Modeling neutrinoless double-beta decay with operators from chiral effective field theory

Jiangming Yao (尧江明)

中山大学物理与天文学院

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Outline

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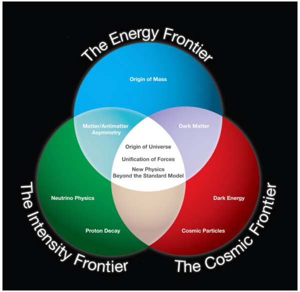
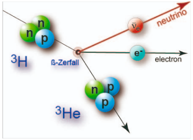
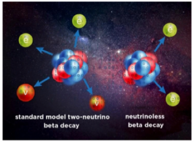
Low-energy nuclear probes of new physics

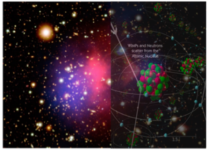




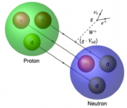
Single-beta decay



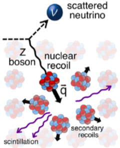
Neutrinoless double beta decay



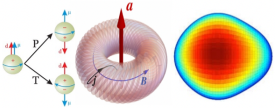
Dark matter direct detection



Superallowed Fermi transitions



Neutrino scattering

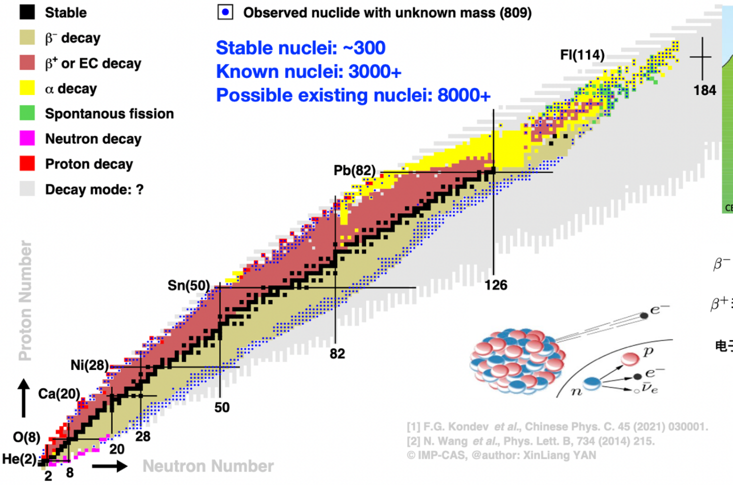


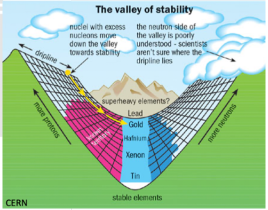
Symmetry-violating moments

- Three frontiers: for new physics
- Atomic nuclei: low-energy probes
- Fundamental interactions and symmetries.
- All about Nuclear Matrix Elements (NME)

Stability of atomic nuclei against single-β decay

Nuclear Chart: decay mode of the ground state nuclide(NUBASE2020)





[1] F.G. Kondev *et al.*, Chinese Phys. C. 45 (2021) 030001.
[2] N. Wang *et al.*, Phys. Lett. B, 734 (2014) 215.
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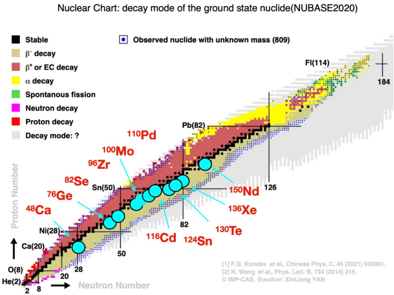
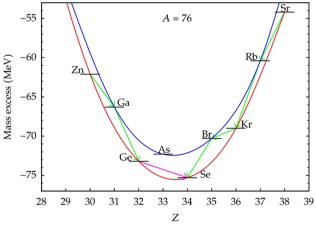
β^- 衰变 $\quad {}^A_Z\mathrm{X}_N \to {}^{\ A}_{Z+1}\mathrm{Y}_{N-1} + \mathrm{e}^- + \bar{\nu}_\mathrm{e},$

β^+ 衰变 $\quad {}^A_Z\mathrm{X}_N \to {}^{\ A}_{Z-1}\mathrm{Y}_{N+1} + \mathrm{e}^+ + \nu_\mathrm{e},$

电子俘获 $\quad {}^A_Z\mathrm{X}_N + \mathrm{e}^- \to {}^{\ A}_{Z-1}\mathrm{Y}_{N+1} + \nu_\mathrm{e},$

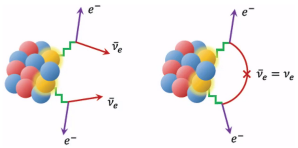
A special decay mode: $0\nu\beta\beta$ decay



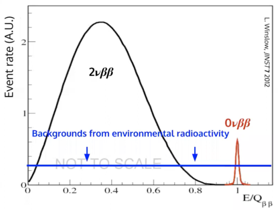


- The two modes of $\beta^-\beta^-$ decay:

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



- Kinetic energy spectrum of electrons



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

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

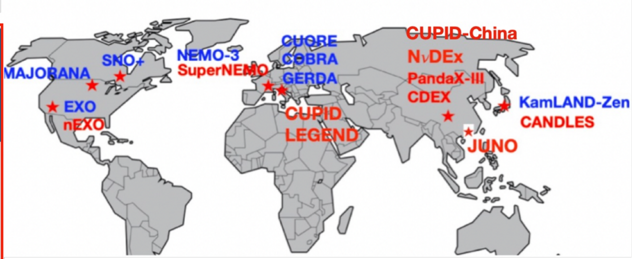
– Transition operator: $\hat{O}^{0\nu}$

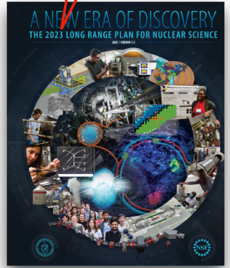
– Nuclear many-body wfs: $\left|\Psi_{I/F}\right\rangle$

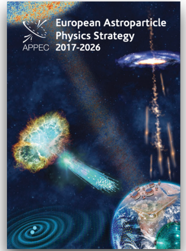
Current and next-generation of experiments

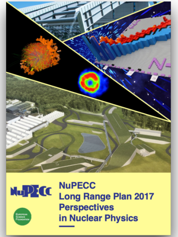
RECOMMENDATION 2
As the highest priority for new experiment construction, we recommend that the United States lead an international consortium that will undertake a neutrinoless double beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques.

One of the most compelling mysteries in all of science is how matter came to dominate over antimatter in the universe. Neutrinoless double beta decay, a process that spontaneously creates matter, may hold the key to solving this puzzle. Observation of this rare nuclear process would unambiguously demonstrate that neutrinos are their own antiparticles and would reveal the origin and scale of neutrino mass. The nucleus provides the only laboratory through which this fundamental physics can be addressed.



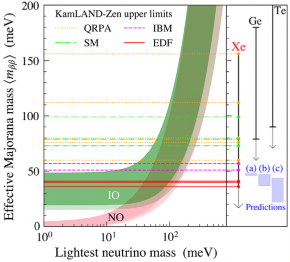






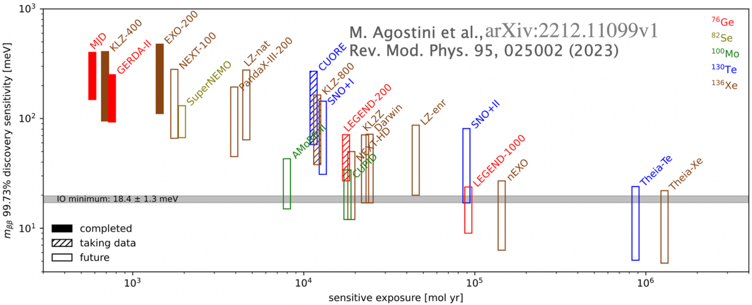
Constraints on neutrino mass from $0\nu\beta\beta$ decay

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]	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)



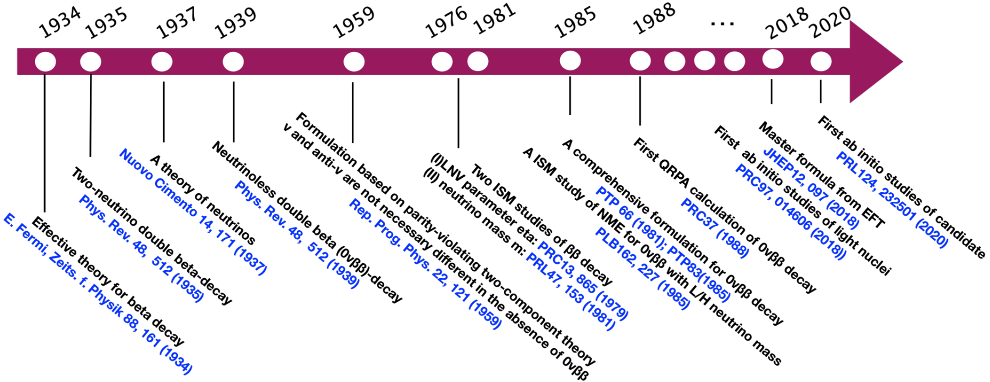
- The neutrino oscillation measurements: $\langle m_{\beta\beta}\rangle \in [20, 50]$ meV for the inverted-ordering (IO) case.
- An uncertainty of a factor of about 3 or even more (originated from the NMEs) in the $\langle m_{\beta\beta}\rangle$ determined by $0\nu\beta\beta$-decay.

Next-generation of experiments

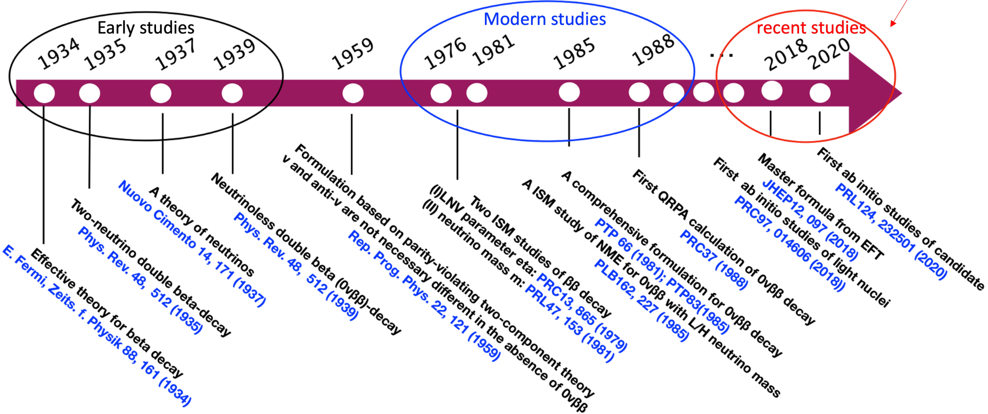


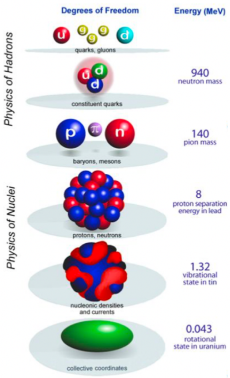
- Lifetime sensitivity of the ton-scale experiments: $> 10^{28}$yr.
- Covering the entire parameter space for the IO neutrino masses depending strongly on the employed NME.

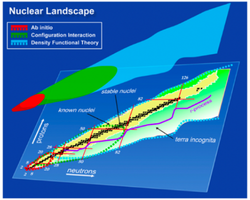
Fermi Goeppert-Mayer Majorana Furry Primakoff Vergados Haxton 吴慧芳 Engel ...

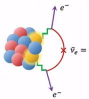


Brief history on modeling the $\beta(\beta\beta)$ decay rate

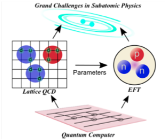




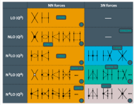




(Lattice) QCD for NP



2010s — **ab initio methods**

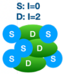


2000s — **High-precision NN interactions** Entem, Machleidt (2003)

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

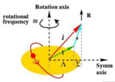
1970s — **Self-consistent mean-field/EDF approaches**

Interacting Boson Models Arima, Iachello (1974) IBM



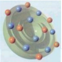
Hill, Griffin, Wheeler (1953,1957) GCM

1950s — **Collective models** Bohr and Mottelson (1953) PRM, BH

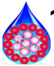


Shell models Bohm, Pines (1951-1953) RPA

Goeppert-Mayer (1949); Haxel, Jensen, and Suess (1949) ISM



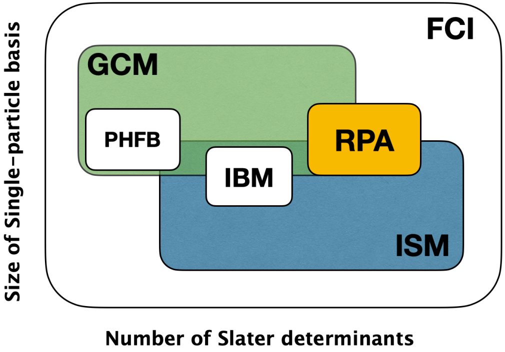
1930s — **Liquid drop model** von Weizsäcker (1935)



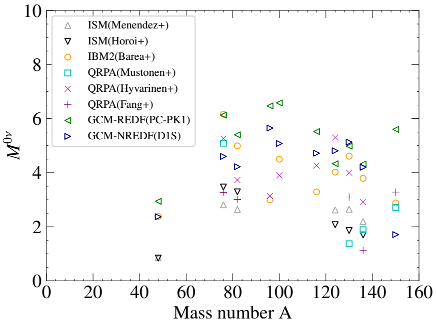
Modern studies with phenom. nuclear forces

- Interacting shell models (ISM) Vergados (1976), Haxton (1981), H.F.Wu (1985, 1993), Caurier (2008), Menéndez (2009), Horoi (2010), Coraggio (2020)
- Particle-number (and angular-momentum) projected BCS (HFB) with a schematic (PP+QQ) hamiltonian Grotz, Klapdor (1985), Chandra (2008), Rath (2010), Hinohara (2014)
- Quasi-particle random-phase approx. (QRPA) with a G-matrix residual interaction Vogel-2ν (1986), Engel (1988), Rodin (2003), Faessler (1998), Simkovic (1999), Fang (2010) or EDF Mustonen (2013), Terasaki (2015), Lv(2023), Bai (2023?)
- Interacting Boson Models (IBM) Barea (2009, 2012)
- GCM+EDFs Rodríguez (2010), Song (2014, 2017), Yao (2015)
- Angular momentum projected interacting shell model based on an effective interaction Iwata, Shimizu (2016), Jiao (2017, 2019) or REDF Wang (2021, 2023)
- Others: Generalized-seniority scheme Engel, Vogel, Ji, Pittel (1989)

Comparison of nuclear models



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



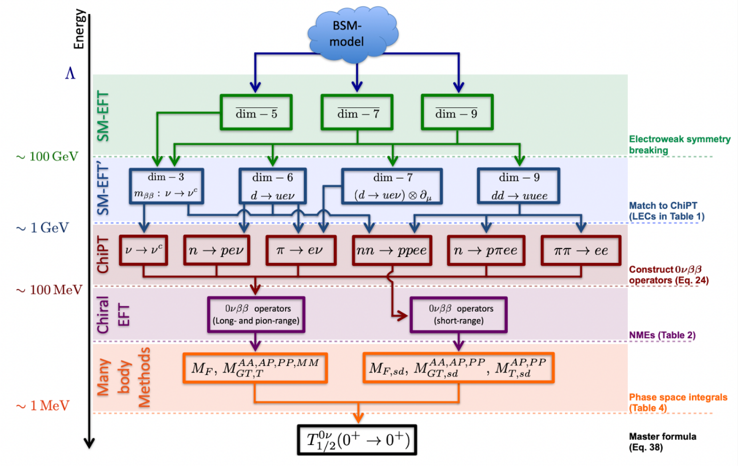
- ISM predicts small NMEs, while IBM and EDF predict large NMEs. Discrepancy is about a factor of THREE or even larger.
- Different models are not equivalent! Different schemes (model spaces and interactions): compare apples to oranges?
- Efforts in resolving the discrepancy: Challenging or even impossible?

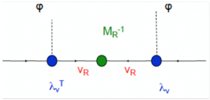
Strategy

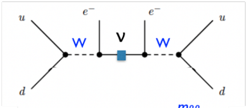
- Operator forms: (Chiral) effective field theory (EFT) to specify the forms of nuclear forces and weak transition operators (at different expansion orders of Q/Λ_χ).
- Low-energy constants (LECs): data on NN scattering and few-body system or Lattice QCD calculations.
- Many-body solvers: A systematically improvable nuclear model to solve the quantum many-body problem.

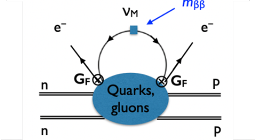
EFT: a model-independent analysis of operators at different energy scales

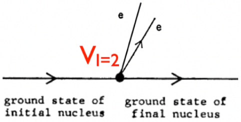
Cirigliano (2018)











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

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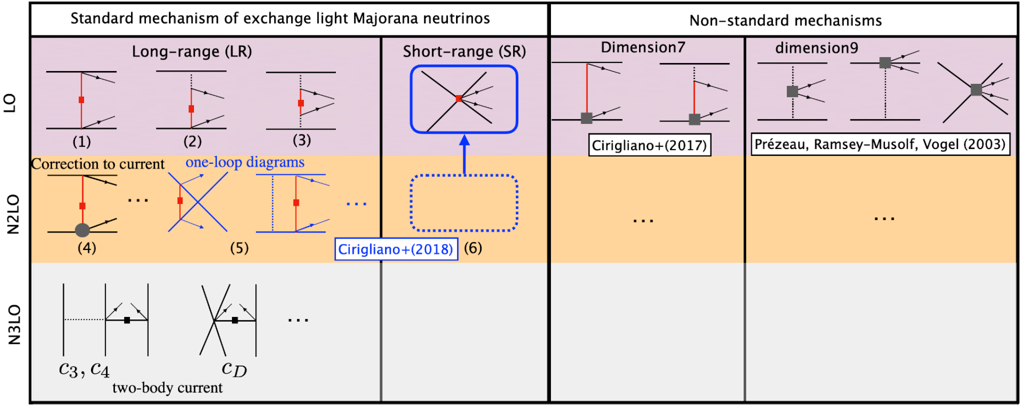
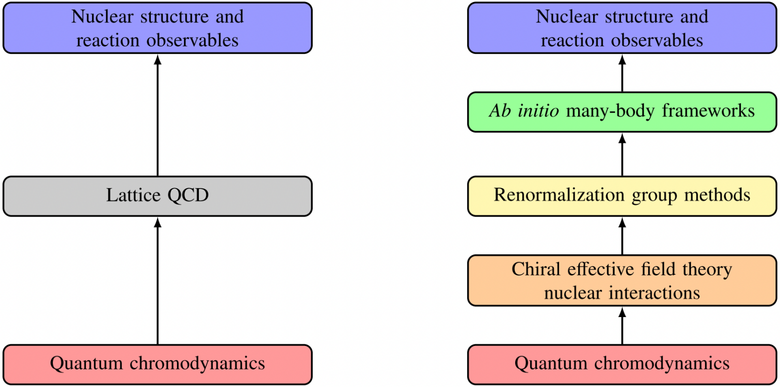
- At E ~100 MeV: operators are expressed in terms of nucleons, pions, and leptons.

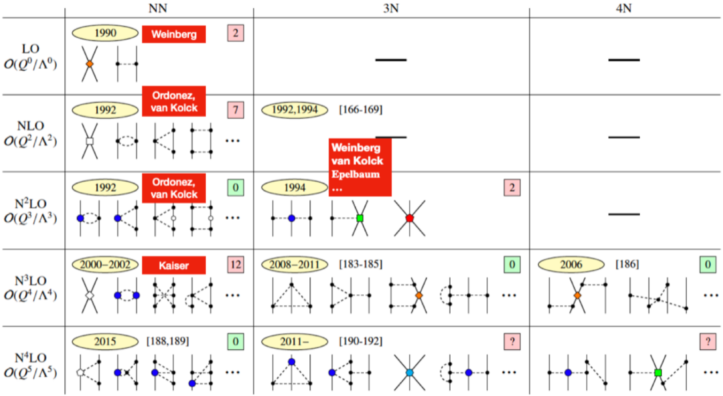




K. Hebeler, Phys. Rep. 890, 1 (2021)

Nuclear forces from chiral EFT

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

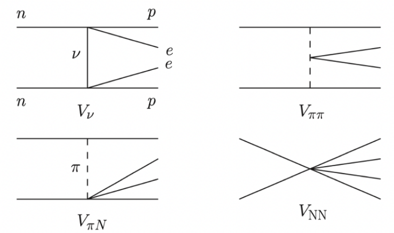


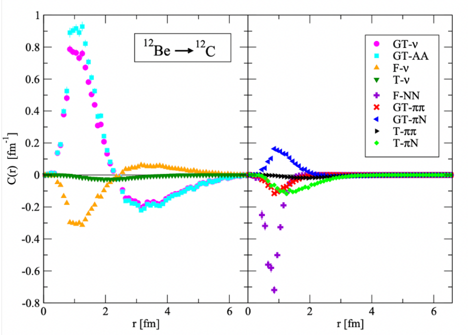
K. Hebeler, Phys. Rep. 890, 1 (2020)

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

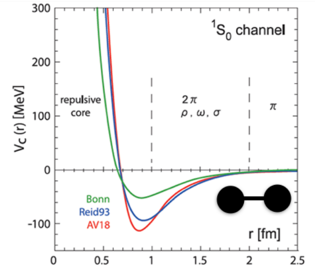
J.-X. Lu et al., PRL128, 142002 (2022)

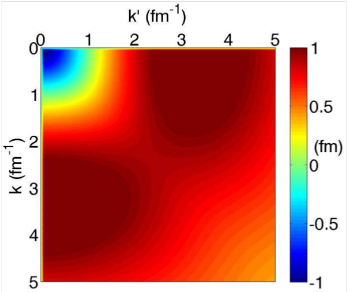
The Monte-Carlo studies of $0\nu\beta\beta$ decay in light nuclei

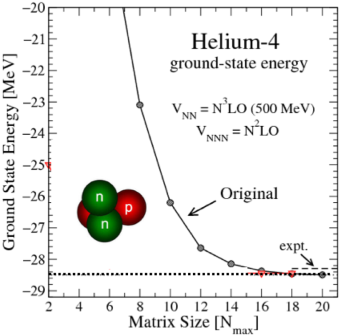




- The variational Monte Carlo (VMC) with the NN(AV18) + 3N(Illinois-7).
- Light Majorana neutrino exchange + multi-TeV (dim9) mechanisms of LNV.
- The N^{2}LO effects captured by nucleon form factors impact the matrix elements at 10% level.
- The non-factorizable terms at N2LO may lead to O(10%) corrections.
- indicating that the NME converges with the chiral expansion order for the weak operators.
- Difficult to extend to the candidate nuclei of $0\nu\beta\beta$ decay.







- 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)

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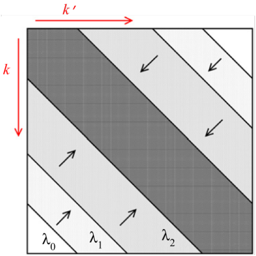
- Apply unitary transformations to Hamiltonian

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

from which one finds the flow equation

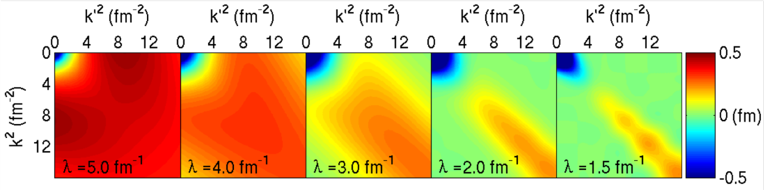
$$\frac{dH_s}{ds} = [\eta_s, H_s], \quad \eta_s = [T_{\rm rel}, H_s]$$

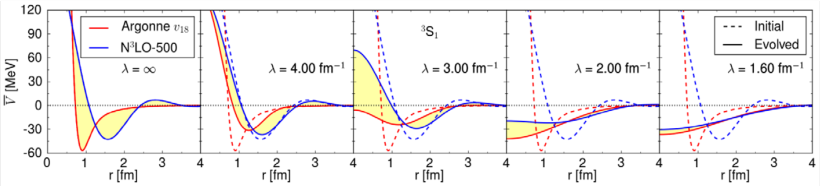


The flow parameter s is usually replaced with $\lambda = s^{-1/4}$ in units of fm^{-1}. S. K. Bogner etal. (2007)

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^{3}LO(500 MeV) potentials $V(r)$.

- The hard core "disappears" in the softened interactions

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

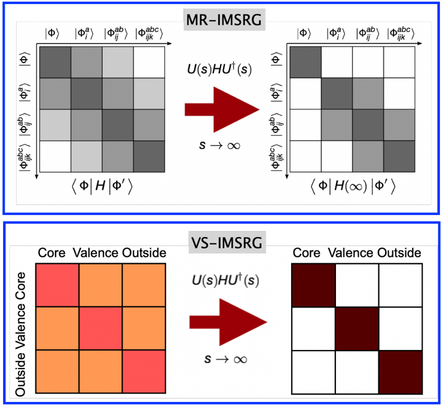
- Unitary transformations

$$H(s) = U(s) H_0 U^\dagger(s)$$

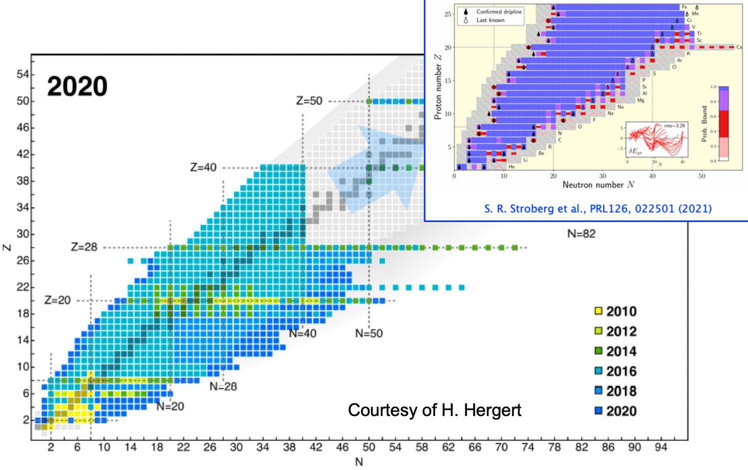
Flow equation

$$\frac{dH(s)}{ds} = [\eta(s), H(s)]$$

- Generator $\eta(s)$: chosen either to decouple a given reference state from its excitations or to decouple the valence space from the excluded spaces.
- Not necessary to construct the whole H matrix, computation complexity scales polynomially with nuclear size.

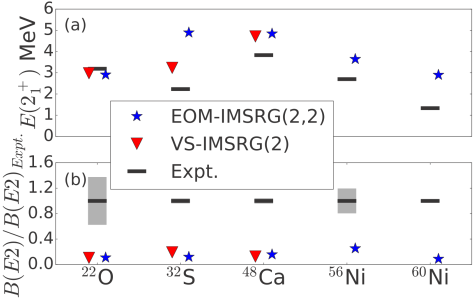


H. Hergert et al., Phys. Rep. 621, 165 (2016); S. R. Stroberg et al., Annu. Rev. Nucl. Part. Sci. 69, 307 (2019)

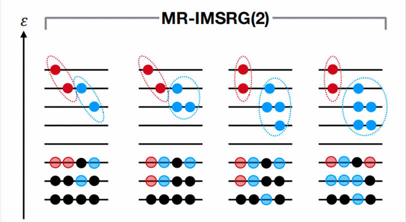


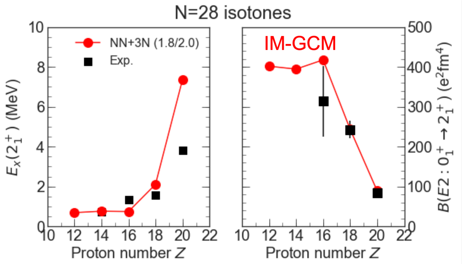
First-principles calculations predict the properties of nearly 700 isotopes between helium and iron

S. R. Stroberg et al., PRL126, 022501 (2021)



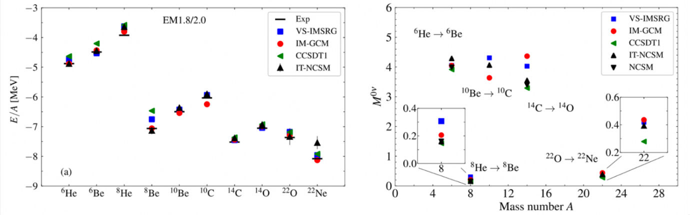
N. M. Parzuchowski et al., PRC(2017)



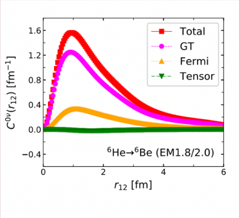


- The single-reference VS-IMSRG(2) is difficult to capture collective correlations.
- The IM-GCM (multi-reference IMSRG+GCM) is capable to describe deformed nuclei.

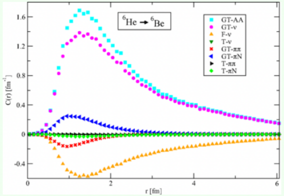
JMY et al., PRC103, 014315 (2021)



IM-GCM (EM1.8/2.0)



S. Pastore et al (2018)



Note: A factor of $-g_A^2$ has been multiplied into the Fermi part.

- Using different ab initio methods but the same input to estimate of the truncation errors of many-body methods.

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

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

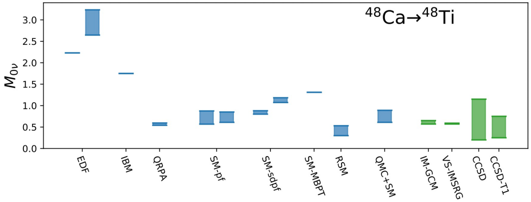
  JMY et al., PRL124, 232501 (2020)

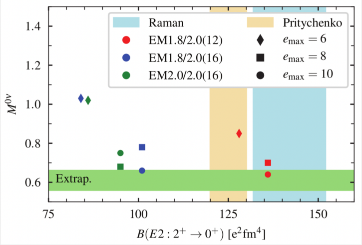
- IMSRG+ISM (VS-IMSRG)

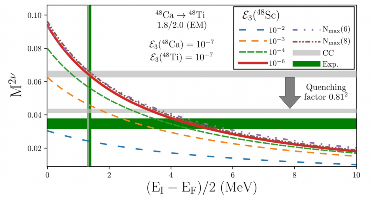
  A. Belley et al., PRL126, 042502 (2021)

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

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







The missing piece in the LO transition operators

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New Leading Contribution to Neutrinoless Double-β Decay

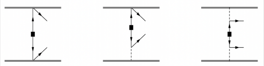
Vincenzo Cirigliano, Wouter Dekens, Jordy de Vries, Michael L. Graesser, Emanuele Mereghetti, Saori Pastore, and Ubirajara van Kolck

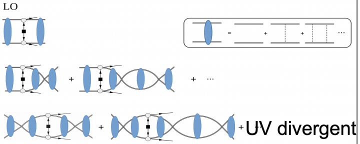
Phys. Rev. Lett. **120**, 202001 – Published 16 May 2018

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

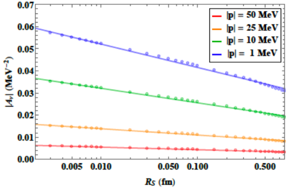
Nuclear force

Transition operator





UV divergent



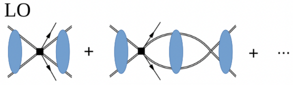
Lines fitted to $\mathcal{A}_\nu = a + b \ln R_S$

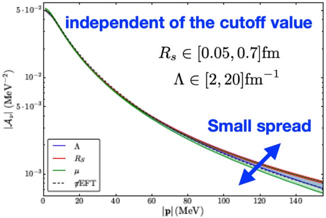
logarithmic dependence on R_s

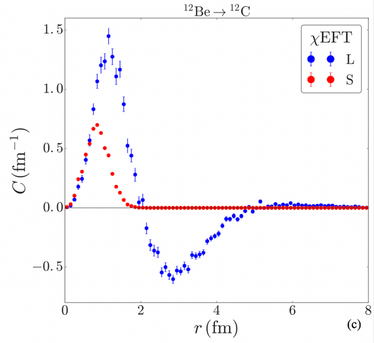
- The transition amplitude is regulator-dependent!
- Needs a counter term at LO in order to ensure renormalizability.

Introducing a contact transition operator

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







A	Model	M_L	M_S	Uncertainty
6	AV18	7.45	0.48	
	χEFT	7.82	1.15	+/-16%
12	AV18	0.653	0.518	
	χEFT	0.725	0.533	+/-73%

V. CIRIGLIANO *et al*. PRC **100**, 055504 (2019)

According to the VMS calculation, the contribution of the contact transition operator

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

to the NME of $0\nu\beta\beta$ decay of

- ^{6}He could be up to $\sim \pm 16\%$
- ^{12}Be could be up to $\sim \pm 73\%$

The actual contribution depends on the value of the LEC g_ν^{NN}, which should be determined by the data of the process or the calculation of a more fundamental theory for the process.

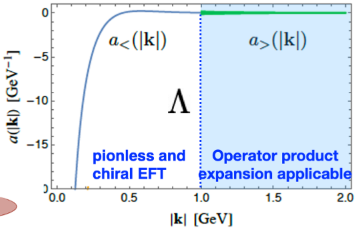
Toward Complete Leading-Order Predictions for Neutrinoless Double β Decay

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

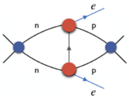
Phys. Rev. Lett. **126**, 172002 (2021) – Published 30 April 2021

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

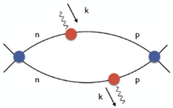
$$\mathcal{A}_\nu \propto \int \frac{d^4k}{(2\pi)^4}\frac{g_{\mu\nu}}{k^2+i\epsilon}\int d^4x\, e^{ik\cdot x}\langle pp|T\{j^\mu_{\rm w}(x)j^\nu_{\rm w}(0)\}|nn\rangle$$



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



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



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**

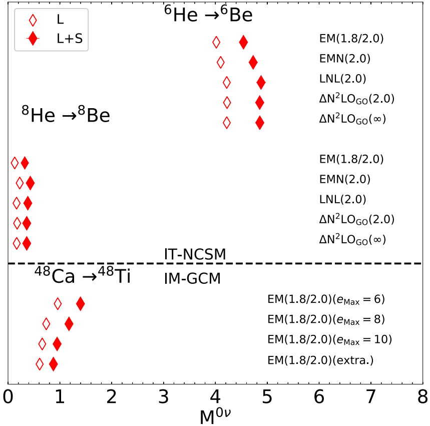
$$\mathcal{A}_\nu(|\mathbf{p}|,|\mathbf{p}'|)\times e^{-i(\delta_{^1S_0}(|\mathbf{p}|)+\delta_{^1S_0}(|\mathbf{p}'|))} = -\left(2.271 - 0.075\,\tilde{\mathcal{C}}_1(4\,M_\pi)\right)\times 10^{-2}\,\mathrm{MeV}^{-2}$$

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

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

The transition amplitude is observable and thus scheme independent.

- 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)

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

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-relativstic EFT.

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

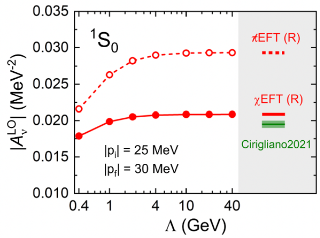
Bethe-Salpeter equation

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

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

Lippmann-Schwinger equation

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



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

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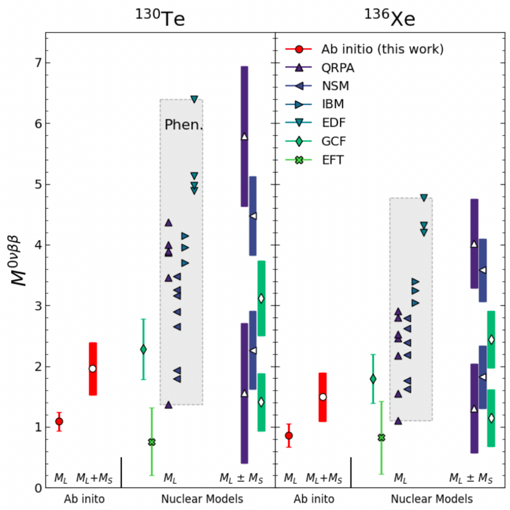
With both the long- and short-range transition operators, the VS-IMSRG method is applied to study the NMEs of heavier candidates:

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

The uncertainty is composed of different sources: nuclear interaction, reference-state, basis extrapolation, closure approximation, and the LEC for the short-range transition operators.

The values are generally smaller than those from phenomenological nuclear models.

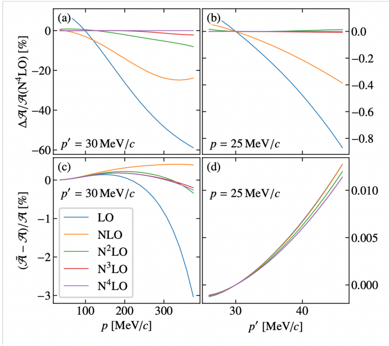
A. Belley et al, arXiv:2307.15156 (2023)



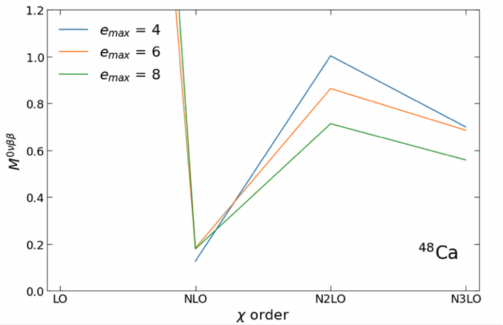
A more comprehensive quantification analysis

different nuclear many-body solvers, convergence of NMEs with chiral expansion orders, etc.

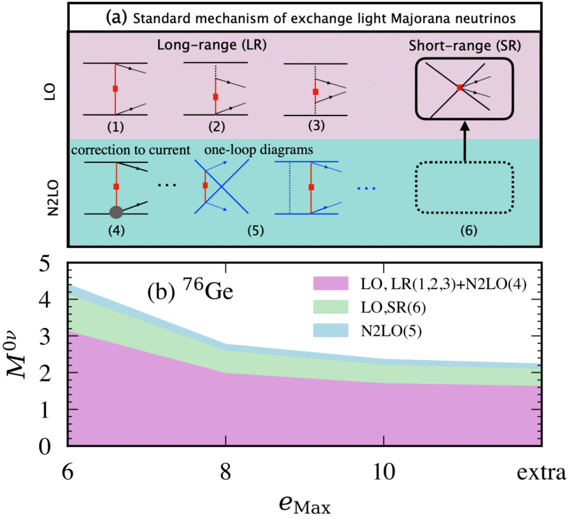
$2n \to 2p + 2e^-$



$^{48}\mathrm{Ca} \to ^{48}\mathrm{Ti} + 2e^-$



- The $\mathcal{A}_\nu(2n \to 2p + 2e^-)$ converges quickly w.r.t. the chiral expansion order of nuclear interactions. Negligible contribution beyond NLO, particular true for low momentum cases. R. Wirth, JMY, H. Hergert, PRL127, 242502 (2021)
- Convergence is slightly slower in candidate nucleus ^{48}Ca.



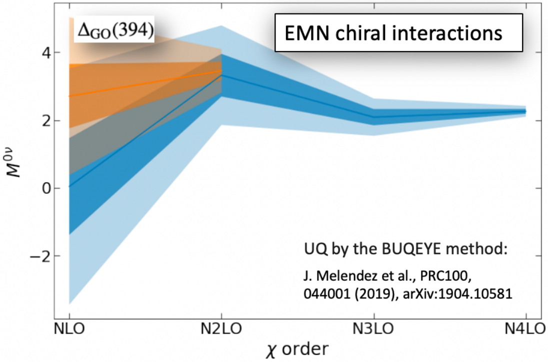
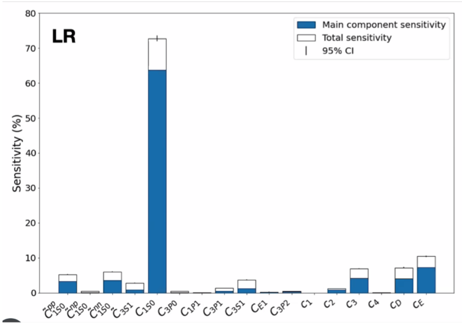


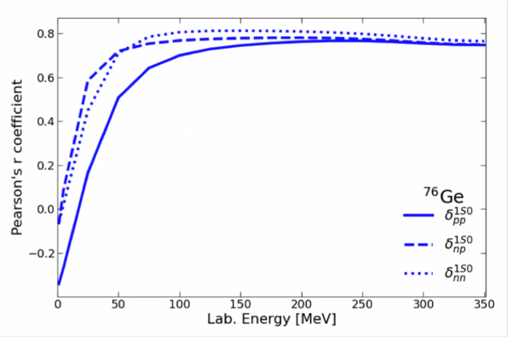
Table 1 | The recommended value for the total NME of $0\nu\beta\beta$ decay in ^{76}Ge, together with the uncertainties from different sources.

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

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

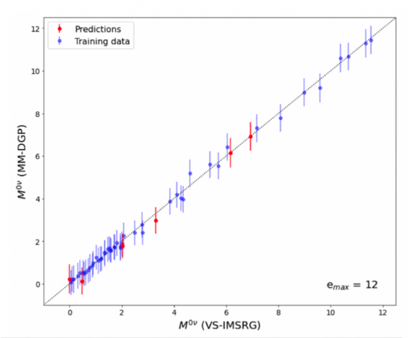
Uncertainty quantification of NME for ^{76}Ge

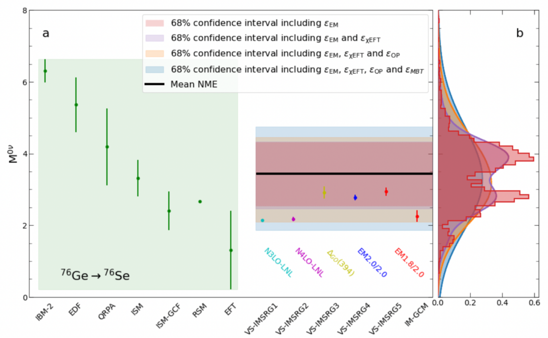




- The long-range part of the NME is sensitive to the LEC $C_{^1S_0}$.
- The phase shift of the $^1S_0$ channel is linearly correlated to the NME.
- The neutron-proton phase-shift δ_{np}^{1S0} at 50 MeV is used to weight the samples.

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)

Summary and perspective

- $0\nu\beta\beta$ 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.

Acknowledgements

Collaborators

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- SCU: Chunlin Bai
- IMP, CAS: Dongliang Fang
- SWU: Longjun Wang
- MSU: Scott Bogner, Heiko Hergert, Roland Wirth
- UNC: Jonathan Engel, A. M. Romero
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- Notre-Dame U: Ragnar Stroberg
- UAM: Benjamin Bally, Tomas Rodriguez

Thank you for your attention!

Beta decay and axial-vector coupling strength g_A

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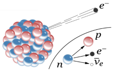
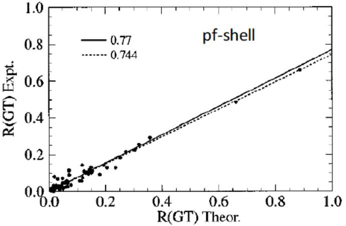
- The half-life of single-beta decay



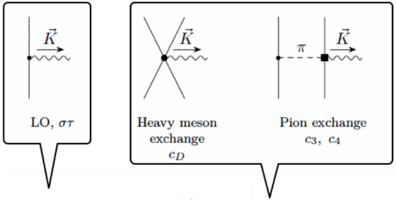
$$t_{1/2} = \frac{\kappa}{f_0(B_F + B_{\rm GT})},$$

$$B_F = \frac{g_V^2}{2J_i+1}|M_F|^2, \quad B_{\rm GT} = \frac{g_A^2}{2J_i+1}|M_{\rm GT}|^2$$

G. Martinez-Pinedo et al, PRC **53**, R2602 (1996)



- The charge-changing axial-vector current



$$\vec{J}^A(\vec{K}) = \sum_j \imath g_A \boldsymbol{\sigma}_j \boldsymbol{\tau}_j^{\pm} e^{\imath \vec{K}\cdot\vec{r}_j}.$$

2B currents

Park, T.-S. et al. PRC67, 055206 (2003);
M. Hoferichter et al., PRD102, 074018 (2020)

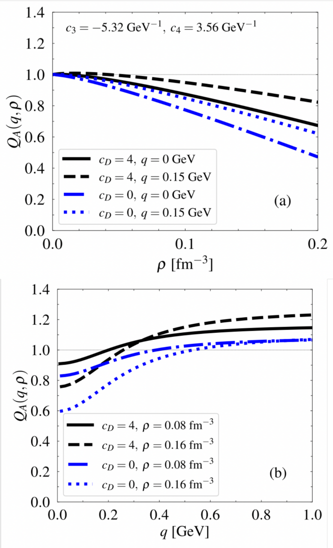
$$g_A^{\rm eff}(q,0,\rho) \equiv g_A\left\{1 - \frac{\rho}{f_\pi^2}\left[-\frac{c_D}{4}\frac{1}{g_A\Lambda_\chi} + \frac{2c_3}{3}\frac{q^2}{4m_\pi^2+q^2} + \frac{I(\rho,0)}{3}\left(2c_4 - c_3 + \frac{1}{2m_p}\right)\right]\right\}$$

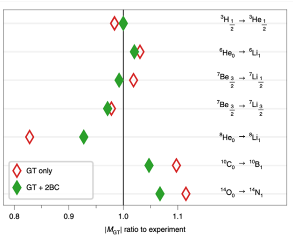
The quenching factor:

$$\mathcal{Q}_A(q,\rho) \equiv g_A^{\text{eff}}(q,\rho)/g_A = 1 + A[q]\rho + B\rho^{1/3} + C$$

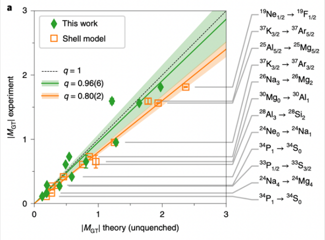
where the coefficients A, B and C are defined as

$$\begin{aligned} A[q] &= \frac{c_D}{4f_\pi^2}\frac{1}{g_A\Lambda_\chi} - \frac{1}{3f_\pi^2}\left[\left(2c_4 - c_3 + \frac{1}{2m_p}\right) + 2c_3\frac{q^2}{4m_\pi^2 + q^2}\right] \\ B &= \frac{m_\pi^2}{f_\pi^2}\left(\frac{2}{3\pi^2}\right)^{2/3}\left(2c_4 - c_3 + \frac{1}{2m_p}\right), \\ C &= -\frac{2m_\pi^3}{3\pi^2 f_\pi^2}\left(2c_4 - c_3 + \frac{1}{2m_p}\right)\tan^{-1}\left(\frac{k_F}{m_\pi}\right). \end{aligned}$$

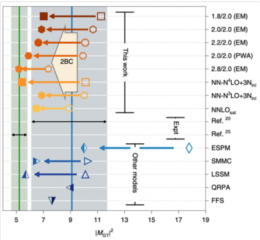




NCSM



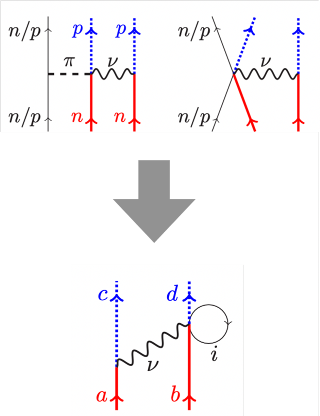
VS-IMSRG

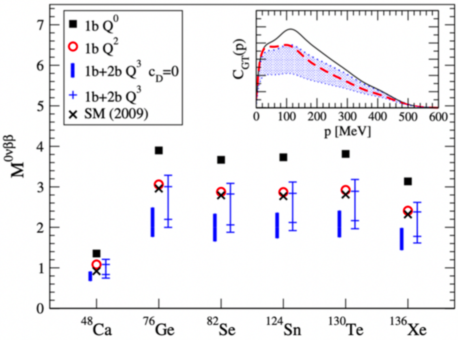


CC

- **VS-IMSRG**: a unitary transformation is constructed to decouple a valence-space Hamiltonian H_{vs}. The eigenstates are obtained by a subsequent diagonalization of the H_{vs}.
- A proper treatment of strong nuclear correlations and the consistency between 2BCs and three-nucleon forces explain the g_A-quenching puzzle in conventional valence-space shell-model calculations.

P. Gysbers et al., Nature Physics 15, 428 (2019)

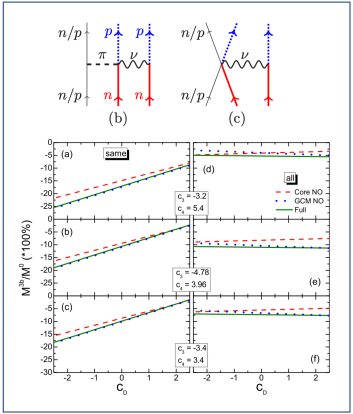


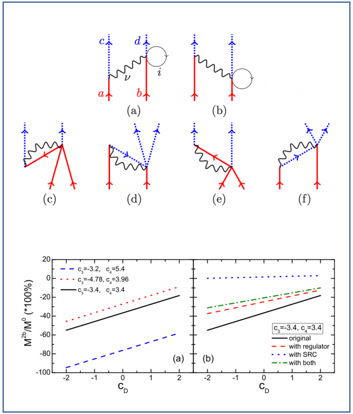


J. Menendez et al., PRL107, 062501 (2011)

- The 2B current changes NMEs ranging from -35% to 10%.

Two-body current effect

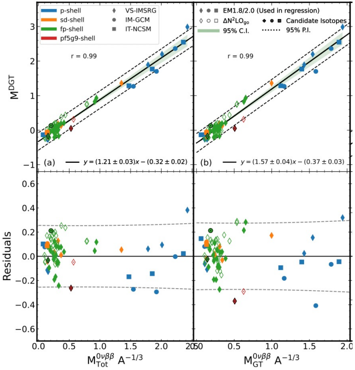


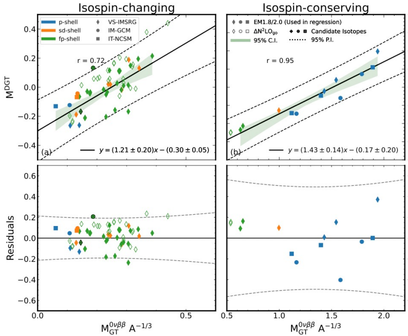


- The 3B operators quench matrix elements by about 10%,
- The 2B operators can produce somewhat larger quenching.

L.J. Wang, J. Engel, JMY, PRC 98, 031301(R) (2018)

Correlation relation between NLDBD and DGT





- Weak correlation between $M^{0\nu}$ and $M^{\rm DGT}$.
- Other observables: $2\nu\beta\beta$ decay, excitation energies?

JMY et al., PRC106, 014315 (2022)

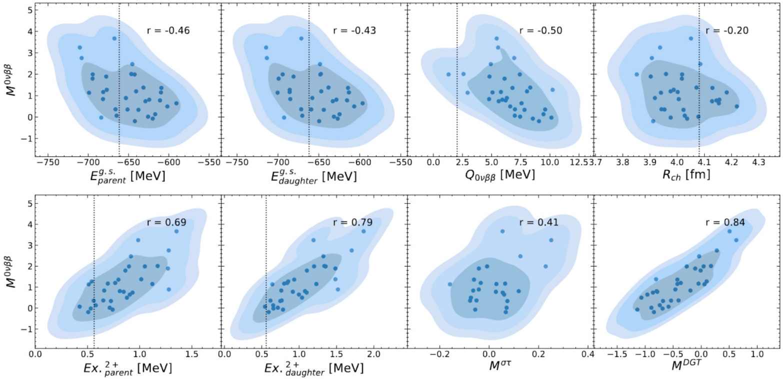


Figure: The correlation between different nuclear observables and $M^{0\nu}$ using 34 LECS samples of the Delta-full $\mathrm{NNLO_{go}}(394)$ interaction.

A. Belley et al., arXiv:2210.05809v1 [nucl-th]