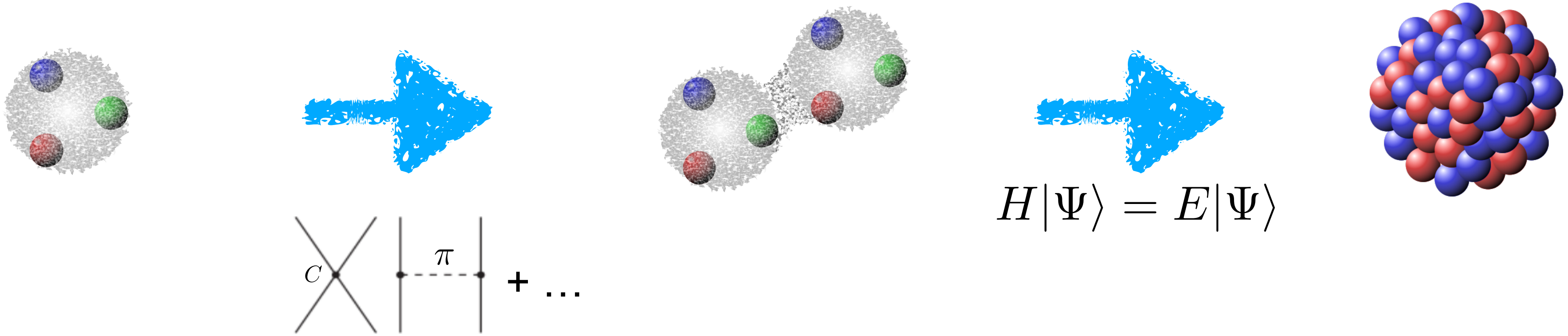
Neutrinoless double-beta decay from valence-space in-medium similarity renormalization group



Takayuki Miyagi

Theoretical and Experimental Approaches for Nuclear Matrix Elements of Double Beta Decays (Dec. 21 2023)

Collaborators

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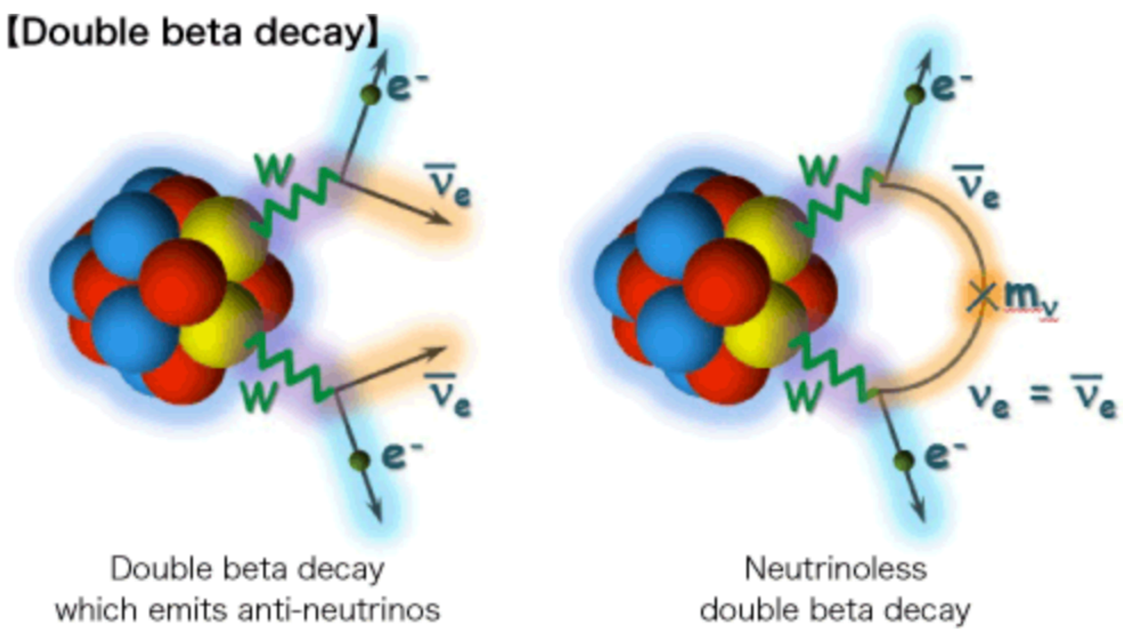
- University of Notre Dame: S. R. Stroberg
- Sun Yat-sen University: J. M. Yao, X. Zhang
- University Paris-Saclay: B. Bally
- University of North Carolina: J. Engel
- Michigan State University: S. K. Bogner, H. Hergert
- Complutense University of Madrid: T. R. Rodriguez
- University of Barcelona: A. M. Romero

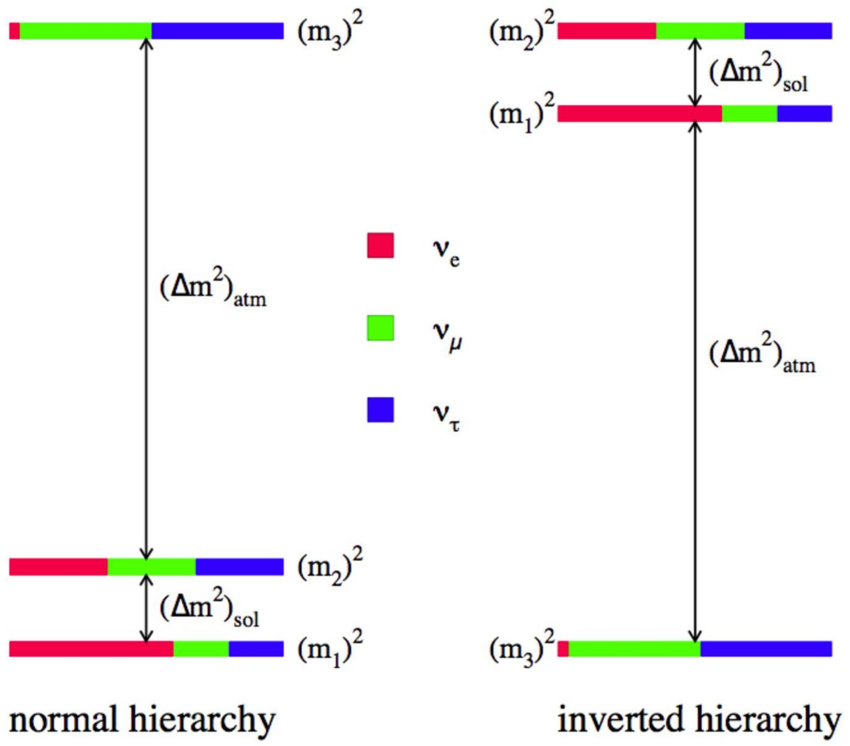
Neutrinoless double-beta decay

- Hypothetic process: it can happen only if the neutrino is its own antiparticle.
- Lepton number violation: $2n \rightarrow 2p + 2e$ $(0 \rightarrow 2)$
- Nature of neutrino

$\Delta m_{21}^2 \sim 7.5 \times 10^{-5}$ eV^2
$|\Delta m_{32}^2| \sim 2.4 \times 10^{-3}$ eV^2



https://wwwkm.phys.sci.osaka-u.ac.jp/en/research/r01.html



Neutrinoless double-beta decay

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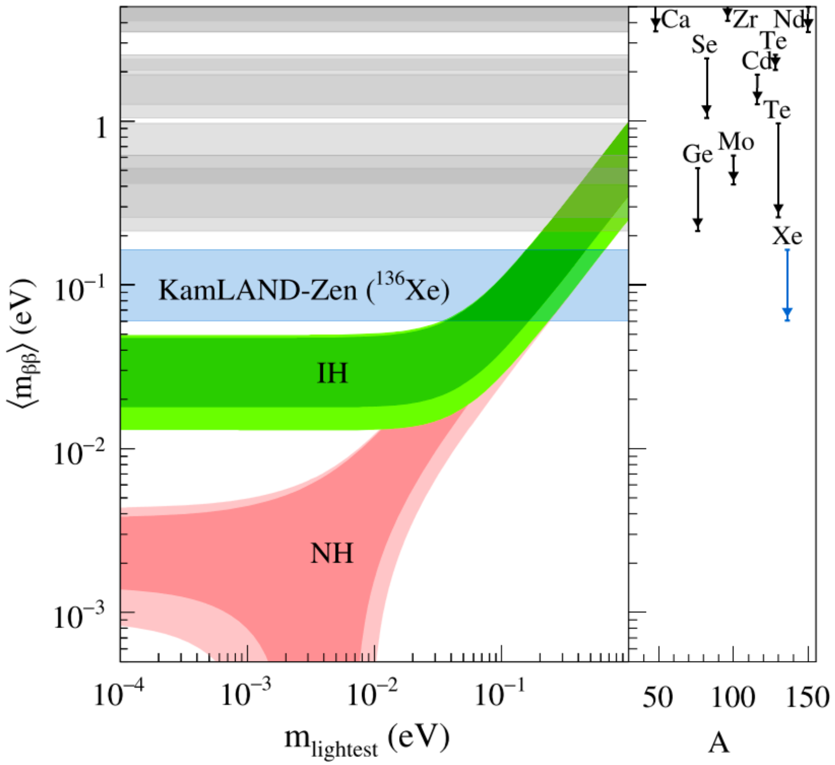
- Half-life formula:

$$(T^{0\nu\beta\beta})^{-1} = G^{0\nu}|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2, \quad \langle m_{\beta\beta}\rangle = \left|\sum_i U_{ei} m_i\right|$$

- $G^{0\nu}$: phase-space factor; known
- $M^{0\nu}$: nuclear matrix element; only theoretically available
- $<m_{\beta\beta}>$: absolute mass scale; unknown

- We need $M^{0\nu}$ as precise as possible.



A. Gando et al., Phys. Rev. Lett. 117, 082503 (2016).

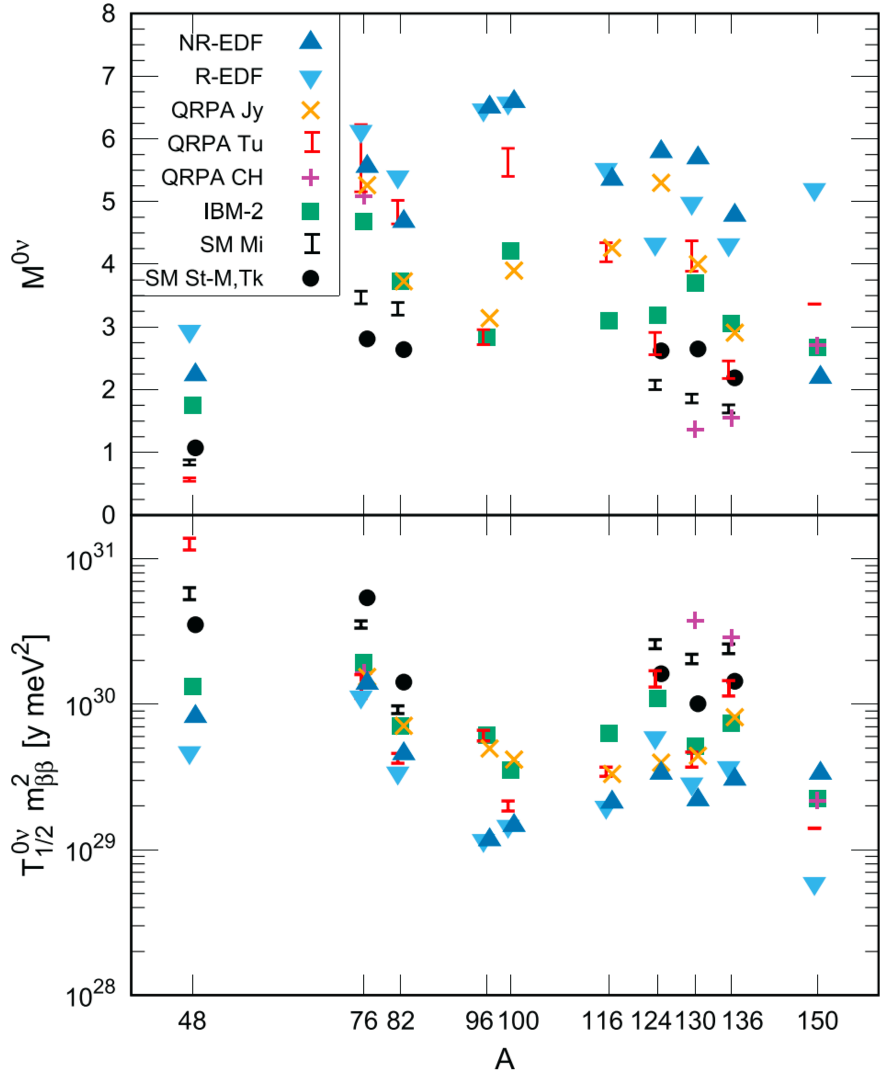
Nuclear matrix element

- Different theories provide different results
- Spread of theory results is factor 3
  - Meaning of the spread is unclear…
- A theoretical calculation with quantified uncertainty

$$H|\Psi_{\mathrm{parent/daughter}}\rangle = E|\Psi_{\mathrm{parent/daughter}}\rangle$$

$$M^{0\nu} = \langle\Psi_{\mathrm{daughter}}|\mathcal{O}^{0\nu}|\Psi_{\mathrm{parent}}\rangle$$

- Reasonable starting nuclear Hamiltonian(s)
- Controllable many-body method(s)
- Operators



J. Engel and J. Menéndez, Reports Prog. Phys. 80, 046301 (2017).

Nuclear ab initio calculation

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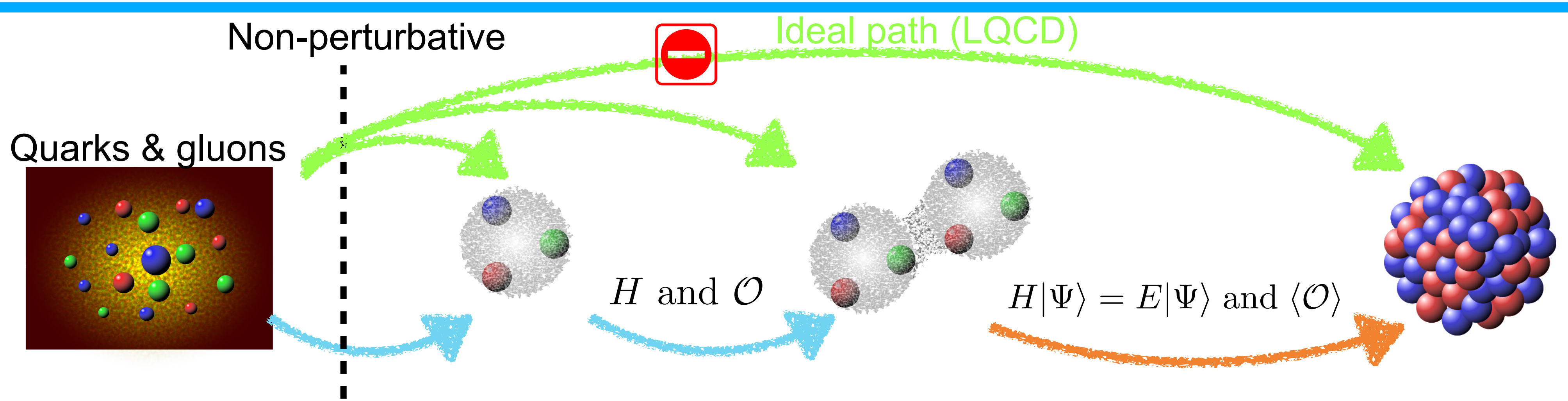

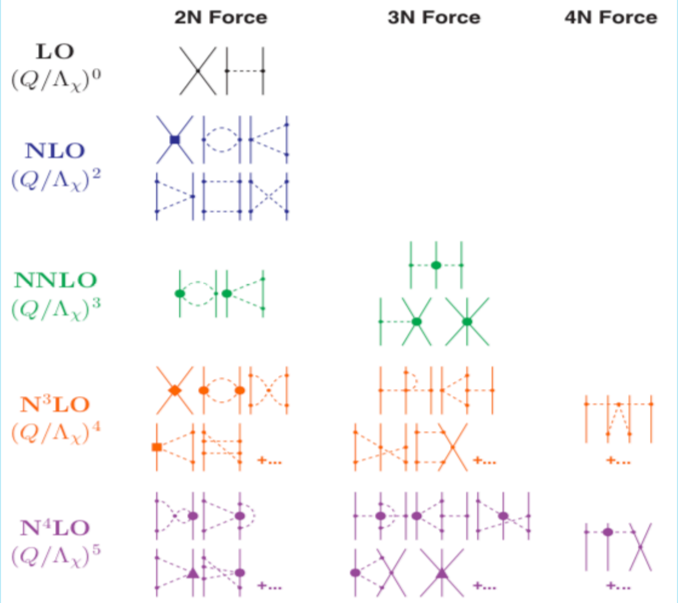

Nuclear many-body problem

- Green’s function Monte Carlo
- No-core shell model
- Nuclear lattice effective field theory
- Self-consistent Green’s function
- Coupled-cluster
- In-medium similarity renormalization group
- Many-body perturbation theory
- …

Nuclear interaction from chiral EFT

Weinberg, van Kolck, Kaiser, Epelbaum, Glöckle, Meißner, Entem, Machleidt, …

- Lagrangian construction
  - ✦ Chiral symmetry
  - ✦ Power counting
- Systematic expansion
  - ✦ Unknown LECs
  - ✦ Many-body interactions
  - ✦ Estimation of truncation error

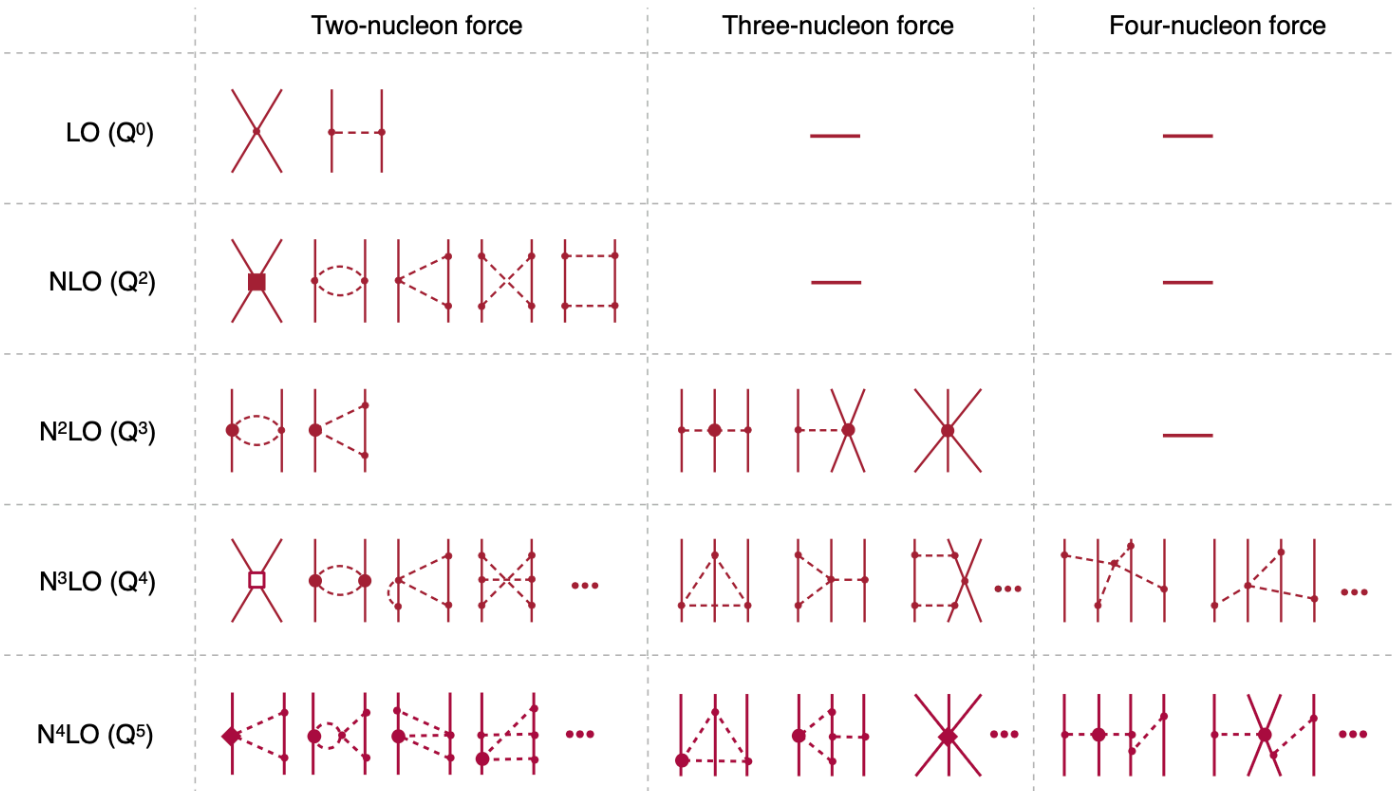

Figure is from E. Epelbaum, H. Krebs, and P. Reinert, Front. Phys. 8, 1 (2020).

Nuclear currents from chiral EFT

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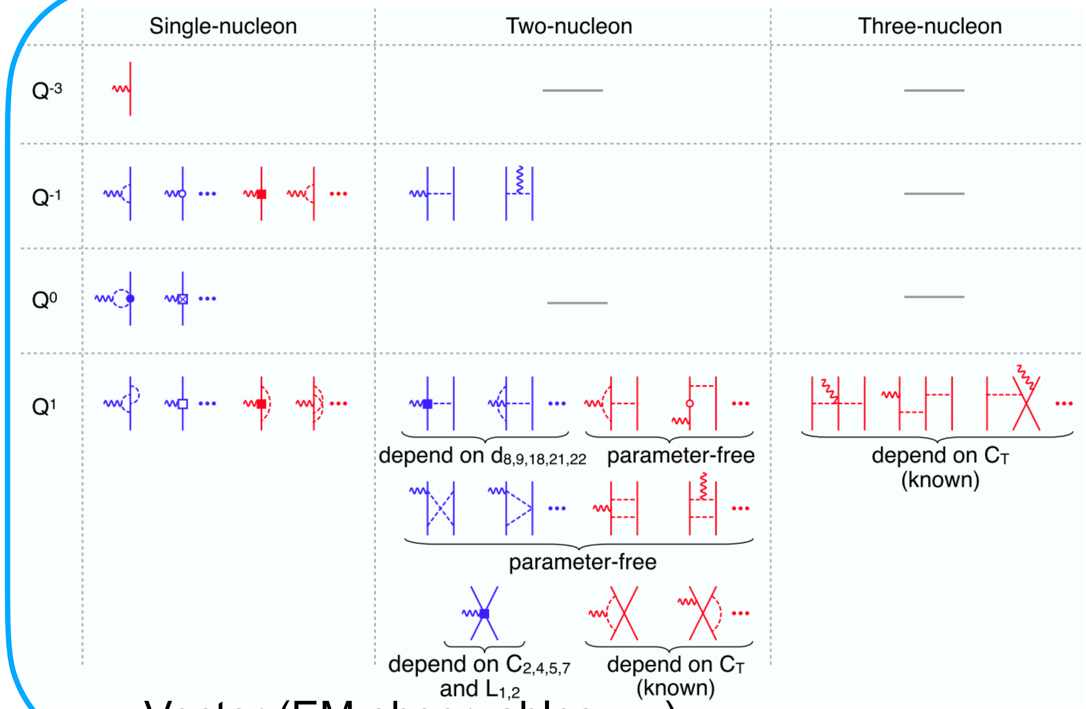
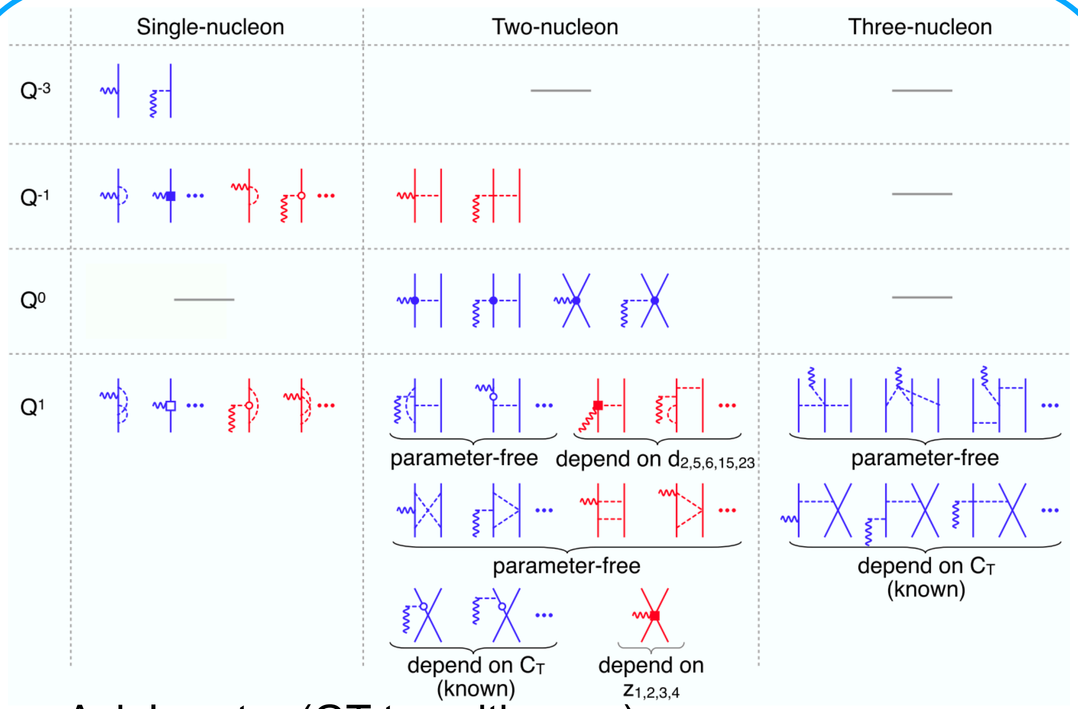
- Nuclear observables (EM properties, beta decay, …) are measured through the interaction between a nucleus and external field.
- Chiral EFT allows us a systematic expansion for charge and current operators.



Vector (EM observables, …)



Axial vector (GT transition, …)

E. Epelbaum, arXiv:1908.09349.

g_A quenching problem

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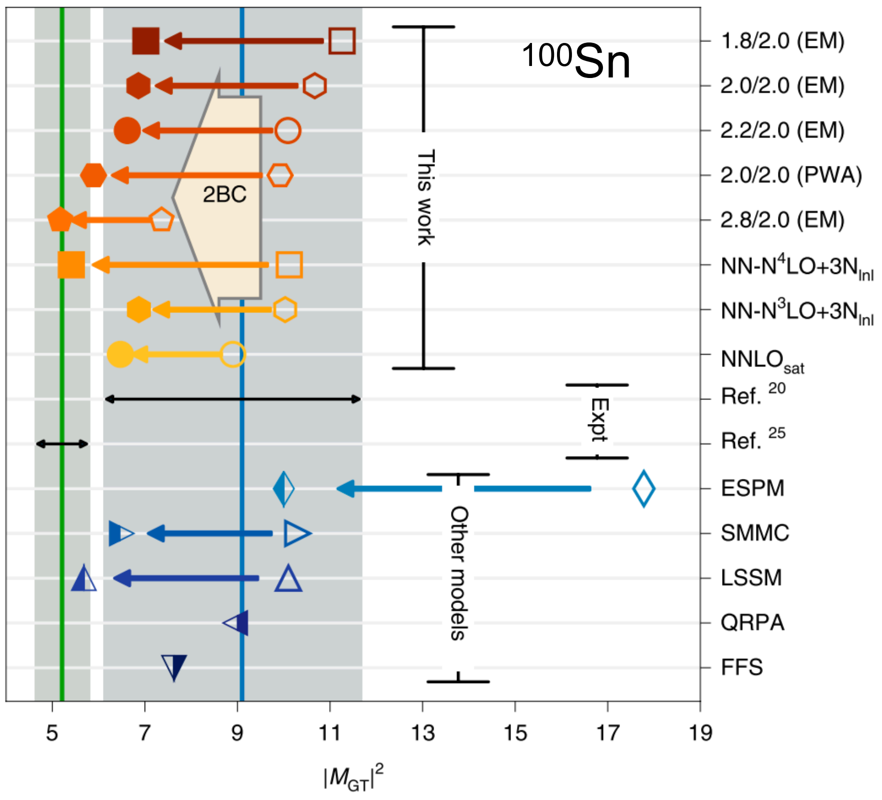
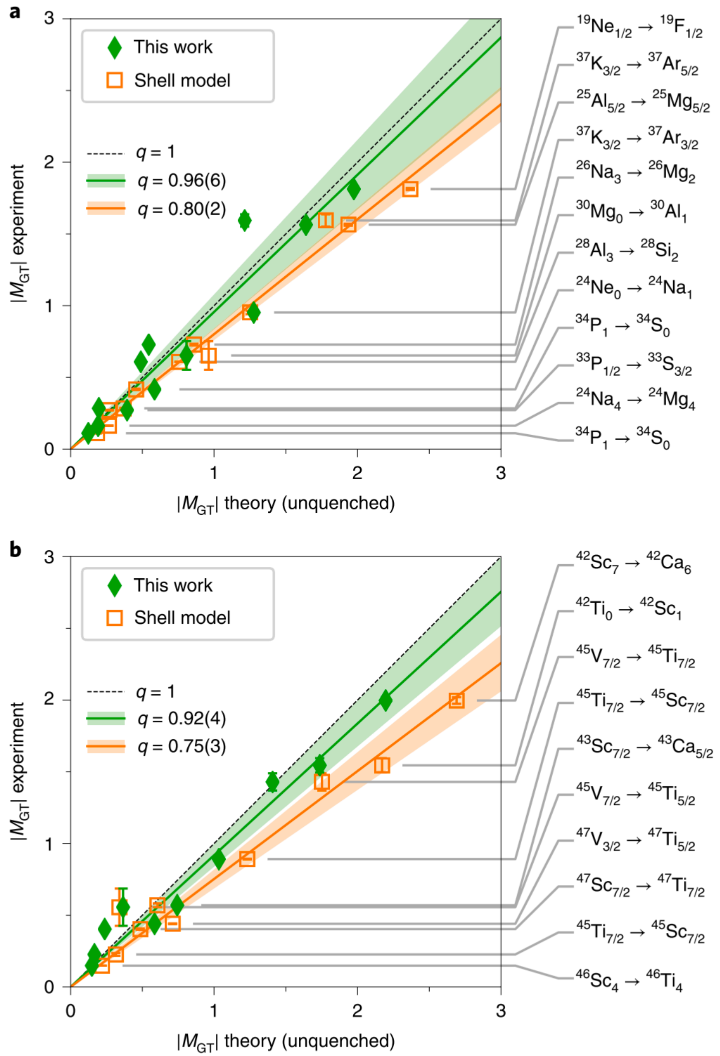
- Quenching problem can be understood by higher-order contribution + many-body correlation

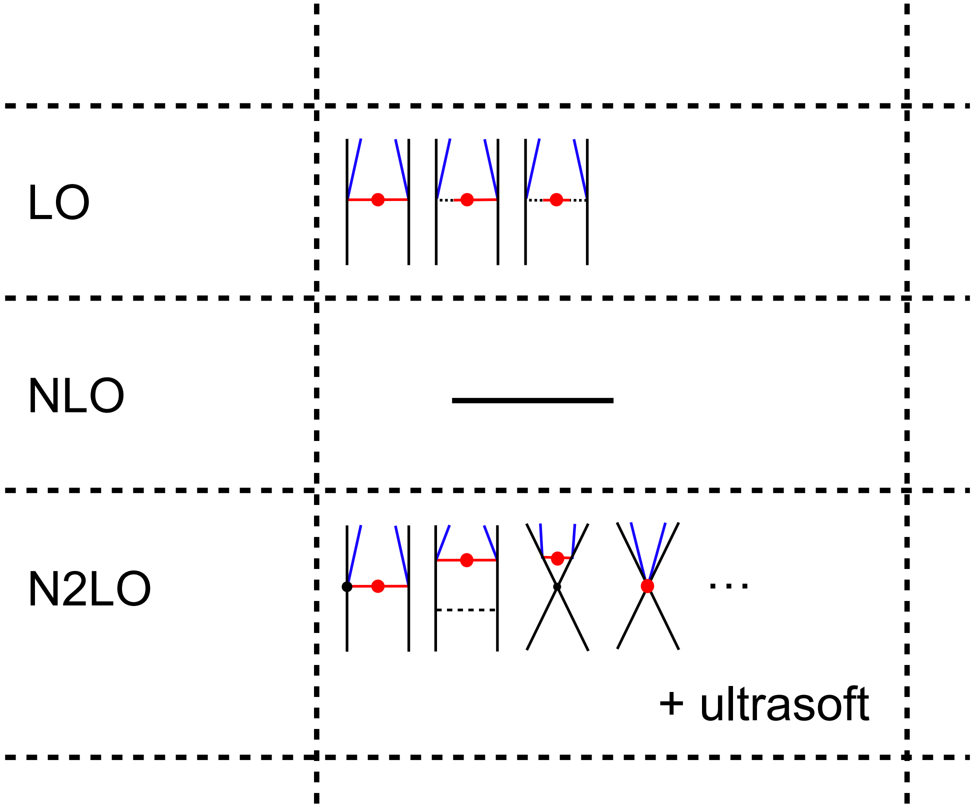


P. Gysbers, et al., Nat. Phys. 15, 428 (2019).



Neutrinoless double-beta decay operator

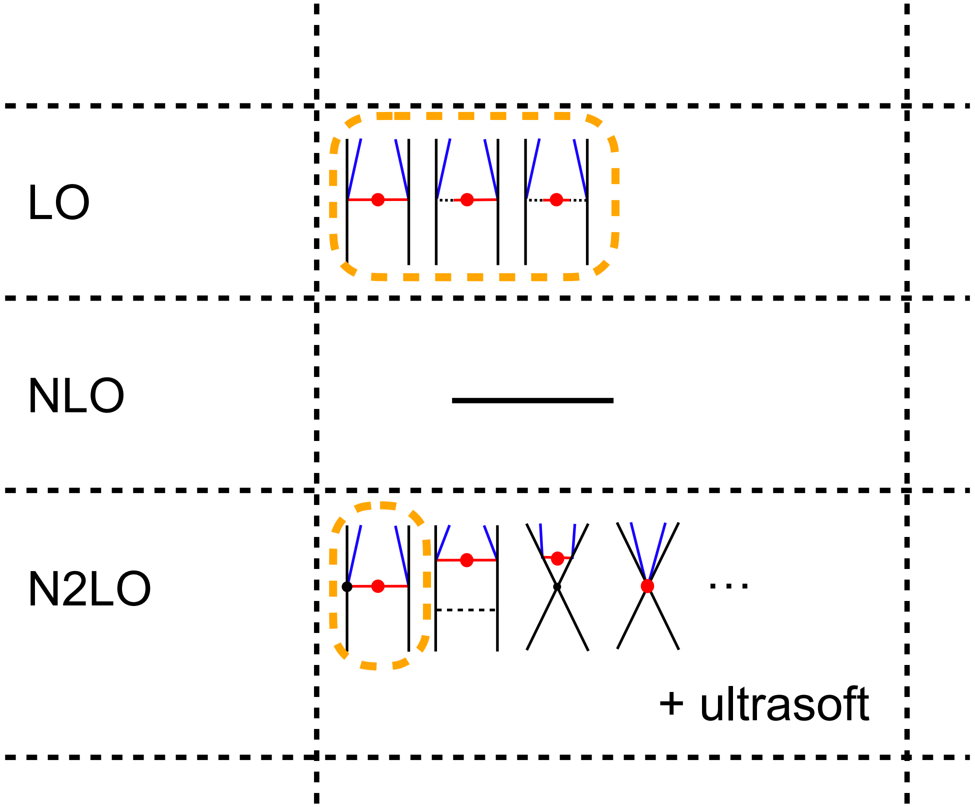
- Chiral EFT allows us a systematic expansion in lepton number violated sector.



V. Cirigliano et al. Phys. Rev. C 97, 065501 (2018).

Neutrinoless double-beta decay operator

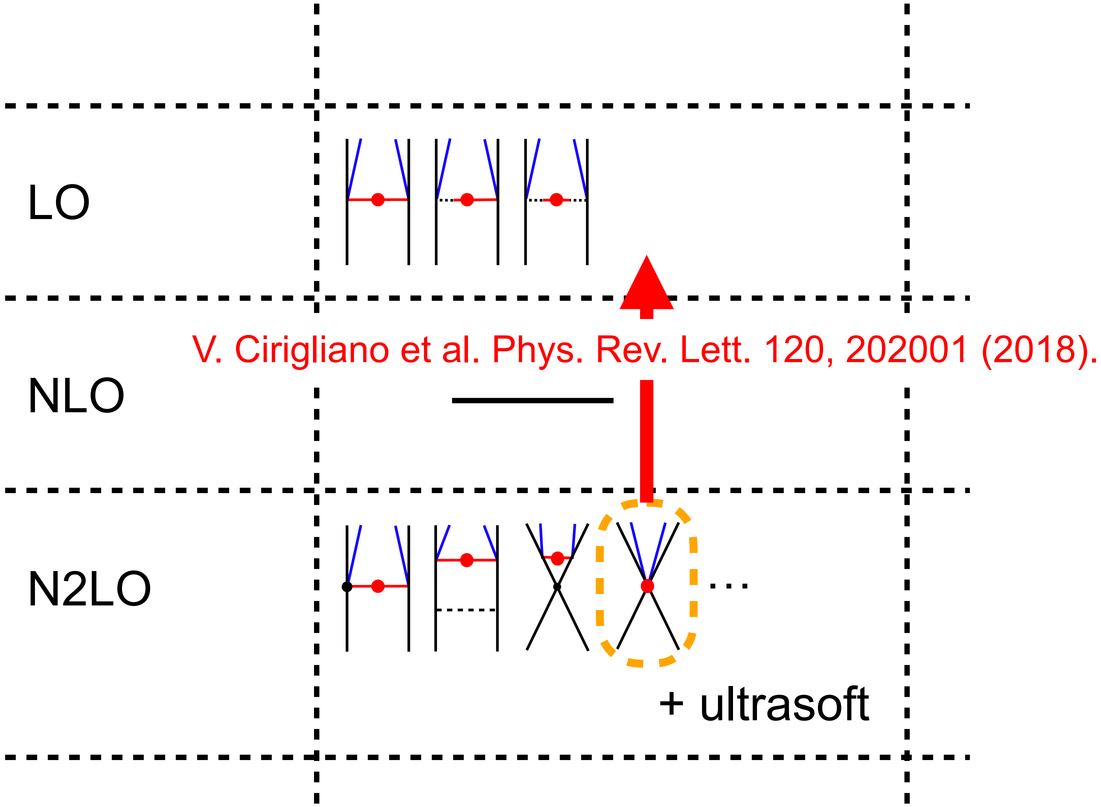
- Chiral EFT allows us a systematic expansion in lepton number violated sector.
  - Long-range contributions are the same as widely used contributions if the denominator energy is appropriately shifted.



V. Cirigliano et al. Phys. Rev. C 97, 065501 (2018).

Neutrinoless double-beta decay operator

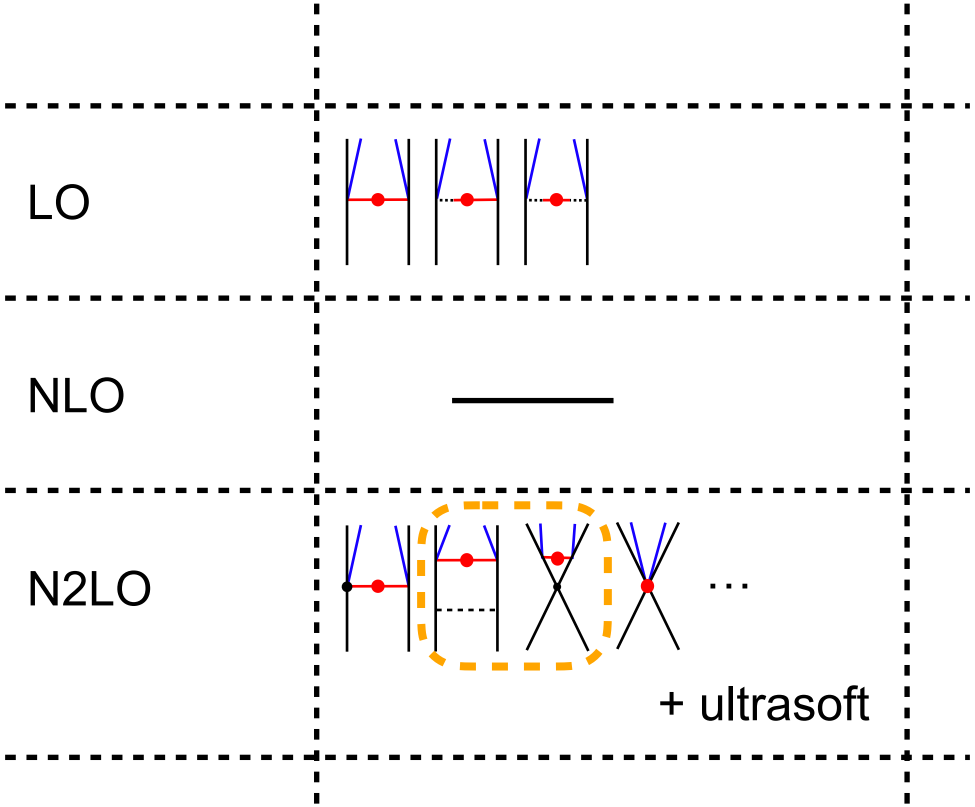
- Chiral EFT allows us a systematic expansion in lepton number violated sector.
  - Long-range contributions are the same as widely used contributions if the denominator energy is appropriately shifted.
  - Short-range contact contribution



V. Cirigliano et al. Phys. Rev. C 97, 065501 (2018).

Neutrinoless double-beta decay operator

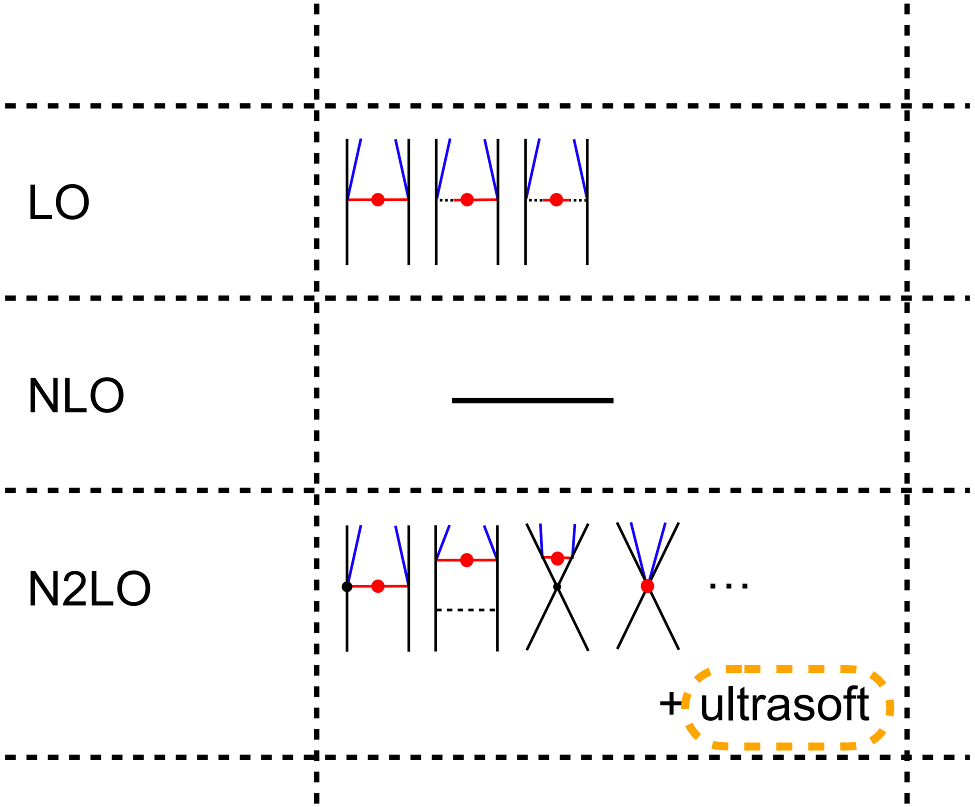
- Chiral EFT allows us a systematic expansion in lepton number violated sector.
  - Long-range contributions are the same as widely used contributions if the denominator energy is appropriately shifted.
  - Short-range contact contribution
  - Loop contributions that cannot be absorbed into corrections of form factors.



V. Cirigliano et al. Phys. Rev. C 97, 065501 (2018).

Neutrinoless double-beta decay operator

- Chiral EFT allows us a systematic expansion in lepton number violated sector.
  - Long-range contributions are the same as widely used contributions if the denominator energy is appropriately shifted.
  - Short-range contact contribution
  - Loop contributions that cannot be absorbed into corrections of form factors.
  - Ultrasoft contributions depends on structure of the intermediate nucleus.

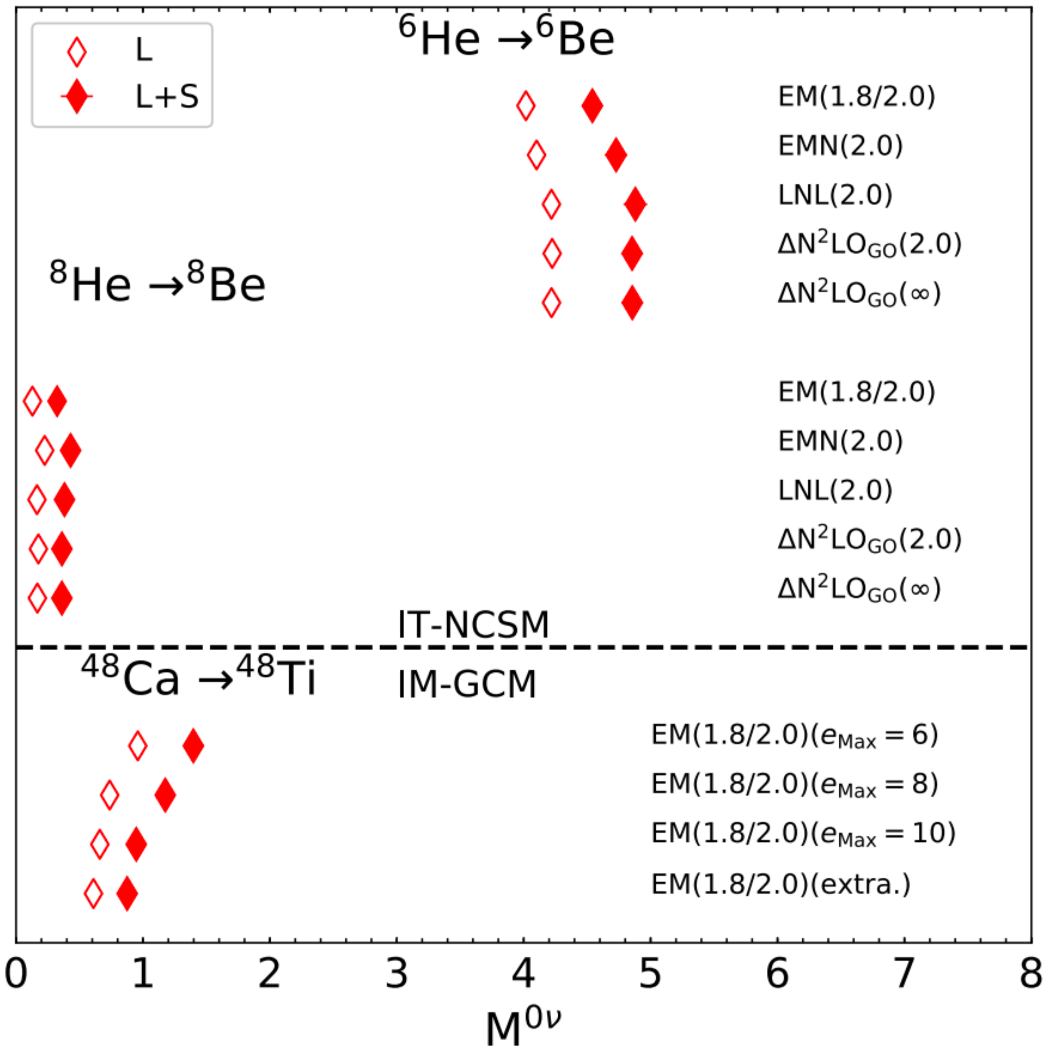


V. Cirigliano et al. Phys. Rev. C 97, 065501 (2018).

Contact term

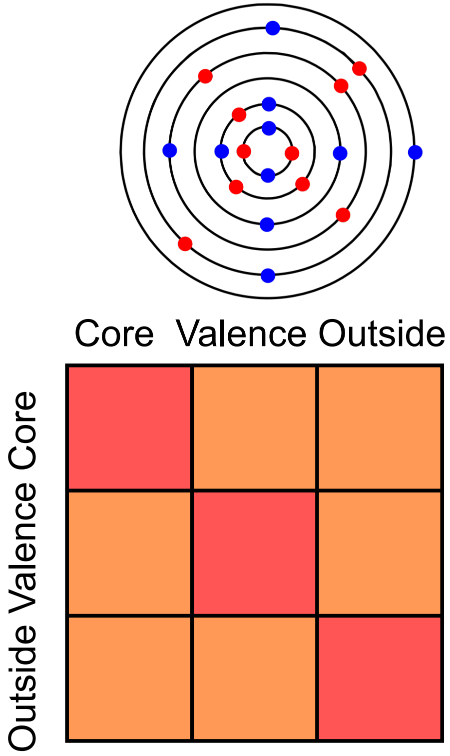
- The contact term strength can be determined by matching nn → pp amplitude with low- and high-energy regions.

- Contact term enhances NME.
  - ✦ ~ 40% for ^{48}Ca

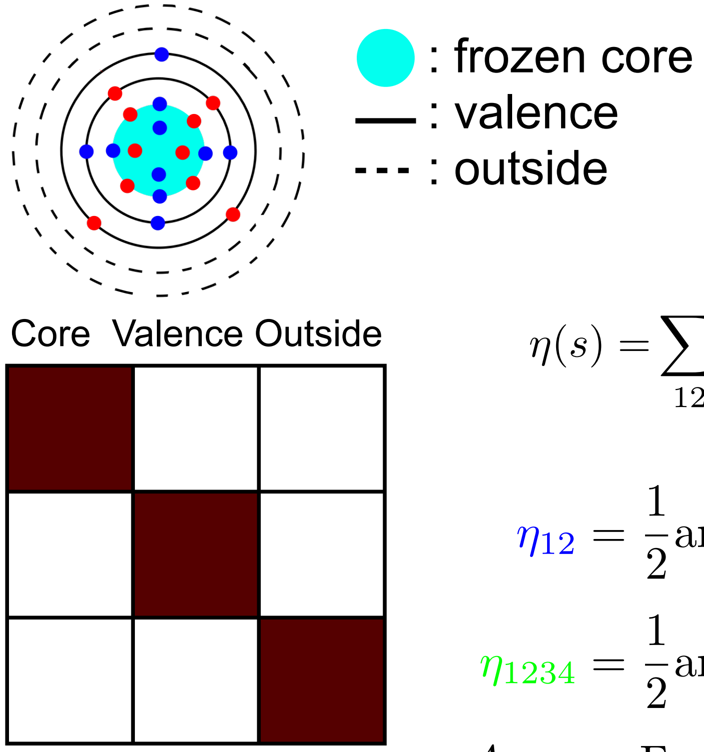


V. Cirigliano et al., J. High Energy Phys. 2021, 289 (2021).
R. Wirth, J. M. Yao, and H. Hergert, Phys. Rev. Lett. 127, 242502 (2021).

Valence-space in-medium similarity renormalization group



evolution



Similarity transformation

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

$$H(s) \approx E(s) + \sum_{12} f_{12}(s)\{a_1^\dagger a_2\} + \frac{1}{4}\sum_{1234} \Gamma_{1234}(s)\{a_1^\dagger a_2^\dagger a_4 a_3\}$$

s: flow parameter

$$\frac{d\Omega}{ds} = \eta(s) - \frac{1}{2}[\Omega(s), \eta(s)] + \cdots$$

$$\eta(s) = \sum_{12} \eta_{12}(s)\{a_1^\dagger a_2\} + \sum_{1234} \eta_{1234}(s)\{a_1^\dagger a_2^\dagger a_4 a_3\}$$

$$\eta_{12} = \frac{1}{2}\arctan\left(\frac{2f_{12}}{f_{11} - f_{22} + \Gamma_{1212} + \Delta}\right)$$

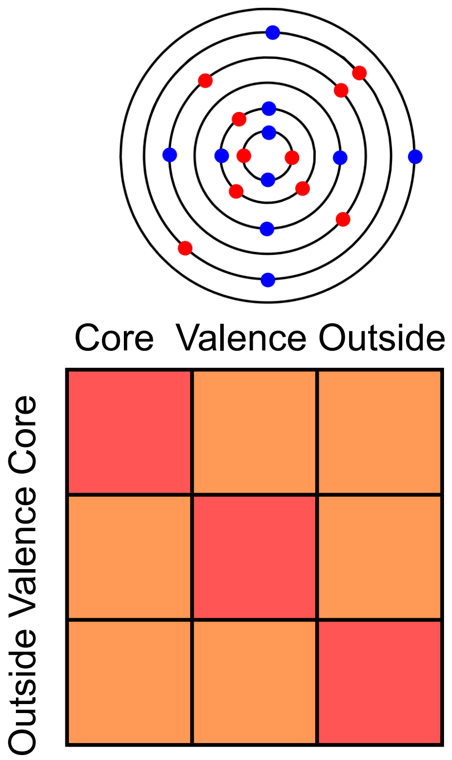
$$\eta_{1234} = \frac{1}{2}\arctan\left(\frac{2\Gamma_{1234}}{f_{11} + f_{22} - f_{33} - f_{44} + A_{1234} + \Delta}\right)$$

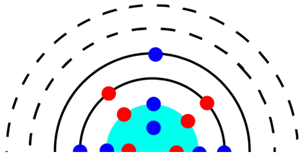
$$A_{1234} = \Gamma_{1212} + \Gamma_{3434} - \Gamma_{1313} - \Gamma_{2424} - \Gamma_{1414} - \Gamma_{2323}$$

f_{12}, Γ_{1234} : matrix element we want to suppress

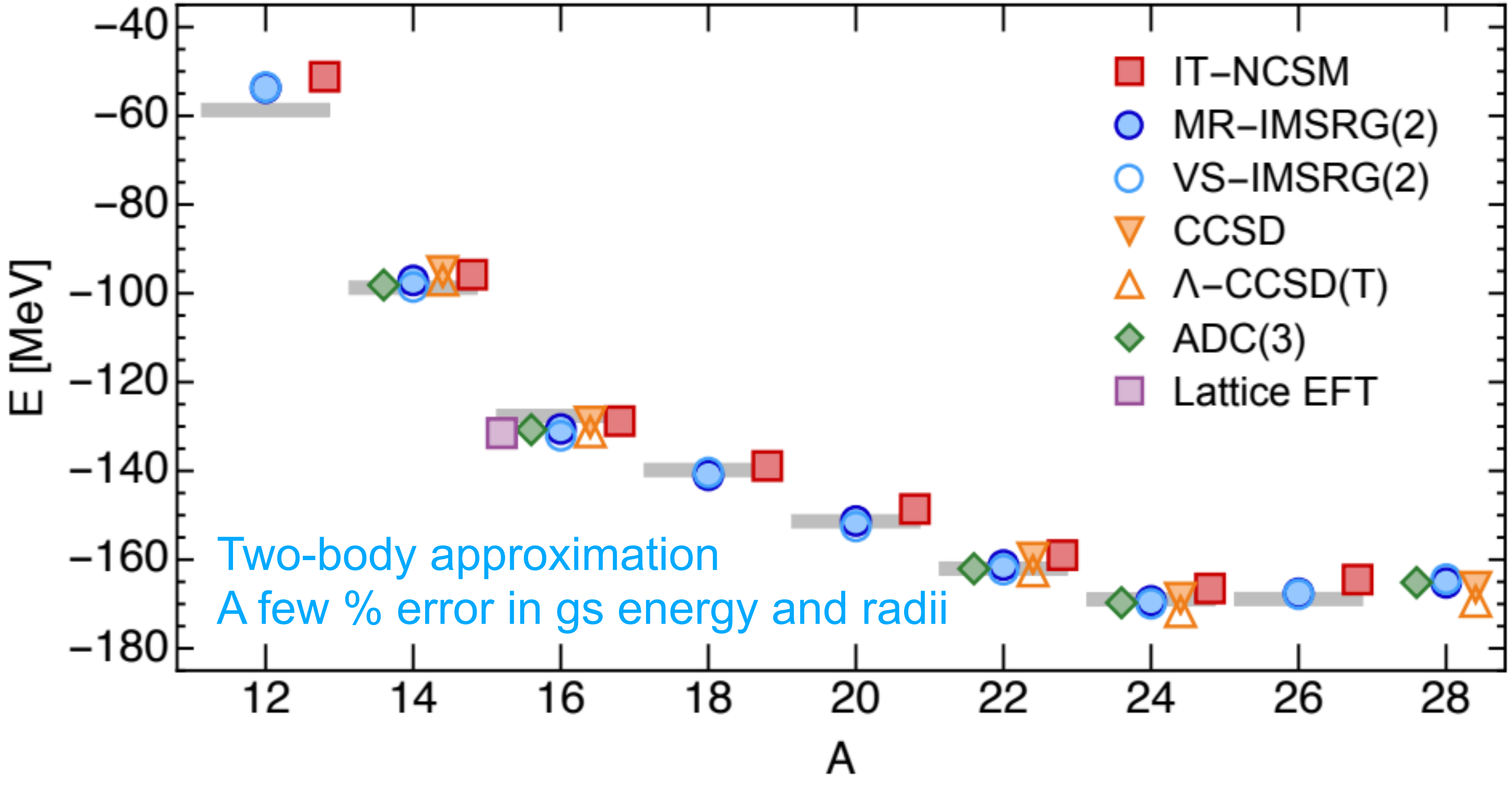
$$\mathcal{O}(s) = e^{\Omega(s)}\mathcal{O}e^{-\Omega(s)} \approx \mathcal{O}^{[0]}(s) + \sum_{12}\mathcal{O}^{[1]}_{12}(s)\{a_1^\dagger a_2\} + \frac{1}{4}\sum_{1234}\mathcal{O}^{[2]}_{1234}(s)\{a_1^\dagger a_2^\dagger a_4 a_3\}$$

Valence-space in-medium similarity renormalization group





evolution



Two-body approximation
A few % error in gs energy and radii

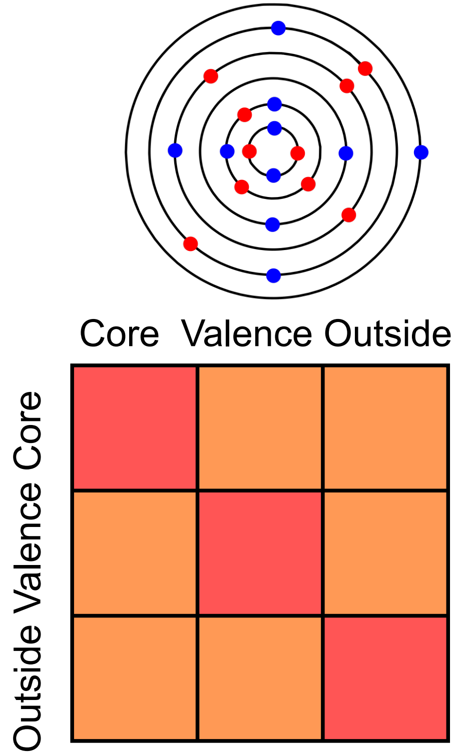
Similarity transformat

H

$$H(s) \approx E(s) + \sum_{12} f_{12}(s)\{a_1^\dagger a_2\} + \frac{1}{4} \sum_{1234}$$

s: flow parameter

Valence-space in-medium similarity renormalization group



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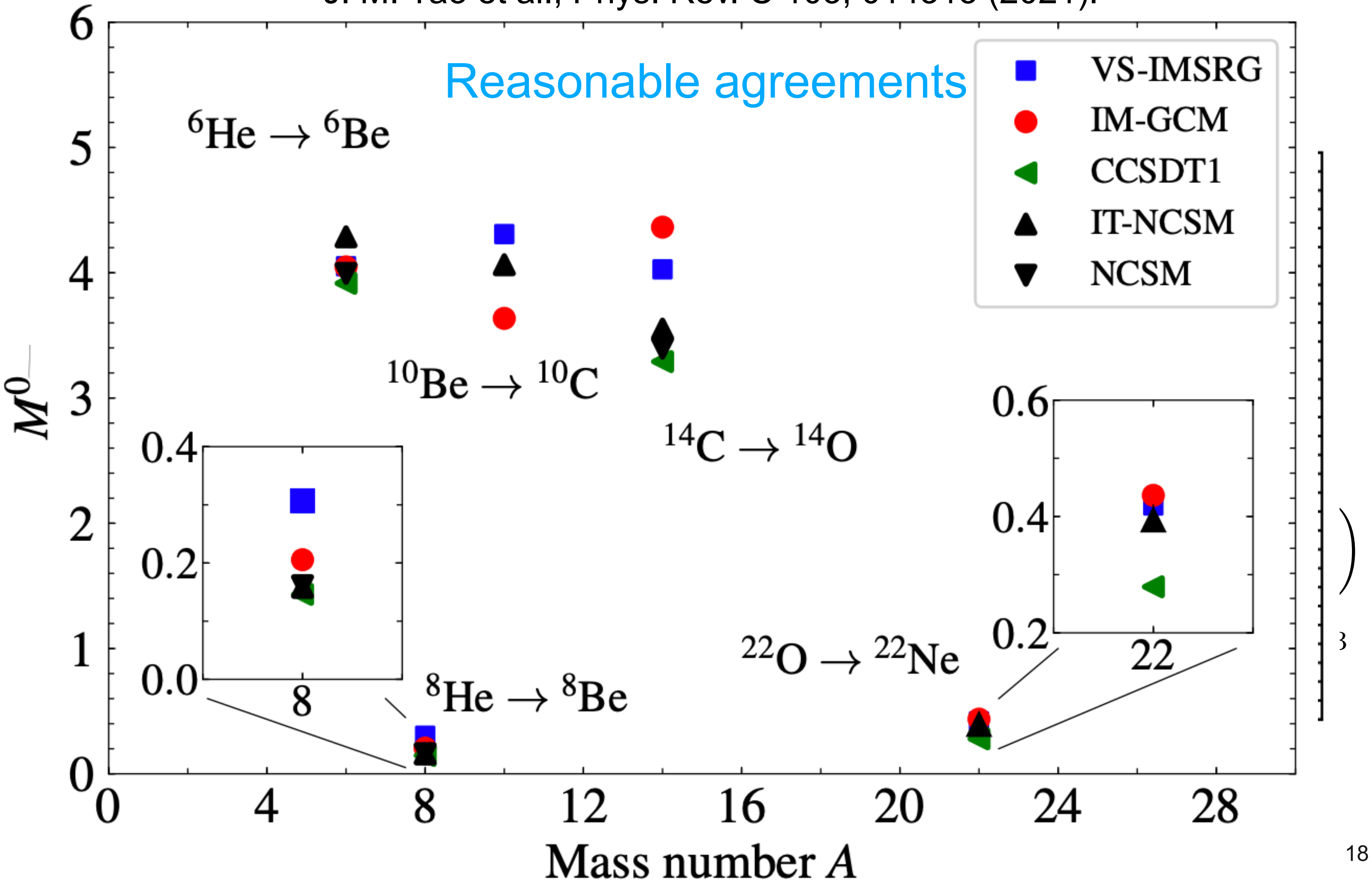
Similarity transfor

$$H$$

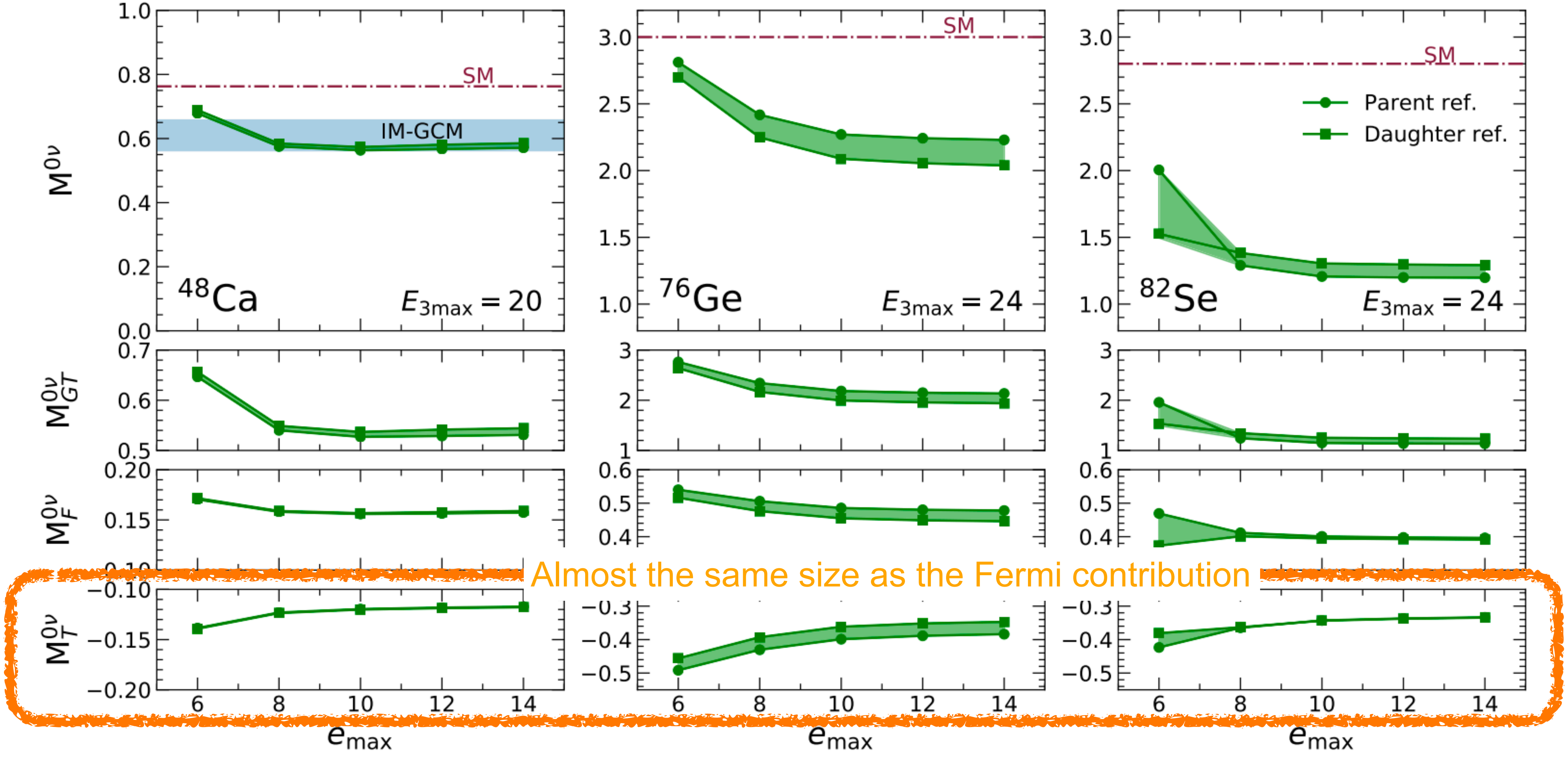
$$H(s) \approx E(s) + \sum_{12} f_{12}(s)\{a_1^\dagger a_2\} \cdot$$

s: flow parameter

J. M. Yao et al., Phys. Rev. C 103, 014315 (2021).



^{48}Ca, ^{76}Ge, and ^{82}Se

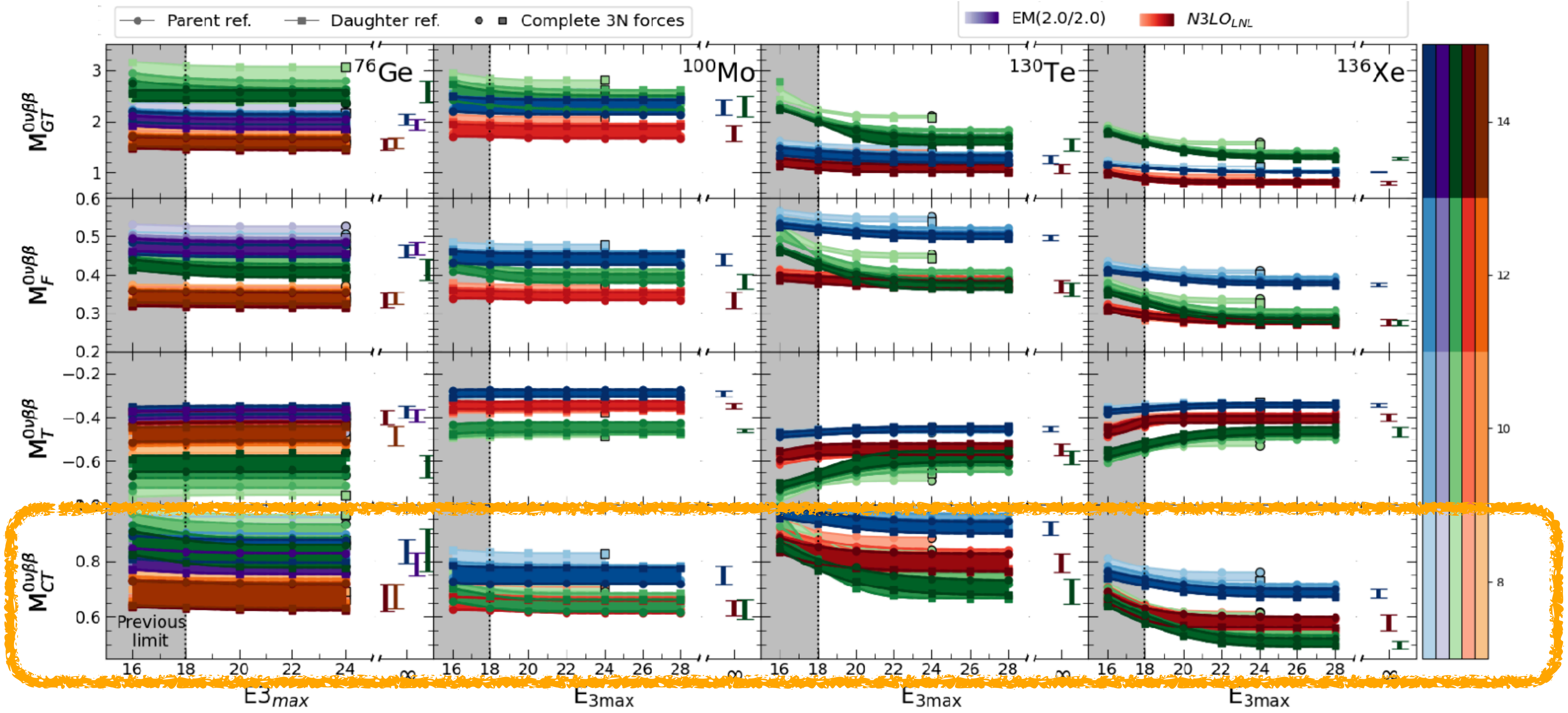


No contact term, not full uncertainty quantification, …

A. Belley et al., Phys. Rev. Lett. 126, 042502 (2021).

Inclusion of the contact term

- The contact term significantly enhances the NME.



A Belley et al., arXiv:2307.15156.

Comparison with results from other methods

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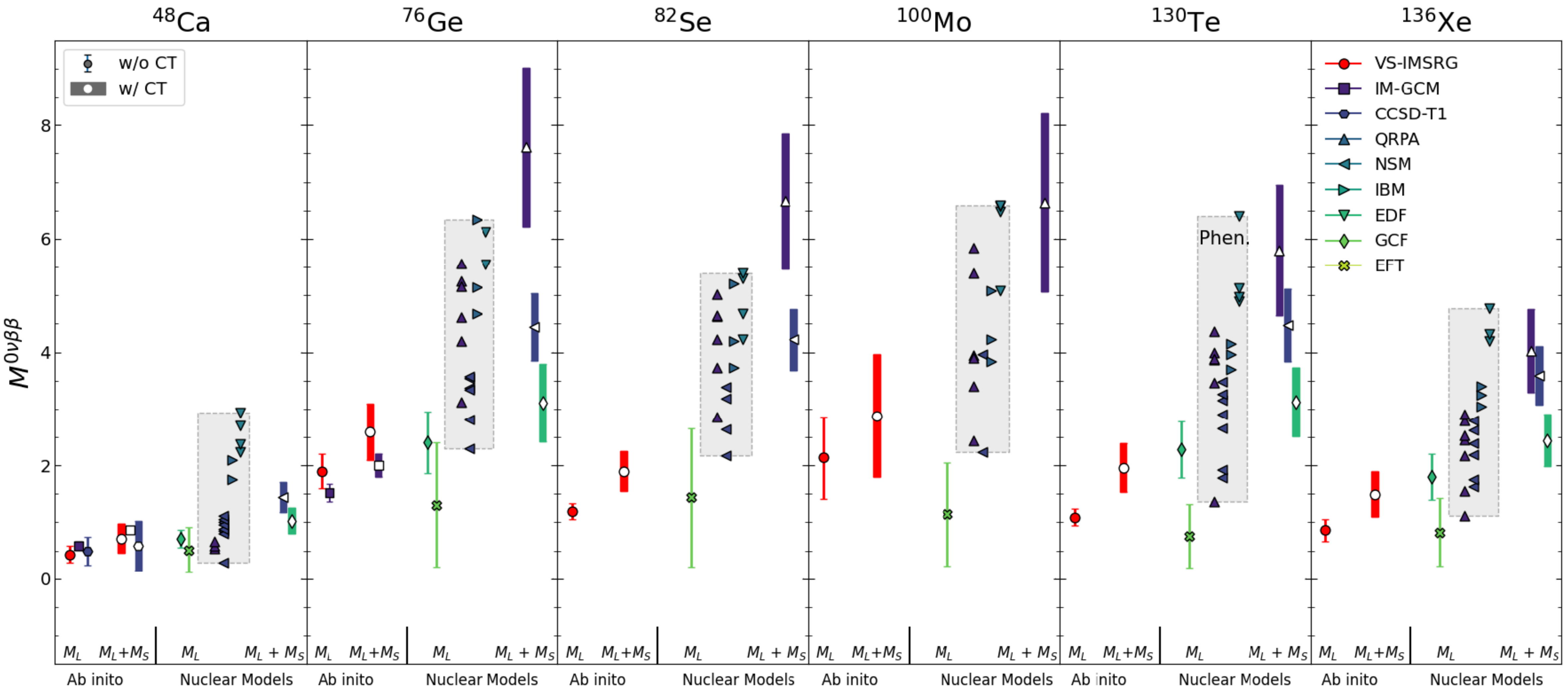
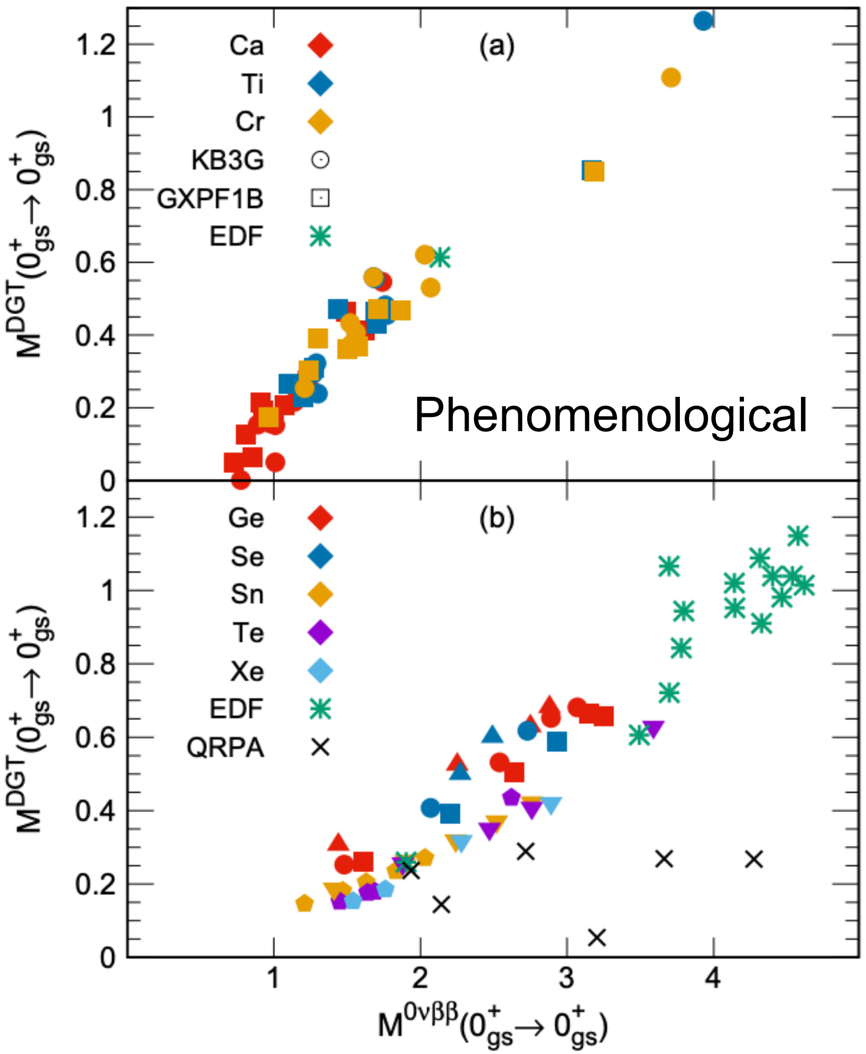
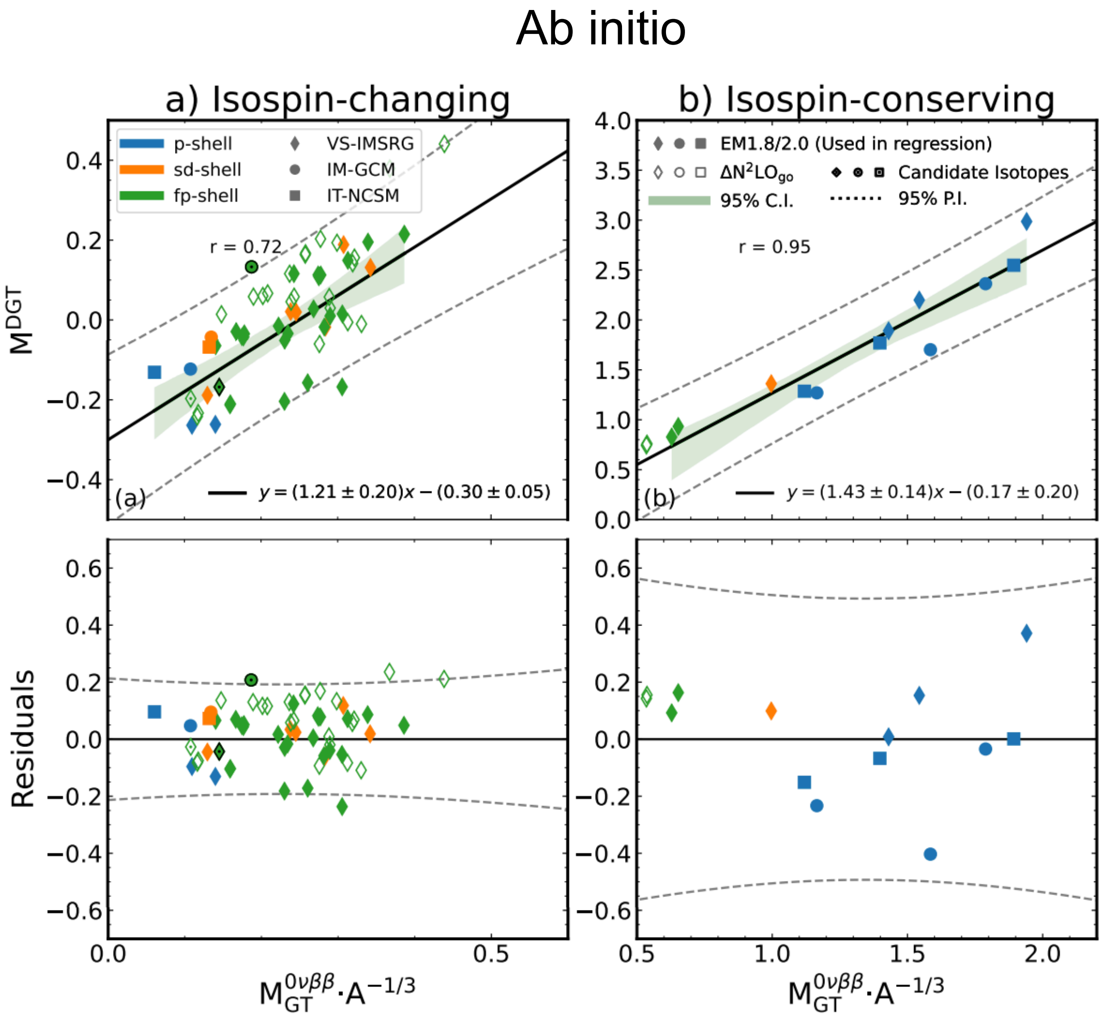


A Belley et al., arXiv:2307.15156.

*Uncertainty is not fully quantified

Correlation: different isotopes

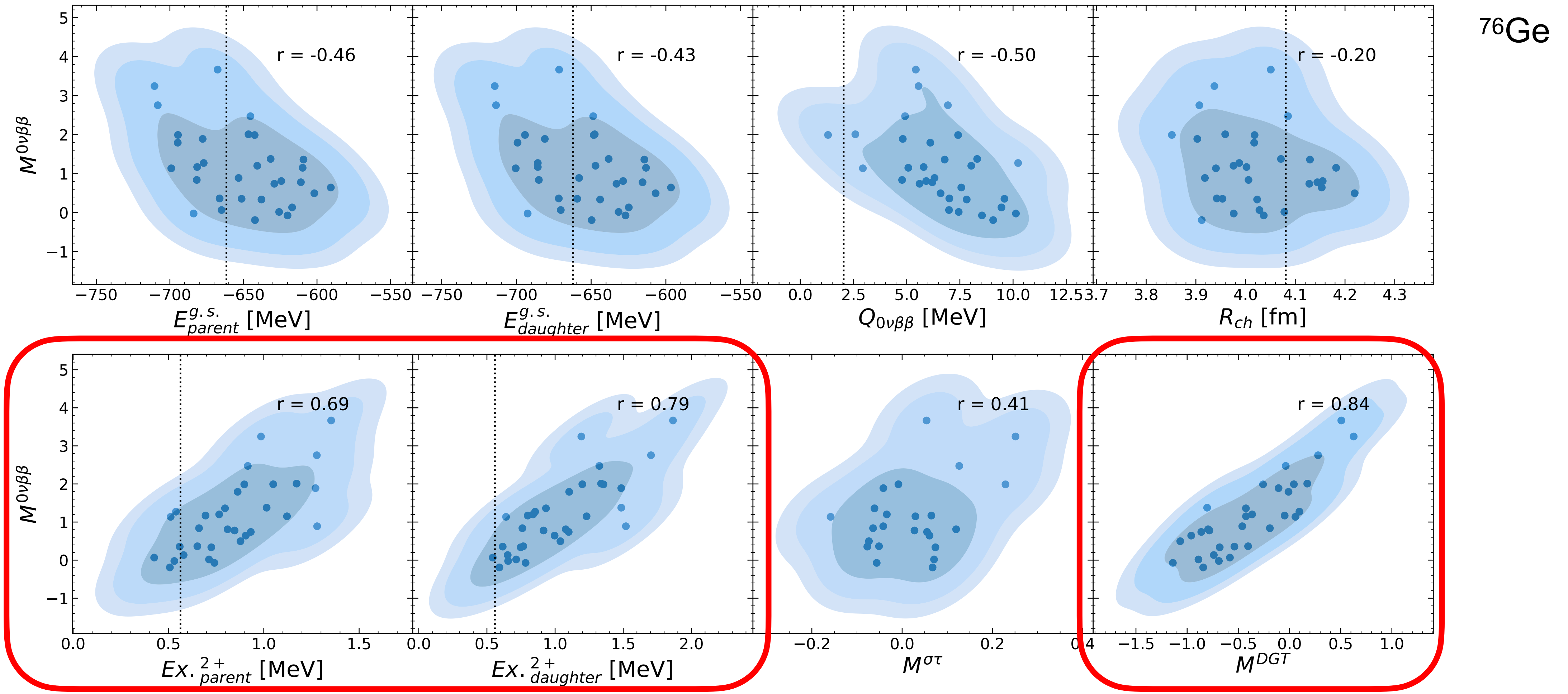




N. Shimizu, J. Menéndez, and K. Yako, Phys. Rev. Lett. 120, 142502 (2018).

J. M. Yao et al., Phys. Rev. C 106, 014315 (2022).

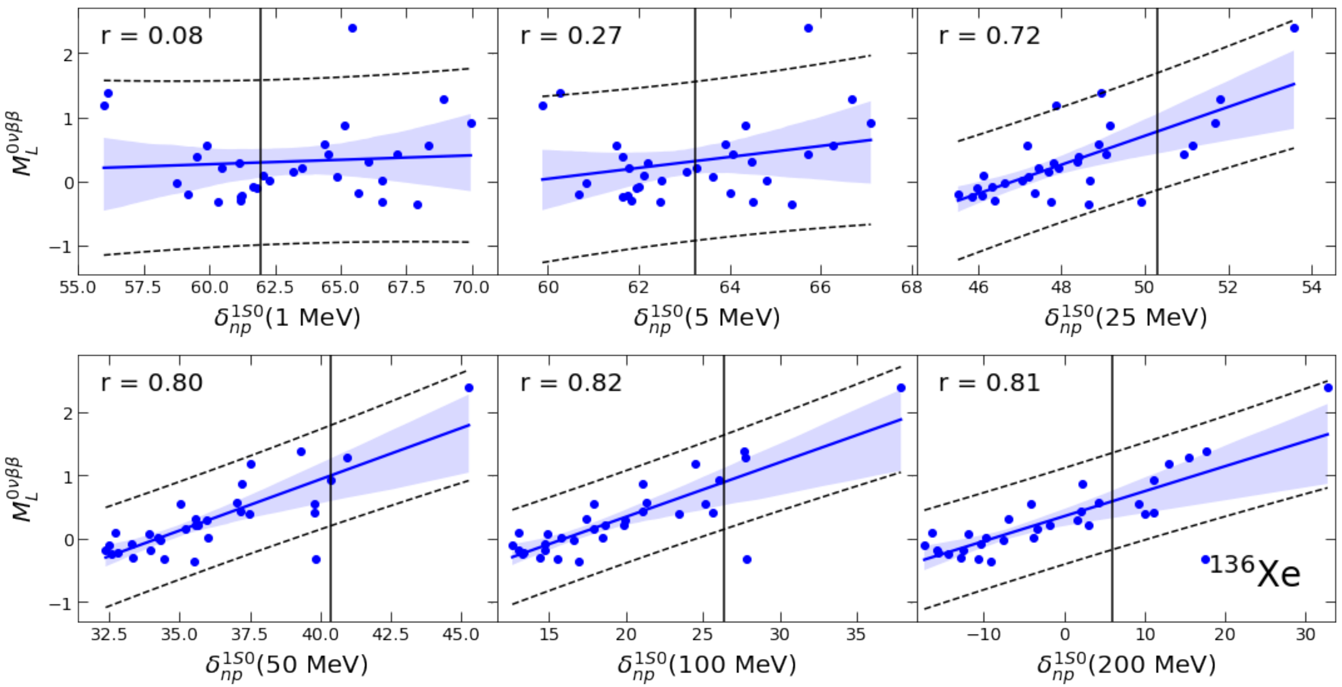
Correlation: different interaction parameter sets



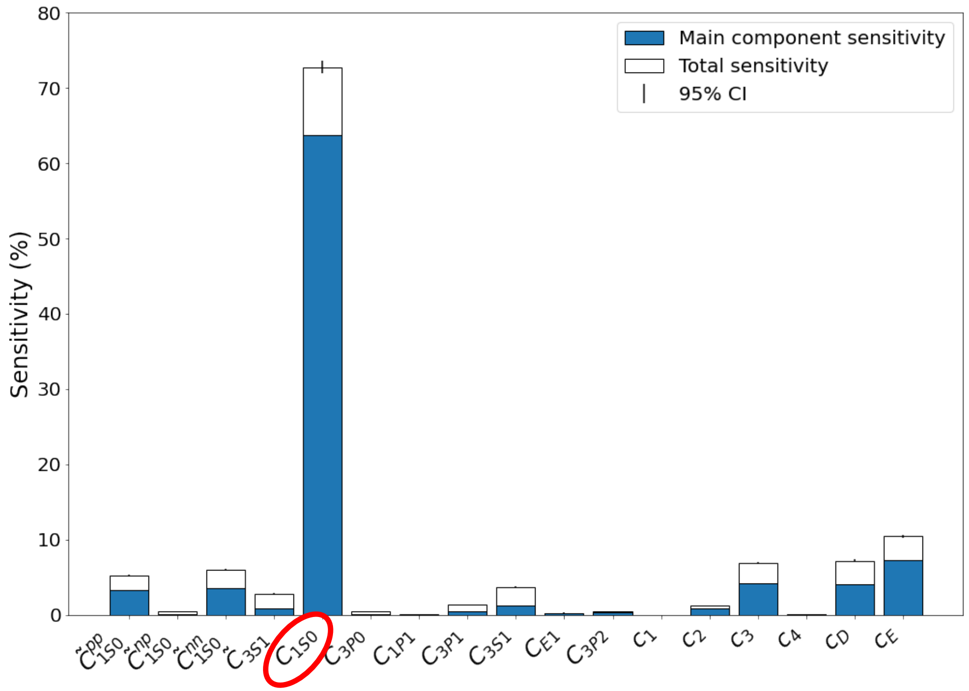
* correlation with 2^+ energy is so far only seen in ^{76}Ge case.

A. Belley et al., arXiv: 2210.05809

Correlation: different interaction parameter sets



Global sensitivity analysis



Intermediate-energy phase shift can constrain the NME.

Belley et al. in prep.

A better uncertainty quantification

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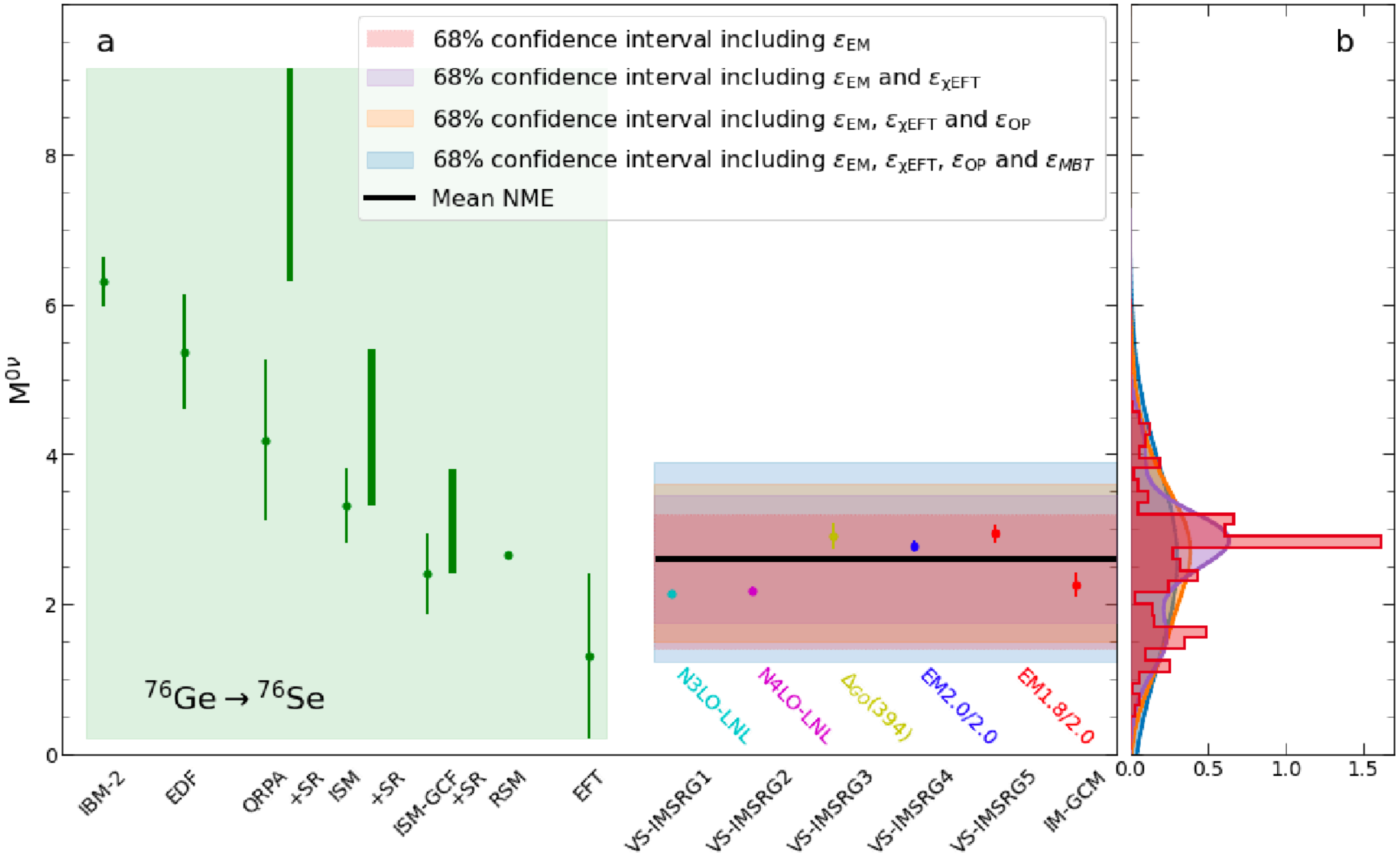
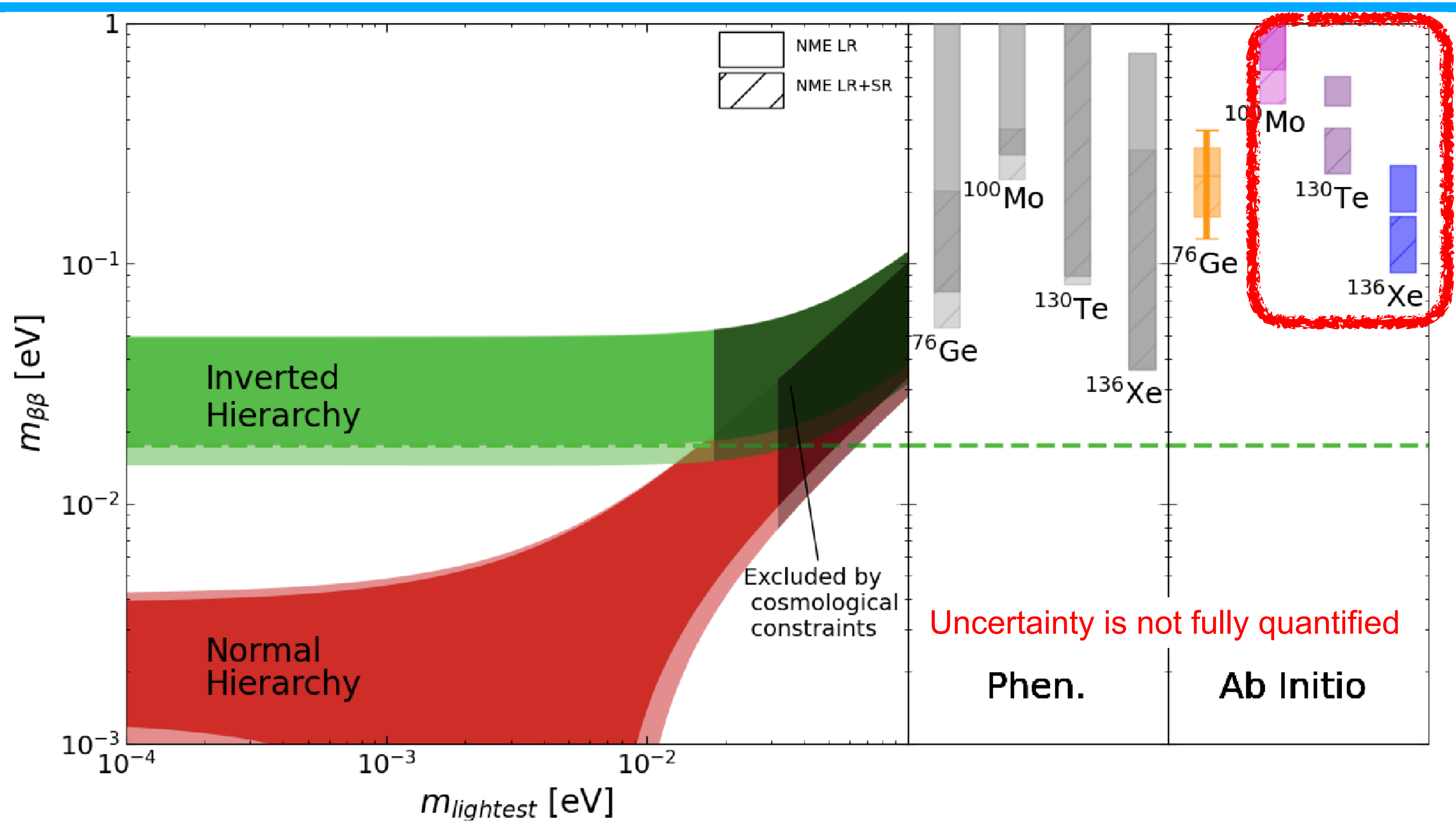
- Uncertainties:
  - Interactions
    - Parameter uncertainty
    - EFT truncation
  - Operator
    - Closure approximation
    - Contact strength
  - Many-body methods
    - VS-IMSRG
    - IM-GCM
  - Emulator



See Jiangming's talk

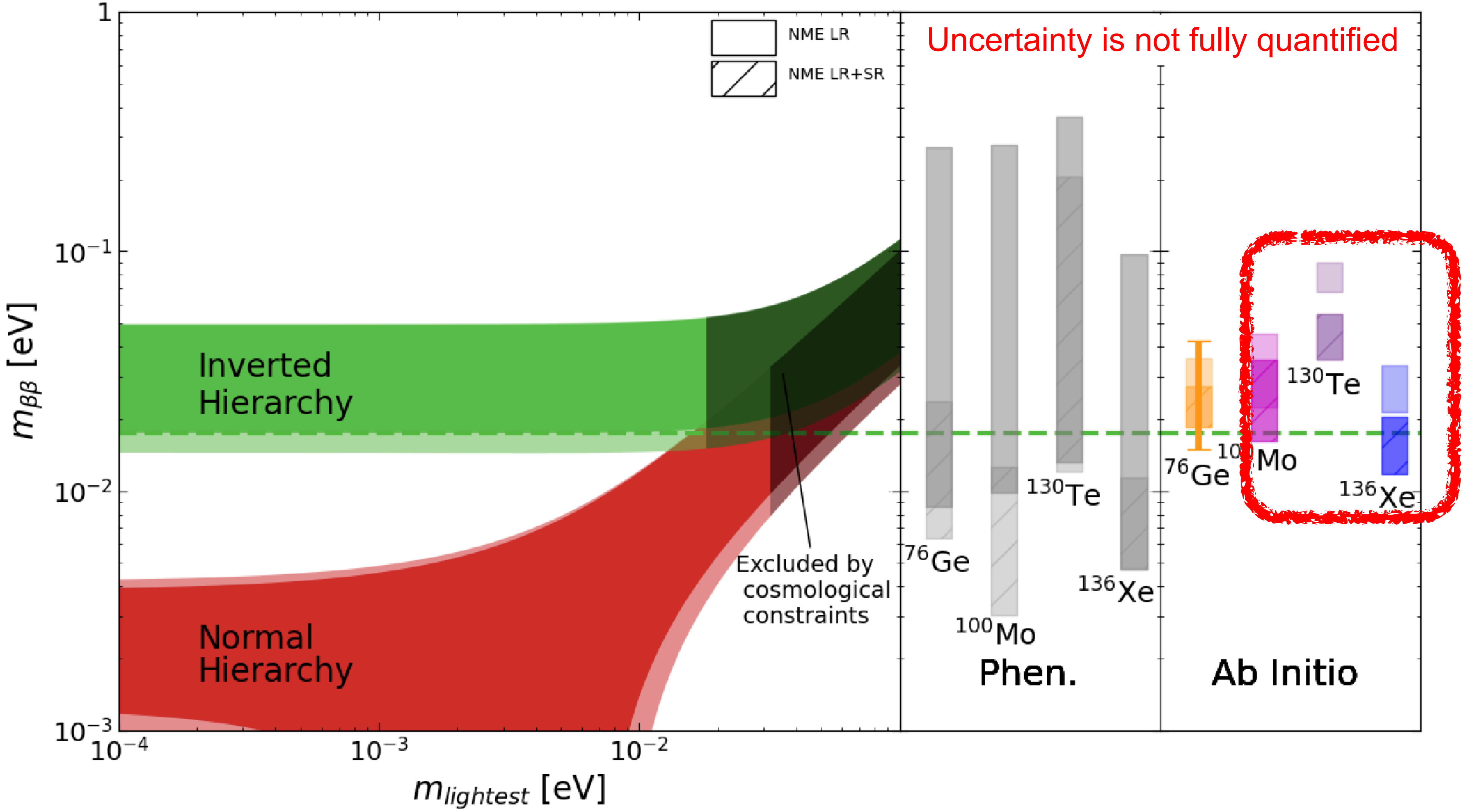
A. Belley et al., arXiv: 2308.15634

Effect on experimental limits



Experimental limits: GERDA (^{76}Ge) Phys. Rev. Lett. 125, 252502, CUPID-Mo (^{100}Mo) Eur. Phys. J. C 82 11, 1033 CUORE(^{130}Te) Nature 604, 53–58, and Kamland Zen (^{136}Xe) Phys. Rev. Lett. 130, 051801.

Effect on future research



Expected limits: LEGEND (^{76}Ge) arXiv:2107.11462,
CUPID (^{100}Mo) arXiv:1907.09376, SNO+(^{130}Te) arXiv:2104.11687and nEXO (^{136}Xe) J. Phys .G 49 1, 015104.

Summary & outlook

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- Ab initio NME calculations are becoming possible for realistic candidate nuclei.
- The short-range contact contribution non-negligibly enhances NME.
- Possible correlation with DGT and 1S0 phase shift.
- Uncertainty quantification is ongoing topic.

- Improve many-body techniques
- Explore and exploit observables that can constrain NME
- Two-body current effect
- …