

$0\nu\beta\beta$ decay - Status of NME and connection to high-energy collisions

Benjamin Bally

EMMI: Light-Ion Collisions 2026 - Heidelberg - 23/09/2026

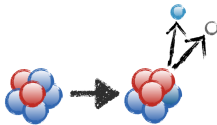


TECHNISCHE
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Courtesy of L. Jokiniemi

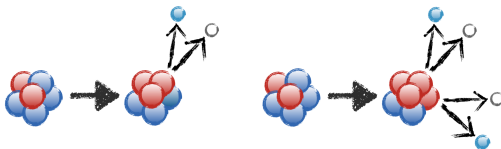


- Single beta decay: very common (most nuclei in the nucleart chart)

Neutrinoless double-beta decay ($0\nu\beta\beta$)



Courtesy of L. Jokiniemi

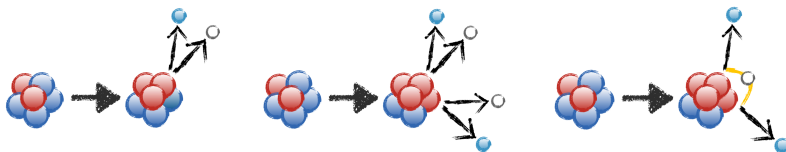


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→ **slowest process ever observed** ($t_{1/2}^{2\nu} \sim 10^{18}-10^{24} \text{ y}$)!

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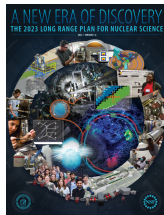
Courtesy of L. Jokiniemi



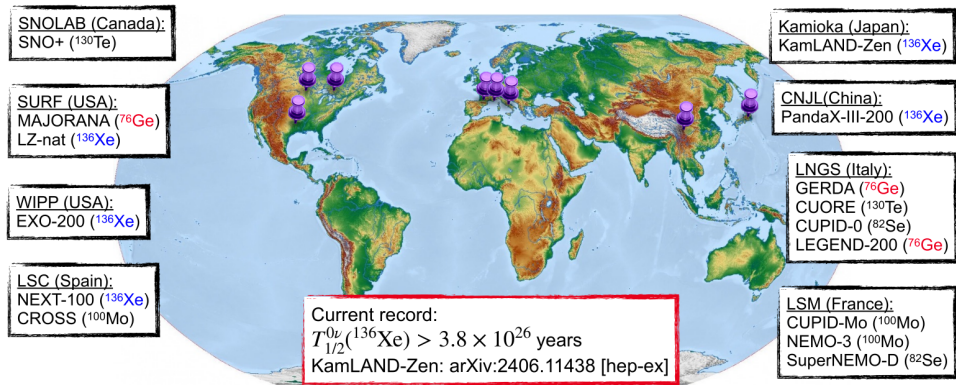
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→ **slowest process ever observed** ($t_{1/2}^{2\nu} \sim 10^{18}\text{-}10^{24}y$)!
- Neutrinoless double beta decay: not observed (yet?)
→ **if it exists, even slower** ($t_{1/2}^{0\nu} \gtrsim 10^{26}y$)!



- **Experimental** and **theoretical** challenge and priority for nuclear physics
- The NuPECC Long Range Plan 2024 for European Nuclear Physics
- A New Era Of Discovery: The 2023 Long-Range Plan For Nuclear Science



Major experiments worldwide



Courtesy of L. Jokiniemi



- Assuming light-neutrino exchange, the half-life of the process $t_{1/2}^{0\nu}$ is

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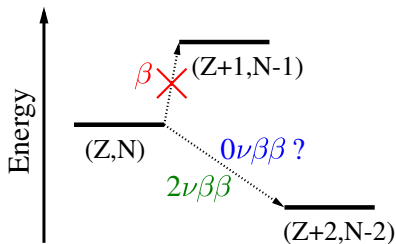
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- What you can do with a reliable NME:

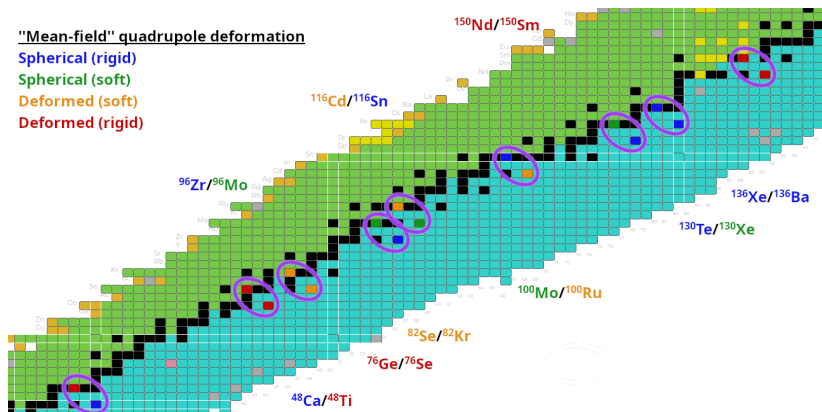
reliable $M^{0\nu}$ + estimate $m_{\beta\beta} \longrightarrow$ estimate $t_{1/2}^{0\nu}$

reliable $M^{0\nu}$ + measured $t_{1/2}^{0\nu} \longrightarrow$ determine $m_{\beta\beta}$ (most useful/likely in practice)



- β decay must be forbidden (energy) or extremely hindered (structure)
- Always competing against $2\nu\beta\beta$

Candidates for the $0\nu\beta\beta$

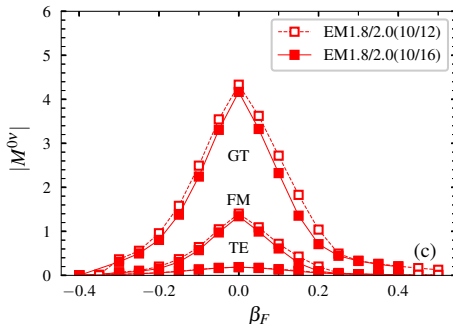


Adapted from NDS-IAEA

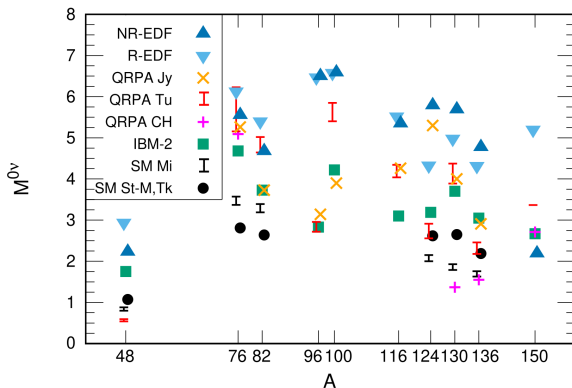
- In practice, limited number of candidates
- But nuclei with different masses and structure properties



- Calculation of NME for $^{48}\text{Ca} \rightarrow ^{48}\text{Ti} + 2e^-$
- ^{48}Ca : fixed spherical deformation $|\Phi_I(\beta_I = 0)\rangle$
- ^{48}Ti : variation of the axial deformation $|\Phi_F(\beta_F)\rangle$

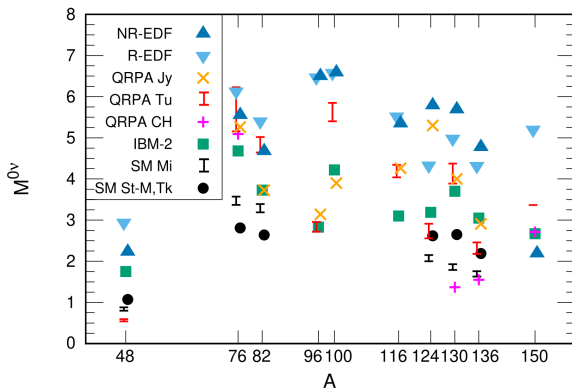


Yao *et al.*, PRL 124, 232501 (2020)



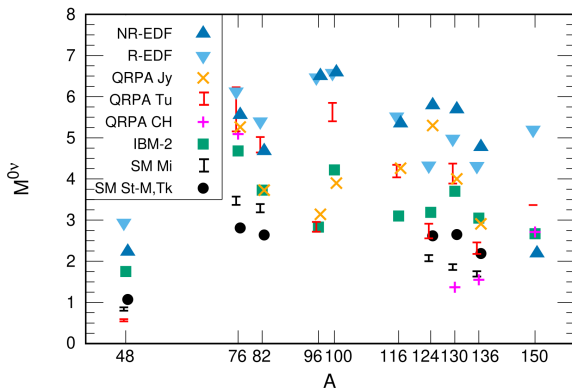
Engel and Menéndez, Rep. Prog. Phys. 80, 046301 (2017)

- Phenomenological methods (using different pheno. approx. for H or $|\Psi\rangle$)



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- Wide spread in the NME values (factor 3 on NME $\Rightarrow$ factor ~ 10 on $t_{1/2}^{0\nu}$)

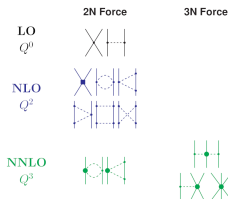


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- Phenomenological methods (using different pheno. approx. for H or $|\Psi\rangle$)
- Wide spread in the NME values (factor 3 on NME $\Rightarrow$ factor ~ 10 on $t_{1/2}^{0\nu}$)
- How to evaluate which one is correct (if any)? $\rightarrow$ **Situation unsatisfying!**



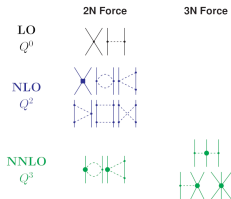
- Profit from progress and advantages of *ab initio* methods
→ Talks by Thomas, Andreas, Gaute, Evgeny
 - ◇ Systematic approach
 - ◇ Predictive power (QCD $\rightarrow$ χ EFT)
 - ◇ Compare different methods based on same inputs
 - ◇ Enables proper uncertainty quantification





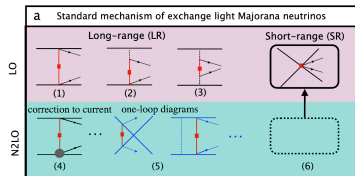
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- Consistent derivation of H and $O^{0\nu}$
→ see talk by Jordy

$$M^{0\nu} = \langle \Psi_f^{Z+2, N-2} | O_{LR}^{LO} + O_{SR}^{LO} + O^{N2LO} | \Psi_i^{Z, N} \rangle$$





- One of the main candidates: $^{76}\text{Ge} \rightarrow ^{76}\text{Se} + 2e^-$
- Combines two flavors of In-Medium Similarity Renormalization Group (IMSRG)
 - ◊ Valence-space IMSRG
 - ◊ In-Medium Generator Coordinate Method → [see talk by Thomas](#)

$$|\Psi_{\epsilon}^{NZJM\pi}\rangle \equiv \lim_{s \rightarrow \infty} U(s) \sum_{\beta, \gamma} \sum_{K=-J}^J f_{\epsilon}^{NZJK\pi}(\beta, \gamma) P_{MK}^J P^{NZ} |\Phi^{\pi}(\beta, \gamma)\rangle$$

- Use an emulator to perform a large number of calculations

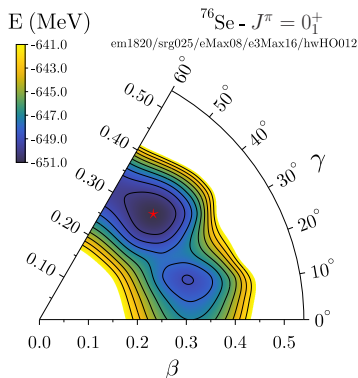
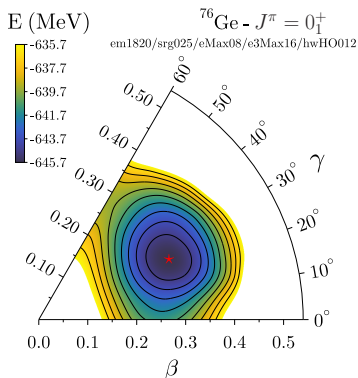


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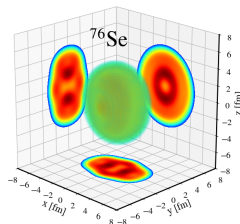
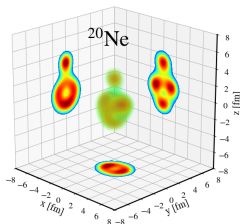
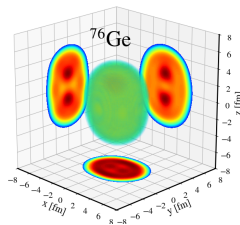
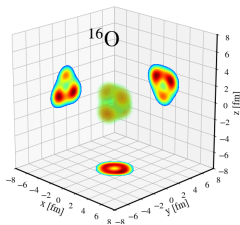
- Use an emulator to perform a large number of calculations
- Uncertainty quantification
 - ◇ Nuclear Hamiltonian (parameters, order)
 - ◇ Many-body method
 - ◇ Operator $O^{0\nu}$
 - ◇ Emulator

Correlated energy surfaces for ^{76}Ge and ^{76}Se



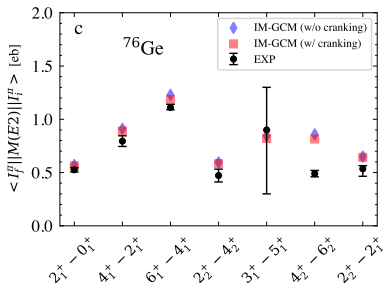
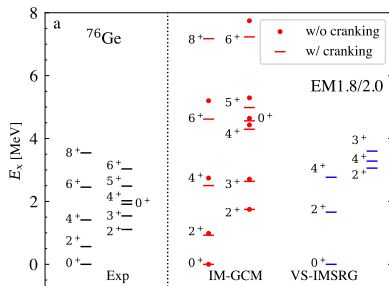
- Both nuclei exhibit an “intrinsic” triaxial energy minimum

Intrinsic one-body density at average deformation



Figures by S. Bofos

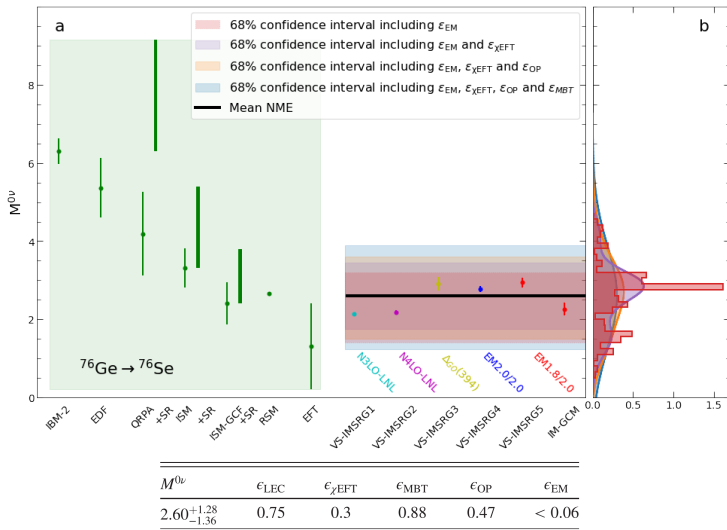
Low-energy spectrum for ^{76}Ge



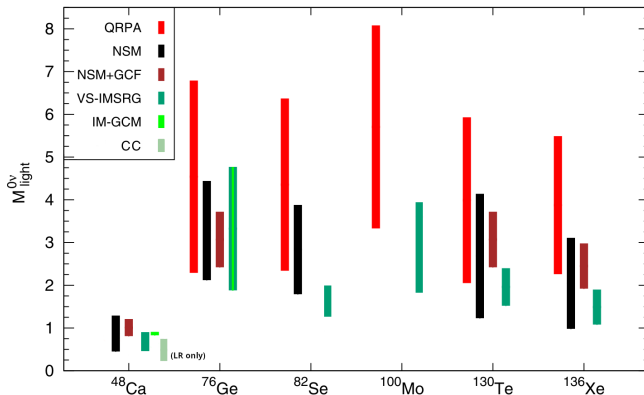
Belley *et al.*, PRL 132, 182502 (2024)

- Energy spectrum rotational but too spread (IM-GCM)
- Excellent agreement with experiment for $E2$ electromagnetic transitions
- Similar agreement for ^{76}Se

NME with uncertainty quantification for $^{76}\text{Ge} \rightarrow ^{76}\text{Se} + 2e^-$



Belley *et al.*, PRL 132, 182502 (2024)



Adapted from Gómez-Cadenas *et al.*, Nuovo Cimento 46, 619 (2023)

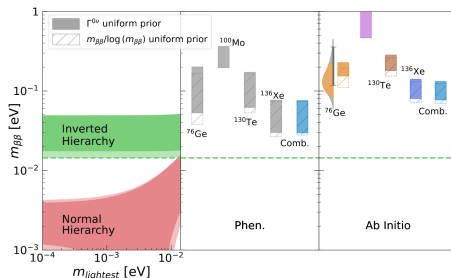
Data partially taken from Belley, PhD thesis, UBC (2024)

- *Ab initio* method(s) now cover main candidates ... **but mostly VS-IMSRG**
⇒ **need other methods!**
- *Ab initio* calculations tend to give smaller NME

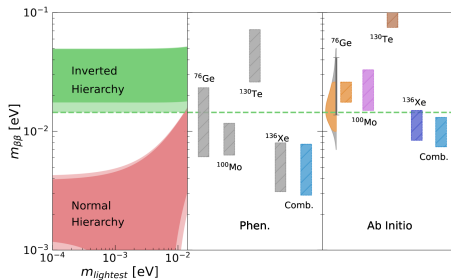
Upper limit/sensitivity for $m_{\beta\beta}$



Current generation
of experiments



Next generation
of experiments



Shickele *et al.*, arXiv:2606.09288 (2026)



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- NMEs for several other “similar” decays have been considered:

- ◇ Two-neutrino double beta decay

Jokiniemi *et al.*, PRC 107, 044305 (2023)

- ◇ Double Gamow-Teller β transition

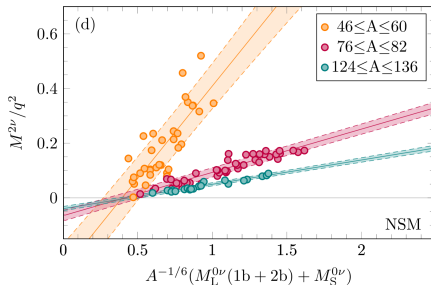
Shimizu *et al.*, PRL 120, 142502 (2018)

- ◇ Double M1 γ transition

Romeo *et al.*, PLB 827, 136965 (2022)

- ◇ Ordinary muon capture

Jokiniemi *et al.*, PRC 100, 014619 (2019)





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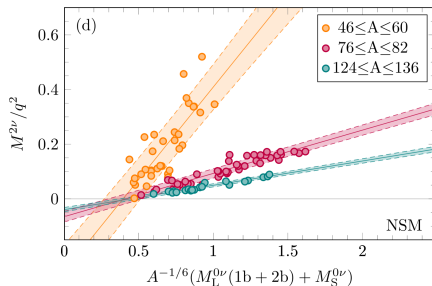
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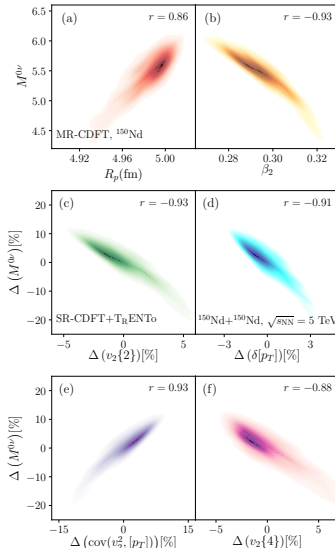
Jokiniemi *et al.*, PRC 100, 014619 (2019)



- **All these decay are still very difficult to observe!**
(and NME is not the observable directly measured)



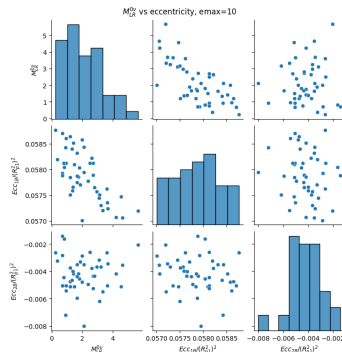
- $0\nu 2\beta$: $^{150}\text{Nd} \rightarrow ^{150}\text{Sm} + 2e^-$
- HIC: ultra-central $^{150}\text{Nd} + ^{150}\text{Nd}$
- Relativistic multi-reference energy density functional (EDF)
 - ◊ 10^3 calculations varying EDF parameters
 - ◊ Compute $M^{0\nu}$
 - ◊ Axial def. β as input for HIC simulations
- Strong correlation between variation of $M^{0\nu}$ and variation of several high-energy observables



Li *et al.*, PRL 135, 022301 (2025)



- **Goal:** similar analysis for $^{76}\text{Ge}/^{76}\text{Se}$ but ...
 - ◇ Using *ab initio* methods
 - ◇ Using new eccentricity operator
→ see talk by Thomas
- Preliminary results from emulator trained on VS-IMSRG calculations



Courtesy of Ahuja and Belley (PRELIMINARY)

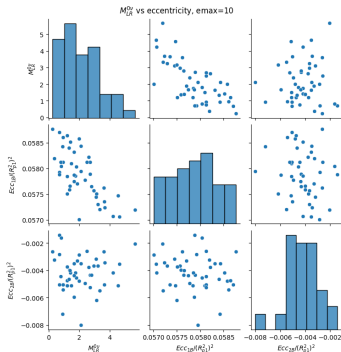
In preparation: correlation for ^{76}Ge using χEFT



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Courtesy of Ahuja and Belley (PRELIMINARY)

- **Next:** train the emulator on PGCM calculations

- ◊ Better adapted to deformation/collectivity
- ◊ Test triaxial calculation with Hamiltonian EM1.8/2.0 and $e_{\text{max}} = 8$
⇒ $\langle \delta \epsilon_2^2 \rangle = 0.0235$ and $\mathcal{B}_2 \approx 0.23$



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Castillo *et al.*, PLB 860, 139181 (2025)



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Use the fastest nuclear reactions to learn about the slowest nuclear decay?



R. Roth
A. Tichai



C. Chenrong
Y. Li
J. Yao



A. Belley



S. Bofos
T. Duguet
J.P. Ebran
M. Frosini
L. Heitz
V. Somà



H. Hergert



J. Engel



T. R. Rodríguez



G. Giacalone
G. Nijss
W. van der Schee



M. Bender