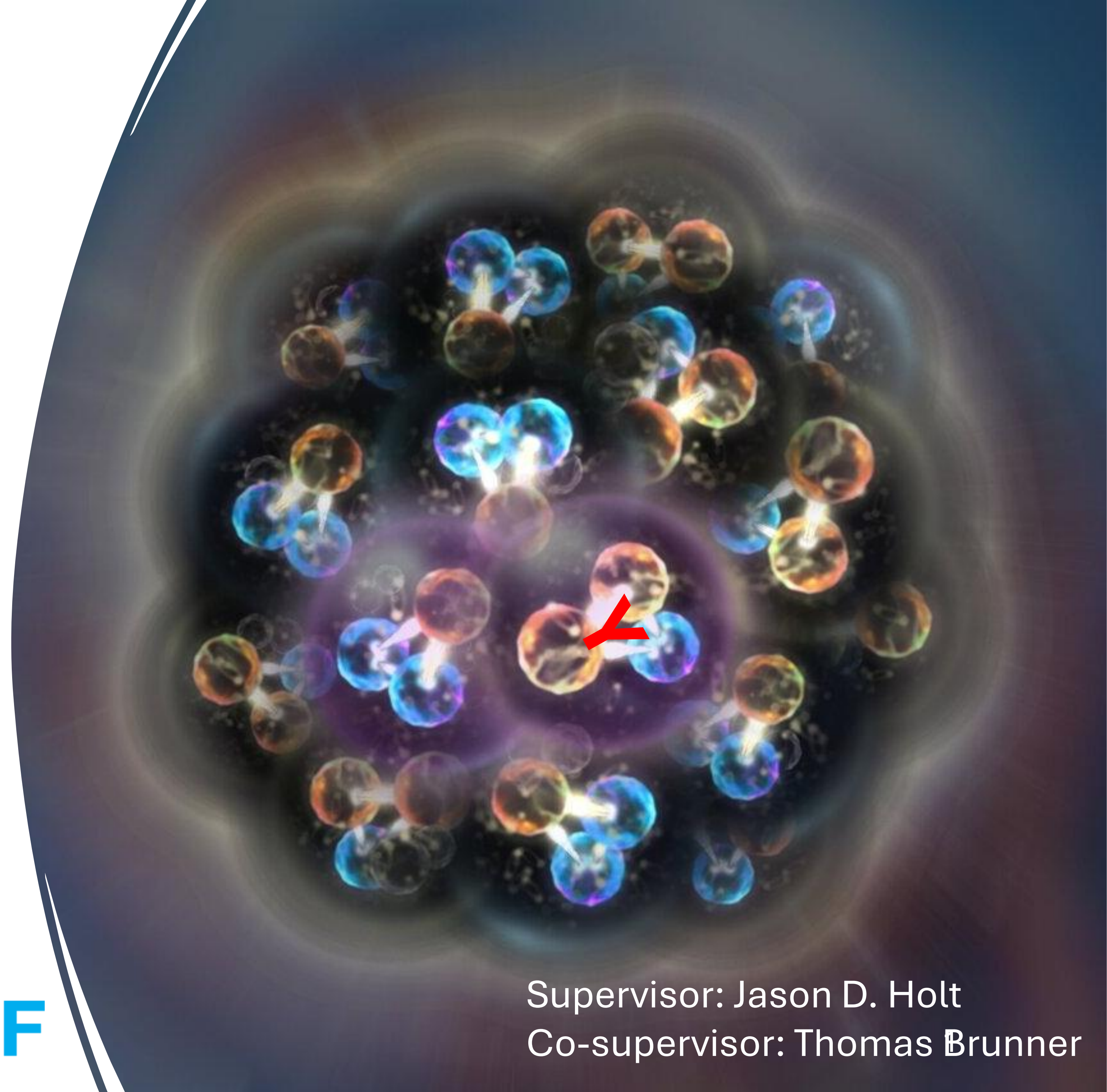
# Short-range decay operators for exotic decay mechanisms

**Alex Todd** (McGill University)

Recommended Values for Neutrinoless Double-Beta Decay Nuclear Matrix Elements

2026



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

# Outline

- Why do we care about short-range NMEs?
- Discussion point: short-range MM operators
- Differentiating LNV mechanisms
- SRG & regulators
- VS-IMSRG NME results
- Exclusion plot in the 3+1 model

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# Why do we care?

**<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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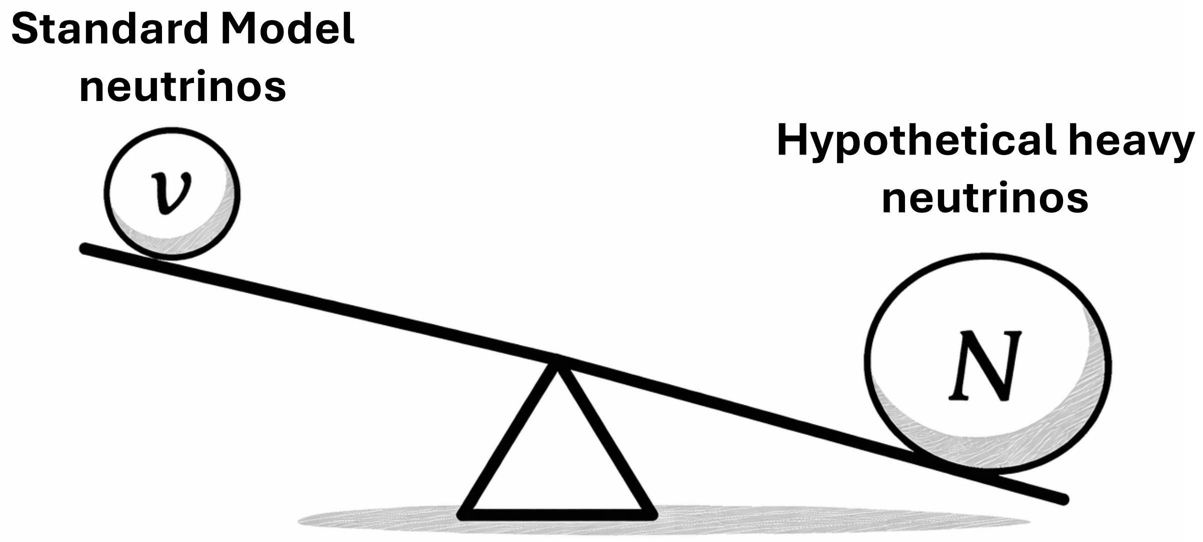

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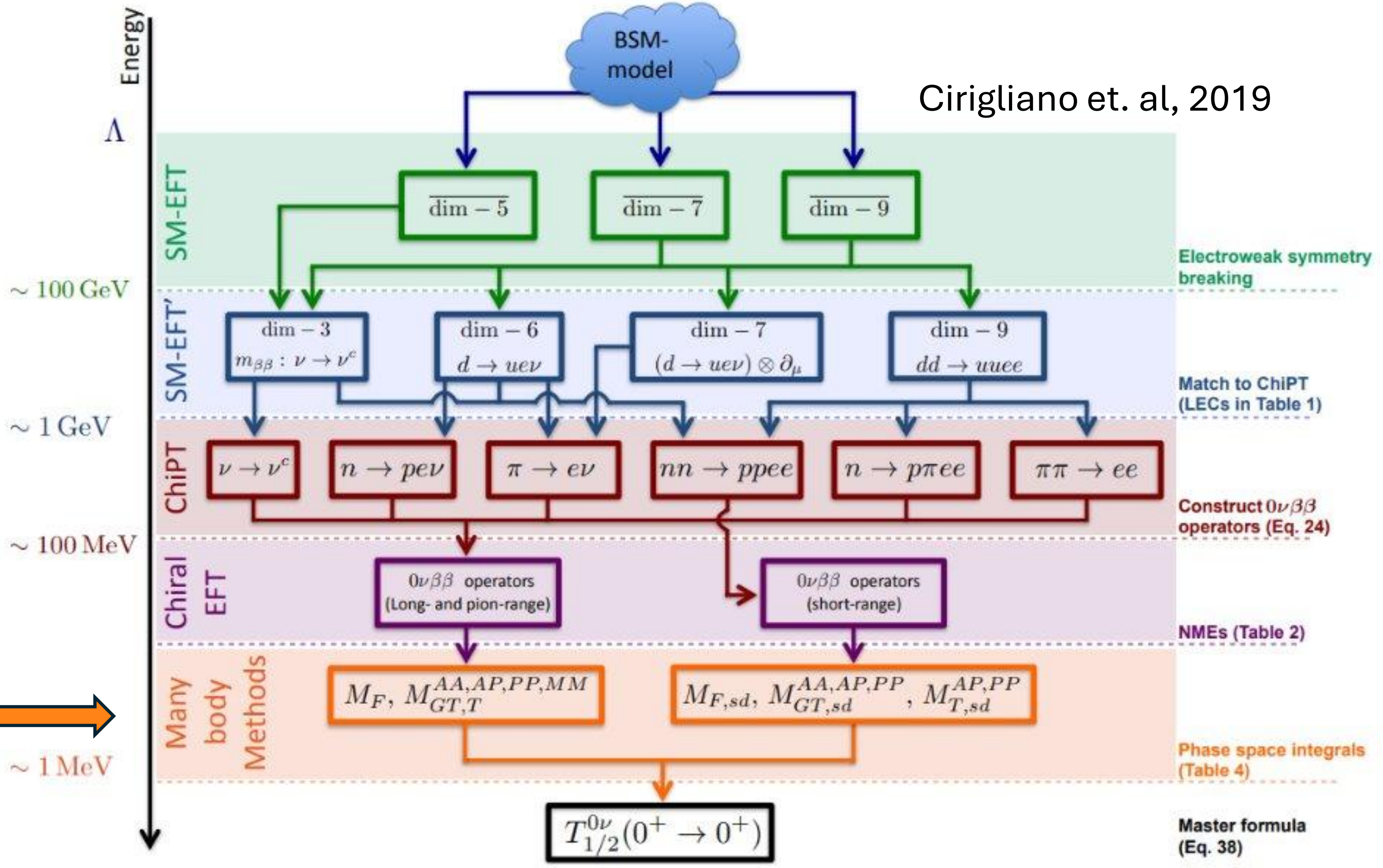
**Requires short-range NMEs**

# Model-independent 0νββ decay ("master formula")

- Leading order decay rate for any LNV mechanism (including up to **dim-9 operators in SM-EFT**) involves a finite set of **NMEs**

- Structure calculations should present NMEs broken down this way




Cirigliano et. al, 2019

# Model-independent 0νββ decay

A= axial
P = pseudoscalar
M = magnetic

**9 long-range NMEs**

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

**6 (8?) short-range NMEs**

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

*Included in some phenomenological calculations

# Light-neutrino-exchange NME

$$
\begin{aligned}
M^{0\nu} = &- \left(\frac{g_V}{g_A}\right)^2 M_{\mathrm{F}} \\
&+ M_{\mathrm{GT}}^{\mathrm{AA}} + M_{\mathrm{GT}}^{\mathrm{AP}} + M_{\mathrm{GT}}^{\mathrm{PP}} + M_{\mathrm{GT}}^{\mathrm{MM}} \\
&+ M_{\mathrm{T}}^{\mathrm{AP}} + M_{\mathrm{T}}^{\mathrm{PP}} + M_{\mathrm{T}}^{\mathrm{MM}} \\
&+ g_\nu^{\mathrm{NN}} \times (\text{some factors}) \times M_{\mathrm{F,sd}}
\end{aligned}
$$

# Light-neutrino-exchange NME

$$M^{0\nu} = -\left(\frac{g_V}{g_A}\right)^2 M_{\mathrm{F}}$$
$$+ M_{\mathrm{GT}}^{\mathrm{AA}} + M_{\mathrm{GT}}^{\mathrm{AP}} + M_{\mathrm{GT}}^{\mathrm{PP}} + M_{\mathrm{GT}}^{\mathrm{MM}}$$
$$+ M_{\mathrm{T}}^{\mathrm{AP}} + M_{\mathrm{T}}^{\mathrm{PP}} + M_{\mathrm{T}}^{\mathrm{MM}}$$
$$+ g_\nu^{\mathrm{NN}} \times (\text{some factors}) \times M_{\mathrm{F,sd}}$$

LEC

Just some masses and stuff

Short-range NME

# What if we just sum all the short-range NMEs?

Sum of AA/AP/PP components

$$\mathcal{M}^{0N} = -\left(\frac{g_V}{g_A}\right)^2 M_{F,sd} + M_{GT,sd} + M_{T,sd},$$

**"Heavy neutrino" benchmark quantity:**

- **Not** a meaningful operator in the EFT framework
- Many phenomenological NME calculations report this total NME
  - ➢ Allows nuclear structure uncertainties to be separate from LEC uncertainties

# Decay rate master formula

$$\left[T_{1/2}^{0\nu}\right]^{-1} = \sum_{\alpha,\beta} G_{\alpha\beta}^{0\nu} \mathrm{Re}[\mathcal{A}_\alpha \mathcal{A}_\beta^*]$$

Sum over "leptonic structures". Each amplitude built out of Wilson coefficients, NMEs, and LECs

# Specific model: 3+1 model

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

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

Sum of Gamow-Teller and tensor parts
Latex this explicitly

**Assumptions:**

- 3 Standard Model neutrinos + 1 heavy sterile neutrino
- Decay rate is saturated by heavy-neutrino-exchange
- Mass of heavy neutrino is at least 1000 MeV

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Remember this for later

Sum of Gamow-Teller and tensor parts
Latex this explicitly

**Assumptions:**

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# What are the short-range operators?

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

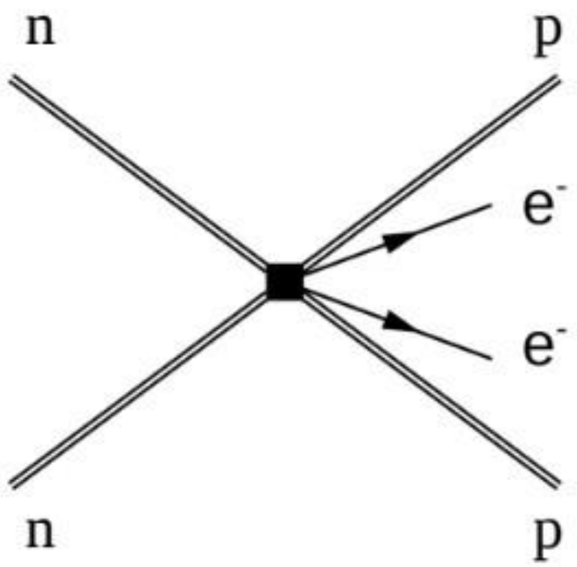
dim-9 :

$dd \to uuee$

dim-3 :

$\nu \to \nu^c$

**Matching to hadronic scale**



# What are the short-range operators?

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- short-range ndent renormaliza

Short-range operators relatively unexplored in nuclear many-body theory

d
$dd$

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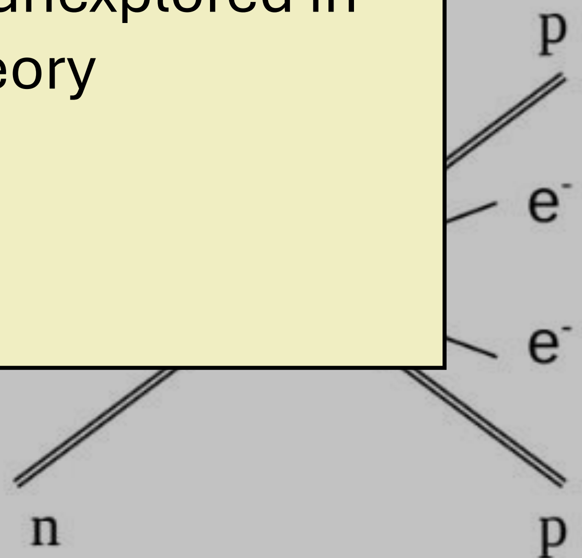

# Outline

- Why do we care about short-range NMEs?
- **Discussion point: short-range MM operators**
- Differentiating LNV mechanisms
- SRG & regulators
- VS-IMSRG NME results
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# Discussion point: short-range MM components

**Long-range**

$$M_{\mathrm{GT}}^{\mathrm{MM}}, M_{\mathrm{T}}^{\mathrm{MM}}$$

**Suppressed**

The long-range MM components are suppressed by order $\epsilon_\chi^2$ in power counting.

$$h_{\mathrm{GT}}^{\mathrm{MM}}(\mathbf{q}^2) = \frac{1}{2} h_{\mathrm{T}}^{\mathrm{MM}}(\mathbf{q}^2) = g_{\mathrm{M}}^2(\mathbf{q}^2) \frac{\mathbf{q}^2}{6 g_{\mathrm{A}}^2 m_{\mathrm{nucl}}^2}$$

$$g_{\mathrm{M}}(\mathbf{q}^2) = (1 + \kappa_1) g_{\mathrm{V}}(\mathbf{q}^2)$$

# Discussion point: short-range MM components

**Long-range**

$$M_{\mathrm{GT}}^{\mathrm{MM}}, M_{\mathrm{T}}^{\mathrm{MM}}$$

**Enhanced**

However, their suppression is reduced by the large isovector magnetic moment of the nucleon.

$$h_{\mathrm{GT}}^{\mathrm{MM}}(\mathbf{q}^2) = \frac{1}{2} h_{\mathrm{T}}^{\mathrm{MM}}(\mathbf{q}^2) = g_{\mathrm{M}}^2(\mathbf{q}^2) \frac{\mathbf{q}^2}{6 g_{\mathrm{A}}^2 m_{\mathrm{nucl}}^2}$$

$$(1+3.7)^2 \sim 22$$

$$g_{\mathrm{M}}(\mathbf{q}^2) = (1+\kappa_1) g_{\mathrm{V}}(\mathbf{q}^2)$$

# Discussion point: short-range MM components

Short-range

$$M^{\mathrm{MM}}_{\mathrm{GT,sd}},\ M^{\mathrm{MM}}_{\mathrm{T,sd}}$$

Enhanced

For short-range MM components, the momentum factors are larger. More enhancement?

$$h^{\mathrm{MM}}_{\mathrm{GT}}(\mathbf{q}^2) = \frac{1}{2} h^{\mathrm{MM}}_{\mathrm{T}}(\mathbf{q}^2) = g^2_{\mathrm{M}}(\mathbf{q}^2) \frac{\mathbf{q}^2}{6 g^2_{\mathrm{A}} m^2_{\mathrm{nucl}}}$$

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**Short-range**

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**Enhanced**

For short-range MM components, the momentum factors are larger. More enhancement?

Spoiler: using the VS-IMSRG, they are large.

$$h^{\mathrm{MM}}_{\mathrm{GT}}(\mathbf{q}^2) = \frac{1}{2} h^{\mathrm{MM}}_{\mathrm{T}}(\mathbf{q}^2) = g^2_{\mathrm{M}}(\mathbf{q}^2)\frac{\mathbf{q}^2}{6 g^2_{\mathrm{A}} m^2_{\mathrm{nucl}}}$$

$$g_{\mathrm{M}}(\mathbf{q}^2) = (1+\kappa_1) g_{\mathrm{V}}(\mathbf{q}^2)$$

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Short-range MM components are omitted in the master-formula. **Why?**

- Are they simply a redundant or over-constraining degree of freedom?

# Discussion point: short-range MM components

Short-range MM components are omitted in the master-formula. Why?

- Are they simply a redundant or over-constraining degree of freedom?
- Or do they only enter at N2LO or higher, so they were neglected?
    - ➢ If so, is their enhancement problematic?

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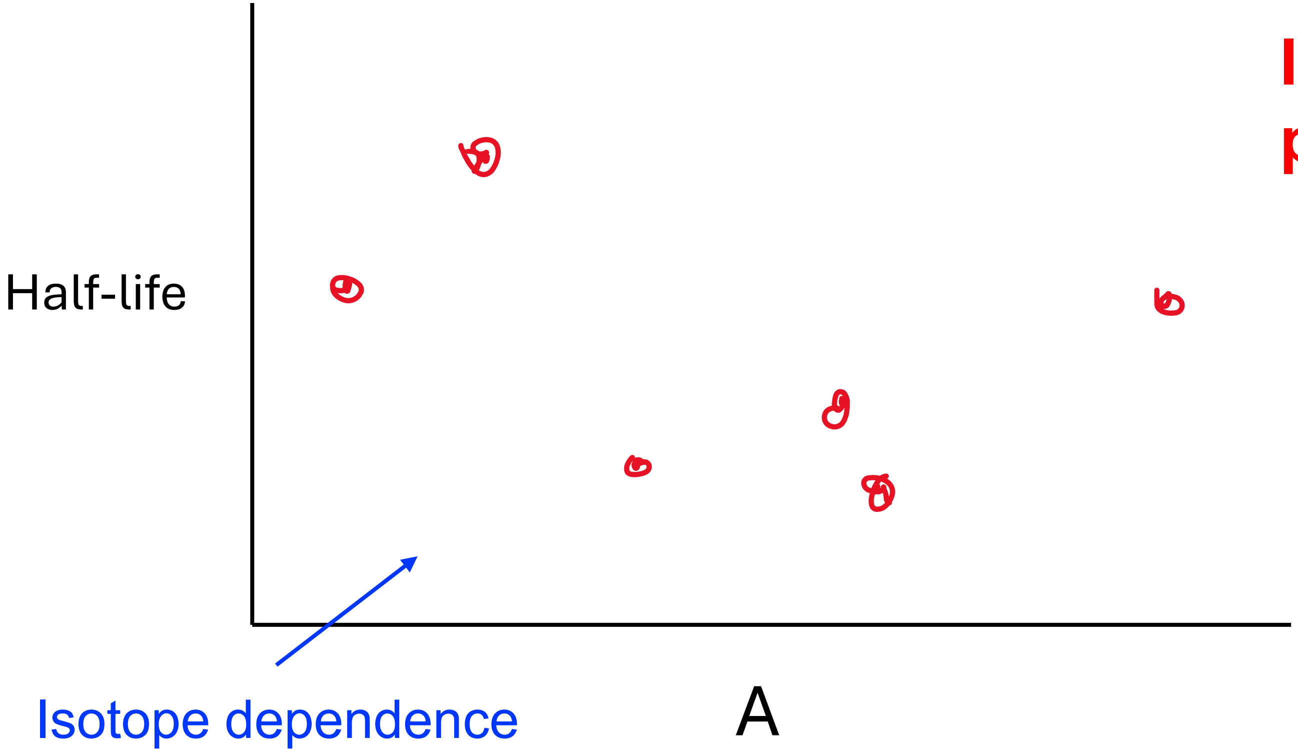
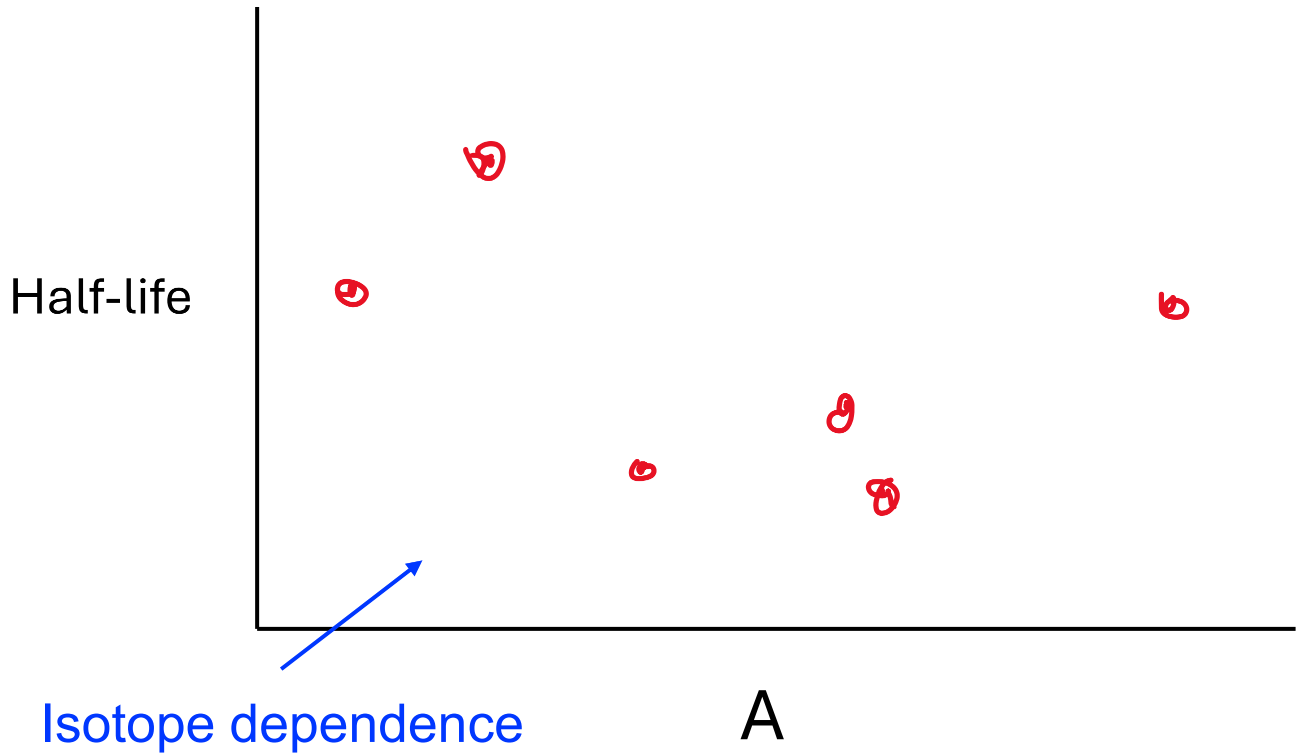
# Differentiating LNV mechanisms




**Imagine tomorrow we obtained several positive 0νββ signals for multiple nuclei.**

**How do we understand which LNV mechanism(s) is (are) responsible?**

# Differentiating LNV mechanisms



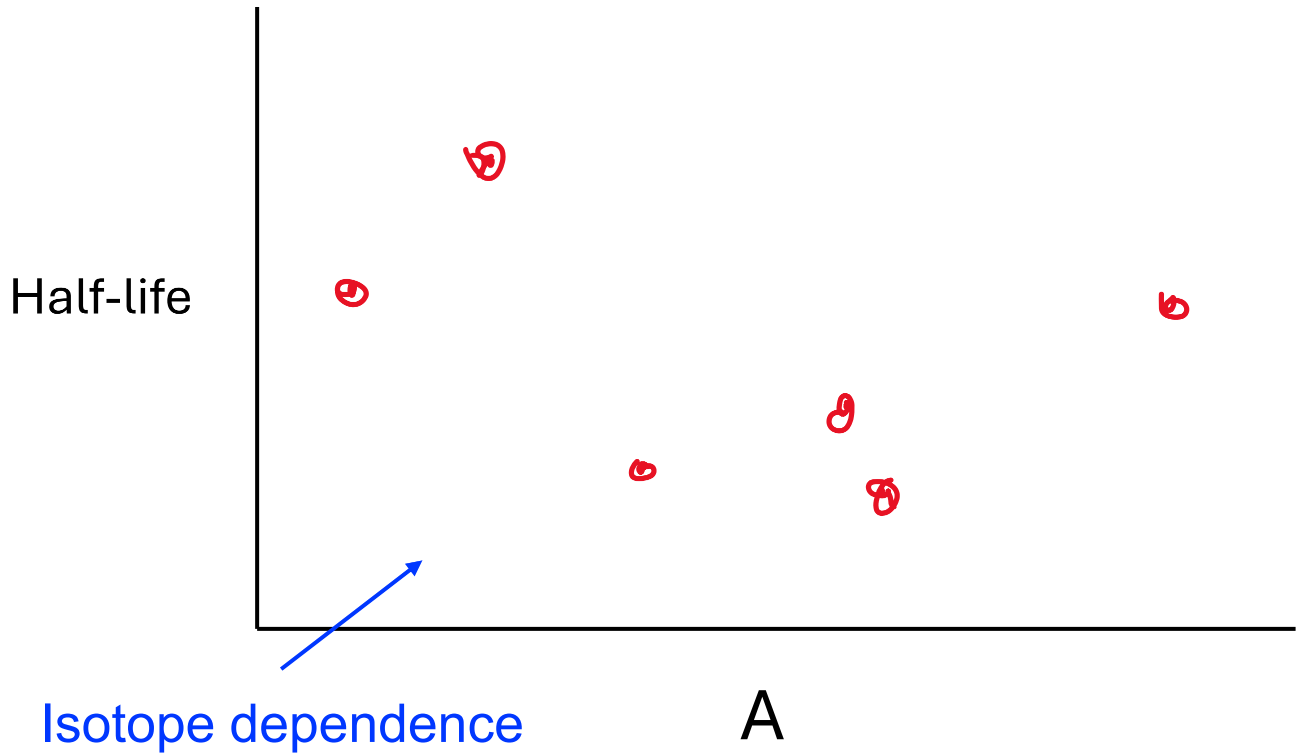

**If you take a ratio of half lives, Wilson coefficients cancel*.**

$$R^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X}) \equiv \frac{T_{1/2}^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X})}{T_{1/2}^{\mathcal{O}_i}(^{76}\mathrm{Ge})}$$

Measures how much slower 0νββ occurs in isotope $^{A}X$ compared to $^{76}Ge$ if operator $O_i$ causes the decay

**Not true if multiple operator groups dominate the decay

# Differentiating LNV mechanisms




**Now ask: do $O_i$ and $O_j$ predict different isotope dependence?**

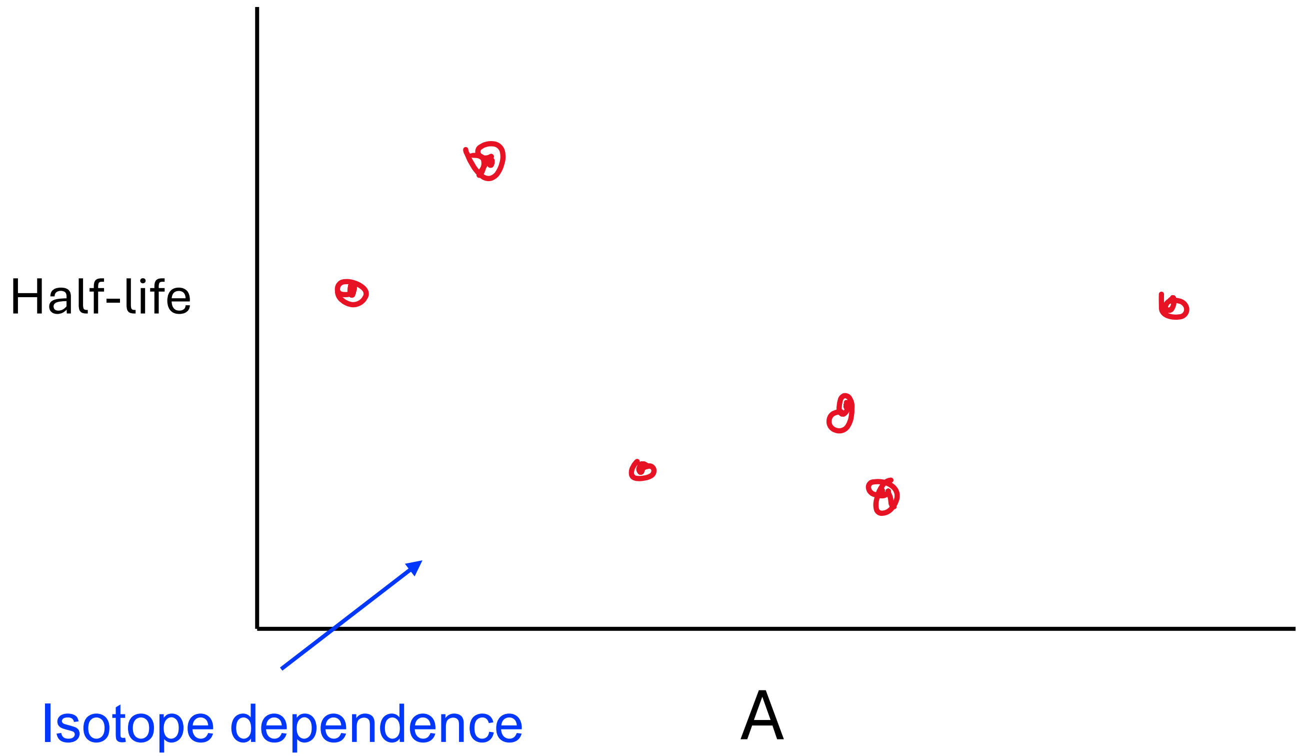
For this, we take the ratio of ratios:

$$R_{ij}(^{A}X) = \frac{R^{\mathcal{O}_i}(^{A}X)}{R^{\mathcal{O}_j}(^{A}X)}$$

If this ratio is ~1, the two operators manifest 0νββ the same way in $^{A}X$.

If this ratio is near 0 or >>1, then the two operators are distinguishable.

# Differentiating LNV mechanisms




Even if we had perfect NMEs/LECs, two operators may not be distinguishable.

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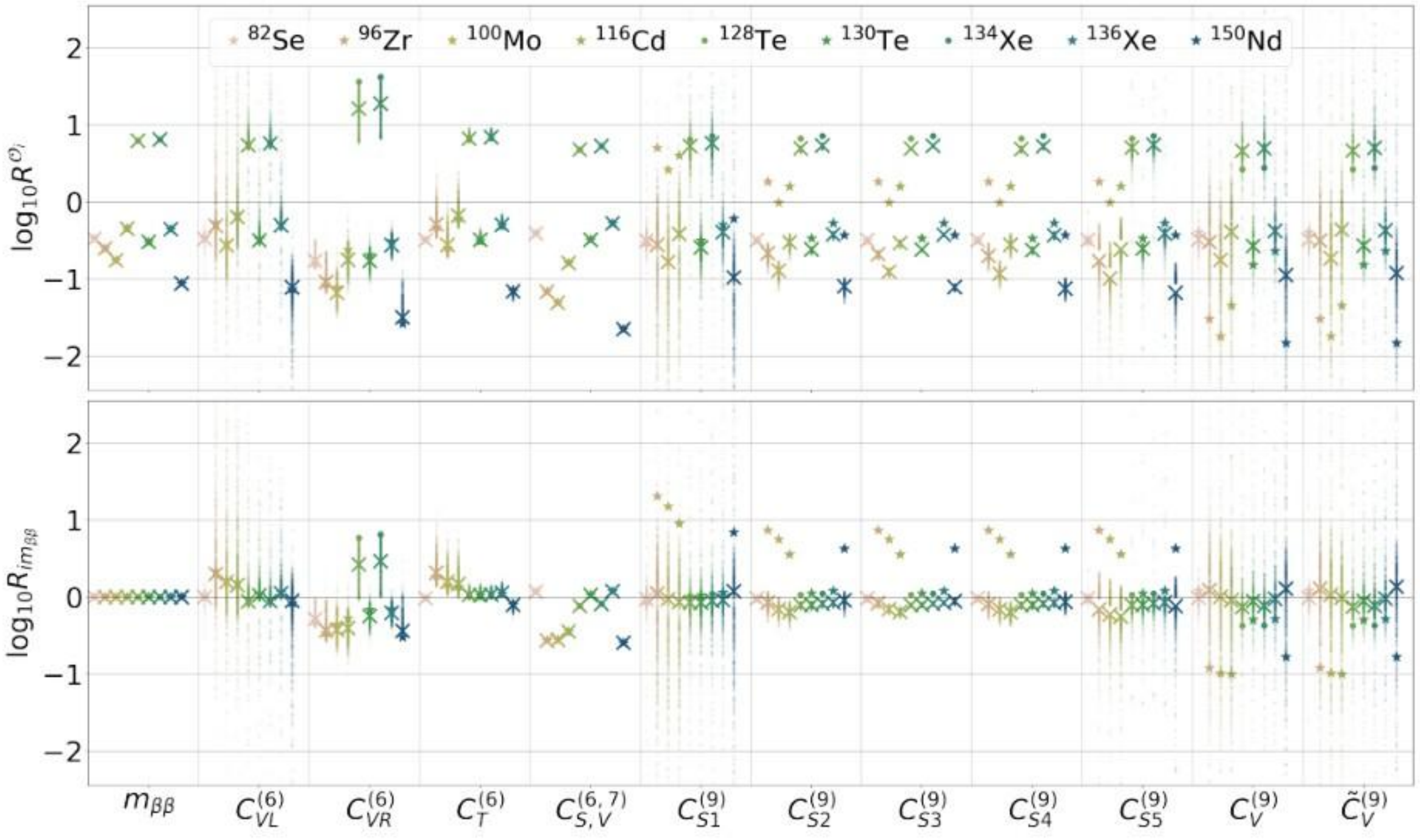
# Differentiating LNV mechanisms (using IBM NMEs)




Different isotopes decay at different rates compared to 76Ge

LECs and NMEs give uncertainty about what operators are distinguishable.

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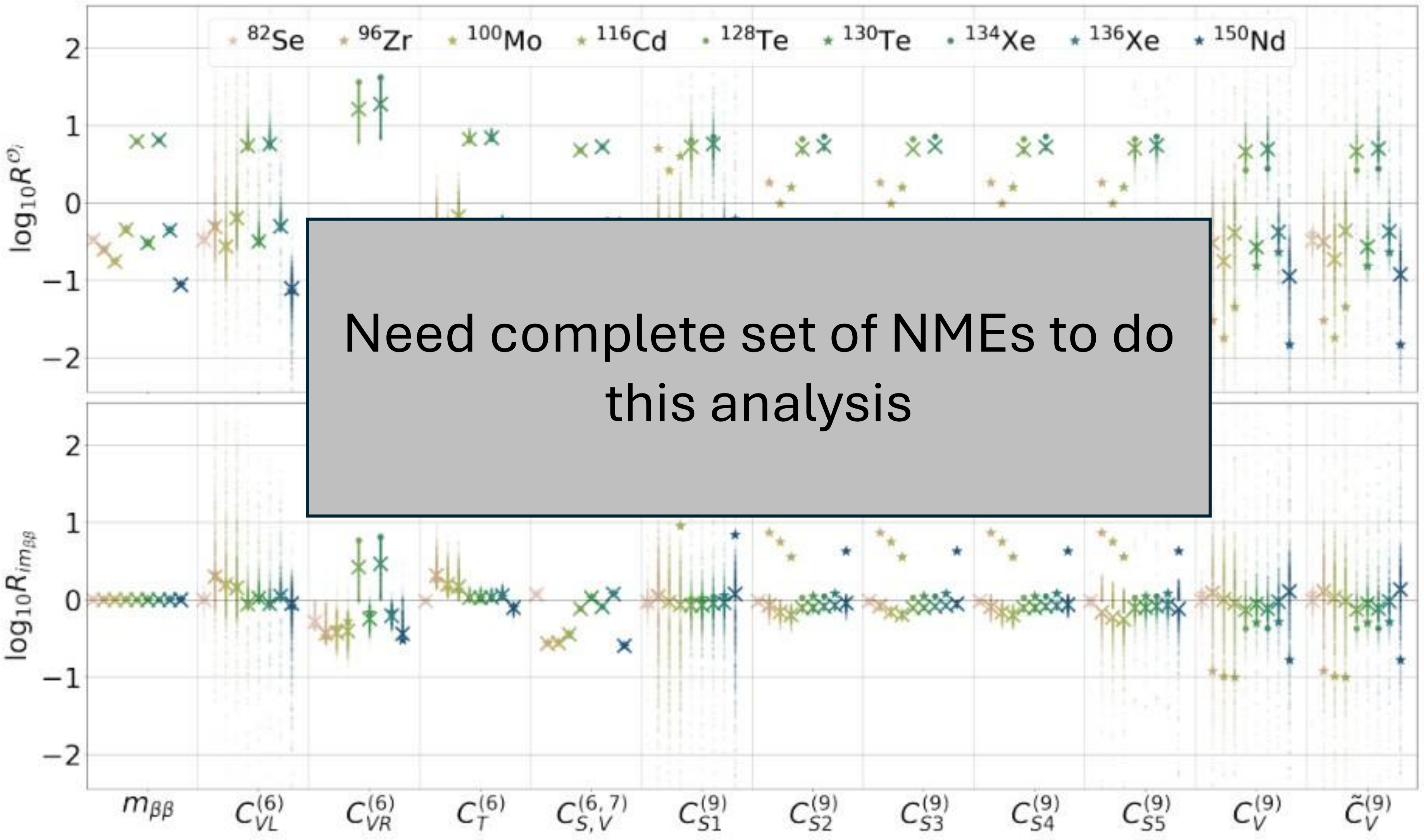


Need complete set of NMEs to do this analysis

Different isotopes decay at different rates compared to 76Ge

LECs and NMEs give uncertainty about what operators are distinguishable.

# Discussion points:

Are there some arguments why these “exotic” mechanisms (non-light-neutrino exchange) are less natural or less expected?

Do we agree we should be reporting the NMEs in the 15 components, to have a model-independent perspective?

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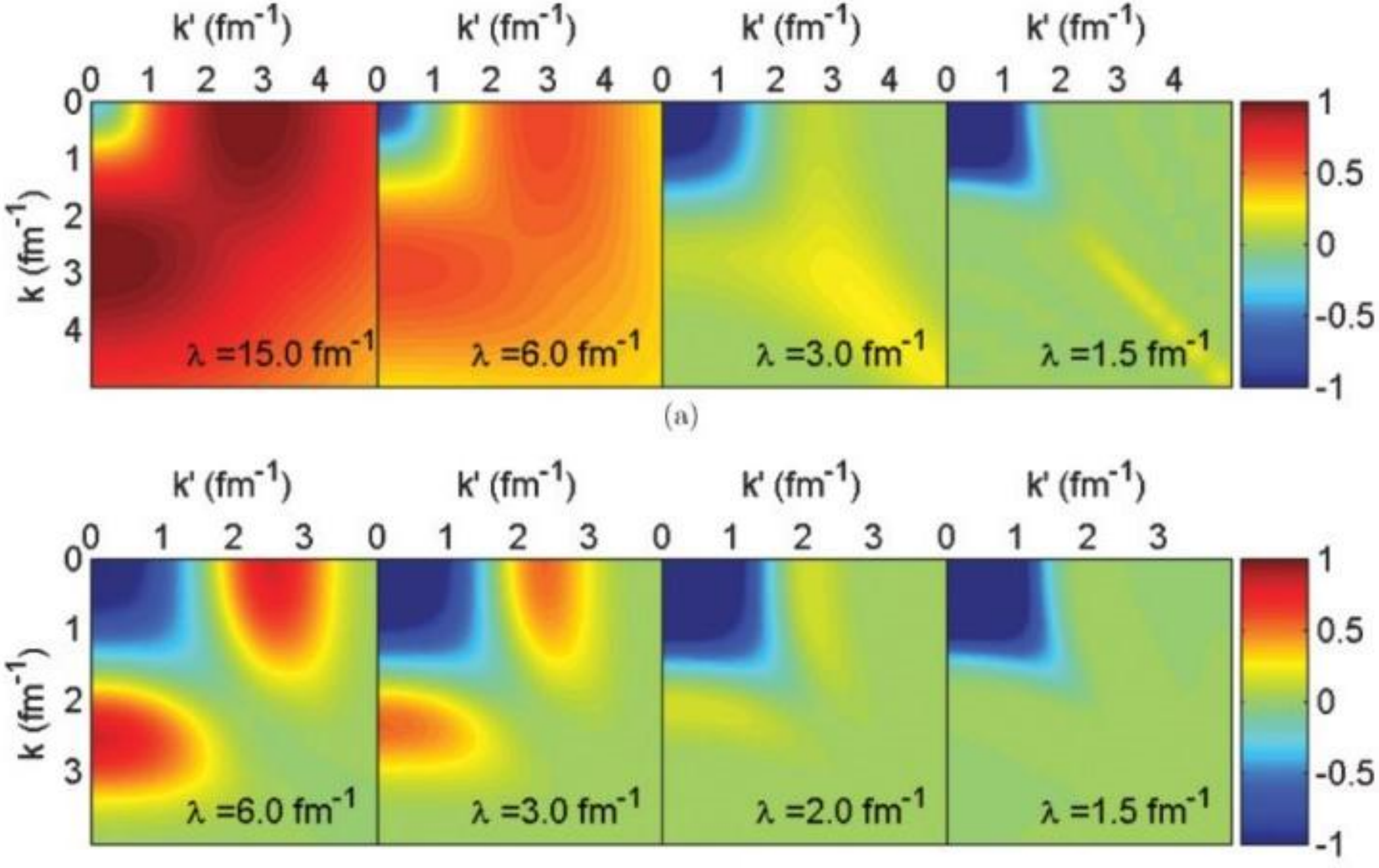
# Be careful with renormalization schemes (SRG + regulators)


**When using the SRG on the Hamiltonian, typically we neglect this on the transition operator**

# Similarity renormalization group (SRG)




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

Short range operators have larger momentum components, so the SRG should have a larger impact.

# N3LO-LNL interaction

2N:

- SRG-evolved to scale 2.0 fm^-1
- Locally-regulated with cutoff 500 MeV

3N:

- SRG-evolved to scale 2.0 fm^-1
- Mixture of local and nonlocal regulators, with cutoffs 650 and 500 MeV respectively

Short-range transition operators should be consistent with this.

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Magic interaction SRG-evolves 2N but keeps 3N bare. No way to consistently treat the transition operator.

# Dipole form factors

When we use the dipole parameterization of the vector and axial form factors, we have [1]

$$g_{\mathrm{V}}(\mathbf{q}^2) = g_{\mathrm{V}} \left(1 + \frac{\mathbf{q}^2}{\Lambda_{\mathrm{V}}^2}\right)^{-2}, \tag{17}$$

$$g_{\mathrm{A}}(\mathbf{q}^2) = g_{\mathrm{A}} \left(1 + \frac{\mathbf{q}^2}{\Lambda_{\mathrm{A}}^2}\right)^{-2} \tag{18}$$

with $\Lambda_{\mathrm{V}} = 850$ MeV and $\Lambda_{\mathrm{A}} = 1086$ MeV.

In an EFT framework, dipole form factors for the vector, axial and magnetic currents are not leading order and resum only a subset of higher-order contributions, thus providing no systematic improvement when applied to leading-order operators

# Regulating consistently

Instead, use regulators that are the same as those in the interaction:

Use

$$g_V(\mathbf{q}^2) = g_V,$$
$$g_A(\mathbf{q}^2) = g_A$$

and multiply by

$$f_{\text{local}}^{\text{NN}}(\mathbf{q}) = \exp\left[-\left(\frac{\mathbf{q}}{\Lambda}\right)^{2n}\right]$$

N3LO-LNL interaction: λ = 500 MeV, n = 3
DeltaGO interaction: λ = 394 MeV, n = 4

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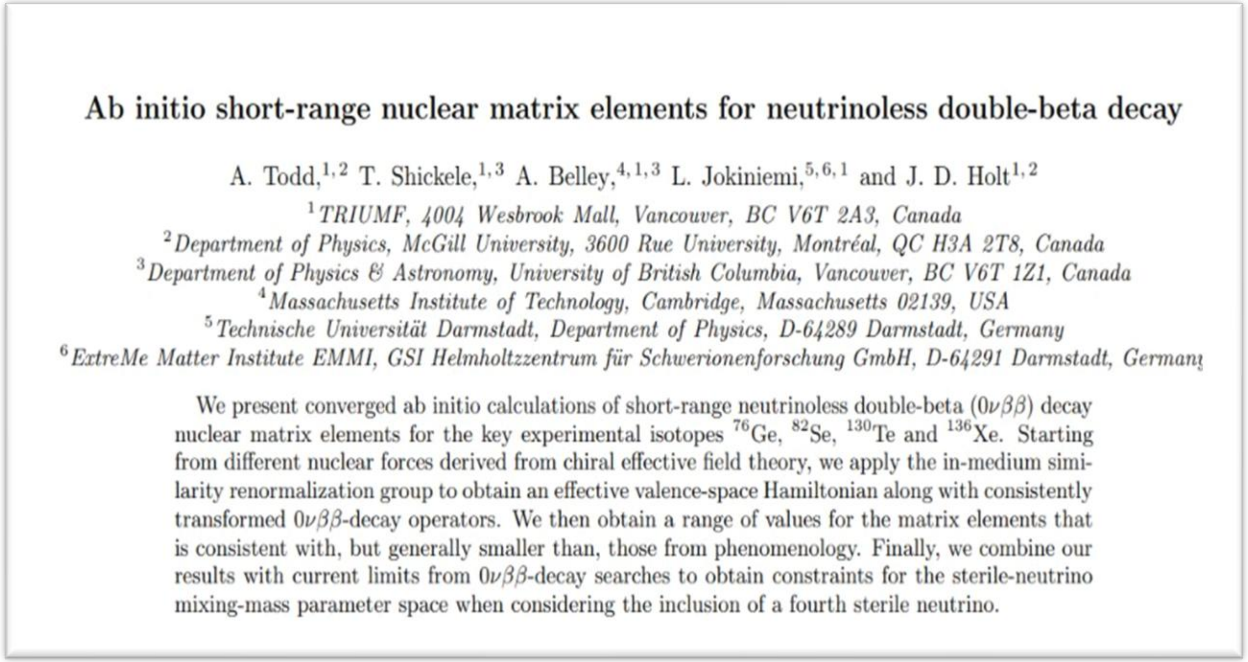
**arXiv:2604.22727**



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

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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.

# Ab initio nuclear theory

$$H\psi_n = E_n\psi_n$$

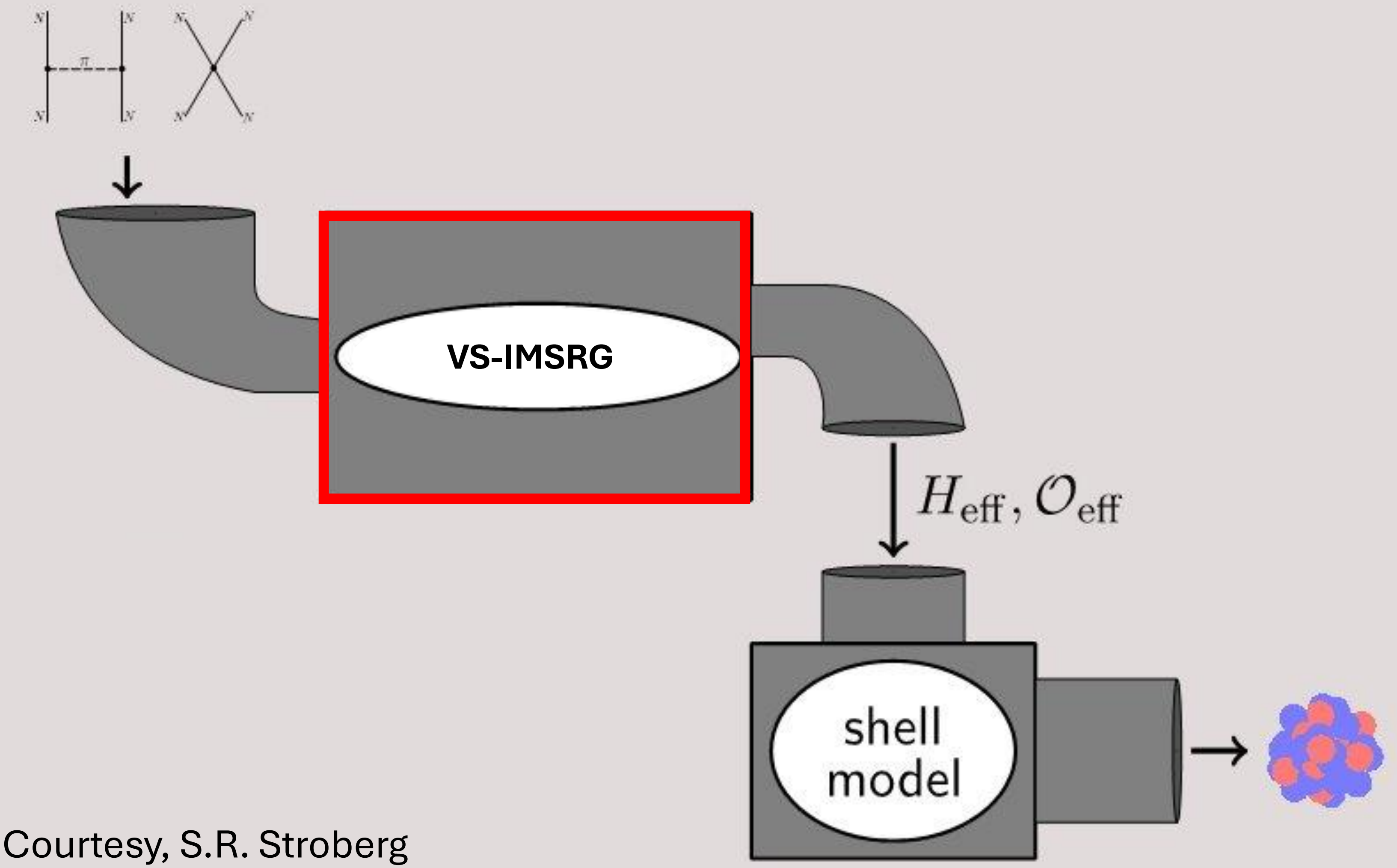
= chiral EFT interactions

+ a (polynomially scaling) many-body method

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

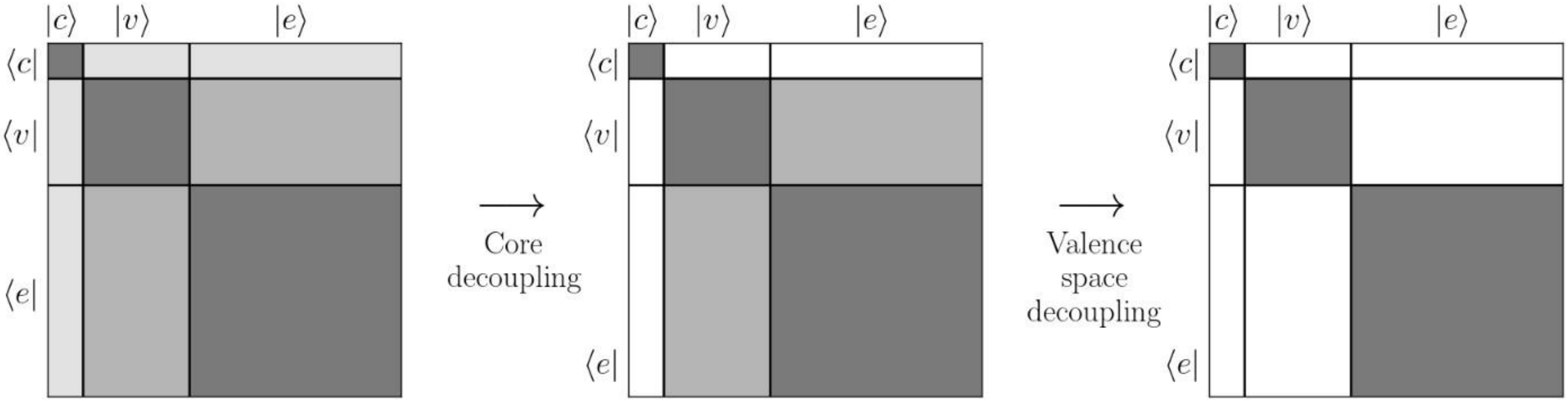
$$\mathcal{O}(s) = e^{\Omega(s)} \mathcal{O} e^{-\Omega(s)}$$

**Continuous unitary transformations of Hamiltonian**



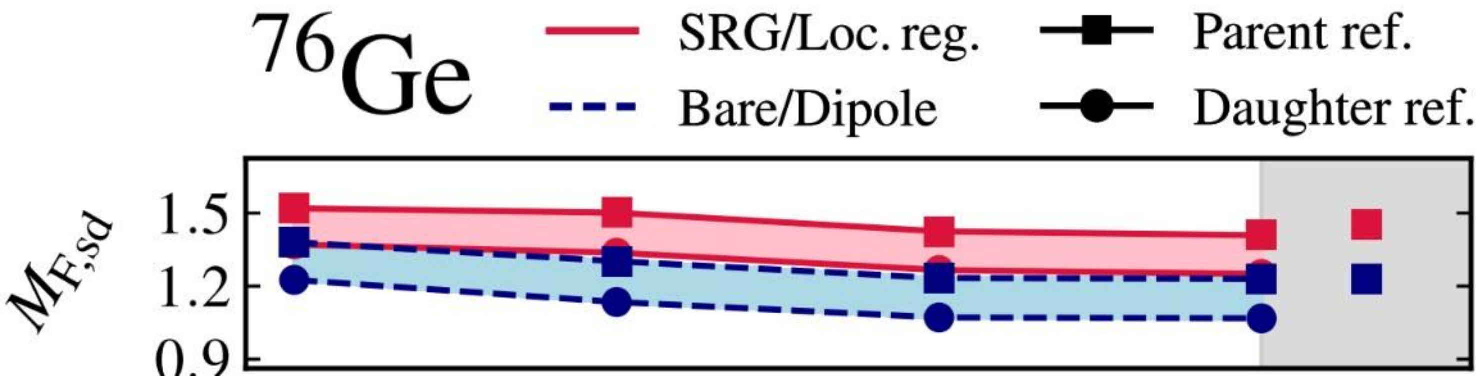

Courtesy, S.R. Stroberg

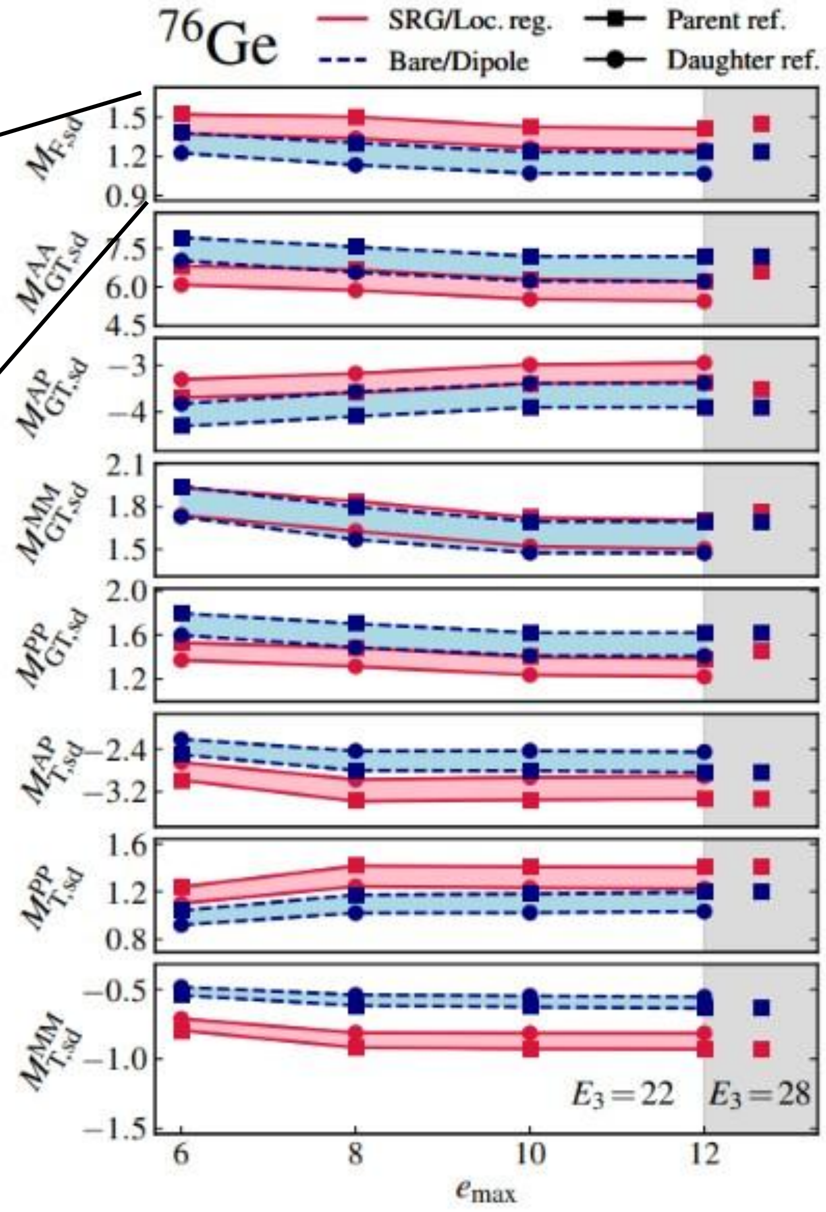
# Valence-space In-medium Similarity Renormalization Group (VS-IMSRG)




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

# Emax convergence

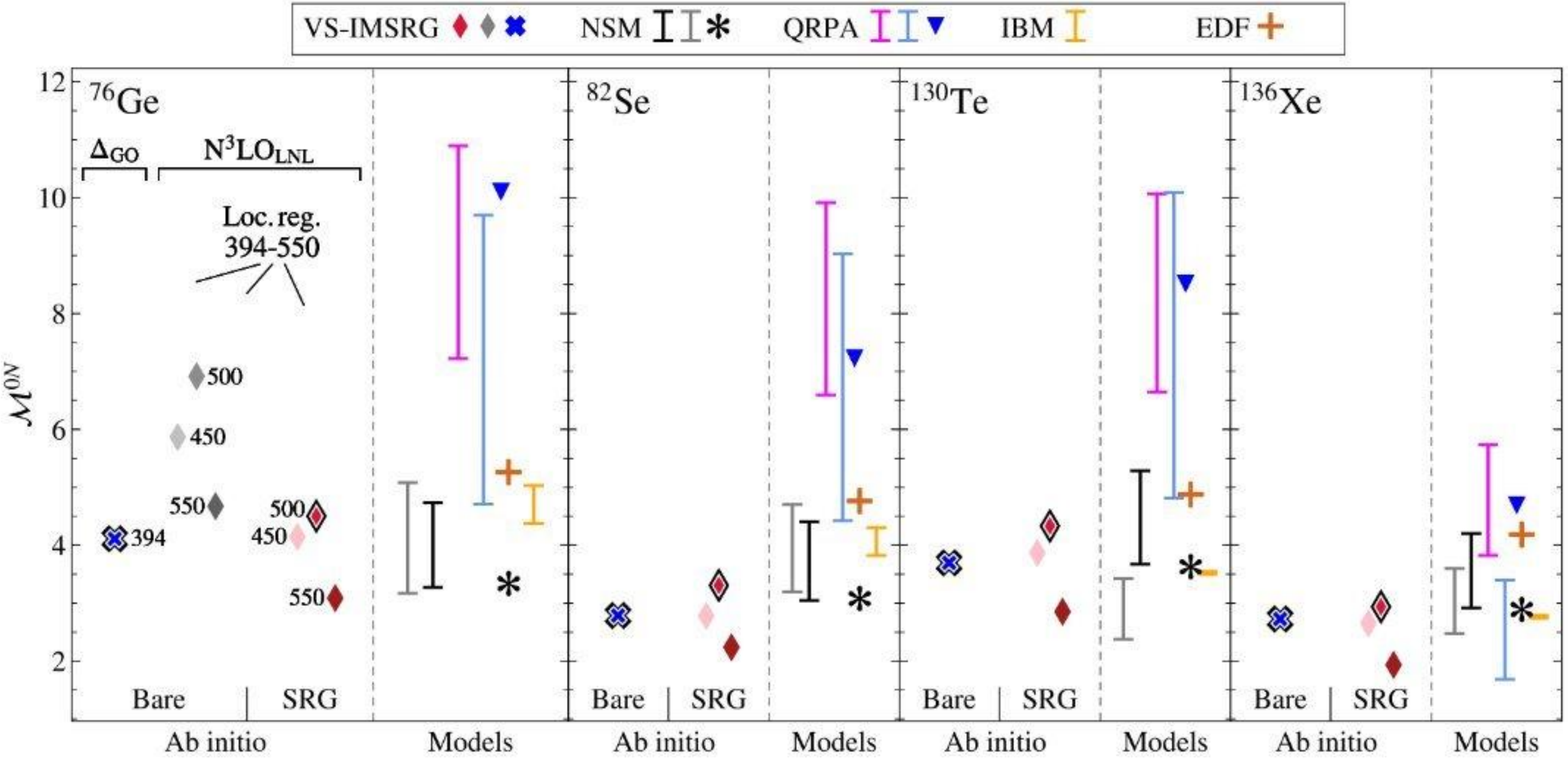



**Conclusions:**

- Using the combination common in literature, **bare operators with dipole form factors**, impacts results, by up to 50%
- Reference state dependence: ~15%

# Final short-range NMEs (benchmark quantity)




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

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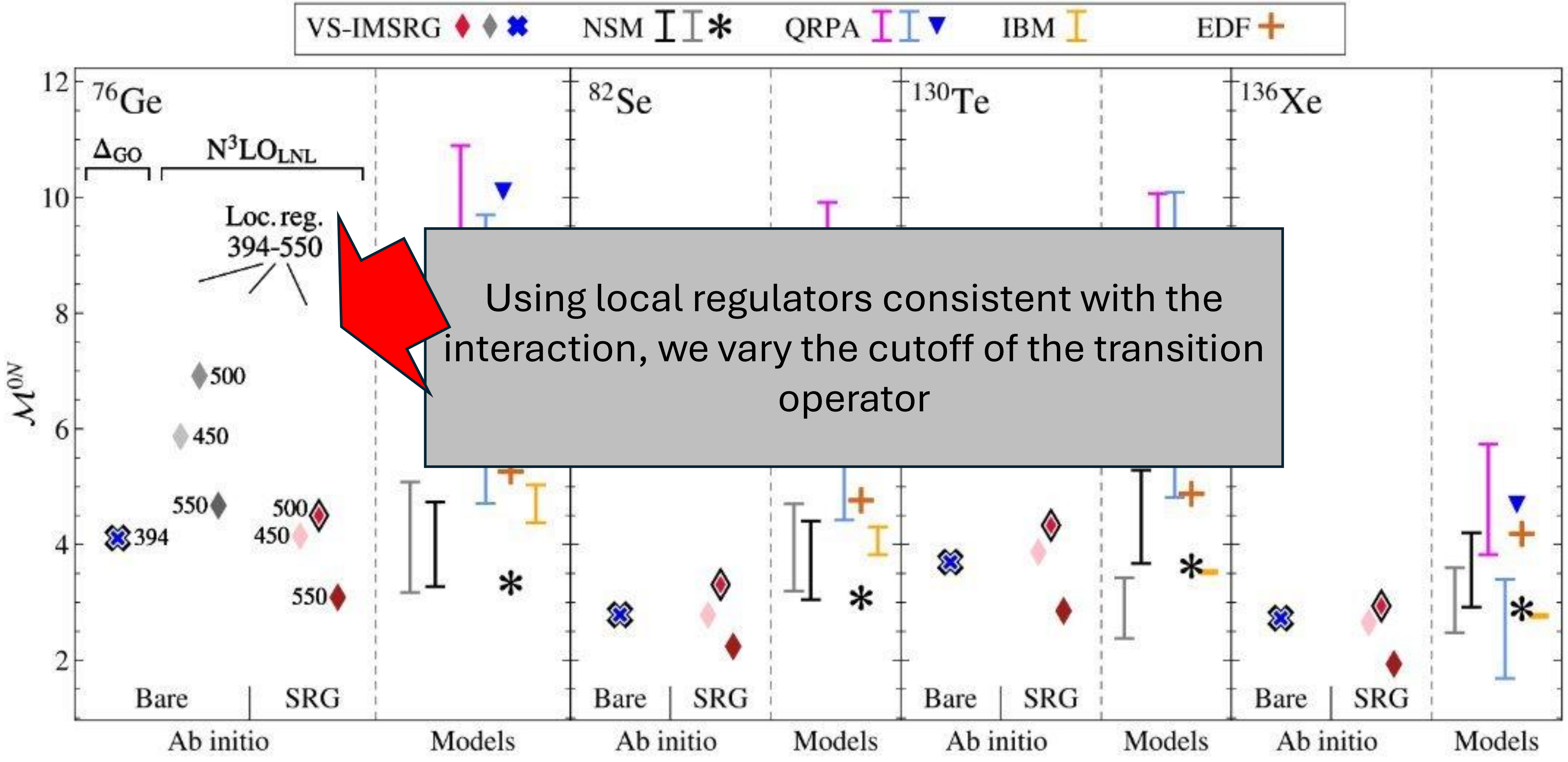


Using local regulators consistent with the interaction, we vary the cutoff of the transition operator

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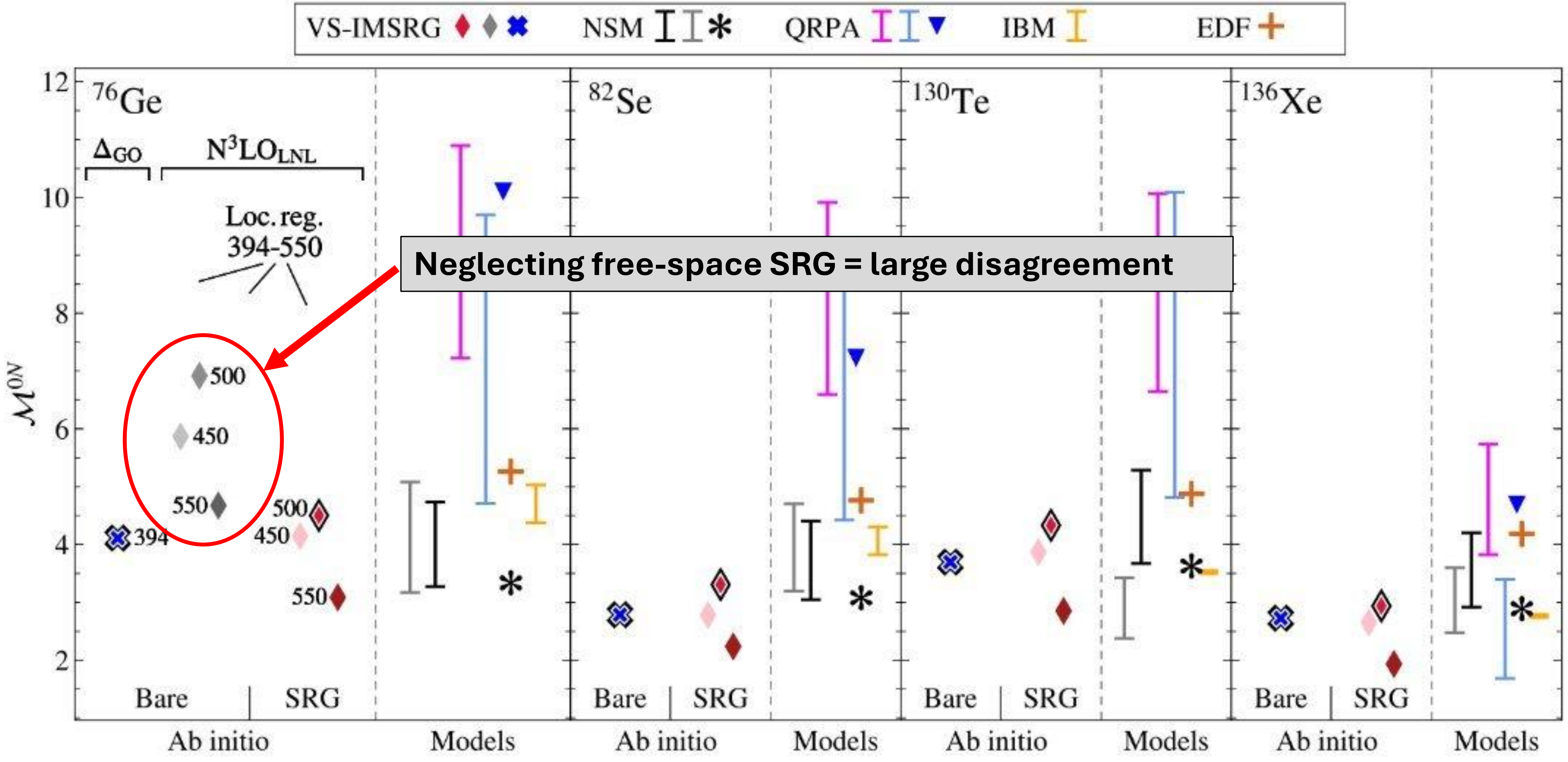


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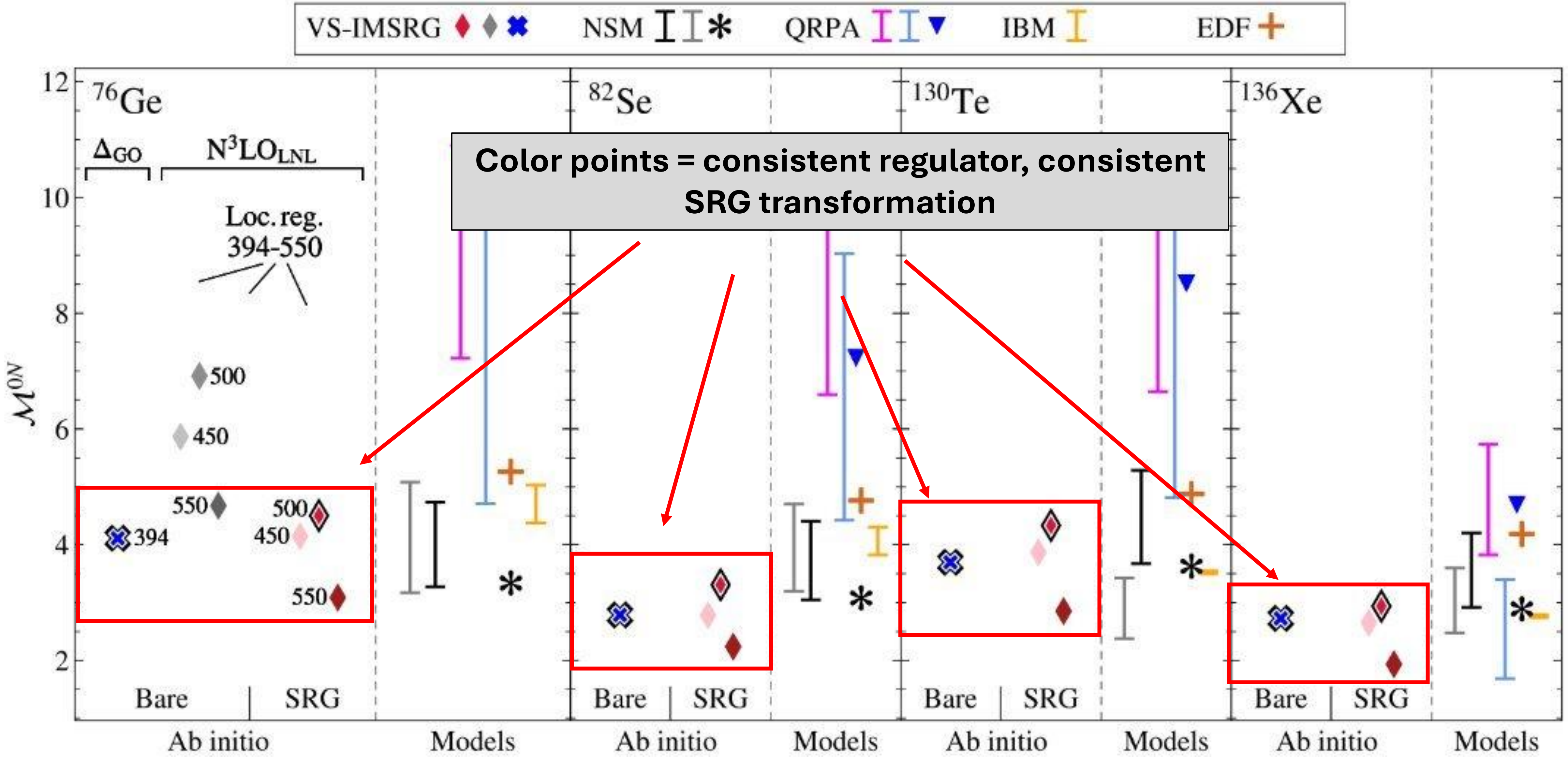


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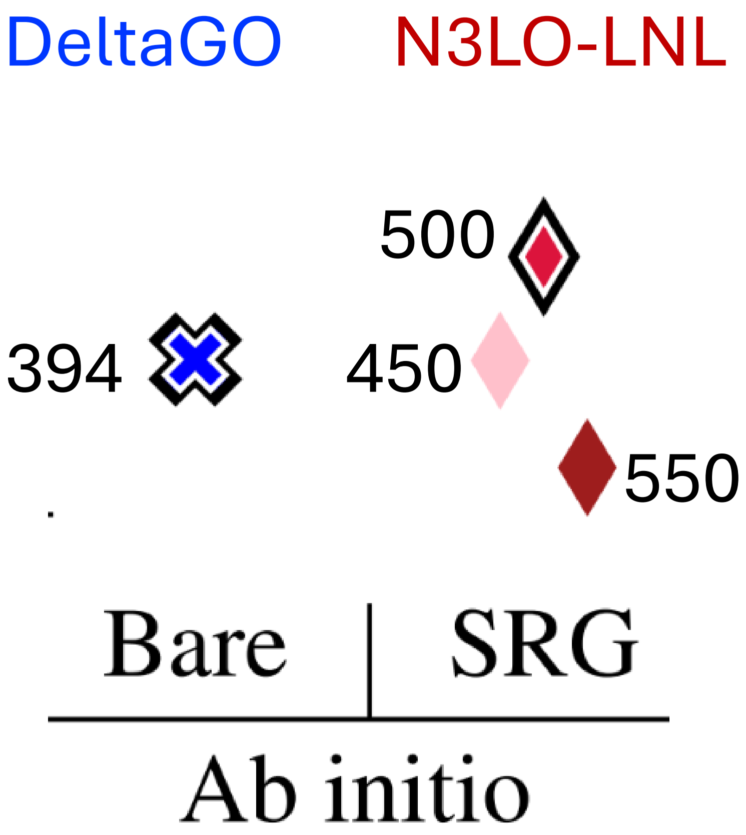
# Discussion point: normal ordering effects



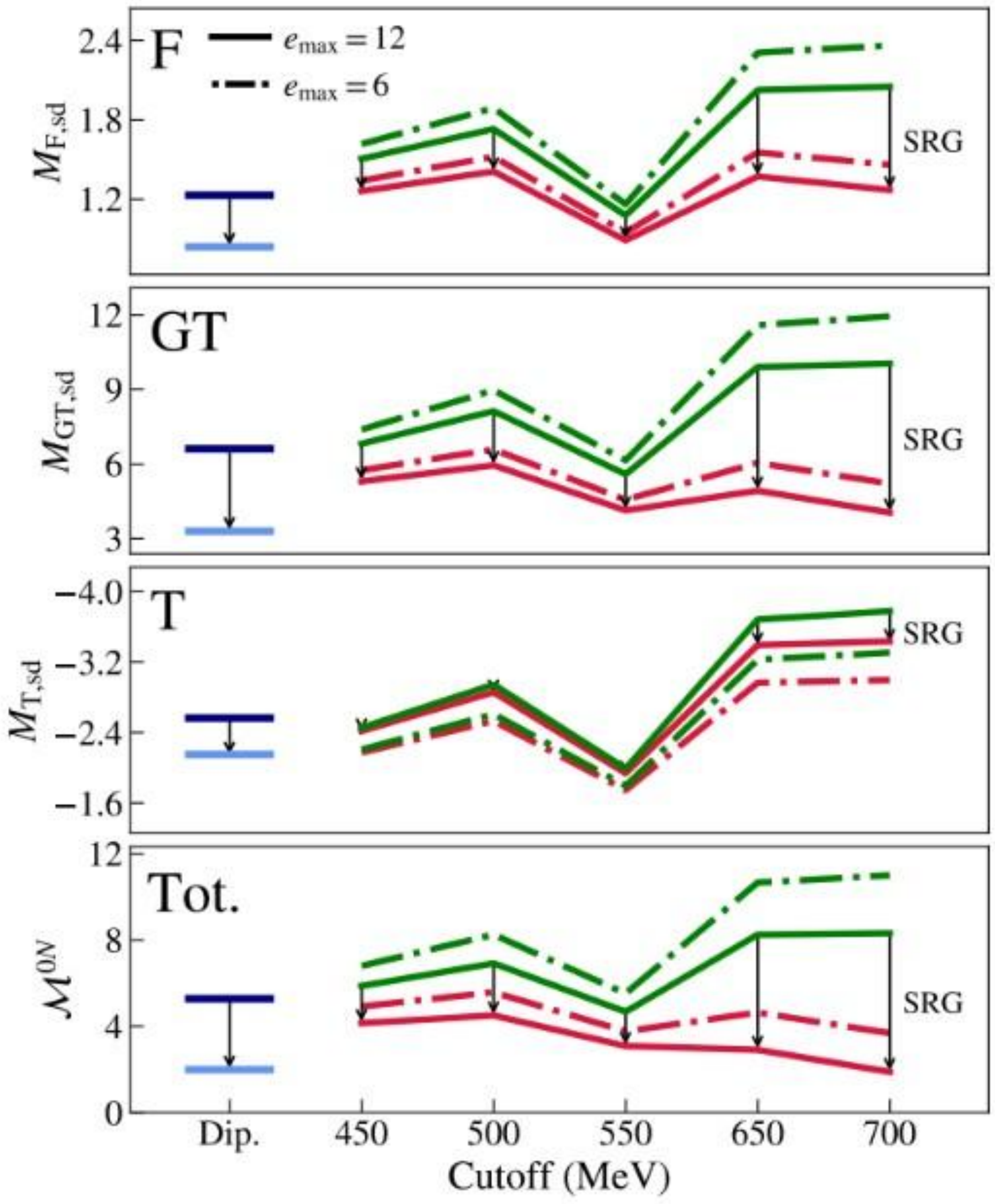

N3LO-LNL mixes cutoffs in the 3N sector. Normal ordering means we get mixtures of cutoffs at the 2-body level.

So what is the best cutoff to choose for the operator?

# Regulator dependence

Examine the cutoff dependence & SRG more closely:

- SRG (red) makes NMEs slightly less cutoff dependent
- SRG universally reduces the NMEs



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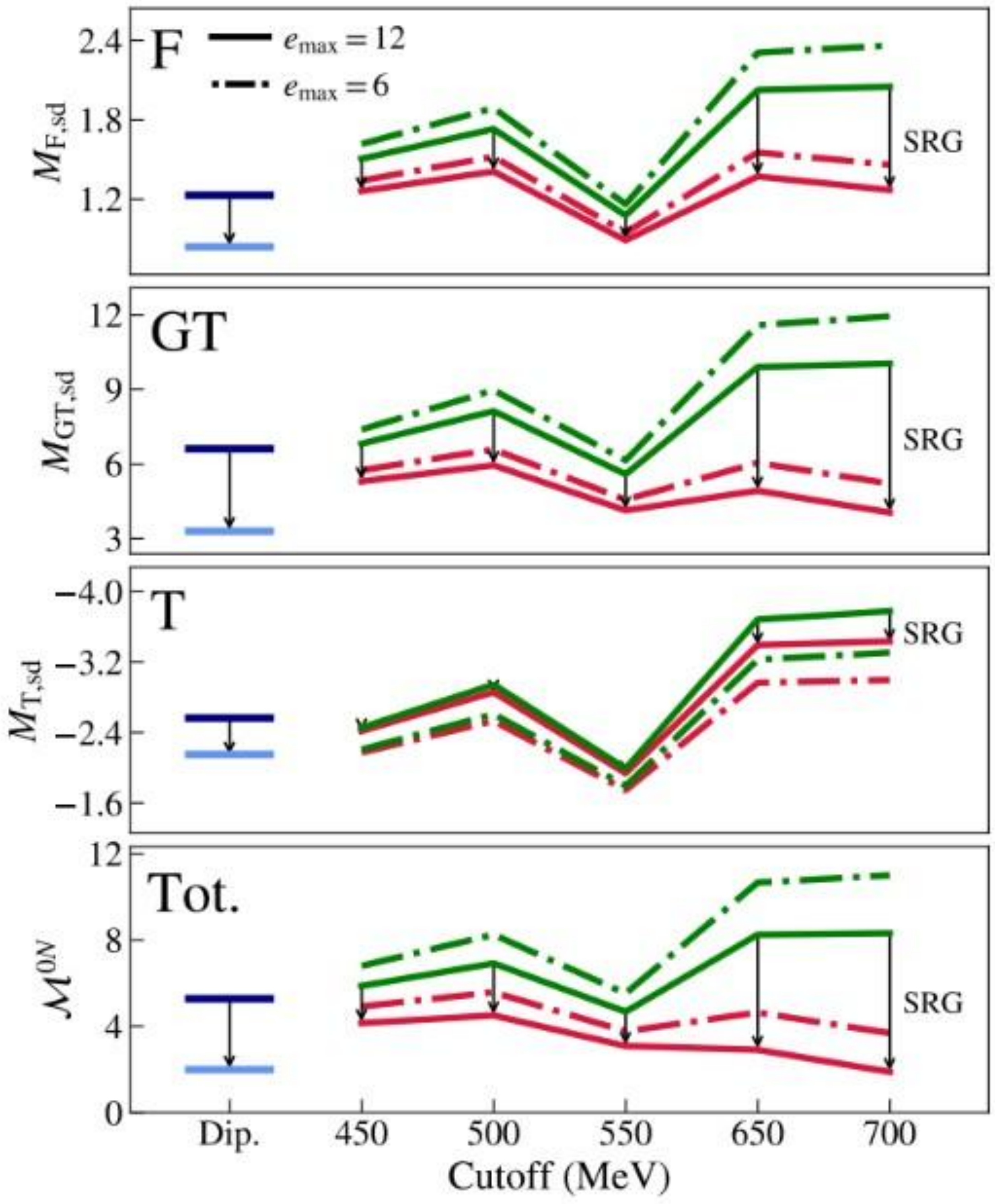
Fits with the theme "be more accurate, get smaller NMEs"



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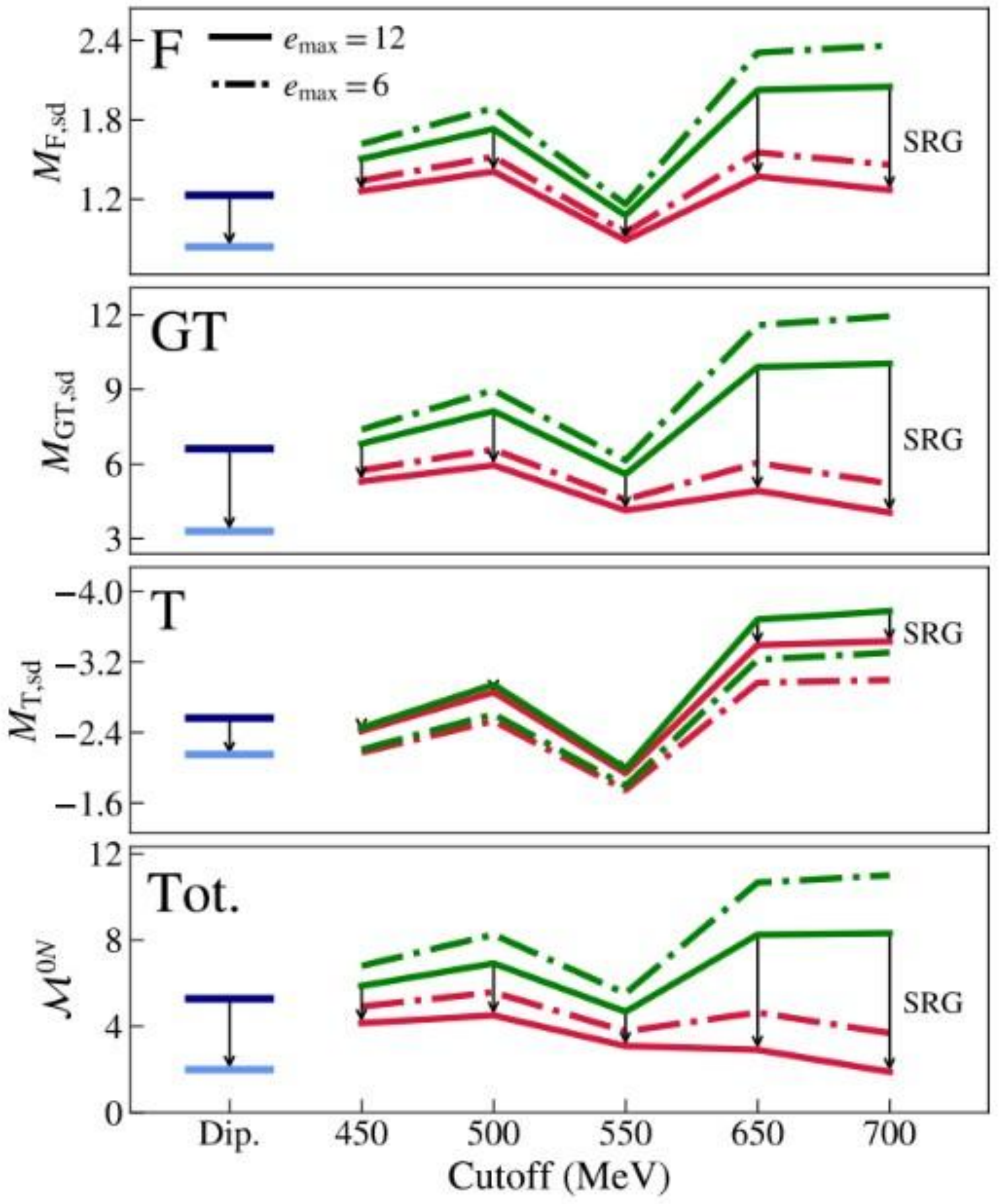
Fits with the theme "be more accurate, get smaller NMEs"

Just wait for the IMSRG(3f2) correction...



# Outline

- Why do we care about short-range NMEs?
- Discussion point: short-range MM operators
- Differentiating LNV mechanisms
- SRG & regulators
- VS-IMSRG NME results
- **<u>Exclusion plot in the 3+1 model</u>**

# Connection to BSM mechanisms

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

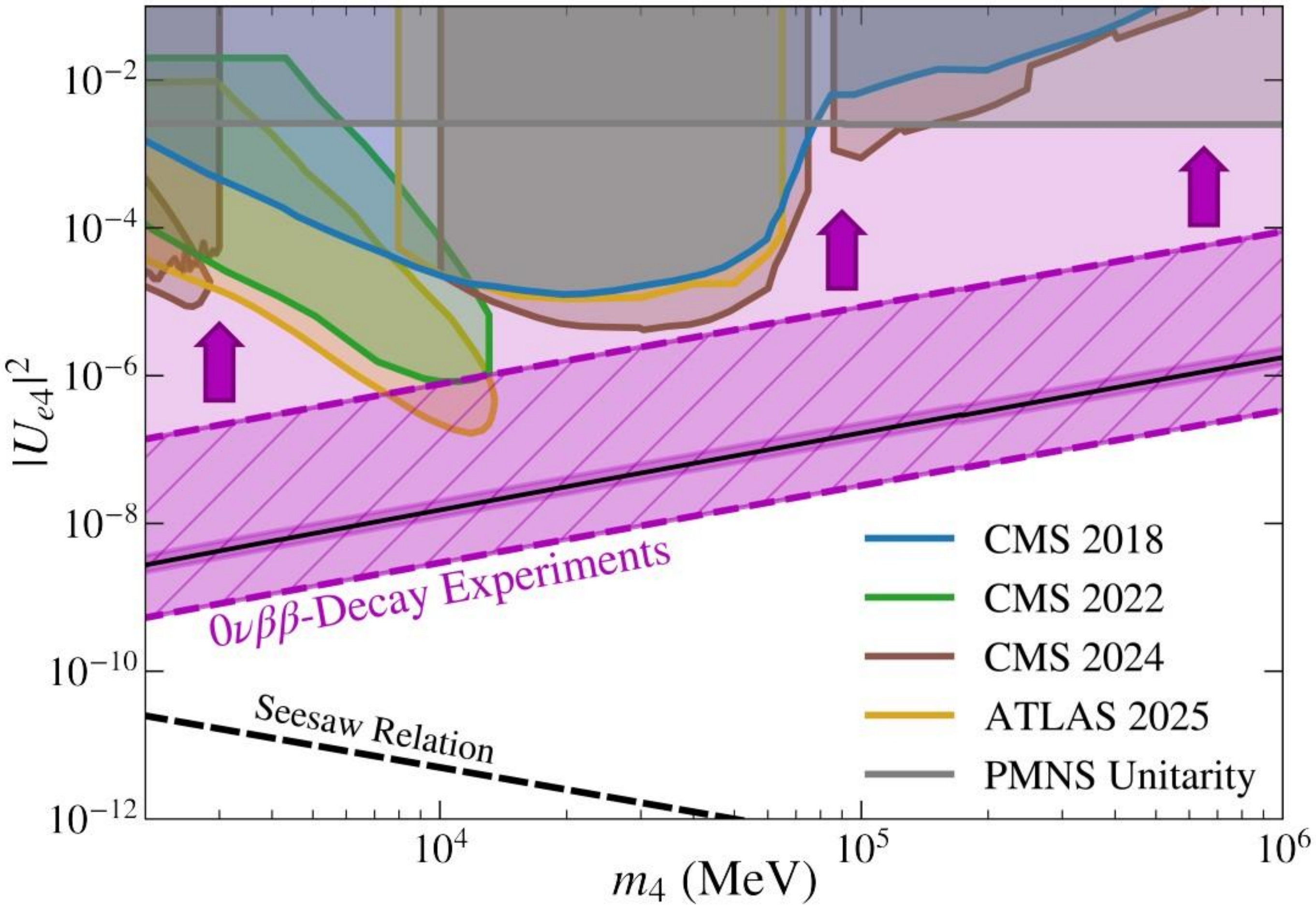
$$\left[T_{1/2}^{0\nu}\right]^{-1} = 4g_A^4 G_{01} V_{ud}^4 \eta(\mu, m_4)^2 |U_{e4}|^4 \frac{m_\pi^4}{m_e^2 m_4^2} \times \left[\frac{5}{6} g_1^{\pi\pi} M_{\rm sd}^{\rm PP} + \frac{g_1^{\pi N}}{2} M_{\rm sd}^{\rm AP} + 2 g_1^{NN} M_{\rm F,sd}\right]^2$$

We combine likelihoods from LEGEND200, CUORE, EXO-200 and KamLANDZen

# Connection to BSM mechanisms

Plot and analysis by Taiki Shickele

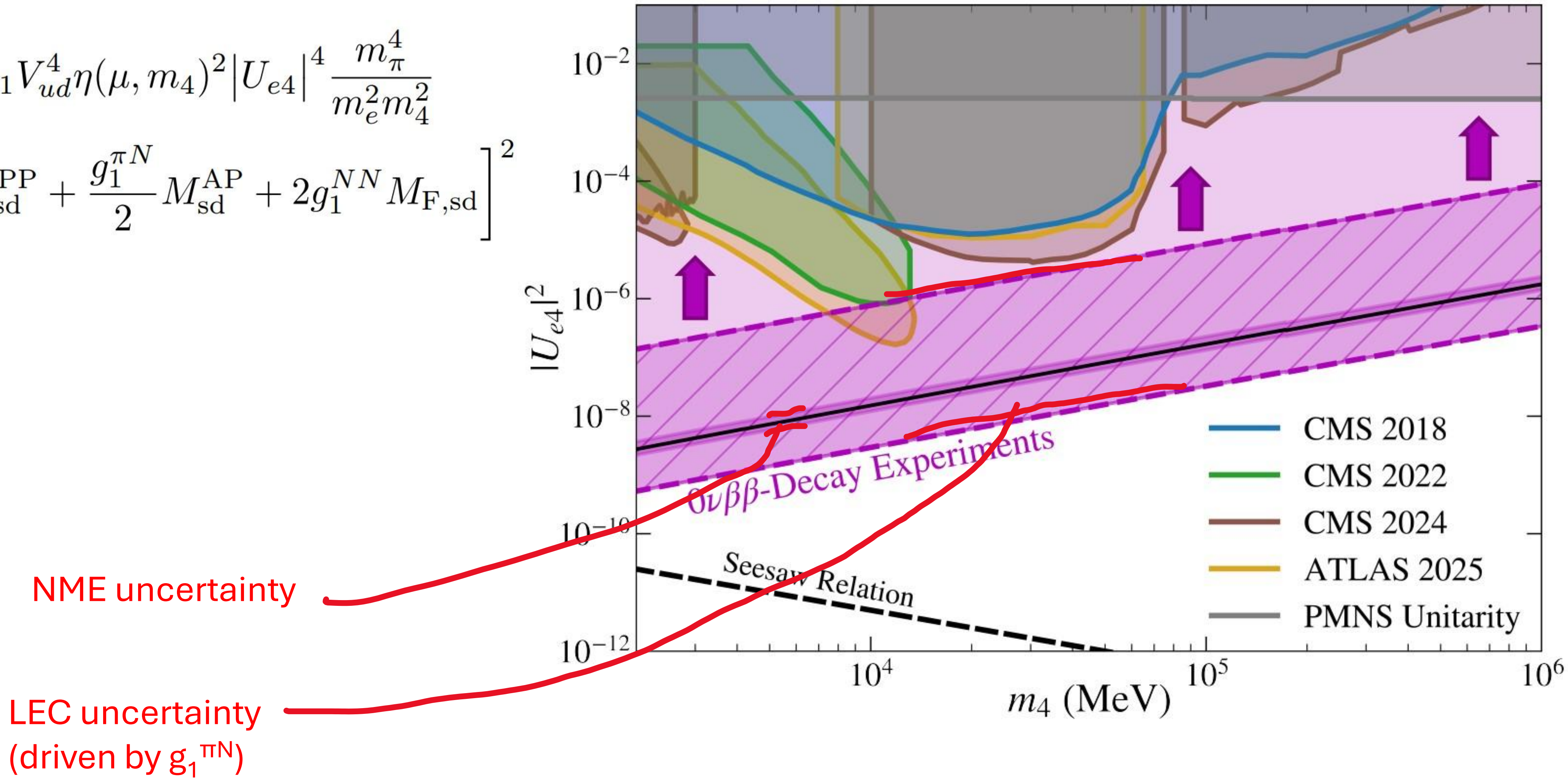
$$\left[T_{1/2}^{0\nu}\right]^{-1} = 4g_A^4 G_{01} V_{ud}^4 \eta(\mu, m_4)^2 \left|U_{e4}\right|^4 \frac{m_\pi^4}{m_e^2 m_4^2} \times \left[\frac{5}{6} g_1^{\pi\pi} M_{\rm sd}^{\rm PP} + \frac{g_1^{\pi N}}{2} M_{\rm sd}^{\rm AP} + 2 g_1^{NN} M_{\rm F,sd}\right]^2$$



# Connection to BSM mechanisms

Plot and analysis by Taiki Shickele

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



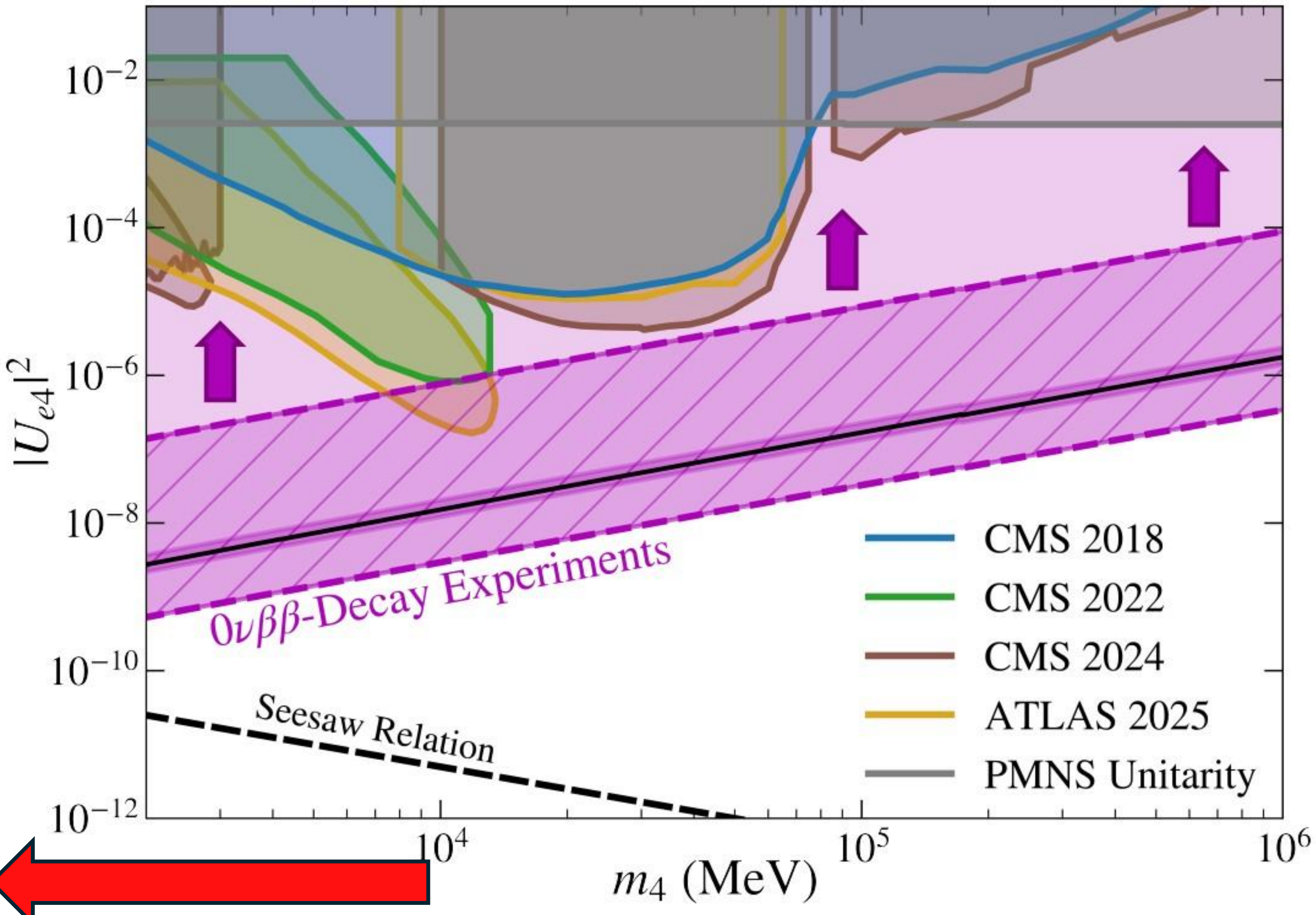



A. Todd, et. al (in prep), arXiv:2604.22727

# Connection to BSM mechanisms

Plot and analysis by Taiki Shickele

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




Taiki has done calculations for the intermediate region between light- and heavy-neutrino exchange, where NMEs become mass dependent.

# Conclusion

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

- Inherent cutoff uncertainty in interactions which mix cutoffs

- 3+1 model shows $0\nu\beta\beta$ can be a competitive probe of heavy neutrinos

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Thank you