Ab Initio Nuclear Theory for Neutrinoless ββ Decay

Short-range Operators and Exotic Mechanisms

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McGill

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Institut canadien de physique nucléaire

Arthur B. McDonald Canadian Astroparticle Physics Research Institute

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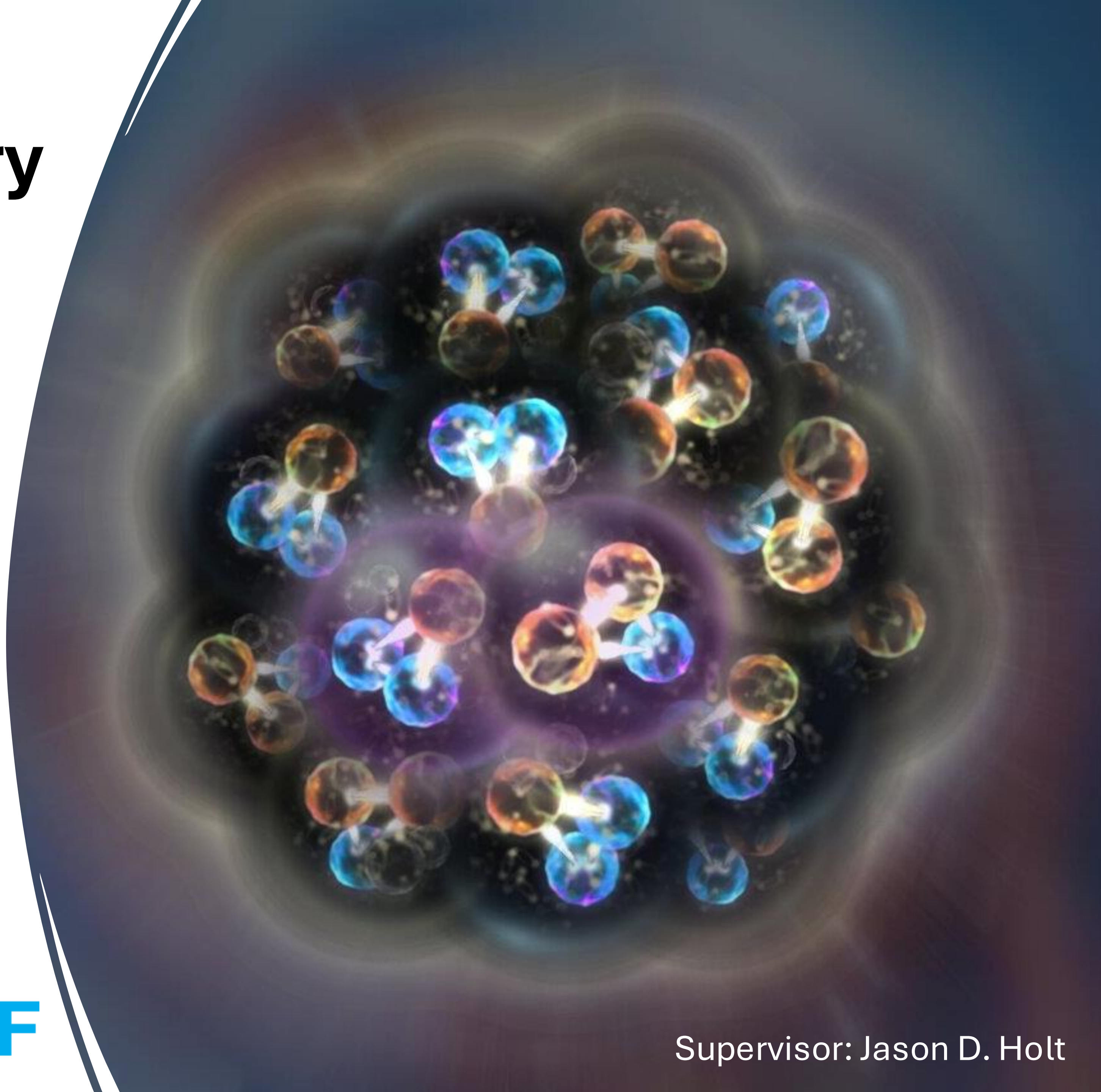
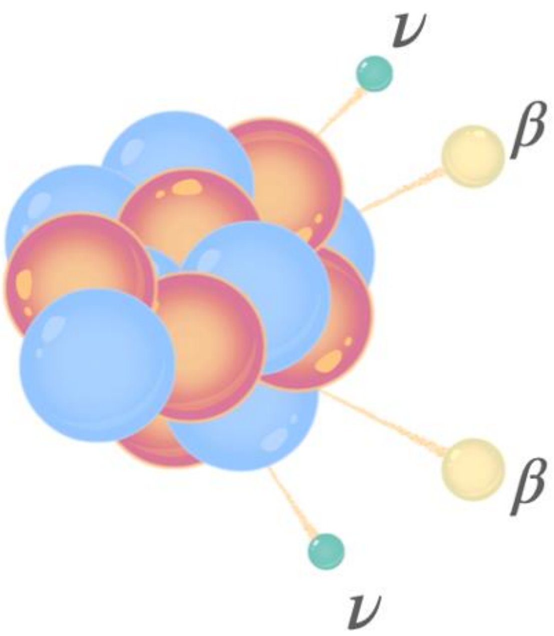


Supervisor: Jason D. Holt

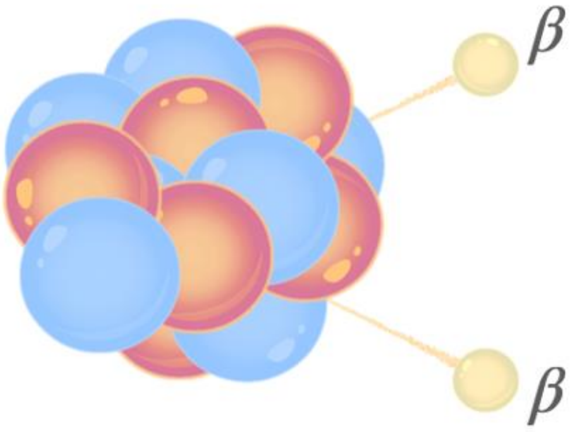
What is neutrinoless ββ decay?

ββ decay (2vββ)



(Observed)

Neutrinoless ββ decay (0vββ)



(Hypothetical)

What is neutrinoless ββ decay?

<u>0νββ probes:</u>

- 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?

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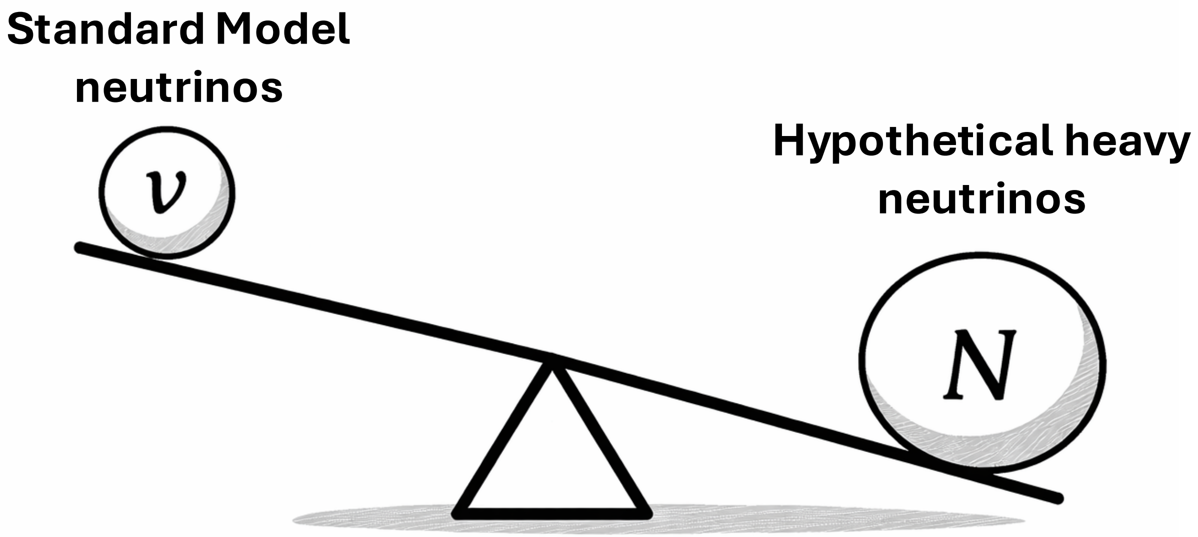

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An observation of 0νββ would immediately confirm these ✅

Interpretations rely on nuclear theory 😬

Decay rate

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

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

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

Half-life (what is measured)

Nuclear matrix element (NME)

Nuclear Matrix Element

Initial and final states

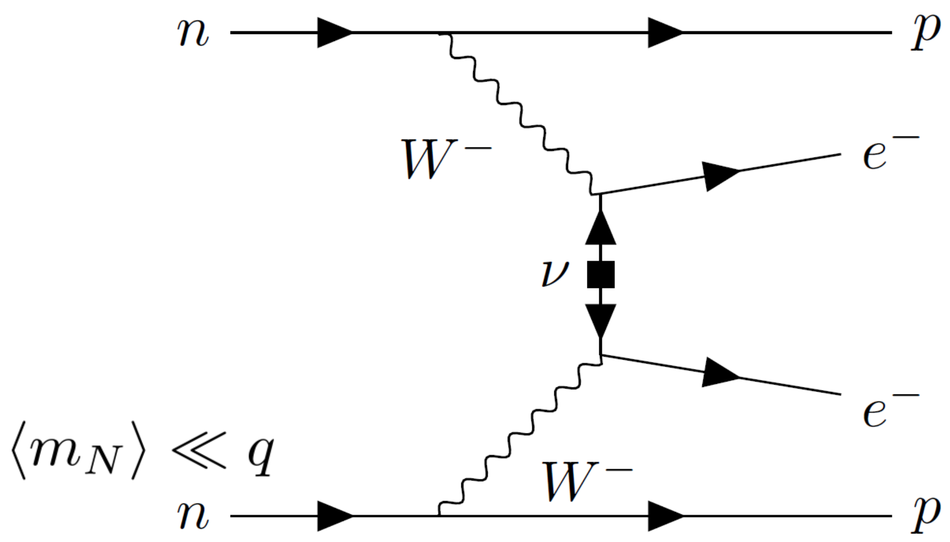
$$\mathcal{M}^{0\nu} = \langle f | \mathcal{O}^{0\nu} | i \rangle$$

Decay operator encodes specific mechanisms

Decay Mechanism Example

Light neutrino exchange (long-range)

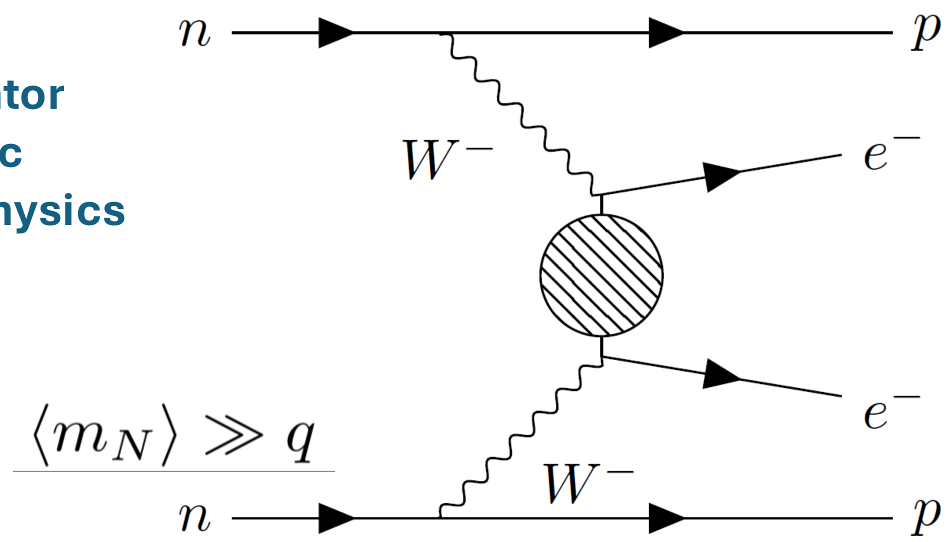
$$\left[T_{1/2}^{0\nu}\right]^{-1}_{\text{light}} = g_A^4 G^{0\nu} |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$



Heavy neutrino exchange (short-range)

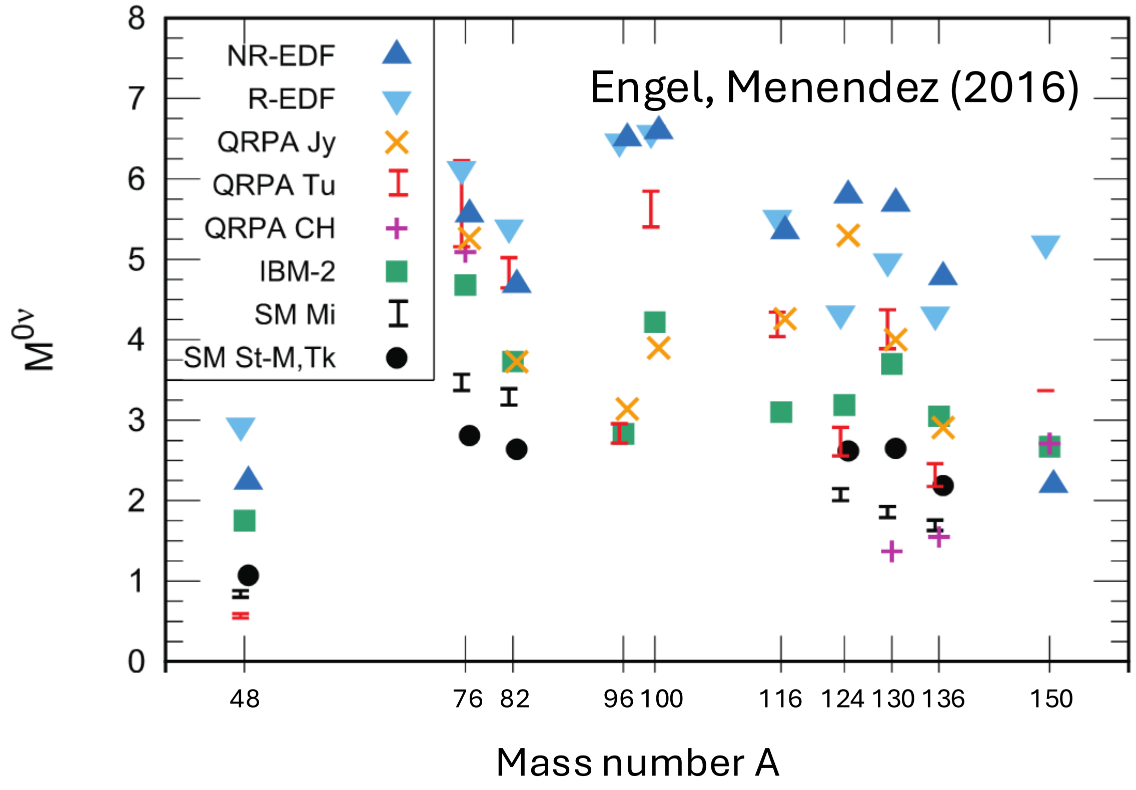
$$\left[T_{1/2}^{0\nu}\right]^{-1}_{\text{heavy}} = g_A^4 G^{0\nu} \left|\frac{m_\pi^2}{m_e \langle m_N \rangle} \mathcal{M}^{0N}\right|^2$$

Contact operator encodes exotic high-energy physics



NME uncertainty

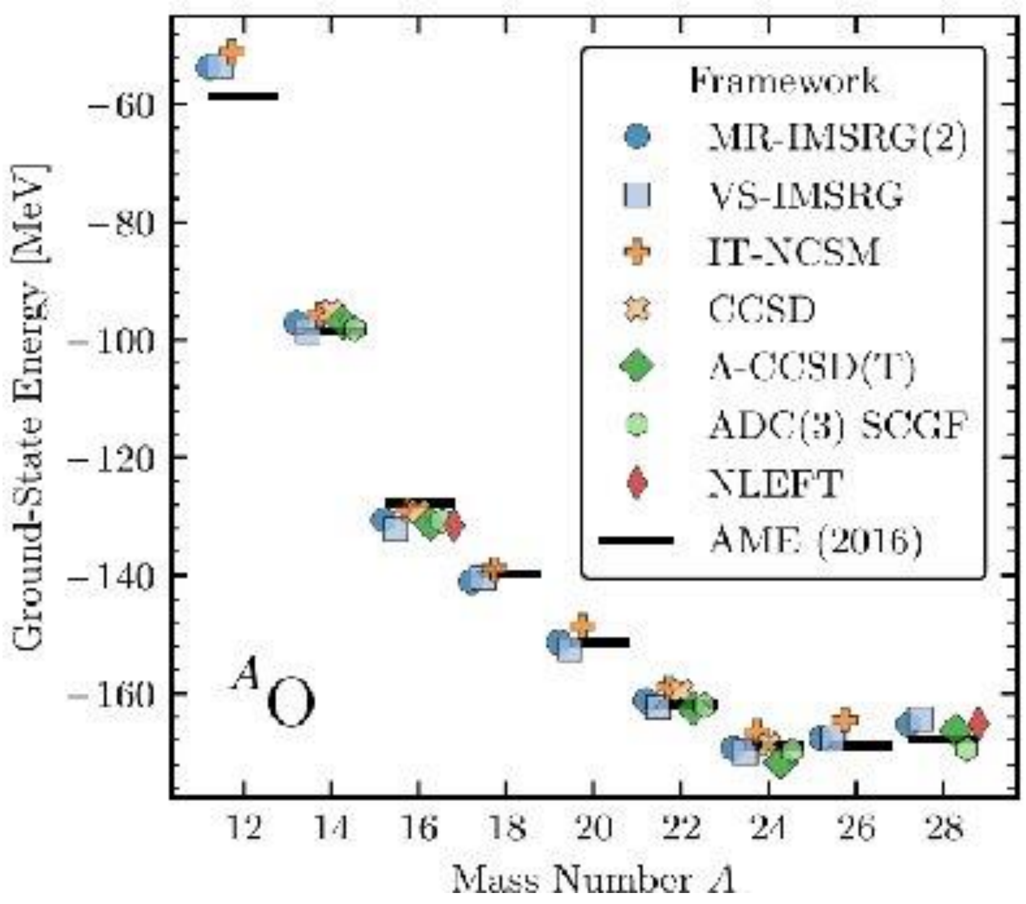
Phenomenological Methods (fit to data)



Large NME uncertainty = large mass uncertainty

NME uncertainty

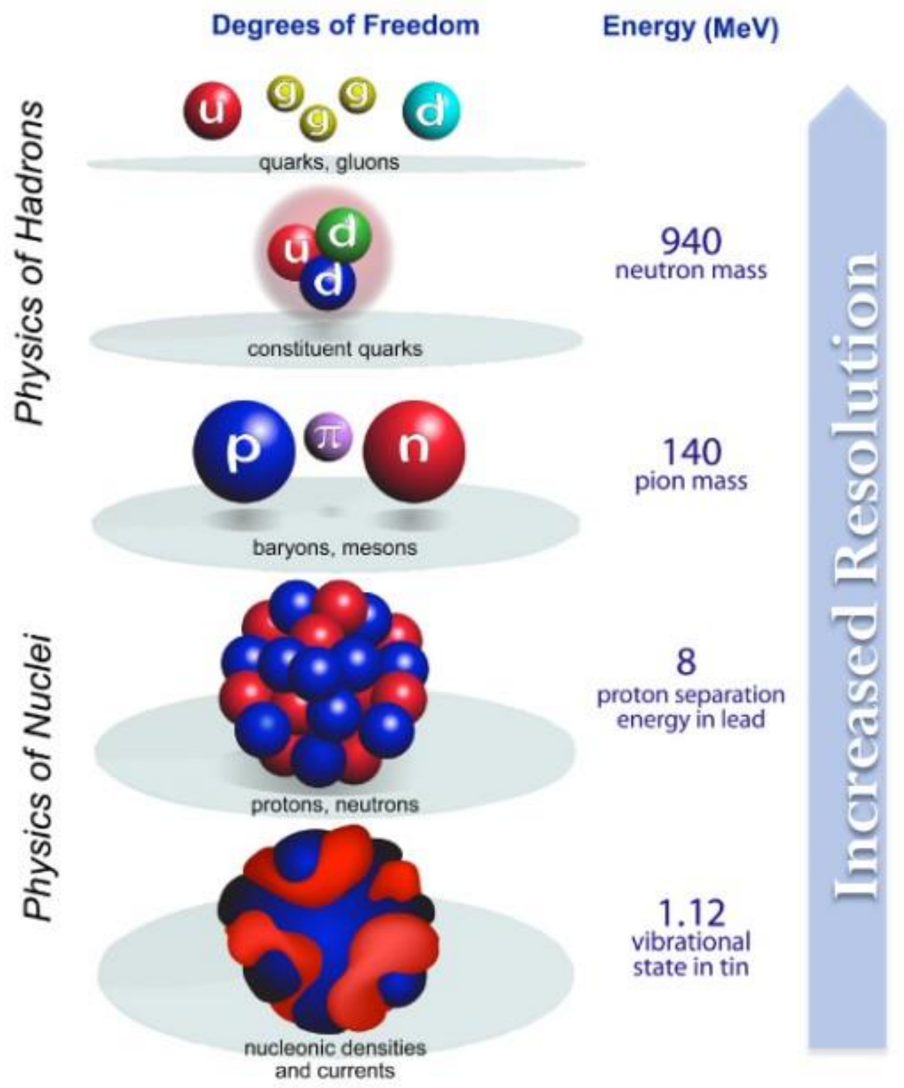
Ab initio Nuclear Theory
(from first-principles)



Nuclear Matrix Element

Why are the NMEs so hard to calculate?

The nucleus is complicated



Phenomenological nuclear models

Fit Hamiltonian to data,
then predict

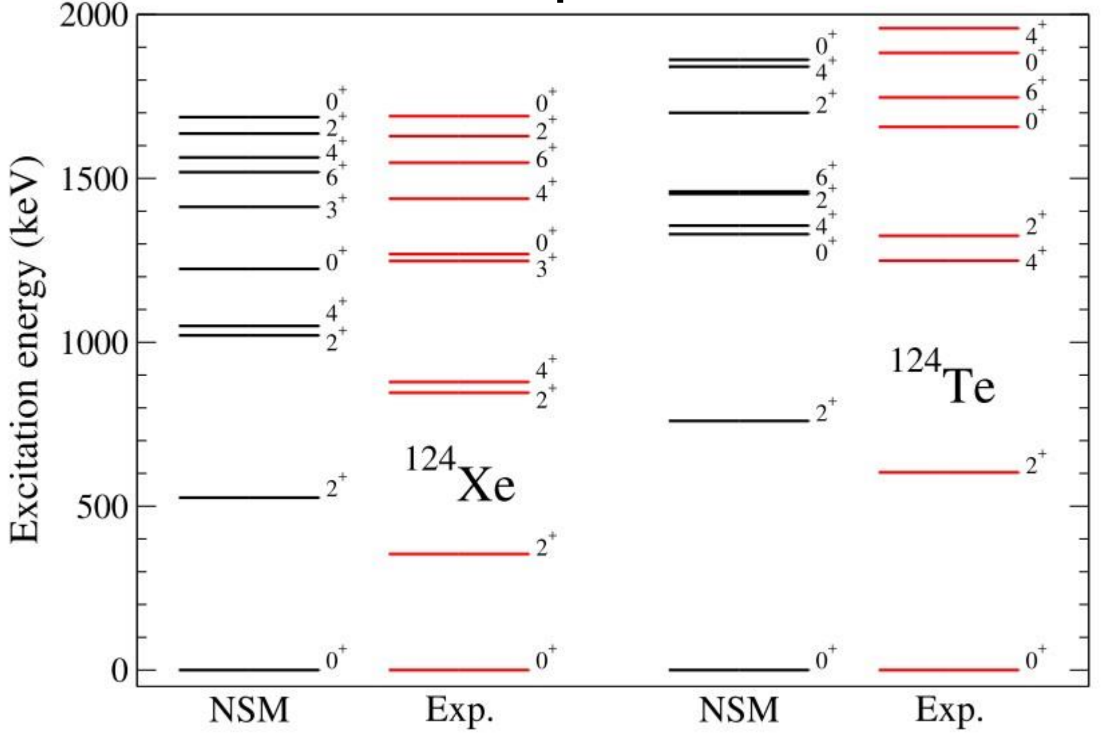
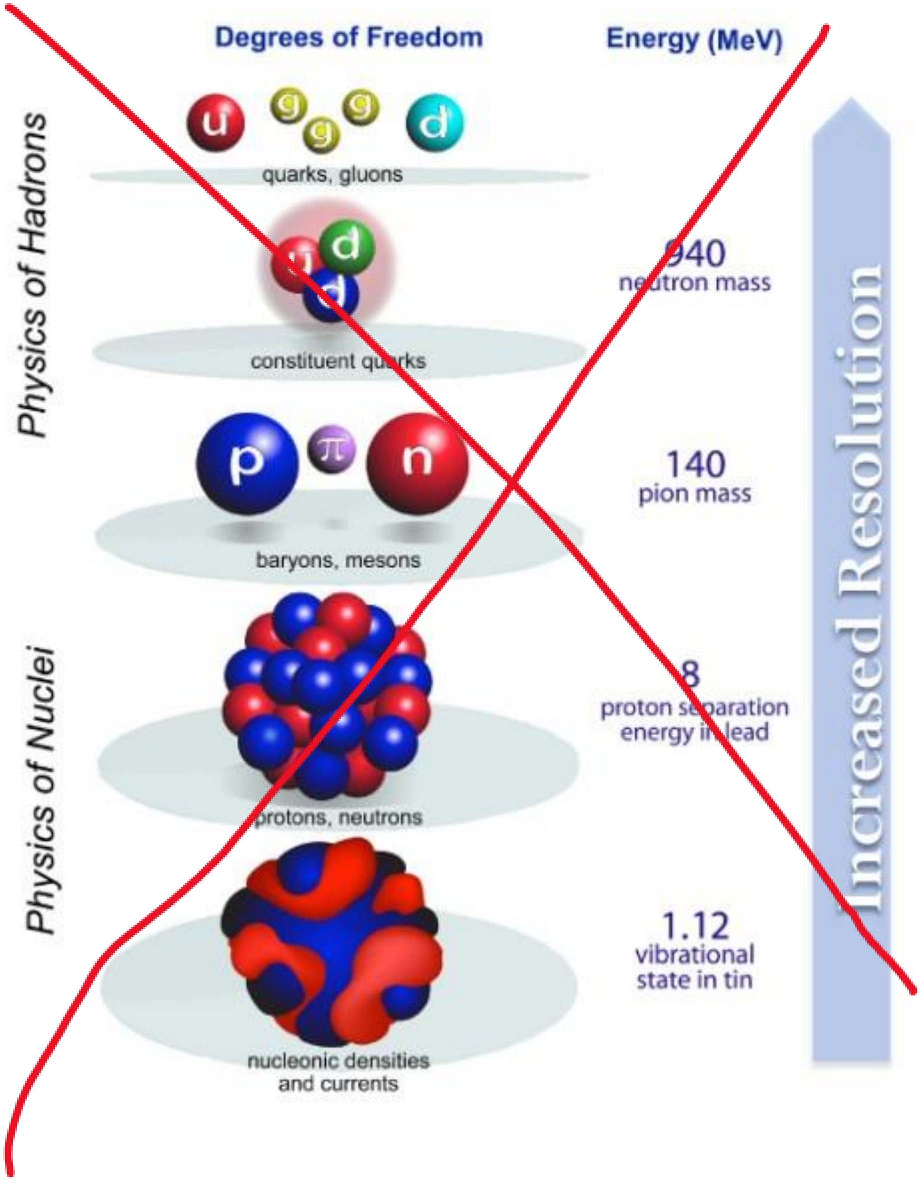
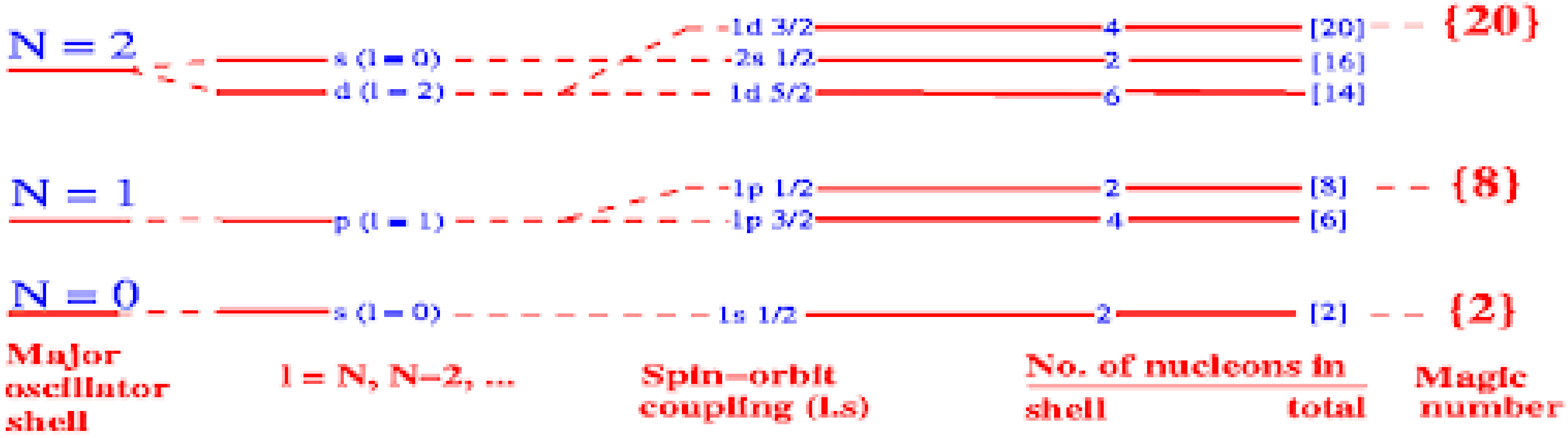


Fig. 1. ^{124}Xe and ^{124}Te excitation spectra obtained by the nuclear shell model (NSM) compared to experiment [74].

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



Nuclear shell-model



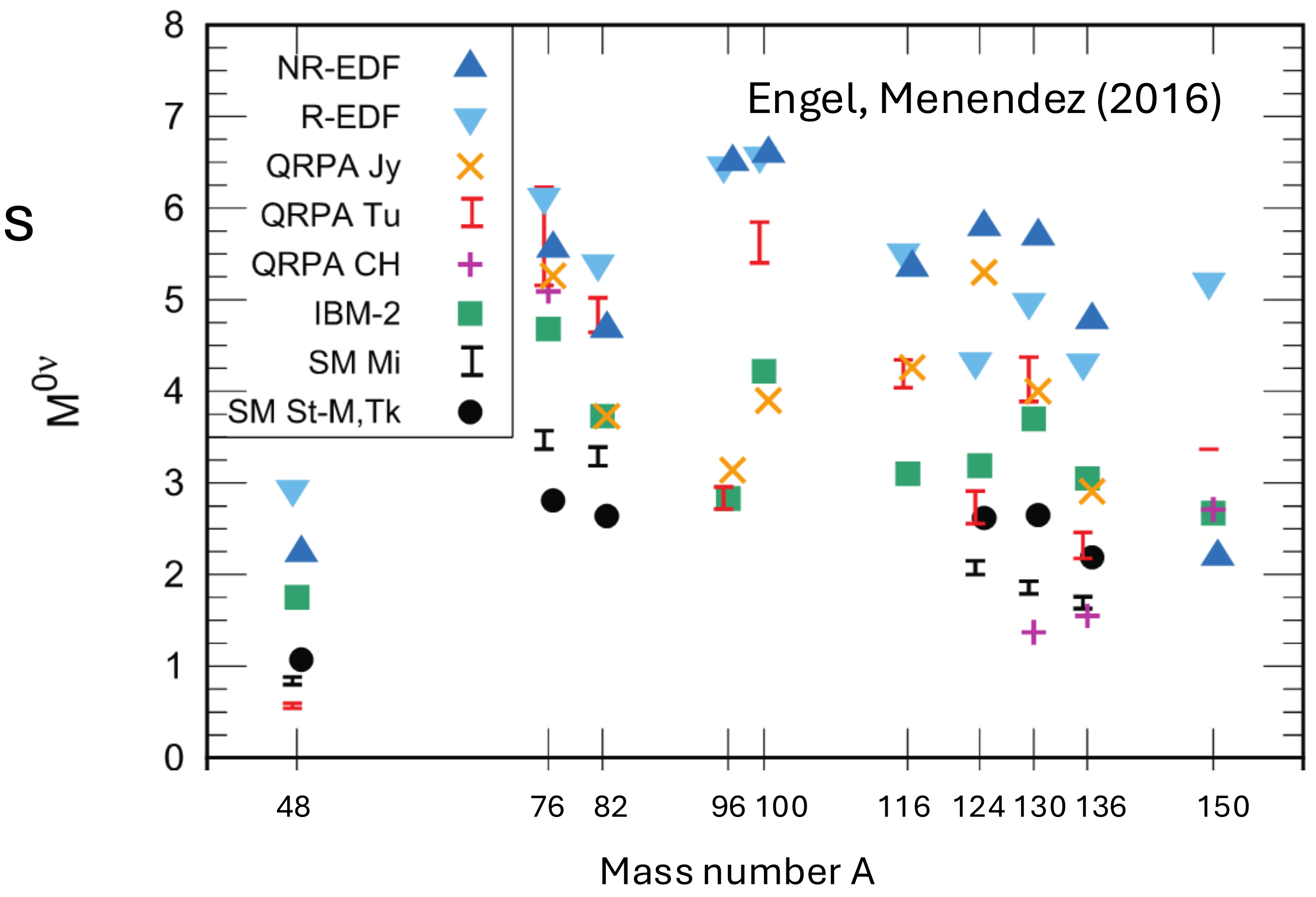
Maria Goeppert-Mayer

"The shell model, although proposed by theoreticians, really corresponds to the **experimentalist's approach**. It was born from a thorough study of the **experimental data**, plotting them in different ways, and looking for interconnections." -Maria Geoppert Mayer

Issues with phenomenological methods

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

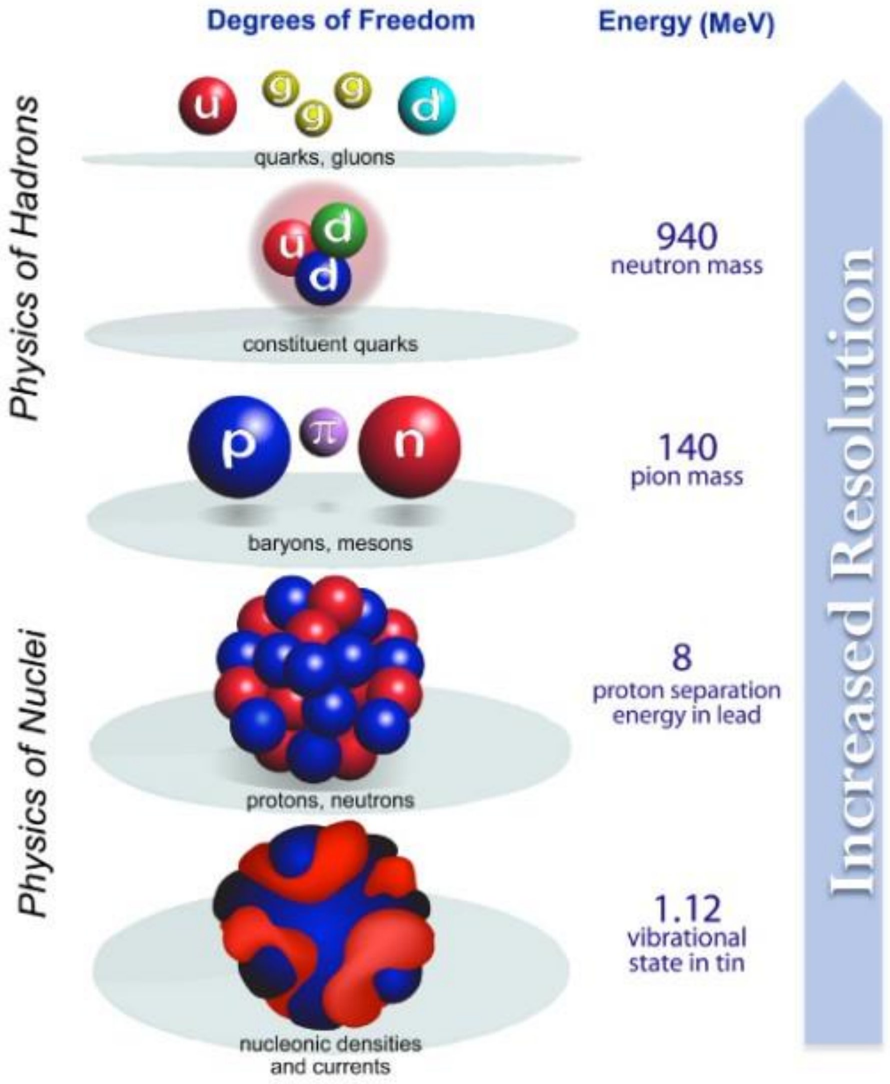
- ➢ Large spread in results
- ➢ No path for understanding uncertainty



We can do better!

Renormalization group:
Effective description of higher-scale physics

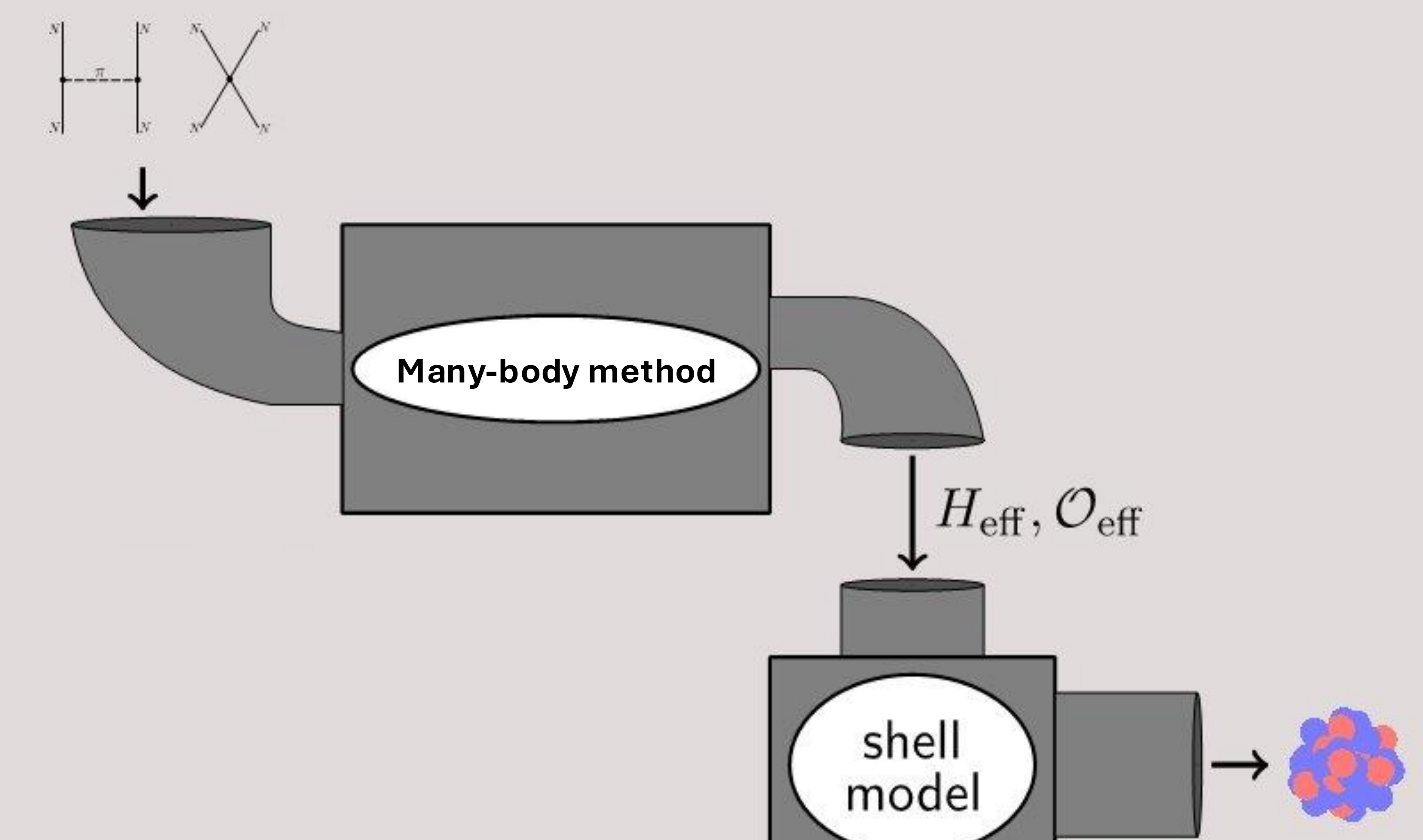
$$H(\Lambda) = T + V_{\rm NN}(\Lambda) + V_{\rm 3N}(\Lambda) + V_{\rm 4N}(\Lambda) + \cdots$$



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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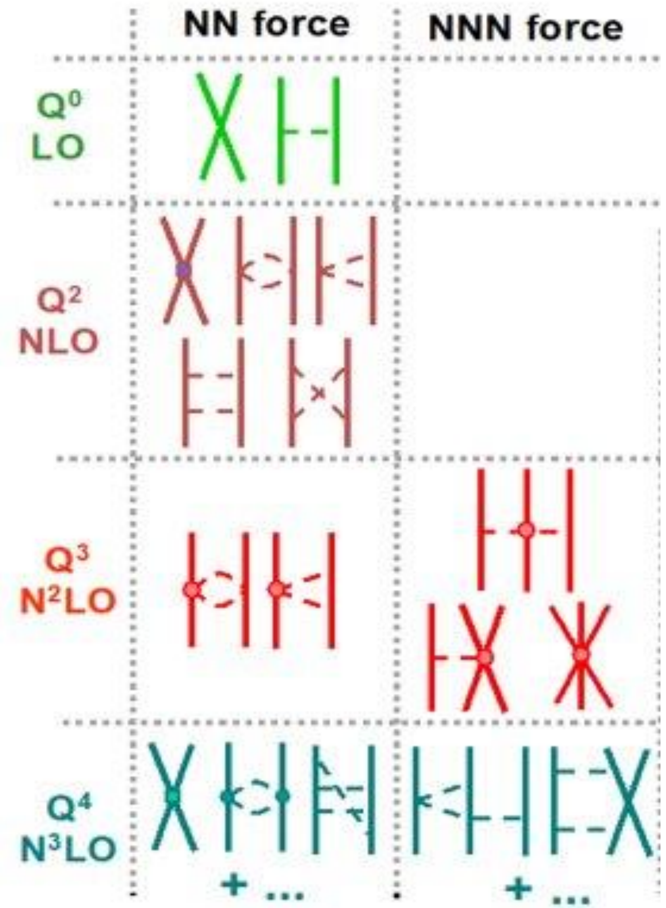

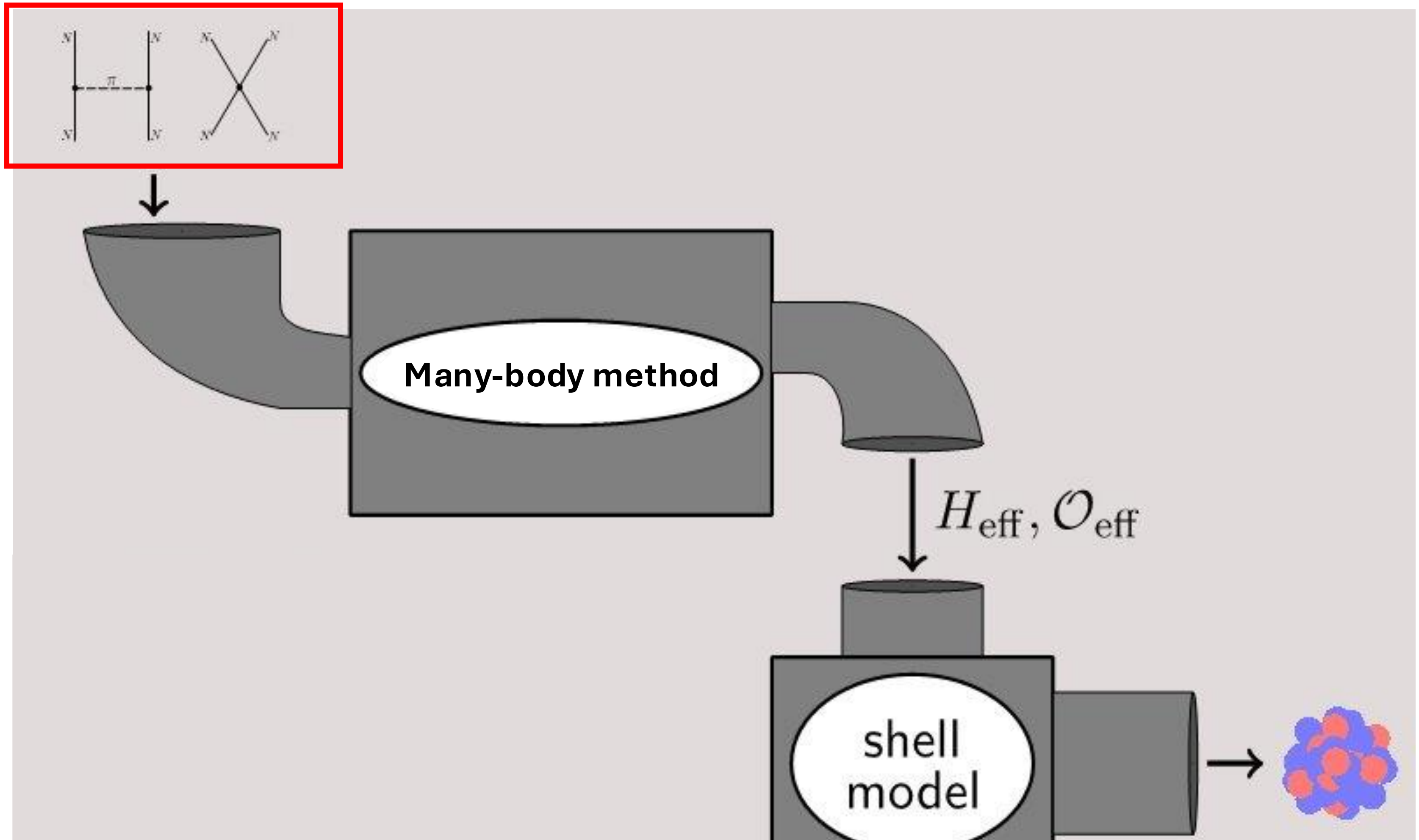

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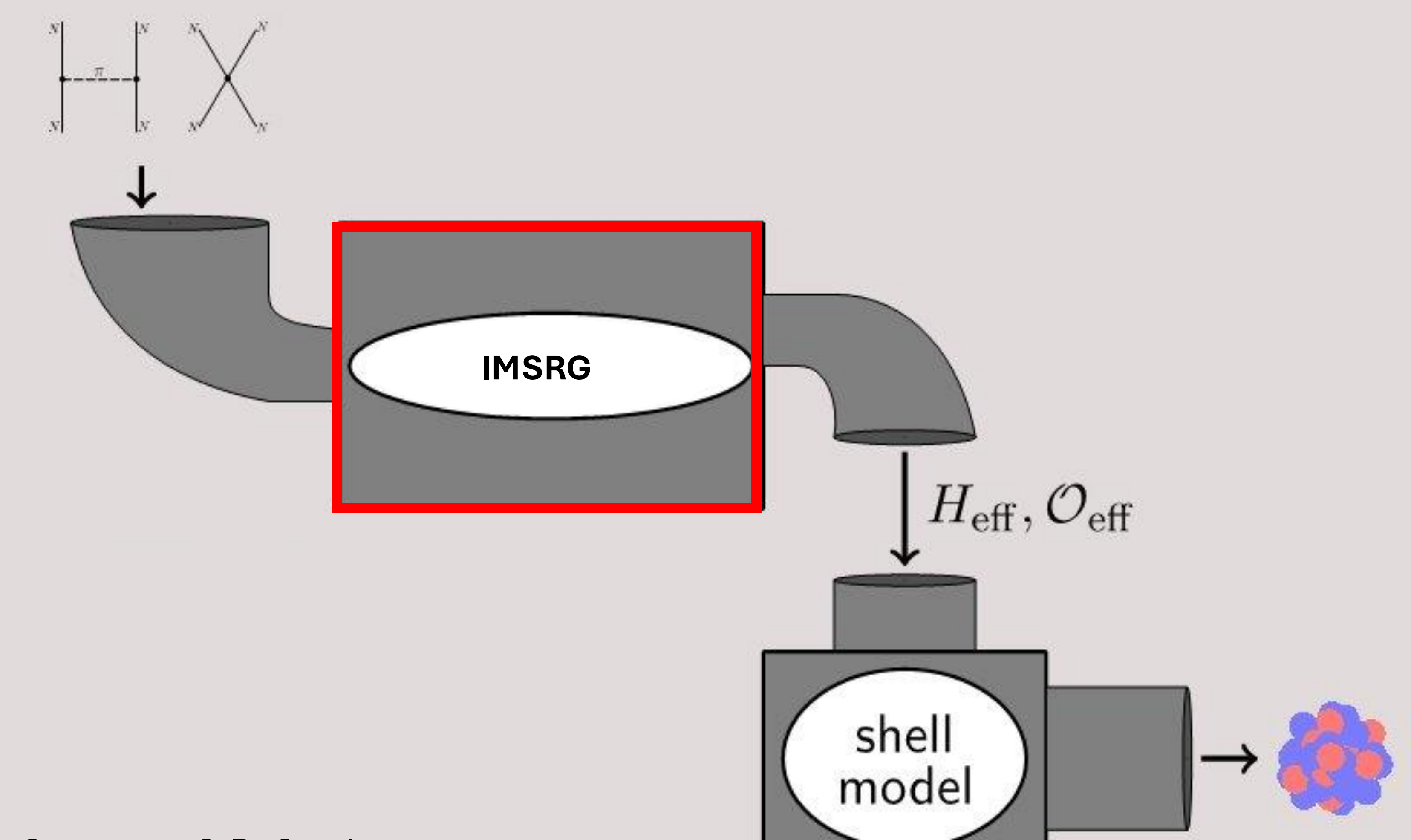
$$H(s) = e^{\Omega(s)} H e^{-\Omega(s)}$$

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

Continuous unitary transformations of Hamiltonian



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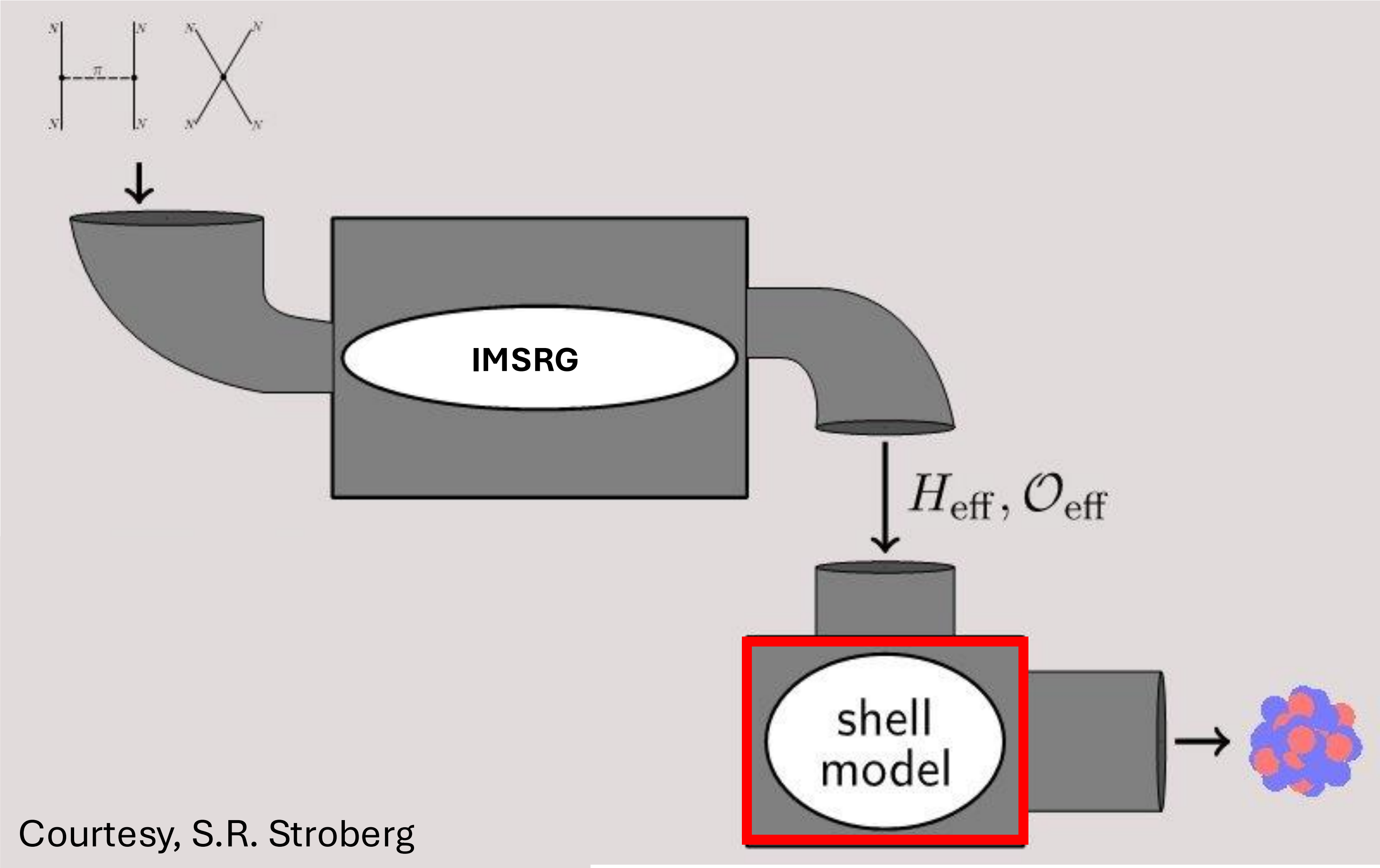
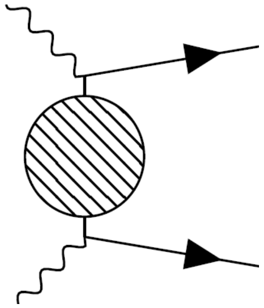


Diagonalize $\mathcal{H}$ **!!**

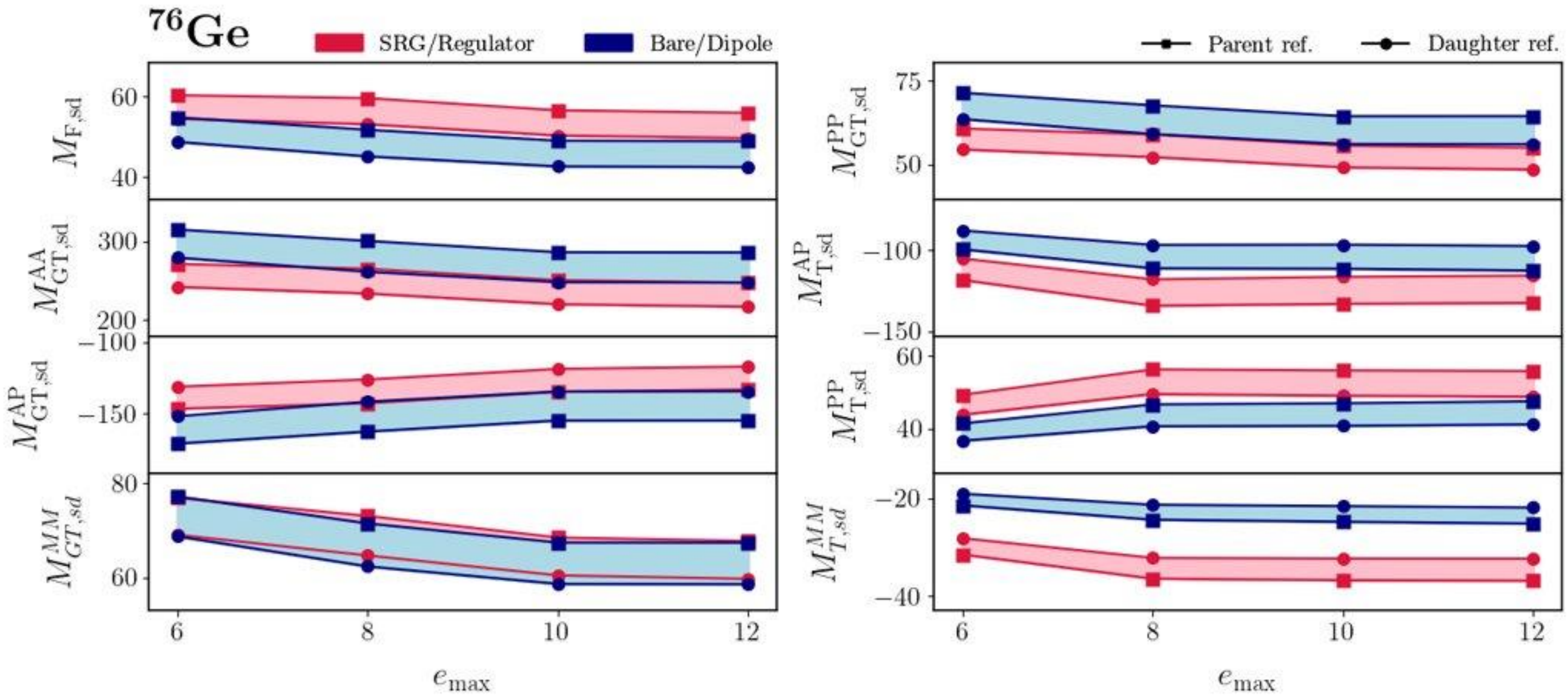


Short-range nuclear matrix elements

Be careful with renormalization

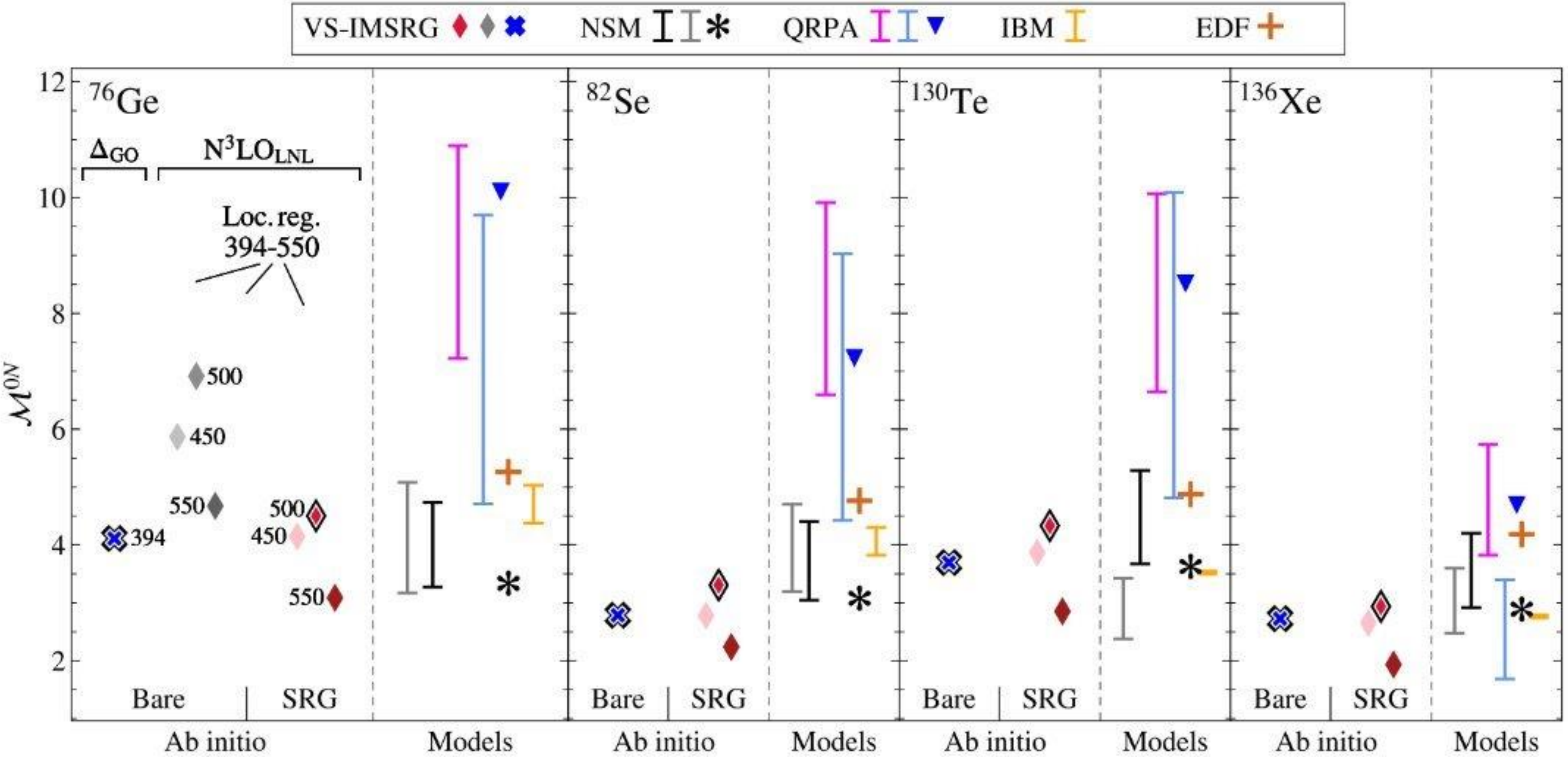
Usually we neglect this; but consistency is important for short-range operators

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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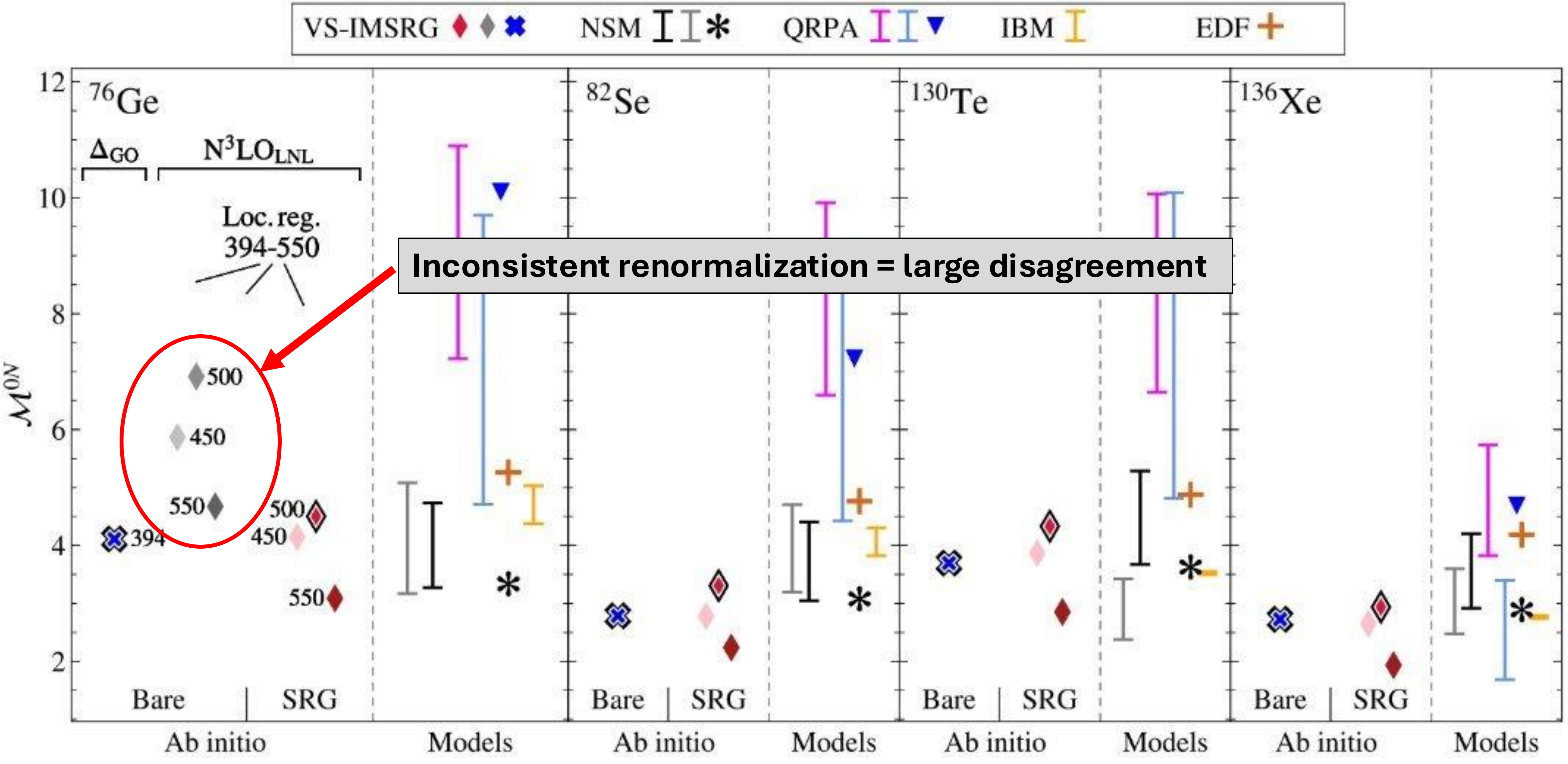

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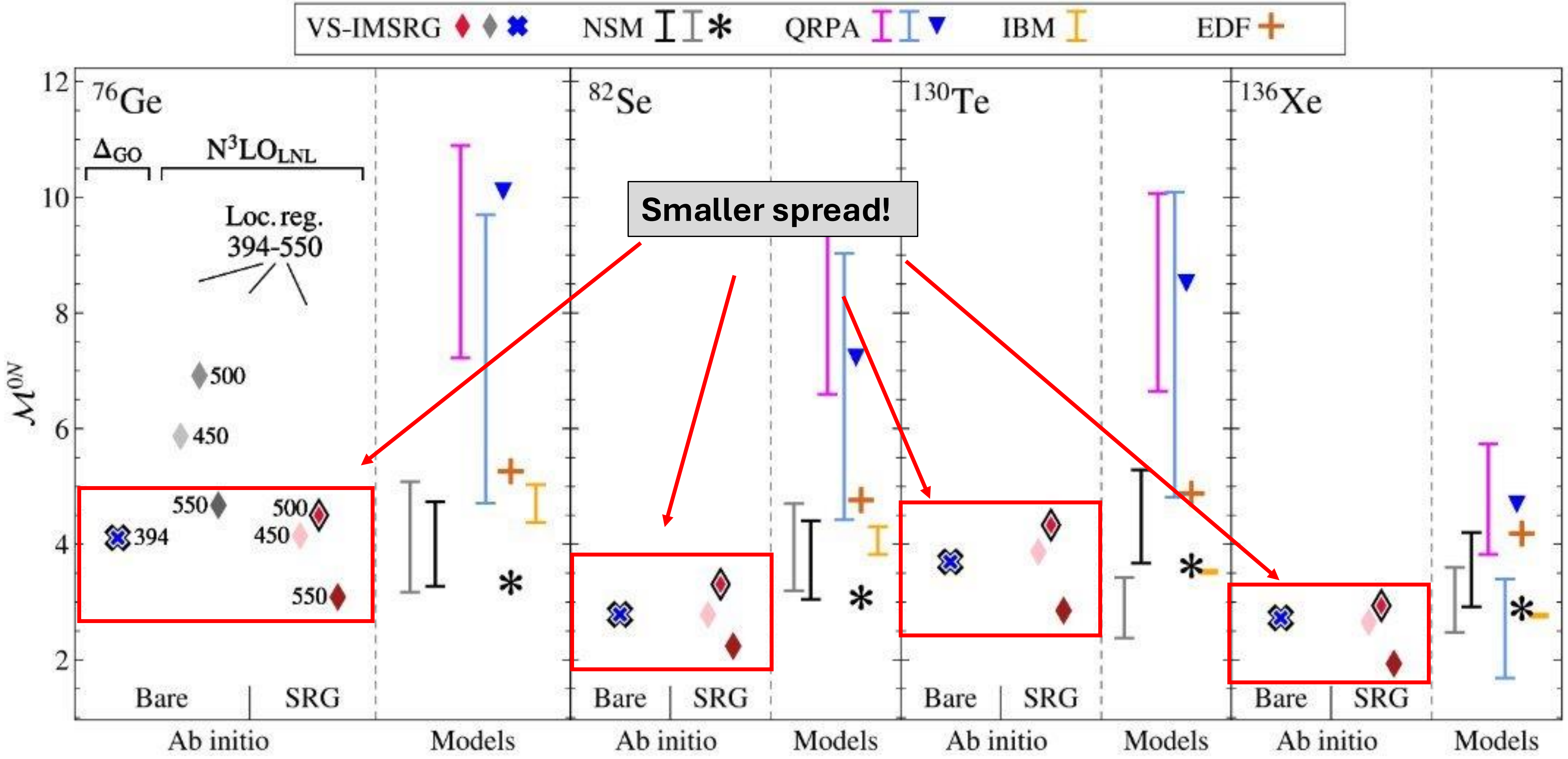

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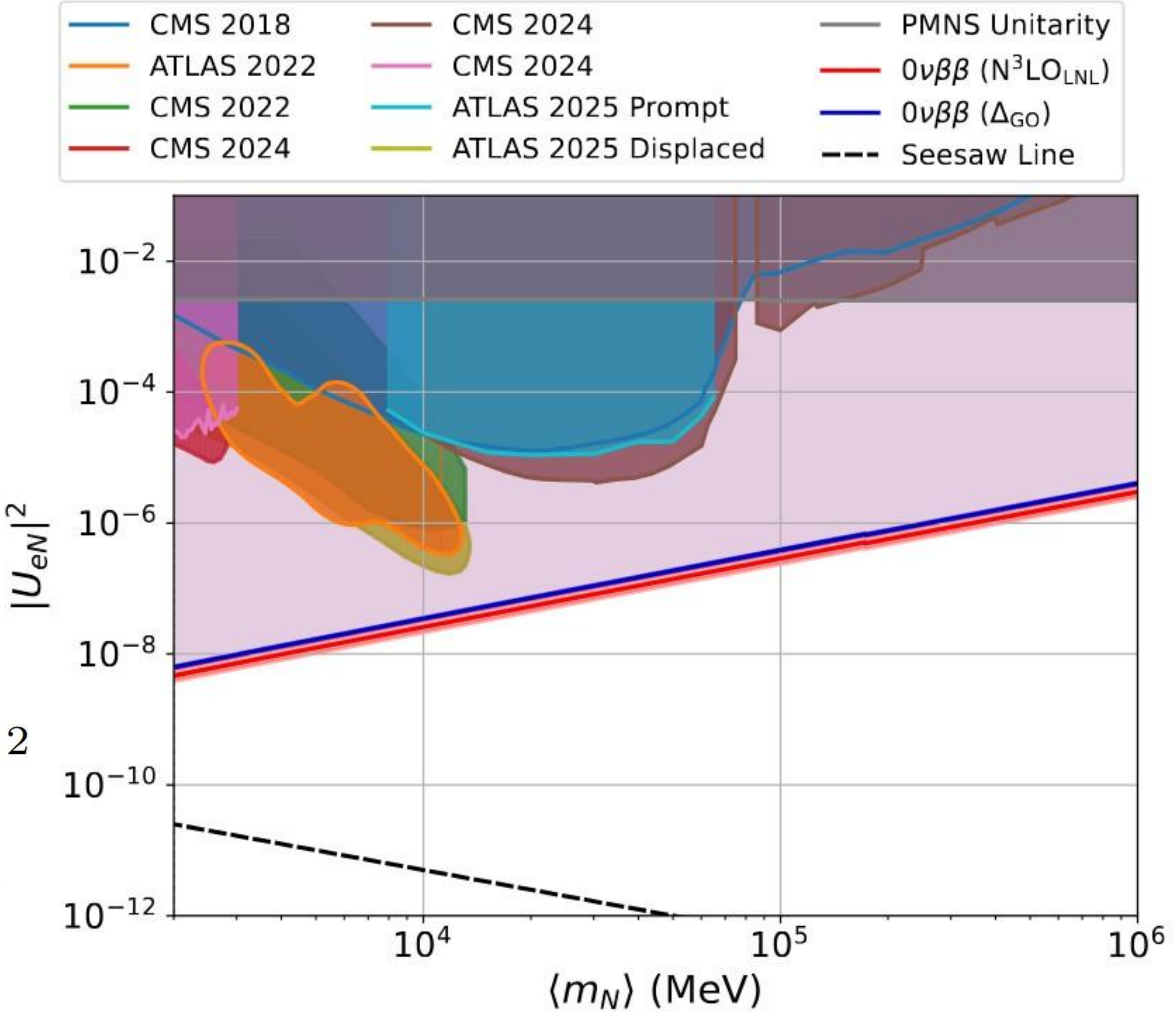
Connection to BSM mechanisms

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

$$\left[T_{1/2}^{0\nu}\right]^{-1} = g_A^4 G_{01} \left|\mathcal{A}_L^{(9)}(m_4)\right|^2$$

$$= \left|\mathcal{M}^{0N}\right|^2 \left|U_{eN} \frac{m_p}{m_4}\right|^2$$



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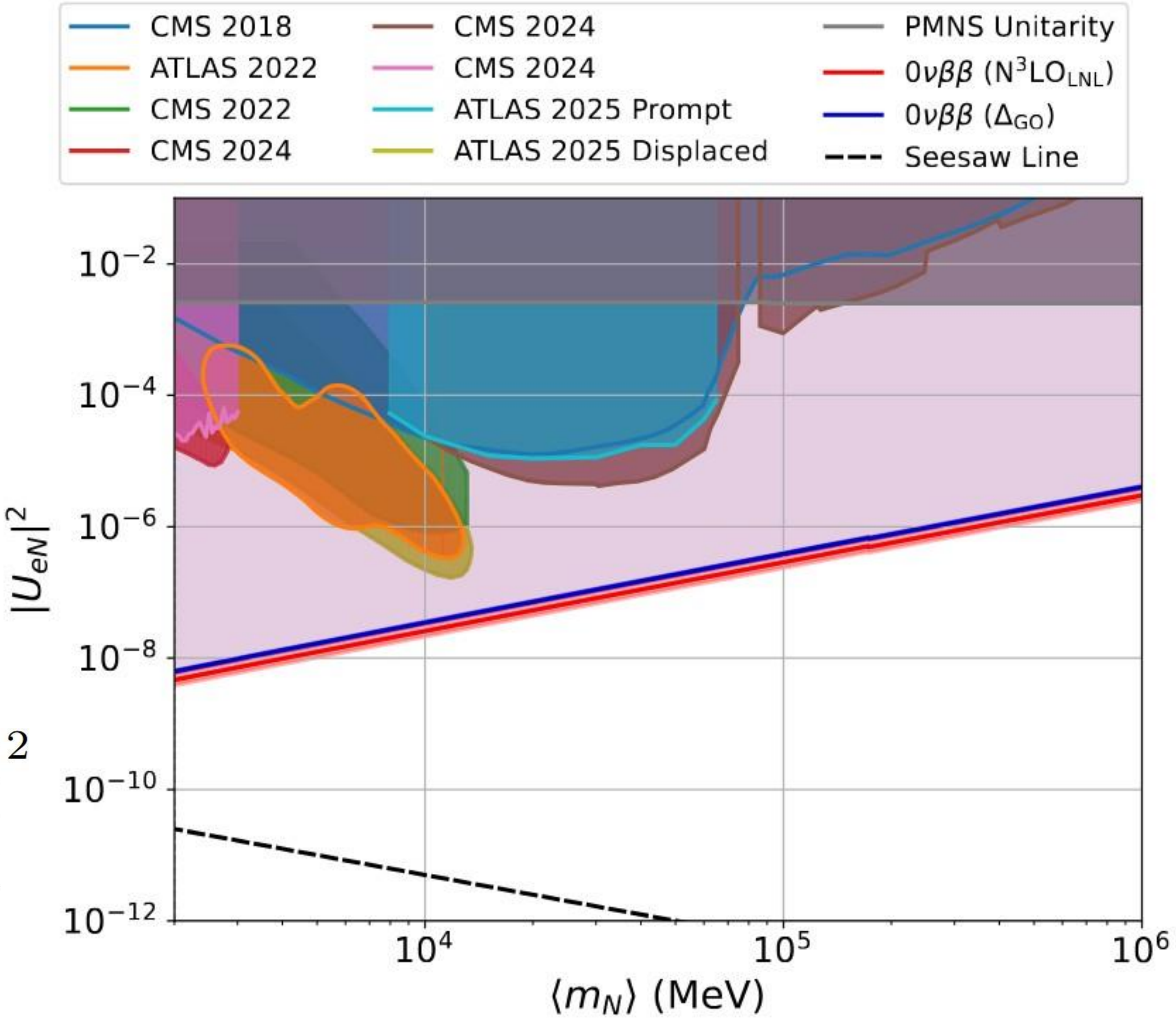

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Taiki Shickele

Antoine Belley

Lotta Jokiniemi

Jason Holt

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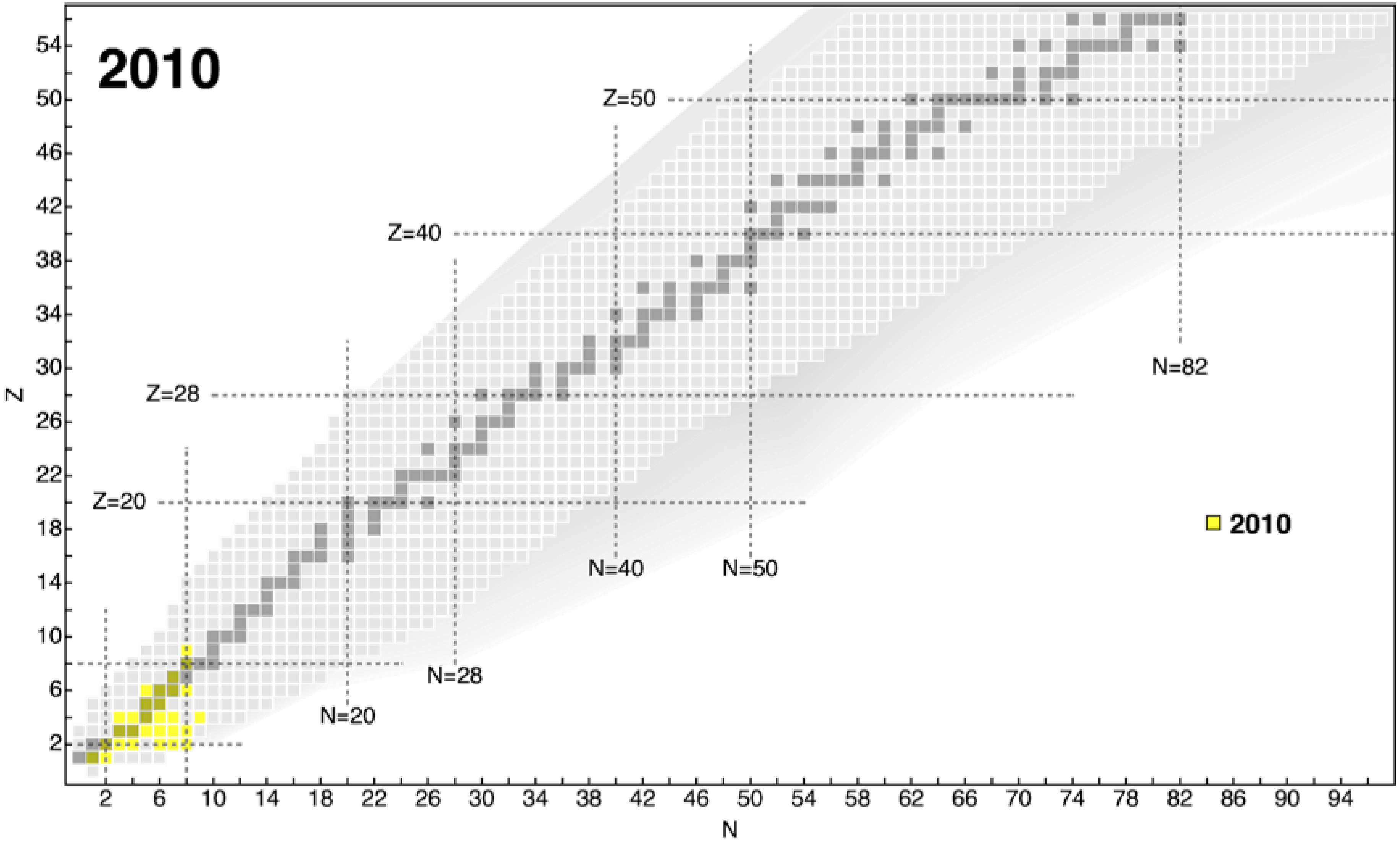
Backup Slides

Ab initio progress



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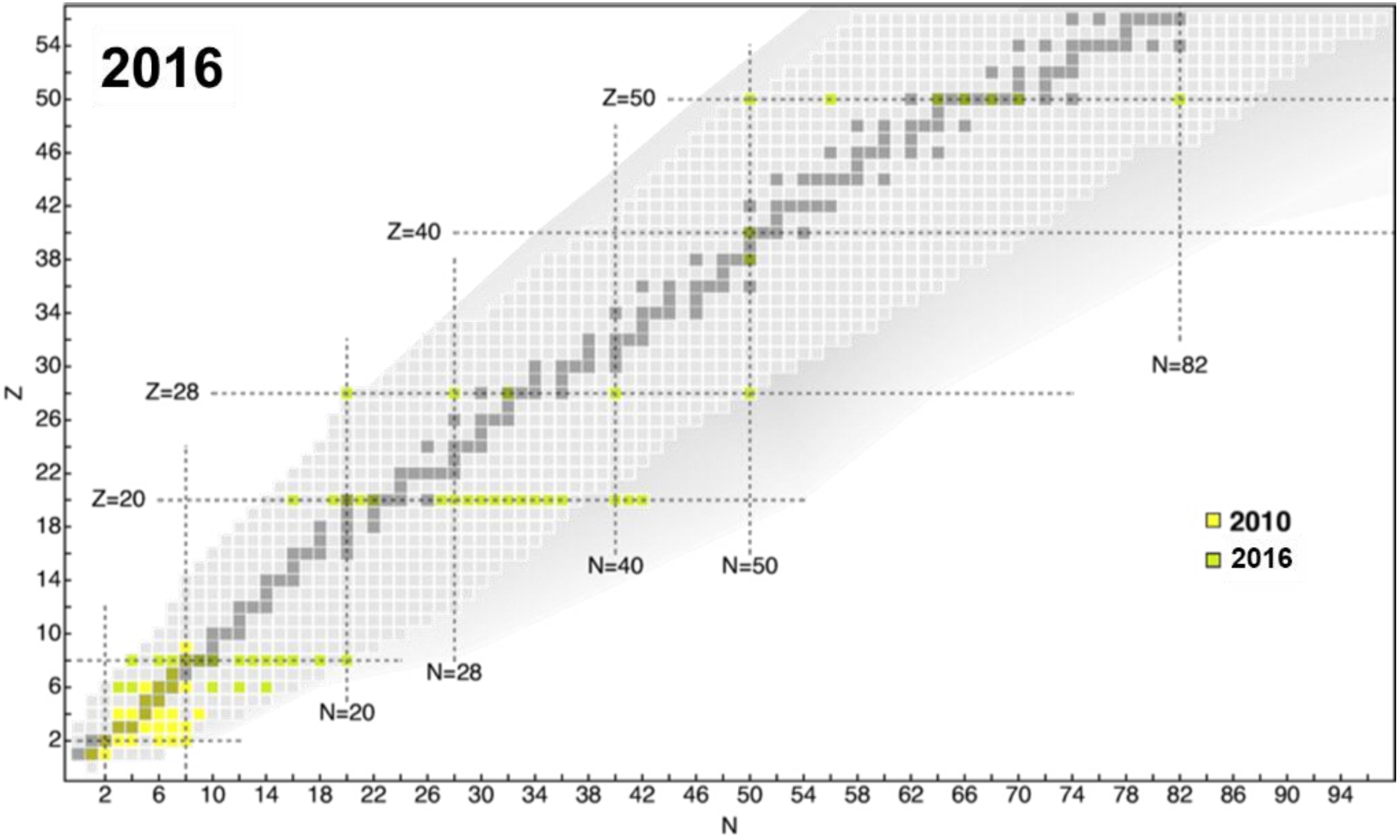

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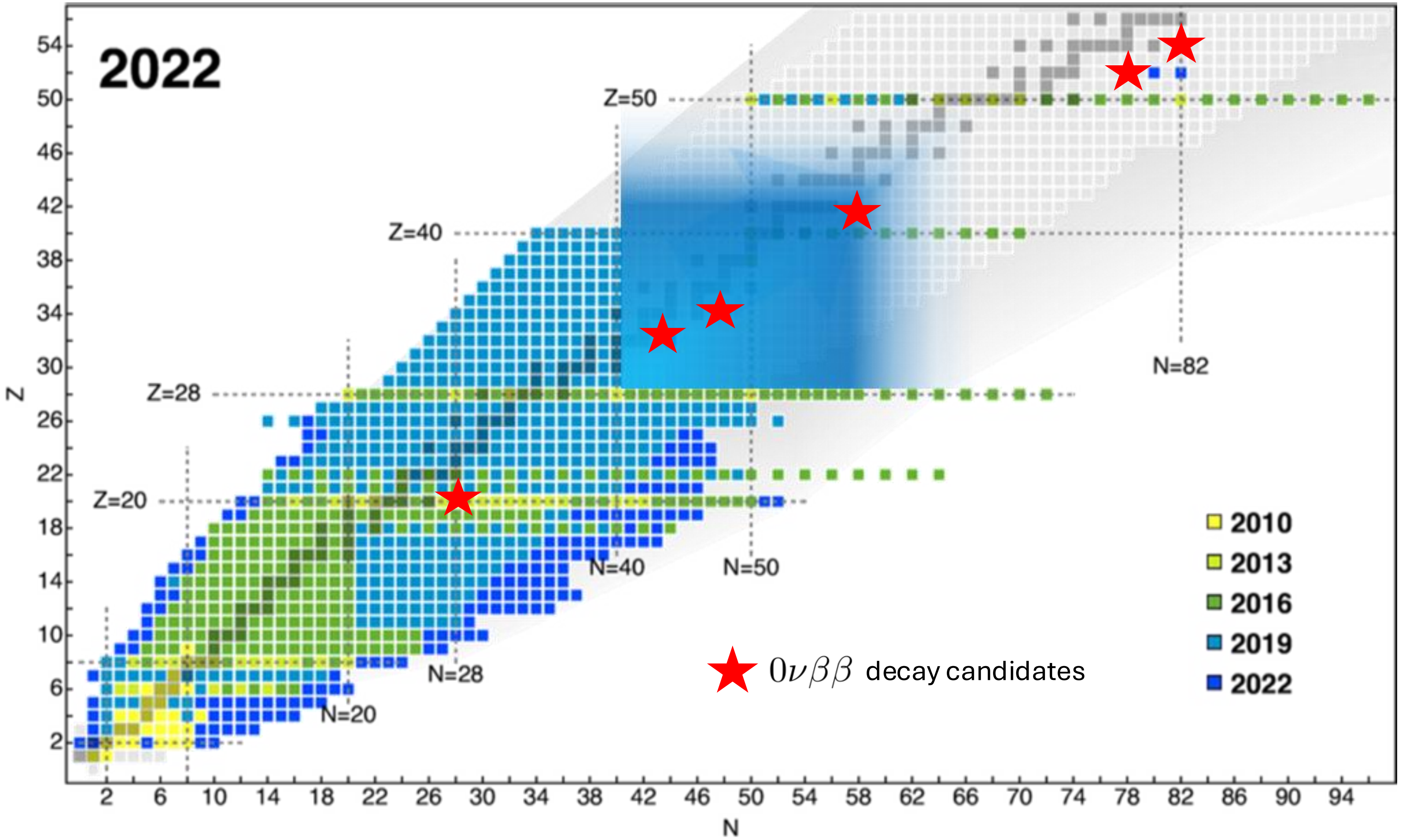
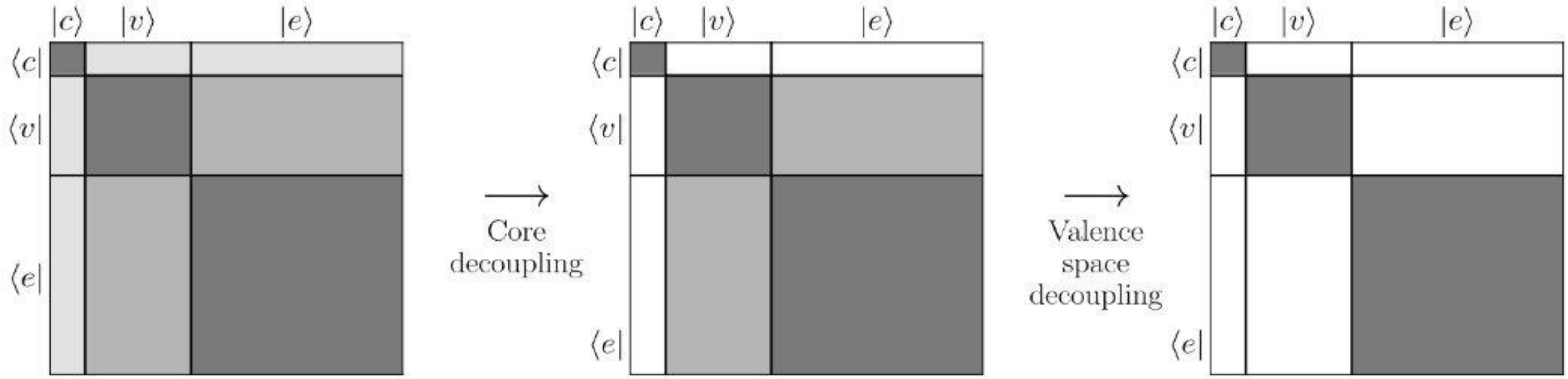
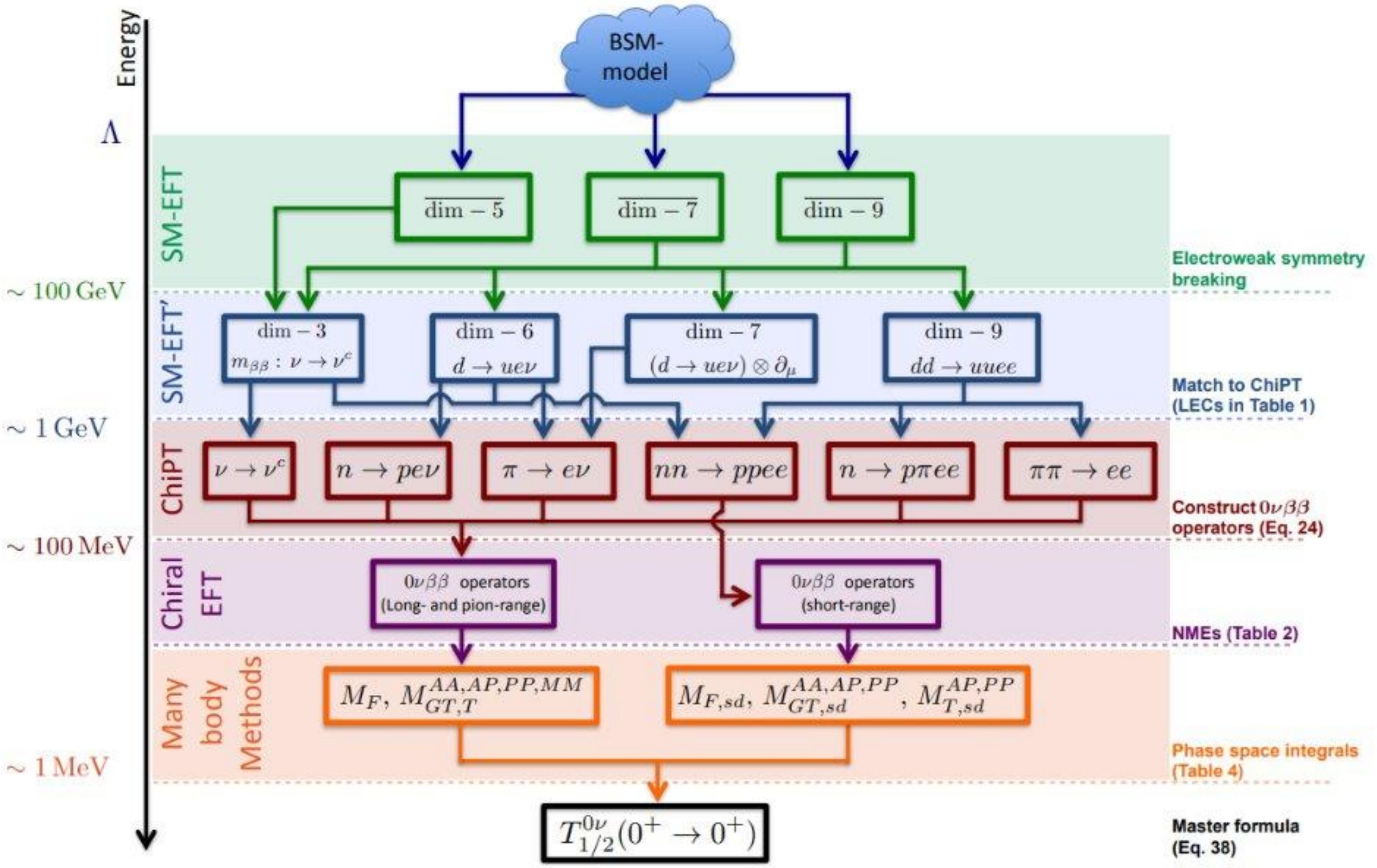


Valence-space In-medium Similarity Renormalization Group (VS-IMSRG)



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

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**

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

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