# NUCLEAR-THEORY DEVELOPMENTS IN THE STUDY OF NEUTRINOLESS DOUBLE-BETA DECAY

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*Institut für Kernphysik, Theoriezentrum, TU Darmstadt*

FRIB-TA Topical Program: Future directions in nuclear beta decay at FRIB,

FRIB, 8-19 September 2025

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# OUTLINE

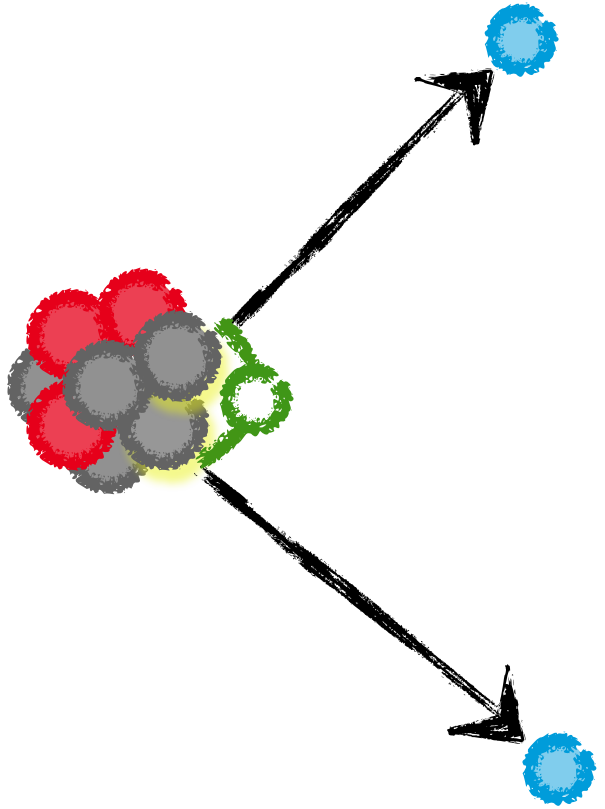

1 Introduction

2 Effective field theory for neutrinoless double-beta decay

3 Probing neutrinoless double-beta decay by nuclear observables

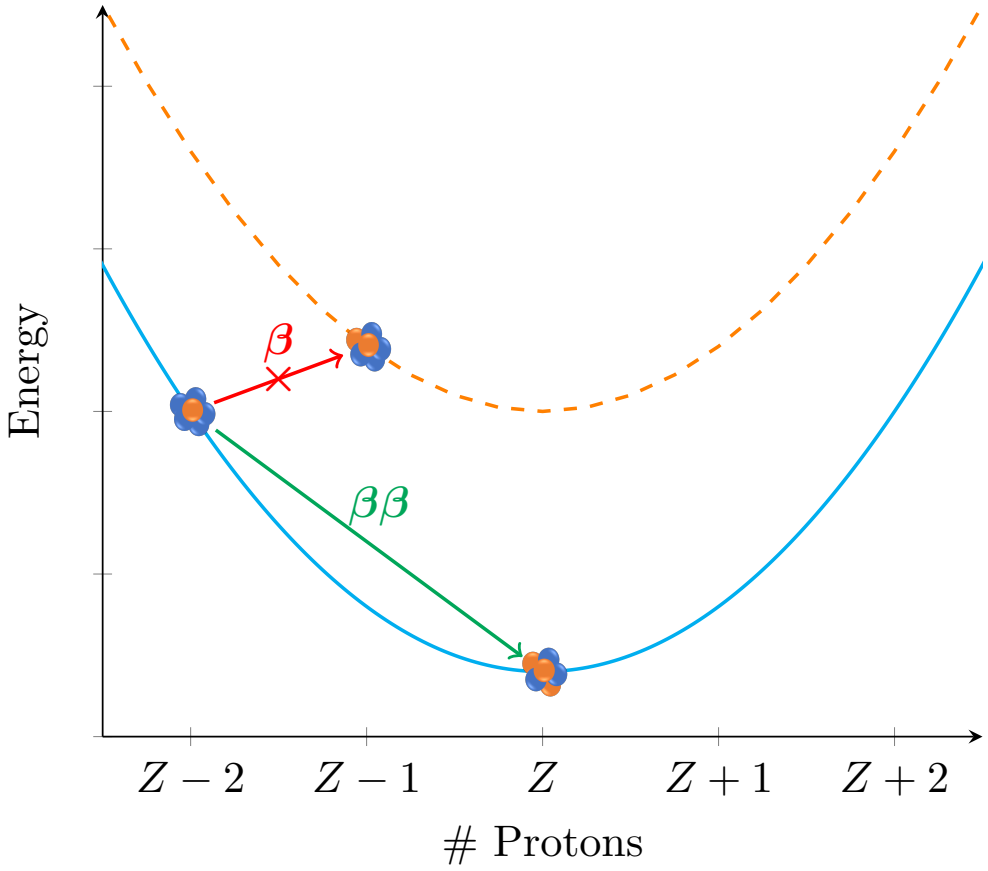
4 Current status

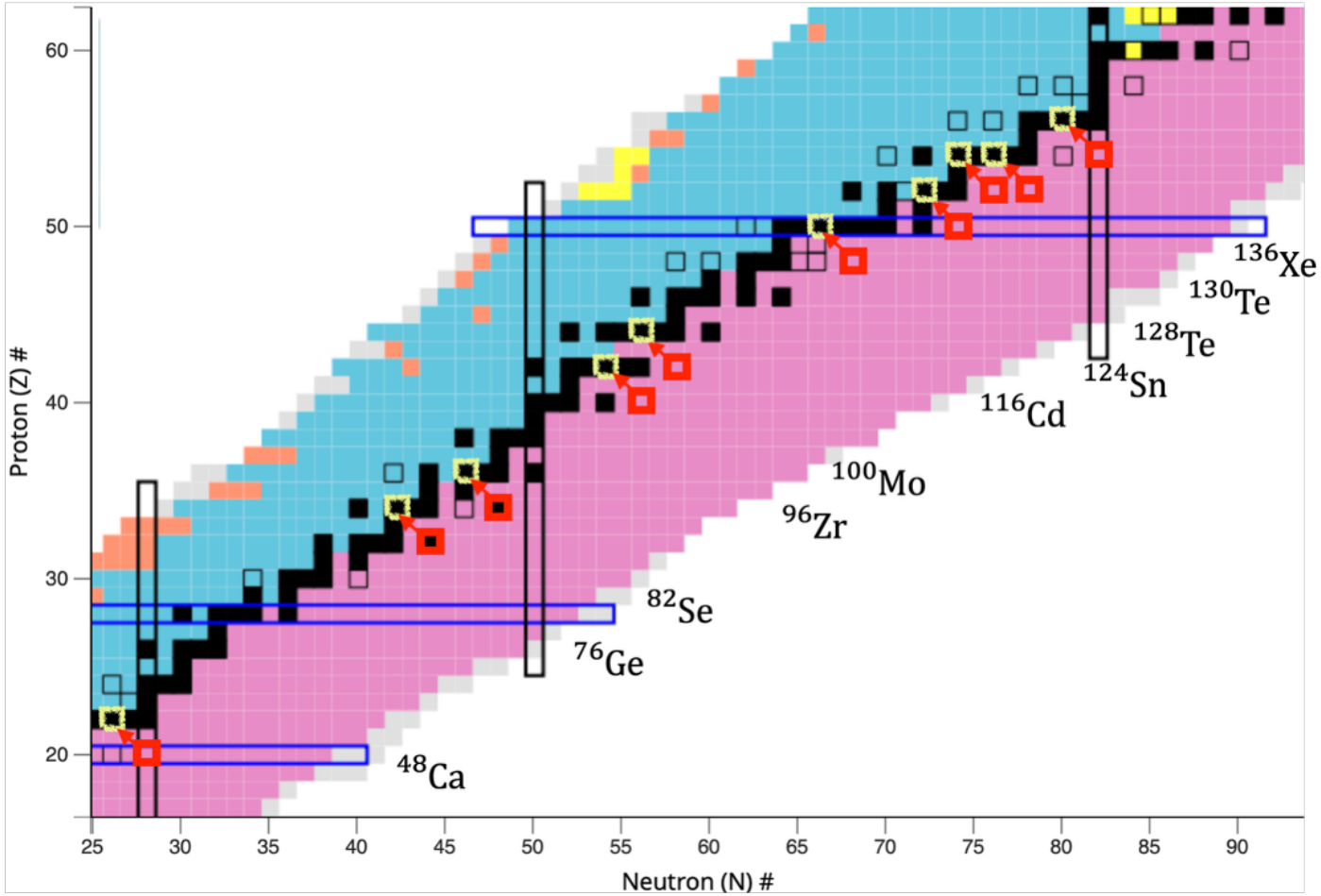
5 Summary and Outlook

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# DOUBLE-BETA DECAY



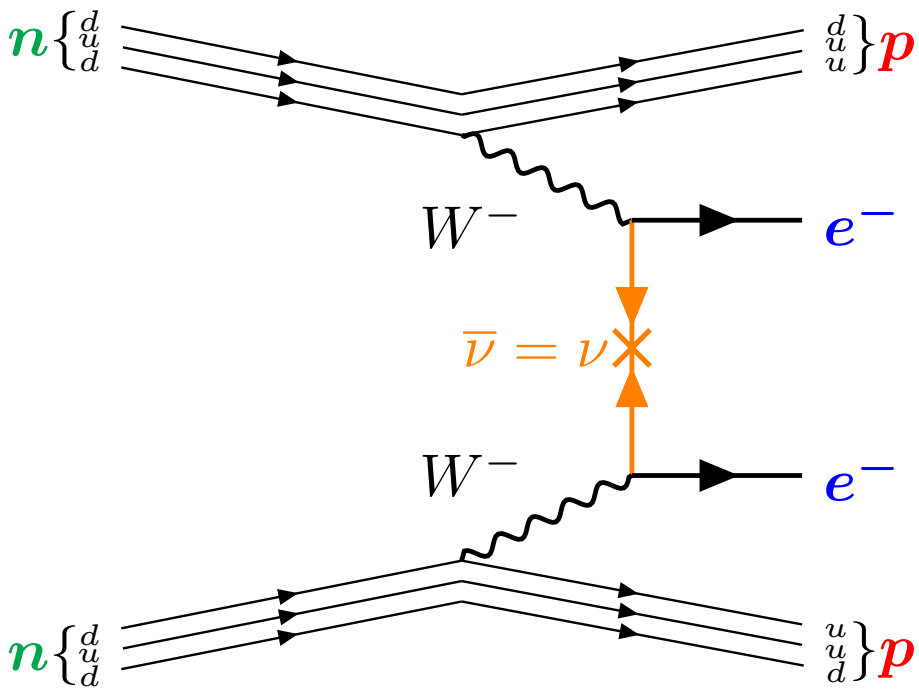




*Modified from nndc.bnl.gov/nudat3/*

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# NEUTRINOLESS DOUBLE-BETA ($0\nu\beta\beta$) DECAY

$$(A, Z) \rightarrow (A, Z+2) + 2e^- \cancel{+ 2\nu_e}$$

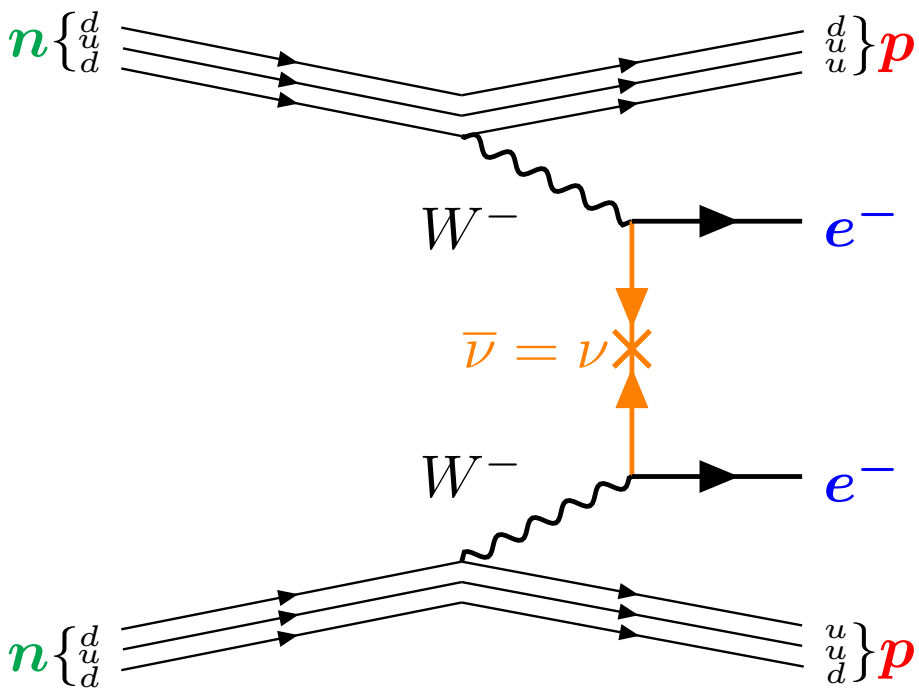


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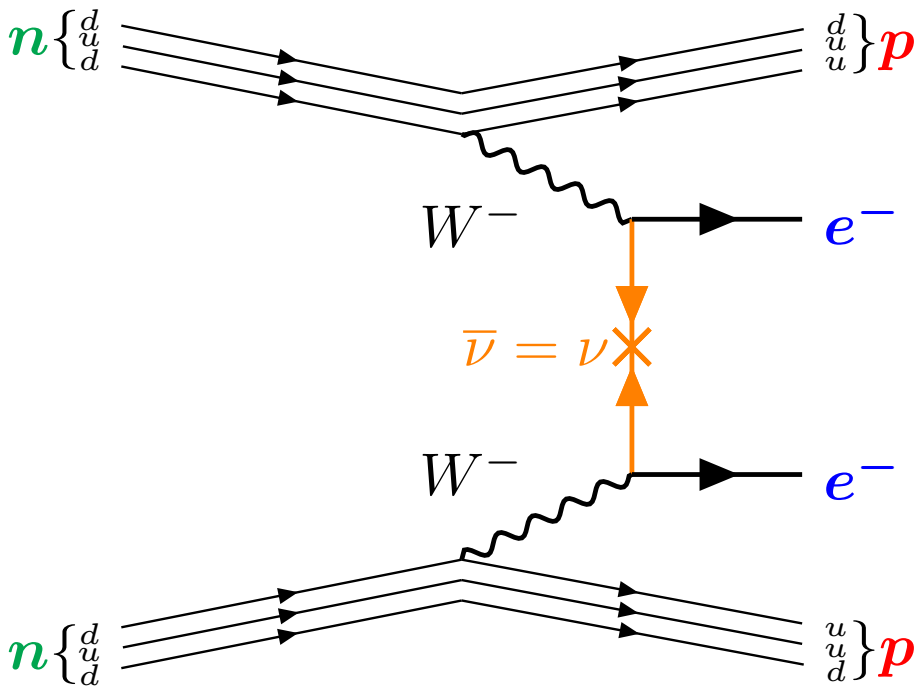


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# NEUTRINOLESS DOUBLE-BETA ($0\nu\beta\beta$) DECAY

- **Violates lepton-number conservation**
- Requires that **neutrinos are Majorana particles**

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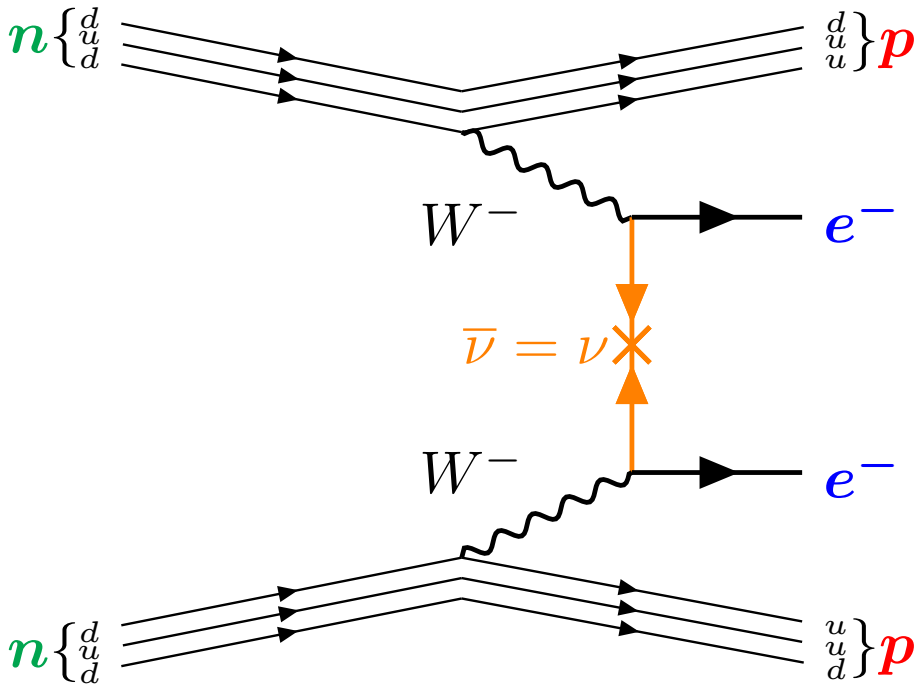


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# NEUTRINOLESS DOUBLE-BETA ($0\nu\beta\beta$) DECAY

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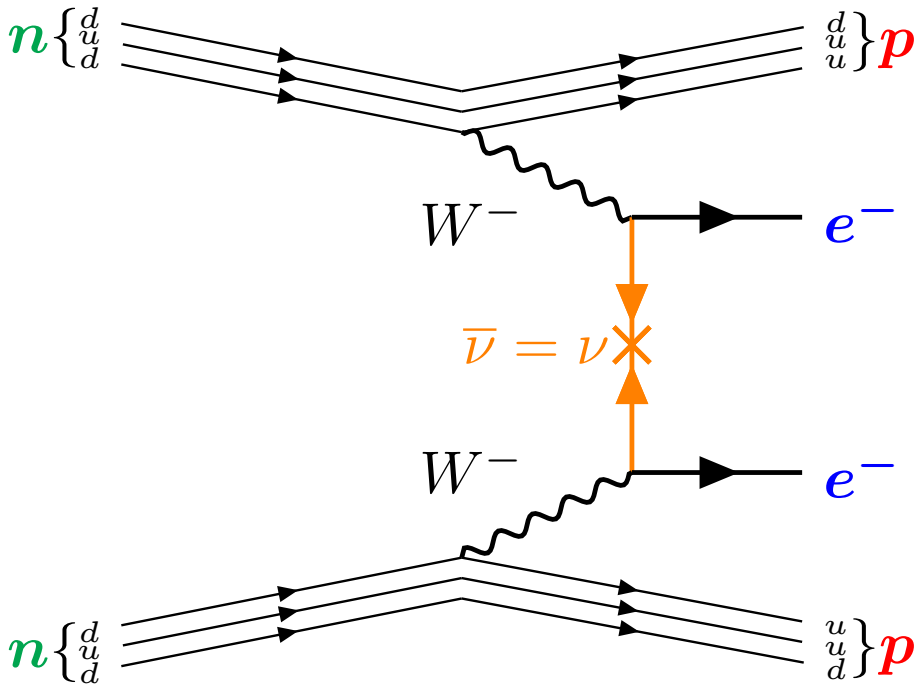
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*($t^{2\nu}_{1/2} \approx 10^{20}$ years, Age of the Universe $\approx 10^{10}$ years)*

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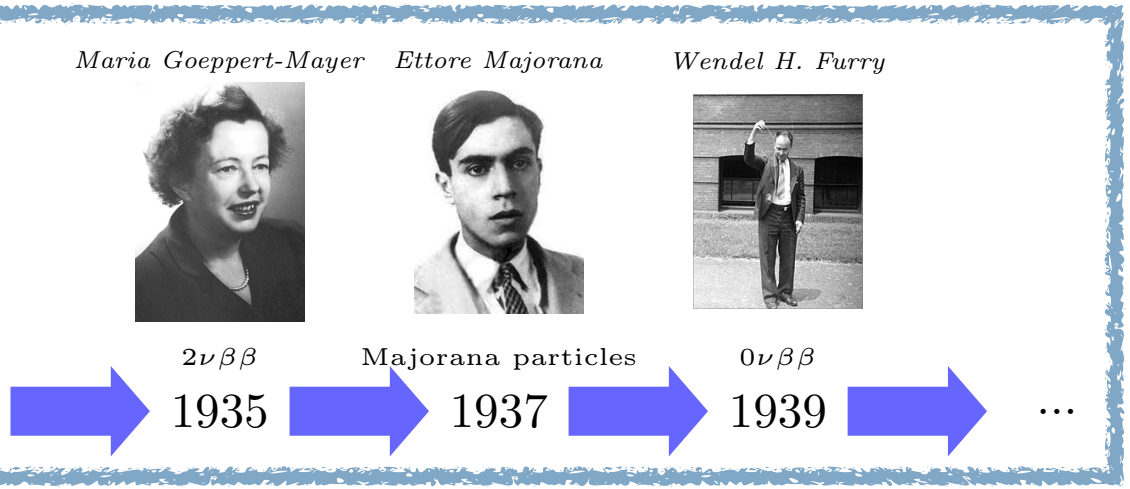


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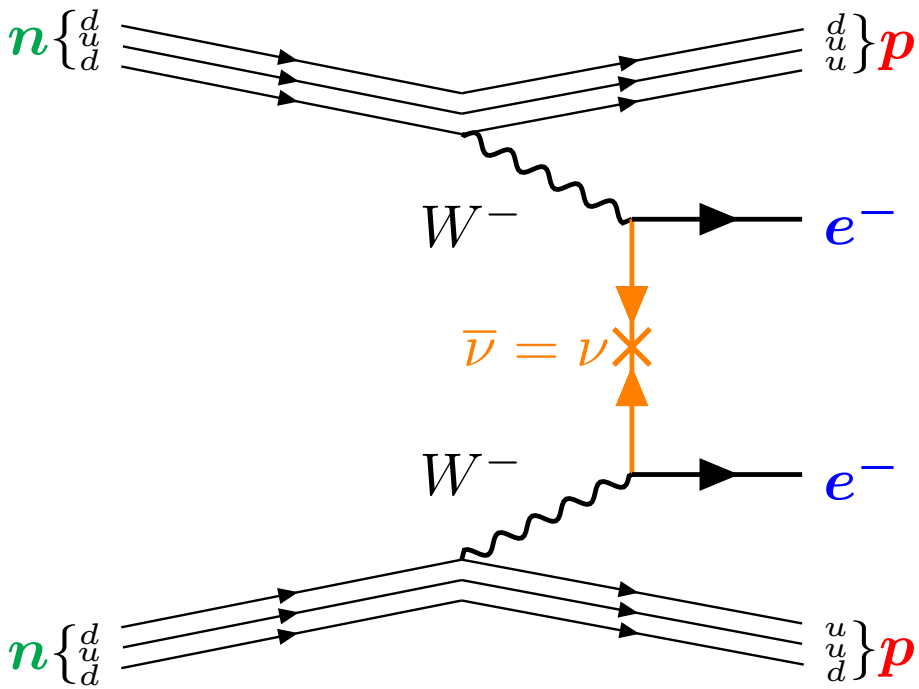
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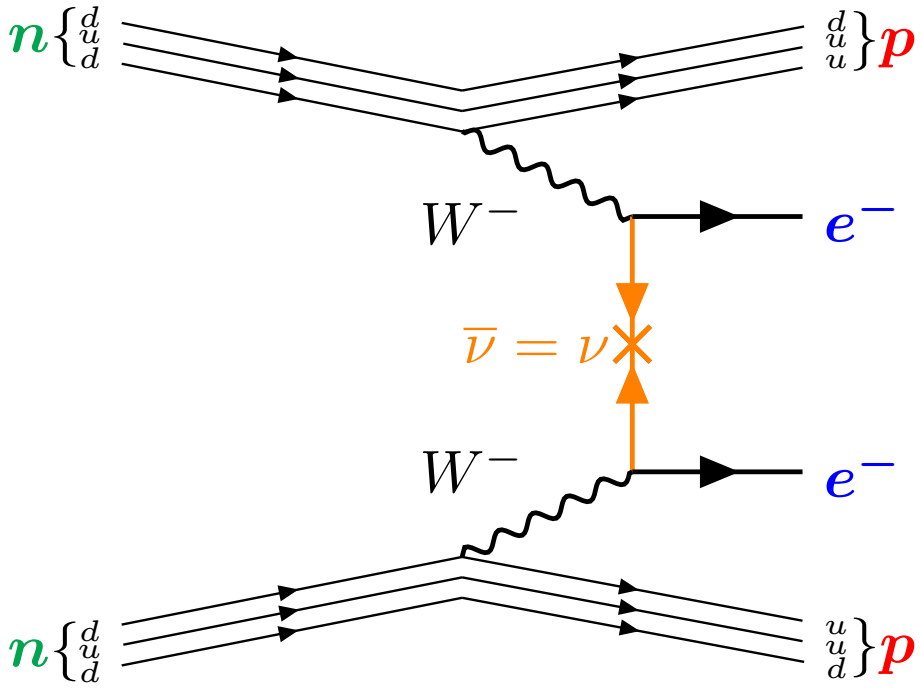



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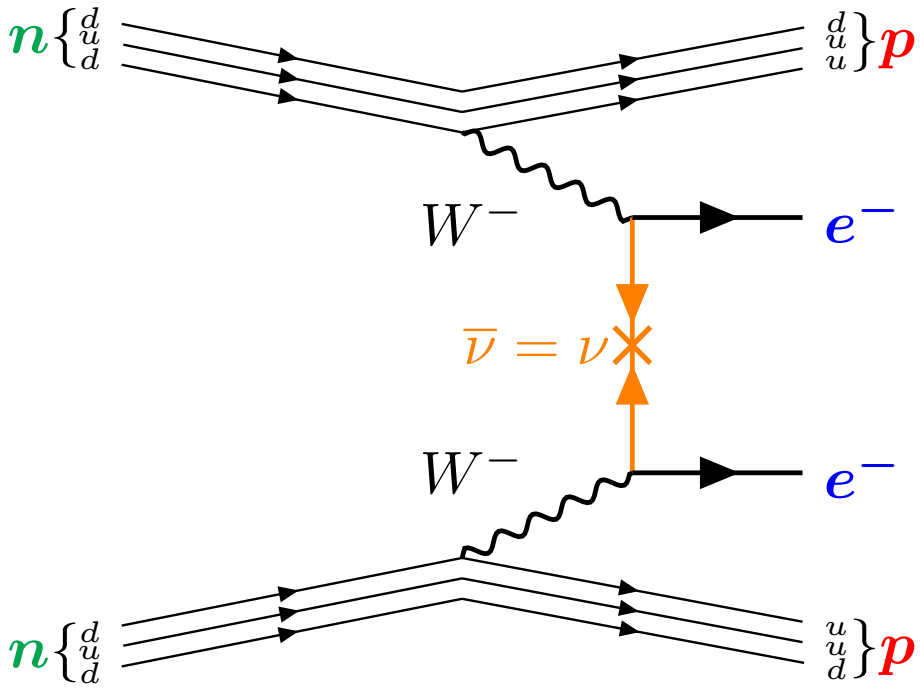
# LIGHT-NEUTRINO EXCHANGE MECHANISM



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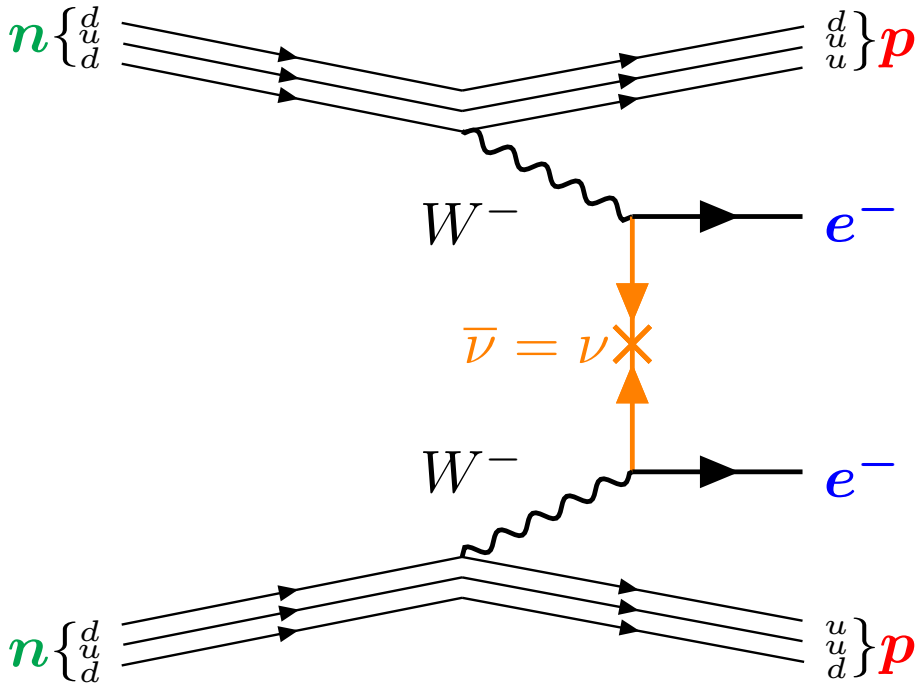
- **Light-neutrino exchange** the most commonly studied mechanism



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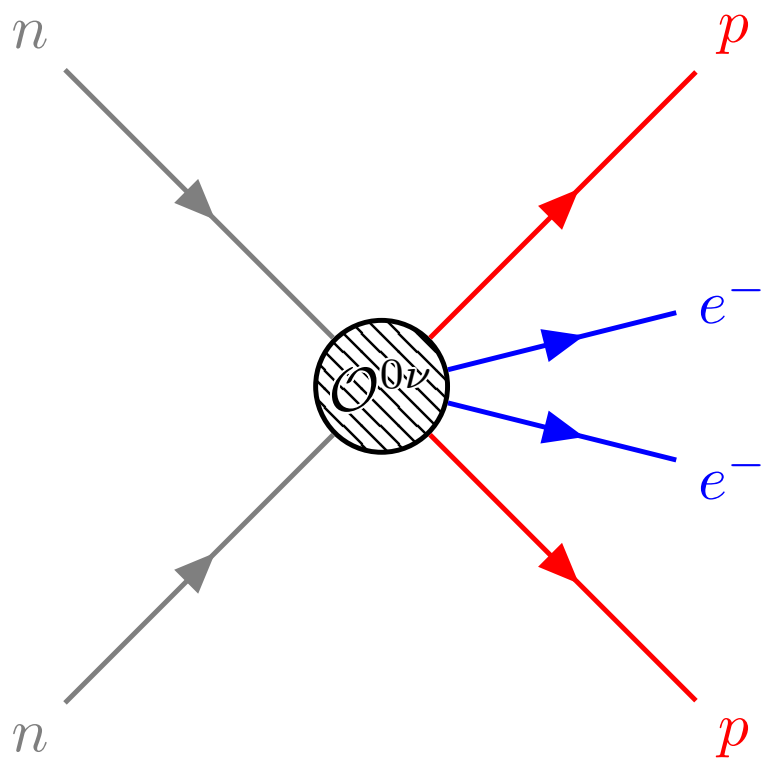
- **Light-neutrino exchange** the most commonly studied mechanism
  - **Does not require introducing additional particles**



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# LIGHT-NEUTRINO EXCHANGE MECHANISM

- **Light-neutrino exchange** the most commonly studied mechanism
  - **Does not require introducing additional particles**
- Other exchange mechanisms (**sterile-neutrino**, scalar, …) are also possible
- In this talk, I will focus on the light-neutrino exchange



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# HALF-LIFE OF $0\nu\beta\beta$ DECAY

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

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# HALF-LIFE OF $0\nu\beta\beta$ DECAY

*Half-life to be measured*

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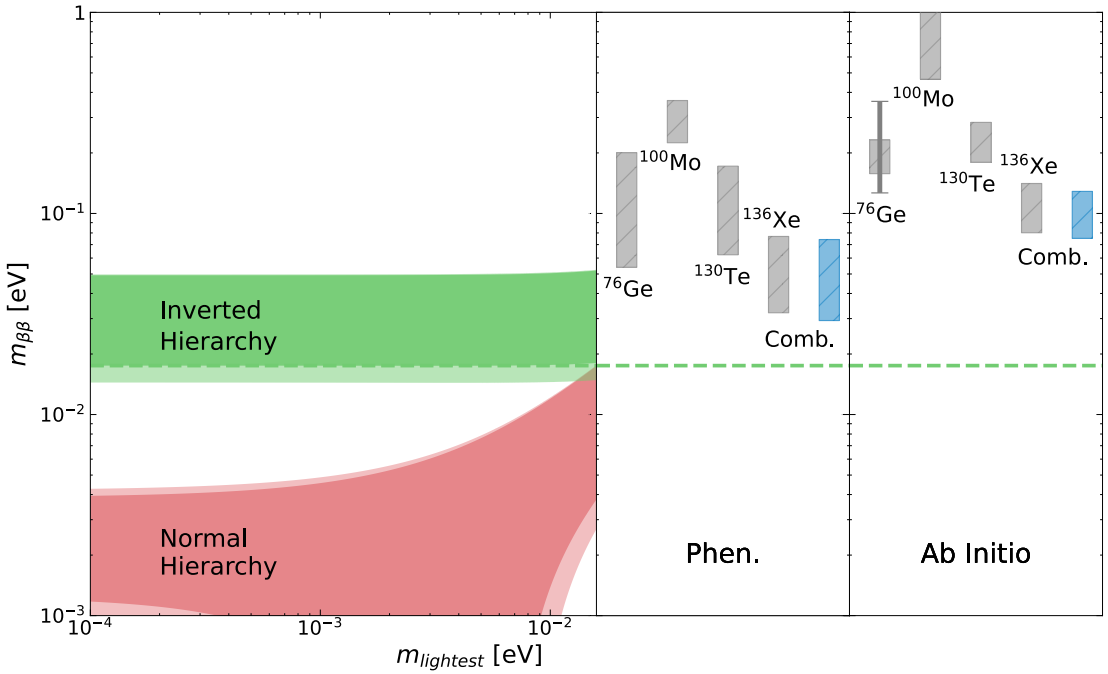
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*Majorana mass*

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




*Shickele, Jokiniemi, Belley, Holt, in preparation*

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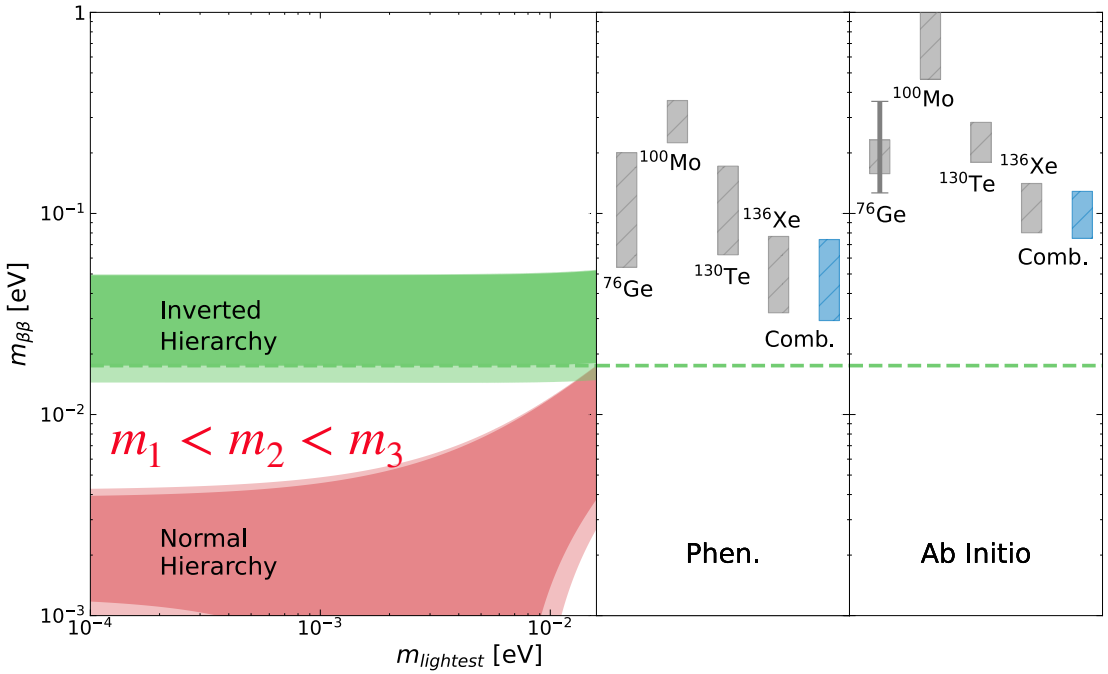
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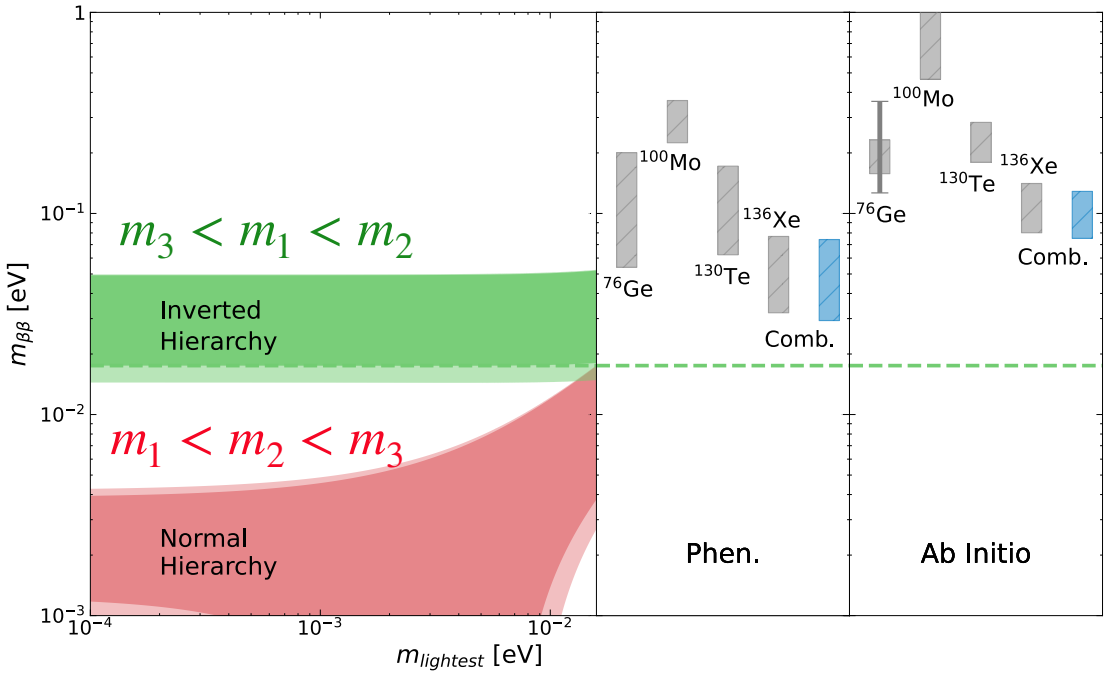
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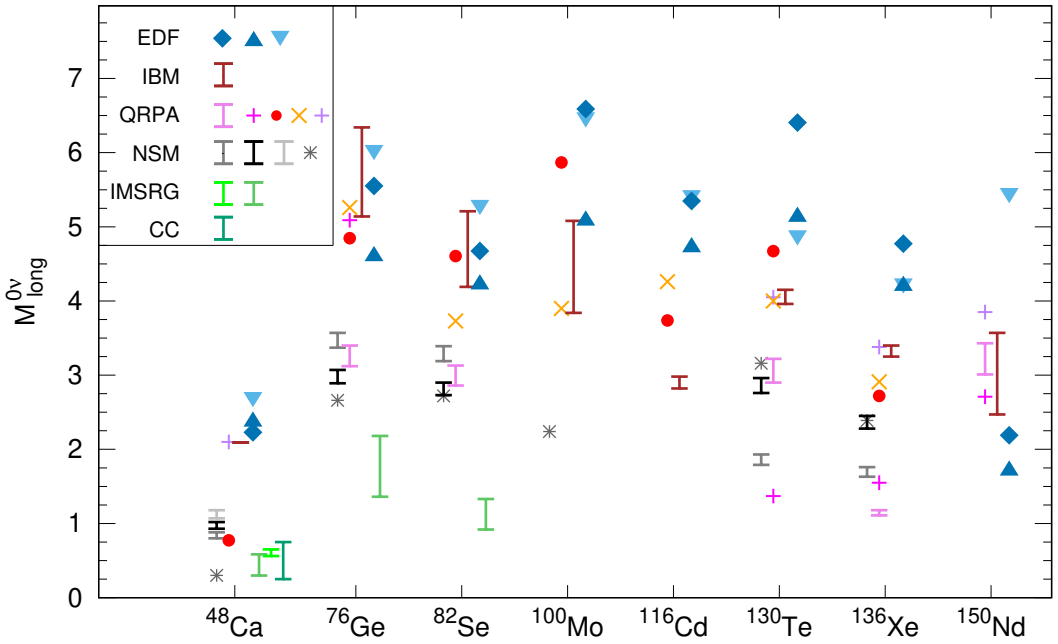
*Half-life to be measured*

*Nuclear matrix element*

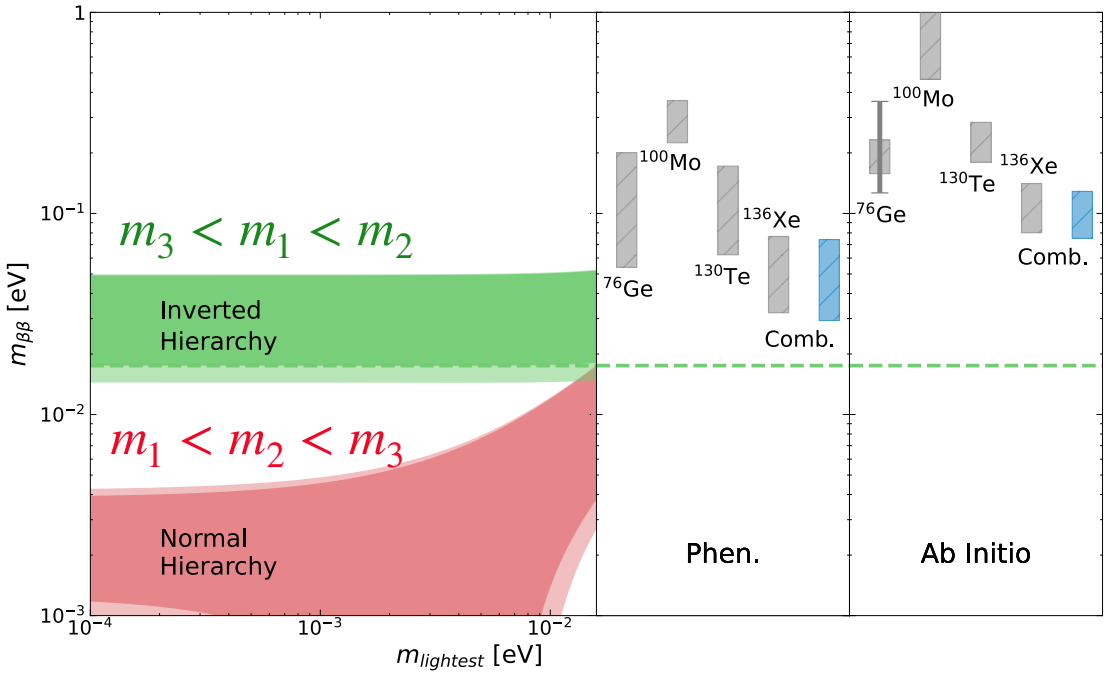
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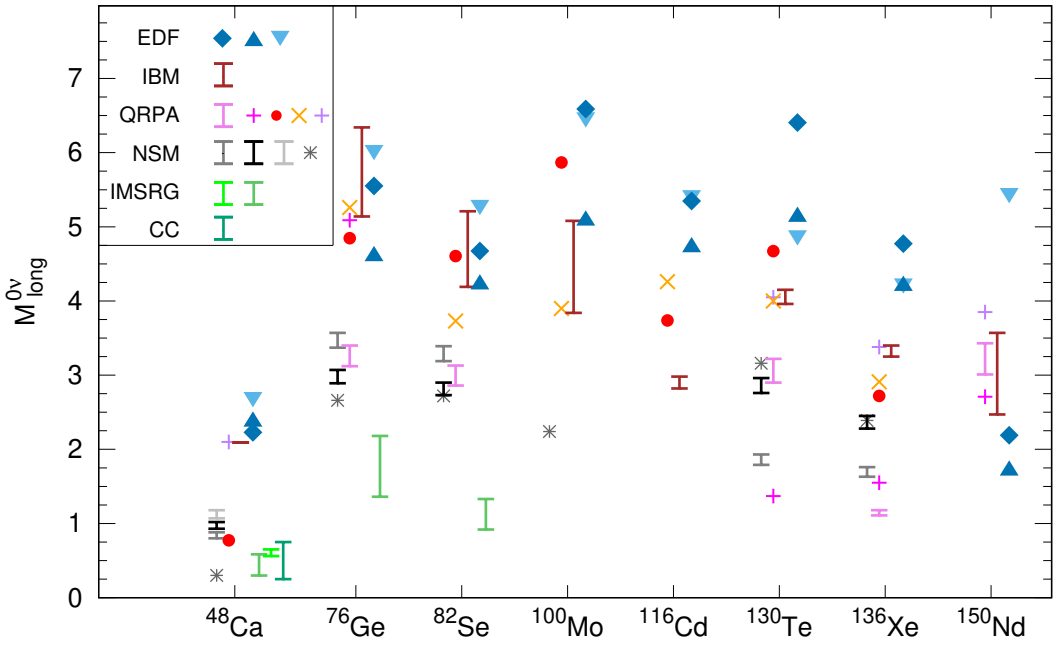
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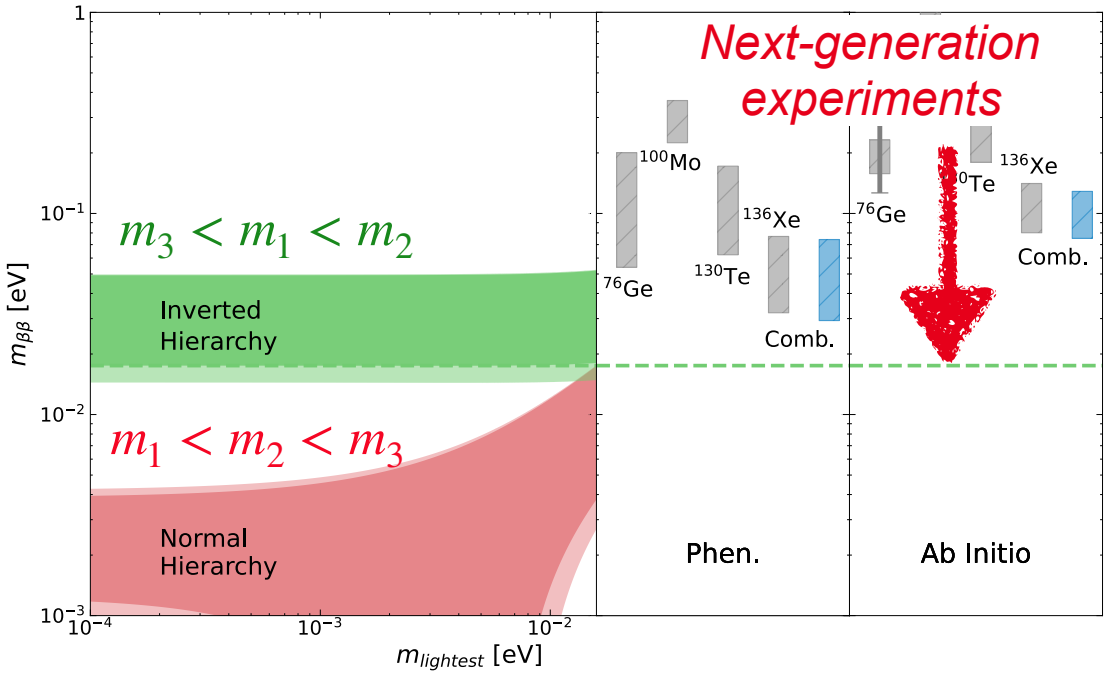
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# THE NUCLEAR MATRIX ELEMENT

$$M^{0\nu} = \langle \Psi^{(A)}_f \,|\, \mathcal{O}^{0\nu} \,|\, \Psi^{(A)}_i \rangle$$

# THE NUCLEAR MATRIX ELEMENT

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

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Initial state wave function

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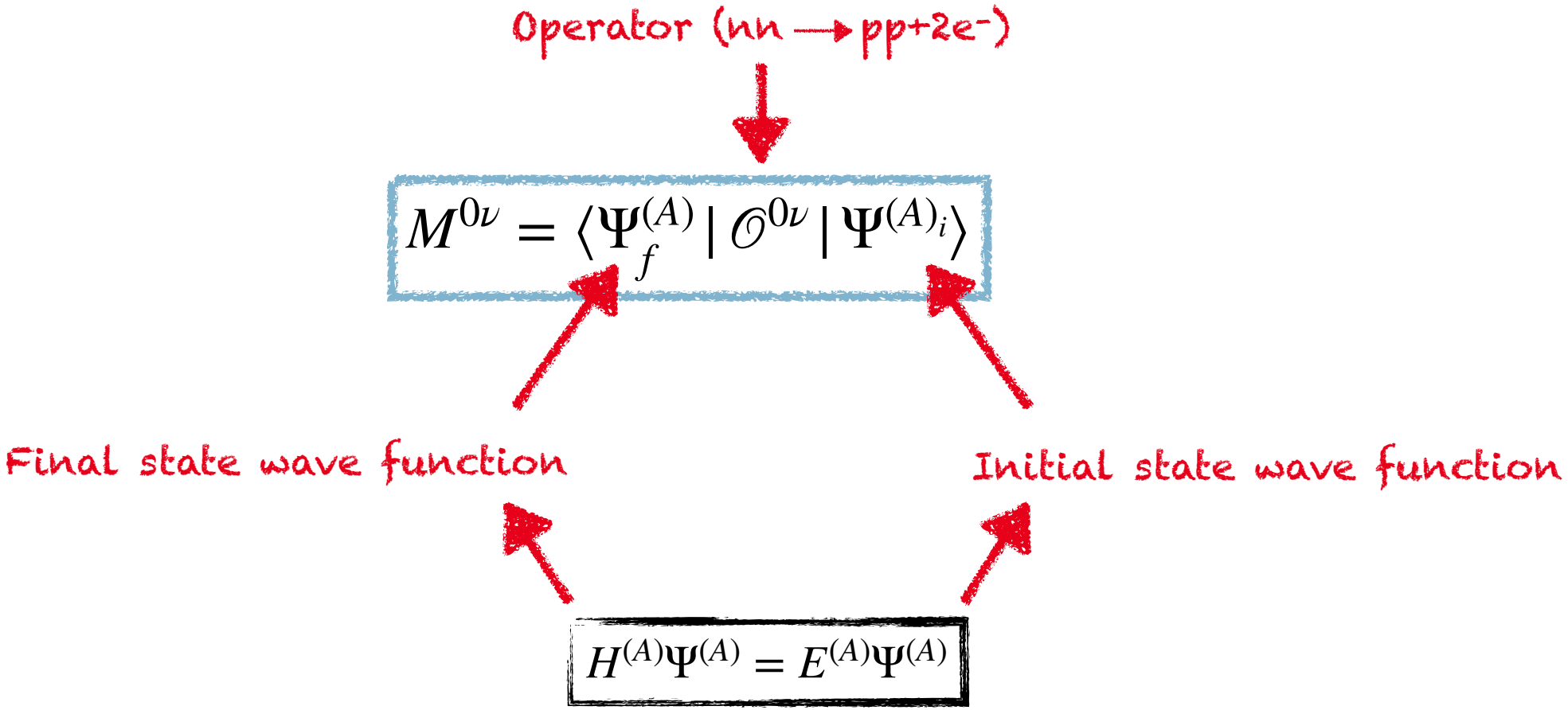
$$M^{0\nu} = \langle \Psi^{(A)}_f \mid \mathcal{O}^{0\nu} \mid \Psi^{(A)}_i \rangle$$

Final state wave function

Initial state wave function

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# THE NUCLEAR MATRIX ELEMENT



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# THE NUCLEAR MATRIX ELEMENT

$$M^{0\nu} = M^{0\nu}_{\mathrm{GT}} - \left(\frac{g_{\mathrm{V}}}{g_{\mathrm{A}}}\right)^2 M^{0\nu}_{\mathrm{F}} + M^{0\nu}_{\mathrm{T}}$$

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$$M^{0\nu}_{\mathrm{X}} = \frac{2R}{\pi g_{\mathrm{A}}^2} \times \langle 0^+_f \,|\, \sum_{m,n} \tau^-_m \tau^-_n \, \mathcal{O}^{(m,n)}_{\mathrm{X}} \int \frac{j_0(qr) h_{\mathrm{X}}(q^2)\, q^2}{q(q+E)} \mathrm{d}q \,|\, 0^+_i \rangle$$

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Neutrino potential

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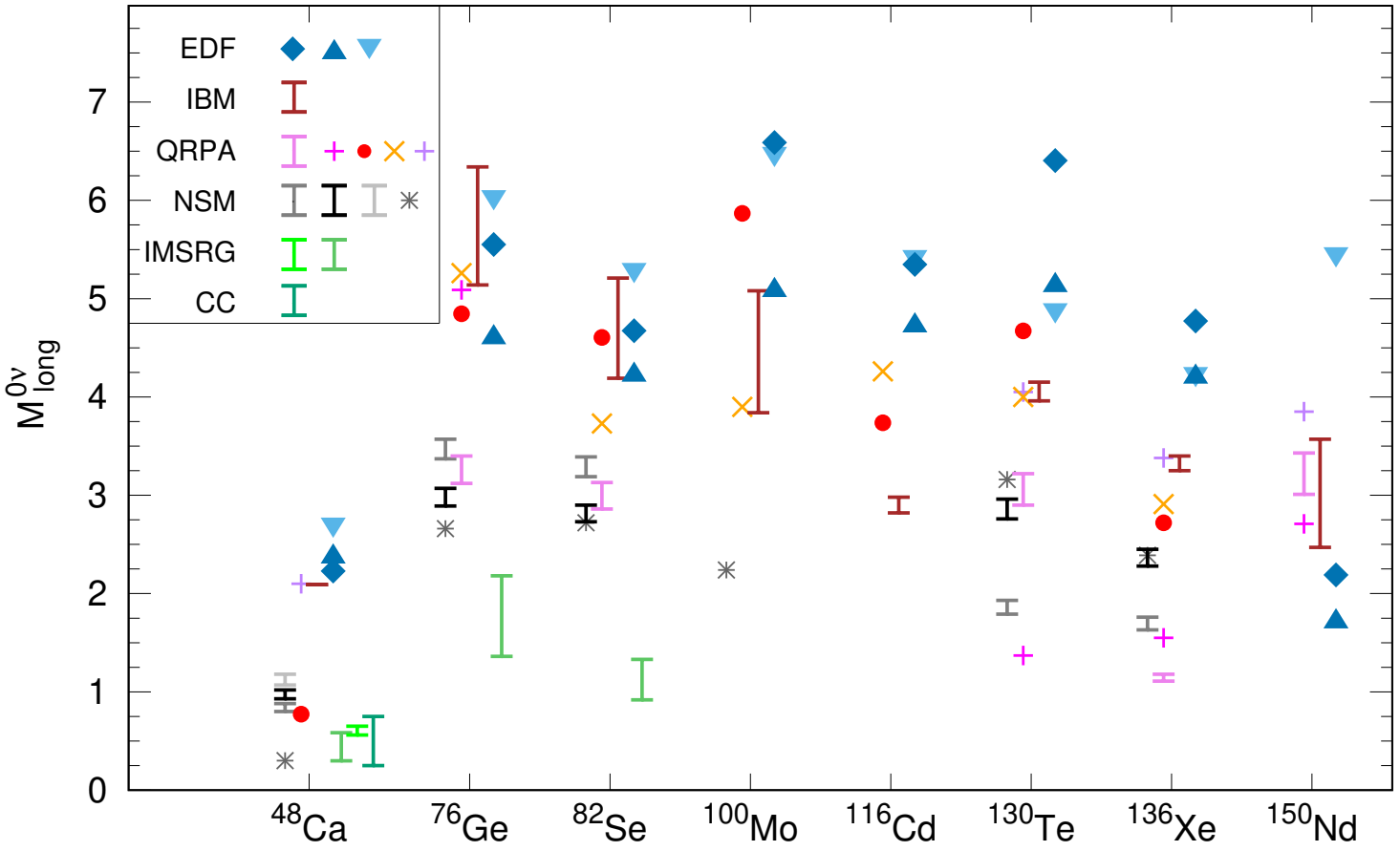
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Neutrino potential

Usually from phenomenological many-body methods

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# LACK OF RELIABLE UNCERTAINTIES

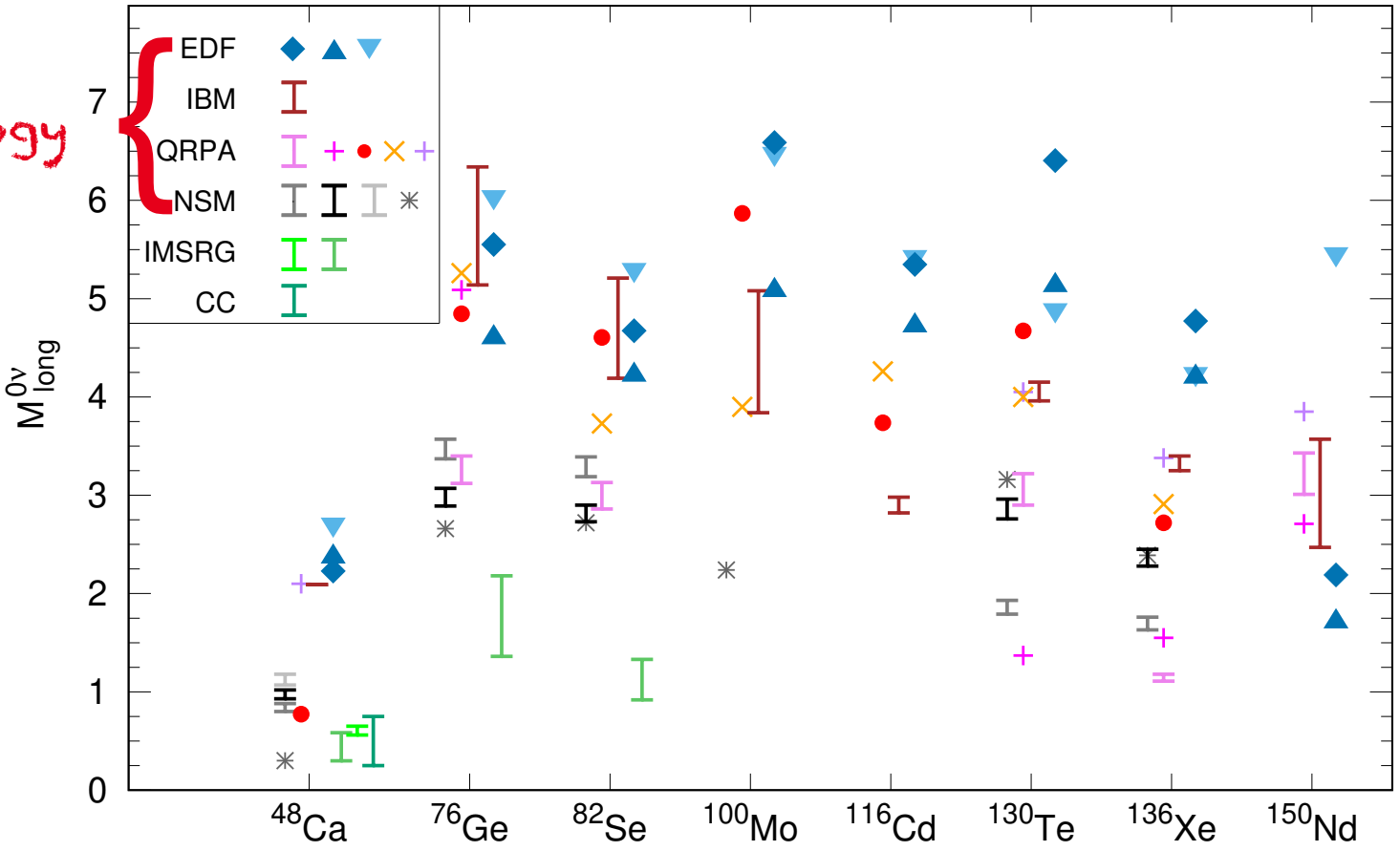



*Agostini et al., Rev. Mod. Phys. 95, 025002 (2023)*

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# LACK OF RELIABLE UNCERTAINTIES

Phenomenology



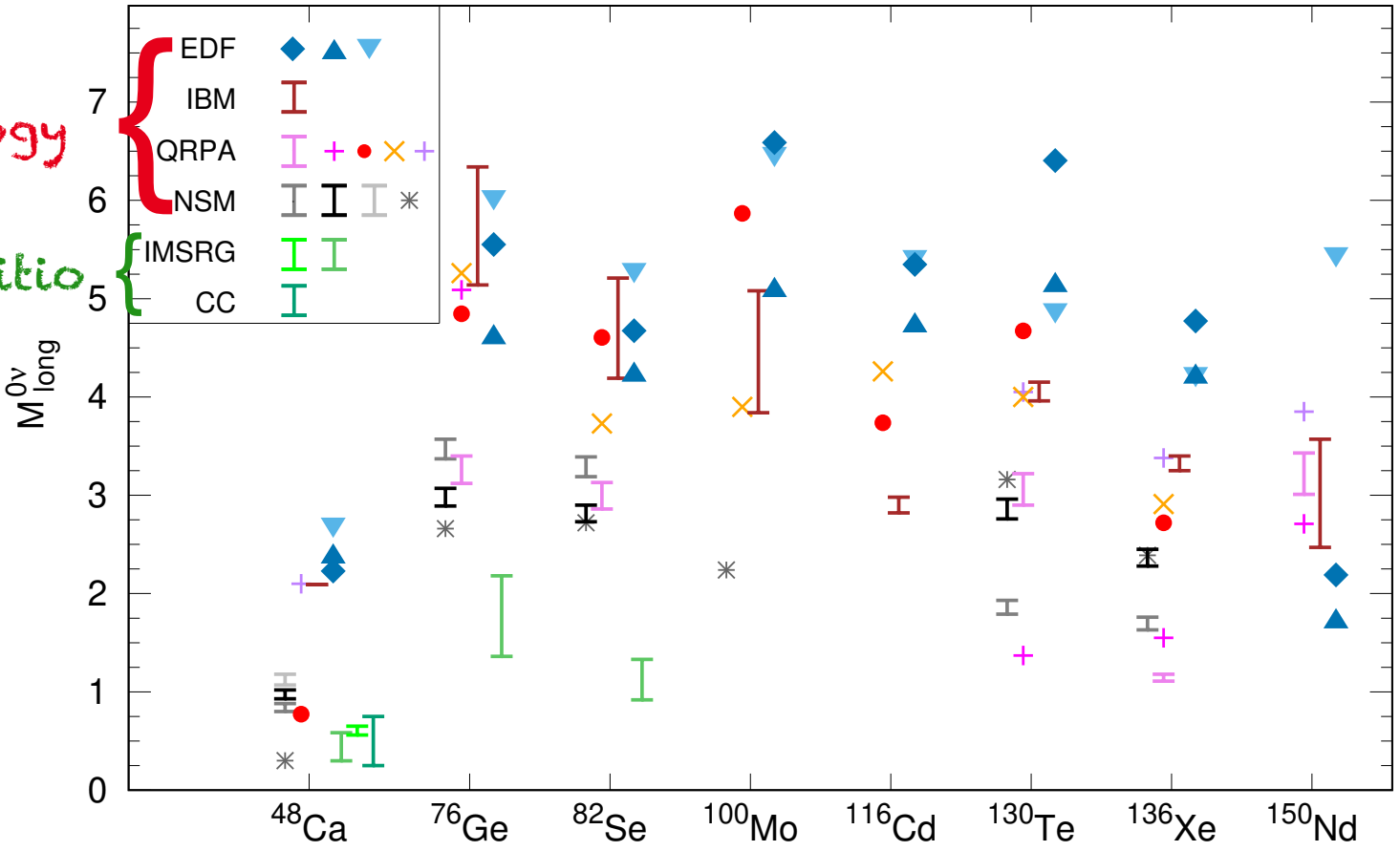

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Phenomenology

Ab initio



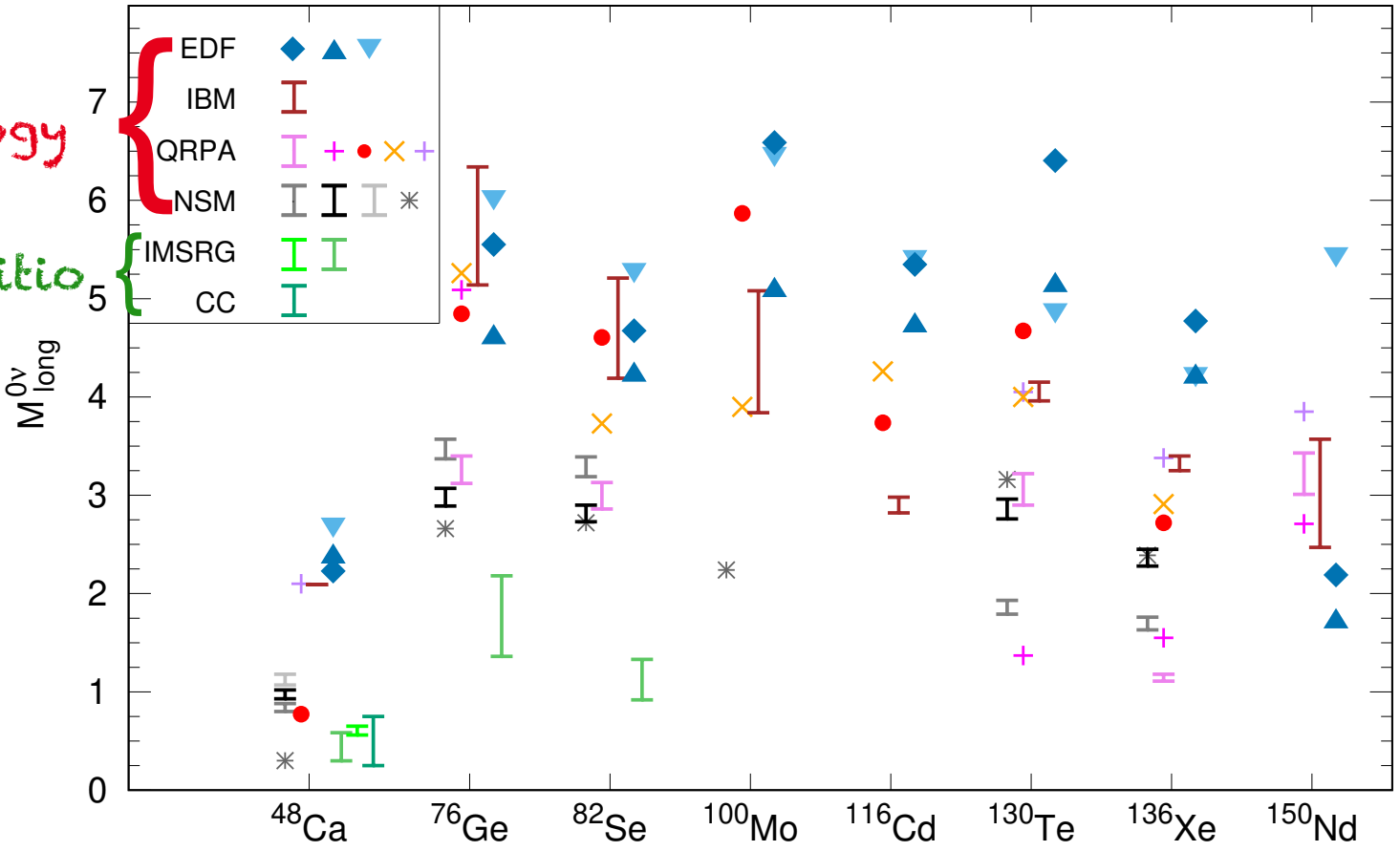

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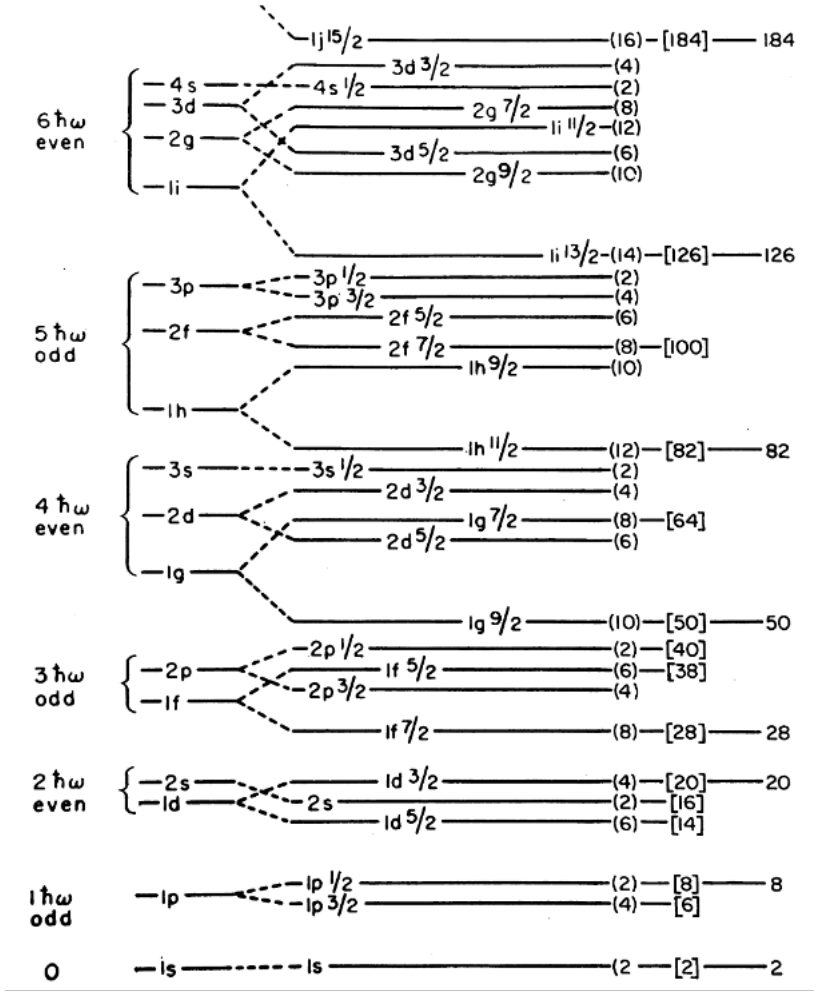

***Ranges*** cover:

- Different parameters/ nuclear interactions
- Different model spaces
- Reference state dependence
- …

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# PHENOMENOLOGICAL MANY-BODY METHODS

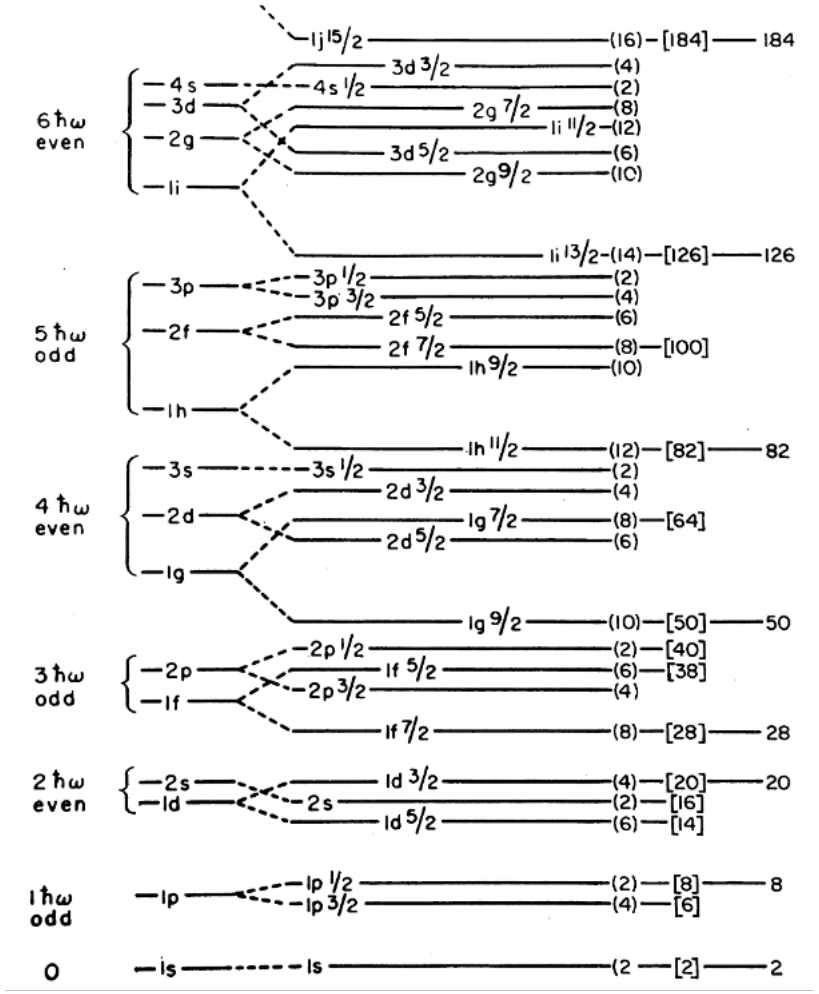



*M. Göppert-Mayer, Science 145, 999 (1964)*

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# PHENOMENOLOGICAL MANY-BODY METHODS

- **Based and *adjusted* on nuclear phenomena**

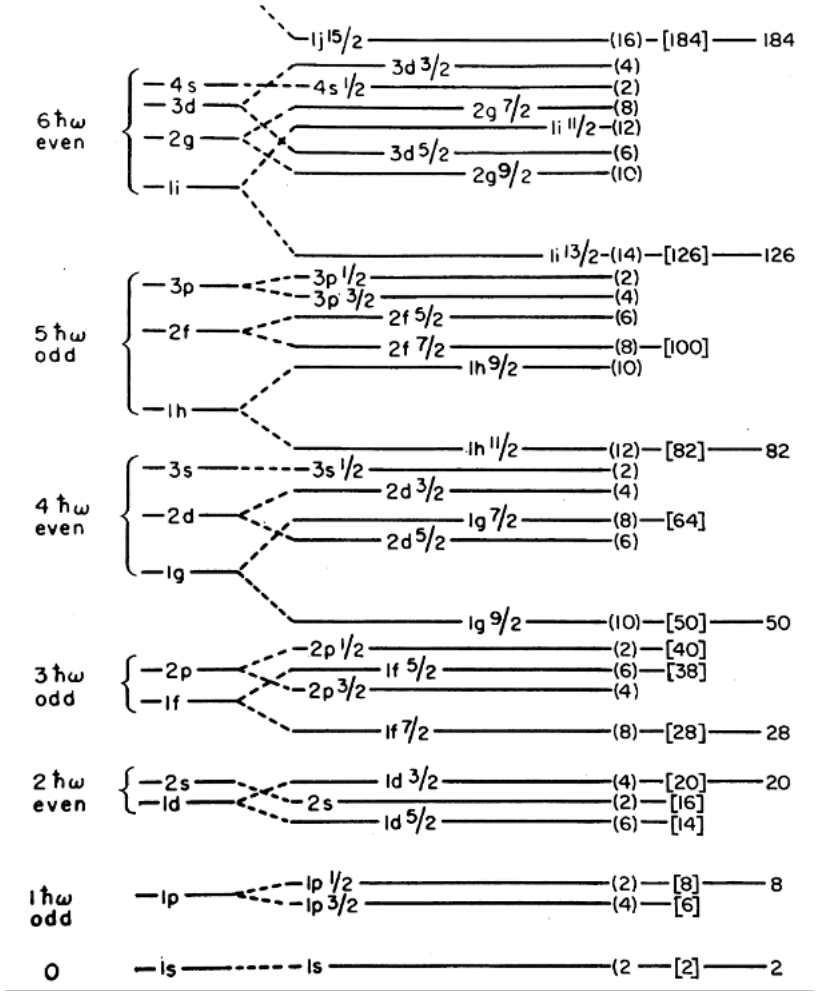



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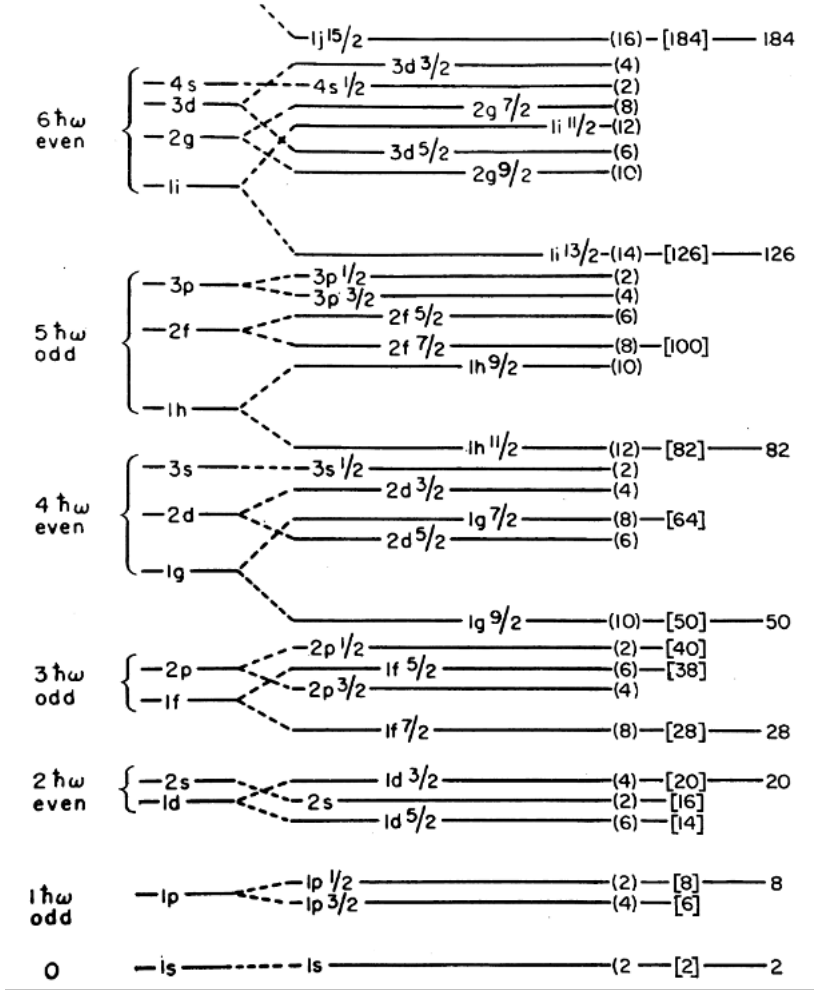



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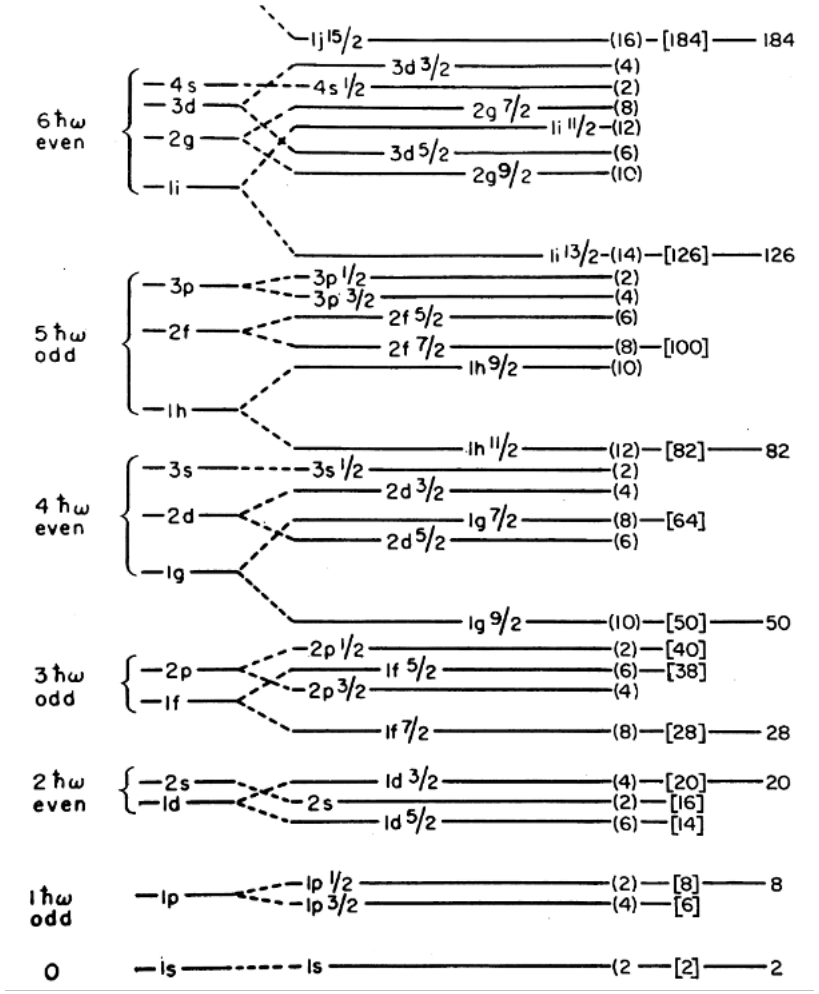



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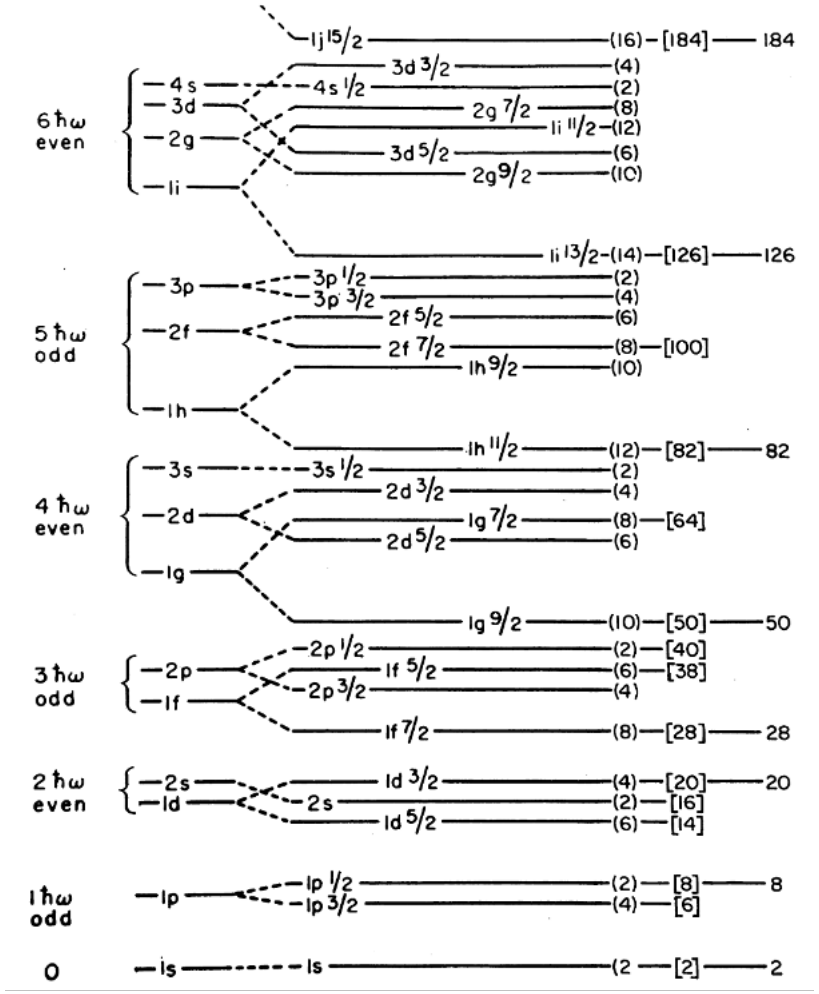



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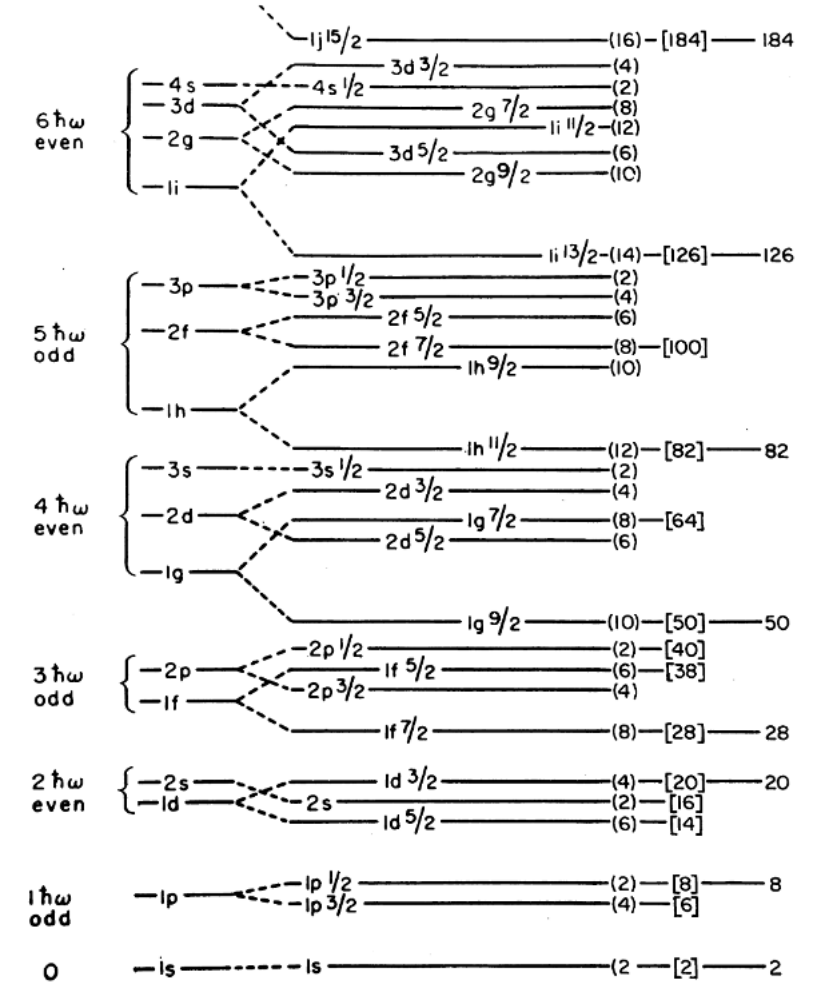



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# AB INITIO NUCLEAR THEORY

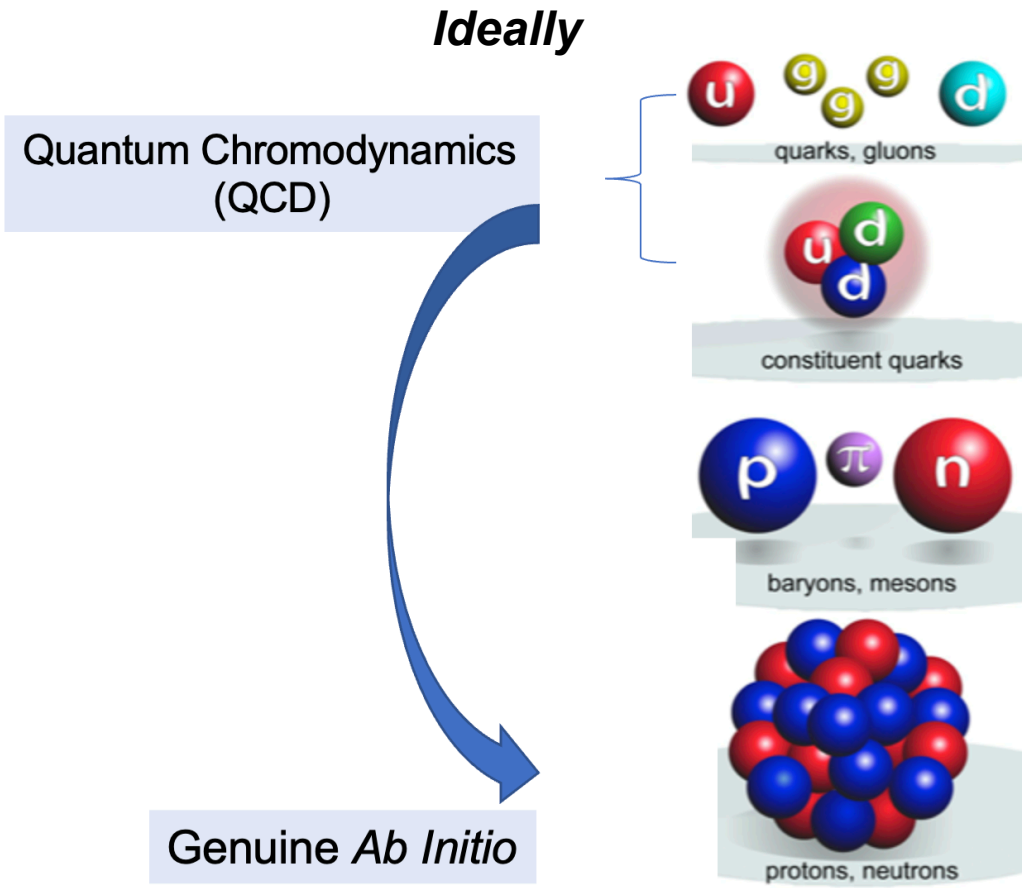



*Figure courtesy of P. Navrátil*

# AB INITIO NUCLEAR THEORY

***Current ab initio***

Quantum Chromodynamics (QCD)

Chiral Effective Field Theory (parameters fitted to NN data)

Current *ab initio* nuclear theory

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

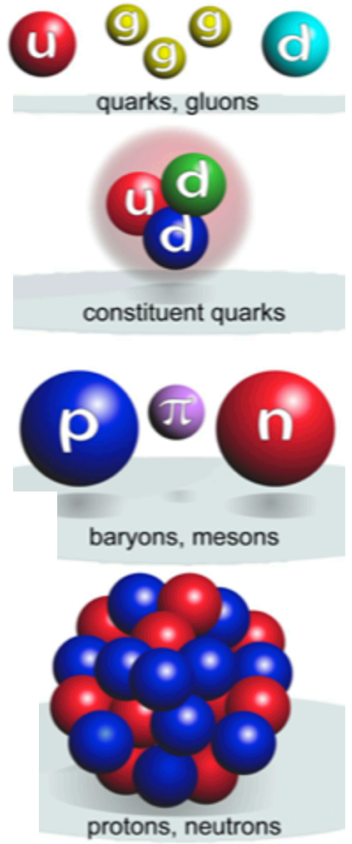



*Figure courtesy of P. Navrátil*

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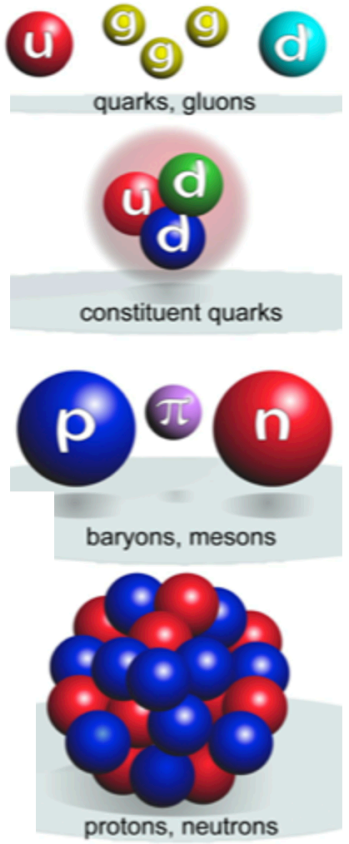
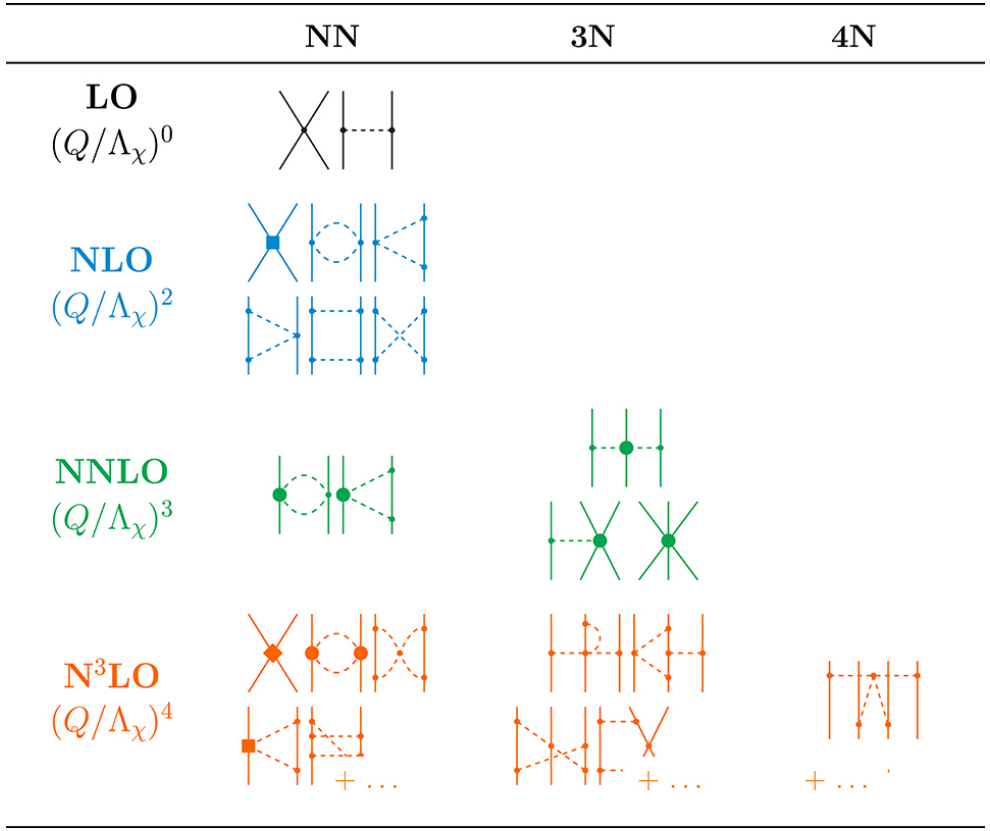



*Figure courtesy of P. Navrátil*

***Chiral expansion of nuclear forces***




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

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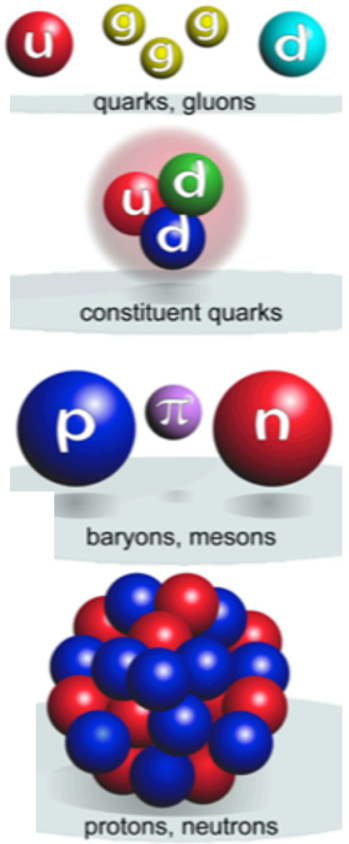
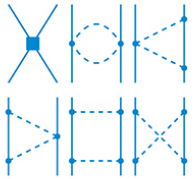
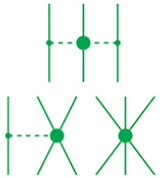
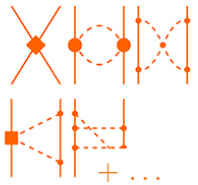
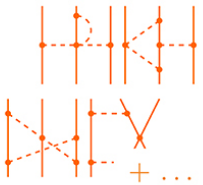



*Figure courtesy of P. Navrátil*

***Chiral expansion of nuclear forces***

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

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

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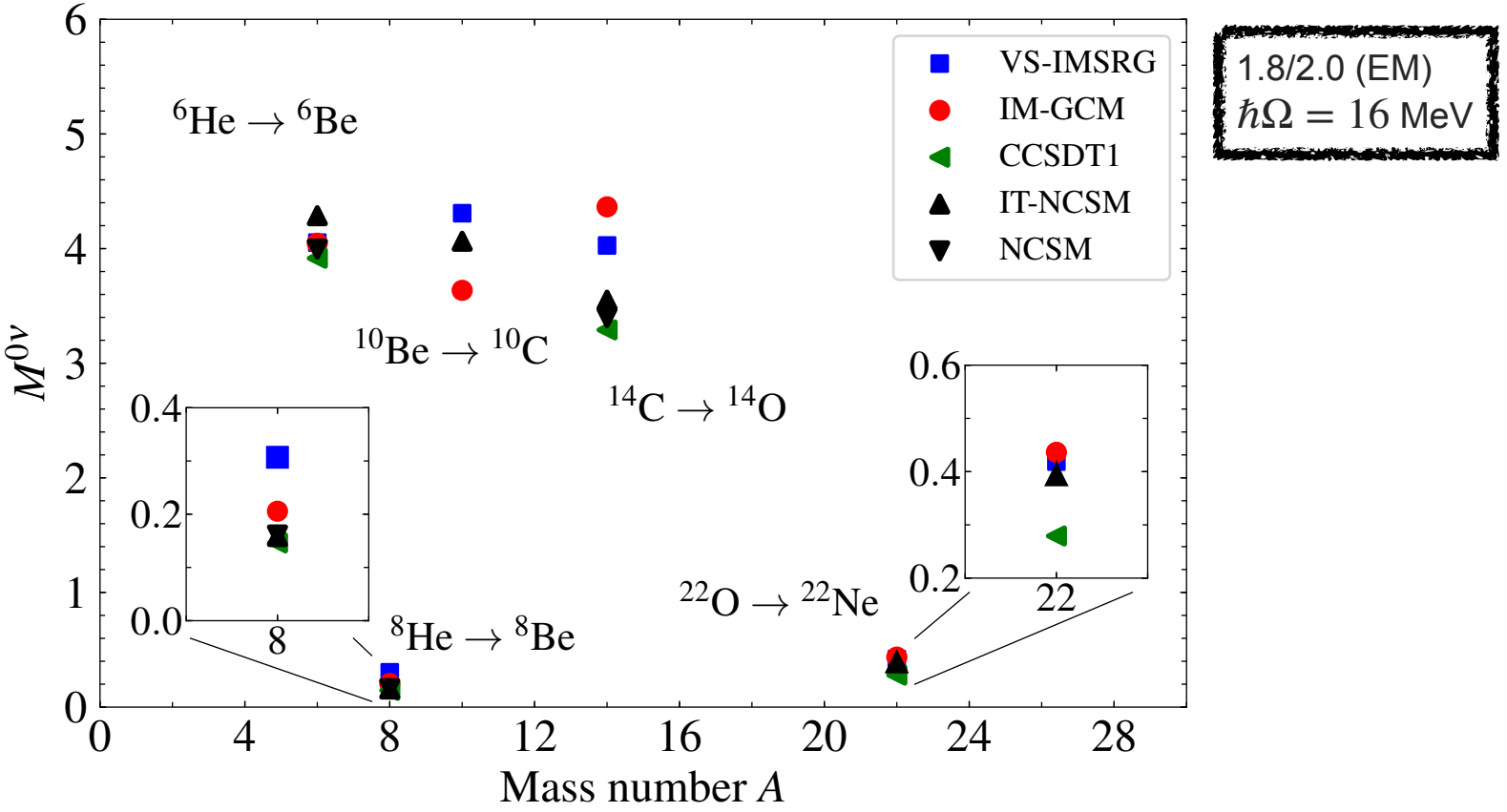
# AB INITIO NUCLEAR THEORY

*"… 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)*

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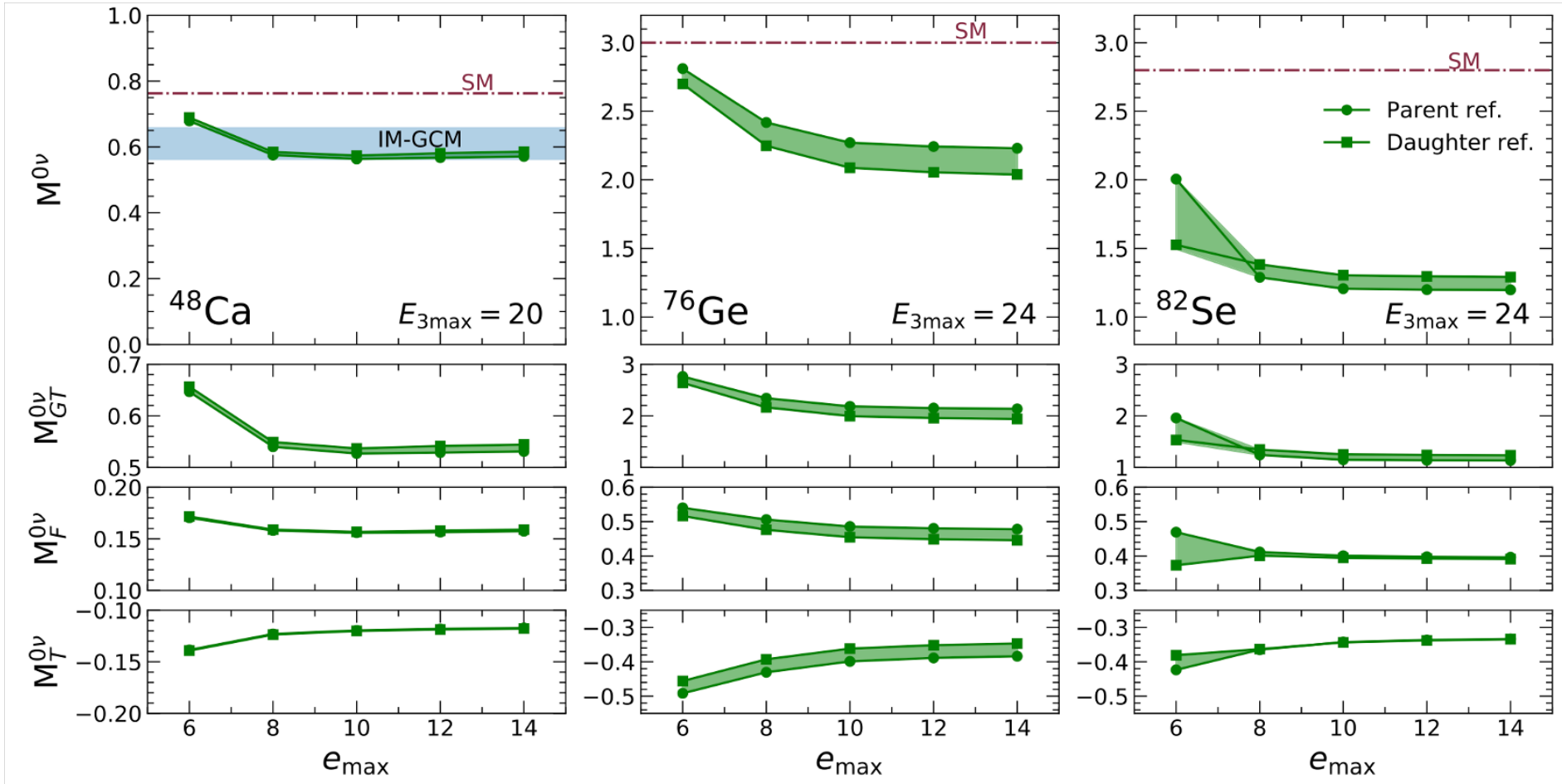
# AB INITIO BENCHMARKS IN LIGHT NUCLEI




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

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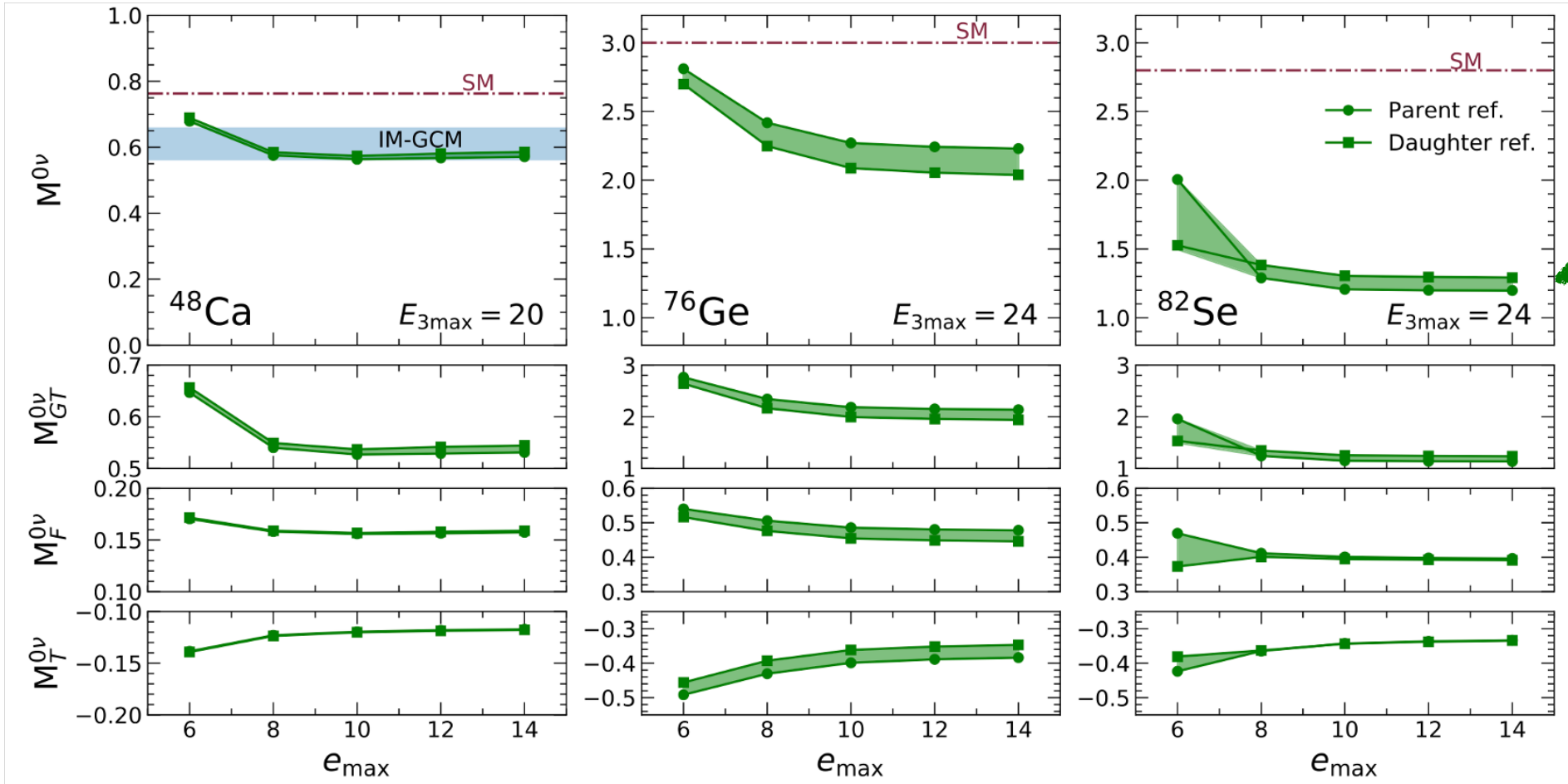
# AB INITIO RESULTS FOR $^{48}$CA, $^{76}$GE, $^{82}$SE




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

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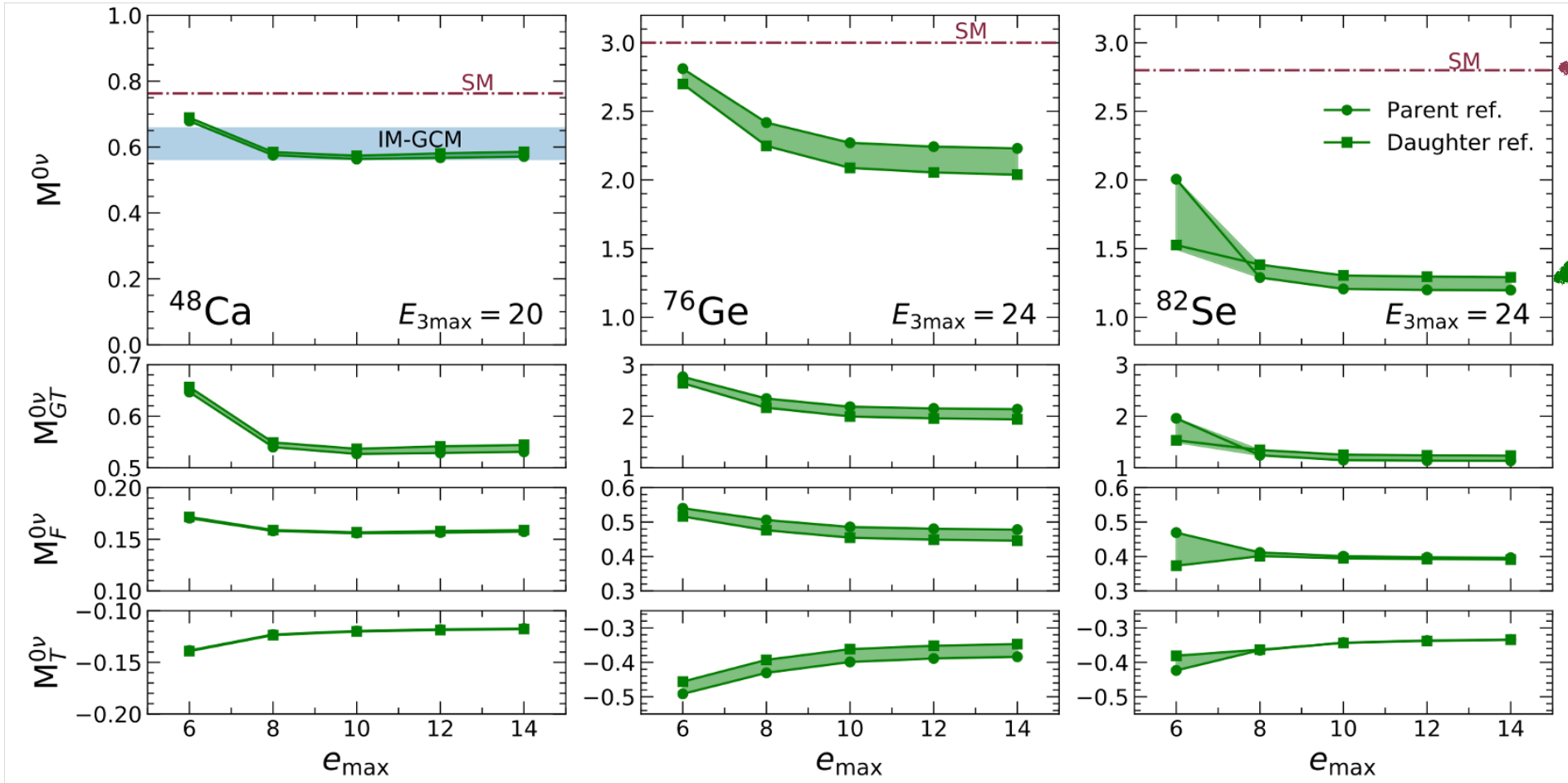



Ab initio VS-IMSRG

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Nuclear shell model

Ab initio VS-IMSRG

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# OUTLINE

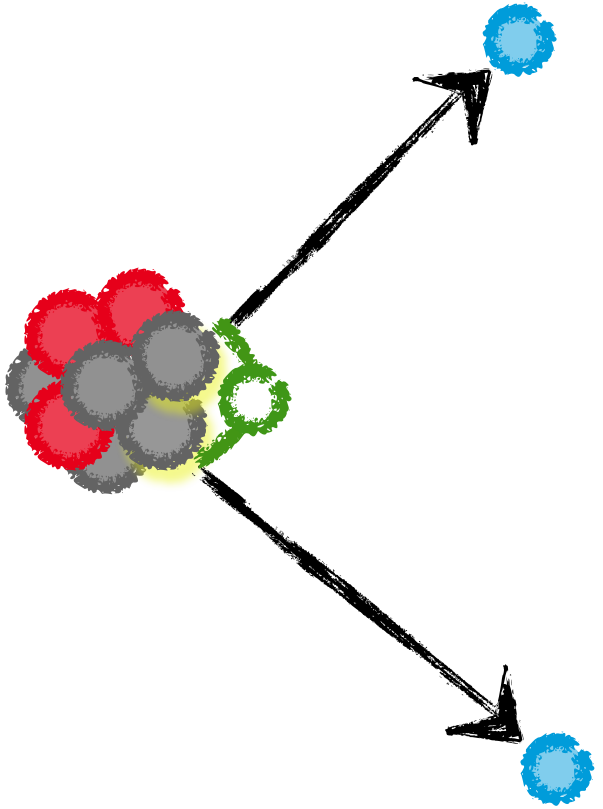

1 Introduction

2 **Effective field theory for neutrinoless double-beta decay**

3 Probing neutrinoless double-beta decay by nuclear observables

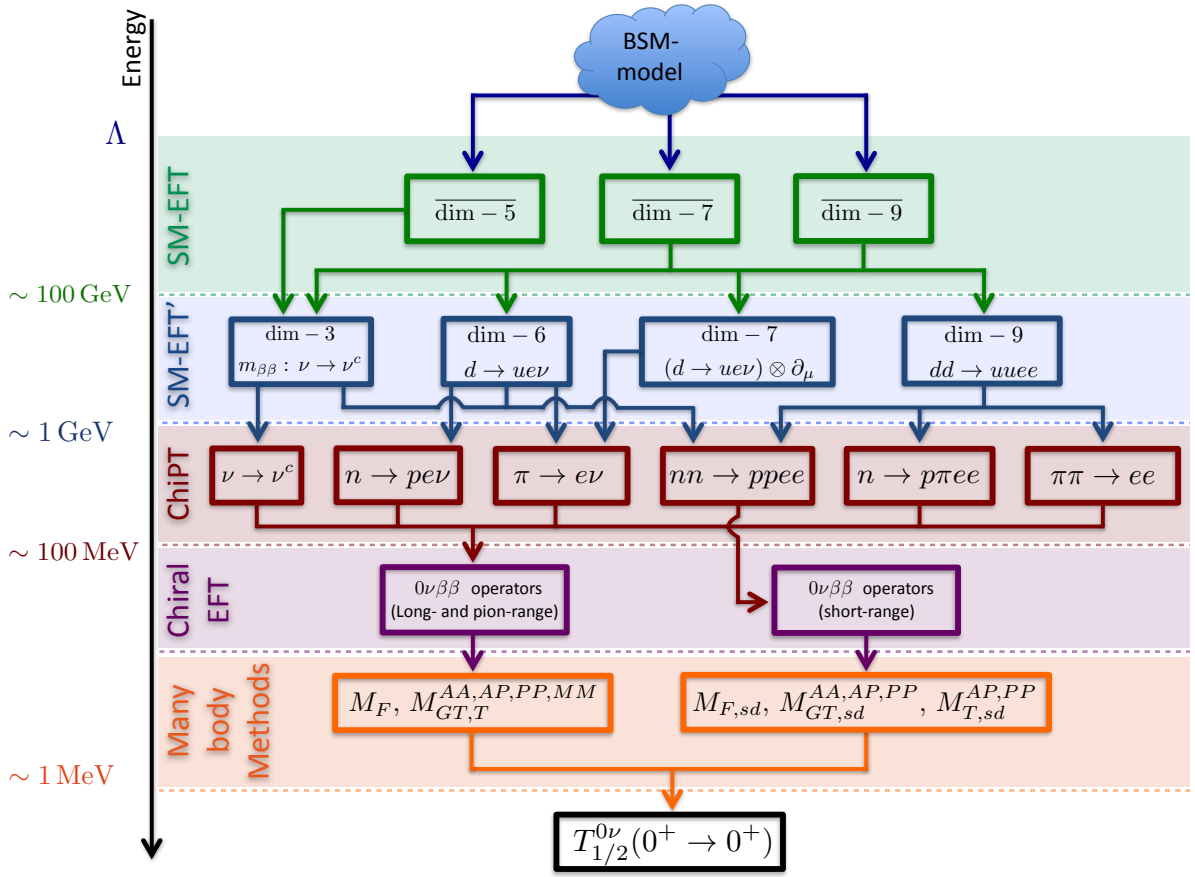
4 Current status

5 Summary and Outlook

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



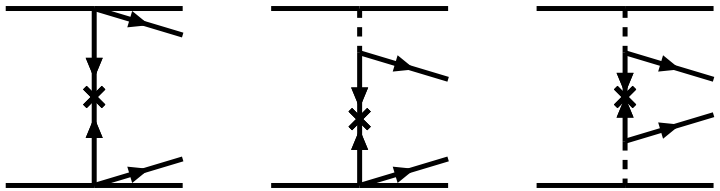

*Cirigliano, Dekens, de Vries, Graesser, Mereghetti, JHEP 12, 097 (2018)*

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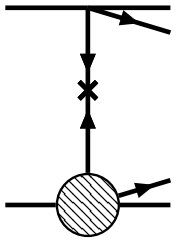
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$$M^{0\nu} = M^{0\nu}_{\mathrm{L}}$$

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



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



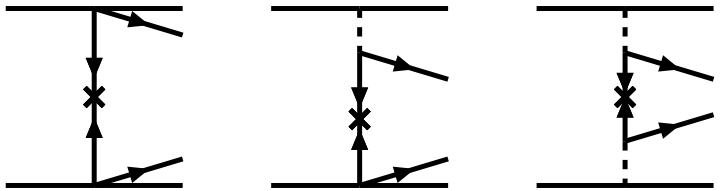
*V. Cirigliano et al., Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)*

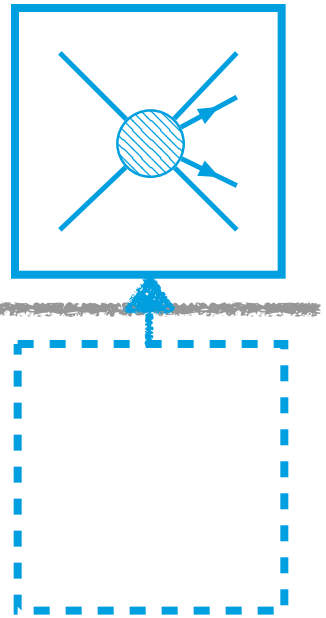
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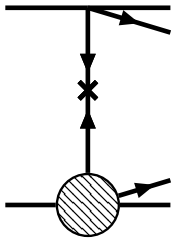
$$M^{0\nu} = M^{0\nu}_{\mathrm{L}} + M^{0\nu}_{\mathrm{S}}$$

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





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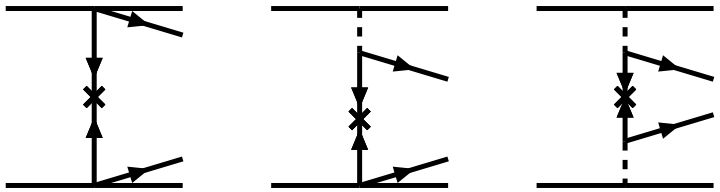
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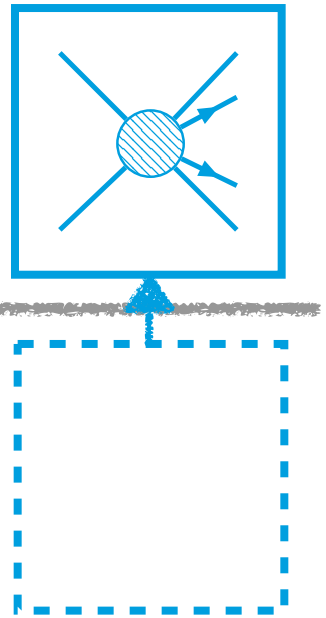
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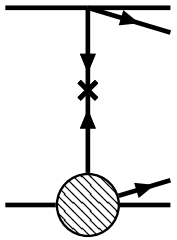
$$M^{0\nu} = M^{0\nu}_{\mathrm{L}} + M^{0\nu}_{\mathrm{S}} + M^{0\nu}_{\mathrm{usoft}}$$

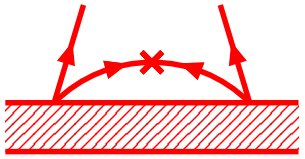
$\left(\frac{Q}{\Lambda_\chi}\right)^0$ LO





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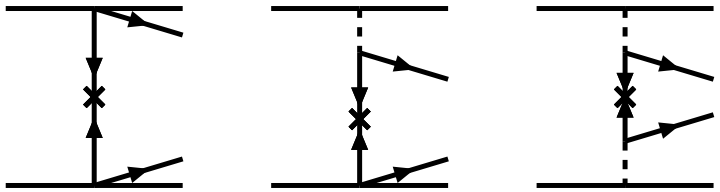
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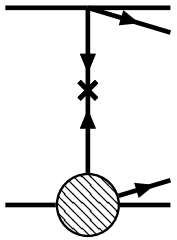
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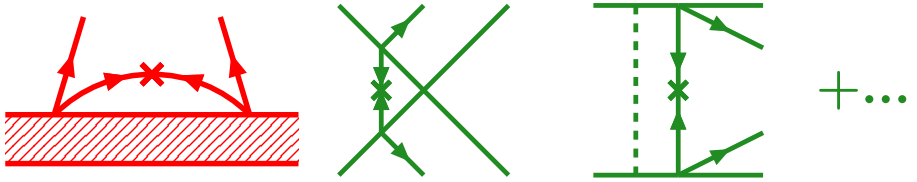
$$M^{0\nu} = M^{0\nu}_{\mathrm{L}} + M^{0\nu}_{\mathrm{S}} + M^{0\nu}_{\mathrm{usoft}} + M^{0\nu}_{\mathrm{loop}}$$

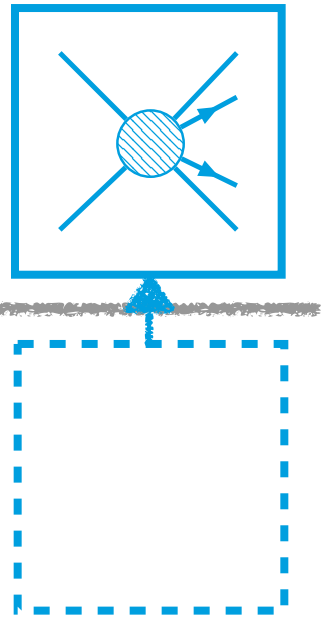
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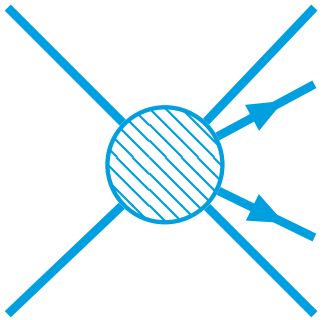


*V. Cirigliano et al., Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)*

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# CONTACT TERM – UNKNOWN COUPLING

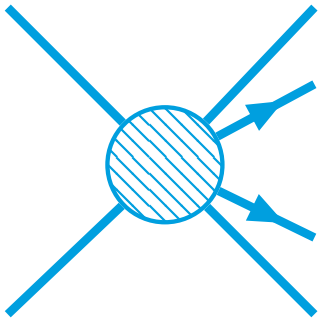
$$M_{\mathrm{S}}^{0\nu} = 2\boldsymbol{g_\nu^{\mathrm{NN}}}\frac{2R}{\pi g_{\mathrm{A}}^2}\langle 0_f^+ | \sum_{m,n}\tau_m^-\tau_n^- \int j_0(qr)\, e^{-q^2/(2\Lambda^2)}\, q^2 \mathrm{d}q \,| 0_i^+\rangle$$



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

# CONTACT TERM – UNKNOWN COUPLING

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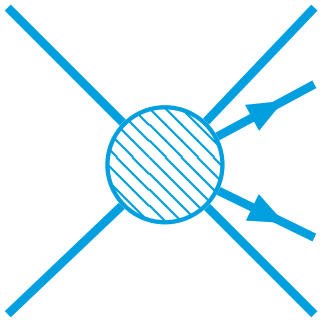


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- New, **unknown**, low-energy constant $\boldsymbol{g_\nu^{\mathrm{NN}}}$

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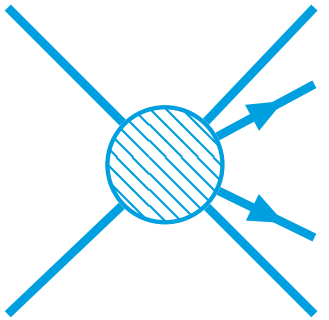


$\sim C_1 \equiv g_\nu^{\mathrm{NN}}$

- New, **unknown**, low-energy constant $\boldsymbol{g_\nu^{\mathrm{NN}}}$
- What to do?

# CONTACT TERM – UNKNOWN COUPLING

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

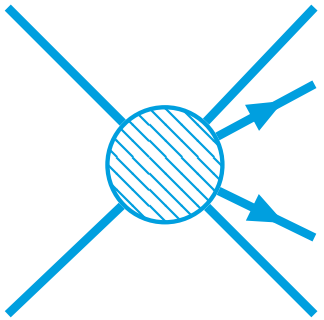


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- What to do?
  - ✘ Fit to **lepton-number violating data**

# CONTACT TERM – UNKNOWN COUPLING

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



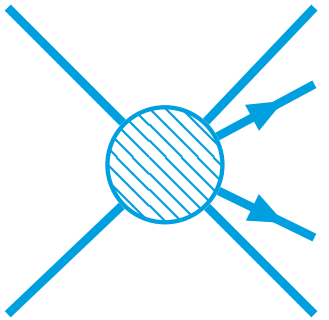
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    *Cirigliano, Davoudi, Engel, Furnstahl, Hagen et al., J. Phys. G. Nucl. Part. Phys. 49, 120502 (2022)*

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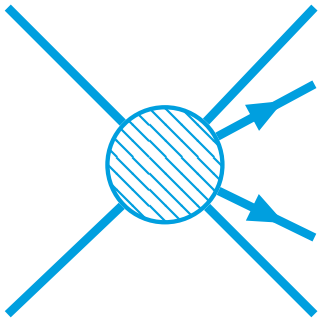
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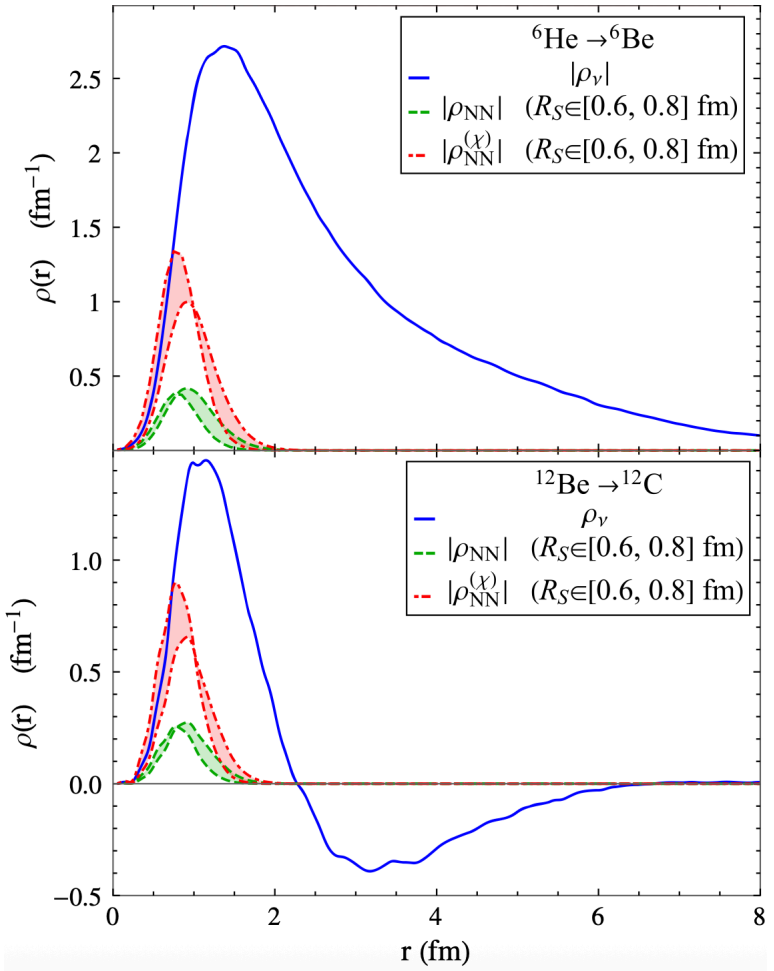
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    *Cirigliano, Dekens, de Vries, Graesser, Mereghetti, Pastore, van Kolck, Phys. Rev. Lett. 120, 202001 (2018)*
  - ✓ Fit to **synthetic data**
    *Cirigliano, Dekens, de Vries, Hoferichter, Mereghetti, Phys. Rev. Lett. 126, 172002 (2021)*

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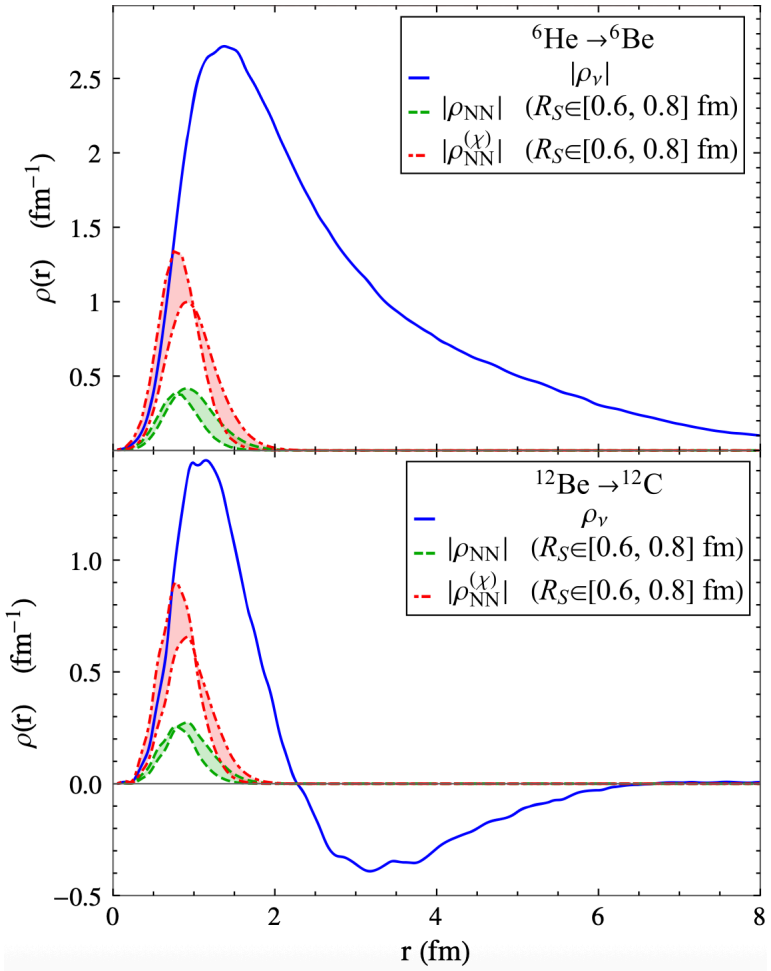

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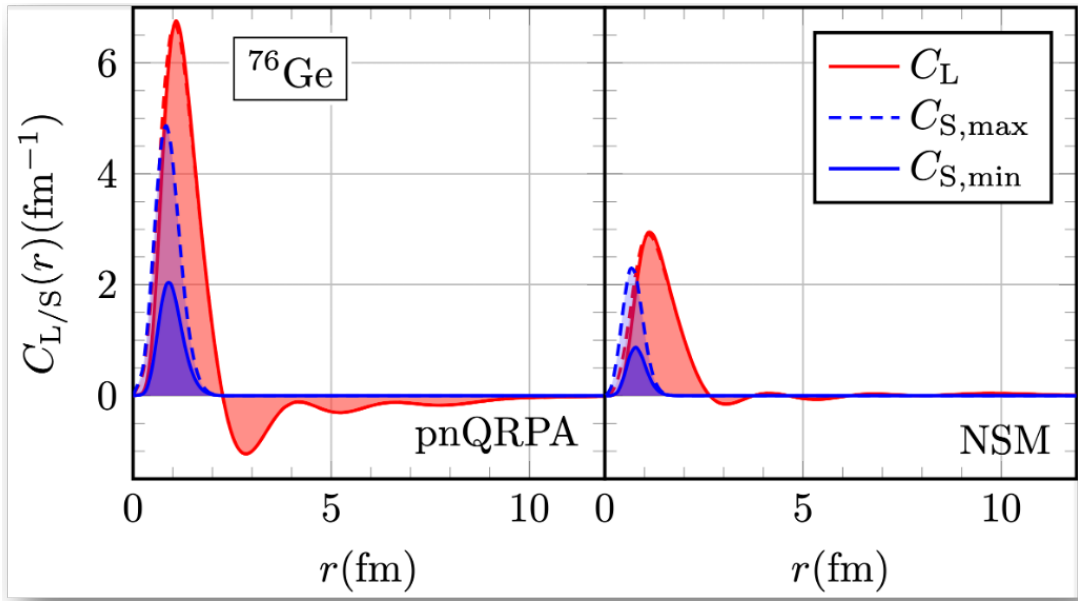

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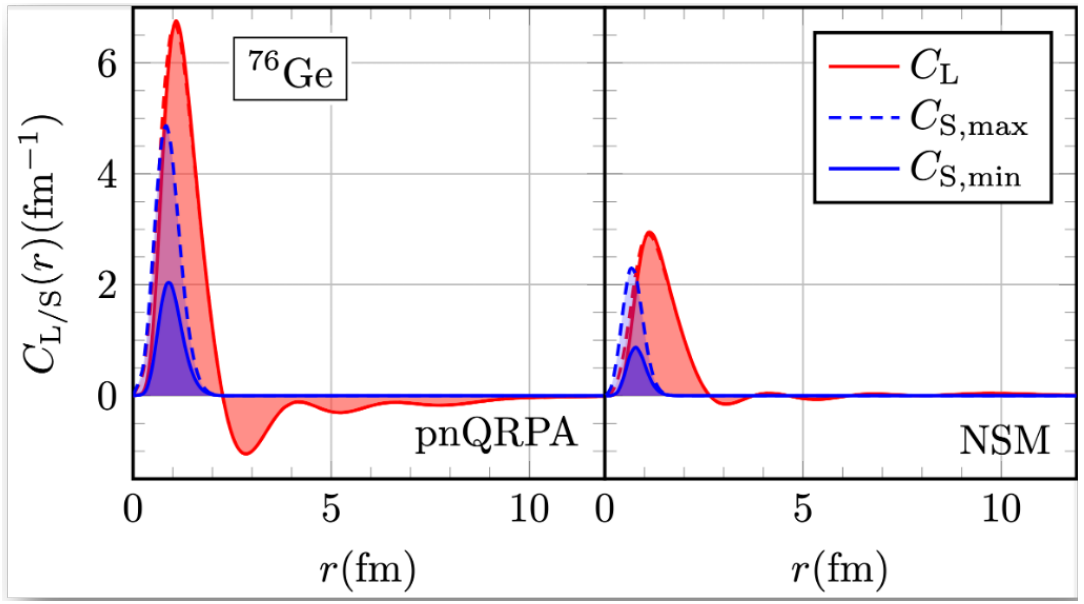

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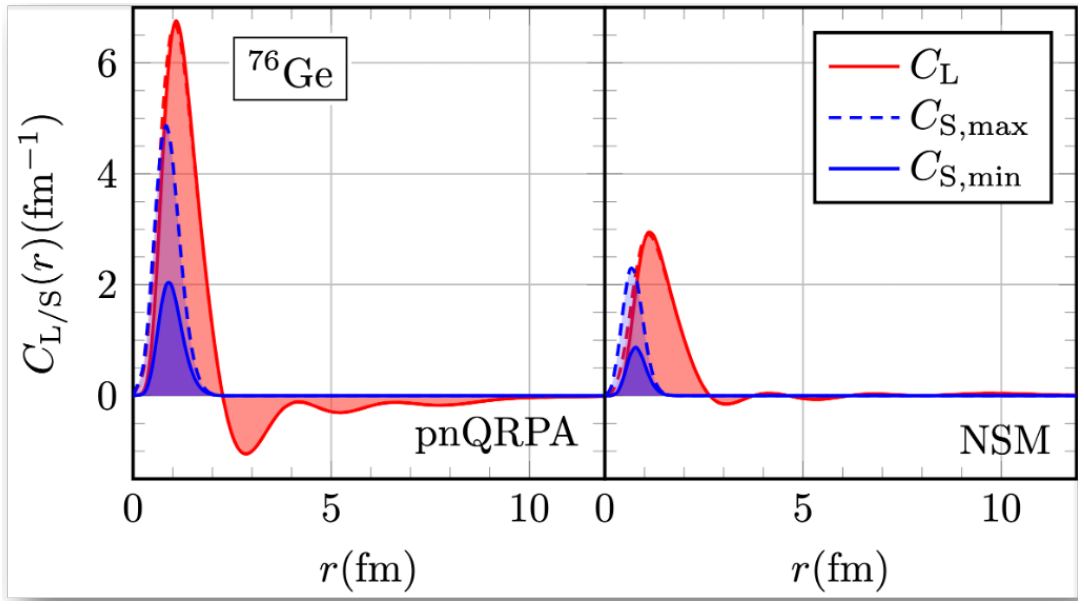

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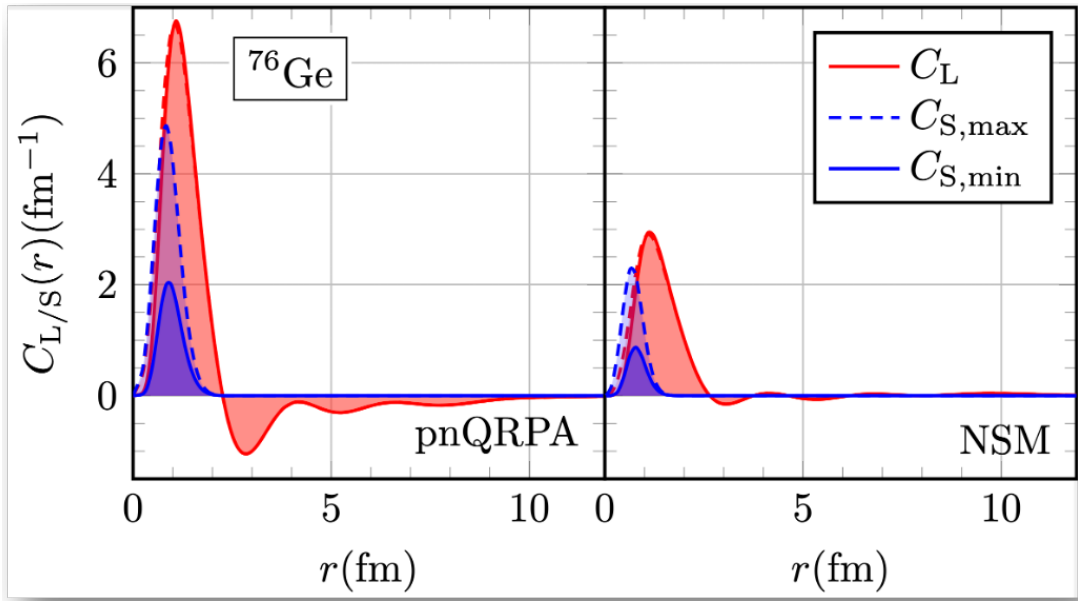

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  *Weiss, Soriano, Lovato, Menéndez, Wiringa, Phys. Rev. C 106, 065501 (2022)*
- VS-IMSRG shows **$\sim 40\% - 90\,\%$ enhancement** in $^{76}$Ge, $^{130}$Te, and $^{136}$Xe
  *Belley, Yao, Bally, Pitcher, Engel, Phys. Rev. Lett. 132, 182502 (2024)*
  *Belley, Miyagi, Stroberg, Holt, arXiv:2307.15156*

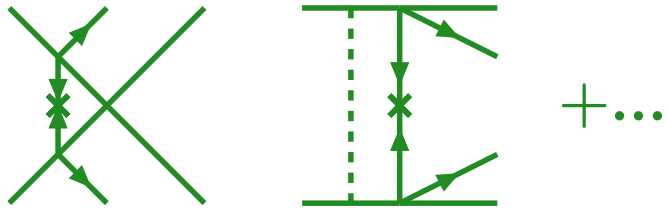



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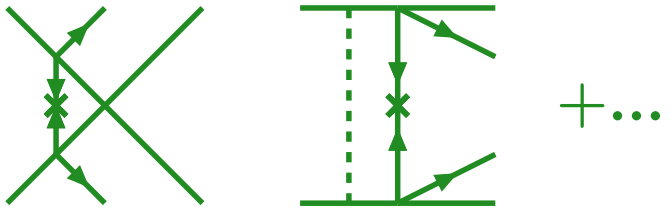
# LOOP CORRECTIONS

$$M^{0\nu}_{\text{loop}} = \frac{4R}{\pi g_{\text{A}}^2}\langle f \,|\, \sum_{a,b} \tau_a^- \tau_b^- \int \mathrm{d}q\; q^2 e^{-q^2/2\Lambda^2} j_u(qr) \boldsymbol{V^{(a,b)}_{\nu,2}} \,|\, i\rangle$$



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# LOOP CORRECTIONS

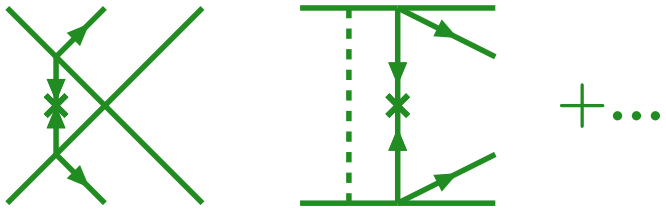


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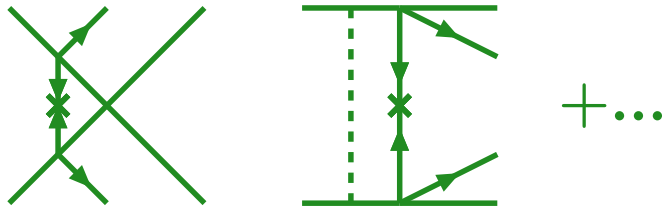
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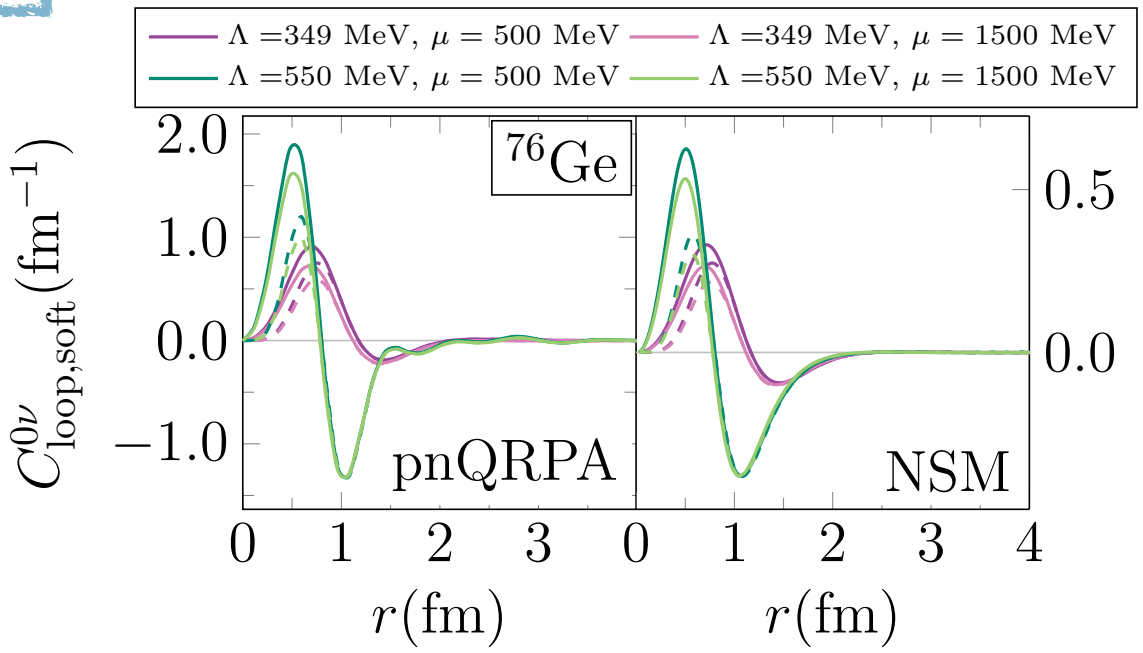
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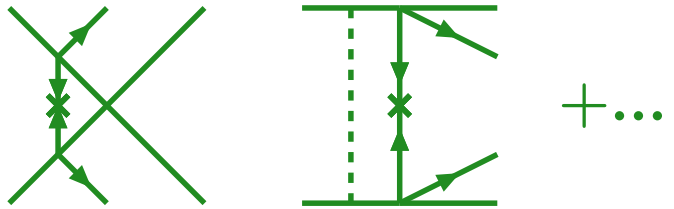
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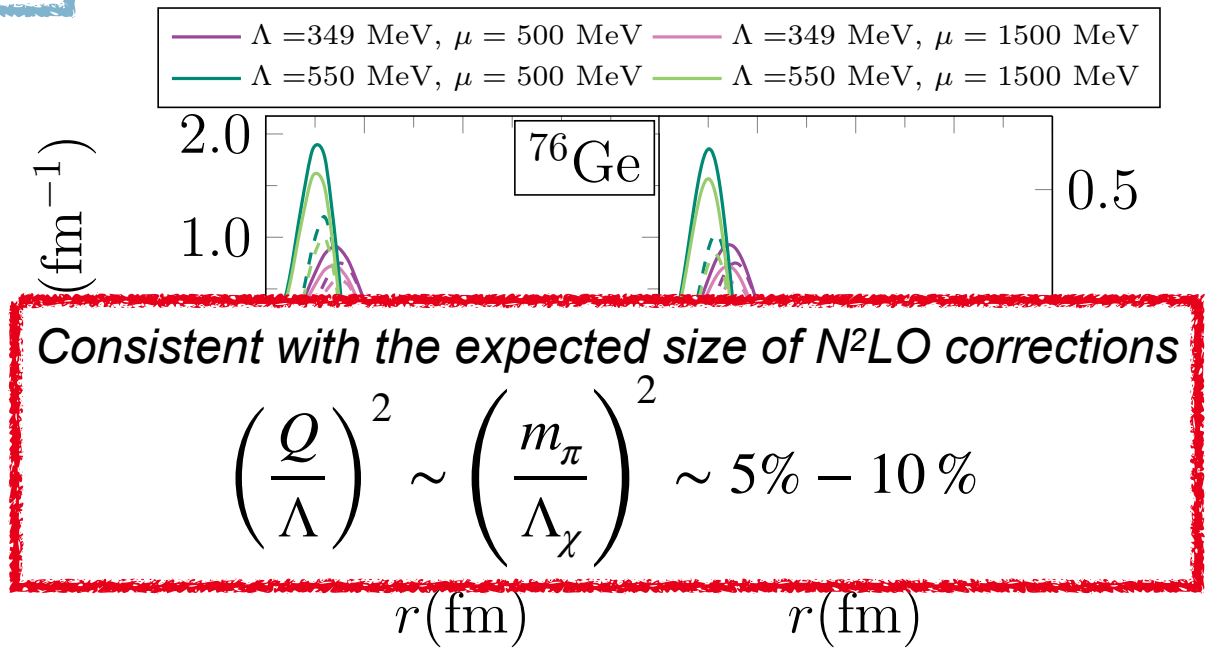
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*Consistent with the expected size of N²LO corrections*

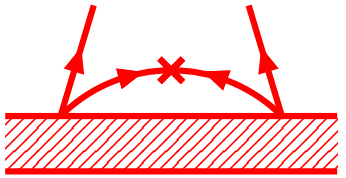
$$\left(\frac{Q}{\Lambda}\right)^2 \sim \left(\frac{m_\pi}{\Lambda_\chi}\right)^2 \sim 5\% - 10\,\%$$

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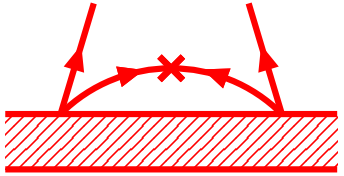
# CONTRIBUTION FROM ULTRASOFT NEUTRINOS

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



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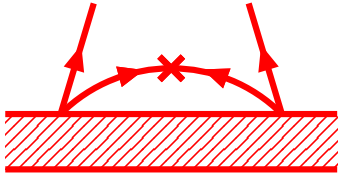


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- Contribution from **"ultrasoft"** **($|\mathbf{k}| \ll k_F \sim 100$ MeV)** neutrinos

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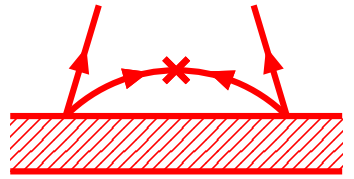
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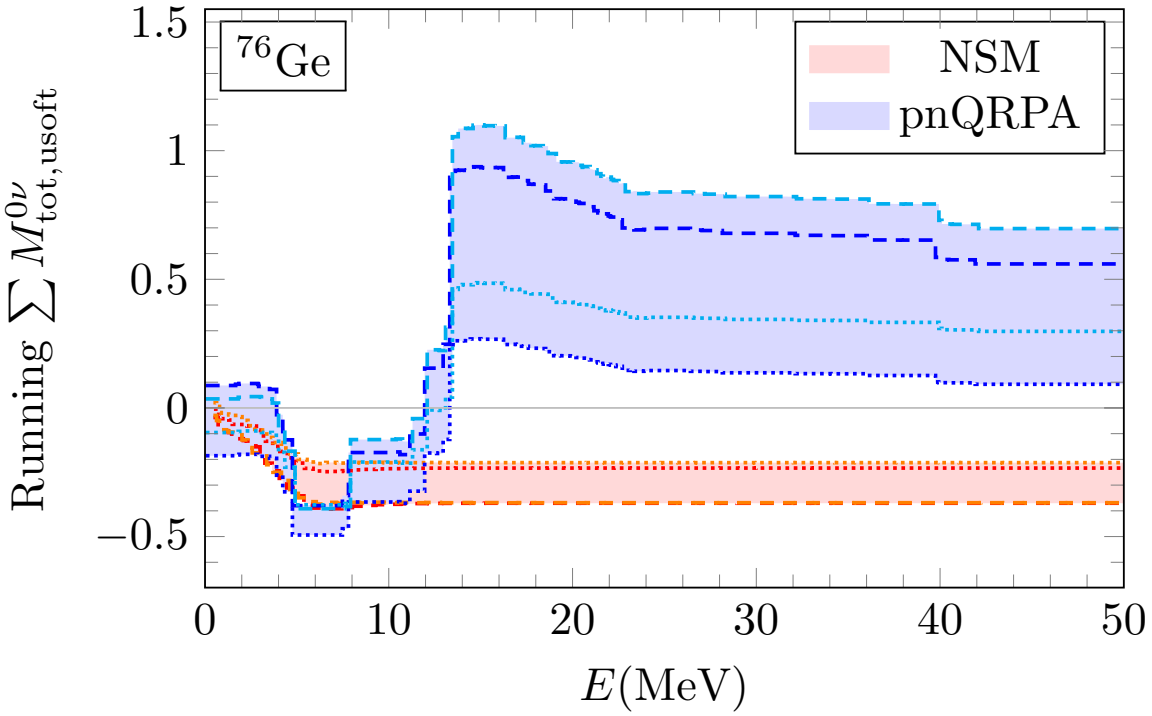
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- According to the NSM and pnQRPA,

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

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



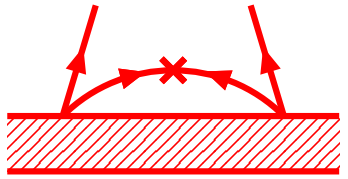



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# CONTRIBUTION FROM ULTRASOFT NEUTRINOS

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

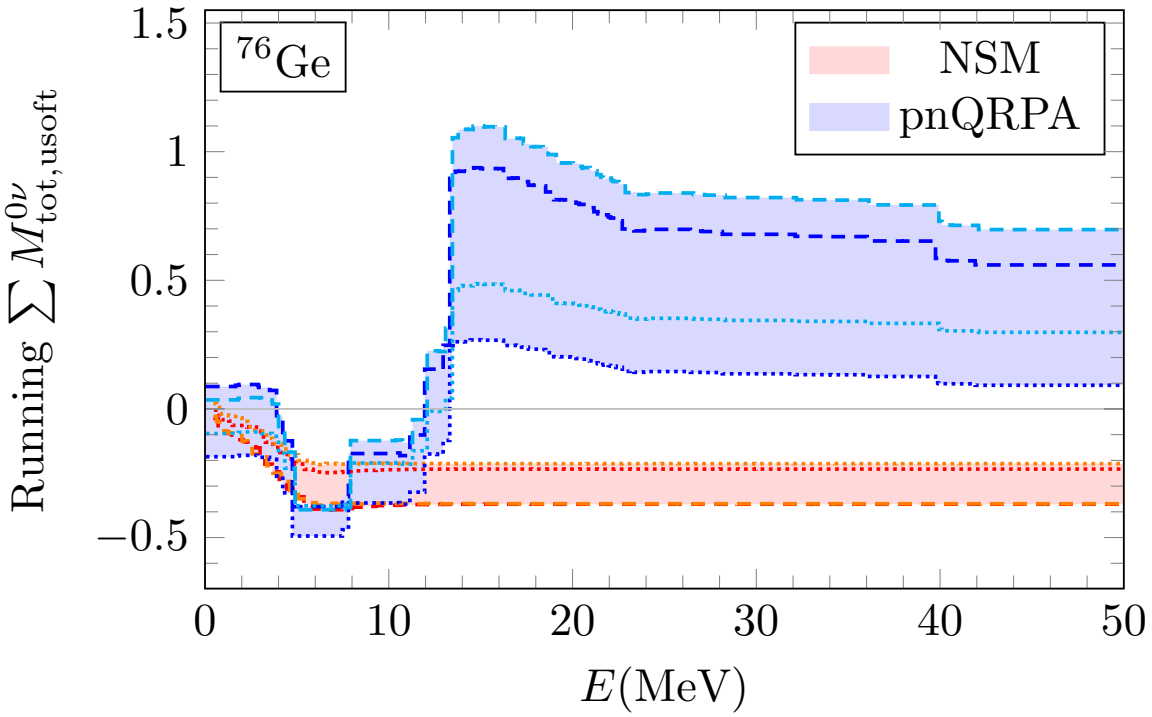


- Contribution from **"ultrasoft" ($|\mathbf{k}| \ll k_F \sim 100$ MeV)** neutrinos
- According to the NSM and pnQRPA,

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

*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)*

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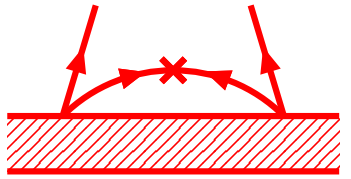
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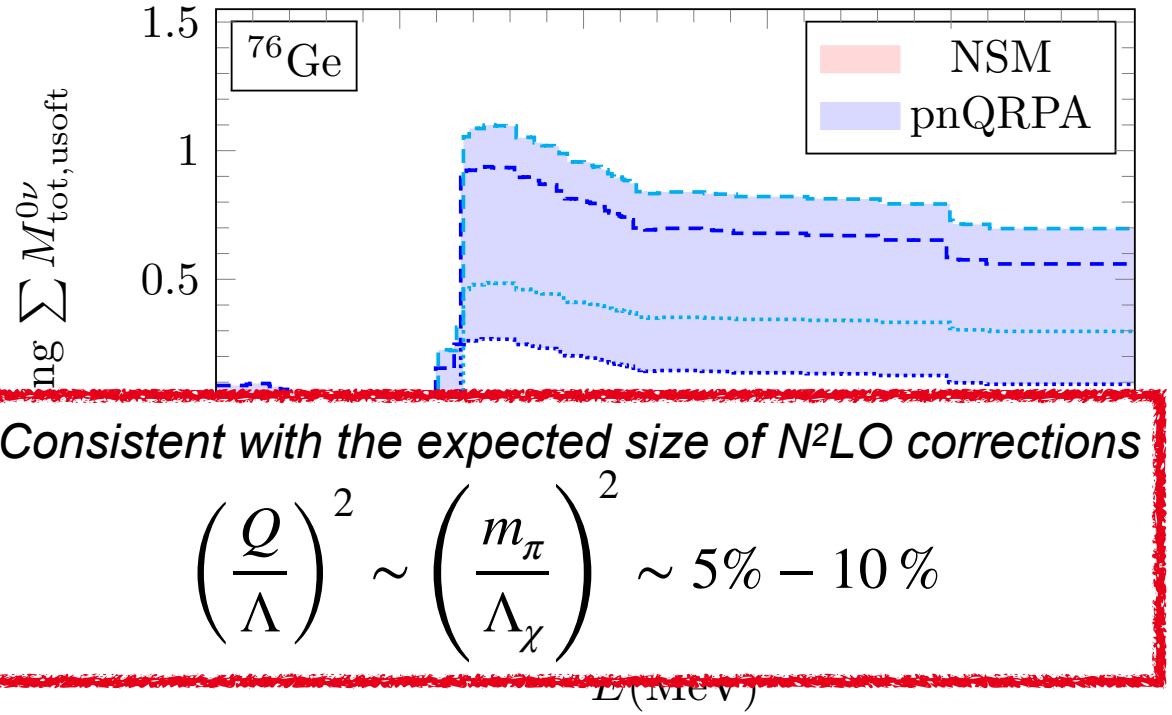
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*Castillo, Jokiniemi, Soriano, Menéndez, Phys. Lett. B 860, 139181 (2025)*

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*Consistent with the expected size of N²LO corrections*

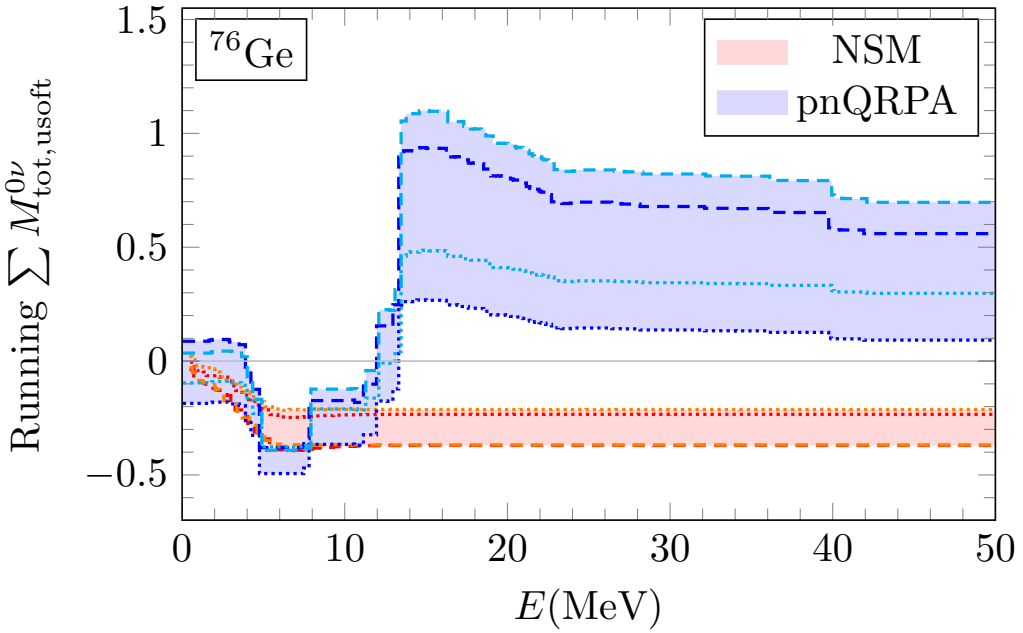
$$\left(\frac{Q}{\Lambda}\right)^2 \sim \left(\frac{m_\pi}{\Lambda_\chi}\right)^2 \sim 5\% - 10\,\%$$

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

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# DISCREPANCIES IN RUNNING SUMS

$$M^{0\nu}_{\text{usoft}} = -\frac{2R}{\pi}\sum_n \langle 0^+_f||\sum_j \tau^-_j \boldsymbol{\sigma}_j||1^+_n\rangle\langle 1^+_n||\sum_k \tau^-_k \boldsymbol{\sigma}_k||0^+_i\rangle \times \left(E_e + E_n - E_i\right) \times \left[\ln\frac{\mu_{\text{us}}}{2\left(E_e + E_n - E_i\right)} + 1\right]$$

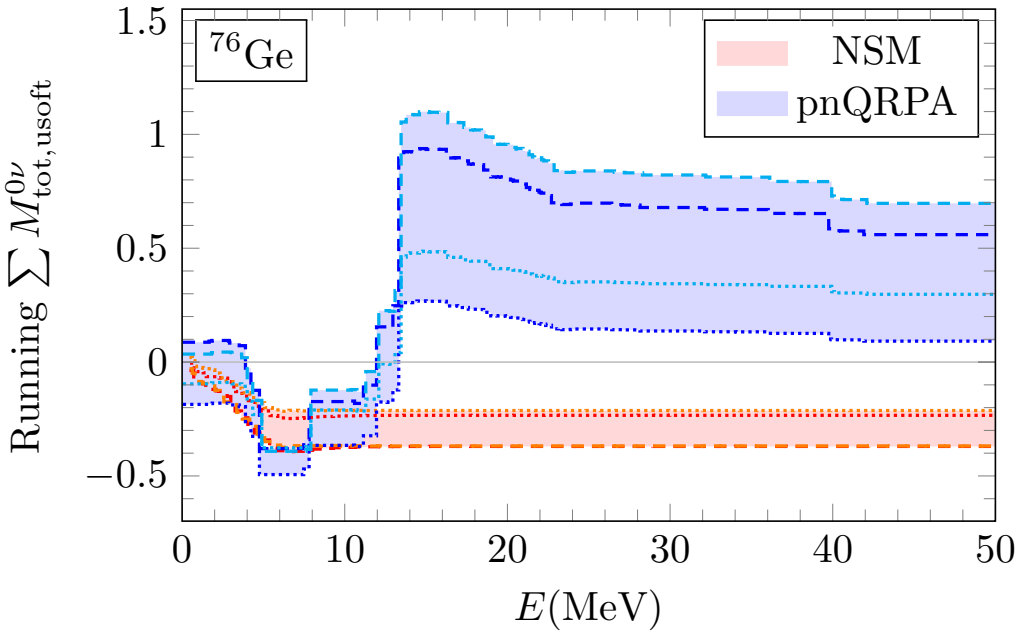



*Castillo, Jokiniemi, Soriano, Menéndez, Phys. Lett. B 860, 139181 (2025)*

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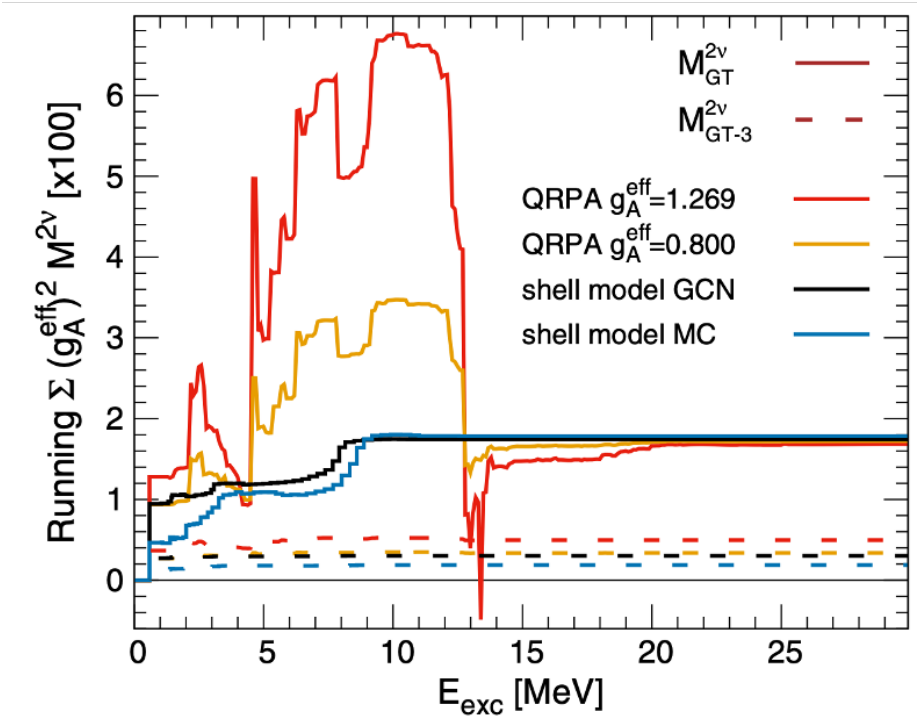
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Castillo, Jokiniemi, Soriano, Menéndez, Phys. Lett. B 860, 139181 (2025)

$$M^{2\nu} = \sum_n \frac{\langle 0^+_f||\sum_j \tau^-_j \boldsymbol{\sigma}_j||1^+_n\rangle\langle 1^+_n||\sum_k \tau^-_k \boldsymbol{\sigma}_k||0^+_i\rangle}{E_n - (E_i + E_f)/2}$$

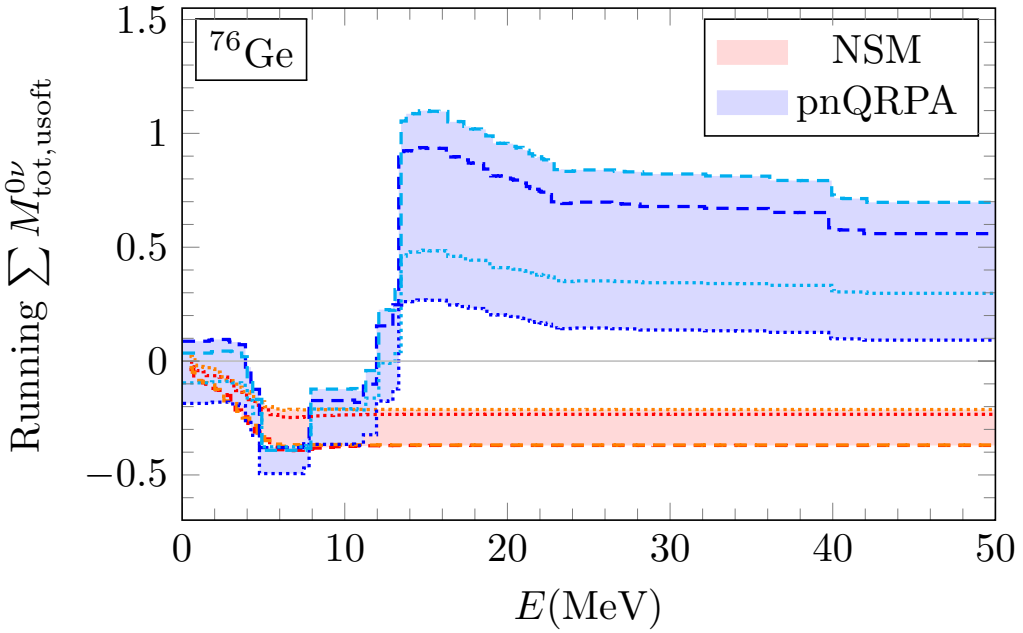



KamLAND-Zen Collaboration, Phys. Rev. Lett. 122, 192501 (2019)

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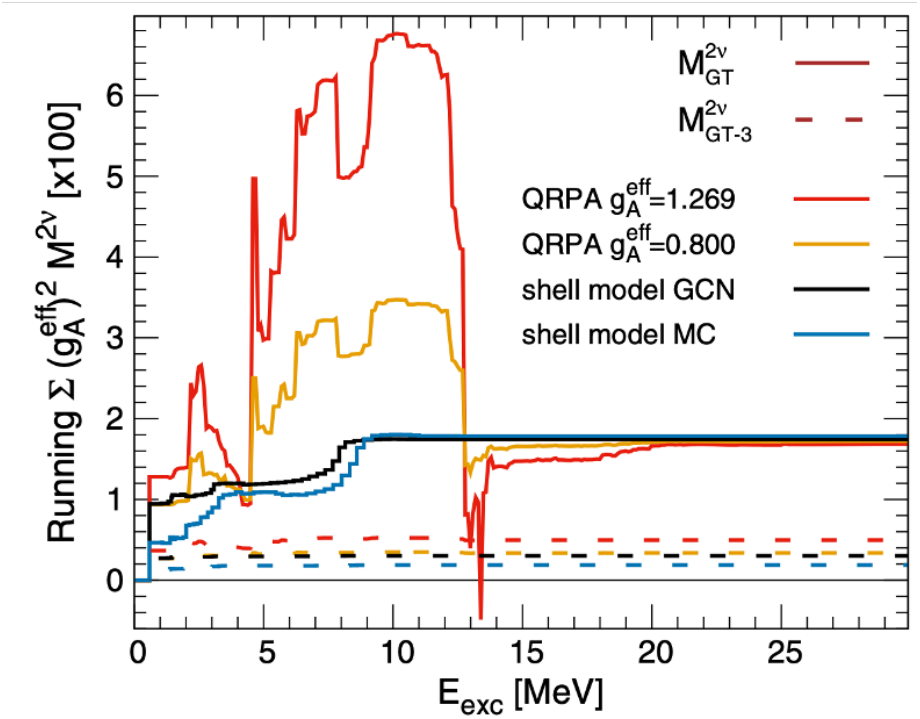
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Castillo, Jokiniemi, Soriano, Menéndez, Phys. Lett. B 860, 139181 (2025)

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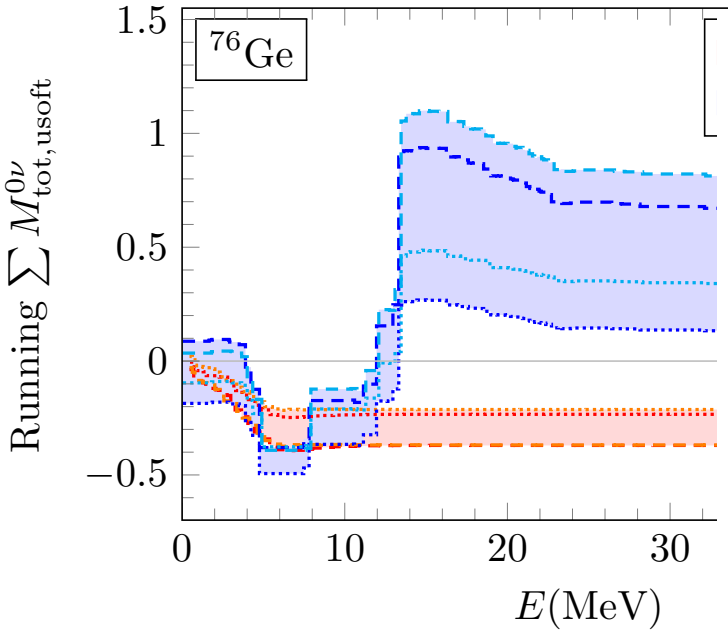

KamLAND-Zen Collaboration, Phys. Rev. Lett. 122, 192501 (2019)

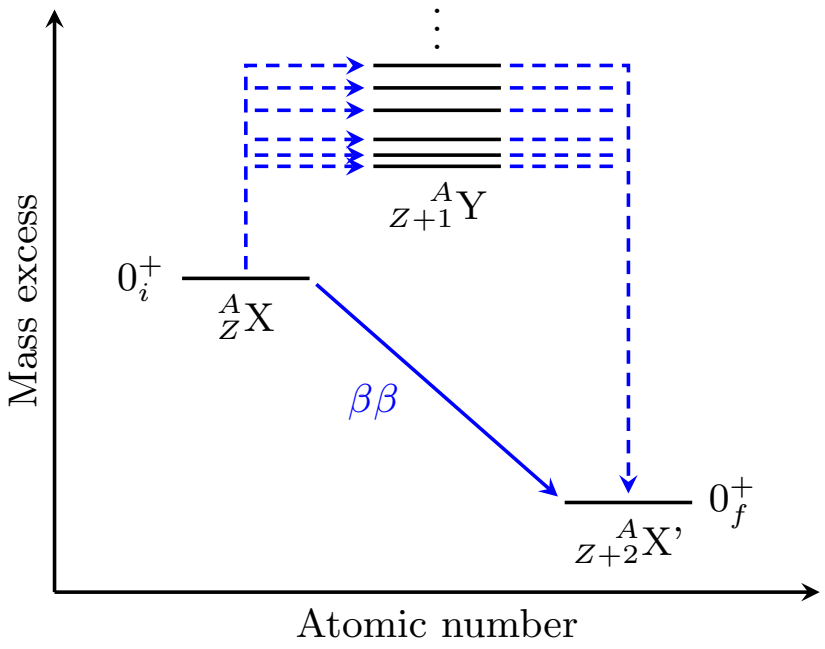
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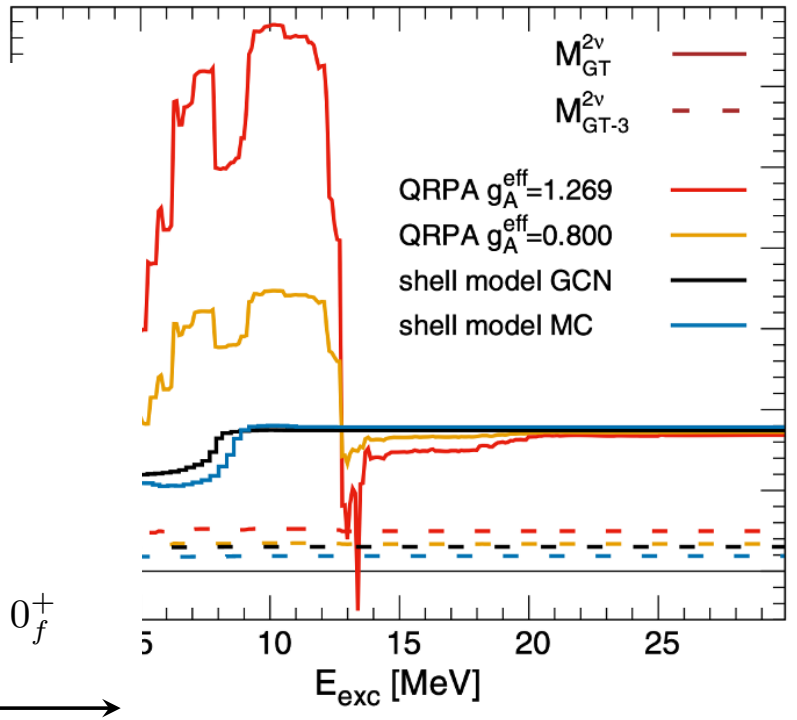
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*Castillo, Jokiniemi, Soriano, Mené*
*Phys. Lett. B 860, 139181 (202*

*oration, Phys. Rev. Lett. 122, 192501 (2019)*

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# OUTLINE

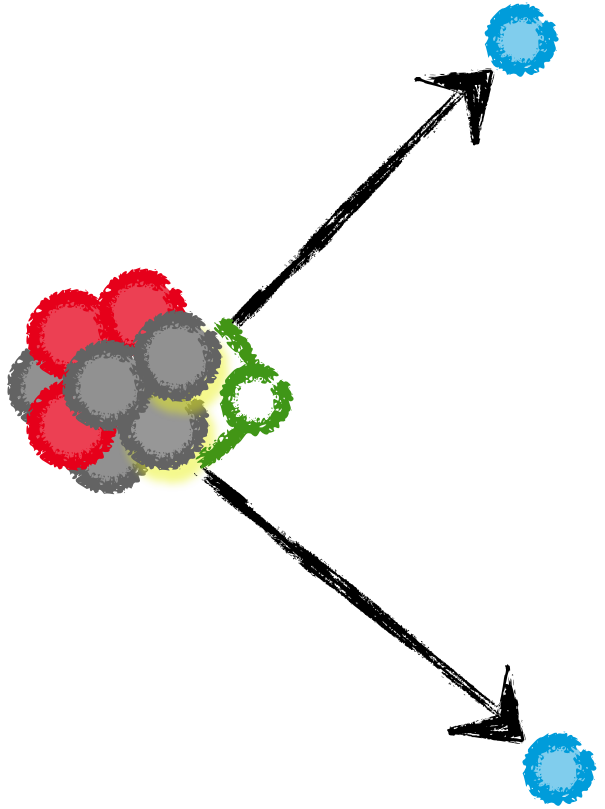
1 Introduction

2 Effective field theory for neutrinoless double-beta decay

**3 Probing neutrinoless double-beta decay by nuclear observables**

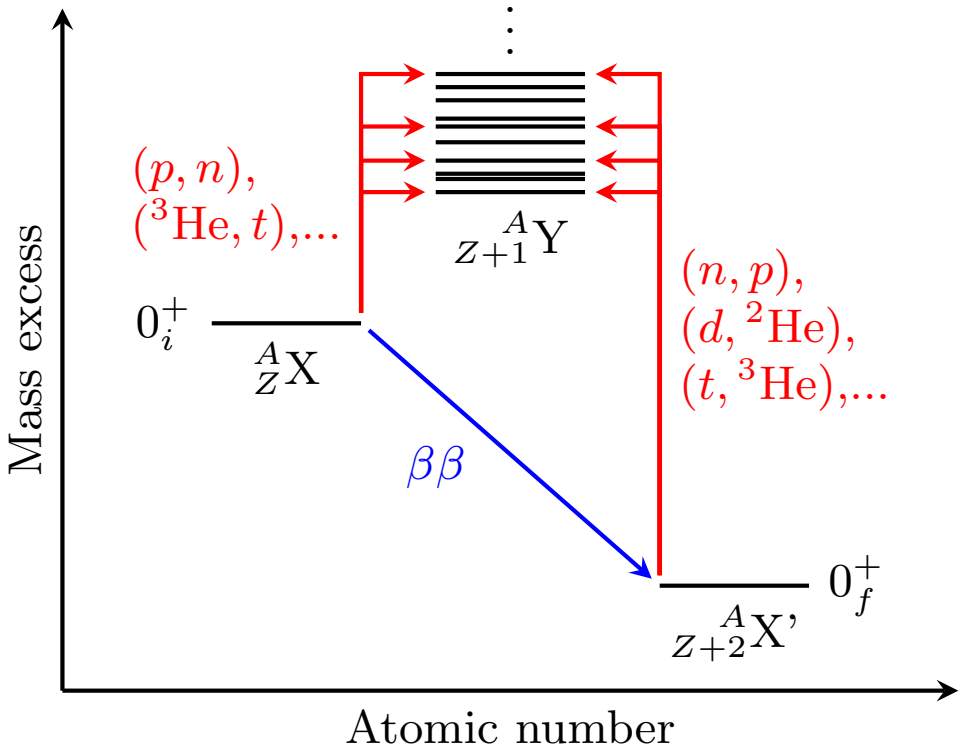
4 Current status

5 Summary and Outlook



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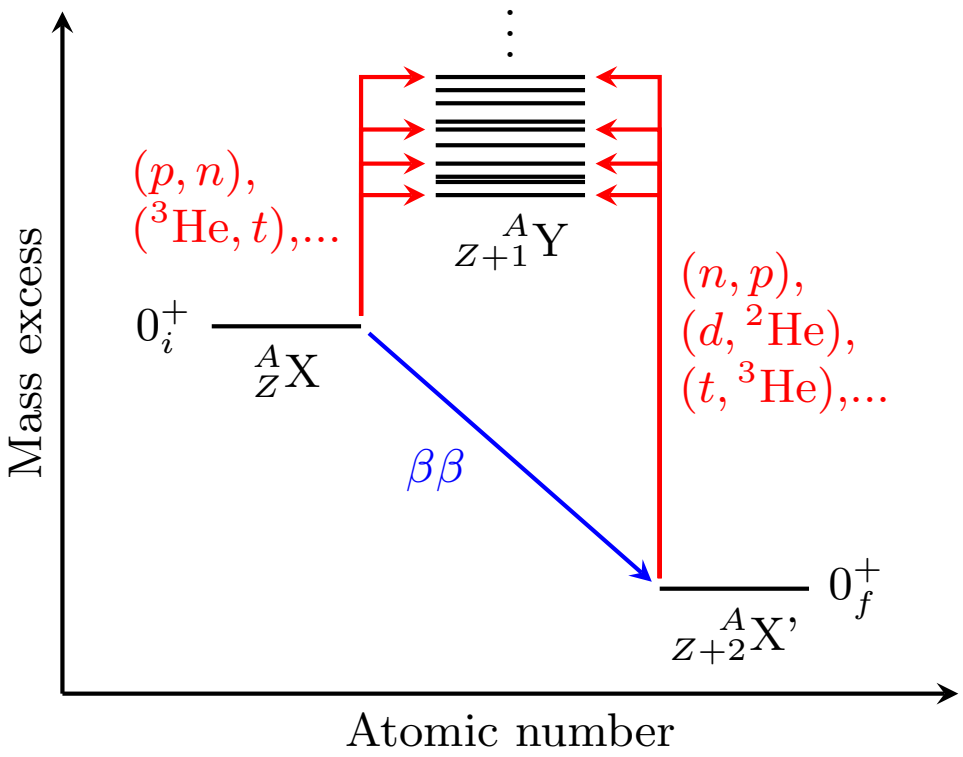
# PROBING $\beta\beta$ DECAYS BY CHARGE-EXCHANGE REACTIONS



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

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

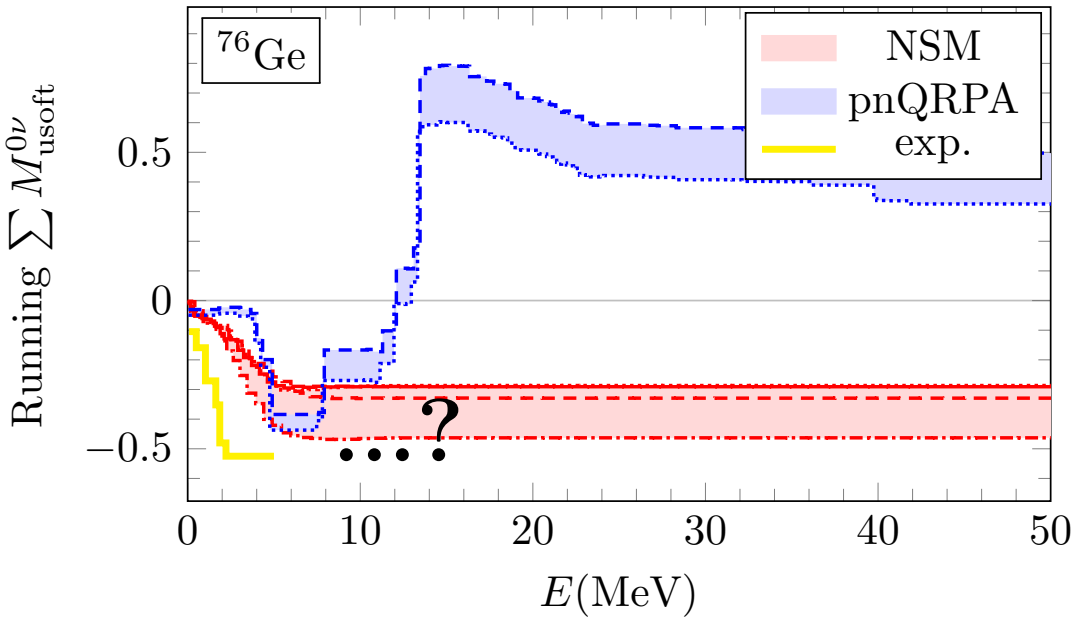


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# PROBING $\beta\beta$ DECAYS BY CHARGE-EXCHANGE REACTIONS

- Charge-exchange reactions can probe **virtual transitions to intermediate states**
- Available **data ends at ~ 5 MeV** (except for $^{48}$Ca)

$^{76}$Ge($^{3}$He,$t$)$^{76}$As:
*Hies et al., Phys. Rev. C 86, 014304 (2012)*
$^{76}$Se($d$,$^{2}$He)$^{76}$As:
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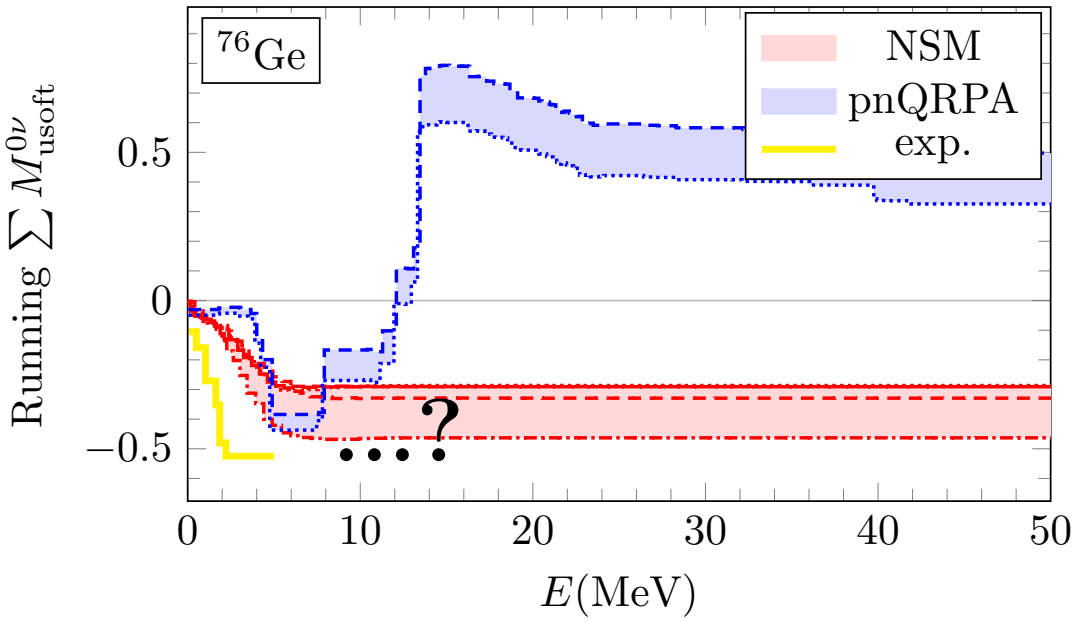

*Castillo, Jokiniemi, Soriano, Menéndez, Phys. Lett. B 860, 139181 (2025)*

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

- 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**

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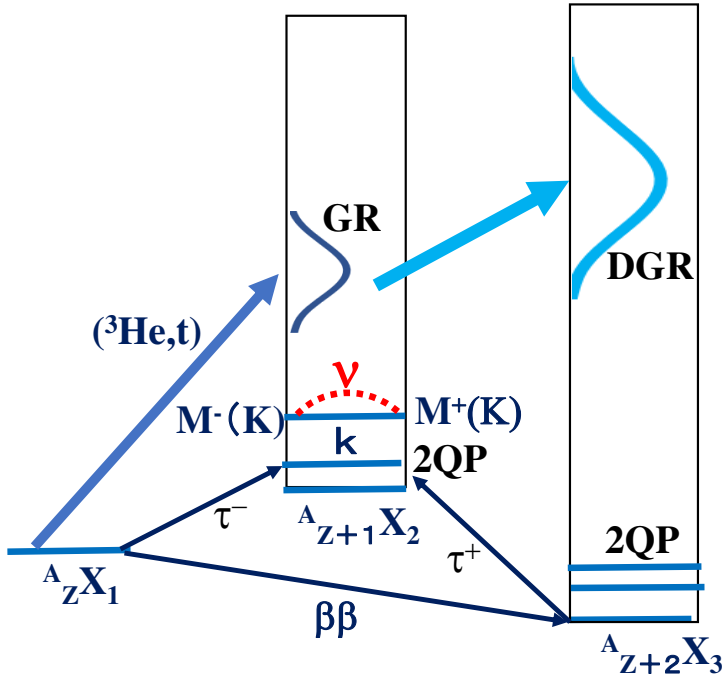



*Castillo, Jokiniemi, Soriano, Menéndez, Phys. Lett. B 860, 139181 (2025)*

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# DOUBLE CHARGE EXCHANGE REACTIONS

$$M_{\mathrm{L}}^{0\nu} = M_{\mathrm{GT}}^{0\nu} - \left(\frac{g_{\mathrm{V}}}{g_{\mathrm{A}}}\right)^2 M_{\mathrm{F}}^{0\nu} + M_{\mathrm{T}}^{0\nu}$$




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

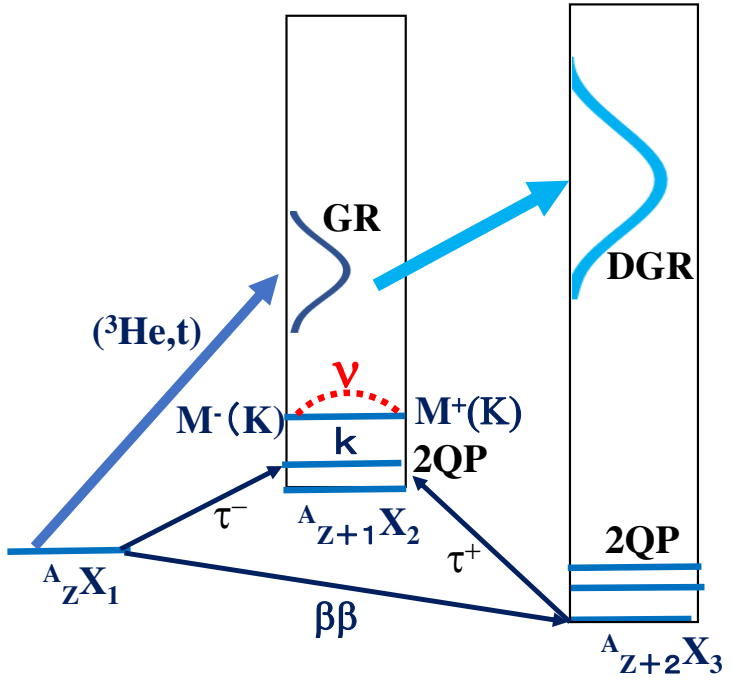
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*Leading component*

$$M_{\mathrm{GT}}^{0\nu} = \langle f \,||\, \sum_{jk} \tau_j^- \tau_k^- \boldsymbol{\sigma}_j \, \boldsymbol{\sigma}_k V_{\mathrm{GT}}(r_{jk}) \,||\, i \rangle$$




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

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# DOUBLE CHARGE EXCHANGE REACTIONS

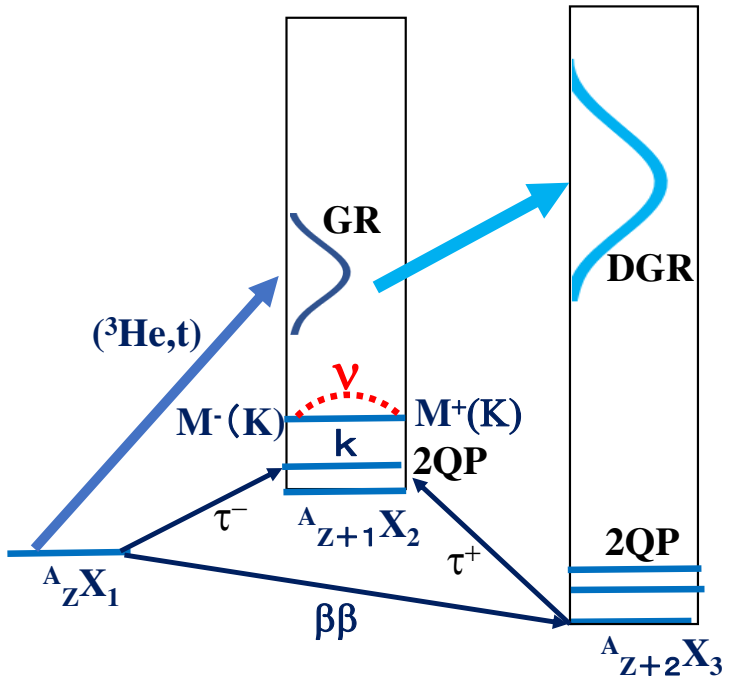
$$M^{0\nu}_{\mathrm{L}} = M^{0\nu}_{\mathrm{GT}} - \left(\frac{g_{\mathrm{V}}}{g_{\mathrm{A}}}\right)^2 M^{0\nu}_{\mathrm{F}} + M^{0\nu}_{\mathrm{T}}$$

*Leading component*

$$M^{0\nu}_{\mathrm{GT}} = \langle f \,||\, \sum_{jk} \tau^-_j \tau^-_k \boldsymbol{\sigma}_j \, \boldsymbol{\sigma}_k V_{\mathrm{GT}}(r_{jk}) \,||\, i \rangle$$

- Double-Gamow-Teller (DGT) strength function

$$B(\mathrm{DGT};\lambda) = \frac{1}{2J_i+1} \left| \langle j \,||\, [\sum_{jk} \boldsymbol{\sigma}_j \, \tau^-_j \times \boldsymbol{\sigma}_k \, \tau^-_k]^{(\lambda)} \,||\, i \rangle \right|^2$$




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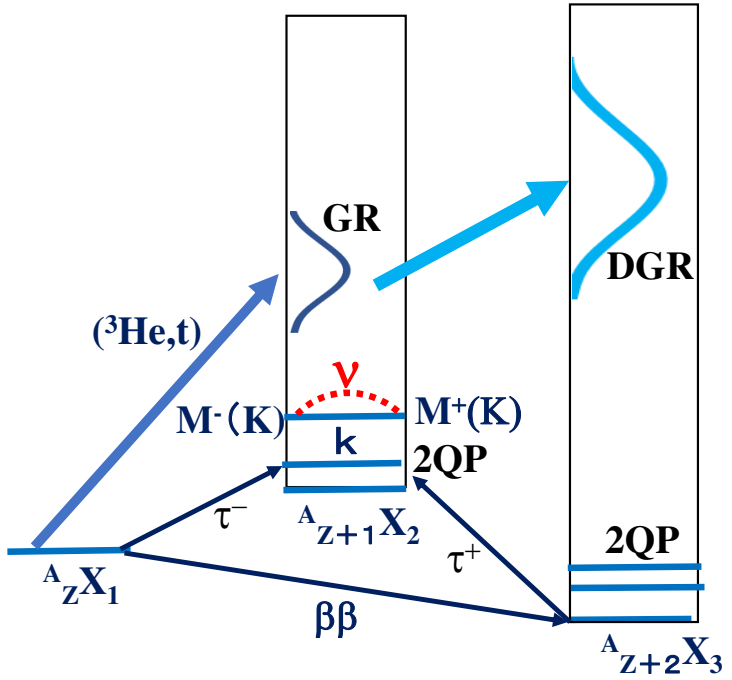
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  - **Very similar operator structures**

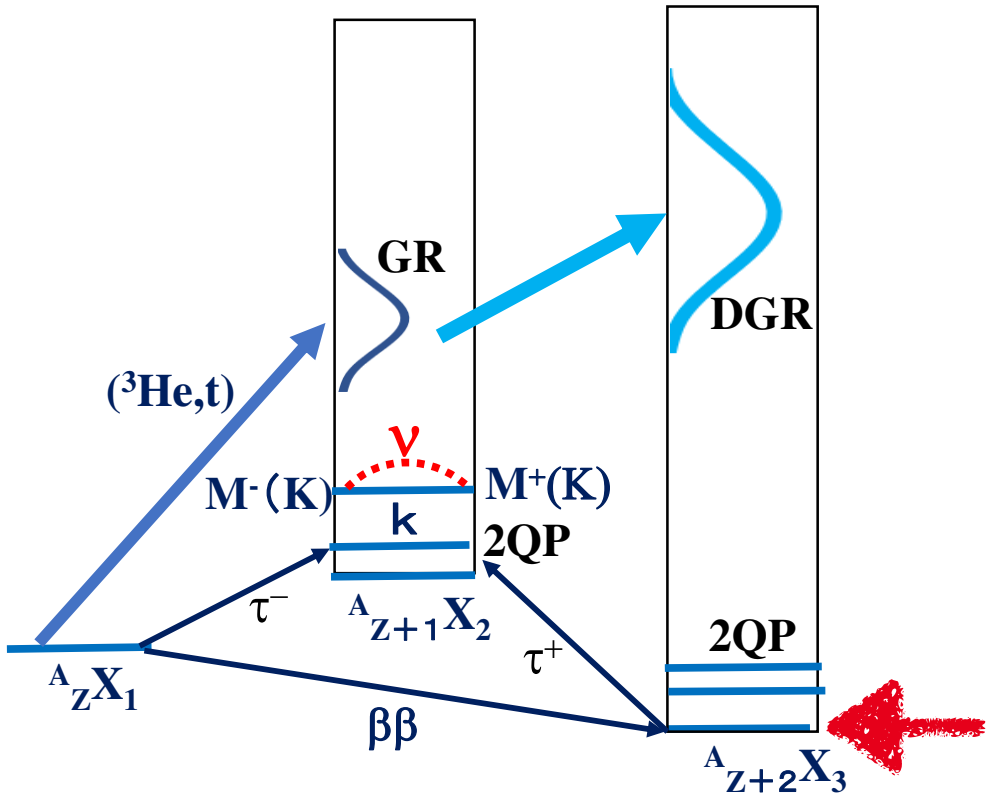



*Ejiri, Jokiniemi, Suhonen, Phys. Rev. C 105, L022501 (2022)*

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

$$M_{\mathrm{DGT}} = -\langle f || [\sum_{jk} \boldsymbol{\sigma}_j \, \tau_j^- \times \boldsymbol{\sigma}_k \, \tau_k^-]^{(0)} || i \rangle$$



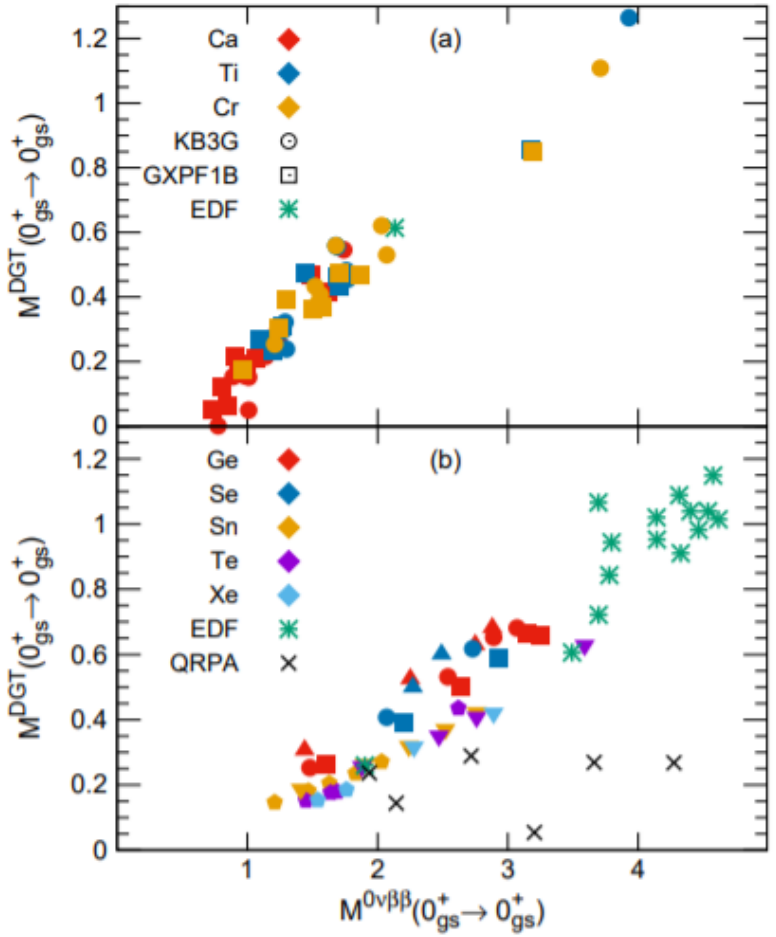

*Ejiri, Jokiniemi, Suhonen, Phys. Rev. C 105, L022501 (2022)*

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



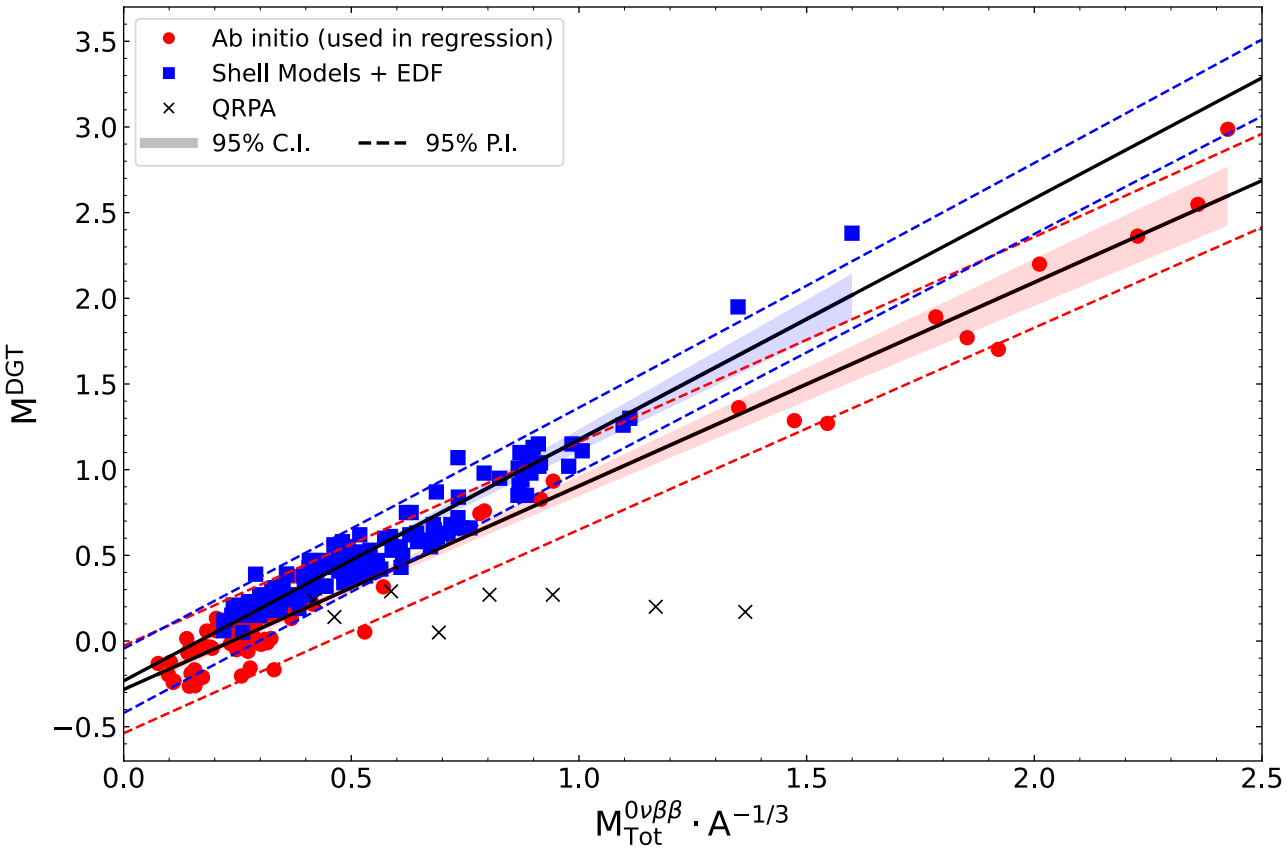

*Shimizu, Menéndez, Yako, Phys. Rev. Lett. 120, 142502 (2018)*

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- Correlation between $M_{\mathrm{L}}^{0\nu}$ and $M_{\mathrm{DGT}}$ first found in nuclear **shell model** and **density functional theory**
- Correlation also holds in ***ab initio*** **VS-IMSRG**



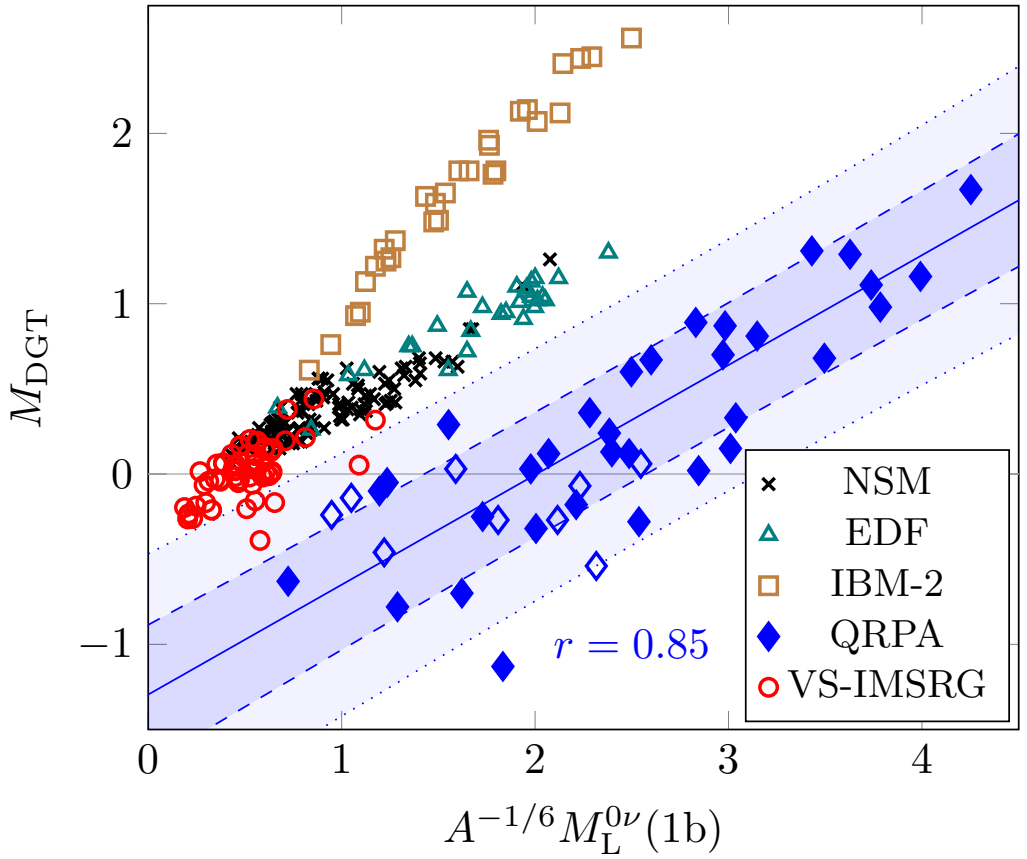

*Yao, Ginnett, Belley et al., Phys. Rev. C 106, 014315 (2022)*

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- Correlation between $M_{\mathrm{L}}^{0\nu}$ and $M_{\mathrm{DGT}}$ first found in nuclear **shell model** and **density functional theory**
- Correlation also holds in ***ab initio* VS-IMSRG**
- … and **QRPA**, when proton-neutron pairing is varied




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

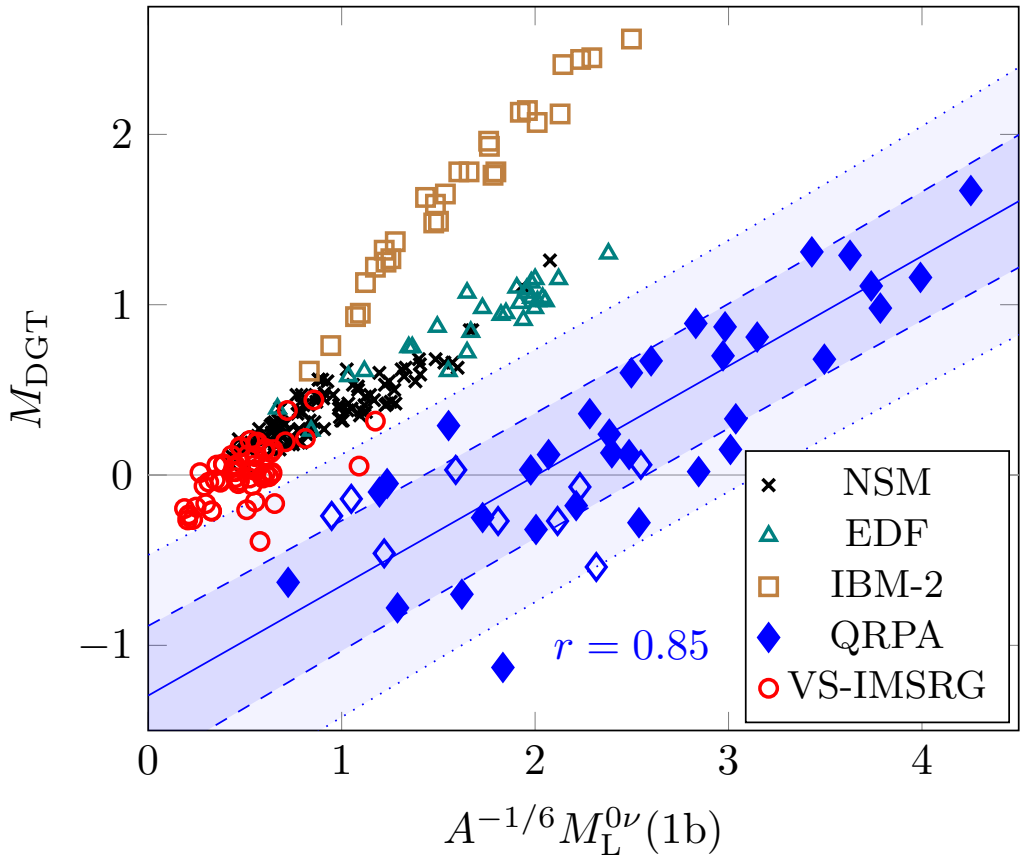
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- Correlation between $M_{\mathrm{L}}^{0\nu}$ and $M_{\mathrm{DGT}}$ first found in nuclear **shell model** and **density functional theory**
- Correlation also holds in ***ab initio* VS-IMSRG**
- … and **QRPA**, when proton-neutron pairing is varied

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




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

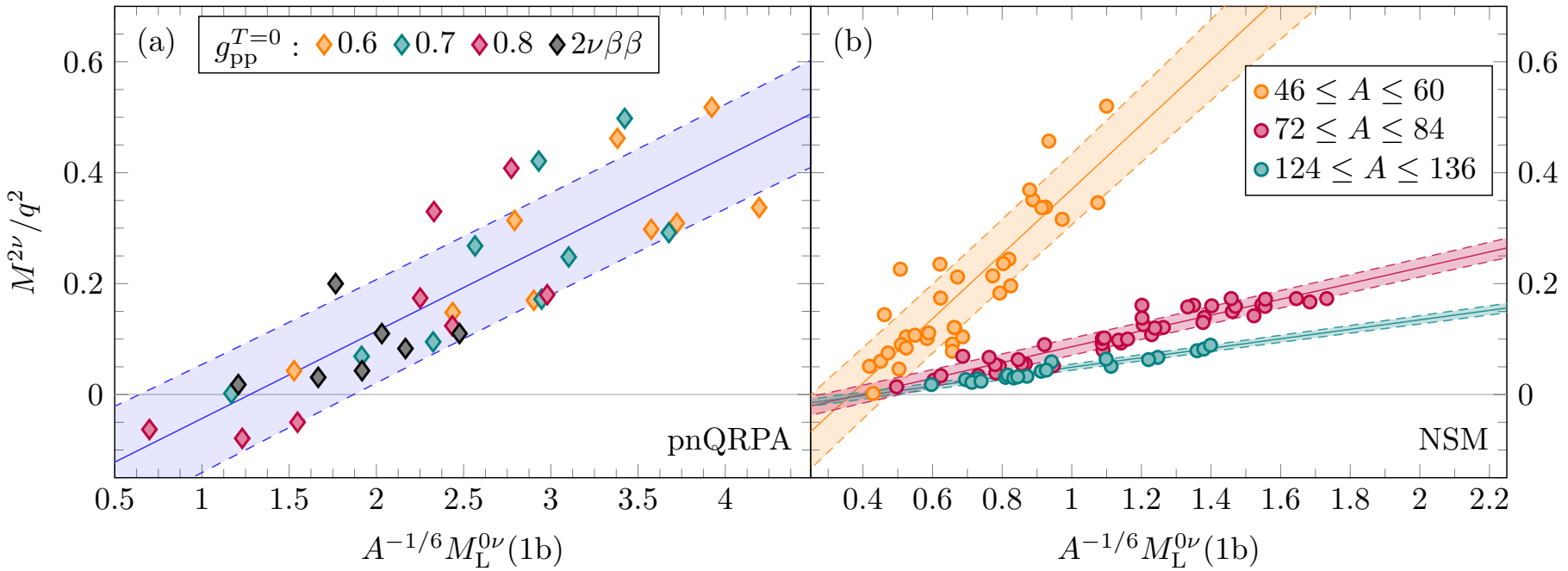
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# PROBING $0\nu\beta\beta$ DECAY BY $2\nu\beta\beta$ DECAY

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# PROBING $0\nu\beta\beta$ DECAY BY $2\nu\beta\beta$ DECAY

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

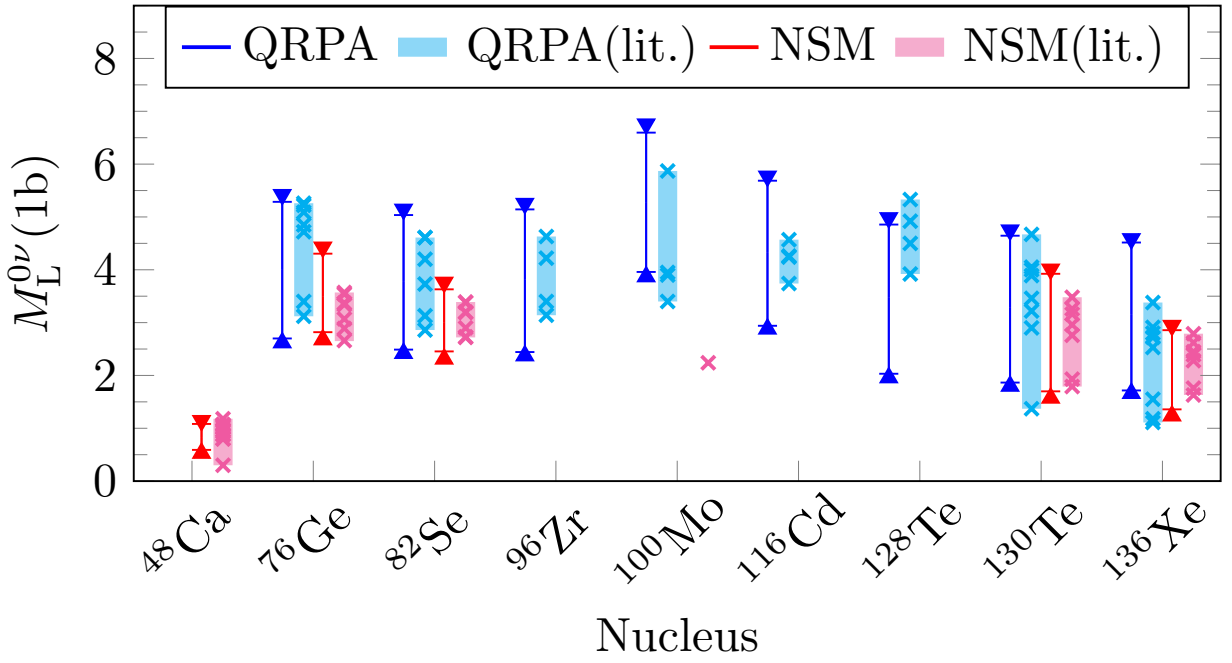



*Jokiniemi, Romeo, Soriano, Menéndez, Phys Rev. C 107, 044305 (2023)*

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# PROBING $0\nu\beta\beta$ DECAY BY $2\nu\beta\beta$ DECAY

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




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

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# OUTLINE

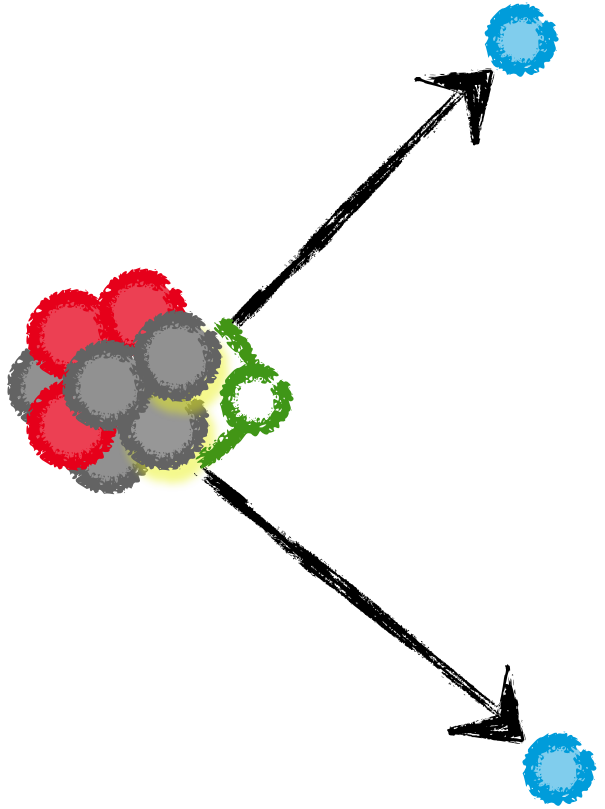

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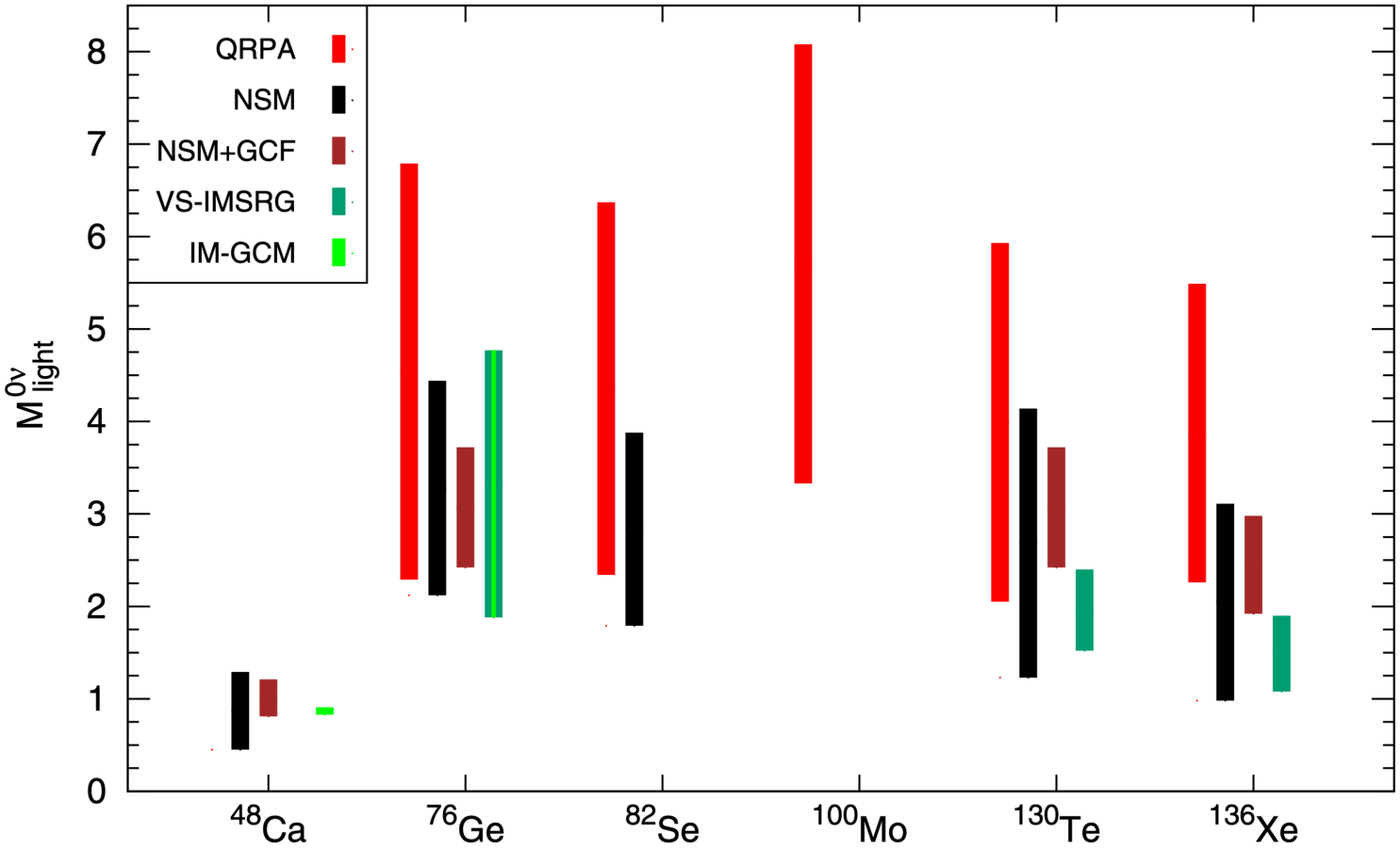
4 **Current status**

5 Summary and Outlook

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# CURRENT STATUS OF THE NUCLEAR MATRIX ELEMENTS

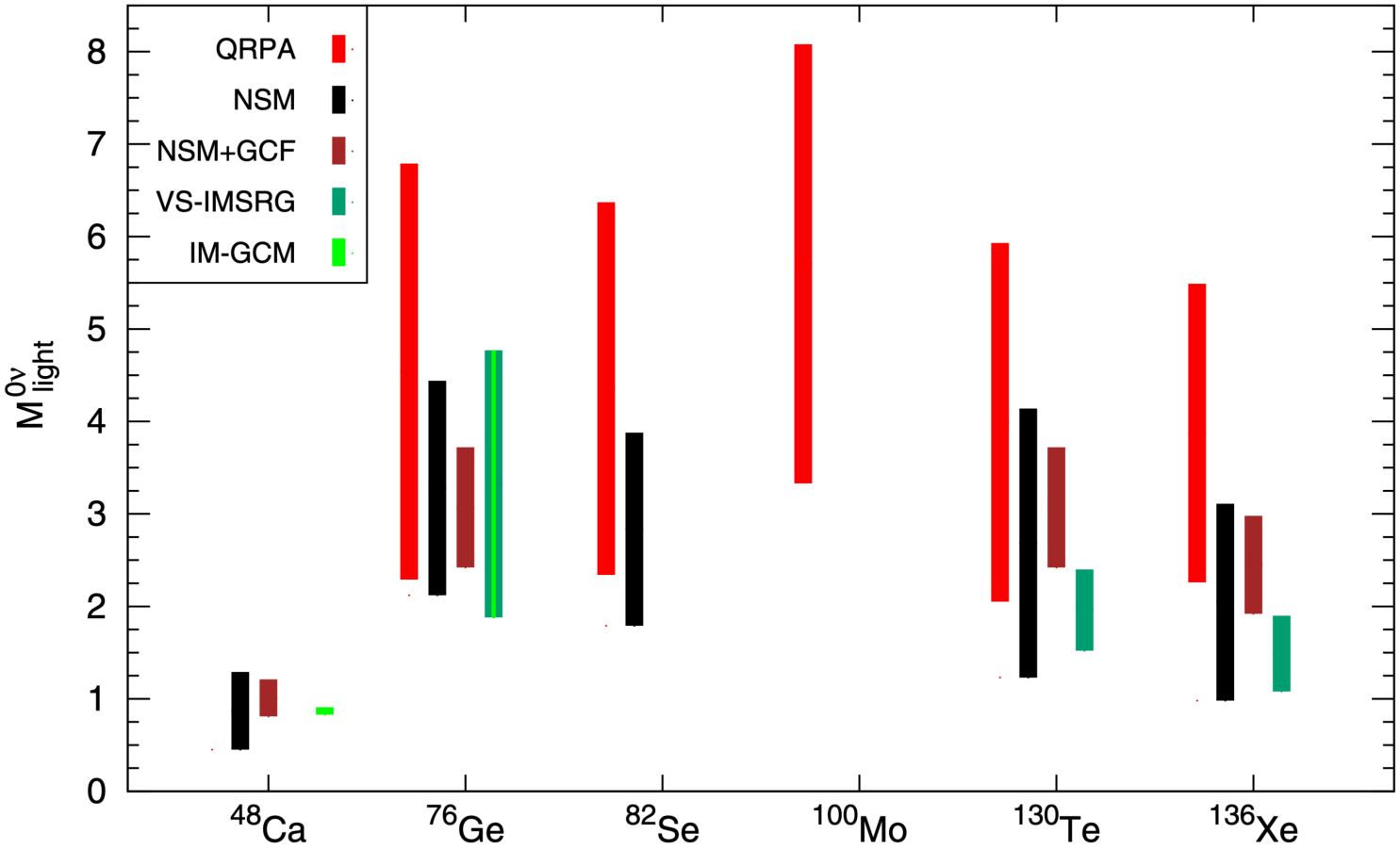



*Gómez-Cadenas, Martín-Albo, Menéndez, Mezzetto, Monrabal, Sorel, La Rivista del Nuovo Cimento 46, 619 (2023)*

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# CURRENT STATUS OF THE NUCLEAR MATRIX ELEMENTS

$M_{\mathrm{L}}^{0\nu} + M_{\mathrm{S}}^{0\nu}$

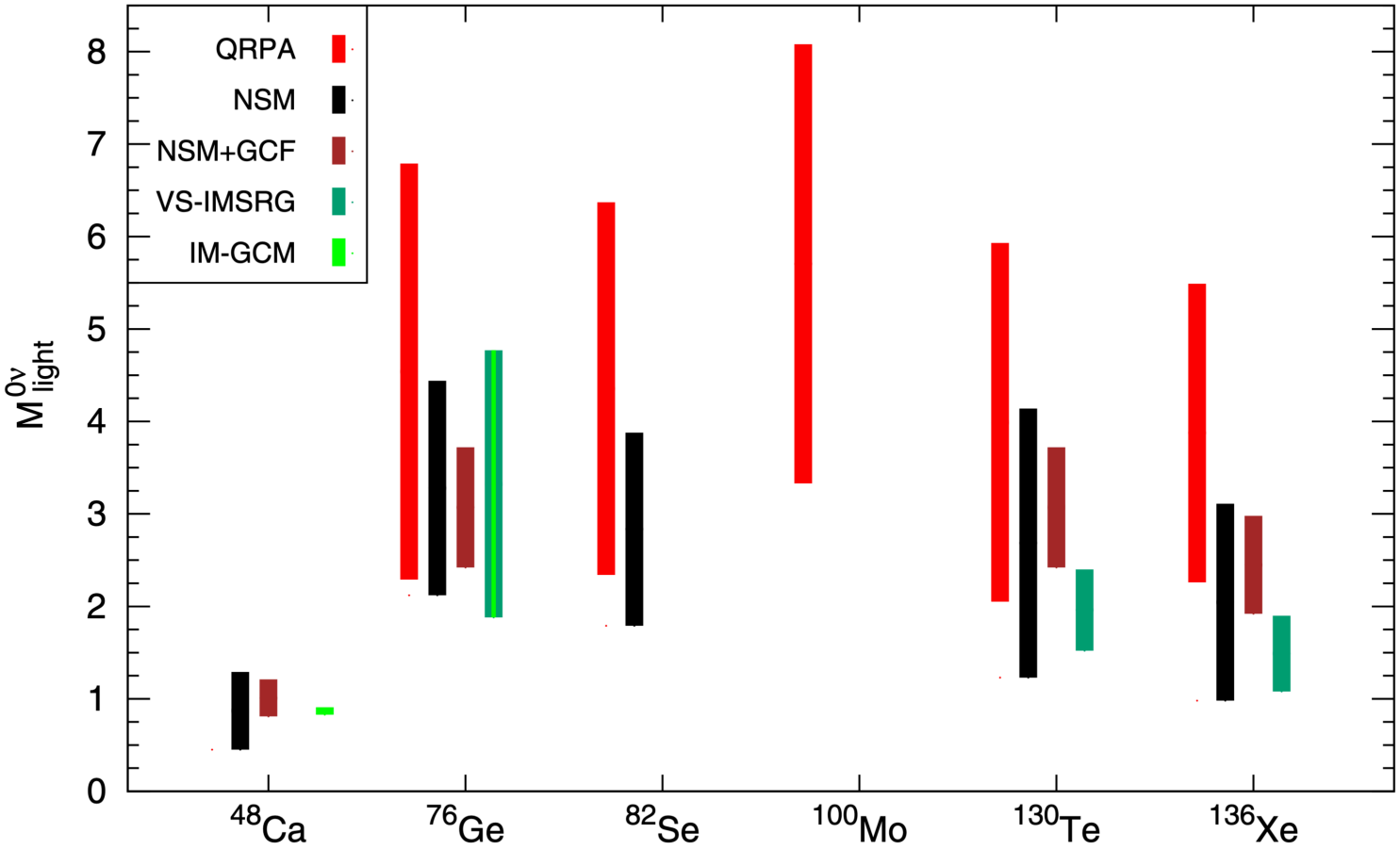



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# CURRENT STATUS OF THE NUCLEAR MATRIX ELEMENTS

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***Ranges*** cover:

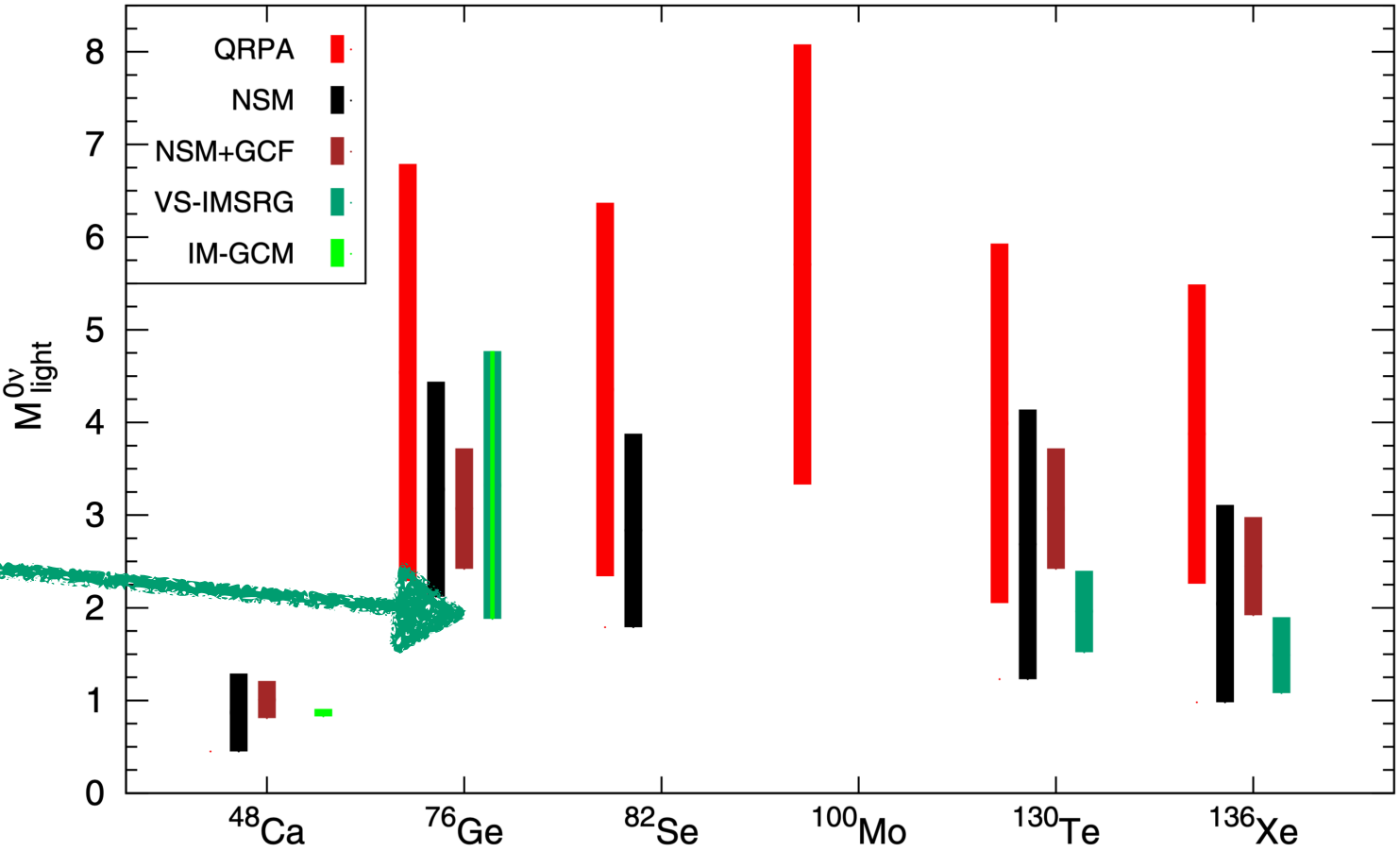
- Different parameters/ nuclear interactions
- Different values of $g_{\nu}^{\mathrm{NN}}$
- …

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# CURRENT STATUS OF THE NUCLEAR MATRIX ELEMENTS

$M_{\mathrm{L}}^{0\nu} + M_{\mathrm{S}}^{0\nu}$




***First NME with quantified uncertainty***

***Ranges*** cover:

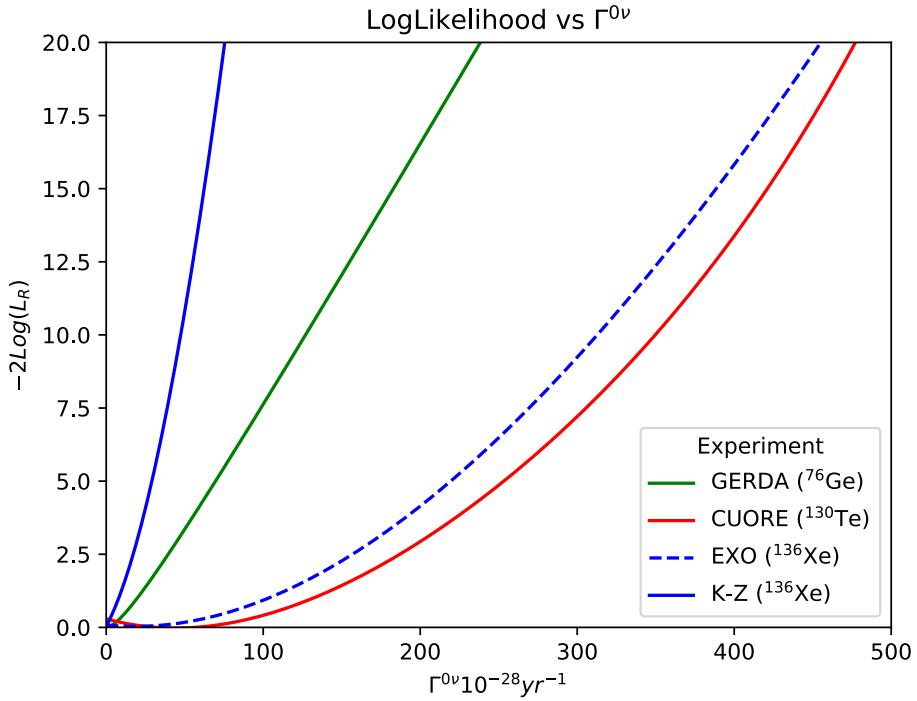
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# WHAT DOES THIS MEAN FOR THE EXPERIMENTS?

***Current best limits***

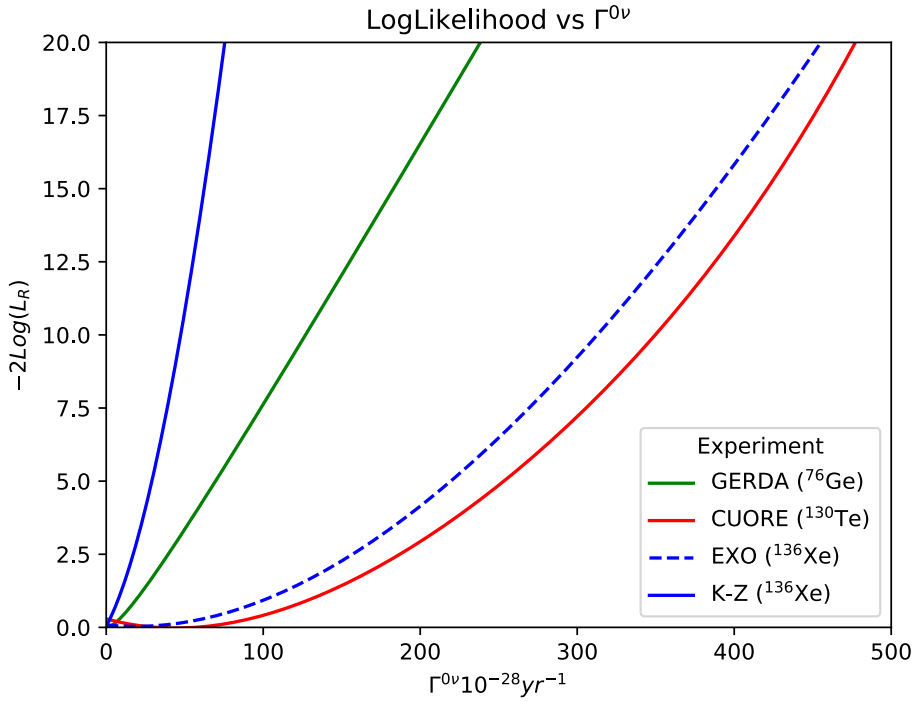


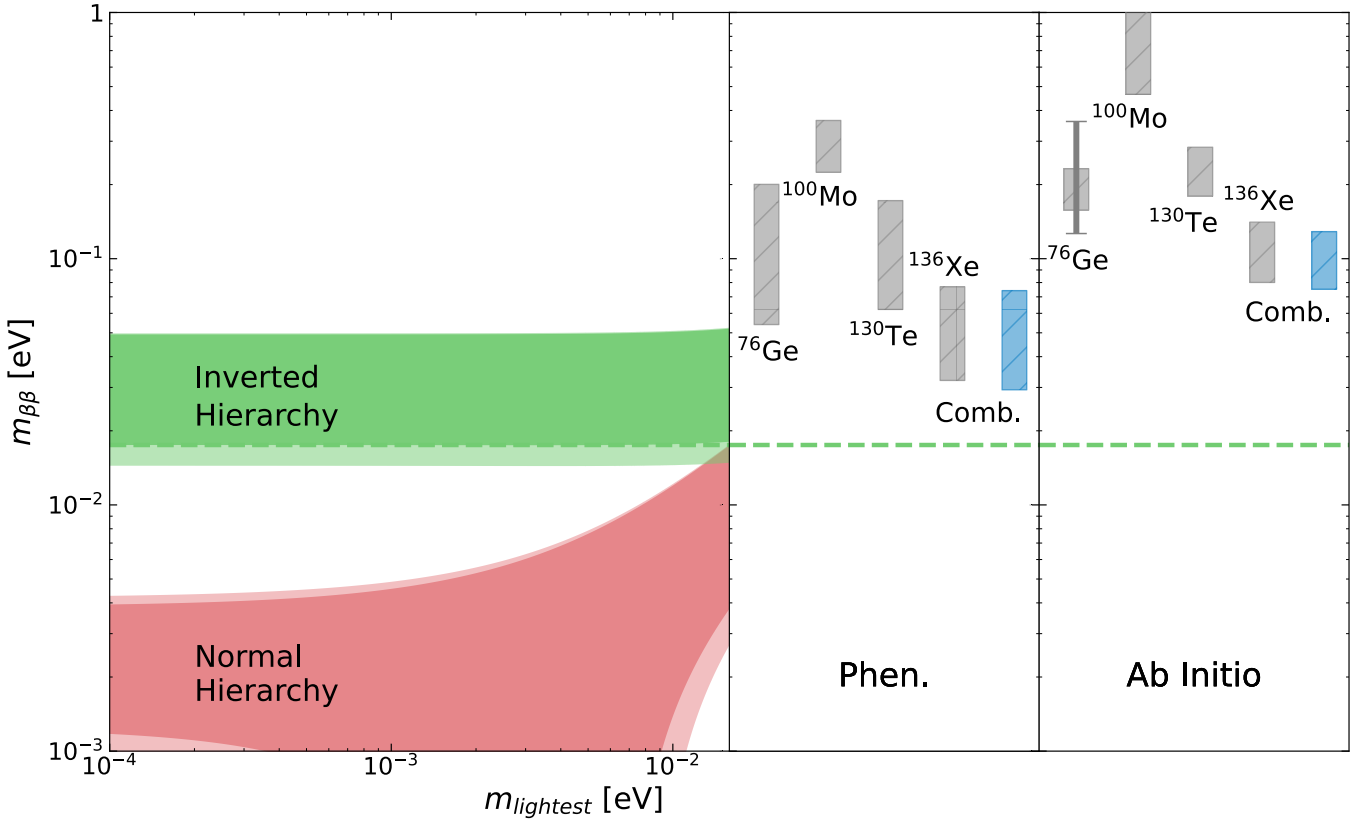

*Shickele, Jokiniemi, Belley, Holt, in preparation*

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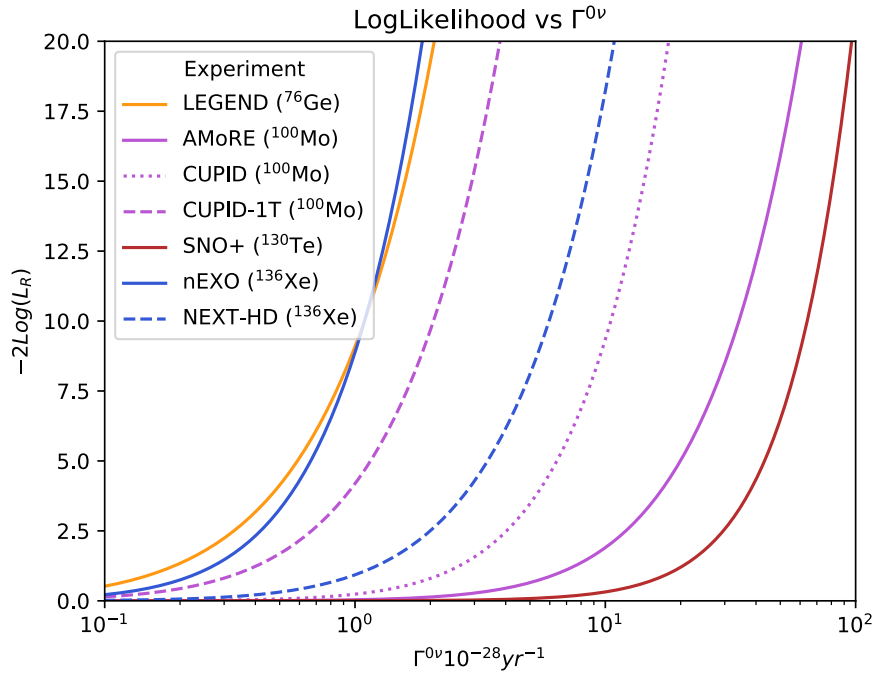



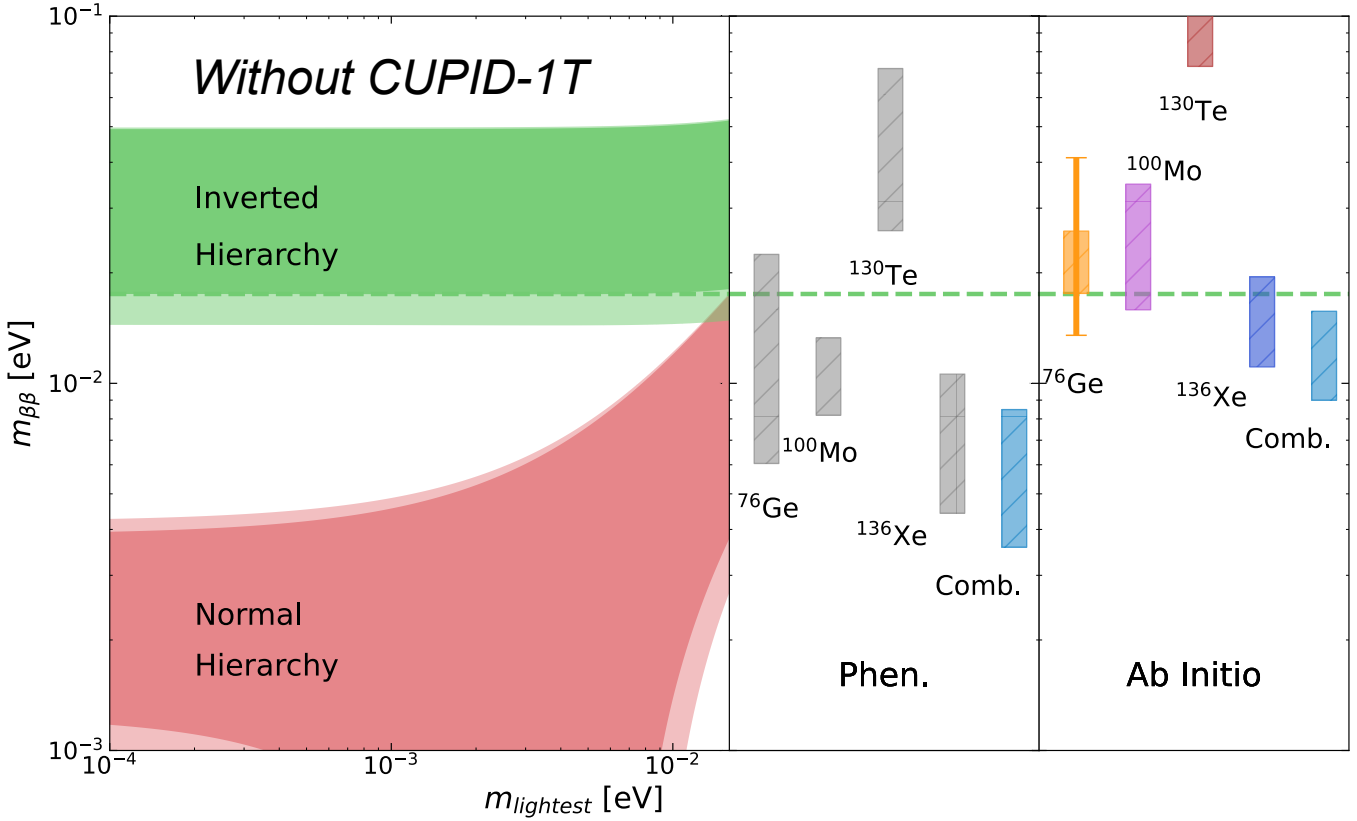

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# WHAT DOES THIS MEAN FOR THE EXPERIMENTS?

***Next-generation experiments***



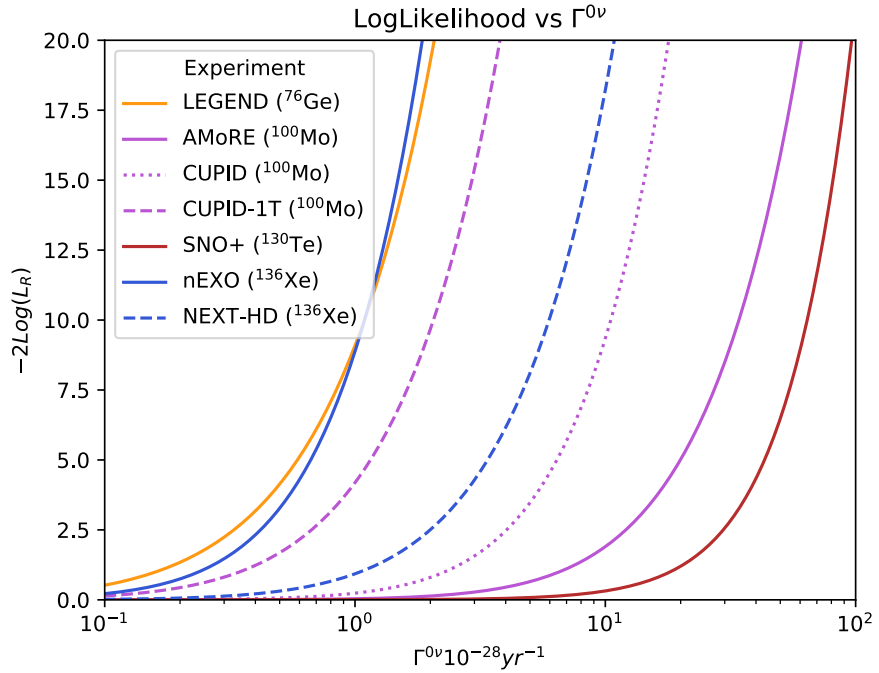



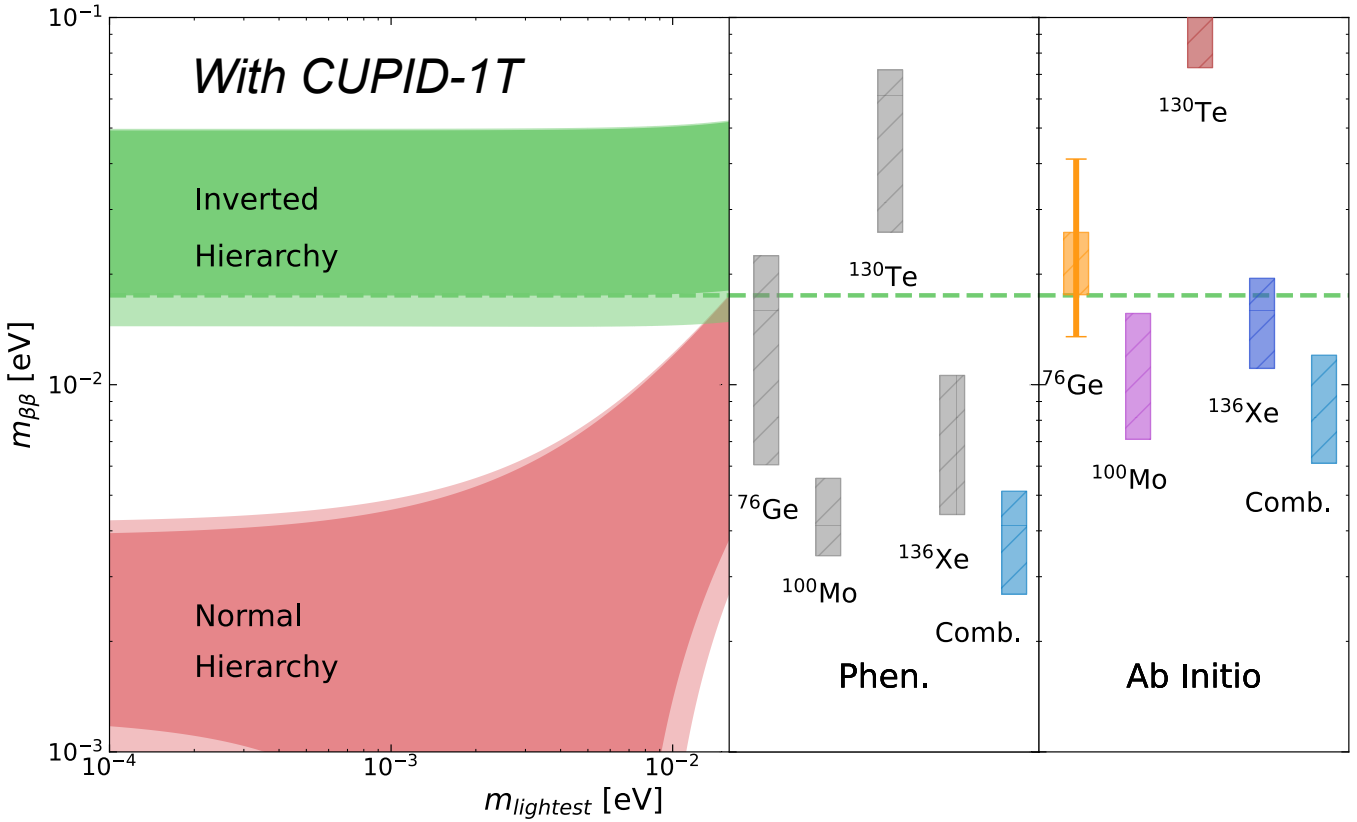

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# WHAT DOES THIS MEAN FOR THE EXPERIMENTS?

***Next-generation experiments***




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# OUTLINE

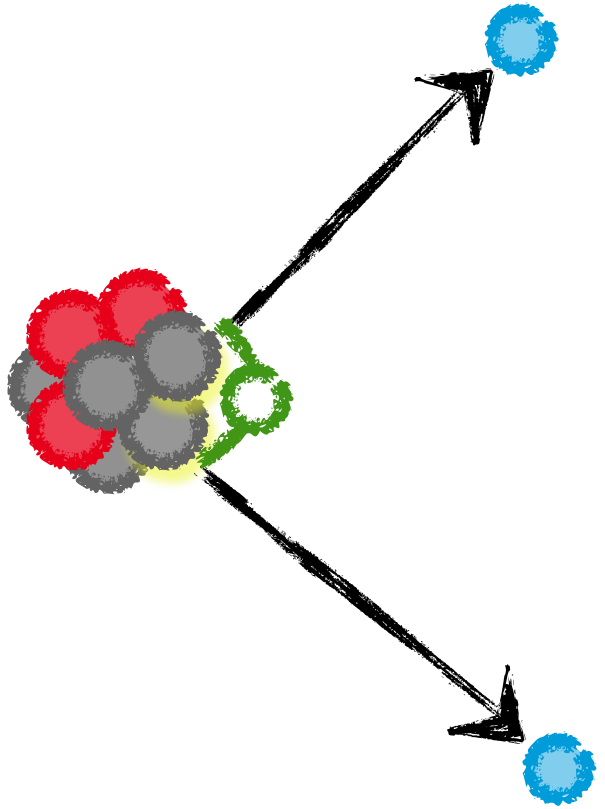

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# SUMMARY AND OUTLOOK

- $0\nu\beta\beta$ decay is a robust yet challenging probe for BSM physics and neutrino properties
- *Ab initio* methods are becoming capable of computing the needed nuclear matrix elements
- $\chi$EFT analysis of the operators allows for uncertainty quantification
- Next-generation experiments likely to fully cover the inverted-hierarchy band of neutrino masses

TODO

- Nuclear deformation
- Two-body currents
- Consistent order-by-order convergence study
- Different mechanisms, …

