# Short-Range Contributions to Neutrinoless ββ Decay from Ab Initio Nuclear Theory

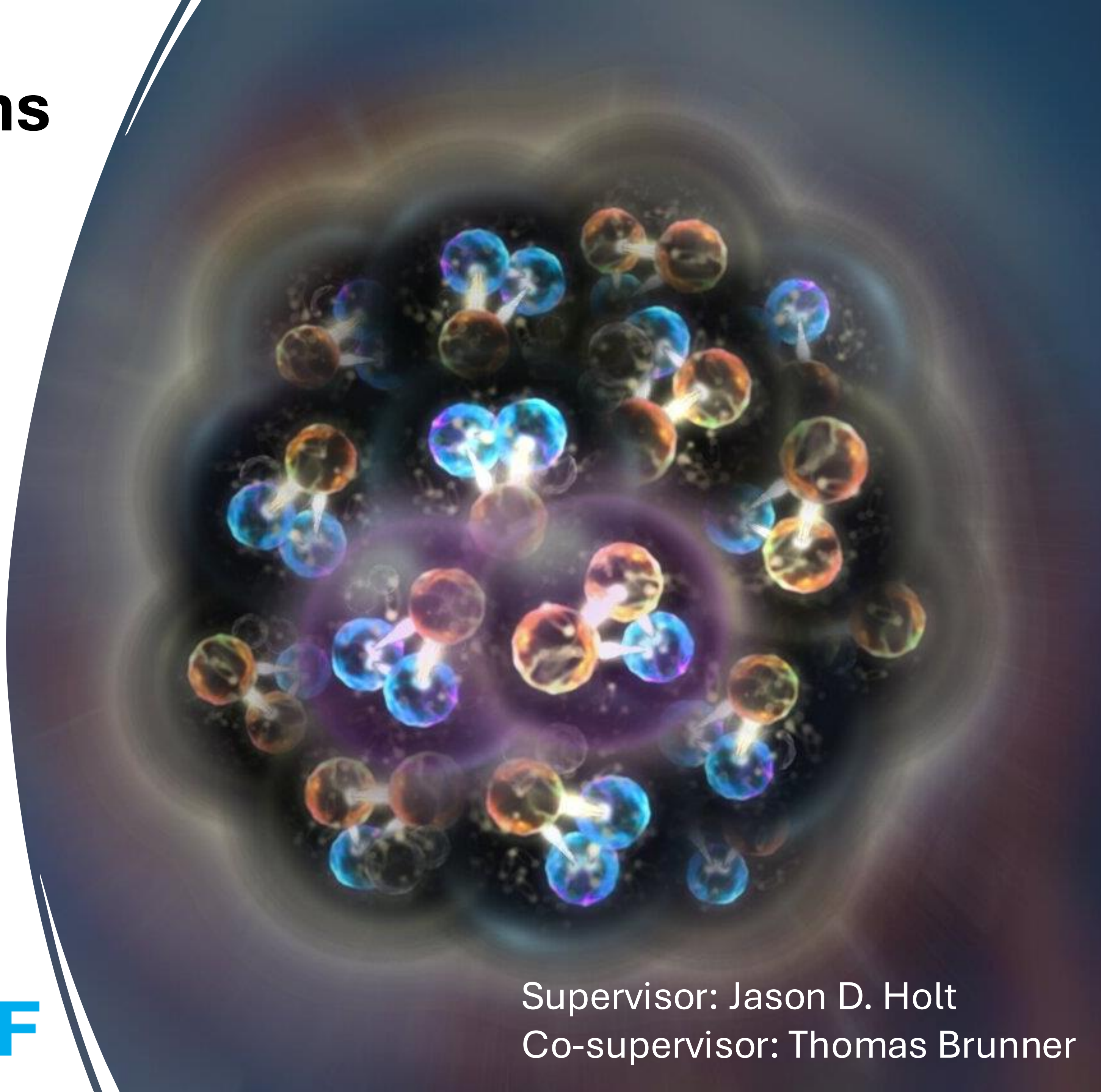
**Alex Todd** (McGill University)

Theory Canada 18

McGill

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

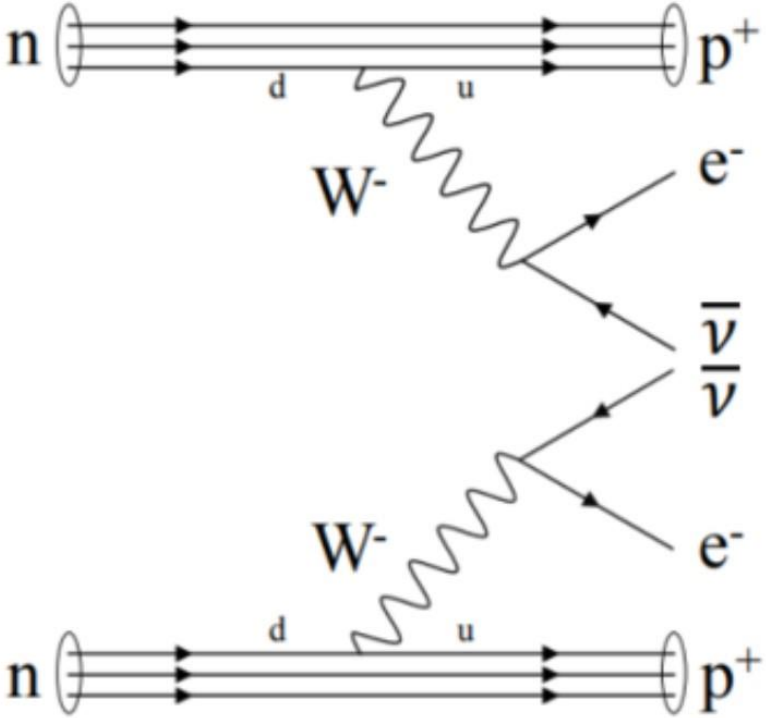
TRIUMF



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

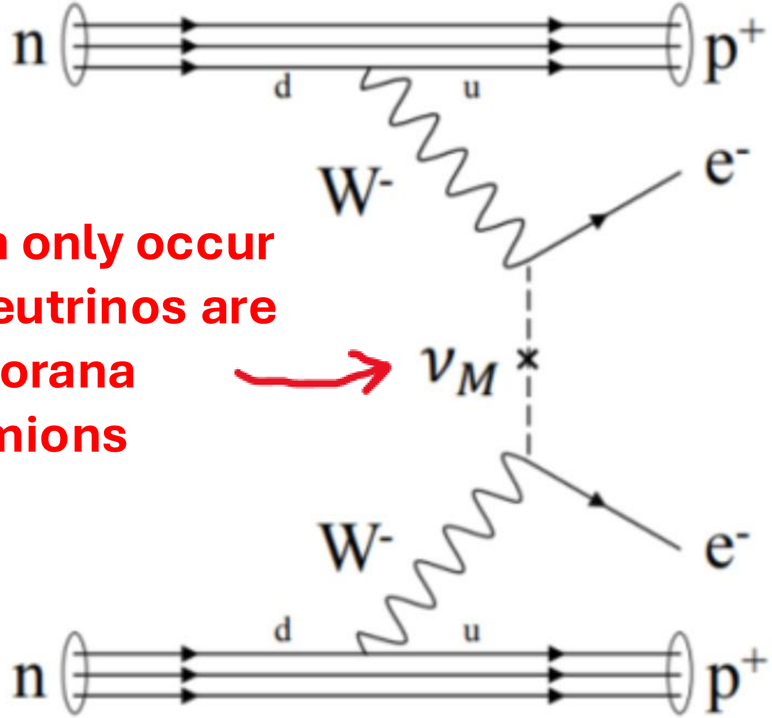
# Neutrinoless ββ decay

## 2νββ (observed)




## 0νββ (hypothetical)

Can only occur if neutrinos are Majorana fermions



# Why do we care?

**<u>0νββ probes:</u>**

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

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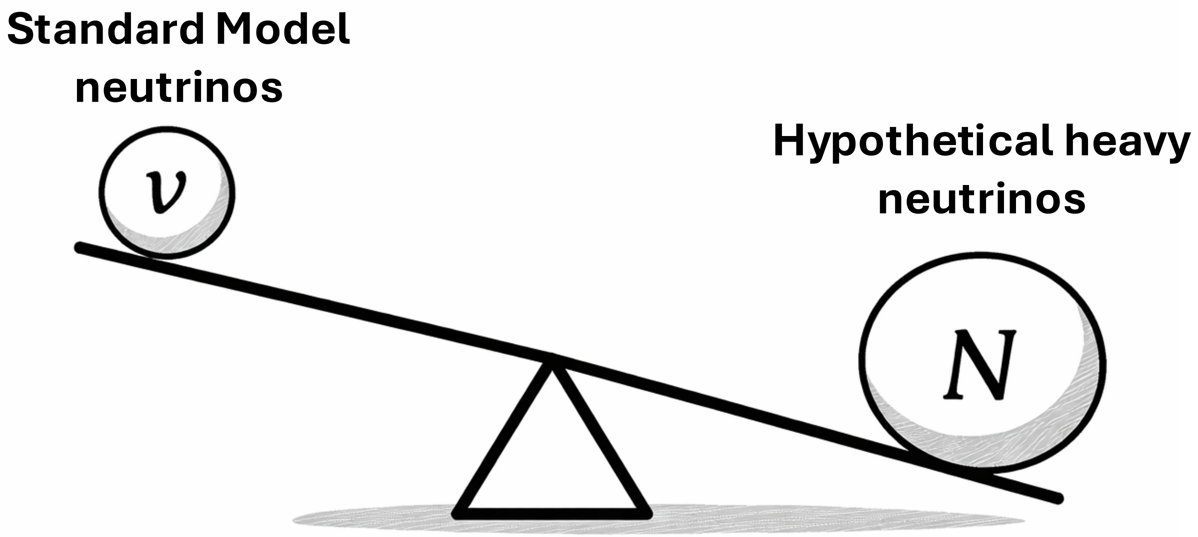

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**An observation of 0νββ would immediately confirm these** ✅

**Interpretations rely on nuclear theory** 😬

# Decay rate

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}\left|\sum_i \eta_i M_i^{0\nu}\right|^2$$

# Decay rate

"new physics" couplings: involves coupling constants and BSM parameters like masses of new particles

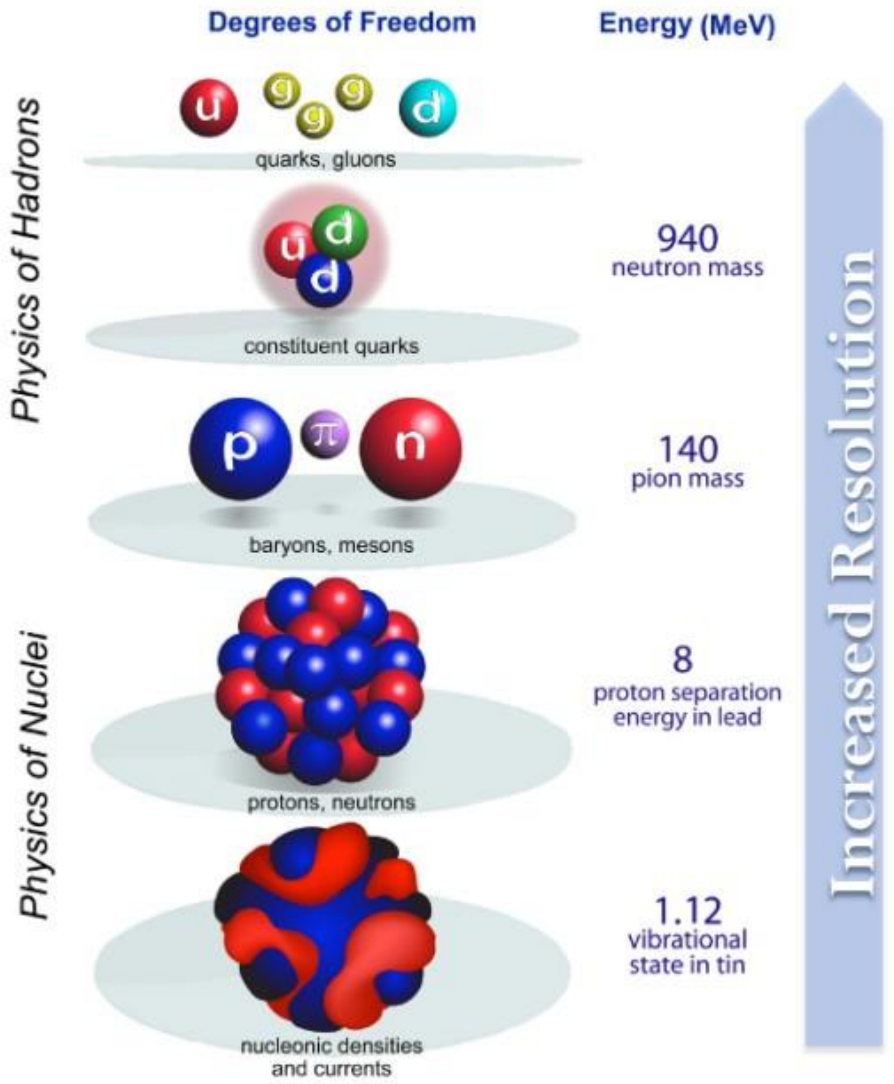
Phase space factor

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}\left|\sum_i \eta_i M_i^{0\nu}\right|^2$$

Half-life (what is measured)

Nuclear matrix element (NME)

# The amplitude is *very hard* to calculate...




- Need effective descriptions of the strong, weak, and electromagnetic interactions in the nuclear many-body system

- Many-body basis is huge: for 2000 single-particle states,

$$\dim \mathcal{H} = \binom{N_{\mathrm{p}}}{Z}\binom{N_{\mathrm{n}}}{N} \xrightarrow{^{136}\mathrm{Xe}} \binom{2000}{54}\binom{2000}{82} \approx 10^{253}$$

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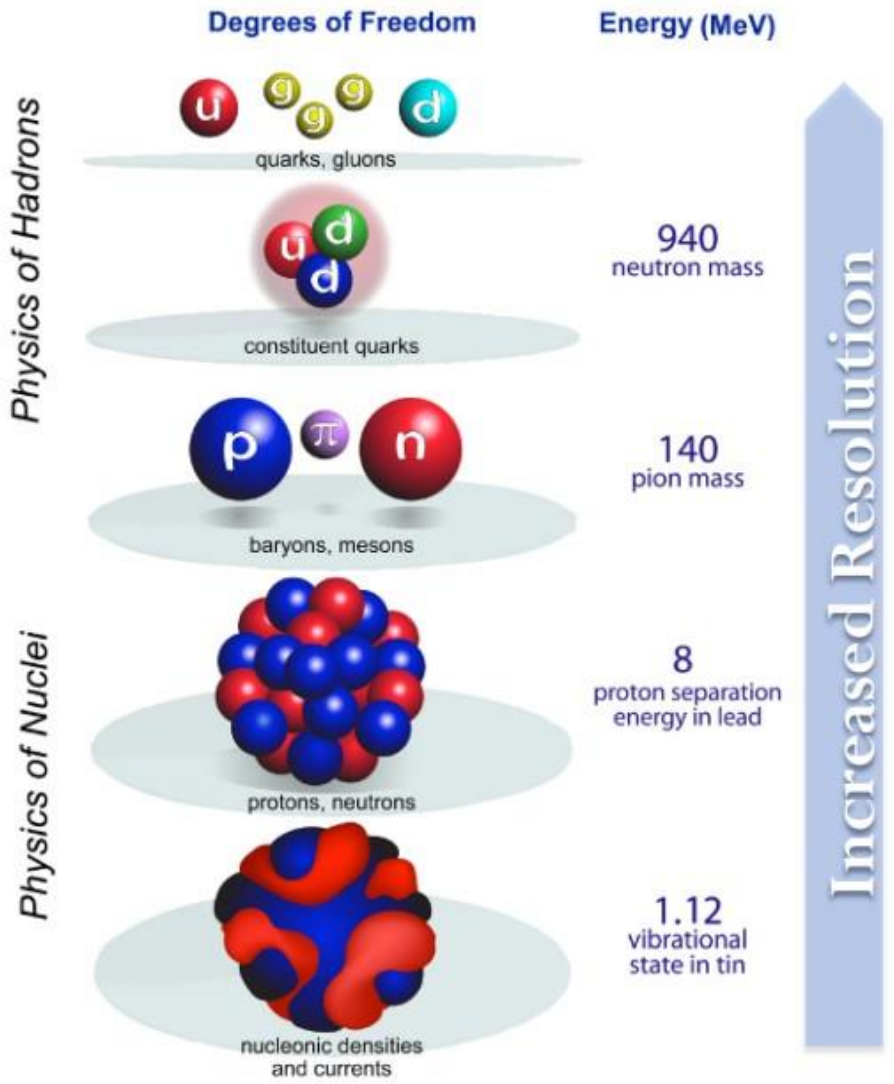


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On Earth, there is ~$10^{23}$ bytes of storage available. 😬

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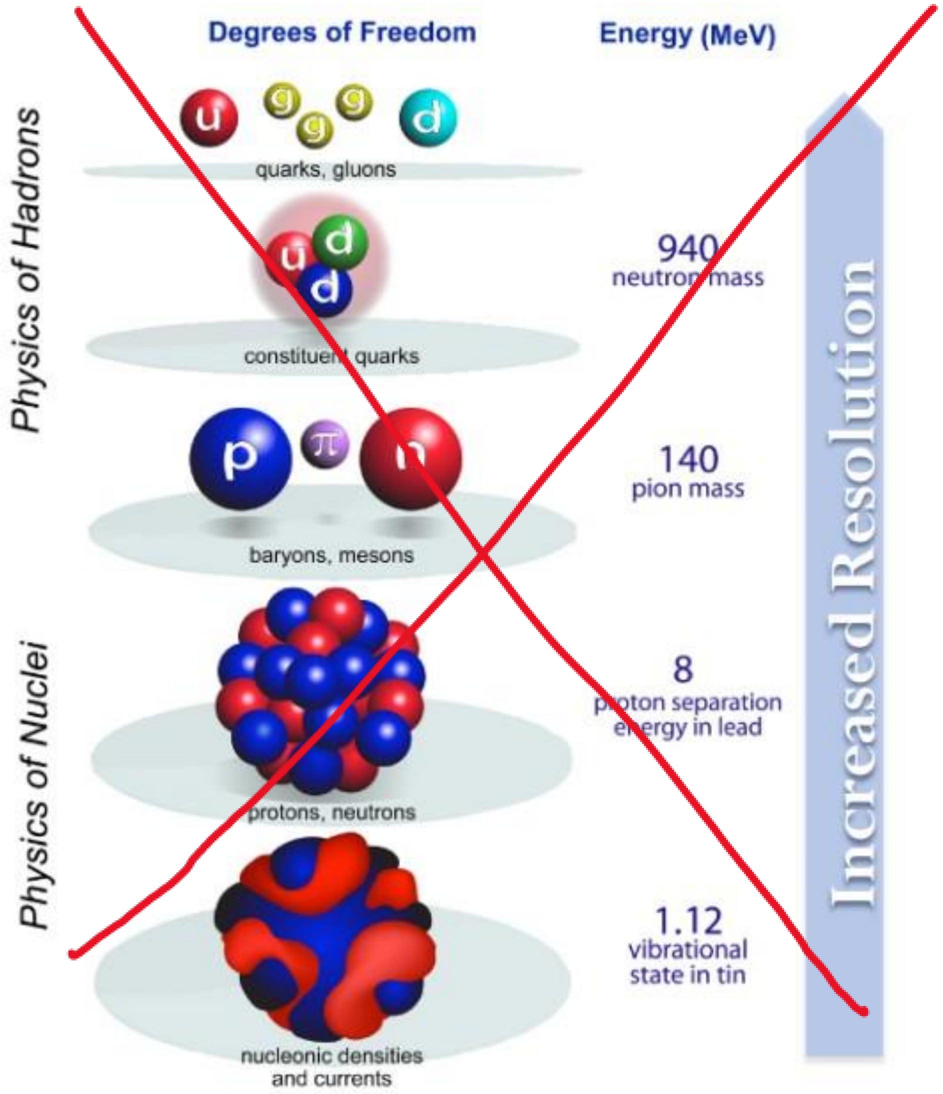



Fit Hamiltonian to data, then predict

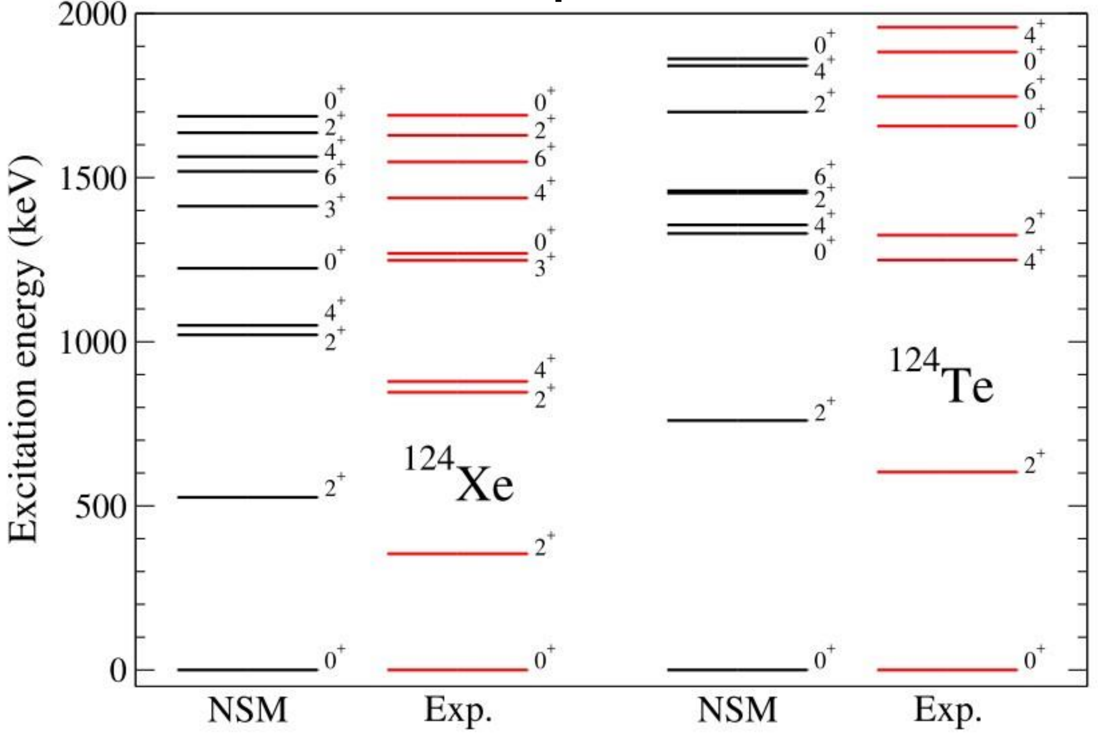


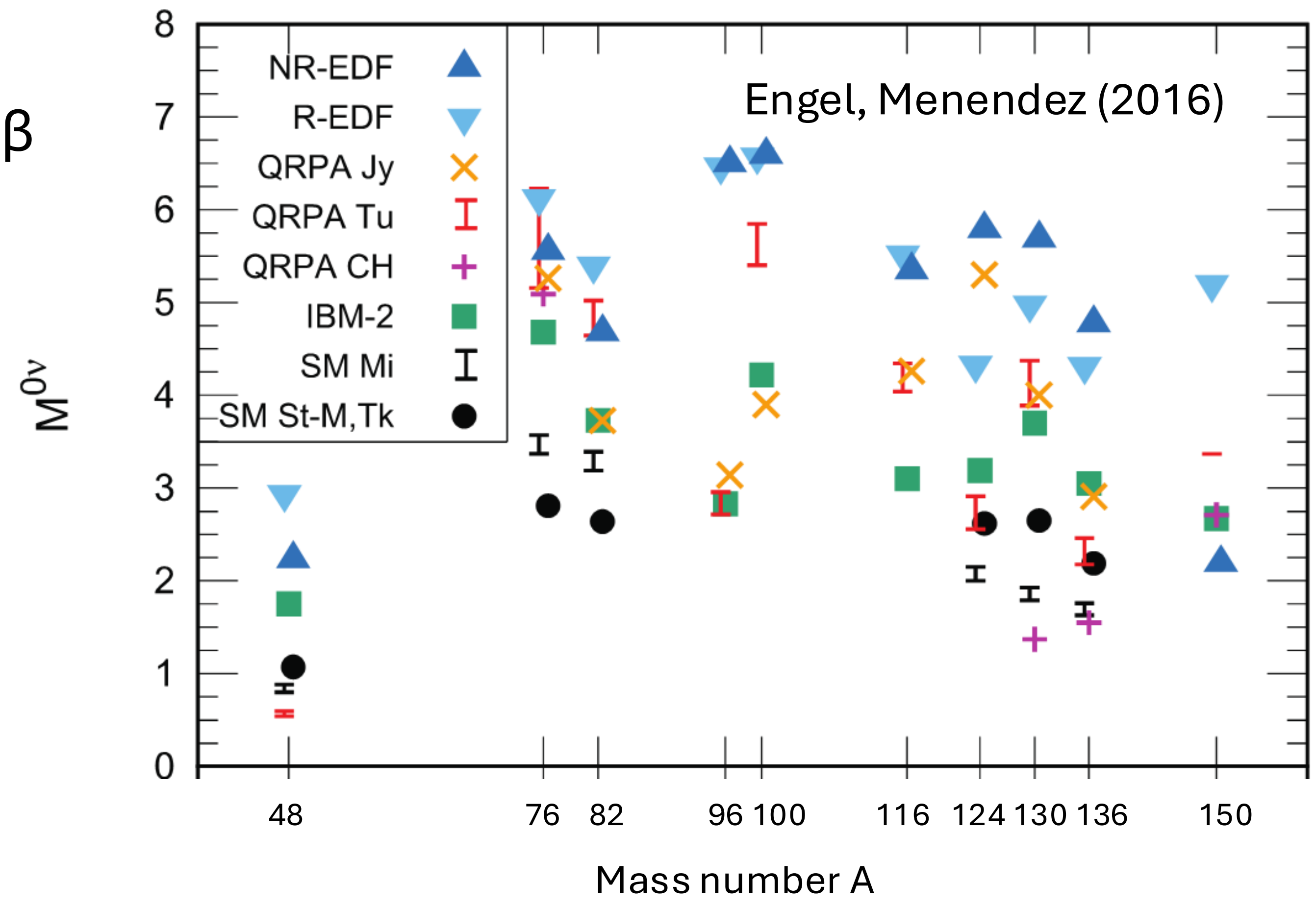

**Fig. 1.** $^{124}$Xe and $^{124}$Te excitation spectra obtained by the nuclear shell model (NSM) compared to experiment [74].

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

# Using phenomenological nuclear models

Methods are **inappropriately extrapolated,** not constrained to 0νββ data

- Large spread in results
- No path for understanding uncertainty



**The NME problem needs to be tackled *ab initio***

Latin for "from the beginning".

# Step 1: Chiral effective field theory

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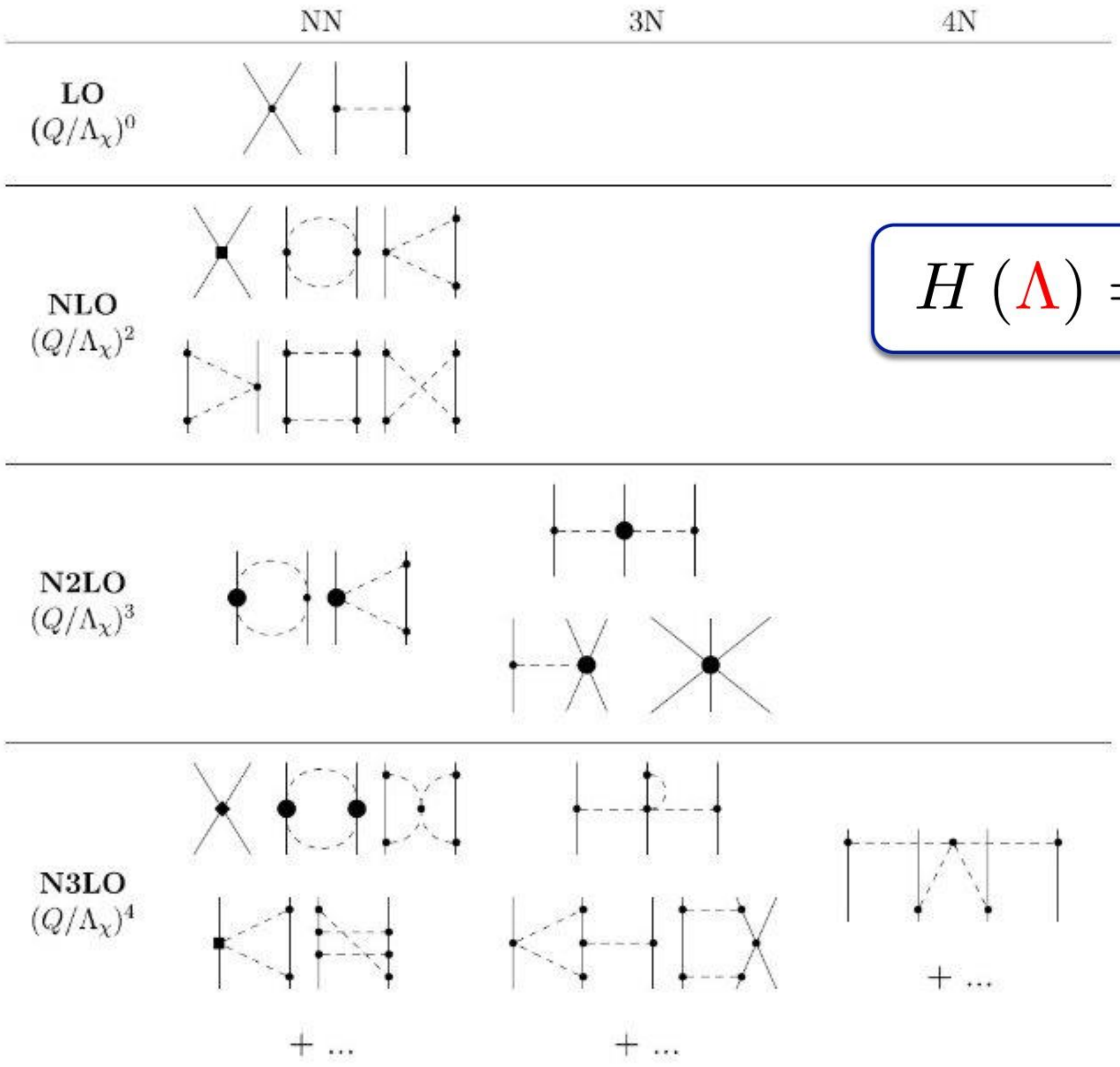



**Effective particles: nucleons and pions**

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

- In practice, we can only keep up to 3N interactions
- Currently we can go to N3LO for NN, N2LO for 3N

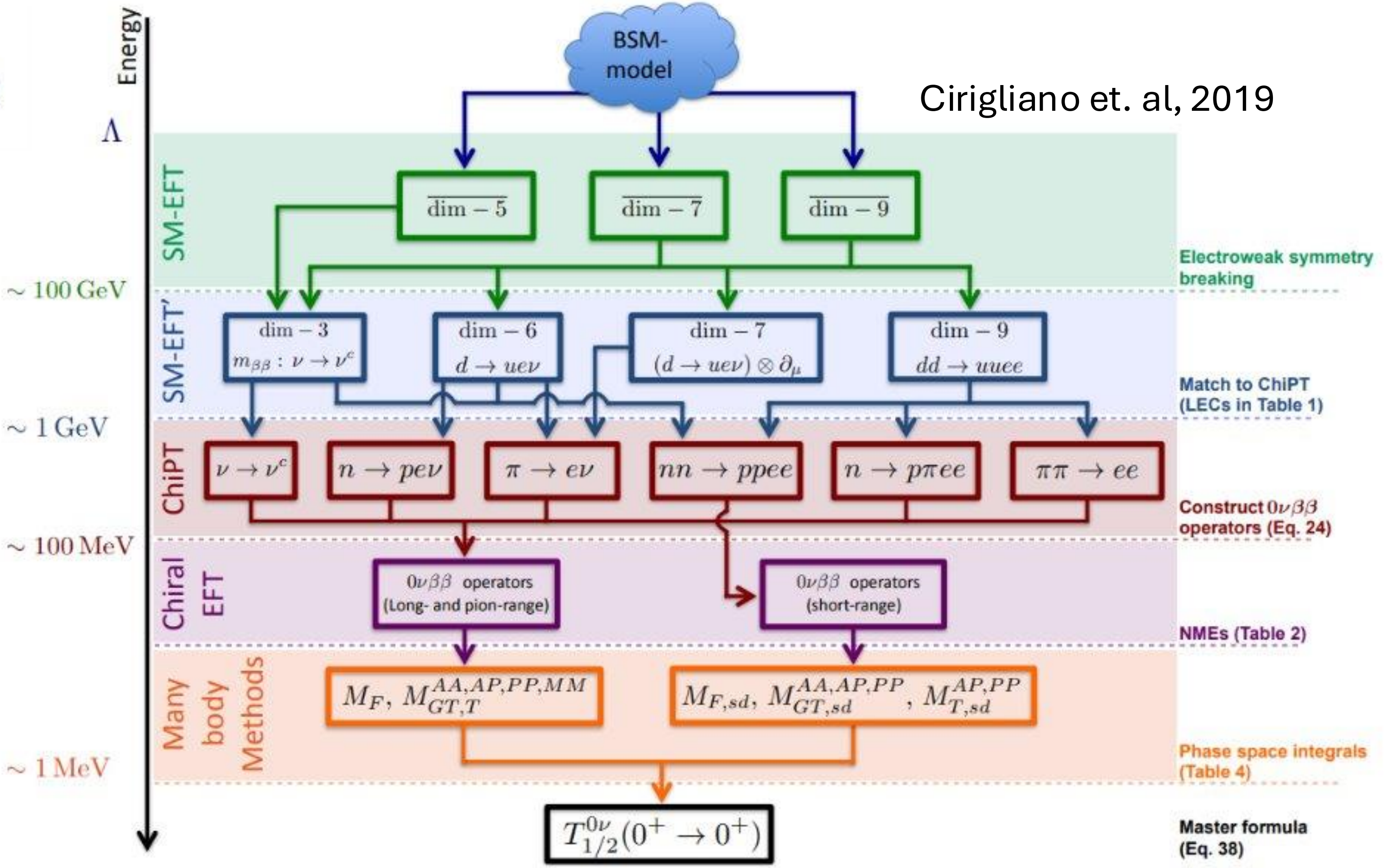
# Model-independent 0νββ decay in chiral EFT

$$H = H_{\text{strong}} + H_{\Delta L=2}$$

New LNV interactions are small. The system is treated perturbatively: nuclear states obtained from $H_{\text{strong}}$, while BSM physics enters through the transition operator.

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

Cirigliano et. al, 2019



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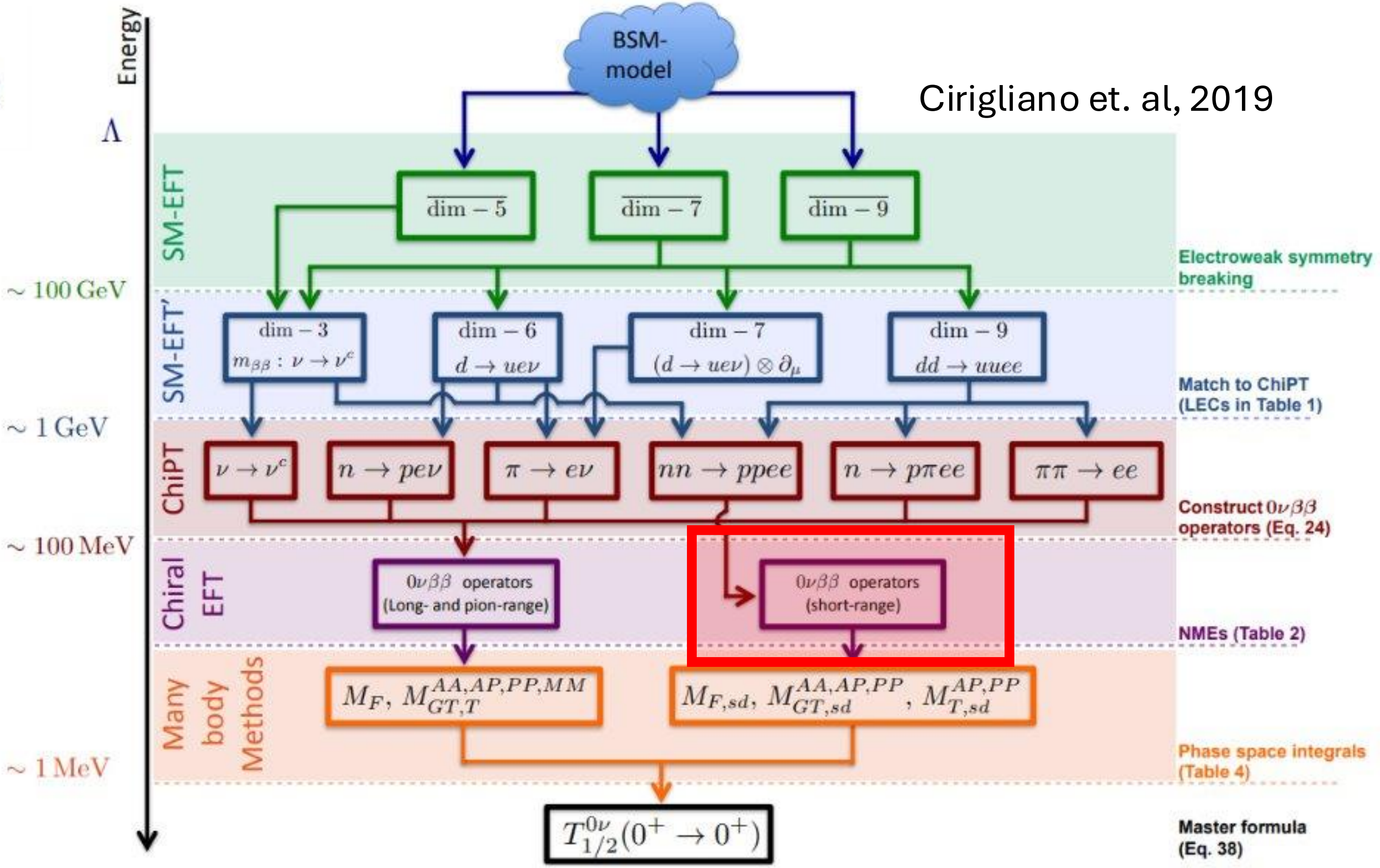
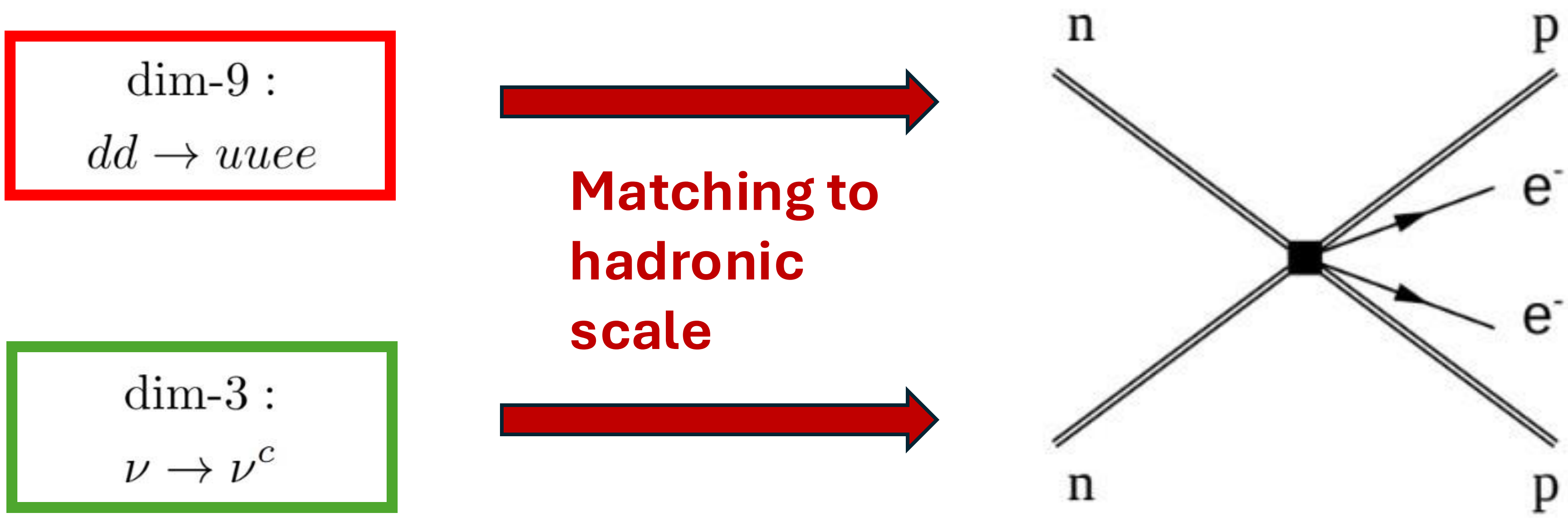



Cirigliano et. al, 2019

# Short-range operators

For this work: only consider "short-range" (contact) operators, relatively unexplored in nuclear theory:

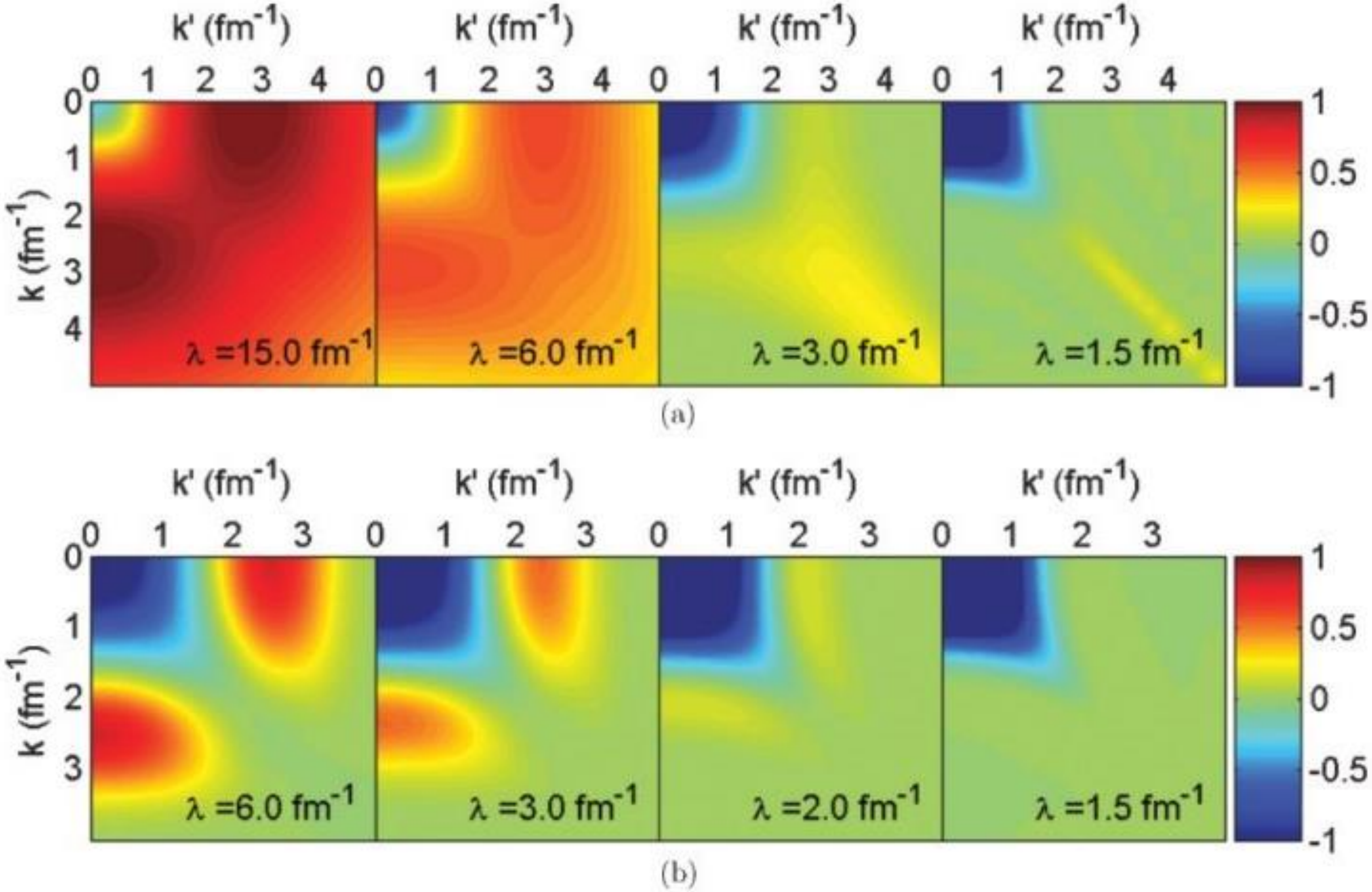
- **dim-9 quark-level operators** generated from integrating out heavy LNV physics
- short-range **counterterm** required for regulator-independent renormalization of the standard dim-3 operator



# Be careful with renormalization schemes (SRG + regulators)


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

# Similarity renormalization group (SRG)




$$H(s) = U(s)H(0)U^\dagger(s)$$

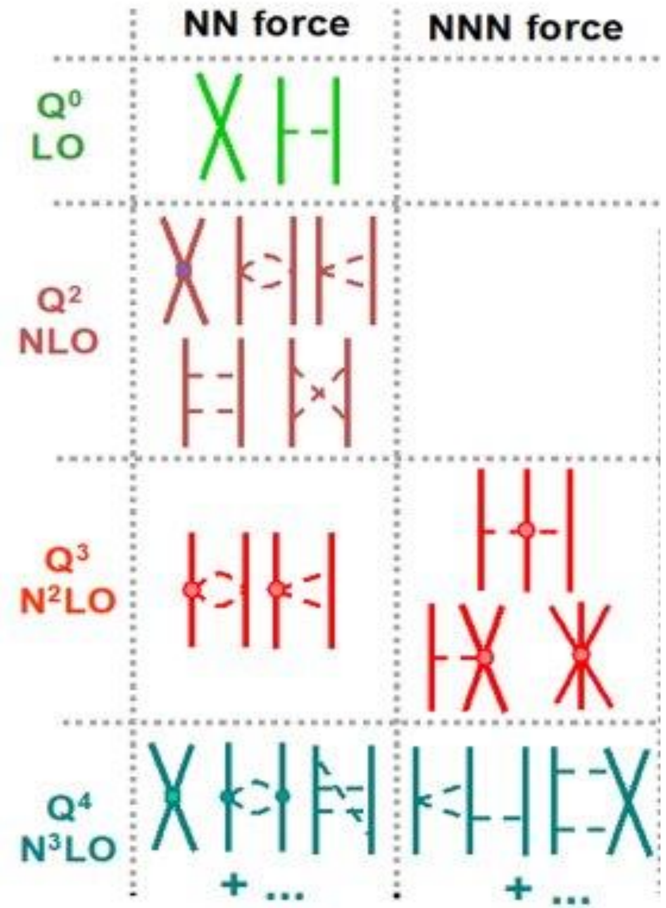
- Originally formulated by Wegner and Wilson independently
- First applied to nuclear theory ~20 years ago by Bogner
- Helps convergence of many-body methods

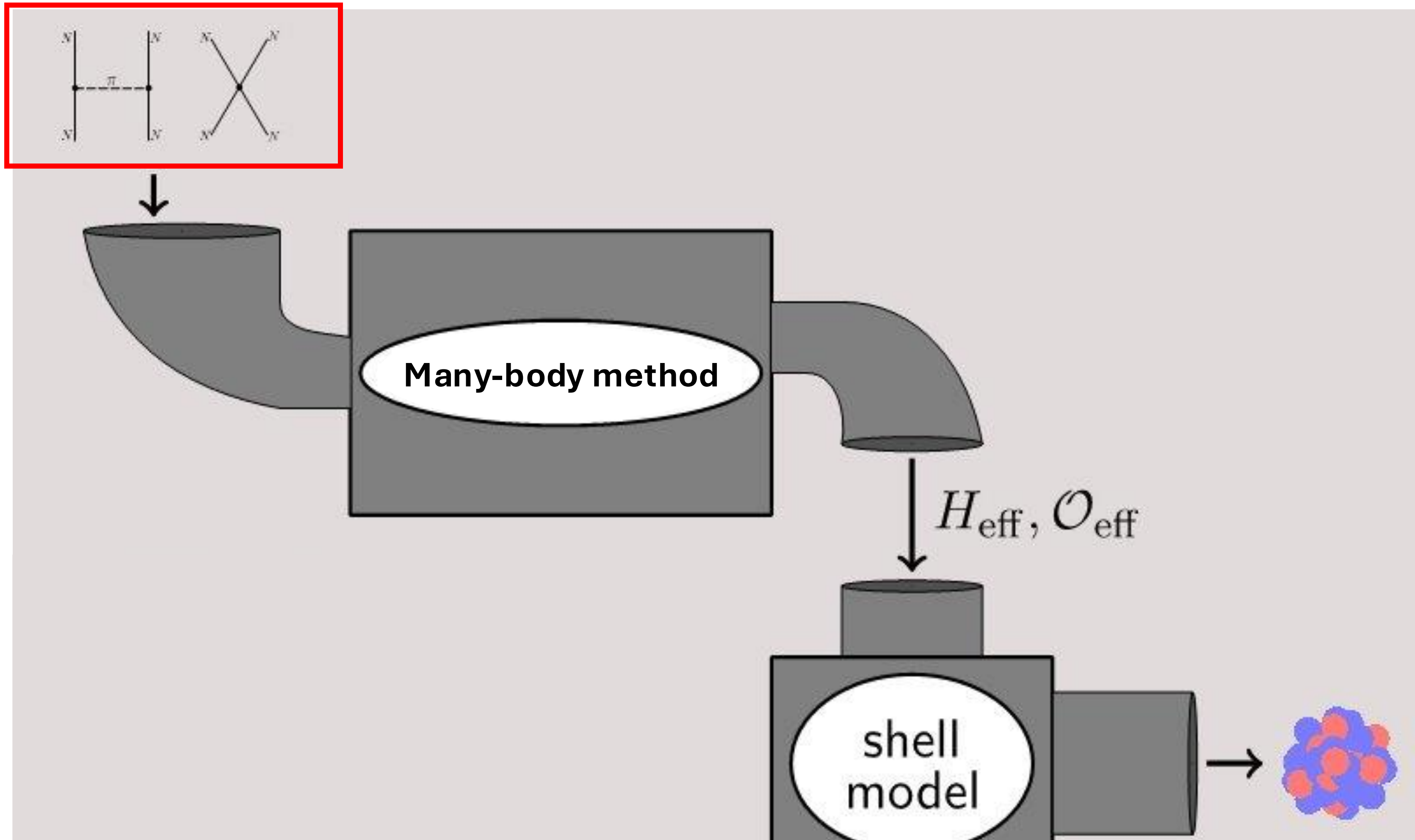
# Step 2: Solving the nuclear many-body problem

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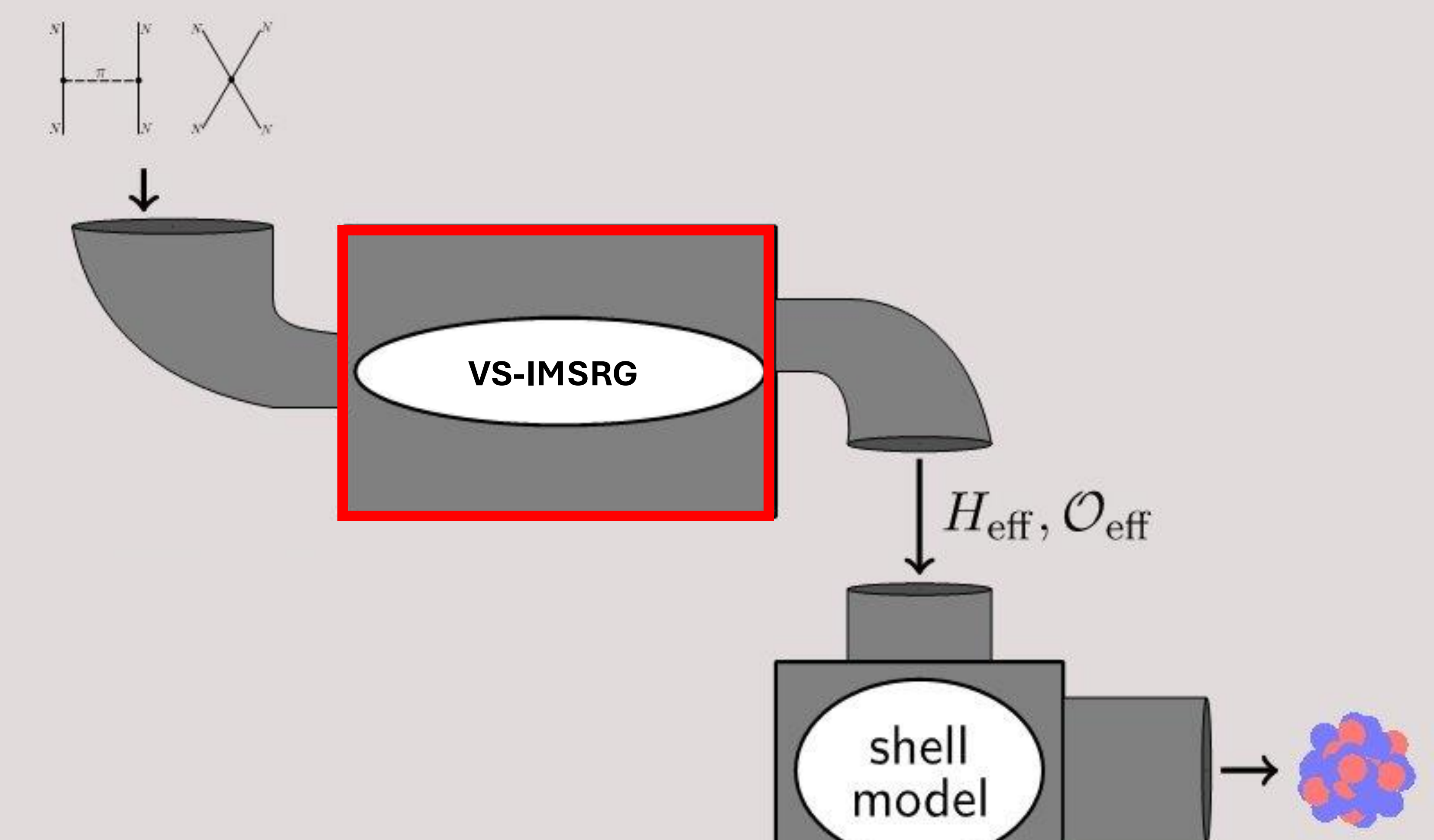
$$H(s) = e^{\Omega(s)} H e^{-\Omega(s)}$$

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

**Continuous unitary transformations of Hamiltonian**

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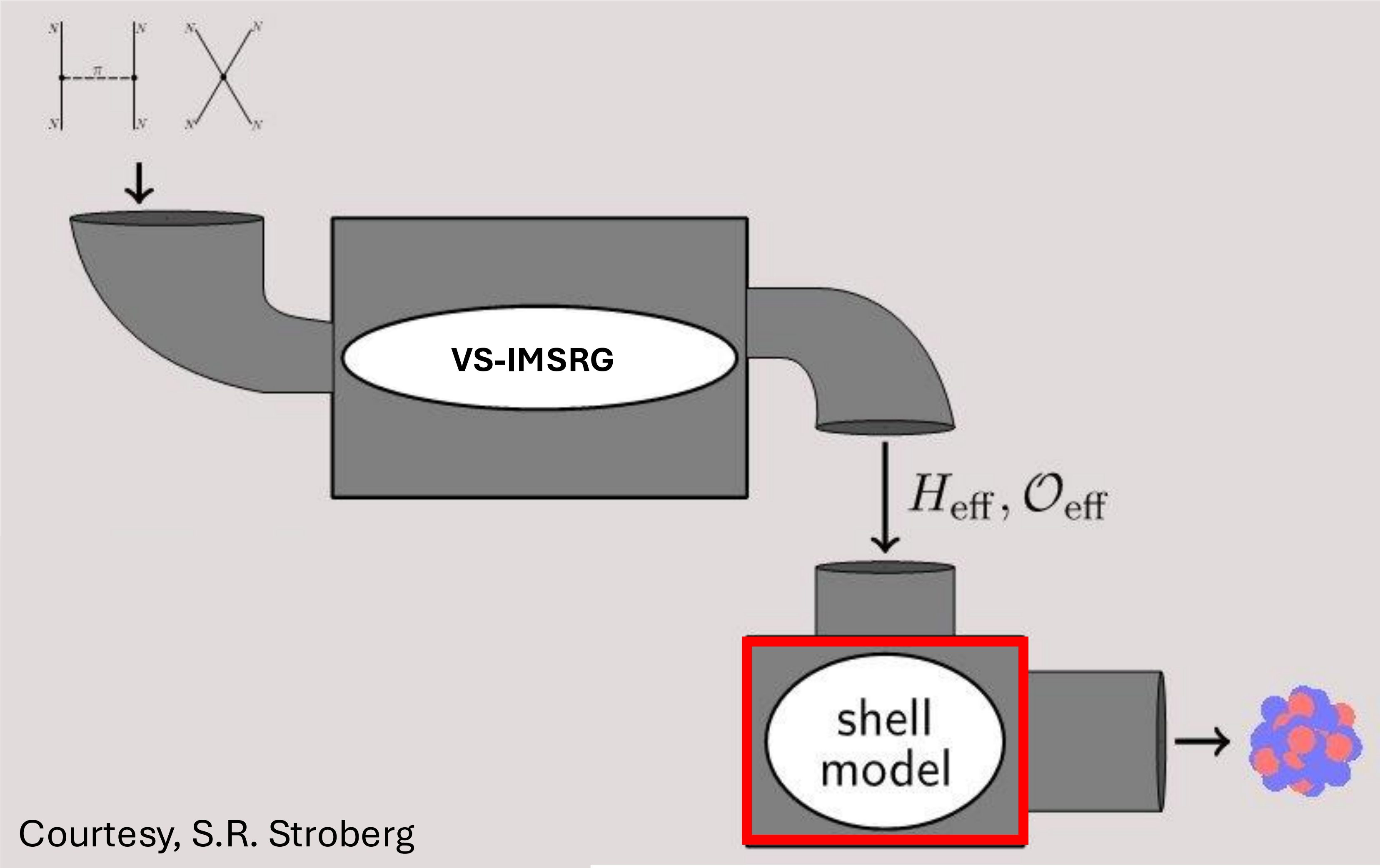
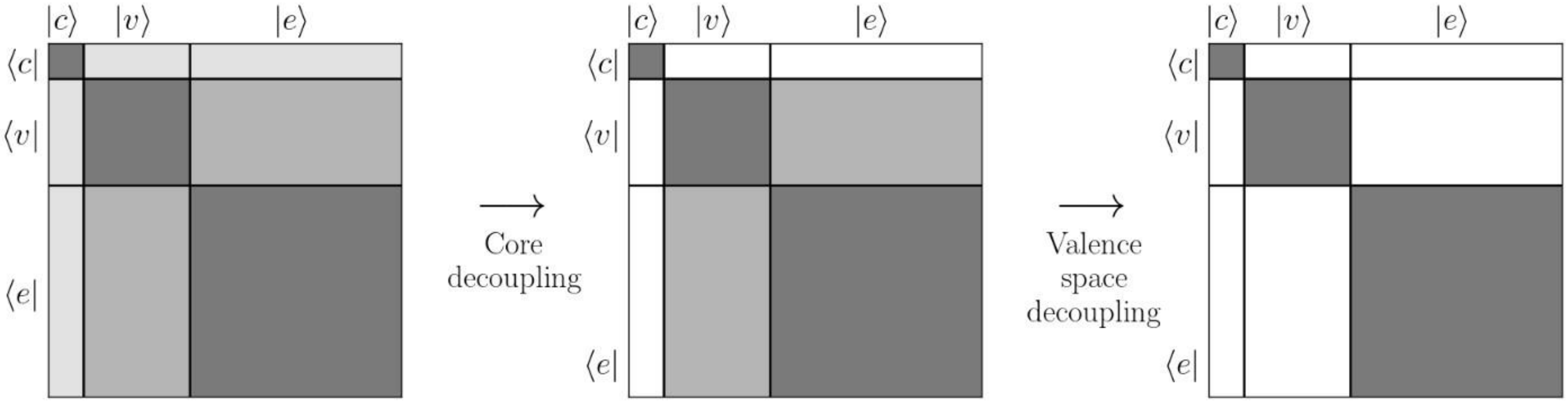
**Diagonalize $\mathcal{H}$ !!**



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




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

# Short-range nuclear matrix element results

arXiv:2604.22727

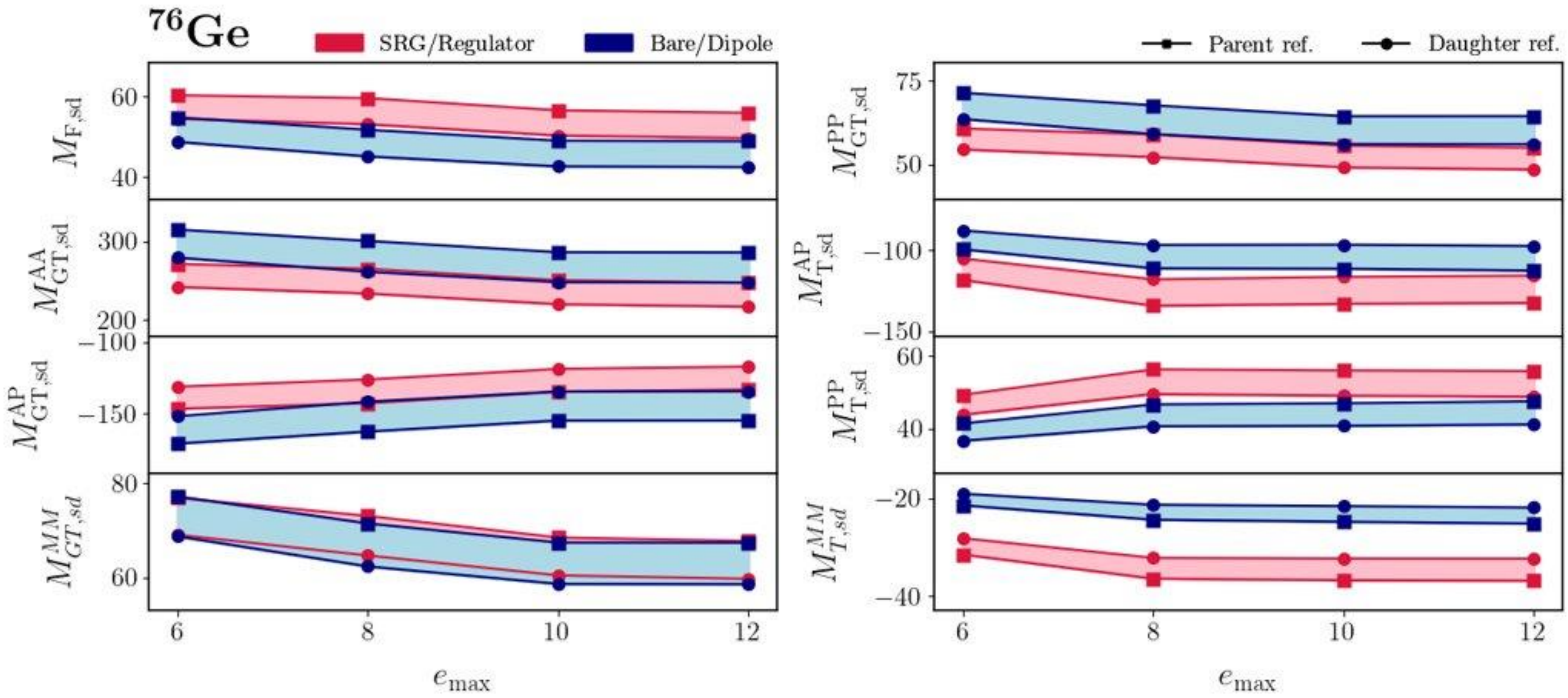
## Ab initio short-range nuclear matrix elements for neutrinoless double-beta decay

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.

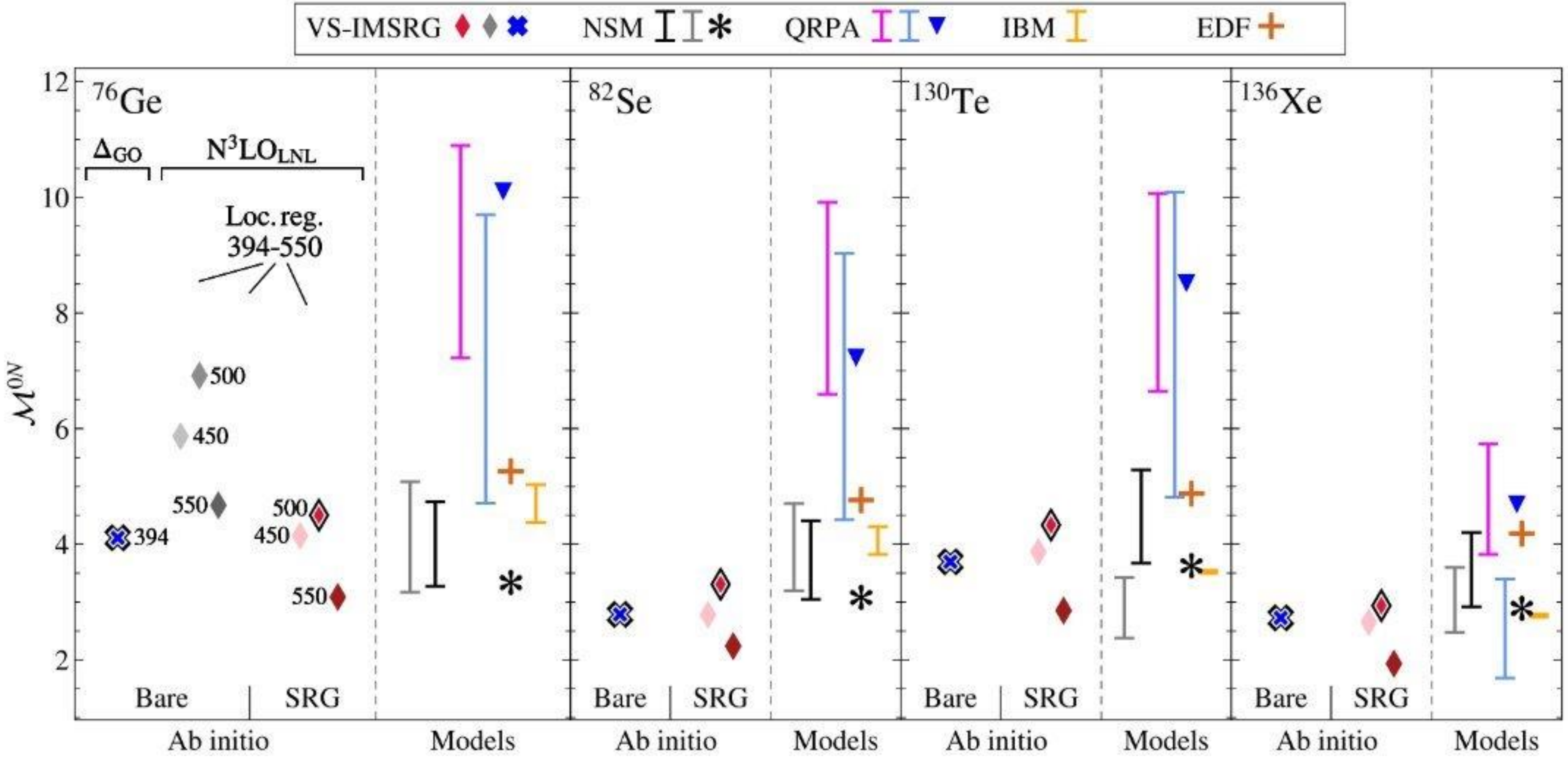
# Convergence in single-particle excitations






A. Todd, et. al (in prep), arXiv:2604.22727

# Final short-range NMEs



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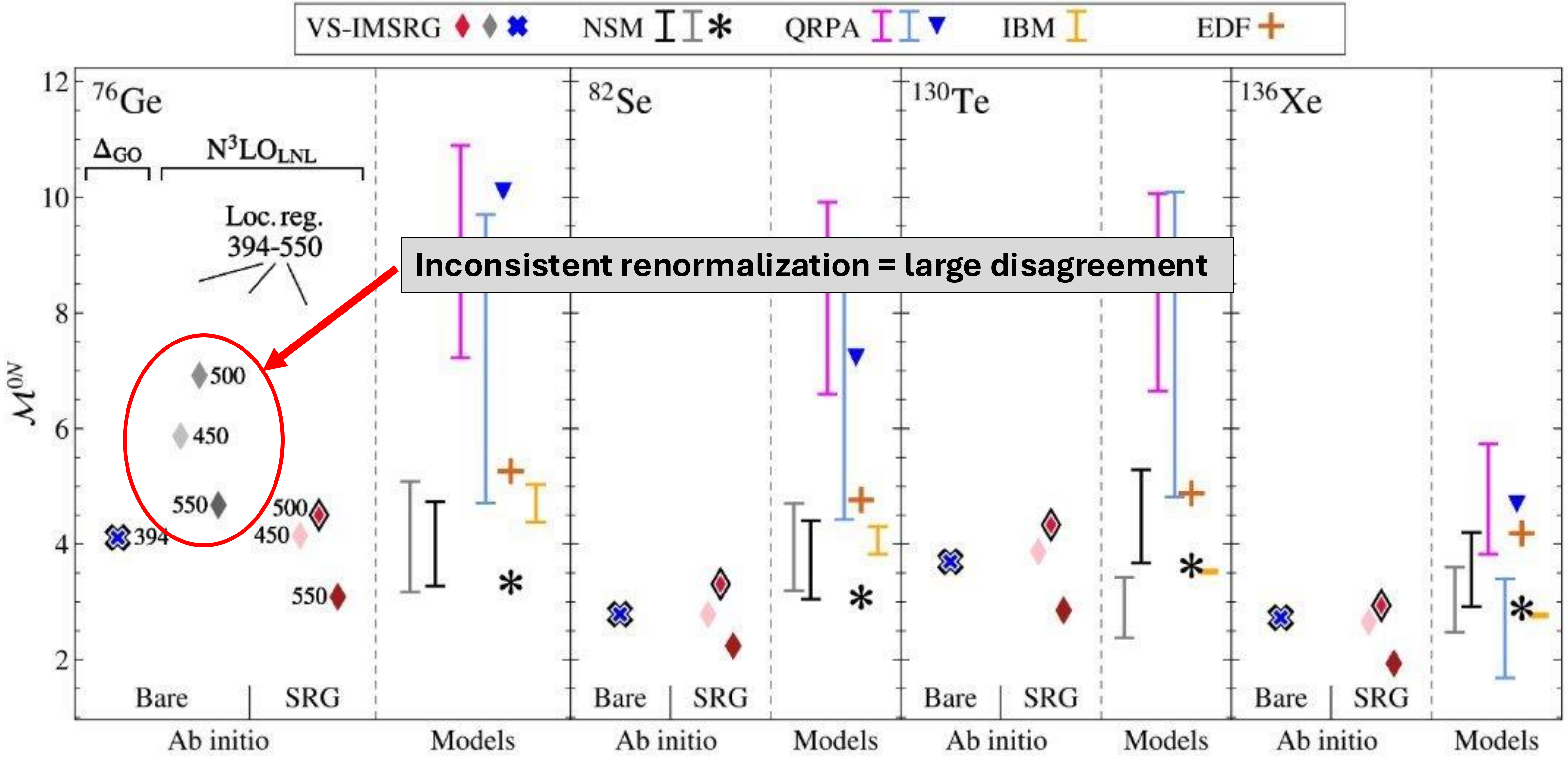




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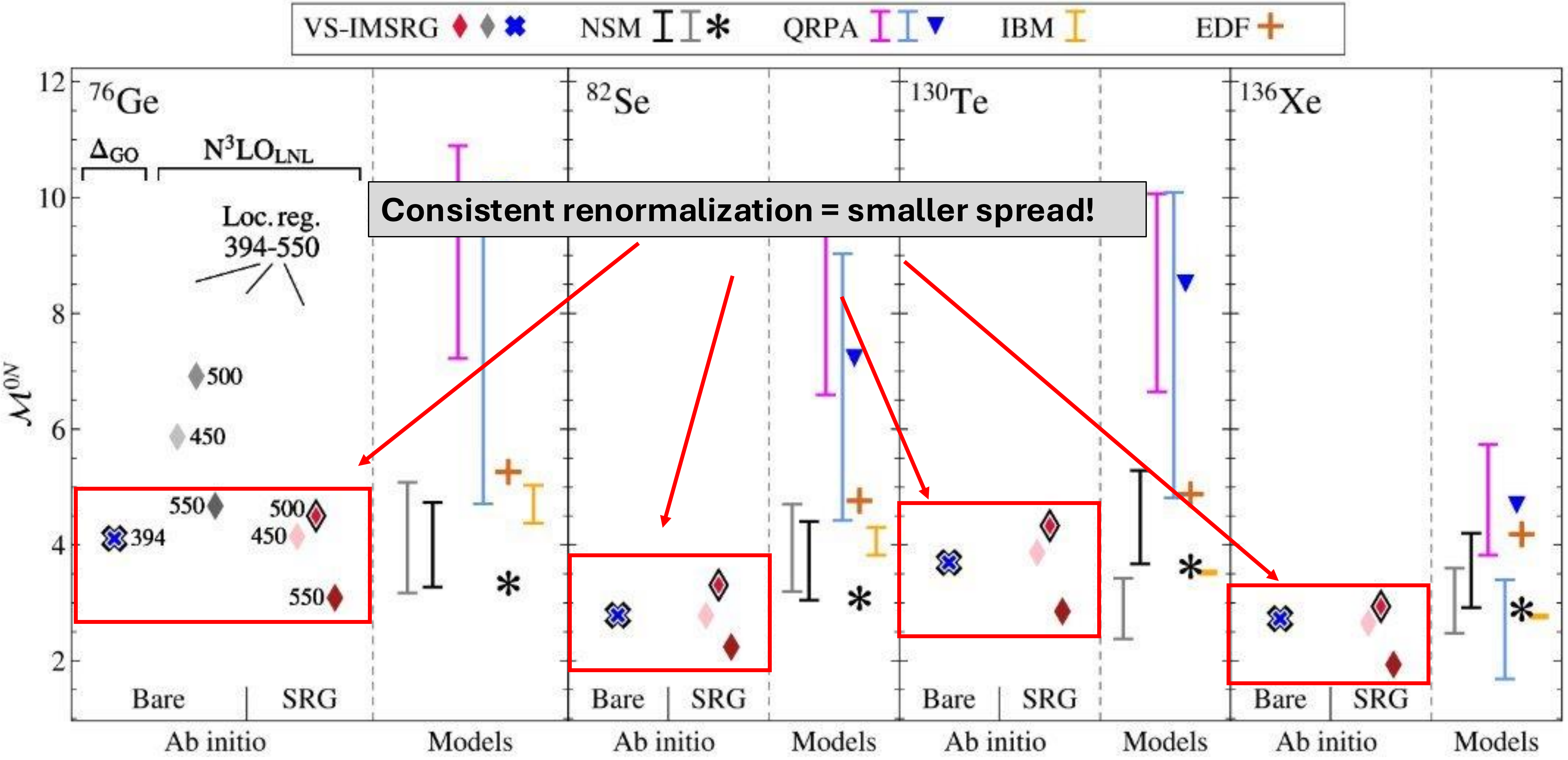

# Connection to BSM mechanisms

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

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

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Plot and analysis by Taiki Shickele

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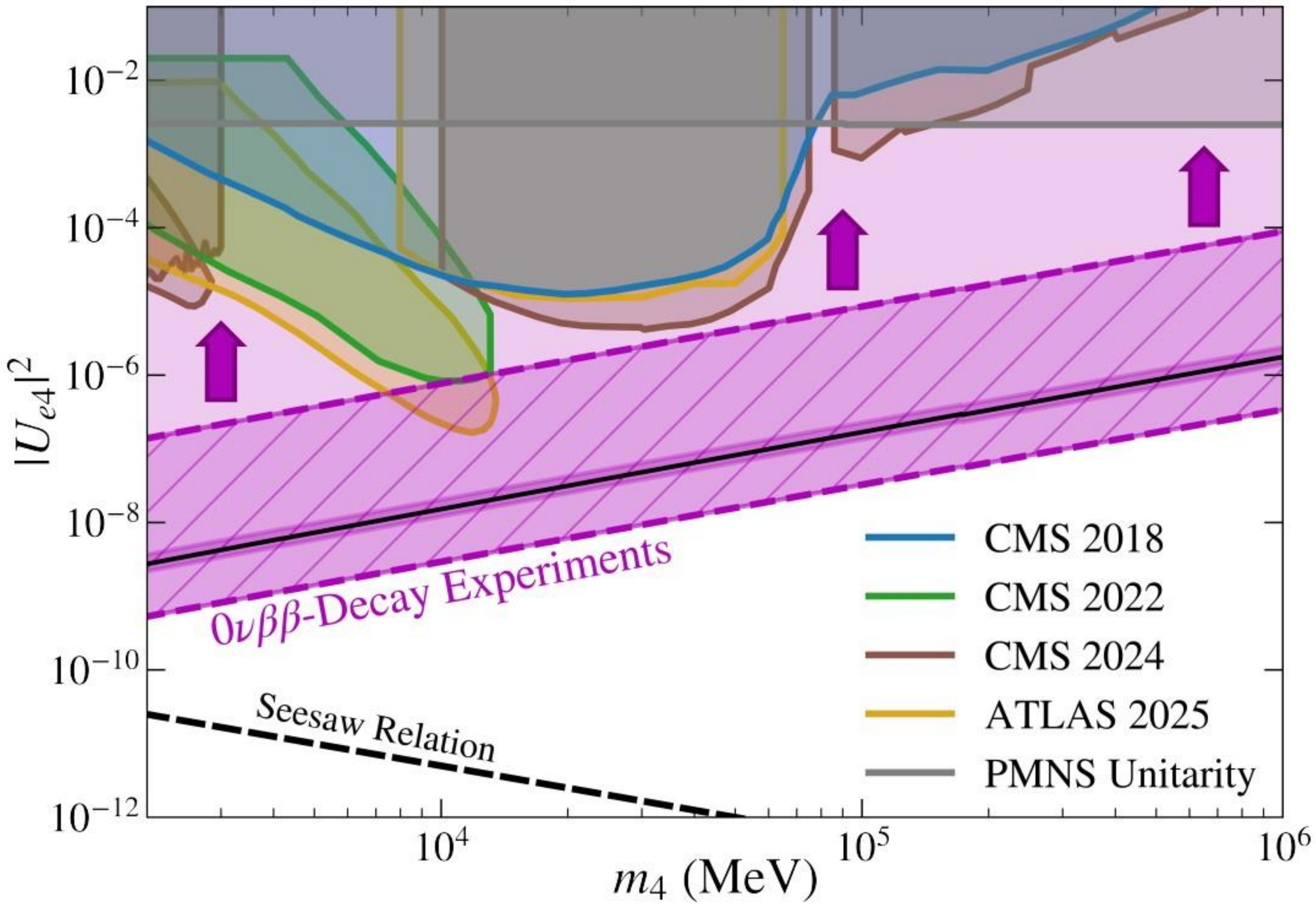

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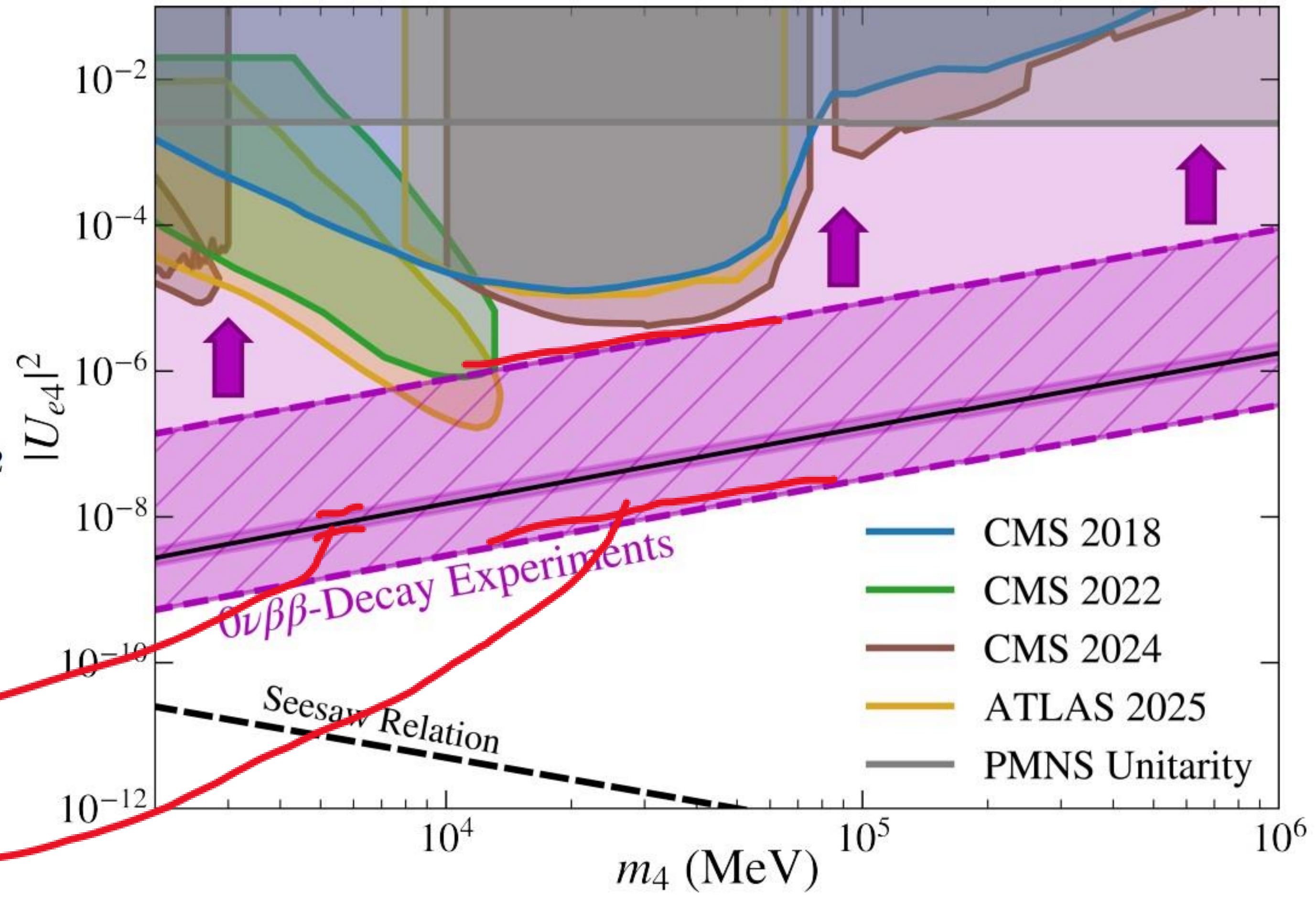


NME uncertainty

LEC uncertainty

# Conclusion and outlook

- 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: $0\nu\beta\beta$ is a competitive probe of heavy neutrinos

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

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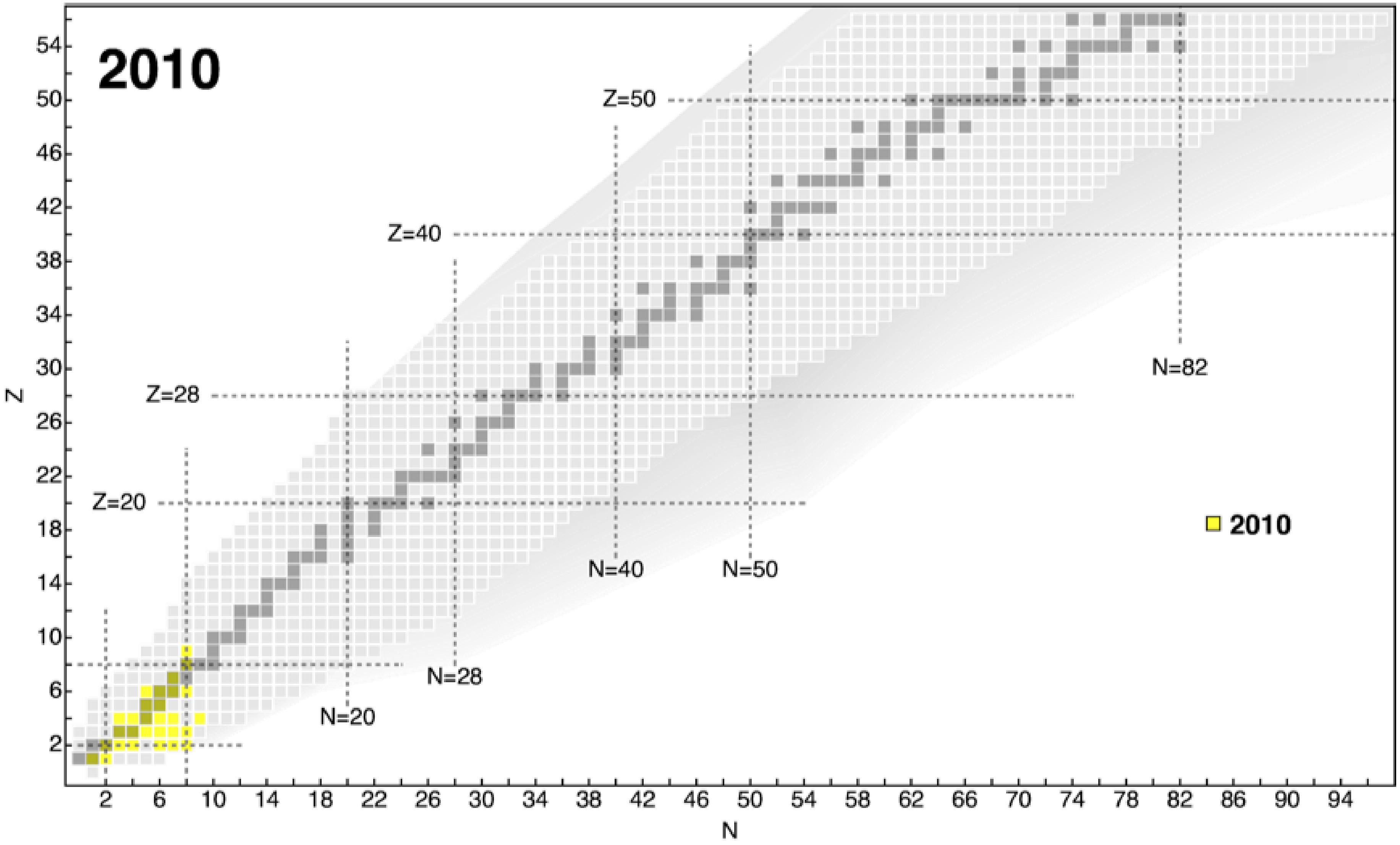
# Backup Slides

# Ab initio progress



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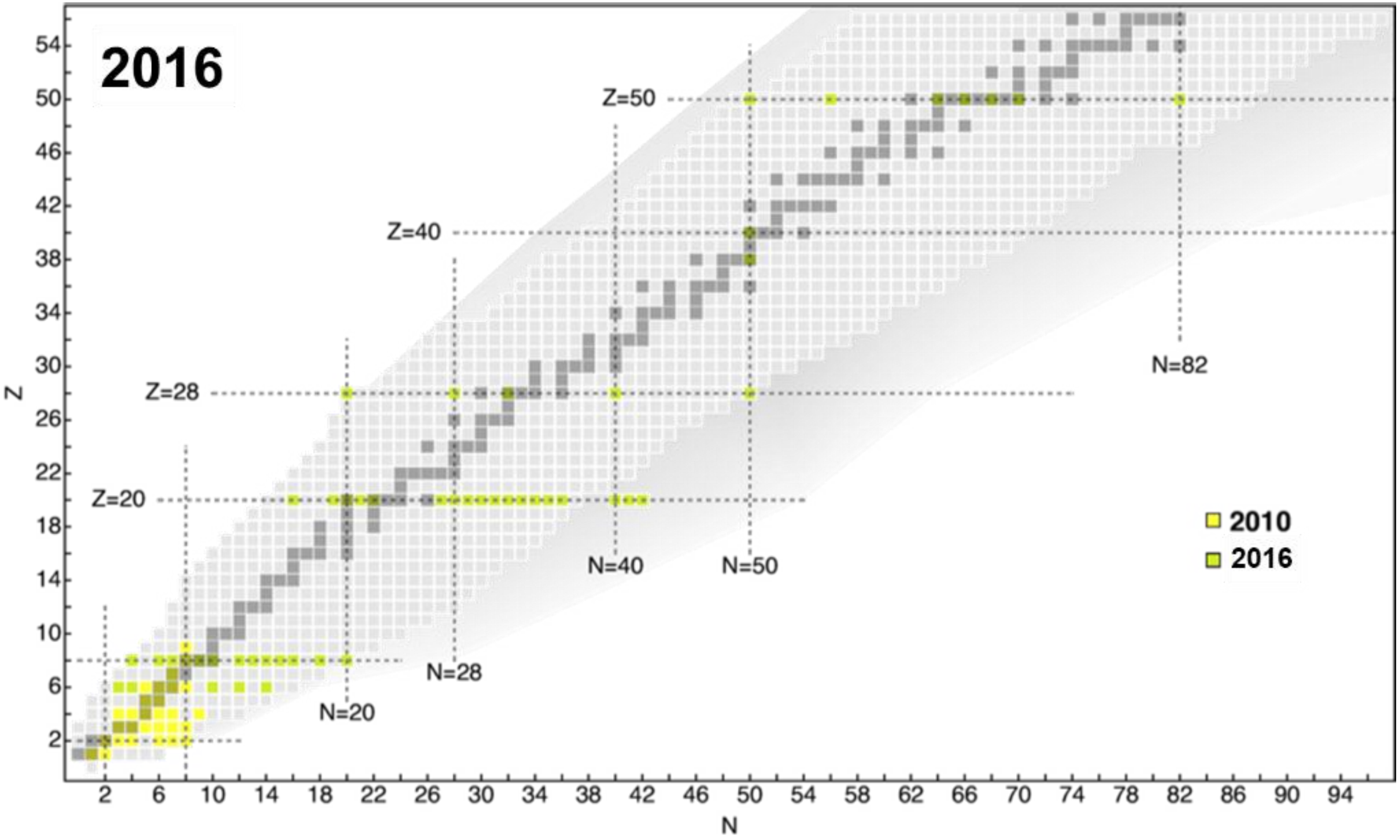

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