LOEWE

Exzellente Forschung für Hessens Zukunft

TECHNISCHE UNIVERSITÄT DARMSTADT

AB INITIO CALCULATIONS ON NEUTRINOLESS DOUBLE-BETA DECAY

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TRIUMF

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

CIPANP 2025, Wisconsin-Madison

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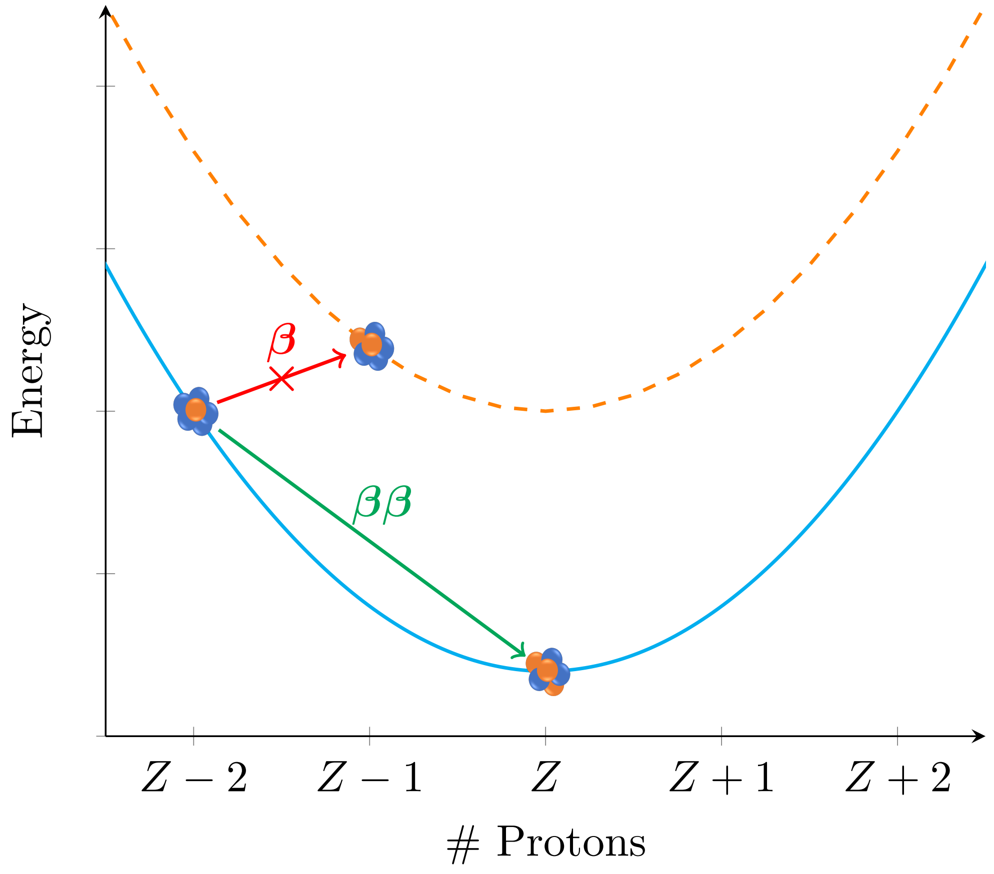
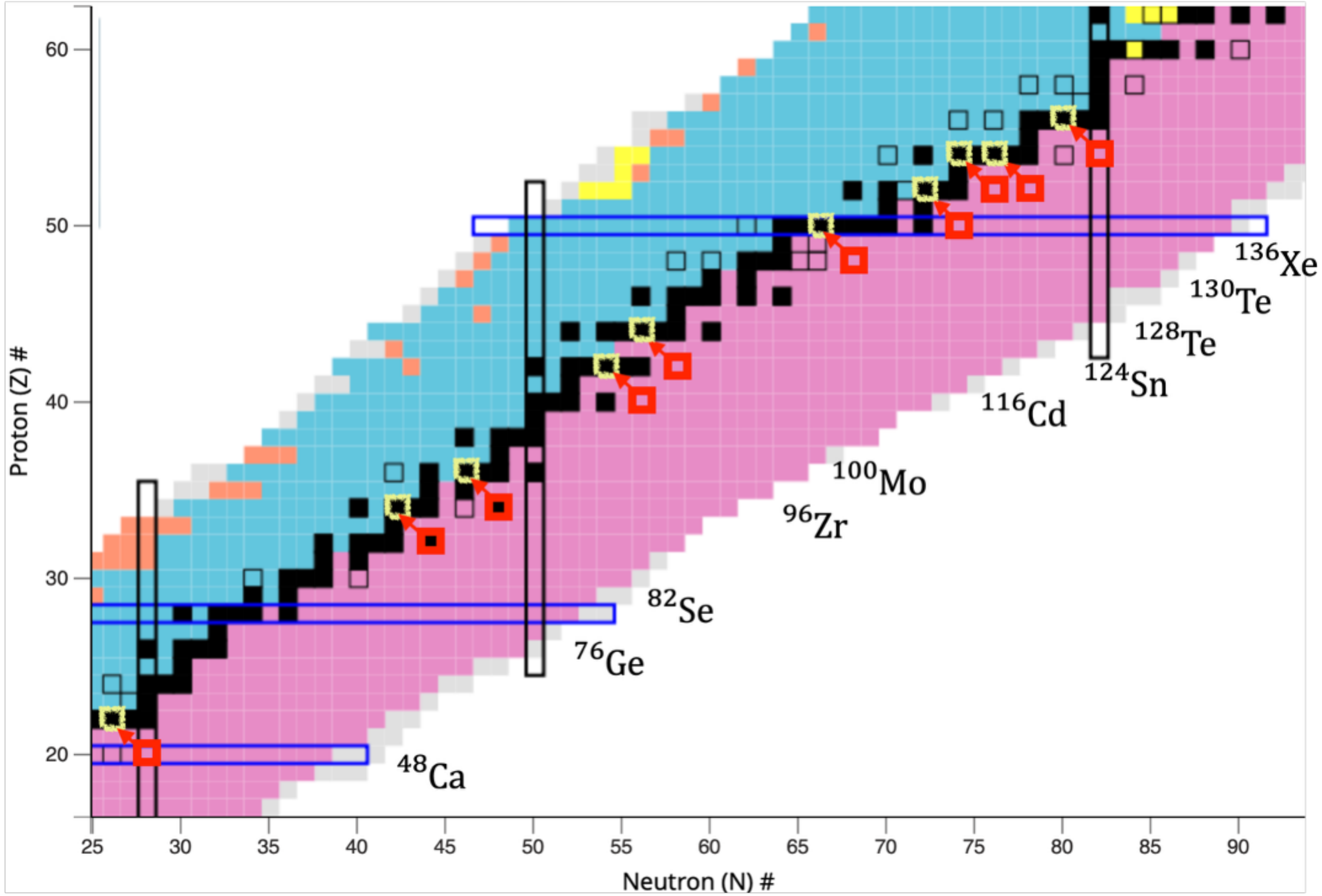
DOUBLE-BETA DECAY





Modified from nndc.bnl.gov/nudat3/

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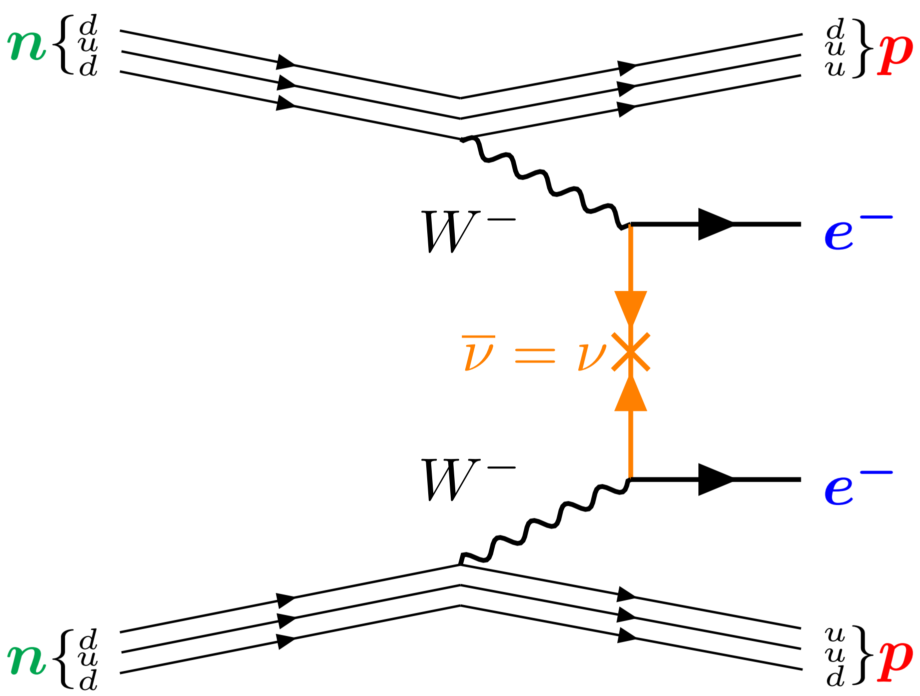
NEUTRINOLESS DOUBLE-BETA ($0\nu\beta\beta$) DECAY

$$\boxed{(A,Z) \rightarrow (A,Z+2) + 2e^- \cancel{+2\overline{\nu}_e}}$$



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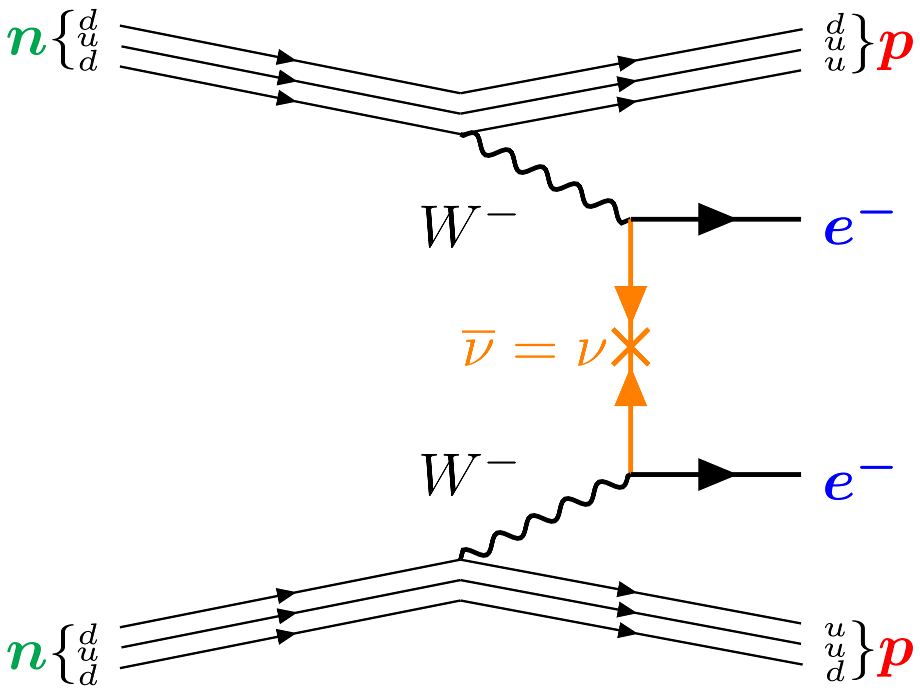
NEUTRINOLESS DOUBLE-BETA ($0\nu\beta\beta$) DECAY

- **Violates lepton-number conservation**

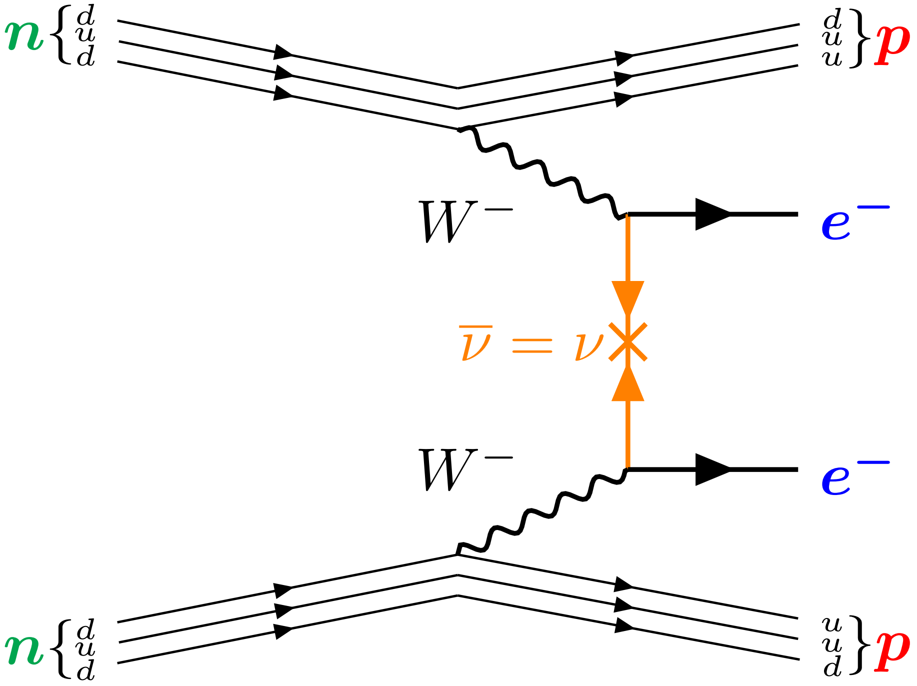
$$\boxed{(A,Z) \rightarrow (A,Z+2) + 2e^- \cancel{+2\bar{\nu}_e}}$$



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

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

$$\boxed{(A,Z) \to (A,Z+2) + 2e^- \cancel{+2\overline{\nu}_e}}$$



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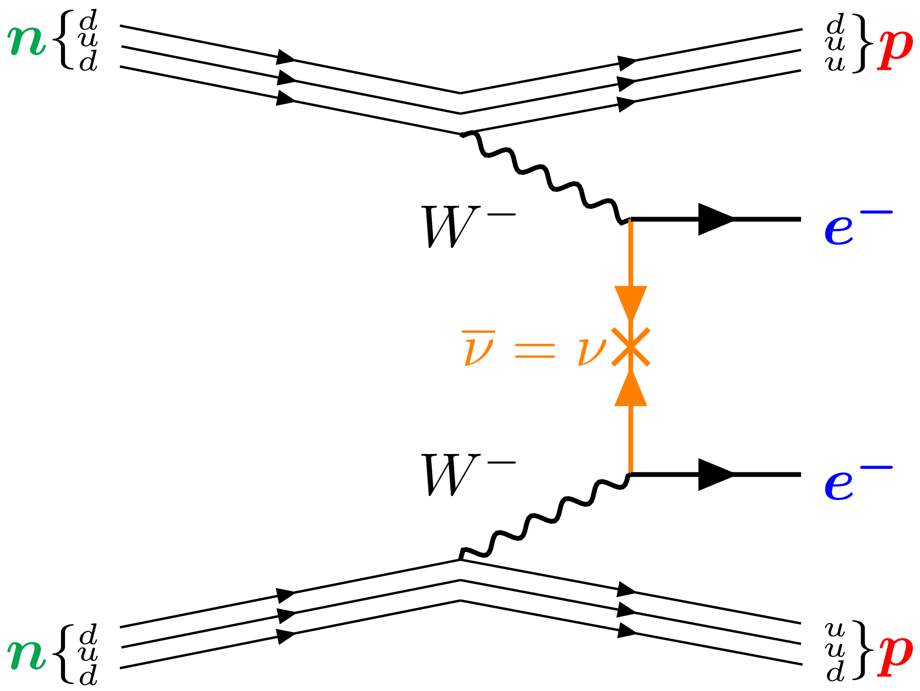
NEUTRINOLESS DOUBLE-BETA ($0\nu\beta\beta$) DECAY

- **Violates lepton-number conservation**
- Requires that **neutrinos are Majorana particles**
- If observed, $t_{1/2}^{0\nu} \gtrsim 10^{25}$ **years**

$$\boxed{(A,Z) \rightarrow (A,Z+2) + 2e^- \cancel{+2\overline{\nu}_e}}$$



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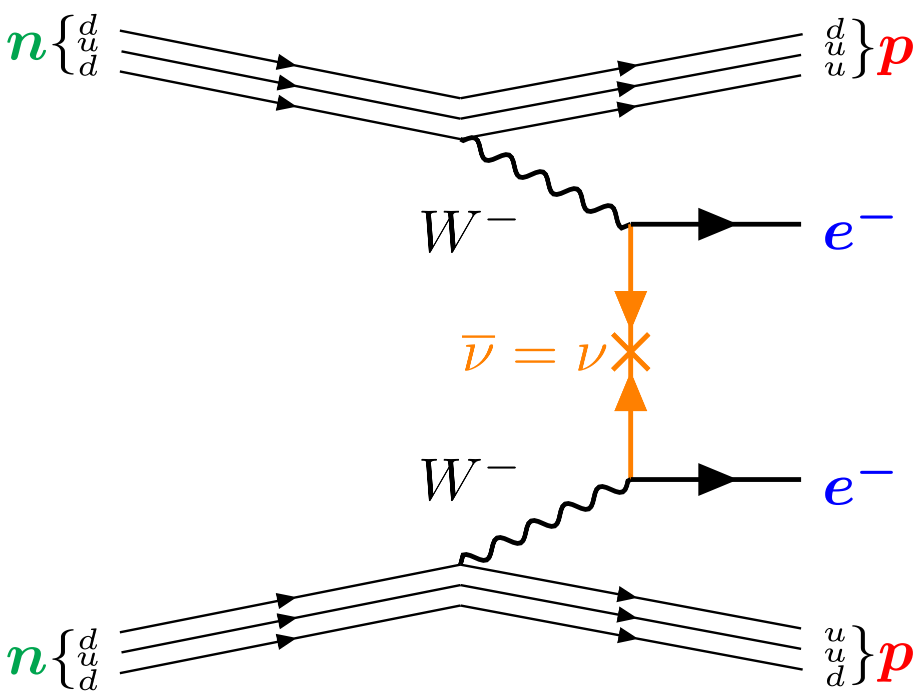
($t_{1/2}^{2\nu} \approx 10^{20}$ years, Age of the Universe $\approx 10^{10}$ years)

$$\boxed{(A,Z) \rightarrow (A,Z+2) + 2e^{-} \cancel{+2\overline{\nu}_e}}$$



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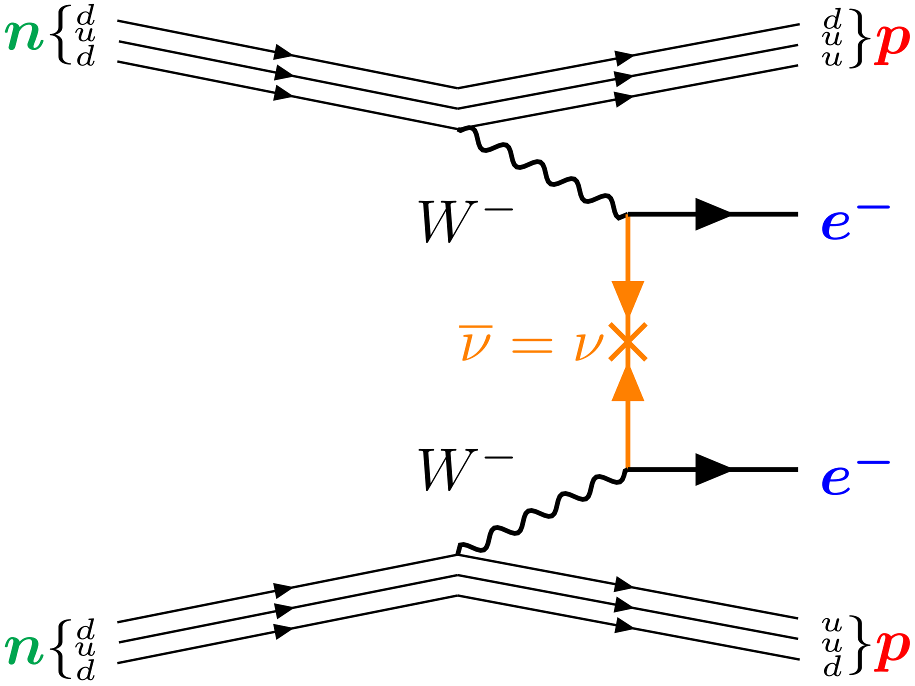
$$(A, Z) \rightarrow (A, Z+2) + 2e^- \cancel{+ 2\bar{\nu}_e}$$

Maria Goeppert-Mayer

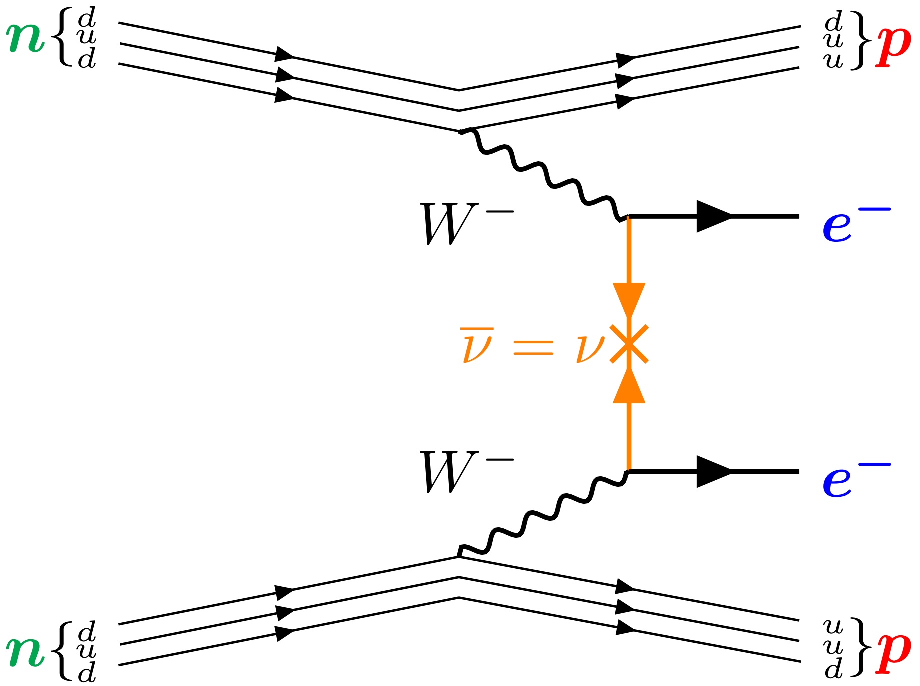
Ettore Majorana

Wendel H. Furry

$2\nu\beta\beta$ 1935 → Majorana particles 1937 → $0\nu\beta\beta$ 1939 → …

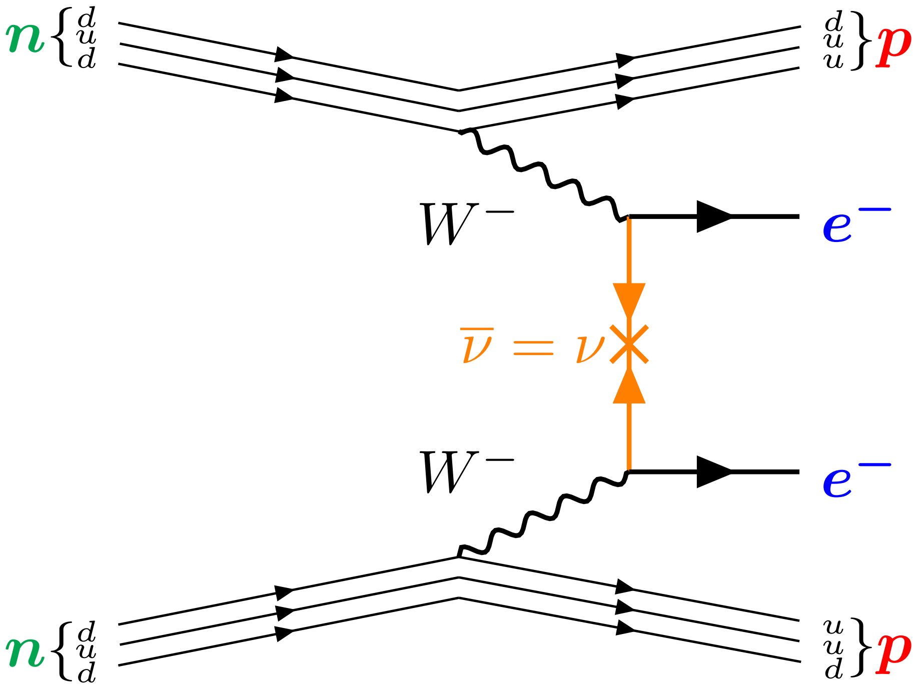


LIGHT-NEUTRINO EXCHANGE MECHANISM



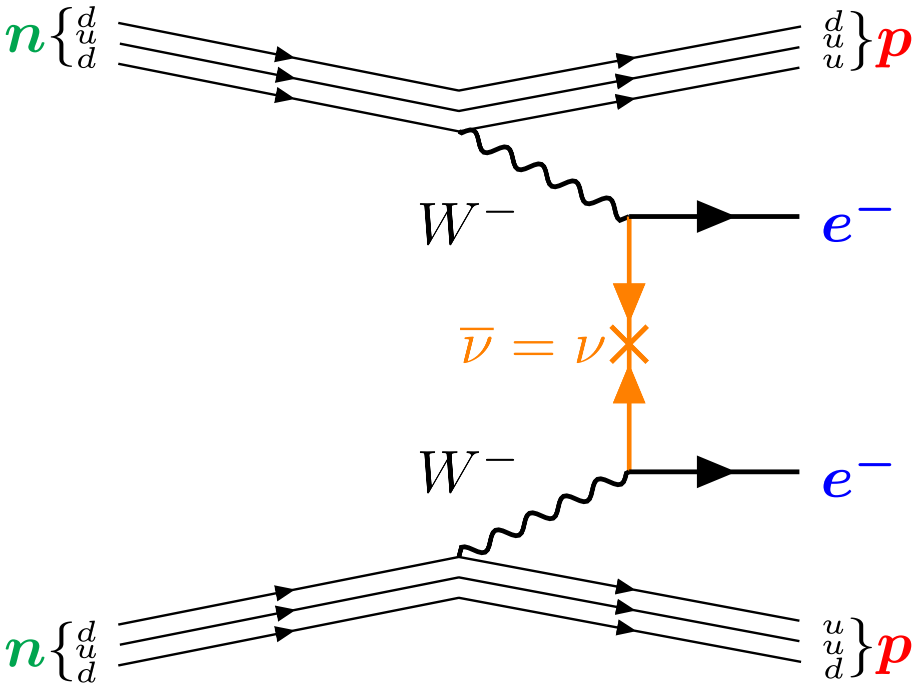
LIGHT-NEUTRINO EXCHANGE MECHANISM

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



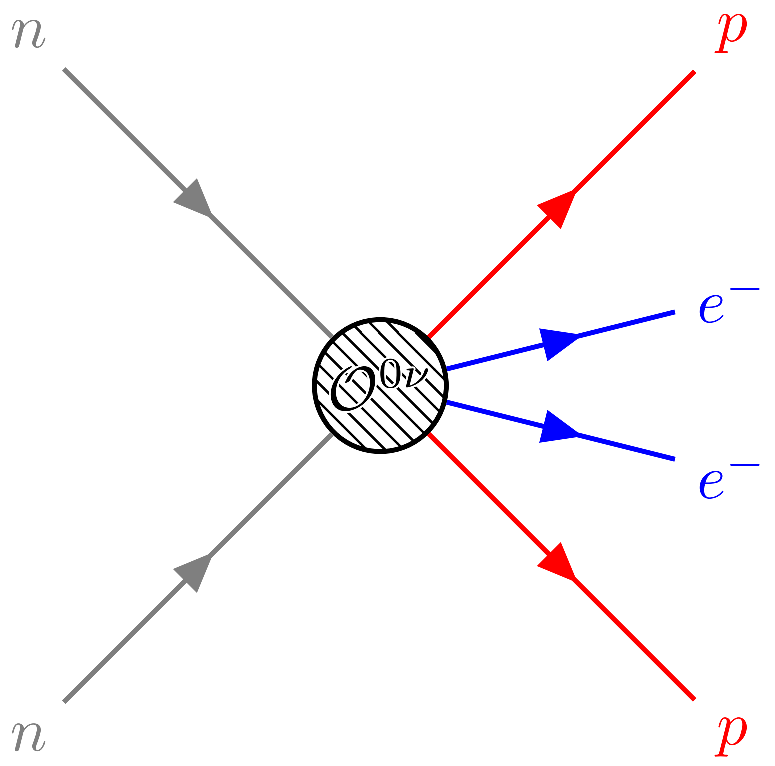
LIGHT-NEUTRINO EXCHANGE MECHANISM

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



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



LIGHT-NEUTRINO EXCHANGE MECHANISM

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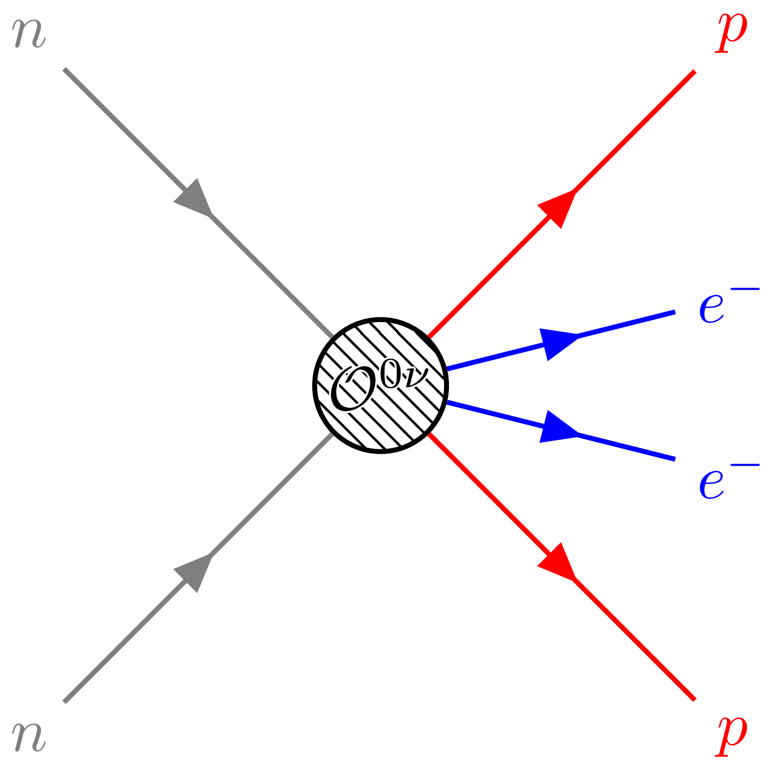
See talk by S. Urrutia Quiroga later in this session



LIGHT-NEUTRINO EXCHANGE MECHANISM

- **Light-neutrino exchange** the most commonly studied mechanism
  - **Does not require introducing additional particles**
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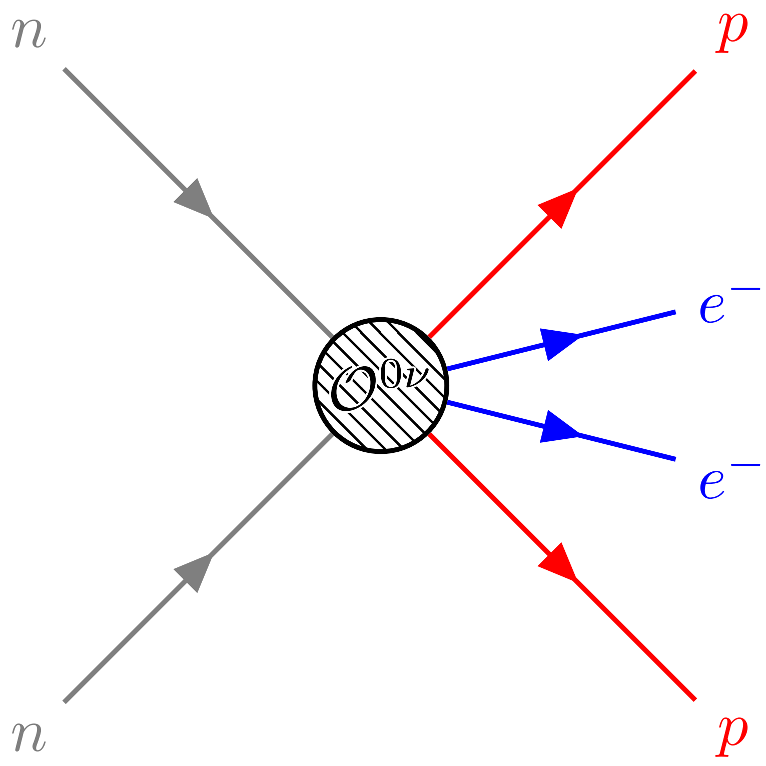
See talk by S. Urrutia Quiroga later in this session

- In this talk, I will focus on the light-neutrino exchange



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

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

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

Half-life to be measured

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

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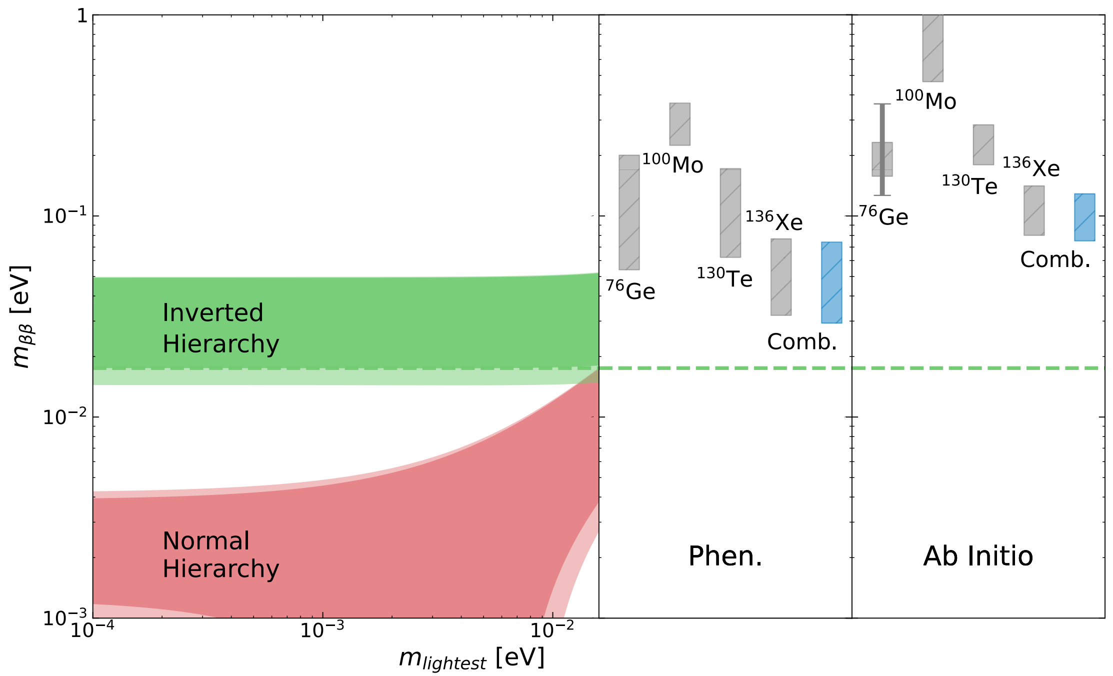
$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Majorana mass

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



Shickele, Jokiniemi, Belley, Holt, in preparation

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

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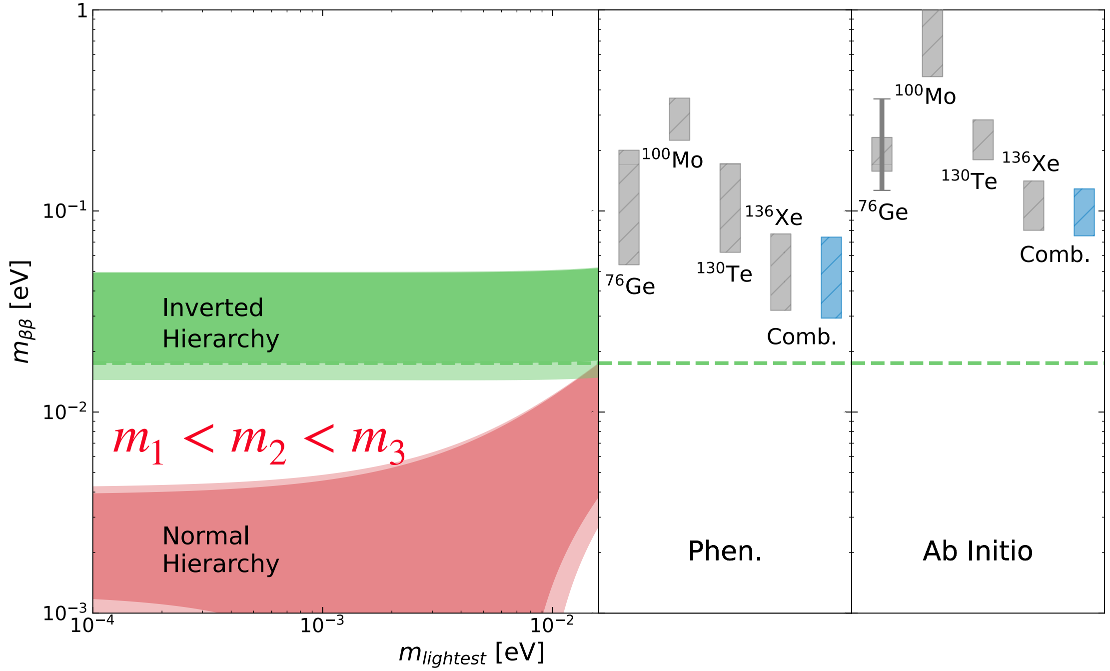

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HALF-LIFE OF $0\nu\beta\beta$ DECAY

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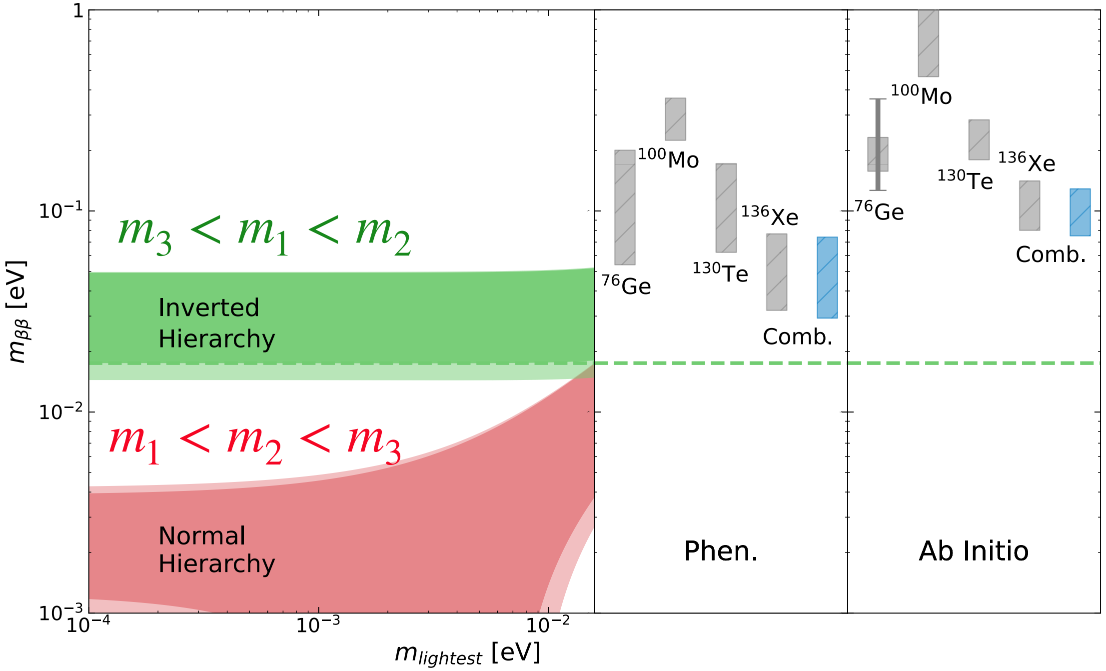

Shickele, Jokiniemi, Belley, Holt, in preparation

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

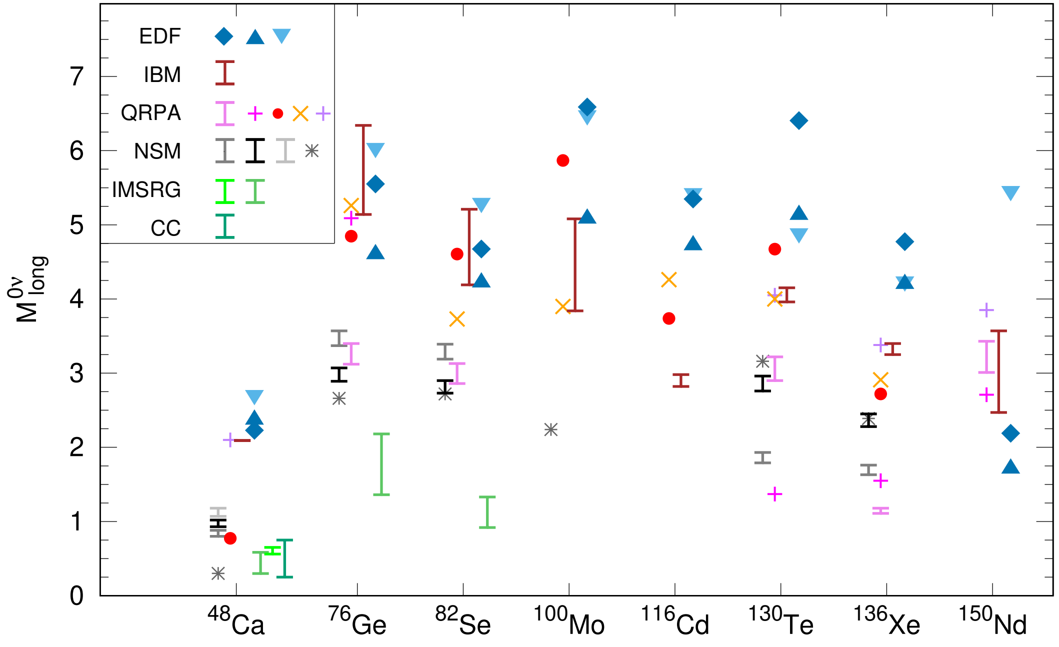
Half-life to be measured

Nuclear matrix element

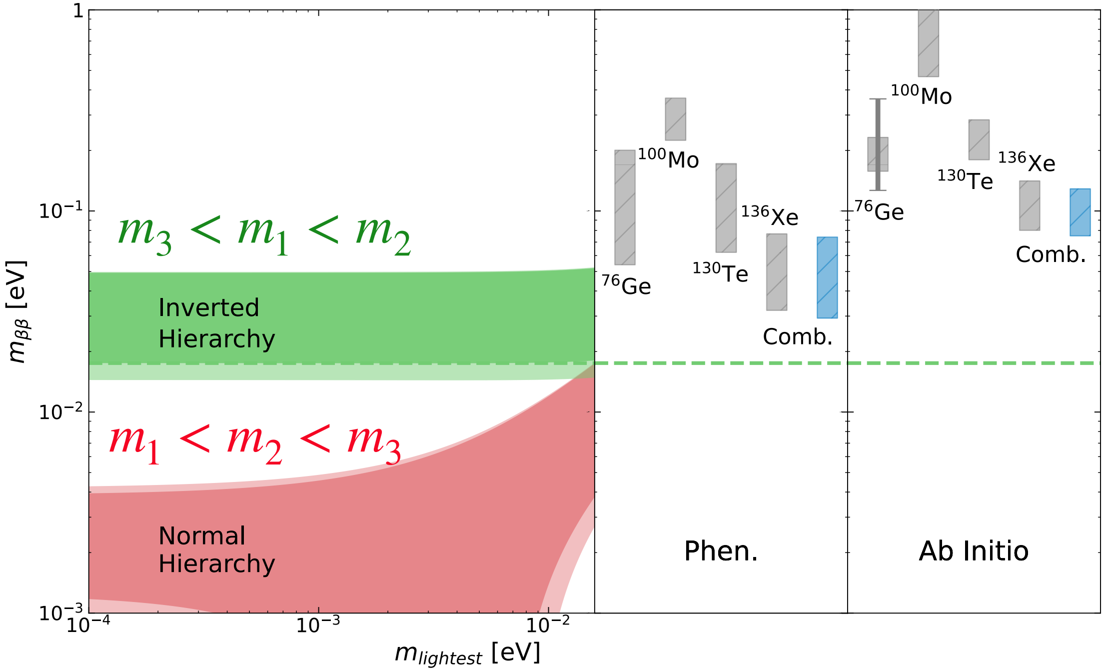
$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Majorana mass

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



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



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

Half-life to be measured

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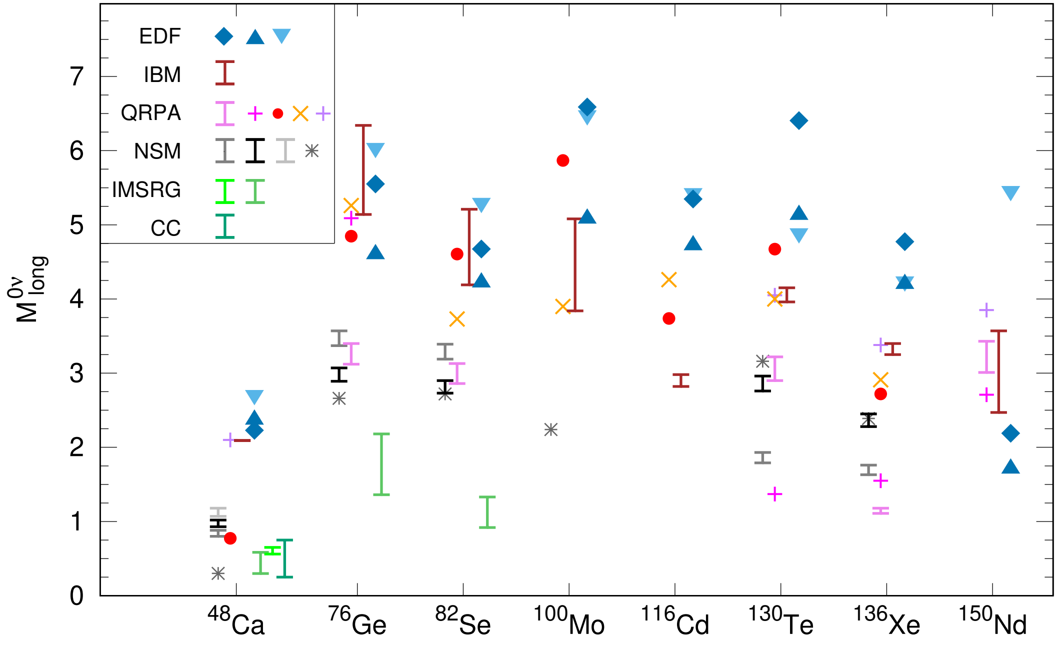

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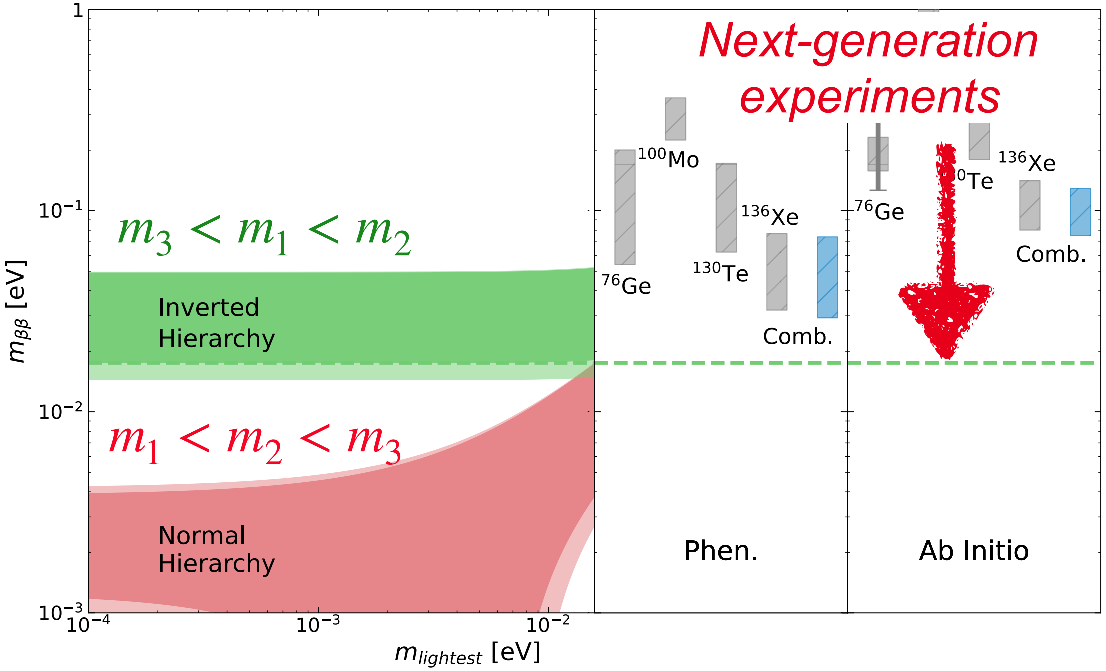

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THE NUCLEAR MATRIX ELEMENT

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

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THE NUCLEAR MATRIX ELEMENT

Operator (nn ⟶ pp+2e⁻)

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Initial state wave function

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THE NUCLEAR MATRIX ELEMENT

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

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

Final state wave function

Initial state wave function

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Final state wave function

Initial state wave function

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

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TRADITIONAL NUCLEAR MATRIX ELEMENT

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

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TRADITIONAL NUCLEAR MATRIX ELEMENT

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

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Neutrino potential

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$$\boxed{\mathcal{O}^{(m,n)}_{\mathrm{GT}} = \boldsymbol{\sigma}_m \cdot \boldsymbol{\sigma}_n}$$

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Neutrino potential

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

$$\mathcal{O}^{(m,n)}_{\mathrm{GT}} = \boldsymbol{\sigma}_m \cdot \boldsymbol{\sigma}_n$$

$$\mathcal{O}^{(m,n)}_{\mathrm{F}} = 1$$

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Neutrino potential

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TRADITIONAL NUCLEAR MATRIX ELEMENT

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

$$\mathcal{O}^{(m,n)}_{\mathrm{GT}} = \boldsymbol{\sigma}_m \cdot \boldsymbol{\sigma}_n$$

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$$\mathcal{O}^{(m,n)}_{\mathrm{T}} = 3[(\boldsymbol{\sigma}_m \cdot \hat{\mathbf{r}})(\boldsymbol{\sigma}_n \cdot \hat{\mathbf{r}})] - \boldsymbol{\sigma}_m \cdot \boldsymbol{\sigma}_n$$

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

Neutrino potential

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Neutrino potential

Usually from phenomenological many-body methods

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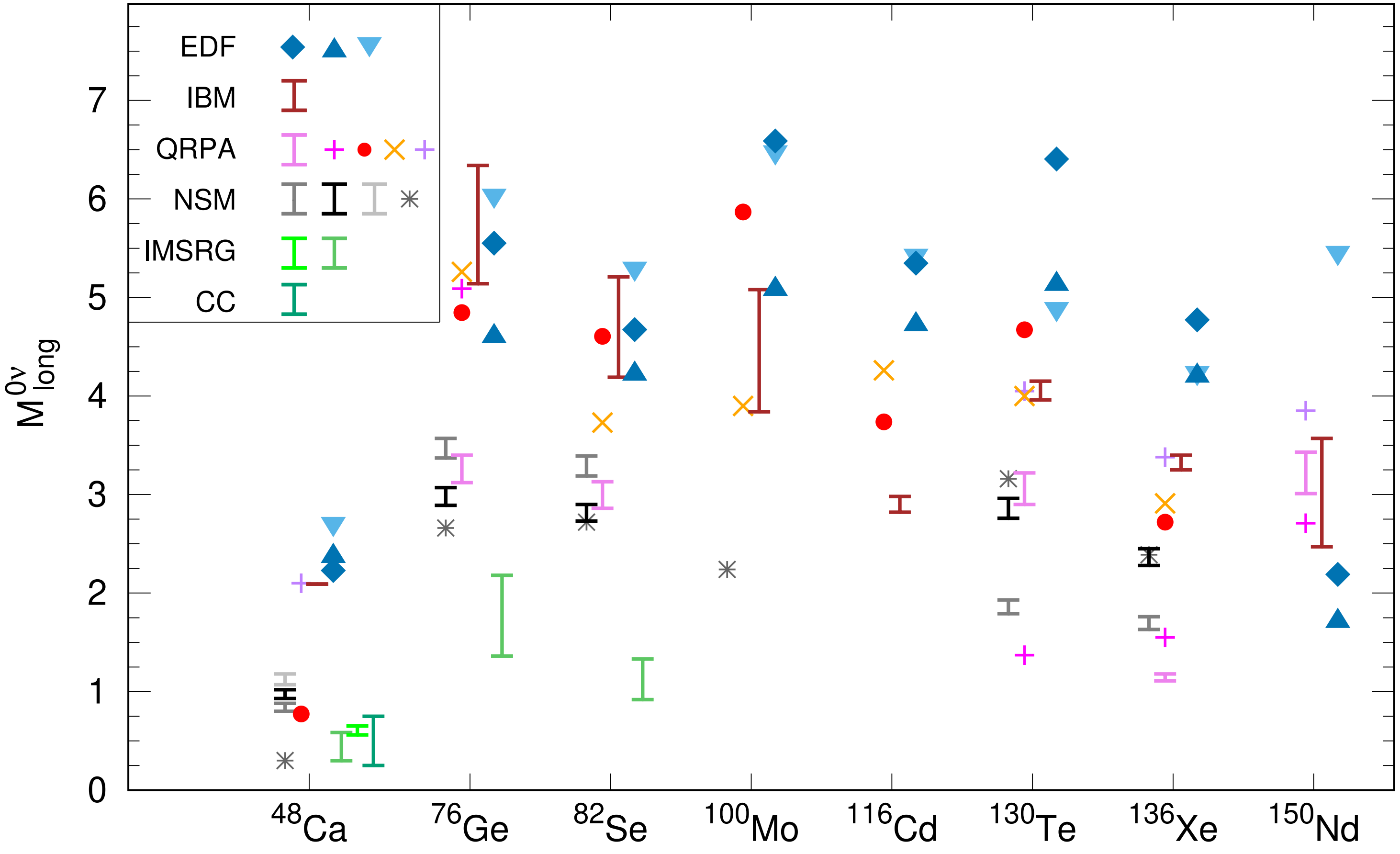
LACK OF RELIABLE UNCERTAINTIES



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

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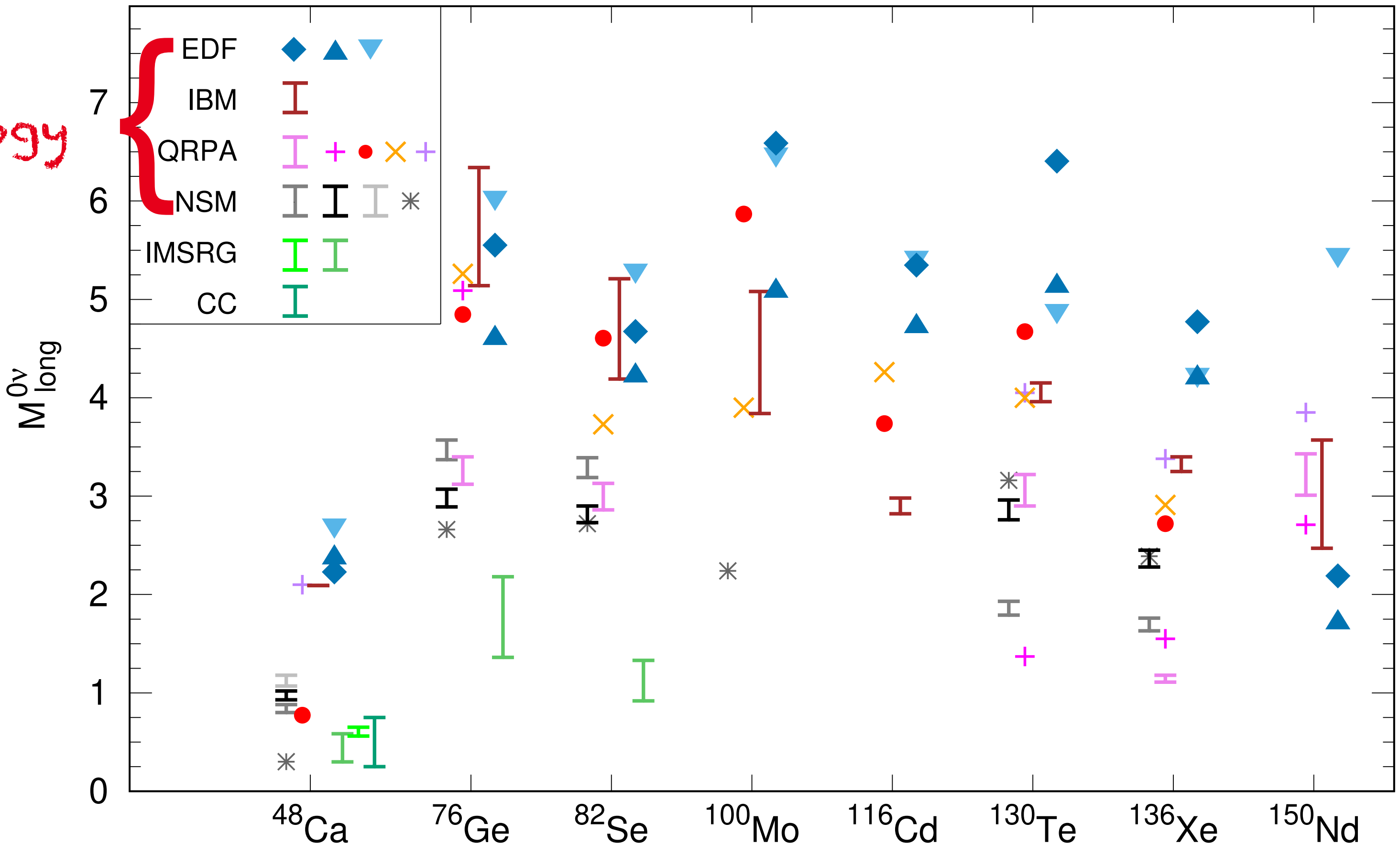
Phenomenology



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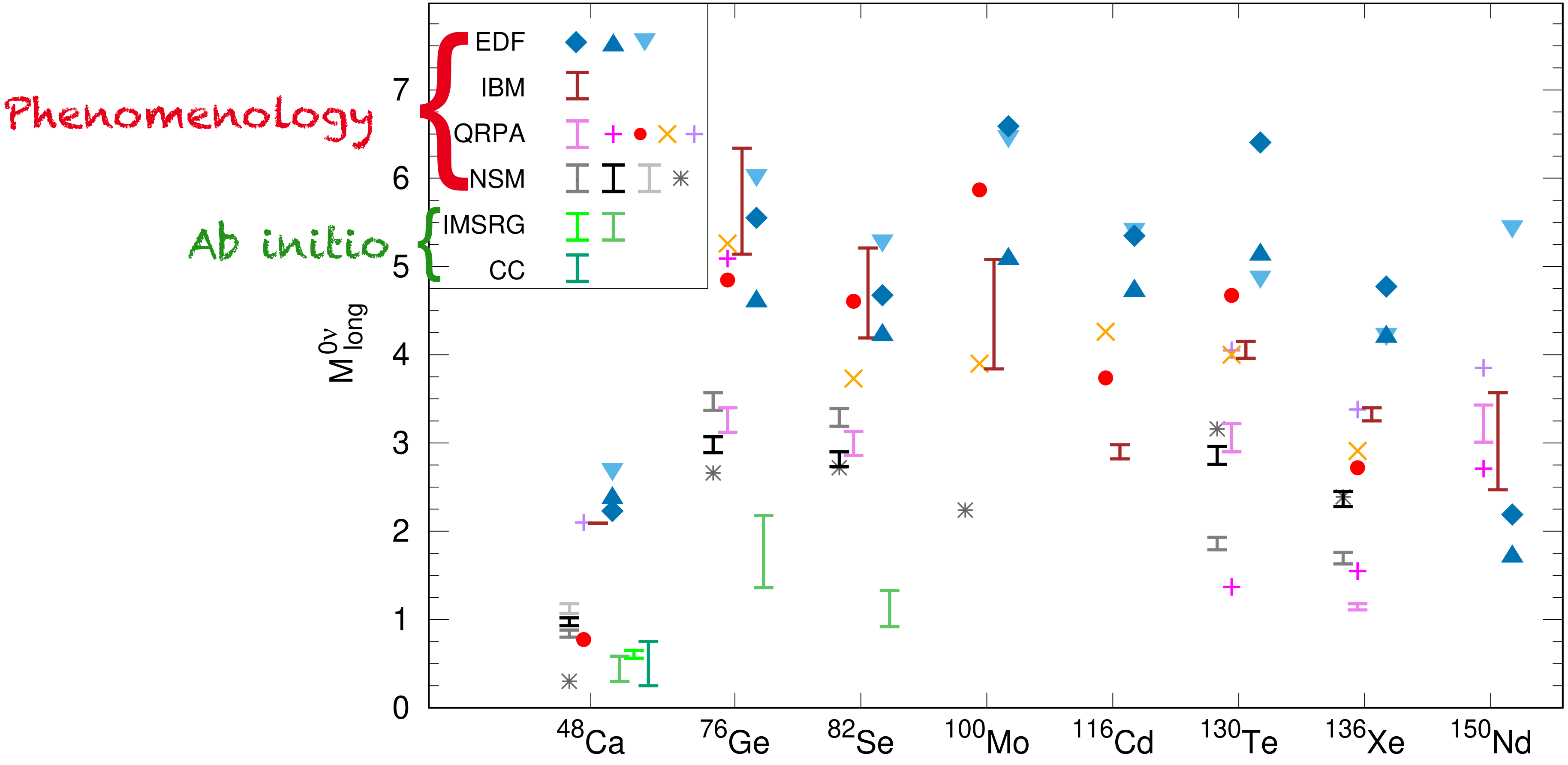

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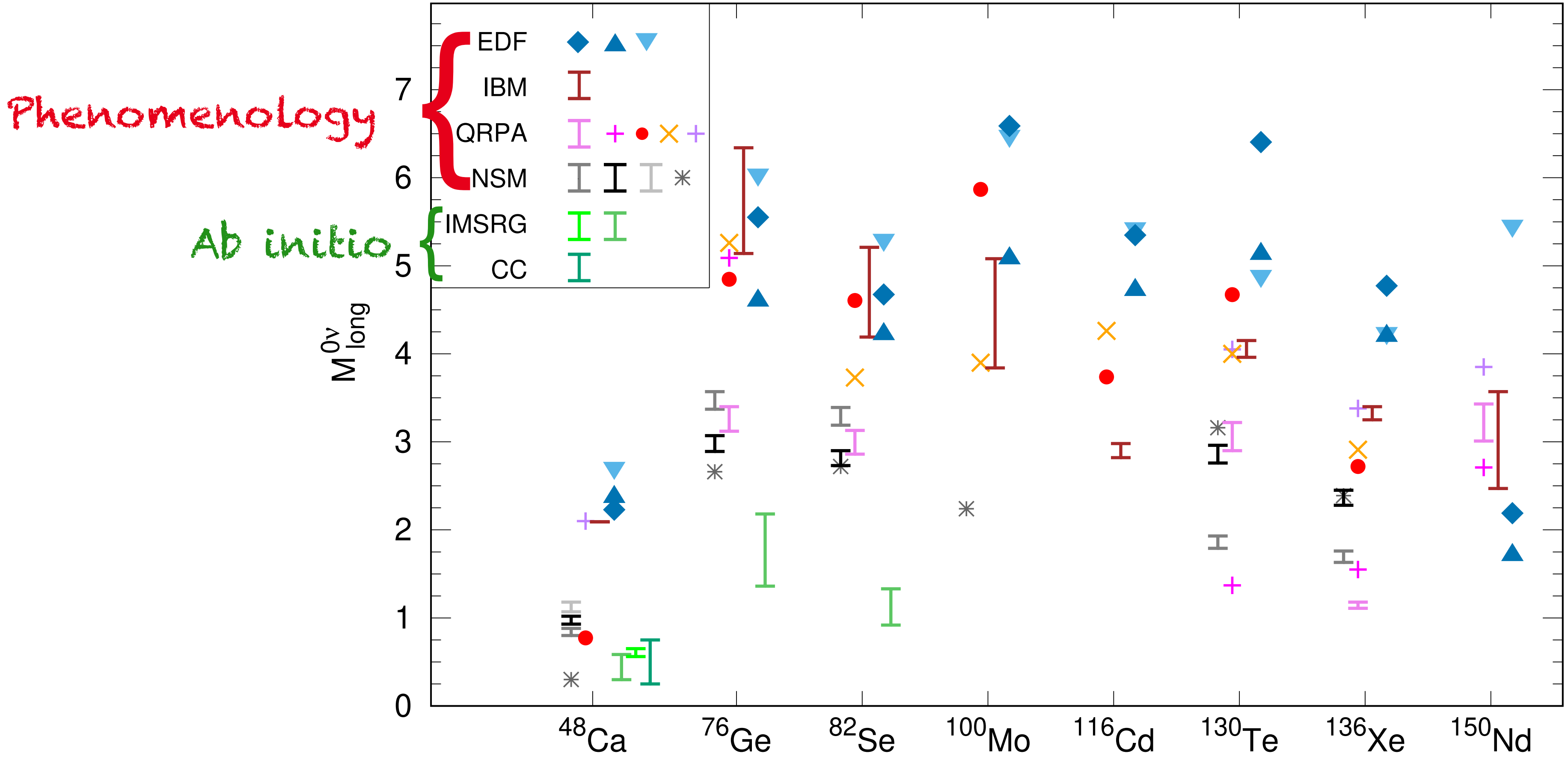

Ranges cover:
- Different parameters/ nuclear interactions
- Different model spaces
- Reference state dependence
- …

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

AB INITIO NUCLEAR THEORY

Ideally

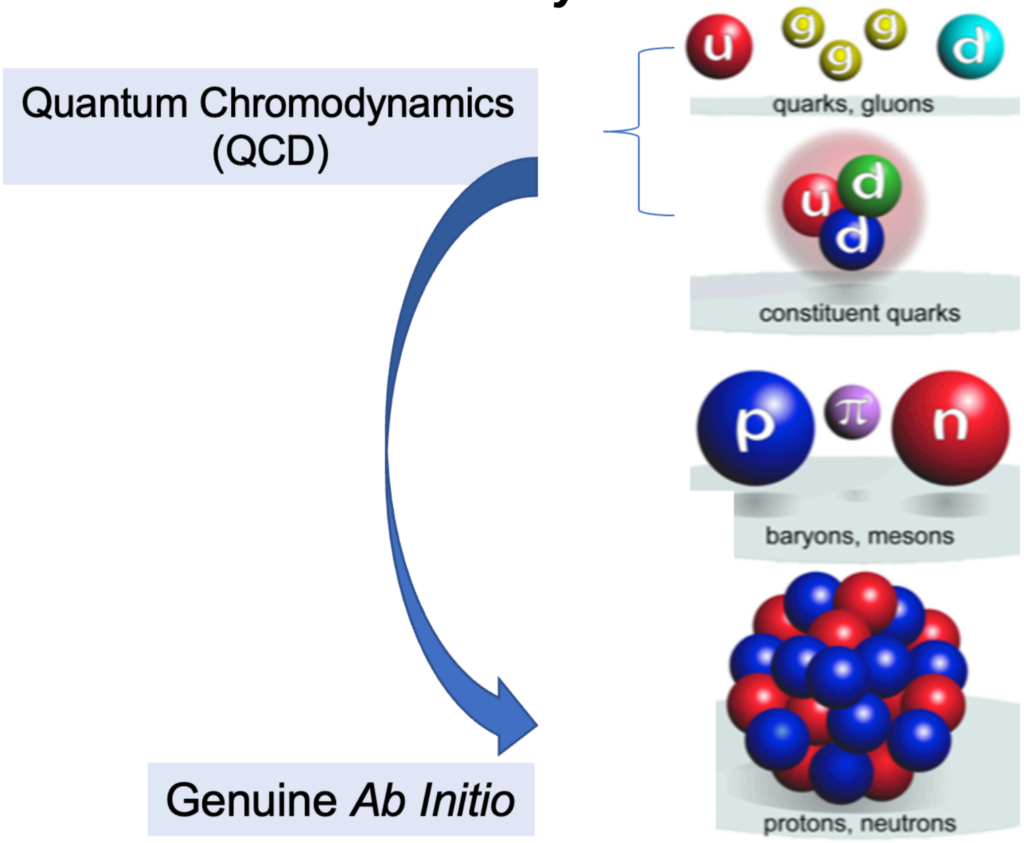

Figure courtesy of P. Navrátil

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AB INITIO NUCLEAR THEORY

Current ab initio

Quantum Chromodynamics (QCD)

Chiral Effective Field Theory (parameters fitted to NN data)

Current *ab initio* nuclear theory

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

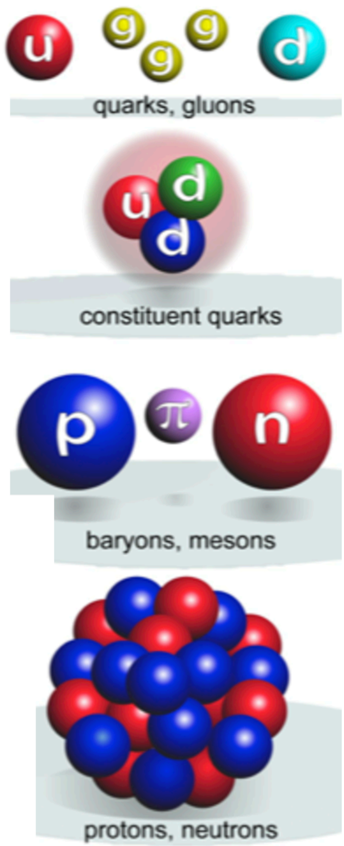

Figure courtesy of P. Navrátil

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AB INITIO NUCLEAR THEORY

Current ab initio

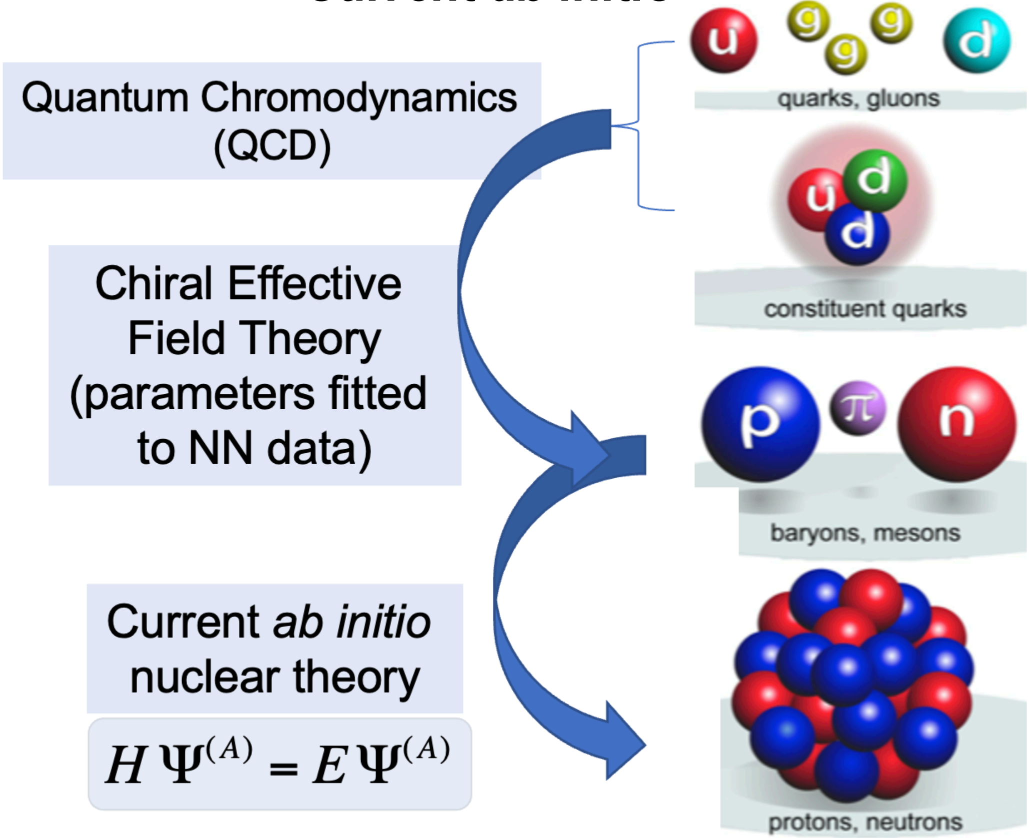
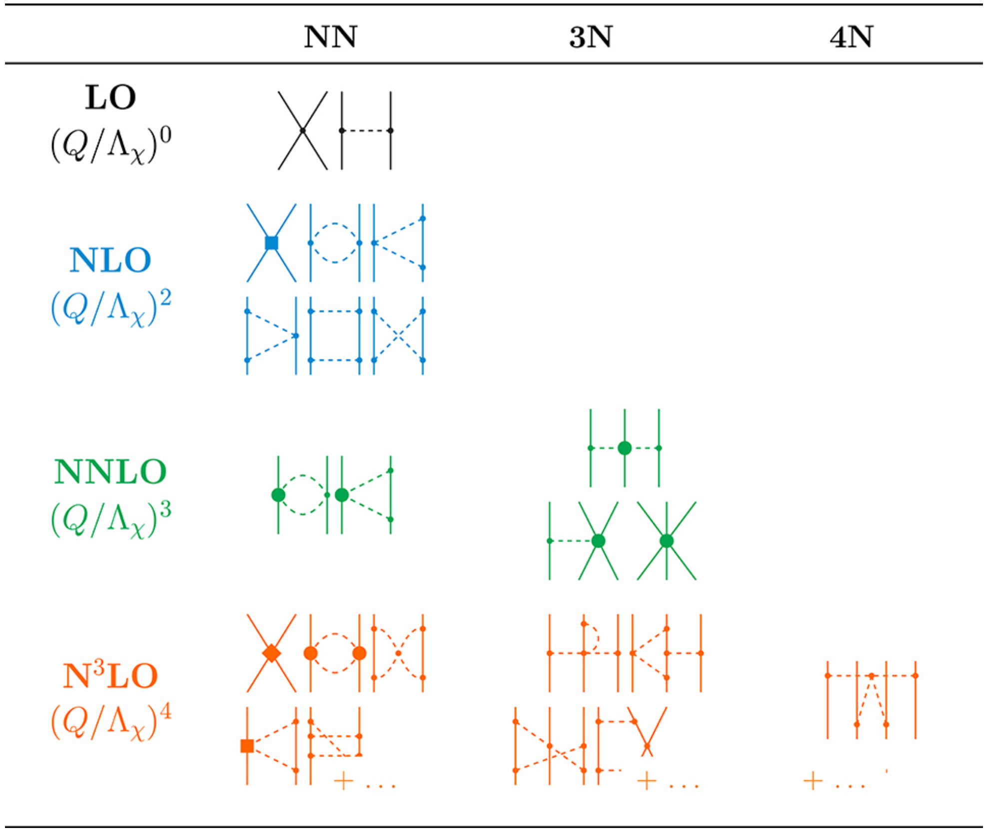


Figure courtesy of P. Navrátil

Chiral expansion of nuclear forces



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

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AB INITIO NUCLEAR THEORY

Current ab initio

Quantum Chromodynamics (QCD)

Chiral Effective Field Theory (parameters fitted to NN data)

Current *ab initio* nuclear theory

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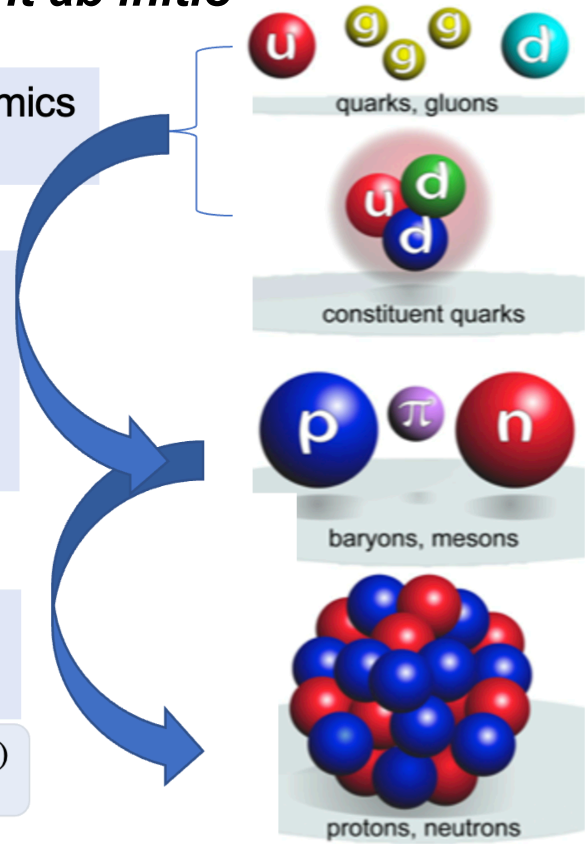
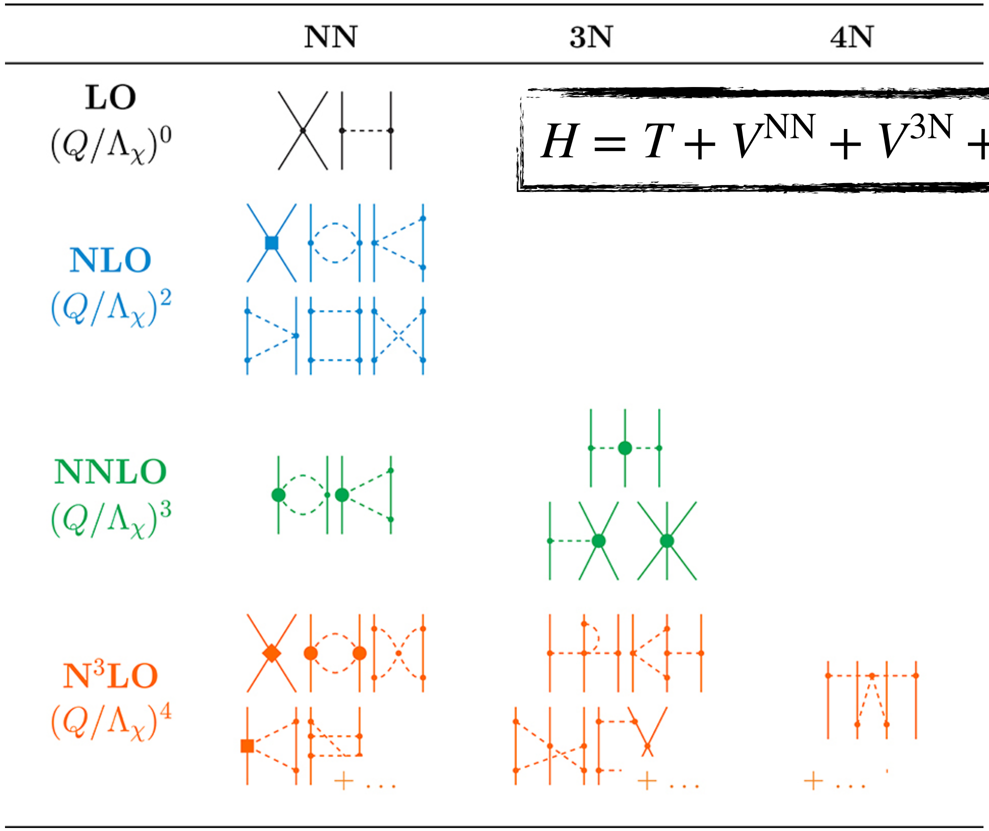


Figure courtesy of P. Navrátil

Chiral expansion of nuclear forces



$$\boxed{H = T + V^{\mathrm{NN}} + V^{3\mathrm{N}} + \ldots}$$

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

TECHNISCHE UNIVERSITÄT DARMSTADT

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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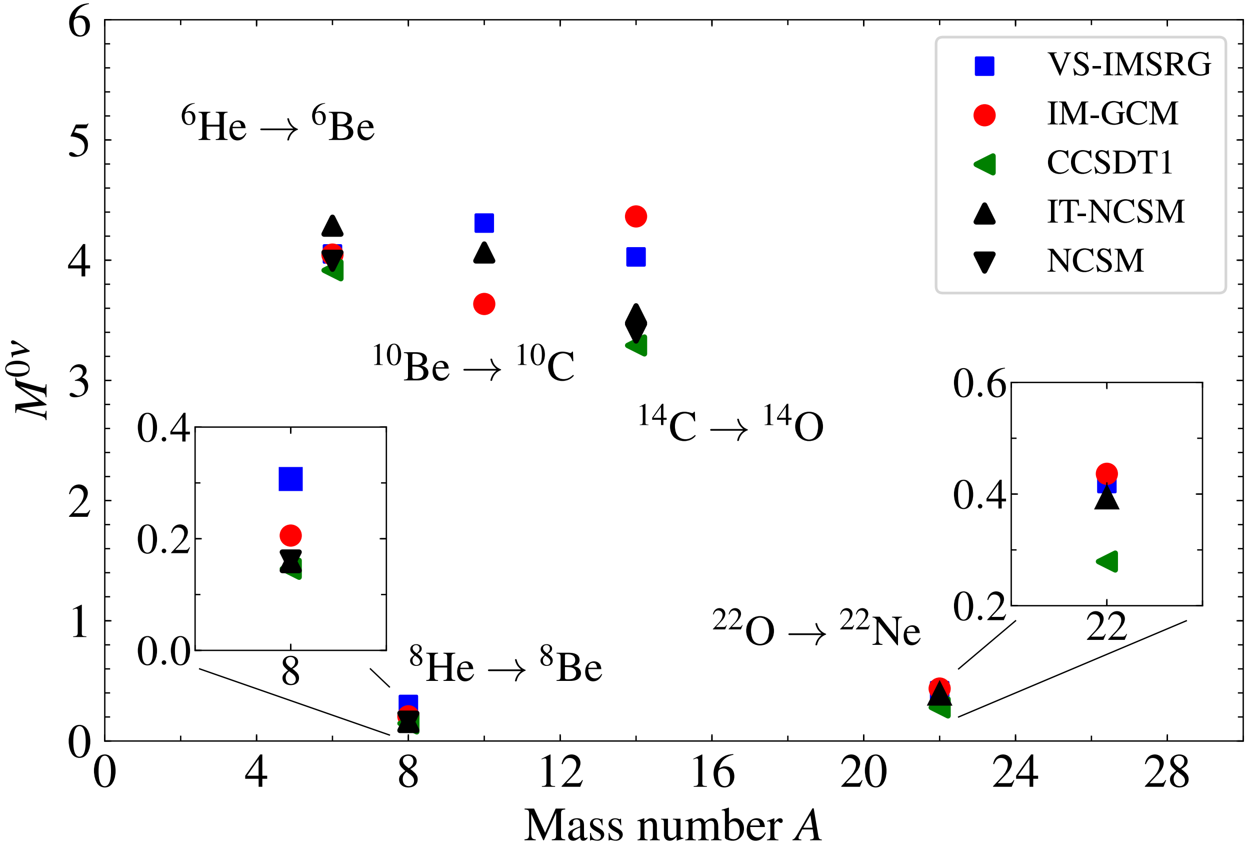
AB INITIO BENCHMARKS IN LIGHT NUCLEI

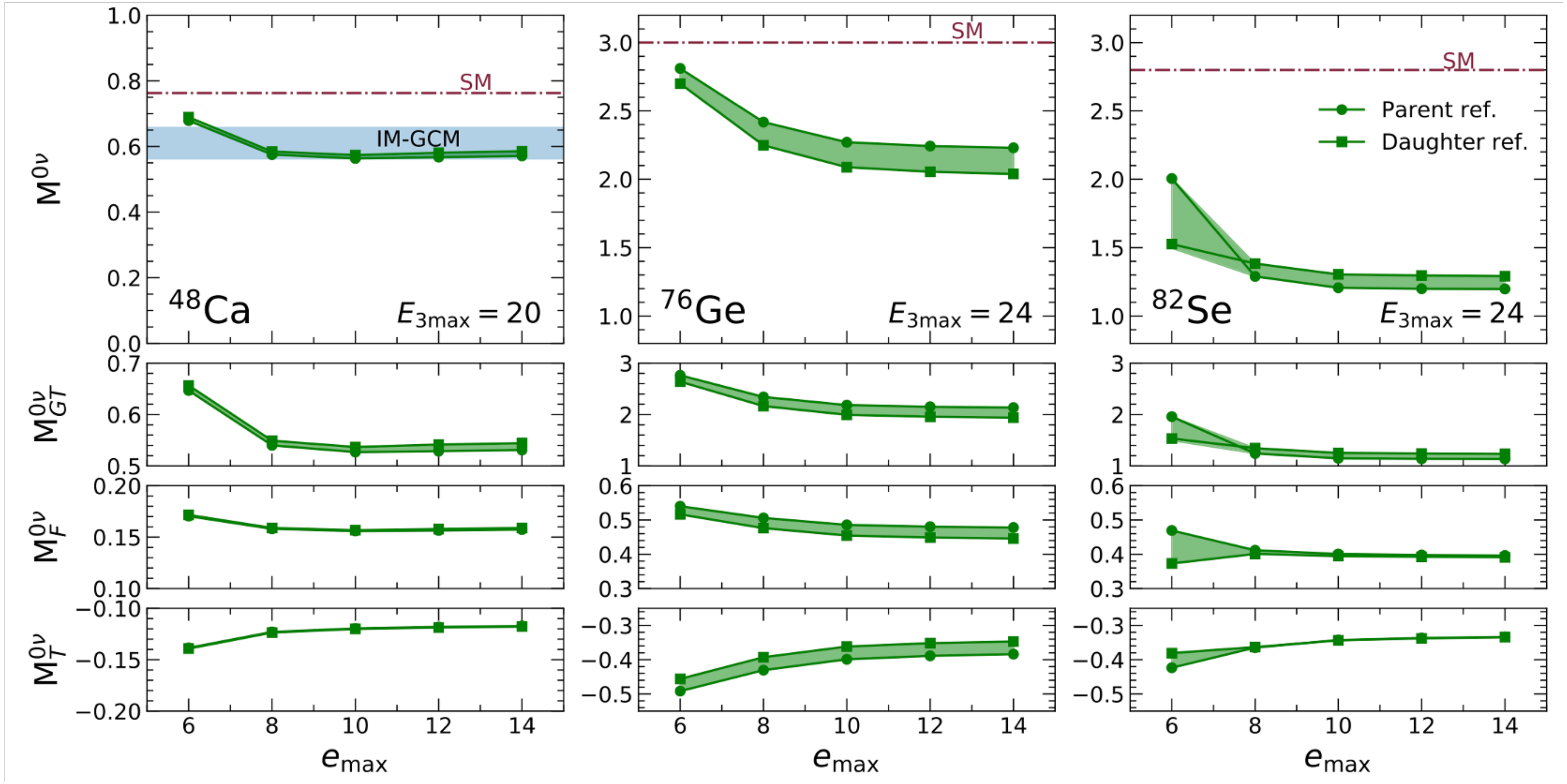


1.8/2.0 (EM)
$\hbar\Omega = 16$ MeV

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

TECHNISCHE UNIVERSITÄT DARMSTADT

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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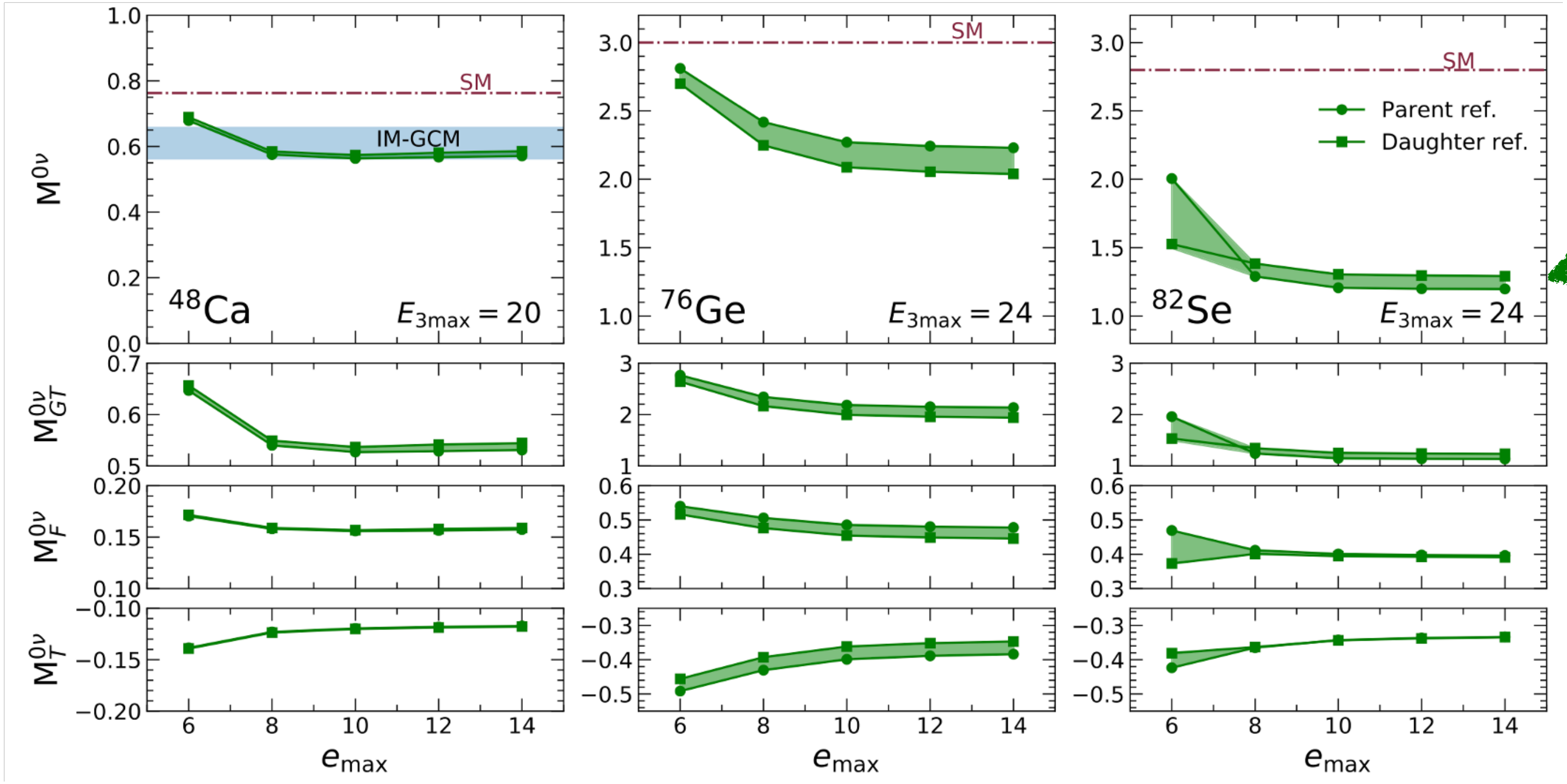

Ab initio
VS-IMSRG

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

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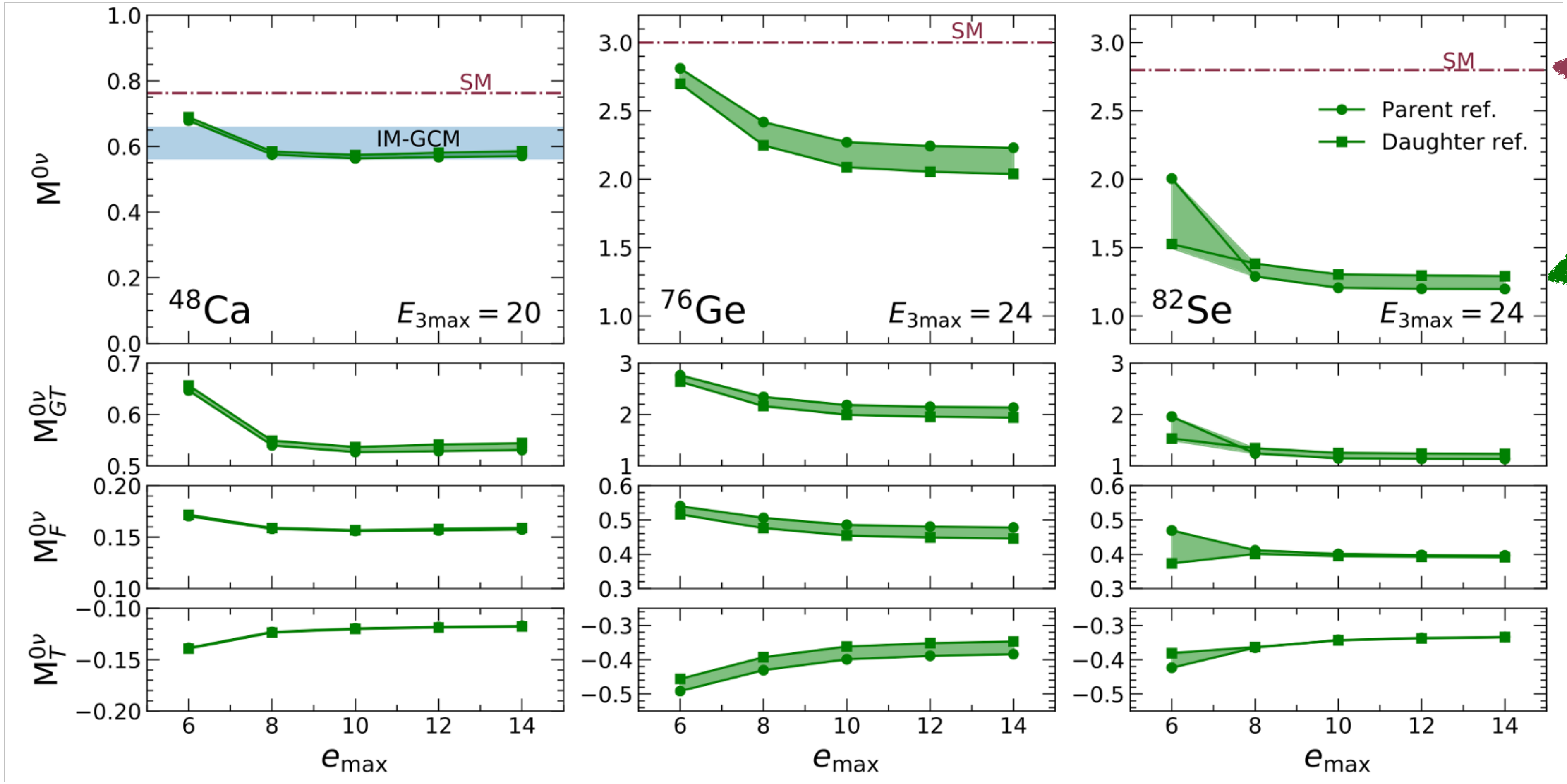

Nuclear shell model

Ab initio VS-IMSRG

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

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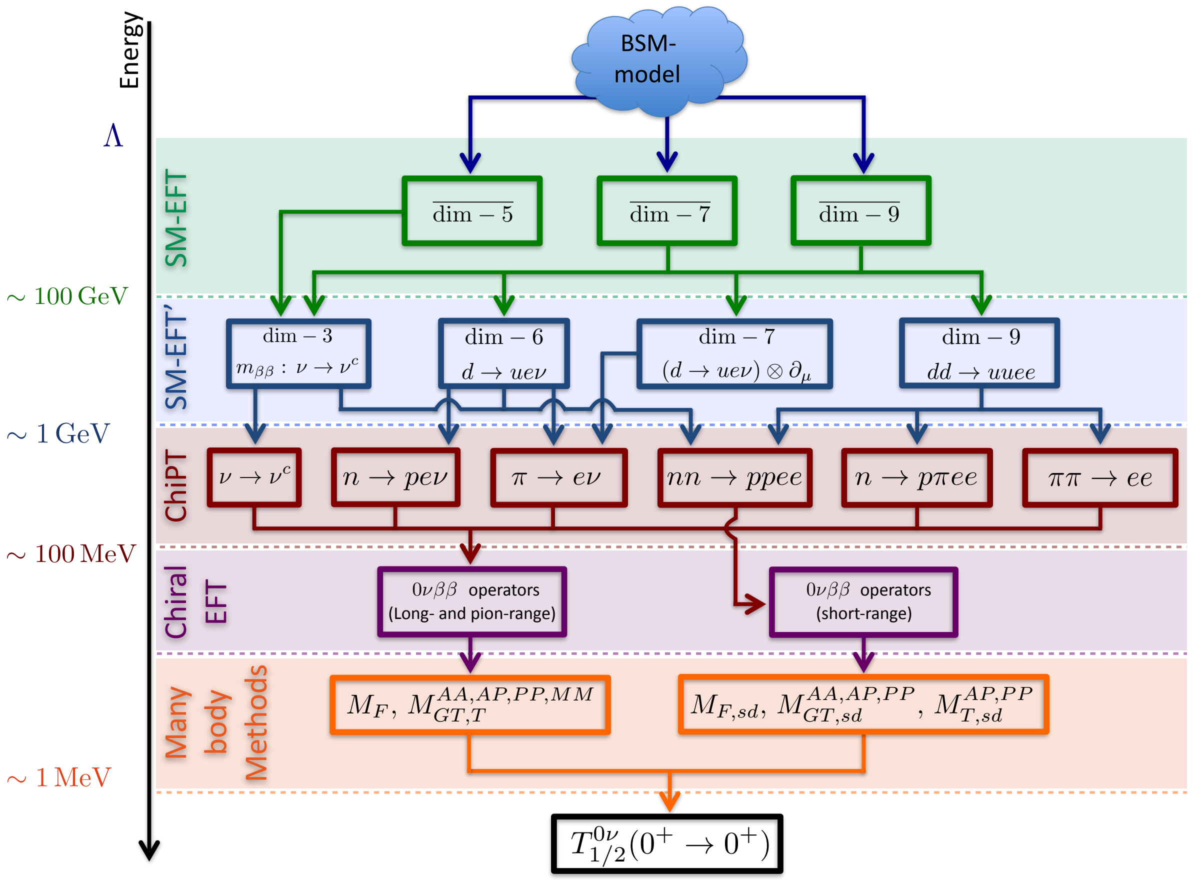
CHIRAL EFFECTIVE THEORY OPERATORS FOR $0\nu\beta\beta$ DECAY

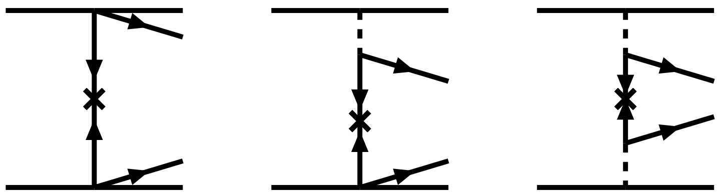


Cirigliano, Dekens, de Vries, Graesser, Mereghetti, JHEP 12, 097 (2018)

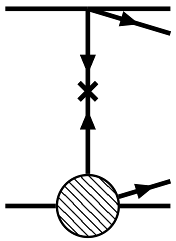
CHIRAL EFFECTIVE THEORY OPERATORS FOR $0\nu\beta\beta$ DECAY

$$\boxed{M^{0\nu} = M_{\mathrm{L}}^{0\nu}}$$

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



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

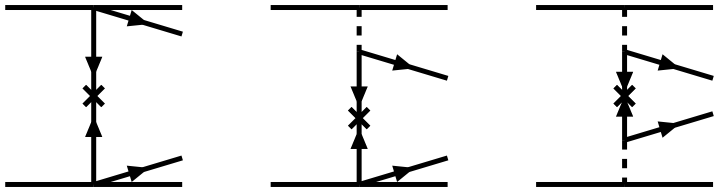


V. Cirigliano et al., Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)

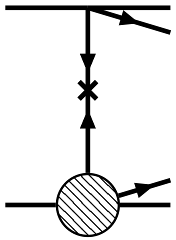
CHIRAL EFFECTIVE THEORY OPERATORS FOR $0\nu\beta\beta$ DECAY

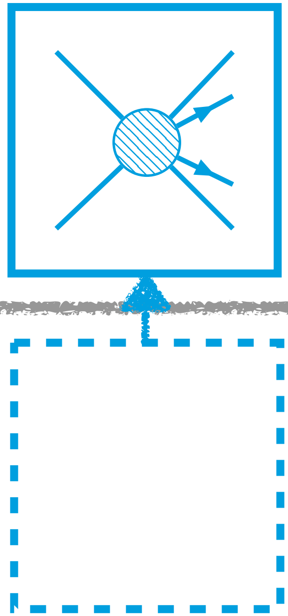
$$M^{0\nu} = M^{0\nu}_{\mathrm{L}} + M^{0\nu}_{\mathrm{S}}$$

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



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



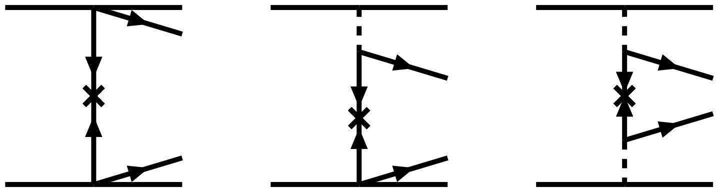


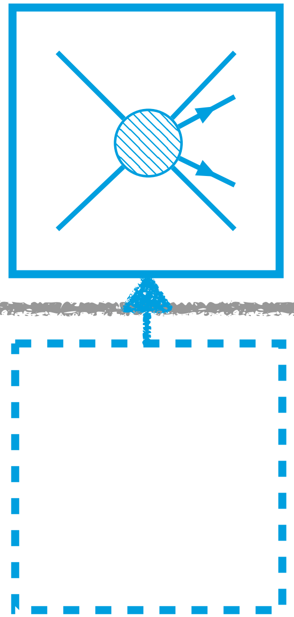
V. Cirigliano et al., Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)

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

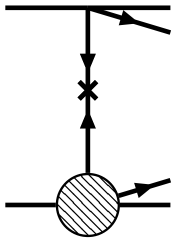
$$M^{0\nu} = M^{0\nu}_{\mathrm{L}} + M^{0\nu}_{\mathrm{S}} + M^{0\nu}_{\mathrm{usoft}}$$

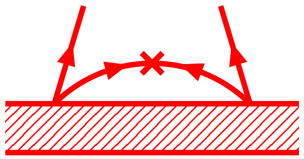
$\left(\frac{Q}{\Lambda_\chi}\right)^0$ LO





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





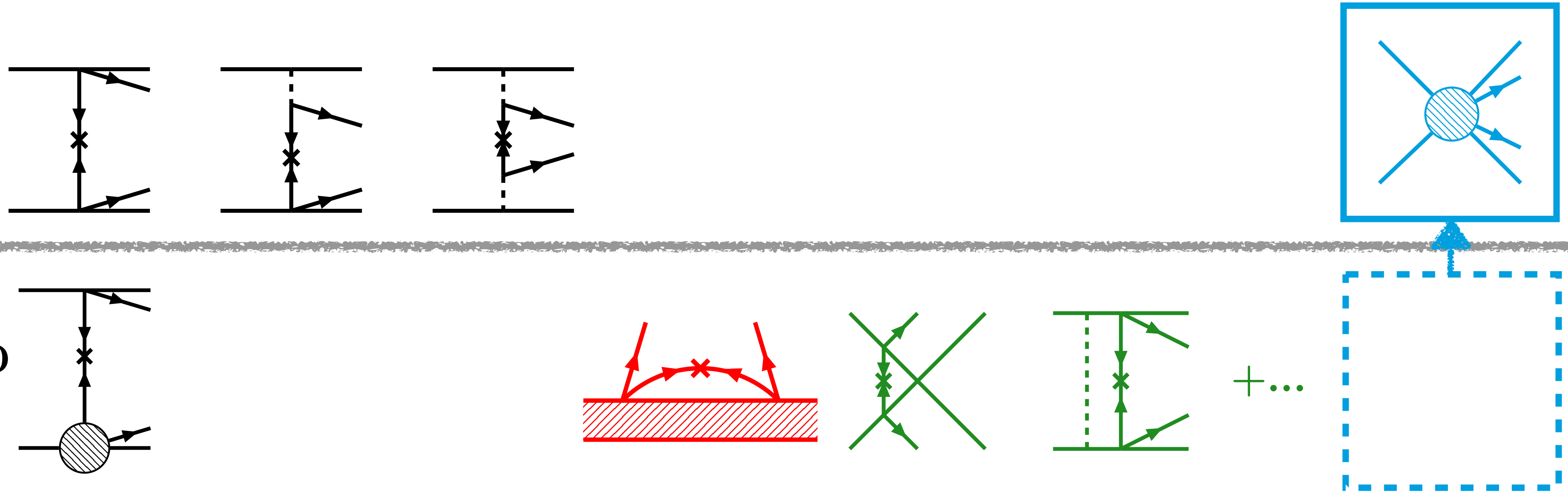
V. Cirigliano et al., Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)

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

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

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

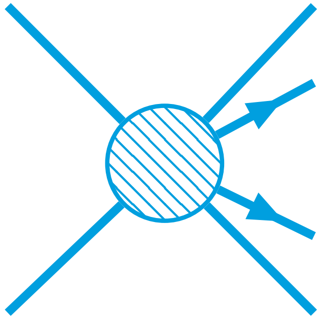
$\left(\frac{Q}{\Lambda_\chi}\right)^2$ **N^{2}LO**



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

CONTACT TERM – UNKNOWN COUPLING

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



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

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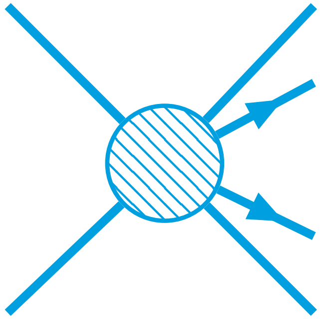

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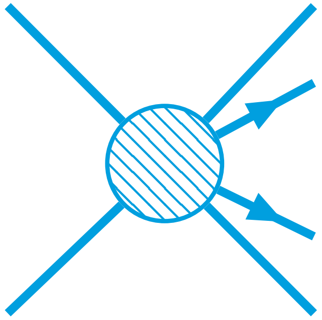

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- What to do?

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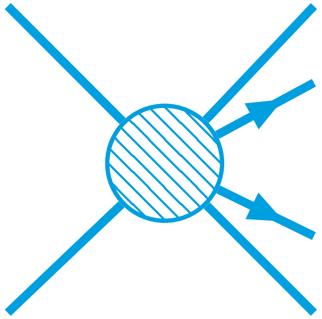

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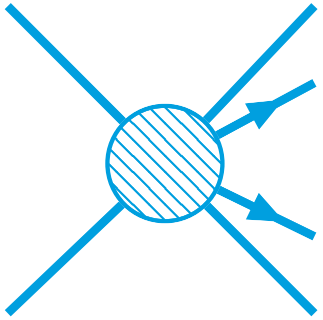

- New, **unknown**, low-energy constant g_{ν}^{NN}
- What to do?
  - ✗ Fit to **lepton-number violating data**
  - ? Determine from **lattice QCD**
    Cirigliano, Davoudi, Engel, Furnstahl, Hagen et al., J. Phys. G. Nucl. Part. Phys. 49, 120502 (2022)

CONTACT TERM – UNKNOWN COUPLING

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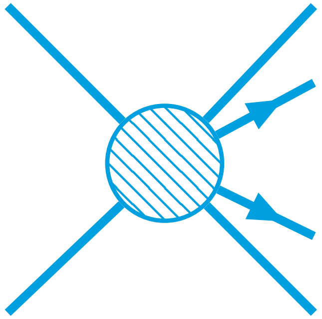

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✓ Fit to **charge-independence breaking** (CIB) term of *NN* scattering:

$$C_1 \sim \frac{C_1 + C_2}{2} = C_{\mathrm{CIB}}$$

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

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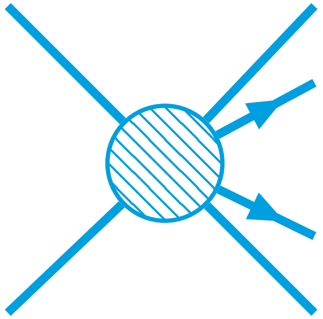

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  - ✓ Fit to **synthetic data**
    Cirigliano, Dekens, de Vries, Hoferichter, Mereghetti, Phys. Rev. Lett. 126, 172002 (2021)

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THE CONTACT TERM

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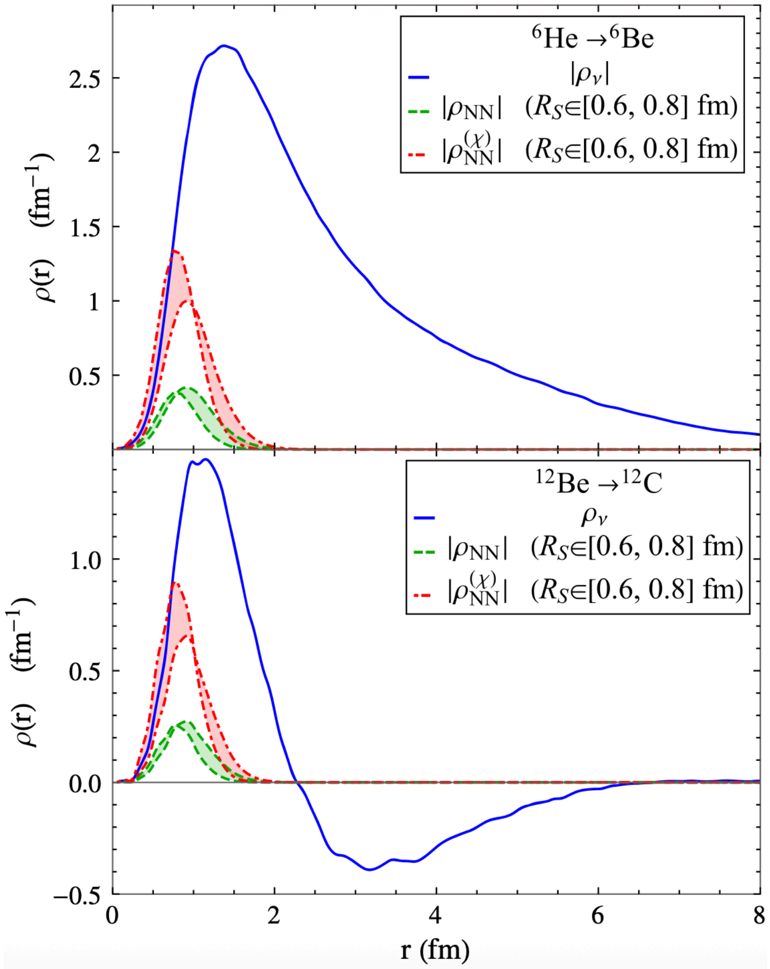

Cirigliano, Dekens, de Vries, Graesser, Mereghetti, Pastore, van Kolck, Phys. Rev. Lett. 120, 202001 (2018)

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- *Ab initio* calculations show a $\sim 10\% - 60\,\%$ **enhancement** of the nuclear matrix elements of light nuclei ($A \leq 12$)
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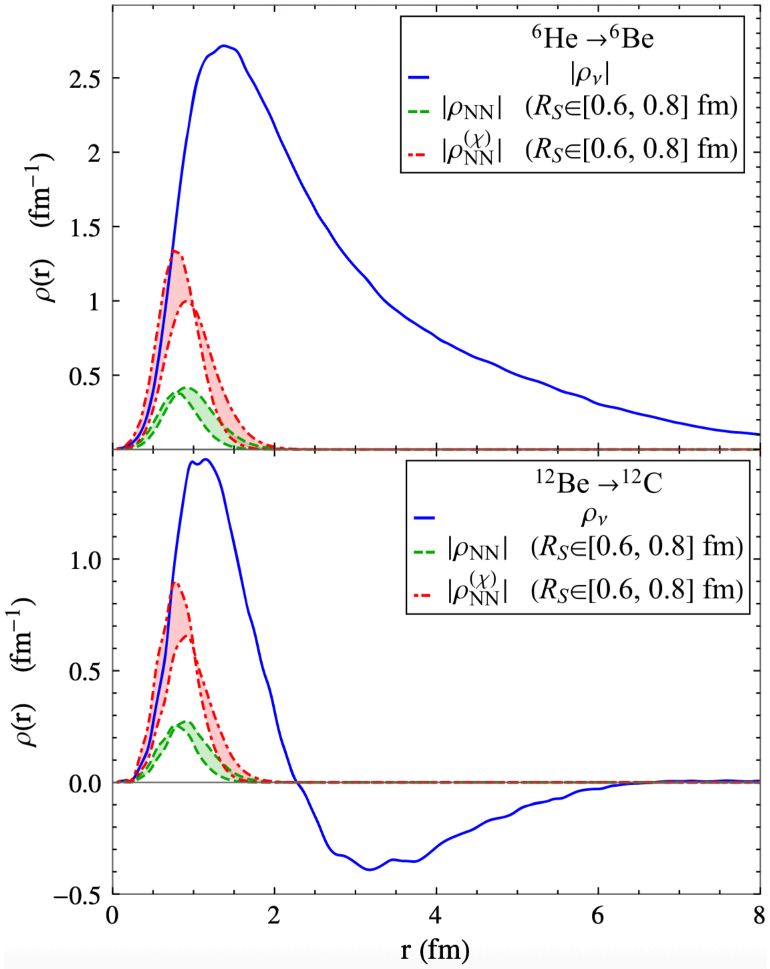

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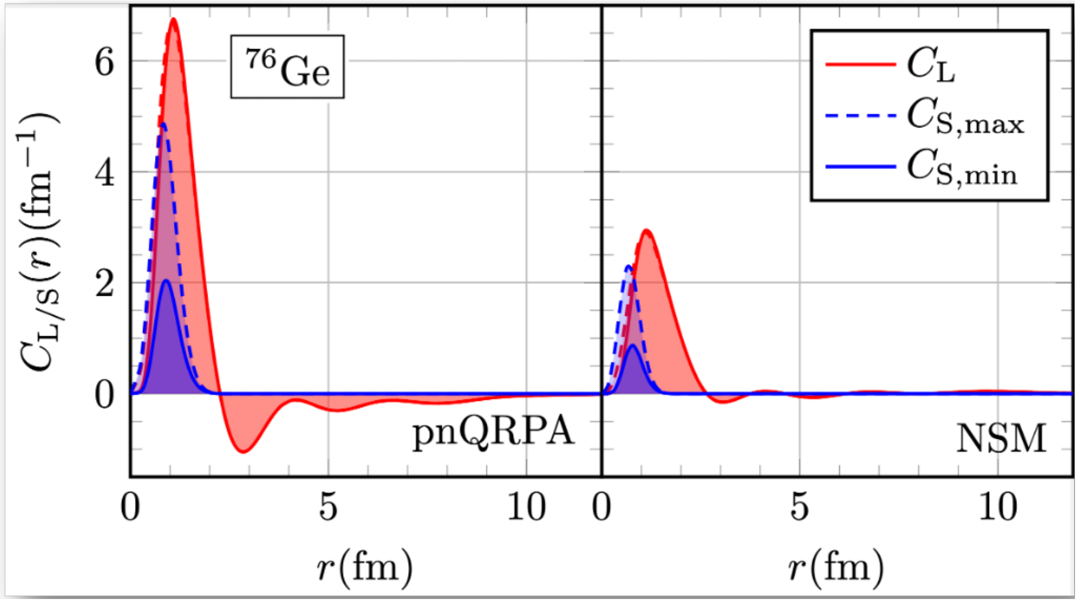

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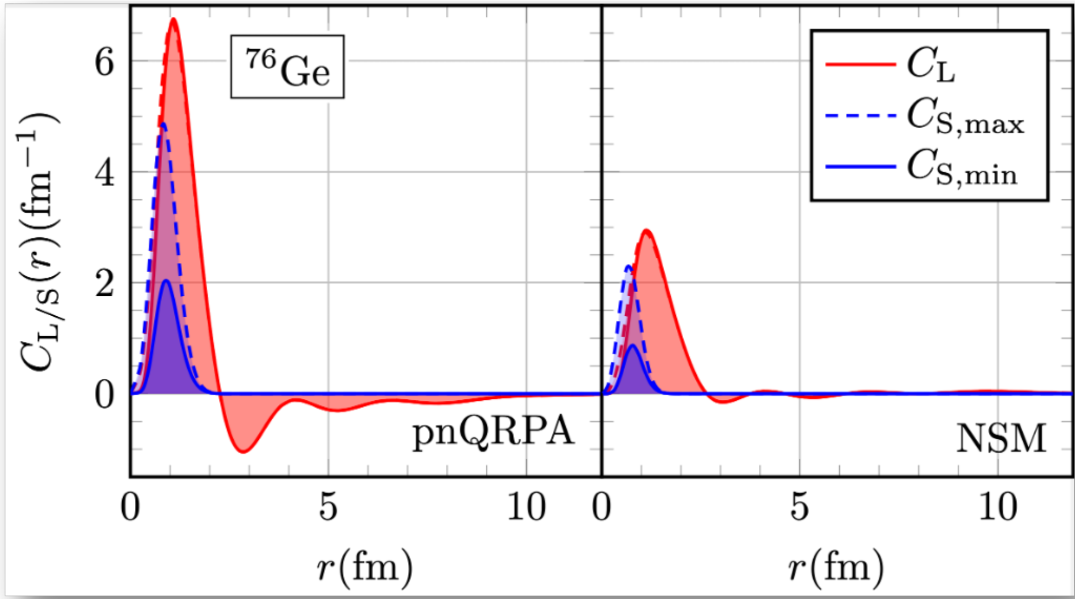

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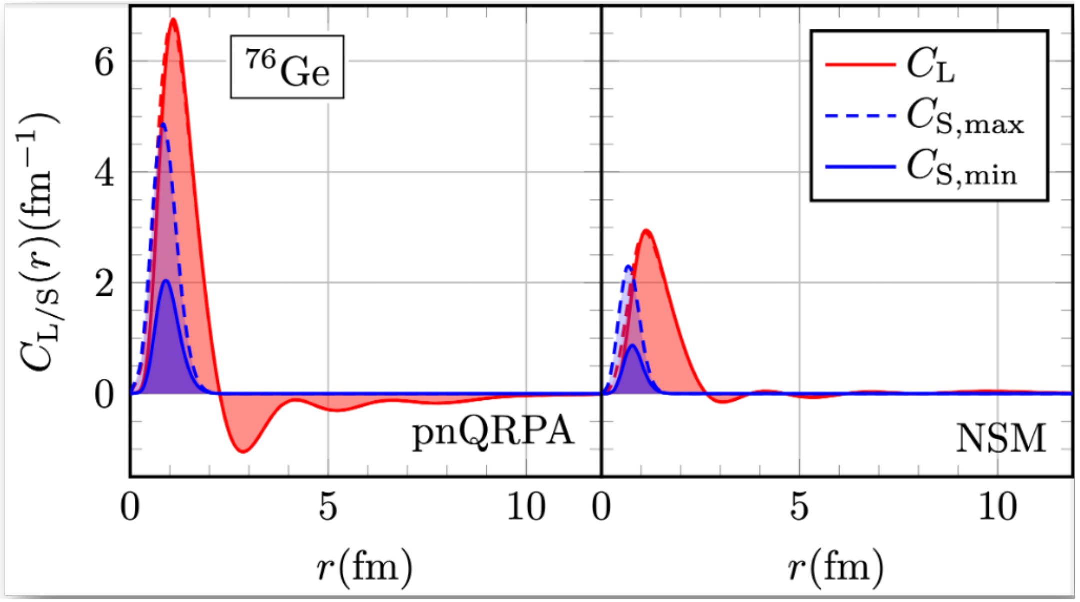
  Weiss, Soriano, Lovato, Menéndez, Wiringa, Phys. Rev. C 106, 065501 (2022)



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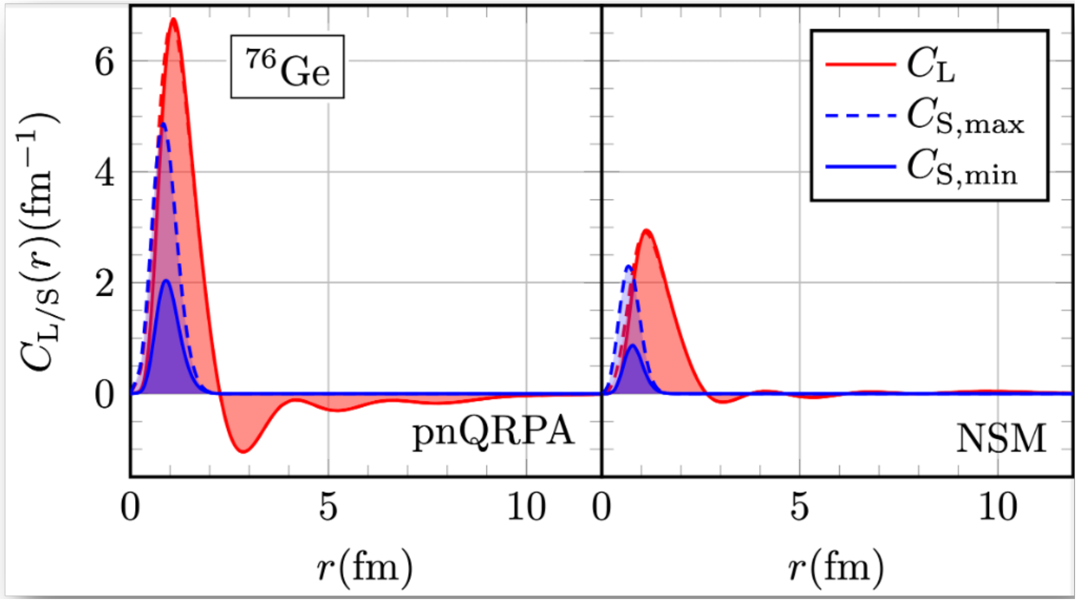
  Weiss, Soriano, Lovato, Menéndez, Wiringa, Phys. Rev. C 106, 065501 (2022)
- VS-IMSRG shows $\sim 40\% - 90\,\%$ **enhancement** in ^{76}Ge, ^{130}Te, and ^{136}Xe
  Belley, Yao, Bally, Pitcher, Engel, Phys. Rev. Lett. 132, 182502 (2024)
  Belley, Miyagi, Stroberg, Holt, arXiv:2307.15156

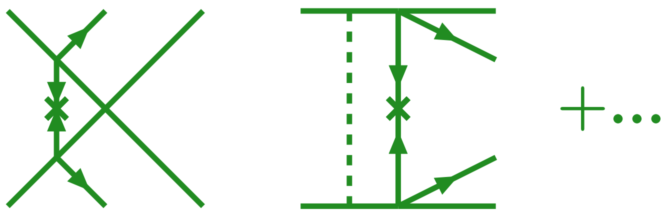


Jokiniemi, Soriano, Menéndez, Phys. Lett. B 823, 136720 (2021)

TECHNISCHE UNIVERSITÄT DARMSTADT

LOOP CORRECTIONS

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



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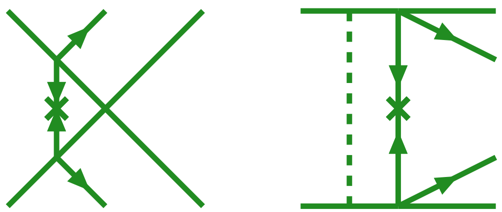
LOOP CORRECTIONS



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

With $\boldsymbol{V_{\nu,2}} = V^{(a,b)}_{\mathrm{VV}} + V^{(a,b)}_{\mathrm{AA}} + \ln\frac{m_\pi^2}{\mu_{\mathrm{us}}^2} V^{(a,b)}_{\mathrm{usoft}} + V^{(a,b)}_{\mathrm{CT}}$

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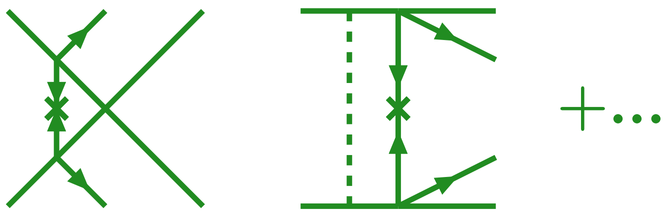

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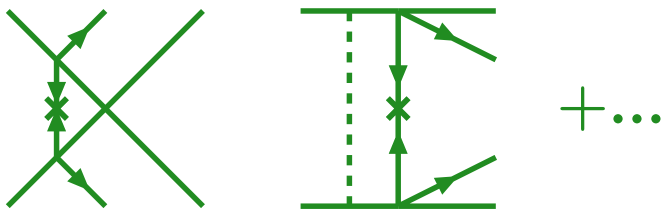

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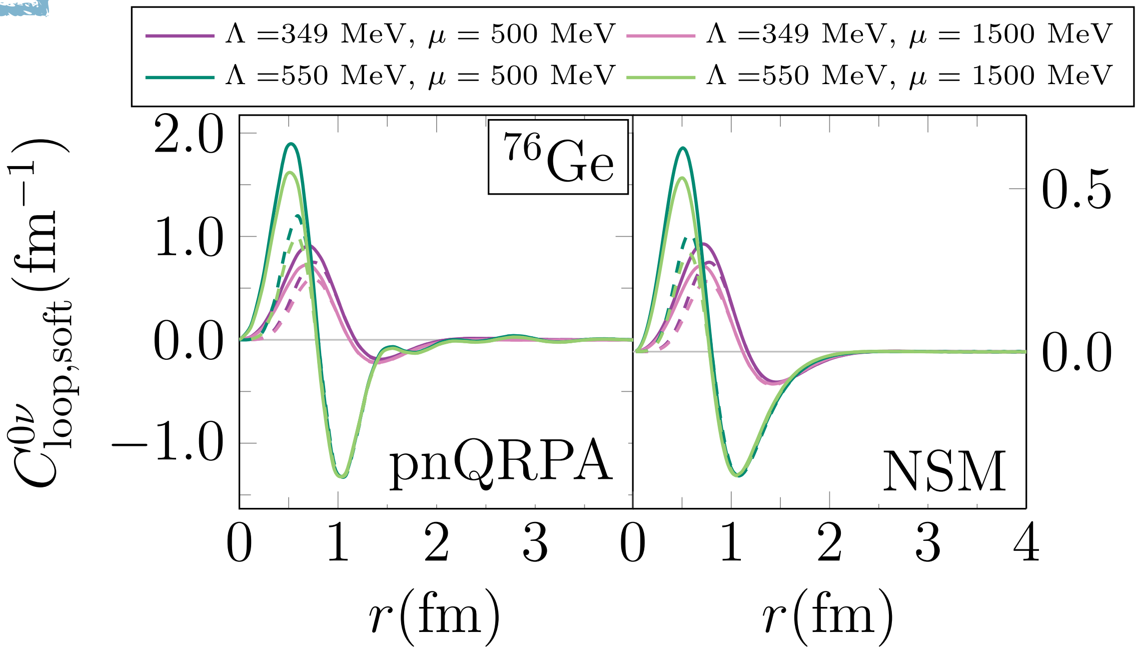

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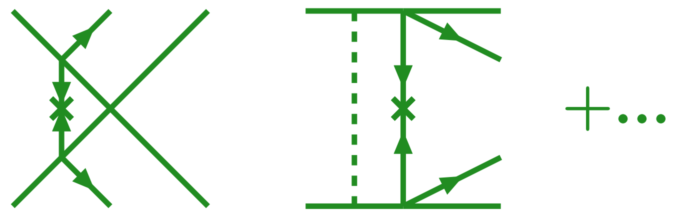

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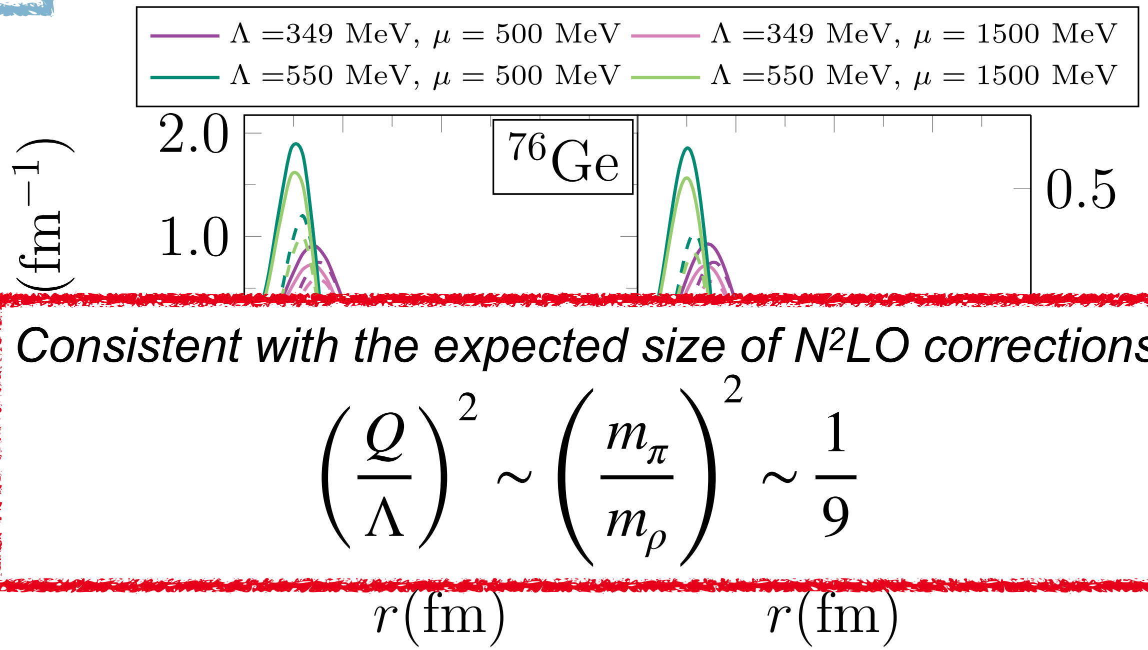

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Castillo, Jokiniemi, Menéndez, Phys. Lett. B 860, 139181 (2025)

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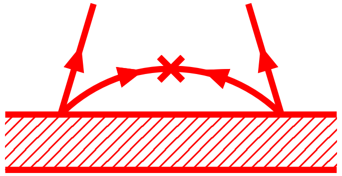
CONTRIBUTION FROM ULTRASOFT NEUTRINOS



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

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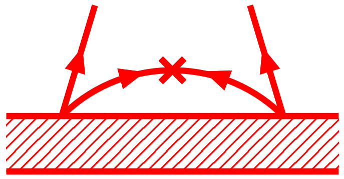

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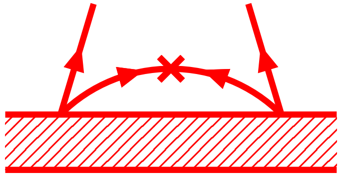

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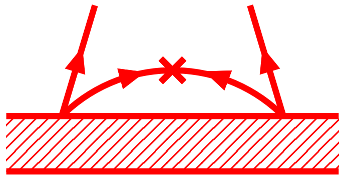

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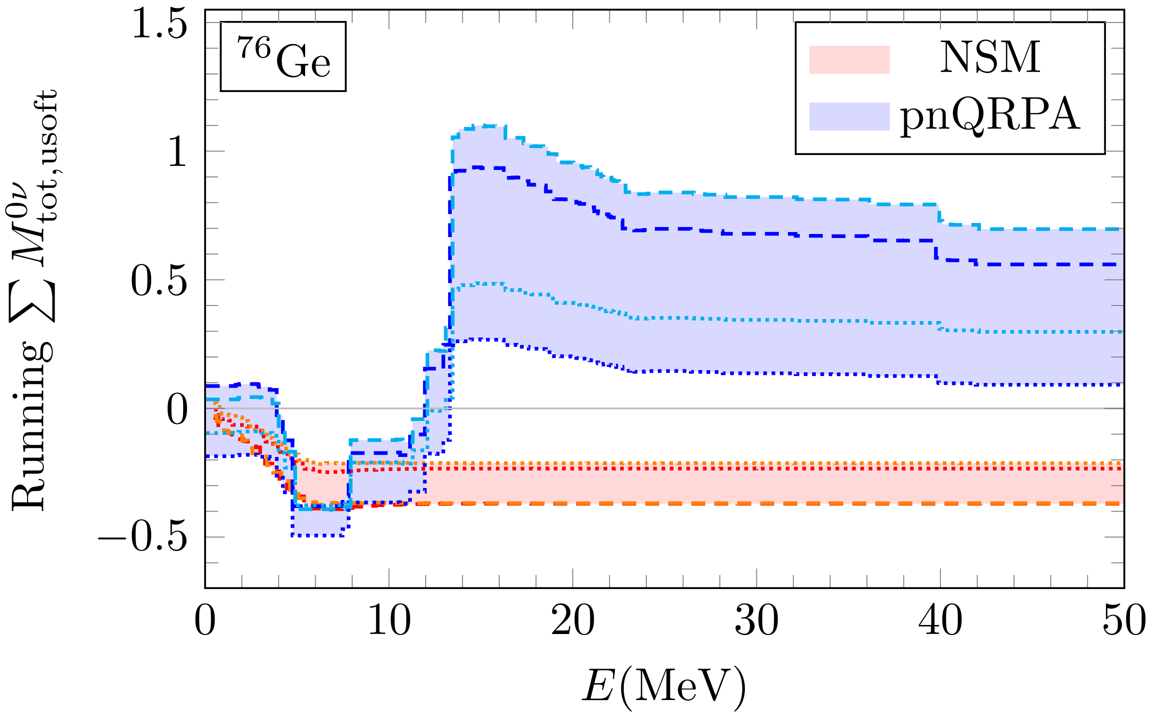
Castillo, Jokiniemi, Soriano, Menéndez, Phys. Lett. B 860, 139181 (2025)



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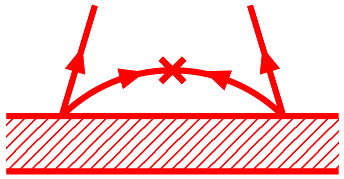

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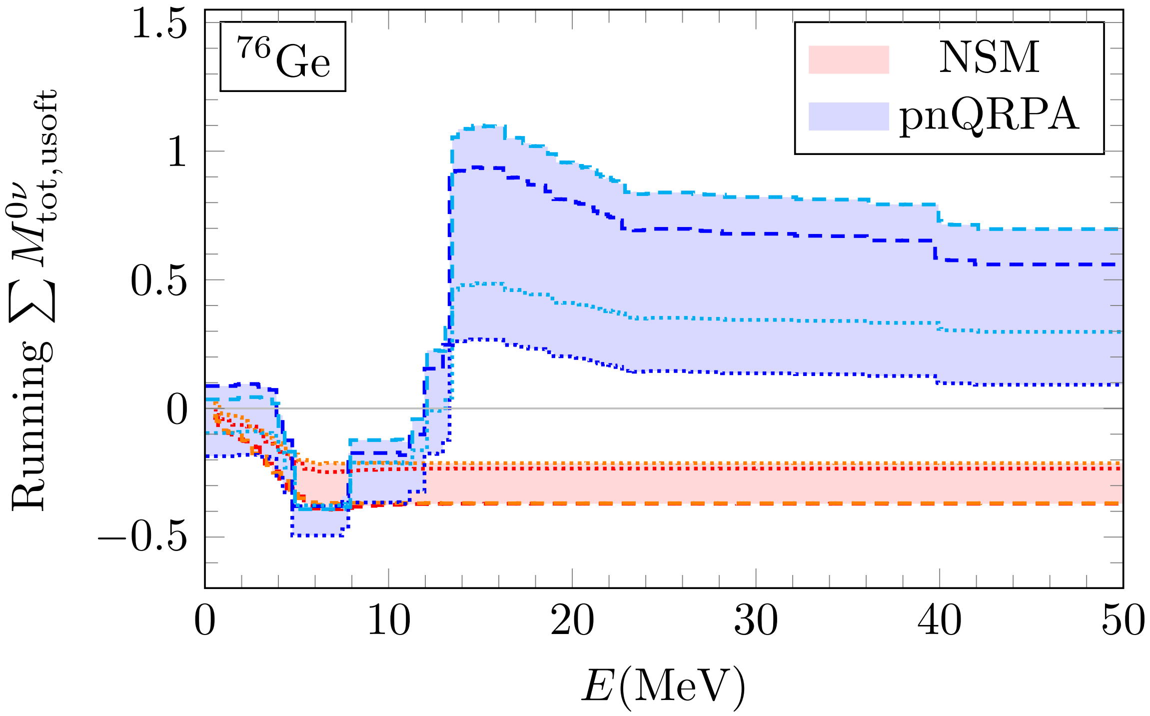
Castillo, Jokiniemi, Soriano, Menéndez, Phys. Lett. B 860, 139181 (2025)

- Can be seen as a "closure correction"



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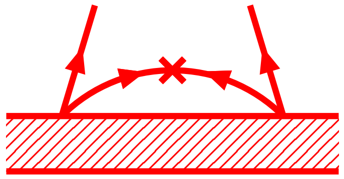

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Castillo, Jokiniemi, Soriano, Menéndez, *Phys. Lett. B 860, 139181 (2025)*

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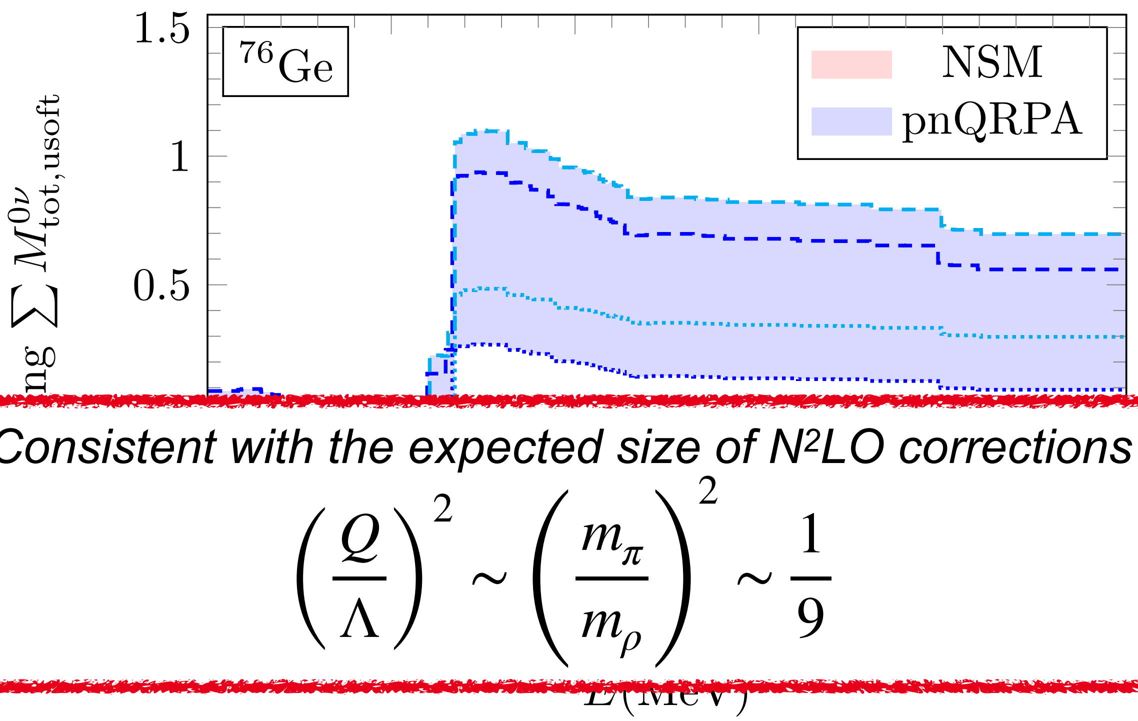

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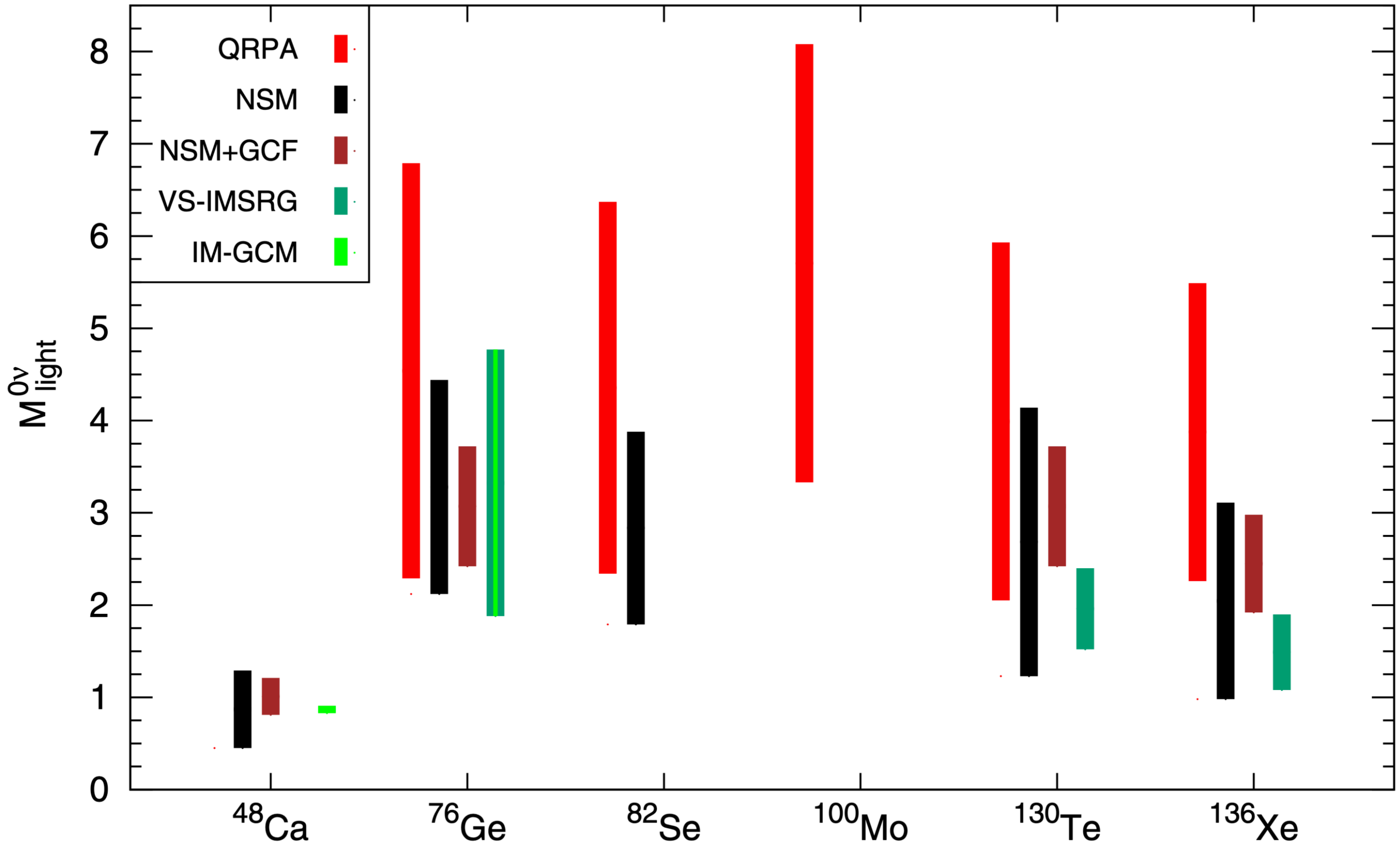
CURRENT STATUS OF THE NUCLEAR MATRIX ELEMENTS



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

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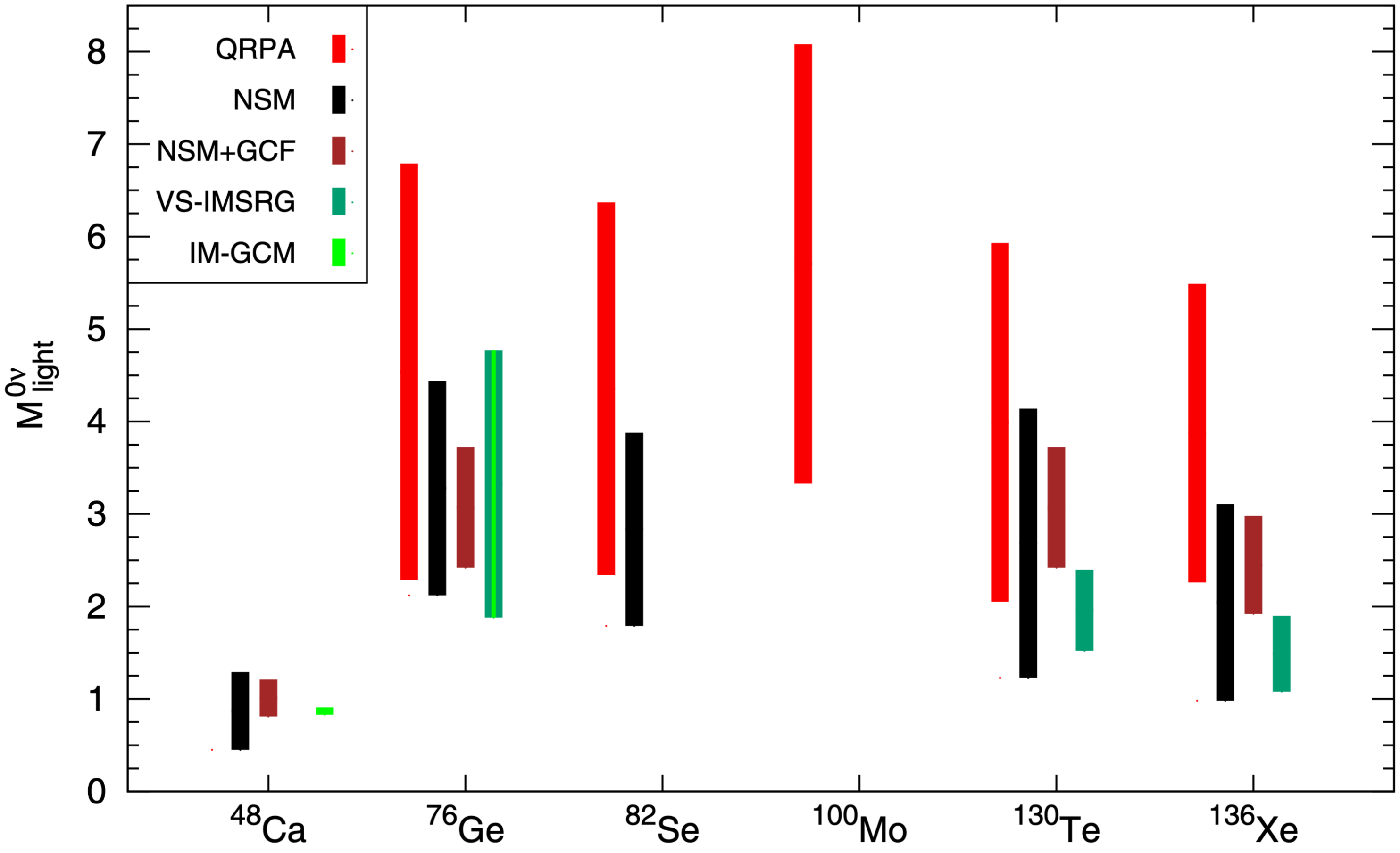
CURRENT STATUS OF THE NUCLEAR MATRIX ELEMENTS

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



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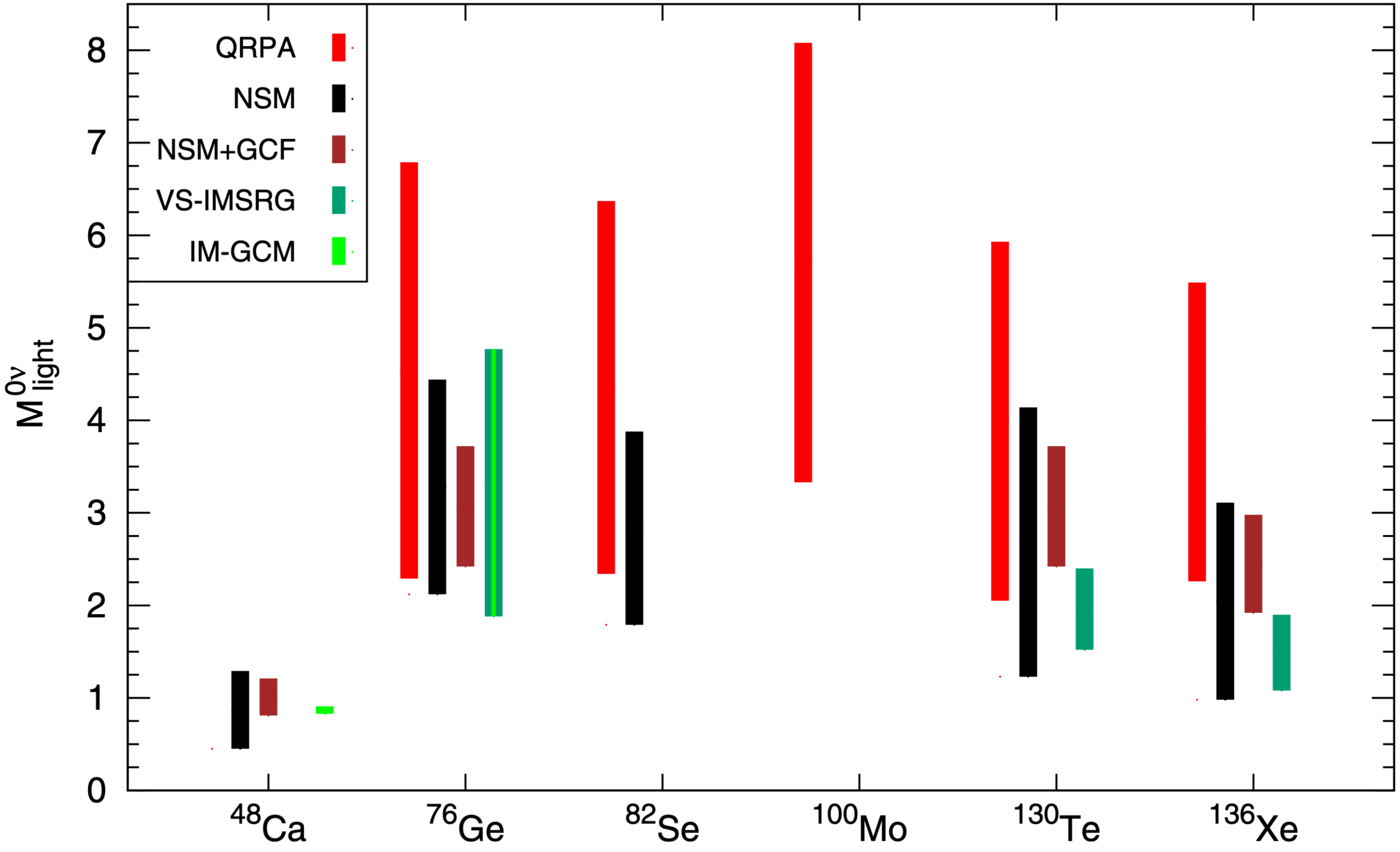

Ranges cover:
- Different parameters/ nuclear interactions
- Different values of g_{ν}^{NN}
- …

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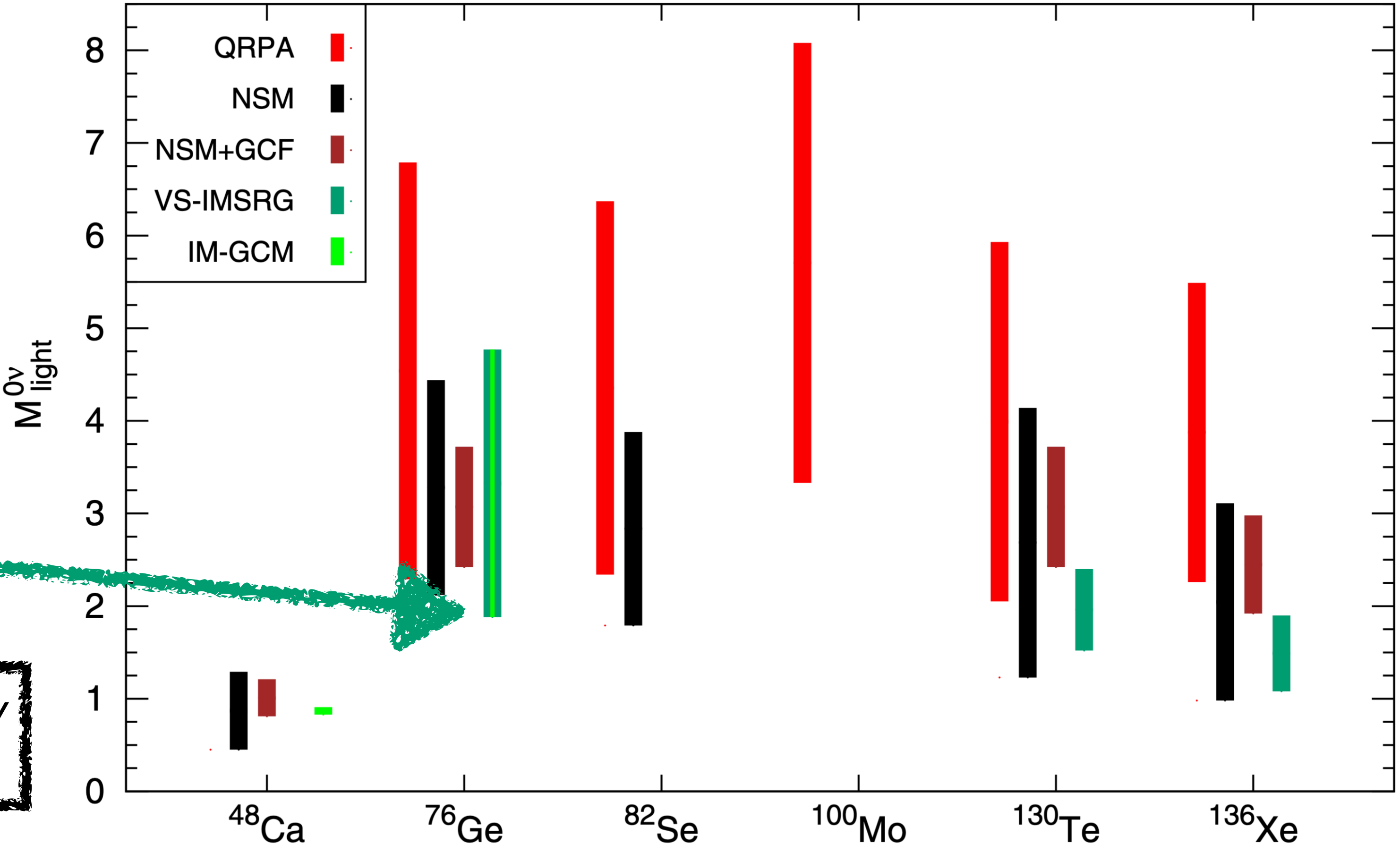
CURRENT STATUS OF THE NUCLEAR MATRIX ELEMENTS

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

First NME with quantified uncertainty

See talk by A. Belley tomorrow 4:23 pm



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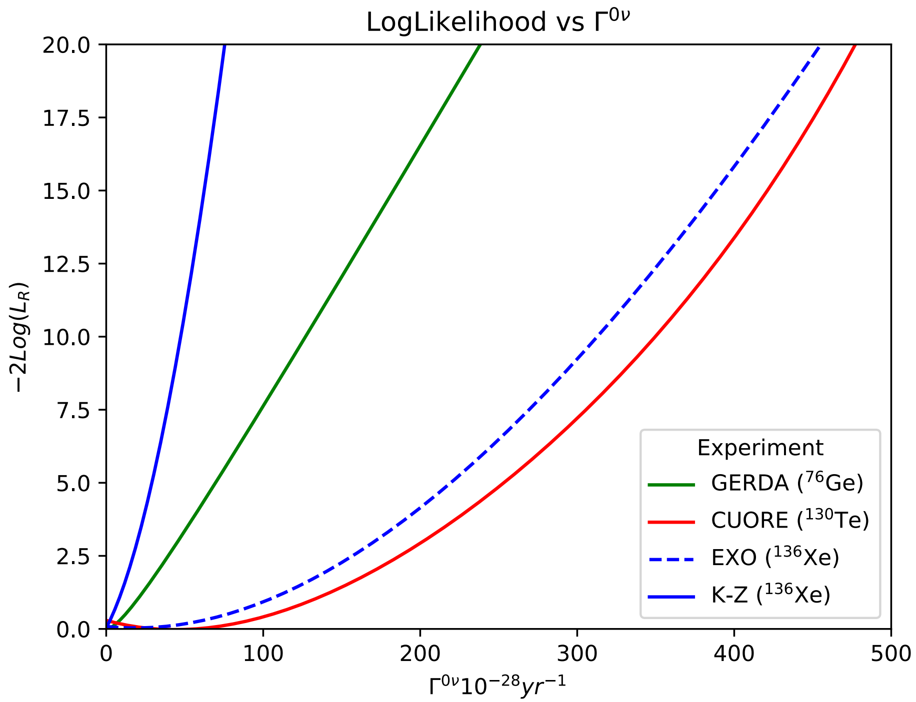
WHAT DOES THIS MEAN FOR THE EXPERIMENTS?

Current best limits



Shickele, Jokiniemi, Belley, Holt, in preparation

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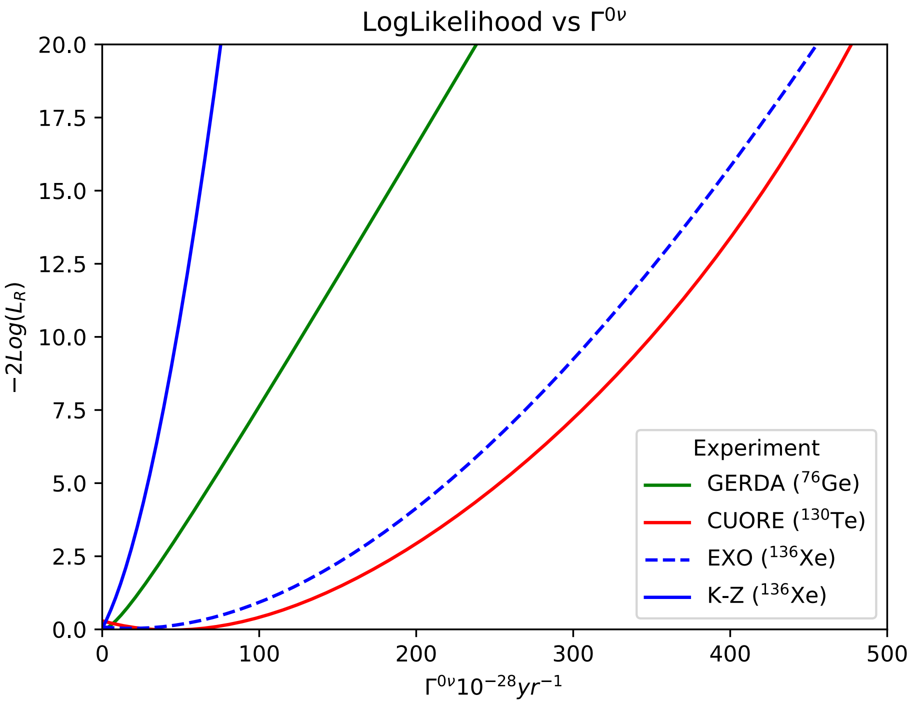

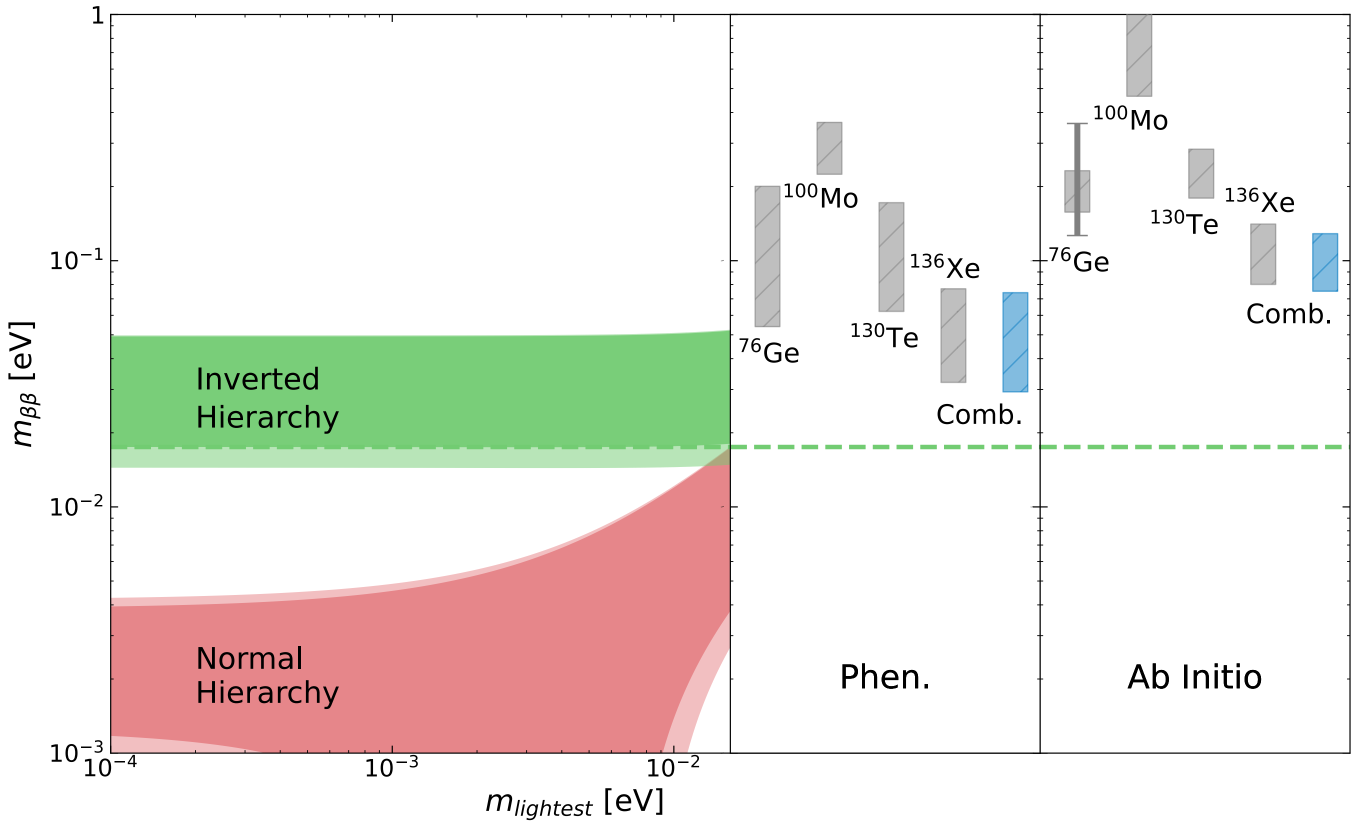

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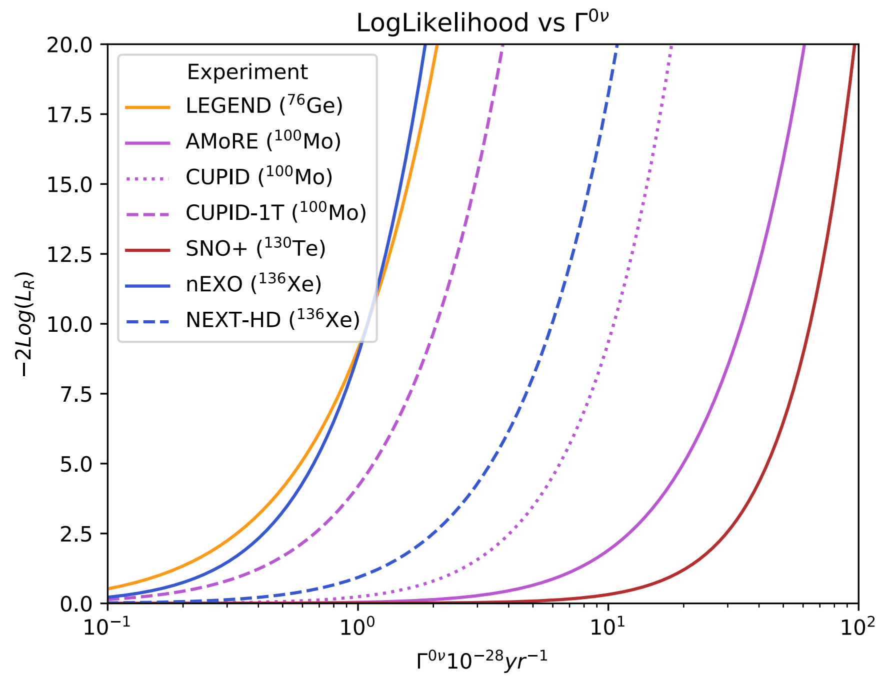
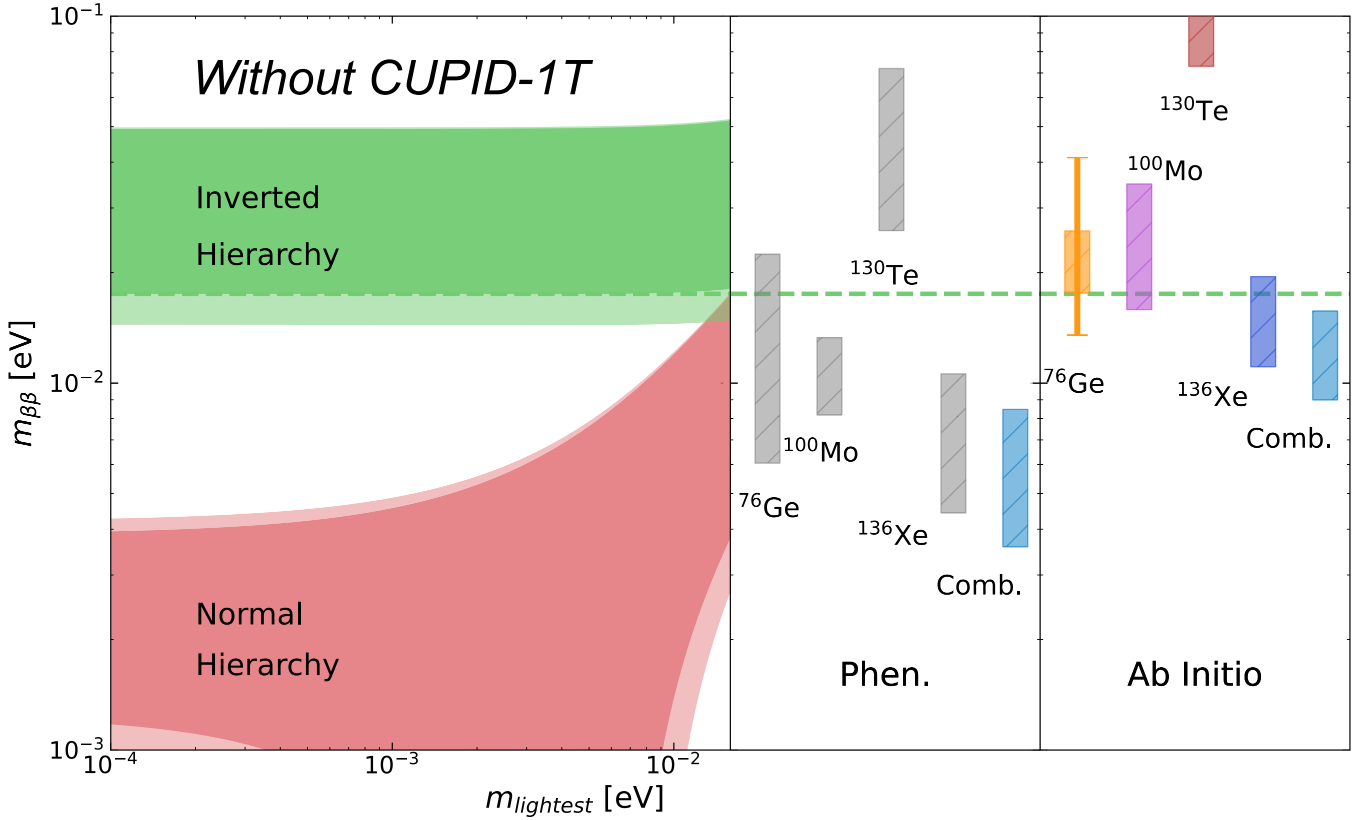
Next-generation experiments





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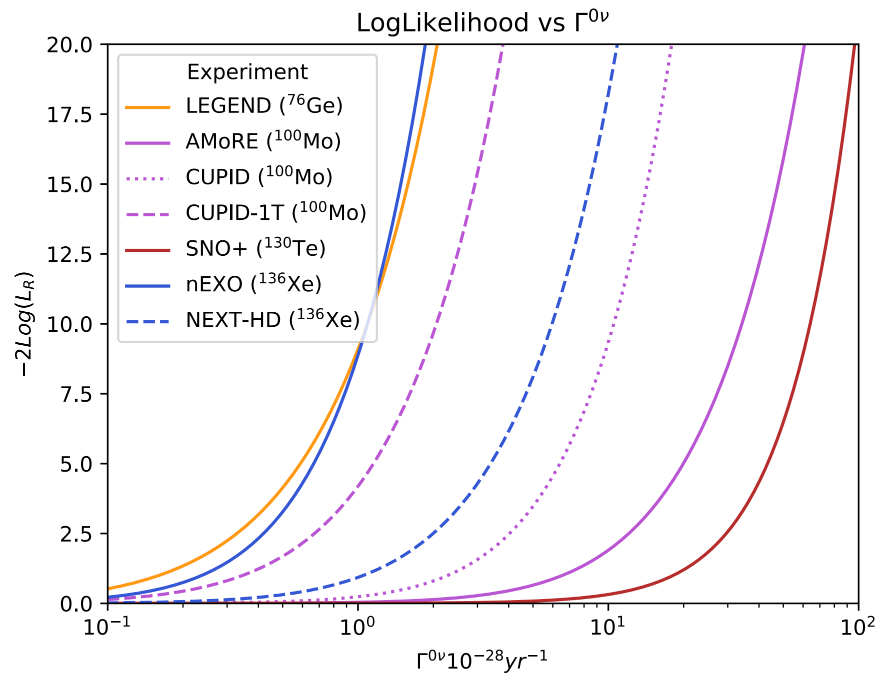

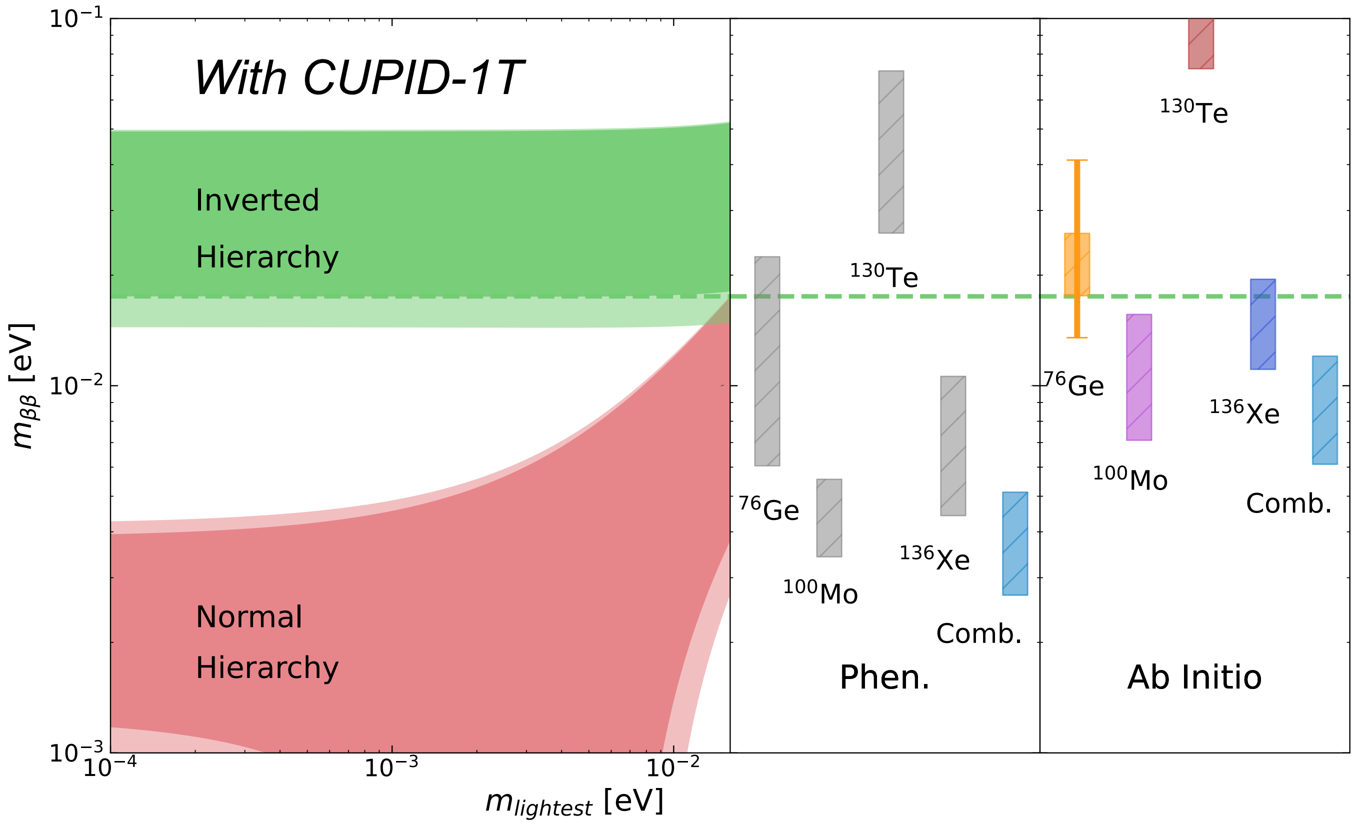

Shickele, Jokiniemi, Belley, Holt, in preparation

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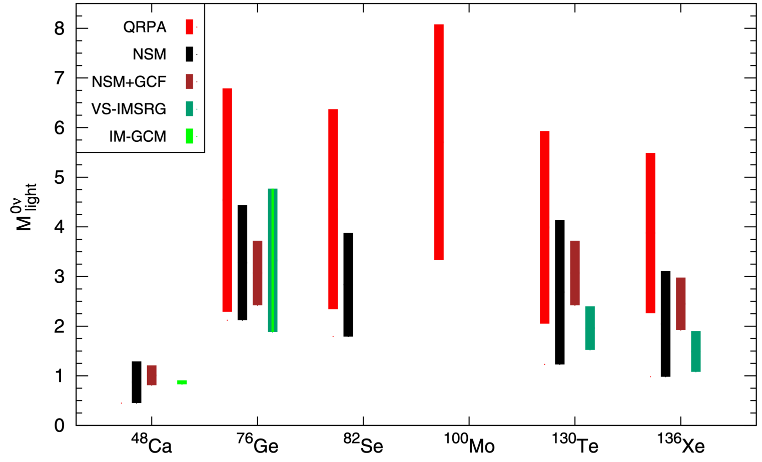
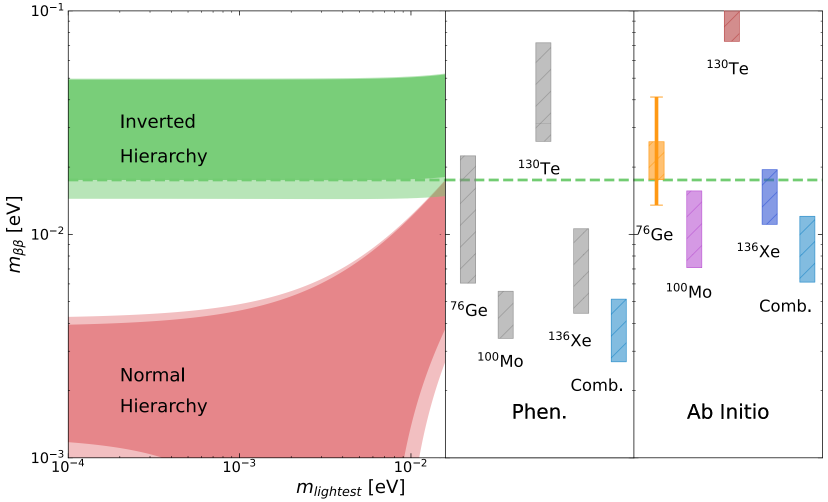
SUMMARY AND OUTLOOK

- $0\nu\beta\beta$ 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
- χEFT 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
- …





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See talk by G. Chambers-Wall tomorrow at 4:46 pm