# Advances in Modeling Nuclear Matrix Elements for New Physics Research

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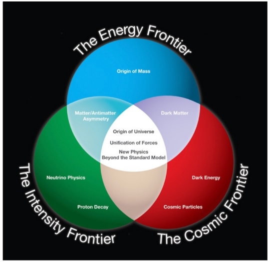
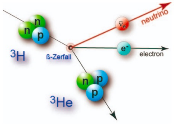
第十届手征有效场论研讨会, Oct. 18, 2025, Nanjing, China

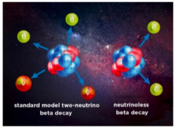
# Outline

# Searching for new physics at low-energy scales

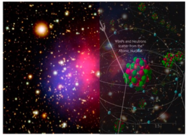


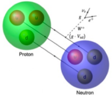

Single–beta decay



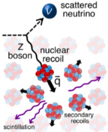

Neutrinoless double beta decay



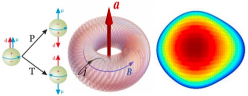
Dark matter direct detection




Superallowed Fermi transitions




Neutrino scattering

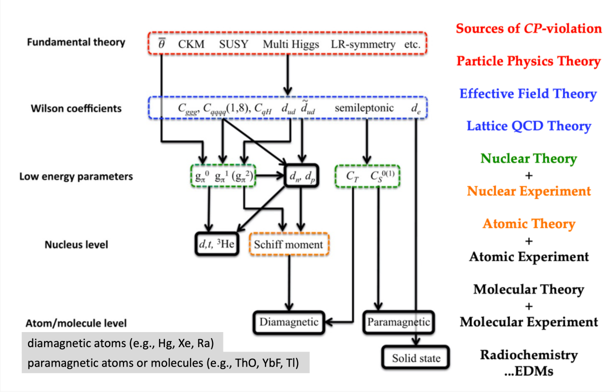



Symmetry-violating moments

- **Open questions**: matter–antimatter asymmetry, new CP violation, Lepton-number violation, Majorana neutrino mass, etc
- **Low-energy scales probes**: (atomic) EDMs, $0\nu\beta\beta$ decay, etc.
- **Physical intepretation**: nuclear matrix elements as a "bridge" connecting measurements and new physics.

# Charge-parity violation and atomic EDMs

- The sources of charge-parity violation (CPV) within the SM (the complex phase of the CKM matrix in weak interactions and the $\theta$ term in QCD) are not sufficient to explain the observed baryon asymmetry of the universe.
- Hypothetical new sources of CPV beyond standard model (BSM), such as SUSY, multi-Higgs models, and LR-symmetry models.




T. Chupp, et al., Rev. Mod. Phys. 91, 015001 (2019); credit to Jaideep Singh.

Observation of any sizable EDMs of elementary or composite particles would indicate new CP violation beyond the SM, potentially solving the baryon asymmetry problem.

- At low-energy scales, chiral Lagrangian constrained by the symmtries of QCD

$$\mathcal{L}_{QCD} \to \mathcal{L}_{\chi EFT} = \mathcal{L}_{NN} + \mathcal{L}_{\pi NN} + \mathcal{L}_{\pi} + \cdots$$

- Systematic expansion in the power of

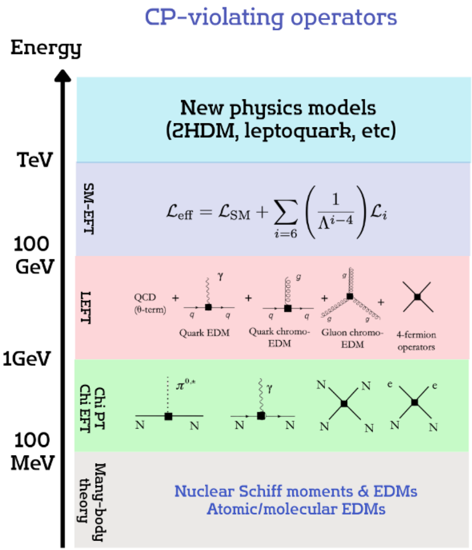
$$Q/\Lambda_\chi \simeq m_\pi/\Lambda_\chi$$

Each terms comes with an unknown LEC.

- Extension to include CP-violating terms

$$\mathcal{L}_{\chi EFT} = \mathcal{L}_{PCTC} + \mathcal{L}_{PVTV} + \cdots$$

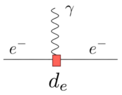
J. de Vries et al., arXiv:2001.09050 [nucl-th]



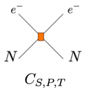
# CP violating operators at low-energy scales and EDMs



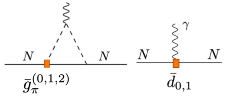
## electron EDM



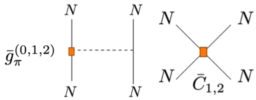

## semileptonic eN interaction




## nucleon EDMs




## nuclear forces




## EDMs of atoms and molecules

$$d_i = \sum_{c_j} \alpha_{i,c_j} c_j = \alpha_{i,d_e} d_e + \alpha_{i,C_S} C_S + \dots$$

## atomic and nuclear structure factors

$$\alpha_{i,c_j} \in \{W_{d,S}, a_{0,1,2}, \cdots\}$$

Large model dependence

## Low-energy parameters

$$c_j \in \{d_e, C_{S,P,T}, d_N, \bar{g}_\pi^{(0,1,2)}, \bar{C}_{1,2}\}$$

- **Paramagnetic systems**: Cs, Tl, YbF, ThO, $HfF^+$

  constraints on $\{d_e, C_S\}$

- **Diamagnetic systems**: Yb, Xe, Hg, Ra, TlF

  constraints on $\{d_N, \bar{g}_\pi^{(0,1,2)}, \bar{C}_{1,2}, C_T\}$

S. Degenkolb et al., arXiv2403.02052 [hep-th]

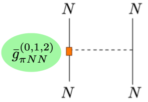
| System $i$ | Measured $d_i$ [$e$ cm] | Upper limit on $\lvert d_i \rvert$ [$e$ cm] | Reference |
|---|---|---|---|
| $n$ | $(0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{syst}}) \cdot 10^{-26}$ | $2.2 \cdot 10^{-26}$ | [47] |
| $^{205}$Tl | $(-4.0 \pm 4.3) \cdot 10^{-25}$ | $1.1 \cdot 10^{-24}$ | [48] |
| $^{133}$Cs | $(-1.8 \pm 6.7_{\text{stat}} \pm 1.8_{\text{syst}}) \cdot 10^{-24}$ | $1.4 \cdot 10^{-23}$ | [49] |
| $HfF^+$ | $(-1.3 \pm 2.0_{\text{stat}} \pm 0.6_{\text{syst}}) \cdot 10^{-30}$ | $4.8 \cdot 10^{-30}$ | [50] |
| ThO | $(4.3 \pm 3.1_{\text{stat}} \pm 2.6_{\text{syst}}) \cdot 10^{-30}$ | $1.1 \cdot 10^{-29}$ | [51] |
| YbF | $(-2.4 \pm 5.7_{\text{stat}} \pm 1.5_{\text{syst}}) \cdot 10^{-28}$ | $1.2 \cdot 10^{-27}$ | [52] |
| $^{199}$Hg | $(2.20 \pm 2.75_{\text{stat}} \pm 1.48_{\text{syst}}) \cdot 10^{-30}$ | $7.4 \cdot 10^{-30}$ | [53,54] |
| $^{129}$Xe | $(-1.76 \pm 1.82) \cdot 10^{-28}$ | $4.8 \cdot 10^{-28}$ | [55,56] |
| $^{171}$Yb | $(-6.8 \pm 5.1_{\text{stat}} \pm 1.2_{\text{syst}}) \cdot 10^{-27}$ | $1.5 \cdot 10^{-26}$ | [57] |
| $^{225}$Ra | $(4 \pm 6_{\text{stat}} \pm 0.2_{\text{syst}}) \cdot 10^{-24}$ | $1.4 \cdot 10^{-23}$ | [58] |
| TlF | $(-1.7 \pm 2.9) \cdot 10^{-23}$ | $6.5 \cdot 10^{-23}$ | [59] |

## CP-violating nuclear force at LO

J. de Vries et al., arXiv2001.09050[nucl-th]

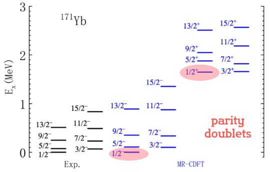
$$\mathcal{L}^{PVTV}_{\pi NN} = \bar{g}^{(0)}_{\pi NN}\bar{N}\boldsymbol{\tau}\cdot\boldsymbol{\pi}N + \bar{g}^{(1)}_{\pi NN}\bar{N}N\pi_z + \bar{g}^{(2)}_{\pi NN}\bar{N}(3\tau_z\pi_z - \boldsymbol{\tau}\cdot\boldsymbol{\pi})N,$$

Nuclear potential $V_{PT}$




## MR-CDFT for structure properties

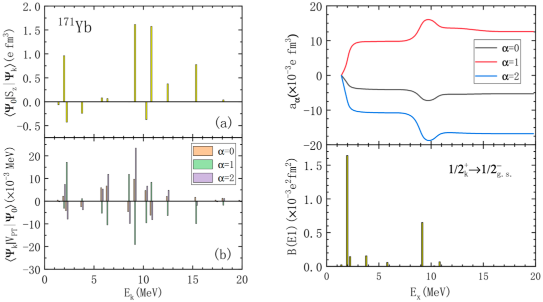
Zhou, Wu, JMY, PRC109, 034305 (2024)




## Nuclear Schiff moment (2rd order perturbation)

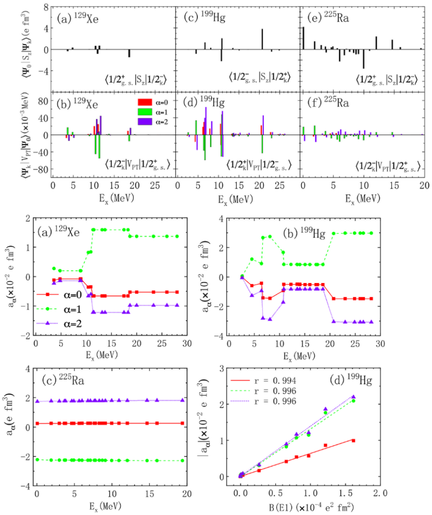
$$S = \sum_{k\neq 0} \frac{\langle\Psi_0|\hat{S}_z|\Psi_k\rangle\langle\Psi_k|\hat{V}_{PT}|\Psi_0\rangle}{E_0 - E_k} + c.c.$$

$$\equiv g_{\pi NN}\sum_{\alpha=0}^{2}\bar{g}^{(\alpha)}_{\pi NN}a_\alpha .$$

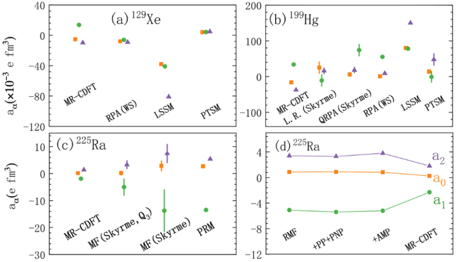


# Nuclear Schiff moments in other candidates

## Decomposition of nuclear Schiff moments




## Comparison with other models




| Nucleus | $a_0$ | $a_1$ | $a_2$ |
|---|---|---|---|
| $^{129}$Xe$^b$ | −0.0052 | +0.0134 | −0.0097 |
| $^{199}$Hg$^b$ | −0.0163 | +0.0327 | −0.0375 |
| $^{225}$Ra$^a$ | +0.15 | −1.9 | +1.3 |
| $^{229}$Th$^a$ | −3.3 | +8.8 | −7.7 |
| $^{229}$Th$^b$ | −21 | +58 | −52 |
| $^{229}$Pa$^a$ | +1.8 | +12 | +10 |
| $^{229}$Pa$^b$ | +9.2 | +60 | +51 |

a: exp energy
b: calc energy

- Unified description of different nuclei at the BMF level
- Large contribution from intermediate states in Xe and Hg
- about 2-3 orders-of-magnitude enhancement in Ra,Th, Pa

Zhou, JMY, Engel, Meng, arXiv2507.01369 [nucl-th]

# Multi-dimensional constraints with new measurements

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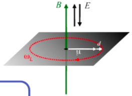
## New Measurement of the EDM of Yb atoms

(USTC group lead by Prof. Zheng-Tian Lu)

procession frequency $\omega_{\pm} = \frac{2(\mu B \pm dE)}{\hbar}$



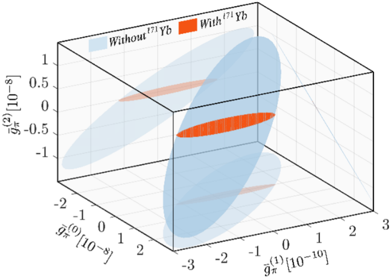

$$d(^{171}\mathrm{Yb}) = (-0.3 \pm 3.7 \pm 1.2) \times 10^{-28}\mathrm{ecm}$$
$$|d(^{171}\mathrm{Yb})| < 7.7 \times 10^{-28}\mathrm{ecm}$$

## Nuclear structure factors from MR-CDFT calculation

| | systems | a_0(efm3) | a_1(efm3) | a_2(efm3) |
|---|---|---|---|---|
| 0 | 129Xe | -0.0052 | 0.0134 | -0.0097 |
| 1 | 171Yb | -0.0053 | 0.0126 | -0.0168 |
| 2 | 199Hg | -0.0163 | 0.0327 | -0.0375 |
| 3 | 205TlF | 0.0110 | 0.0760 | 0.0232 |
| 4 | 225Ra | 0.1500 | -1.9000 | 1.3000 |

Zhou, JMY, Engel, Meng, arXiv2507.01369 [nucl-th]

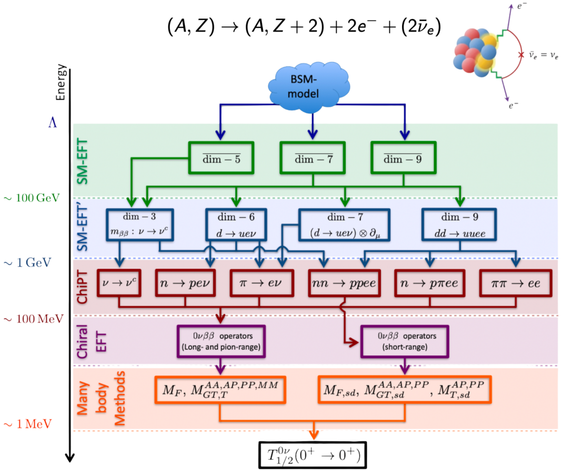
## Global analysis of the limits on the parameter space




$$\bar{g}_\pi^{(0)} \in [-1.3 \times 10^{-9}, 1.5 \times 10^{-9}]$$
$$\bar{g}_\pi^{(1)} \in [-7.3 \times 10^{-11}, 1.3 \times 10^{-10}]$$
$$\bar{g}_\pi^{(2)} \in [-6.4 \times 10^{-10}, 5.9 \times 10^{-10}]$$

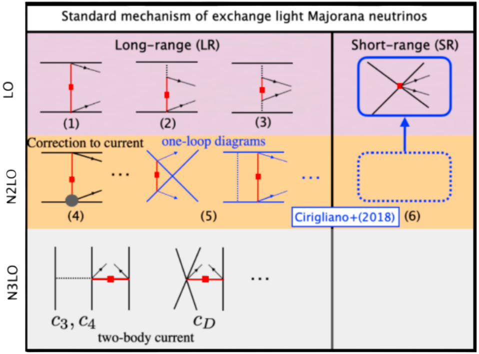
## Lepton-number violating operators for neutrinoless double-beta decay

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




## The $0\nu\beta\beta$ decay operators in the chiral EFT

**Power Counting:** $\nu = 2A + 2L - 2 + \sum_i (\frac{n_f}{2} + d - 2 + n_e)_i$



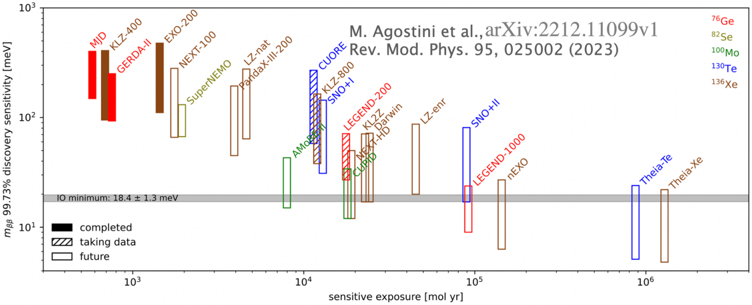
# Theoretical studies of $0\nu\beta\beta$ decay and neutrino physics



- The $0\nu\beta\beta$ decay rate in the standard mechanism:

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

- Whether or not the ton-scale experiments are able to cover the entire parameter space for the IO case depends strongly on the accuracy of the NME.



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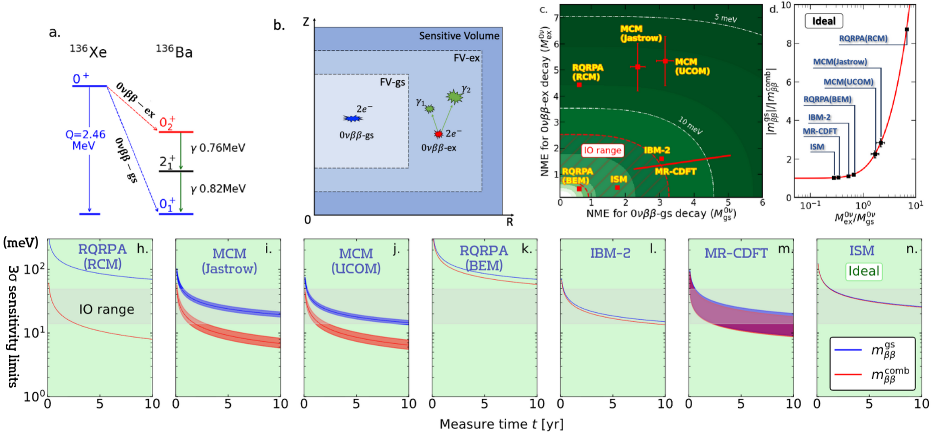
## Combined multi-transition analysis

## 10-year data acquisition on XLZD and the PandaX-xT




The effectiveness strongly depends on the NMEs, which currently exhibit significant discrepancies across different nuclear models.

Ding, Han, Wang, JMY, arXiv2508.17413 [nucl-th]

# A proposal to reduce the uncertainty of the NMEs

- angular distribution of heavy-ion collision

$$\frac{dN_{ch}}{d^2\mathbf{p}} \propto \frac{dN_{ch}}{p_T dp_T}\left(1+\sum_{n>1} 2\, v_n \cos n(\phi-\phi_n)\right)$$

where $v_2$ is strongly correlated with the initial-state ellipticity parameter, $\varepsilon_2$

- observables of interest

$$\Delta(v_2\{2\}) \equiv \frac{1}{2}\Delta\left(\langle v_2^2\rangle\right),$$

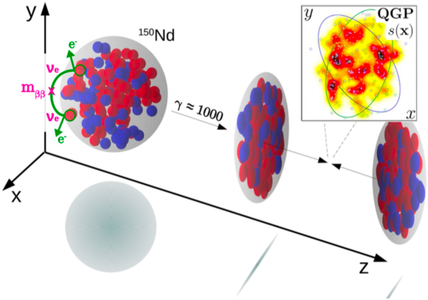
$$\Delta(\delta[p_T]) \equiv \frac{1}{2}\Delta\left(\langle(\delta[p_T])^2\rangle\right),$$

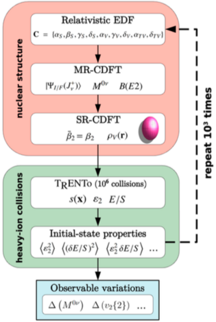
$$\Delta\left(\mathrm{cov}(v_2^2,[p_T])\right) \equiv \frac{1}{3}\Delta\left(\langle v_2^2\delta[p_T]\rangle\right),$$

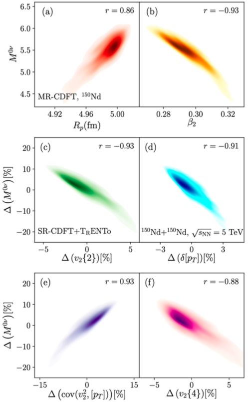
$$\Delta(v_2\{4\}) \equiv \frac{1}{4}\Delta\left(2\langle v_2^2\rangle^2-\langle v_2^4\rangle\right)$$

- Relative variation of an observable

$$\Delta(O) = \frac{O-\langle O\rangle_C}{|\langle O\rangle_C|}$$




Y. Li, X. Zhang, G. Giacalone, JMY, PRL135, 022301 (2025)

Open questions: model-dependence? nucleus-dependence?

# The first-wave of ab initio studies of $0\nu\beta\beta$ decay in $^{48}$Ca

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

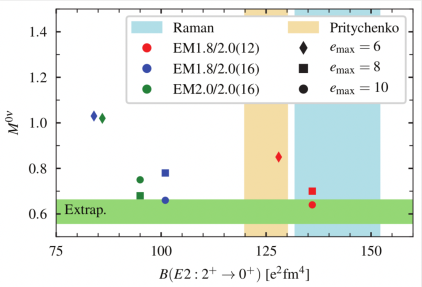
  JMY et al., PRL124, 232501 (2020)

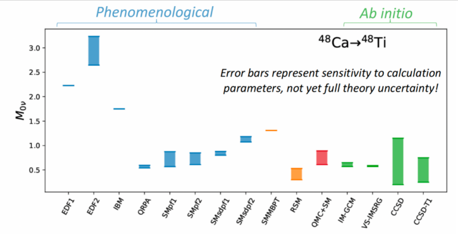
- Valence-space shell model+IMSRG (VS-IMSRG)

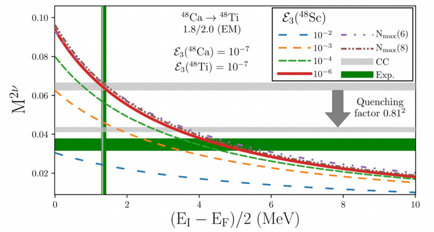
  A. Belley et al., PRL126, 042502 (2021)

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

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

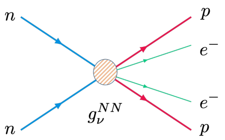


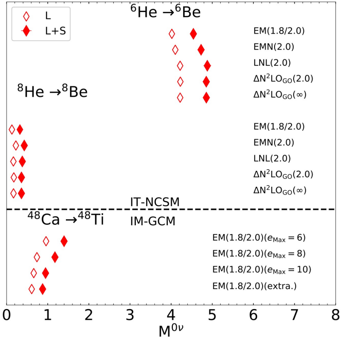



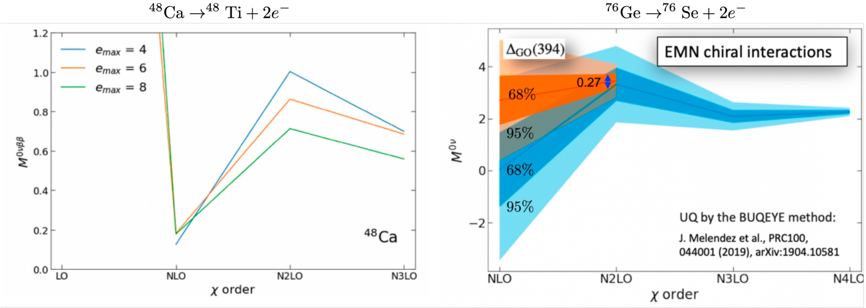
- A contact transition operator which could either enhance or quench the $0\nu\beta\beta$ decay, is needed to be promoted to LO to ensure renormalizibility. V. Cirigliano et al., PRL120, 202001 (2018)
- We determine the unknown LEC $g_\nu^{NN}$ of the contact operator, consistent with the employed chiral interaction (EM1.8/2.0), based on the synthetic data for the process $2n \to 2p + 2e^-$. V. Cirigliano et al., PRL126, 172002 (2021)
- The contact term turns out to enhance the NME for $^{48}$Ca by 43(7)%, thus reducing the half-life $T_{1/2}^{0\nu}$ significantly.

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



# The error of EFT truncation on nuclear forces




- The NME converges with respect to the chiral expansion order $\chi$ of nuclear forces for candidate nuclei $^{48}$Ca and $^{76}$Ge.
- The EFT truncation error is shrinking with the increase of $\chi$ expansion order $\nu$.

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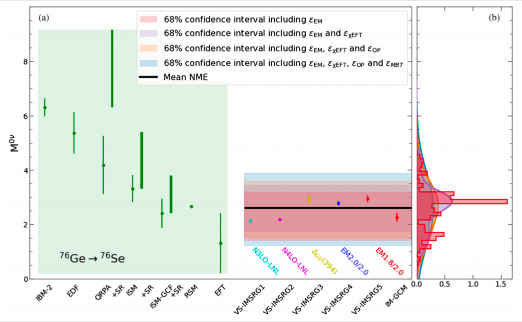
truncation of transition operators | Emulator error

$$M^{0\nu} = M^{0\nu}_k + \epsilon_{\chi\mathrm{EFT}} + \epsilon_{\mathrm{MBT}} + \epsilon_{\mathrm{OP}} + \epsilon_{\mathrm{EM}},$$

truncation of nuclear forces | many-body truncation

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

| $M^{0\nu}$ | $\epsilon_{\mathrm{LEC}}$ | $\epsilon_{\chi\mathrm{EFT}}$ | $\epsilon_{\mathrm{MBT}}$ | $\epsilon_{\mathrm{OP}}$ | $\epsilon_{\mathrm{EM}}$ |
|---|---|---|---|---|---|
| $2.60^{+1.28}_{-1.36}$ | 0.75 | 0.3 | 0.88 | 0.47 | $< 0.06$ |

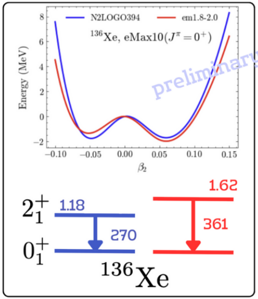


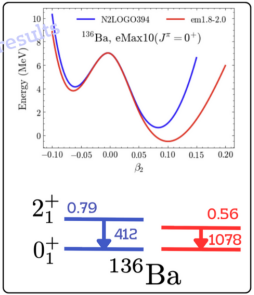

- Our recommended value $M^{0\nu} = 2.60^{+1.28}_{-1.36}$.
- Together with the best half-life limit: $> 1.8 \times 10^{26}$ yr, it sets the upper limit $\langle m_{\beta\beta}\rangle = 187^{+205}_{-62}$ meV, and the sensitivity of the next-generation experiment $\langle m_{\beta\beta}\rangle = 22^{+24}_{-7}$ meV, covering almost the entire range of IO hierarchy.

A. Belley, JMY et al., PRL132, 182502 (2024)

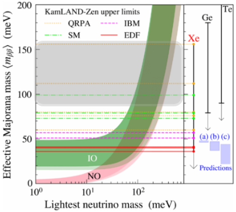
# Extension to the $0\nu\beta\beta$ decay of $^{136}$Xe





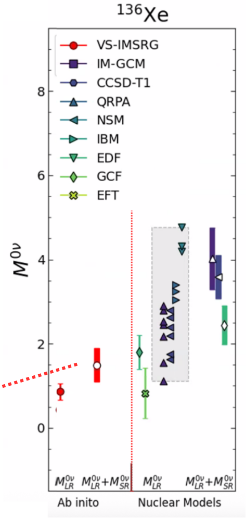




KamLAND-Zen: $T_{1/2}^{0\nu} > 2.3 \times 10^{26}$ yr at 90% C.L.




| | IM-GCM | VS-IMSRG |
|---|---|---|
| NME | 1.15(N2LOGO394)<br>1.34 (EM1.8-2.0) | [1.08, 1.90] |
| $<m_{\beta\beta}>$ | 0.13-0.15 eV | 0.09-0.16 MeV |

large uncertainty




Ding, JMY, et al. in preparation (2025)

A. Belley et al., arXiv2307.15156 [nucl-th]

# Summary and outlook

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Nuclear physics plays an important role in the search for new physics at low-energy scales.

- Accurate nuclear matrix elements (NMEs) are crucial for designing and interpreting the experiments, including the searches for atomic EDM, $0\nu\beta\beta$ decay, etc.
- We developed a novel nuclear ab initio framework which allows us to determine the values of NMEs and their uncertainties using the operators derived consistently within the chiral EFT.
- We have successfully applied our method to compute the NMEs of $0\nu\beta\beta$ decay in light candidate nuclei. Its application to nuclear Schiff moment is more challenging, but it is on the way.

Outlook: extending nuclear ab initio methods for Schiff moments, and reducing the uncertainty in the NMEs of $0\nu\beta\beta$ decay.

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This work is supported in part by the National Natural Science Foundation of China (Grant Nos. 12375119 and 12141501), the Guangdong Basic and Applied Basic Research Foundation (2023A1515010936).

# Thank you for your attention!