The nuclear bridge to new physics: Theoretical challenges in neutrinoless $\beta\beta$ decay

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Engel et al. Rep. Prog. Phys. 80, 046301, 2017

OUTLINE

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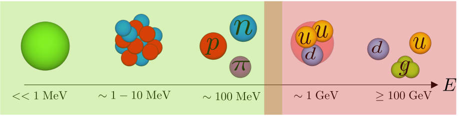
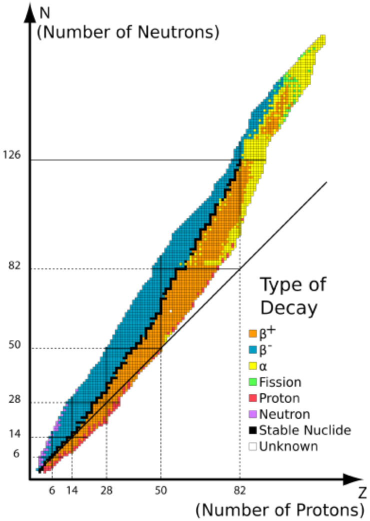
INTRODUCTION

THE ATOMIC NUCLEUS

- Self-bound system of A nucleons (protons and neutrons)
- Bound by the strong force
- Weak decays and electromagnetic repulsion
- Nuclear physics→Quantum ChromoDynamics (QCD):
  - High energy: quarks and gluons
  - Low energy: nucleons and pions

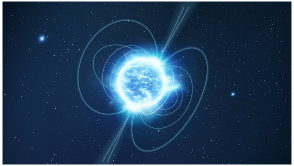




https://chem.libretexts.org

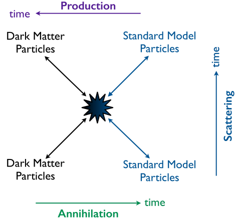
NUCLEAR DECAYS

Neutron stars

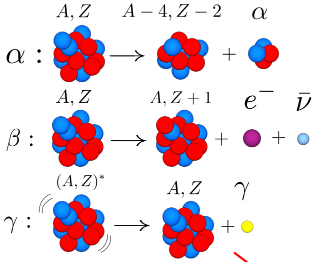


https://www.space.com/22180-neutron-stars.html

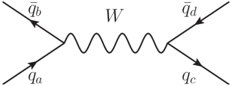
Dark Matter



https://particleastro.brown.edu/dark-matter/

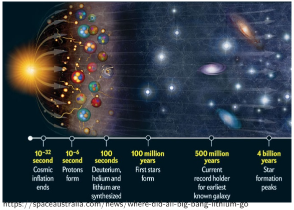


Weak interaction's test



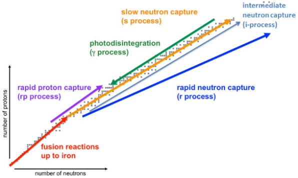
Pasztor et al. arXiv.1103.5057 ,2011

Big Bang Nucleosynthesis



https://spaceaustralia.com/news/where-did-all-big-bang-lithium-go

$r-$, $s-$ and $p-$processes



https://ejc2014.sciencesconf.org

$\beta\beta$ DECAY

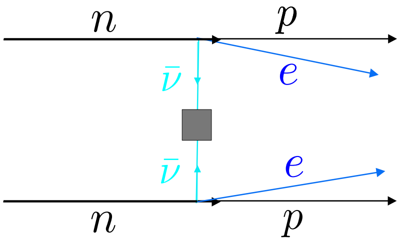
$\beta\beta$ DECAY

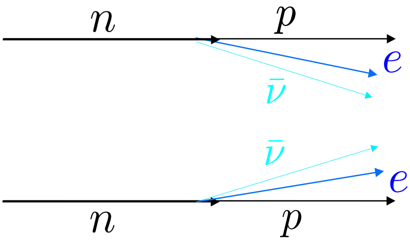
$0\nu\beta\beta : 2n \rightarrow 2p + 2e^-$

- Beyond Standard Model $\rightarrow$ Lepton Number Violation
- Majorana Fermions
- Hypothetical decay

$2\nu\beta\beta : 2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e$

- Standard Model allowed $\rightarrow$ Lepton Number Conservation
- Dirac Fermions
- Already measured





Engel et al. Rep. Prog. Phys. 80, 046301, 2017

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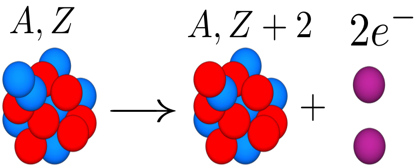
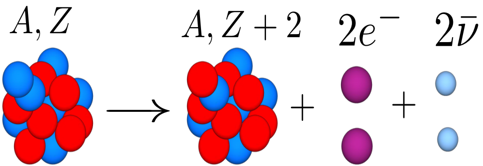
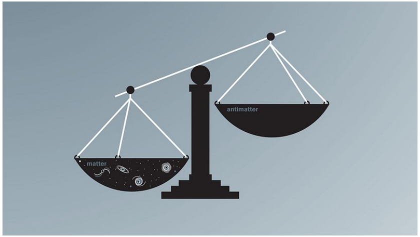




$0\nu\beta\beta$: BEYOND STANDARD MODEL IMPLICATIONS

Matter-antimatter asymetry

- Baryogenesis connection via leptogenesis
- Constrain on CP-Violating phases
- New physics model discrimination



https://legend-exp.org/science/neutrinoless-bb-decay/the-matter-antimatter-asymetry

Neutrino physics

- Neutrino's nature
- Neutrino mass ordering
- Neutrino mass mechanism
- Exotic particles: right-handed neutrinos?

https://amsler.web.cern.ch/NPIOP/Seesaw.pdf

EXPERIMENTS

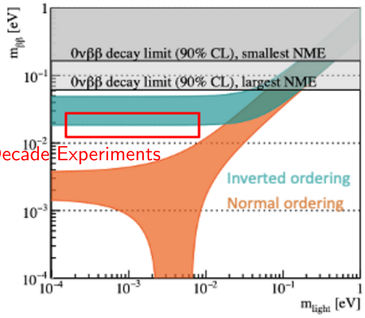
$$\left(T_{1/2}^{\beta\beta}\right)^{-1} \propto g_A^4 G_0 |M^{\beta\beta}|^2 m_{\beta\beta}^2$$

$M^{\beta\beta} \equiv$ Nuclear matrix elements

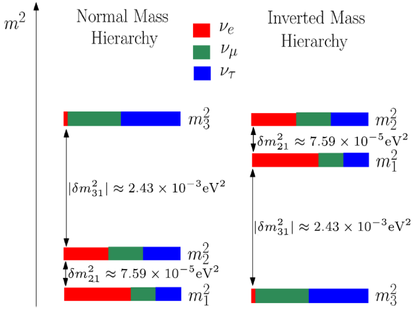
$G_0 \equiv$ Phase-space factor (PSF)

$g_A \equiv$ Axial coupling to the nucleon

$m_{\beta\beta} \equiv$ Effective neutrino mass



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

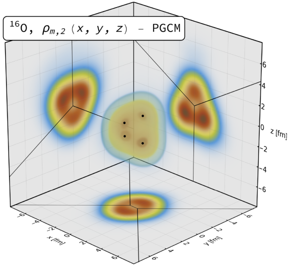


https://www.mpi-hd.mpg.de/lin/research_st.en.html

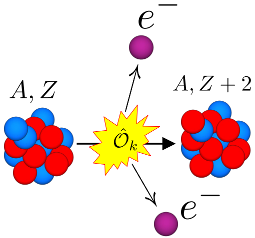
NUCLEAR MATRIX ELEMENTS

$$M^{\beta\beta} = \langle 0_f^+ | \sum_{a,b} \hat{O}_k \tau_a^- \tau_b^- | 0_i^+ \rangle$$

Nuclear state wavefunctions



Decay operator



Giacalone et al. Phys. Rev. Lett. 135, 012302, 2025

WAVEFUNCTIONS: THE NUCLEAR MANY-BODY PROBLEM

$$H|\psi\rangle = E|\psi\rangle$$

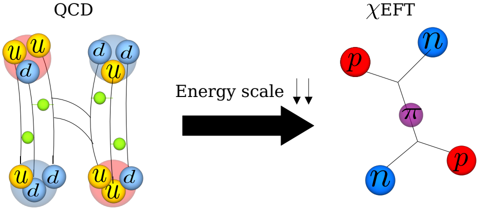
- $H \equiv$ Hamiltonian
- $E \equiv$ Energy
- $|\psi\rangle \equiv$ state wavefunction

Hamiltonian

- Discretized QCD
- $\chi-$Effective Field Theory (χEFT)
- Phenomenological: Fitted to NN data

Many-body methods

- Lattice QCD
- NCSM, QMC, IMSRG, CC...
- NSM, QRPA, EDF...



NUCLEAR MATRIX ELEMENTS

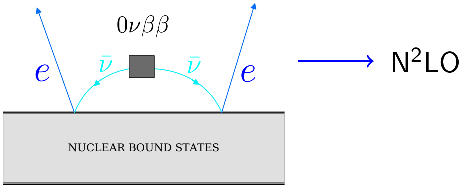
Wavefunctions

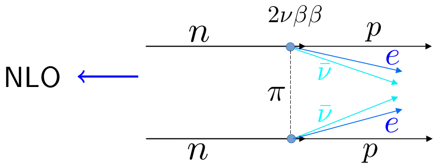
- Nuclear Shell Model (NSM) and Quasiparticle Random Phase Approximation (QRPA)
- Phenomenological Hamiltonian

Decay operators

- Chiral Effective Field Theory (χEFT) (LO+NLO+N^{2}LO...)
- $\hat{\mathcal{O}}_k \equiv$ Spin-space operator
- $\tau^- \equiv$ Ladder isospin operator

$$M^{\beta\beta} = \langle 0_f^+ | \sum_{a,b} \hat{\mathcal{O}}_k \tau_a^- \tau_b^- | 0_i^+ \rangle$$





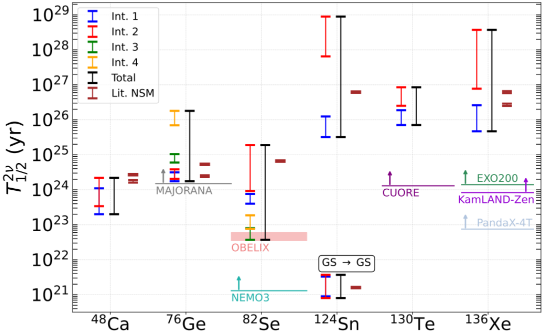
Cirigliano et al. Phys. Rev. C 97, 065501, 2018
el Morabit et al. JHEP, 06, 082, 2025

RESULTS

$2\nu\beta\beta$: DECAY TO EXCITED STATES

$M^{2\nu} \equiv$ LO NME

- $+$ Additional PSFs and subleading NMEs
- $+$ χEFT corrections up to NLO



DC, Frycz, Menéndez, Benavente, submitted Phys. Lett. B

Results

- Main uncertainty comes from different Hamiltonians: Deformation of initial and final states plays a key role
- 2 different GT operators: Bare and renormalized

Coraggio et al. Phys. Rev. C, 100, 014316, 2019

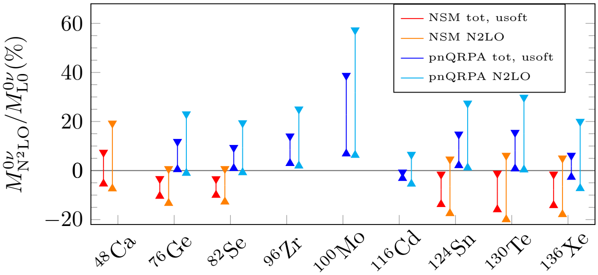
- ^{76}Ge: Experimental evidence close to theoretical predictions
- ^{82}Se: Lower bound prediction within experimental indication

$0\nu\beta\beta$: TOTAL N^{2}LO NMEs

$$M^{0\nu} = M^{0\nu}_{\rm LO} + M^{0\nu}_{\rm N^2LO} = M^{0\nu}_{\rm L} + M^{0\nu}_{\rm S} + M^{0\nu}_{\rm usoft} + M^{0\nu}_{\rm loops}$$

χEFT expectations: $(5-10)\%$

- $M^{0\nu}_{\rm L(S)} \equiv$ Long(Short)-range NME
- $M^{0\nu}_{\rm usoft} \equiv$ ultrasoft NME
- $M^{0\nu}_{\rm loops} \equiv$ loop terms



DC, Jokiniemi, Menéndez, Phys. Lett. B 860, 2025

Results

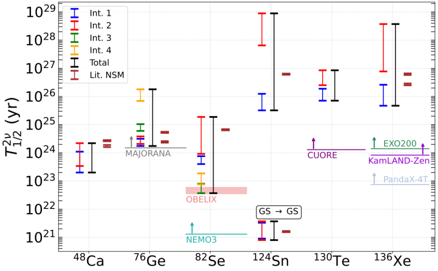
- N^{2}LO contributions: Non-negligible
- Different sign between many-body methods: ultrasoft NME
- $|M^{0\nu}_{\rm N^2LO}/M^{0\nu}_{\rm LO}|$:
  - NSM $\leq 20\%$
  - QRPA $\leq 30\%$
- Central values: $|M^{0\nu}_{\rm N^2LO}/M^{0\nu}_{\rm LO}| \sim (5-15)\%$

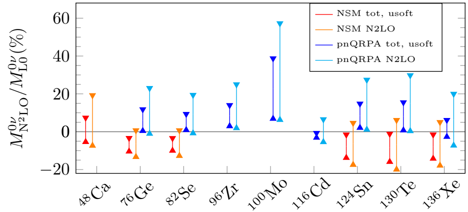
SUMMARY

SUMMARY AND OUTLOOK

Summary

- NMEs crucial to understand beyond standard model physics
- $0\nu\beta\beta$ N^{2}LO NMEs and $2\nu\beta\beta$ half-lives ($0^+_{GS} \rightarrow 0^+_1$)
- ^{76}Ge and ^{82}Se predictions close to experimental evidence





Outlook

- Use other methods for the wf
- Extend the decay operator study to higher order corrections
- Potential near-term measurements (^{76}Ge and ^{82}Se)

Thank you for your attention!

Neutrinoless $\beta\beta$ decay nuclear matrix elements complete up to N^2LO in heavy nuclei

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Two-neutrino $\beta\beta$ decay to excited states at next-to-leading order

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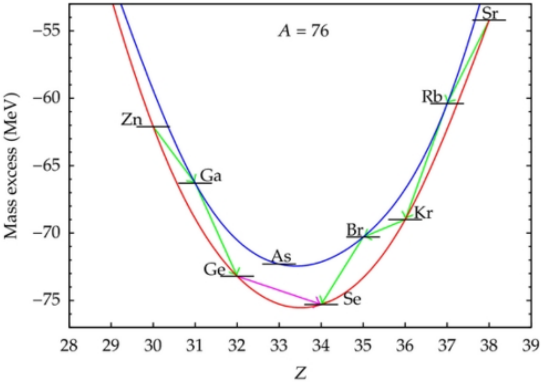
BACKUP SLIDES

$\beta\beta$ DECAY

- ^{76}Ge: β decay forbidden
- Energy difference between odd-odd nuclei and even-even nuclei$\rightarrow$ Pairing
- $\beta\beta$ decay allowed:
  $^{76}\text{Ge} \rightarrow {}^{82}\text{Se}$ $(Q_{\beta\beta} > 0)$
- $Q_{\beta\beta} = E_i - E_f - 2m_e$
  - $Q_{\beta\beta} \equiv Q-$value for $\beta\beta$ decay
  - $m_e \equiv$ Electron mass
  - $E_i \equiv$ Initial energy
  - $E_f \equiv$ Final energy



Giuliani, et al. Adv. High Energy Phys, 2012, 857016, 2012.

NUCLEAR SHELL MODEL

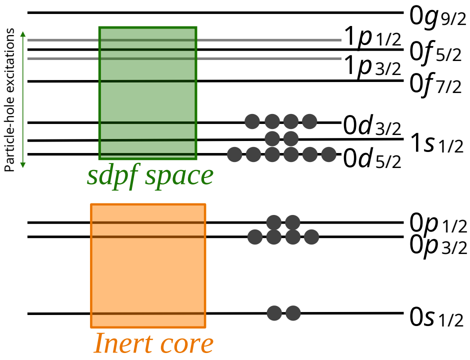
Hamiltonian

- To solve the Schrödinger equation $\rightarrow H_{\text{eff}}|0^+_{\text{GS}}\rangle = E|0^+_{\text{GS}}\rangle$
- $H_{\text{eff}} \equiv$ Phenomenological Hamiltonian. Fitted to experimental data (NN scattering) and renormalized within each valence space
- Good description of nuclear spectroscopy

Orbitals

- Empty orbitals
- Valence Space $\rightarrow H_{\text{eff}}$
- Inert Core

^{40}Ca:



Caurier et al. Rev. Mod. Phys. 77, 427, 2005

PHENOMENOLOGICAL INTERACTIONS

pf –shell interactions($A = 40 - 80$)

- KB3G: Kuo-Brown interaction Mass dependence and monopole modifications
- GXPF1A: Bonn-C potential Two-body matrix elements from $A = 47 - 66$

pfg –shell interaction($A = 56 - 100$)

- JUN45: Bonn-C interaction 133 two-body matrix elements, 4 single-particle energies with $A = 63 - 96$
- GCN2850: G-matrix, fit to 300 energy levels
- JJ4BB
- RG.PROLATE

$sdgh$–shell($A = 100 - 140$)

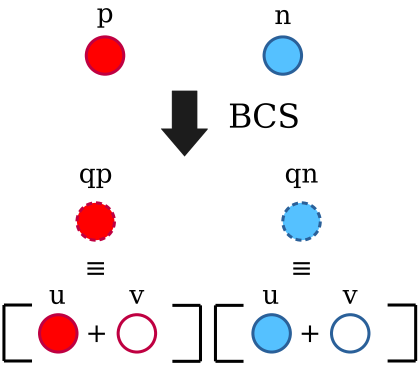
- GCN5082
- QX5082: Bonn-C potential Binding energies of 157 low-lying yrast states from $^{102-132}Sn$

QUASI-PARTICLE RANDOM PHASE APPROXIMATION

QRPA

- $|\mathrm{QRPA}\rangle = |0^+\rangle \rightarrow$ Reference state
- $n = 0 \rightarrow 2$ harmonic oscillator shells above the Fermi level
- Larger valence spaces than NSM but less complex correlations between nucleons (less paremeters to fit in the Hamiltonian)

Suhonen, Springer-Verlag, Berlin Heidelberg, 2007



$$|\mathrm{QRPA}\rangle = \sum_{\mathrm{pn}} (\mathrm{a_n qp} + \mathrm{b_n qn})$$

Credit, Jokiniemi

$0\nu\beta\beta$: χEFT DIAGRAMS

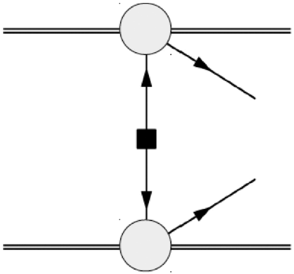
$$M^{0\nu} = M^{0\nu}_{\rm L} + M^{0\nu}_{\rm S} + M^{0\nu}_{\rm usoft} + M^{0\nu}_{\rm loops}$$

Leading Order (LO)$\rightarrow$already computed

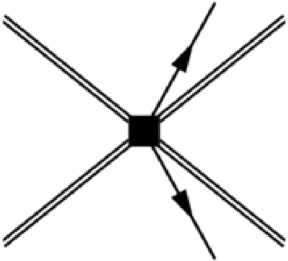
Jokiniemi et al. Phys. Lett. B, 823, 136720, 2021

$q \equiv$ Transferred momentum

- Long-range(L)
  ($q \sim$ 100MeV $+q-$dependent N^{2}LO)



- Short-range(S)
  ($q >> 100$ MeV)



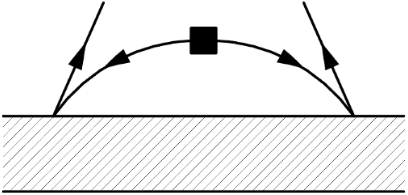
Cirigliano et al. Phys. Rev. C 97, 065501, 2018

$0\nu\beta\beta$: χEFT DIAGRAMS

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

$q \equiv$ Transferred momentum

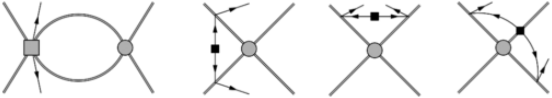
- Ultrasoft(usoft) ($q << 100$MeV)



Next-to-next leading order(N^{2}LO)→New terms

DC, Jokiniemi, Menéndez, Phys. Lett. B 860, 2025

- Loop terms (soft(3)+ultrasoft(1))



Cirigliano et al. Phys. Rev. C 97, 065501, 2018

$$M^{0\nu}_{\rm L} = M^{0\nu}_{\rm L,GT} + M^{0\nu}_{\rm L,F} + M^{0\nu}_{\rm L,T}$$

Finite Size Corrections:
$q-$dependent N^{2}LO ($g_A^2(q^2)$, $g_V^2(q^2)$)

$$M^{0\nu}_{\rm S} \propto g_\nu^{NN} e^{-q^2/\Lambda^2}$$

$g_\nu^{NN} \equiv$ Nucleon-Nucleon coupling
$\Lambda \equiv$ Gaussian cutoff

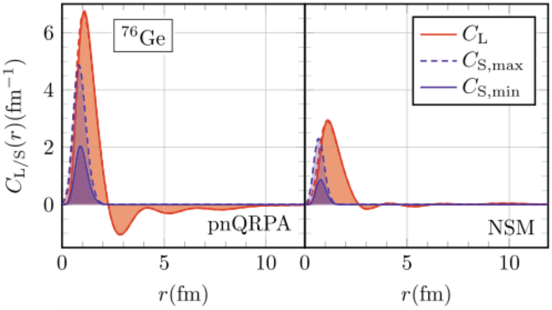
Results

- NSM: $M^{0\nu}_{\rm S}/M^{0\nu}_{\rm L} = +(15-50)\%$
- QRPA: $M^{0\nu}_{\rm S}/M^{0\nu}_{\rm L} = +(30-80)\%$

Jokiniemi et al. Phys. Lett. B 823, 136720, 2021

$$M^{0\nu}_{\rm L/S} = \int_0^\infty C_{\rm L/S}(r)dr$$

- Hard Neutrinos
- Soft Neutrinos



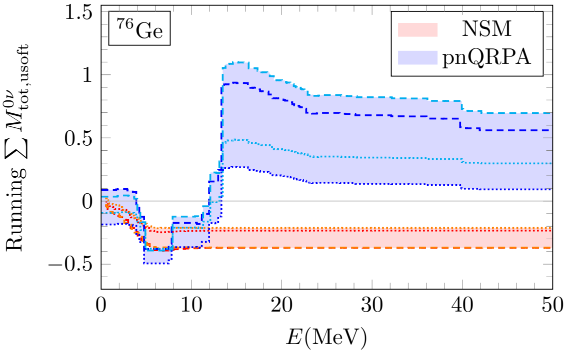
Jokiniemi et al. Phys. Lett. B 823, 136720, 2021

- Study of the intermediate states dependence of the total ultrasoft NMEs
- $M^{0\nu}_{\rm usoft} \propto \langle 0^+_f|{\rm GT}|1^+_n\rangle\langle 1^+_n|{\rm GT}|0^+_i\rangle \cdot \ln(\mu_{\rm us})$
- $\mu_{\rm us} = \frac{m_\pi}{2} \ldots 2m_\pi \equiv$ Ultrasoft scale$\rightarrow$Main uncertainty

Results

Different behaviour between models around 10 MeV$\rightarrow$Different sign

$$M^{0\nu}_{\rm tot,usoft} = M^{0\nu}_{\rm usoft} + M^{0\nu}_{\rm tot,usoft}$$



Jokiniemi et al. Phys. Lett. B 823, 136720, 2021

Non-closure:

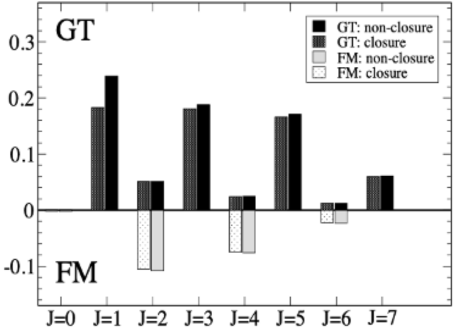
$$M^{0\nu}_{\rm non-cl} \propto \frac{\langle 0_f^+|J_\mu(x)|J_n^\pi\rangle\langle J_n^\pi|J^\mu(y)|0_n^+\rangle}{q(q+E_n-\frac{1}{2}(E_f+E_i))} \rightarrow$$

- $q \simeq k_F \simeq 100\text{MeV}$
- $E_n - \frac{1}{2}(E_i + E_f) \rightarrow 0$
- $J_\mu J^\mu = h_{\rm GT} + h_{\rm F} + h_{\rm T}$

Closure:

$$\rightarrow M^{0\nu}_{\rm L} \propto \frac{\langle 0_f^+|J_\mu(x)J^\mu(y)|0_n^+\rangle}{q^2}$$

- Main difference comes from $\mathrm{GT}|1_n^+\rangle$
- Same dependence as $M^{0\nu}_{\rm usoft}$



Sen'kov, Horoim Phys. Rev. C 88, 064312

$0\nu\beta\beta$: CLOSURE VS NON-CLOSURE

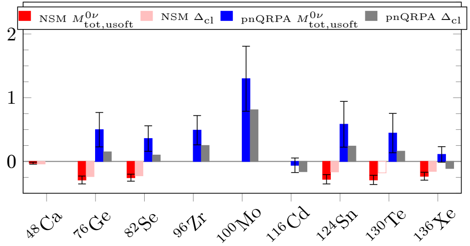
- According to χEFT the ultrasoft term must be the main contribution beyond the closure approximation:
  $M^{0\nu}_{\mathrm{non-cl}} - M^{0\nu}_{\mathrm{L}} = \Delta_{\mathrm{cl}} \sim M^{0\nu}_{\mathrm{tot,usoft}}$

Cirigliano et al. Phys. Rev. C 97, 065501, 2018

Results

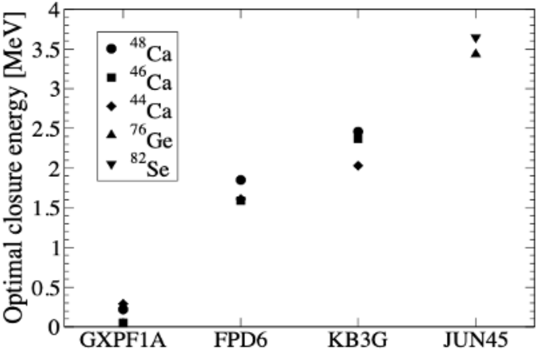
- Agreement in the sign between Δ_{cl} and $M^{0\nu}_{\mathrm{tot,usoft}}$
- NSM: Good agreement with χEFT
- QRPA: Milder agreement with χEFT

Important uncertainties due to μ_{us} dependence



DC, Jokiniemi, Menéndez, Soriano, Phys. Lett. B, 860, 2025

$0\nu\beta\beta$: CLOSURE ENERGIES



Neacsu, Horoi, Phys. Rev. C, 91, 024309, 2015

Nucleus	Interaction	$\langle E_n \rangle$ (MeV)
^{48}Ca	KB3G	2.5
^{48}Ca	GXPF1A	0.23
^{76}Ge	JUN45	3.5
^{82}Se	JUN45	3.6
^{136}Xe	GCN5082	3.7

Sarkar et al. arXiv:2406.13417v1, 2024

$0\nu\beta\beta$: LOOP NMEs

$$M^{0\nu}_{\text{loops,soft}} = M^{0\nu}_{AA,\text{loops}} + M^{0\nu}_{VV,\text{loops}} + M^{0\nu}_{CT,\text{loops}}$$

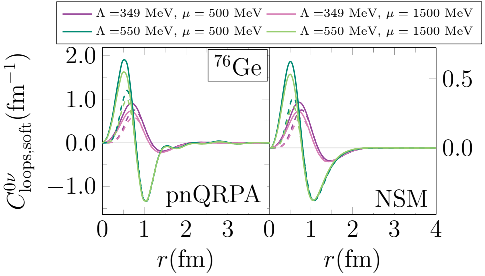
Results

- Important contributions in short-range distances
- Similar behaviour between models
- Main dependence $\rightarrow \Lambda$
  - $\Lambda = 349$ MeV $\Lambda = 550$ MeV
- Most reliable: $\Lambda = 349$

Uncertainties: H_{eff}, μ, Λ

$\mu \equiv$ Renormalization scale

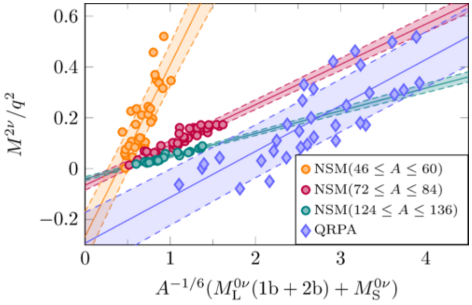
$$M^{0\nu}_{\text{loops,soft}} = \int_0^\infty C^{0\nu}_{\text{loops,soft}}(r)dr$$



DC, Jokiniemi, Menéndez, Soriano, Phys. Lett. B, 860, 2025

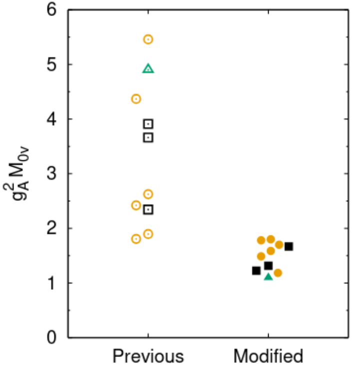
$0\nu\beta\beta$-$2\nu\beta\beta$ CONNECTION

Good correlation: systematic calculation of different nuclei



Jokiniemi et al. Phys. Rev. C 107, 044305, 2023

^{136}Xe: Uncertainty reduction of $0\nu\beta\beta$ NME using $2\nu\beta\beta$ experimental data



Civitarese et al. arXiv.2509.16605, 2025

$2\nu\beta\beta$: HALF-LIFE UP TO NLO

$$T^{2\nu}_{1/2} = g_A^4 (M_{\mathrm{GT}}^{-1})^2 \Delta_0 [G_0^{2\nu} + \xi_{31} \frac{\Delta_2}{\Delta_0} G_2^{2\nu} + G_4^{2\nu} (\xi_{51} \frac{\Delta_2}{\Delta_0} + \frac{1}{3}\xi_{31}^2) + G_{22}^{2\nu} + G_M^{2\nu}]$$

Taylor expansion

- $\xi_{31} = \frac{M_{\mathrm{GT}}^{-3}}{M_{\mathrm{GT}}^{-1}}$
- $\xi_{51} = \frac{M_{\mathrm{GT}}^{-5}}{M_{\mathrm{GT}}^{-1}}$
- $M_{\mathrm{GT}}^{-2m-1} \propto \frac{\langle 0_f^+ | \mathrm{GT} | 1_n^+ \rangle \langle 1_n^+ | \mathrm{GT} | 0_i^+ \rangle}{(E_n - \frac{1}{2}(E_i + E_f))^{2m+1}}$

Šimkovic et al. Phys. Rev. C, 97, 034315, 2018

NLO Corrections

- $G_M^{2\nu} \equiv$ New weak magnetism contribution
- $\Delta_0, \ \Delta_2 \equiv$ one-pion exchange terms and WM insertion (same NMEs than $M_{\mathrm{L}}^{0\nu}(m_\pi)$)

el Morabit et al. JHEP, 06, 082, 2025