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Recent Advances in the Nuclear Matrix Elements for Neutrinoless Double-Beta Decay

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Fifth Gogny Conference, Paris, 10/12/2024

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

Discovery, accelerated

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Outline

Introduction

Corrections to $0\nu\beta\beta$-Decay Nuclear Matrix Elements

Correlations with other observables to constrain the matrix elements

Summary and Outlook

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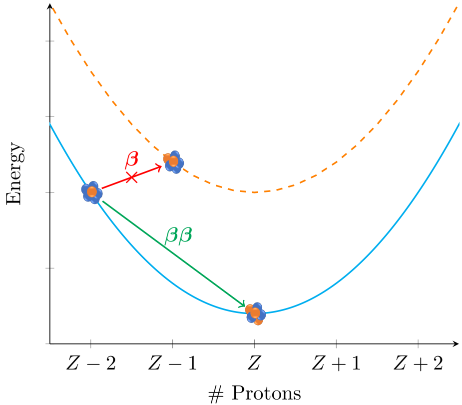
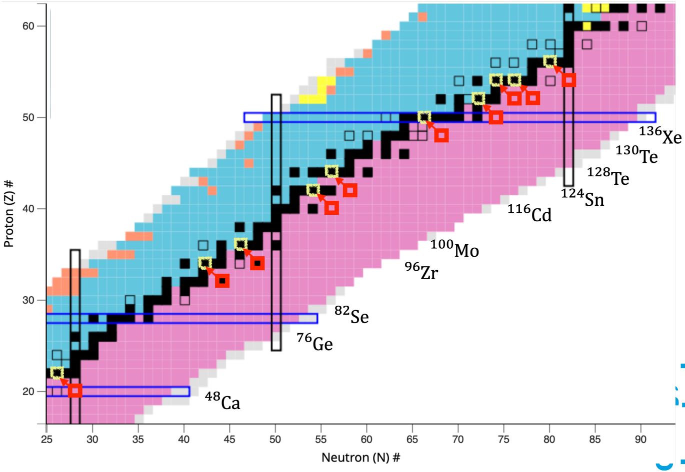
Double-Beta Decay





nndc.bnl.gov

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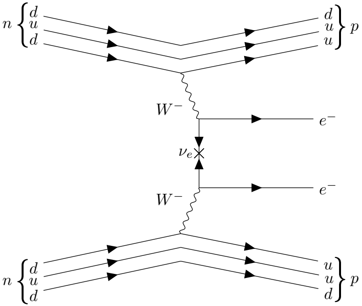
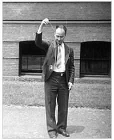
Neutrinoless Double-Beta ($0\nu\beta\beta$) Decay

- **Violates lepton-number conservation**

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



Maria Goeppert-Mayer	*Ettore Majorana*	*Wendell H. Furry*
		
$2\nu\beta\beta$	Majorana particles	$0\nu\beta\beta$
1935 →	1937 →	1939 → …

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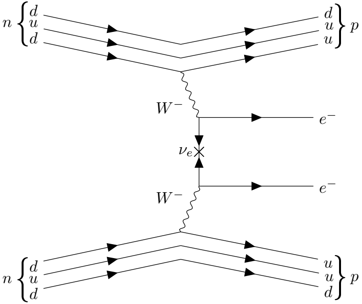
Neutrinoless Double-Beta ($0\nu\beta\beta$) Decay

- **Violates lepton-number conservation**
- Requires that **neutrinos are Majorana particles**

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



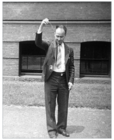
Maria Goeppert-Mayer

$2\nu\beta\beta$

Ettore Majorana

Majorana particles

Wendell H. Furry



$0\nu\beta\beta$

1935 → 1937 → 1939 → ⋯

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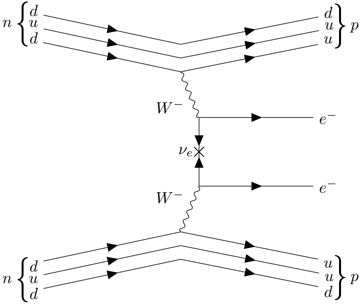
Neutrinoless Double-Beta ($0\nu\beta\beta$) Decay

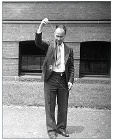
- **Violates lepton-number conservation**
- Requires that **neutrinos are Majorana particles**
- If observed, $t_{1/2}^{0\nu} \gtrsim 10^{25}$ **years**

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



Maria Goeppert-Mayer | *Ettore Majorana* | *Wendell H. Furry*





$2\nu\beta\beta$ | Majorana particles | $0\nu\beta\beta$

1935 → 1937 → 1939 → …

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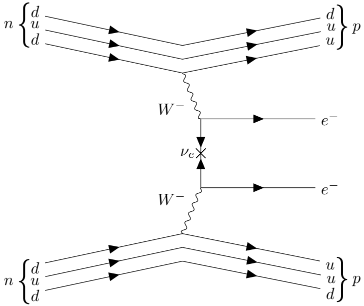
Neutrinoless Double-Beta ($0\nu\beta\beta$) Decay

- **Violates lepton-number conservation**
- Requires that **neutrinos are Majorana particles**
- If observed, $t_{1/2}^{0\nu} \gtrsim 10^{25}$ **years**
  ($t_{1/2}^{2\nu} \approx 10^{20}$ years,
  age of the Universe $\approx 10^{10}$ years)

$$(A,Z) \to (A,Z+2) + 2e^{-} \cancel{+2\nu_e}$$



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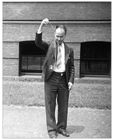

$2\nu\beta\beta$ | Majorana particles | $0\nu\beta\beta$

1935 → 1937 → 1939 → …

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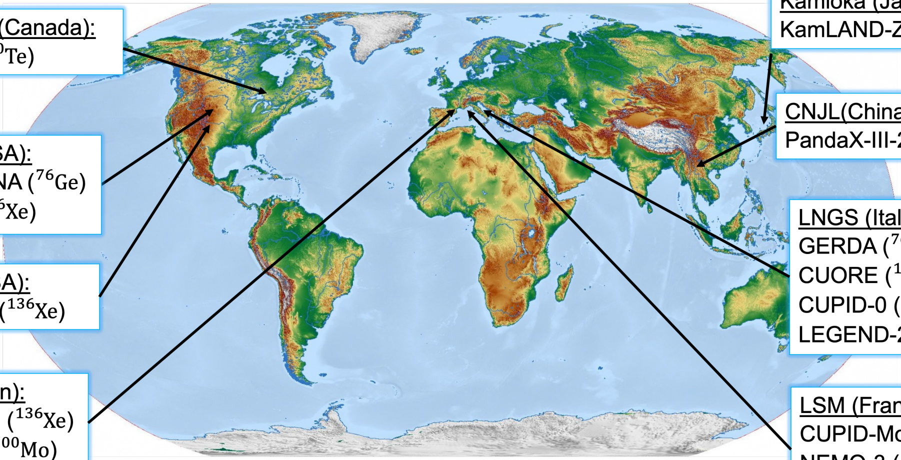
$0\nu\beta\beta$-Decay Experiments



SNOLAB (Canada):
SNO+ (^{130}Te)

SURF (USA):
MAJORANA (^{76}Ge)
LZ-nat (^{136}Xe)

WIPP (USA):
EXO-200 (^{136}Xe)

LSC (Spain):
NEXT-100 (^{136}Xe)
CROSS (^{100}Mo)

Kamioka (Japan):
KamLAND-Zen (^{136}Xe)

CNJL(China):
PandaX-III-200 (^{136}Xe)

LNGS (Italy):
GERDA (^{76}Ge)
CUORE (^{130}Te)
CUPID-0 (^{82}Se)
LEGEND-200 (^{76}Ge)

LSM (France):
CUPID-Mo (^{100}Mo)
NEMO-3 (^{100}Mo)
SuperNEMO-D (^{82}Se)

Current record: $t_{1/2}^{0\nu\beta\beta}(^{136}\mathrm{Xe}) > 3.8\times10^{26}$ years

KamLAND-Zen, arXiv:2407:11438

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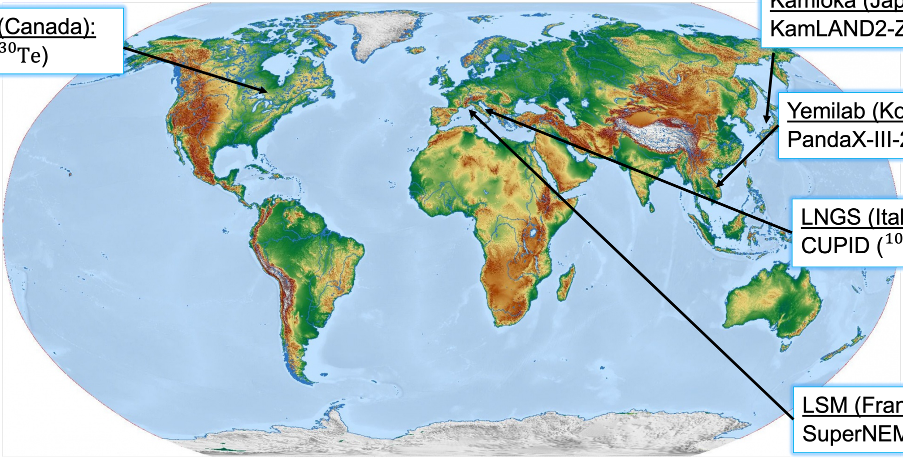
Next-Generation $0\nu\beta\beta$-Decay Experiments



SNOLAB (Canada): SNO+II (^{130}Te)

Kamioka (Japan): KamLAND2-Zen (^{136}Xe)

Yemilab (Korea): PandaX-III-200 (^{136}Xe)

LNGS (Italy): CUPID (^{100}Mo)

LSM (France): SuperNEMO (^{82}Se)

+nEXO (^{136}Xe), LEGEND-1000 (^{76}Ge), NEXT-HD (^{136}Xe), Darwin (^{136}Xe), …

M. Agostini et al., Rev. Mod. Phys. 95, 025002 (2023)

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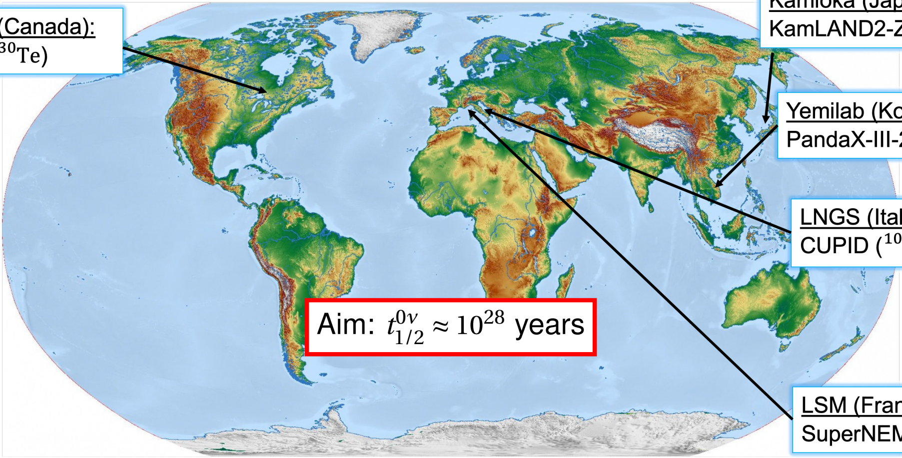
Next-Generation $0\nu\beta\beta$-Decay Experiments



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Aim: $t_{1/2}^{0\nu} \approx 10^{28}$ years

+nEXO (^{136}Xe), LEGEND-1000 (^{76}Ge), NEXT-HD (^{136}Xe), Darwin (^{136}Xe), …

M. Agostini et al., Rev. Mod. Phys. 95, 025002 (2023)

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$0\nu\beta\beta$-Decay Half-Life

What would be measured

$$\boxed{\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G_{0\nu} |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2}$$

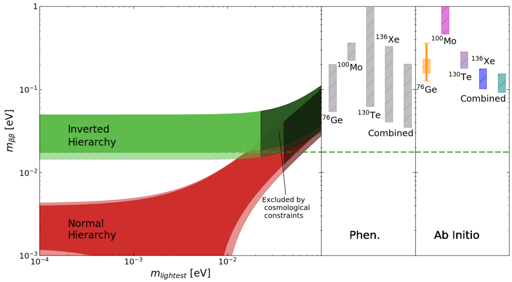
$0\nu\beta\beta$-Decay Half-Life

What would be measured

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G_{0\nu} |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Majorana mass

$m_{\beta\beta} = \sum_k (U_{ek})^2 m_k$



T. Shickele, LJ, A. Belley, J. D. Holt, in preparation

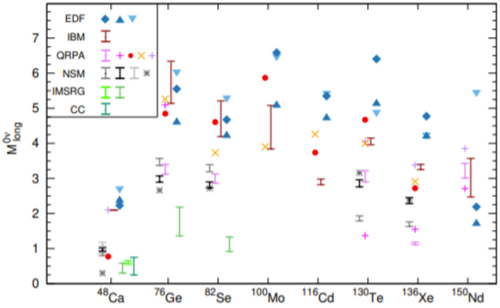
$0\nu\beta\beta$-Decay Half-Life

What would be measured

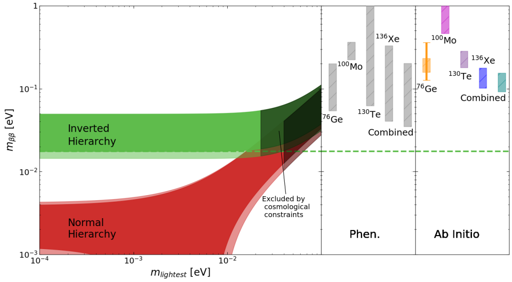
$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G_{0\nu} |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Majorana mass
$m_{\beta\beta} = \sum_k (U_{ek})^2 m_k$

Nuclear matrix element



M. Agostini et al., Rev. Mod. Phys. **95**, 025002 (2023)



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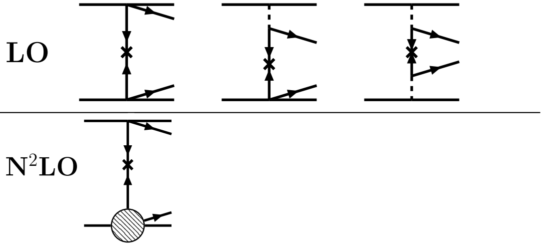
Effective-Field-Theory Corrections to $0\nu\beta\beta$ Decay

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} |M_L^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

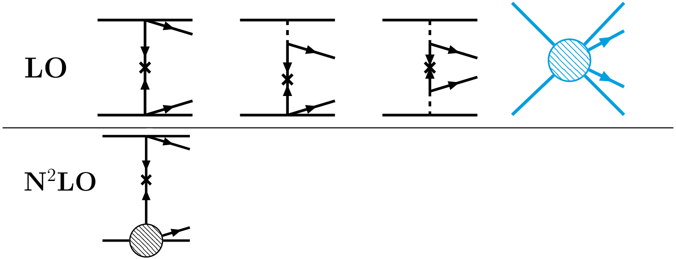
V. Cirigliano et al., Phys. Rev. C 97, 065501 (2018), Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)



Effective-Field-Theory Corrections to $0\nu\beta\beta$ Decay

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} |M_L^{0\nu} + M_S^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

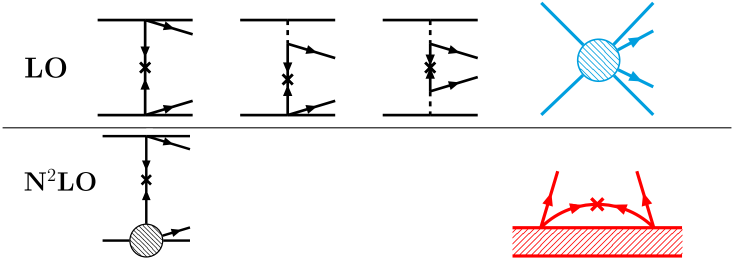
V. Cirigliano et al., Phys. Rev. C 97, 065501 (2018), Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)



Effective-Field-Theory Corrections to $0\nu\beta\beta$ Decay

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} |M_L^{0\nu} + M_S^{0\nu} + M_{usoft}^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

V. Cirigliano et al., Phys. Rev. C 97, 065501 (2018), Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)



Effective-Field-Theory Corrections to $0\nu\beta\beta$ Decay

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} |M_L^{0\nu} + M_S^{0\nu} + M_{usoft}^{0\nu} + M_{N^2LO}^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

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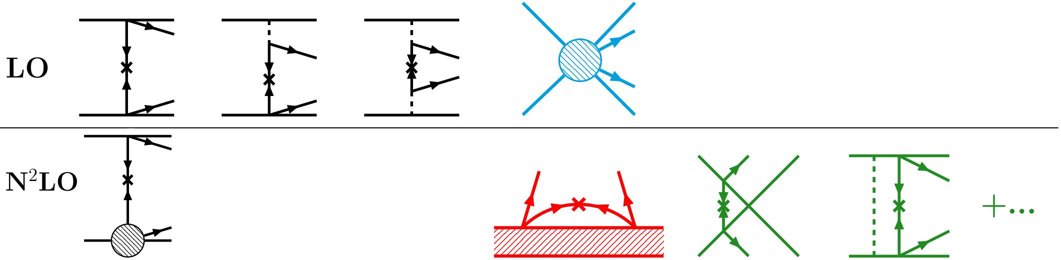

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Traditional $0\nu\beta\beta$-Decay Operators

$$M^{0\nu} = \frac{R}{g_{\mathbf{A}}^2} \int \frac{\mathbf{dk}}{2\pi^2} \frac{e^{i\mathbf{k}(\mathbf{x}-\mathbf{y})}}{|\mathbf{k}|} \sum_n \frac{\langle f \big| J_\mu(\mathbf{x}) \,|n\rangle \langle n| J^\mu(\mathbf{y}) \,|i\rangle}{|\mathbf{k}| + E_n - \frac{1}{2}(E_i + E_f)}$$

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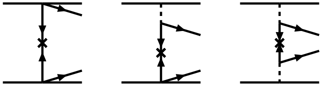
- Traditionally, the nuclear current includes the leading-order (LO) transition operators

$$\mathscr{J}^0 = \tau [g_V(0)]$$

$$\boldsymbol{J} = \tau [g_A(0)\boldsymbol{\sigma} - g_P(0)\boldsymbol{p}(\boldsymbol{p}\cdot\boldsymbol{\sigma})]$$

LO



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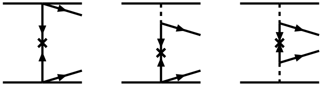
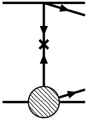
LO



- and next-to-next-to-leading-order (N^{2}LO) corrections absorbed into **form factors** and **induced weak-magnetism terms**

$$\mathscr{J}^0 = \tau [g_V(p^2)]$$
$$\boldsymbol{J} = \tau \left[g_A(p^2)\boldsymbol{\sigma} - g_P(p^2)\boldsymbol{p}(\boldsymbol{p}\cdot\boldsymbol{\sigma}) + i g_M(p^2) \frac{\boldsymbol{\sigma}\times\boldsymbol{p}}{2m_N} \right]$$

N^{2}LO

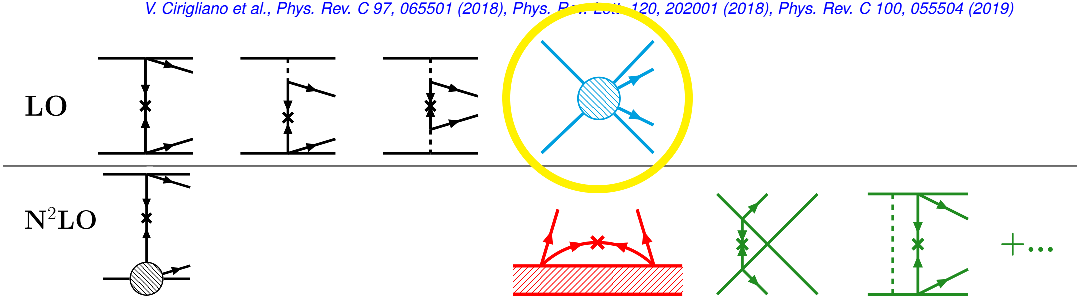


Discovery, accelerated

Leading-order short-range contribution to $0\nu\beta\beta$ decay

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} |M_L^{0\nu} + M_S^{0\nu} + M_{\text{usoft}}^{0\nu} + M_{\text{N}^2\text{LO}}^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

V. Cirigliano et al., Phys. Rev. C 97, 065501 (2018), Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)



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Contact Term in pnQRPA and Nuclear Shell Model (NSM)

- The contact term reads

$$M_{\mathrm{S}}^{0\nu} = \frac{2R}{\pi g_{\mathrm{A}}^2} \langle 0_f^+ | \sum_{m,n} \tau_m^- \tau_n^- \int j_0(qr)\, h_{\mathrm{S}}(q^2)\, q^2 \mathrm{d}q | 0_i^+ \rangle$$

with

$$h_{\mathrm{S}}(q^2) = 2 g_{\nu}^{\mathrm{NN}}\, e^{-q^2/(2\Lambda^2)} .$$

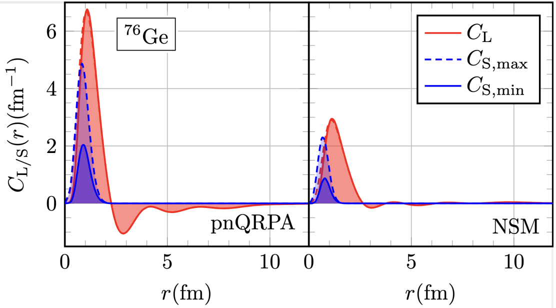
$$\int C_{\mathrm{L/S}}(r) \mathrm{d}r = M_{\mathrm{L/S}}^{0\nu}$$

In pnQRPA:

$M_{\mathrm{S}}/M_{\mathrm{L}} \approx 30\% - 80\%$

In NSM:

$M_{\mathrm{S}}/M_{\mathrm{L}} \approx 15\% - 50\%$



*LJ, P. Soriano and J. Menéndez, Phys. Lett. B **823**, 136720 (2021)*

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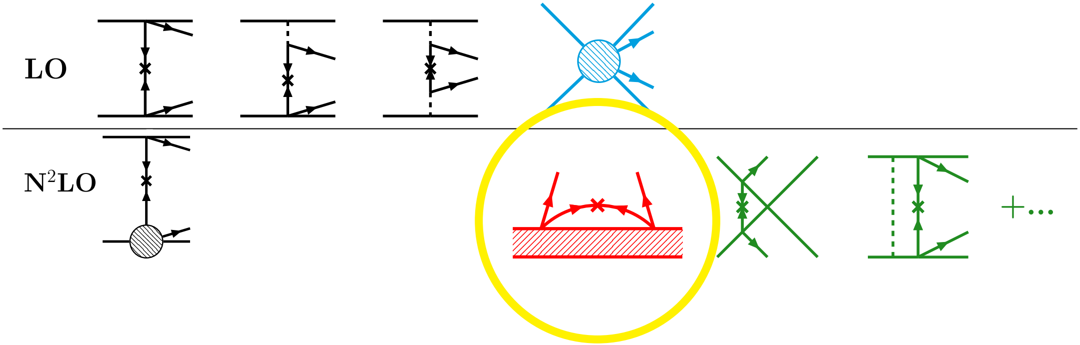
Ultrasoft-neutrino contribution to $0\nu\beta\beta$ decay

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} |M_L^{0\nu} + M_S^{0\nu} + M_{usoft}^{0\nu} + M_{N^2LO}^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

V. Cirigliano et al., Phys. Rev. C 97, 065501 (2018), Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)



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Ultrasoft Neutrinos in pnQRPA and NSM

- Contribution of ultrasoft neutrinos ($|\mathbf{k}| << k_{\mathrm{F}} \approx 100$ **MeV**) to $0\nu\beta\beta$ decay:

V. Cirigliano et al., Phys. Rev. C 97, 065501 (2018)

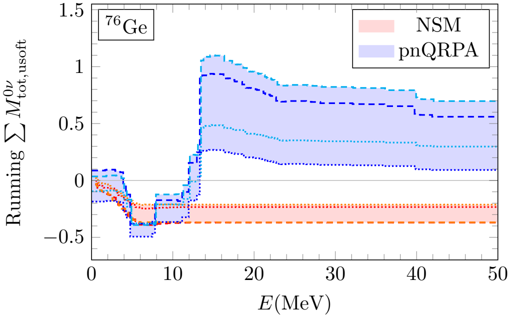
$$M^{0\nu}_{\mathrm{usoft}} = -\frac{2R}{\pi}\sum_n \langle f||\sum_a \boldsymbol{\sigma}_a\tau^+_a||n\rangle\langle n||\sum_b \boldsymbol{\sigma}_b\tau^+_b||i\rangle$$
$$\times (E_e + E_n - E_i)\left(\ln\frac{\mu_{\mathrm{us}}}{2\,(E_e+E_n-E_i)}+1\right)$$

In pnQRPA:

$|M^{0\nu}_{\mathrm{usoft}}/M^{0\nu}_{\mathrm{L}}| \leq 30\%$

In NSM:

$|M^{0\nu}_{\mathrm{usoft}}/M^{0\nu}_{\mathrm{L}}| \leq 10\%$



D. Castillo, LJ, P. Soriano, J. Menéndez, arXiv:2408.03373

N^2LO Loop Corrections to $0\nu\beta\beta$ Decay

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} |M_L^{0\nu} + M_S^{0\nu} + M_{usoft}^{0\nu} + M_{N^2LO}^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

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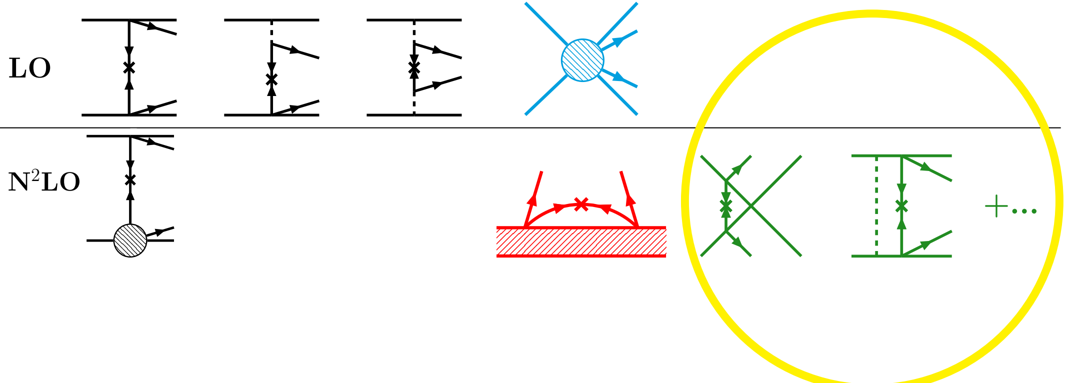


N^{2}LO Loop Corrections in pnQRPA and NSM

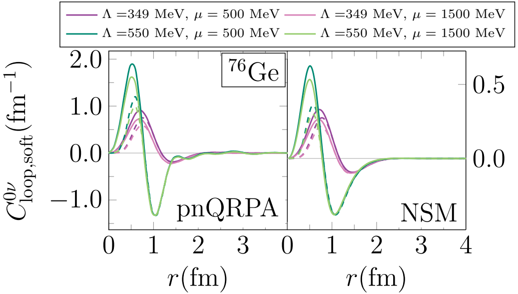
- The N^{2}LO loop corrections read as

$$M^{0\nu}_{\text{loops}} = \frac{4R}{\pi g_A^2}\langle 0_f^+|\sum_{a,b}\tau_a^-\tau_b^-\int e^{-\frac{q^2}{2\Lambda^2}} j_u(qr)\, V^{(a,b)}_{\nu,2}\, q^2 \mathrm{d}q|0_i^+\rangle$$

with

$$V^{(a,b)}_{\nu,2} = V^{(a,b)}_{\text{VV}} + V^{(a,b)}_{\text{AA}} + \ln\frac{m_\pi^2}{\mu_{\text{us}}^2} V^{(a,b)}_{\text{us}} + V^{(a,b)}_{\text{CT}}$$

$$\int C^{0\nu}_{\text{N}^2\text{LO}}(r)\mathrm{d}r = M^{0\nu}_{\text{loops}}$$



D. Castillo, LJ, P. Soriano, J Menéndez, arXiv:2408.03373

In pnQRPA:

$|M_{\text{N}^2\text{LO}}/M_{\text{L}}| \approx 2\% - 10\%$

In NSM:

$|M_{\text{N}^2\text{LO}}/M_{\text{L}}| \approx 4\% - 10\%$

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$0\nu\beta\beta$ Decay vs Double-Charge-Exchange Reactions

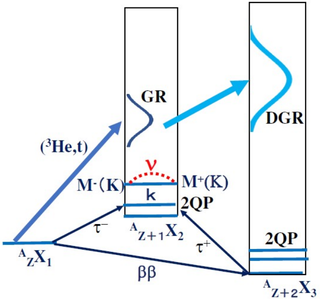
$$M^{0\nu} = M^{0\nu}_{\rm GT} - \left(\frac{g_V}{g_A}\right)^2 M^{0\nu}_{\rm F} + M^{0\nu}_{\rm T} + M^{0\nu}_{\rm S} + M^{0\nu}_{\rm N^2LO}$$

Leading contribution

$$M^{0\nu}_{\rm GT} = \langle f || \sum_{jk} \tau^-_j \tau^-_k \sigma^-_j \sigma^-_k V_{\rm GT}(r_{jk}) || i \rangle$$

- Double-Gamow-Teller (DGT) strength function

$$B(\mathrm{DGT};\lambda) = \frac{1}{2J_i+1} |\langle f || [\sum_{jk} \boldsymbol{\sigma}_j \tau^-_j \times \boldsymbol{\sigma}_k \tau^-_k]^{(\lambda)} || i \rangle|^2$$



H. Ejiri, LJ, J. Suhonen, Phys. Rev. C 105, L022501 (2022)

TRIUMF

$0\nu\beta\beta$ Decay vs Double-Charge-Exchange Reactions

$$M^{0\nu} = M^{0\nu}_{\rm GT} - \left(\frac{g_V}{g_A}\right)^2 M^{0\nu}_{\rm F} + M^{0\nu}_{\rm T} + M^{0\nu}_{\rm S} + M^{0\nu}_{\rm N^2LO}$$

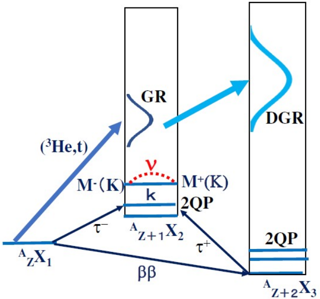
Leading contribution

$$M^{0\nu}_{\rm GT} = \langle f || \sum_{jk} \tau^-_j \tau^-_k \sigma^-_j \sigma^-_k V_{\rm GT}(r_{jk}) || i \rangle$$

- Double-Gamow-Teller (DGT) strength function

$$B(\mathrm{DGT};\lambda) = \frac{1}{2J_i+1} |\langle f || [\sum_{jk} \sigma_j \tau^-_j \times \sigma_k \tau^-_k]^{(\lambda)} || i \rangle|^2$$

  - **Could we probe $0\nu\beta\beta$ decay by DGT reactions?**

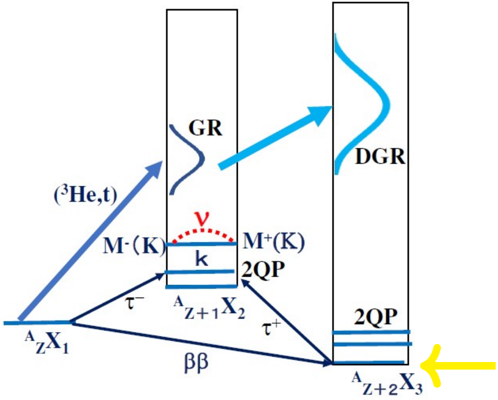


H. Ejiri, LJ, J. Suhonen, Phys. Rev. C 105, L022501 (2022)

Discovery, accelerated

Correlations Between DGT and $0\nu\beta\beta$ Decay

$$M_{\mathrm{DGT}} = -\langle 0^+_{\mathrm{gs,f}} || [\sum_{jk} \boldsymbol{\sigma}_j \tau^-_j \times \boldsymbol{\sigma}_k \tau^-_k]^{(0)} || 0^+_{\mathrm{gs,i}} \rangle$$



H. Ejiri, LJ, J. Suhonen, Phys. Rev. C 105, L022501 (2022)

Discovery, accelerated

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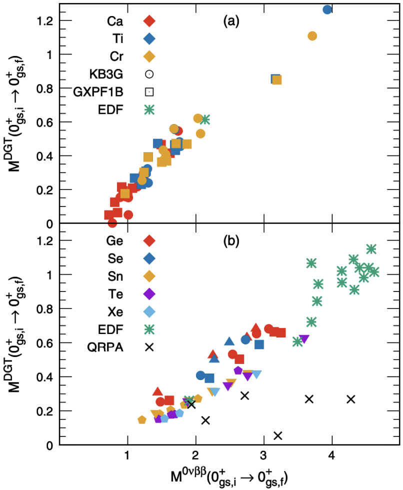

N. Shimizu, J. Menéndez, K. Yako, Phys. Rev. Lett. 120, 142502 (2018)

Discovery, accelerated

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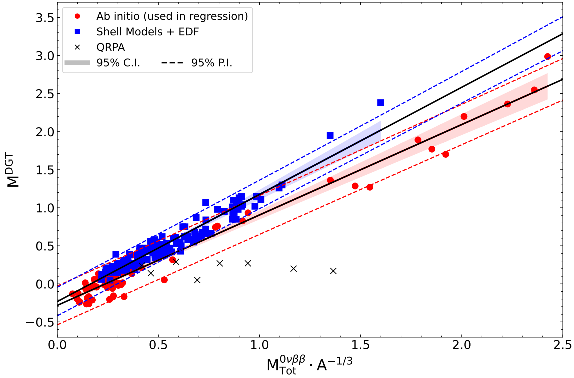
- Correlation also holds in *ab initio* **VS-IMSRG**



J. M. Yao, I. Ginnett, A. Belley et al., Phys. Rev. C 106, 014315 (2022)

Discovery, accelerated

TRIUMF

Correlations Between DGT and $0\nu\beta\beta$ Decay

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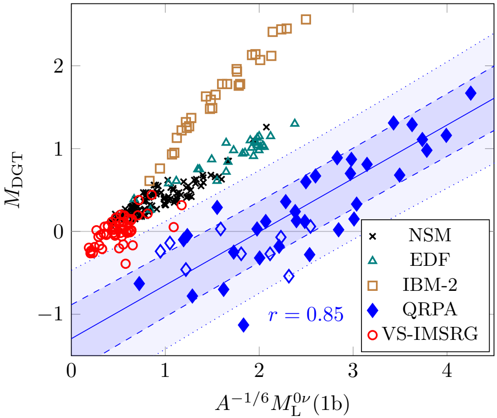
- Correlation between $M^{0\nu}$ and M_{DGT} found in **nuclear shell model** and **EFT**
- Correlation also holds in *ab initio* **VS-IMSRG**
- ...and **QRPA**, when proton-neutron pairing varied
  - **Observation of M_{DGT} → constraints for $M^{0\nu}$**



LJ, J. Menéndez, Phys. Rev. C 107, 044316 (2023)

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TRIUMF

Probing $0\nu\beta\beta$ Decay by $2\nu\beta\beta$ Decay

- ***How about $2\nu\beta\beta$ decay?***

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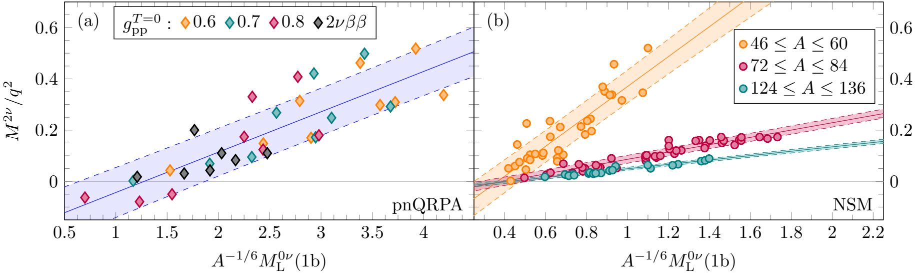
Probing $0\nu\beta\beta$ Decay by $2\nu\beta\beta$ Decay

- ***How about $2\nu\beta\beta$ decay?***
- $2\nu\beta\beta$-decay also correlated with $0\nu\beta\beta$-decay!

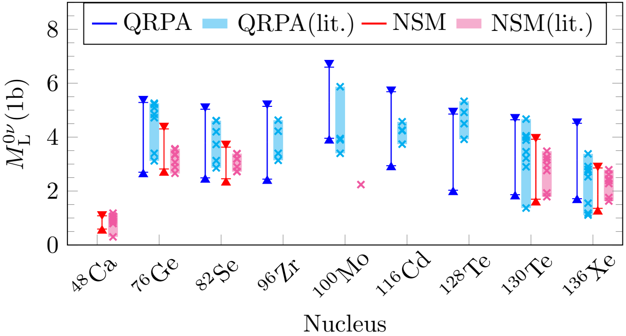


*LJ, B. Romeo, P. Soriano and J. Menéndez, Phys. Rev. C **107**, 044305 (2023)*

TRIUMF

Probing $0\nu\beta\beta$ Decay by $2\nu\beta\beta$ Decay

- ***How about $2\nu\beta\beta$ decay?***
- $2\nu\beta\beta$-decay also correlated with $0\nu\beta\beta$-decay!
- We can use the existing data to estimate $0\nu\beta\beta$-decay NMEs!



*LJ, B. Romeo, P. Soriano and J. Menéndez, Phys. Rev. C **107**, 044305 (2023)*

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Outline

Introduction

Corrections to $0\nu\beta\beta$-Decay Nuclear Matrix Elements

Correlations with other observables to constrain the matrix elements

Summary and Outlook

Discovery, accelerated

TRIUMF

Summary

- χEFT corrections to $0\nu\beta\beta$-decay seem to respect the power counting, but N^{2}LO corrections still significant
- Correlation between $0\nu\beta\beta$ and $2\nu\beta\beta$ decays helped us predict $0\nu\beta\beta$-decay NMEs with uncertainties
- Correlations with DGT and M1M1 transitions with future data can help us further constrain the NMEs

For the Future...

- Test $M^{0\nu}_{\mathrm{usoft}}$ predictions with data from charge-exchange reactions (currently limited at ~ 5 MeV)
- Study N^{2}LO corrections to $M^{0\nu}$ with consistent Hamiltonians in an *ab initio* framework
- Study correlation between $0\nu\beta\beta$ and $2\nu\beta\beta$ decay in an *ab initio* framework

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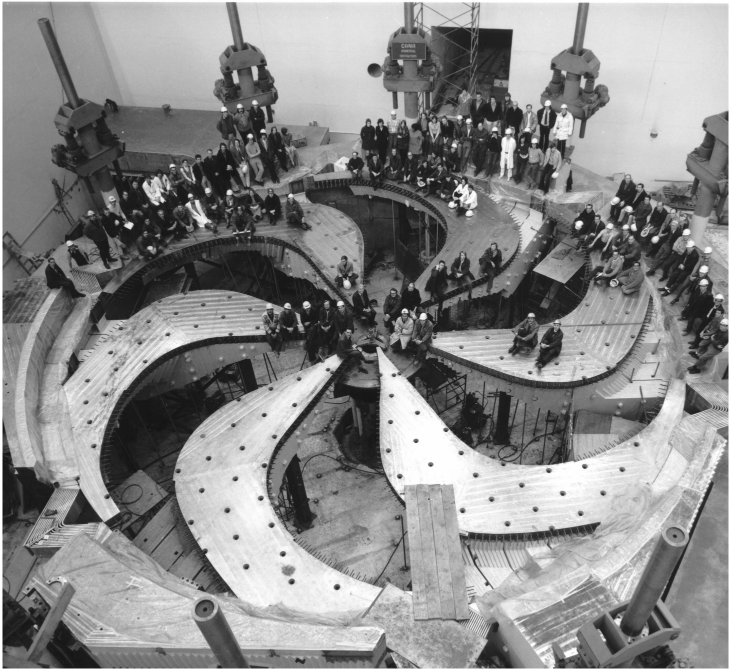
Thank you

Merci



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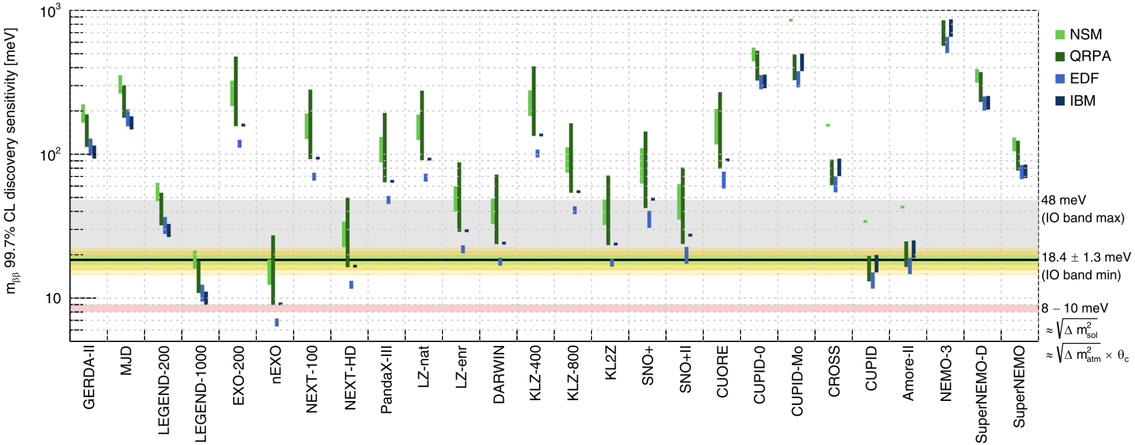
Next generation experiments



M. Agostini et al., Rev. Mod. Phys. ***95****, 025002 (2023)*

Effective Neutrino Masses

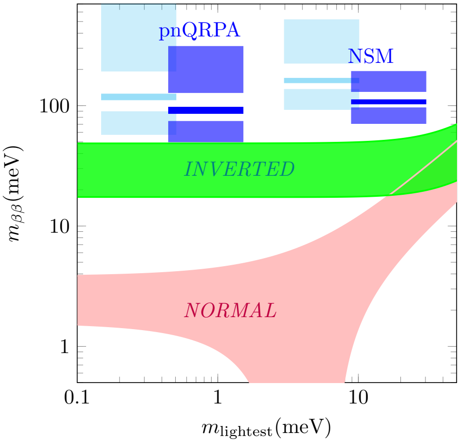
- Effective neutrino masses combining the likelihood functions of GERDA (^{76}Ge), CUORE (^{130}Te), EXO-200 (^{136}Xe) and KamLAND-Zen (^{136}Xe)

*S. D. Biller, Phys. Rev. D **104**, 012002 (2021)*

- Middle bands: $M_{\mathrm{L}}^{(0\nu)}$

  Lower bands: $M_{\mathrm{L}}^{(0\nu)} + M_{\mathrm{S}}^{(0\nu)}$

  Upper bands: $M_{\mathrm{L}}^{(0\nu)} - M_{\mathrm{S}}^{(0\nu)}$



*LJ, P. Soriano and J. Menéndez, Phys. Lett. B **823**, 136720 (2021)*

Discovery, accelerated

Traditional nuclear matrix elements of neutrinoless double-beta decay

$$M^{0\nu} = \frac{R}{g_{\mathbf{A}}^2} \int \frac{\mathbf{dk}}{2\pi^2} \frac{e^{i\mathbf{k}(\mathbf{x}-\mathbf{y})}}{E_\nu} \sum_n \frac{\langle f | J_\mu(\mathbf{x}) | n \rangle \langle n | J^\mu(\mathbf{y}) | i \rangle}{E_\nu + E_n - \frac{1}{2}(E_i + E_f) - \frac{1}{2}(E_1 - E_2)}$$

- Energy of the virtual neutrino typically $E_\nu = \sqrt{m_\nu^2 + \mathbf{k}^2} \sim |\mathbf{k}| \sim k_{\mathrm{F}} \sim 100$ **MeV** ("soft neutrinos")

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TRIUMF

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Discovery, accelerated

TRIUMF

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$$\rightarrow M^{0\nu} = \frac{R}{g_A^2} \int \frac{d\mathbf{k}}{2\pi^2} \frac{e^{i\mathbf{k}(\mathbf{x}-\mathbf{y})}}{|\mathbf{k}|} \sum_n \frac{\langle f | J_\mu(\mathbf{x}) | n \rangle \langle n | J^\mu(\mathbf{y}) | i \rangle}{|\mathbf{k}| + E_n - \frac{1}{2}(E_i + E_f)}$$

TRIUMF

Closure approximation

Without closure approximation:

$$M^{0\nu} \propto \sum_n \frac{\langle f | J_\mu(\mathbf{x}) | n \rangle \langle n | J^\mu(\mathbf{y}) | i \rangle}{|\mathbf{k}| + E_n - \frac{1}{2}(E_i + E_f)}$$

With closure approximation:

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TRIUMF

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Closure approximation

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Closure approximation

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TRIUMF

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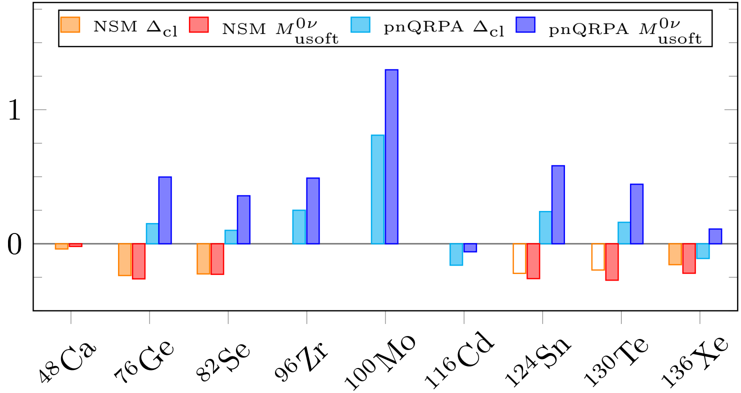
- Typically used **with other nuclear methods**

Discovery, accelerated

Ultrasoft Neutrinos as Closure Correction



$$\Delta_{\rm cl} = M^{0\nu}_{\rm non-cl} - M^{0\nu}_{\rm cl}$$

LJ, D. Castillo, P. Soriano, J. Menéndez, in preparation

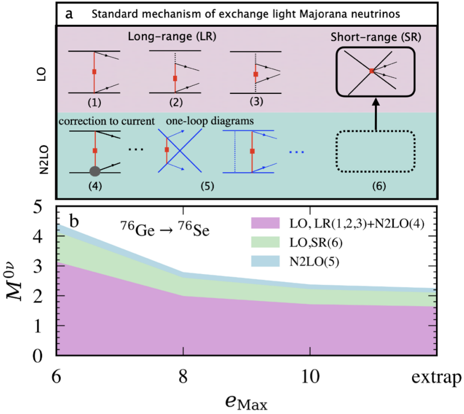
Similar effects found in *ab initio* studies

- In ^{76}Ge:

$$M^{0\nu}_{\mathrm{S}}/M^{0\nu}_{\mathrm{L}} \sim 40\%\,,$$

$$M^{0\nu}_{\mathrm{N^2LO}}/M^{0\nu}_{\mathrm{L}} \sim 5\%^{a}$$

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



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[a] There were some errors found in the paper

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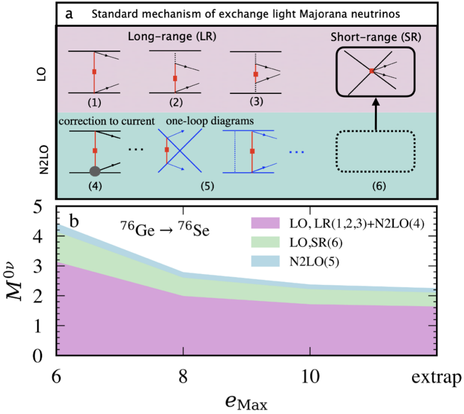
- In ^{130}Te and ^{136}Xe:

$$M^{0\nu}_{S}/M^{0\nu}_{L} \sim 20\% - 120\%$$

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



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

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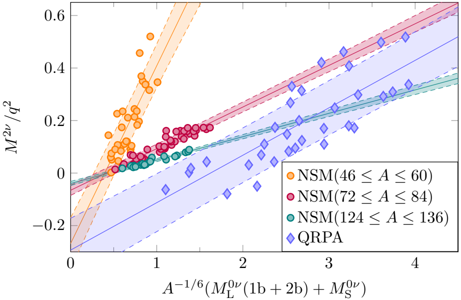
Discovery, accelerated

Probing $0\nu\beta\beta$ Decay by $2\nu\beta\beta$ Decay

Two-Body Currents & Contact Term

- Correlations survive when adding approximate two-body currents (2BCs) and the contact term



LJ, B. Romeo, P. Soriano and J. Menéndez, Phys. Rev. C ***107****, 044305 (2023)*

TRIUMF

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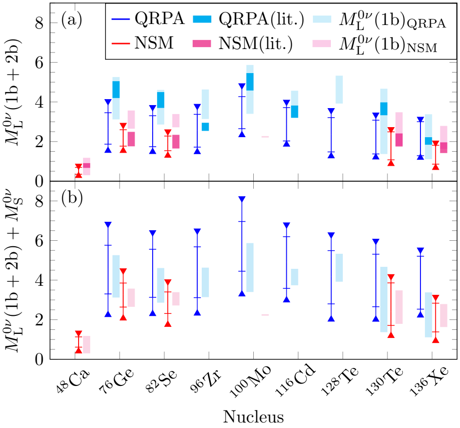
J. Menéndez, D. Gazit, A. Schwenk, Phys. Rev. Lett. 107, 062501 (2011)

J. Engel, F. Šimkovic, P. Vogel, Phys. Rev. C 89, 064308 (2014)



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Discovery, accelerated

TRIUMF

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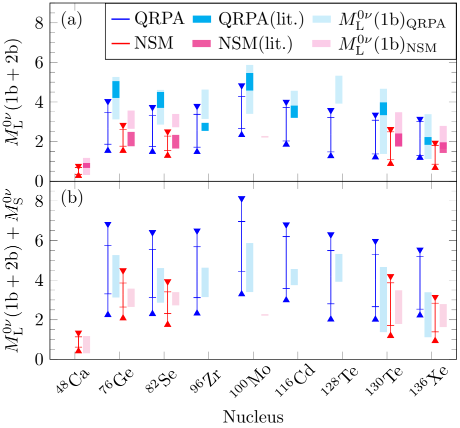
- 2BCs and the contact term largely cancel each other



*LJ, B. Romeo, P. Soriano and J. Menéndez, Phys. Rev. C **107**, 044305 (2023)*

Discovery, accelerated