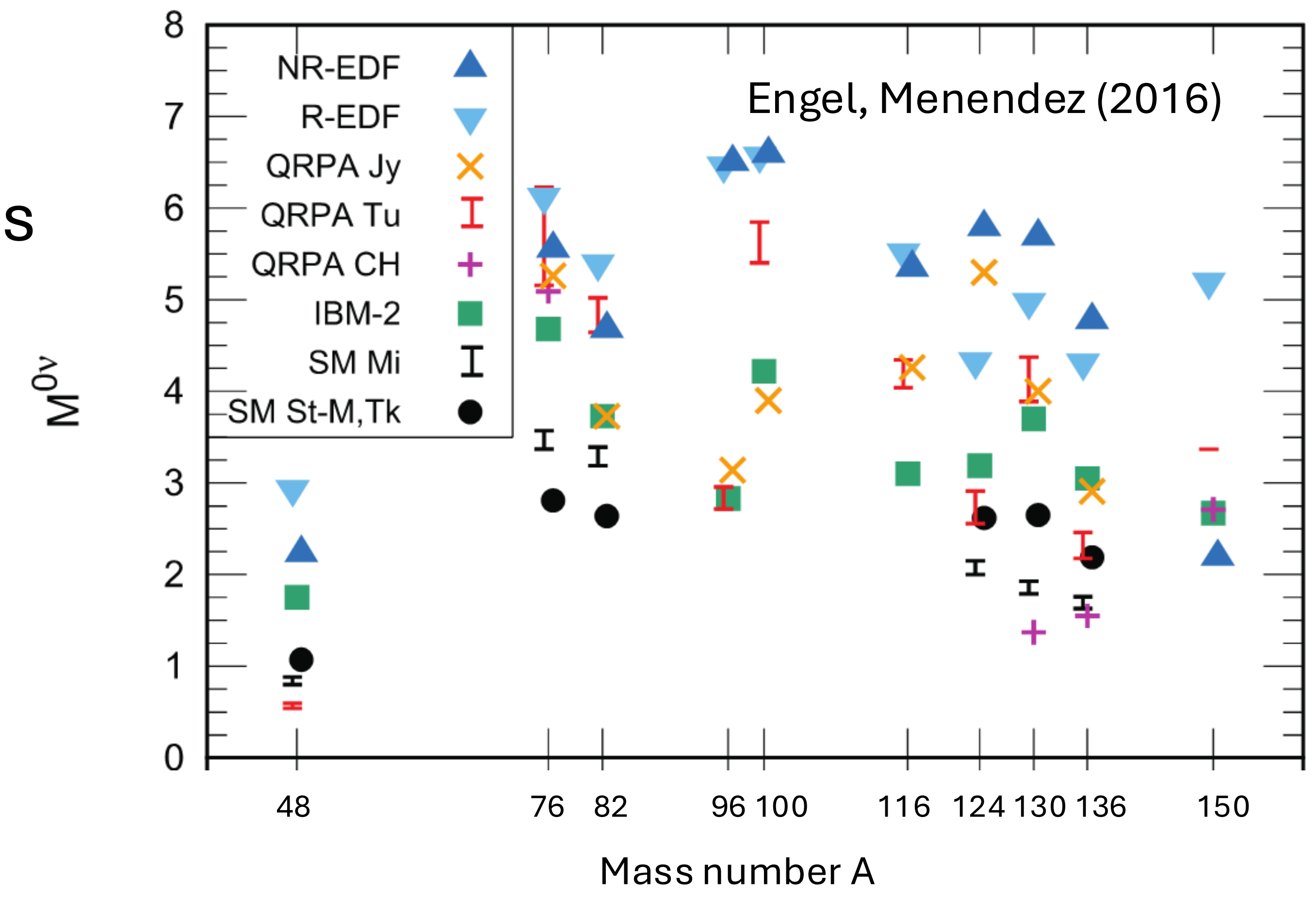
E.A. Coello Pérez, J. Menéndez, A. Schwenk (2019)



# Issues with phenomenological methods

Methods are **inappropriately extrapolated** to where there is no data...

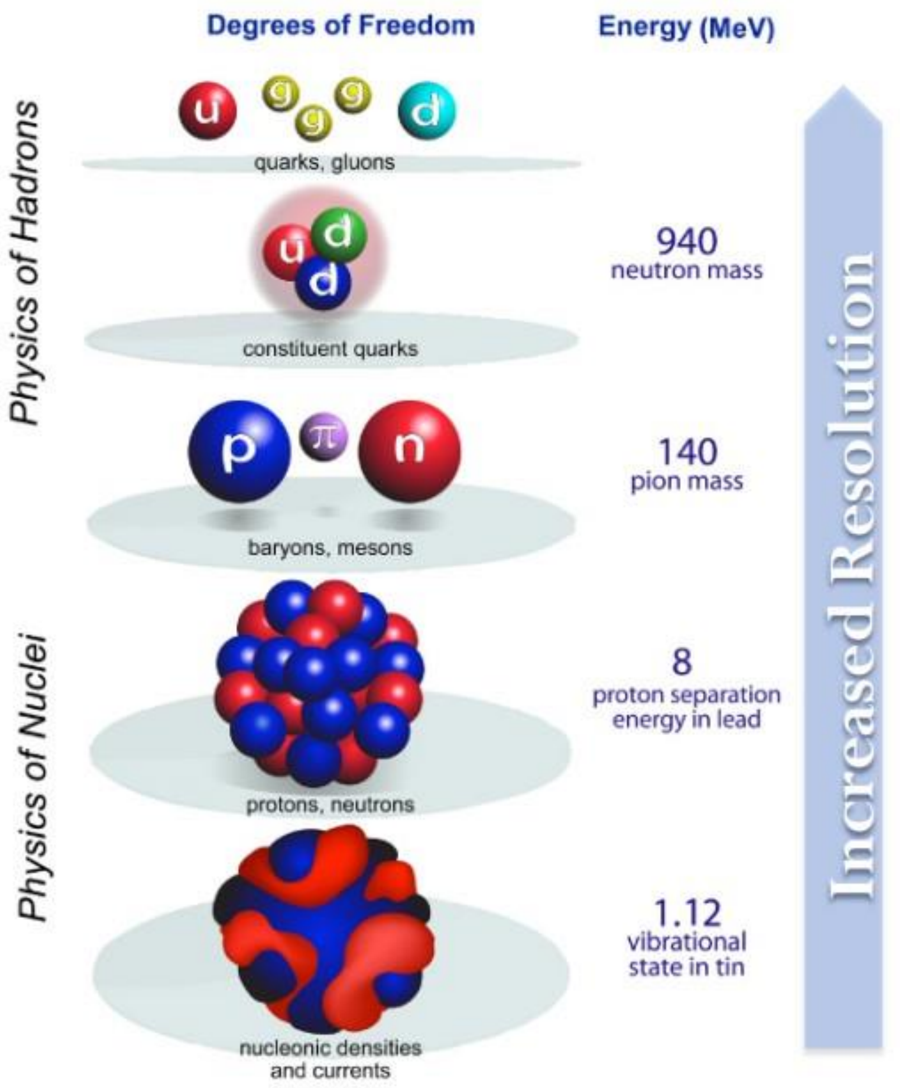
- ➢ Large spread in results
- ➢ No path for understanding uncertainty



# We can do better!

**Renormalization group:**
**Effective description of higher-scale physics**

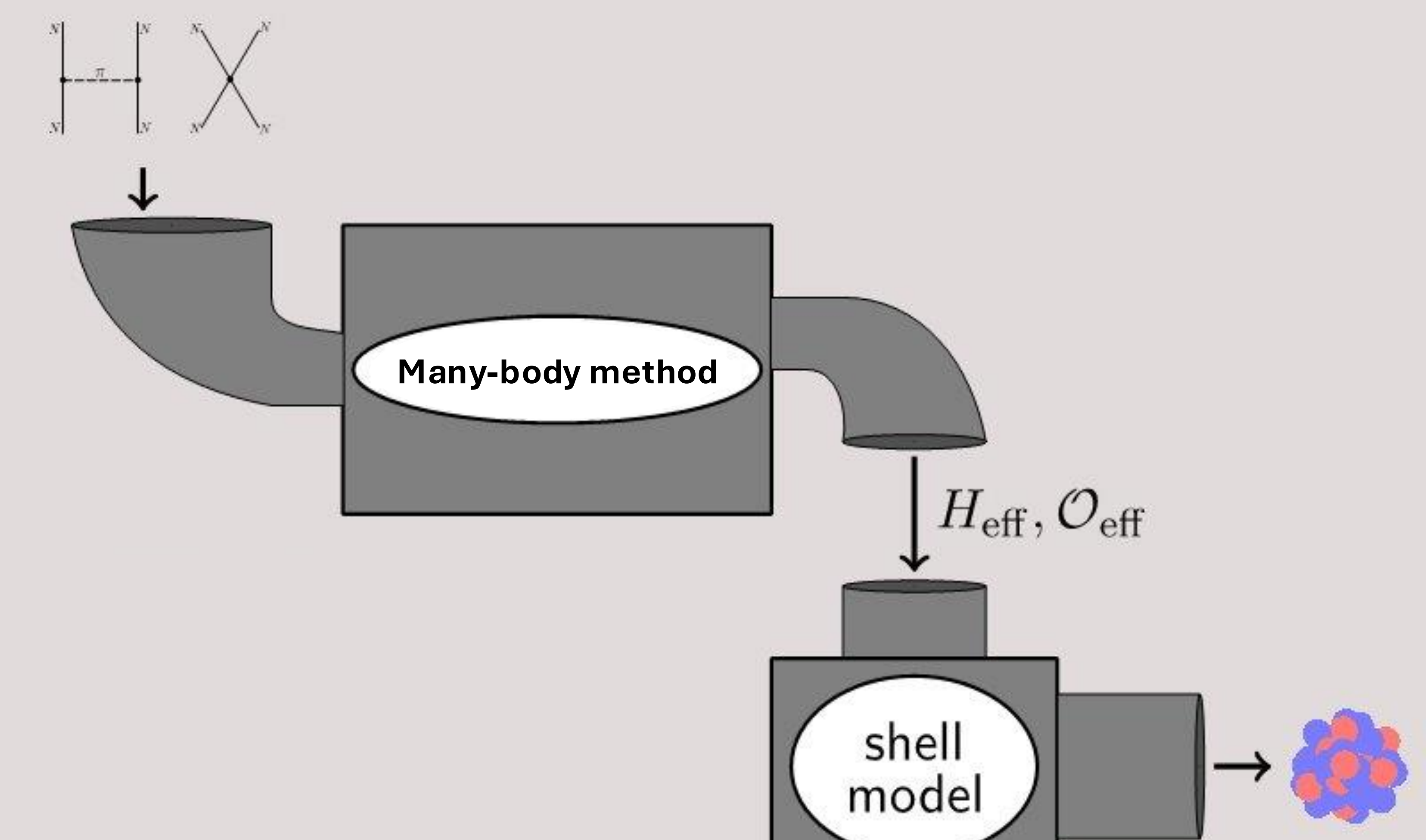
$$H(\Lambda) = T + V_{\mathrm{NN}}(\Lambda) + V_{3\mathrm{N}}(\Lambda) + V_{4\mathrm{N}}(\Lambda) + \cdots$$



# Ab initio nuclear theory

$$H\psi_n = E_n\psi_n$$

= chiral EFT interactions
+ a (polynomially scaling) many-body method




Courtesy, S.R. Stroberg

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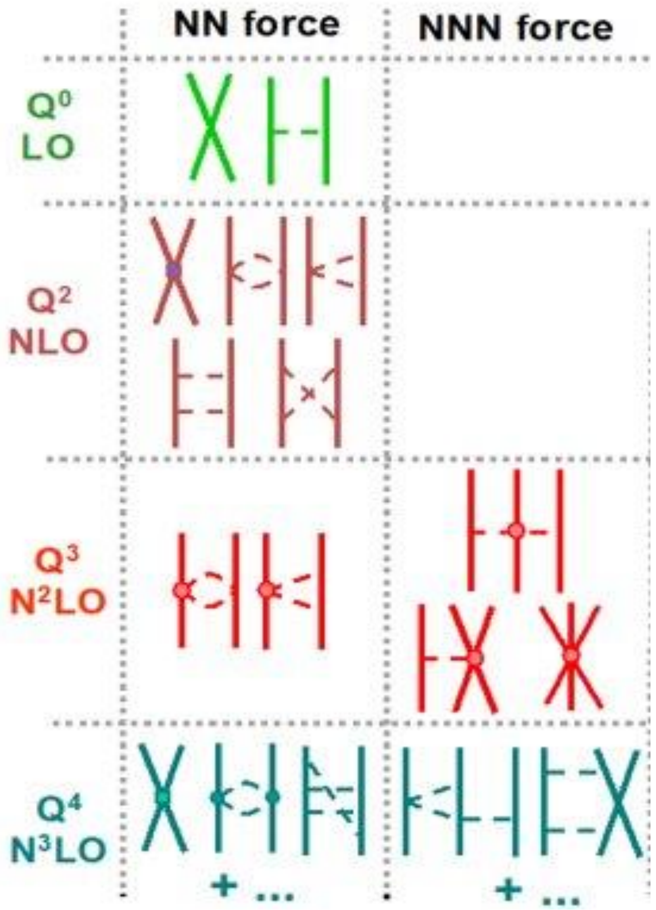


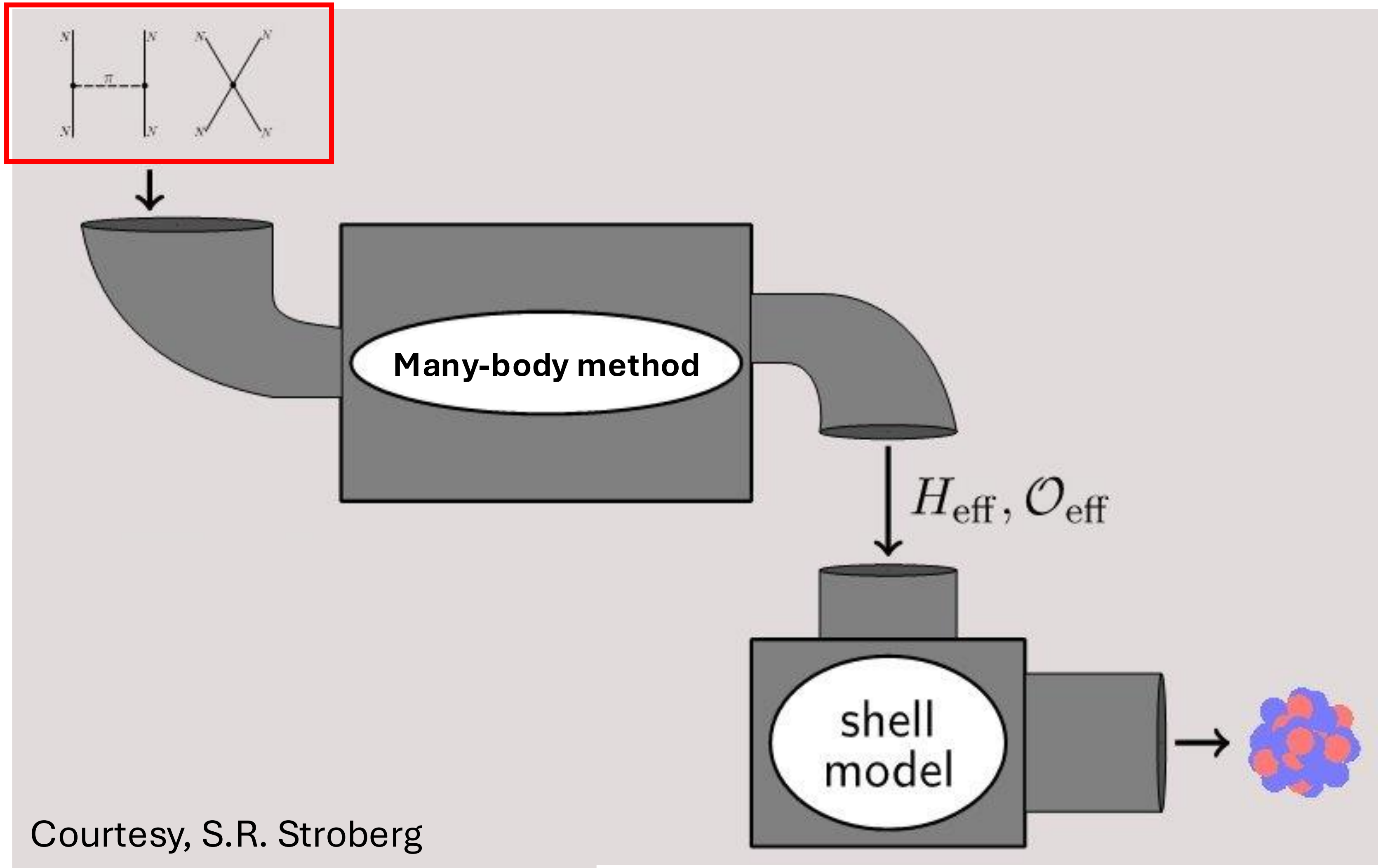


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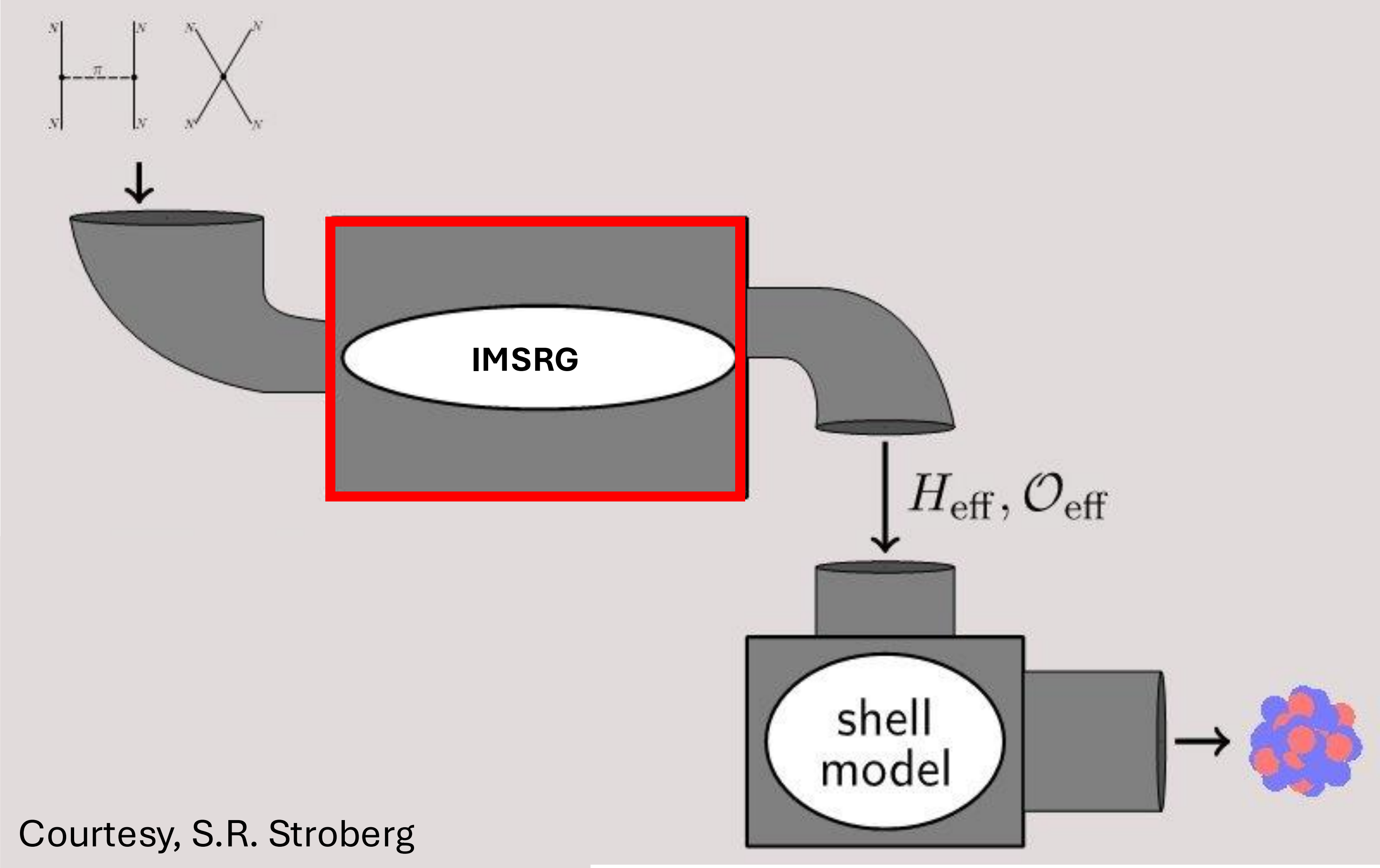
$$H(s) = e^{\Omega(s)} H e^{-\Omega(s)}$$

$$\mathcal{O}(s) = e^{\Omega(s)} \mathcal{O} e^{-\Omega(s)}$$

**Continuous unitary transformations of Hamiltonian**



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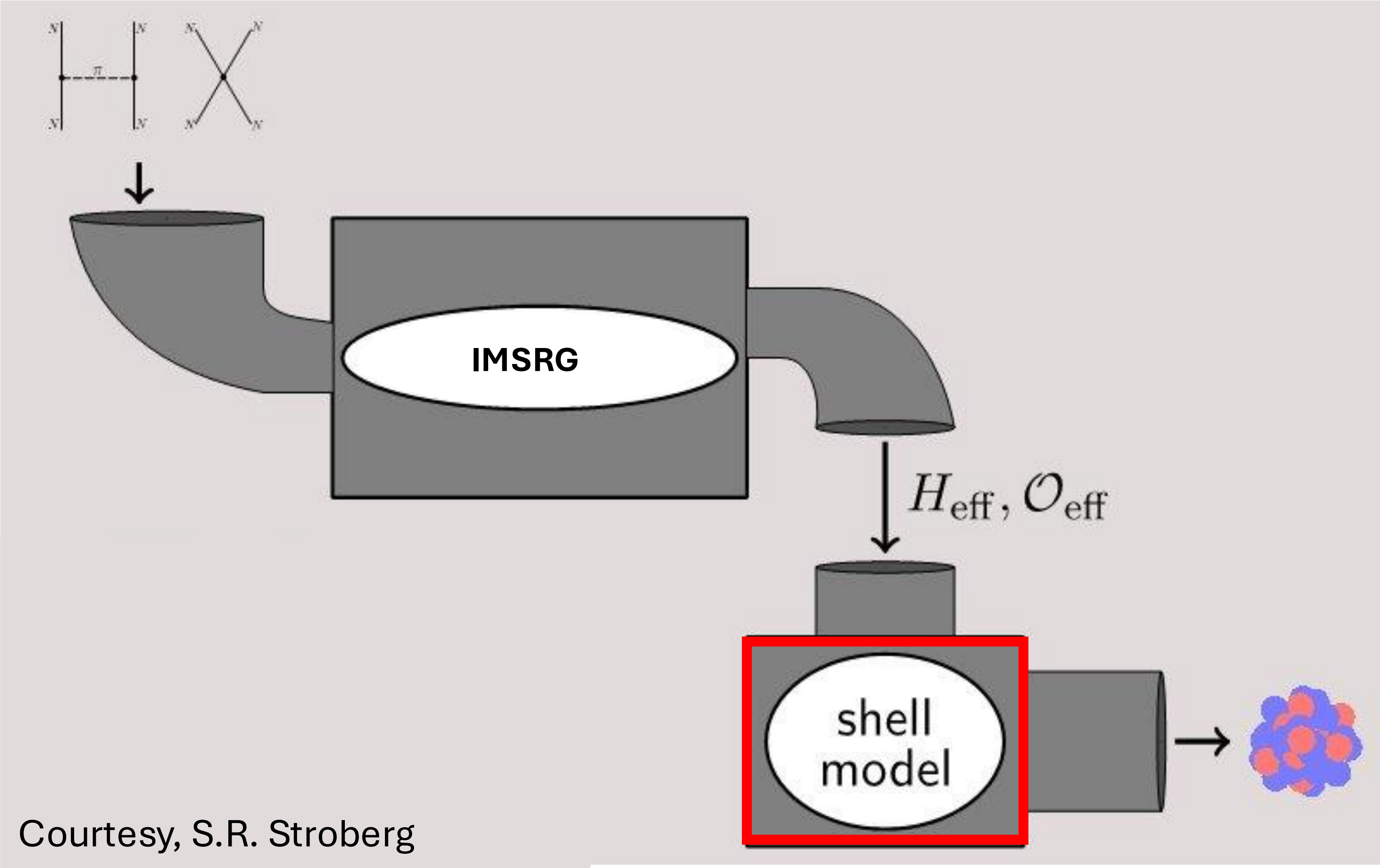
**Diagonalize $\mathcal{H}$ !!**



# Short-range nuclear matrix elements results

**arXiv:2604.22727**

## Ab initio short-range nuclear matrix elements for neutrinoless double-beta decay

A. Todd,[1,2] T. Shickele,[1,3] A. Belley,[4,1,3] L. Jokiniemi,[5,6,1] and J. D. Holt[1,2]

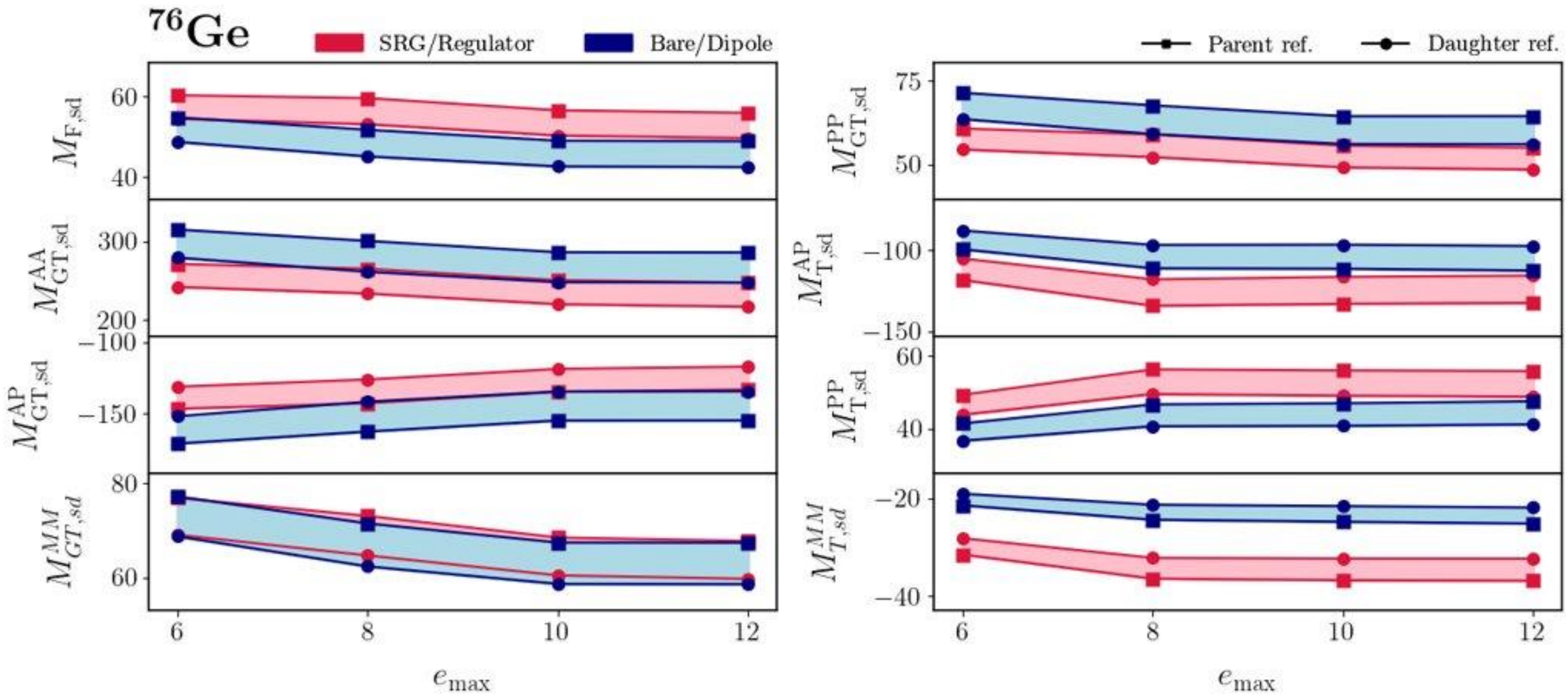
[1] *TRIUMF, 4004 Wesbrook Mall, Vancouver, BC V6T 2A3, Canada*
[2] *Department of Physics, McGill University, 3600 Rue University, Montréal, QC H3A 2T8, Canada*
[3] *Department of Physics & Astronomy, University of British Columbia, Vancouver, BC V6T 1Z1, Canada*
[4] *Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[5] *Technische Universität Darmstadt, Department of Physics, D-64289 Darmstadt, Germany*
[6] *ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany*

We present converged ab initio calculations of short-range neutrinoless double-beta ($0\nu\beta\beta$) decay nuclear matrix elements for the key experimental isotopes $^{76}$Ge, $^{82}$Se, $^{130}$Te and $^{136}$Xe. Starting from different nuclear forces derived from chiral effective field theory, we apply the in-medium similarity renormalization group to obtain an effective valence-space Hamiltonian along with consistently transformed $0\nu\beta\beta$-decay operators. We then obtain a range of values for the matrix elements that is consistent with, but generally smaller than, those from phenomenology. Finally, we combine our results with current limits from $0\nu\beta\beta$-decay searches to obtain constraints for the sterile-neutrino mixing-mass parameter space when considering the inclusion of a fourth sterile neutrino.

# Be careful with renormalization


**Usually we neglect this; but consistency is important for short-range operators**

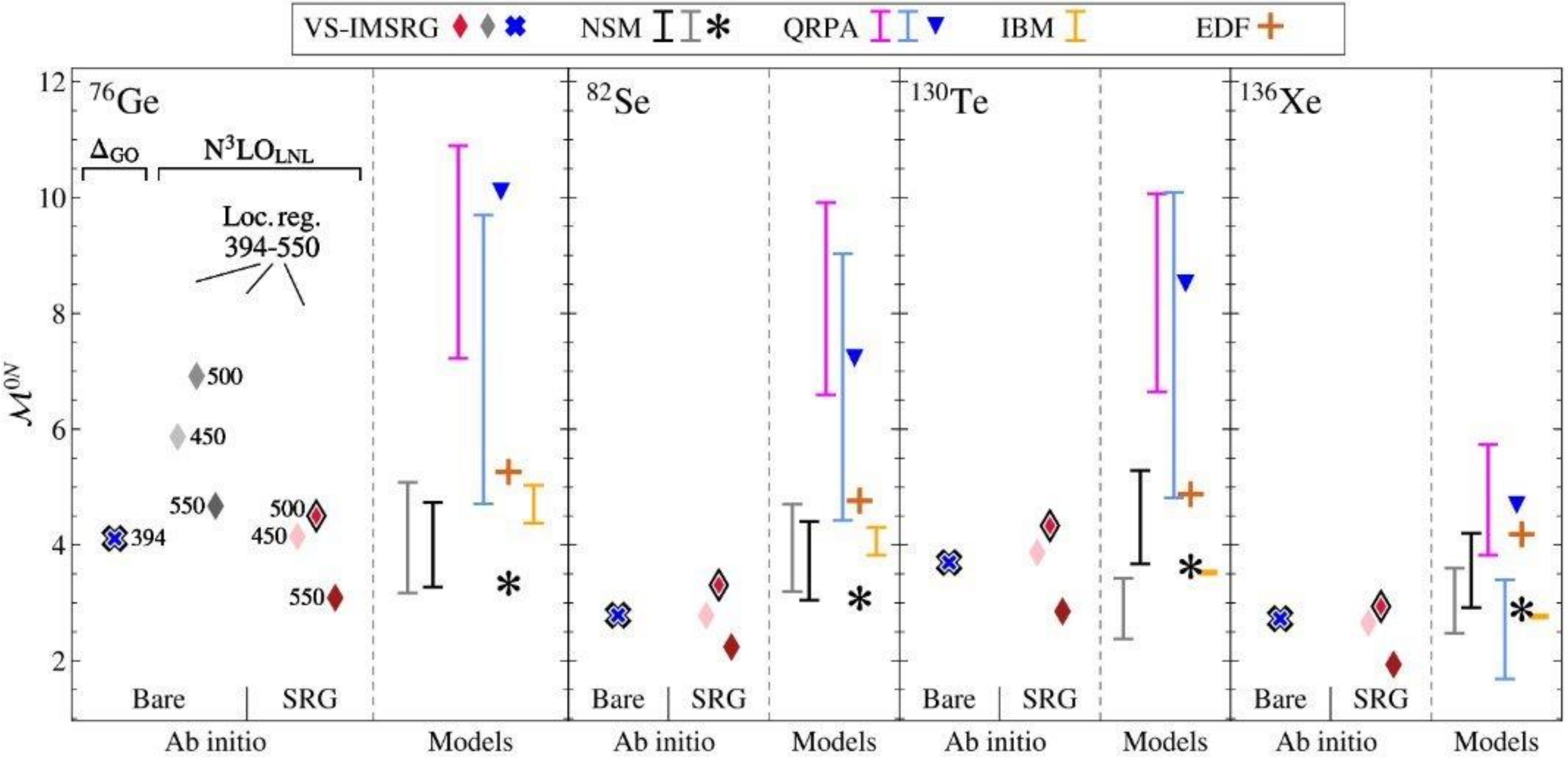
# Convergence in single-particle excitations






A. Todd, T. Shickele, A. Belley, L. Jokiniemi J. D. Holt (in prep)

# Final short-range NMEs



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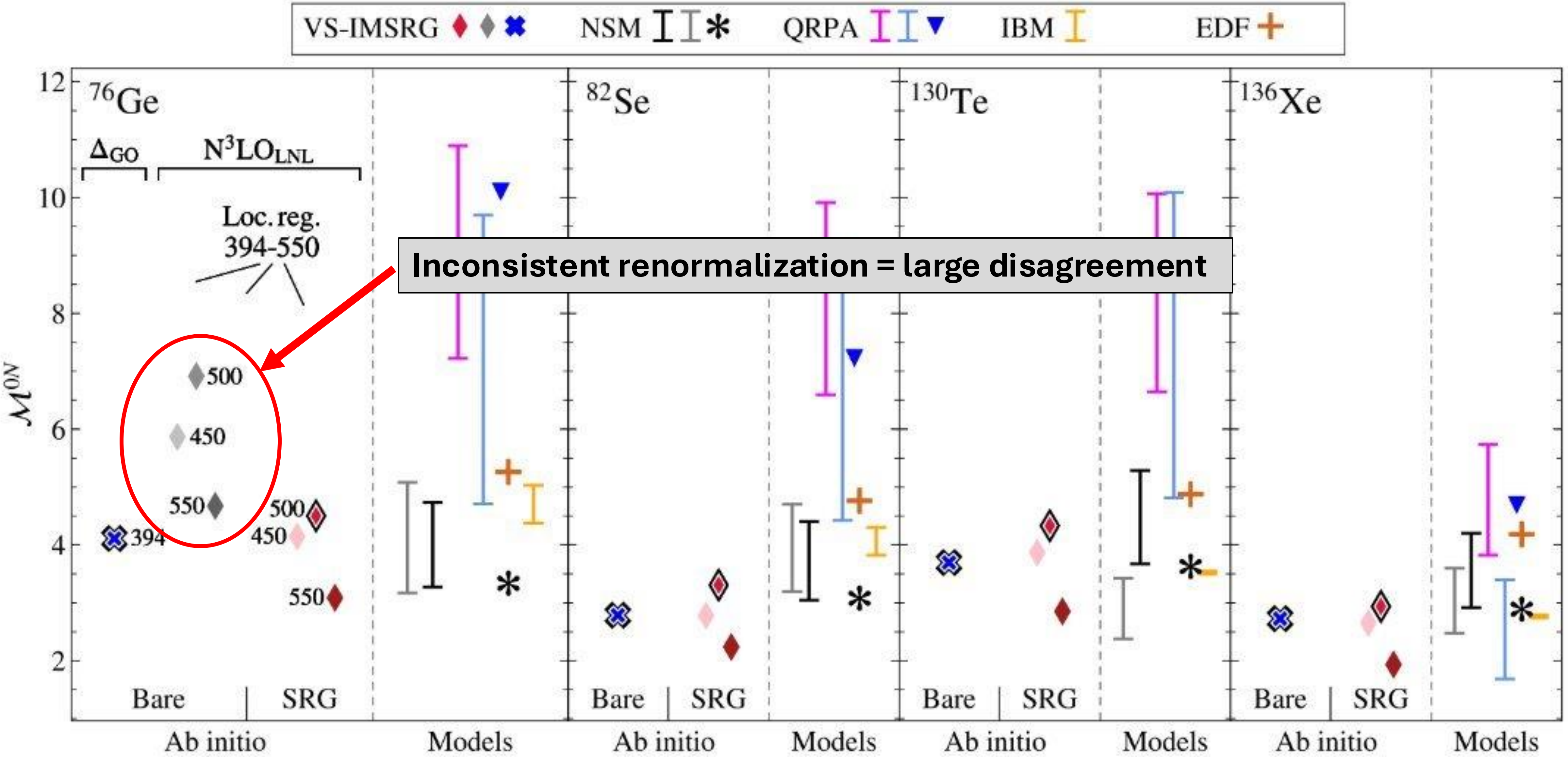




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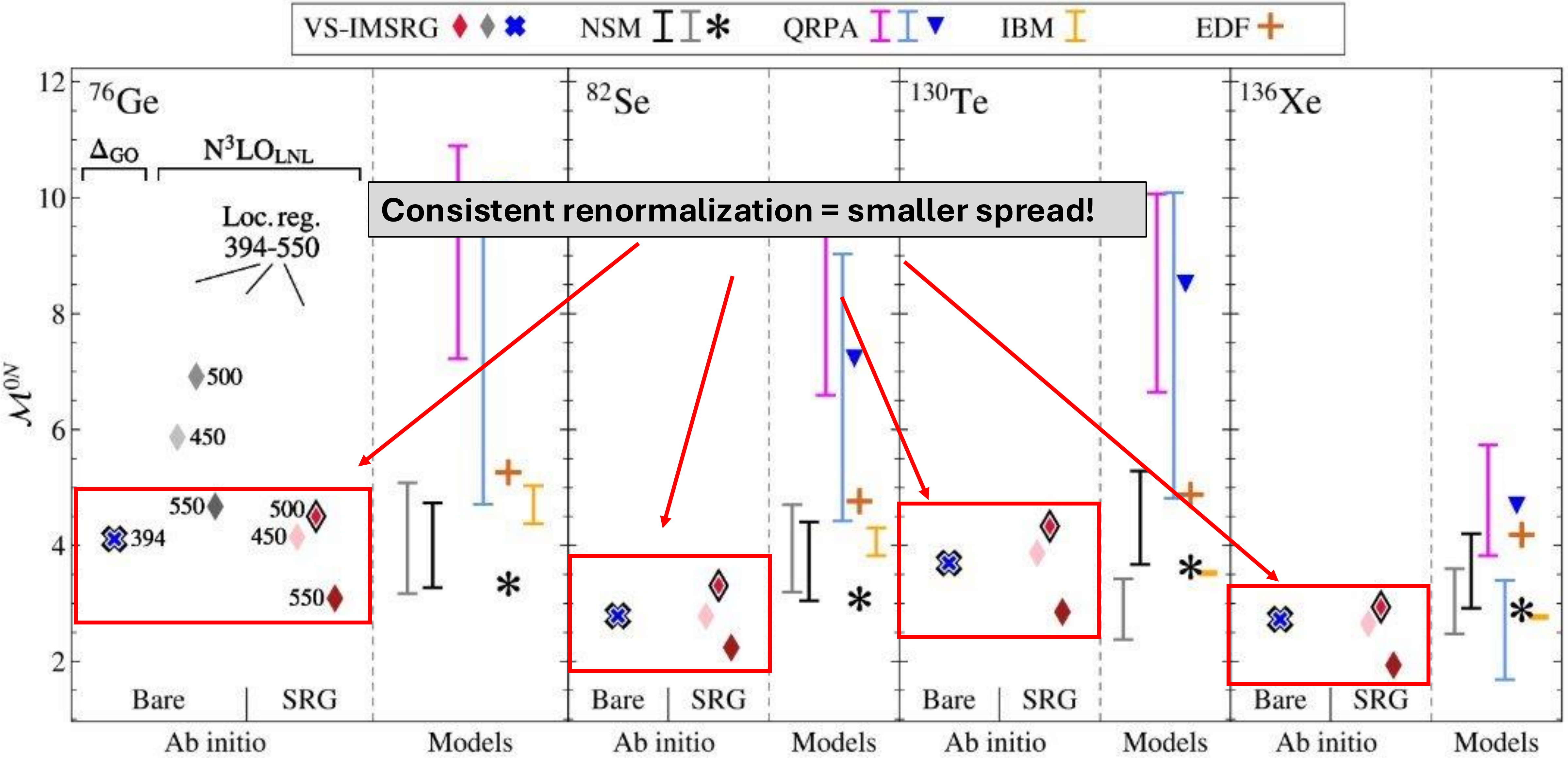




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# Connection to BSM mechanisms

Assume 3+1 model, with heavy neutrino-exchange dominating the amplitude:

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



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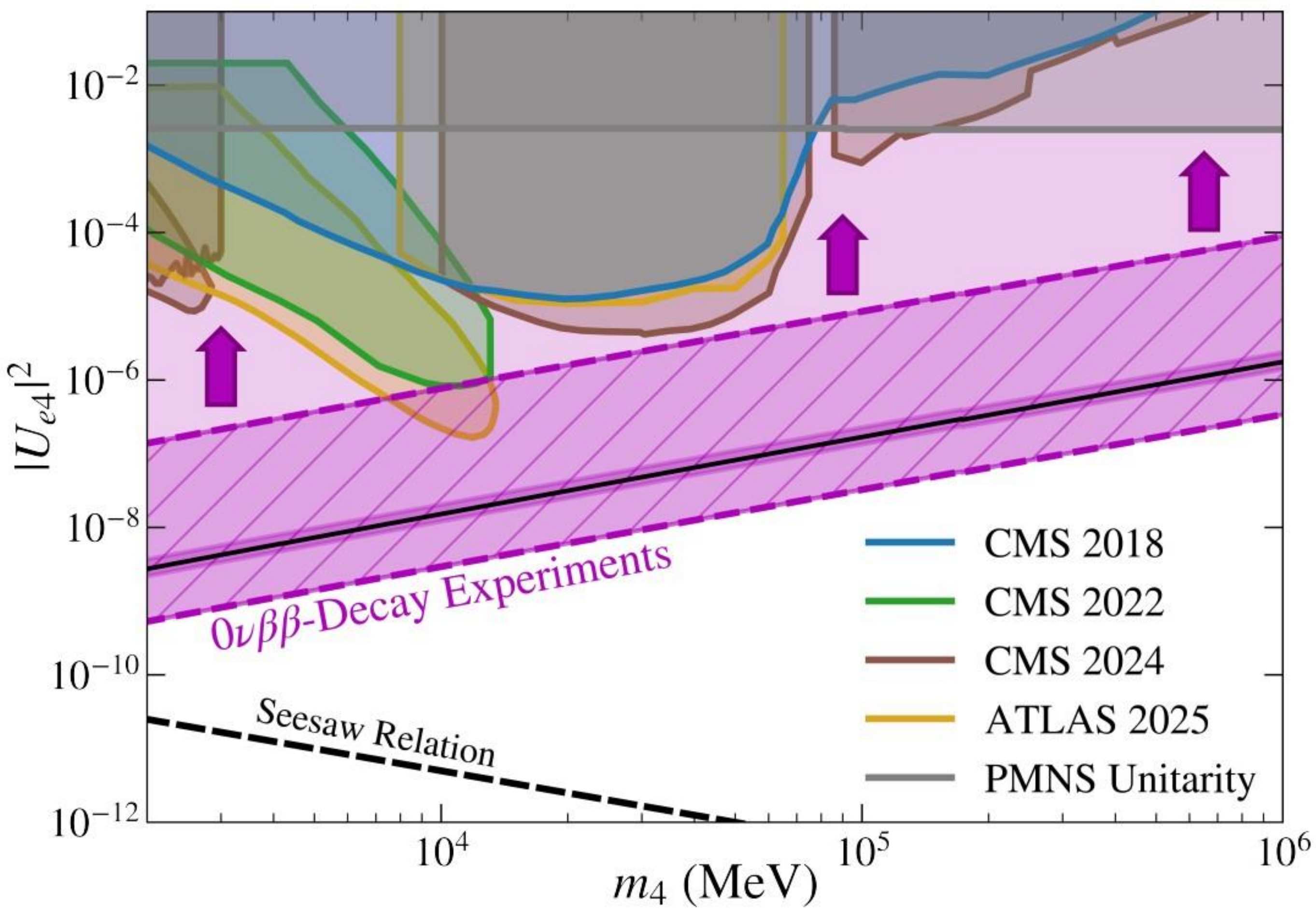



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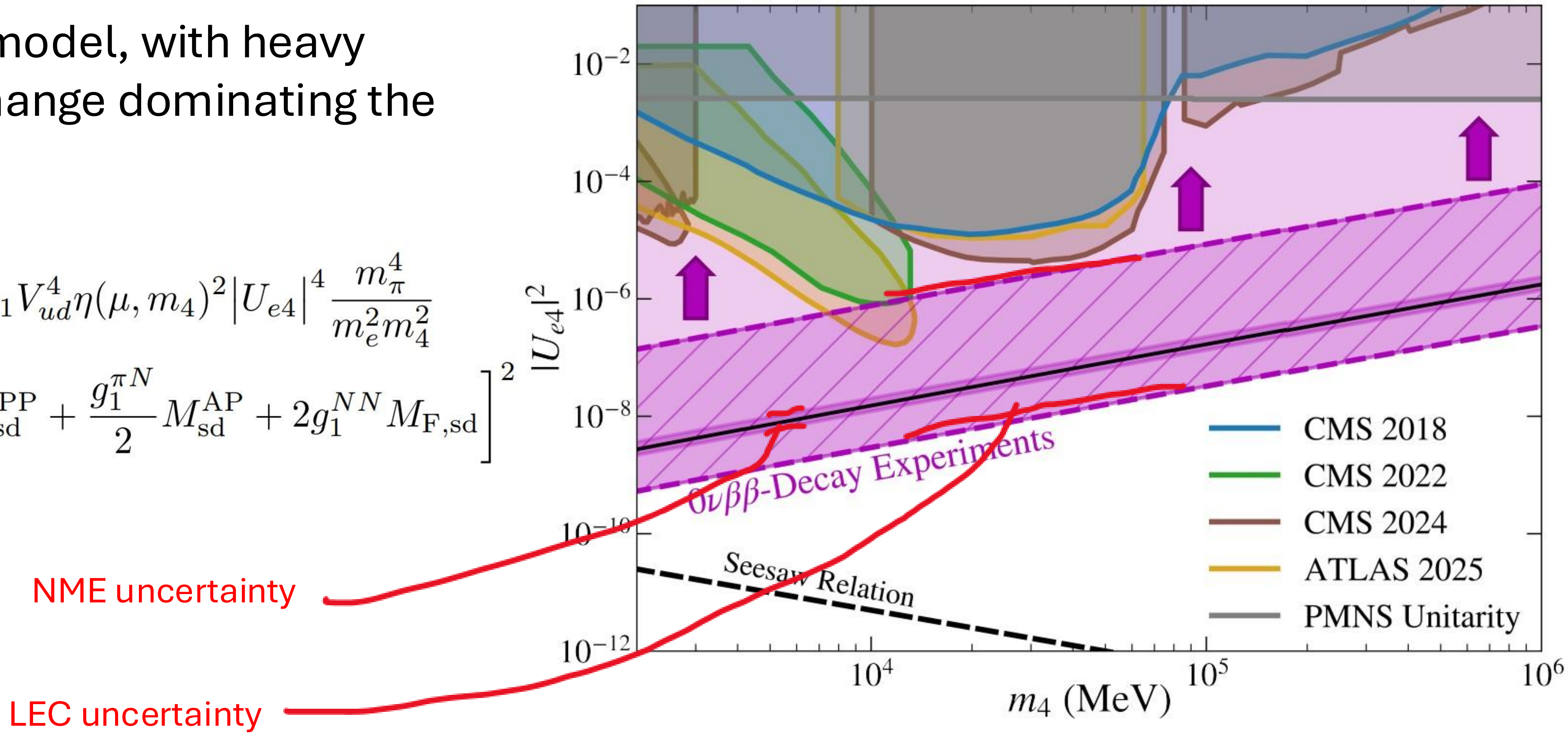




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**Conclusions:**

- Short-range operators are sensitive to different schemes: consistent regulators and SRG transformations are required

- Overall much smaller spread than phenomenonelogical approaches. This is encouraging given the radically different approach.

- 3+1 model: Current $0\nu\beta\beta$ limits competitively probe heavy neutrinos

**Outlook:**

- Uncertainty quantification
- Taking higher-orders within our method: 3-body operators, N2LO operator contributions

Collaborators: Taiki Shickele, Antoine Belley, Lotta Jokiniemi, Jason Holt

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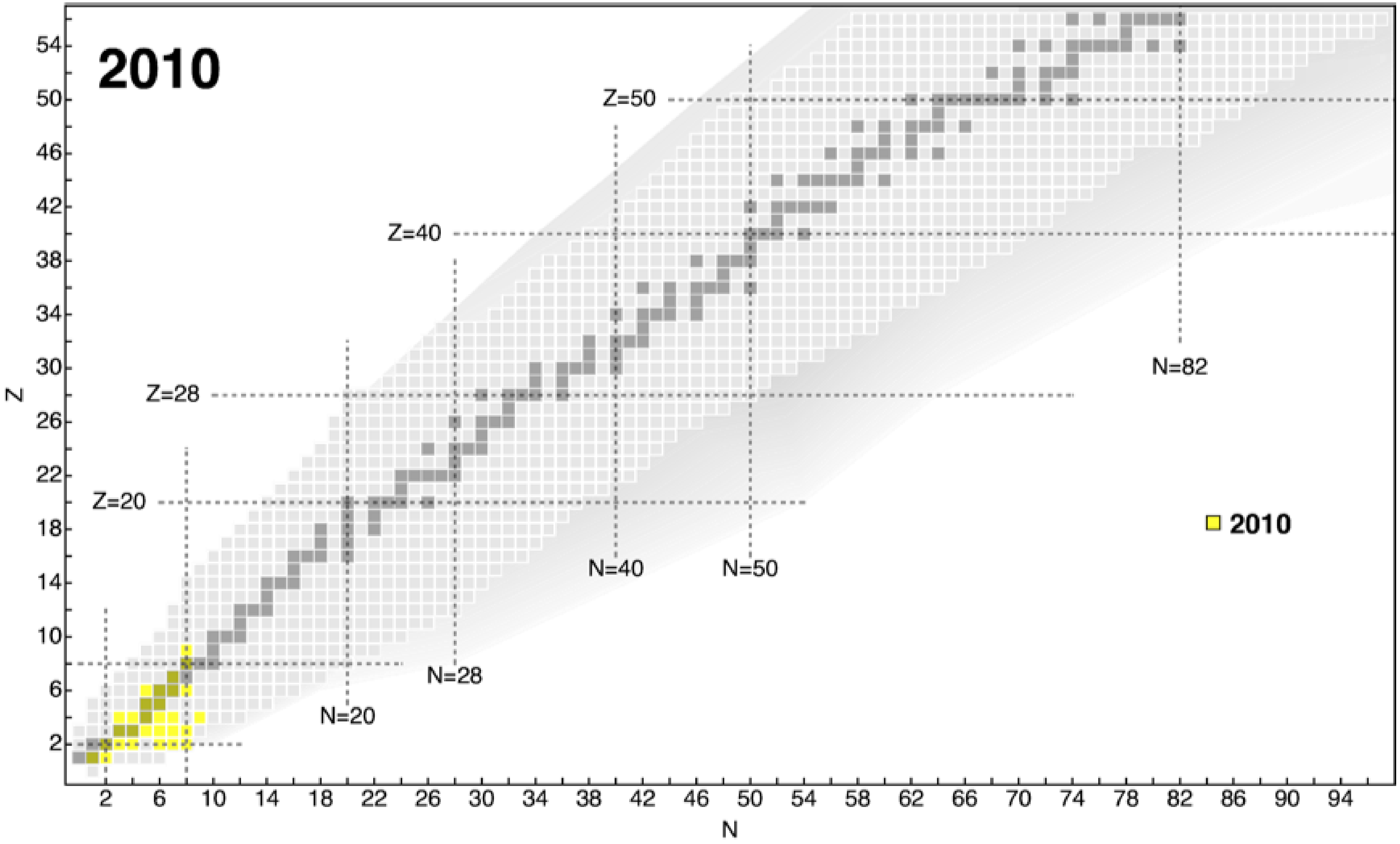
# Backup Slides

# Ab initio progress



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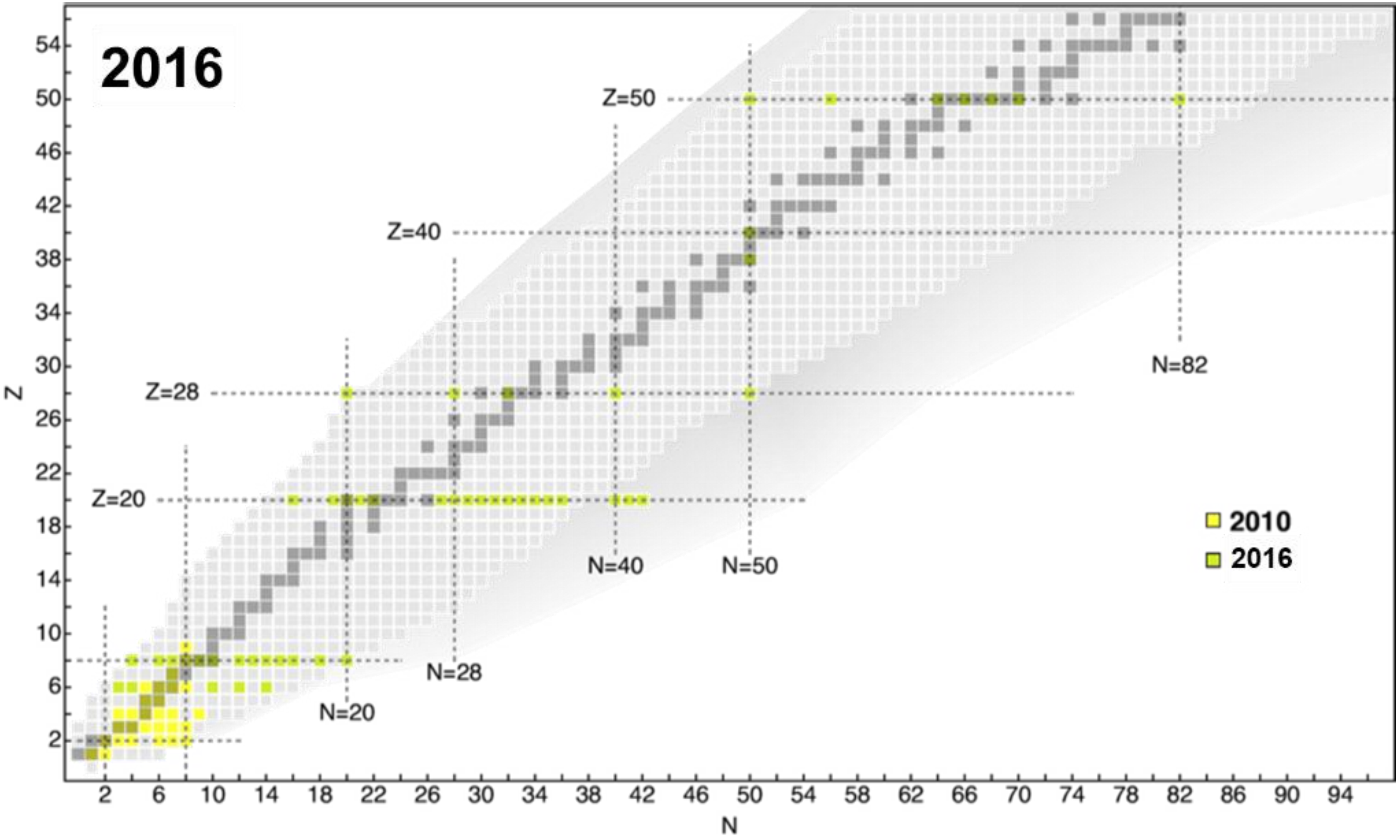

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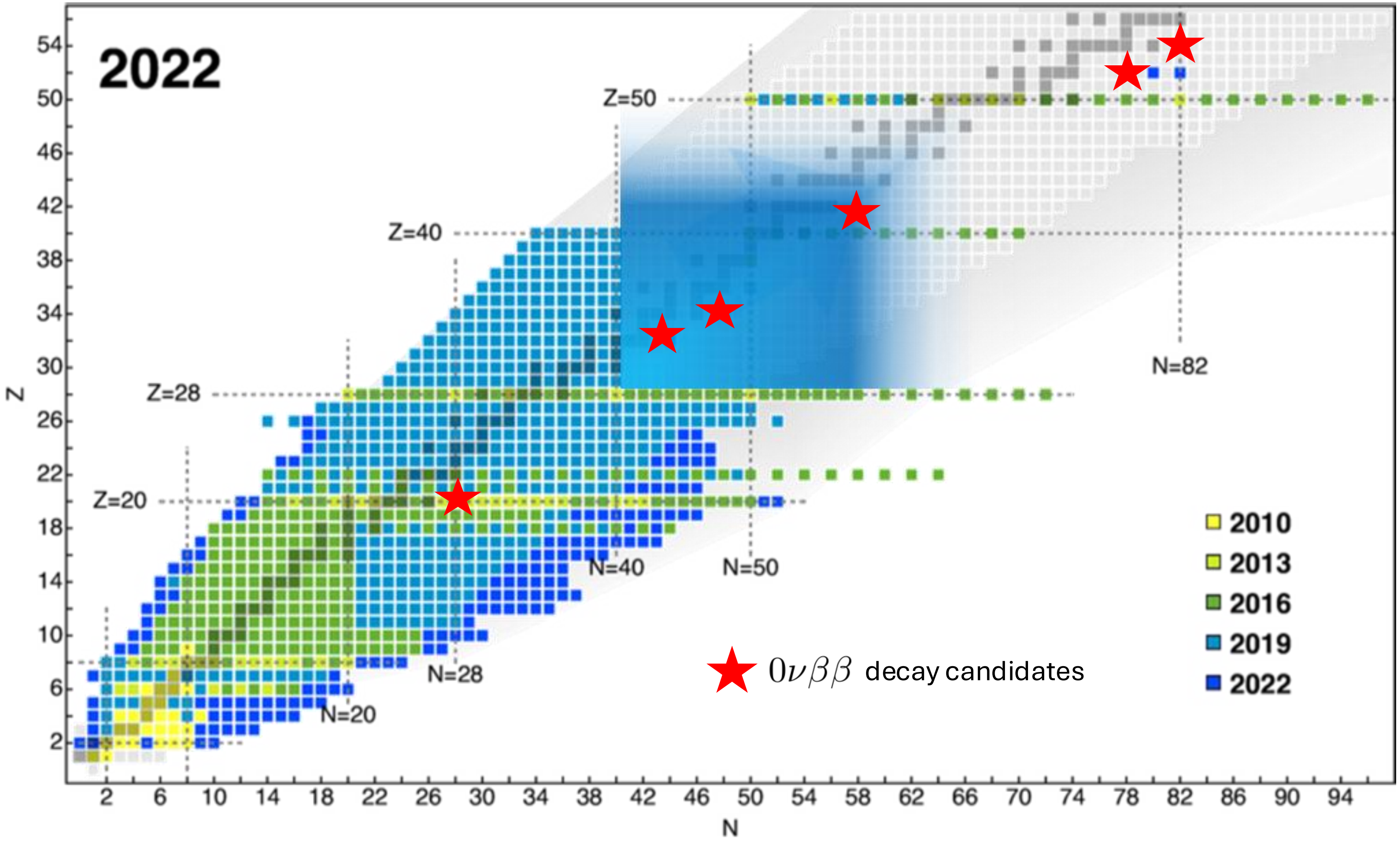
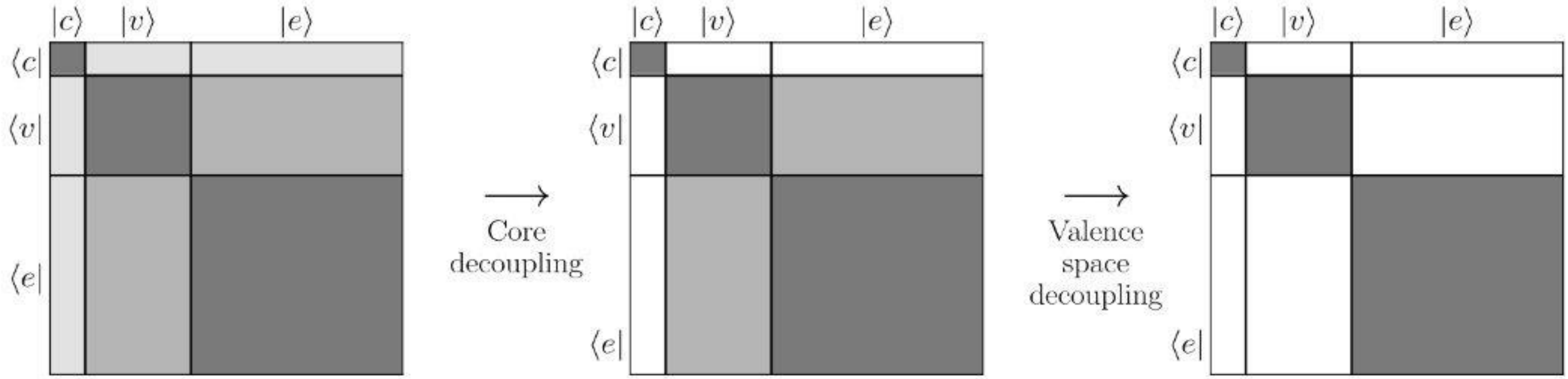
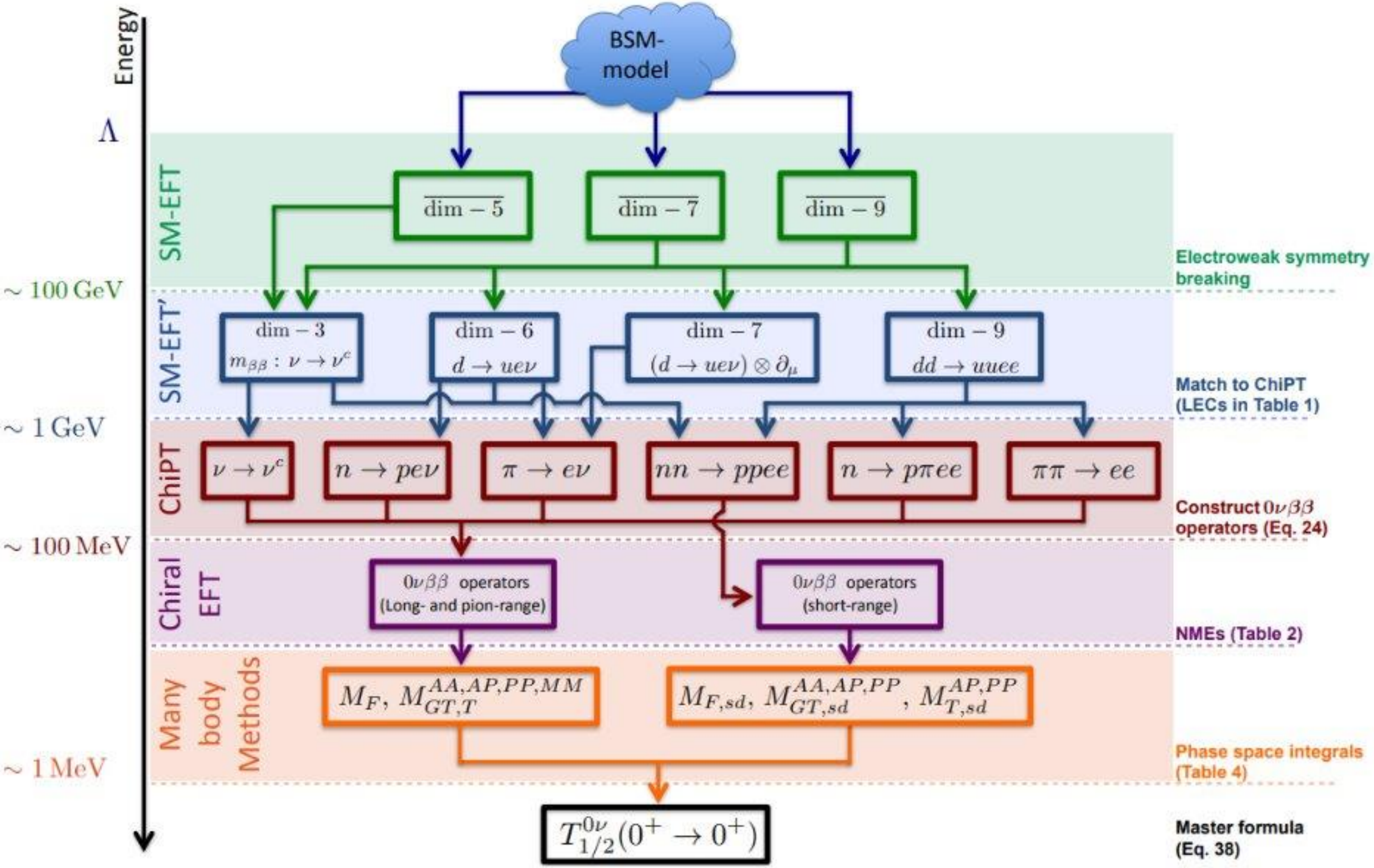


# Valence-space In-medium Similarity Renormalization Group (VS-IMSRG)




$$H(s) = e^{\Omega(s)} H(0) e^{-\Omega(s)} = \sum_{k=0}^{\infty} \frac{1}{k!} [\Omega(s), H(0)]^{(k)} = H + [\Omega, H] + \frac{1}{2}[\Omega, [\Omega, H]] + \cdots$$

# 0vββ "master formula"



# Model independence

***Leading order* decay rate for any BSM mechanism can be built out of 9 long-range NMEs and 8 short-range NMEs**

$$M_{\rm F},\, M_{\rm GT}^{\rm AA},\, M_{\rm GT}^{\rm AP},\, M_{\rm GT}^{\rm PP},\, M_{\rm GT}^{\rm MM},\, M_{\rm T}^{\rm AA},\, M_{\rm T}^{\rm AP},\, M_{\rm T}^{\rm PP},\, M_{\rm T}^{\rm MM}$$

$$M_{\rm F,sd},\, M_{\rm GT,sd}^{\rm AA},\, M_{\rm GT,sd}^{\rm AP},\, M_{\rm GT,sd}^{\rm PP},\, M_{\rm GT,sd}^{\rm MM},\, M_{\rm T,sd}^{\rm AP},\, M_{\rm T,sd}^{\rm PP},\, M_{\rm T,sd}^{\rm MM}$$