



LOEWE

Exzellente Forschung für
Hessens Zukunft



TECHNISCHE
UNIVERSITÄT
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PROBING NEUTRINOLESS DOUBLE-BETA DECAY BY NUCLEAR OBSERVABLES

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INT Program 26-2a “*Recommended Values for Neutrinoless Double-Beta Decay Nuclear Matrix Elements*”,
Seattle, June 29 – July 24, 2026

COLLABORATORS



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UNIVERSITY

A. Todd



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at CHAPEL HILL

B. Romeo



K. Kravvaris



A. Belley



OUTLINE

- 1** Introduction
- 2** Opportunities with next-generation $0\nu\beta\beta$ -decay experiments
- 3** Probing neutrinoless double-beta decay by muon capture
- 4** Correlations of $0\nu\beta\beta$ decay and other observables
- 5** Summary



$0\nu\beta\beta$ DECAY MEDIATED BY LIGHT- NEUTRINO EXCHANGE

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e} \right)^2$$



$0\nu\beta\beta$ DECAY MEDIATED BY LIGHT-NEUTRINO EXCHANGE

Half-life to be measured

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e} \right)^2$$

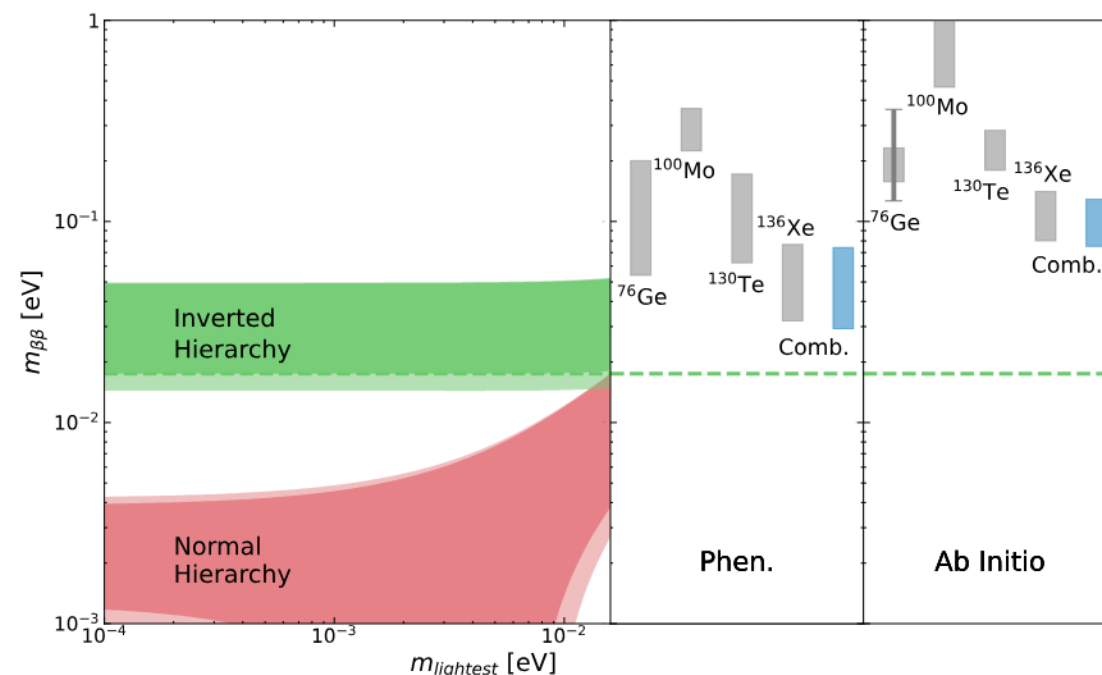
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Majorana mass

$$m_{\beta\beta} = \sum_k (U_{ek})^2 m_k$$



Shickele, Jokiniemi, Belley, Holt, in preparation

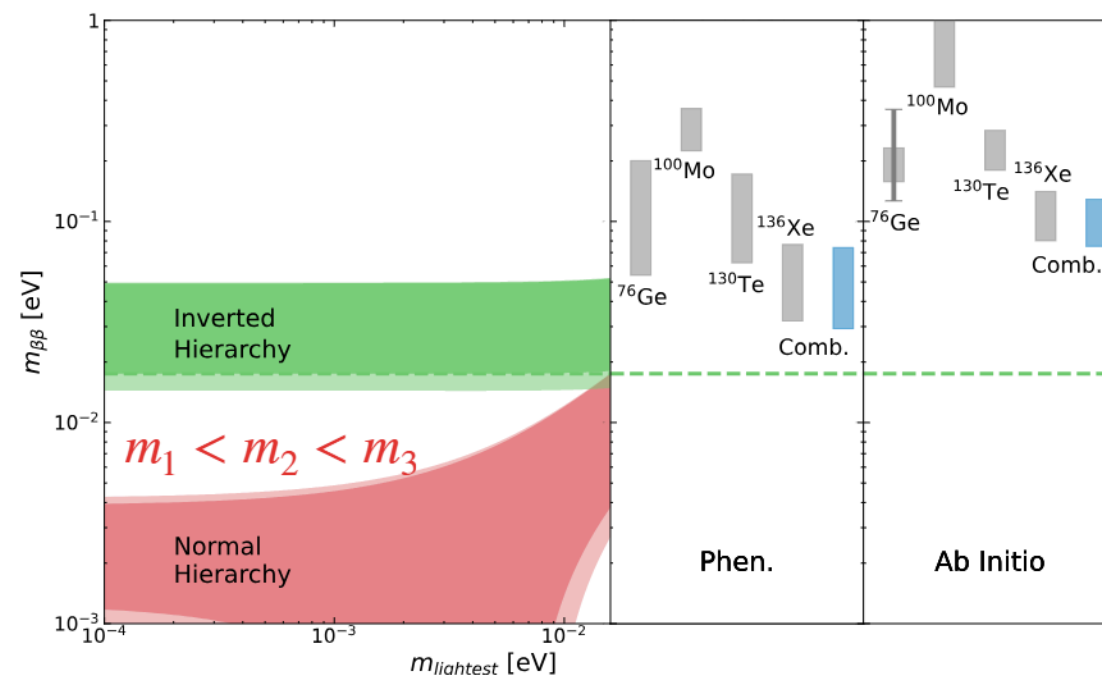
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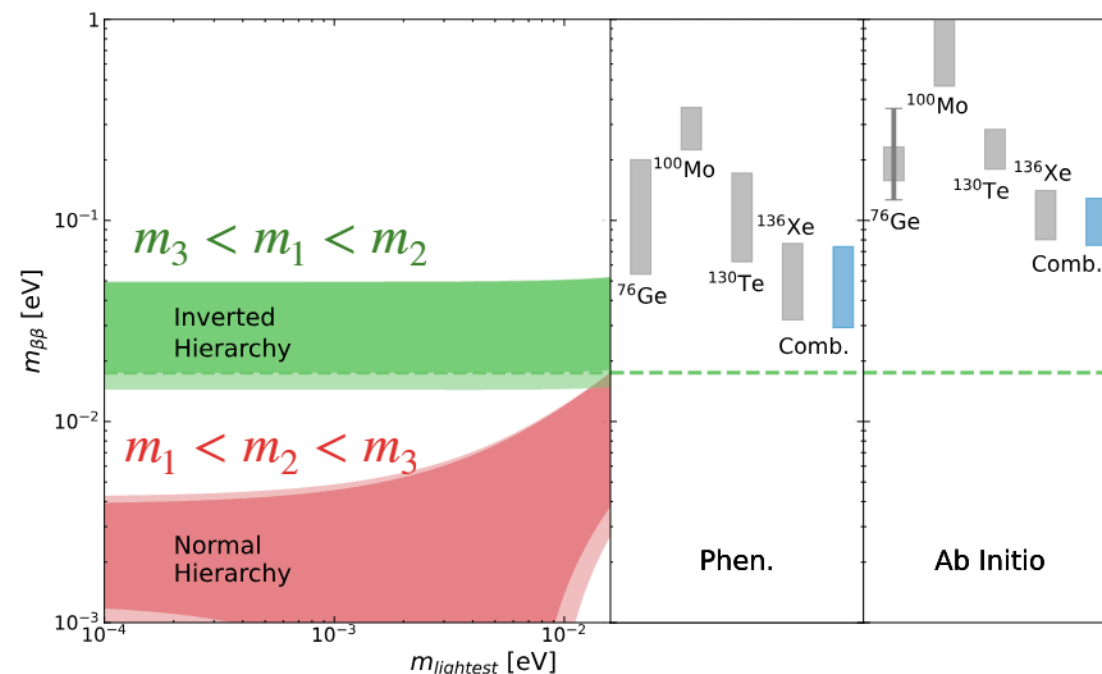
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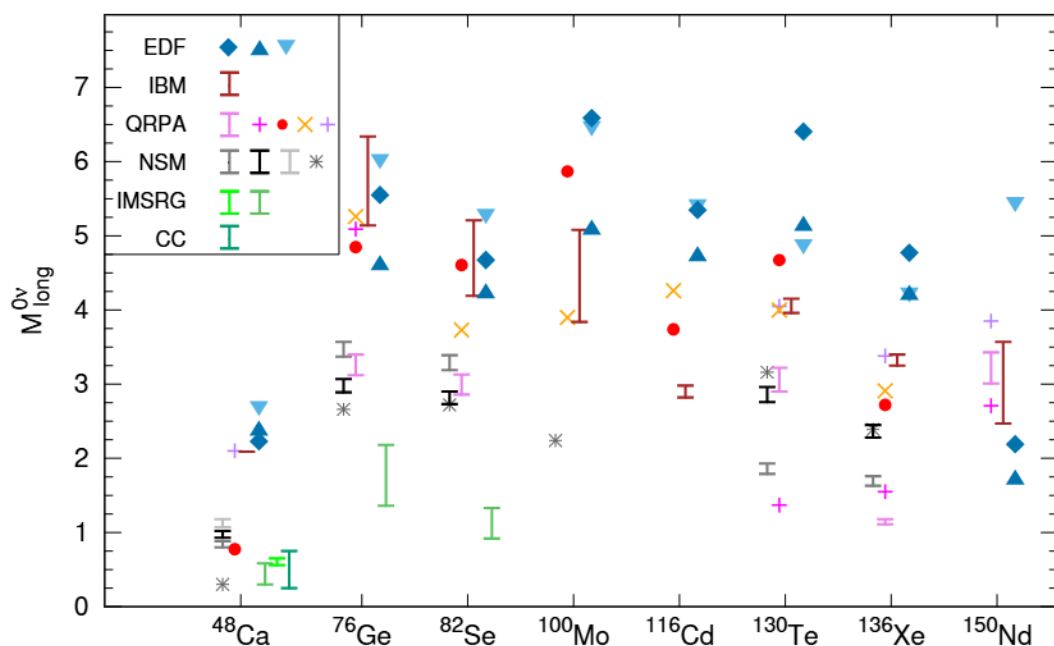
Half-life to be measured

Nuclear matrix element

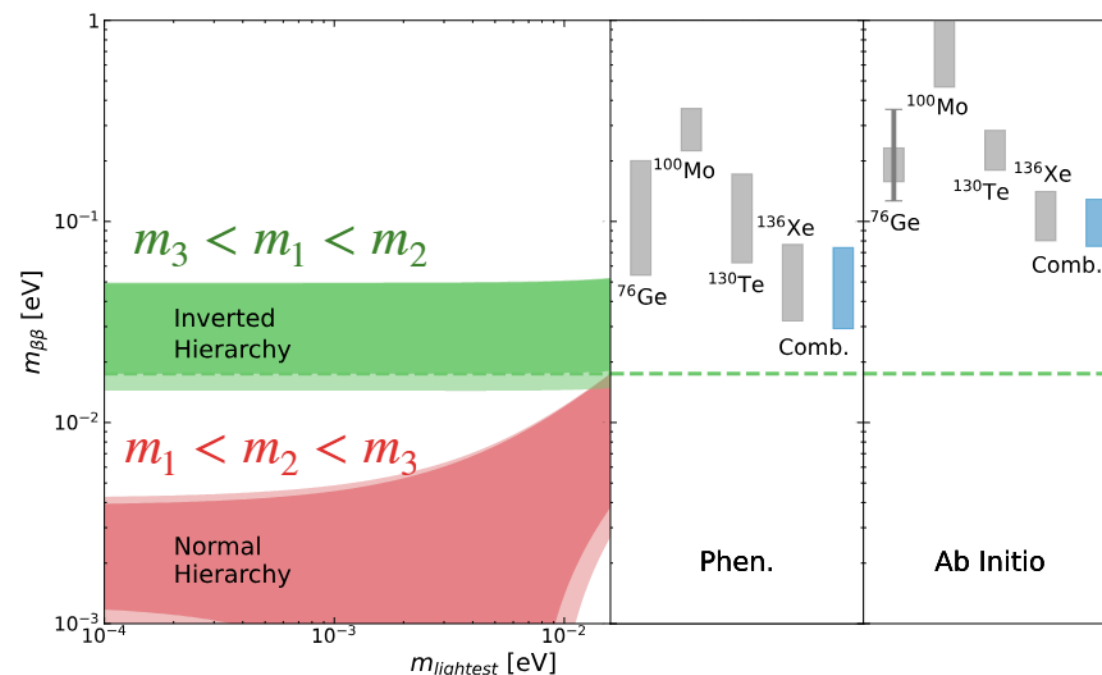
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Agostini et al., Rev. Mod. Phys. 95, 025002 (2023)



Shickele, Jokiniemi, Belley, Holt, in preparation

$0\nu\beta\beta$ DECAY MEDIATED BY LIGHT-NEUTRINO EXCHANGE

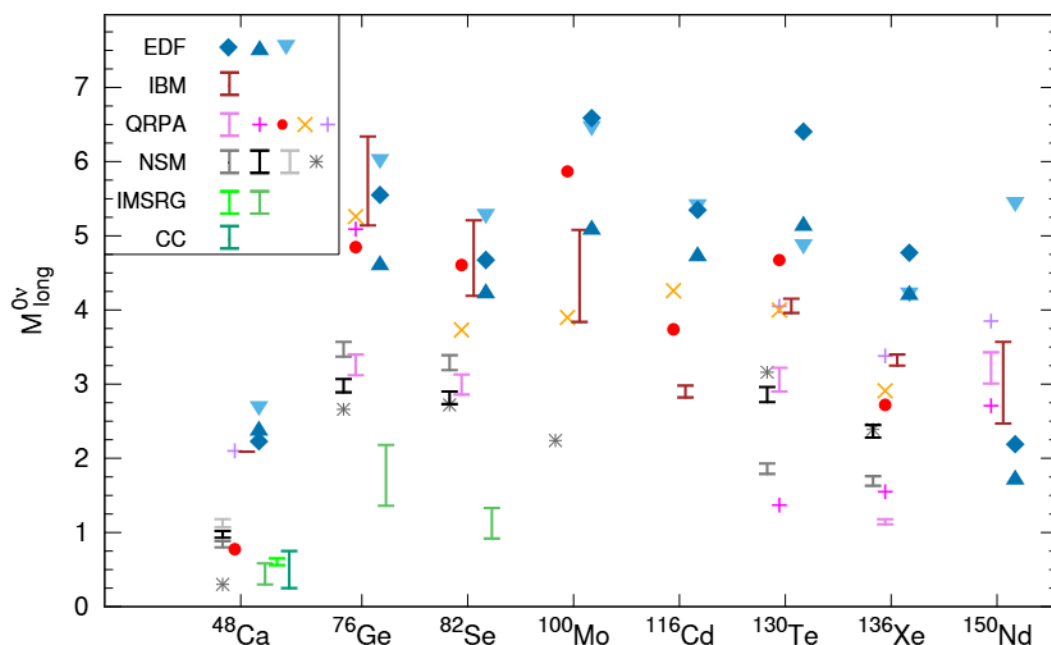
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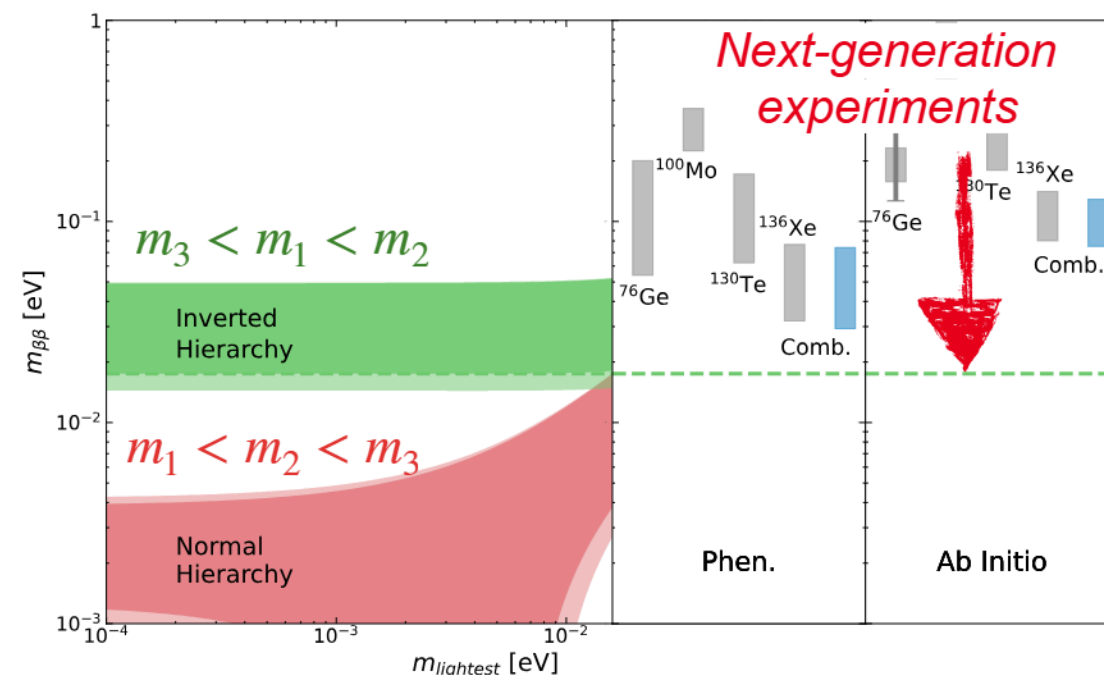
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Agostini et al., Rev. Mod. Phys. 95, 025002 (2023)



Shickele, Jokiniemi, Belley, Holt, in preparation



THE NUCLEAR MATRIX ELEMENT

$$M^{0\nu} = \langle \Psi_f^{(A)} | \mathcal{O}^{0\nu} | \Psi_i^{(A)} \rangle$$



THE NUCLEAR MATRIX ELEMENT

Operator ($nn \rightarrow pp + 2e^-$)



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Initial state wave function

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Operator ($nn \rightarrow pp + 2e^-$)



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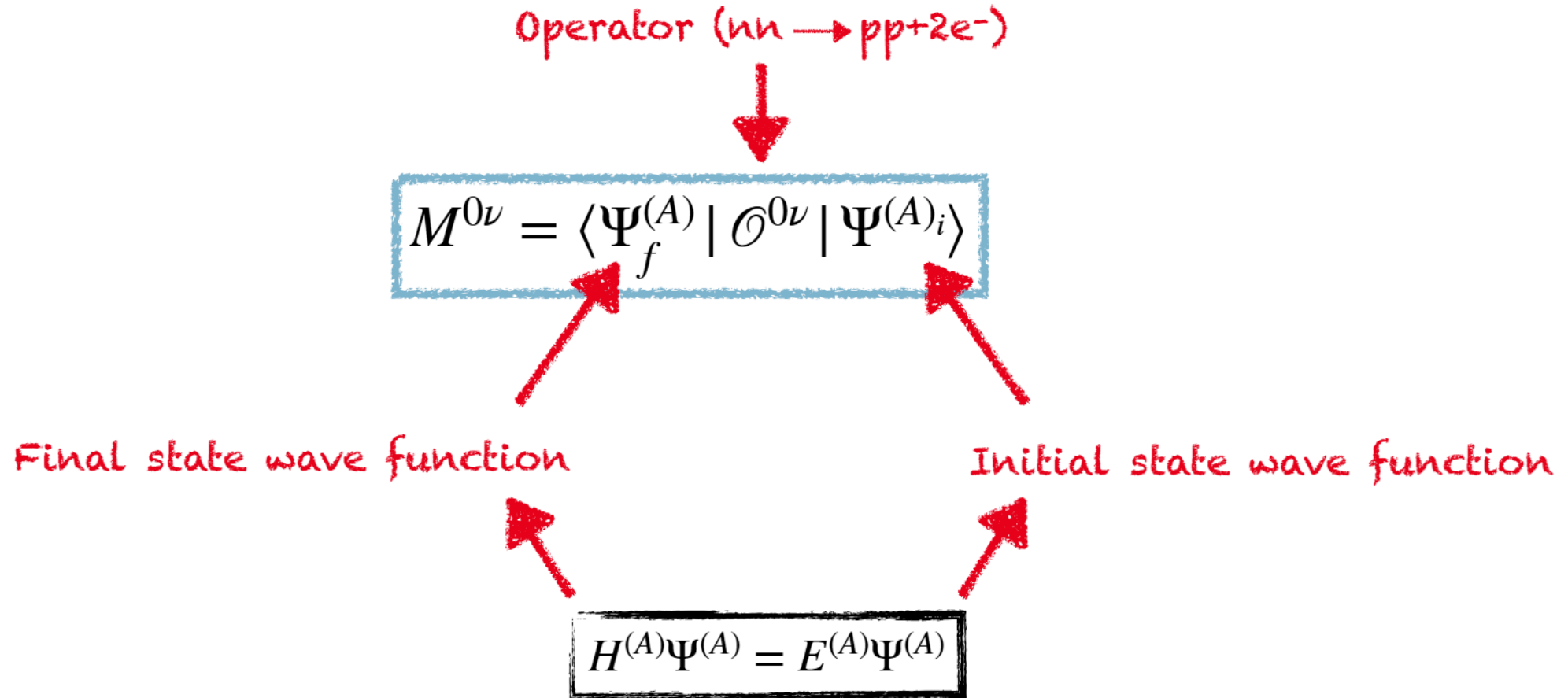


Final state wave function



Initial state wave function

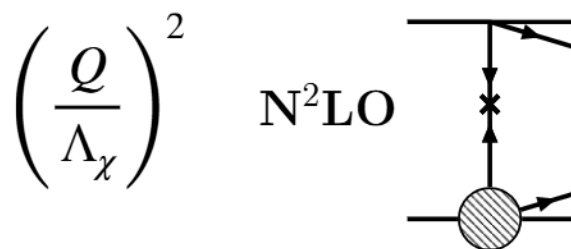
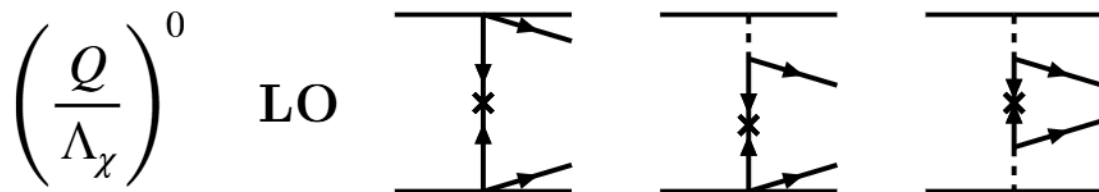
THE NUCLEAR MATRIX ELEMENT



CHIRAL EFFECTIVE THEORY OPERATORS FOR $0\nu\beta\beta$ DECAY

$$M^{0\nu} = M_L^{0\nu}$$

$$M_L^{0\nu} = M_{\text{GT}}^{0\nu} - \left(\frac{g_V}{g_A} \right)^2 M_F^{0\nu} + M_T^{0\nu}$$

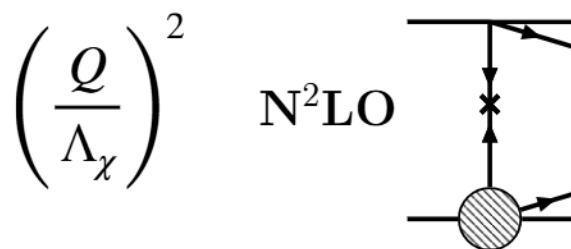
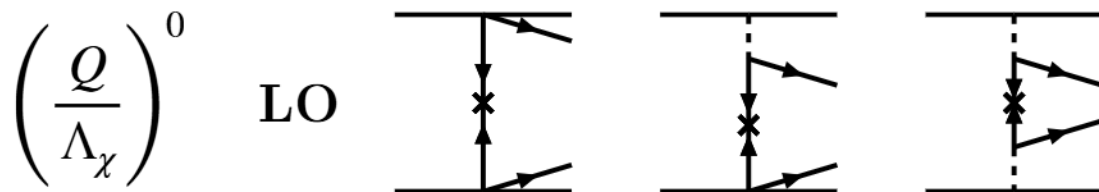


V. Cirigliano et al., *Phys. Rev. Lett.* 120, 202001 (2018), *Phys. Rev. C* 100, 055504 (2019)

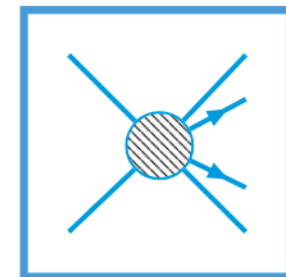
CHIRAL EFFECTIVE THEORY OPERATORS FOR $0\nu\beta\beta$ DECAY

$$M^{0\nu} = M_L^{0\nu} + M_S^{0\nu}$$

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15% – 90 %

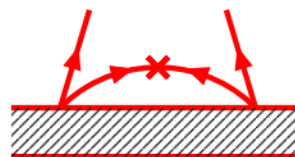
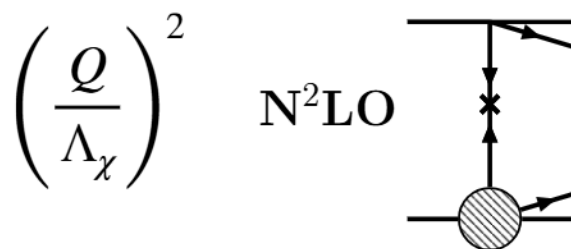
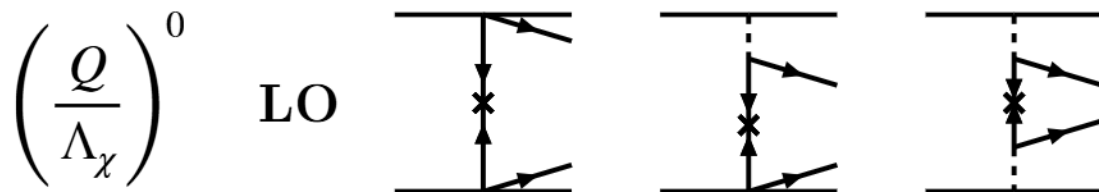


V. Cirigliano et al., *Phys. Rev. Lett.* 120, 202001 (2018), *Phys. Rev. C* 100, 055504 (2019)

CHIRAL EFFECTIVE THEORY OPERATORS FOR $0\nu\beta\beta$ DECAY

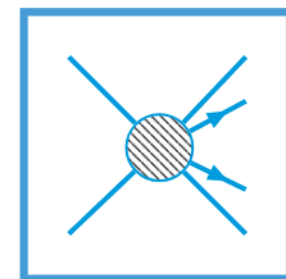
$$M^{0\nu} = M_L^{0\nu} + M_S^{0\nu} + M_{\text{usoft}}^{0\nu}$$

$$M_L^{0\nu} = M_{\text{GT}}^{0\nu} - \left(\frac{g_V}{g_A}\right)^2 M_F^{0\nu} + M_T^{0\nu}$$



5% – 10 %

15% – 90 %

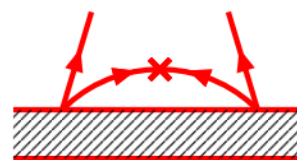
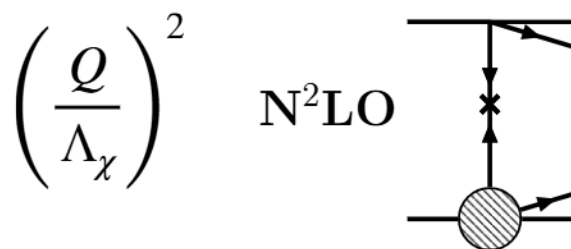
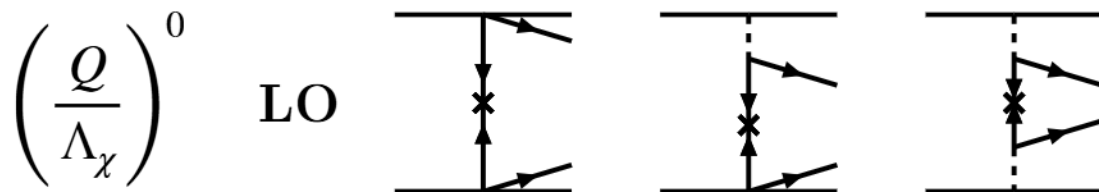


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CHIRAL EFFECTIVE THEORY OPERATORS FOR $0\nu\beta\beta$ DECAY

$$M^{0\nu} = M_L^{0\nu} + M_S^{0\nu} + M_{\text{usoft}}^{0\nu} + M_{\text{loop}}^{0\nu}$$

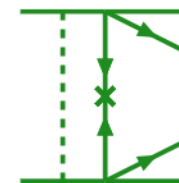
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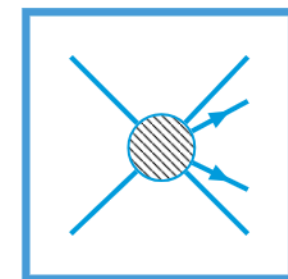


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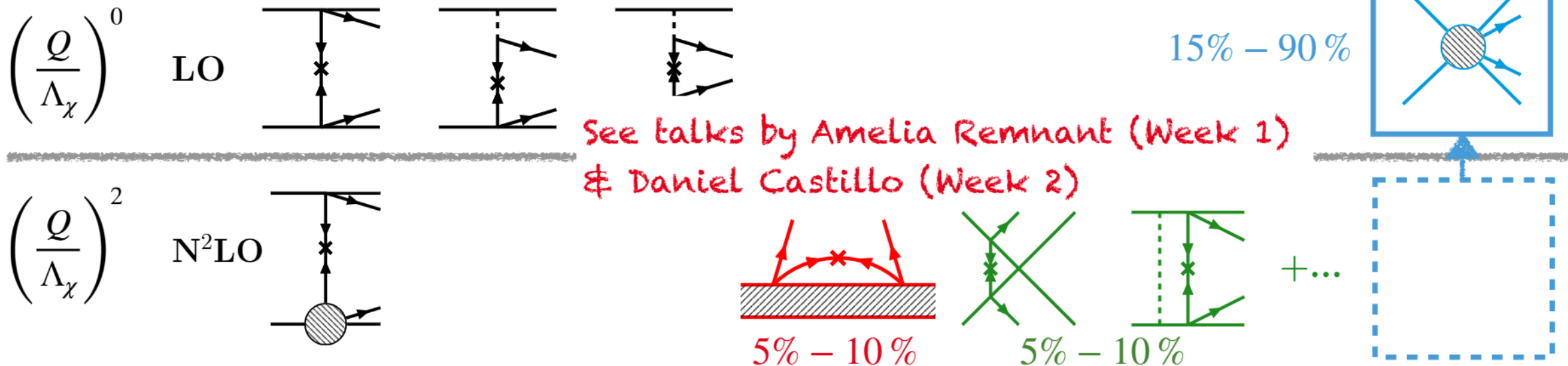


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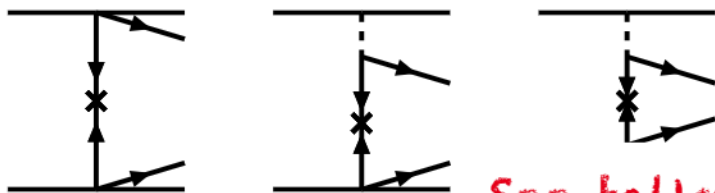
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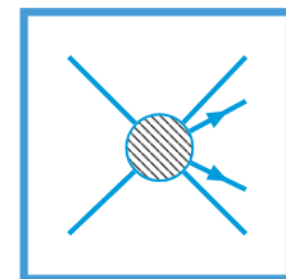
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$$\left(\frac{Q}{\Lambda_\chi} \right)^0$$

LO

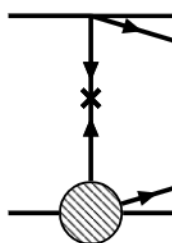


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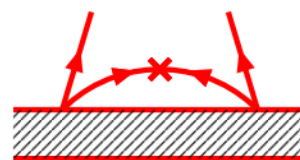


$$\left(\frac{Q}{\Lambda_\chi} \right)^2$$

N²LO



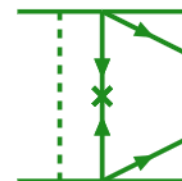
See talks by Amelia Remnant (Week 1)
& Daniel Castillo (Week 2)



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+ ...



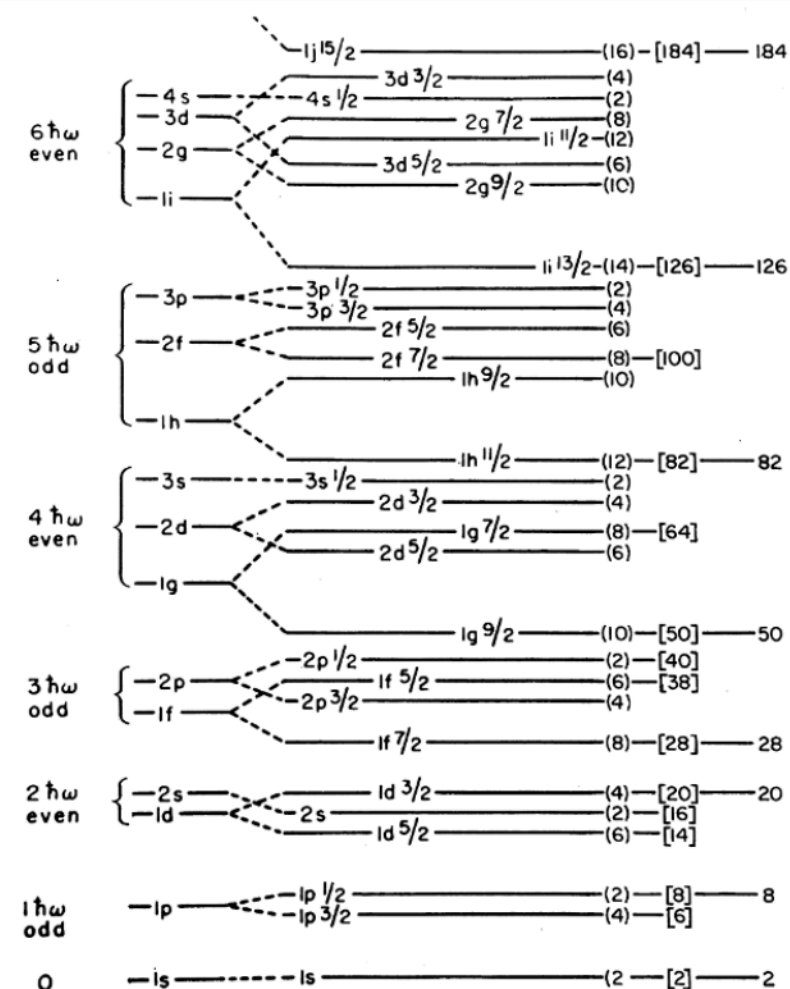
N³LO

3-nucleon potentials *Chambers-Wall et al. arXiv:2510.21564*

V. Cirigliano et al., Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)



PHENOMENOLOGICAL MANY-BODY METHODS

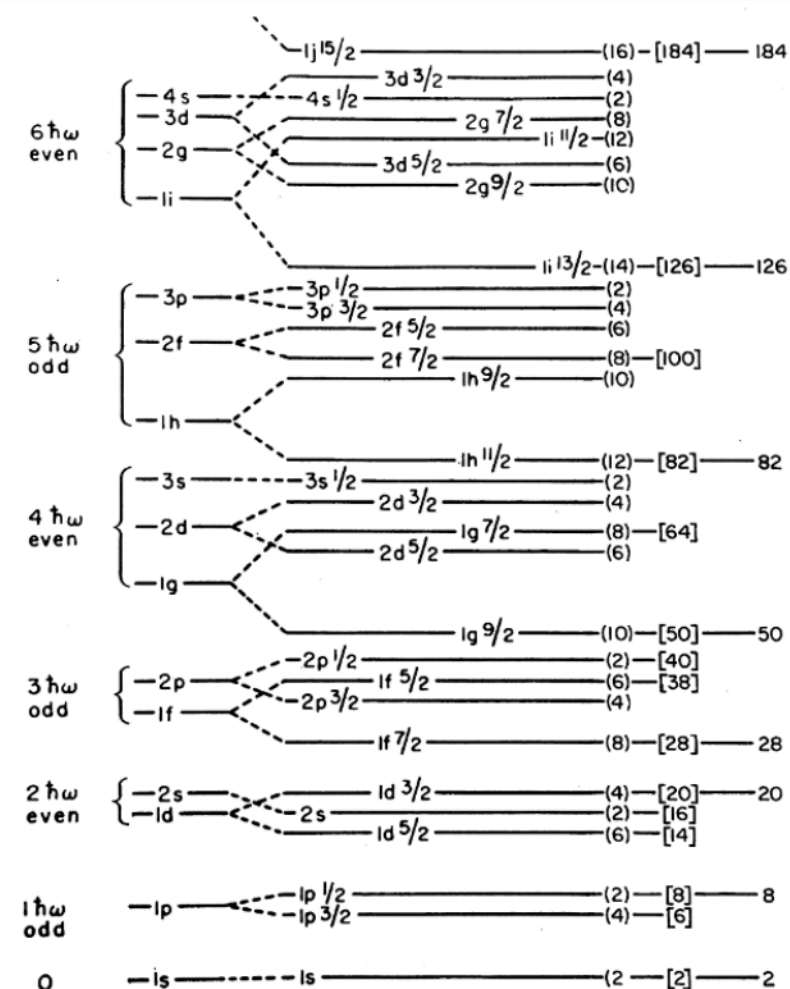


M. Göppert-Mayer, Science 145, 999 (1964)



PHENOMENOLOGICAL MANY-BODY METHODS

- Based and *adjusted* on nuclear phenomena

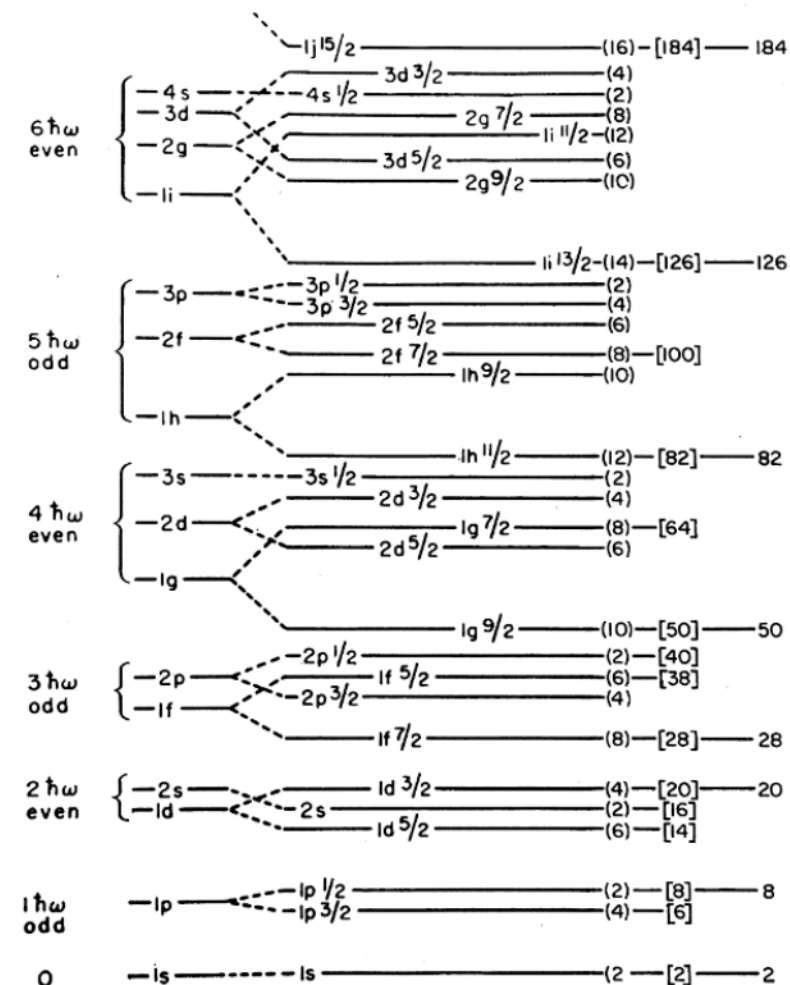


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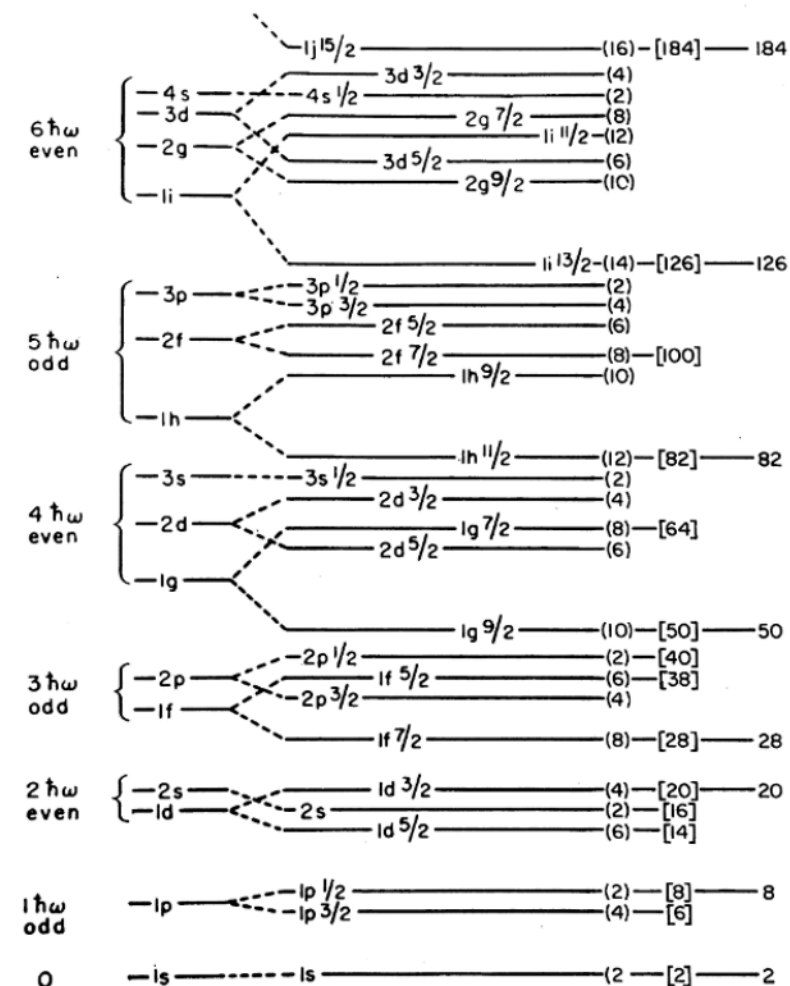


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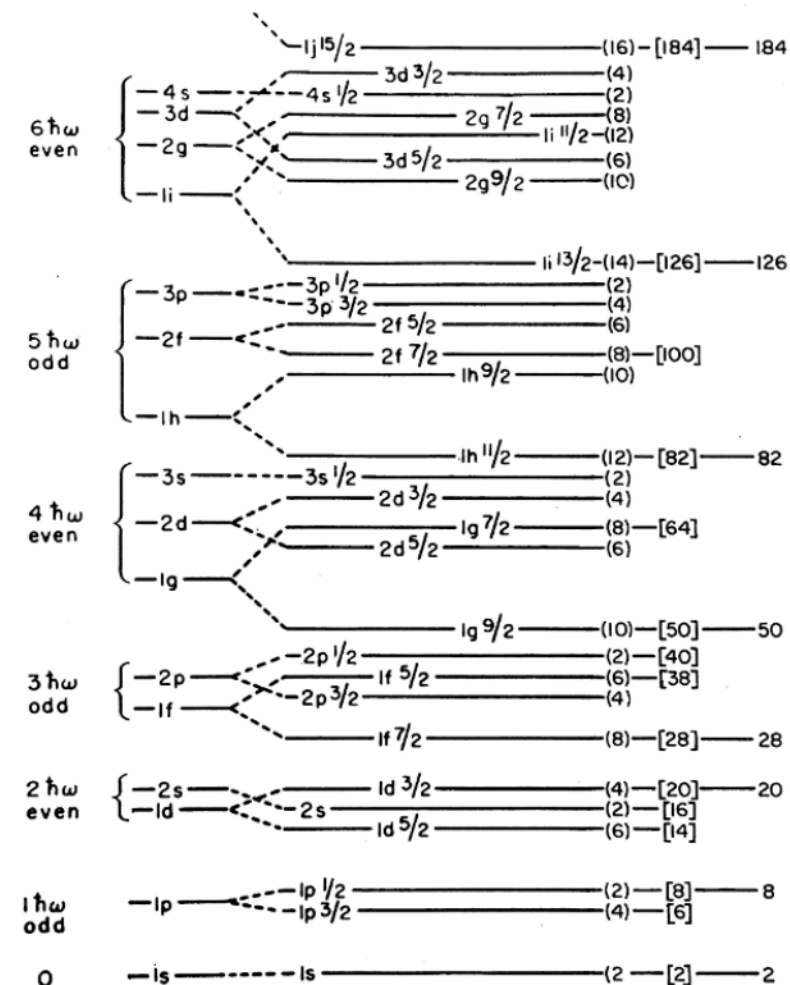
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- Examples:
 - Nuclear Shell Model (NSM)
Solves the Schrödinger equation in valence space with empirical Hamiltonian



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Describes nuclear excitations as two-quasiparticle mixings in large model space

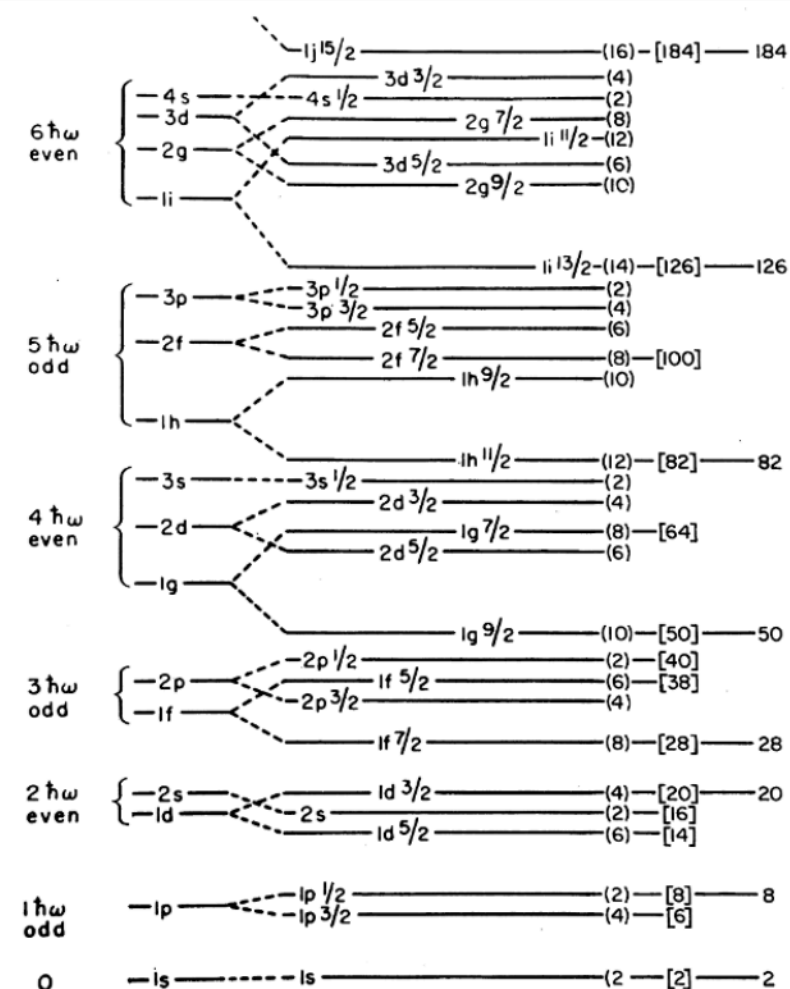


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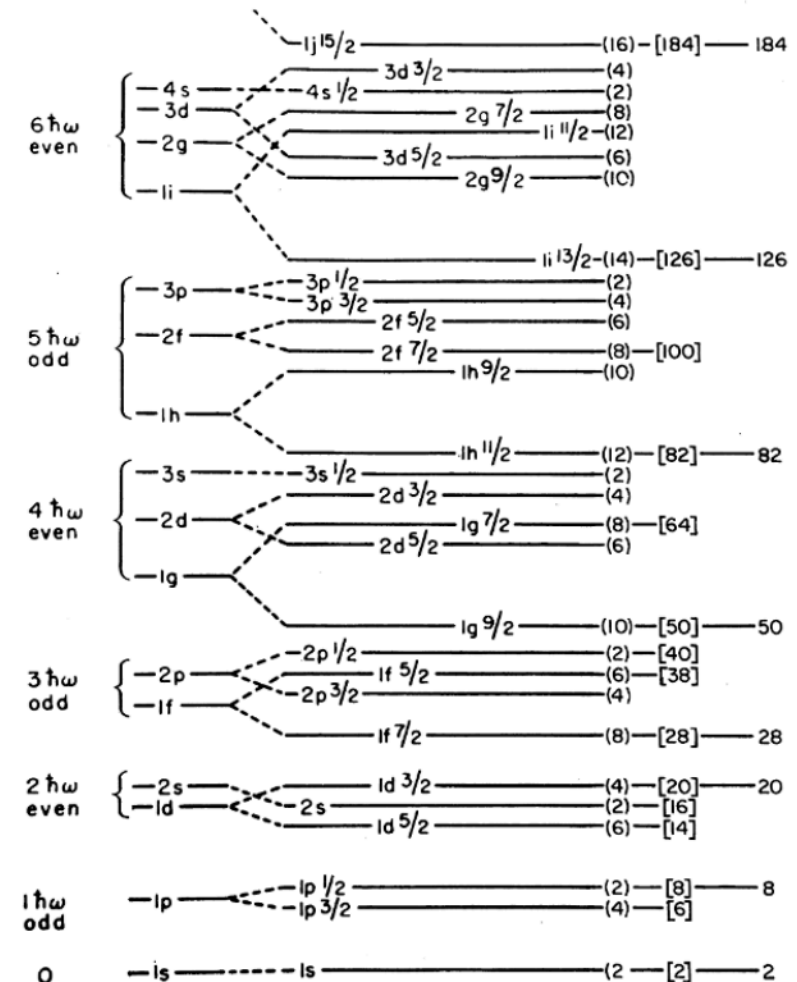
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Describes nuclear excitations as boson excitations in the valence space



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Describes nuclear excitations as two-quasiparticle mixings in large model space
 - Interacting Boson Model (IBM)
Describes nuclear excitations as boson excitations in the valence space
 - Energy Density Functional (EDF) theory
Solves the nuclear many-body problem in large model spaces starting from density functionals



M. Göppert-Mayer, Science 145, 999 (1964)

AB INITIO (LAT. FROM THE BEGINNING) NUCLEAR THEORY

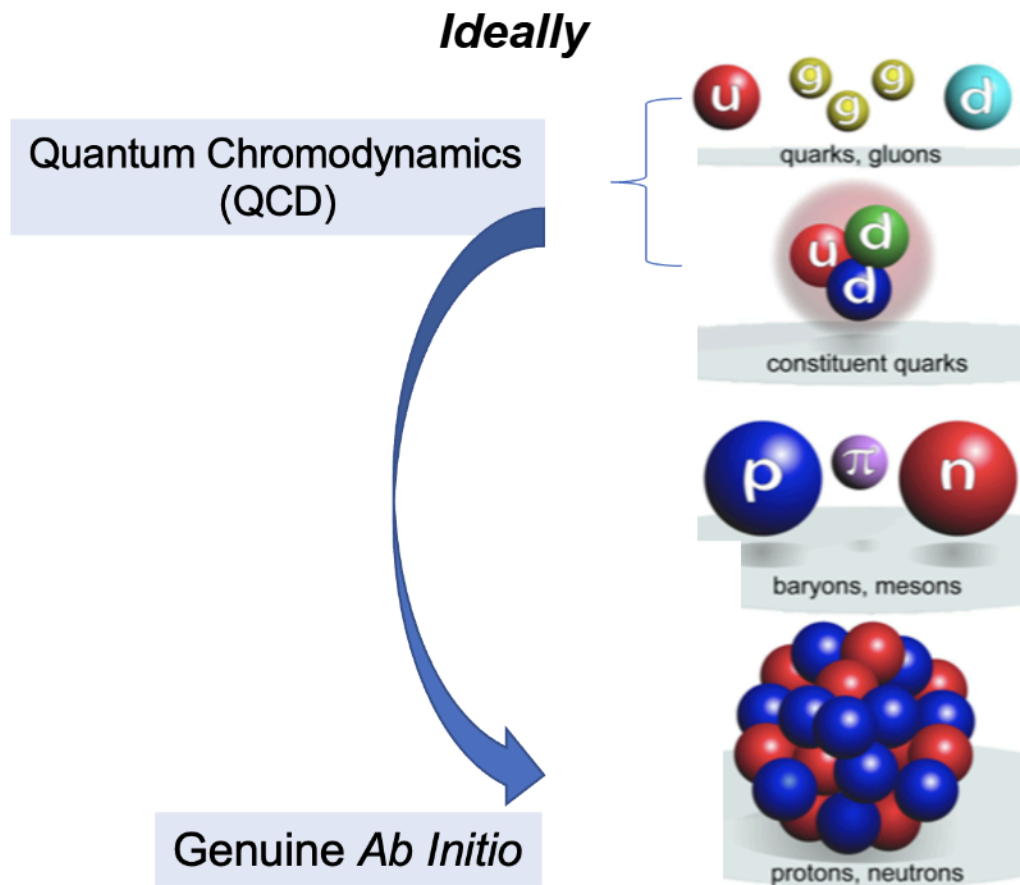


Figure courtesy of P. Navrátil

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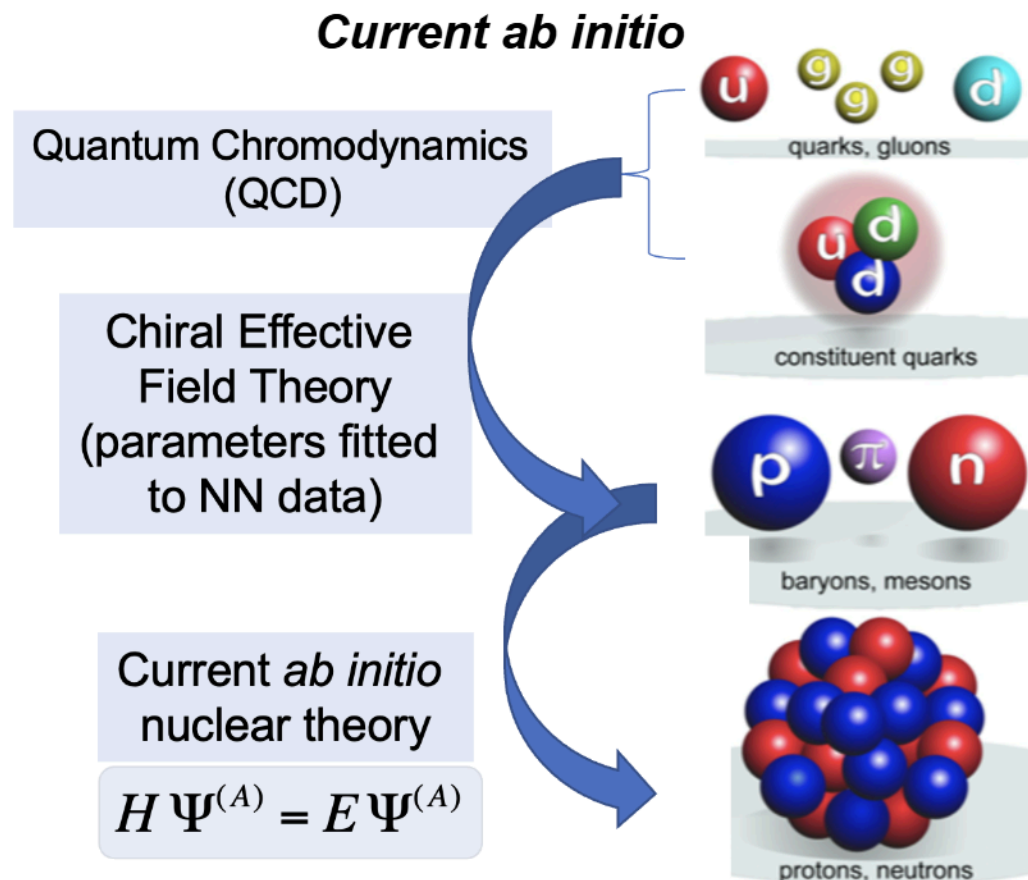


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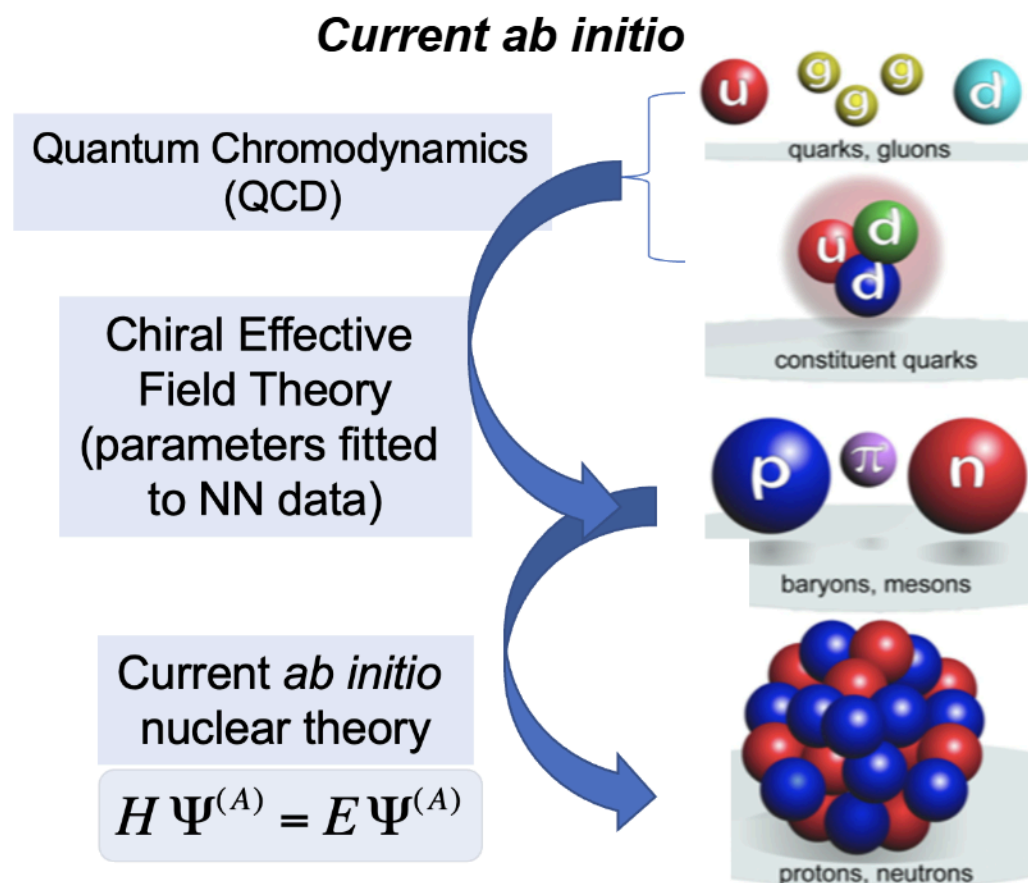


Figure courtesy of P. Navrátil

Chiral expansion of nuclear forces

	NN	3N	4N
LO $(Q/\Lambda_\chi)^0$			
NLO $(Q/\Lambda_\chi)^2$			
NNLO $(Q/\Lambda_\chi)^3$			
N ³ LO $(Q/\Lambda_\chi)^4$			

H. Hergert, *Front. Phys.* 8 (2020)

AB INITIO (LAT. FROM THE BEGINNING) NUCLEAR THEORY

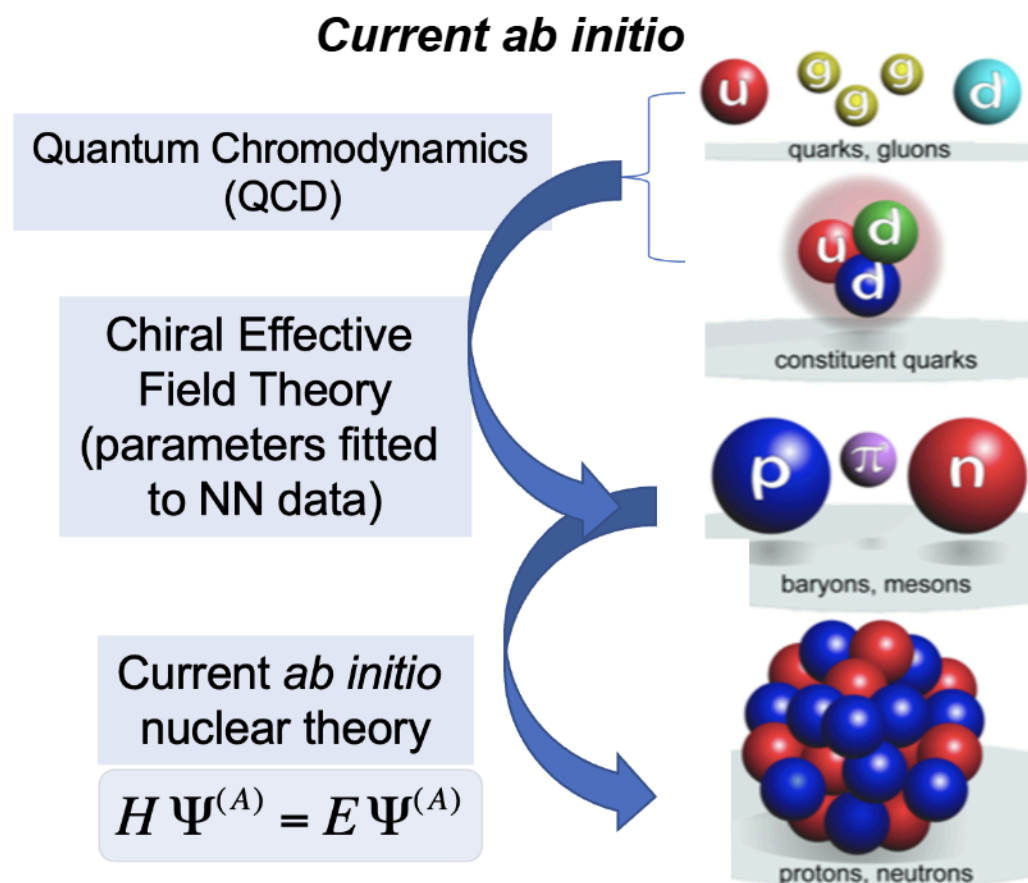
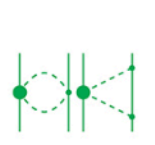
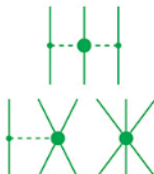
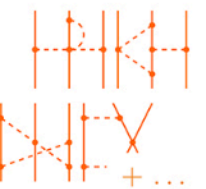


Figure courtesy of P. Navrátil

Chiral expansion of nuclear forces

	NN	3N	4N
LO $(Q/\Lambda_\chi)^0$		$H = T + V^{NN} + V^{3N} + \dots$	
NLO $(Q/\Lambda_\chi)^2$			
NNLO $(Q/\Lambda_\chi)^3$			
N ³ LO $(Q/\Lambda_\chi)^4$			

H. Hergert, *Front. Phys.* 8 (2020)

AB INITIO (LAT. FROM THE BEGINNING) NUCLEAR THEORY

Current *ab initio*

Quantum Chromodynamics
(QCD)



Chiral expansion of nuclear forces

	NN	3N	4N
LO (Q/Λ_χ) ⁰		$H = T + V^{\text{NN}} + V^{\text{3N}} + \dots$	

“... we interpret the **ab initio** method to be a **systematically improvable** approach for **quantitatively** describing nuclei using the **finest resolution scale possible** while **maximizing its predictive capabilities**”

Ekström, Forssén, Hagen, Jansen, Jiang, and Papenbrock, Front. Phys. 11, 1129094 (2023)

Current *ab initio*
nuclear theory

$$H \Psi^{(A)} = E \Psi^{(A)}$$

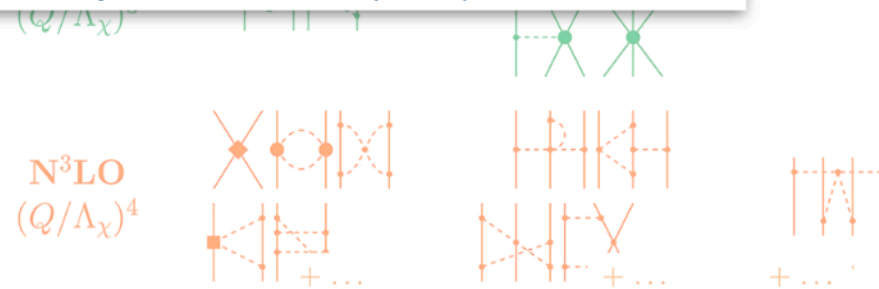
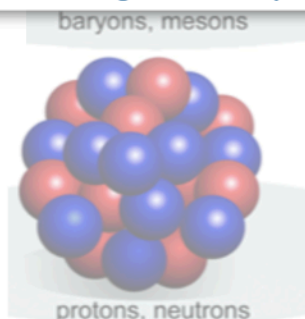
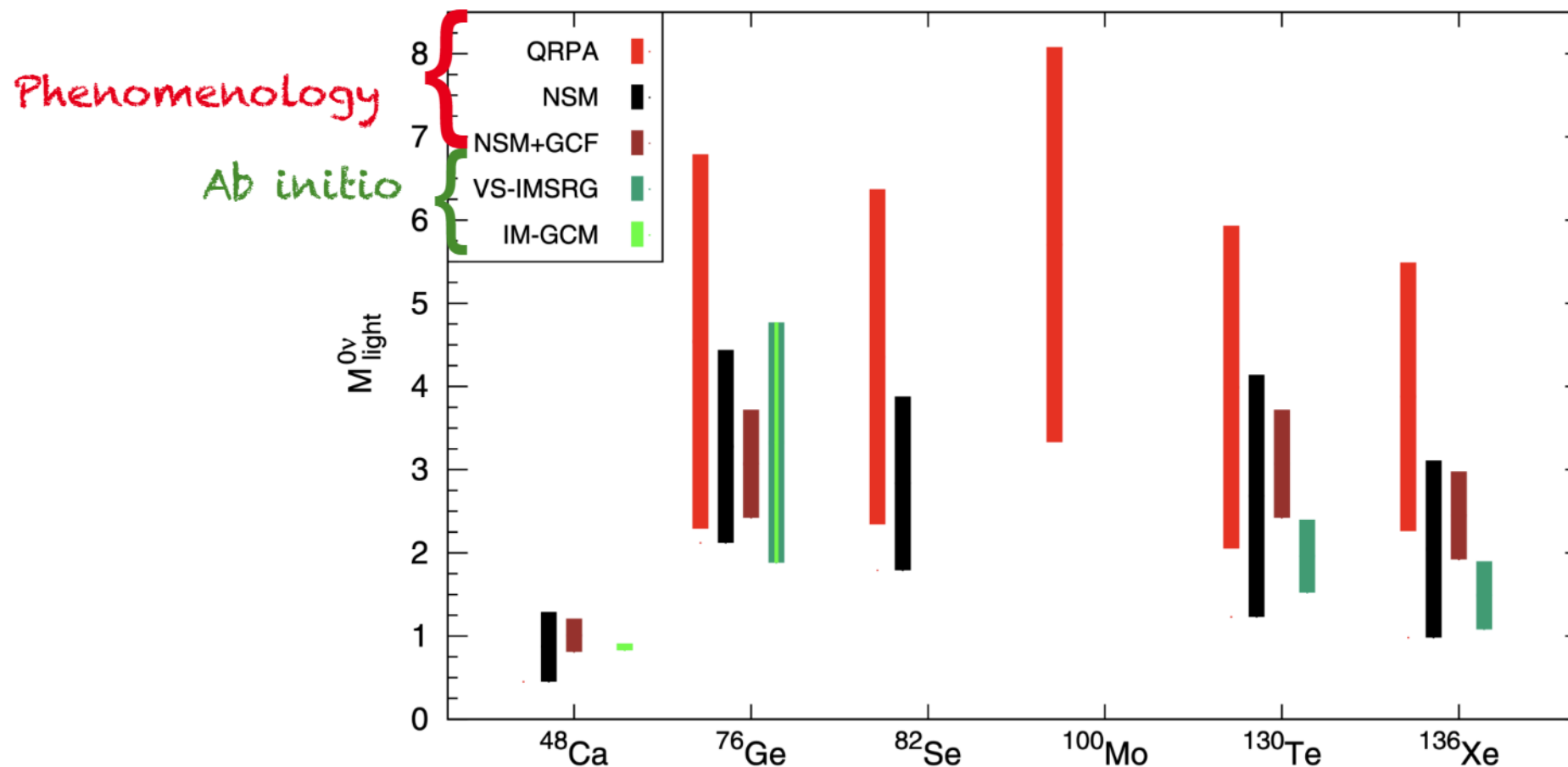


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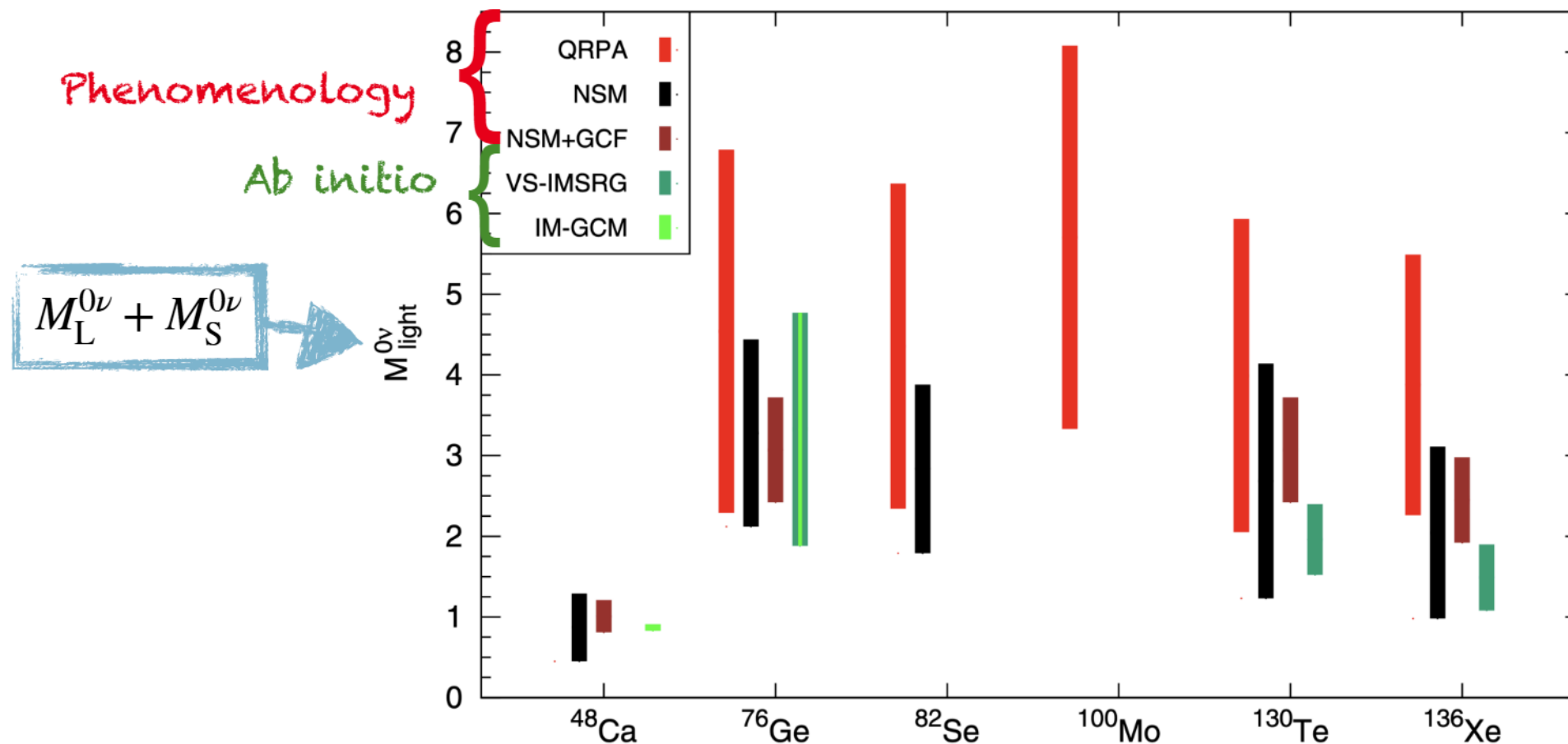
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CURRENT STATUS OF THE NUCLEAR MATRIX ELEMENTS



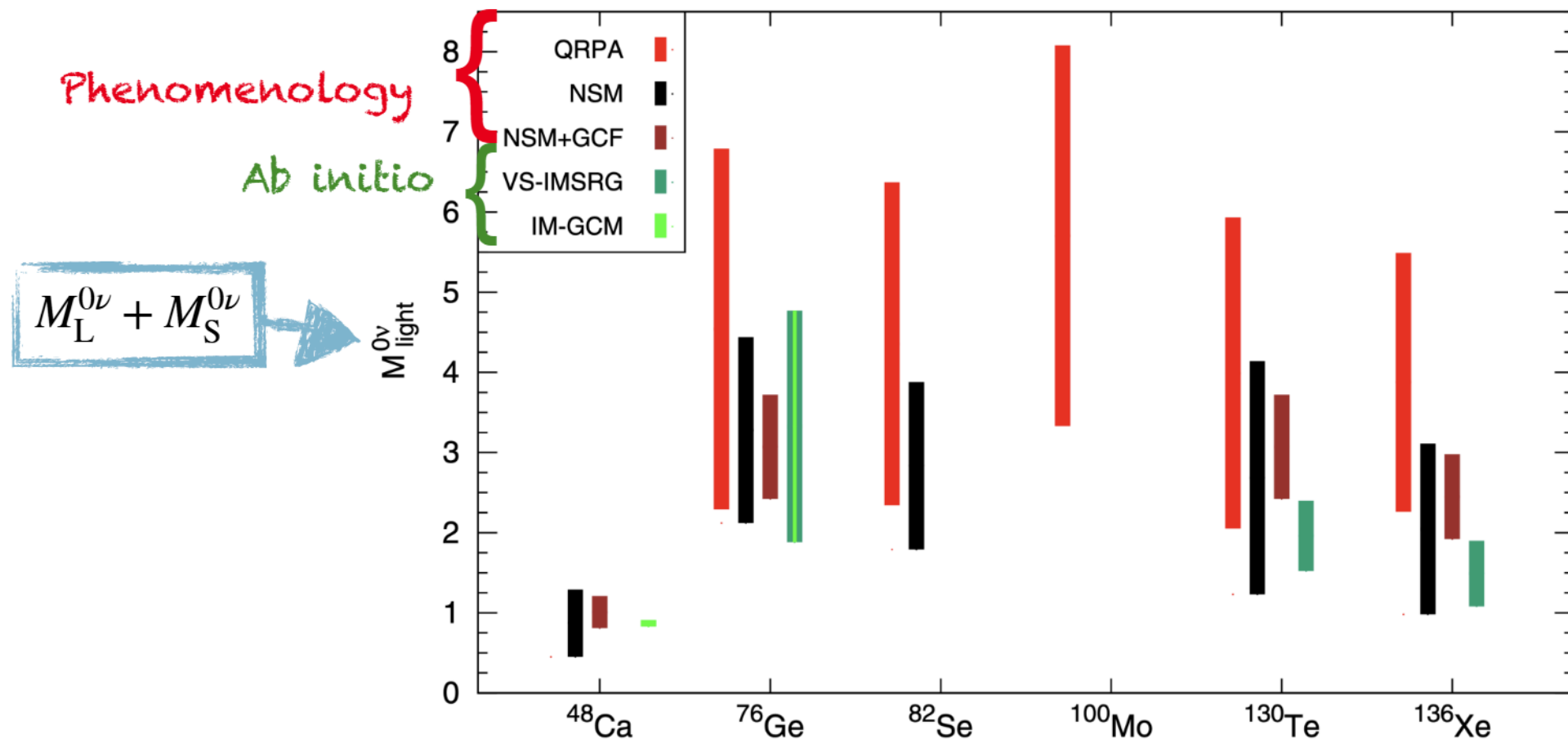
Gómez-Cadenas, Martín-Albo, Menéndez, Mezzetto, Monrabal, Sorel, *La Rivista del Nuovo Cimento* 46, 619 (2023)

CURRENT STATUS OF THE NUCLEAR MATRIX ELEMENTS



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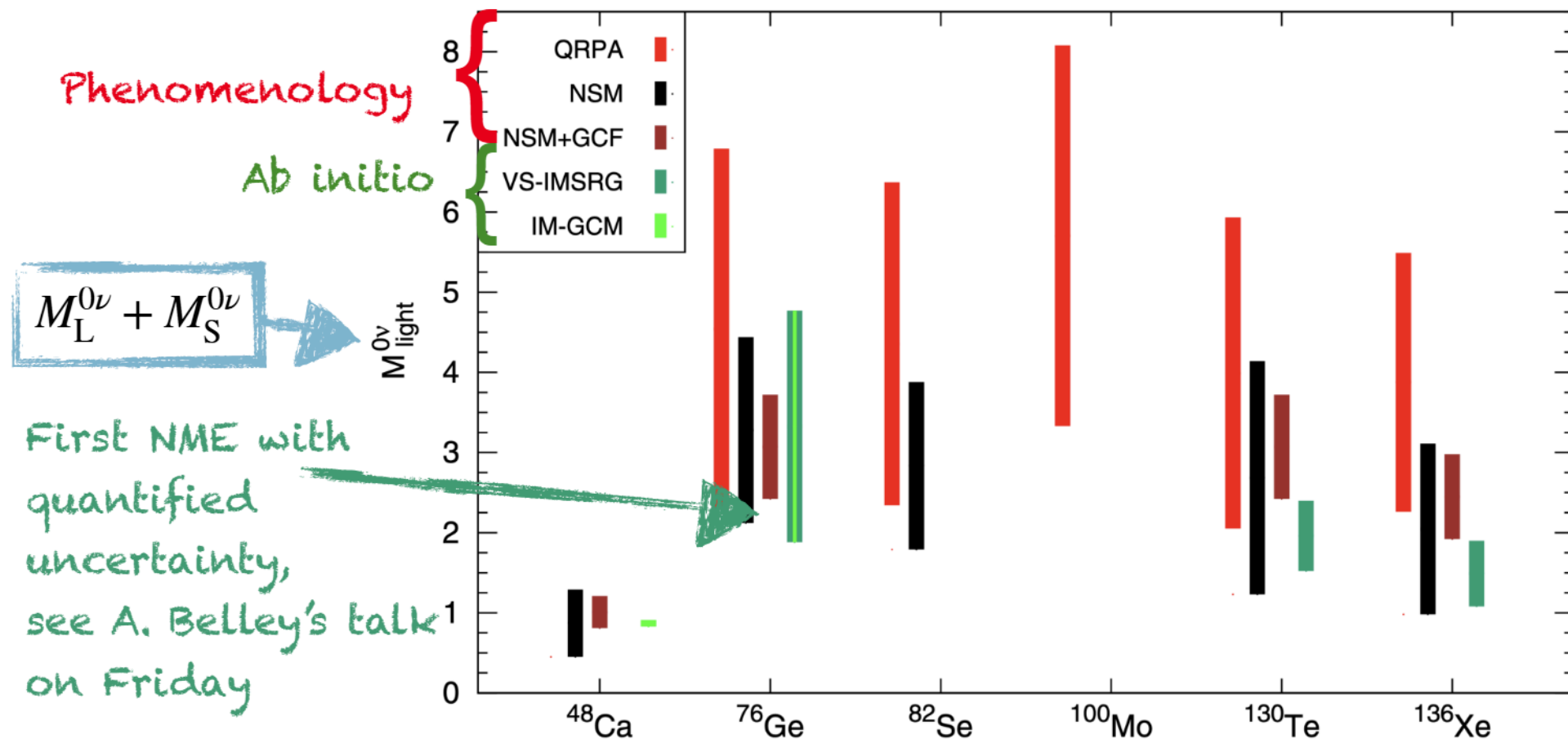


Ranges cover:

- Different **parameters/** nuclear **interactions**
- Different values of g_{ν}^{NN}
- ...

Gómez-Cadenas, Martín-Albo, Menéndez, Mezzetto, Monrabal, Sorel, *La Rivista del Nuovo Cimento* 46, 619 (2023)

CURRENT STATUS OF THE NUCLEAR MATRIX ELEMENTS

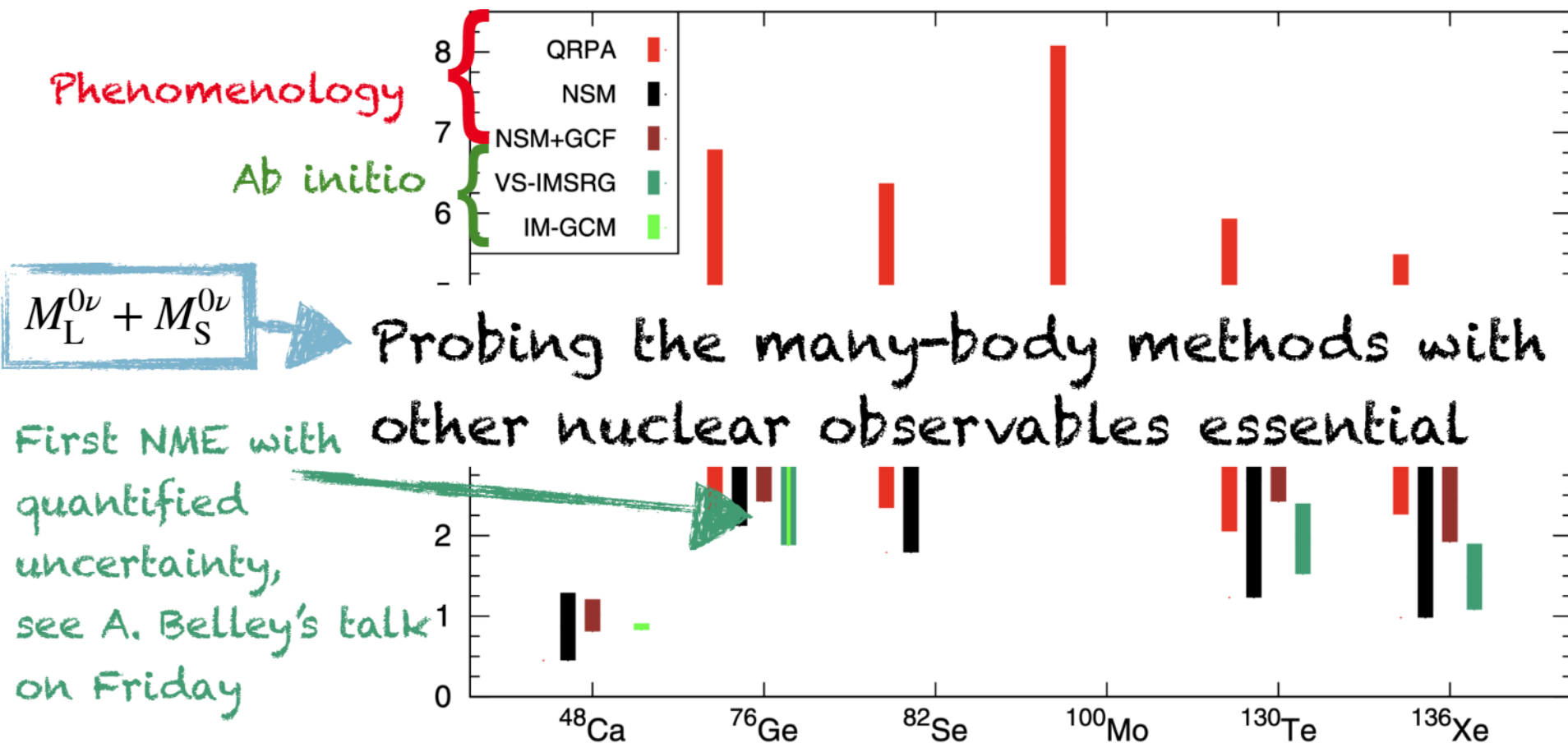


Ranges cover:

- Different parameters/ nuclear interactions
- Different values of g_{ν}^{NN}
- ...

Gómez-Cadenas, Martín-Albo, Menéndez, Mezzetto, Monrabal, Sorel, *La Rivista del Nuovo Cimento* 46, 619 (2023)

CURRENT STATUS OF THE NUCLEAR MATRIX ELEMENTS



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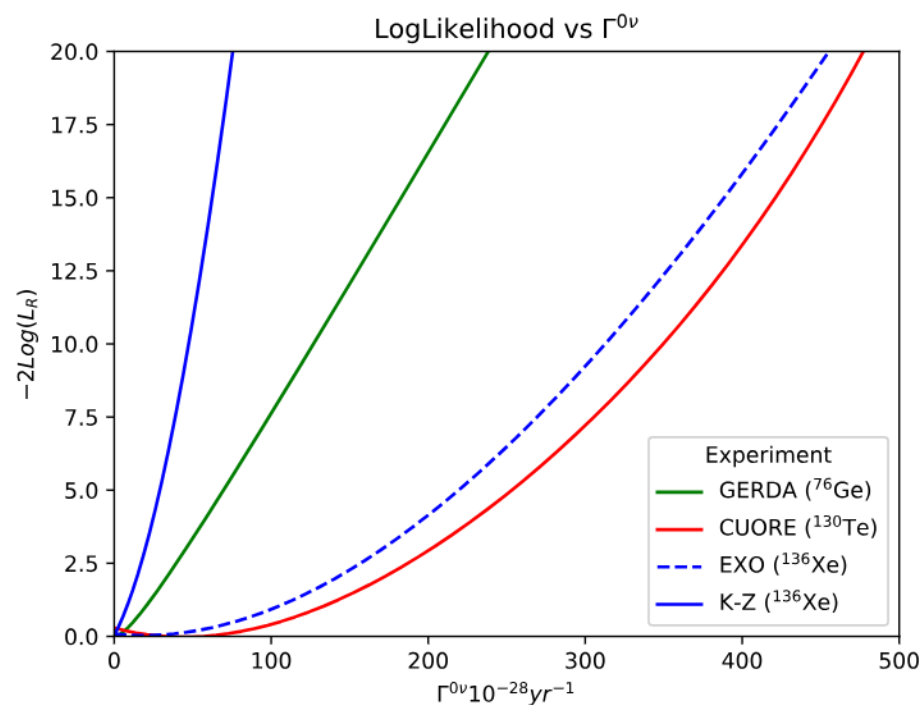


OUTLINE

- 1 Introduction
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GLOBAL MASS LIMITS FROM $0\nu\beta\beta$ DECAY

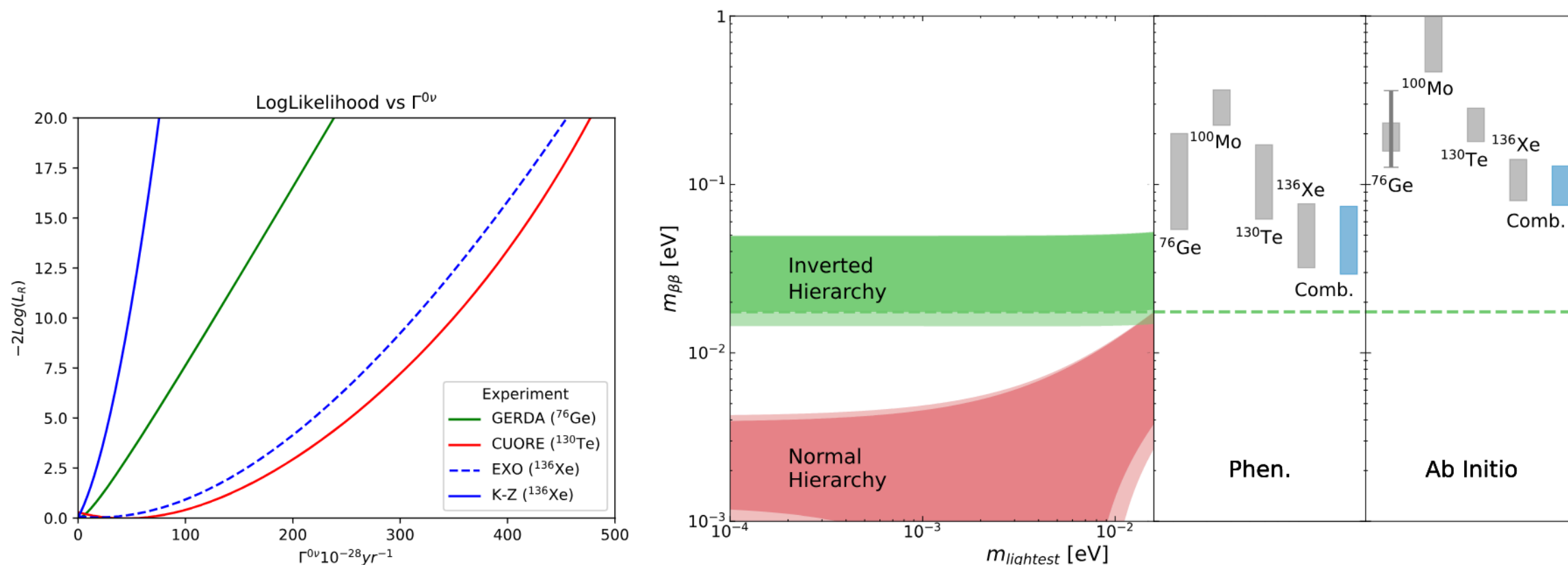
Current best limits



Shickele, Jokiniemi, Belley, Holt, arXiv:2606.09288 (accepted for Phys. Rev. D)

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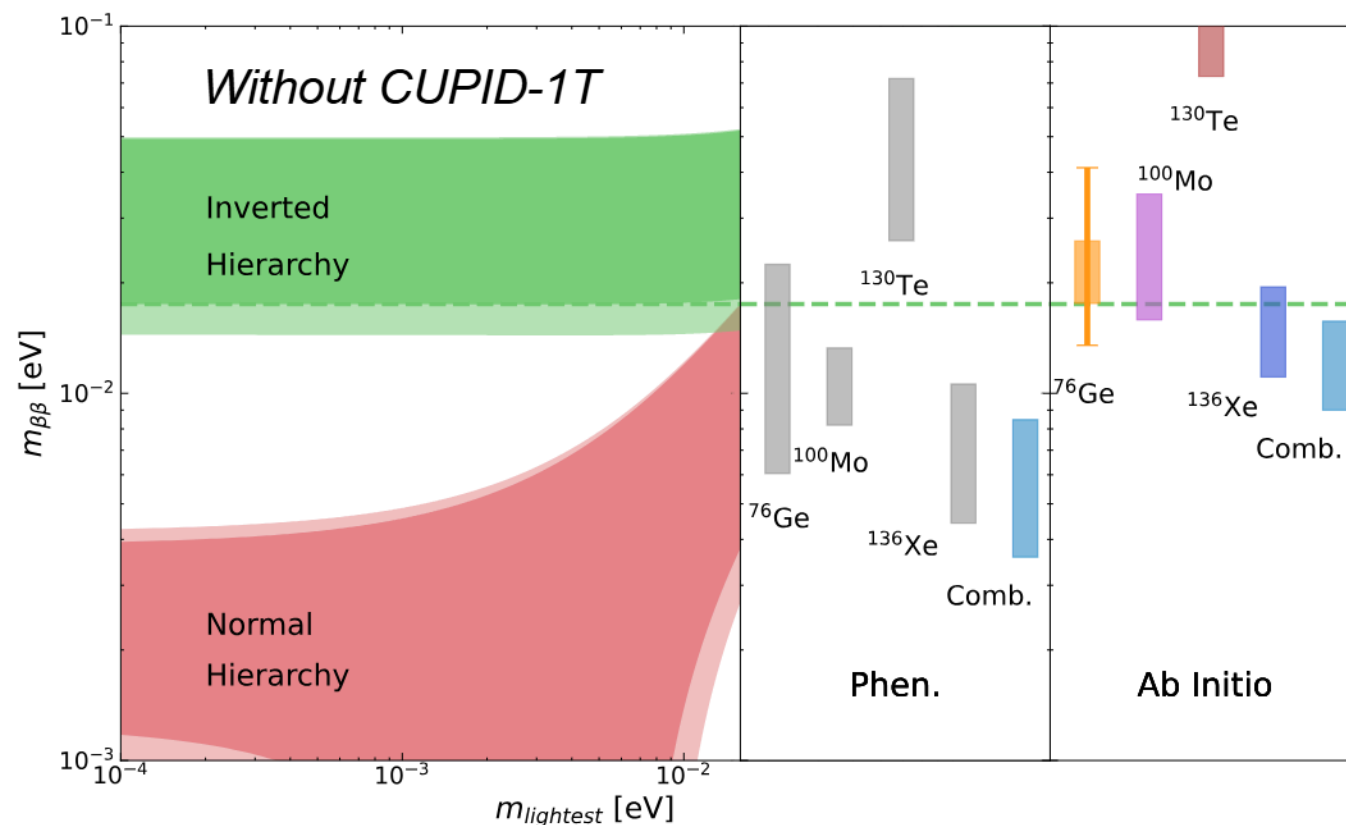
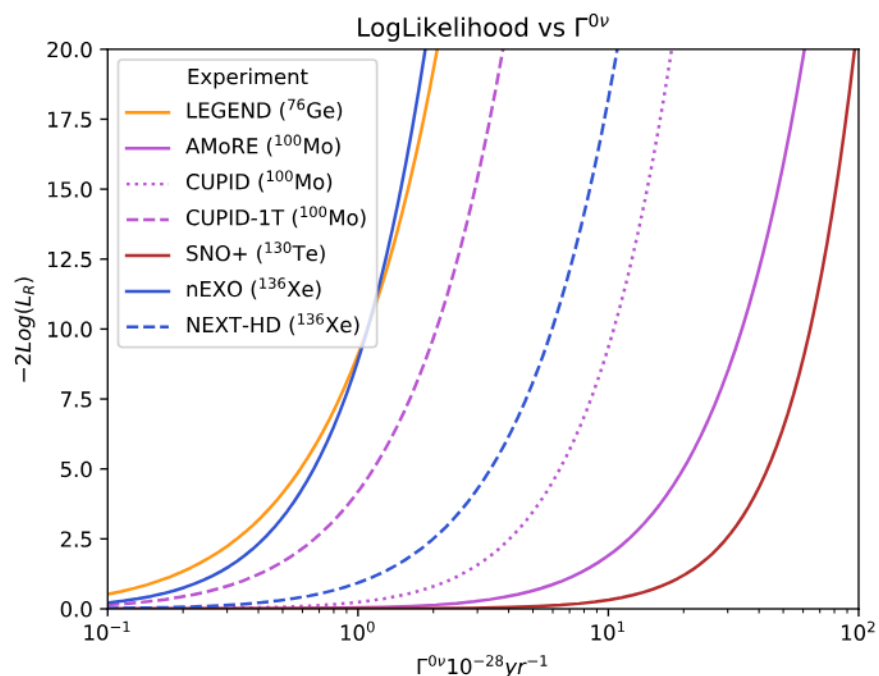
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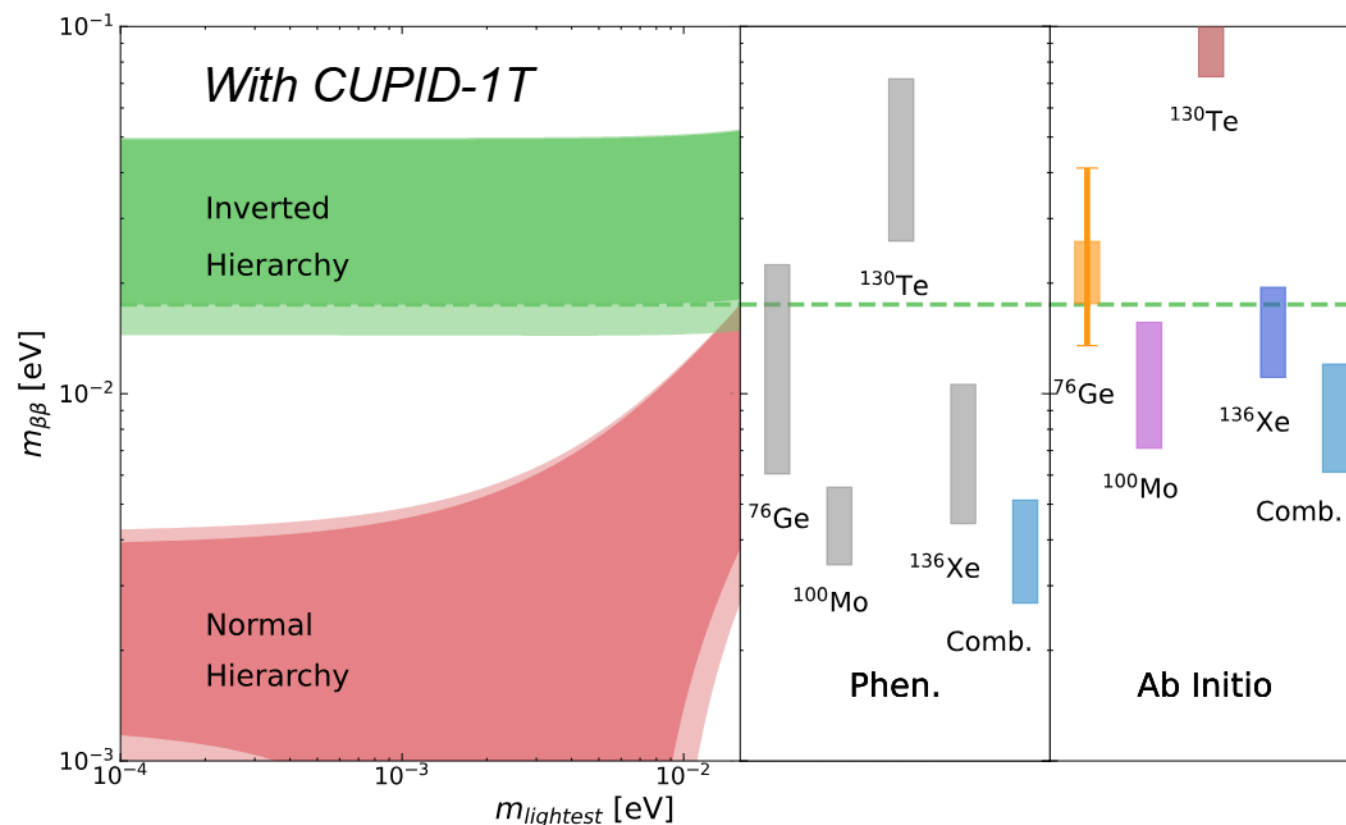
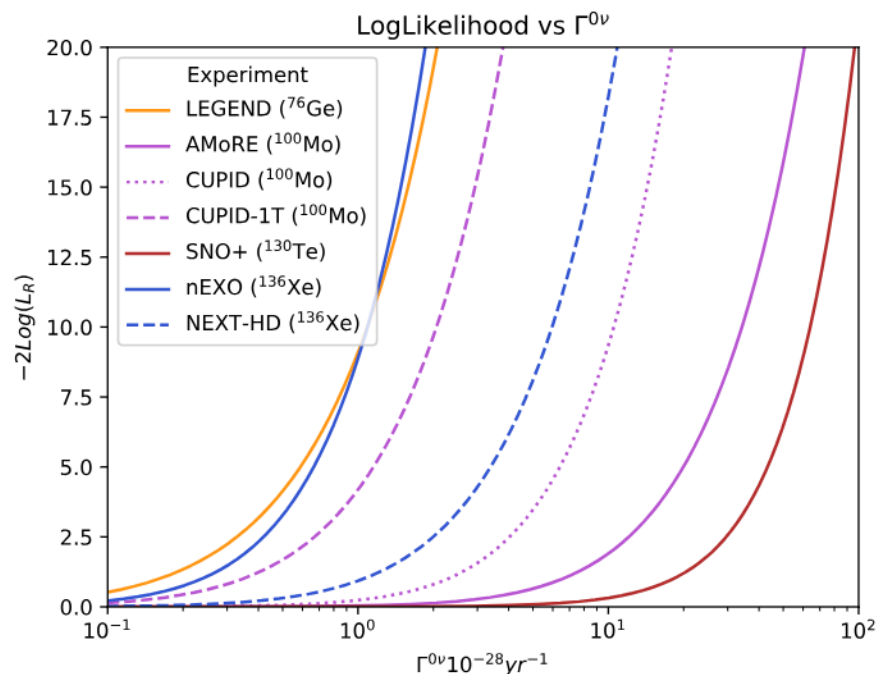
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NEW OBSERVATIONS WITH NEXT-GENERATION EXPERIMENTS?

■ ^{126}Xe

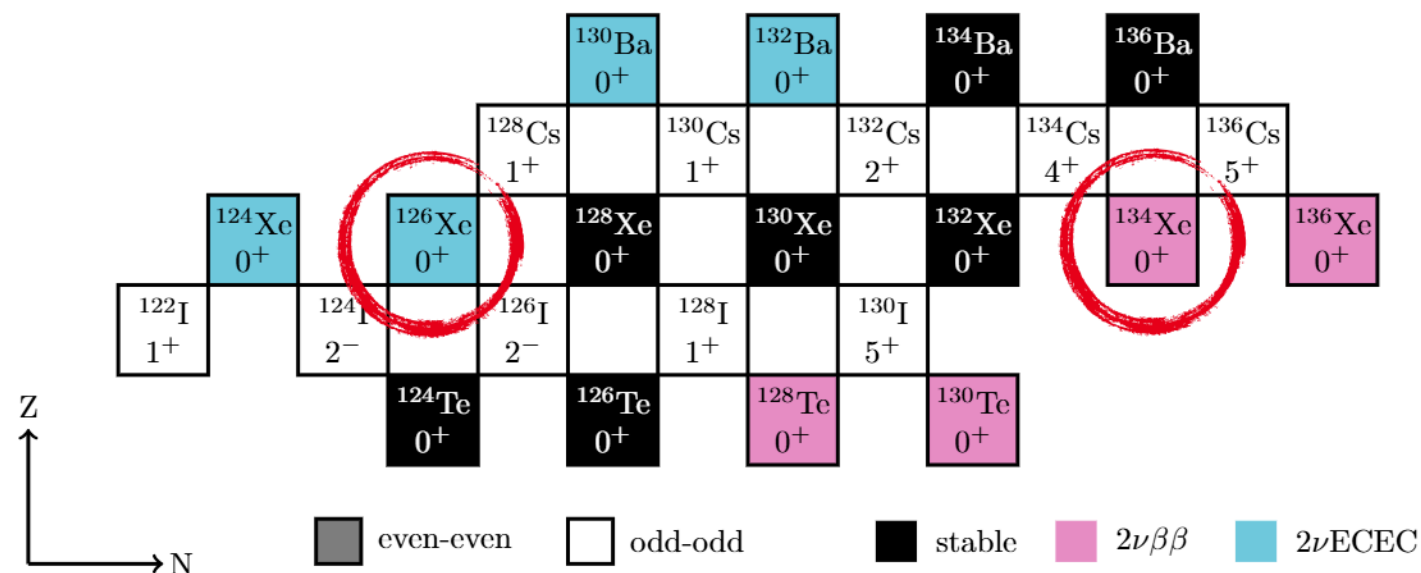
Abundance: 0.089(3) %

$$Q_{\text{ECEC}} = 917.8(14) \text{ keV}$$

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Abundance: 10.436(35) %

$$Q_{\beta\beta} = 824.2(3) \text{ keV}$$



*Brase, Jokiniemi, Kauppinen, Romeo, Kotila, Menéndez, Schwenk,
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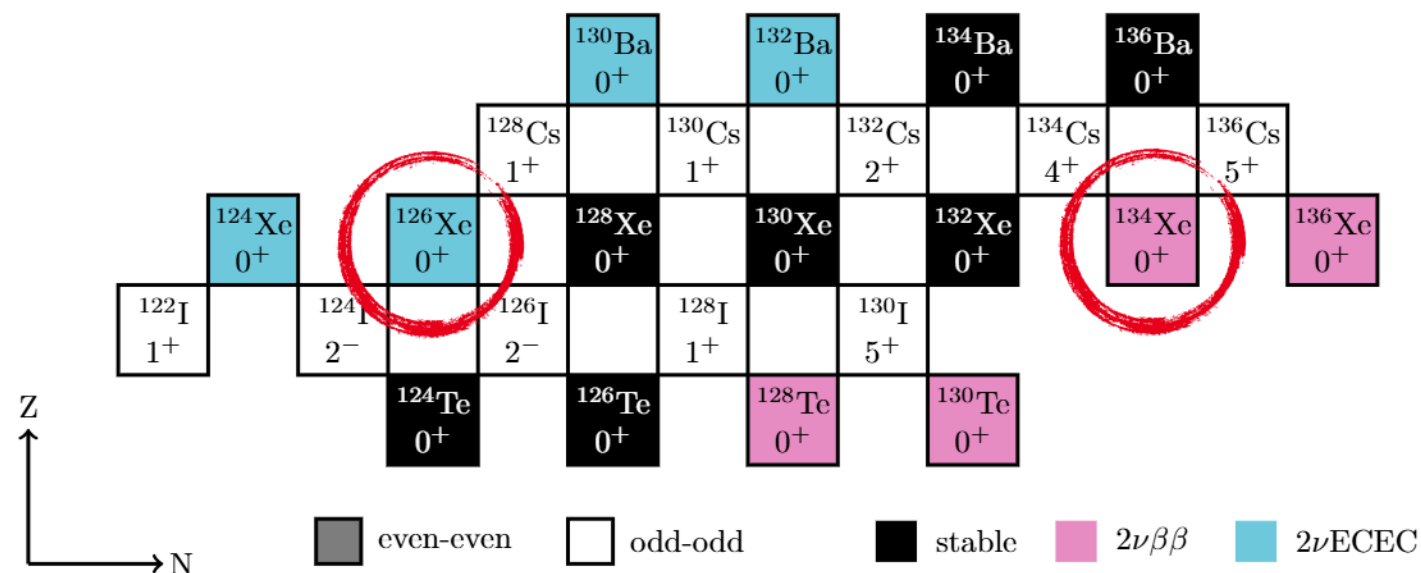
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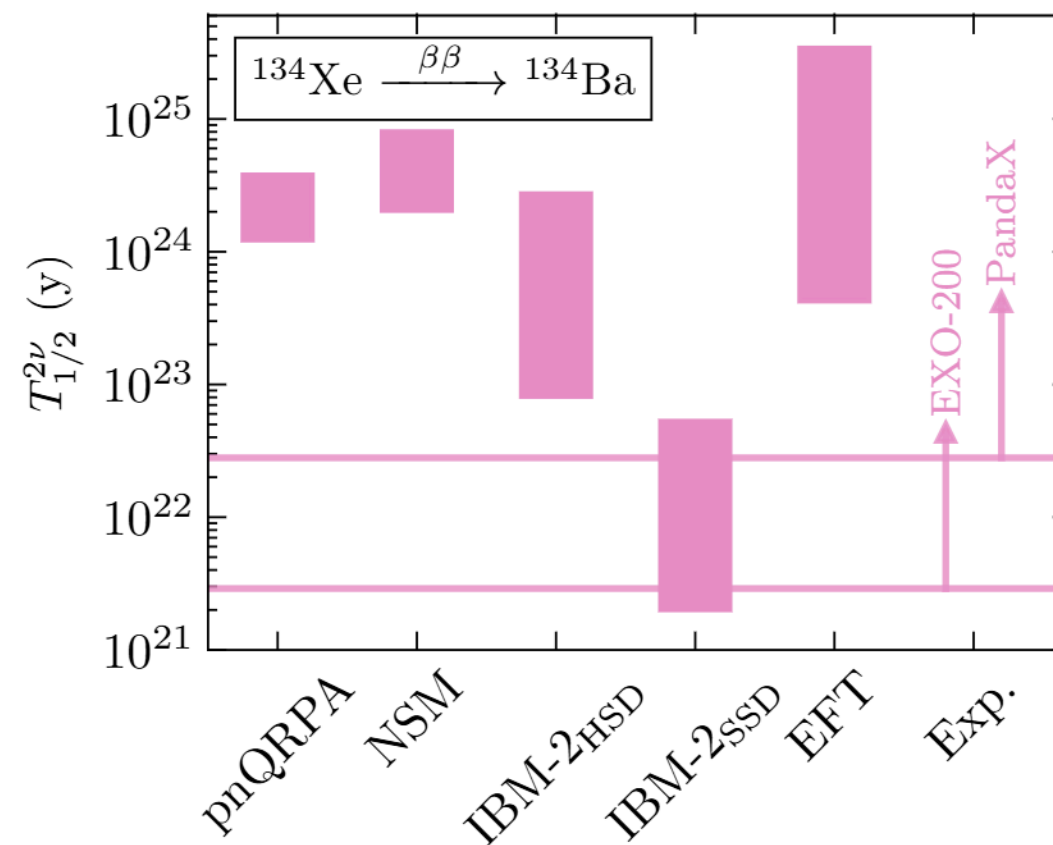
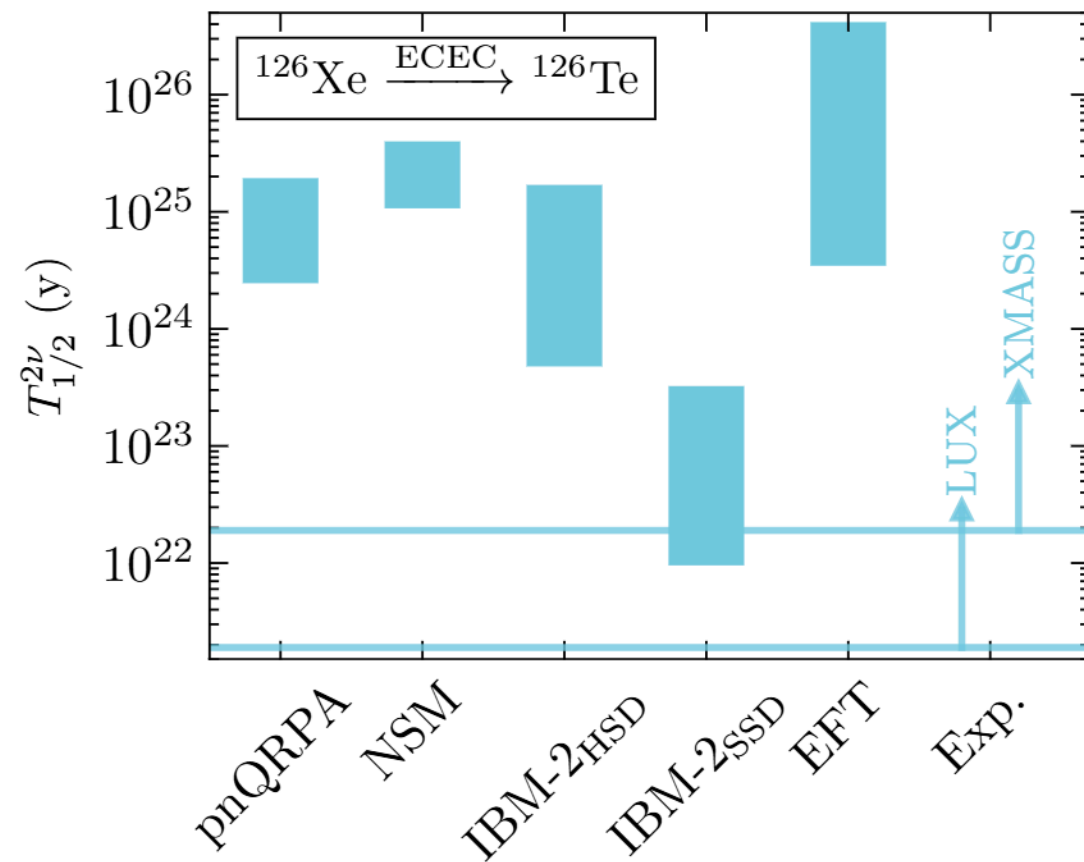
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$2\nu\beta\beta$ / $2\nu\text{ECEC}$ decays perhaps observable in next-generation xenon experiments

Brase, Jokiniemi, Kauppinen, Romeo, Kotila, Menéndez, Schwenk, in preparation

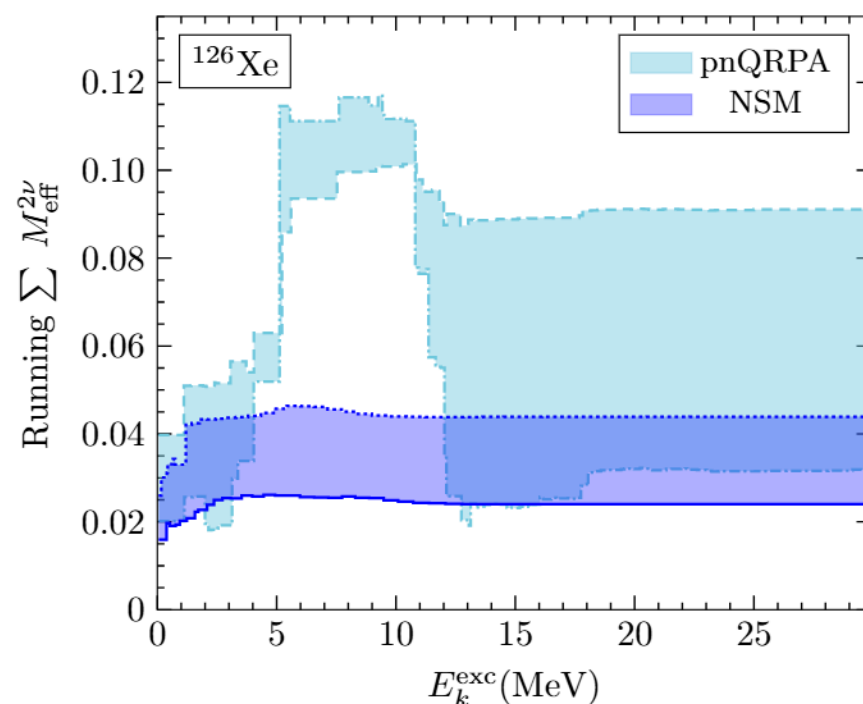
PREDICTED HALF-LIVES



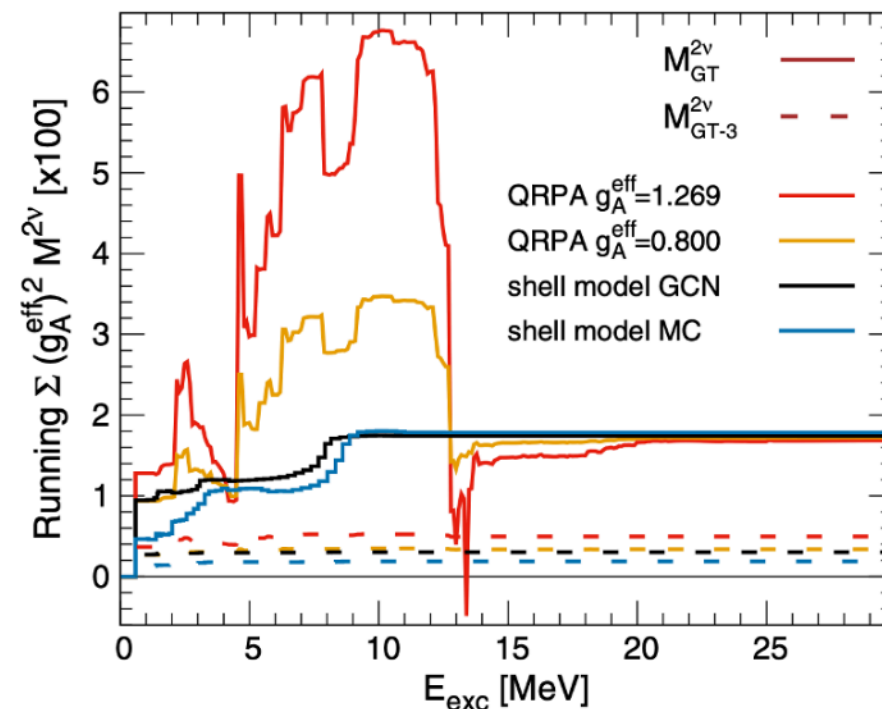
*Brase, Jokiniemi, Kauppinen, Romeo, Kotila, Menéndez, Schwenk,
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DISCREPANCIES IN RUNNING SUMS

$$M^{2\nu} = \sum_k \frac{\langle 0_f^+ \| \sum_j \tau_j^- \sigma_j \| 1_k^+ \rangle \langle 1_k^+ \| \sum_k \tau_k^- \sigma_k \| 0_i^+ \rangle}{E_k - (E_i + E_f)/2}$$



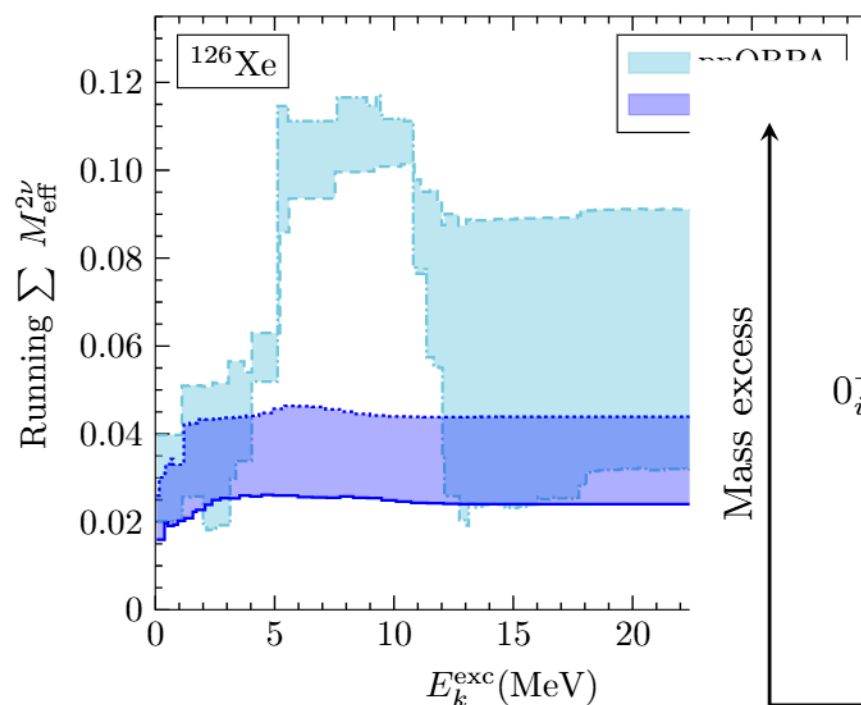
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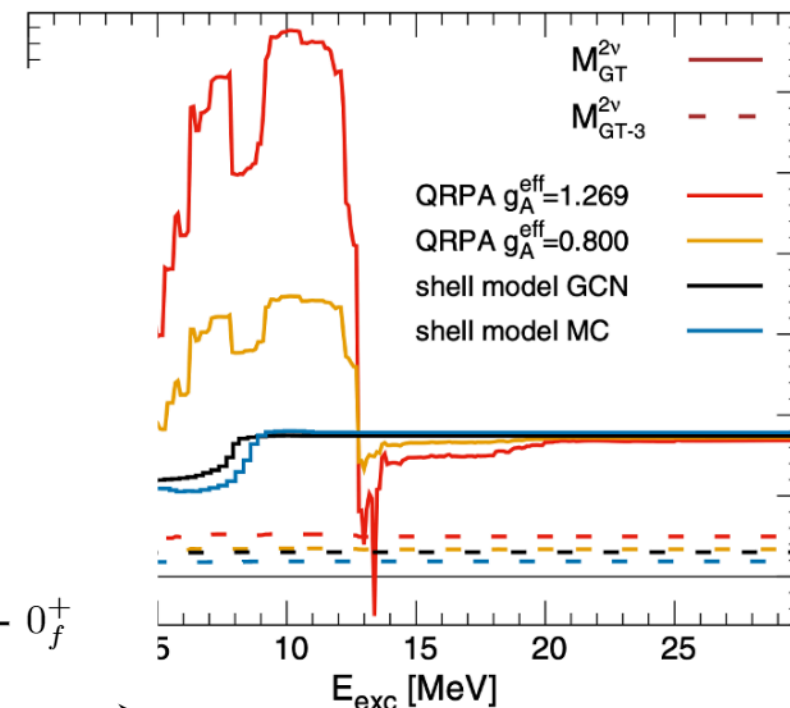
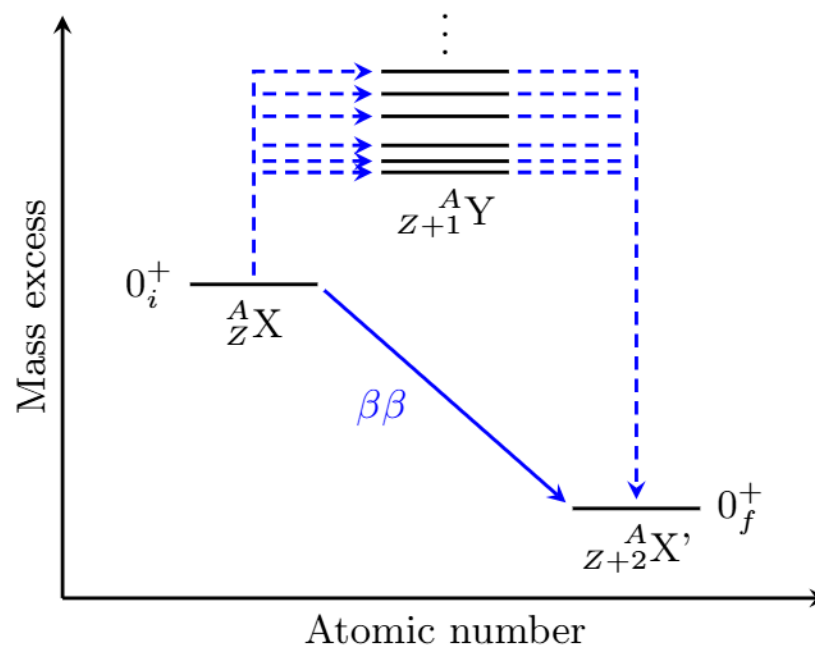
KamLAND-Zen Collaboration, *Phys. Rev. Lett.* 122, 192501 (2019)

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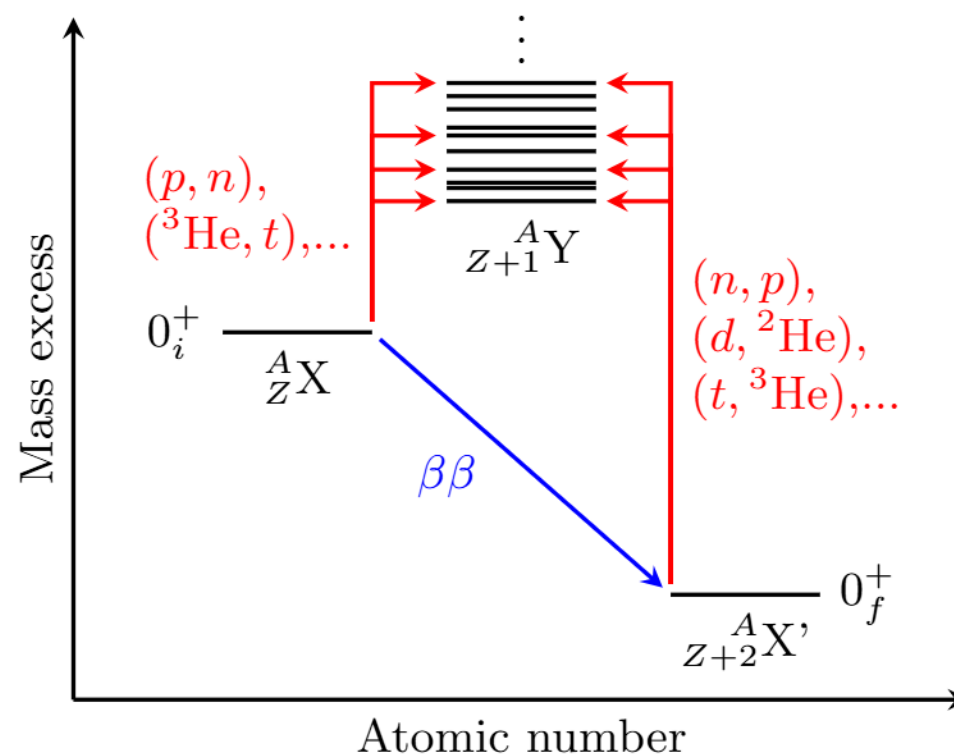


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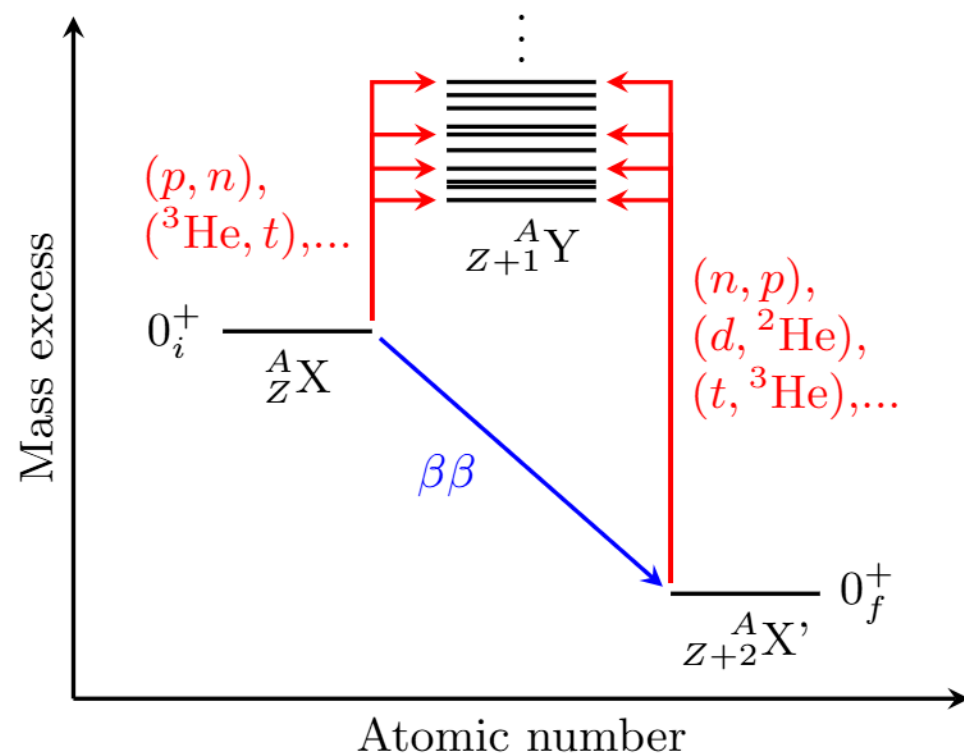
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PROBING $\beta\beta$ DECAYS BY CHARGE-EXCHANGE REACTIONS



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- Charge-exchange reactions can probe **virtual transitions to intermediate states**



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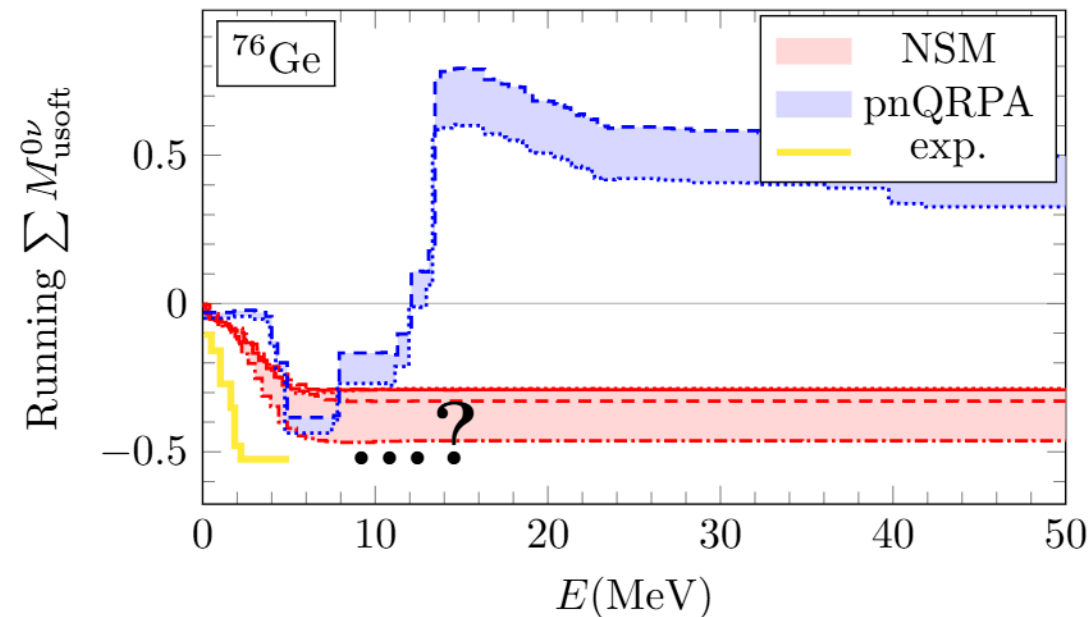
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- Available **data ends at ~ 5 MeV** (except for ^{48}Ca)

$^{76}\text{Ge}(^3\text{He}, t)^{76}\text{As}$:

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Phys. Lett. B 860, 139181 (2025)*

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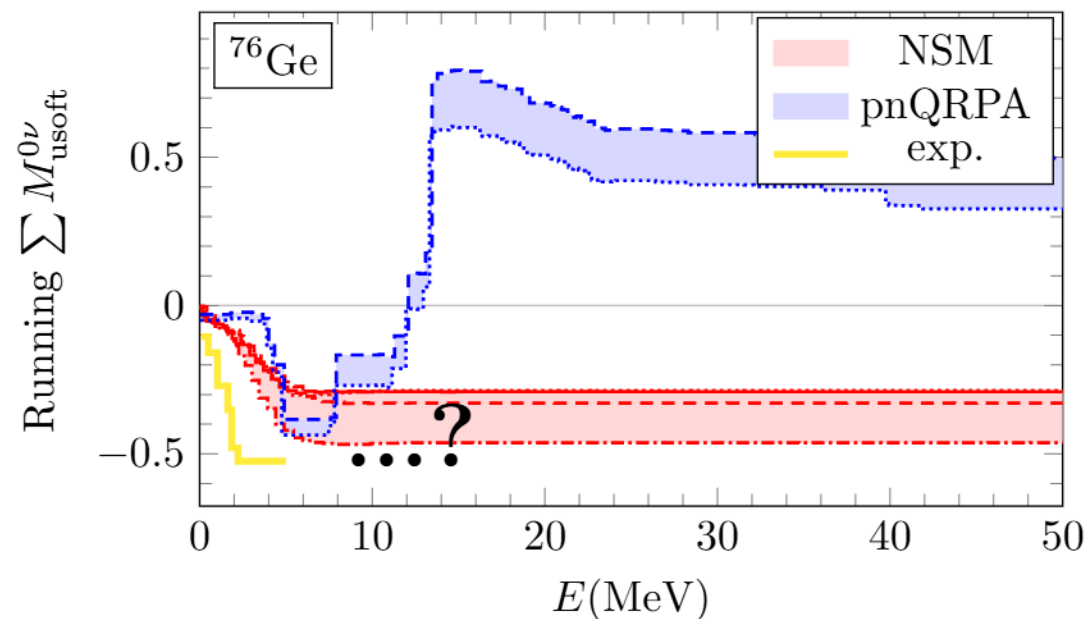
- Charge-exchange reactions can probe **virtual transitions to intermediate states**
- Available **data ends at ~ 5 MeV** (except for ^{48}Ca)
- Measurement of these reactions up to high energies in $\beta\beta$ triplets would also help **benchmark *ab initio* calculations**

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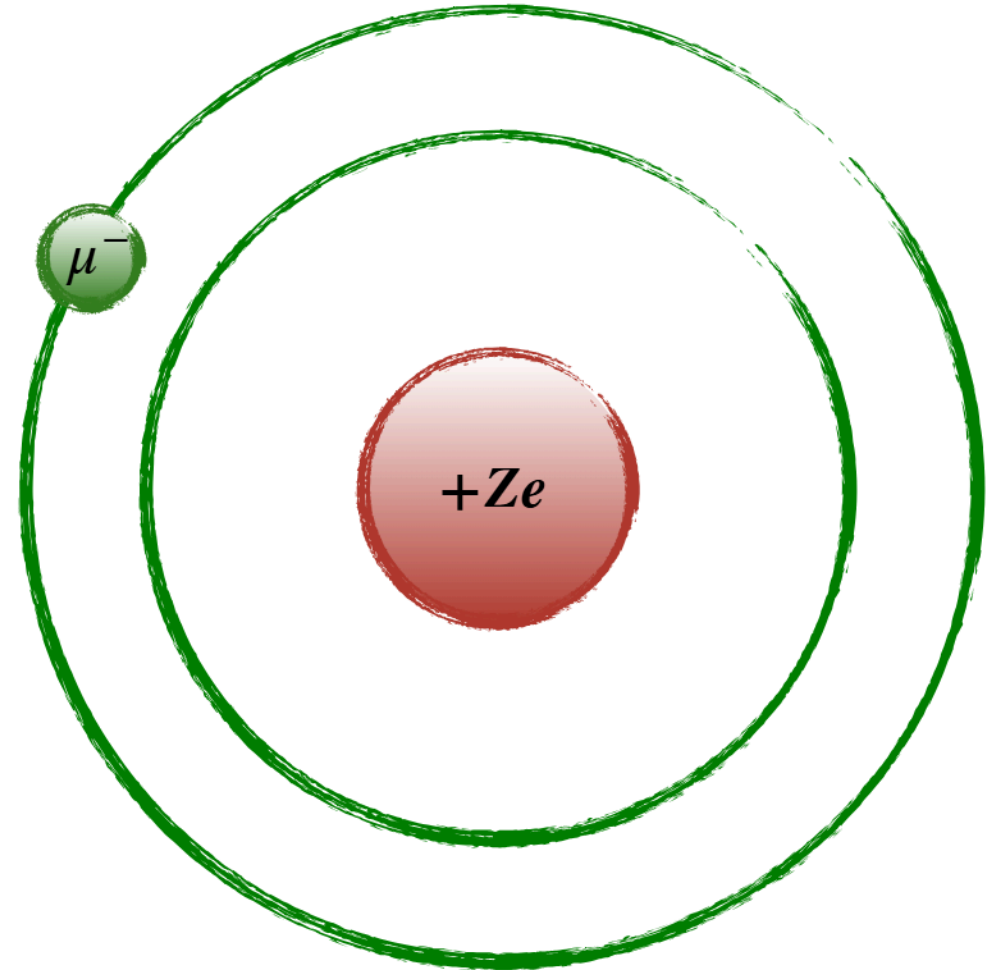


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OUTLINE

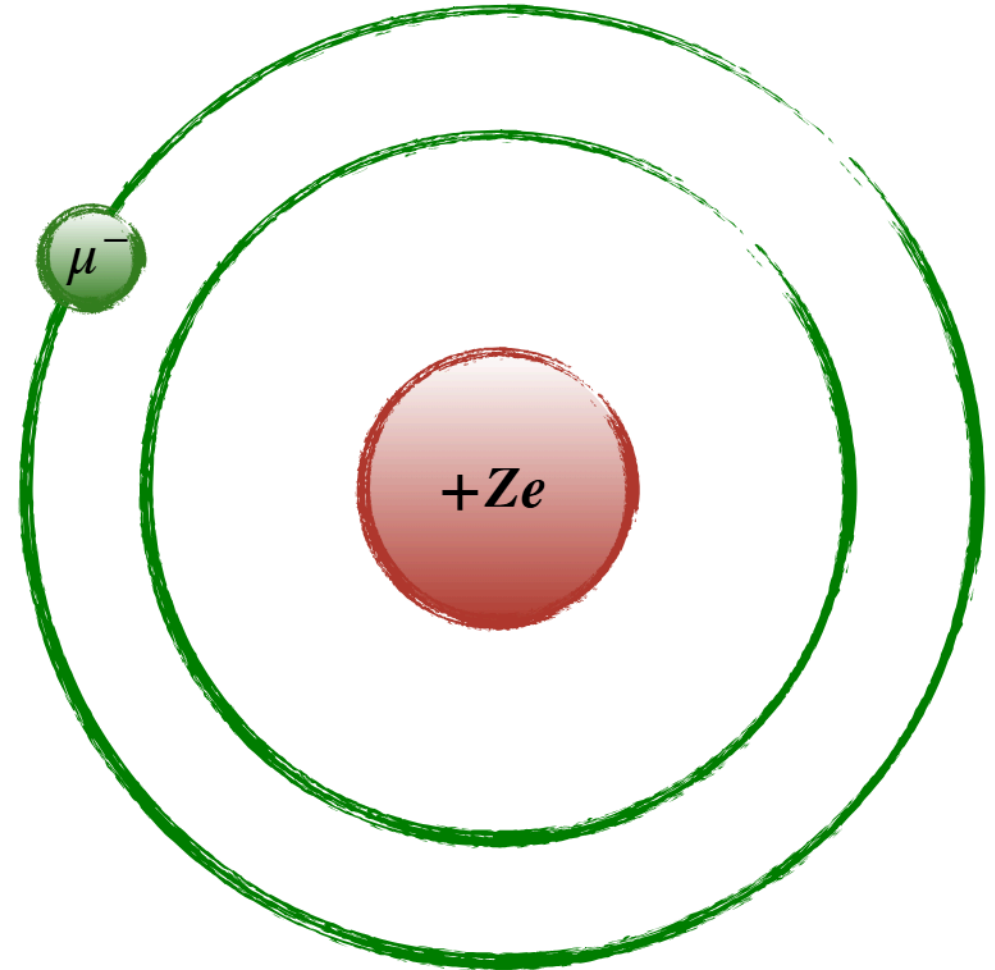
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ORDINARY MUON CAPTURE



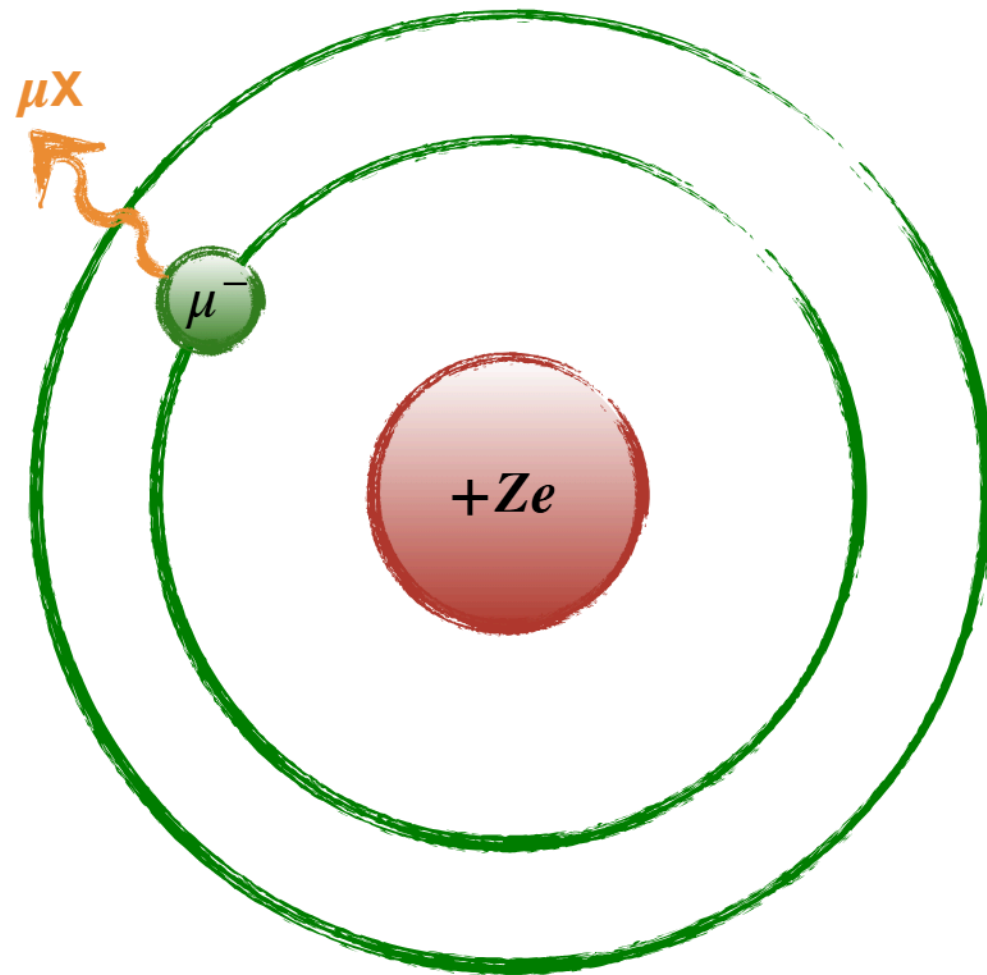
ORDINARY MUON CAPTURE

- Starting point: **a muonic atom**



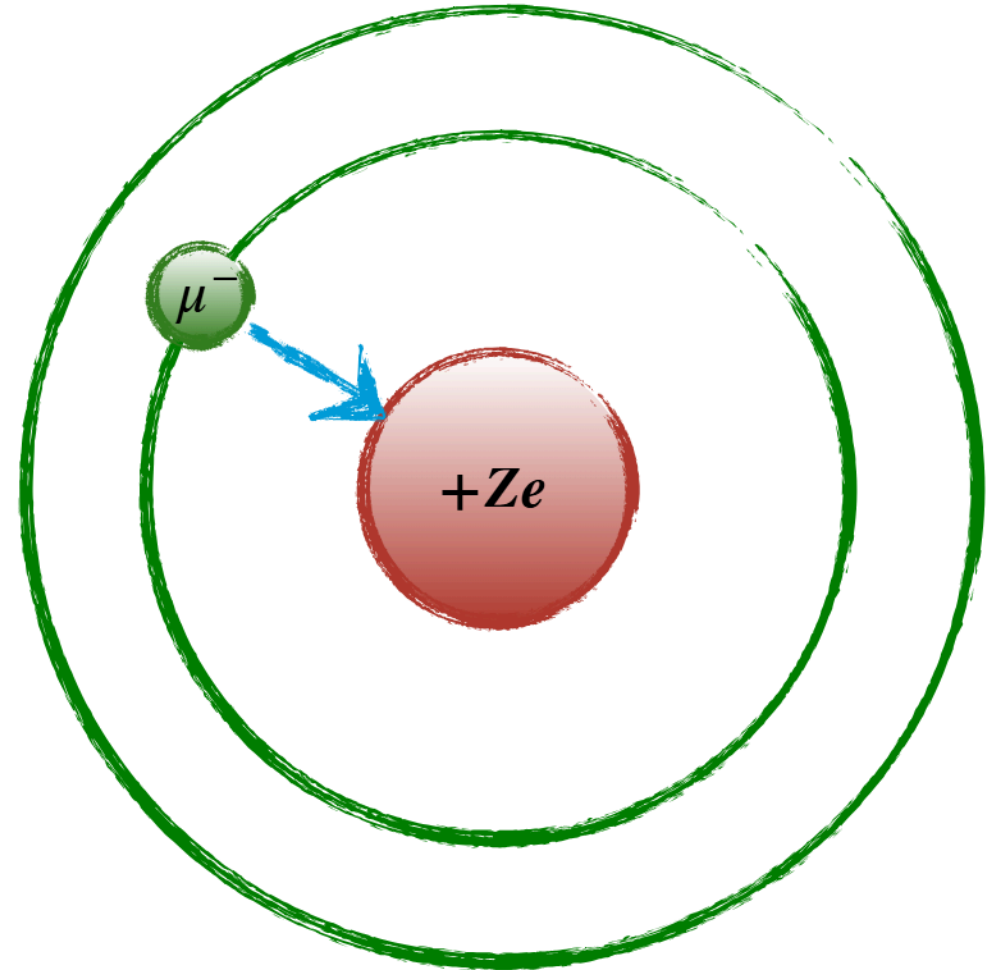
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- Starting point: **a muonic atom**
- The muon quickly transitions to the lowest, **$1s_{1/2}$ orbit**



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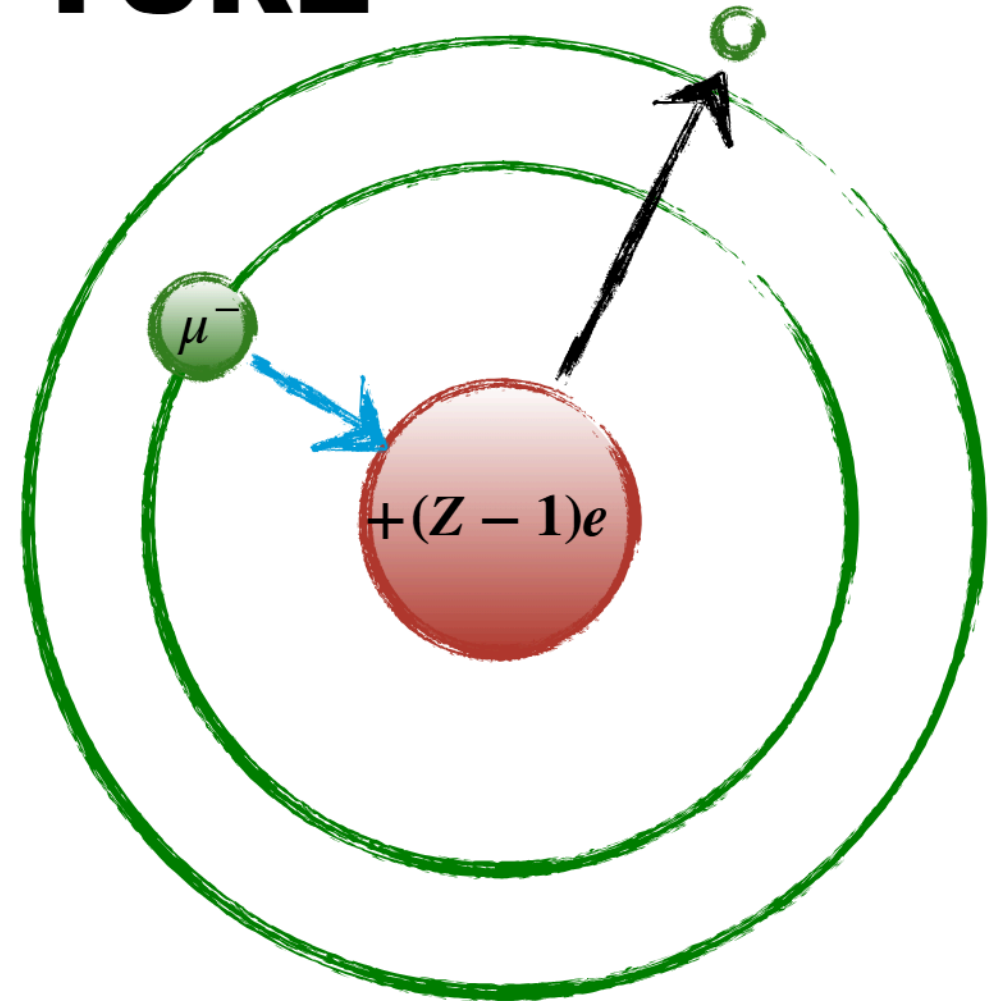
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$$\mu^- + {}^A_Z\text{X}(J_f^{\pi_f}) \rightarrow \nu_\mu + {}^A_{Z-1}\text{Y}(J_i^{\pi_i})$$

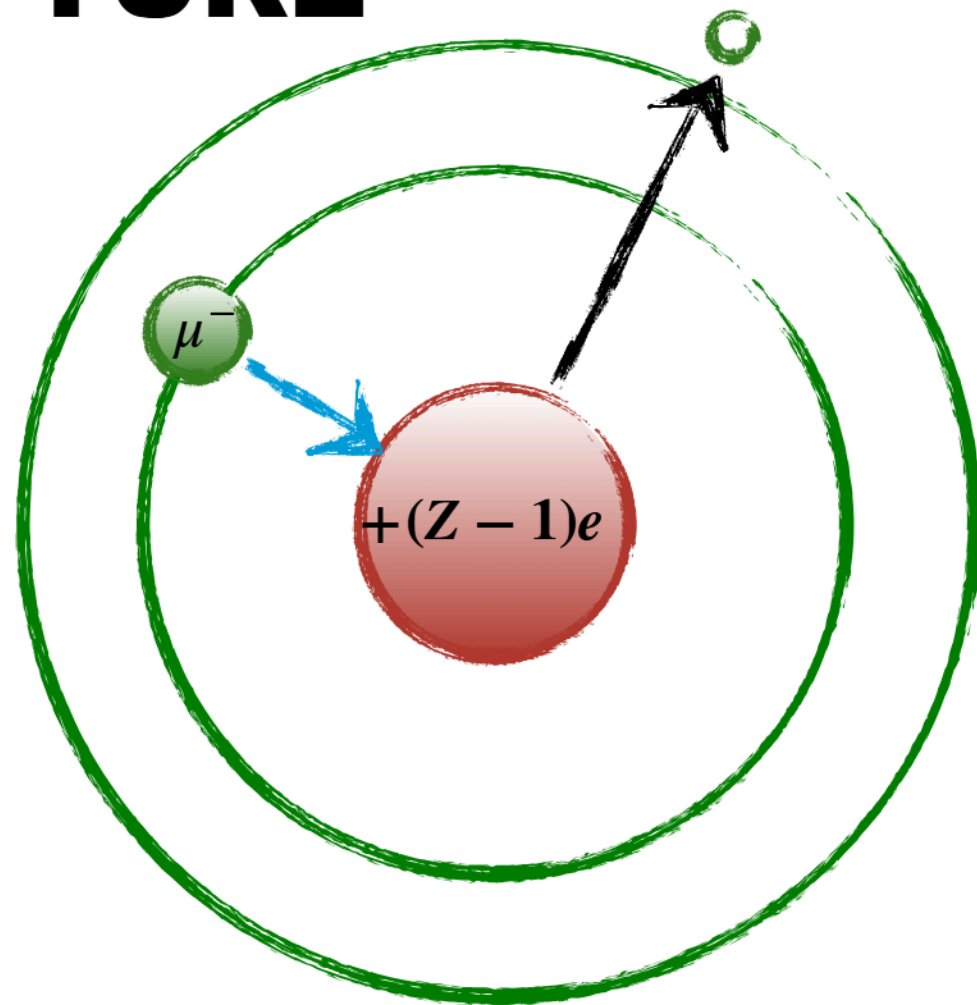


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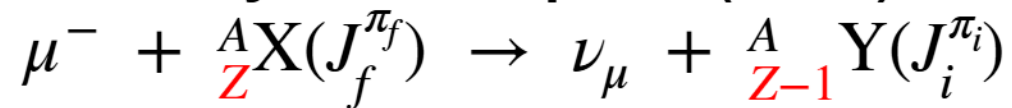
$$\mu^- + {}^A_Z X(J_f^{\pi_f}) \rightarrow \nu_\mu + {}^A_{Z-1} Y(J_i^{\pi_i}) + \gamma$$



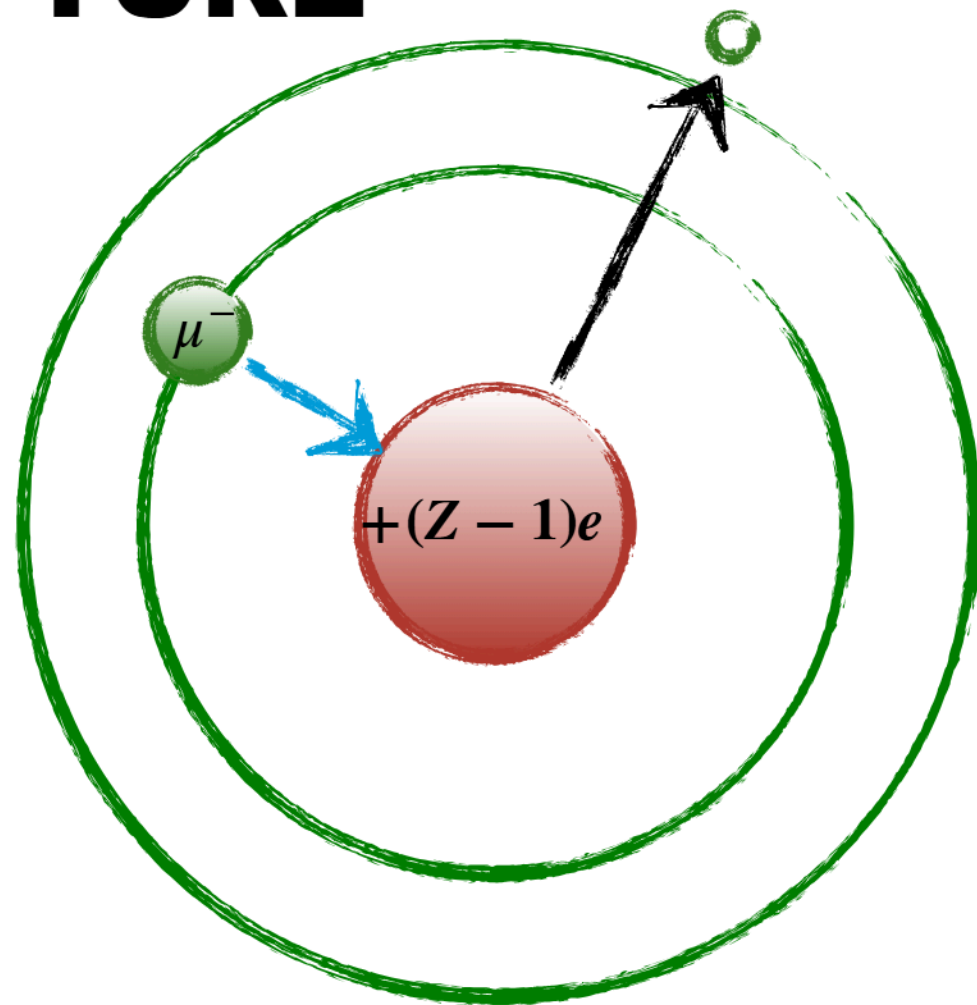
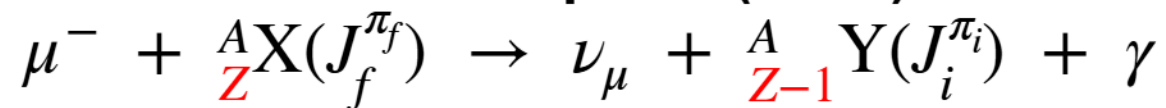
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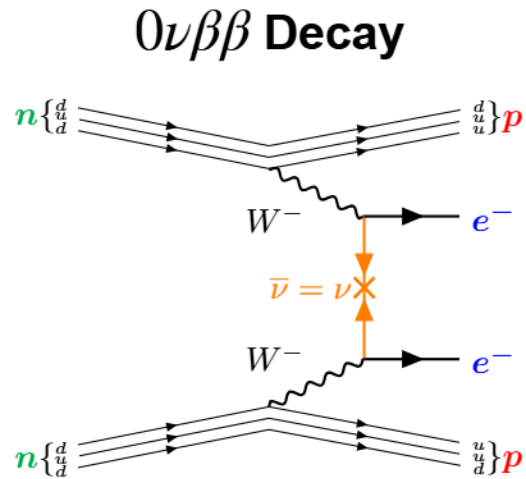
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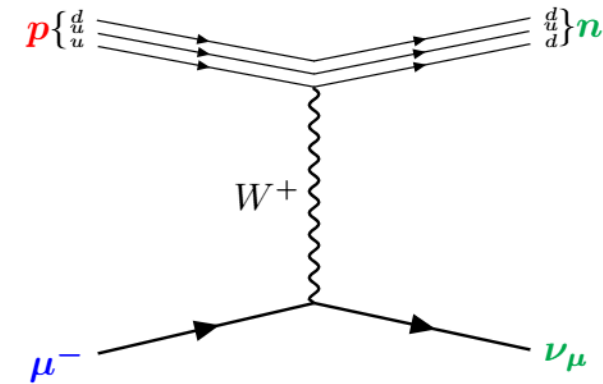
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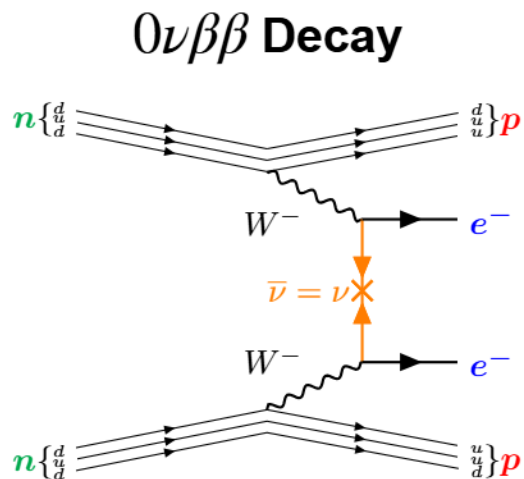
$0\nu\beta\beta$ DECAY VS. ORDINARY MUON CAPTURE



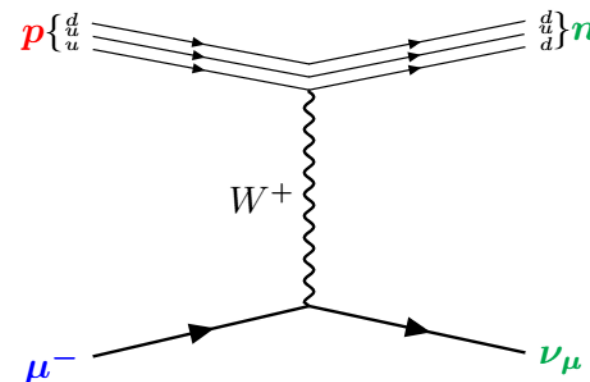
Ordinary Muon Capture



$0\nu\beta\beta$ DECAY VS. ORDINARY MUON CAPTURE

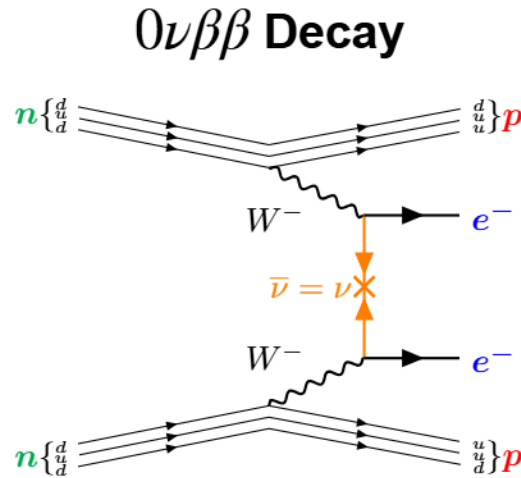


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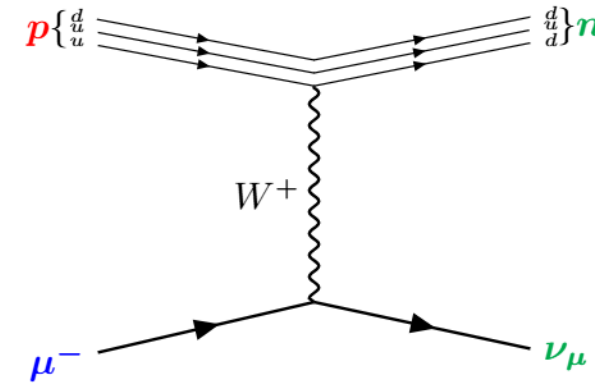
- $q \approx 1/|\mathbf{r}_1 - \mathbf{r}_2| \approx 100 - 200 \text{ MeV}$

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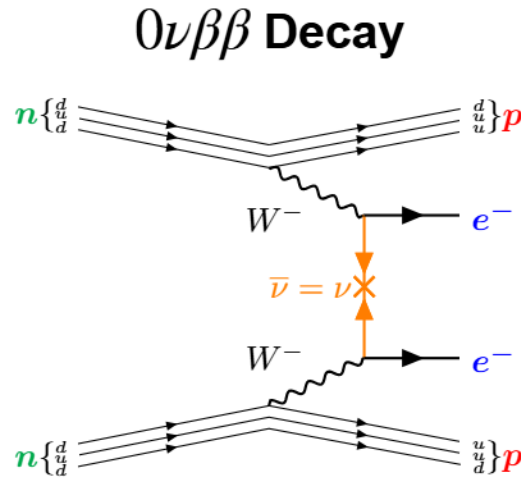
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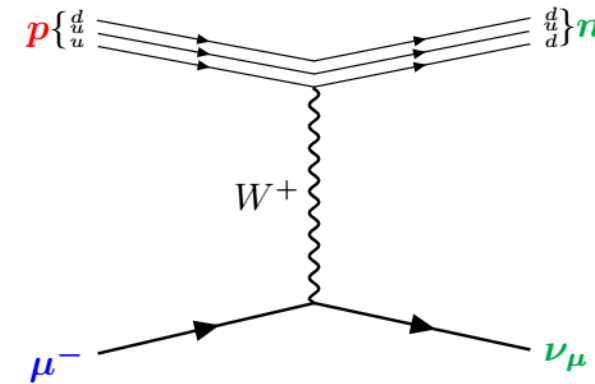
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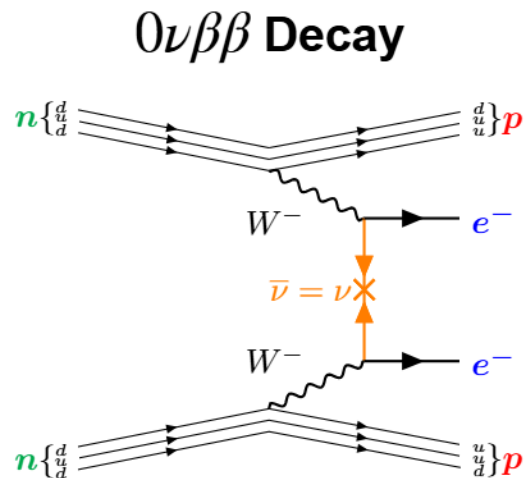
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- **No experimental signal so far**

Ordinary Muon Capture



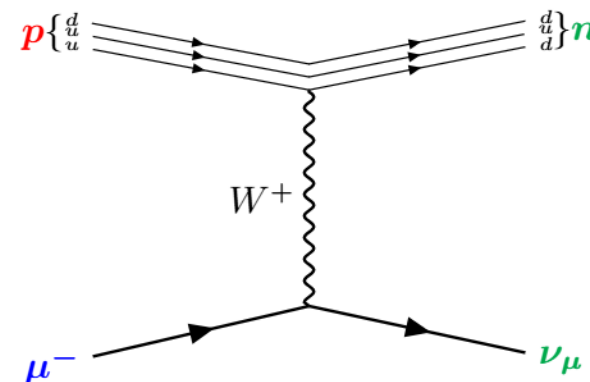
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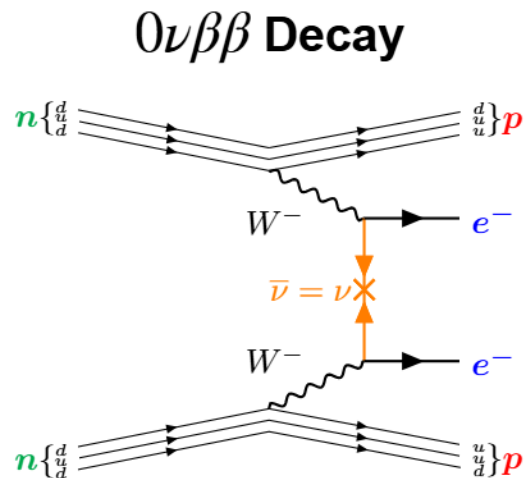
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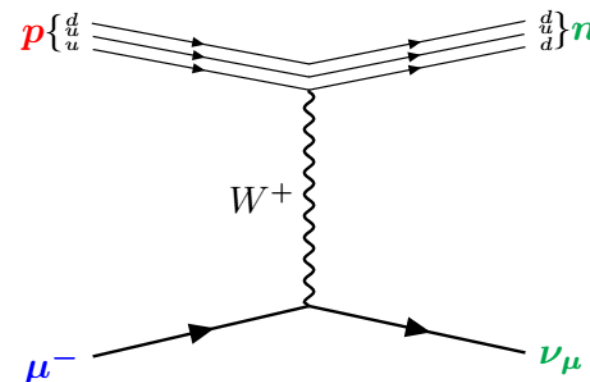


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$0\nu\beta\beta$ DECAY VS. ORDINARY MUON CAPTURE



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$$j^{\alpha\dagger} = \bar{\Psi} [g_V(\mathbf{q}^2)\gamma^\alpha + ig_M(\mathbf{q}^2)\frac{\sigma^{\alpha\beta}}{2M}q_\beta - g_A(\mathbf{q}^2)\gamma^\alpha\gamma_5 - g_P(\mathbf{q}^2)q^\alpha\gamma_5] \Psi$$

MONUMENT (OMC4DBD) EXPERIMENT @ PSI

Eur. Phys. J. C (2024) 84:1188
<https://doi.org/10.1140/epjc/s10052-024-13470-6>

THE EUROPEAN
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Regular Article

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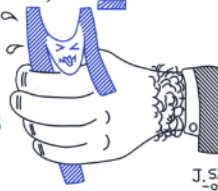
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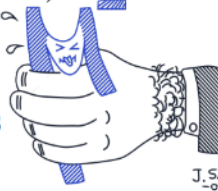
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- Aim 1: Measure OMC in $\beta\beta$ -decay nuclei



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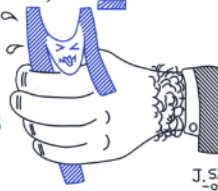
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- **Aim 1:** Measure OMC in $\beta\beta$ -decay nuclei
- **Aim 2:** Measure **partial** and **total** OMC rates in light nuclei accessible by *ab initio* nuclear theory



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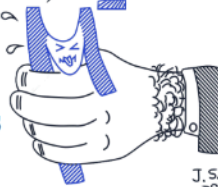
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Experimental Physics

The MONUMENT experiment: ordinary muon capture studies for $0\nu\beta\beta$ decay

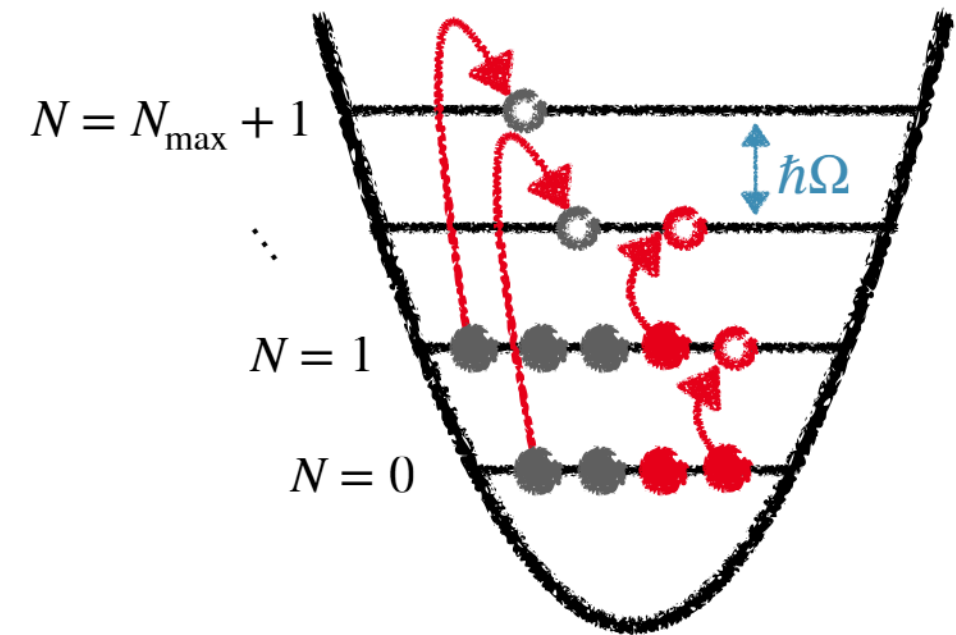


G. R. Araujo¹, D. Bajpai², L. Baudis¹, V. Belov^{4,5}, E. Bossio^{5,6,a}, T. E. Cocolios⁷, H. Ejiri⁸, M. Fomina⁴, K. Gusev^{4,5}, I. H. Hashim⁹, M. Heines⁷, S. Kazartsev⁴, A. Knecht¹⁰, E. Mondragón^{5,b}, Z. W. Ng⁹, I. Ostrovskiy^{2,3}, F. Othman⁹, N. Rumyantseva^{4,5}, S. Schönert⁵, M. Schwarz⁵, E. Shevchik⁴, M. Shirchenko⁴, Yu. Shitov¹¹, E. O. Sushenok⁴, J. Suhonen^{12,13}, S. M. Vogiatzi¹⁰, C. Wiesinger⁵, I. Zhitnikov⁴, D. Zinatulina⁴

- **Aim 1:** Measure OMC in $\beta\beta$ -decay nuclei
- **Aim 2:** Measure **partial** and **total** OMC rates in light nuclei accessible by *ab initio* nuclear theory



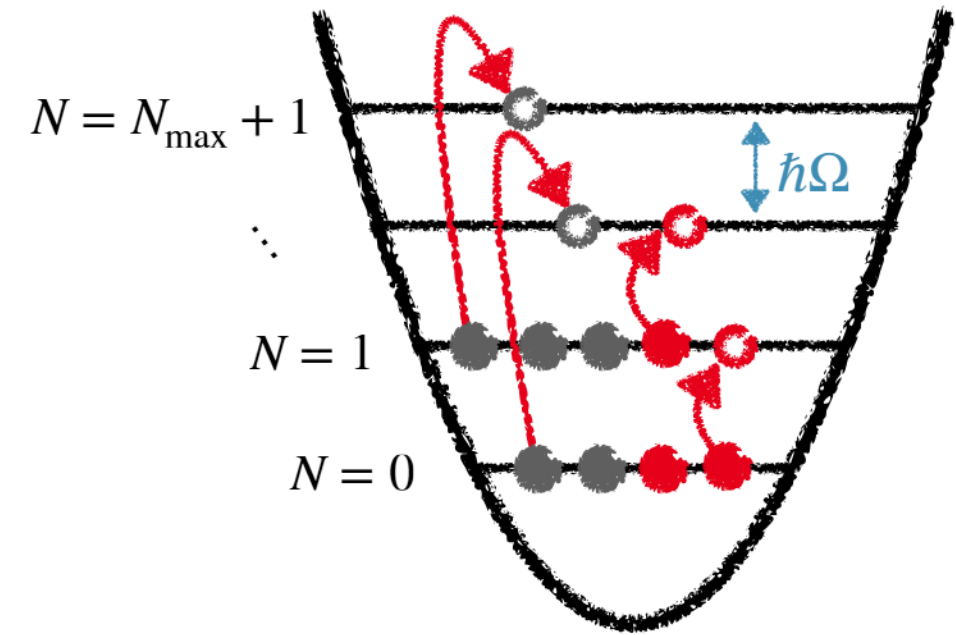
NO-CORE SHELL MODEL (NCSM)



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- Solve the nuclear many-body problem

$$H^{(A)}\Psi^{(A)}(\mathbf{r}_1, \mathbf{r}_2, \dots, \mathbf{r}_A) = E^{(A)}\Psi^{(A)}(\mathbf{r}_1, \mathbf{r}_2, \dots, \mathbf{r}_A)$$



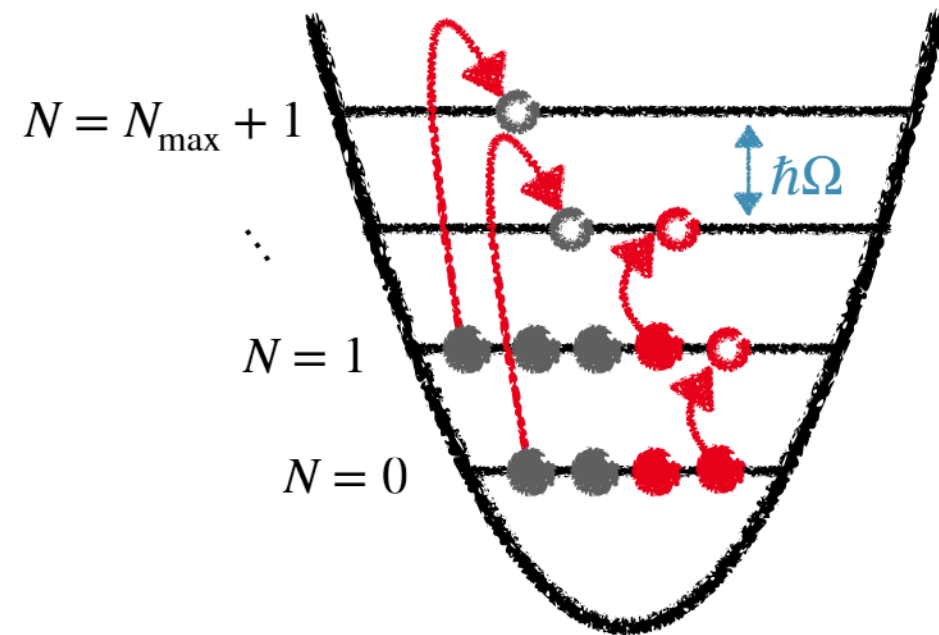
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- **Two- (NN)** and **three-body (3N)** forces from χ EFT:

$$H^{(A)} = \sum_{i=1}^A \frac{p_i^2}{2m} + \sum_{i<j=1}^A V_{ij}^{\text{NN}}(\mathbf{r}_i - \mathbf{r}_j) + \sum_{i<j<k=1}^A V_{ijk}^{\text{3N}}$$



NO-CORE SHELL MODEL (NCSM)

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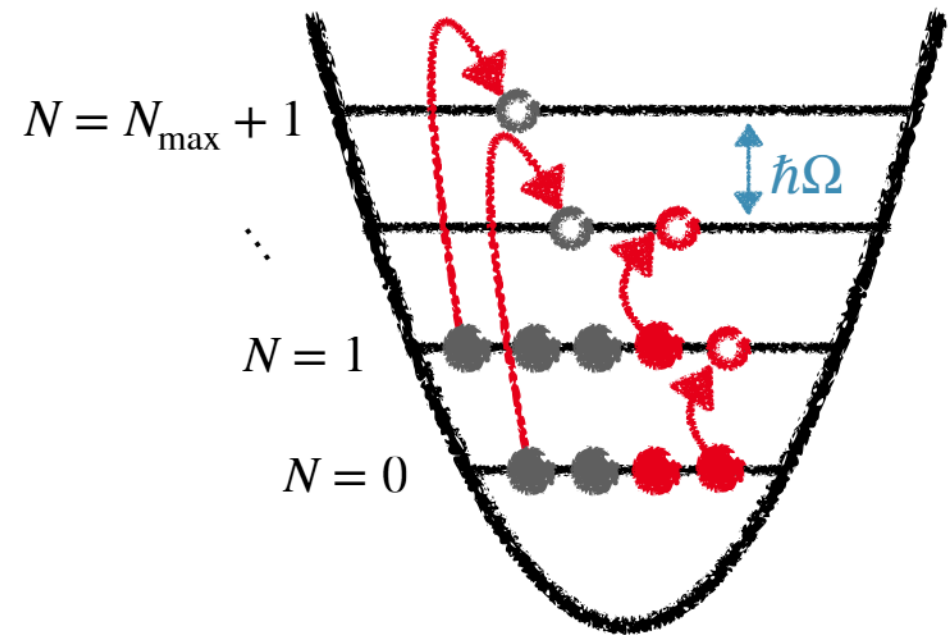
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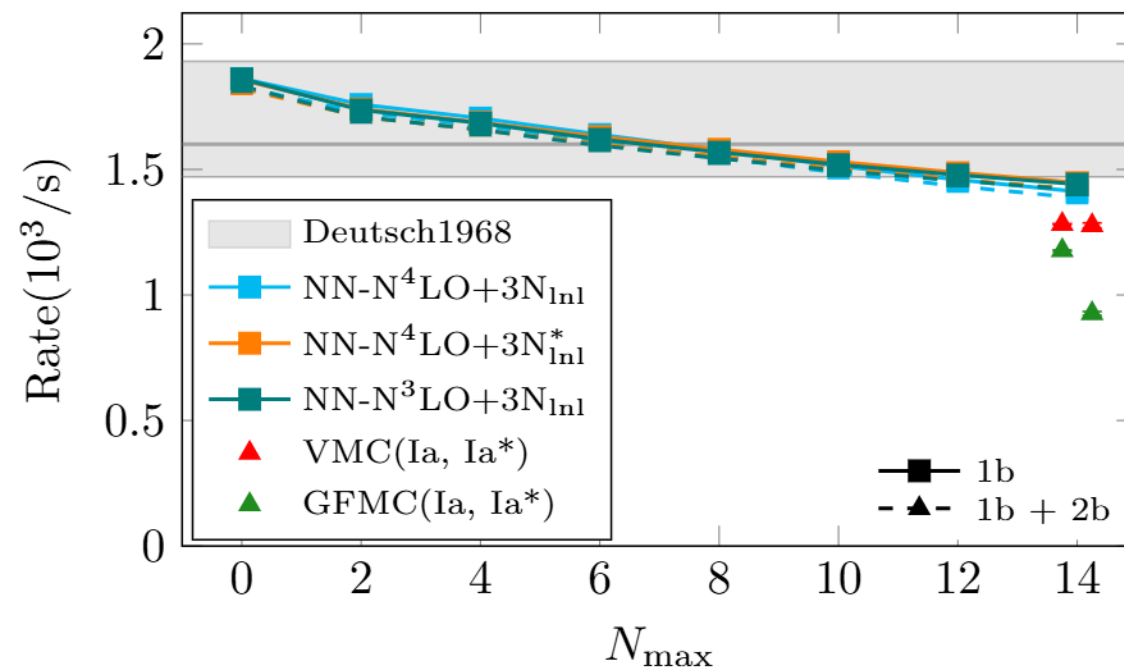
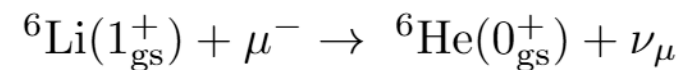
$$H^{(A)} = \sum_{i=1}^A \frac{p_i^2}{2m} + \sum_{i<j=1}^A V_{ij}^{\text{NN}}(\mathbf{r}_i - \mathbf{r}_j) + \sum_{i<j<k=1}^A V_{ijk}^{\text{3N}}$$

- Expansion in Harmonic Oscillator (HO) basis:

$$\Psi^{(A)} = \sum_{N=0}^{N_{\max}} \sum_j = c_{Nj} \Phi_{Nj}^{\text{HO}}(\mathbf{r}_1, \mathbf{r}_2, \dots, \mathbf{r}_A)$$

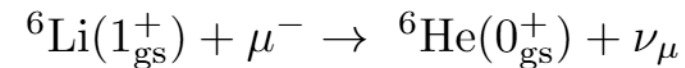


MUON CAPTURE ON ${}^6\text{Li}$

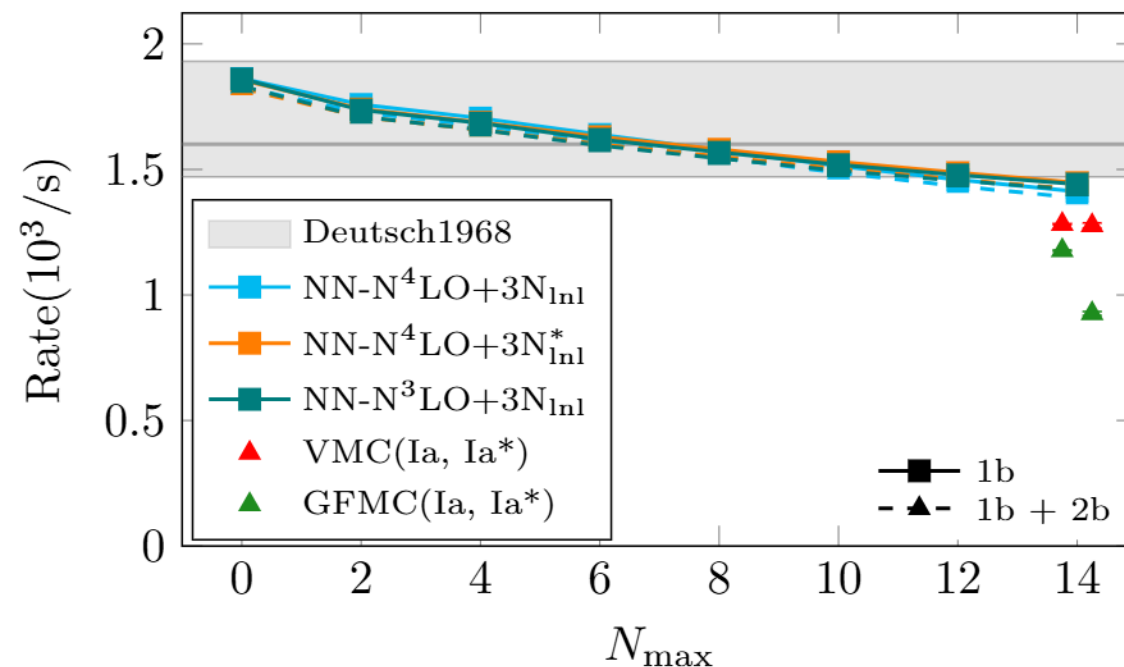


*LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C
109, 065501 (2024)*

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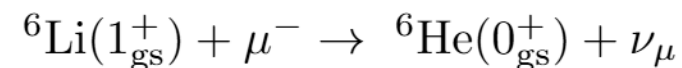


- No-core shell model slightly underestimates the experiment



*LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C
109, 065501 (2024)*

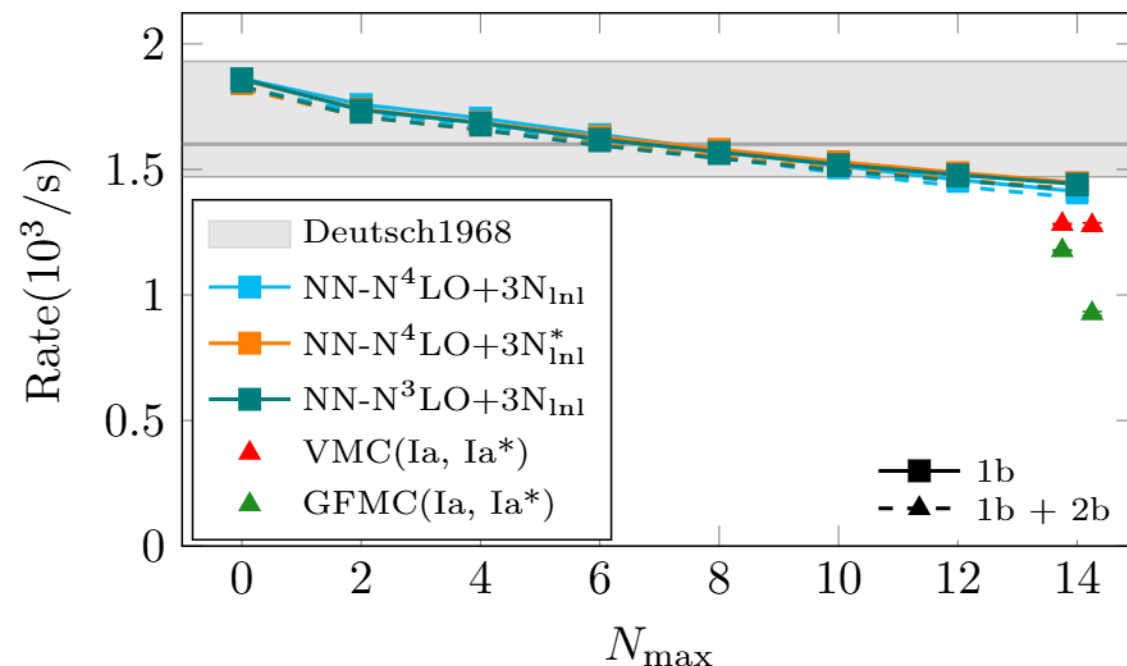
MUON CAPTURE ON ${}^6\text{Li}$



- No-core shell model slightly underestimates the experiment
- Results consistent with other *ab initio* methods:

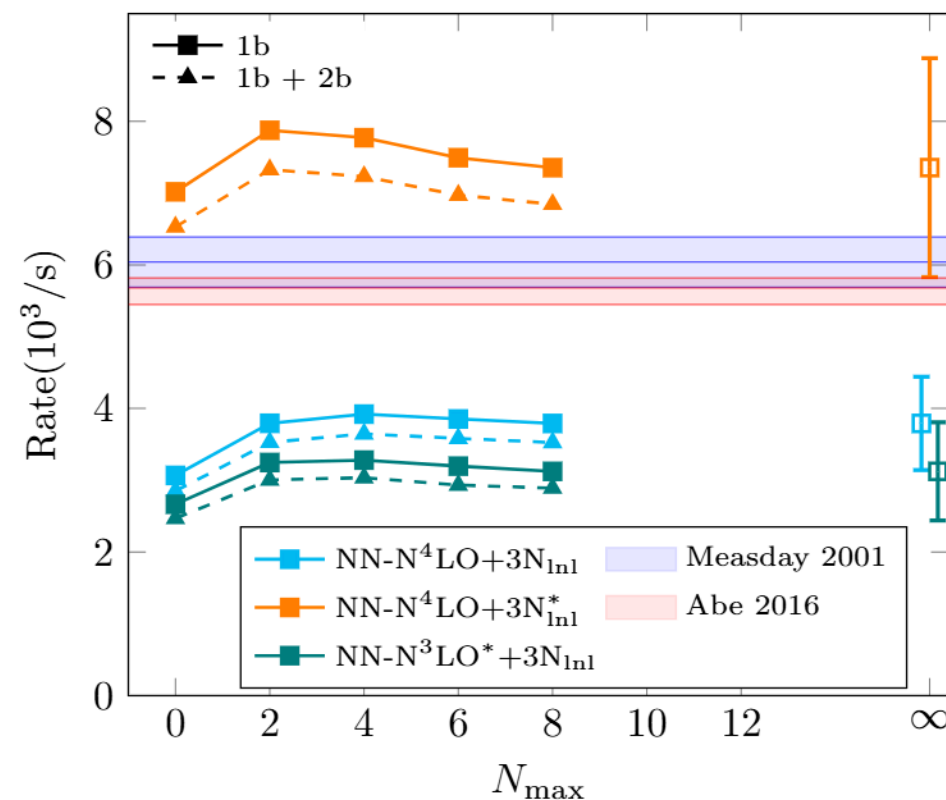
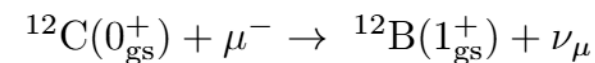
Variational Monte Carlo (VMC) and
Green's Function Monte Carlo (GFMC)

G. B. King et al., Phys. Rev. C 105, L042501 (2022)



LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C 109, 065501 (2024)

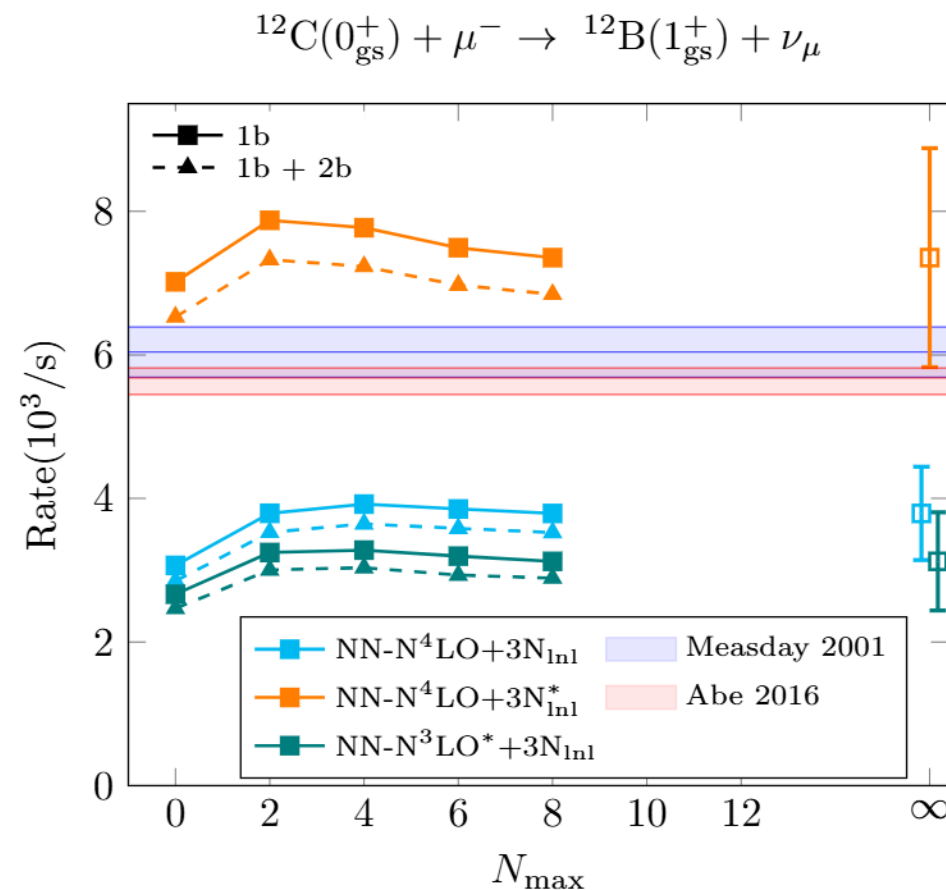
MUON CAPTURE ON ^{12}C



*LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C
109, 065501 (2024)*

MUON CAPTURE ON ^{12}C

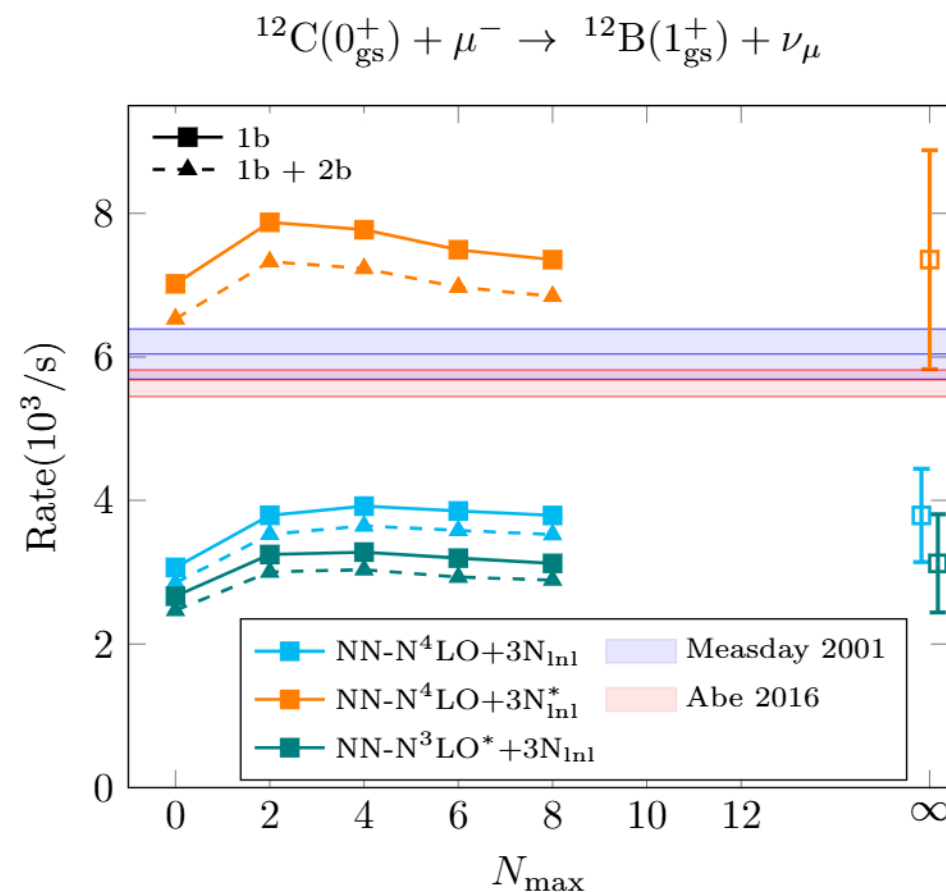
- Significant interaction dependence



LJ, P. Navrátil, J. Kotila, K. Kravvaris, *Phys. Rev. C*
109, 065501 (2024)

MUON CAPTURE ON ^{12}C

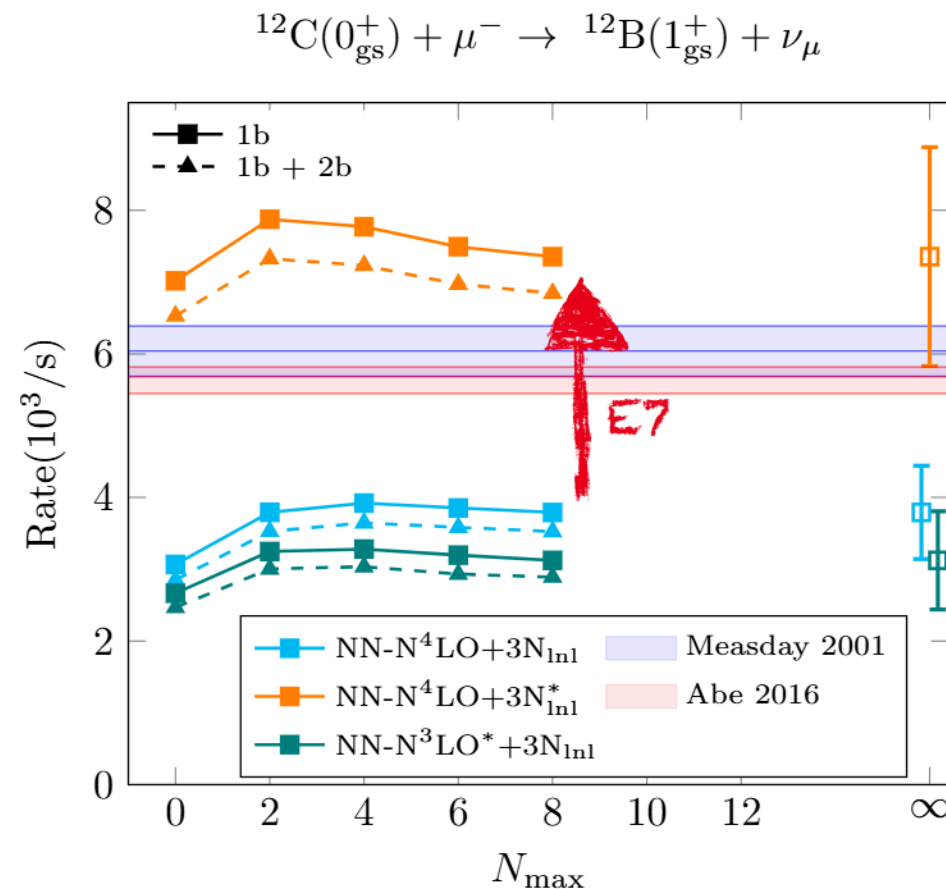
- Significant interaction dependence
 - The $\text{NN} - \text{N}^4\text{LO} + 3\text{N}_{\text{Inl}}^*$ interaction with the subleading 3N term (E7) most consistent with experiments
Girlanda, Kievsky, Viviani, Phys. Rev. C 84, 014001 (2011)



LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C 109, 065501 (2024)

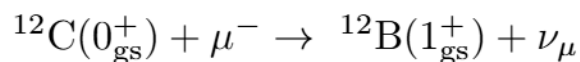
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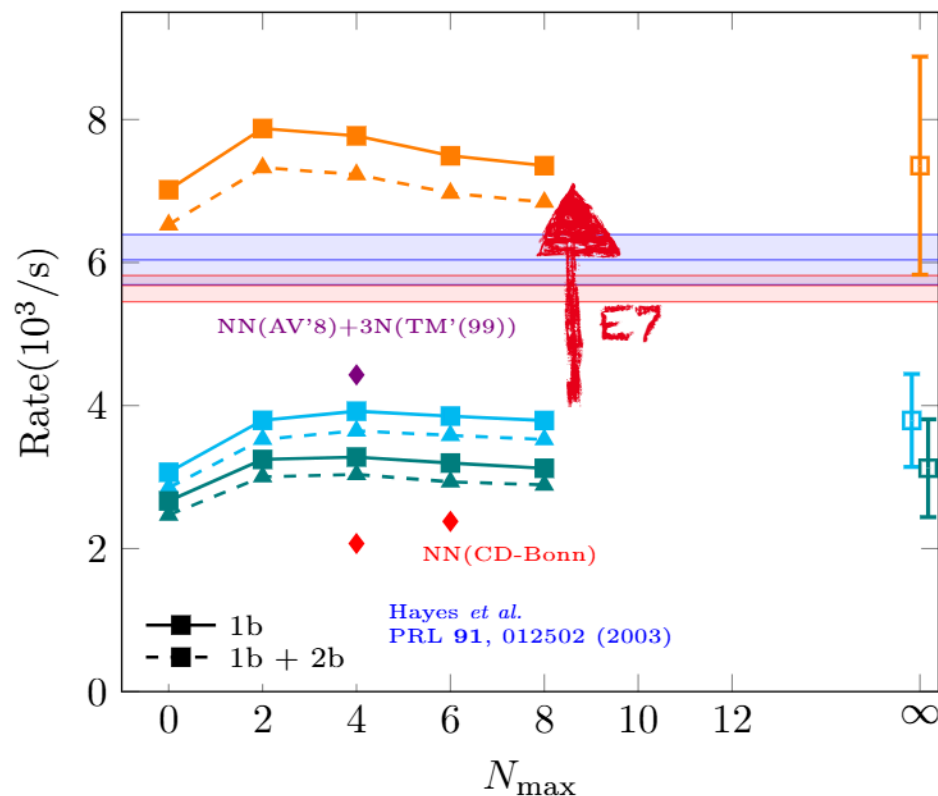


LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C 109, 065501 (2024)

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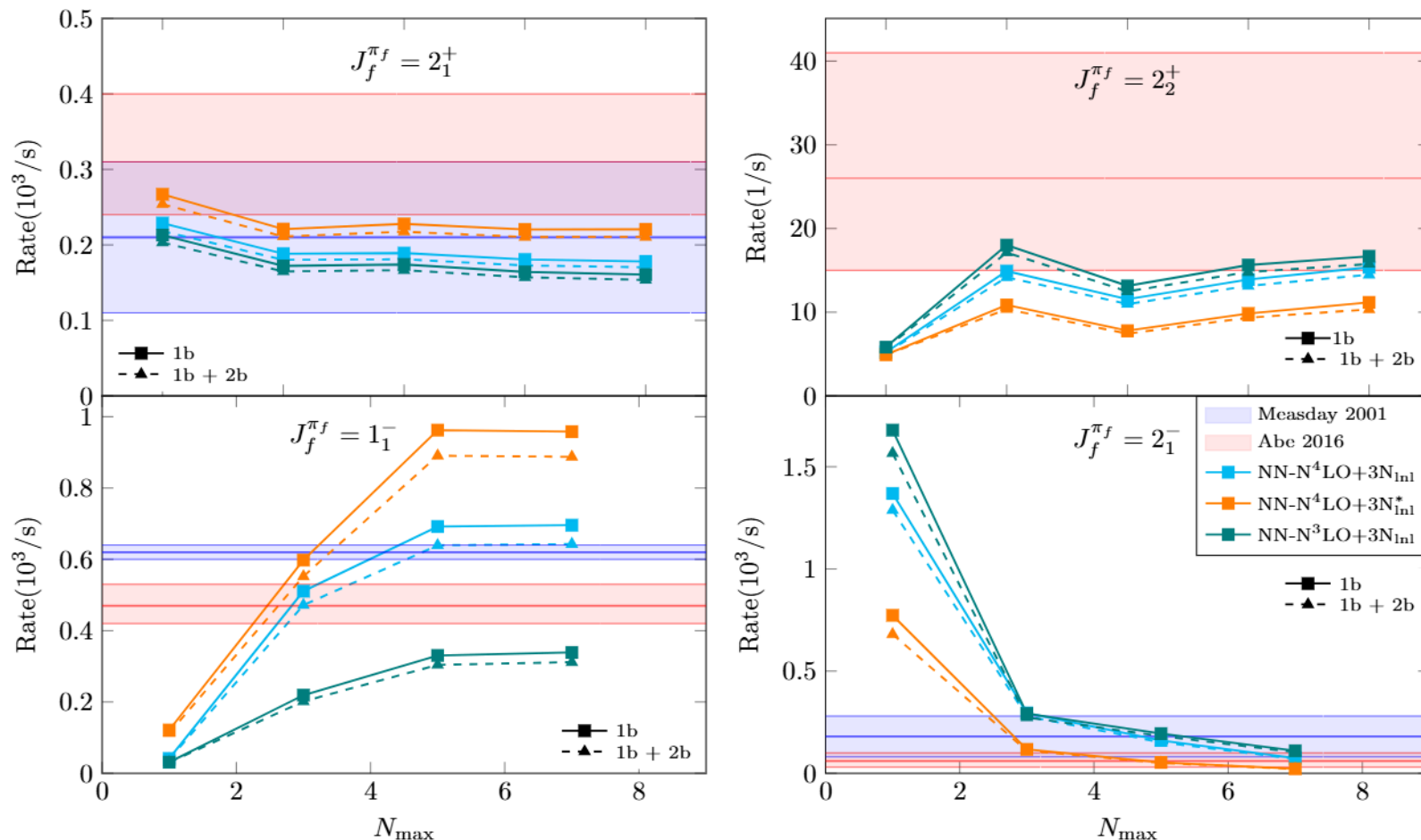


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Girlanda, Kievsky, Viviani, Phys. Rev. C 84, 014001 (2011)
- 3-body forces essential to reproduce the measured rate



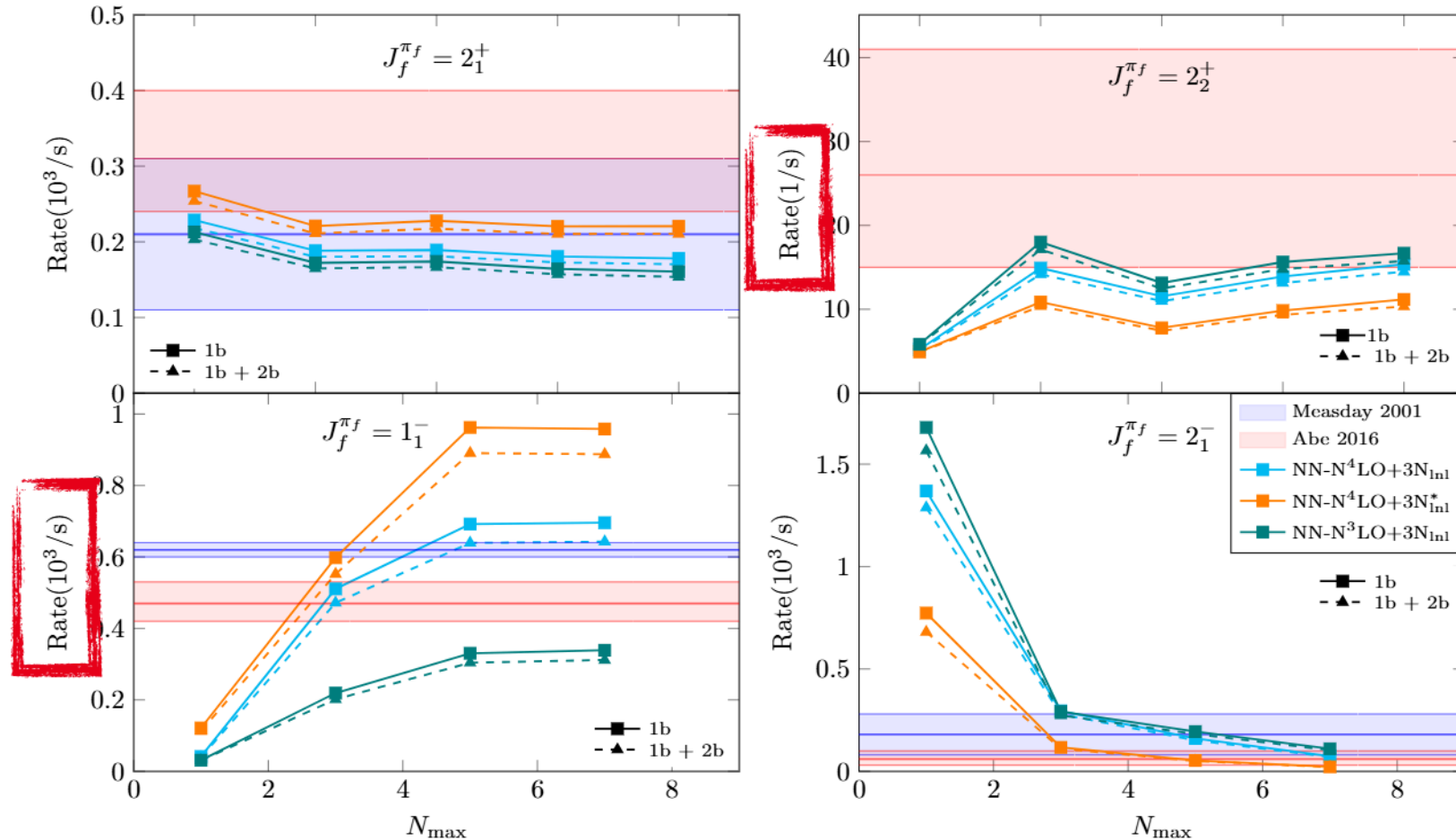
LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C 109, 065501 (2024)

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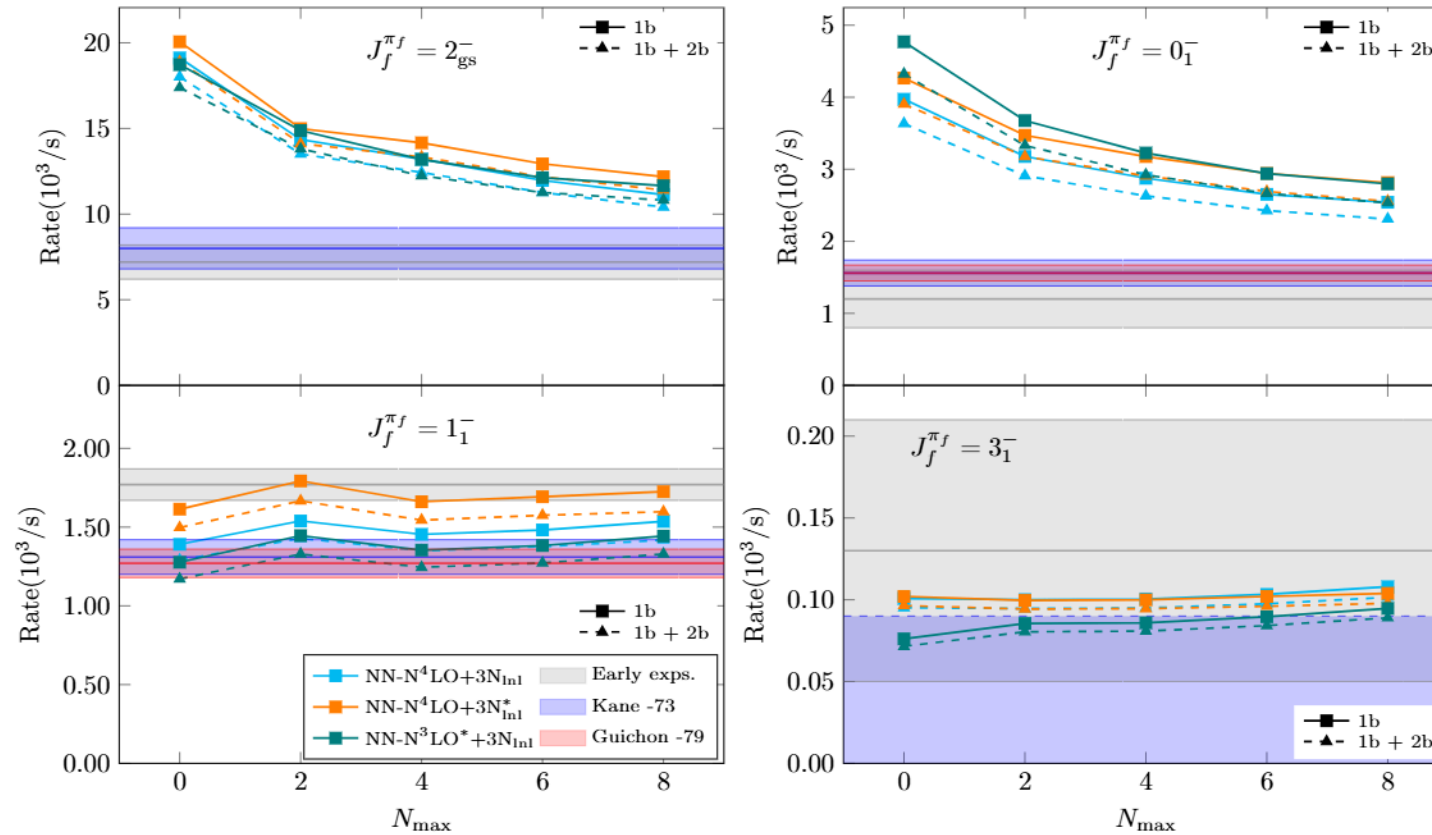
LJ, P. Navrátil, J. Kotila, K. Kravvaris, *Phys. Rev. C* 109, 065501 (2024)

MUON CAPTURE ON ^{12}C



LJ, P. Navrátil, J. Kotila, K. Kravvaris, *Phys. Rev. C* 109, 065501 (2024)

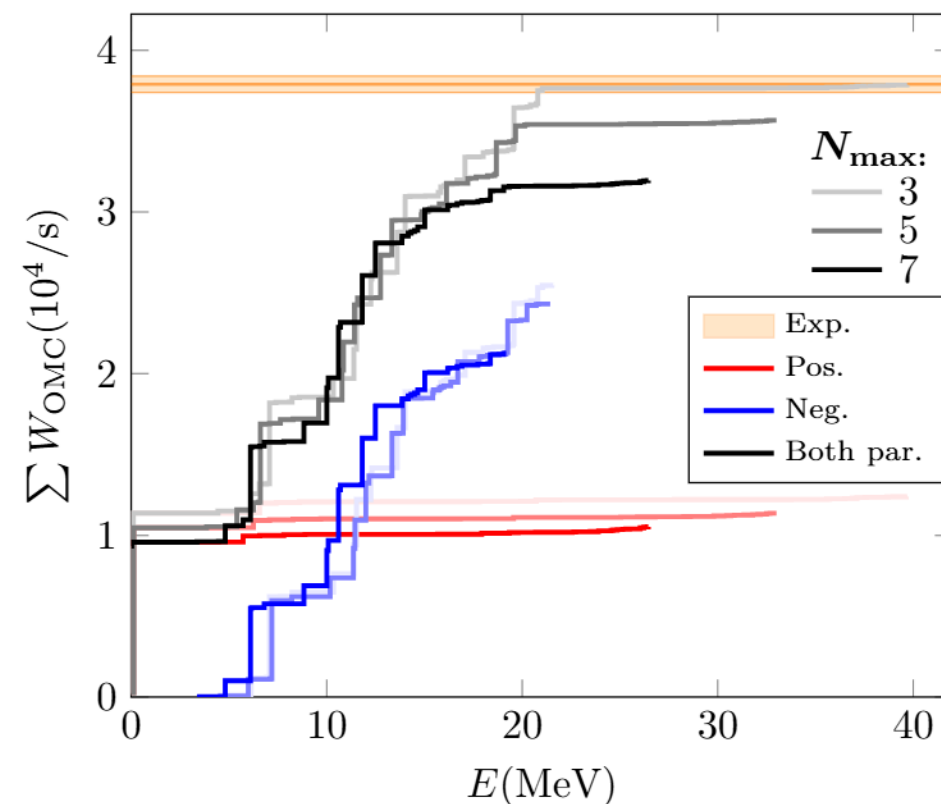
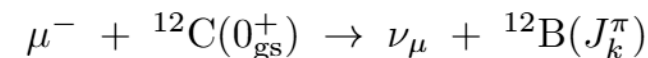
MUON CAPTURE ON ^{16}O



LJ, P. Navrátil, J. Kotila, K. Kravvaris, *Phys. Rev. C* 109, 065501 (2024)

TOTAL MUON CAPTURE RATES

$$W_{\text{tot.}} = \sum_f W(i \rightarrow f)$$

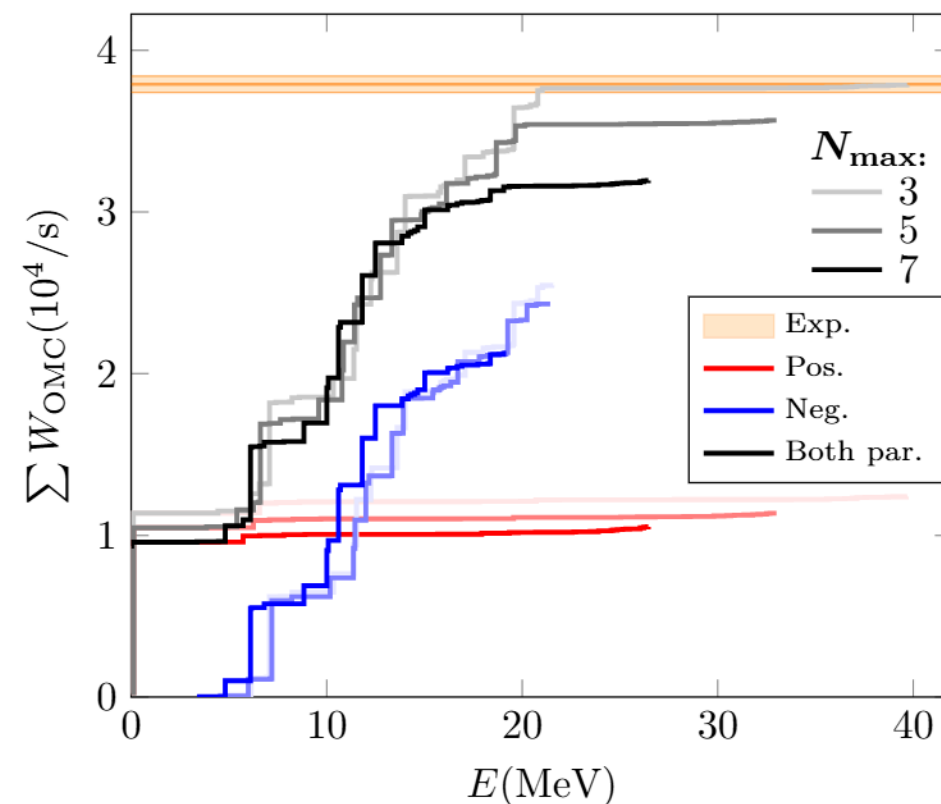
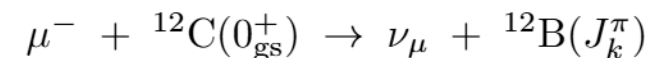


*LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C
109, 065501 (2024)*

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- Rates obtained by summing over **~50 final states of each parity**

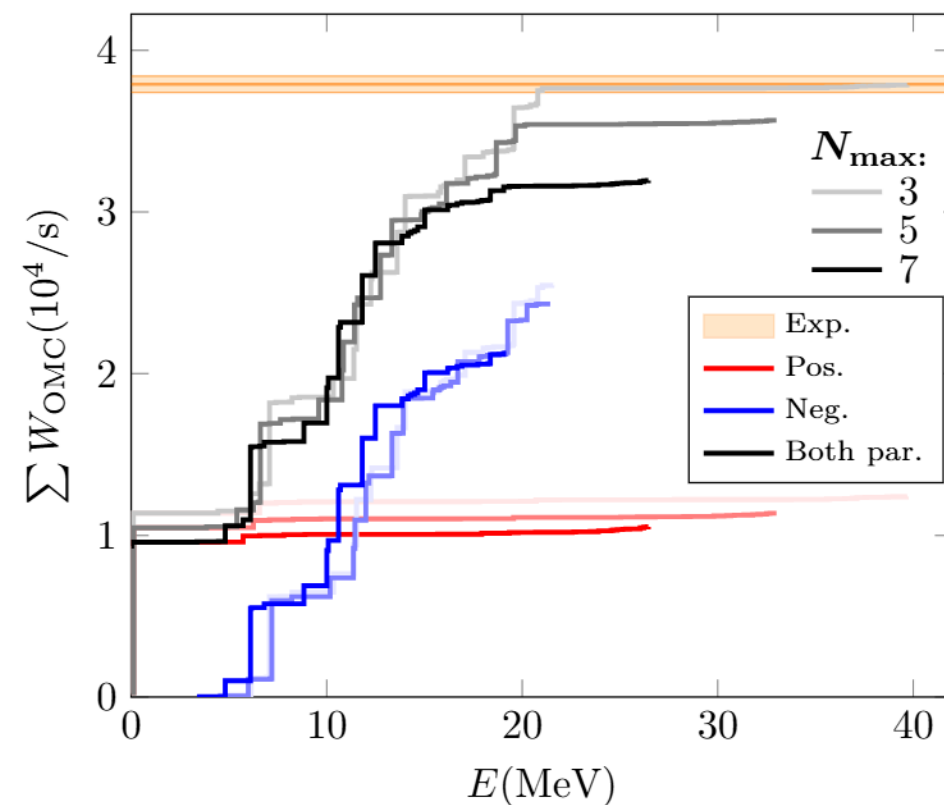
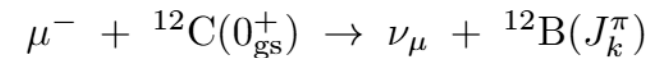


*LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C
109, 065501 (2024)*

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- Rates obtained by summing over **~50 final states of each parity**
- Summing up the rates up to ~20 MeV, we capture **~85% of the total rate** in both ^{12}C and ^{16}N

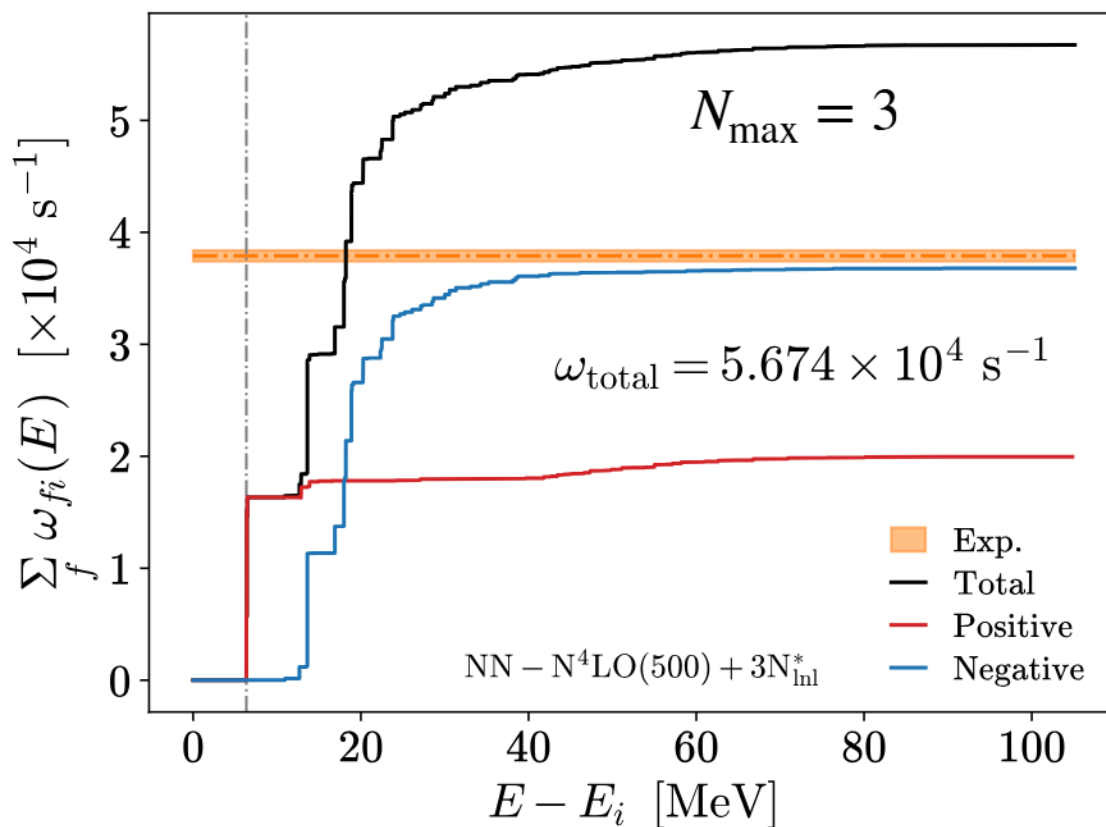


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- **Better estimation of the total rates using the Lanczos strength function method underway**



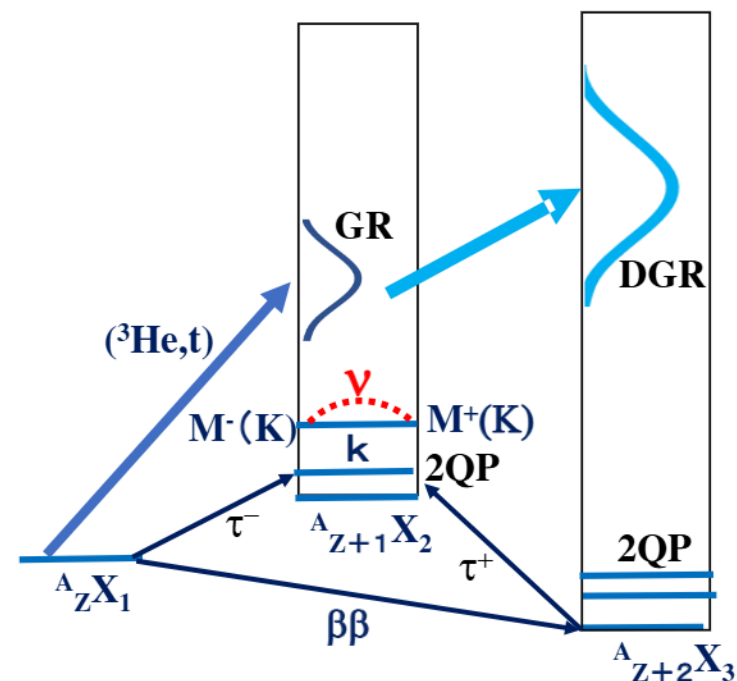
*D. Araujo Najera, M. Gennari, LJ, M. Drissi,
P. Navrátil, work in progress*

OUTLINE

- 1** Introduction
- 2** Opportunities with next-generation $0\nu\beta\beta$ -decay experiments
- 3** Probing neutrinoless double-beta decay by muon capture
- 4** **Correlations of $0\nu\beta\beta$ decay and other observables**
- 5** Summary

DOUBLE CHARGE EXCHANGE REACTIONS

$$M_L^{0\nu} = M_{GT}^{0\nu} - \left(\frac{g_V}{g_A} \right)^2 M_F^{0\nu} + M_T^{0\nu}$$



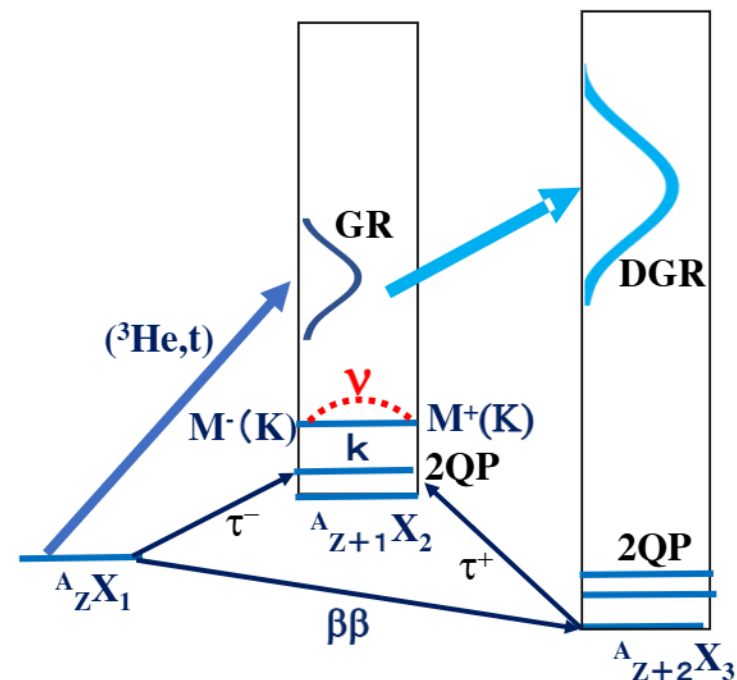
Ejiri, Jokiniemi, Suhonen, Phys. Rev. C 105, L022501 (2022)

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$$M_L^{0\nu} = M_{GT}^{0\nu} - \left(\frac{g_V}{g_A} \right)^2 M_F^{0\nu} + M_T^{0\nu}$$

Leading component

$$M_{GT}^{0\nu} = \langle f || \sum_{jk} \tau_j^- \tau_k^- \sigma_j \sigma_k V_{GT}(r_{jk}) || i \rangle$$



Ejiri, Jokiniemi, Suhonen, Phys. Rev. C 105, L022501 (2022)

DOUBLE CHARGE EXCHANGE REACTIONS

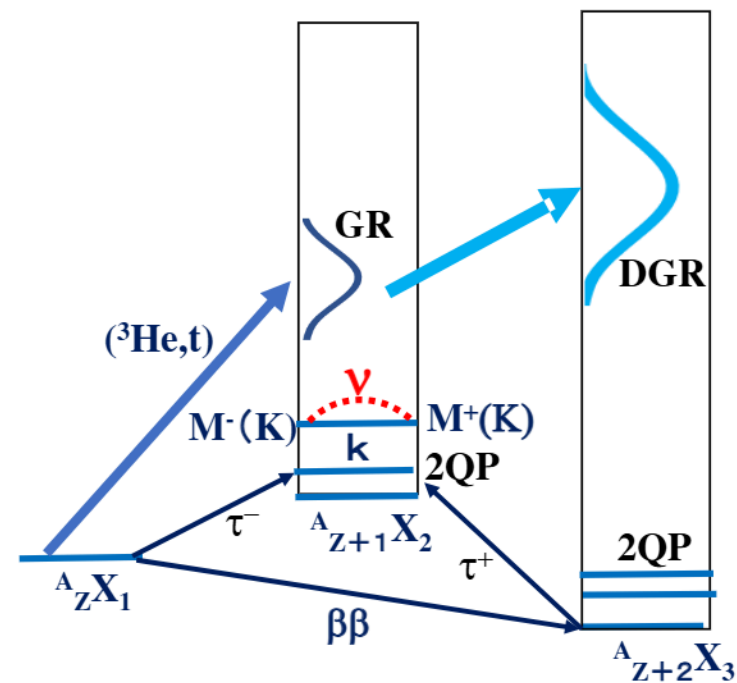
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- Double-Gamow-Teller (DGT) strength function

$$B(\text{DGT}; \lambda) = \frac{1}{2J_i + 1} | \langle f || [\sum_{jk} \sigma_j \tau_j^- \times \sigma_k \tau_k^-]^{(\lambda)} || i \rangle |^2$$



Ejiri, Jokiniemi, Suhonen, *Phys. Rev. C* 105, L022501 (2022)

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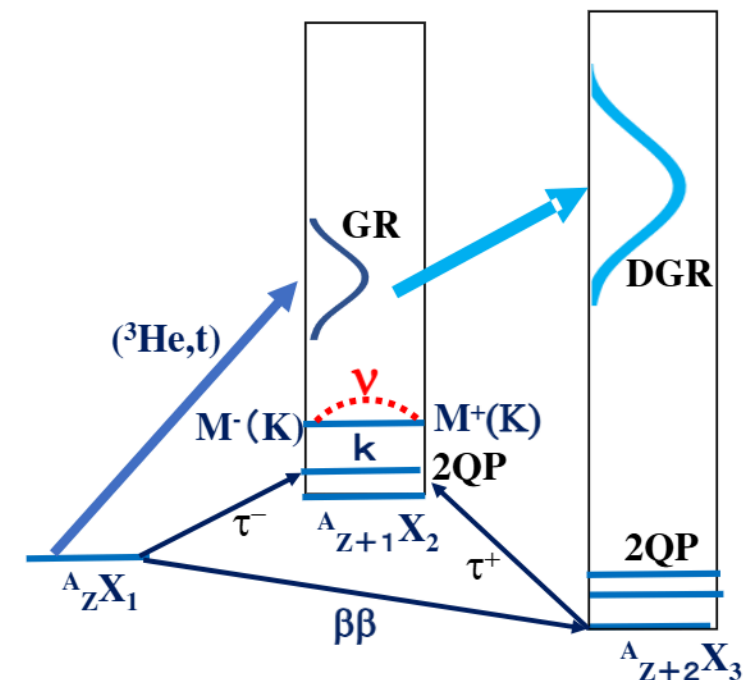
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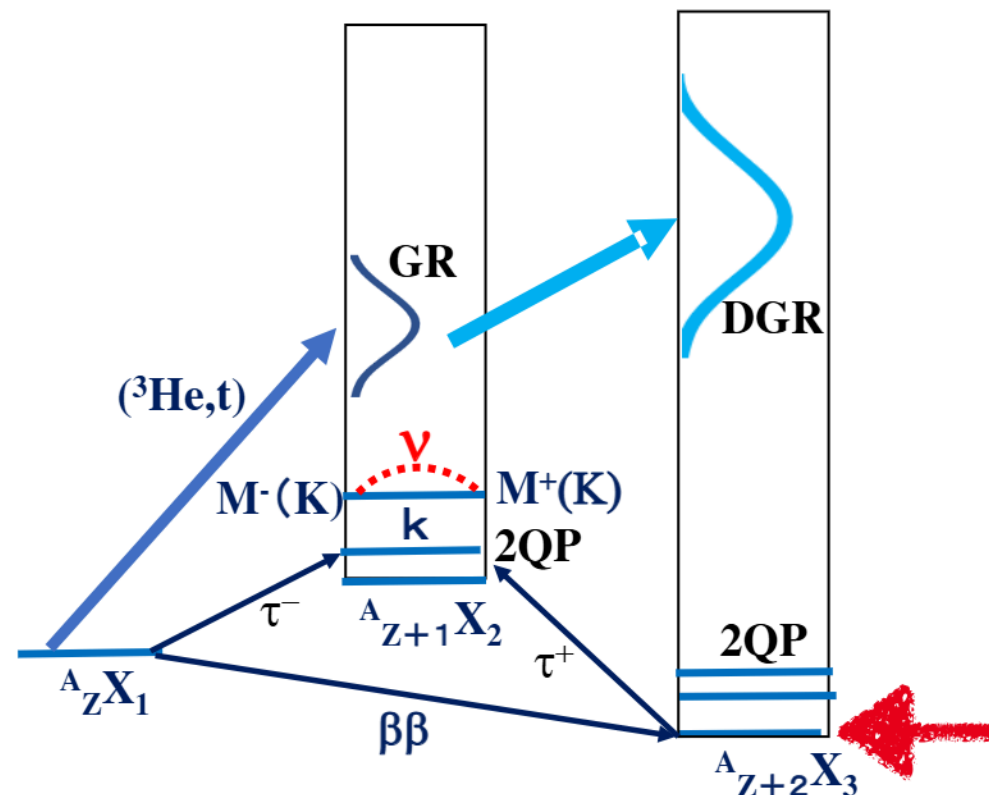
- Very similar operator structures



Ejiri, Jokiniemi, Suhonen, *Phys. Rev. C* 105, L022501 (2022)

CORRELATIONS BETWEEN DGT AND $0\nu\beta\beta$ DECAY

$$M_{\text{DGT}} = - \langle f || [\sum_{jk} \sigma_j \tau_j^- \times \sigma_k \tau_k^-]^{(0)} || i \rangle$$

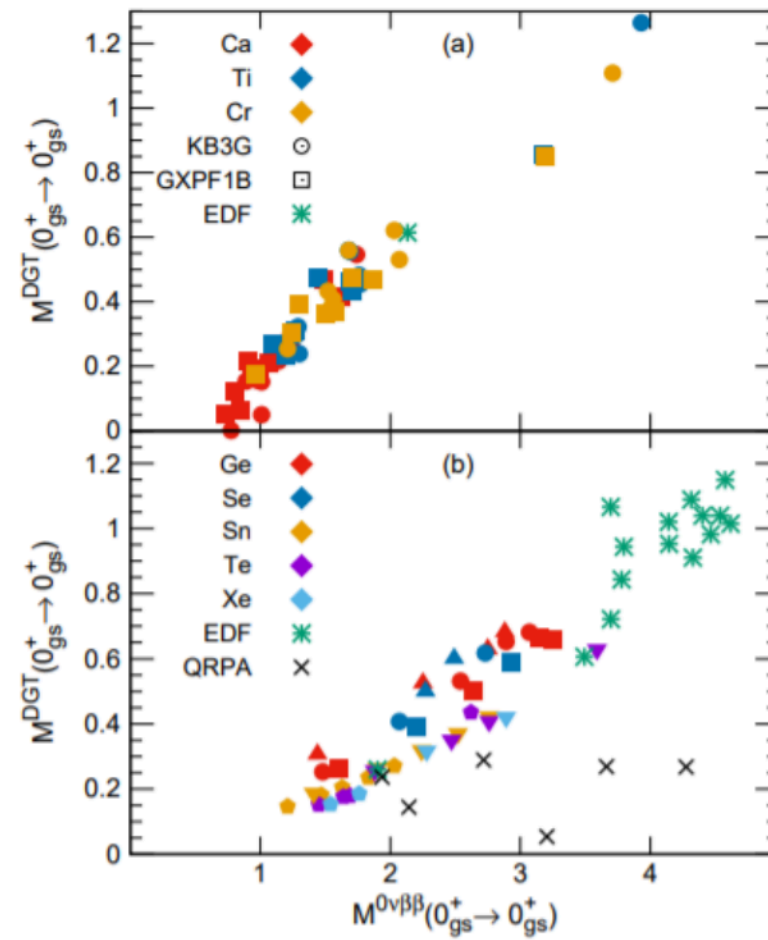


Ejiri, Jokiniemi, Suhonen, Phys. Rev. C 105, L022501 (2022)

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- Correlation between $M_L^{0\nu}$ and M_{DGT} first found in nuclear **shell model** and **density functional theory**

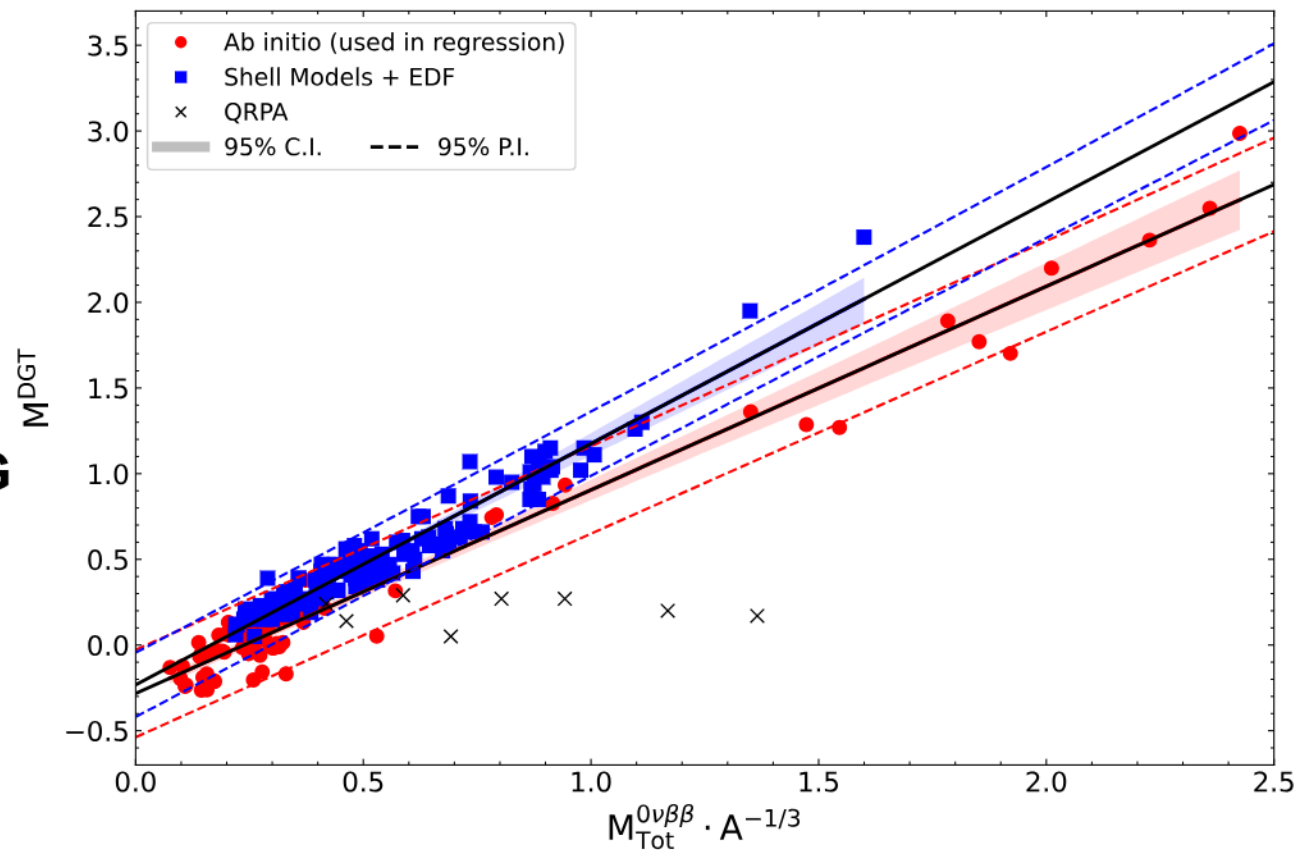


Shimizu, Menéndez, Yako, *Phys. Rev. Lett.* 120, 142502 (2018)

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- Correlation also holds in ***ab initio* VS-IMSRG**

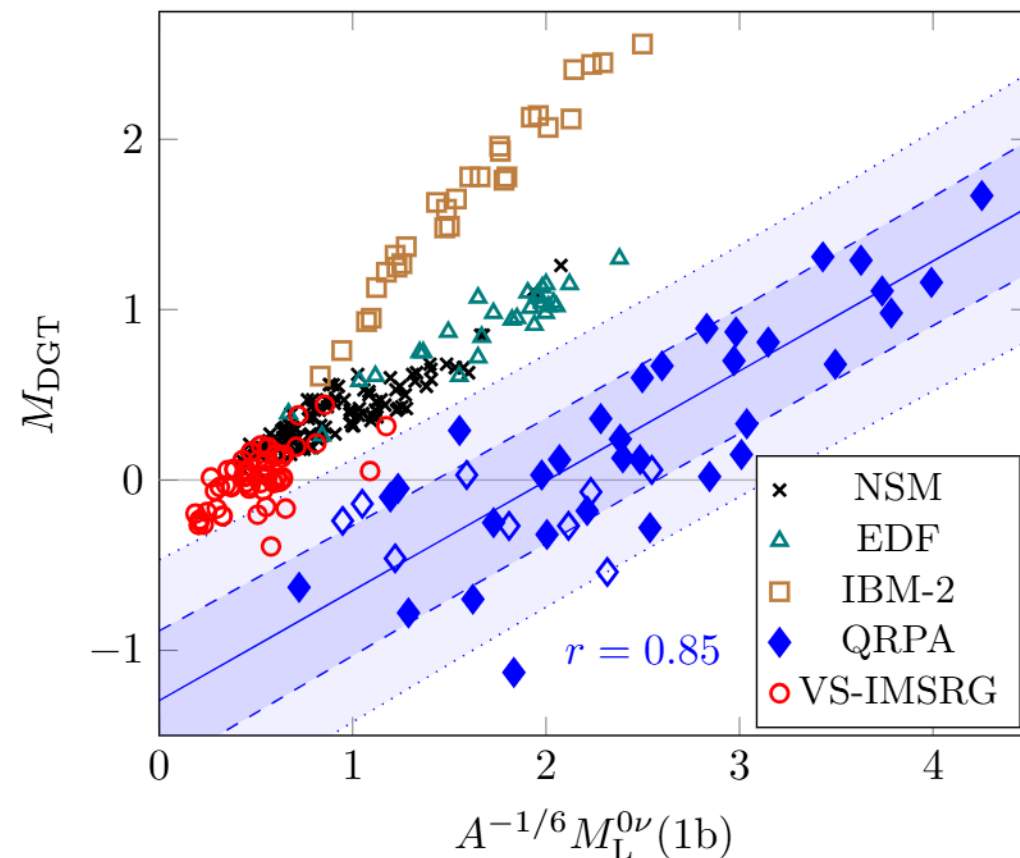


Yao, Ginnett, Belley et al., Phys. Rev. C 106, 014315 (2022)

CORRELATIONS BETWEEN DGT AND $0\nu\beta\beta$ DECAY

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- ... and **QRPA**, when proton-neutron pairing is varied



Jokiniemi, Menéndez, *Phys. Rev. C* 107, 044316 (2024)

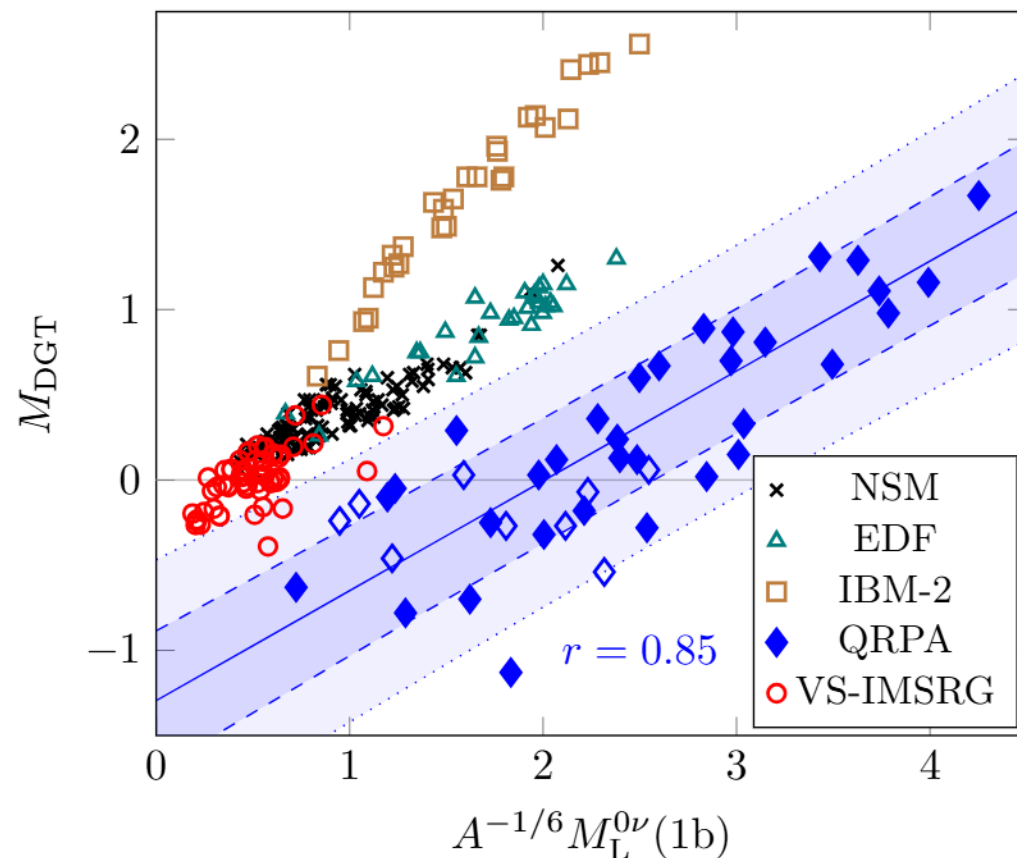
CORRELATIONS BETWEEN DGT AND $0\nu\beta\beta$ DECAY

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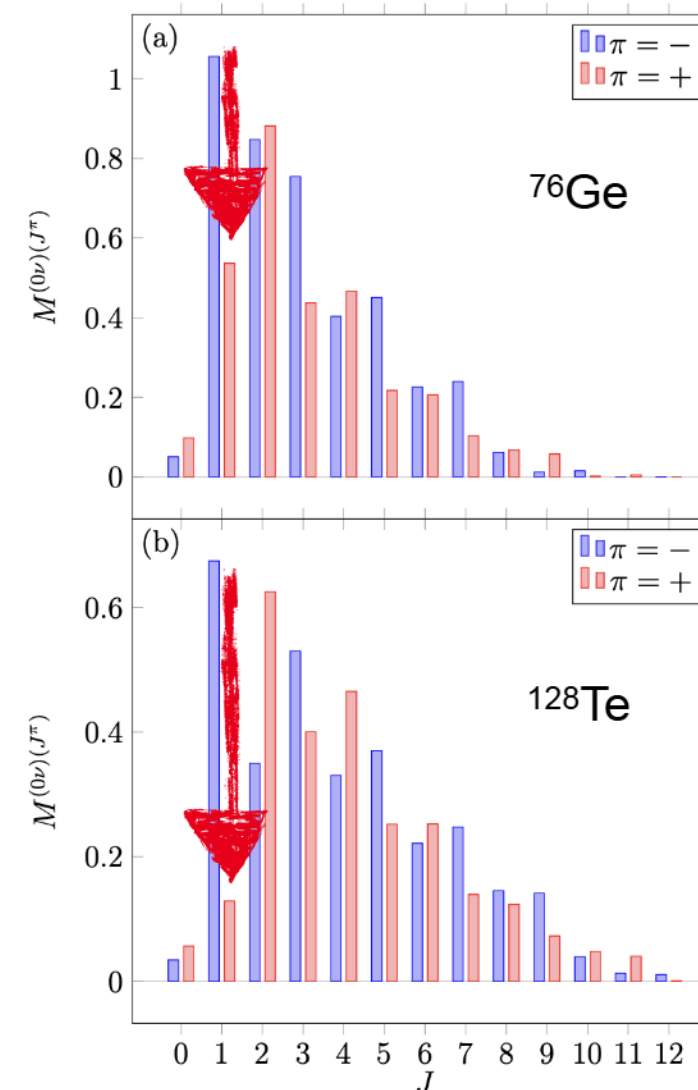
Observation of DGT strength would help constrain $M^{0\nu}$



Jokiniemi, Menéndez, *Phys. Rev. C* 107, 044316 (2024)



ROLE OF THE 1^+ STATES

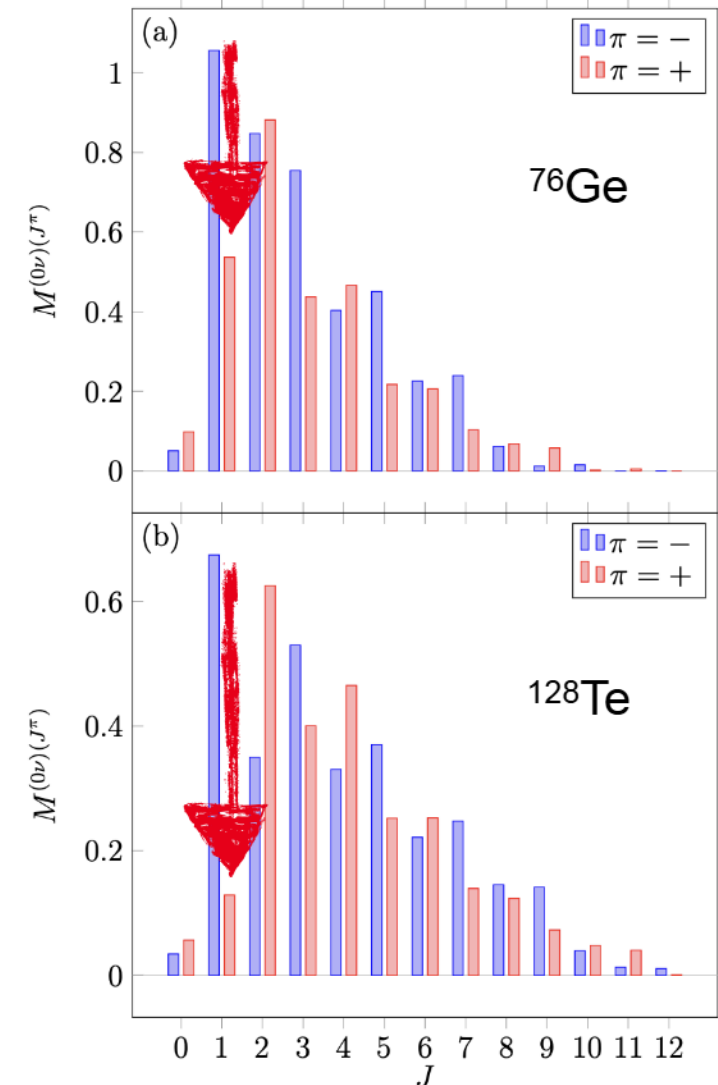


Jokiniemi, Ejiri, Frekers, Suhonen,
Phys. Rev. C **98**, 024608 (2018)

ROLE OF THE 1^+ STATES

- In the pnQRPA, no closure approximation used:

$$\begin{aligned}
 M_K^{0\nu} = & \sum_{J^\pi k_1 k_2} \sum_{\mathcal{J} \, pp' nn'} (-1)^{j_n + j_{p'} + J + \mathcal{J}} \widehat{\mathcal{F}} \left\{ \begin{matrix} j_p & j_n & J \\ j_{n'} & j_{p'} & \mathcal{J} \end{matrix} \right\} \\
 & \times \langle pp' : \mathcal{J} \| H_K(r, E_k) f_{\text{SRC}}^2(r) \mathcal{O}_K \tau_1^- \tau_2^- \| nn' : \mathcal{J} \rangle \\
 & \times \langle 0_f^+ \| [c_{p'}^\dagger \tilde{c}_{n'}]_J \| J_{k_1}^\pi \rangle \langle J_{k_1}^\pi | J_{k_2}^\pi \rangle \langle J_{k_2}^\pi \| [c_p^\dagger \tilde{c}_n]_J \| 0_i^+ \rangle
 \end{aligned}$$



Jokiniemi, Ejiri, Frekers, Suhonen,
Phys. Rev. C **98**, 024608 (2018)

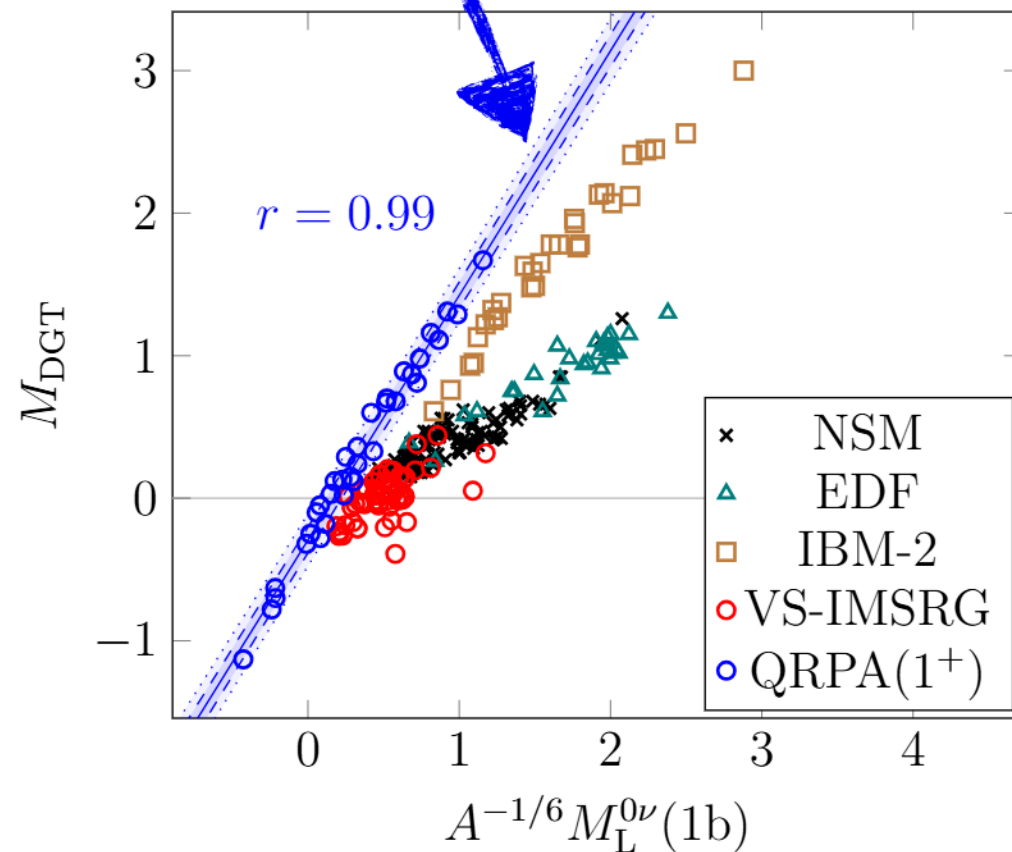
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 \end{aligned}$$

- 1^+ states often not the dominating contributions

Correlation with 1^+ states only



Jokiniemi, Menéndez, *Phys. Rev. C* 107, 044316 (2023)



CORRELATIONS BETWEEN $0\nu\beta\beta$ AND $2\nu\beta\beta$ DECAYS



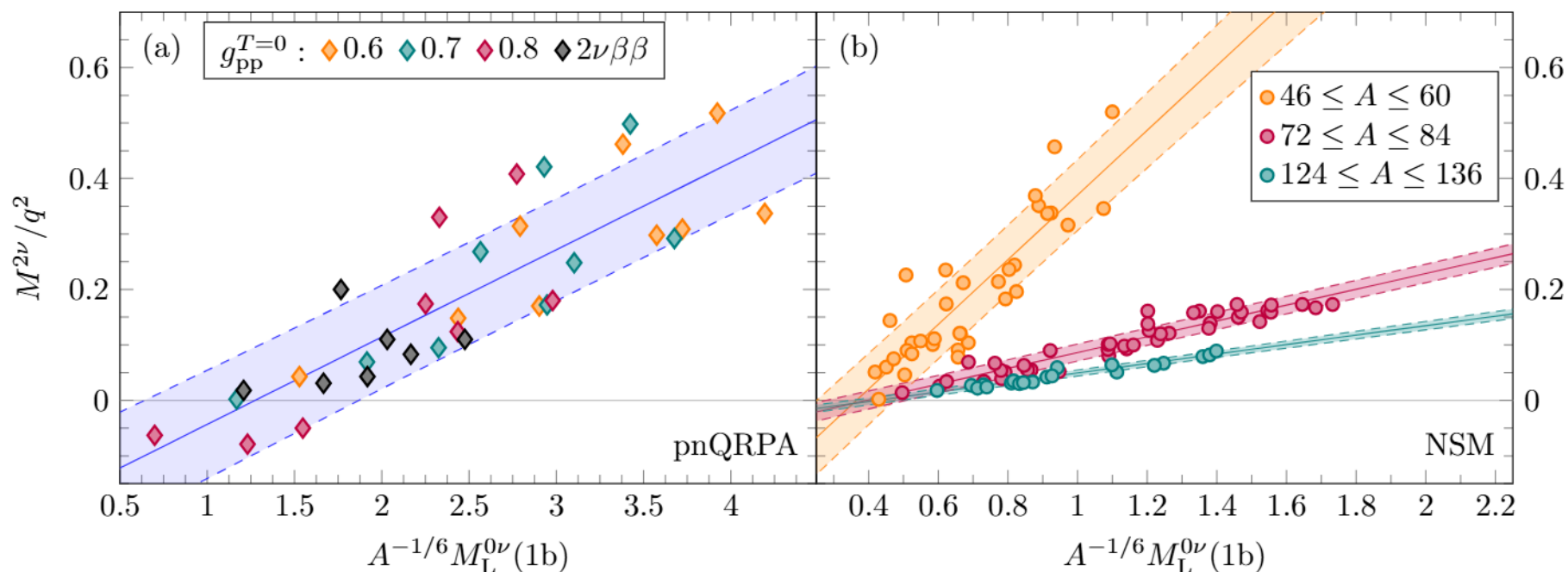
CORRELATIONS BETWEEN $0\nu\beta\beta$ AND $2\nu\beta\beta$ DECAYS

$$M^{2\nu} = \sum_n \frac{\langle 0_f^+ \| \sum_j \tau_j^- \sigma_j \| 1_n^+ \rangle \langle 1_n^+ \| \sum_k \tau_k^- \sigma_k \| 0_i^+ \rangle}{E_n - (E_i + E_f)/2}$$

CORRELATIONS BETWEEN $0\nu\beta\beta$ AND $2\nu\beta\beta$ DECAYS

- $2\nu\beta\beta$ decay also correlated with $0\nu\beta\beta$ decay

$$M^{2\nu} = \sum_n \frac{\langle 0_f^+ \| \sum_j \tau_j^- \sigma_j \| 1_n^+ \rangle \langle 1_n^+ \| \sum_k \tau_k^- \sigma_k \| 0_i^+ \rangle}{E_n - (E_i + E_f)/2}$$

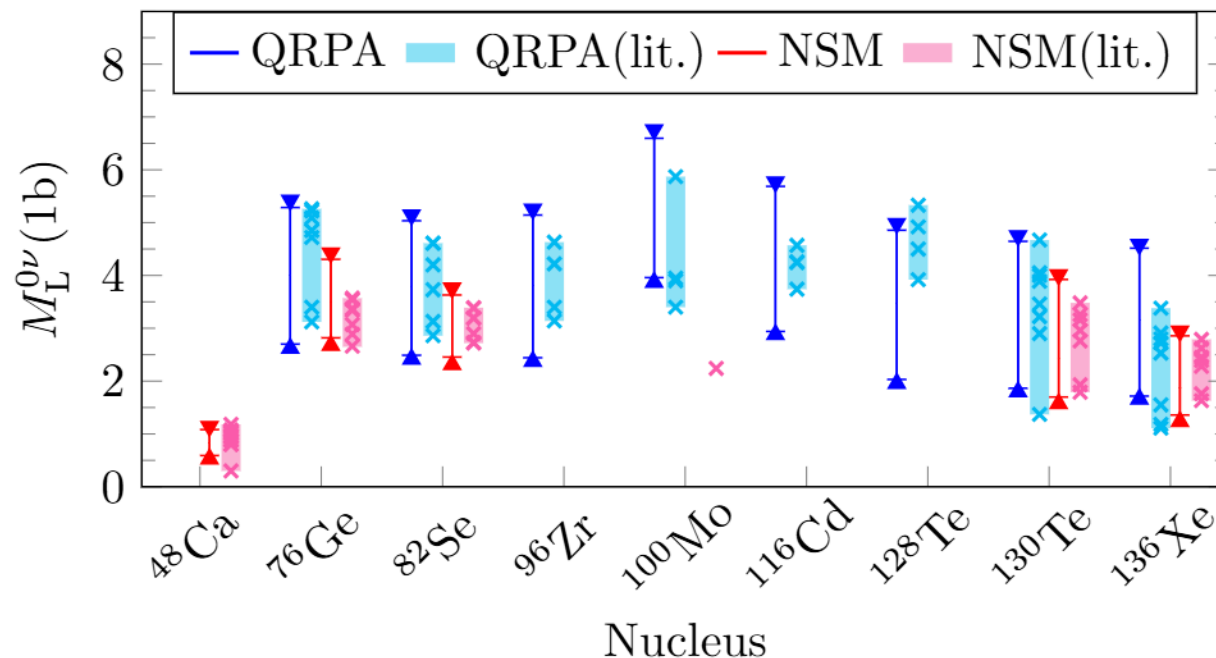


Jokiniemi, Romeo, Soriano, Menéndez, *Phys Rev. C* 107, 044305 (2023)

CORRELATIONS BETWEEN $0\nu\beta\beta$ AND $2\nu\beta\beta$ DECAYS

- $2\nu\beta\beta$ decay also correlated with $0\nu\beta\beta$ decay
- We can use existing data to estimate $0\nu\beta\beta$ -decay NMEs with uncertainties

$$M^{2\nu} = \sum_n \frac{\langle 0_f^+ \| \sum_j \tau_j^- \sigma_j \| 1_n^+ \rangle \langle 1_n^+ \| \sum_k \tau_k^- \sigma_k \| 0_i^+ \rangle}{E_n - (E_i + E_f)/2}$$



Jokiniemi, Romeo, Soriano, Menéndez, *Phys. Rev. C* 107, 044305 (2023)

CORRELATIONS BETWEEN $0\nu\beta\beta$ AND $2\nu\beta\beta$ DECAYS

- Correlations also found in statistical shell-model studies in

- ^{48}Ca

Horoj, Neacsu, Stoica, Phys. Rev. C 106, 054302 (2022)

- ^{76}Ge

Horoj, Neacsu, arXiv:2605.21657

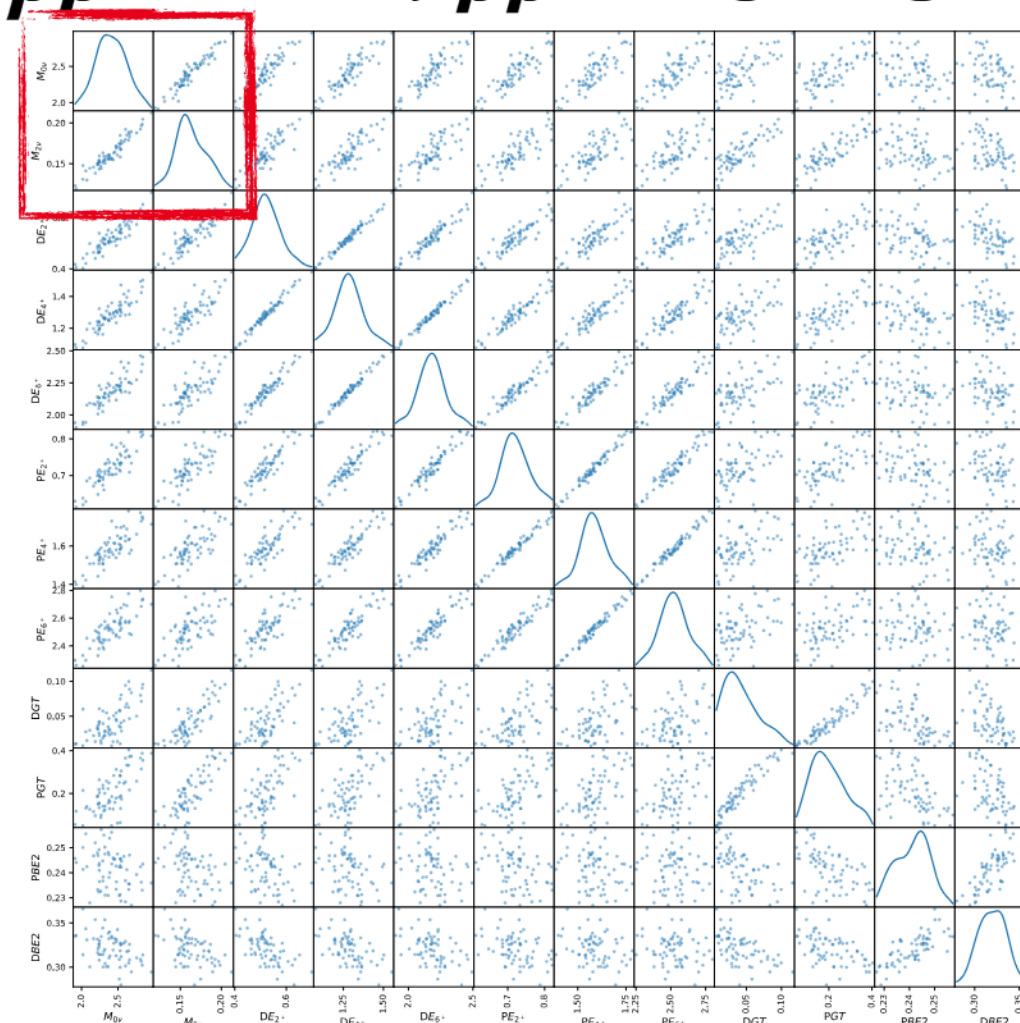
- ^{82}Se

Neacsu, Horoj, Symmetry 2024, 16(8), 974

- ^{136}Xe

Horoj, Neacsu, Stoica, Phys. Rev. C 107, 045501 (2023)

Horoj, Universe 10 (6), 252



Horoj, Neacsu, arXiv:2605.21657

AB INITIO CORRELATION BETWEEN $0\nu\beta\beta$ AND $2\nu\beta\beta$ DECAYS

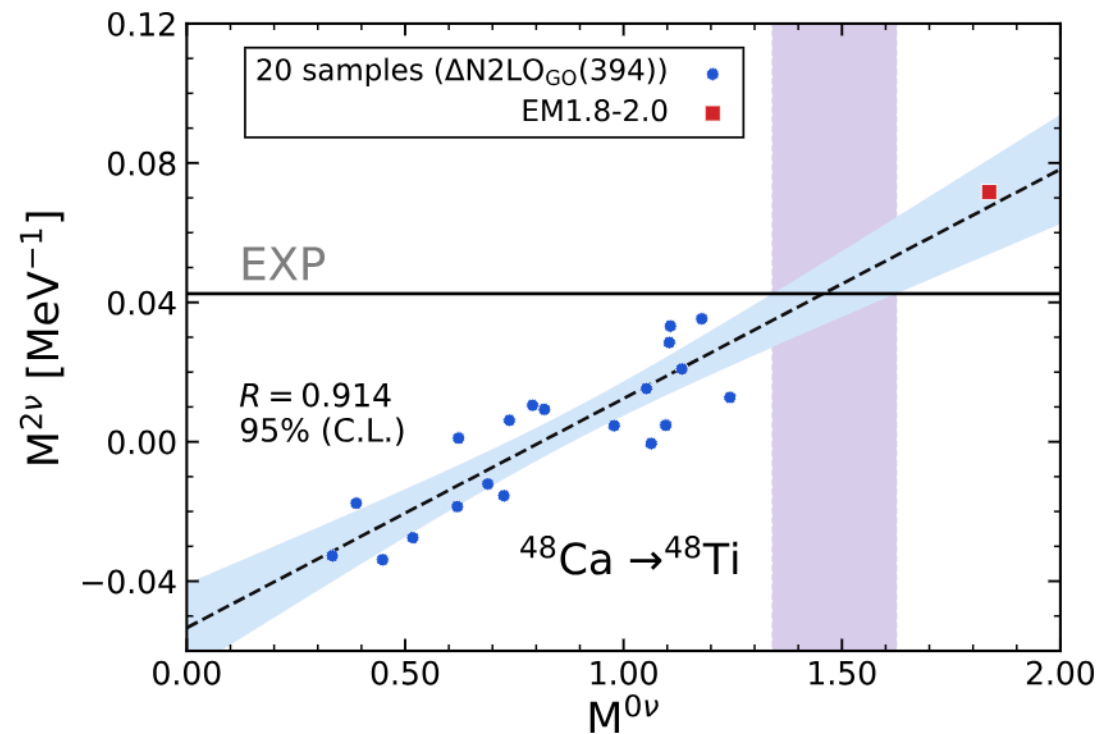
- In-Medium No-Core Configuration Interaction (IM-NCCI) method:

solve $H^{(A)} |\Psi\rangle = E |\Psi\rangle$ with

$$|\Psi\rangle = D_0 |\Phi\rangle + \sum_{m,i} a_m^\dagger a_i |\Phi\rangle + \sum_{mnij} a_m^\dagger a_n^\dagger a_i a_j |\Phi\rangle + \dots$$

and χ EFT Hamiltonians

$$H^{(A)} = \sum_{i=1}^A \frac{p_i^2}{2m} + \sum_{i<j=1}^A V_{ij}^{\text{NN}}(\mathbf{r}_i - \mathbf{r}_j) + \sum_{i<j<k=1}^A V_{ijk}^{\text{3N}}$$



Lian, Ding, Bai, Yao, arXiv:2605.19479

AB INITIO CORRELATION BETWEEN $0\nu\beta\beta$ AND $2\nu\beta\beta$ DECAYS

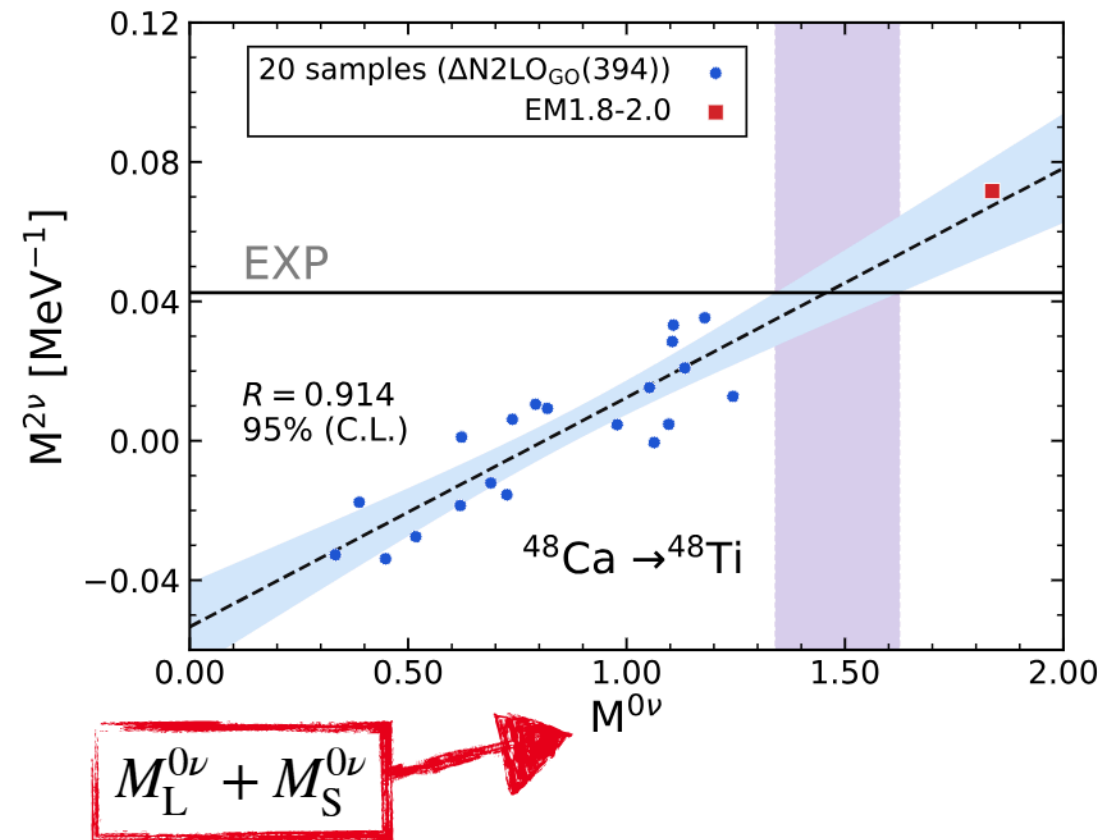
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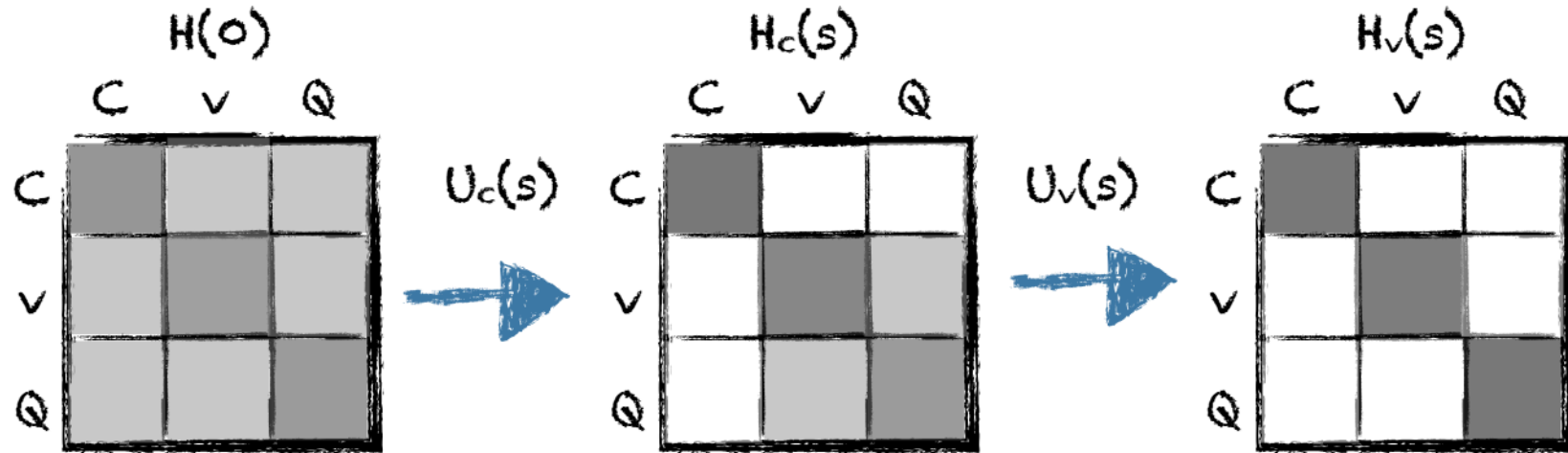
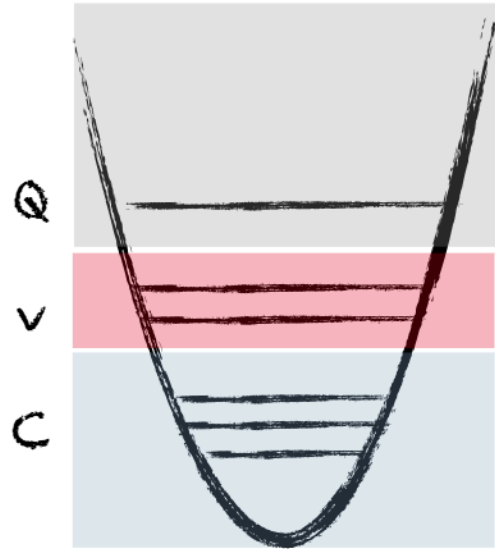
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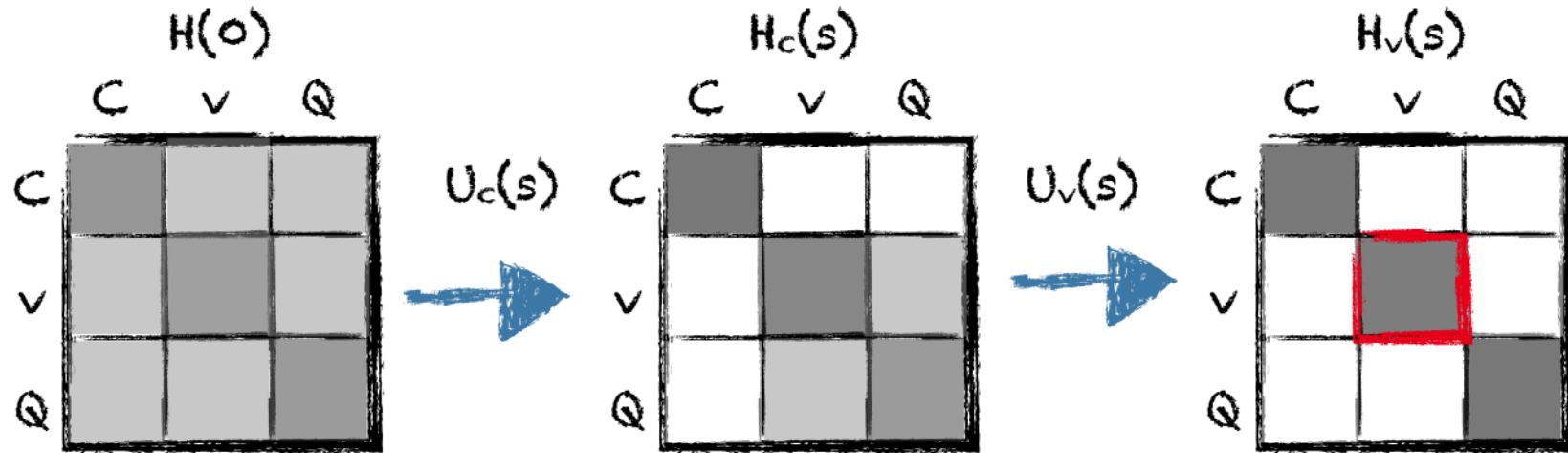
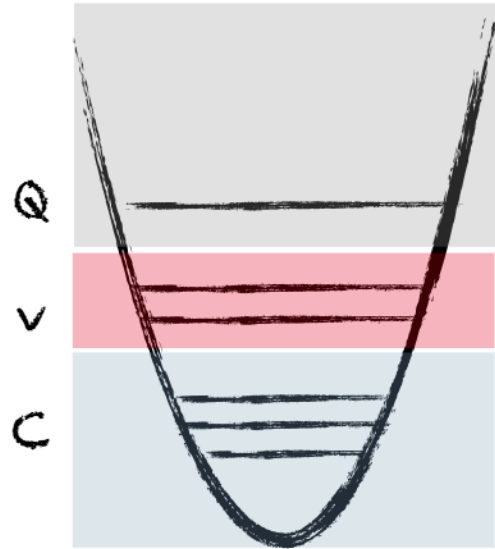
Lian, Ding, Bai, Yao, arXiv:2605.19479

$2\nu\beta\beta$ DECAY WITH VS-IMSRG(2)



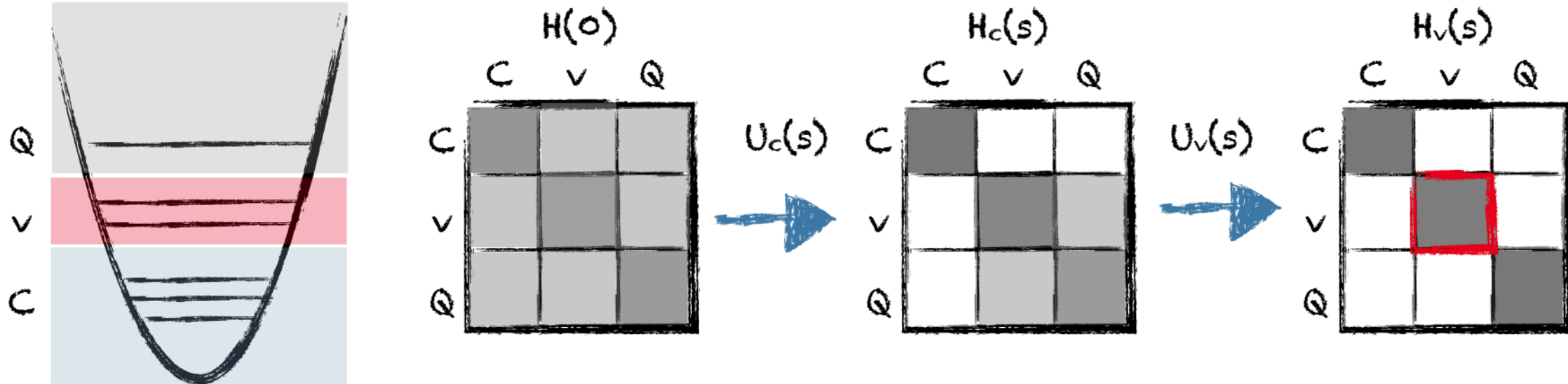
Stroberg et al., Phys. Rev. Lett. 118, 032502 (2017)

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Stroberg et al., Phys. Rev. Lett. 118, 032502 (2017)

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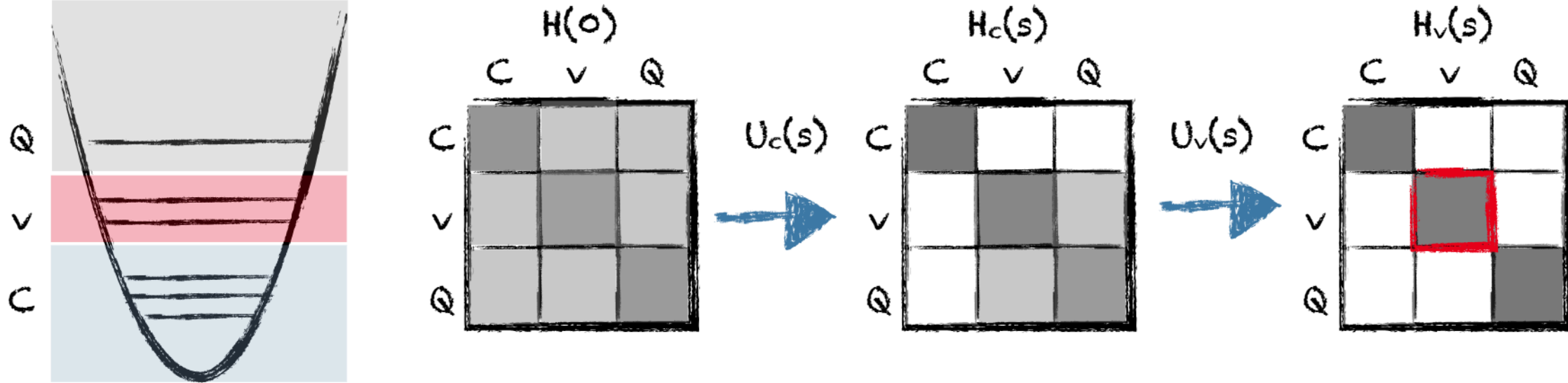


- Start from normal-ordered Hamiltonian

$$H(0) = E_0 + \sum_{ij} f_{ij} \{a_i^\dagger a_j\} + \frac{1}{4} \sum_{ijkl} \Gamma_{ijkl} \{a_i^\dagger a_j^\dagger a_l a_k\} \left(+ \frac{1}{36} \sum_{ijklmn} W_{ijklmn} \{a_i^\dagger a_j^\dagger a_k^\dagger a_n a_m a_l\} \right)$$

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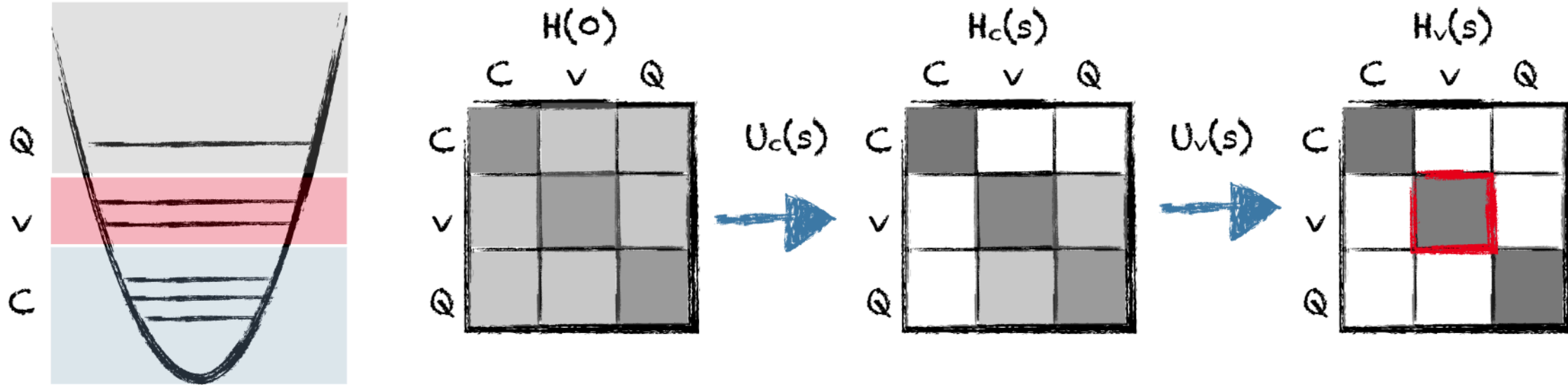
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- Hamiltonian truncated at two-body level: $H(s) = e^\Omega H e^{-\Omega} = H + [\Omega, H]_{0,1,2} + \frac{1}{2} [\Omega, [\Omega, H]]_{0,1,2} + \dots$

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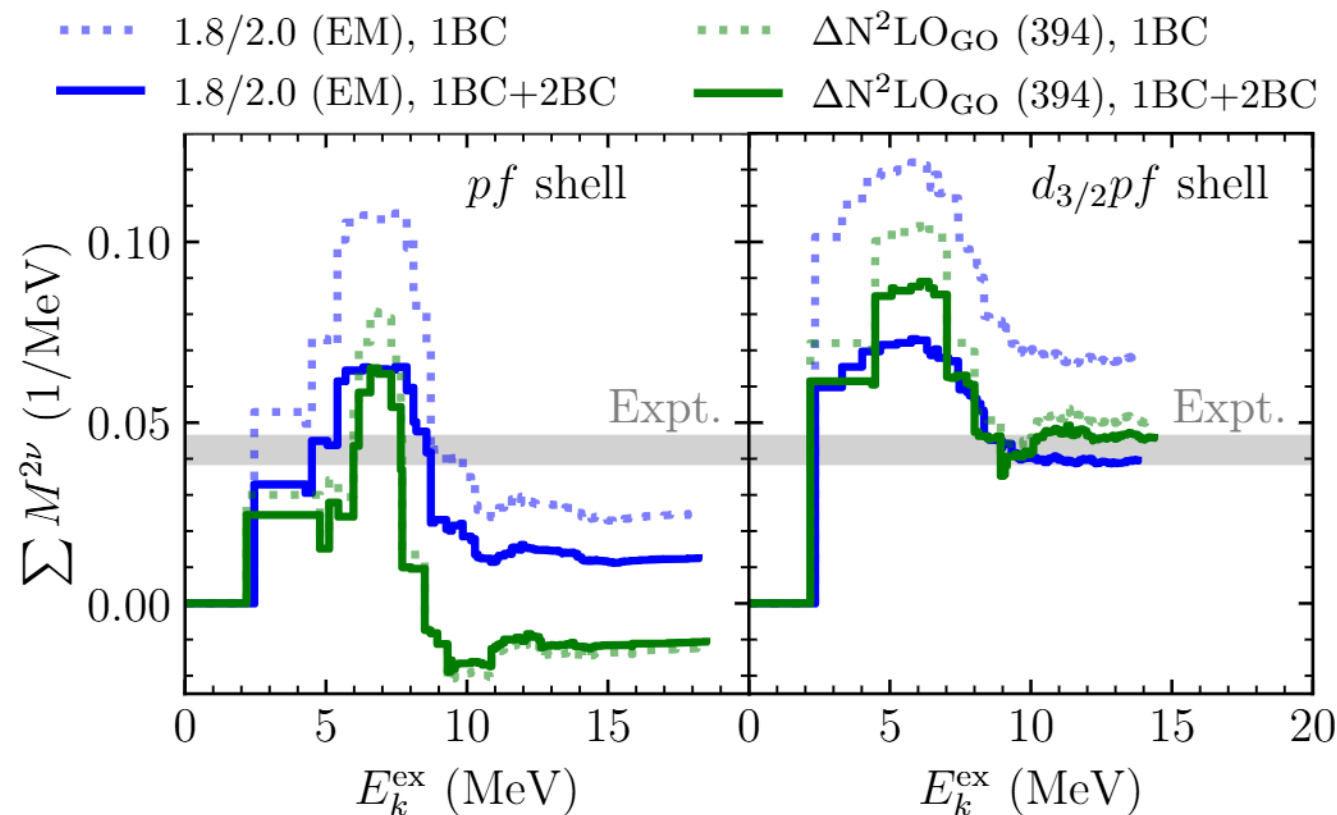
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Stroberg et al., Phys. Rev. Lett. 118, 032502 (2017)

$2\nu\beta\beta$ DECAY WITH VS-IMSRG(2)



Li, Jokiniemi, Schwenk, [arXiv:2607.11733](https://arxiv.org/abs/2607.11733)

$2\nu\beta\beta$ DECAY WITH VS-IMSRG(2)

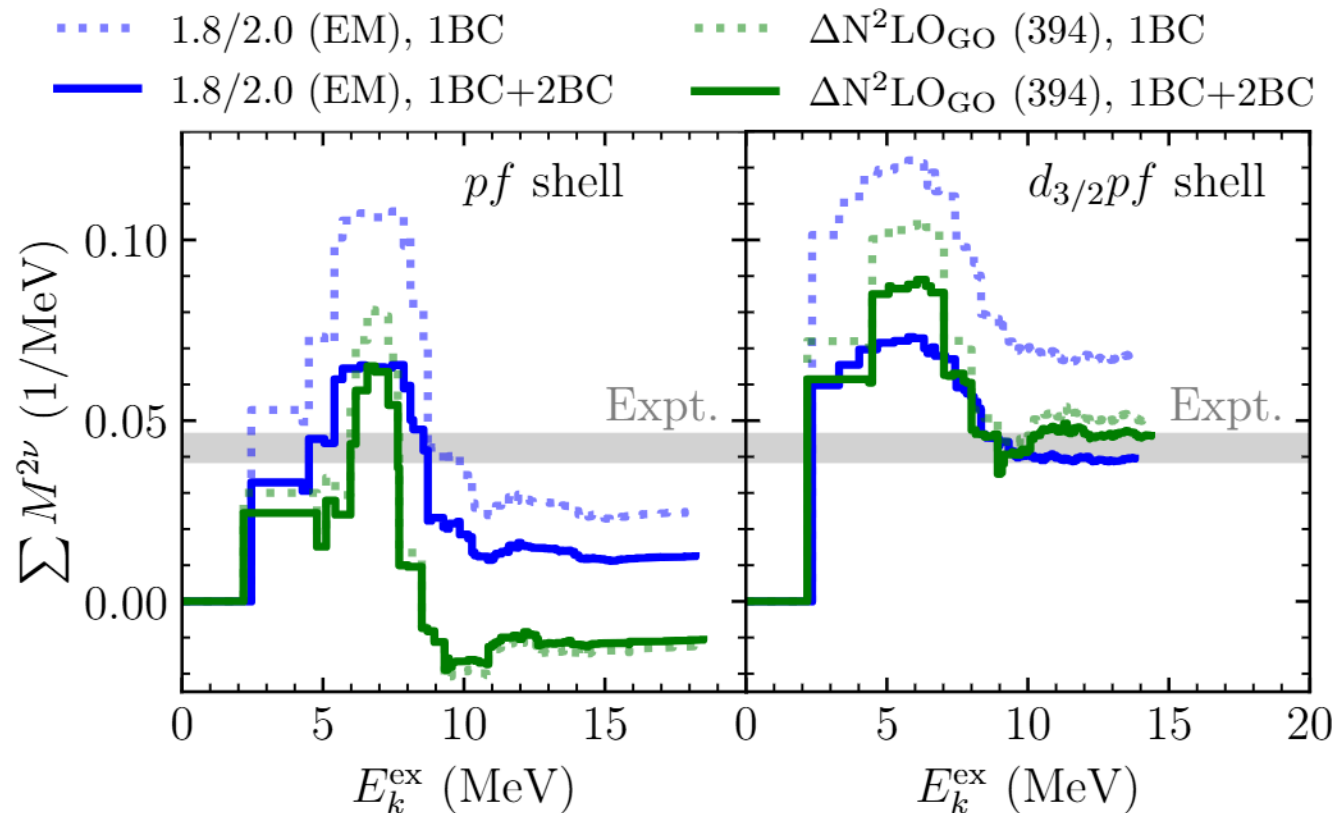
Two different χ EFT NN+3N interactions:

1.8/2.0 (EM)

Hebeler et al., *Phys. Rev. C* 83, 031301 (2011)

$\Delta N^2 LO_{GO}$

Jiang et al., *Phys. Rev. C* 102, 054301 (2020)



Li, Jokiniemi, Schwenk, *arXiv:2607.11733*

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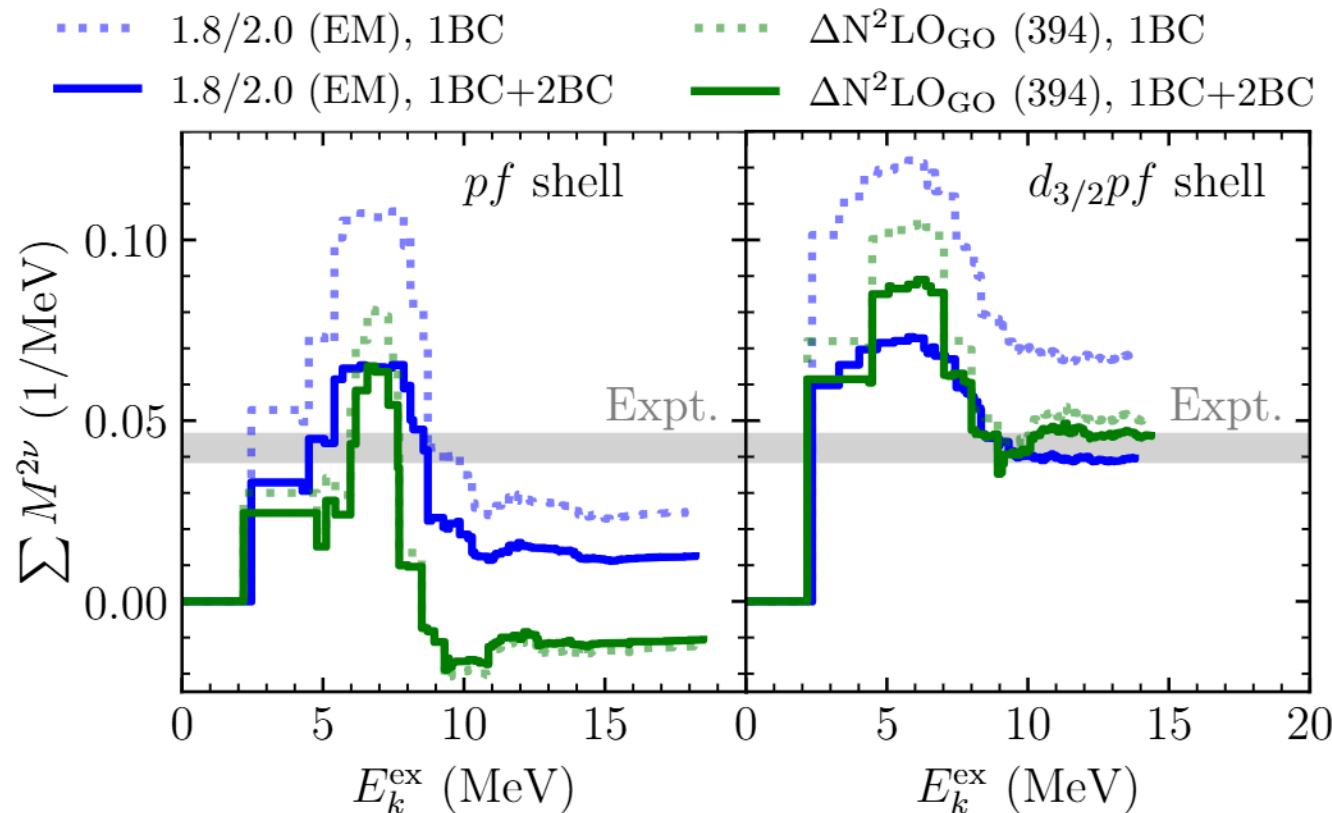
- One- and two-body axial currents

$$\mathbf{J} = \mathbf{J}_{1b} + \mathbf{J}_{2b}^{ct} + \mathbf{J}_{1b}^{1\pi}$$

Park et al., Phys. Rev. C 67, 055206 (2003)

Krebs et al., Ann. Phys. 378, 317 (2017)

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Li, Jokiniemi, Schwenk, arXiv:2607.11733

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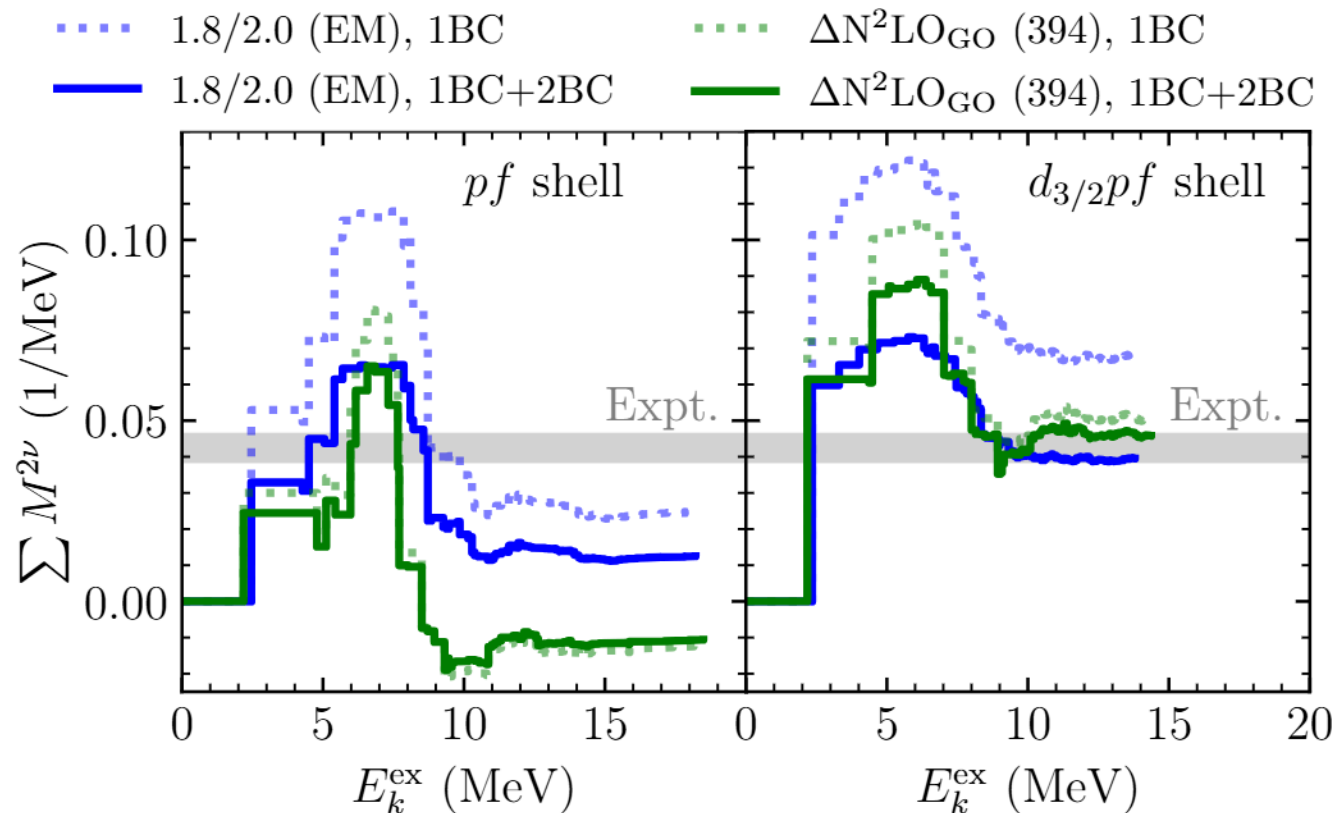
Krebs et al., Ann. Phys. 378, 317 (2017)

Klos et al., Eur. Phys. J. A (2018) 54: 76

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- $d_{3/2}pf$ shell (^{32}S core)



Li, Jokiniemi, Schwenk, arXiv:2607.11733

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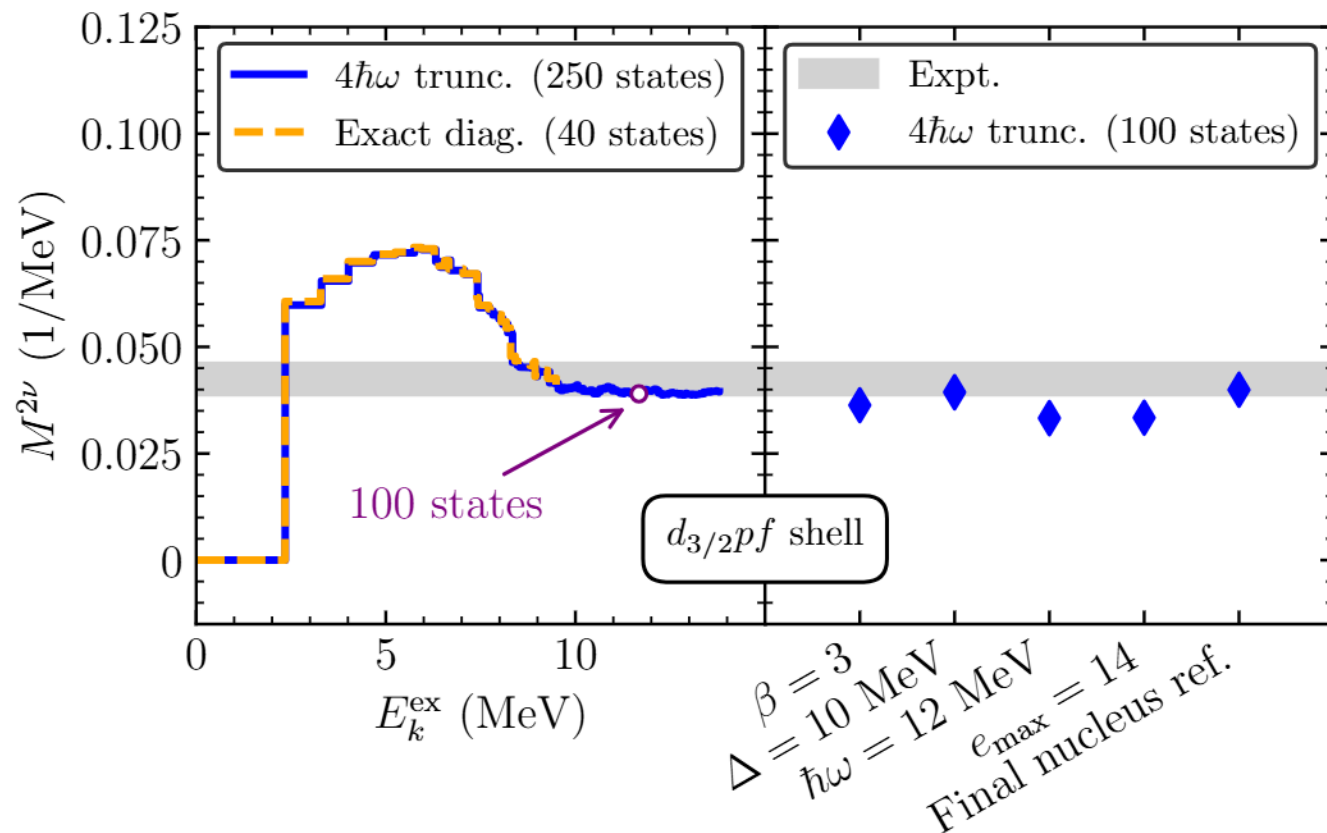
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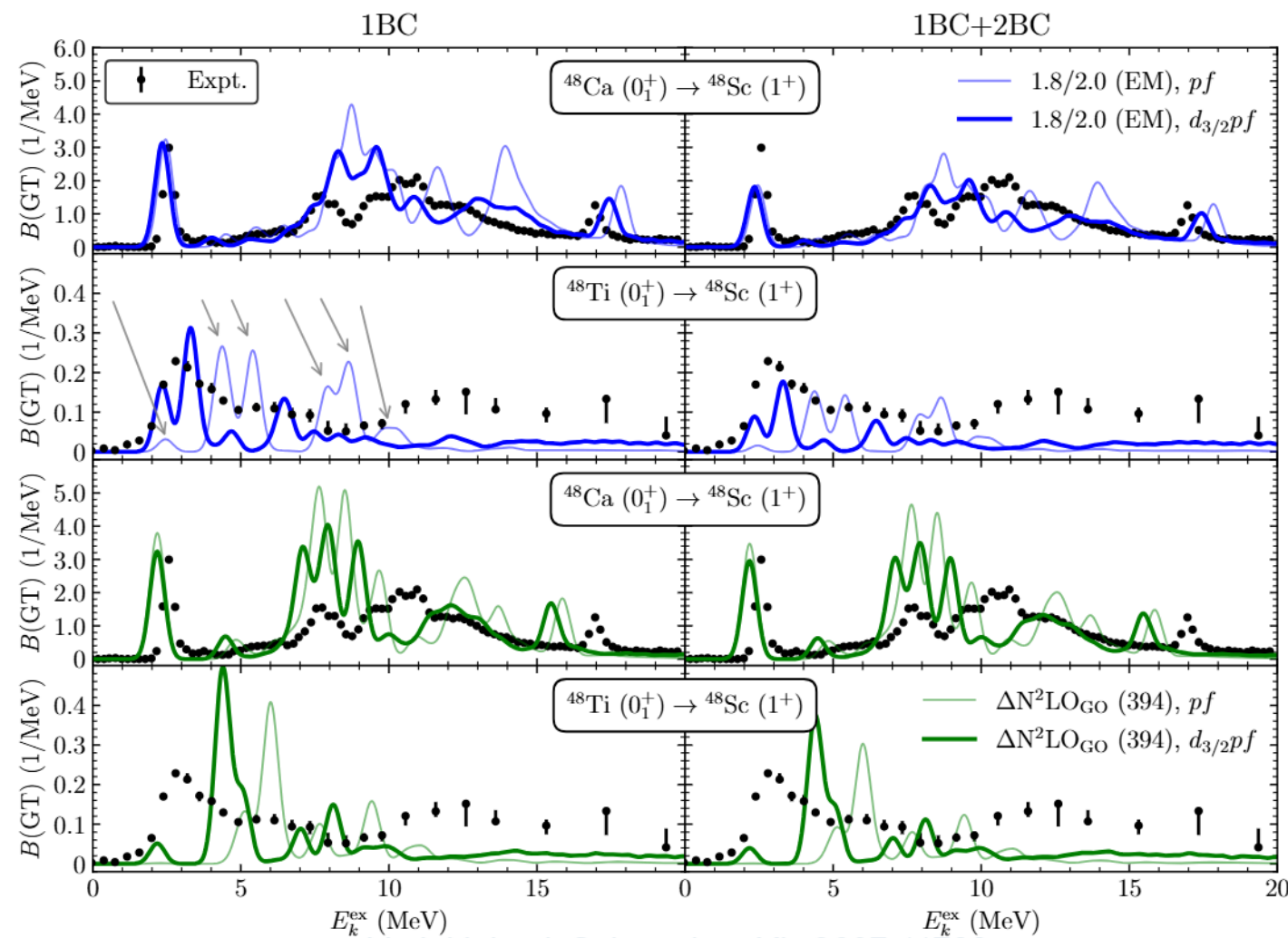
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Li, Jokiniemi, Schwenk, arXiv:2607.11733

BENCHMARKS WITH GAMOW-TELLER STRENGTHS

$$B(\text{GT}) = \frac{1}{2J+1} |\langle f || \mathbf{GT} || i \rangle|^2$$



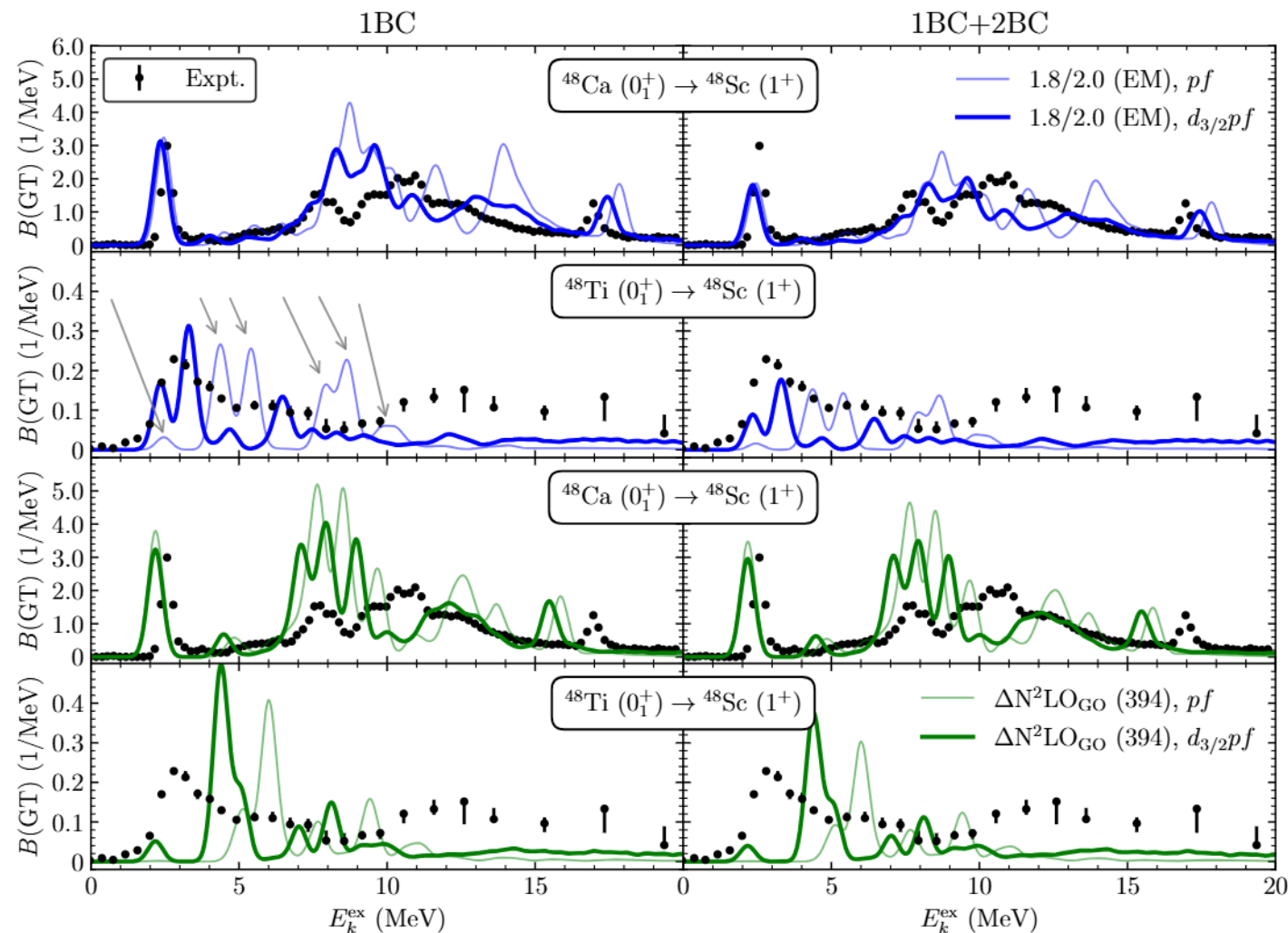
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Yako et al., Phys. Rev. Lett. 103, 012503 (2009)

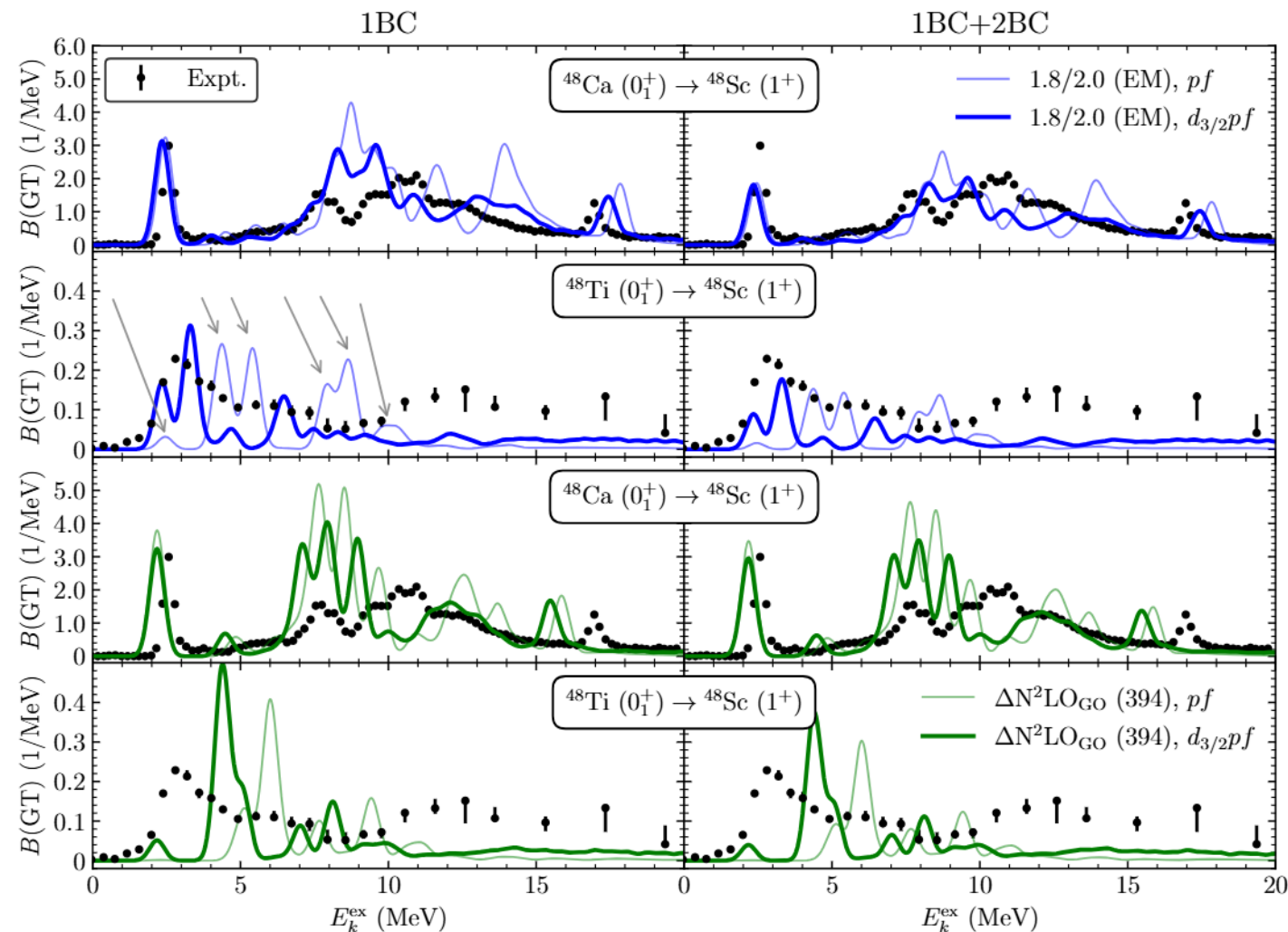


Li, Jokiniemi, Schwenk, arXiv:2607.11733

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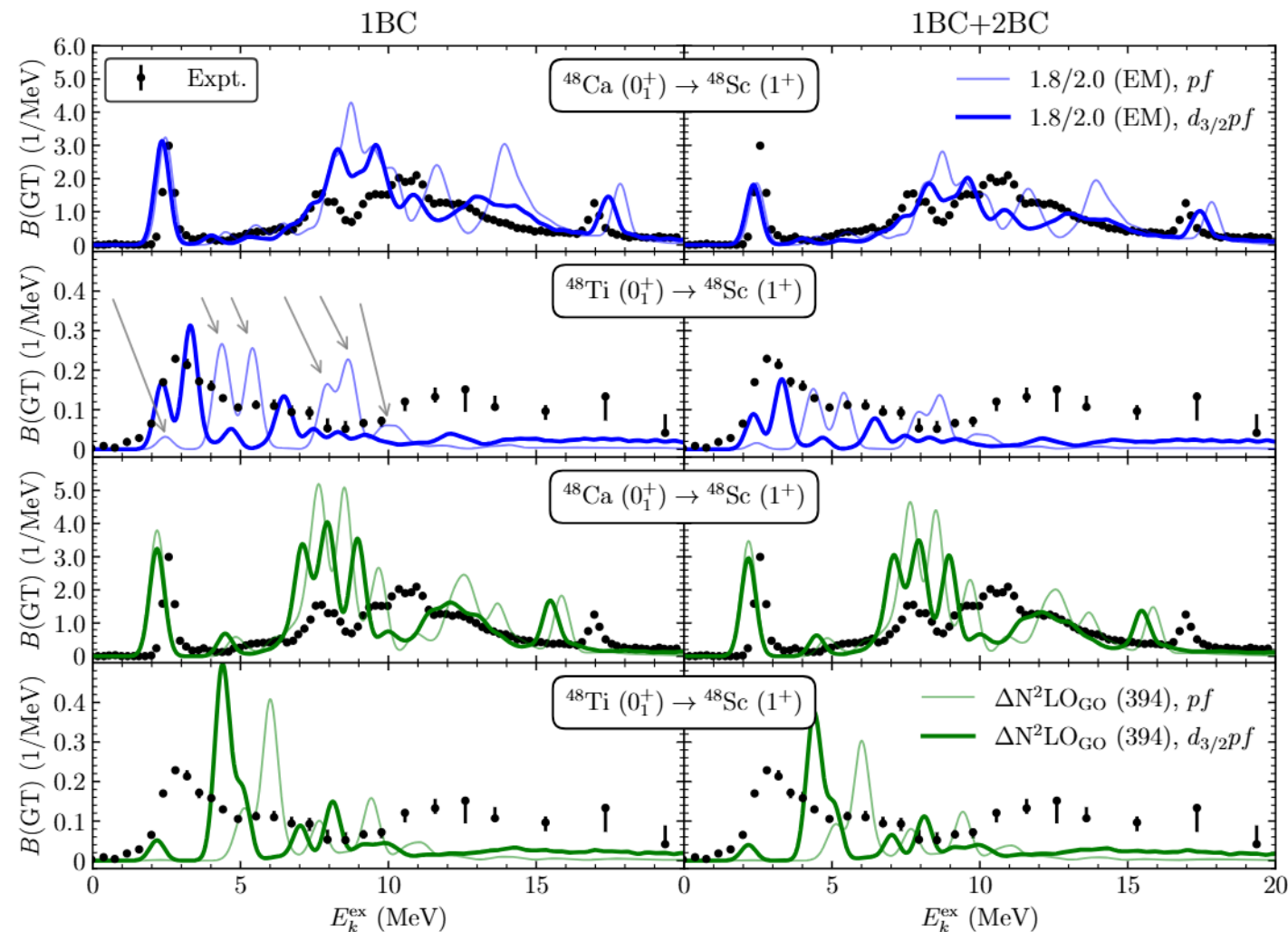


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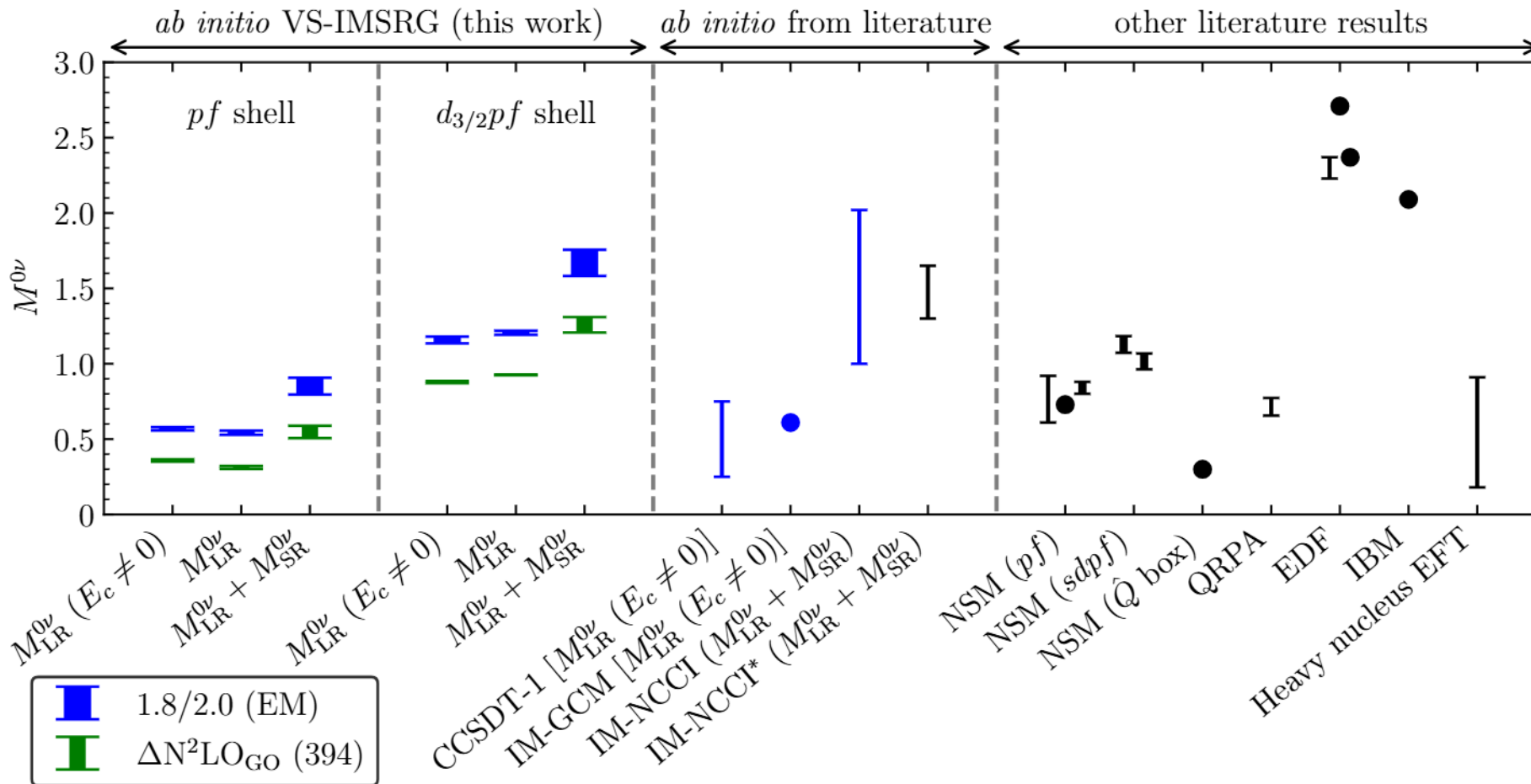
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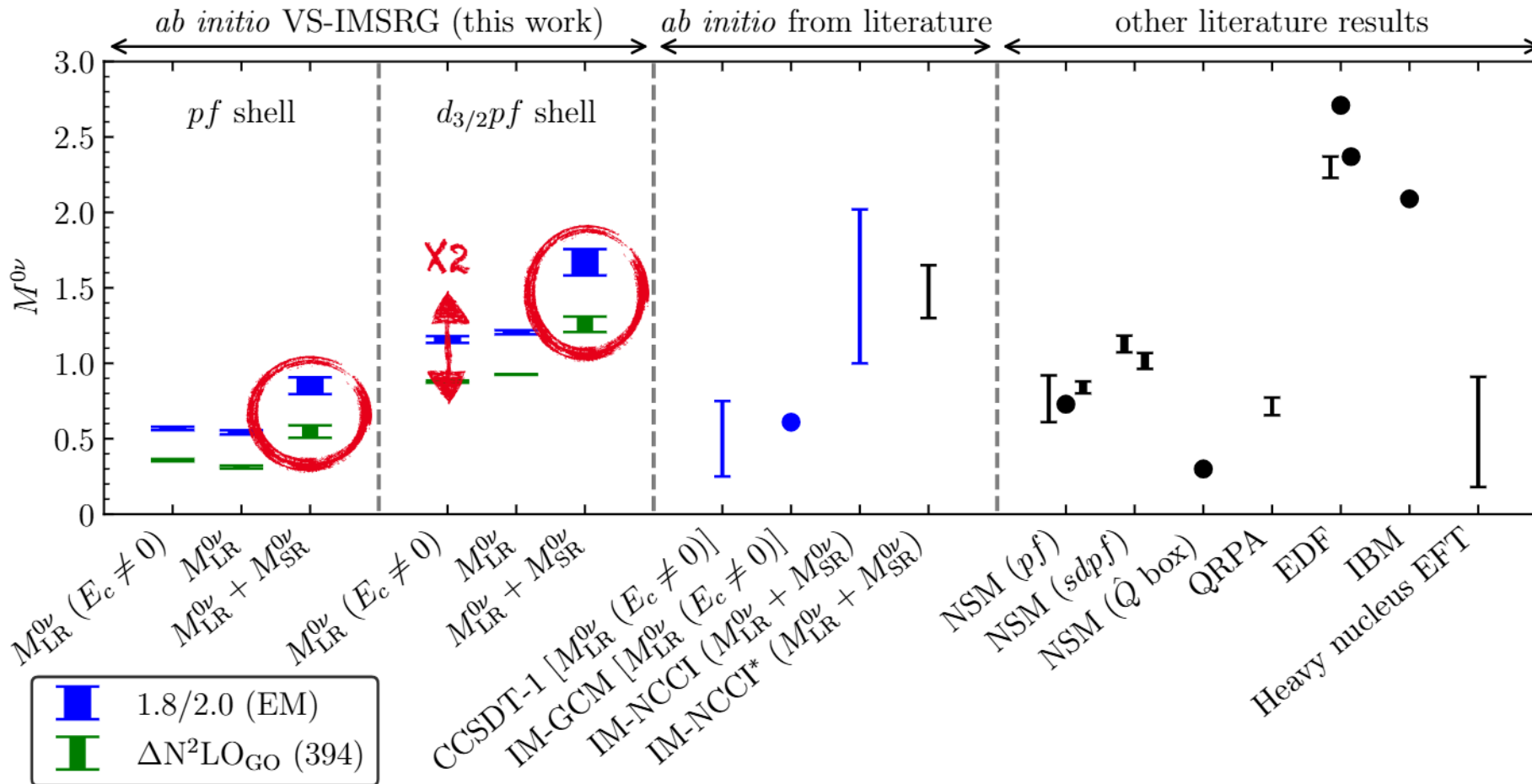
Li, Jokiniemi, Schwenk, arXiv:2607.11733

HOW DOES THIS AFFECT $0\nu\beta\beta$ DECAY?



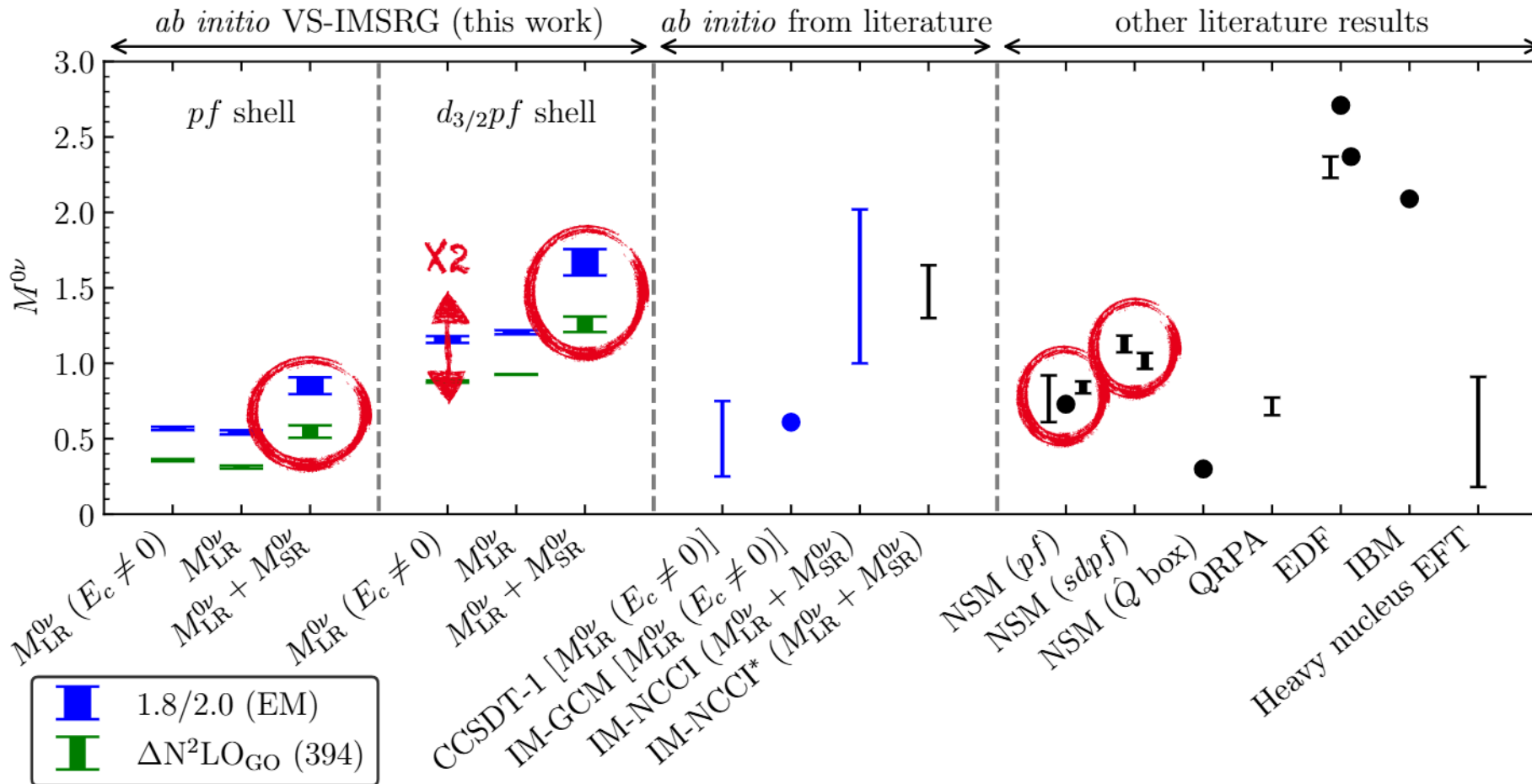
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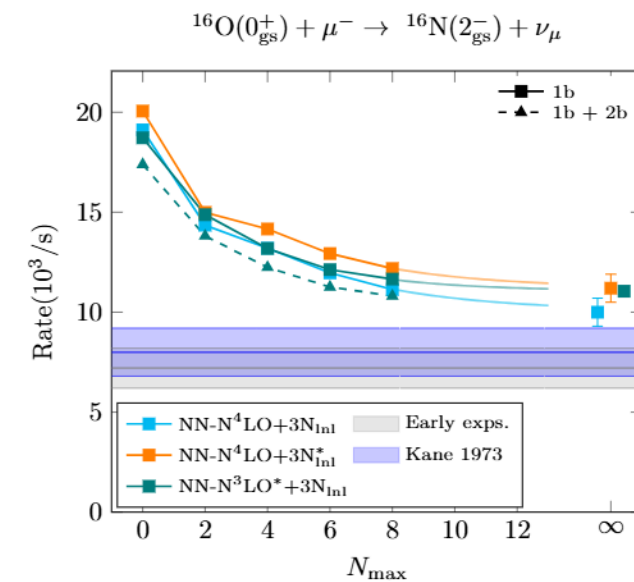
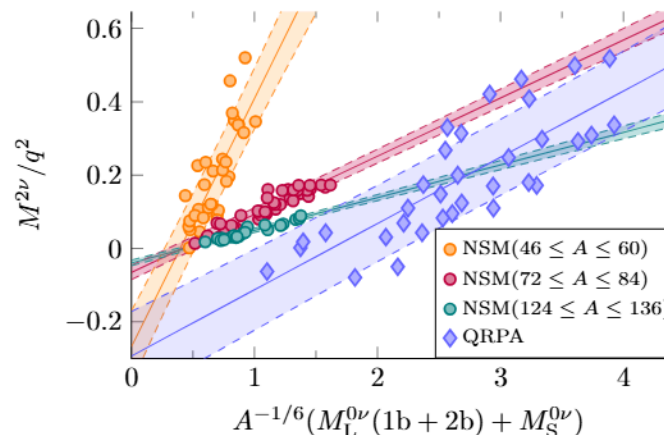
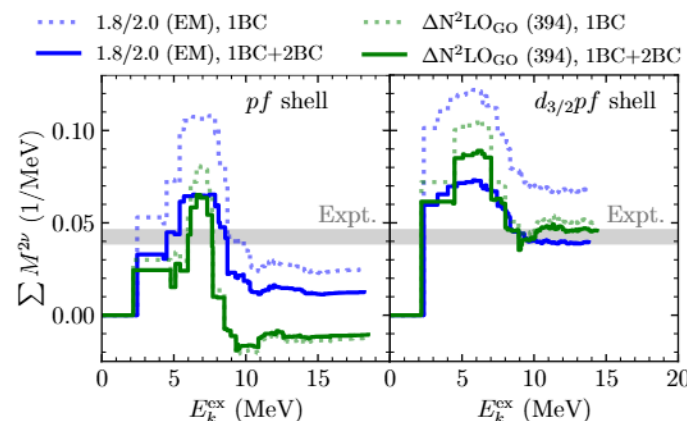
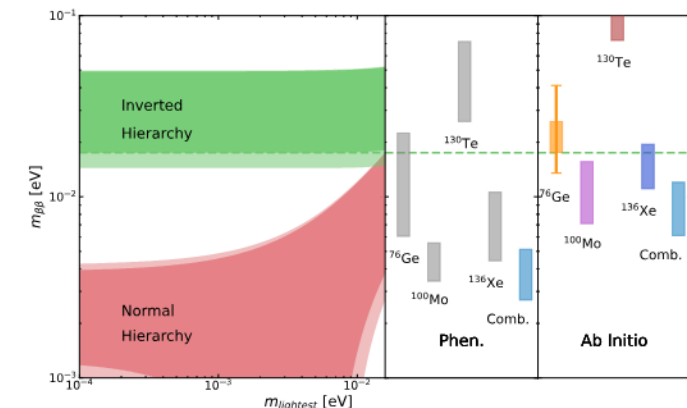
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Li, Jokiniemi, Schwenk, arXiv:2607.11733

SUMMARY

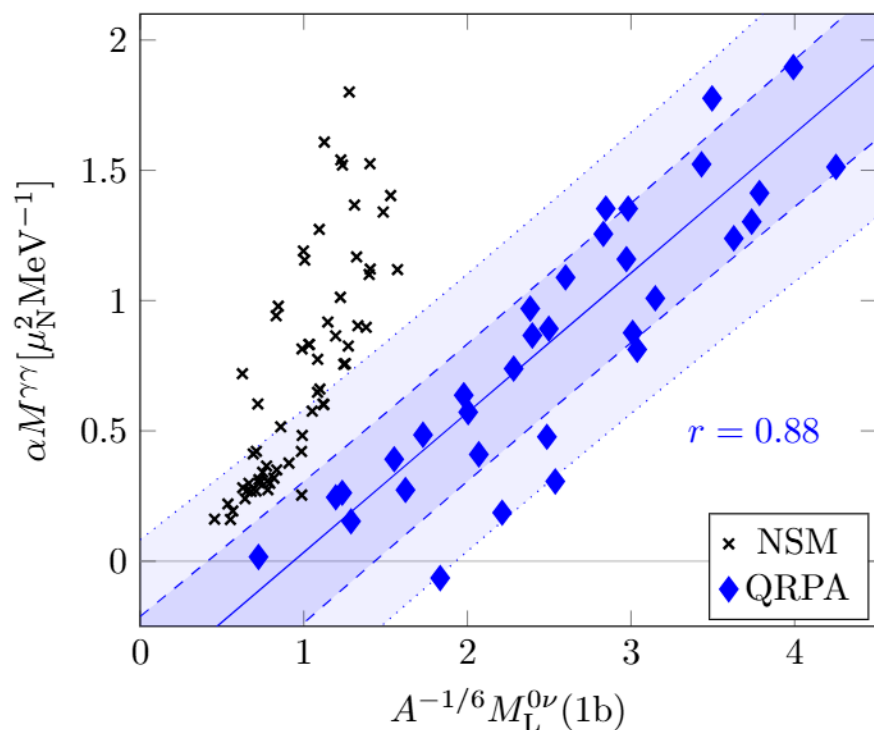
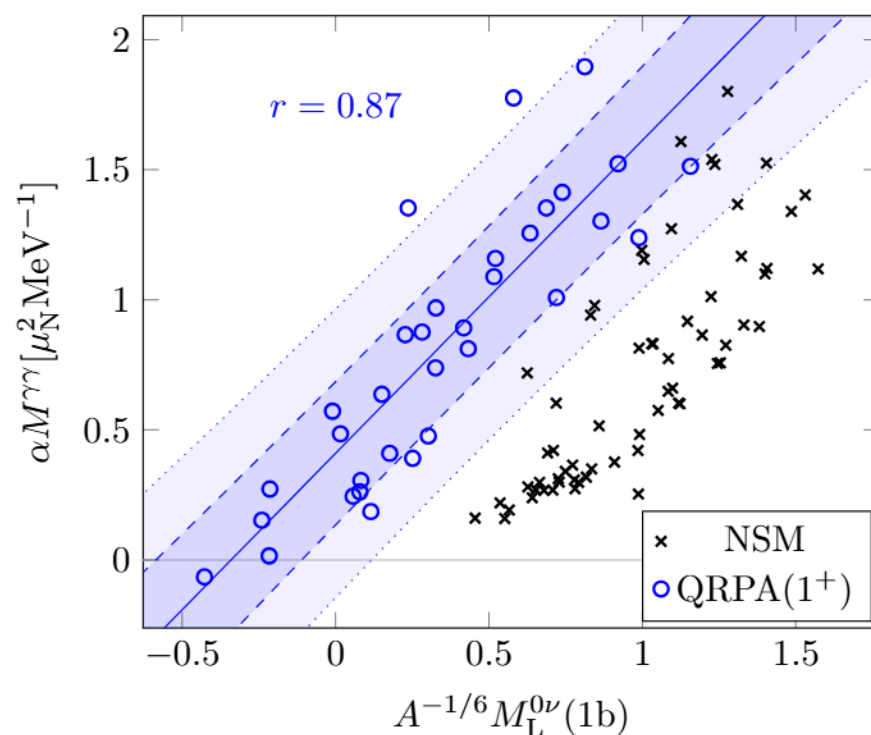
- Next-generation $0\nu\beta\beta$ -decay experiments likely to fully cover the inverted-hierarchy band of neutrino masses
- Muon capture a good probe for high-momentum electroweak currents
- Correlations with different observables help constrain the $0\nu\beta\beta$ -decay matrix elements
- Important correlations were missing from *ab initio* calculations of $\beta\beta$ decays of $^{48}\text{Ca} \rightarrow$ *How about heavier cases?*





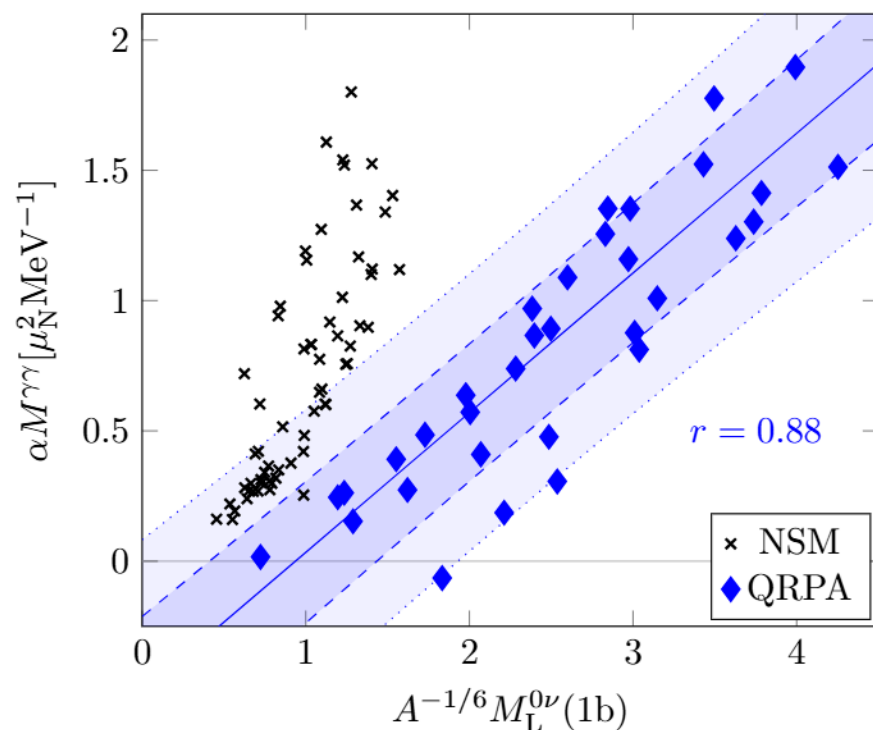
BACK-UP

CORRELATION BETWEEN $\gamma\gamma$ AND $0\nu\beta\beta$ DECAYS WITH 1^+ STATES ONLY

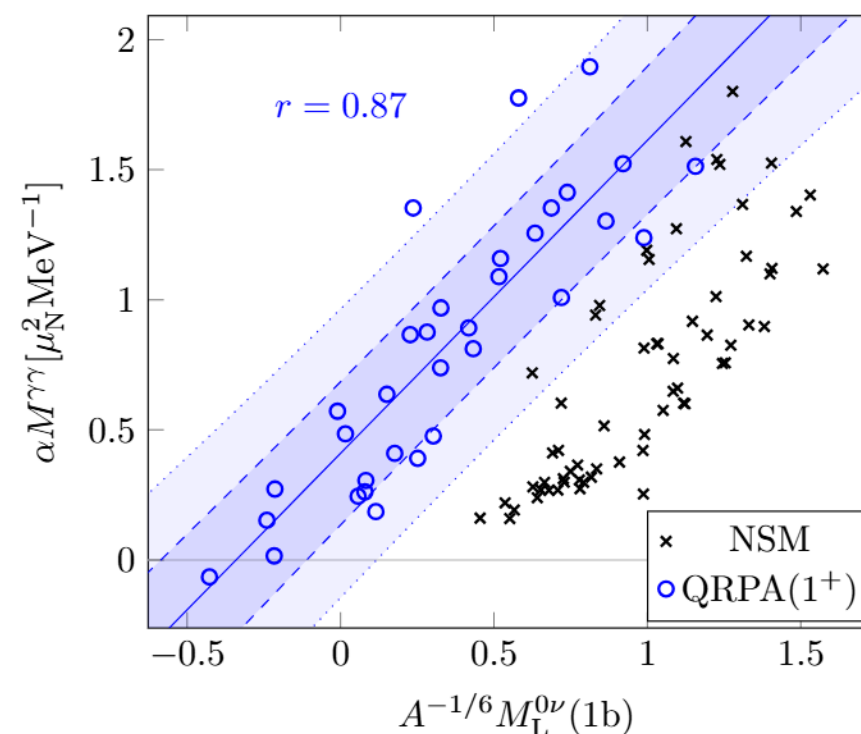
 All J^π states included in $M^{0\nu}$

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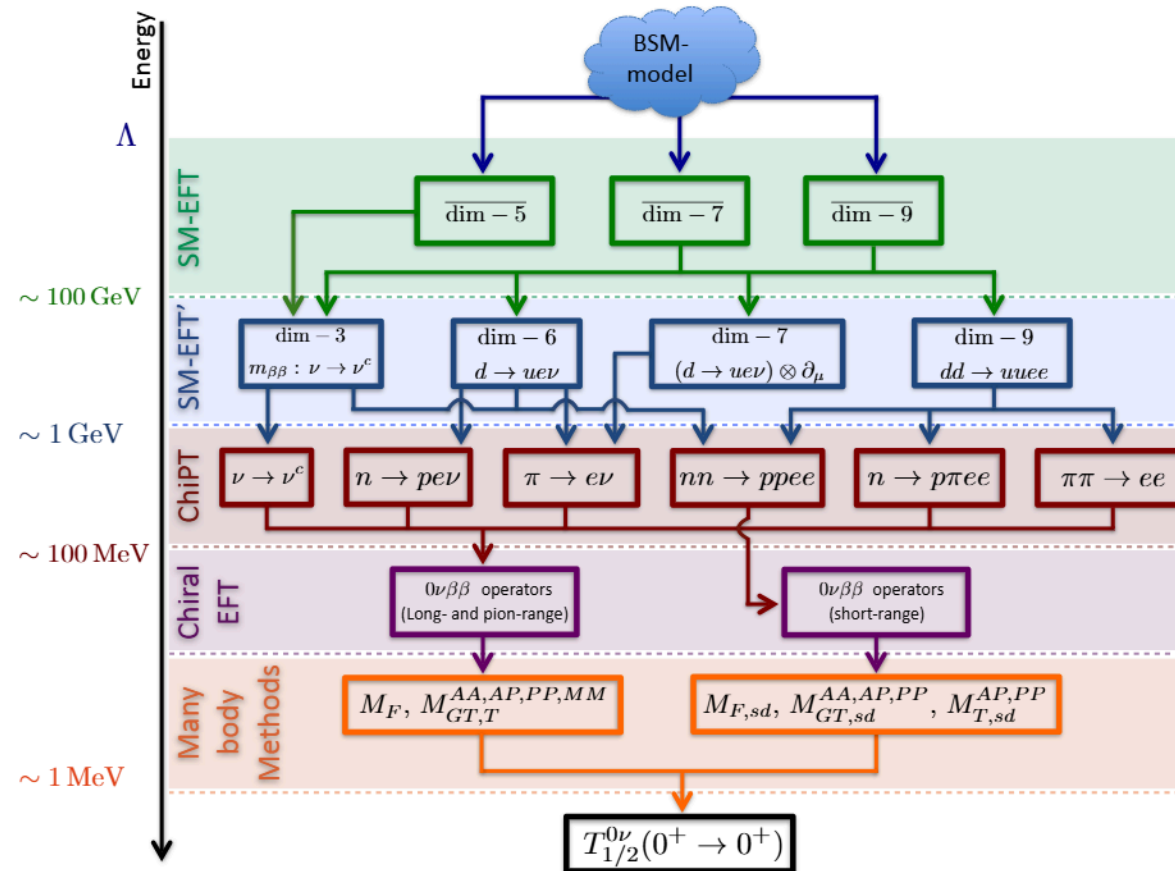


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Jokiniemi, Menéndez, *Phys. Rev. C* 107, 044316 (2023)

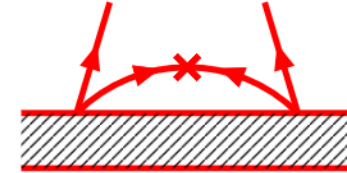
CHIRAL EFFECTIVE THEORY OPERATORS FOR $0\nu\beta\beta$ DECAY



Cirigliano, Dekens, de Vries, Graesser, Mereghetti, JHEP 12, 097 (2018)

CONTRIBUTION FROM ULTRASOFT NEUTRINOS

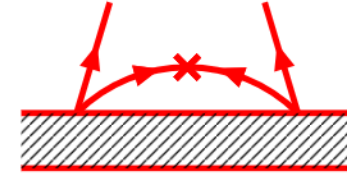
$$M_{\text{usoft}}^{0\nu} = -\frac{2\pi}{R} \sum_n \langle f \| \sum_a \tau_a^- \sigma_a \| n \rangle \langle n \| \sum_b \tau_b^- \sigma_b \| i \rangle \\ \times (E_e + E_n - E_i) \left(\ln \frac{\mu_{\text{us}}}{2(E_e + E_n - E_i)} + 1 \right)$$



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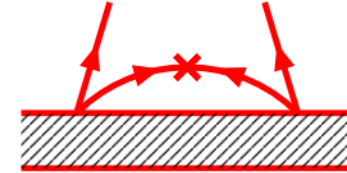
- Contribution from “**ultrasoft**”
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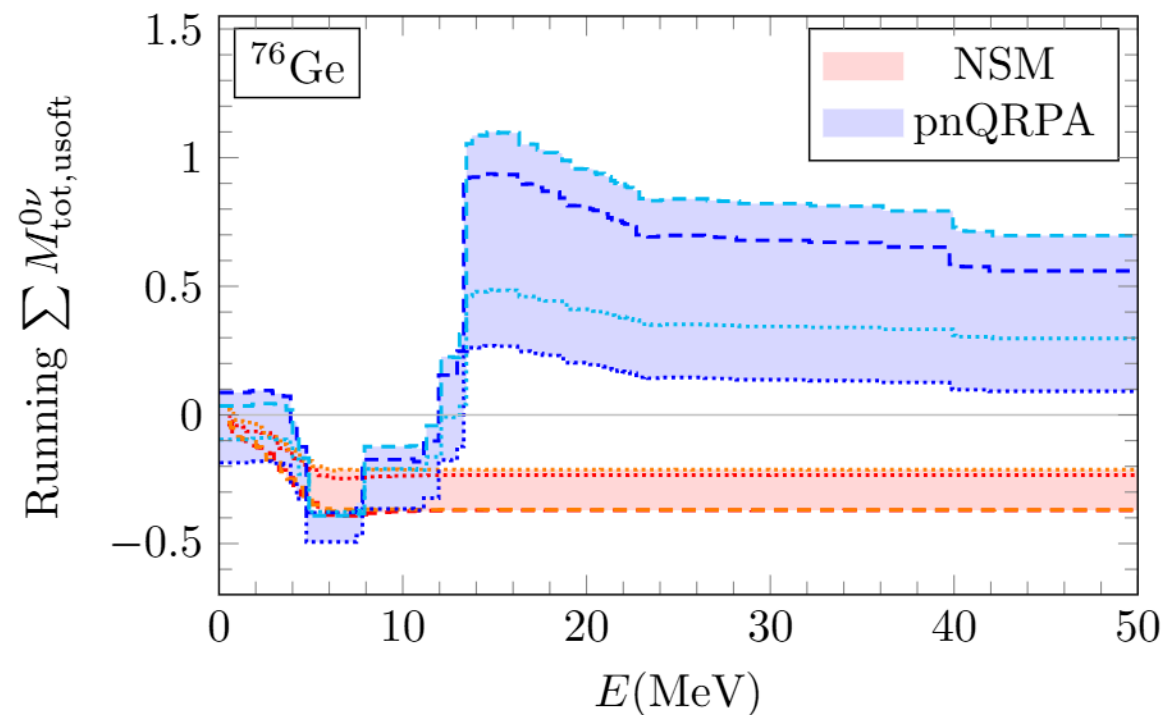
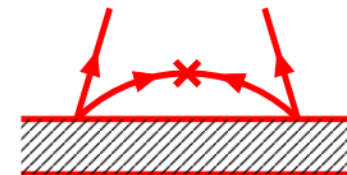
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- According to the NSM and pnQRPA,

$$\left| \frac{M_{\text{usoft}}^{0\nu}}{M_{\text{LO}}^{0\nu}} \right| \sim 5\% - 10\%$$

Castillo, Jokiniemi, Soriano, Menéndez, *Phys. Lett. B* 860, 139181 (2025)



Castillo, Jokiniemi, Soriano, Menéndez, *Phys. Lett. B* 860, 139181 (2025)

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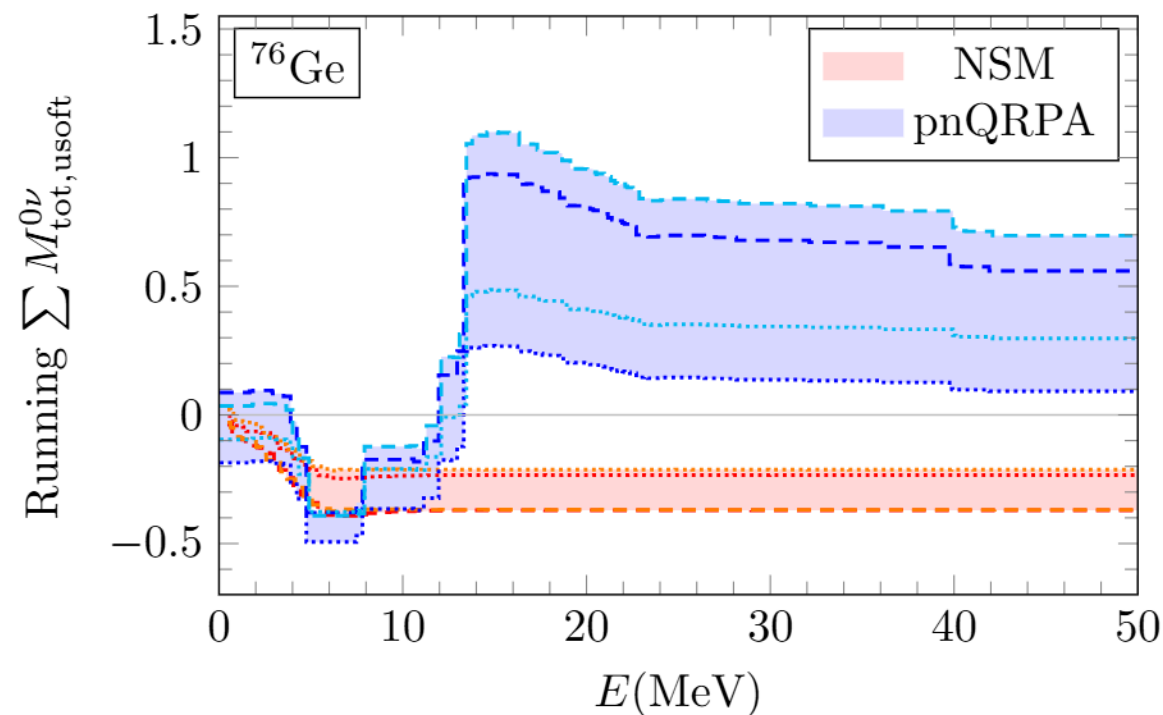
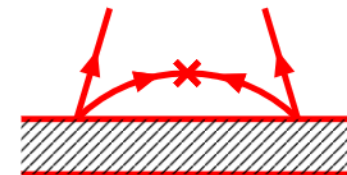
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Castillo, Jokiniemi, Soriano, Menéndez, *Phys. Lett. B* 860, 139181 (2025)

- Can be seen as a “closure correction”



Castillo, Jokiniemi, Soriano, Menéndez, *Phys. Lett. B* 860, 139181 (2025)

CONTRIBUTION FROM ULTRASOFT NEUTRINOS

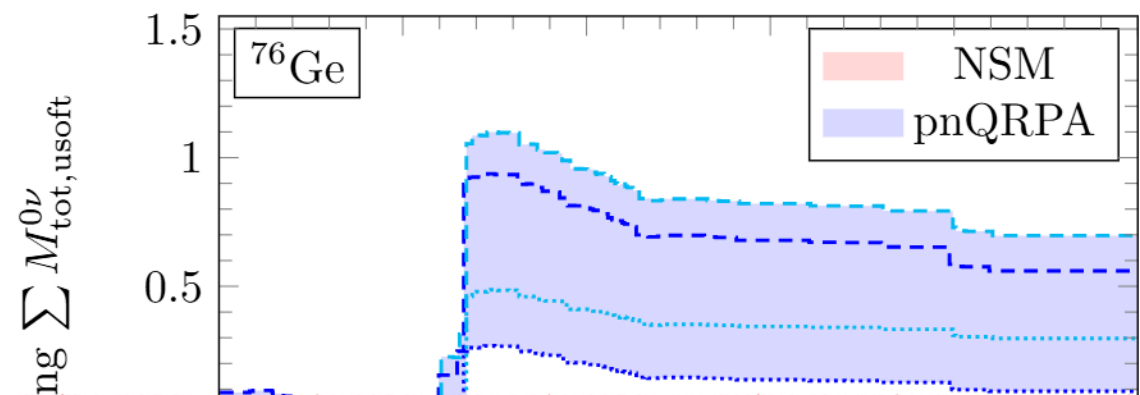
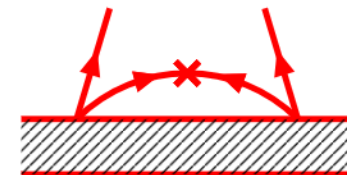
$$M_{\text{usoft}}^{0\nu} = -\frac{2\pi}{R} \sum_n \langle f || \sum_a \tau_a^- \sigma_a || n \rangle \langle n || \sum_b \tau_b^- \sigma_b || i \rangle \times (E_e + E_n - E_i) \left(\ln \frac{\mu_{\text{us}}}{2(E_e + E_n - E_i)} + 1 \right)$$

- Contribution from “**ultrasoft**” ($|\mathbf{k}| \ll k_F \sim 100 \text{ MeV}$) neutrinos
- According to the NSM and pnQRPA,

$$\left| \frac{M_{\text{usoft}}^{0\nu}}{M_{\text{LO}}^{0\nu}} \right| \sim 5\% - 10\%$$

Castillo, Jokiniemi, Soriano, Menéndez, *Phys. Lett. B* 860, 139181 (2025)

- Can be seen as a “closure correction”



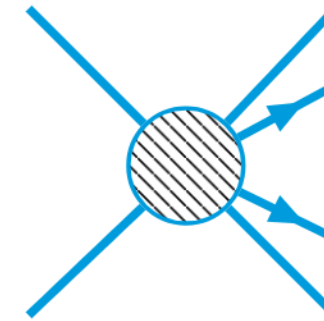
Consistent with the expected size of $N^2\text{LO}$ corrections

$$\left(\frac{Q}{\Lambda} \right)^2 \sim \left(\frac{m_\pi}{\Lambda_\chi} \right)^2 \sim 5\% - 10\%$$

Castillo, Jokiniemi, Soriano, Menéndez, *Phys. Lett. B* 860, 139181 (2025)

CONTACT TERM – UNKNOWN COUPLING

$$M_S^{0\nu} = 2g_\nu^{\text{NN}} \frac{2R}{\pi g_A^2} \langle 0_f^+ \| \sum_{m,n} \tau_m^- \tau_n^- \int j_0(qr) e^{-q^2/(2\Lambda^2)} q^2 dq \| 0_i^+ \rangle$$

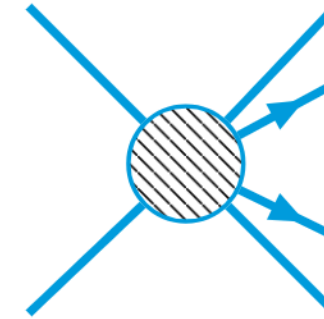


$$\sim C_1 \equiv g_\nu^{\text{NN}}$$

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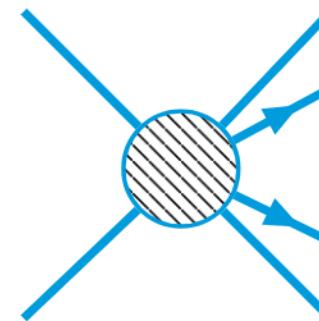


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- What to do?

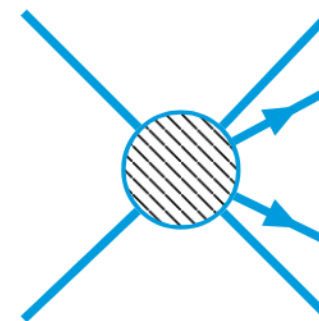


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 - ✗ Fit to lepton-number violating data



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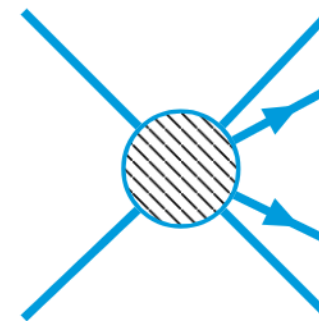
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? Determine from lattice QCD

Cirigliano, Davoudi, Engel, Furnstahl, Hagen et al., J. Phys. G. Nucl. Part. Phys. 49, 120502 (2022)



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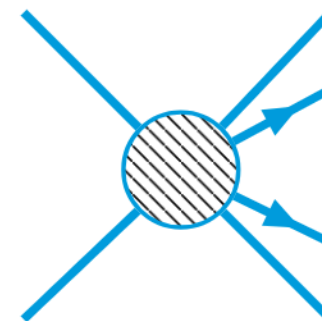
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Cirigliano, Dekens, de Vries, Graesser, Mereghetti, Pastore, van Kolck, Phys. Rev. Lett. 120, 202001 (2018)



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Cirigliano, Davoudi, Engel, Furnstahl, Hagen et al., J. Phys. G. Nucl. Part. Phys. 49, 120502 (2022)

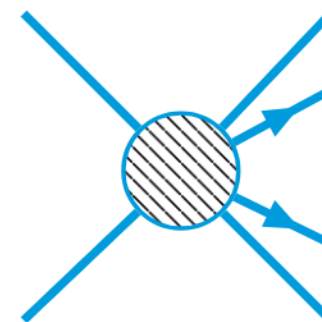
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Cirigliano, Dekens, de Vries, Graesser, Mereghetti, Pastore, van Kolck, Phys. Rev. Lett. 120, 202001 (2018)

✓ Fit to **synthetic data**

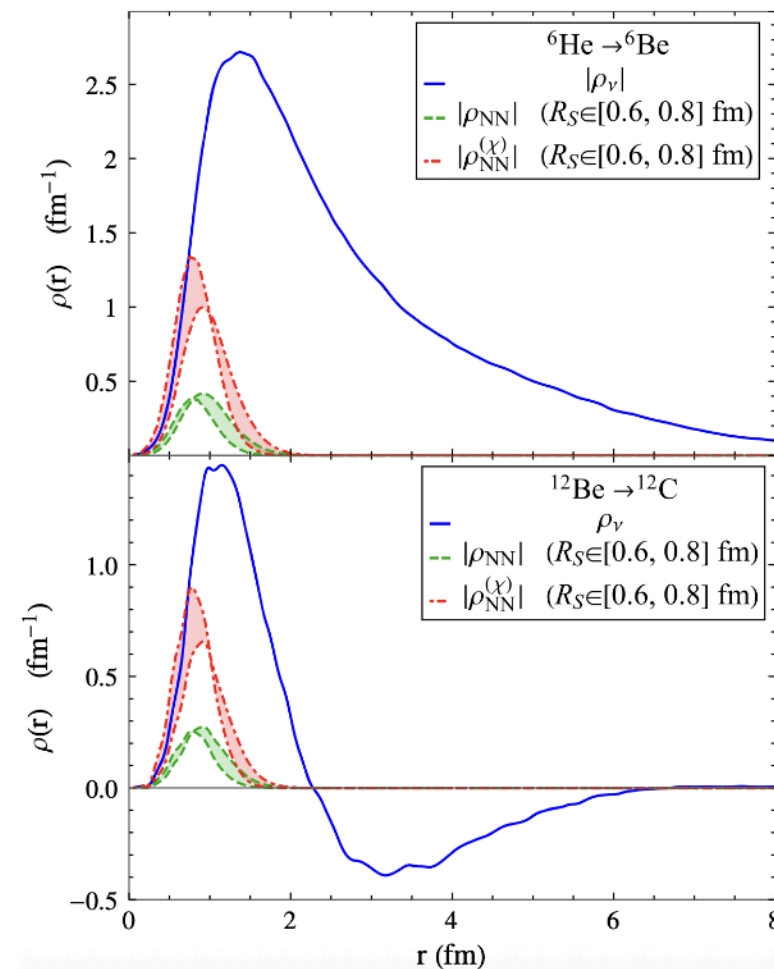
Cirigliano, Dekens, de Vries, Hoferichter, Mereghetti, Phys. Rev. Lett. 126, 172002 (2021)



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THE CONTACT TERM

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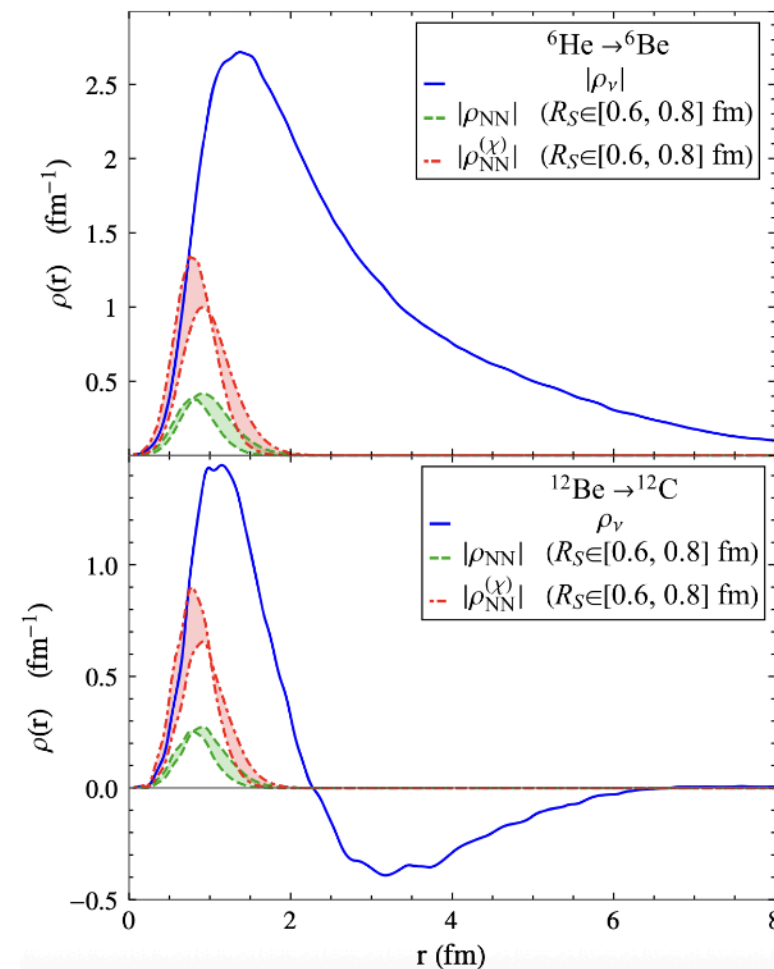
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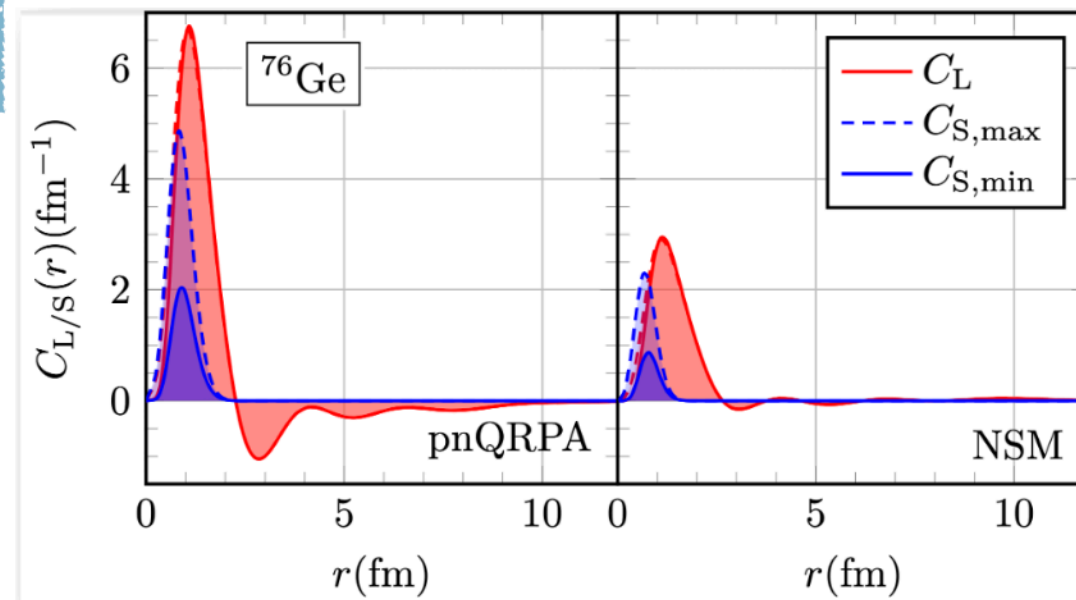
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Jokiniemi, Soriano, Menéndez, Phys. Lett. B 823, 136720 (2021)



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Jokiniemi, Soriano, Menéndez, Phys. Lett. B 823, 136720 (2021)

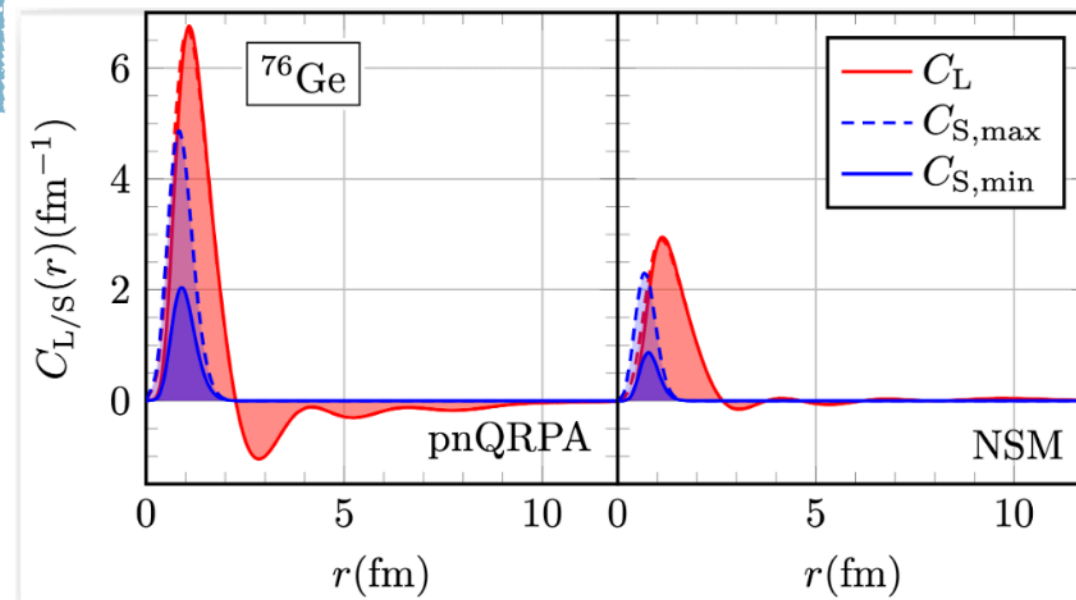
- (Hybrid) *ab initio* methods have also seen **$\sim 25\% - 90\%$ enhancements** in ^{48}Ca , ^{76}Ge , ^{130}Te , and ^{136}Xe

Weiss, Soriano, Lovato, Menéndez, Wiringa, Phys. Rev. C 106, 065501 (2022)

Wirth, Yao, Hergert, Phys. Rev. Lett. 127, 242502 (2021)

Belley, Yao, Bally, Pitcher, Engel, Phys. Rev. Lett. 132, 182502 (2024)

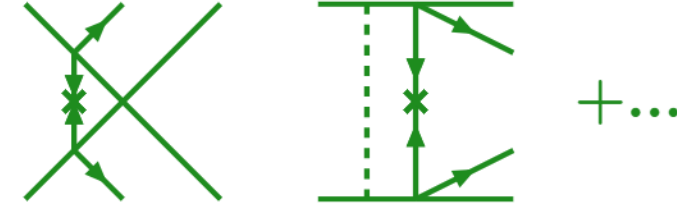
Belley, Miyagi, Stroberg, Holt, arXiv:2307.15156



Jokiniemi, Soriano, Menéndez, Phys. Lett. B 823, 136720 (2021)

LOOP CORRECTIONS

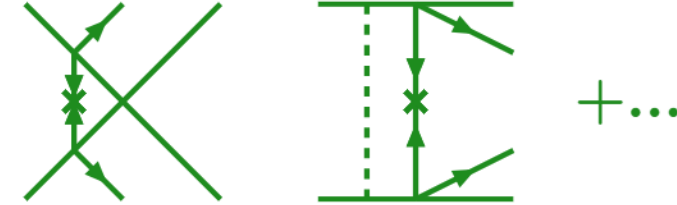
$$M_{\text{loop}}^{0\nu} = \frac{4R}{\pi g_A^2} \langle f || \sum_{a,b} \tau_a^- \tau_b^- \int dq \, q^2 e^{-q^2/2\Lambda^2} j_u(qr) \mathbf{V}_{\nu,2}^{(a,b)} || i \rangle$$



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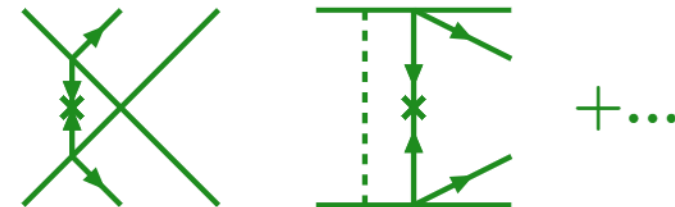


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Pastore, Carlson, Cirigliano, Dekens, Mereghetti, Wiringa, Phys. Rev. C 97, 014606 (2018)

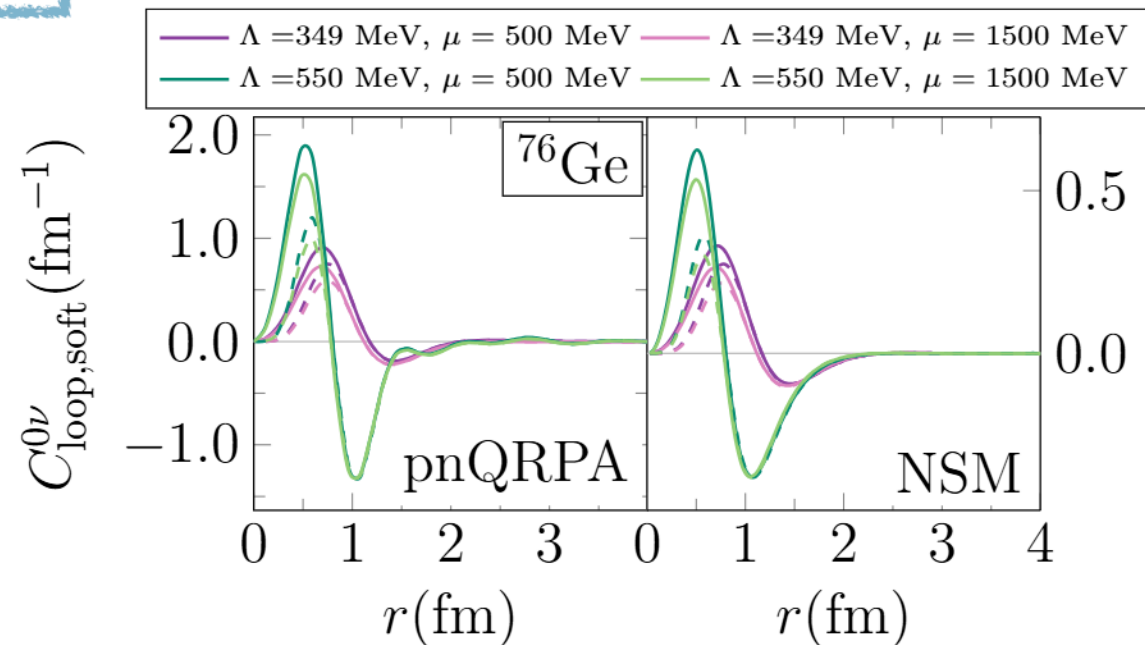
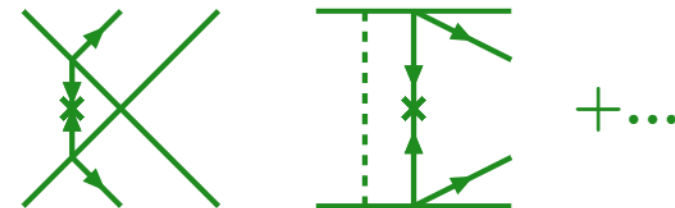


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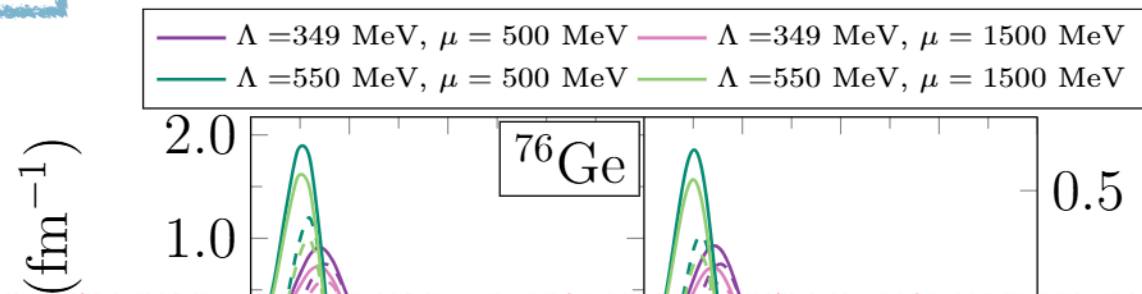
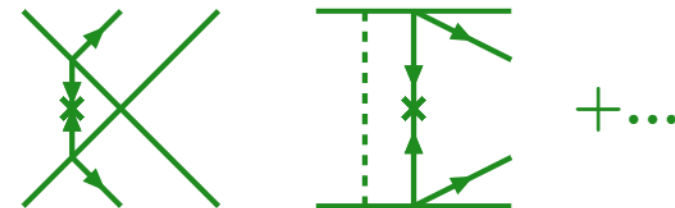
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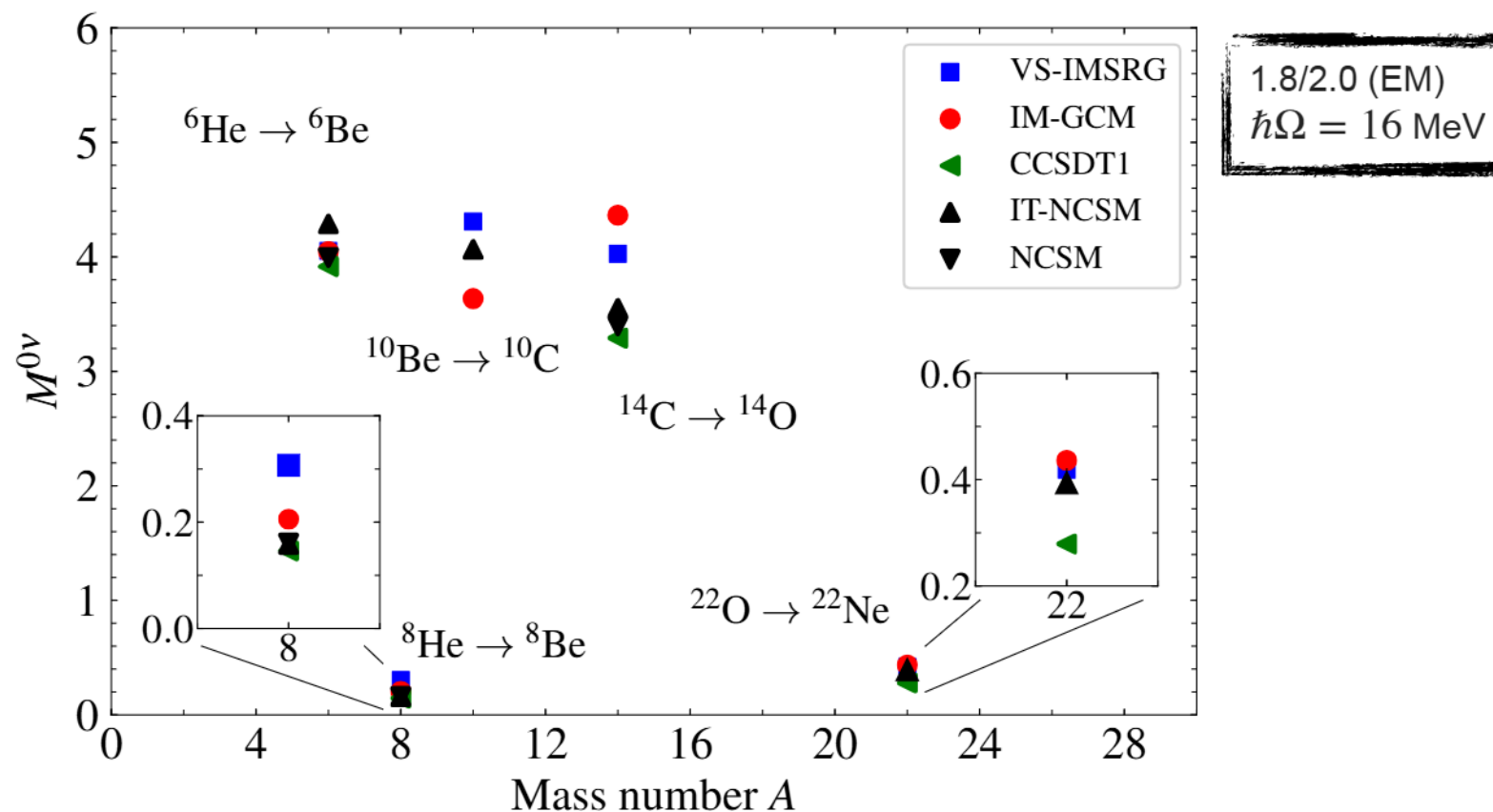


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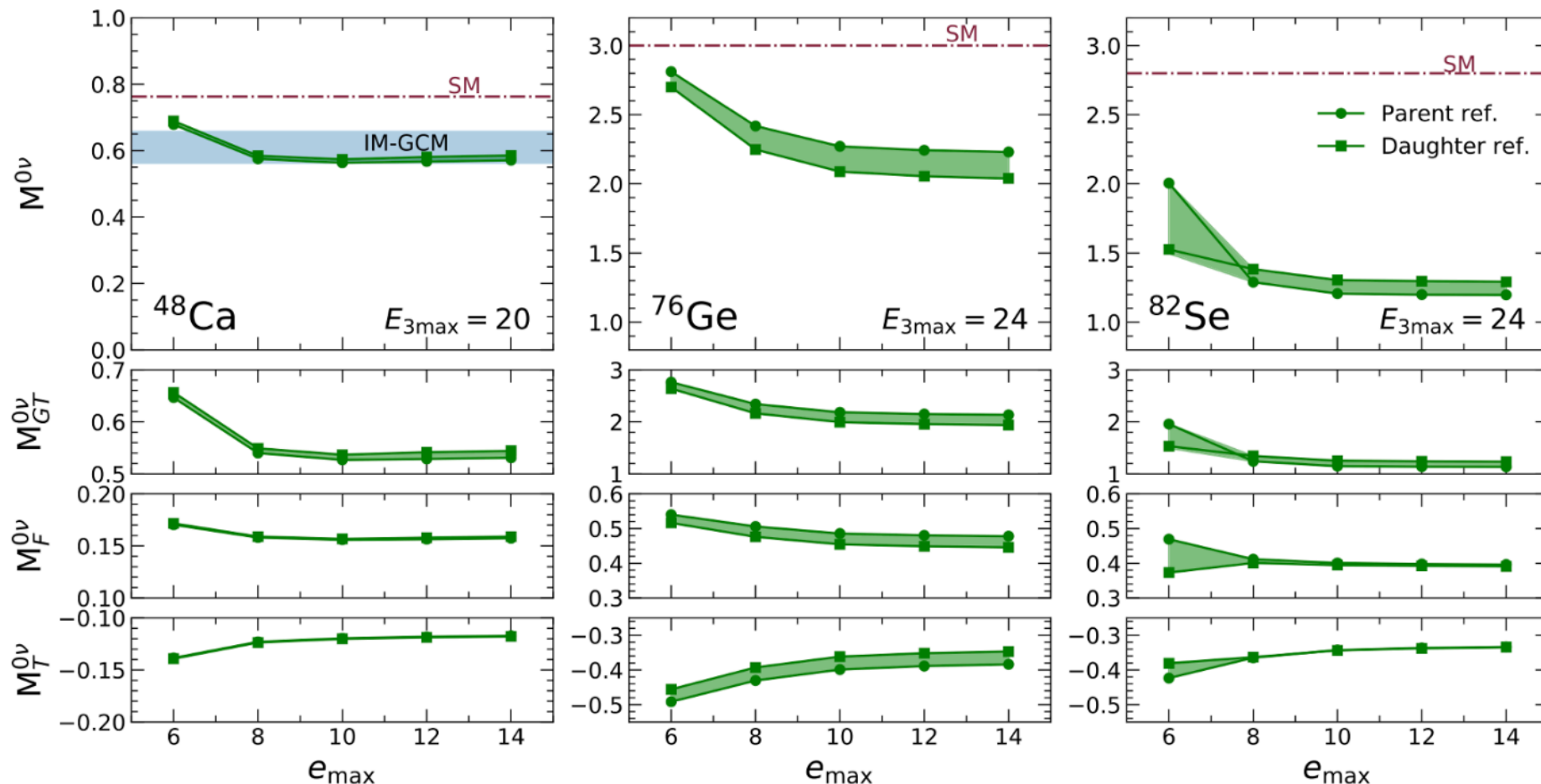
Castillo, Jokiniemi, Menéndez, Phys. Lett. B 860, 139181 (2025)

AB INITIO BENCHMARKS IN LIGHT NUCLEI



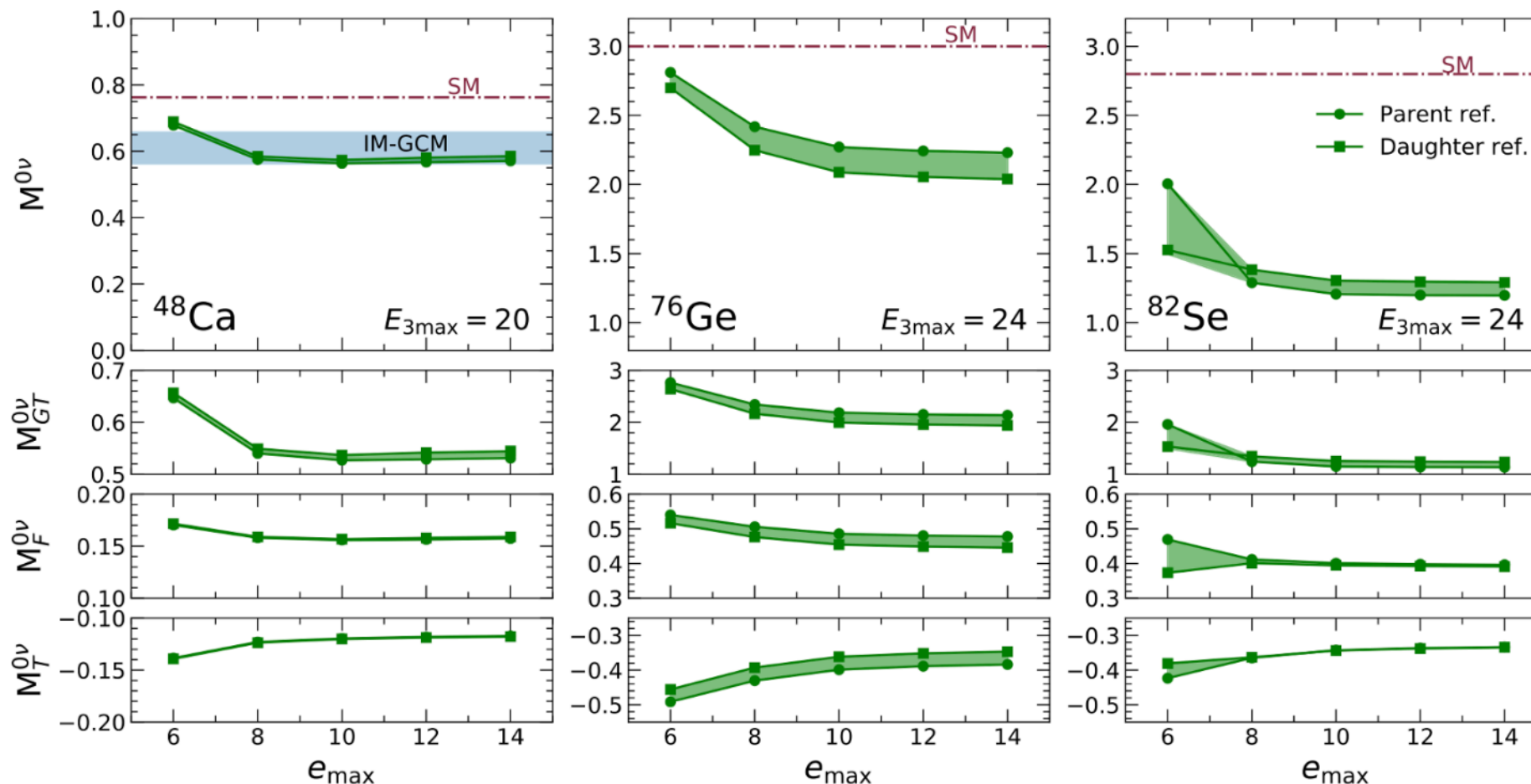
Yao, Belley, Wirth, Miyagi, Payne, Stroberg, Herbert, Holt, *Phys. Rev. C* **103**, 014315 (2021)

AB INITIO RESULTS FOR ^{48}Ca , ^{76}Ge , ^{82}Se



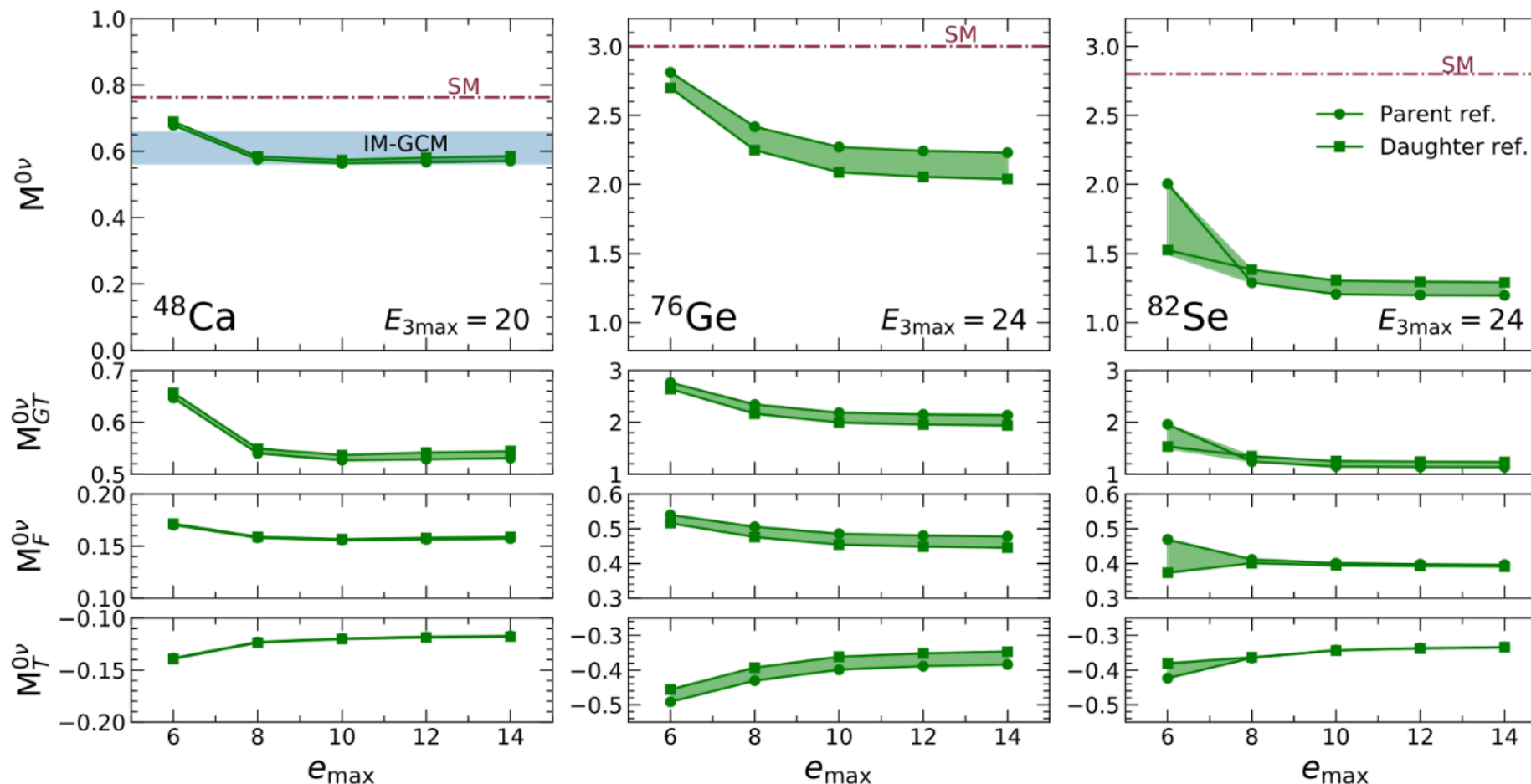
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Nuclear
shell model

Ab initio
VS-IMSRG

Belley, Payne, Stroberg, Miyagi, Holt, Phys. Rev. Lett. 126, 042502 (2021)