PROBING NEUTRINOLESS DOUBLE-BETA DECAY BY NUCLEAR OBSERVABLES

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TRIUMF

Arthur B. McDonald
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EMMI Physics Day 2025, GSI, Darmstadt, July 22, 2025

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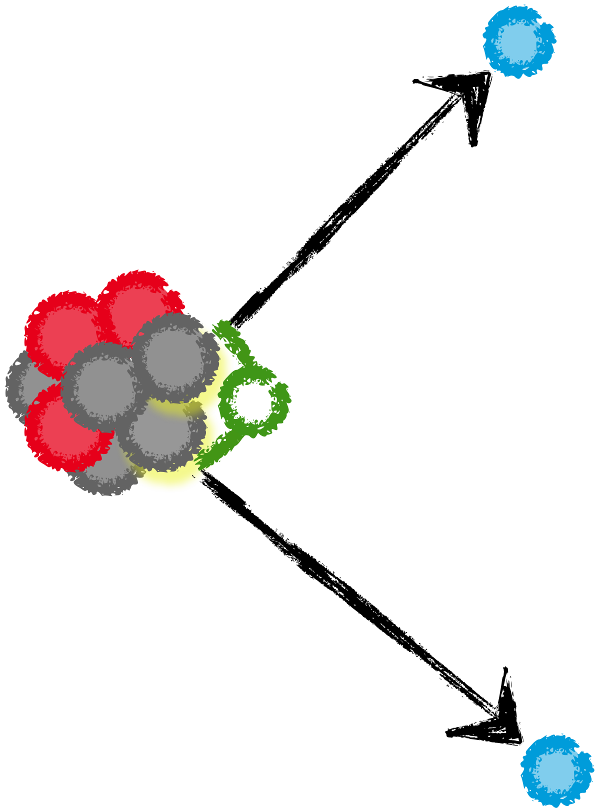
OUTLINE



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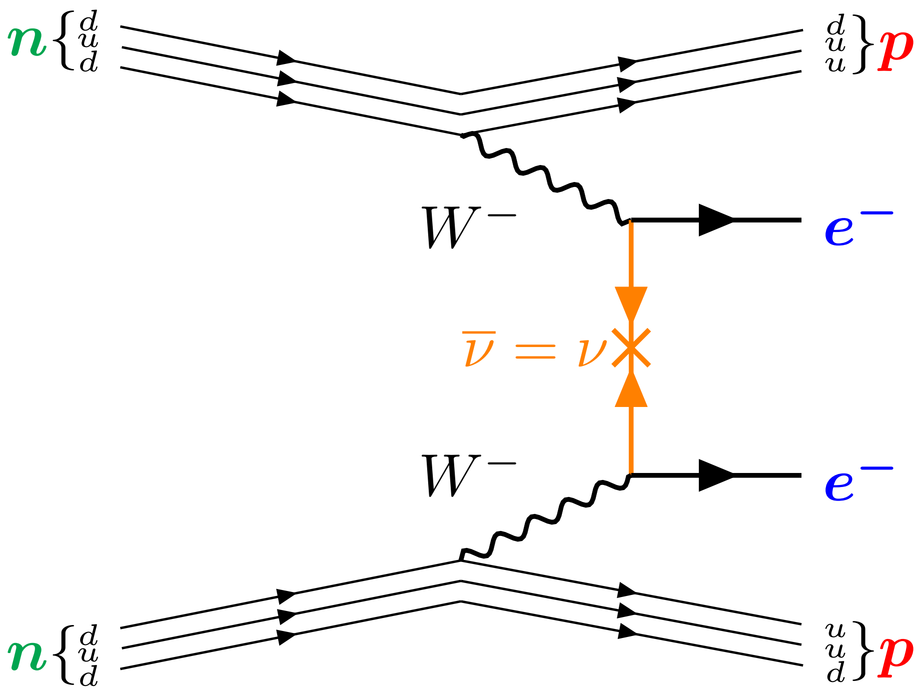
NEUTRINOLESS DOUBLE-BETA ($0\nu\beta\beta$) DECAY

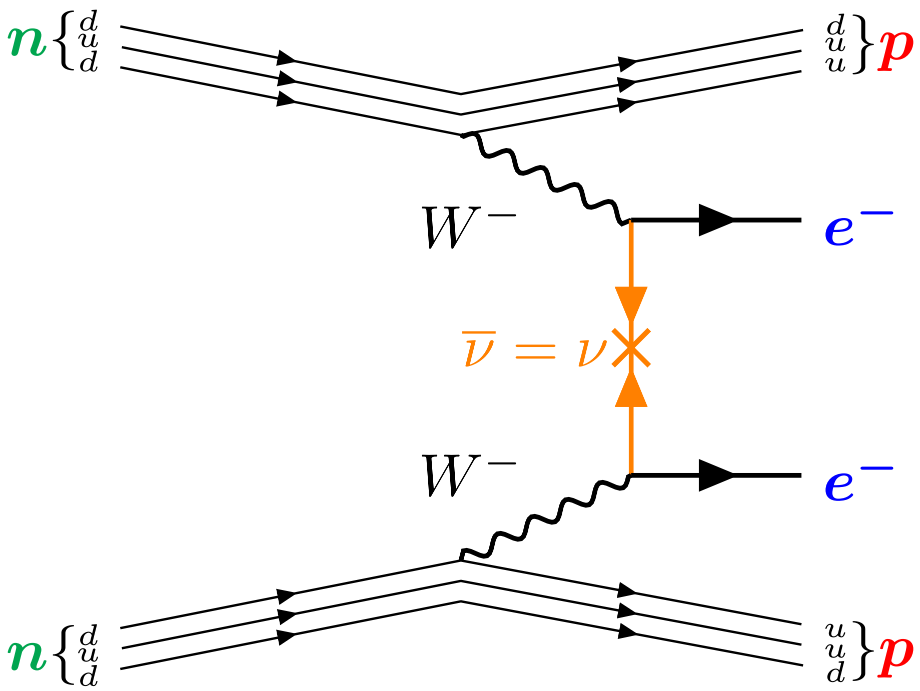
$$(A,Z) \rightarrow (A,Z+2) + 2e^- \cancel{+2\overline{\nu}_e}$$



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

- Violates lepton-number conservation

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



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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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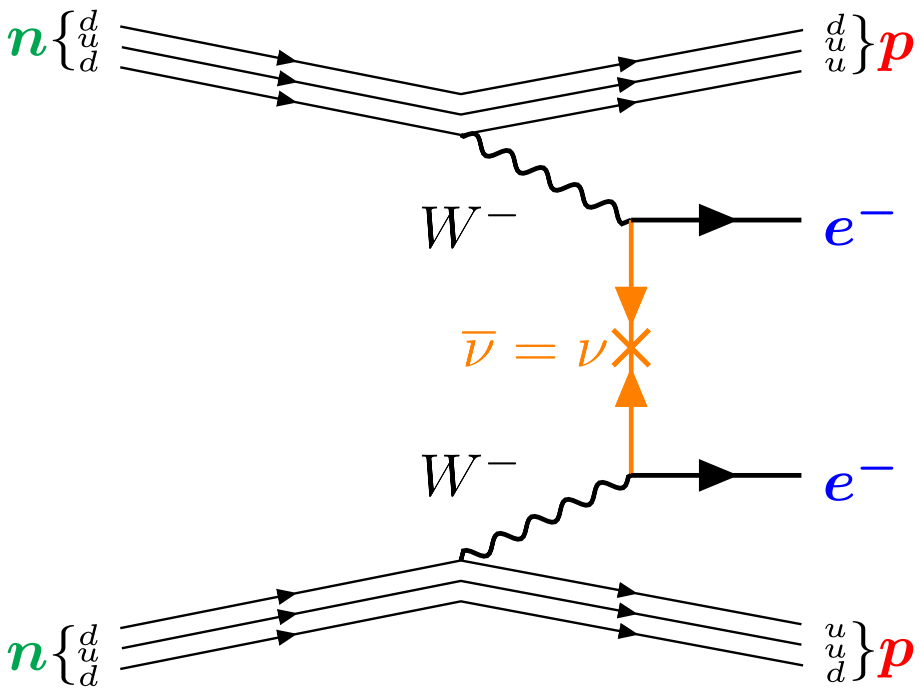

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- If observed, $t_{1/2}^{0\nu} \gtrsim 10^{25}$ **years**

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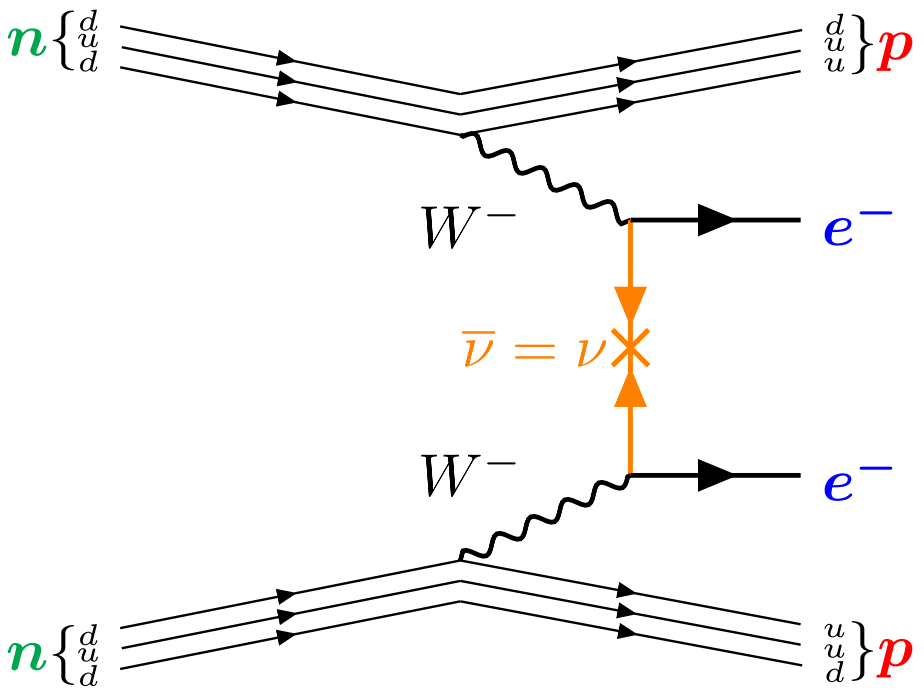

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($t_{1/2}^{2\nu} \approx 10^{20}$ years, Age of the Universe $\approx 10^{10}$ years)

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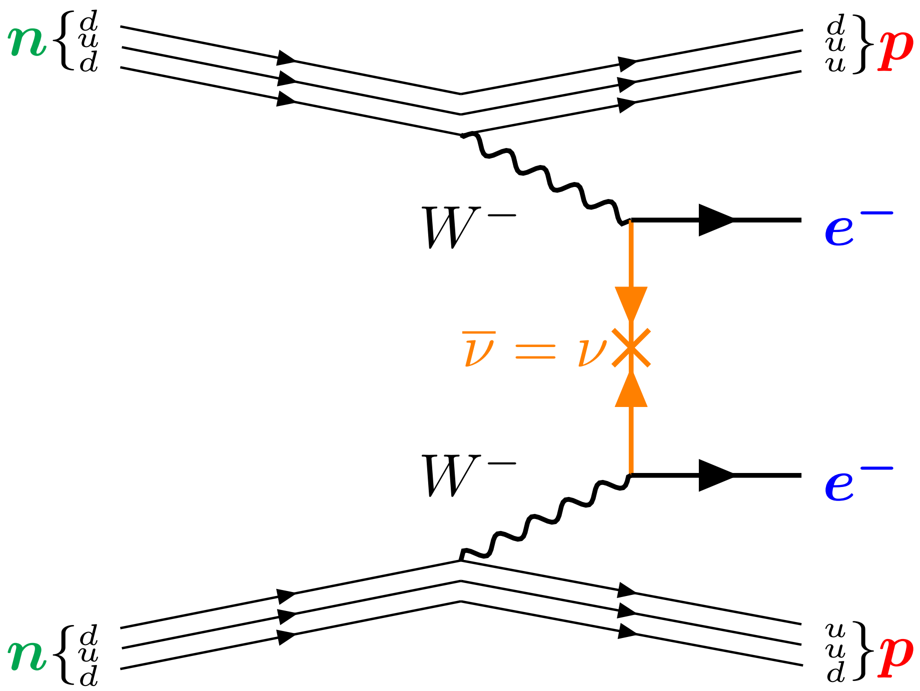

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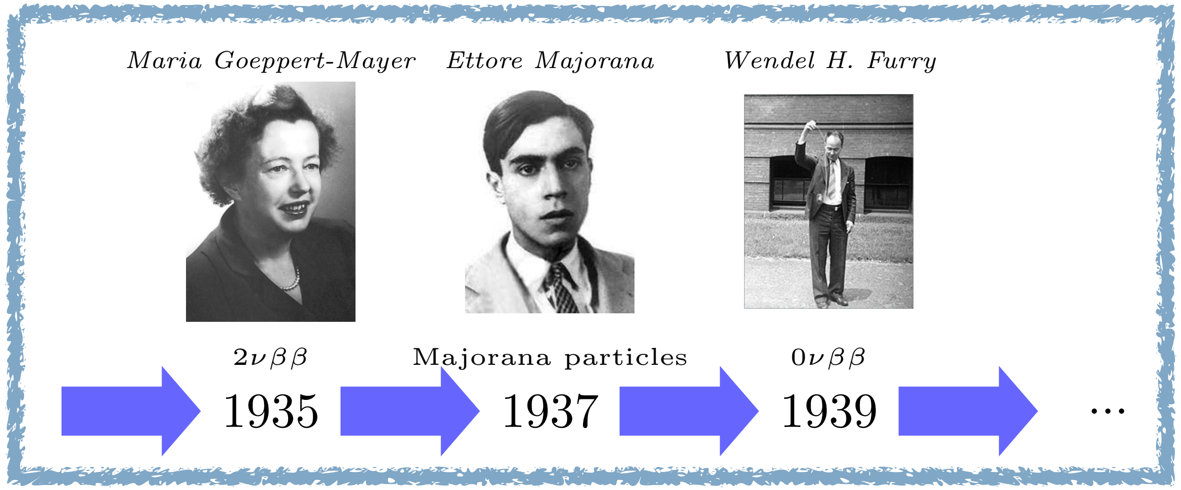
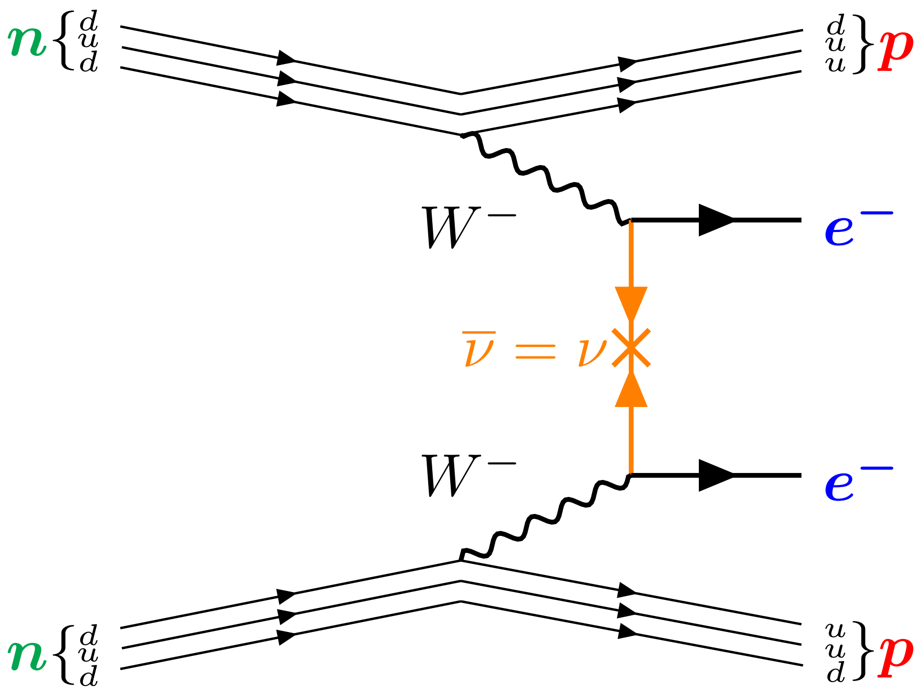
($t_{1/2}^{2\nu} \approx 10^{20}$ *years, Age of the Universe* $\approx 10^{10}$ *years*)

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





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

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

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

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

Half-life to be measured

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

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Majorana mass

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

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

Half-life to be measured

Nuclear matrix element

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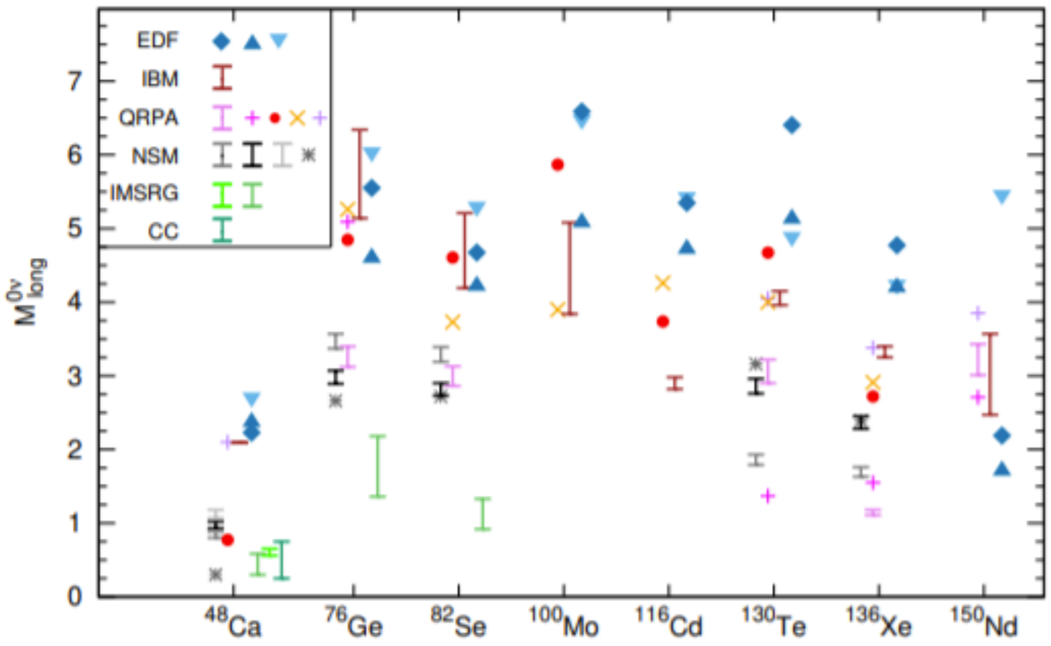

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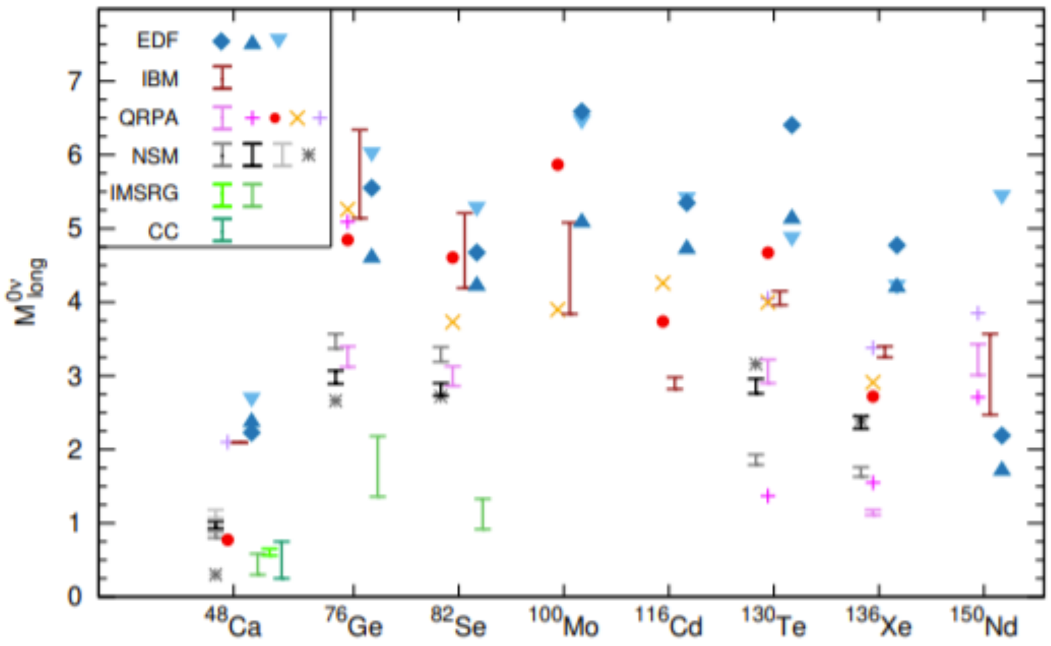

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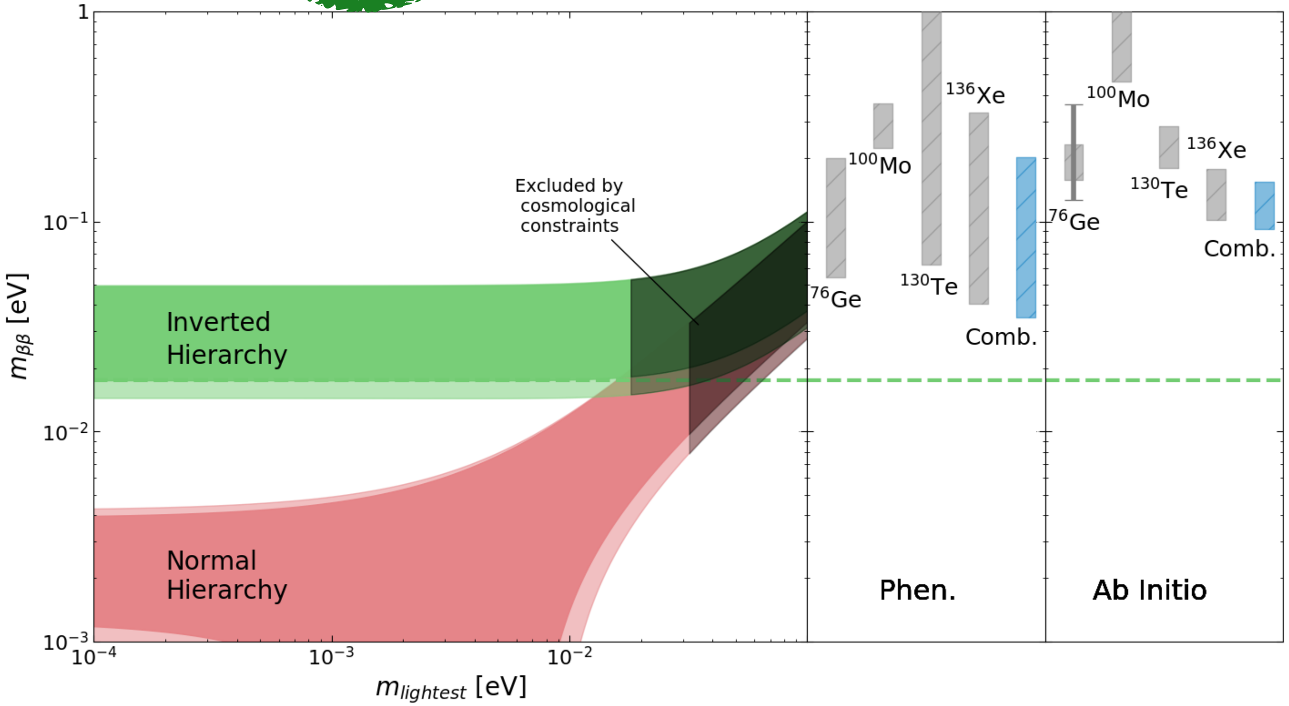

Shickele, Jokiniemi, Belley, Holt, in preparation

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

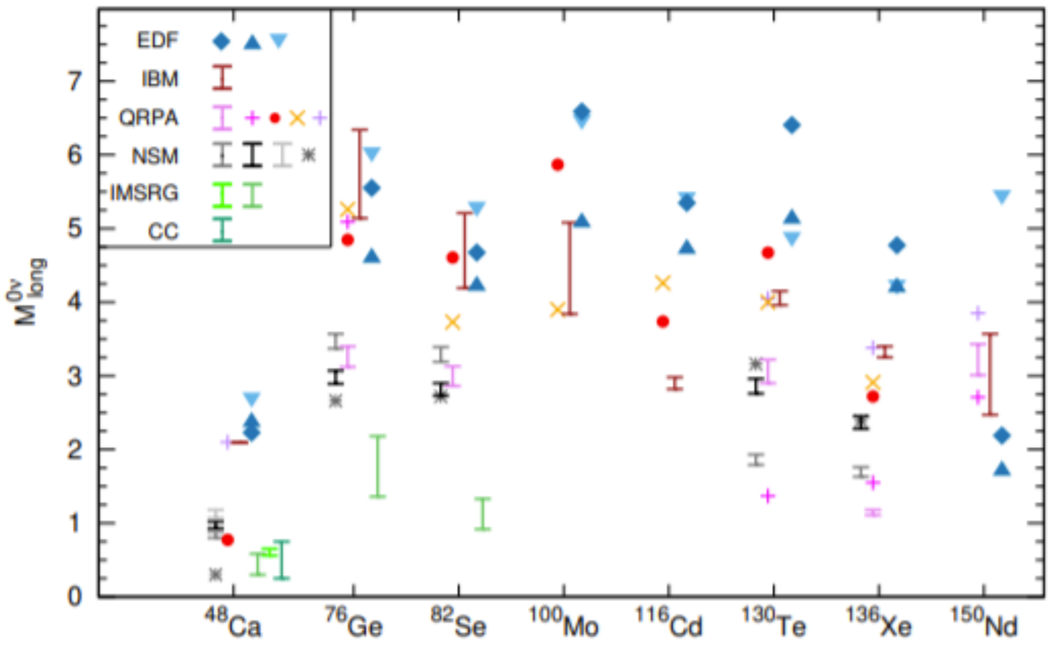
Half-life to be measured

Nuclear matrix element

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

Majorana mass

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



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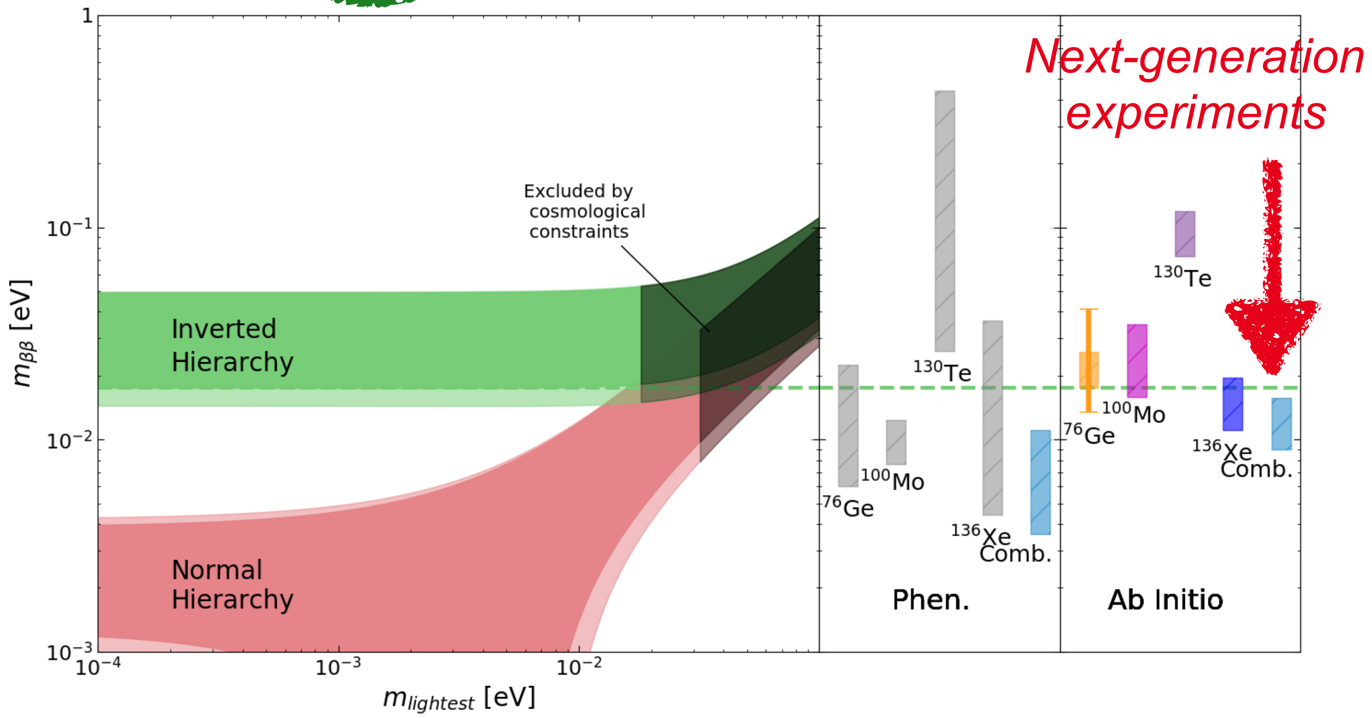

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NUCLEAR MATRIX ELEMENT OF $0\nu\beta\beta$ DECAY

$$M^{0\nu} = \langle \Psi_f^{(A)} \| \sum_{a,b} V_x(q) \mathcal{O}_x \tau_a^- \tau_b^- \| \Psi_i^{(A)} \rangle$$

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Operators

$$\tau_a^- \tau_b^- : \quad nn \to pp,$$

$$\mathcal{O}_{\rm GT} = \boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b \, , \; \mathcal{O}_F = 1 \, , \; \mathcal{O}_{\rm T} = S_{a,b}^{\rm T}$$

$$V_\alpha(q) = \frac{R_{Nucl}}{2\pi^2} \frac{h_\alpha(q^2)}{|\mathbf{q}|(|\mathbf{q}| + \bar{E})}$$

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Nuclear wave functions

From nuclear many-body theory

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

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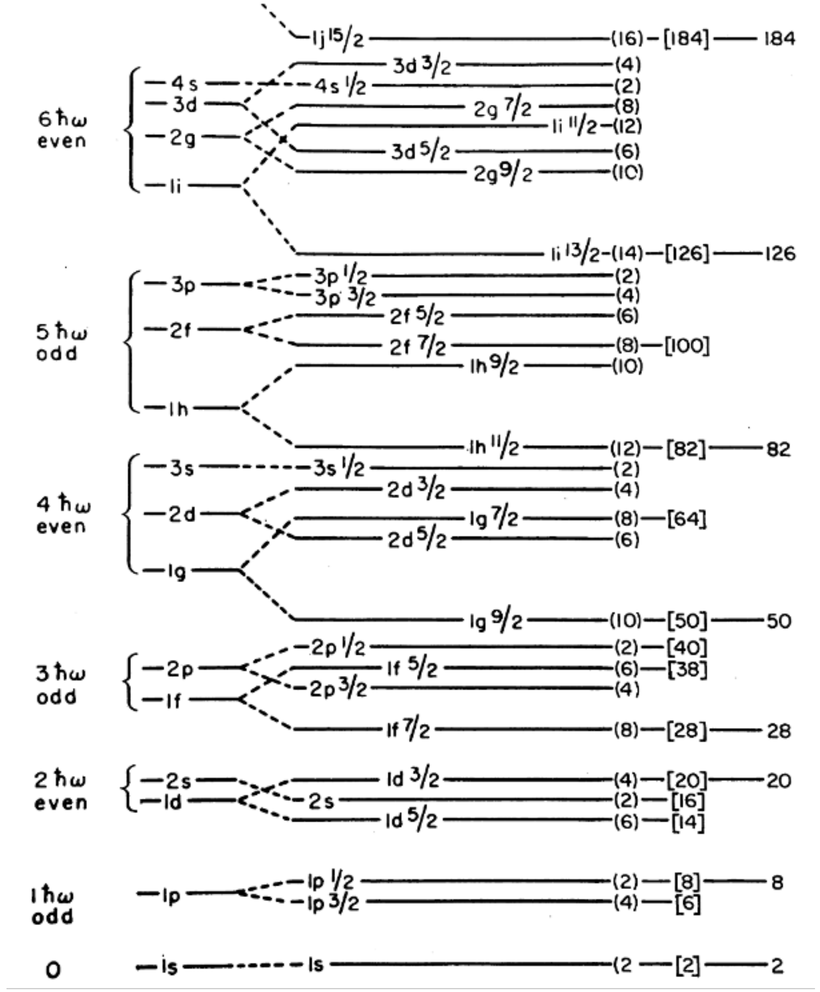
PHENOMENOLOGICAL MANY-BODY METHODS



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

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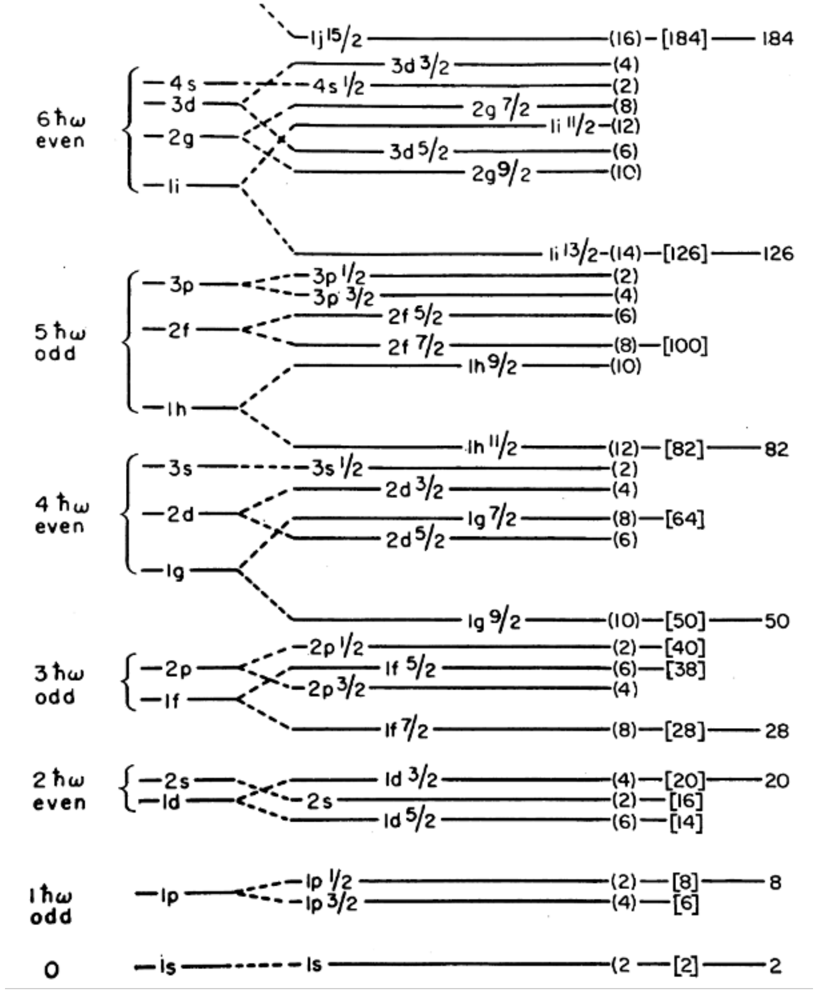
PHENOMENOLOGICAL MANY-BODY METHODS

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



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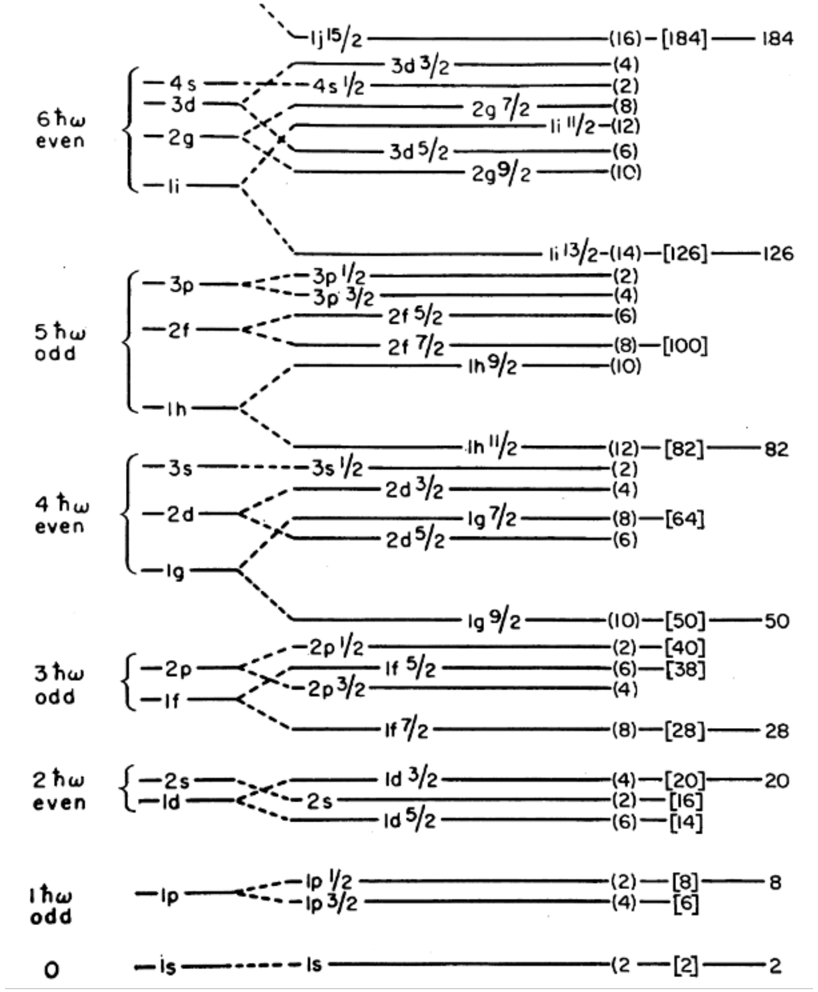

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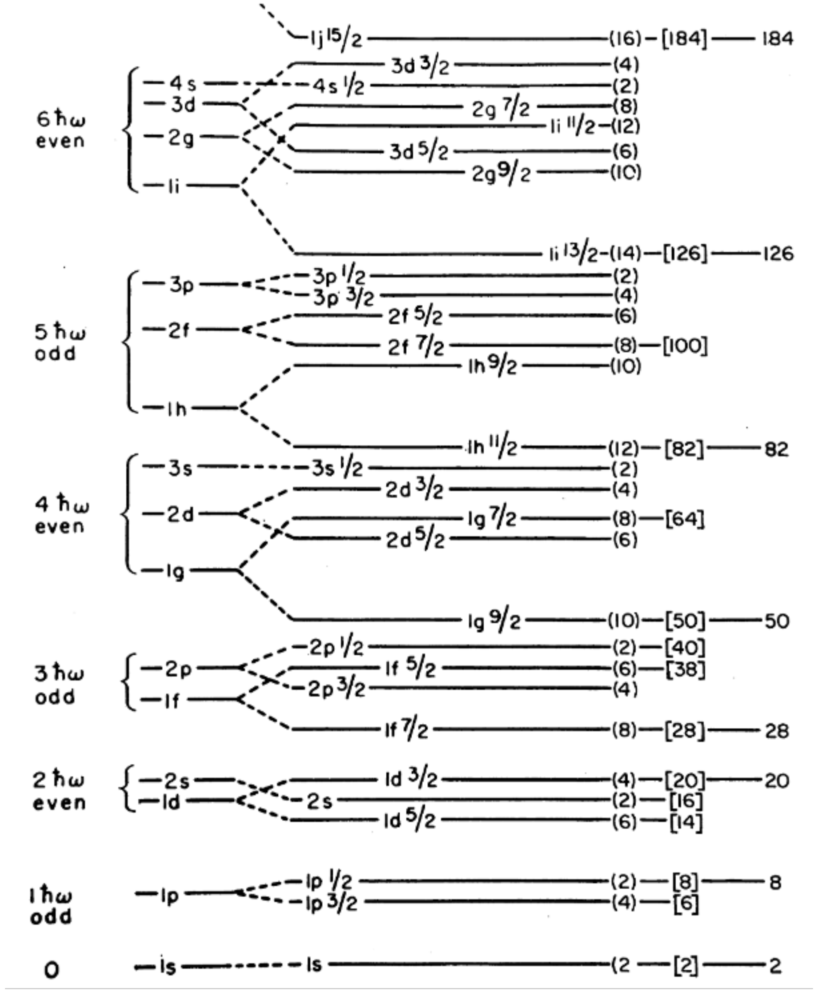

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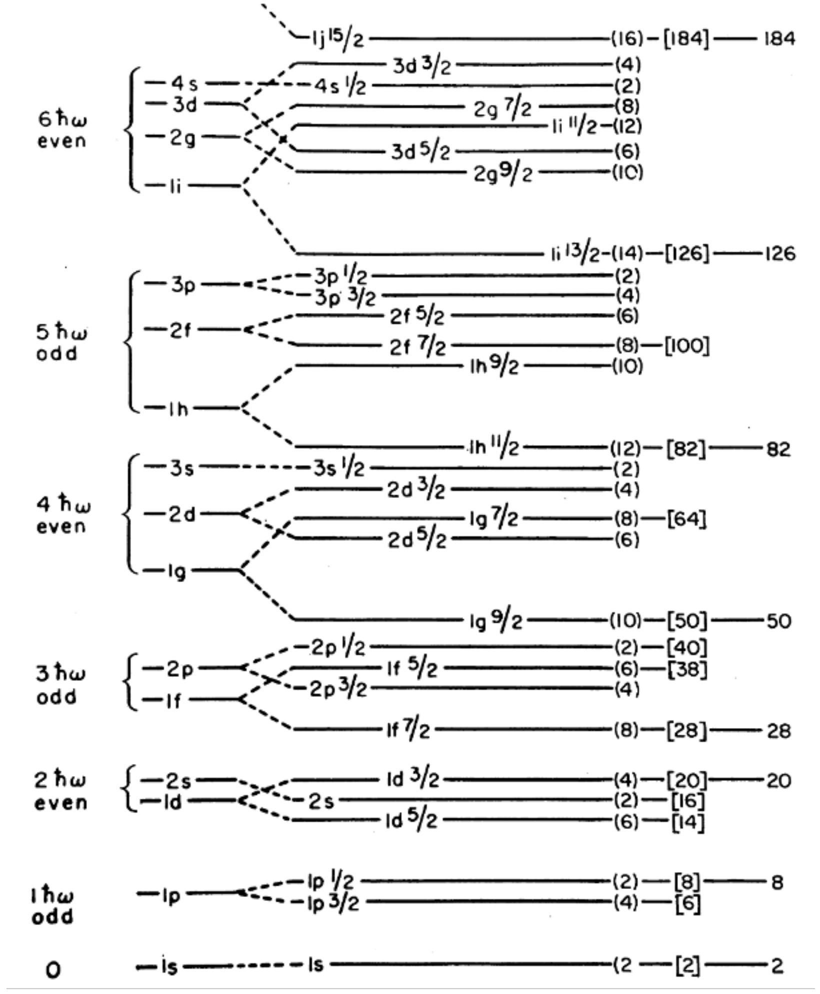
    Large model spaces, but restricted to simple quasiparticle excitations



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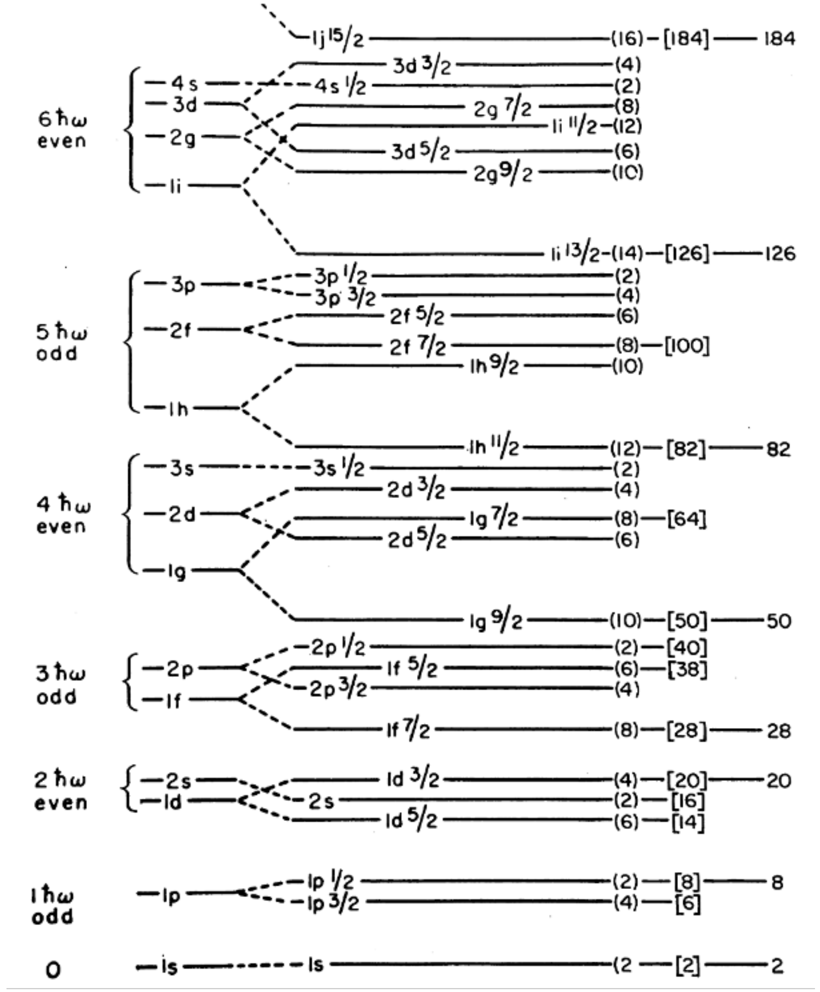
    Small valence spaces, missing pairing correlations



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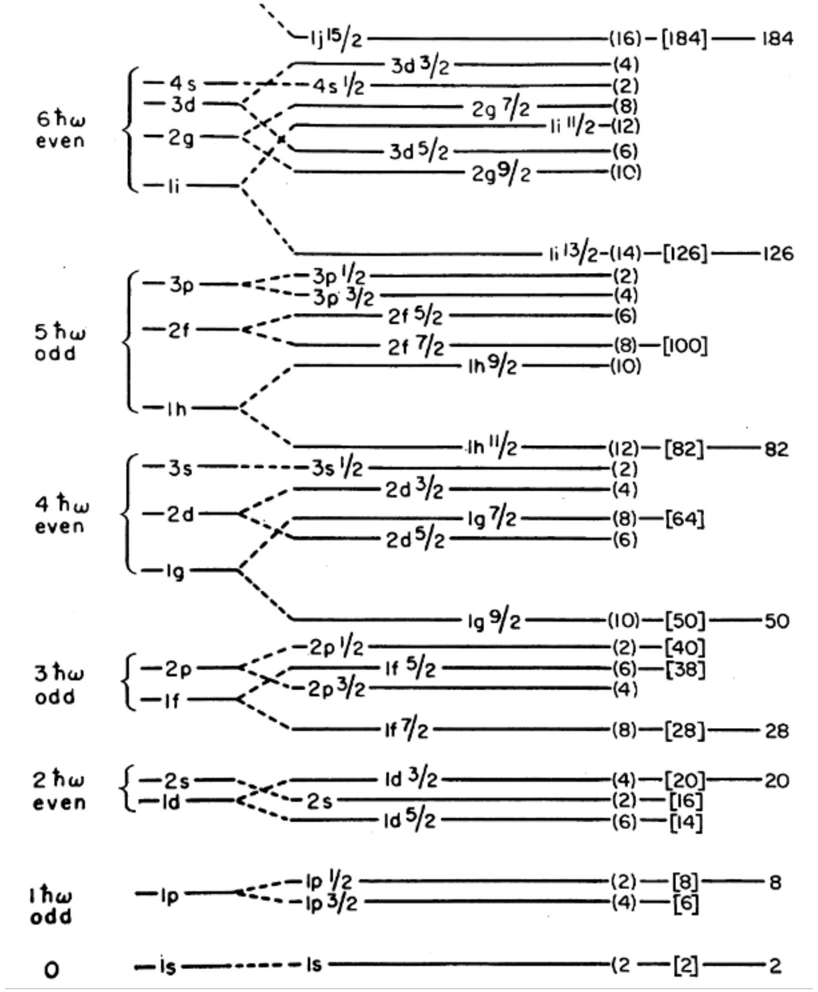
  - **Interacting Boson Model (IBM)**
    Small valence spaces, missing pairing correlations
  - **Energy Density Functional (EDF) theory**
    Large model spaces, missing pairing correlations



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AB INITIO NUCLEAR THEORY

Ideally

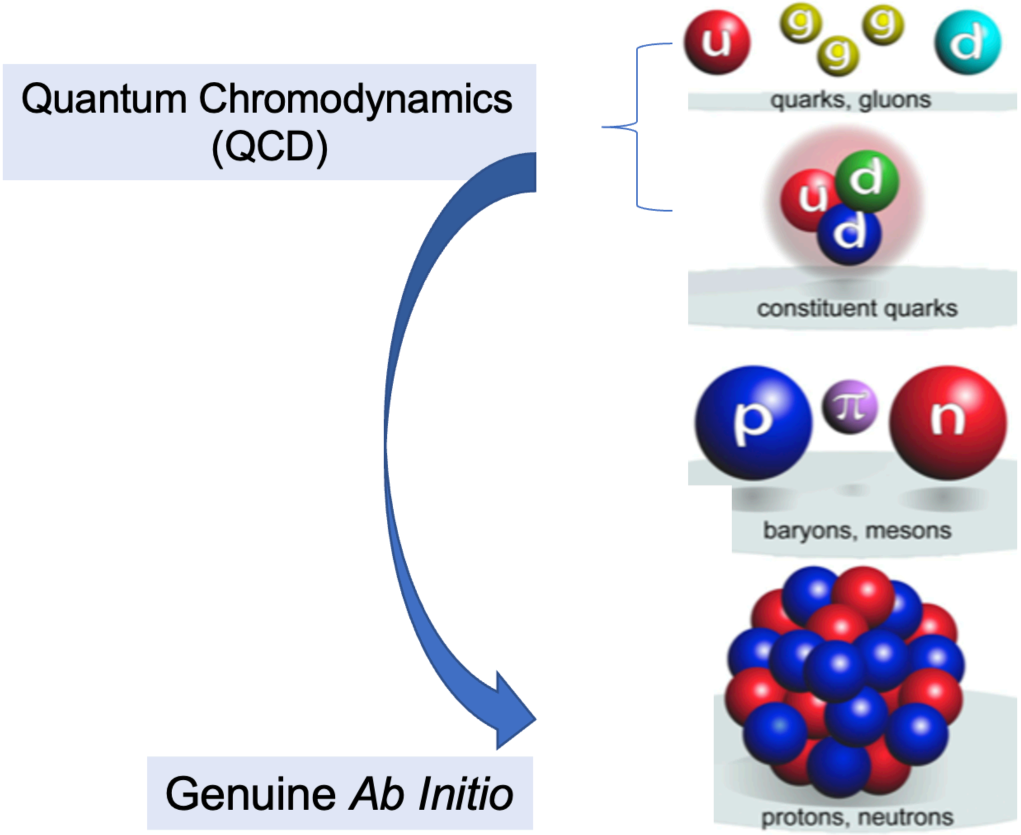

Figure courtesy of P. Navrátil

AB INITIO NUCLEAR THEORY

Current ab initio

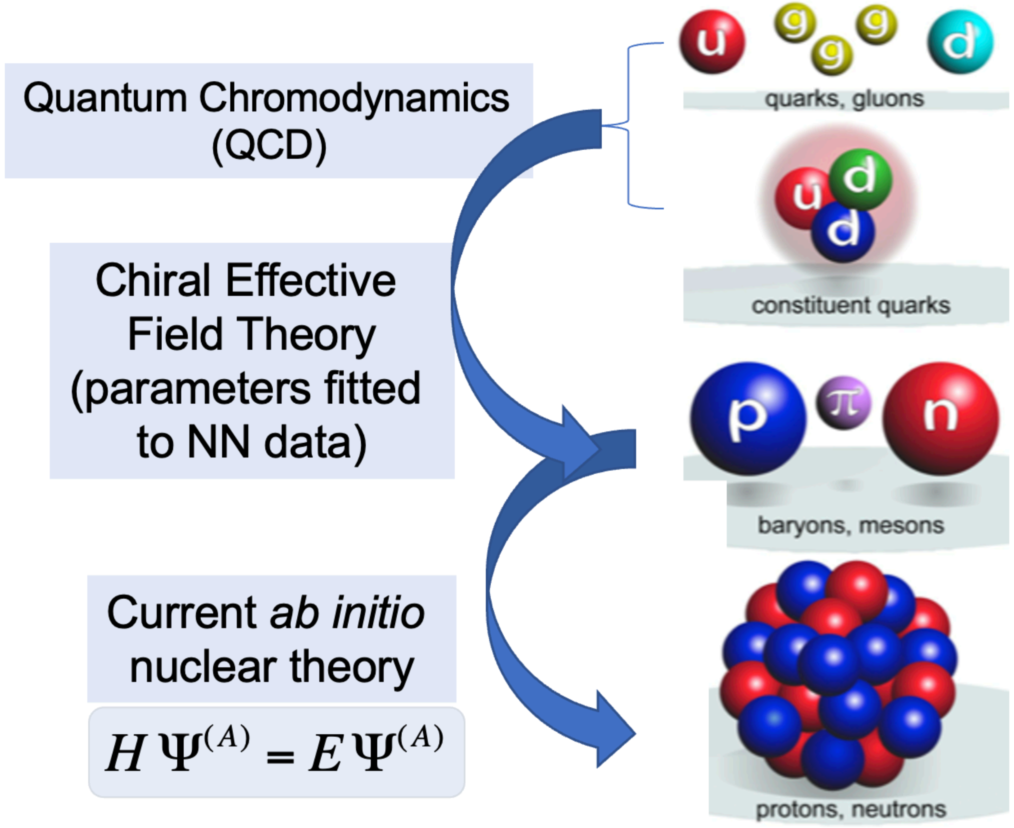

Figure courtesy of P. Navrátil

AB INITIO NUCLEAR THEORY

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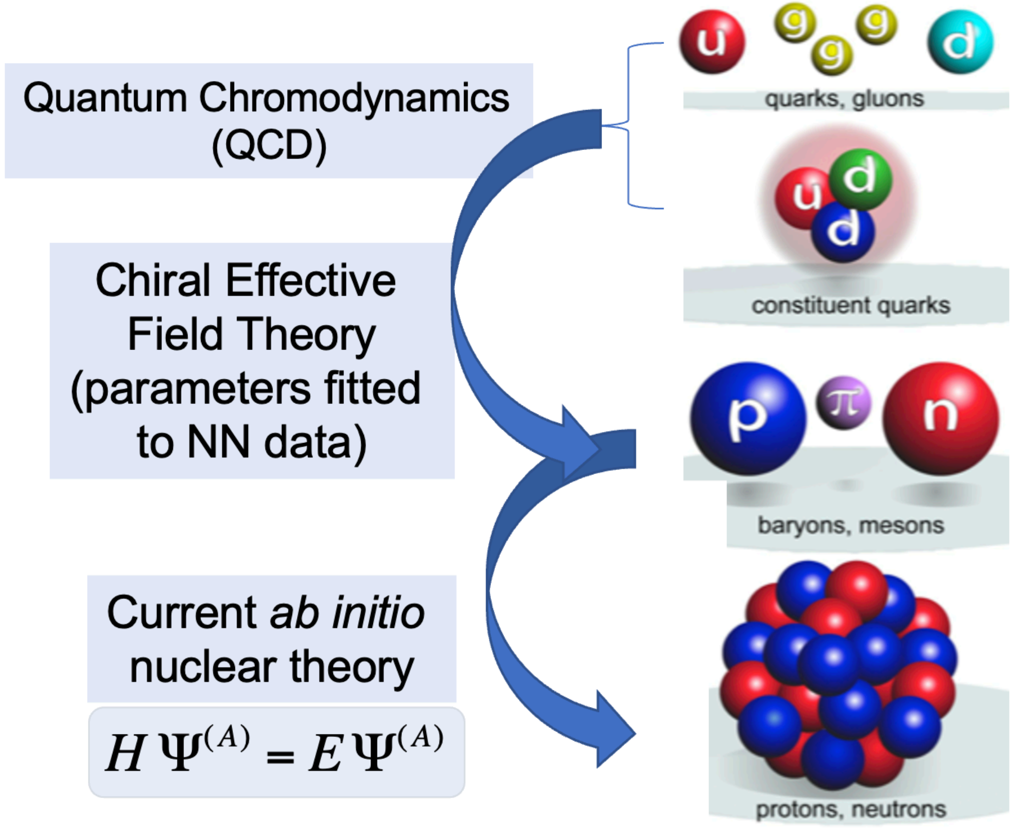
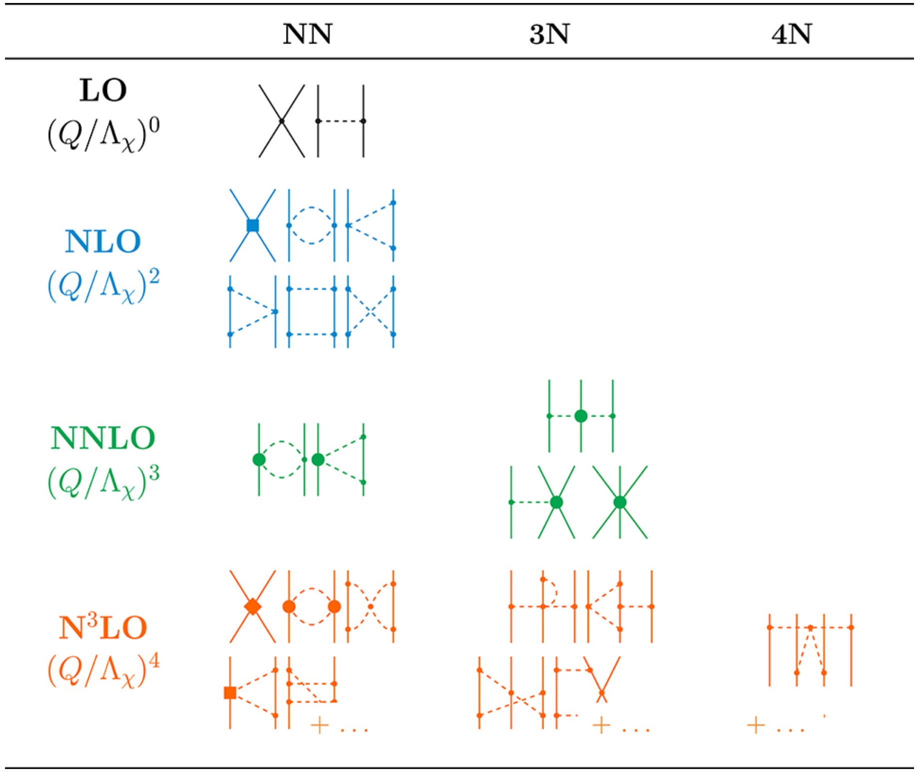


Figure courtesy of P. Navrátil

Chiral expansion of nuclear forces



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

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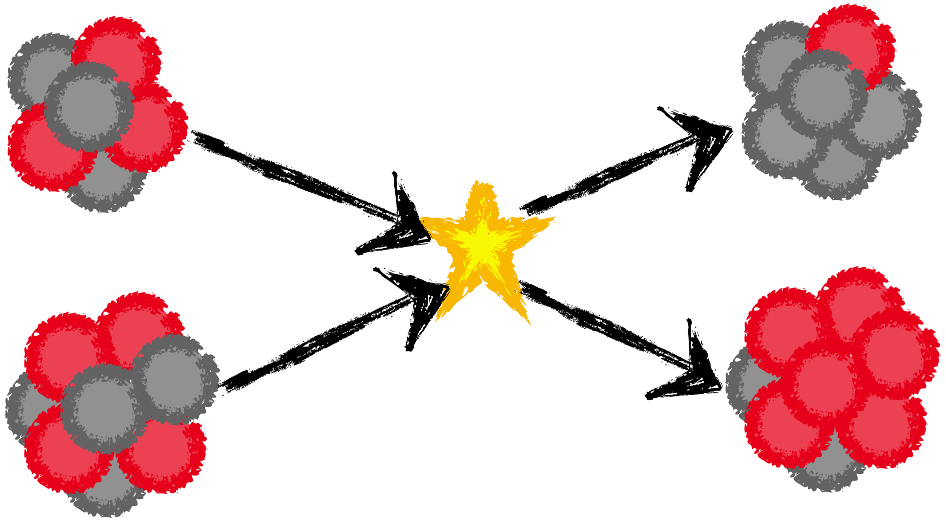
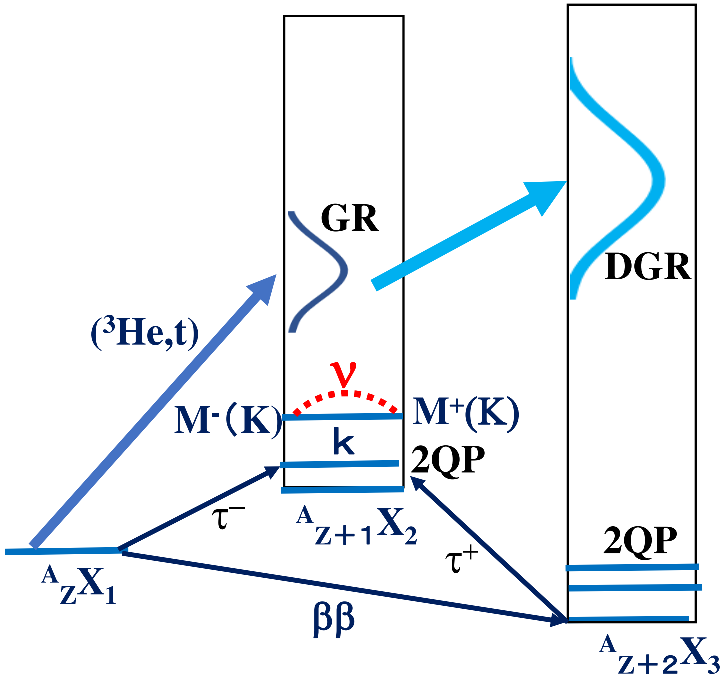


DOUBLE CHARGE EXCHANGE REACTIONS

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



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

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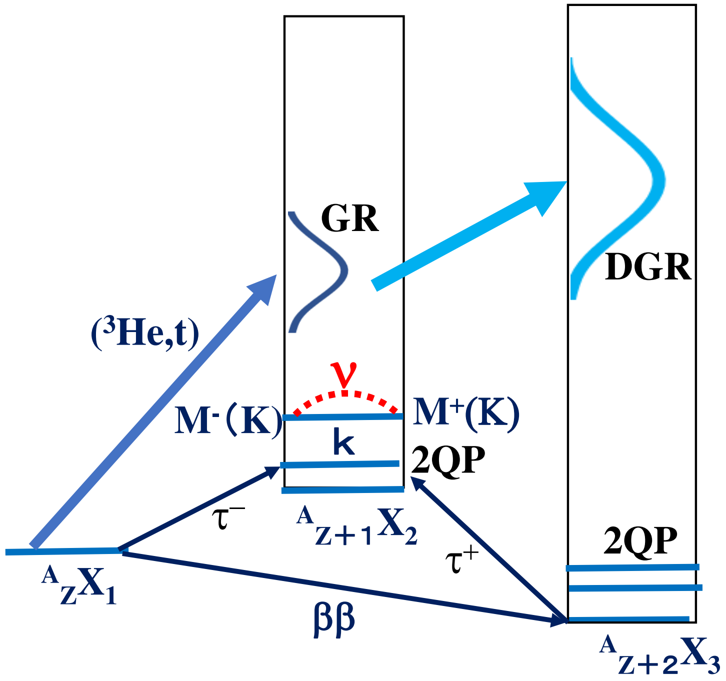
Leading component

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



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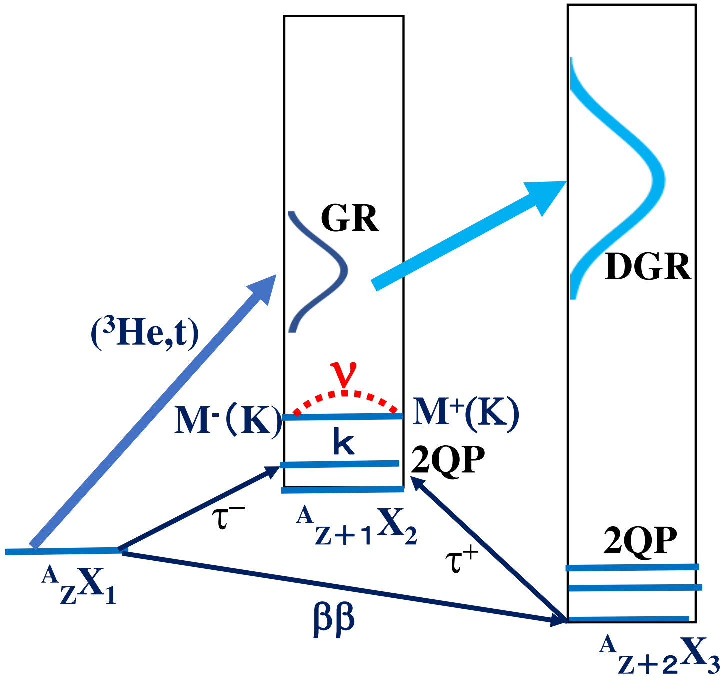
- Double-Gamow-Teller (DGT) strength function

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



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

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DOUBLE CHARGE EXCHANGE REACTIONS

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

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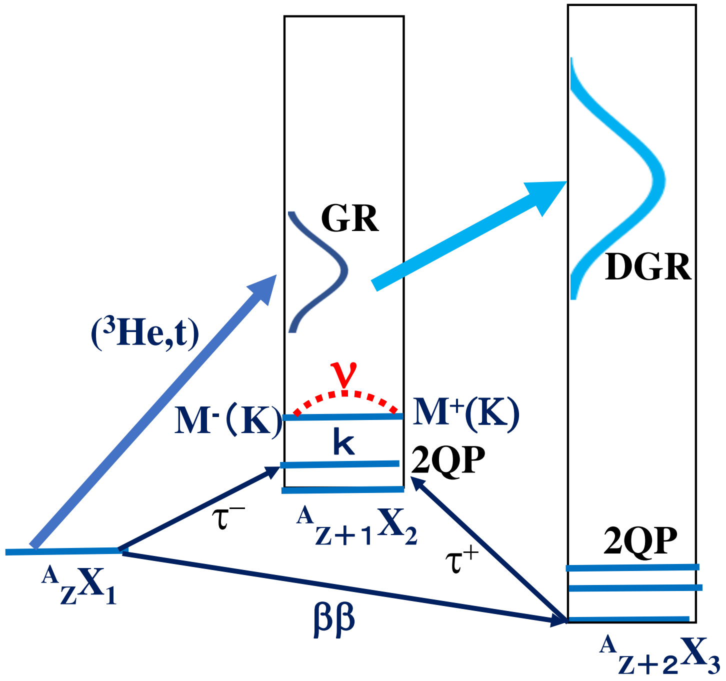
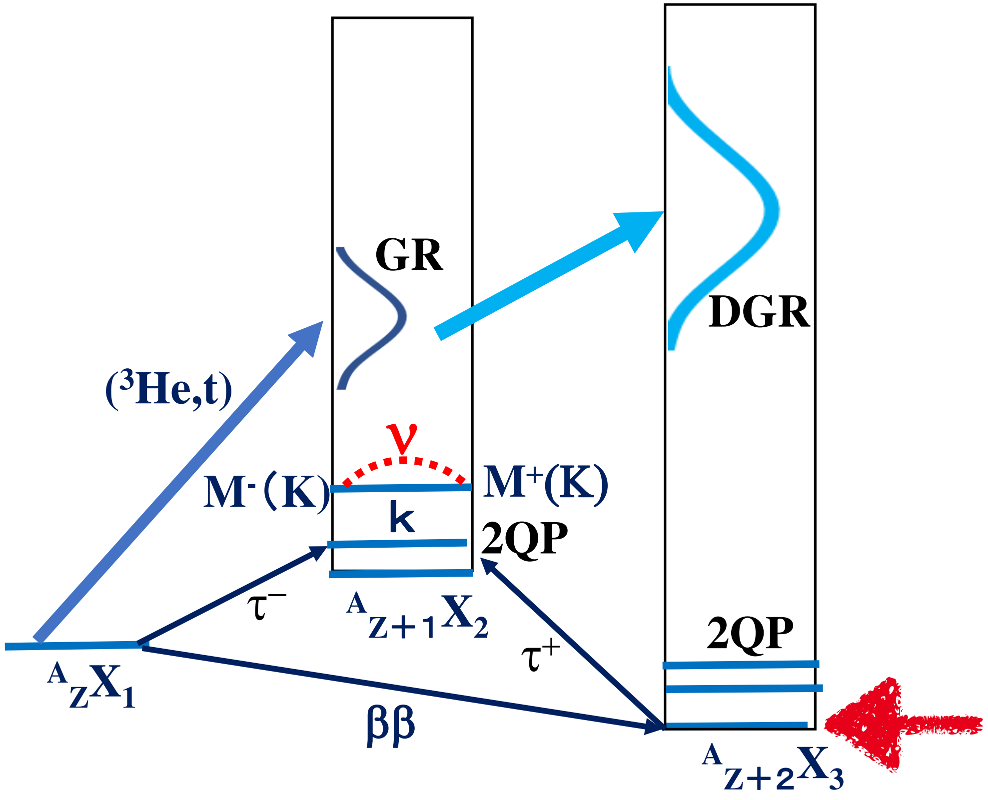
  - **Very similar operator structures**



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

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

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



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

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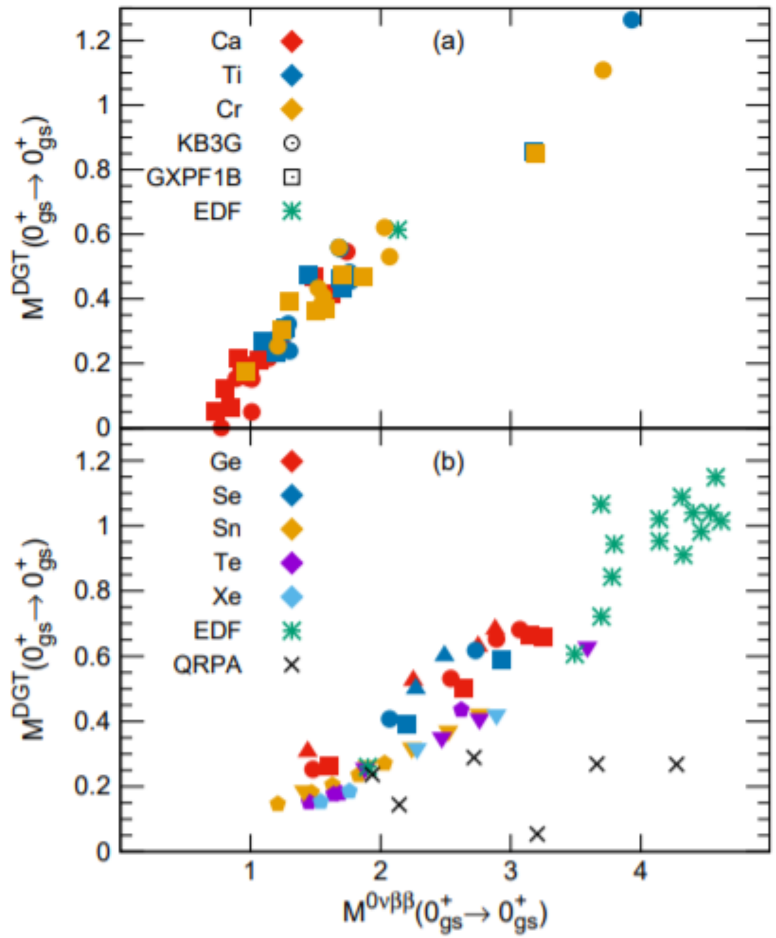
$$M_{\mathrm{DGT}} = -\langle f\,||\,[\sum_{jk} \boldsymbol{\sigma}_j\, \tau_j^- \times \boldsymbol{\sigma}_k\, \tau_k^-]^{(0)}\,||\,i\rangle$$

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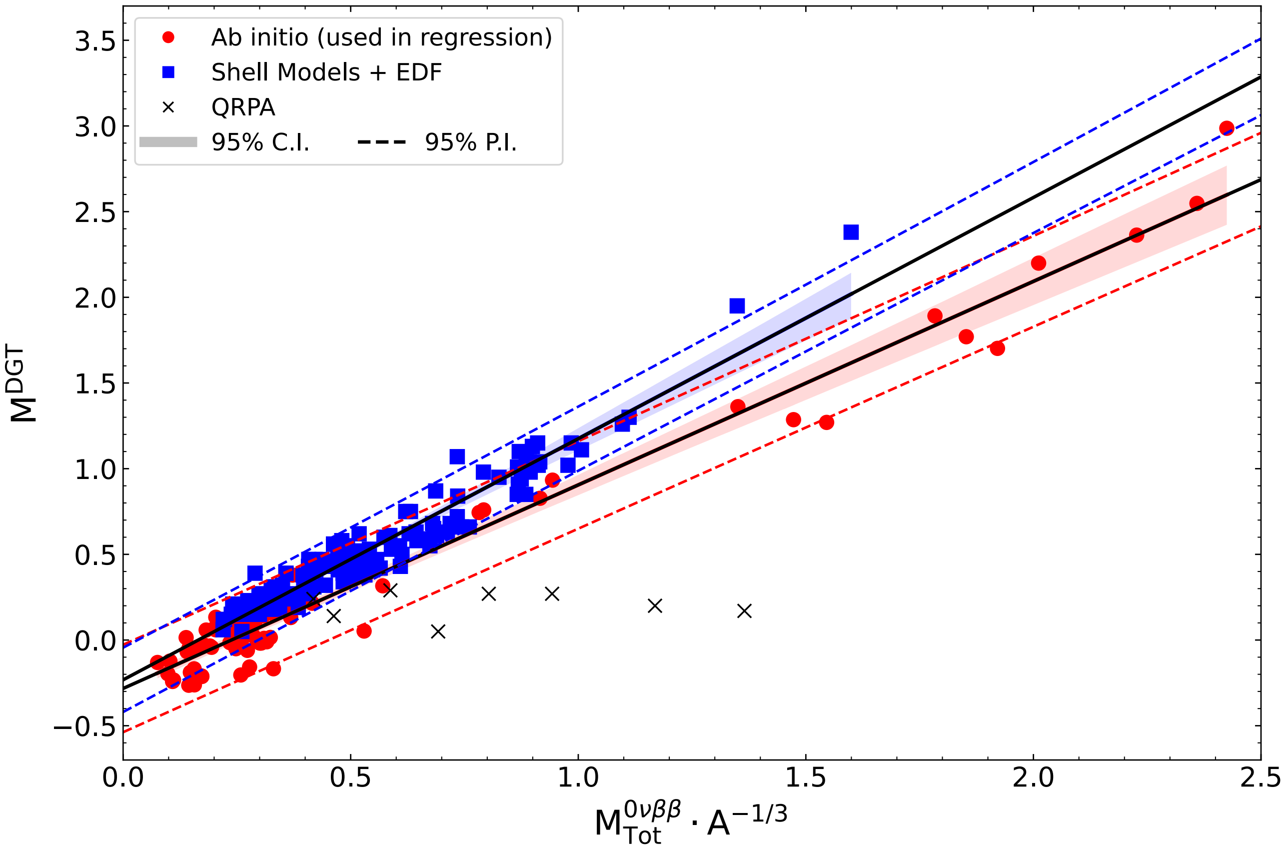
$$M_{\rm DGT} = -\langle f\,||\,[\sum_{jk} \boldsymbol{\sigma}_j\, \tau_j^- \times \boldsymbol{\sigma}_k\, \tau_k^-]^{(0)}\,||\,i\rangle$$

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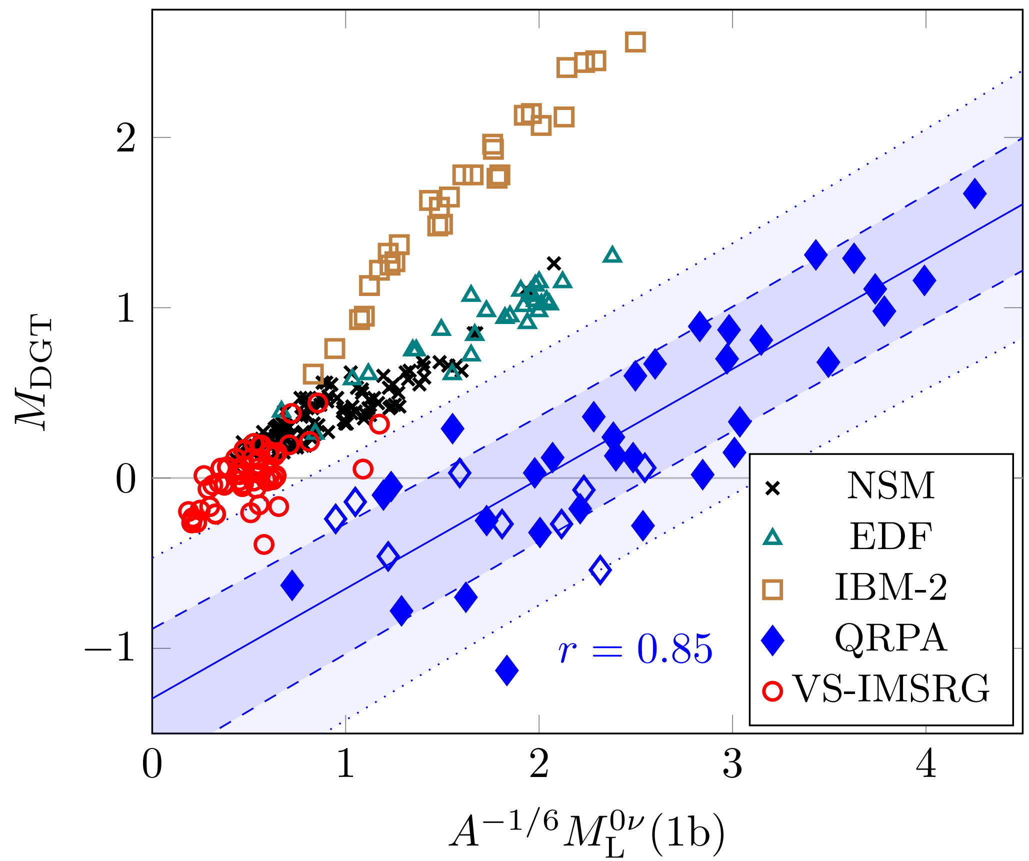
- Correlation between $M_{\rm L}^{0\nu}$ and $M_{\rm DGT}$ first found in nuclear **shell model** and **density functional theory**
- Correlation also holds in ***ab initio* VS-IMSRG**
- … and **QRPA**, when proton-neutron pairing is varied



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

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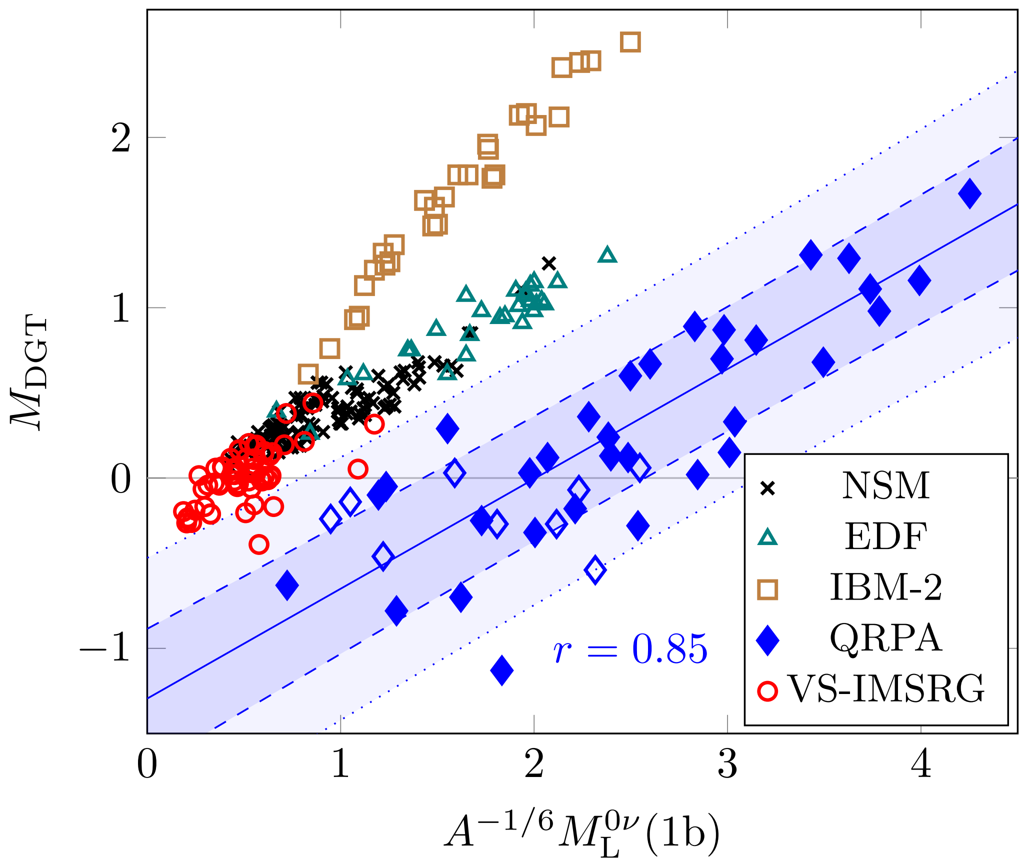
CORRELATIONS BETWEEN DGT AND $0\nu\beta\beta$ DECAY

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

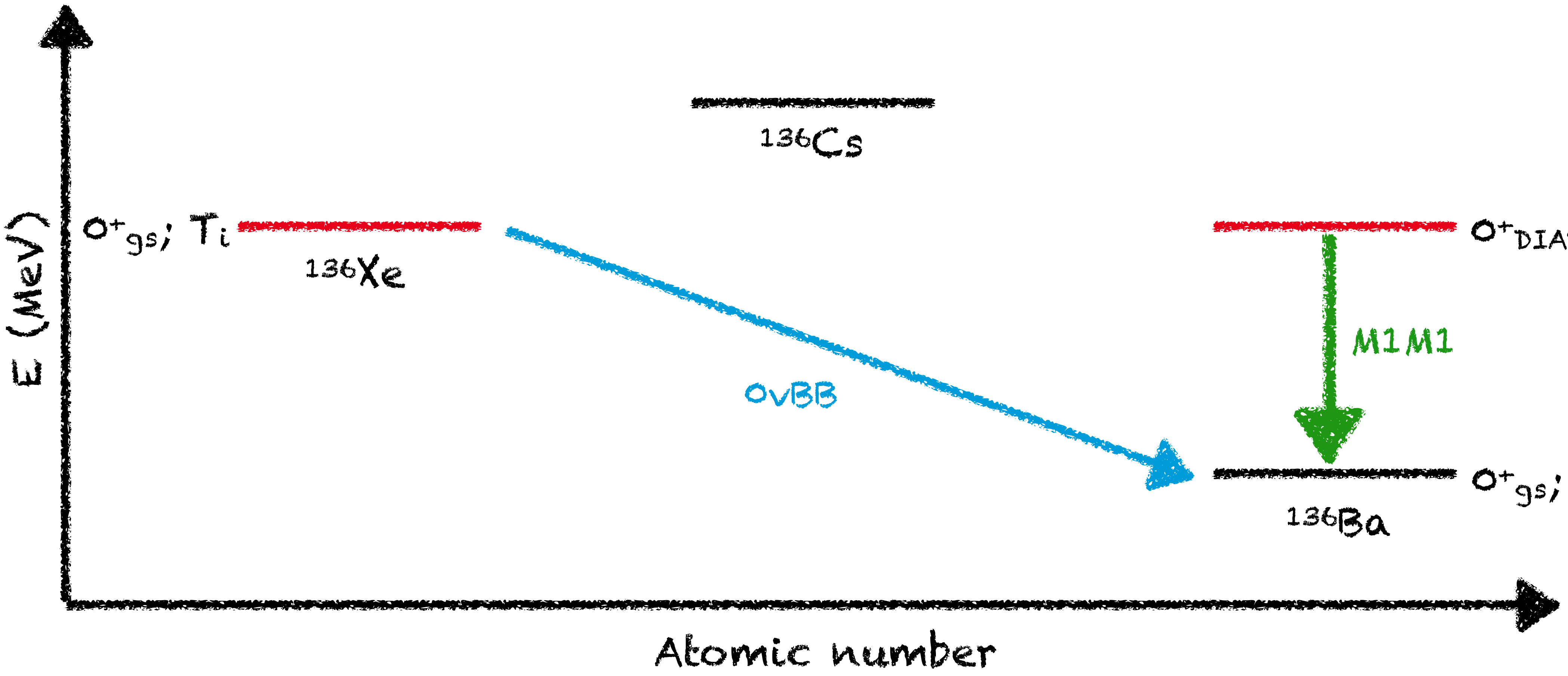
- Correlation between $M_{\mathrm{L}}^{0\nu}$ and M_{DGT} first found in nuclear **shell model** and **density functional theory**
- Correlation also holds in ***ab initio*** **VS-IMSRG**
- … and **QRPA**, when proton-neutron pairing is varied

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



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

PROBING $0\nu\beta\beta$ DECAYS BY $\gamma\gamma$ DECAYS



CORRELATIONS BETWEEN $0\nu\beta\beta$ DECAY AND DOUBLE-M1 TRANSITIONS

$$M^{\gamma\gamma}(\mathrm{M1M1}) = \sum_k \frac{\langle 0_f^+ || \mathbf{M1} || 1_k^+ \rangle \langle 1_k^+ || \mathbf{M1} || 0_i^+ \rangle}{E_k - (E_i + E_f)/2} ,$$

$$\mathbf{M1} = \mu_N \sqrt{\frac{3}{4\pi}} \sum_{a=1}^{A} (g_i^l \boldsymbol{\ell}_i + g_i^s \mathbf{s}_i)$$

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$$\mathbf{M1} = \mu_N \sqrt{\frac{3}{4\pi}} \sum_{a=1}^{A} (g_i^l \boldsymbol{\ell}_i + g_i^s \mathbf{s}_i)$$

- **Double-M1 decay of the double-isobaric analog state** can be related to the $0\nu\beta\beta$ decay

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CORRELATIONS BETWEEN $0\nu\beta\beta$ DECAY AND DOUBLE-M1 TRANSITIONS

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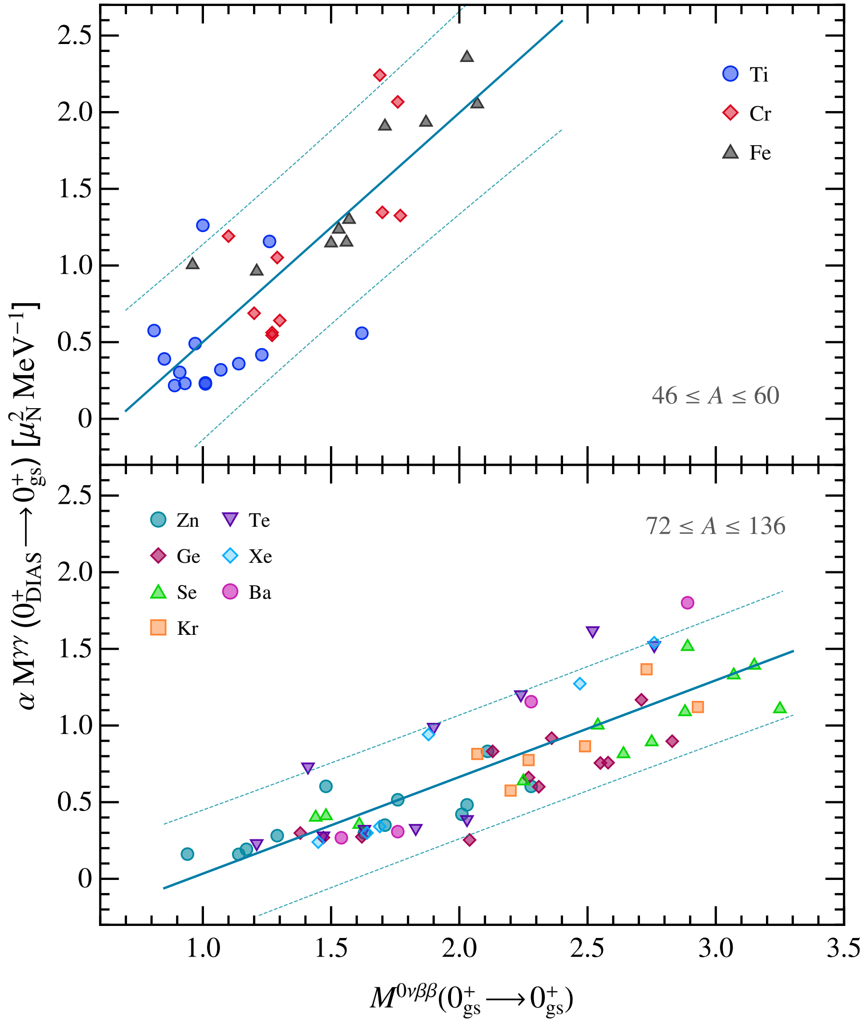
- **Double-M1 decay of the double-isobaric analog state** can be related to the $0\nu\beta\beta$ decay
- Correlations between corresponding nuclear matrix elements found in the **nuclear shell model**



B. Romeo, J. Menéndez, C. Peña, Phys. Lett. B 827, 136965 (2022)

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CORRELATIONS BETWEEN $0\nu\beta\beta$ DECAY AND DOUBLE-M1 TRANSITIONS

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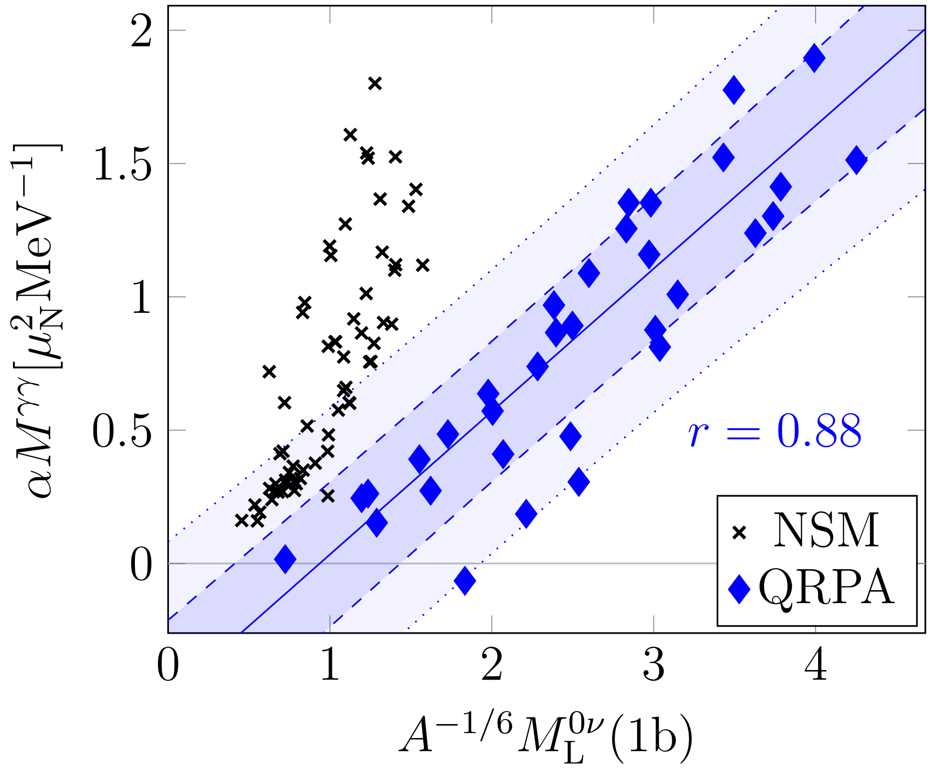
- **Double-M1 decay of the double-isobaric analog state** can be related to the $0\nu\beta\beta$ decay
- Correlations between corresponding nuclear matrix elements found in the **nuclear shell model**
- Correlation also found in the **pnQRPA**



LJ, J. Menéndez, Phys. Rev. C 107, 044316 (2023)

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

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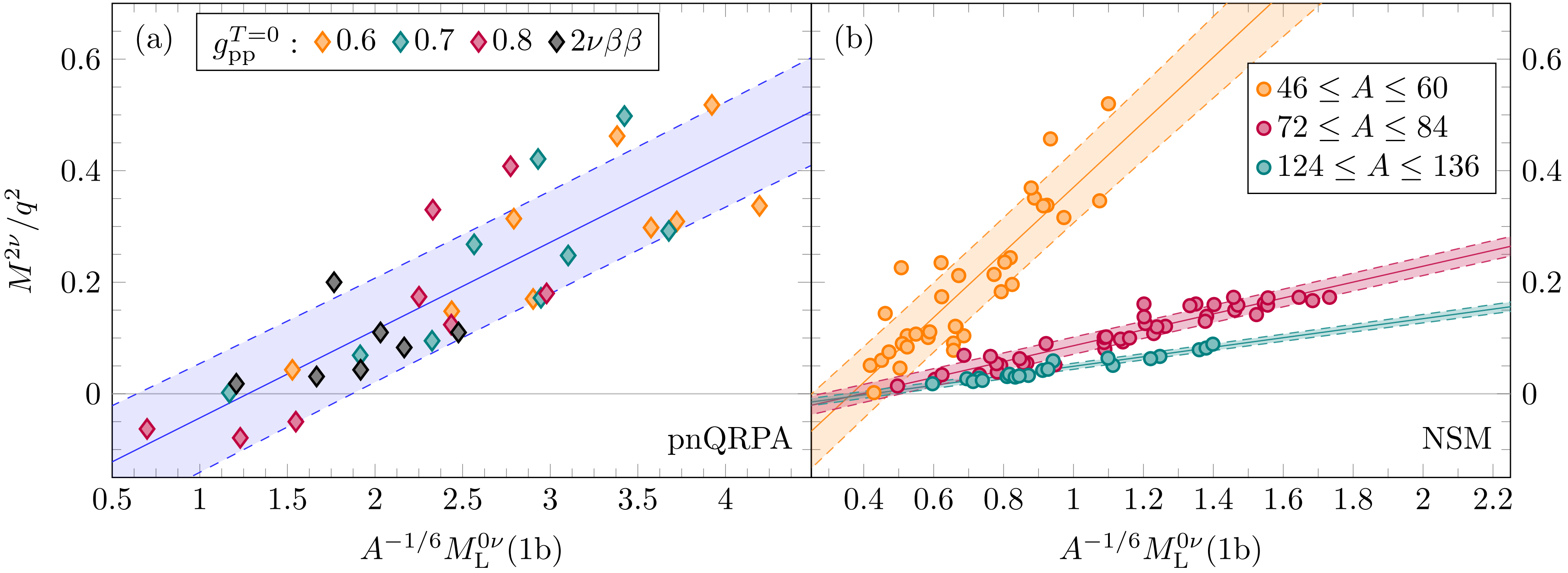
PROBING $0\nu\beta\beta$ DECAY BY $2\nu\beta\beta$ DECAY

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



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

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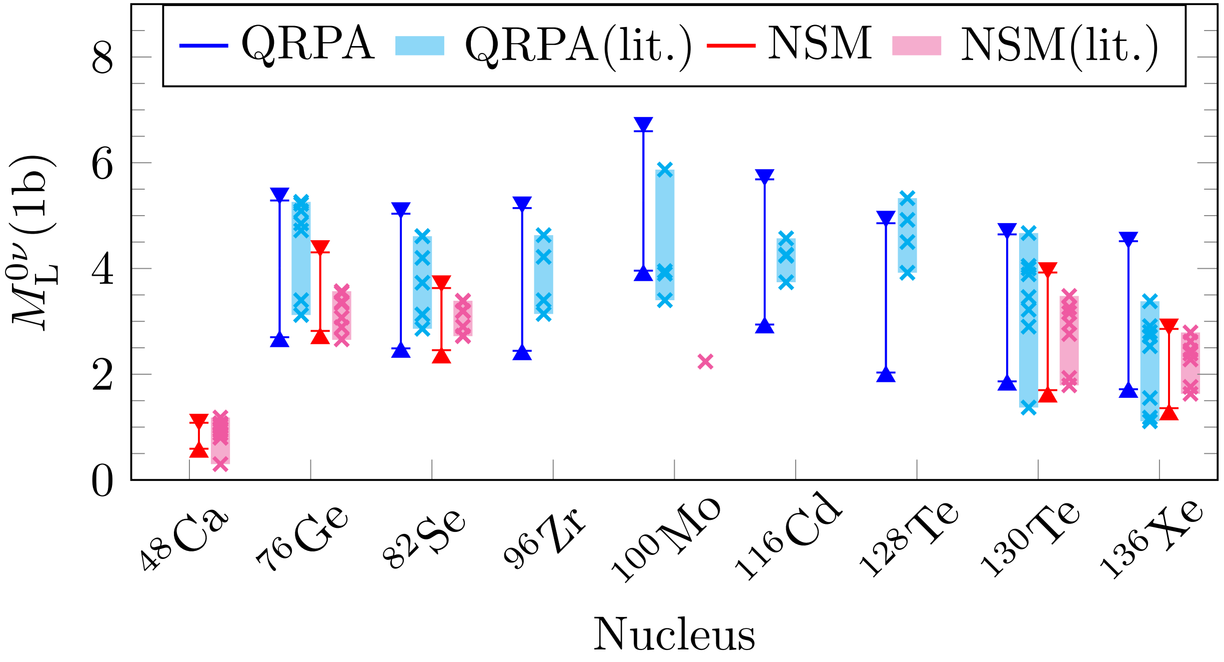
PROBING $0\nu\beta\beta$ DECAY BY $2\nu\beta\beta$ DECAY

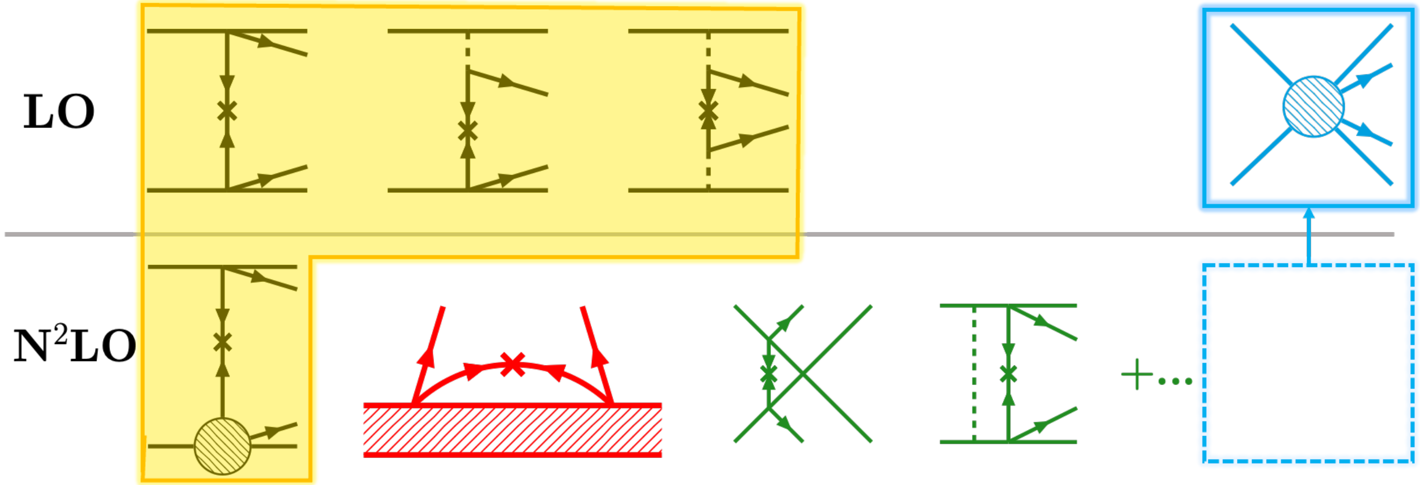
- **$2\nu\beta\beta$ decay** also **correlated** with **$0\nu\beta\beta$ decay**
- We can use existing data to estimate **$0\nu\beta\beta$-decay NMEs with uncertainties**



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

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

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



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

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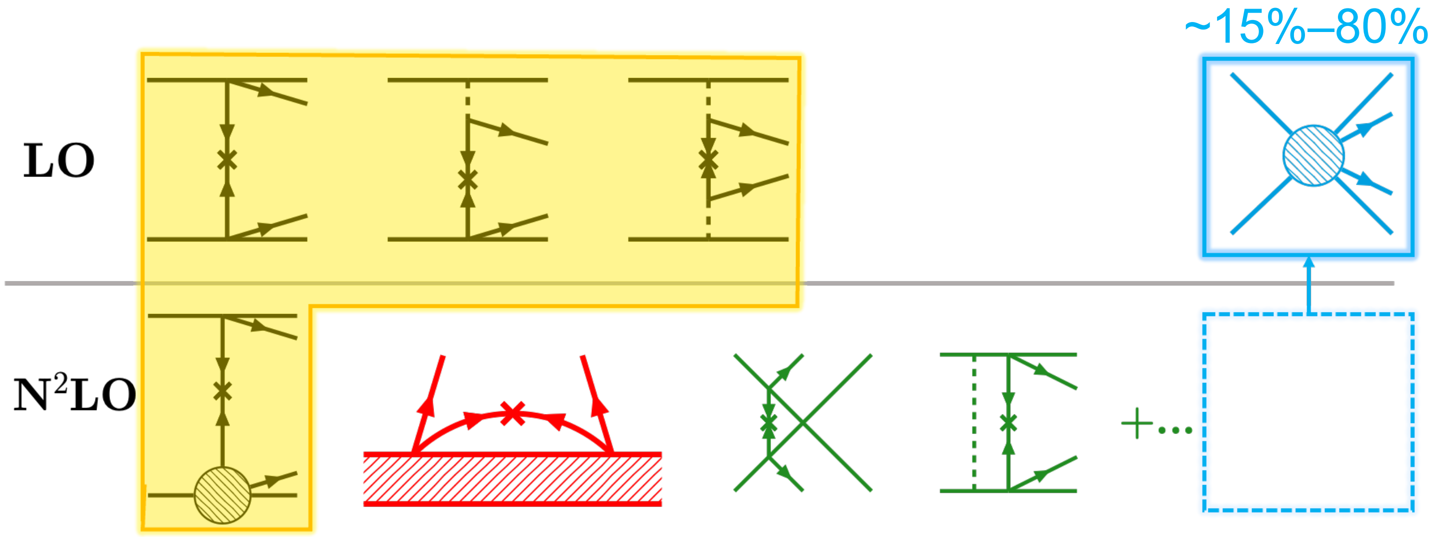
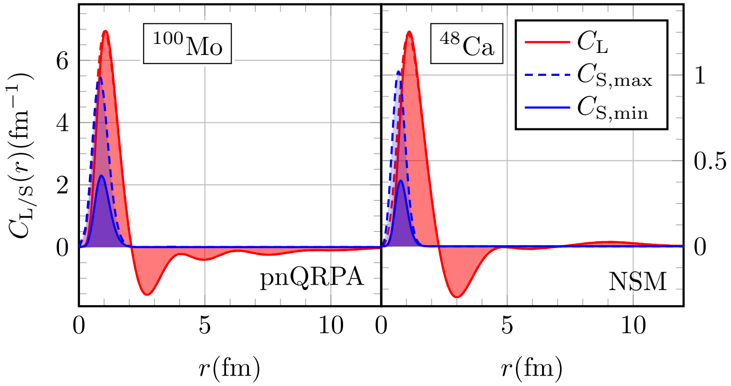
CHIRAL EFFECTIVE THEORY FOR $0\nu\beta\beta$ DECAY

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





LJ, P. Soriano, J. Menéndez, Phys. Lett. B 823, 136720 (2021)

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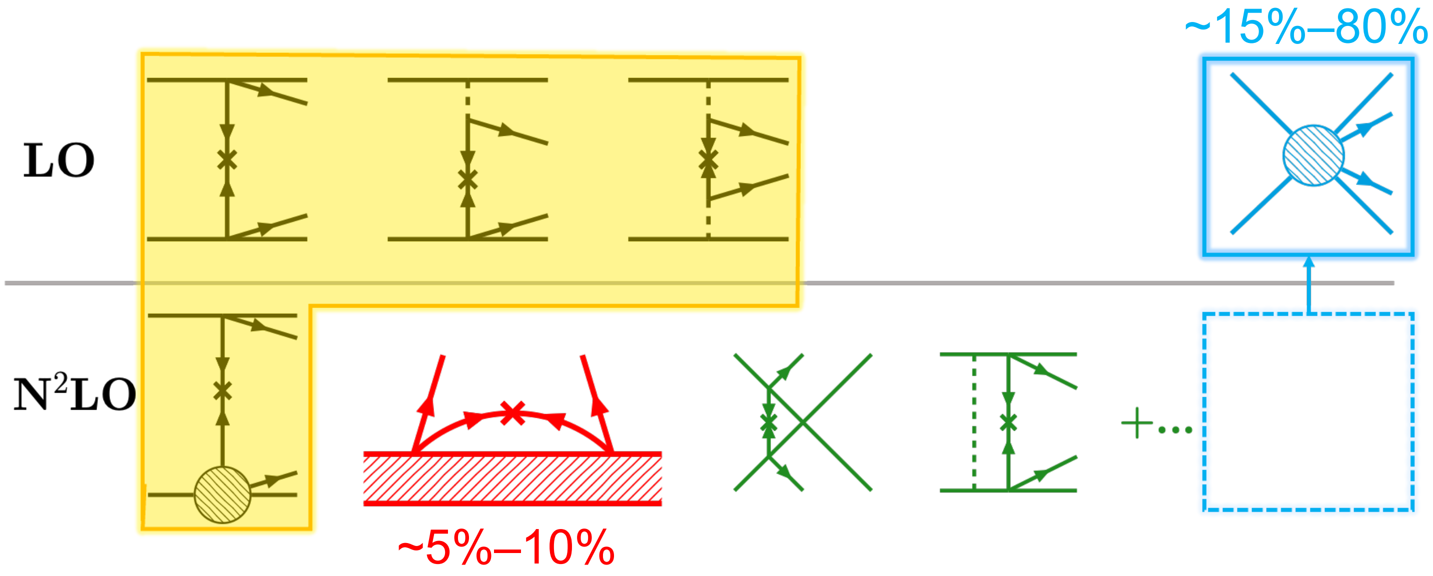
CHIRAL EFFECTIVE THEORY FOR $0\nu\beta\beta$ DECAY

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



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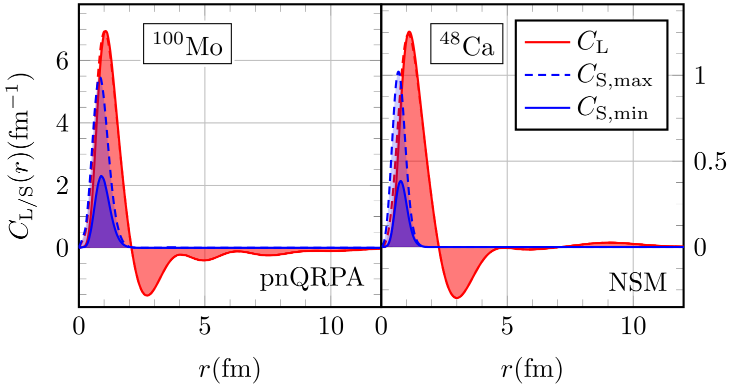

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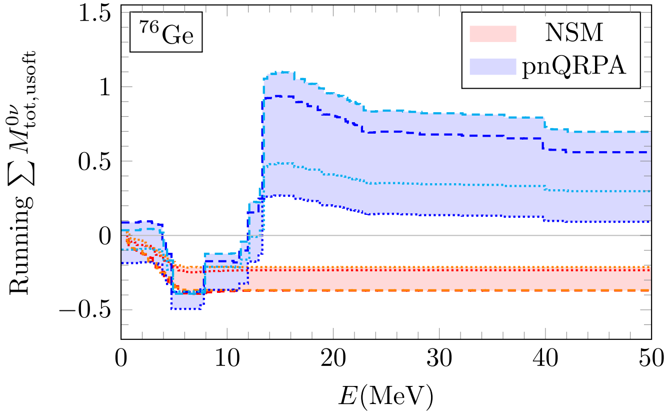

D. Castillo, LJ, J. Menéndez, Phys. Lett. B 860, 139181 (2025)

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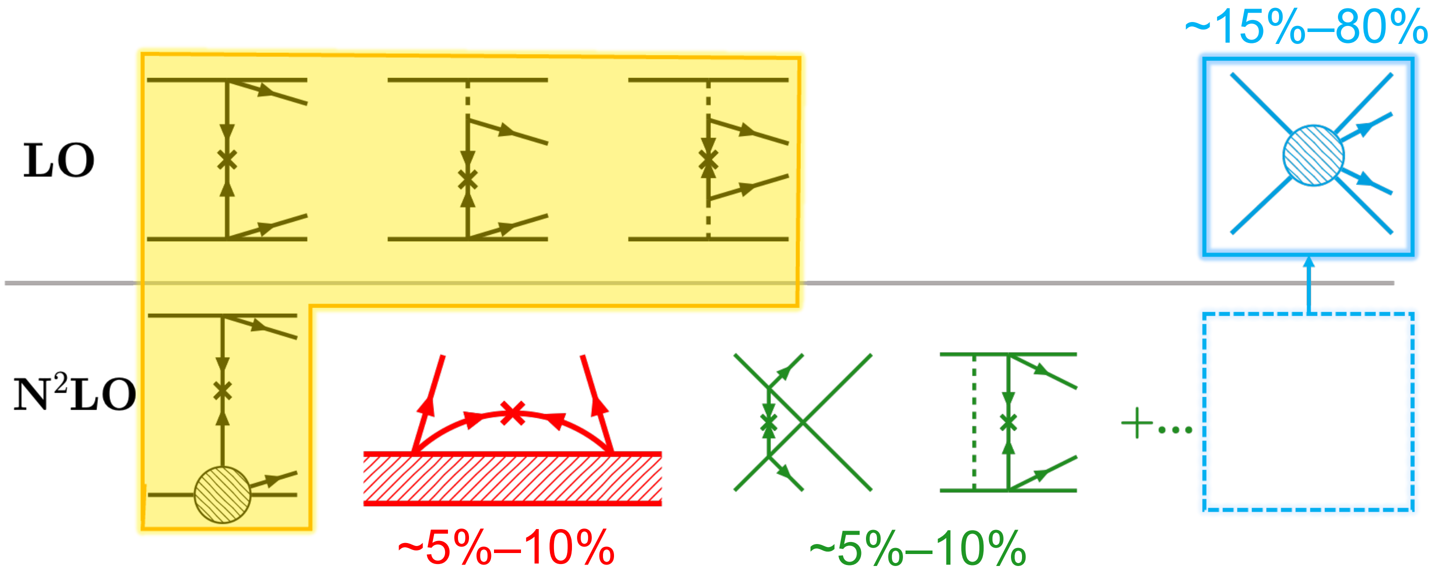
CHIRAL EFFECTIVE THEORY FOR $0\nu\beta\beta$ DECAY

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



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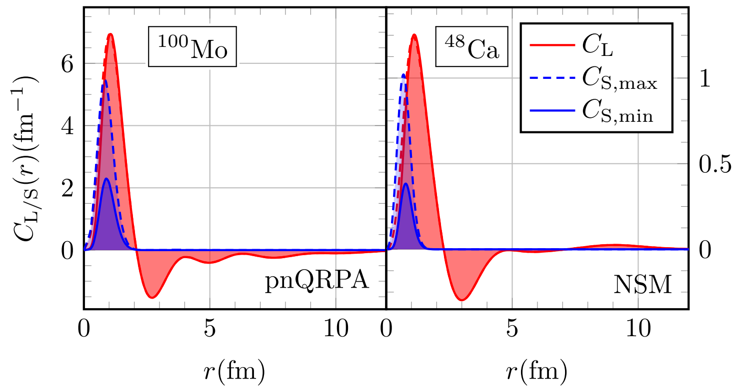

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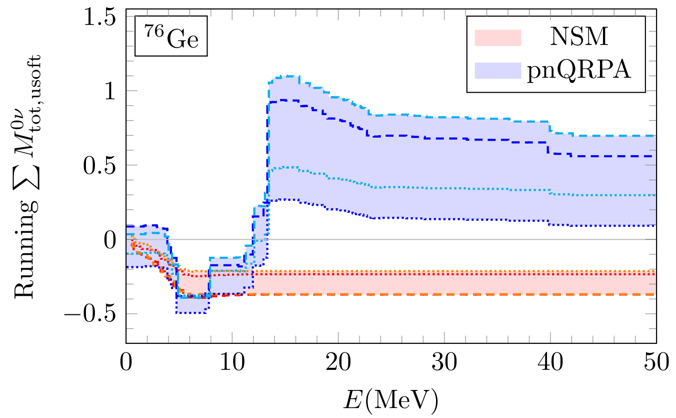

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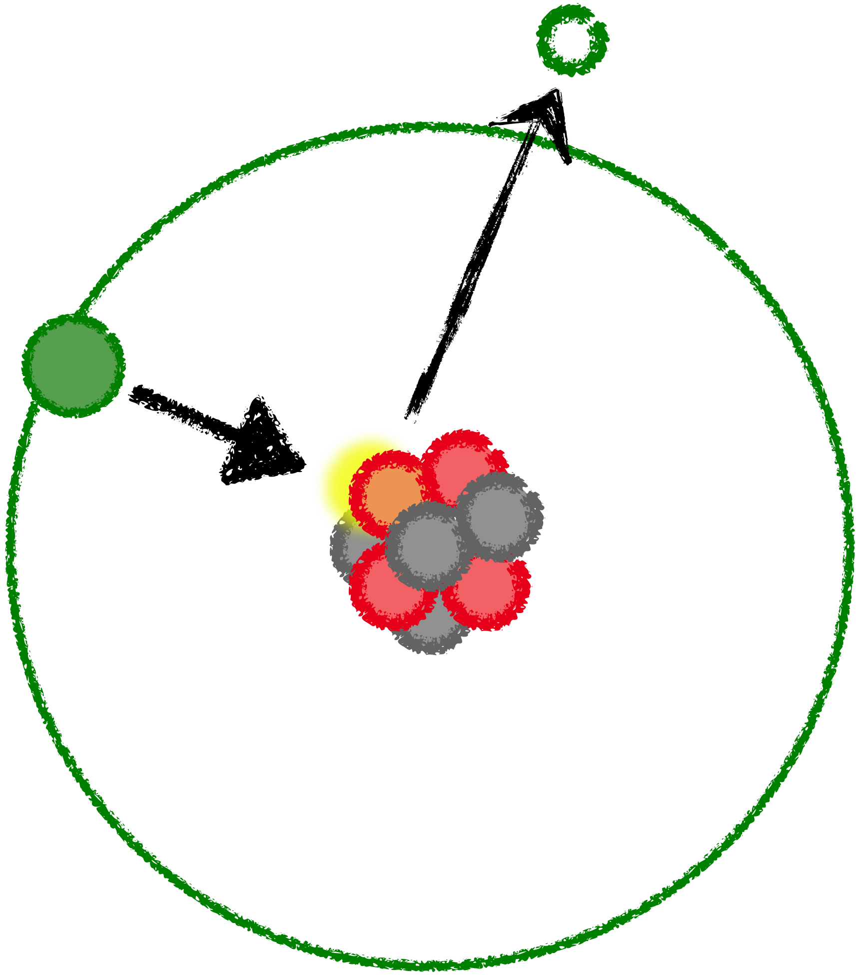
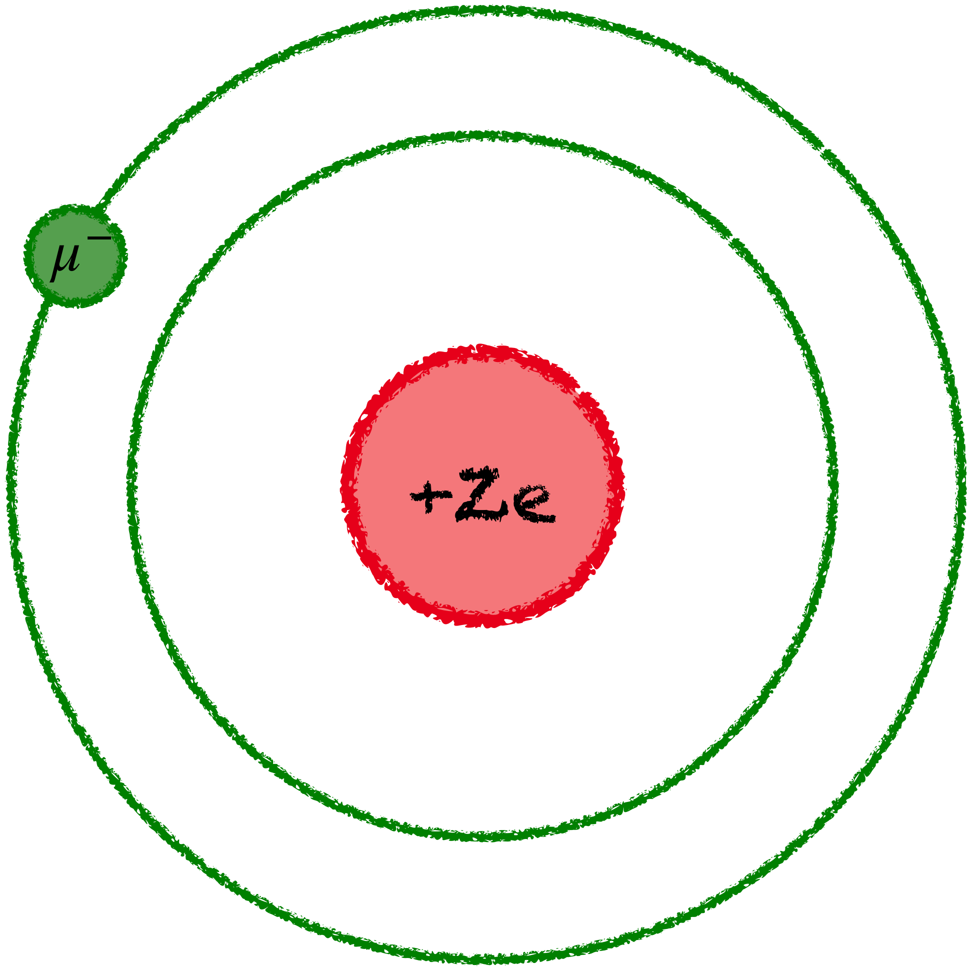
OUTLINE

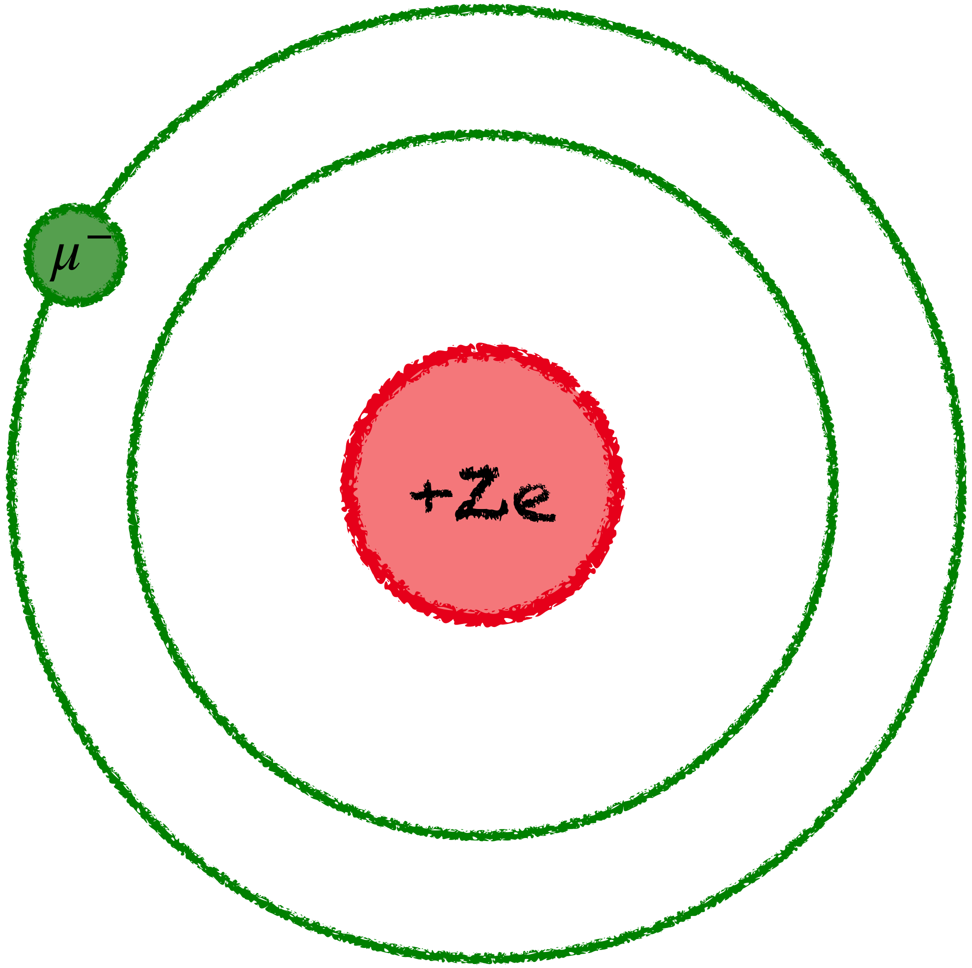


ORDINARY MUON CAPTURE



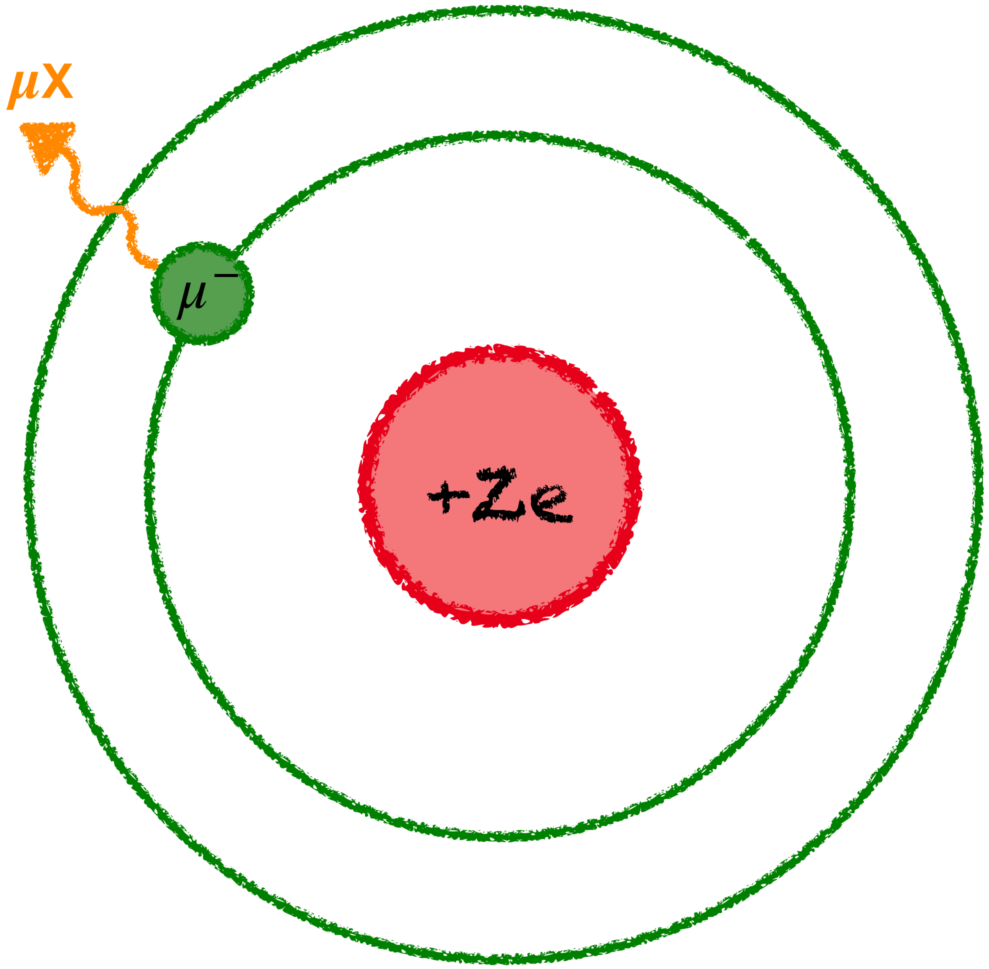
ORDINARY MUON CAPTURE

- Starting point: **a muonic atom**



ORDINARY MUON CAPTURE

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



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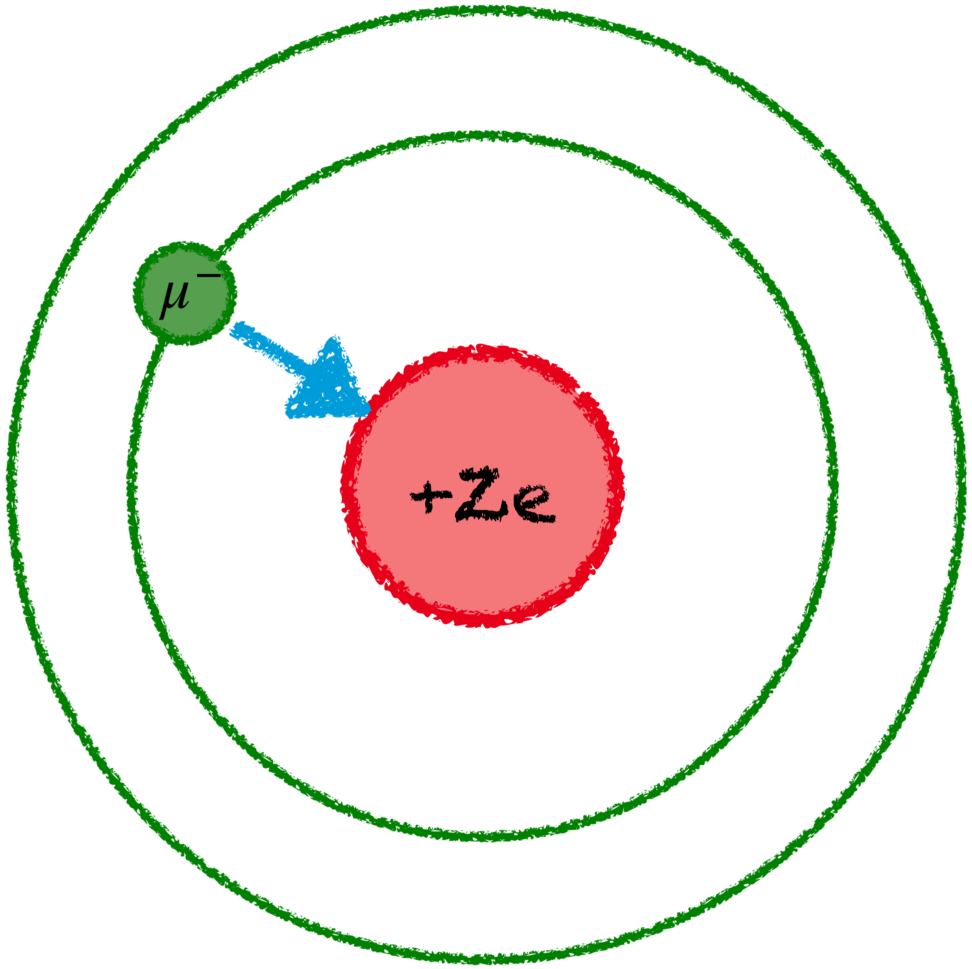

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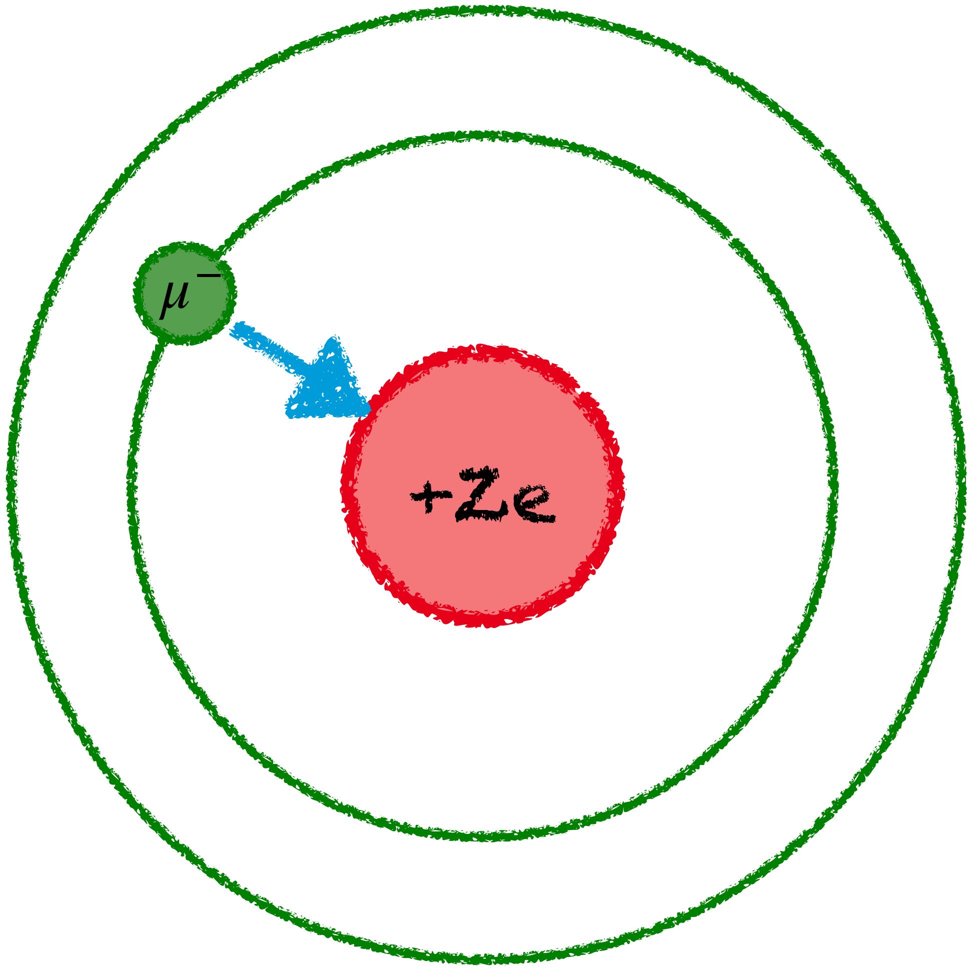
$$\mu^- + {}^{A}_{Z}\mathrm{X}(J_f^{\pi_f}) \rightarrow \nu_\mu + {}^{A}_{Z-1}\mathrm{Y}(J_i^{\pi_i})$$



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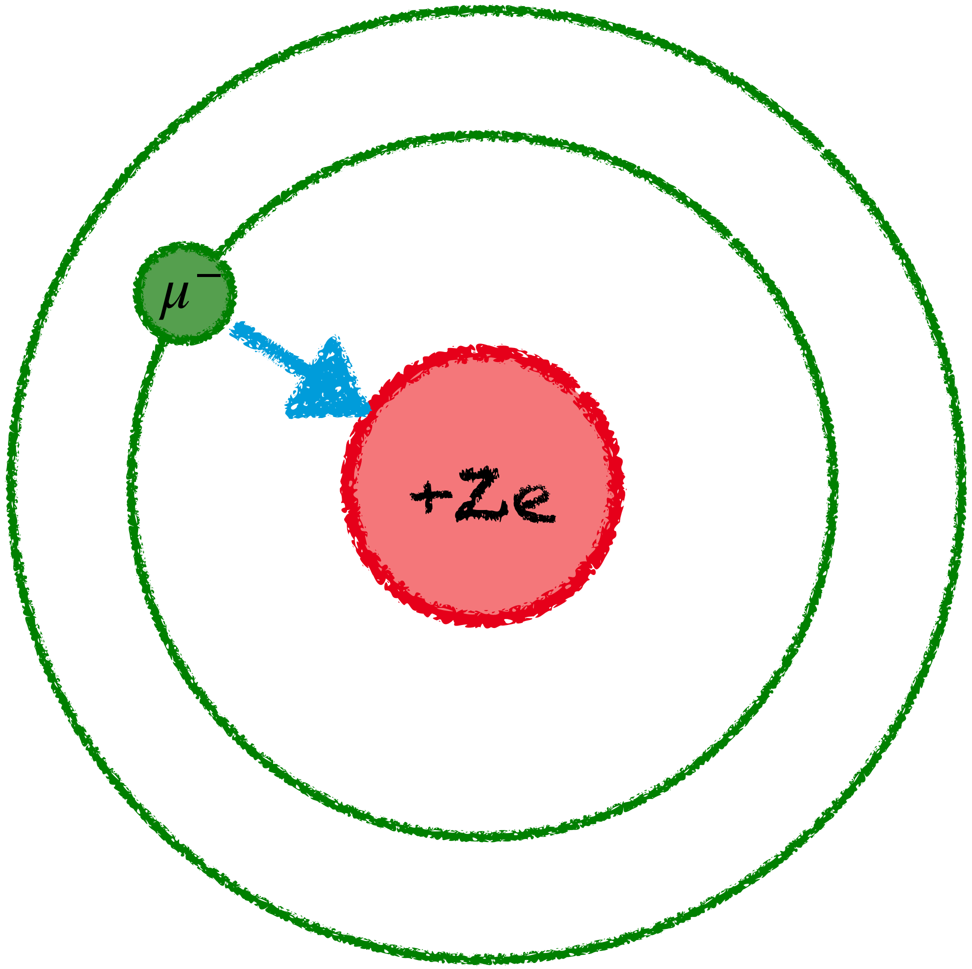
    $$\mu^- + {}^{A}_{Z}\mathrm{X}(J_f^{\pi_f}) \rightarrow \nu_\mu + {}^{A}_{Z-1}\mathrm{Y}(J_i^{\pi_i}) + \gamma$$



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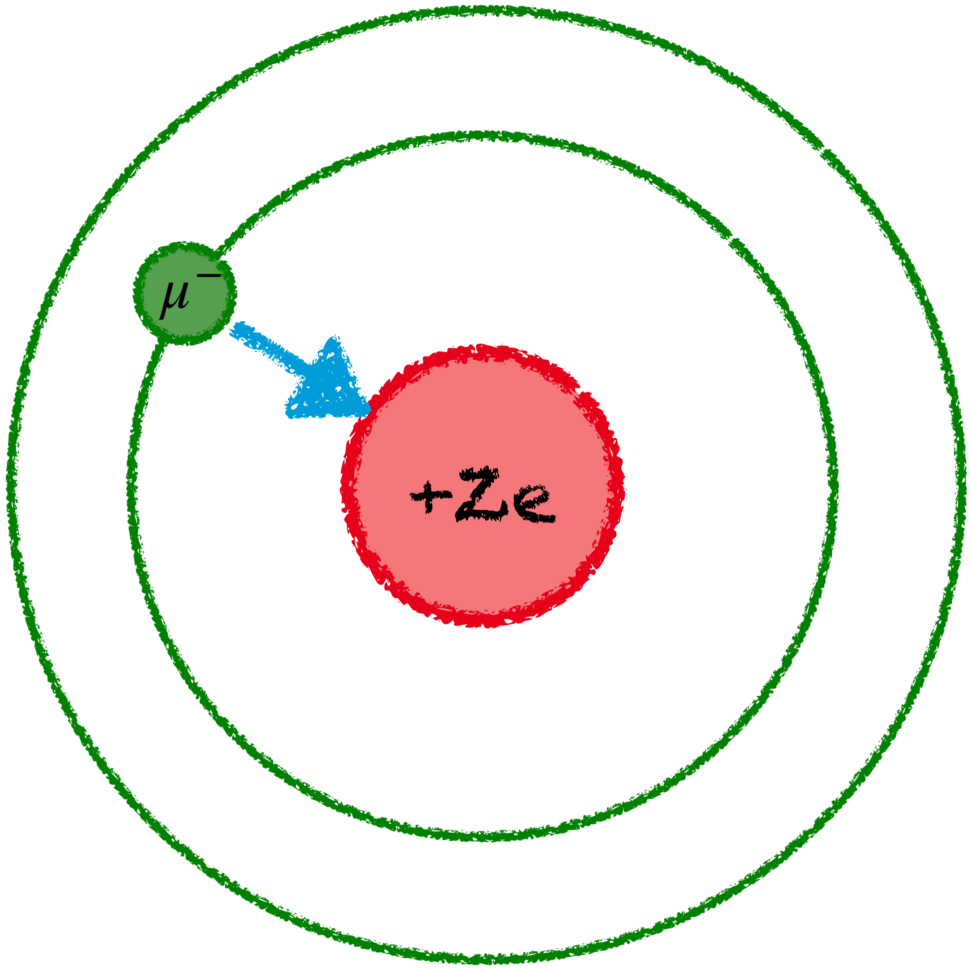

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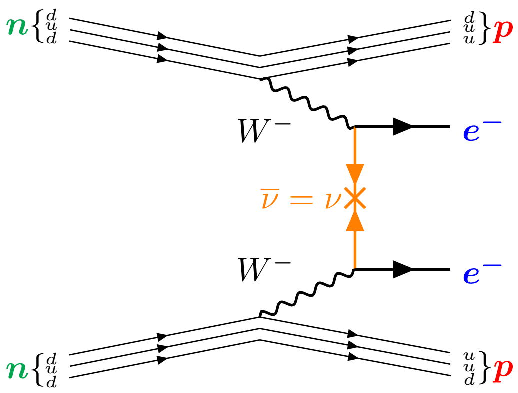
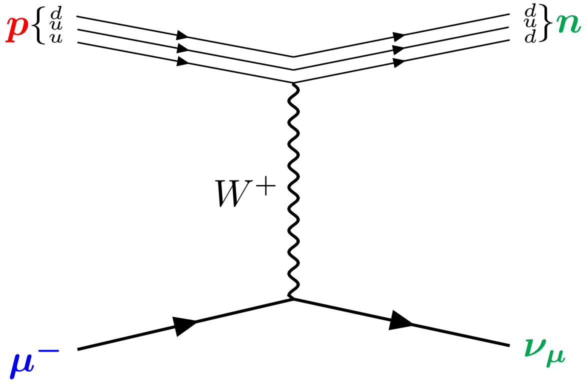
$0\nu\beta\beta$ DECAY VS. ORDINARY MUON CAPTURE

$0\nu\beta\beta$ Decay



Ordinary Muon Capture



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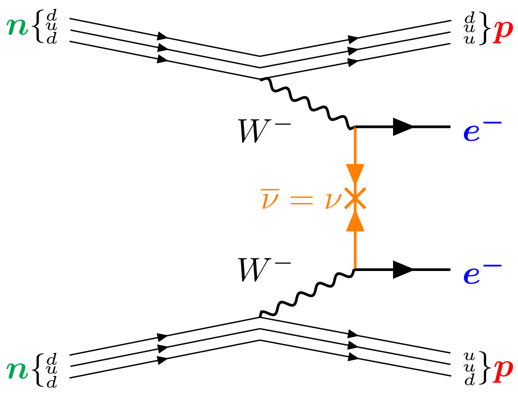

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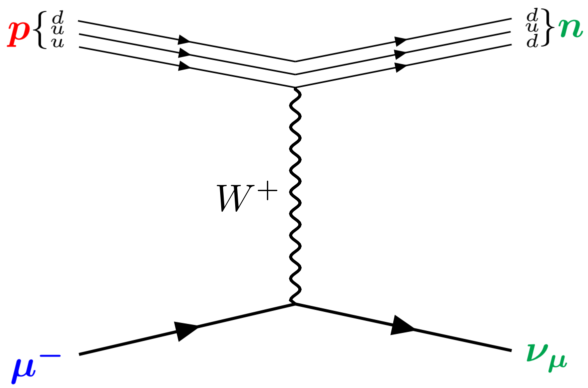
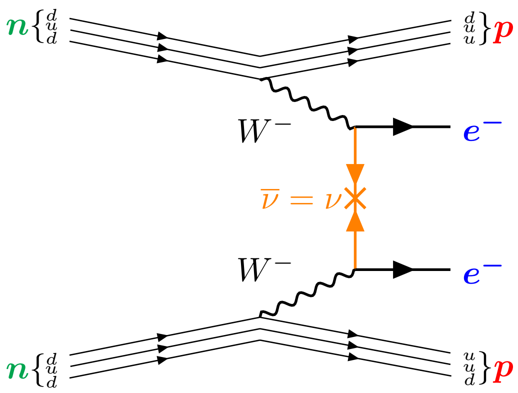


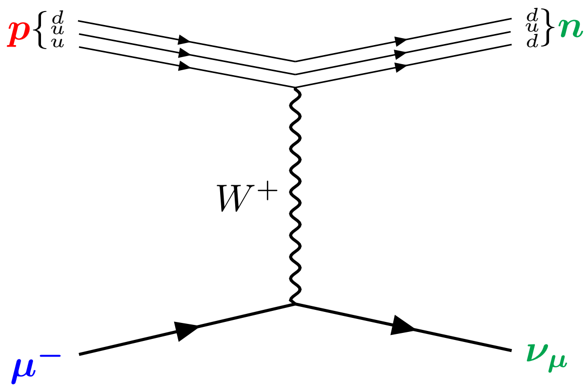
- $q \approx 1/|\mathbf{r}_1 - \mathbf{r}_2| \approx 100 - 200$ MeV

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

$0\nu\beta\beta$ **Decay**



Ordinary Muon Capture



- $q \approx 1/|\mathbf{r}_1 - \mathbf{r}_2| \approx 100 - 200$ MeV
- $q \approx m_\mu + E_i - E_f \approx 100$ MeV

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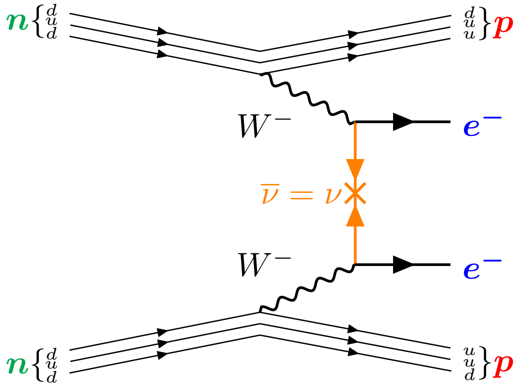
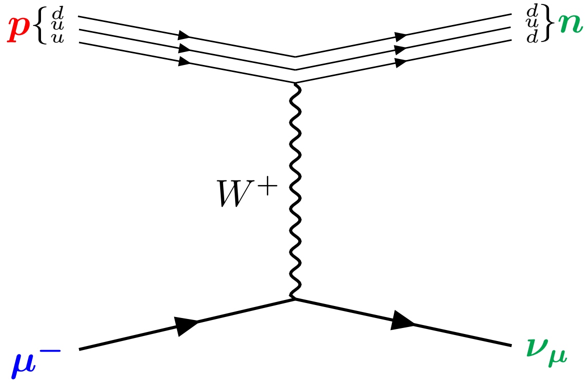
$0\nu\beta\beta$ DECAY VS. ORDINARY MUON CAPTURE

$0\nu\beta\beta$ Decay



Ordinary Muon Capture



- $q \approx 1/|\mathbf{r}_1 - \mathbf{r}_2| \approx 100 - 200$ MeV
- No experimental signal so far

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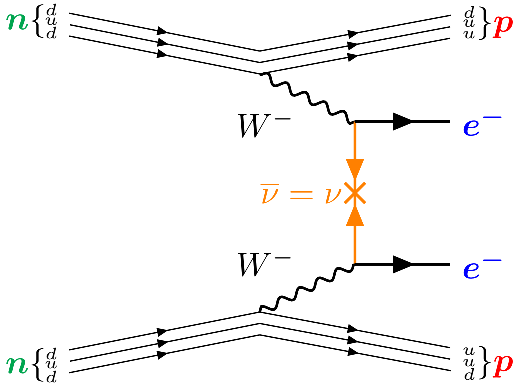
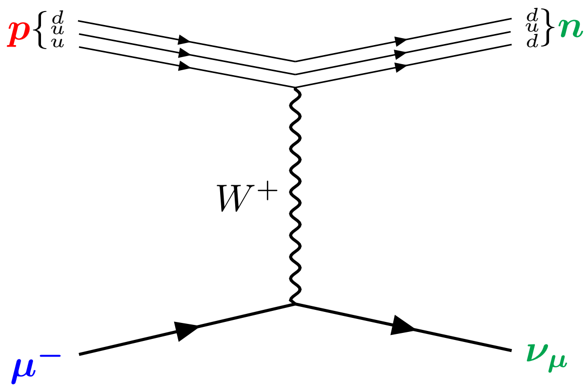
$0\nu\beta\beta$ DECAY VS. ORDINARY MUON CAPTURE

$0\nu\beta\beta$ **Decay**



Ordinary Muon Capture



- $q \approx 1/|\mathbf{r}_1 - \mathbf{r}_2| \approx 100 - 200 \text{ MeV}$
- **No experimental signal so far**

- $q \approx m_\mu + E_i - E_f \approx 100 \text{ MeV}$
- **Has been measured**

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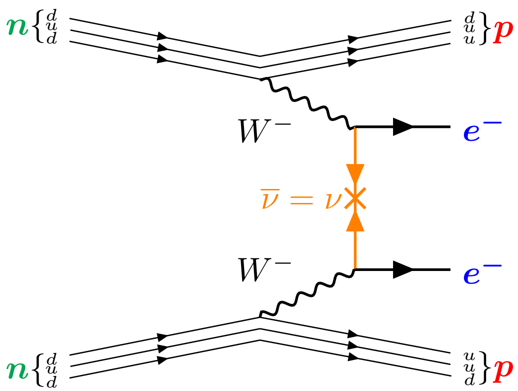
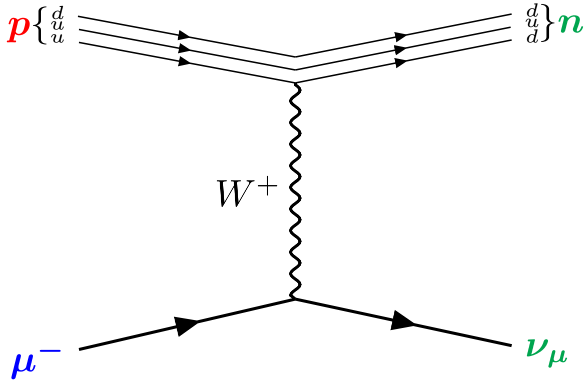
$0\nu\beta\beta$ DECAY VS. ORDINARY MUON CAPTURE

$0\nu\beta\beta$ Decay



Ordinary Muon Capture



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- Has been measured

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

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MONUMENT (OMC4DBD) EXPERIMENT @ PSI

Eur. Phys. J. C (2024) 84:1188
https://doi.org/10.1140/epjc/s10052-024-13470-6
THE EUROPEAN PHYSICAL JOURNAL C
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Regular Article

Experimental Physics

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

G. R. Araujo[1], D. Bajpai[2], L. Baudis[1], V. Belov[4,5], E. Bossio[5,6,a], T. E. Cocolios[7], H. Ejiri[8], M. Fomina[4], K. Gusev[4,5], I. H. Hashim[9], M. Heines[7], S. Kazartsev[4], A. Knecht[10], E. Mondragón[5,b], Z. W. Ng[9], I. Ostrovskiy[2,3], F. Othman[9], N. Rumyantseva[4,5], S. Schönert[5], M. Schwarz[5], E. Shevchik[4], M. Shirchenko[4], Yu Shitov[11], E. O. Sushenok[4], J. Suhonen[12,13], S. M. Vogiatzi[10], C. Wiesinger[5], I. Zhitnikov[4], D. Zinatulina[4]

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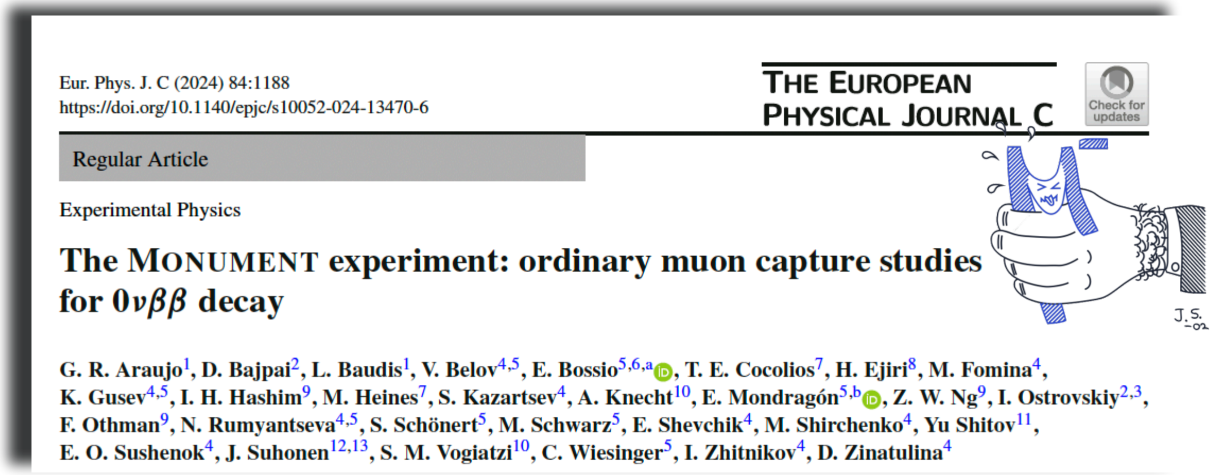
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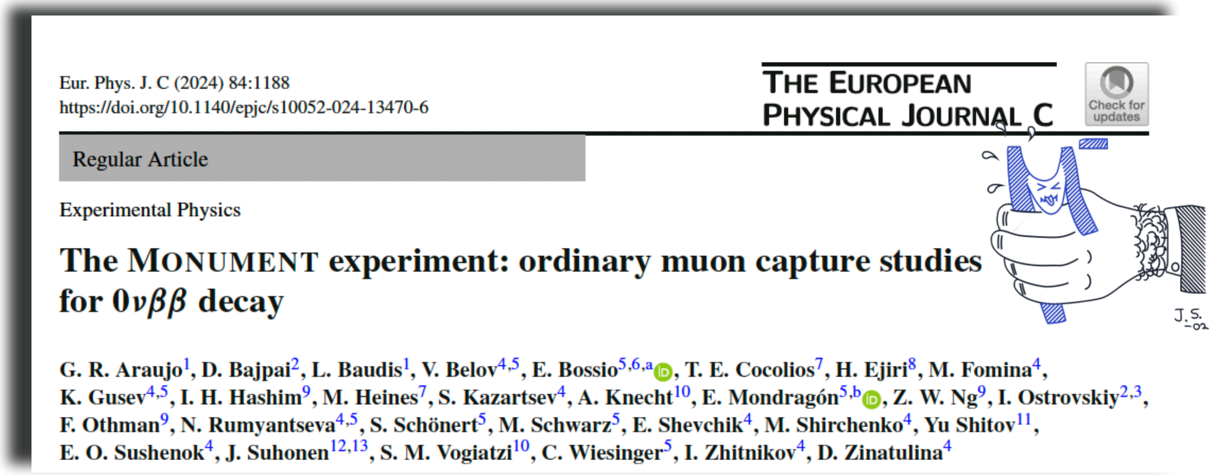
MONUMENT (OMC4DBD) EXPERIMENT @ PSI


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

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article

Experimental Physics

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

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TECHNISCHE UNIVERSITÄT DARMSTADT

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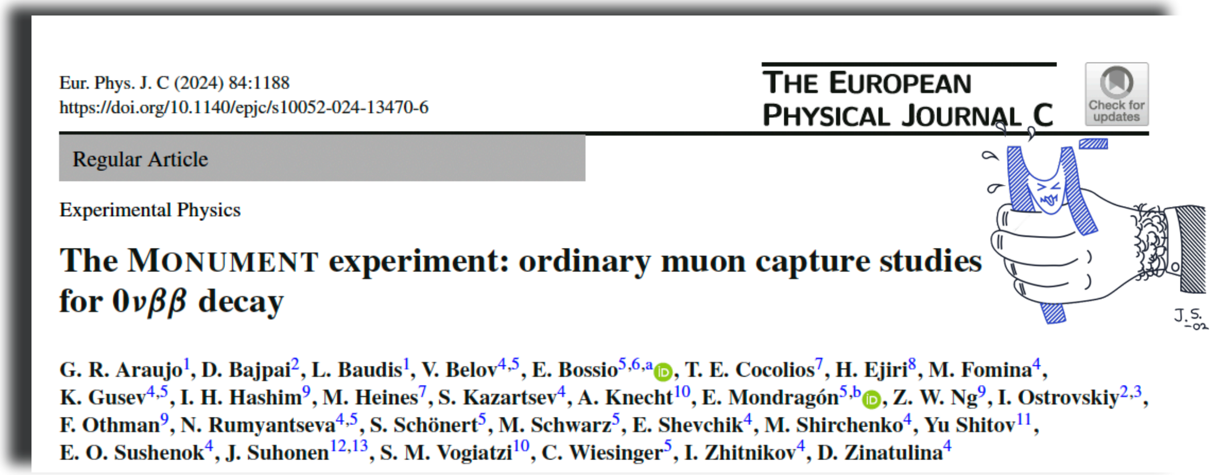

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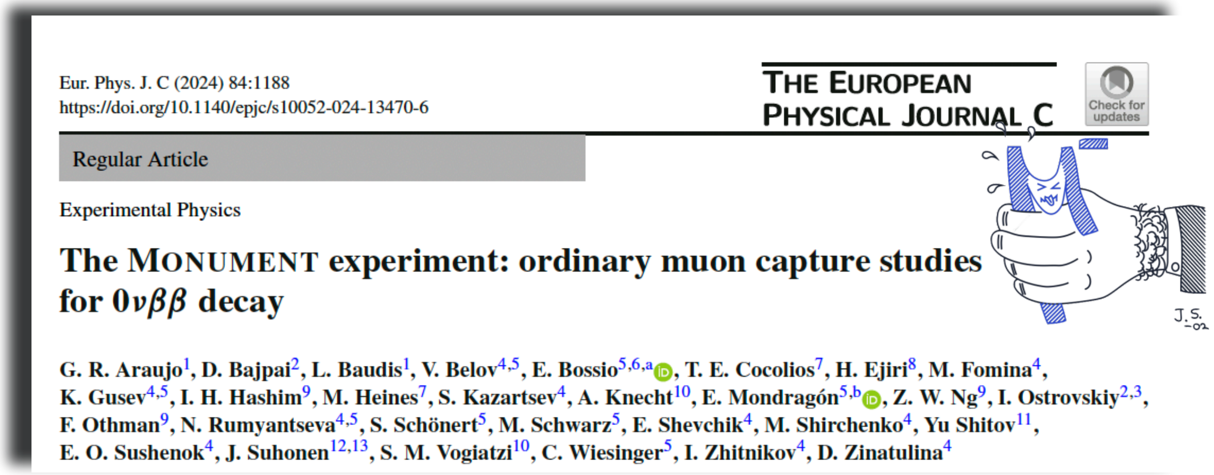

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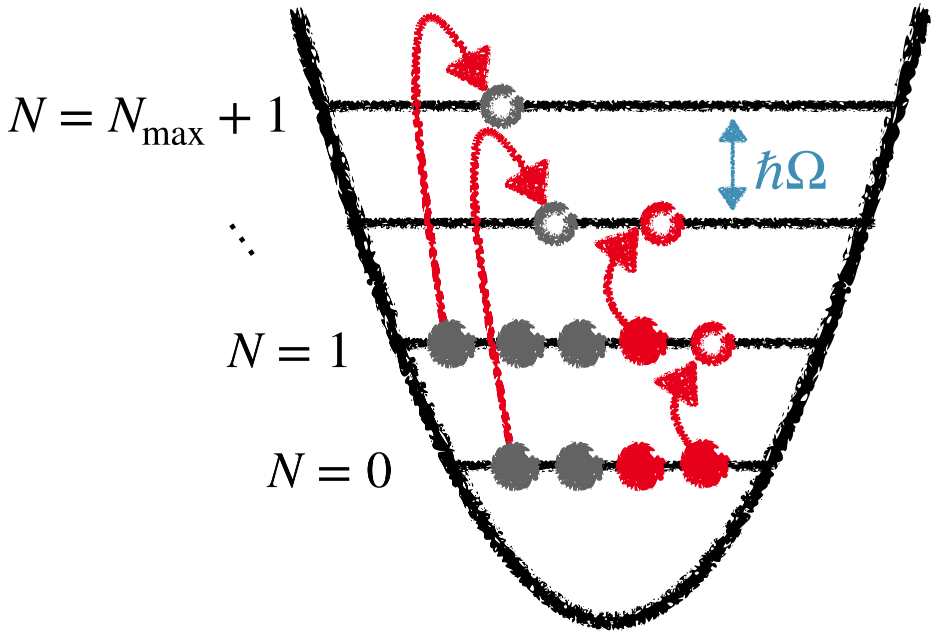
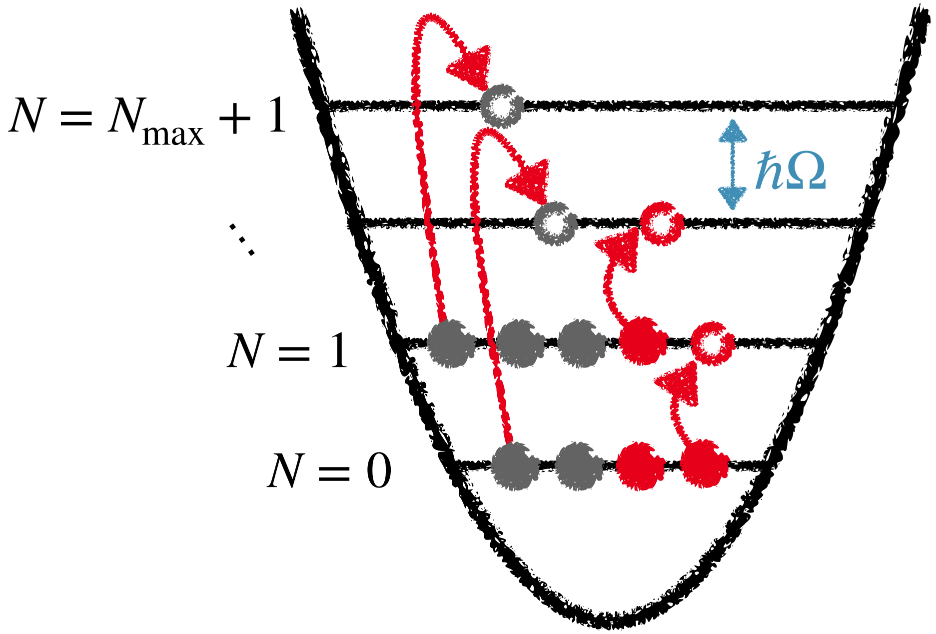
NO-CORE SHELL MODEL (NCSM)



NO-CORE SHELL MODEL (NCSM)

- Solve the nuclear many-body problem

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



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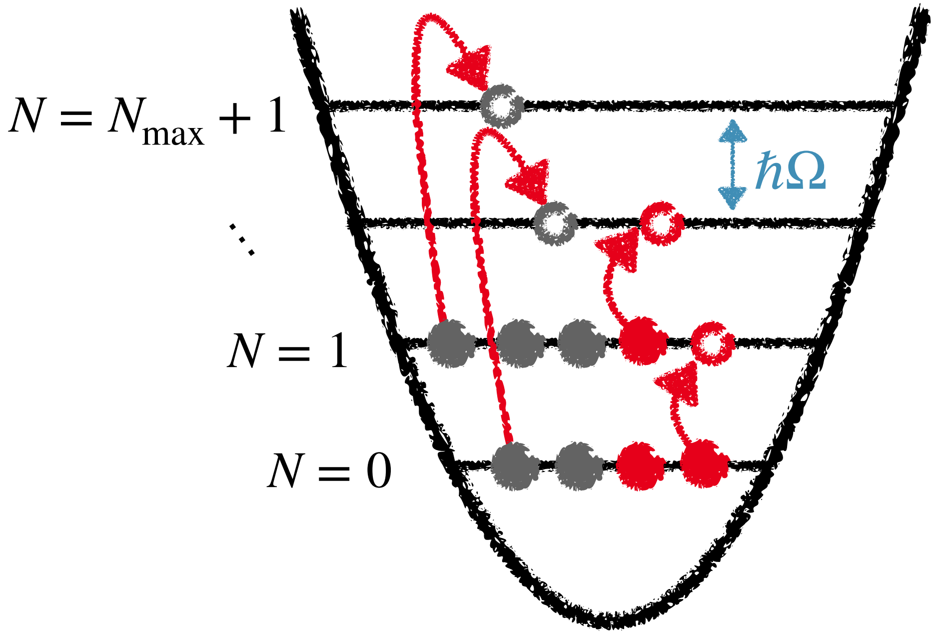
- **Two- (NN)** and **three-body (3N)** forces from χEFT:

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



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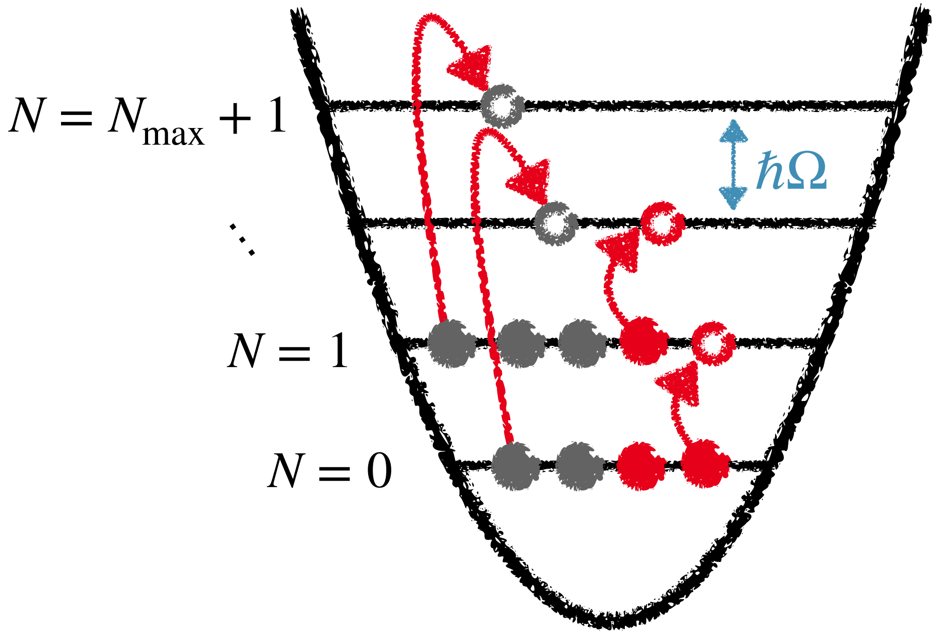
- Expansion in Harmonic Oscillator (HO) basis:

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



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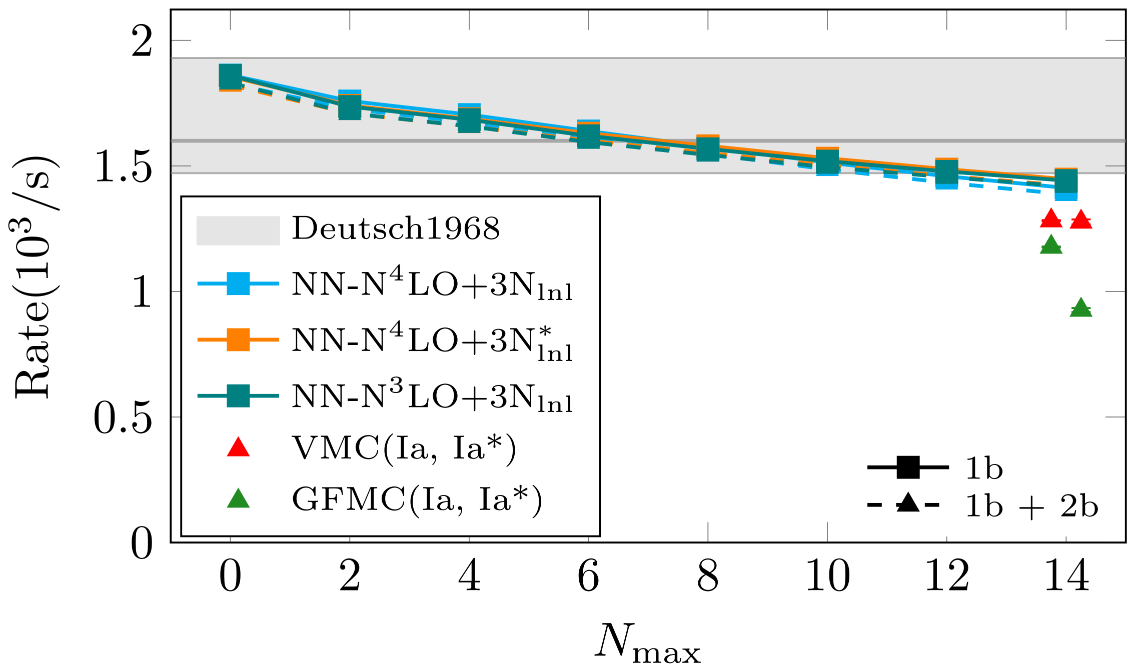
MUON CAPTURE ON ^{6}LI

$$^6\mathrm{Li}(1^+_{\mathrm{gs}}) + \mu^- \to {}^6\mathrm{He}(0^+_{\mathrm{gs}}) + \nu_\mu$$



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

MUON CAPTURE ON ^{6}LI

- Calculations slightly **underestimate the experiment**

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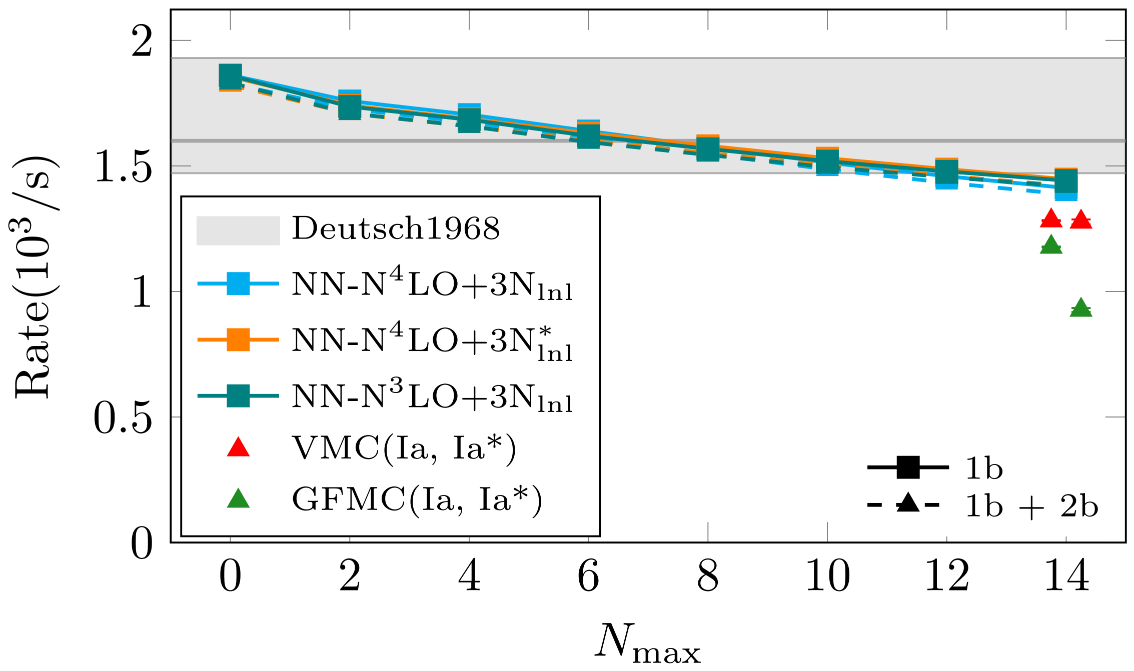

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- Calculations slightly **underestimate the experiment**
- No-core shell model **consistent with other *ab initio* methods**: **Variational Monte Carlo (VMC)** and **Green's Function Monte Carlo (GFMC)**
  G. B. King et al., Phys. Rev. C 105, L042501 (2022)

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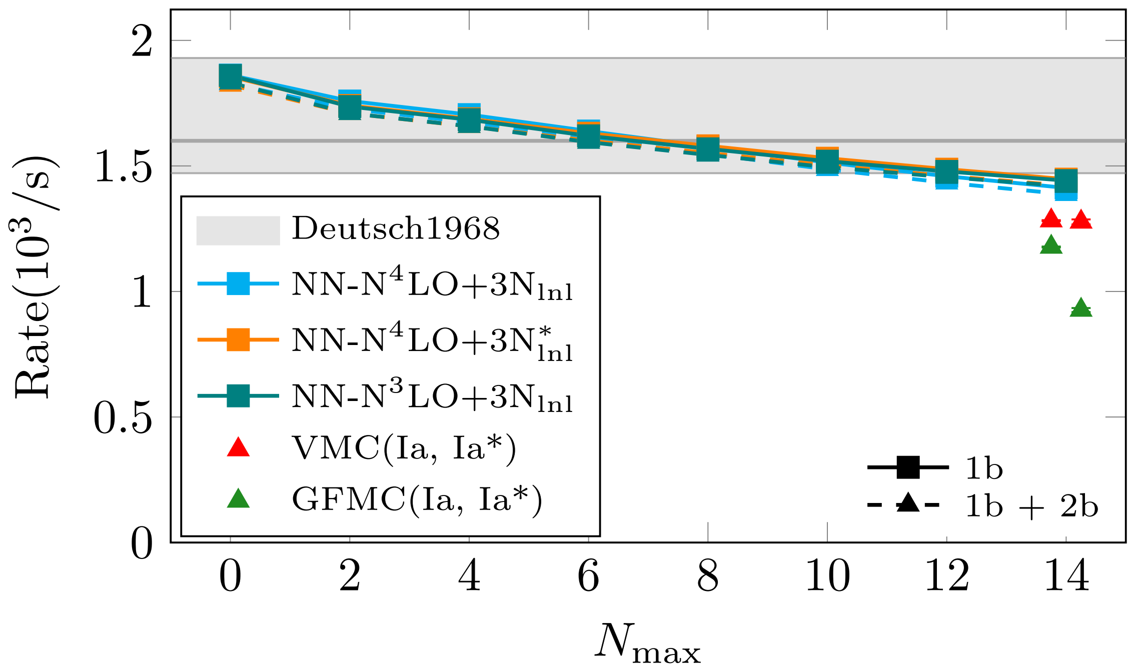

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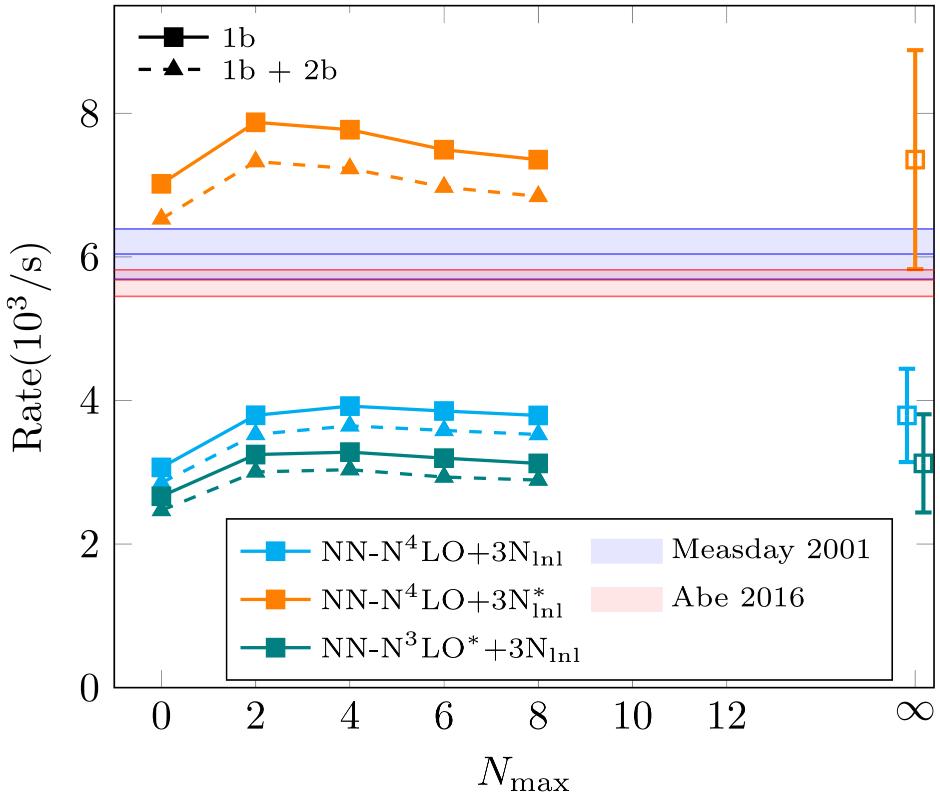
TECHNISCHE UNIVERSITÄT DARMSTADT

MUON CAPTURE TO THE GROUND-STATE OF ^{12}B

$$^{12}\mathrm{C}(0^+_{\mathrm{gs}}) + \mu^- \rightarrow \; ^{12}\mathrm{B}(1^+_{\mathrm{gs}}) + \nu_\mu$$



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

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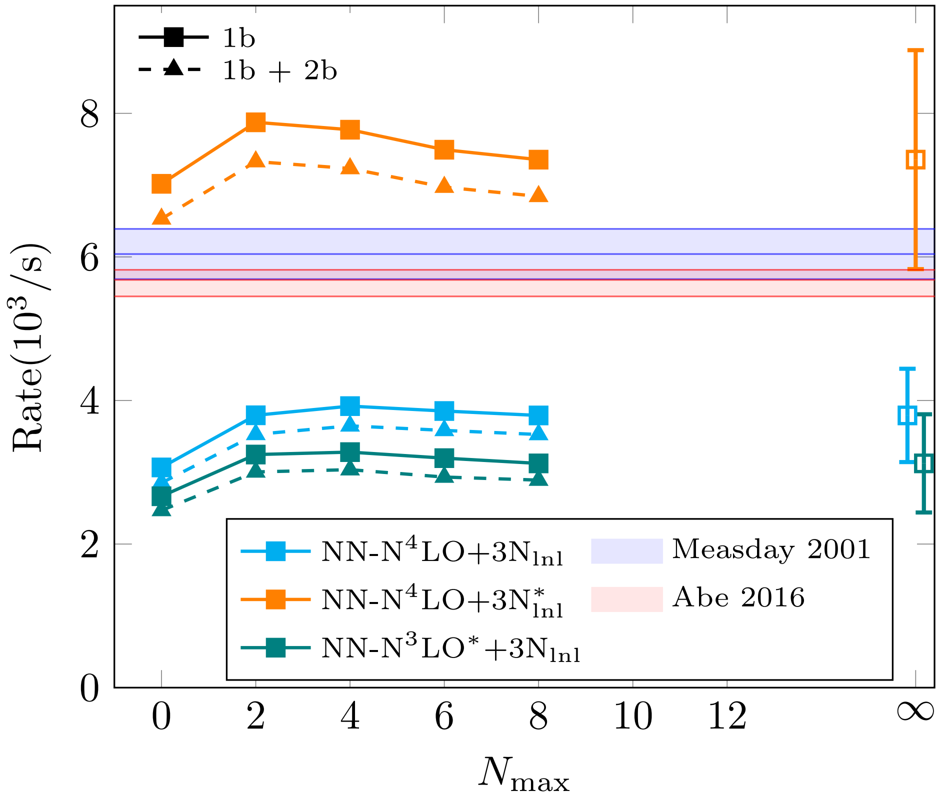

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  - The $\mathbf{NN-N^4LO+3N^*_{lnl}}$ interaction with the **subleading 3N term** (E7) most consistent with experiments
    Girlanda, Kievsky, Viviani, Phys. Rev. C 84, 014001 (2011)

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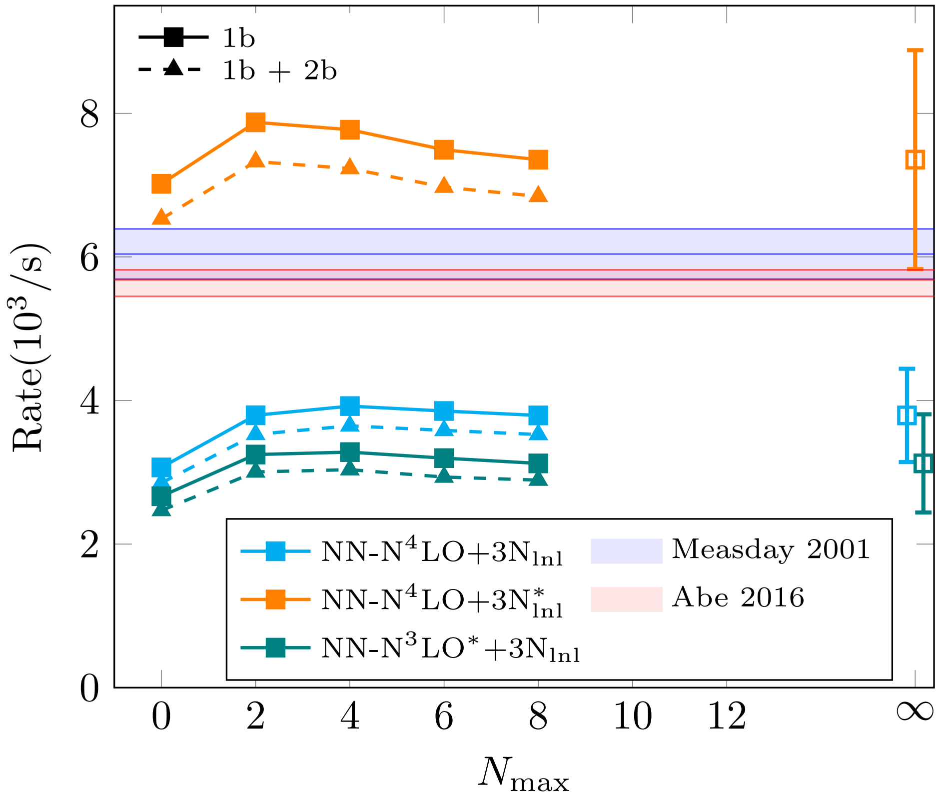

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- **3-body forces essential** to reproduce the measured rate

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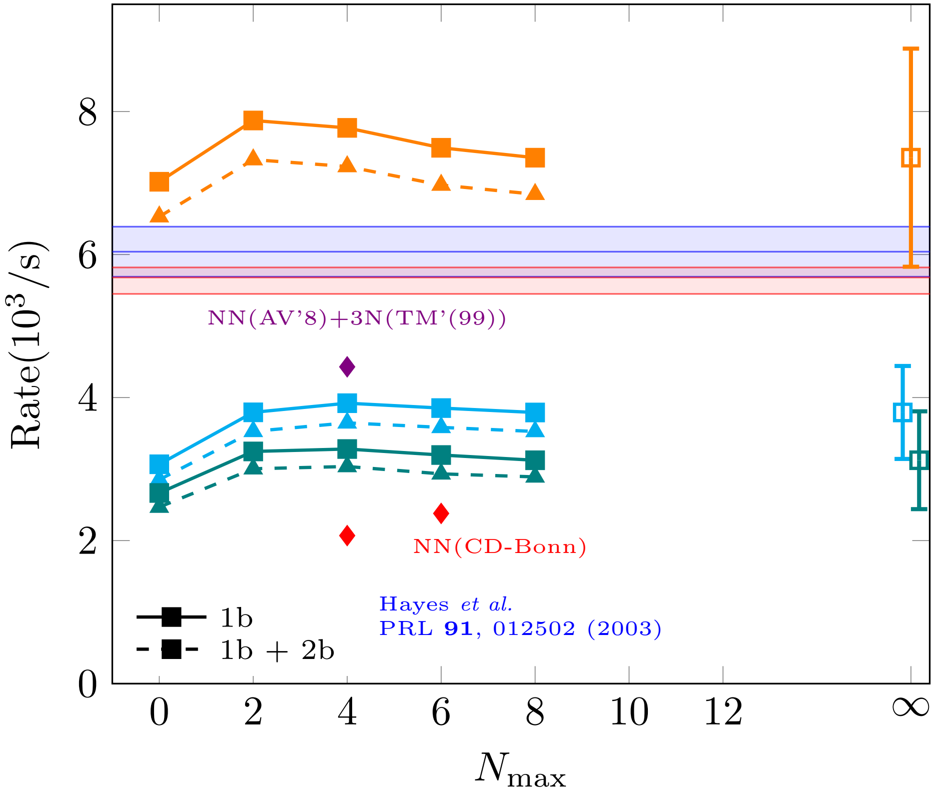

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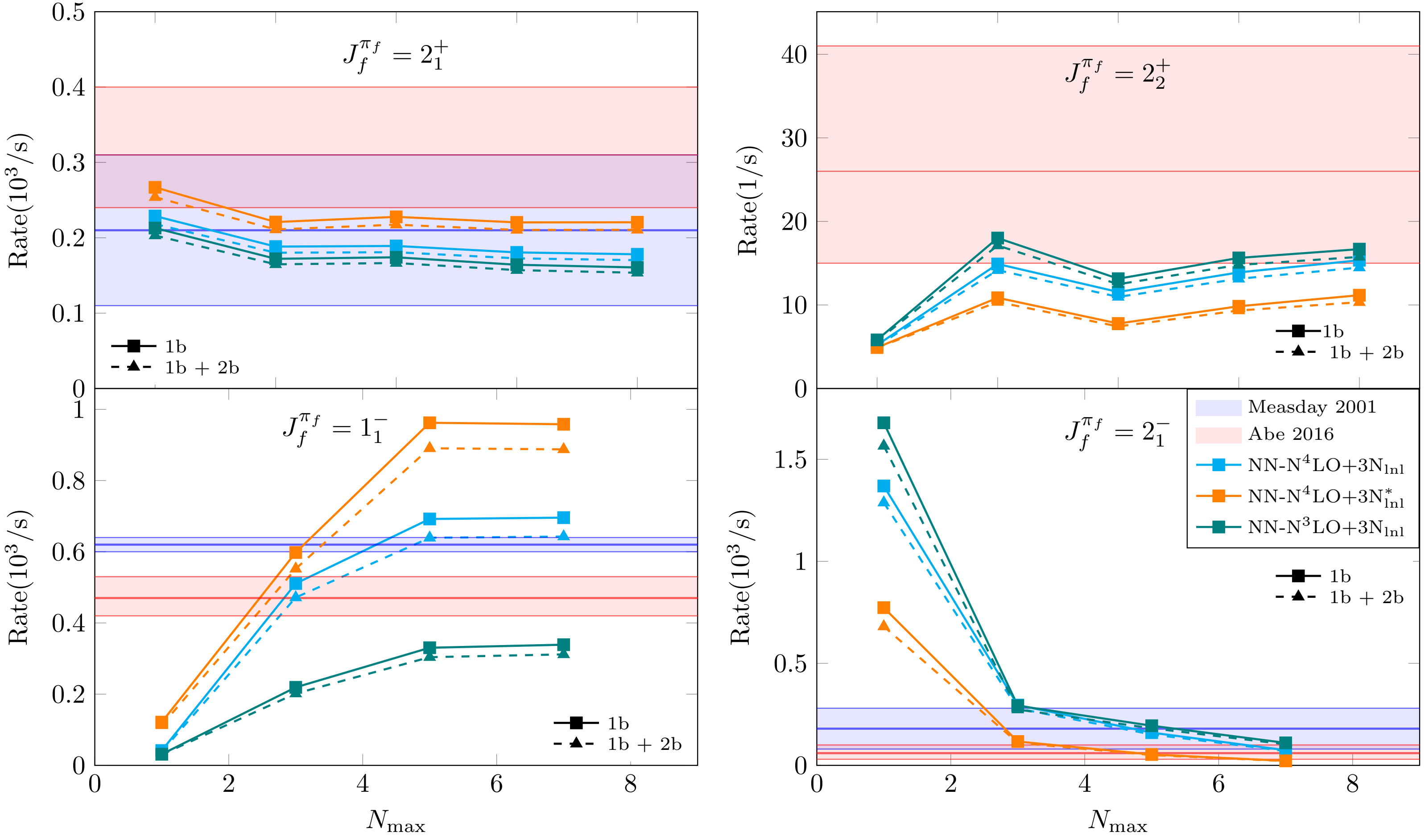
MUON CAPTURE TO THE EXCITED STATES OF ^{12}B



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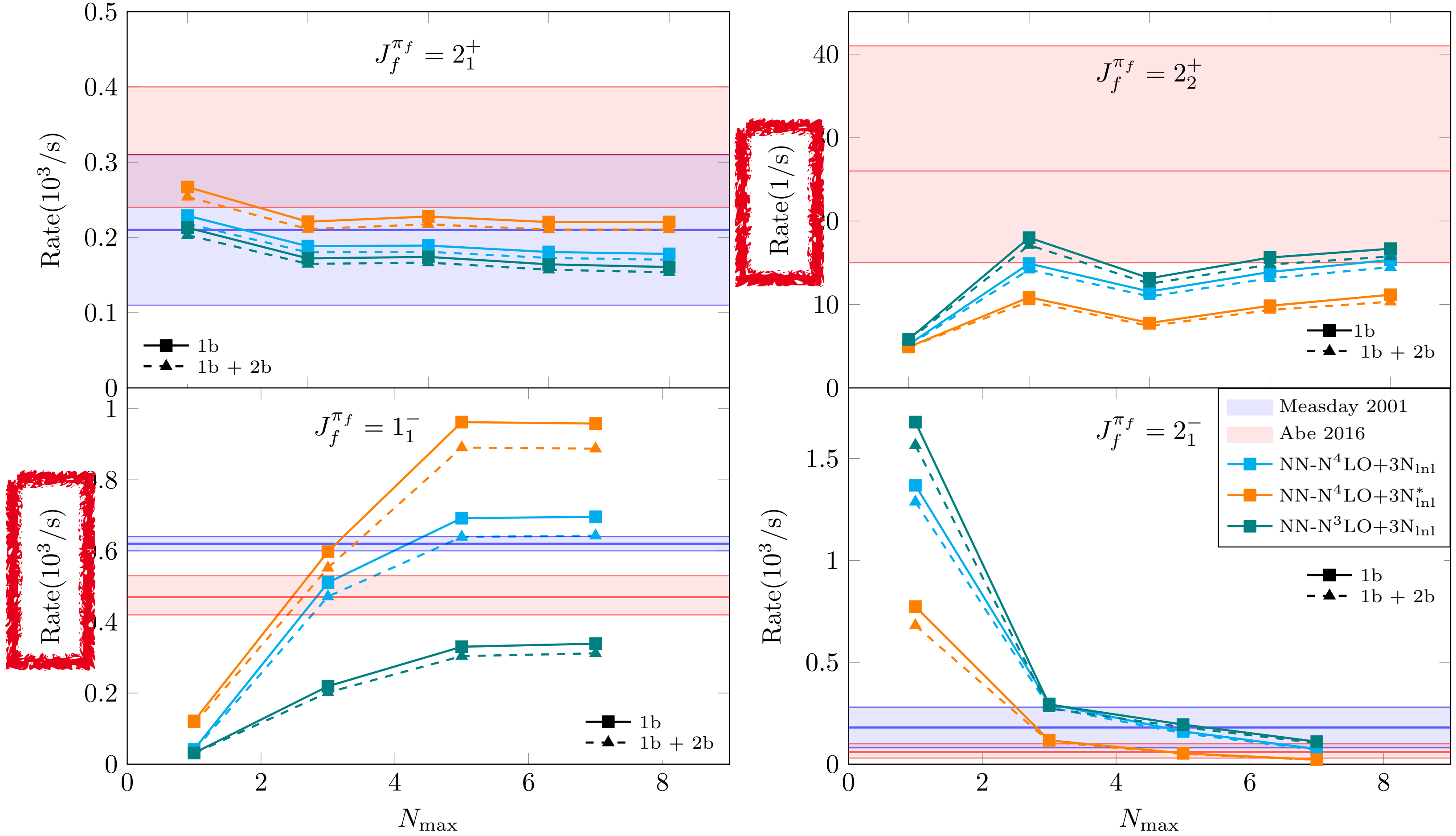

LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C 109, 065501 (2024)

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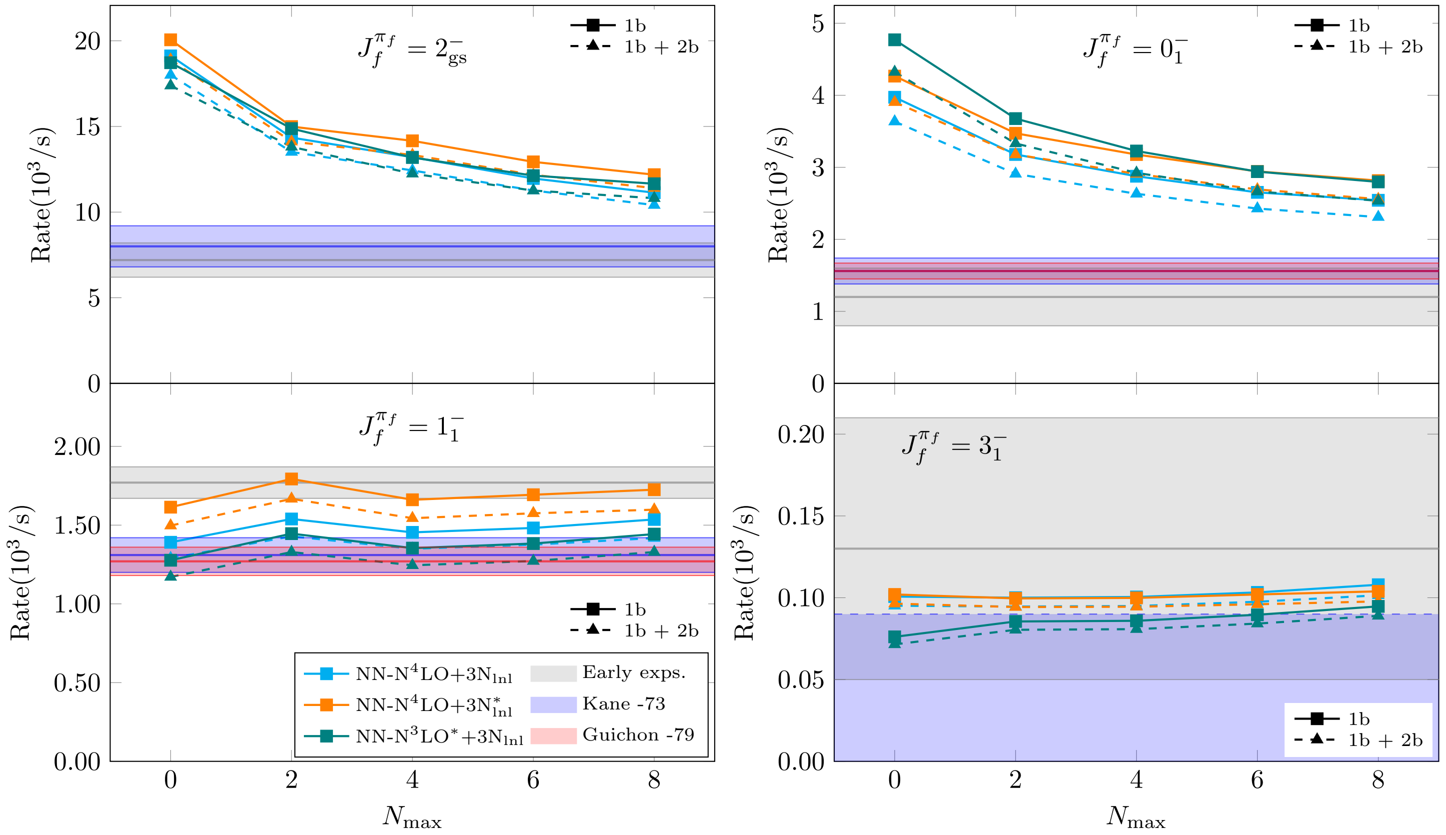
MUON CAPTURE ON ^{16}O

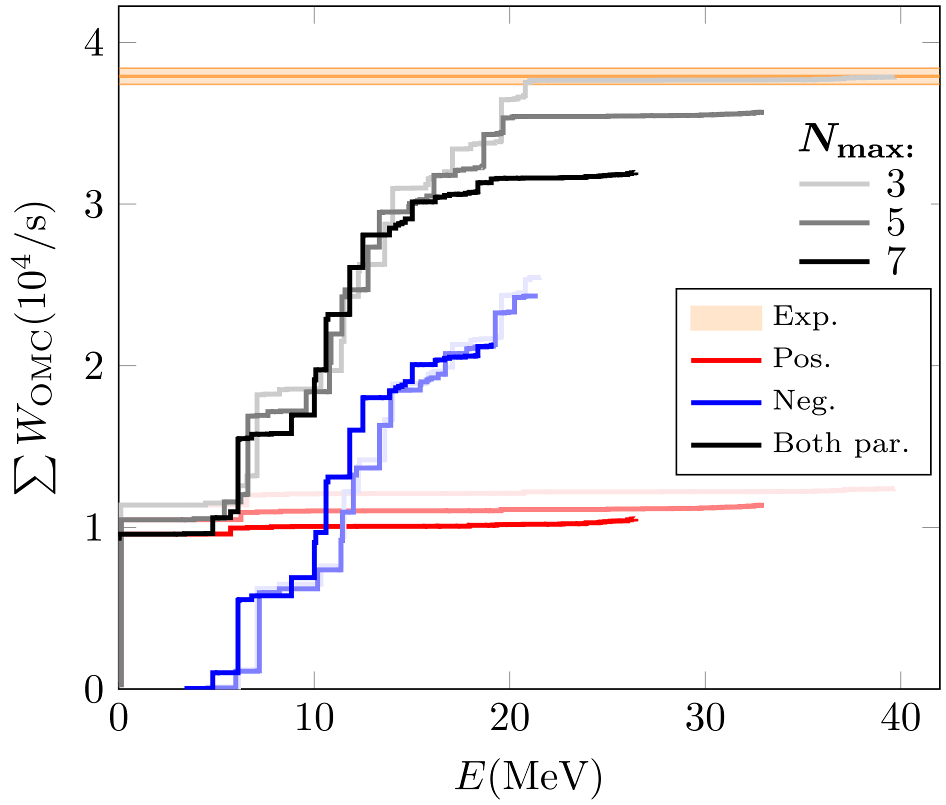


LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C 109, 065501 (2024)

TOTAL MUON CAPTURE RATES

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

$$\mu^- + {}^{12}\mathrm{C}(0^+_{\mathrm{gs}}) \to \nu_\mu + {}^{12}\mathrm{B}(J^\pi_k)$$



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

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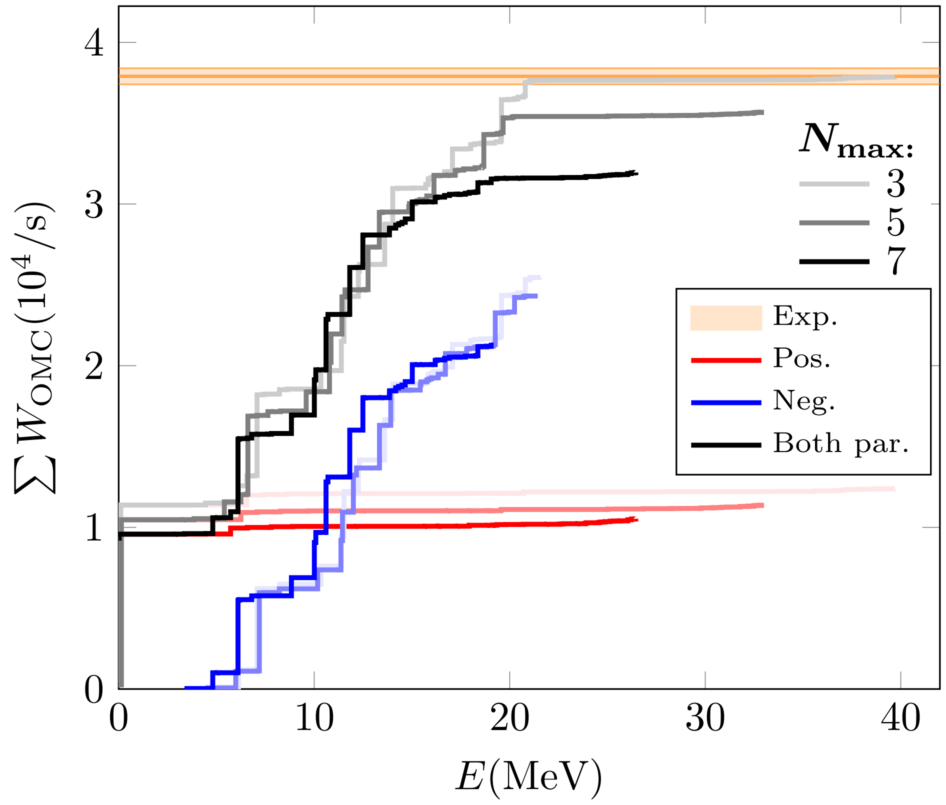

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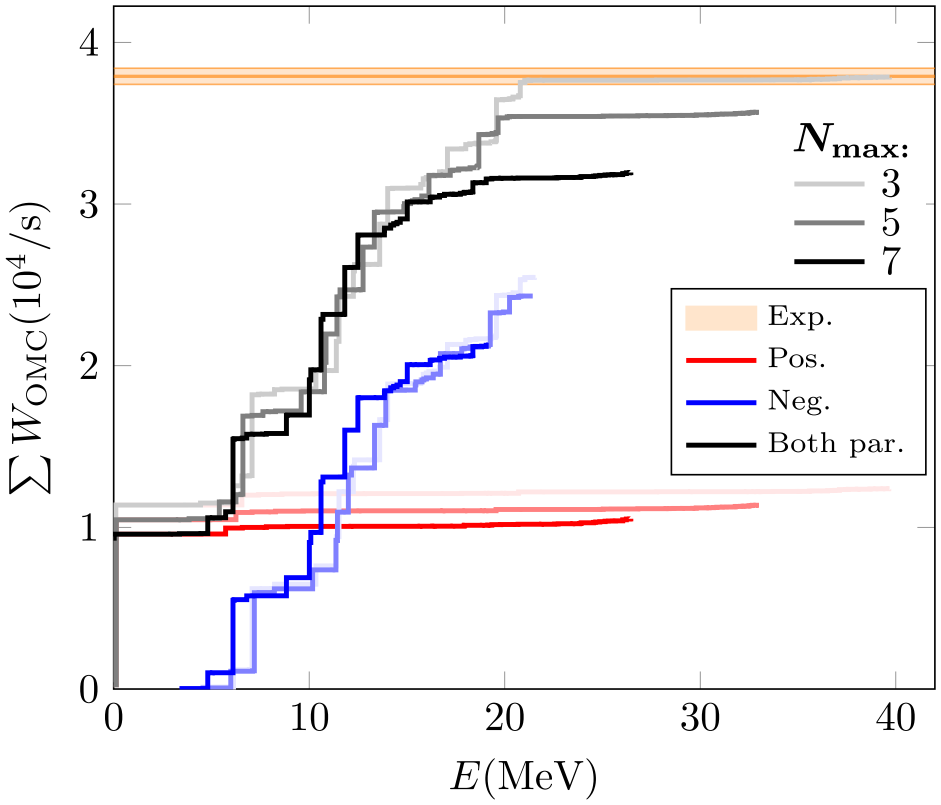

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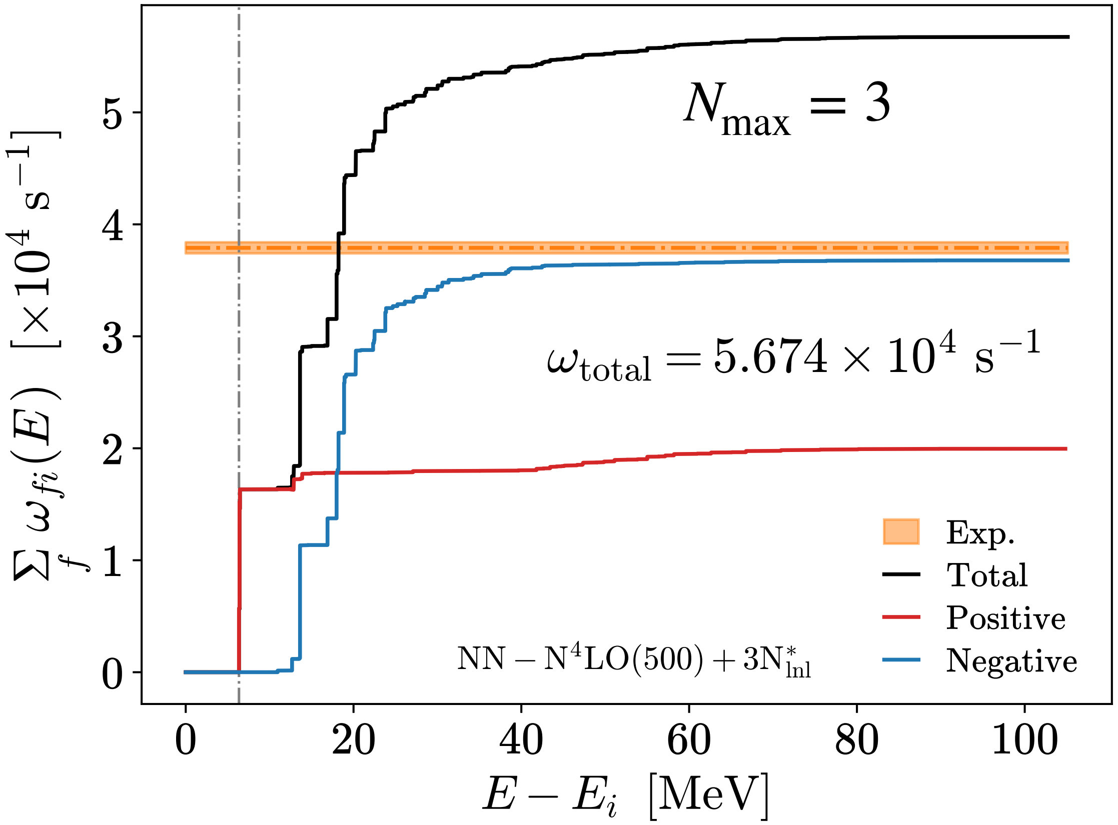
- **Better estimation of the total rates using the Lanczos strength function method underway**

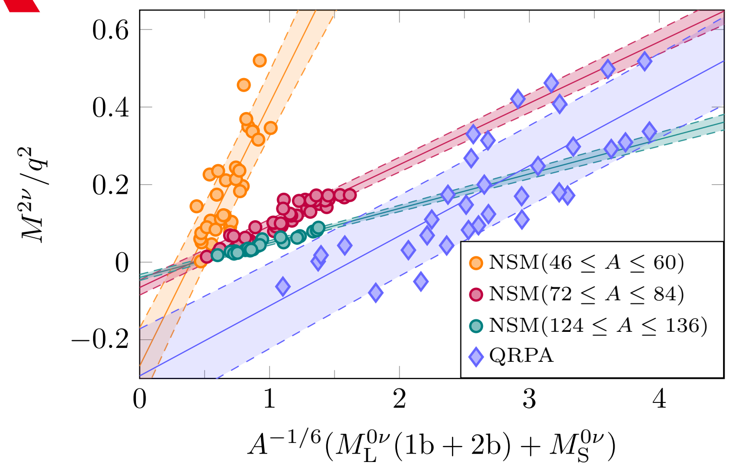


D. Araujo Najera, M. Gennari, LJ, M. Drissi, P. Navrátil, work in progress

SUMMARY AND OUTLOOK

- We found correlations between the nuclear matrix elements of $0\nu\beta\beta$ decay and DGT reactions, M1M1 decay and $2\nu\beta\beta$ decay
- Ordinary muon capture on light nuclei is well described by *ab initio* nuclear theory

- Consistent study of the χEFT corrections to $0\nu\beta\beta$ decay in an *ab initio* framework
- Extend the *ab initio* studies on muon capture in heavier nuclei including exact two-body currents
- Study other nuclear-weak processes for BSM searches ($\mu^- \to e^+$, β decays, …)



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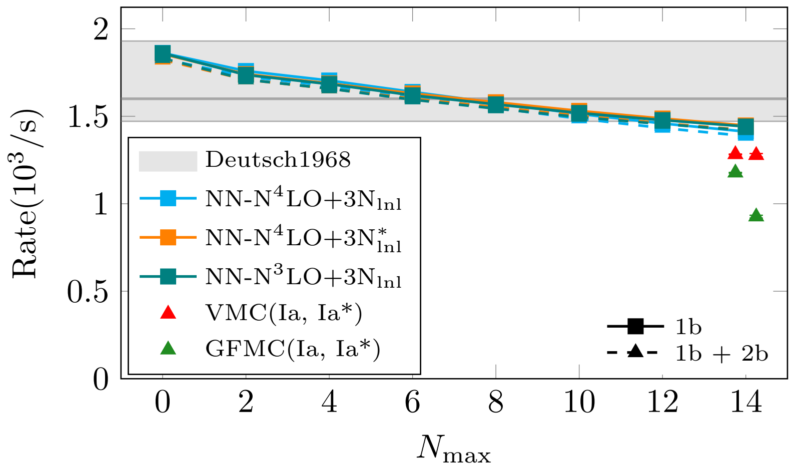

THANK YOU TO COLLABORATORS

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