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Charge-Exchange Reactions as Probes of Neutrinoless Double-Beta Decays

Lotta Jokiniemi
TRIUMF, Theory Department

NN2024 Conference, Whistler, BC Canada
22/08/2024

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

Discovery, accelerated

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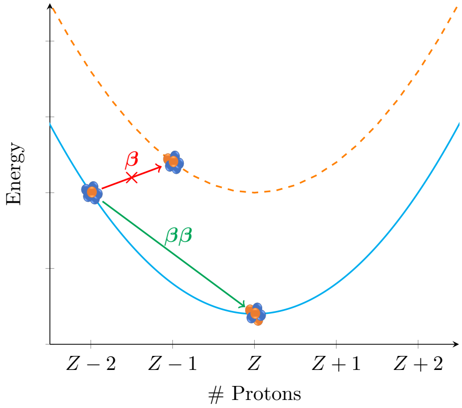
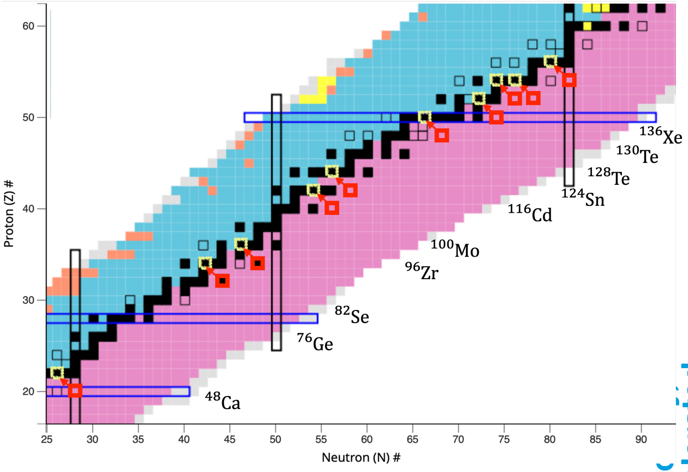
Double-Beta Decay





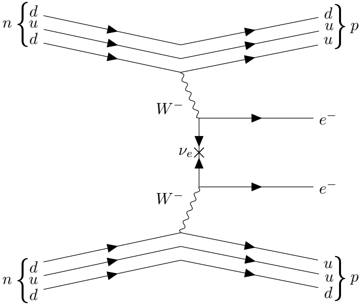
nndc.bnl.gov

Disc… accelerated

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

- **Violates lepton-number conservation**

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



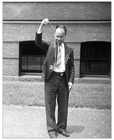
Maria Goeppert-Mayer

$2\nu\beta\beta$

Ettore Majorana

Majorana particles

Wendell H. Furry



$0\nu\beta\beta$

1935 → 1937 → 1939 → …

Discovery, accelerated

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

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- Requires that **neutrinos are Majorana particles**

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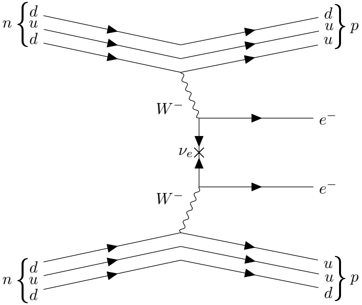

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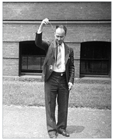

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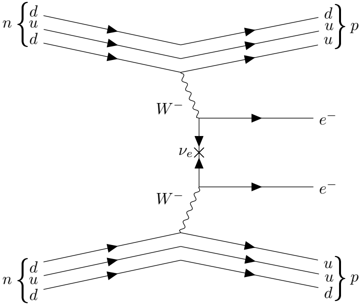
Neutrinoless Double-Beta ($0\nu\beta\beta$) Decay

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

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



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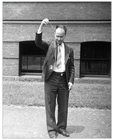

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Discovery, accelerated

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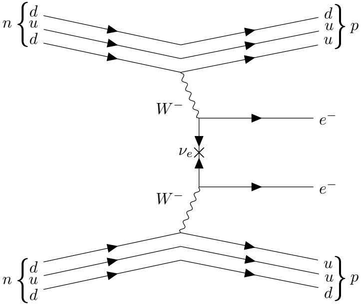
- **Violates lepton-number conservation**
- Requires that **neutrinos are Majorana particles**
- If observed, $t^{0\nu}_{1/2} \gtrsim 10^{25}$ **years**
  ($t^{2\nu}_{1/2} \approx 10^{20}$ years,
  age of the Universe $\approx 10^{10}$ years)

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



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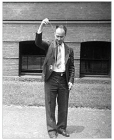
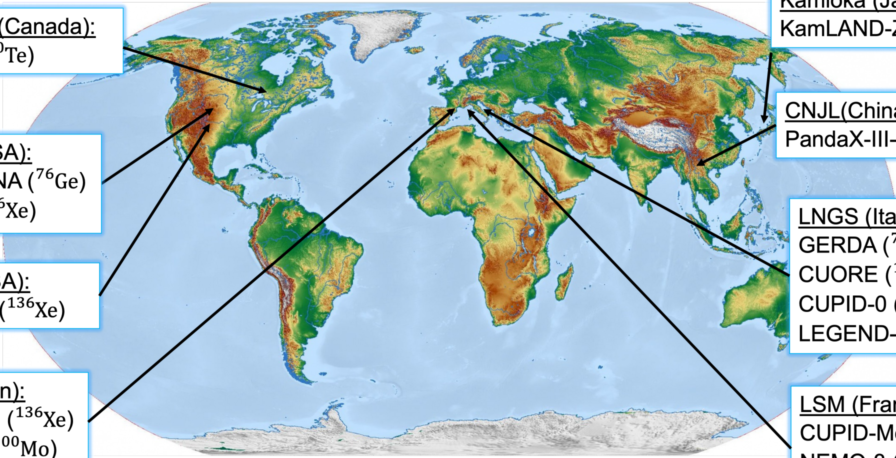


$0\nu\beta\beta$

1939

…

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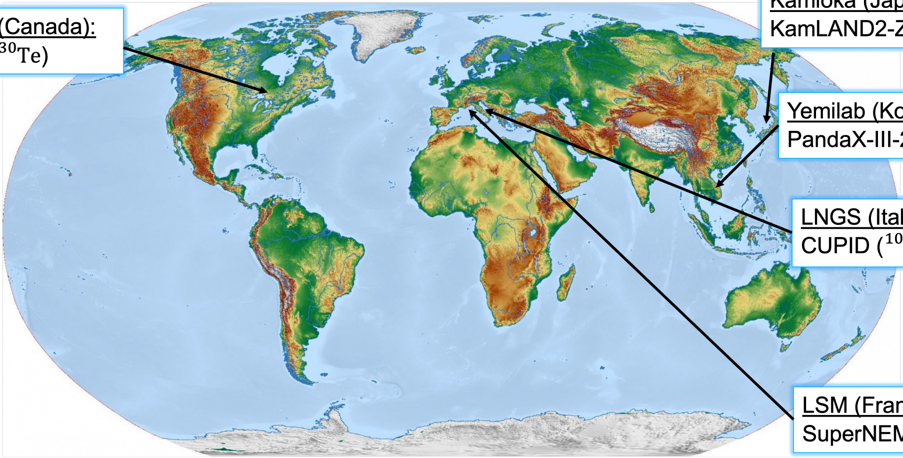
Next-Generation $0\nu\beta\beta$-Decay Experiments



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

Kamioka (Japan):
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Yemilab (Korea):
PandaX-III-200 ($^{136}\mathrm{Xe}$)

LNGS (Italy):
CUPID ($^{100}\mathrm{Mo}$)

LSM (France):
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+nEXO ($^{136}\mathrm{Xe}$), LEGEND-1000 ($^{76}\mathrm{Ge}$), NEXT-HD ($^{136}\mathrm{Xe}$), Darwin ($^{136}\mathrm{Xe}$), …

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

Discovery, accelerated

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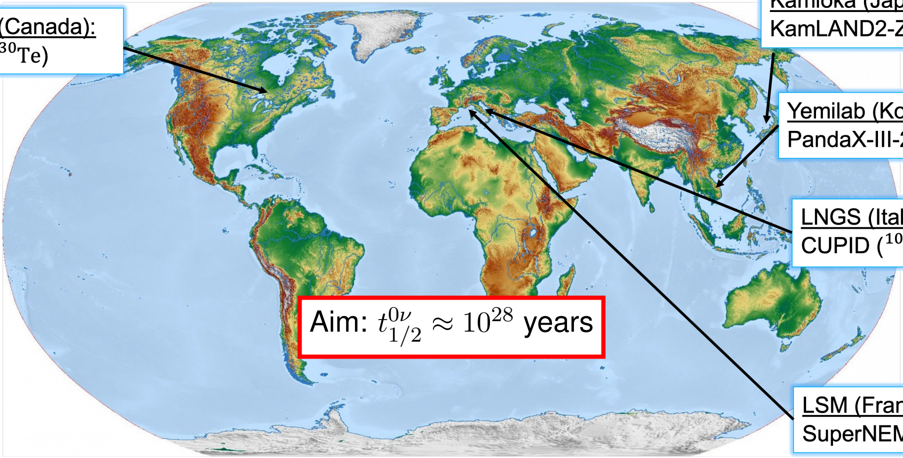

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Aim: $t^{0\nu}_{1/2} \approx 10^{28}$ years

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

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

Discovery, accelerated

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

What would be measured

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

Discovery, accelerated

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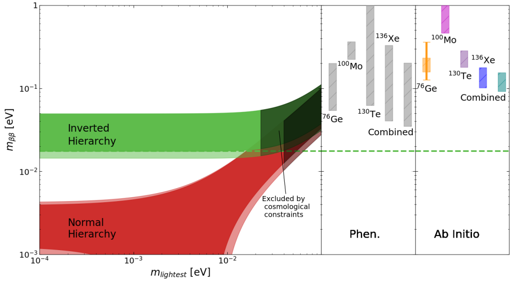
Majorana mass

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



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

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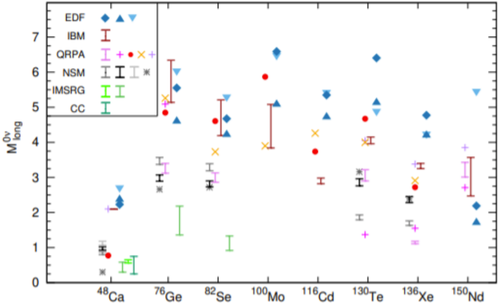
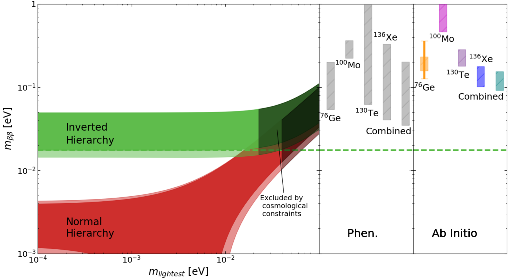
Nuclear matrix element



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



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What Can We Learn from Double-Charge-Exchange Reactions?

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

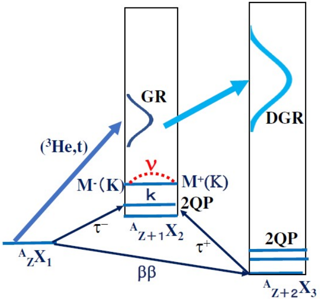
$$M^{0\nu} = M^{0\nu}_{\mathrm{GT}} - \left(\frac{g_{\mathrm{V}}}{g_{\mathrm{A}}}\right)^2 M^{0\nu}_{\mathrm{F}} + M^{0\nu}_{\mathrm{T}} + M^{0\nu}_{\mathrm{S}}$$

Leading contribution

$$\boldsymbol{M^{0\nu}_{\mathrm{GT}} = \langle f || \sum_{jk} \tau_j^- \tau_k^- \sigma_j^- \sigma_k^- V_{\mathrm{GT}}(r_{jk}) || i \rangle}$$

- 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)

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

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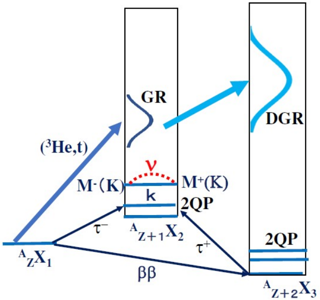
  - **Could we probe $0\nu\beta\beta$ decay by DGT reactions?**



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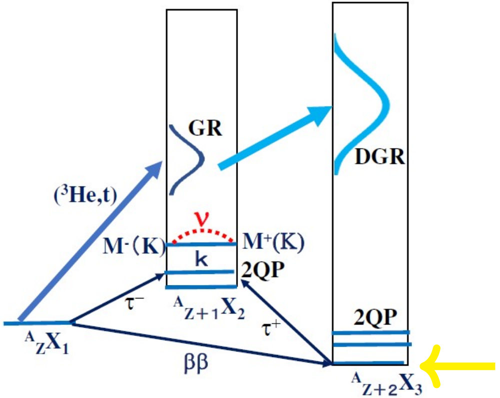
Correlations Between DGT and $0\nu\beta\beta$ Decay

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



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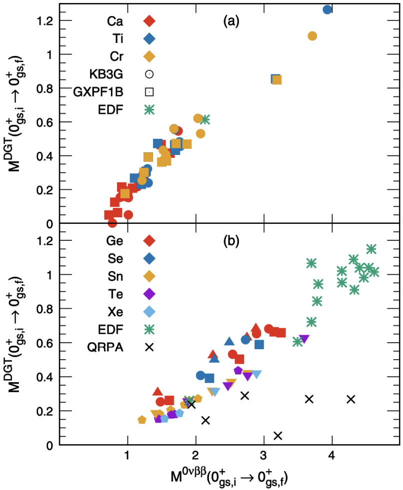
- Correlation between $M^{0\nu}$ and M_{DGT} found in **nuclear shell model** and **EFT**



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

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

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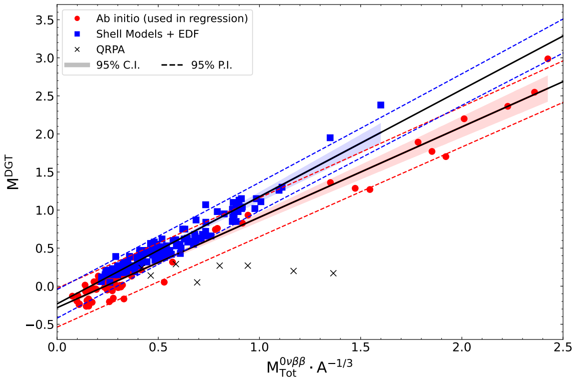
- Correlation between $M^{0\nu}$ and M_{DGT} found in **nuclear shell model** and **EFT**
- Correlation also holds in *ab initio* **VS-IMSRG**



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

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

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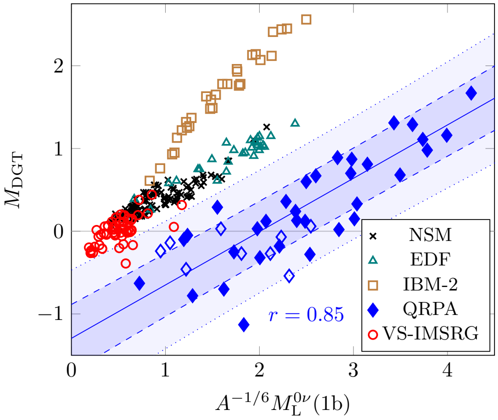
- Correlation between $M^{0\nu}$ and M_{DGT} found in **nuclear shell model** and **EFT**
- Correlation also holds in *ab initio* **VS-IMSRG**
- ...and **QRPA**, when proton-neutron pairing varied
    - **Observation of $M_{\mathrm{DGT}} \rightarrow$ constraints for $M^{0\nu}$**



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

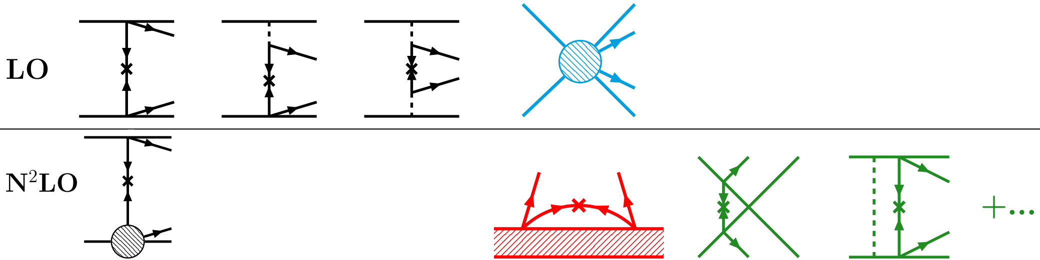
Discovery, accelerated

Could We Learn Something from Single-Charge-Exchange Reactions?

χEFT Analysis of $0\nu\beta\beta$ Decay

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

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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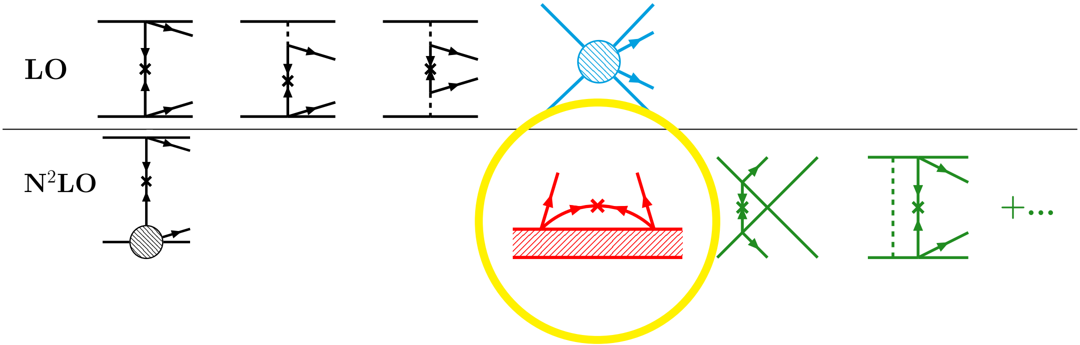

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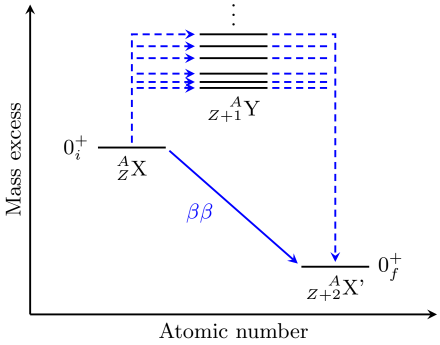
$M^{0\nu}_{\rm usoft}$ Evaluated in pnQRPA and NSM

- A N^{2}LO correction from "ultrasoft" ($|\mathbf{k}| << k_{\rm F} \approx 100$ MeV) neutrinos:

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



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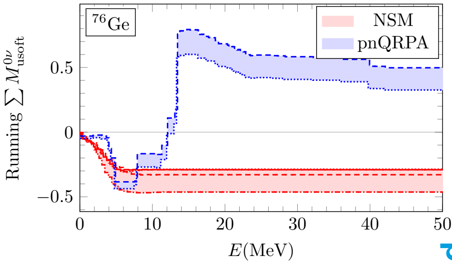
- A $\approx 10\%$ increase in pnQRPA, and $\approx 10\%$ decrease in nuclear shell model



D. Castillo, LJ, P. Soriano, J. Menéndez, arXiv:2408:03373

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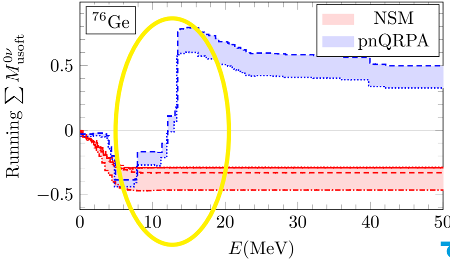

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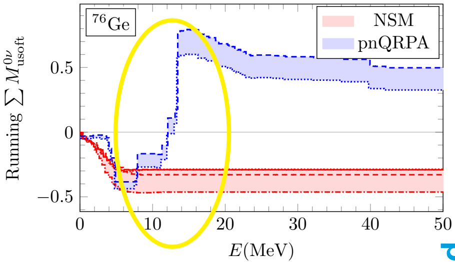

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- Many potential explanations:

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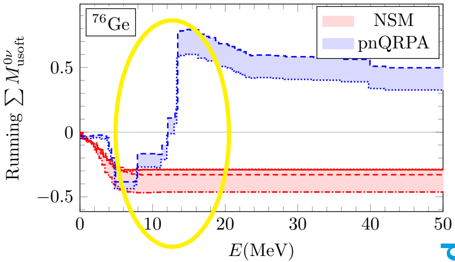
  - **Missing spin-orbit partners** in NSM?



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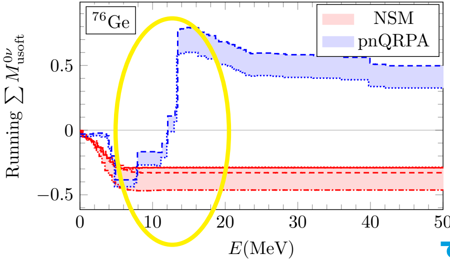
- A $\approx 10\%$ increase in pnQRPA, and $\approx 10\%$ decrease in nuclear shell model
- Many potential explanations:
  - **Missing spin-orbit partners** in NSM?
  - **Missing correlations** in pnQRPA?



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Discovery, accelerated

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- A N^{2}LO correction from "ultrasoft" ($|\mathbf{k}| << k_F \approx 100$ MeV) neutrinos:

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

- A $\approx 10\%$ increase in pnQRPA, and $\approx 10\%$ decrease in nuclear shell model
- Many potential explanations:
  - **Missing spin-orbit partners** in NSM?
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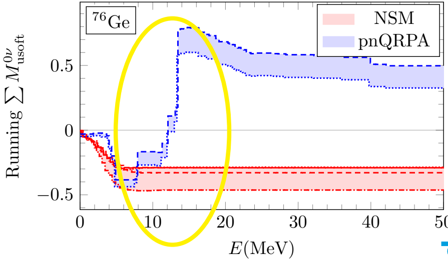
  - **Deformation?**



D. Castillo, LJ, P. Soriano, J. Menéndez, arXiv:2408:03373

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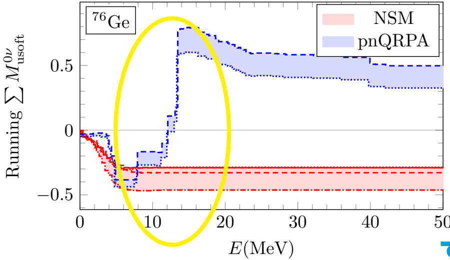
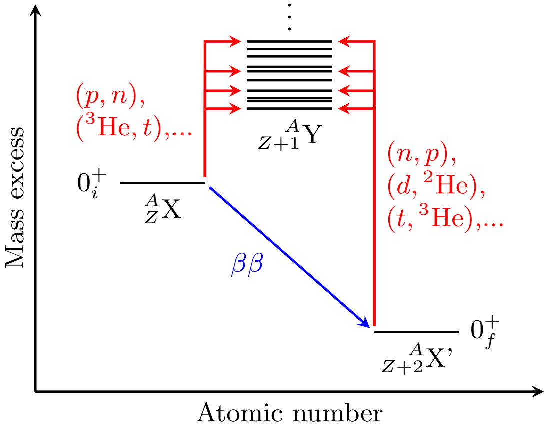


D. Castillo, LJ, P. Soriano, J. Menéndez, arXiv:2408:03373

Discovery, accelerated

Charge-Exchange Reactions as Probes of $M^{0\nu}_{\text{usoft}}$

- Charge-exchange reactions can probe the virtual transitions



Charge-Exchange Reactions as Probes of $M^{0\nu}_{\rm usoft}$

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^{76}Ge(^{3}He, t)^{76}As: *J. H. Hies et al., Phys. Rev. C 86, 014304 (2012)*

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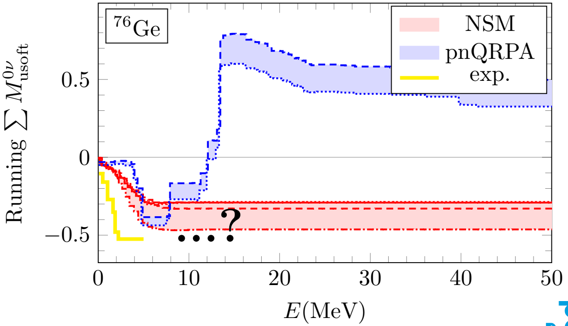

Modified from: D. Castillo, LJ, P. Soriano, J. Menéndez, arXiv:2408:03373

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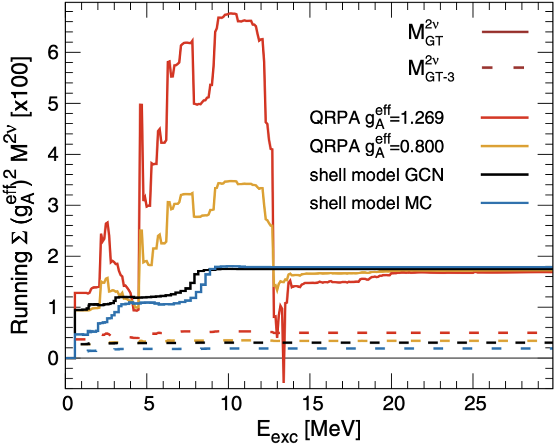

KamLAND-Zen, Phys. Rev. Lett. 122, 192501 (2019)

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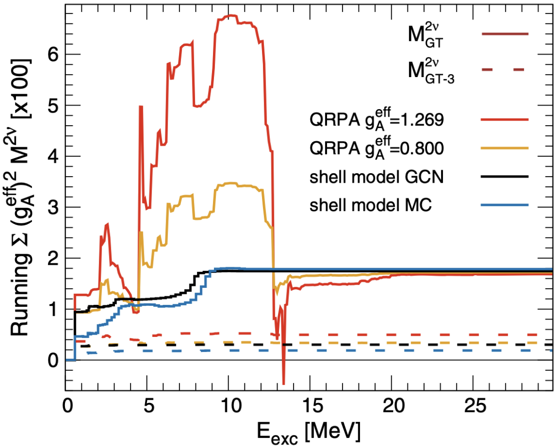
- Charge-exchange reactions **can also probe $2\nu\beta\beta$ decays**
  - **Good benchmark for future ab initio studies**



KamLAND-Zen, Phys. Rev. Lett. 122, 192501 (2019)

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Summary

- Theoretical efforts needed in the hunt for $0\nu\beta\beta$ decay
- **Correlations between $0\nu\beta\beta$ decay and double charge-exchange reactions** may help constrain the $0\nu\beta\beta$-decay nuclear matrix elements
- Measuring **single-charge-exchange reactions up to high excitation energies** would help probe
  - N^2LO corrections to $0\nu\beta\beta$ decays
  - $2\nu\beta\beta$-decay calculations

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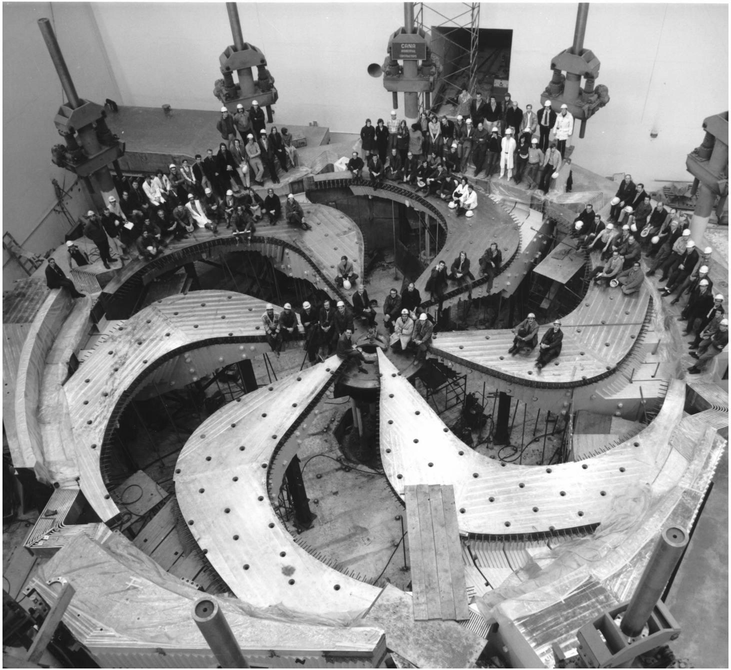
Thank you
Merci



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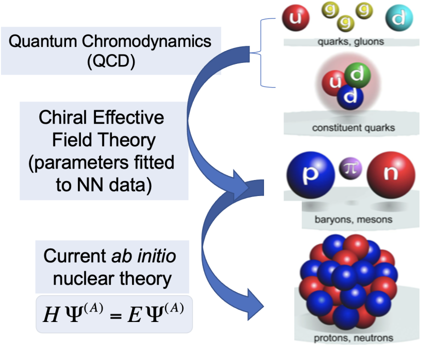
Nuclear Many-body Methods

- *Ab initio methods* (IMSRG, NCSM,...)



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Nuclear Many-body Methods

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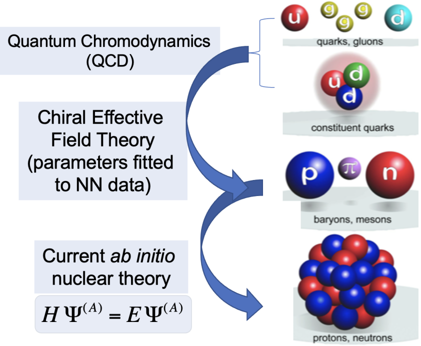
  - **Aim to solve nuclear Schrödinger equation (SE) with interactions between nucleons**



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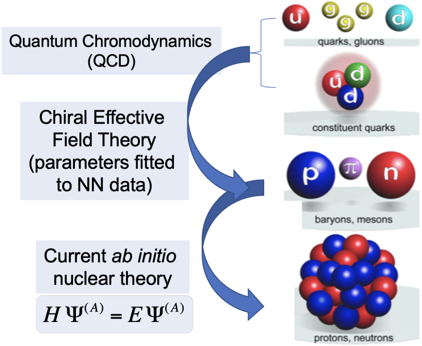

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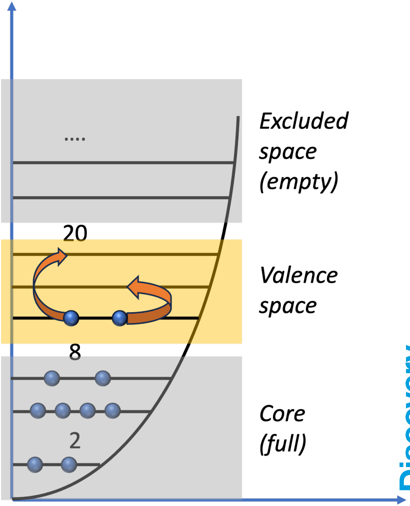

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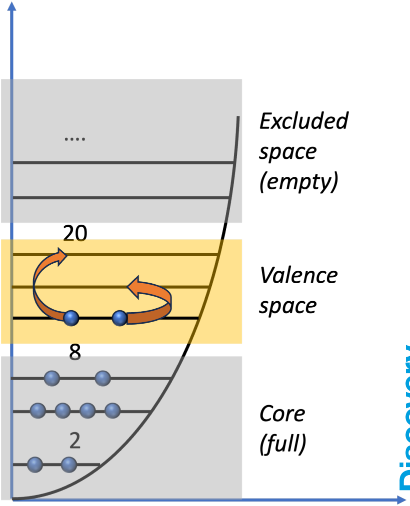

Discovery, accelerated

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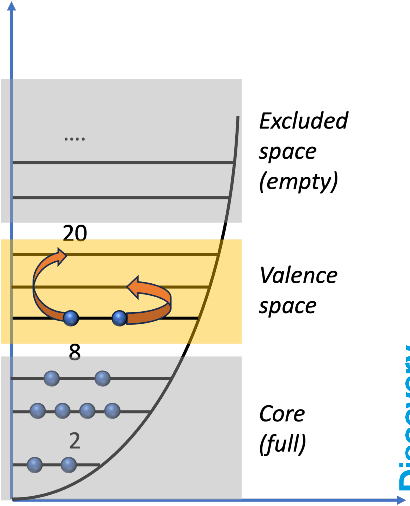

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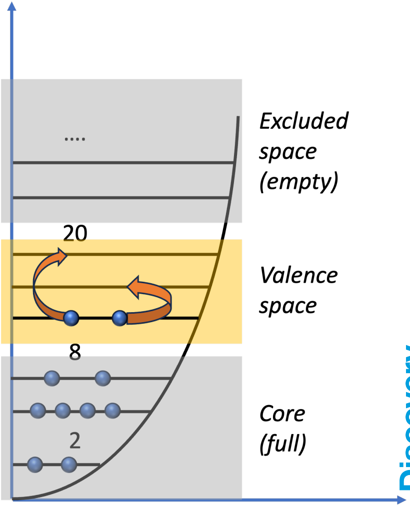

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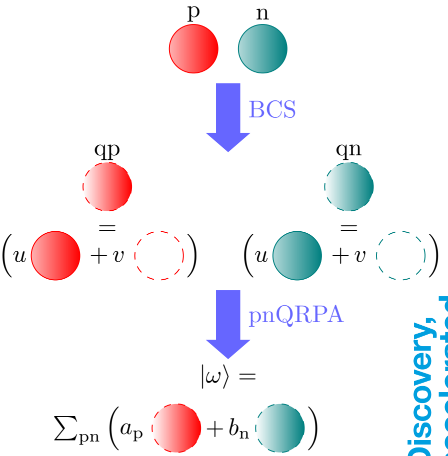

Discovery, accelerated

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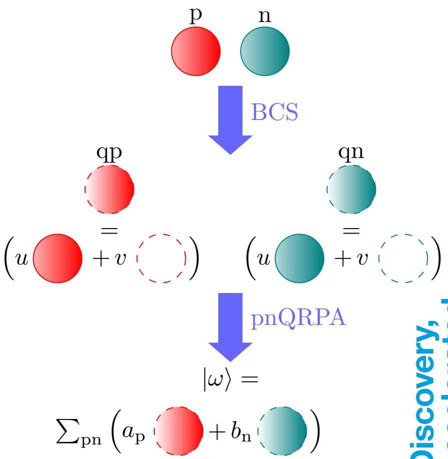

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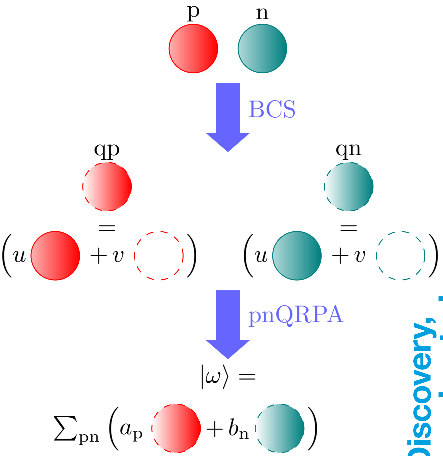

TRIUMF

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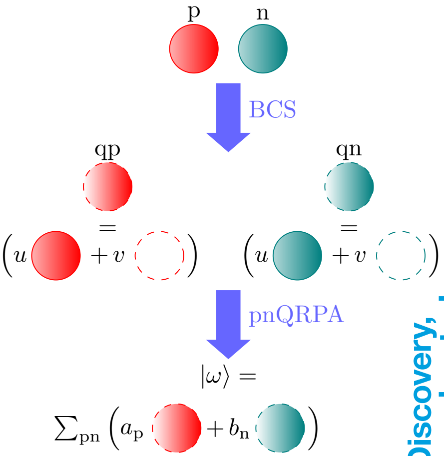

Discovery, accelerated

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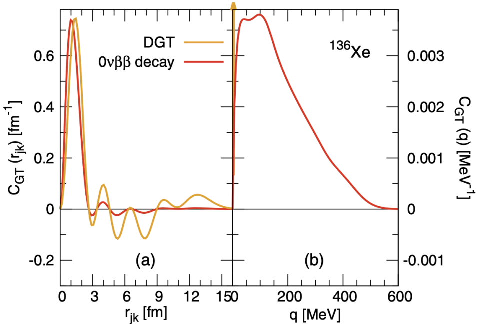
TRIUMF

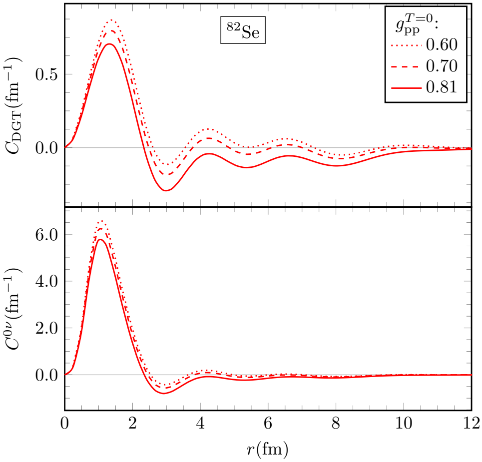
Radial Densities of $M^{0\nu}$ and M_{DGT}

$$M^{0\nu}_{\mathrm{L}} = \int_0^\infty C^{0\nu}(r)\mathrm{d}r\ ,$$

$$M_{\mathrm{DGT}} = \int_0^\infty C_{\mathrm{DGT}}(r)\mathrm{d}r$$



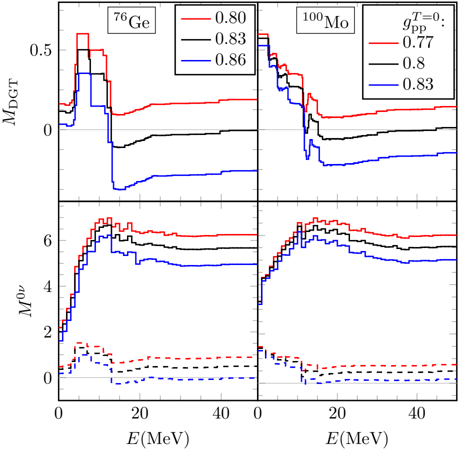
N. Shimizu, J. Menéndez, K. Yako, Phys. Rev. Lett. 120, 142502 (2018)



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

Discovery, accelerated

Running Sums of $M^{0\nu}$ and M_{DGT}



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

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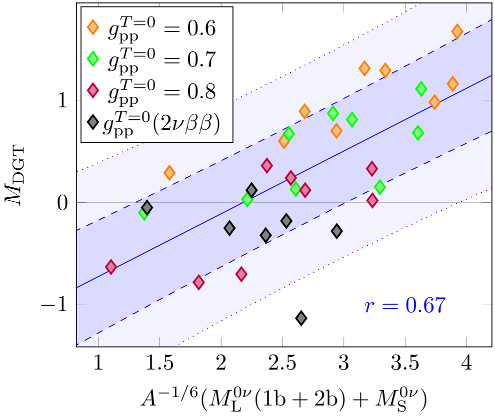
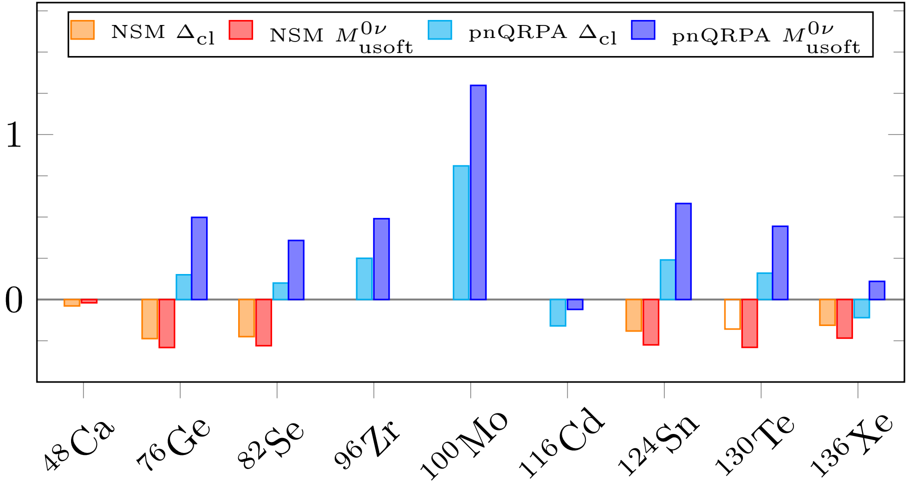
Correlation Survives 2BCs and Short-Range



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

$M^{0\nu}_{\rm usoft}$ as a Closure Correction



D. Castillo, LJ, P. Soriano, J. Menéndez, arXiv:2408:03373

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

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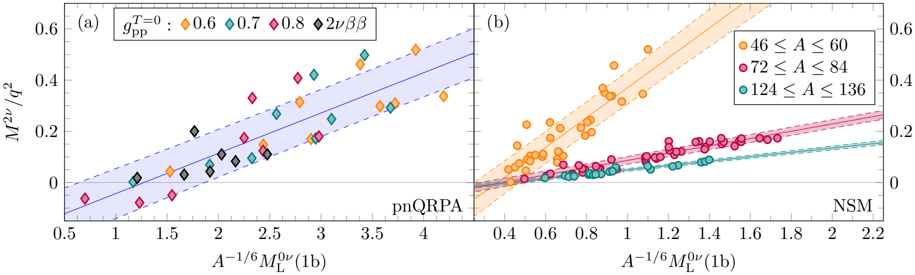

*LJ, B. Romeo, P. Soriano and J. Menéndez, Phys. Rev. C **107**, 044305 (2023)*

Discovery, accelerated

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

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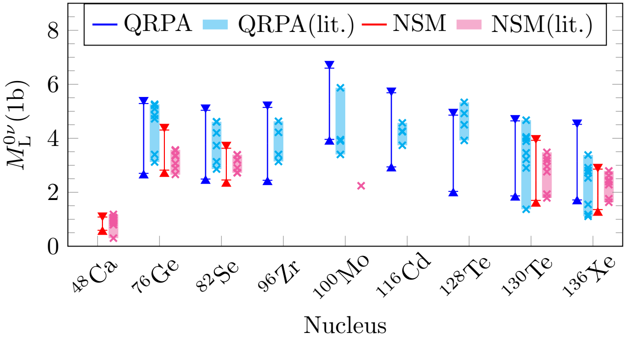
- We can use the existing data to estimate $0\nu\beta\beta$-decay NMEs!



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

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