Advances in

modeling neutrinoless double-beta decay in atomic nuclei with operators from chiral effective field theory

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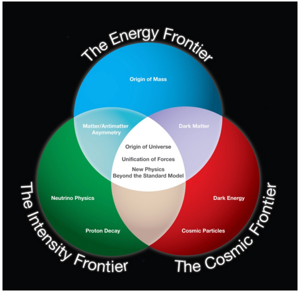
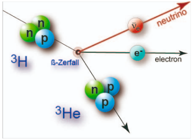
第八届手征有效场论研讨会，河南开封，2023年10月28日

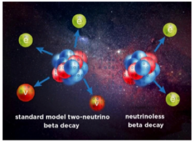
Outline

Low-energy nuclear probes into new physics

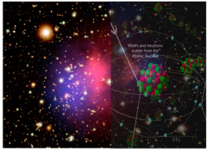




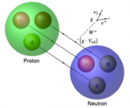
Single−beta decay



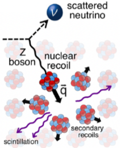
Neutrinoless double beta decay



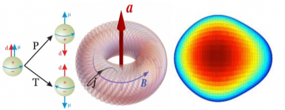
Dark matter direct detection



Superallowed Fermi transitions

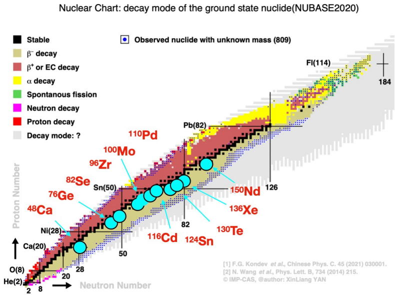


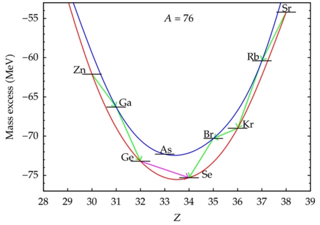
Neutrino scattering



Symmetry-violating moments

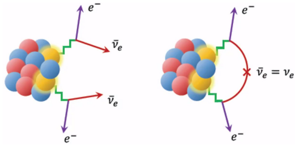
- Three frontiers: HE, LS, HP
- Atomic nuclei: low-energy probes
- $\beta(\beta)$ decay, WIMP-nucleus scattering, etc.
- All about Nuclear Matrix Elements (NME)



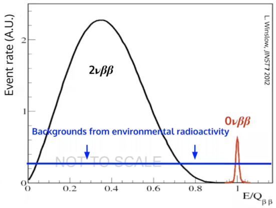


- The two modes of $\beta^-\beta^-$ decay:

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



- Kinetic energy spectrum of electrons



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Neutrino oscillation

- From mass to flavor states

$$|\nu_\alpha\rangle = \sum_{j=1}^{N=3} U^*_{\alpha j} |\nu_j\rangle .$$

- $\Delta m^2_{ij}(\neq 0)$, and $\theta_{ij}(\neq 0)$.

Open questions

- The nature of neutrinos.
- Neutrino mass m_j and its origin.

The observation of $0\nu\beta\beta$ decay would provide answers.

If $0\nu\beta\beta$ decay is driven by exchanging light massive Majorana neutrinos:

$$\langle m_{\beta\beta}\rangle \equiv |\sum_{j=1}^{3} U^2_{ej} m_j| = \left[\frac{m_e^2}{g_A^4 G_{0\nu} T^{0\nu}_{1/2} |M^{0\nu}|^2}\right]^{1/2}$$

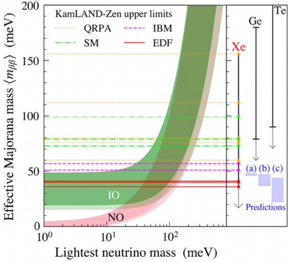
- U_{ej}: elements of the PMNS matrix
- $G_{0\nu}$: phase-space factor
- $M^{0\nu}$: the nuclear matrix element

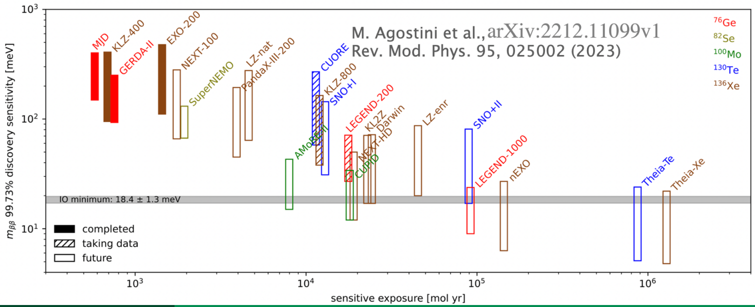
$$M^{0\nu} = \langle \Psi_F | \hat{O}^{0\nu} | \Psi_I \rangle$$

– Transition operator: $\hat{O}^{0\nu}$
– Nuclear many-body wfs: $|\Psi_{I/F}\rangle$

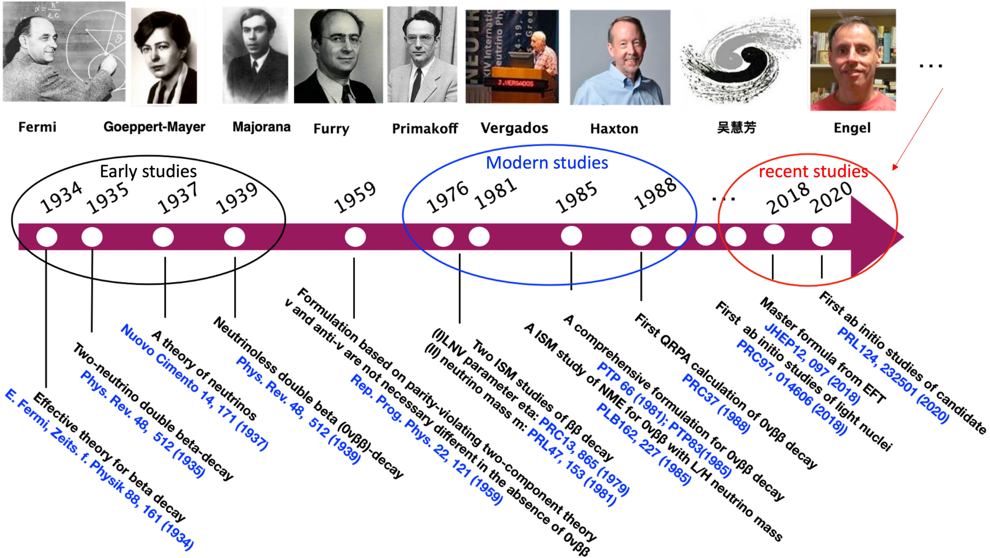
Constraints on neutrino mass from $0\nu\beta\beta$ decay

Isotope	$G_{0\nu}$ $[10^{-14}\ \mathrm{yr}^{-1}]$	$M^{0\nu}$ [min, max]	$T^{0\nu}_{1/2}$ [yr]	$\langle m_{\beta\beta}\rangle$ [meV]	Experiments References
^{48}Ca	2.48	[0.85, 2.94]	$> 5.8\cdot 10^{22}$	[2841, 9828]	CANDLES: PRC78, 058501 (2008)
^{76}Ge	0.24	[2.38, 6.64]	$> 1.8\cdot 10^{26}$	[73, 180]	GERDA: PRL125, 252502(2020)
^{82}Se	1.01	[2.72, 5.30]	$> 4.6\cdot 10^{24}$	[277, 540]	CUPID-0: PRL129, 111801 (2023)
^{96}Zr	2.06	[2.86, 6.47]	$> 9.2\cdot 10^{21}$	[3557, 8047]	NPA847, 168 (2010)
^{100}Mo	1.59	[3.84, 6.59]	$> 1.5\cdot 10^{24}$	[310, 540]	CUPID-Mo: PRL126, 181802(2021)
^{116}Cd	0.48	[3.29, 5.52]	$> 2.2\cdot 10^{23}$	[1766, 2963]	PRD 98, 092007 (2018)
^{130}Te	1.42	[1.37, 6.41]	$> 2.2\cdot 10^{25}$	[90, 305]	CUORE: Nature 604, 53(2022)
^{136}Xe	1.46	[1.11, 4.77]	$> 2.3\cdot 10^{26}$	[36, 156]	KamLAND-Zen: PRL130, 051801(2023)
^{150}Nd	6.30	[1.71, 5.60]	$> 2.0\cdot 10^{22}$	[1593, 5219]	NEMO-3: PRD 94, 072003 (2016)

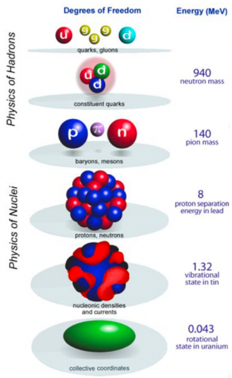


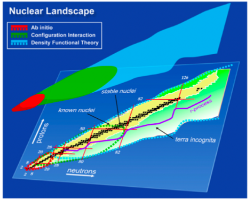


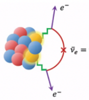
Brief history on modeling the $\beta(\beta\beta)$ decay rate



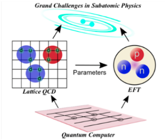
Development of nuclear models





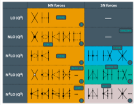


(Lattice) QCD for NP



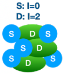
2010s — **ab initio methods**

2000s — **High-precision NN interactions** Entem, Machleidt (2003)

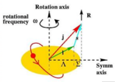


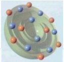
1990s — **Chiral EFT for NN interaction** Weinberg (1991)

1970s — **Self-consistent mean-field/EDF approaches**
Interacting Boson Models Arima, Iachello (1974) IBM

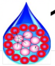


1950s — Hill, Griffin, Wheeler (1953,1957) GCM
Collective models Bohr and Mottelson (1953) PRM, BH
Shell models Bohm, Pines (1951-1953) RPA
Goeppert-Mayer (1949);
Haxel, Jensen, and Suess (1949) ISM

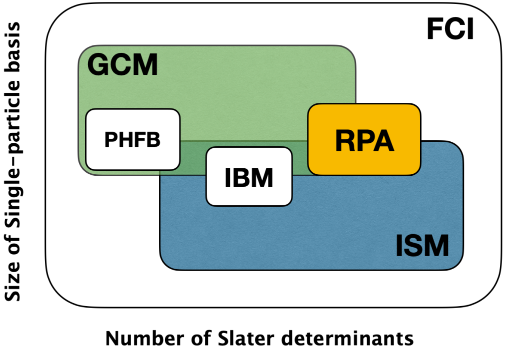




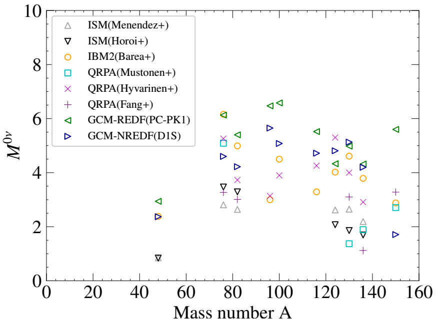
1930s — **Liquid drop model** von Weizsäcker (1935)



Comparison of nuclear models



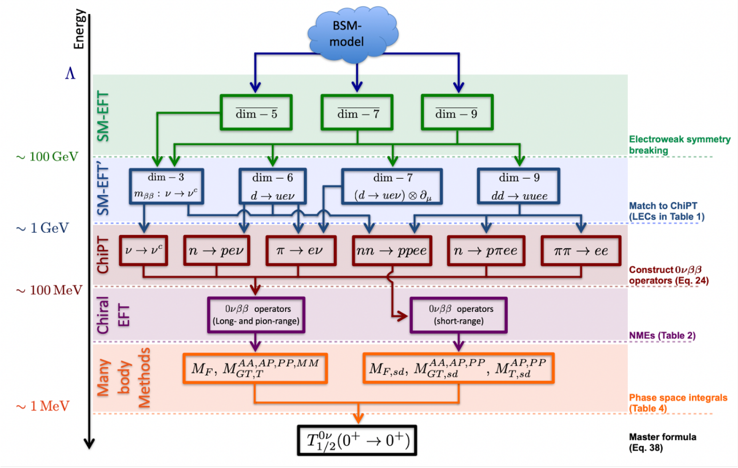
JMY, J. Meng, Y.F. Niu, P. Ring, PPNP 126, 103965 (2022)

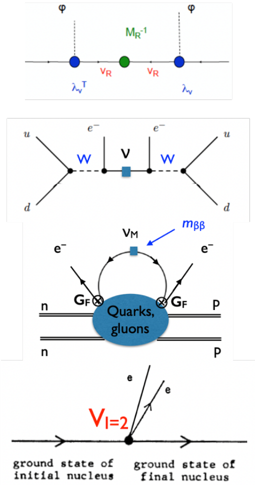


- ISM predicts small NMEs, while IBM and EDF predict large NMEs. Discrepancy is about a factor of THREE or even larger.
- Different models are not equivalent! Different schemes (model spaces and interactions): compare apples to oranges?
- Efforts in resolving the discrepancy: Challenging or even impossible?

EFT: a model-independent analysis of operators at different energy scales

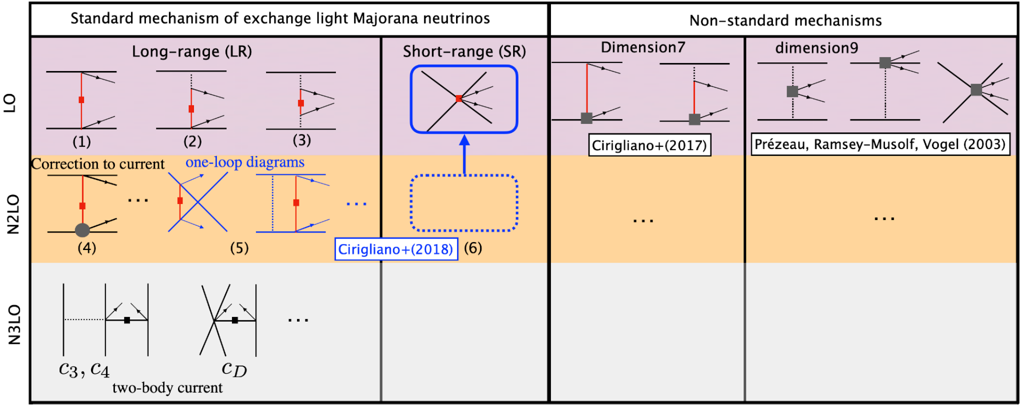
Cirigliano (2018)





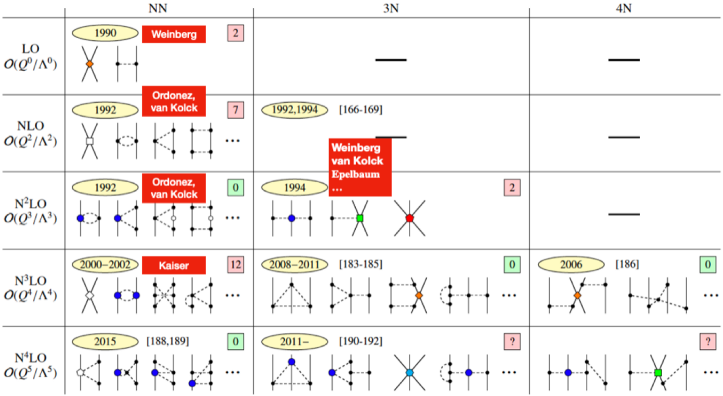
$0\nu\beta\beta$ decay operators from chiral EFT

- At $E \sim$100 MeV: operators are expressed in terms of nucleons, pions, and leptons.



Nuclear forces from chiral EFT

- Non-relativistic chiral 2N+3N interactions (Weinberg power counting and others)



K. Hebeler, Phys. Rep. 890, 1 (2020)

- Relativistic chiral 2N interaction (up to N^{2}LO, different PC from the NR case)

J.-X. Lu et al., PRL128, 142002 (2022)

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Ab initio methods for the lightest candidate ^{48}Ca

- Multi-reference in-medium generator coordinate method (IM-GCM)

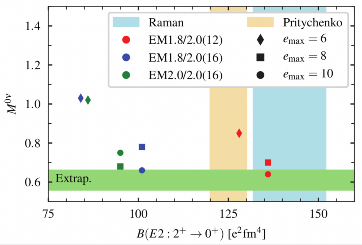
  JMY et al., PRL124, 232501 (2020)

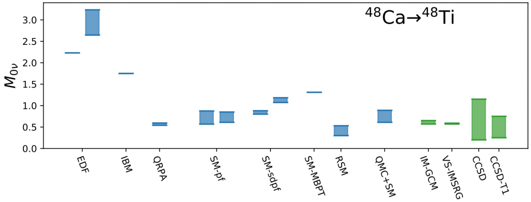
- IMSRG+ISM (VS-IMSRG)

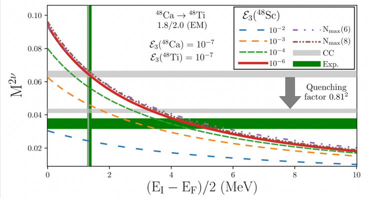
  A. Belley et al., PRL126, 042502 (2021)

- Coupled-cluster with singlets, doublets, and partial triplets (CCSDT1) .

  S. Novario et al., PRL126, 182502 (2021)







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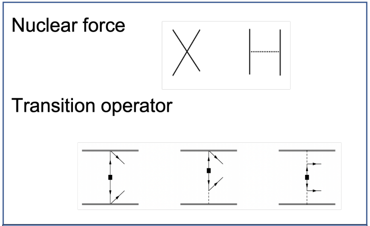
The missing piece in the LO transition operators

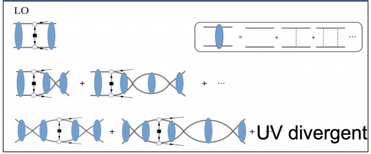
Featured in Physics | Editors' Suggestion | Open Access

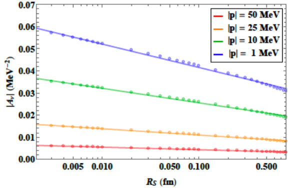
New Leading Contribution to Neutrinoless Double-β Decay

Vincenzo Cirigliano, Wouter Dekens, Jordy de Vries, Michael L. Graesser, Emanuele Mereghetti, Saori Pastore, and Ubirajara van Kolck
Phys. Rev. Lett. **120**, 202001 – Published 16 May 2018

Physics See Synopsis: A Missing Piece in the Neutrinoless Beta-Dec





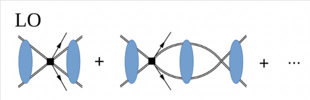


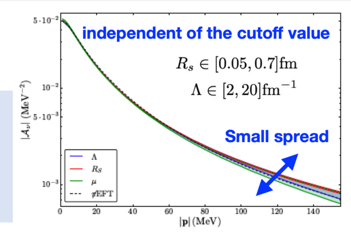
Lines fitted to $\mathcal{A}_\nu = a + b \ln R_S$

logarithmic dependence on R_S

Introducing a contact transition operator

$$V_{\nu,S} = -2 g_\nu^{NN} \tau^{(1)+} \tau^{(2)+}$$





- The transition amplitude is regulator-dependent!
- Needs a counter term at LO in order to ensure renormalizability.

The contact transition operator for $0\nu\beta\beta$ decay

Toward Complete Leading-Order Predictions for Neutrinoless Double β Decay

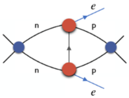
Vincenzo Cirigliano, Wouter Dekens, Jordy de Vries, Martin Hoferichter, and Emar Mereghetti

Phys. Rev. Lett. **126**, 172002 (2021) – Published 30 April 2021

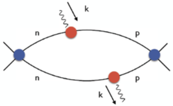
- **Cottingham formula** W.N. Cottingham, Ann. Phys. 25, 424 (1963)

$$\mathcal{A}_\nu \propto \int \frac{d^4k}{(2\pi)^4} \frac{g_{\mu\nu}}{k^2+i\epsilon} \int d^4x\, e^{ik\cdot x} \langle pp|T\{j_{\rm w}^\mu(x) j_{\rm w}^\nu(0)\}|nn\rangle$$

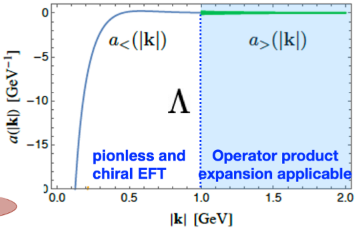
$$\mathcal{A}_\nu =$$



$$\propto \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2+i\epsilon}$$



forward Compton amplitude



$$\mathcal{A}_\nu^{\rm full} = \int_0^\infty d|\mathbf{k}|\; a^{\rm full}(|\mathbf{k}|) = \mathcal{A}^< + \mathcal{A}^>\,,$$

$$\mathcal{A}^< = \int_0^\Lambda d|\mathbf{k}|\; a_<(|\mathbf{k}|)\,,$$

$$\mathcal{A}^> = \int_\Lambda^\infty d|\mathbf{k}|\; a_>(|\mathbf{k}|)\,,$$

- **Synthetic datum**

$$\mathcal{A}_\nu(|\mathbf{p}|,|\mathbf{p}'|) \times e^{-i(\delta_{^1S_0}(|\mathbf{p}|)+\delta_{^1S_0}(|\mathbf{p}'|))} = -\Big(2.271 - 0.075\, \tilde{\mathcal{C}}_1(4\,M_\pi)\Big) \times 10^{-2}\,{\rm MeV}^{-2}$$

$$|\mathbf{p}| = 25\,{\rm MeV}\ (|\mathbf{p}'| = 30\,{\rm MeV}) \qquad = -1.95(5)_{\tilde{\mathcal{C}}_1} \times 10^{-2}\,{\rm MeV}^{-2}\,,$$

Uncertainty from the estimate of the **inelastic** contributions

The transition amplitude is observable and thus scheme independent.

A recent study in the relativistic chiral EFT shows that

- the $nn \to ppe^-e^-$ transition amplitude $\mathcal{A}_\nu$ is regulator-independent, thus no need to introduce the contact transition operator.
- The predicted $\mathcal{A}_\nu = 0.02085\mathrm{MeV}^{-2}$, about 10% larger than the value by Cirigliano (2021).
- The discrepancy could be attributed to the different power counting: the LO of relativistic chiral EFT contains partial N2LO contribution of non-relativvstic EFT.

Y.L. Yang and P. W. Zhao, arXiv:2308.03356v1 (2023)

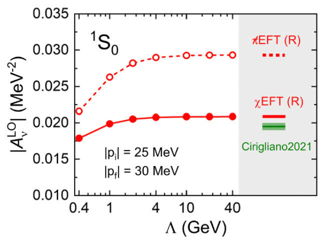
Bethe-Salpeter equation

$$T(\vec{p}\,', \vec{p}) = V(\vec{p}\,', \vec{p}) + \int \frac{d^3p''}{(2\pi)^3} V(\vec{p}\,', \vec{p}\,'') \frac{M_N^2}{E_{p''}} \frac{1}{p^2 - p''^2 + i\epsilon} T(\vec{p}\,'', \vec{p})$$

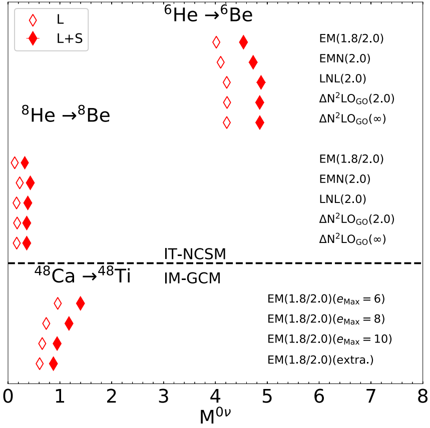
$$E_{p''} \equiv \sqrt{M_N^2 + p''^2}.$$

Lippmann-Schwinger equation

$$\widehat{T}(\vec{p}\,', \vec{p}) = \widehat{V}(\vec{p}\,', \vec{p}) + \int d^3p'' \widehat{V}(\vec{p}\,', \vec{p}\,'') \frac{M_N}{p^2 - p''^2 + i\epsilon} \widehat{T}(\vec{p}\,'', \vec{p})$$



- The LEC g_ν^{NN} consistent with the employed chiral interaction (EM1.8/2.0) is determined based on the synthetic data.
- The contact term turns out to enhance (instead of qunech) the NME for ^{48}Ca by 43(7)%, thus the half-life $T_{1/2}^{0\nu\beta\beta}$ is only half of the previously expected value.
- The uncertainty (7%) is due to the synthetic data which can be reduced by using an accurate value of the LEC (g_ν^{NN}).



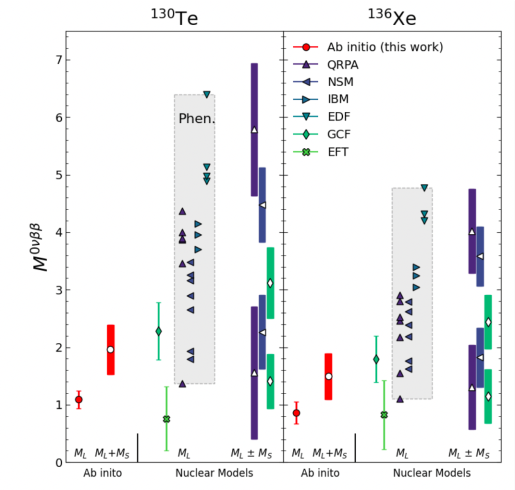
R. Wirth, JMY, H. Hergert, PRL127, 242502 (2021)

VS-IMSRG method for $0\nu\beta\beta$ decay of heavier candidates

With both the long- and short-range transition operators, the VS-IMSRG method is applied to study the NMEs of heavier candidates:

- For ^{130}Te, $M^{0\nu}_{L+S} \in [1.52, 2.40]$
- For ^{136}Xe, $M^{0\nu}_{L+S} \in [1.08, 1.90]$

Sources of uncertainty: Nuclear interaction, reference-state, basis extrapolation, closure approximation, and the LEC for the short-range transition operators.



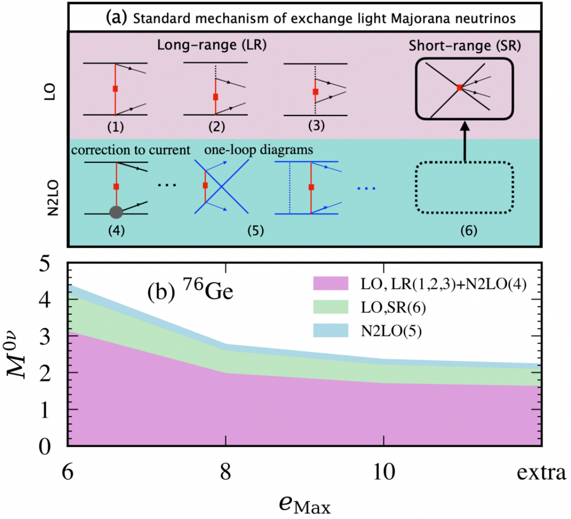
A. Belley et al, arXiv:2307.15156 (2023)

A more comprehensive uncertainty analysis in order

including the errors from

- many-body truncations
- chiral expansion orders

Convergence w.r.t. chiral expansion order for ^{76}Ge



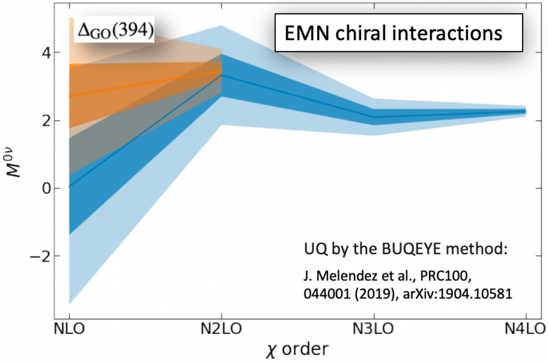
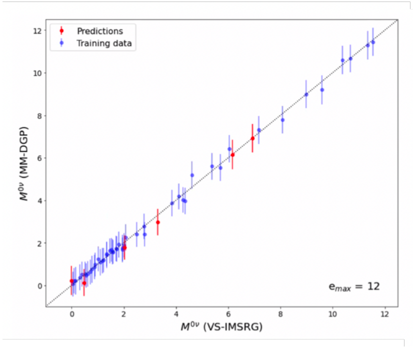


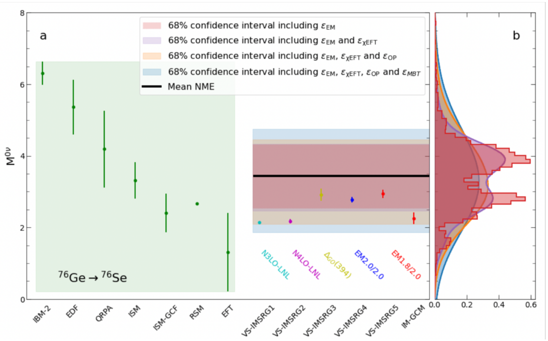
Table 1 | The recommended value for the total NME of $0\nu\beta\beta$ decay in ^{76}Ge, together with the uncertainties from different sources.

$M^{0\nu}$	ϵ_{LEC}	$\epsilon_{\chi EFT}$	ϵ_{MBT}	ϵ_{OP}	ϵ_{EM}
$3.44^{+1.33}_{-1.56}$	0.9	0.3	0.8	0.5	<0.06

A. Belley, JMY et al, arXiv:2308.15634 (2023)

Uncertainty quantification of NME for ^{76}Ge





- Emulator, 8188 samples of chiral interactions, phase shift, $M^{0\nu} = 3.44^{+1.33}_{-1.56}$.
- Current upper limit for the effective neutrino mass $\langle m_{\beta\beta}\rangle = 141^{+117}_{-39}$ meV.
- The next-generation ton-scale Germanium experiment ($\sim 1.3 \times 10^{28}$ yr): $m_{\beta\beta} = 17^{+14}_{-5}$ meV, covering almost the entire range of IO hierarchy.

A. Belley, JMY et al, arXiv:2308.15634 (2023)

- $0\nu\beta\beta$ decay: lepton-number-violation process, a complementary way to determine the absolute mass scale of neutrinos.
- Next-generation experiments: tonne-scale detectors with a half-life sensitivity up to 10^{28} years.
- Large uncertainty in NMEs: systematical uncertainty, impacting extracted neutrino mass, attracting a lot of efforts from nuclear community.
- Ab initio studies of NMEs: remarkable progress, disclosing non-trivial contributions from high-energy light neutrinos. The NMEs for heavier candidate nuclei (^{48}Ca, ^{76}Ge, ^{82}Se, ^{130}Te, ^{136}Xe) have been computed. Convergence w.r.t. the chiral expansion order is rather rapid.

Next

- Considering higher-order nuclear interactions, reducing many-body truncation errors, and finding more constraints to shrink the uncertainty.
- Contributions from other mechanisms.

Collaborators

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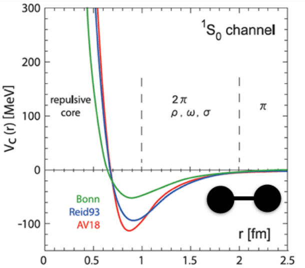
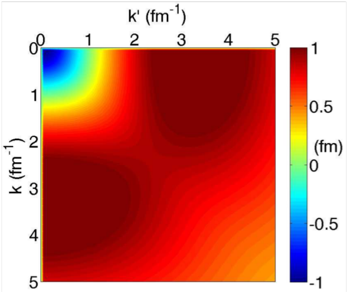
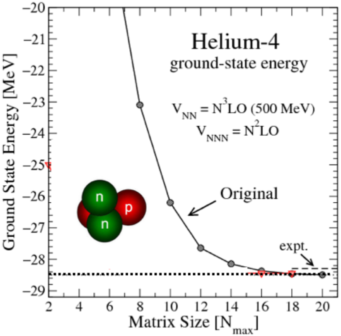
Thank you for your attention!







- Repulsive core & strong tensor force: low and high k modes strongly coupled.
- non-perturbative, poorly convergence in basis expansion methods.

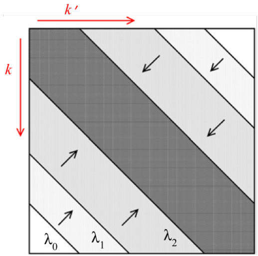
S. Bogner et al., PPNP (2010)

- Apply unitary transformations to Hamiltonian

$$H_s = U_s H U_s^\dagger \equiv T_{\rm rel} + V_s$$

from which one finds the flow equation

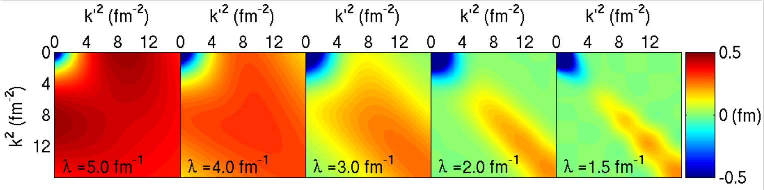
$$\frac{dH_s}{ds} = [\eta_s, H_s], \quad \eta_s = [T_{\rm rel}, H_s]$$

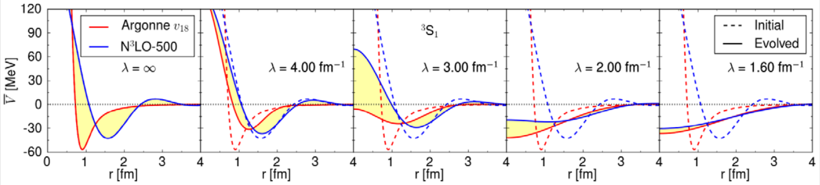


The flow parameter s is usually replaced with $\lambda = s^{-1/4}$ in units of fm^{-1}. S. K. Bogner etal. (2007)

Evolution of the potential

$$\frac{dV_s(k,k')}{ds} = -(k^2 - k'^2)V_s(k,k') + \frac{2}{\pi}\int_0^\infty q^2 dq (k^2 + k'^2 - 2q^2) V_s(k,q) V_s(q,k')$$





Local projection of AV18 and N^3LO(500 MeV) potentials $V(r)$.

- The hard core ”disappears” in the softened interactions

S. K. Bogner et al. (2010); Wendt et al. (2012)

ab initio description of deformed nuclei