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Shedding Light on Neutrinoless Double-Beta Decay Nuclear Matrix Elements

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2nd Joint Canada-APCTP Meeting on Nuclear Theory

ICCUB

UNIVERSITAT DE BARCELONA

SUOMEN KULTTUURIRAHASTO

Discovery, accelerated

Outline

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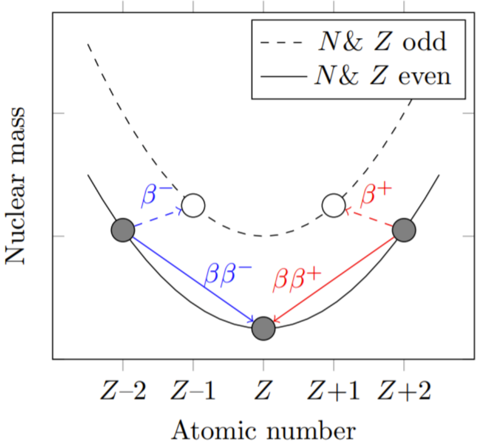
Double-Beta Decay

$$\beta^- : \mathrm{n} \to \mathrm{p} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$$
$$\beta^+ : \mathrm{p} \to \mathrm{n} + \mathrm{e}^+ + \nu_\mathrm{e}$$

- May happen, when **β-decay is not allowed / suppressed**



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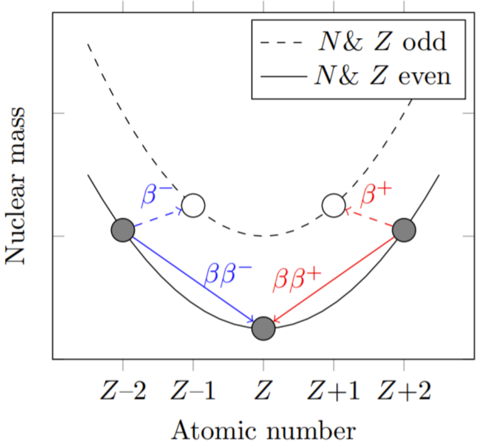
- Two modes:



Double-Beta Decay

$$\beta^- : \; n \rightarrow p + e^- + \bar{\nu}_e$$
$$\beta^+ : \; p \rightarrow n + e^+ + \nu_e$$

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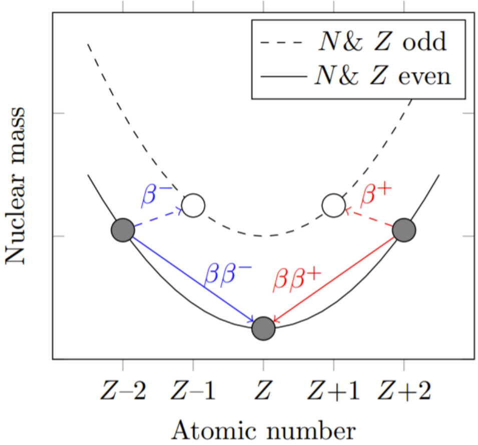
- Two modes:
  - Standard two-neutrino $\beta\beta$ decay ($2\nu\beta\beta$)



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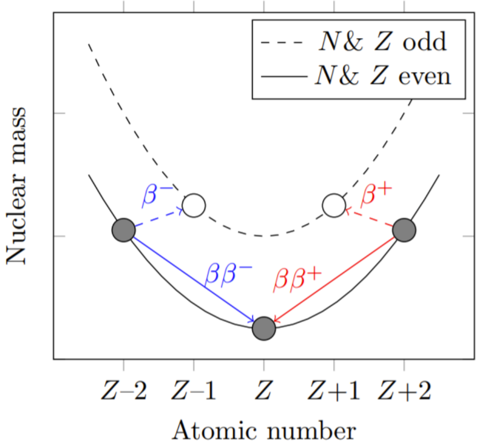
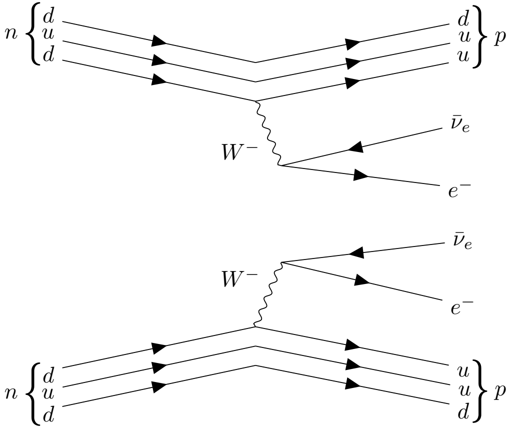
- May happen, when **β-decay is not allowed / suppressed**
- Two modes:
  - Standard two-neutrino $\beta\beta$ decay ($2\nu\beta\beta$)
  - Hypothetical **neutrinoless $\beta\beta$ ($0\nu\beta\beta$) decay**



Two-Neutrino Double-Beta ($2\nu\beta\beta$) Decay

$$^{A}_{Z}\mathrm{X}_{N} \rightarrow ^{A}_{Z+2}\mathrm{Y}_{N-2} + 2e^{-} + 2\bar{\nu}_e$$

- Allowed by the Standard Model



$q \sim 1$ **MeV**

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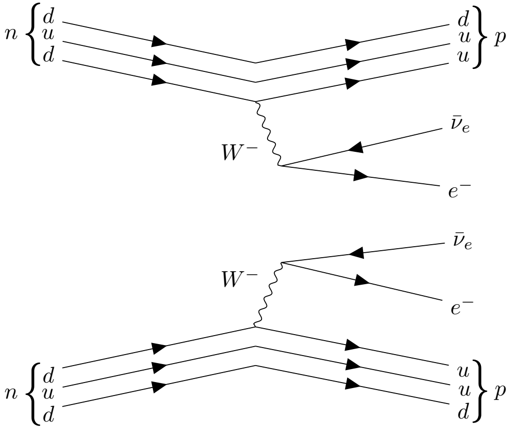

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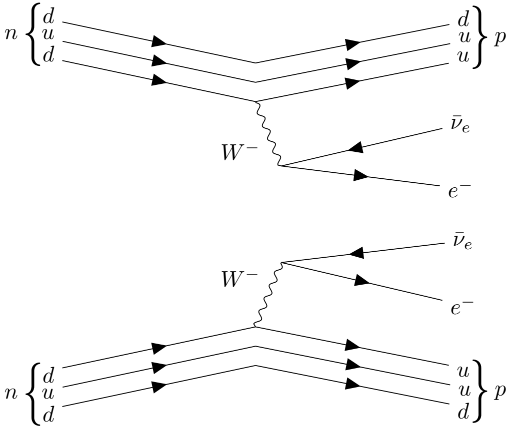
  - **$t^{2\nu}_{1/2} \gtrsim 10^{20}$ years**
    (age of the Universe: $\sim 10^{10}$ years)



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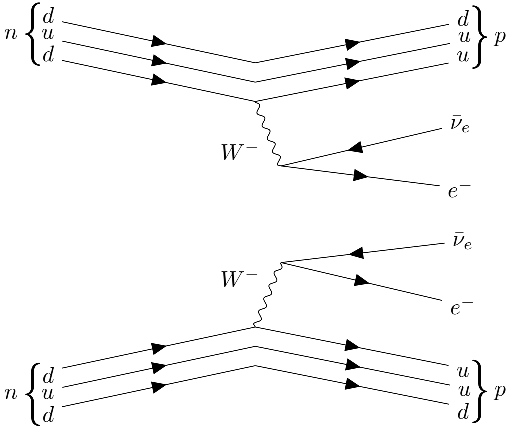
  - $t^{2\nu}_{1/2} \gtrsim 10^{20}$ **years**
    (age of the Universe: $\sim 10^{10}$ years)
  - **Rarest measured nuclear process!**



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

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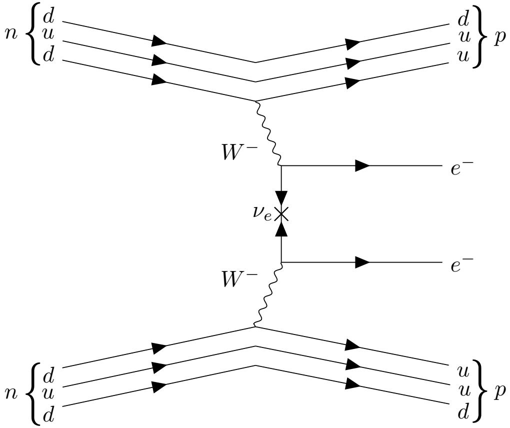
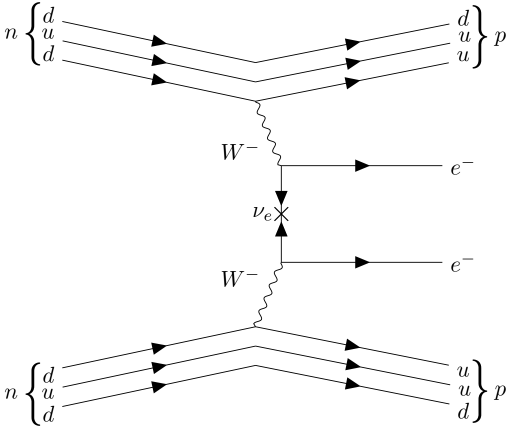


$q \sim 100$ MeV

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

$$\boxed{{}^{A}_{Z}\mathrm{X}_{N} \rightarrow {}^{A}_{Z+2}\,\mathrm{Y}_{N-2} + 2e^{-}}$$

- Requires that the **neutrino is its own antiparticle**



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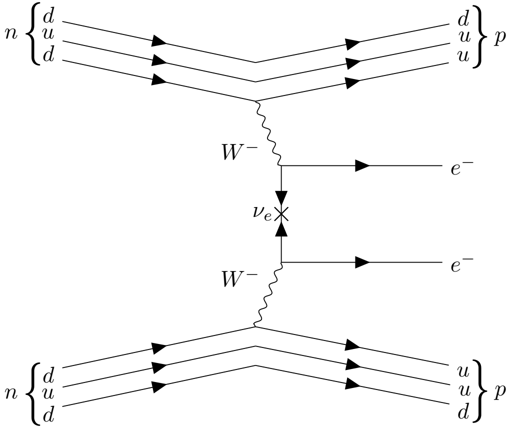

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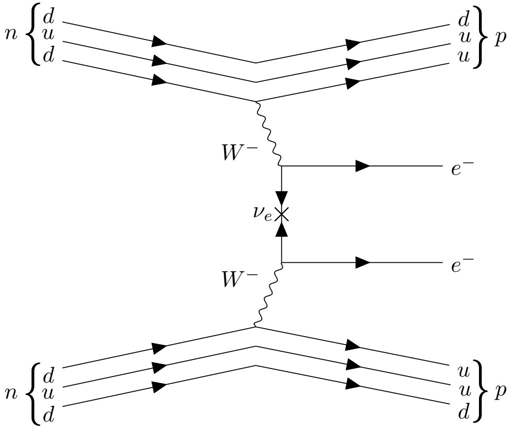
- $\frac{1}{t_{1/2}^{0\nu}} \propto \left|\frac{m_{\beta\beta}}{m_e}\right|^2, \quad m_{\beta\beta} = \sum_i^{\text{light}} U_{ei}^2 m_i$
  $\rightarrow$ **Neutrino masses!**



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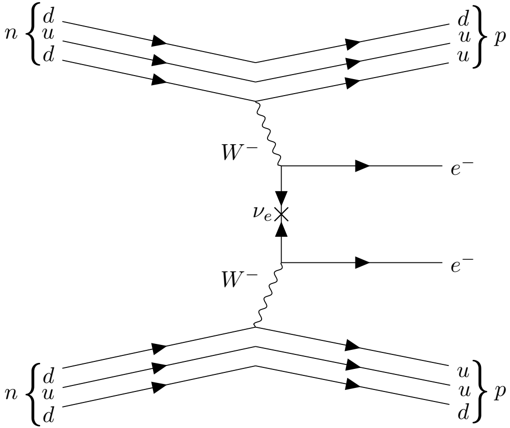

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Discovery, accelerated

Half-life of $0\nu\beta\beta$ Decay

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

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New physics

Discovery, accelerated

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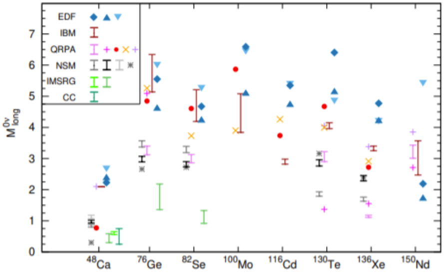

M. Agostini et al., arXiv:2202.01787 (2022)

Discovery, accelerated

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Nuclear Matrix Elements for $\beta\beta$ Decays

- For $0\nu\beta\beta$ decay

$$M_{\mathrm{L}}^{0\nu} = M_{\mathrm{GT}}^{0\nu} - \left(\frac{g_{\mathrm{V}}}{g_{\mathrm{A}}}\right)^2 M_{\mathrm{F}}^{0\nu} - M_{\mathrm{T}}^{0\nu} \ ,$$

where (for $K = \mathrm{GT}, \mathrm{F}, \mathrm{T}$)

$$M_K^{0\nu} = \frac{2R}{\pi g_{\mathrm{A}}^2} \sum_{k,ab} (0_f^+ || \mathcal{O}_{K\,b}\, H_K(r_{ab}, E_k) || 0_i^+)$$

with $\mathcal{O}_{\mathrm{GT}} = \tau_a^- \tau_b^- \boldsymbol{\sigma}_a \boldsymbol{\sigma}_b$, $\mathcal{O}_{\mathrm{F}} = \tau_a^- \tau_b^-$,
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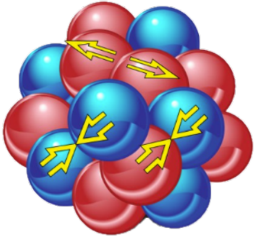
- For $\mathbf{2}\nu\beta\beta$ decay

$$M^{2\nu} = \sum_k \frac{(0_f^+ || \tau^- \boldsymbol{\sigma} || 1_k^+)(1_k^+ || \tau^- \boldsymbol{\sigma} || 0_i^+)}{(E_k - (E_i + E_f)/2 + m_e)/m_e}$$

Nuclear Many-body Methods

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



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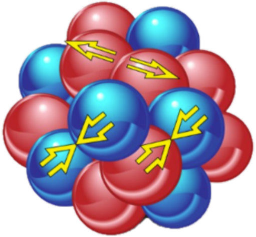

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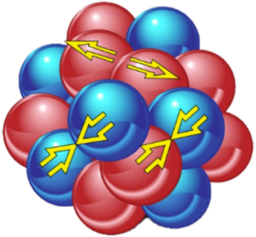

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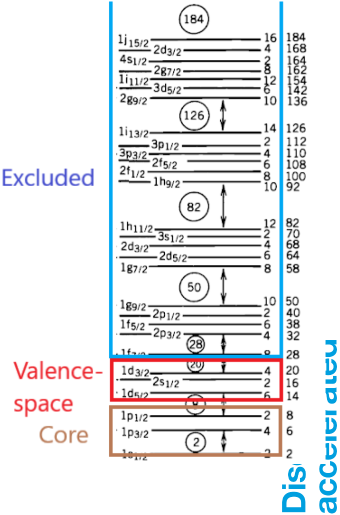

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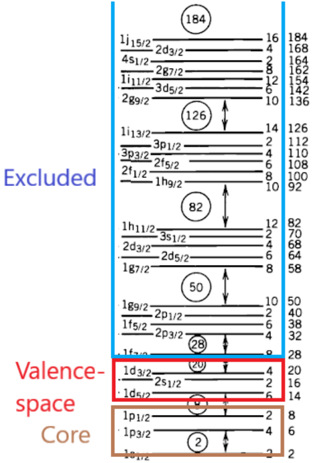

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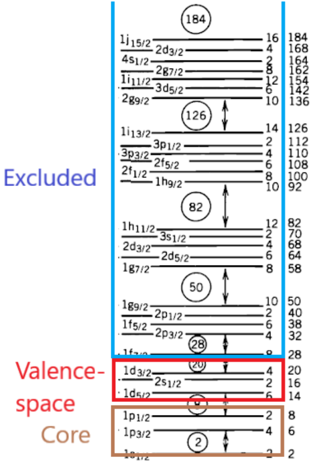

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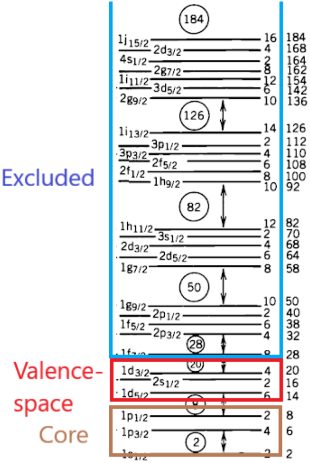

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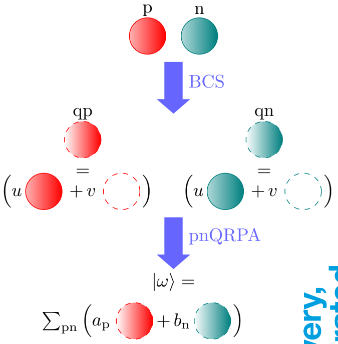

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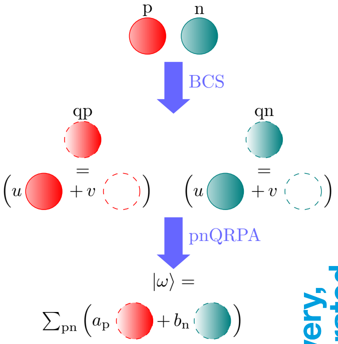

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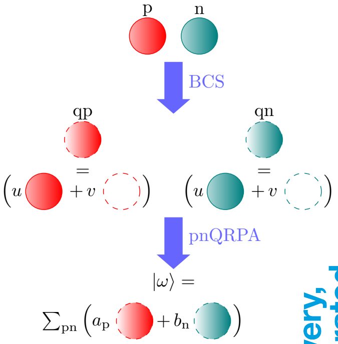

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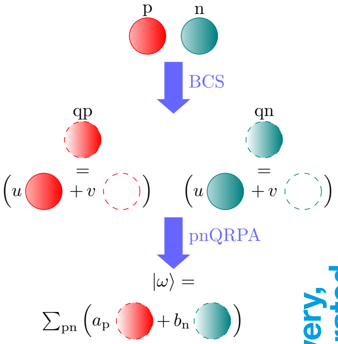

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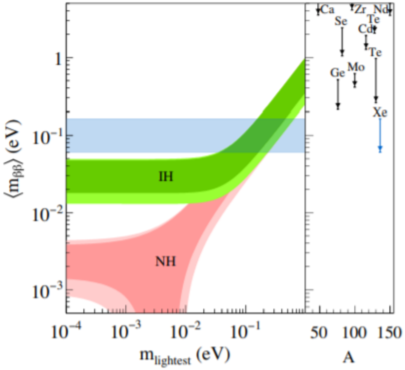
Current Status of $0\nu\beta\beta$-Decay Experiments

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

- Large-scale experiments: CUORE(Italy), GERDA(Italy), CUPID(Italy), MAJORANA(US), EXO-200(US), KamLAND-Zen(Japan), ...

NH: $m_1 < m_2 < m_3$

IH: $m_3 < m_1 < m_2$



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

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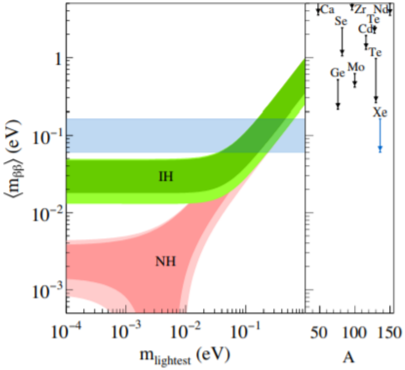
- Large-scale experiments: CUORE(Italy), GERDA(Italy), CUPID(Italy), MAJORANA(US), EXO-200(US), KamLAND-Zen(Japan), ...
- Currently, most stringent half-life limit $t^{0\nu}_{1/2}(^{136}\mathrm{Xe}) \geq 2.3 \times 10^{26}\ y$

KamLAND-Zen Collaboration, arXiv:2203.02139 (2022)

NH: $m_1 < m_2 < m_3$

IH: $m_3 < m_1 < m_2$



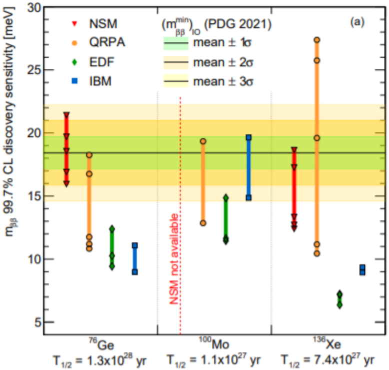
J. Engel and J. Menéndez, Rep. Prog. Phys. ***80***,*046301 (2017)*

Discovery, accelerated

Next-Generation Experiments

GOAL

Reaching the inverted-hierarchy region of neutrino masses



*M. Agostini et al., Phys. Rev. C **104**, L042501 (2021)*

TRIUMF

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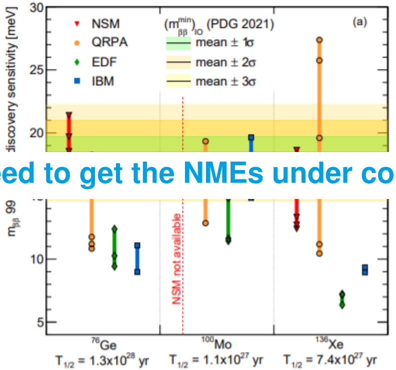


We need to get the NMEs under control!

M. Agostini et al., Phys. Rev. C ***104****, L042501 (2021)*

Discovery, accelerated

Outline

Introduction

Improved Double-Beta-Decay Calculations

Other Nuclear Observables as Probes of Neutrinoless Double-Beta Decay

Ab Initio Muon-Capture Studies

Summary

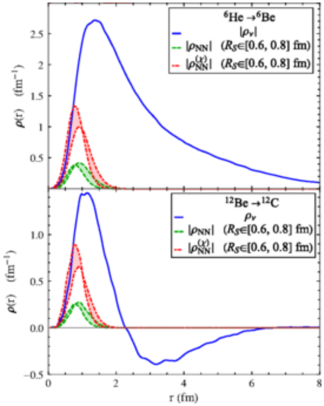
TRIUMF

The Contact Term

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

- Contact term may enhance the NMEs by up to **80%** in light nuclei

V. Cirigliano et al., PRC **100**, 055504 (2019), PRL **120**, 202001 (2018)



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

TRIUMF

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  V. Cirigliano et al., PRC **100**, 055504 (2019), PRL **120**, 202001 (2018)

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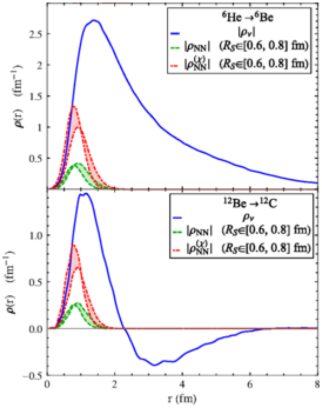
  M. Wirth, J. M. Yao and H. Hergert, Phys. Rev. Lett. **127**, 242502 (2021)



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Discovery, accelerated

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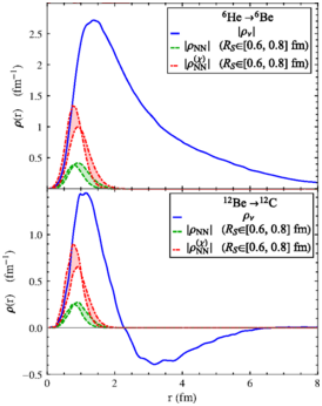
- **How about the heavier nuclei?**



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

Discovery, accelerated

Contact Term in pnQRPA and NSM

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

with

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

[1] V. Cirigliano *et al.*, PRC 100, 055504 (2019)

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TRIUMF

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Discovery, accelerated

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- ~~Fix to lepton-number-violating data~~
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- Estimate by Charge-Independence-Breaking (CIB) term: $g_{\nu}^{\mathrm{NN}} \approx \frac{1}{2}(\mathcal{C}_1 + \mathcal{C}_2)$

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Couplings (g_{ν}^{NN}) and scales (Λ) of the Gaussian regulator [1].

$g_{\nu}^{\mathrm{NN}}(\mathrm{fm}^2)$	Λ (MeV)
-0.67	450
-1.01	550
-1.44	465
-0.91	465
-1.44	349
-1.03	349

[1] V. Cirigliano *et al.*, PRC 100, 055504 (2019)

Discovery, accelerated

Contact Term in pnQRPA and NSM

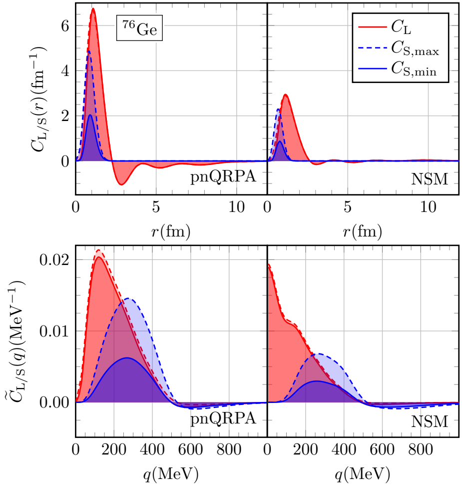
$$\int C_{\mathrm{L/S}}(r)\mathrm{d}r = M^{0\nu}_{\mathrm{L/S}} = \int \widetilde{C}_{\mathrm{L/S}}(q)\mathrm{d}q$$

In pnQRPA:

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

In NSM:

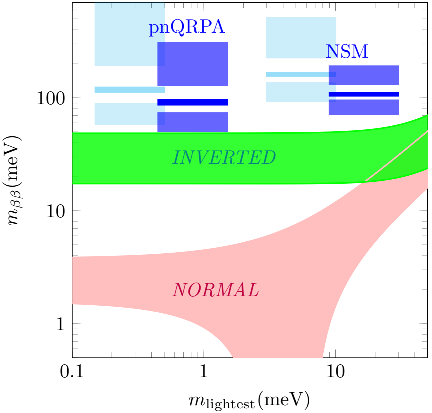
$M_{\mathrm{S}}/M_{\mathrm{L}} \approx 15 - 50\%$



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

Effective Neutrino Masses

- Effective neutrino masses combining the likelihood functions [2] of GERDA (^{76}Ge), CUORE (^{130}Te), EXO-200 (^{136}Xe) and KamLAND-Zen (^{136}Xe)



LJ, P. Soriano and J. Menéndez,

*Phys. Lett. B **823**, 136720 (2021)*

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

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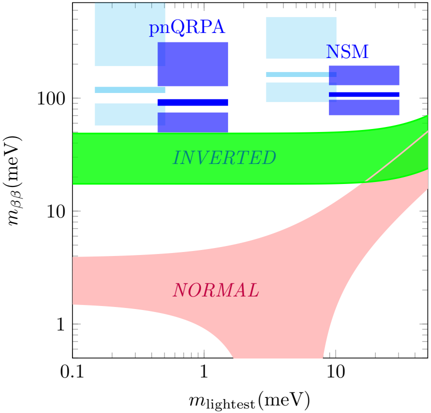
- Middle bands: $M_{\mathbf{L}}^{\mathbf{0}\nu}$
  Lower bands: $M_{\mathbf{L}}^{\mathbf{0}\nu} + M_{\mathbf{S}}^{\mathbf{0}\nu}$
  Upper bands: $M_{\mathbf{L}}^{\mathbf{0}\nu} - M_{\mathbf{S}}^{\mathbf{0}\nu}$



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

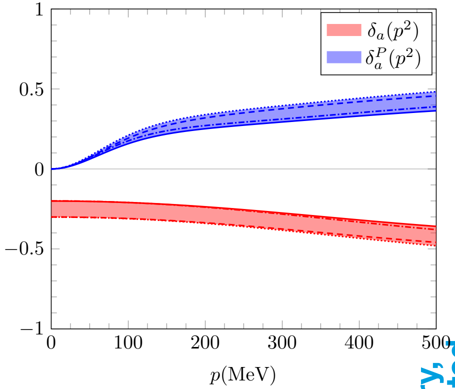
[2] S. D. Biller, Phys. Rev. D **104**, 012002 (2021)

Hadronic Two-Body Currents (2BCs)

- The effect of the two-body currents can be approximated by

$$\begin{cases} g_{\rm A}(p^2) \rightarrow g_{\rm A}(p^2) + \boldsymbol{\delta_a(p^2)}, \\ g_{\rm P}(p^2) \rightarrow g_{\rm P}(p^2) - \frac{2m_{\rm N}}{p^2}\, \boldsymbol{\delta_a^P(p^2)} \end{cases}$$

M. Hoferichter, J. Menéndez and A. Schwenk, Phys. Rev. D **102**, 074018 (2020)



LJ, B. Romeo, P. Soriano and J. Menéndez, arXiv:2207.05108

TRIUMF

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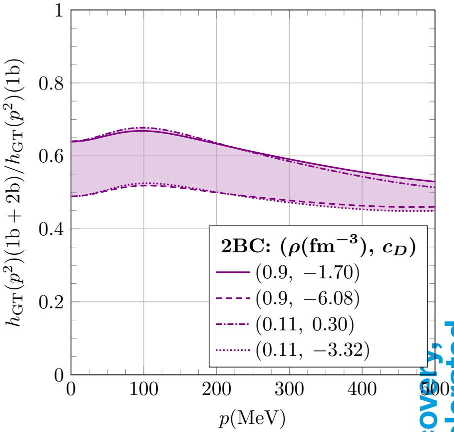
M. Hoferichter, J. Menéndez and A. Schwenk, Phys. Rev. D **102**, 074018 (2020)

- 2BCs reduce $0\nu\beta\beta$-decay NMEs by some $\mathbf{25-45\%}$



LJ, B. Romeo, P. Soriano and J. Menéndez, arXiv:2207.05108

Discovery, accelerated

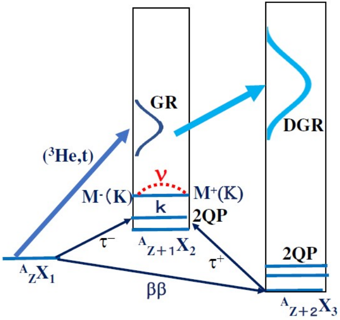
TRIUMF

Outline

Discovery, accelerated

Probing $0\nu\beta\beta$-Decay by Charge-Exchange Reactions

- Charge-exchange reactions (**strong interaction**) can probe the $0\nu\beta\beta$ decay (**weak interaction**)

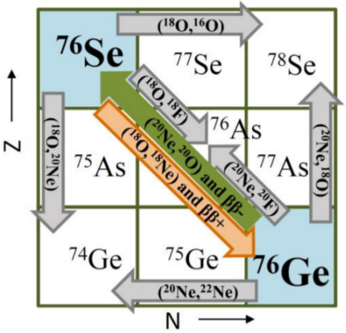


*H. Ejiri, LJ, J. Suhonen, Phys. Rev. C **105**, L022501 (2022)*

Discovery, accelerated

Probing $0\nu\beta\beta$-Decay by Charge-Exchange Reactions

- Charge-exchange reactions (**strong interaction**) can probe the $0\nu\beta\beta$ decay (**weak interaction**)
- Ground-state-to-ground-state **double charge-exchange reactions** would probe $0\nu\beta\beta$-decay NMEs



*F. Cappuzzello et al. (NUMEN Collab.) EPJA **54** 72 (2018)*

$M^{0\nu}$ Correlated with M_{DGT} - or Is It?

$$M_{\text{DGT}} = (0^+_{\text{gs,f}}|| \sum_{j,k} [\boldsymbol{\sigma}_j \tau_j^- \times \boldsymbol{\sigma}_k \tau_k^-]^0 || 0^+_{\text{gs,i}})$$

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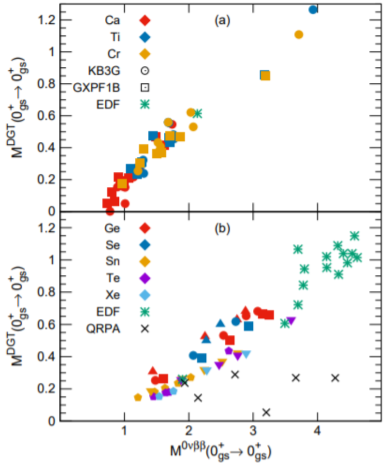
  N. Shimizu, J. Menéndez and K. Yako, Phys. Rev. Lett. **120**, 142502 (2018),

  and IBM-2

  F. F. Deppisch *et al.*, Phys. Rev. D **102**, 095016 (2020), J. Barea *et al.*, Phys. Rev. C **91**, 034304 (2015)



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- Correlation can also be found in *ab initio* frameworks

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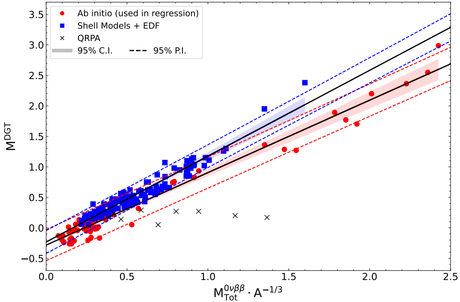

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Discovery, accelerated

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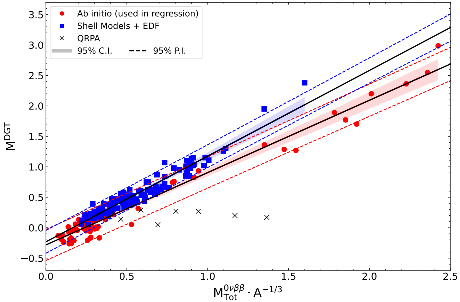
  - **See A. Belley's talk!**



*J. M. Yao et al., Phys. Rev. C **106**, 014315 (2022)*

TRIUMF

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  J. M. Yao *et al.*, Phys. Rev. C **106**, 014315 (2022)

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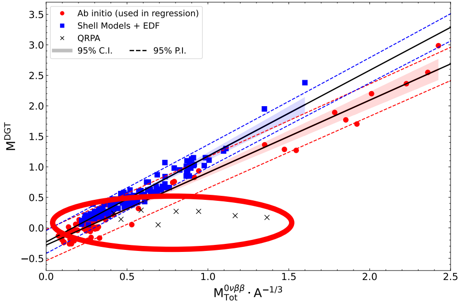
- **But not in QRPA (Why?)**



J. M. Yao et al., Phys. Rev. C ***106**, 014315 (2022)*

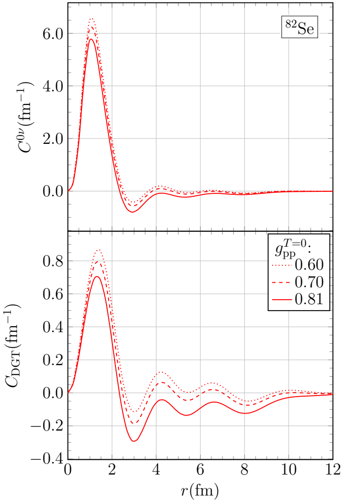
Discover accelerated

TRIUMF

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

$$M_{\mathrm{L}}^{0\nu} = \int_0^\infty C^{0\nu}(r)\mathrm{d}r \ ,$$
$$M_{\mathrm{DGT}} = \int_0^\infty C_{\mathrm{DGT}}(r)\mathrm{d}r$$

- M_{DGT} more sensitive to proton-neutron pairing (g_{pp}) than $M^{0\nu}$



LJ, J. Menéndez, in preparation

Discovery, accelerated

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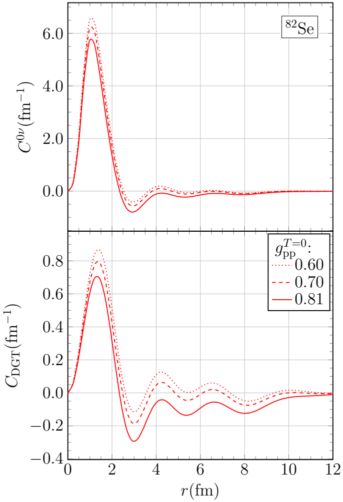
- Decreasing g_{pp} makes DGT more short-ranged (like $0\nu\beta\beta$ decay)



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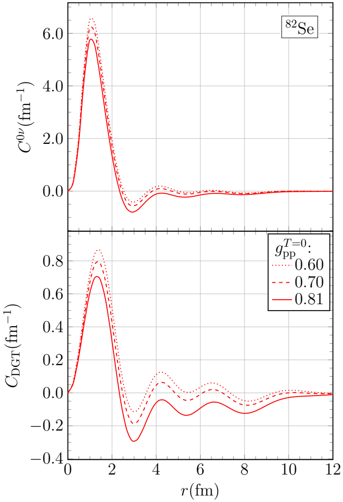
- M_{DGT} more sensitive to proton-neutron pairing (g_{pp}) than $M^{0\nu}$
- Decreasing g_{pp} makes DGT more short-ranged (like $0\nu\beta\beta$ decay)
- **What if we free the value of g_{pp}?**

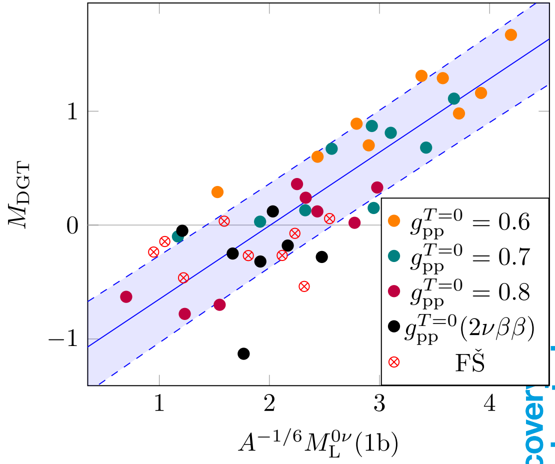


LJ, J. Menéndez, in preparation

TRIUMF

$M^{0\nu}$ vs. M_{DGT} in pnQRPA

- By varying $g_{\mathrm{pp}}^{T=0}$ we observe a **correlation in QRPA**

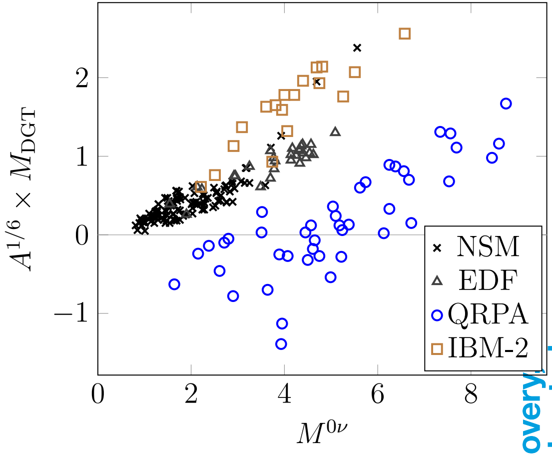


LJ and J. Menéndez, in preparation

Discovery, accelerated

$M^{0\nu}$ vs. $M_{\rm DGT}$ in pnQRPA

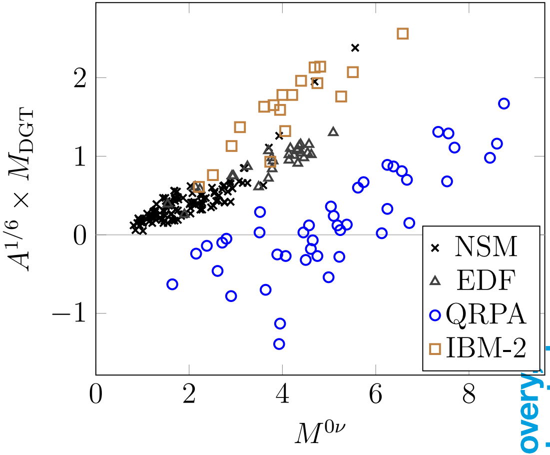
- By varying $g_{\rm pp}^{T=0}$ we observe a **correlation in QRPA**
- Correlation different from other models



LJ and J. Menéndez, in preparation

$M^{0\nu}$ vs. M_{DGT} in pnQRPA

- By varying $g_{\mathrm{pp}}^{T=0}$ we observe a **correlation in QRPA**
- Correlation different from other models
  - Maybe not surprising, given the dispersion of $M^{0\nu}$'s...



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TRIUMF

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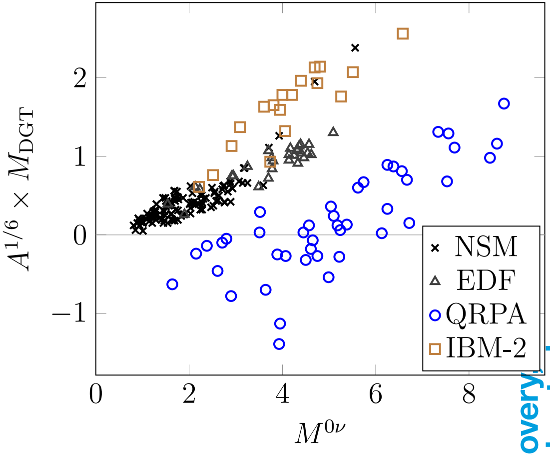
- By varying $g_{\text{pp}}^{T=0}$ we observe a **correlation in QRPA**
- Correlation different from other models
  - Maybe not surprising, given the dispersion of $M^{0\nu}$'s...
  - ...and different approaches (closure/non-closure,...)



LJ and J. Menéndez, in preparation

Discovery, accelerated

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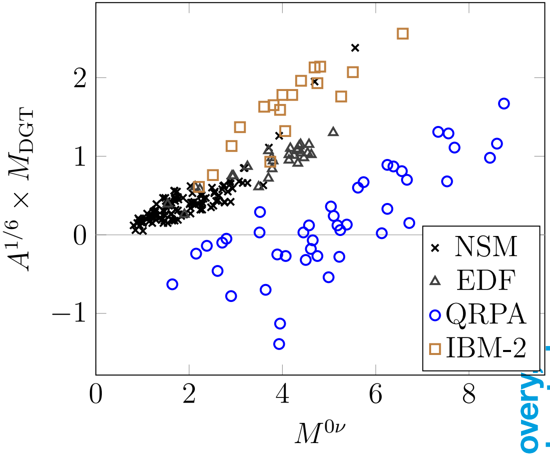
- Correlation different from other models
  - Maybe not surprising, given the dispersion of $M^{0\nu}$'s...
  - ...and different approaches (closure/non-closure,...)
- **Measuring DGT reaction could help constrain $M^{0\nu}$!**



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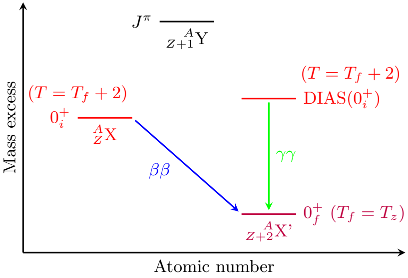
Probing $0\nu\beta\beta$ Decay by Gamma Decays

- Double magnetic dipole (M1) decay (**electromagnetic interaction**) can be related to $0\nu\beta\beta$ decay (**weak interaction**)



$$M^{\gamma\gamma}(M1M1) = \sum_n \frac{(0^+_{\rm f}||\mathbf{M_1}||1^+_n)(1^+_n||\mathbf{M_1}||0^+_{\rm i})}{E_n - (E_i + E_f)/2},$$

$$\mathbf{M_1} = \mu_N \sqrt{\frac{3}{4\pi}} \sum_{i=1}^{A} (g^l_i \boldsymbol{\ell}_i + g^s_i \mathbf{s}_i)$$

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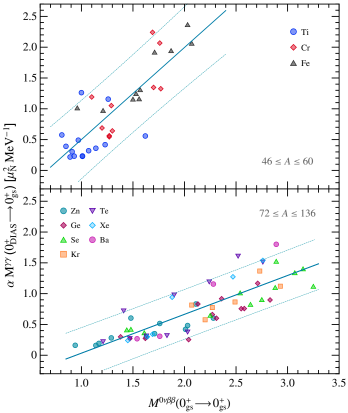
B. Romeo, J. Menéndez, C. Peña-Garay, Phys. Lett. B **827**, 136965 (2022)



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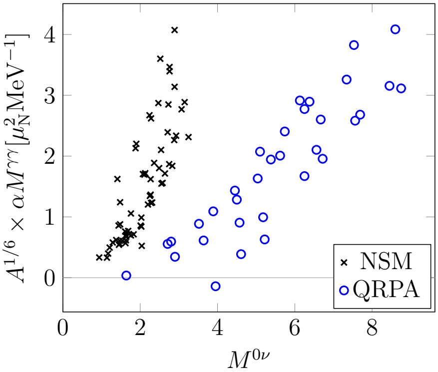
- Correlation also found in QRPA



LJ, J. Menéndez, in preparation

Discovery, accelerated

TRIUMF

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

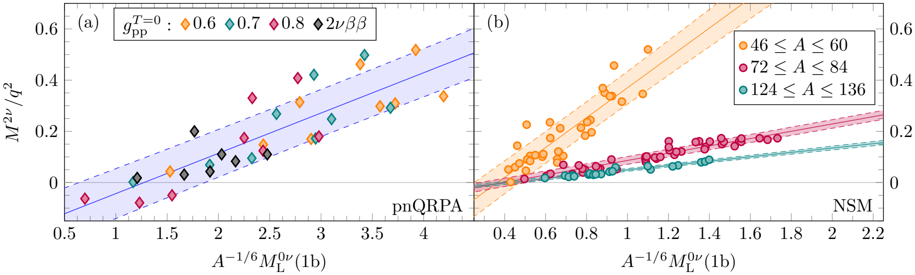
- ***How about $2\nu\beta\beta$ decay?***

Discovery, accelerated

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!

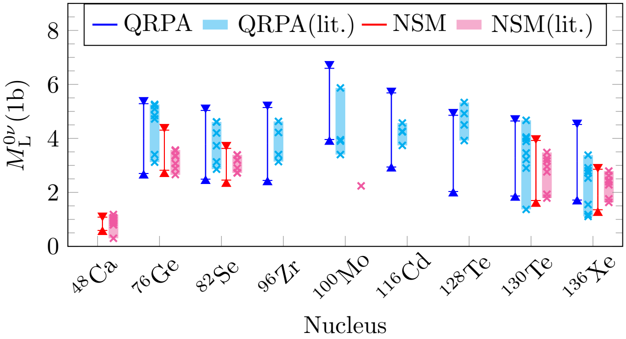


LJ, B. Romeo, P. Soriano and J. Menéndez, arXiv:2207.05108

Discovery, accelerated

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!



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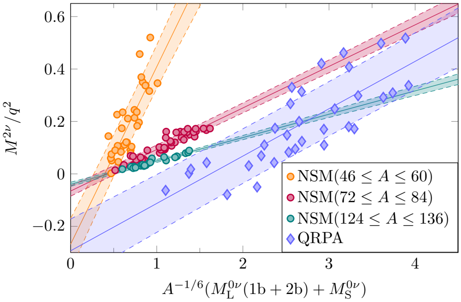
Two-Body Currents & Contact Term

- Correlations survive when adding the 2BCs and the contact term



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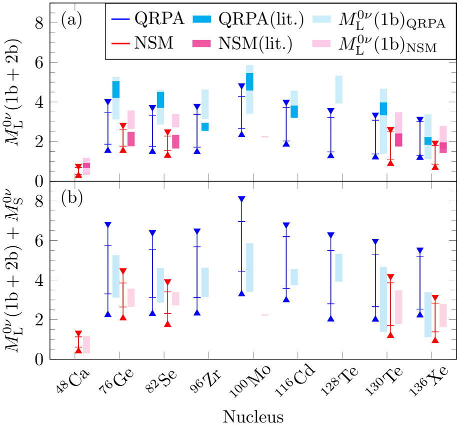

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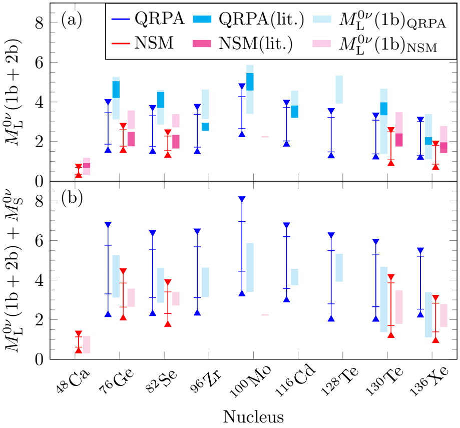

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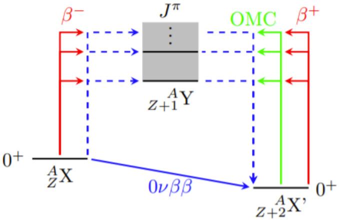
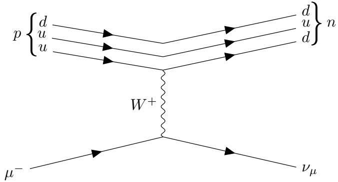
Discovery, accelerated

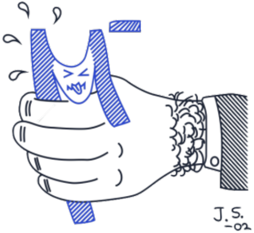
Outline

Discovery, accelerated

Ordinary Muon Capture (OMC) vs. $0\nu\beta\beta$







MONUMENT (OMC4DBD)

$$\mu^- + {}^{A}_{Z}\mathrm{X}(J_i^{\pi_i}) \rightarrow \nu_\mu + {}_{Z-1}^{A}\mathrm{Y}(J_f^{\pi_f})$$

Discovery, accelerated

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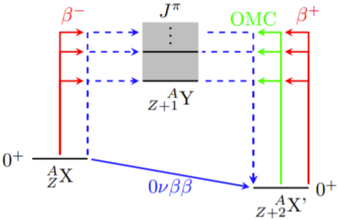

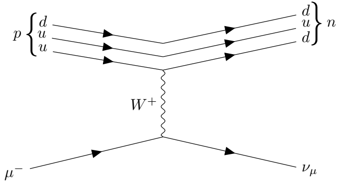

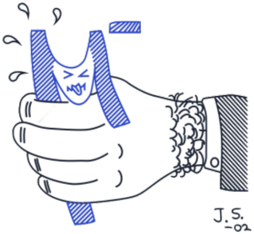

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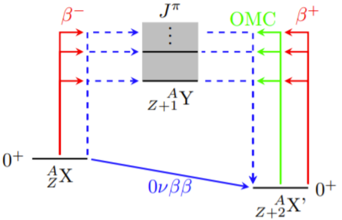

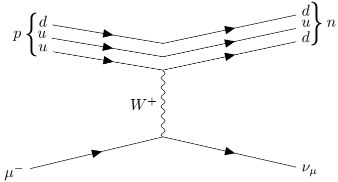

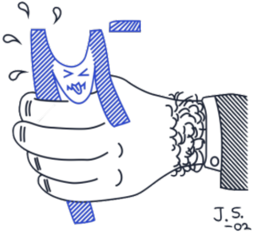

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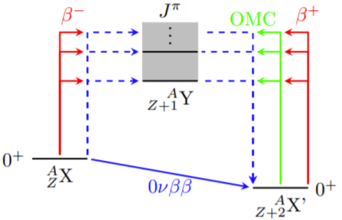

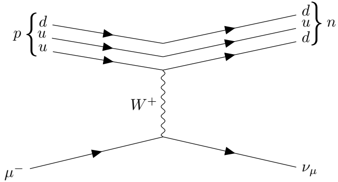

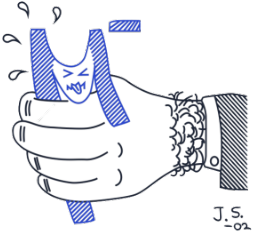

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Discovery, accelerated

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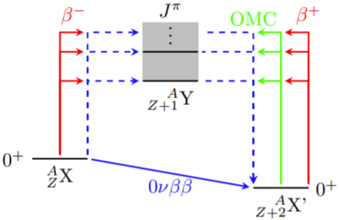

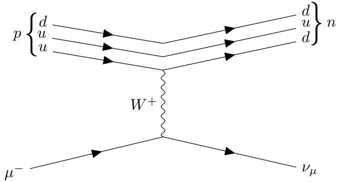

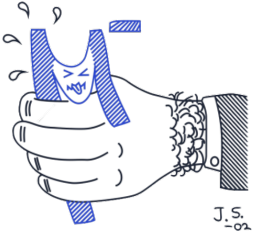

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- **Both the axial vector coupling g_A and the pseudoscalar coupling g_P involved**
  - $\rightarrow$ Similar to $0\nu\beta\beta$ decay!

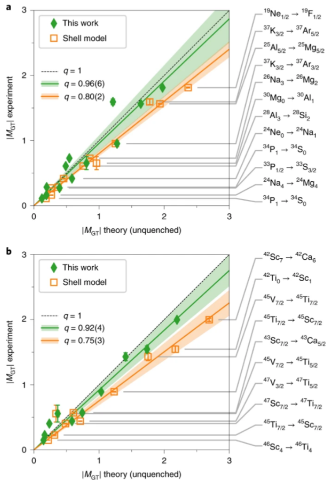
Discovery, accelerated

TRIUMF

g_A Quenching at High Momentum Exchange?

- Recently, **first *ab initio* solution to g_A quenching puzzle** was proposed for β-decay

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



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Discovery, accelerated

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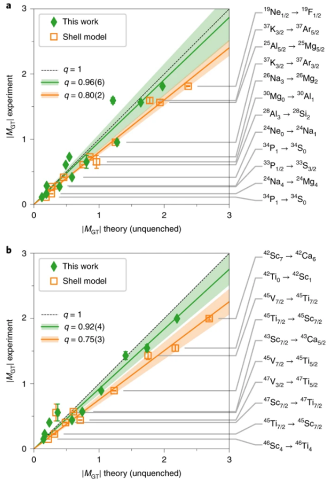

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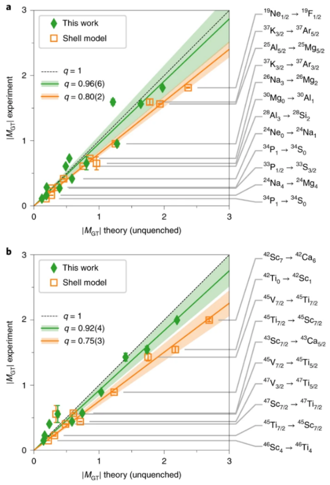
  - **OMC could provide a hint!**



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Muon-Capture Theory

- Interaction Hamiltonian → capture rate:

$$W(J_i \to J_f) = \frac{2J_f+1}{2J_i+1}\left(1-\frac{q}{m_\mu + AM}\right) q^2 \sum_{\kappa u} |g_\mathrm{V} M_\mathrm{V} + g_\mathrm{A} M_\mathrm{A} + g_\mathrm{P} M_\mathrm{P}|^2$$

PHYSICAL REVIEW VOLUME 118, NUMBER 2 APRIL 15, 1960

Theory of Allowed and Forbidden Transitions in Muon Capture Reactions*

MASATO MORITA
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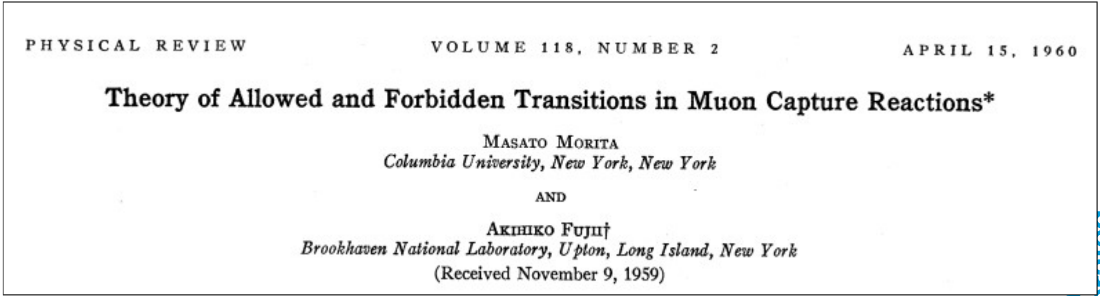

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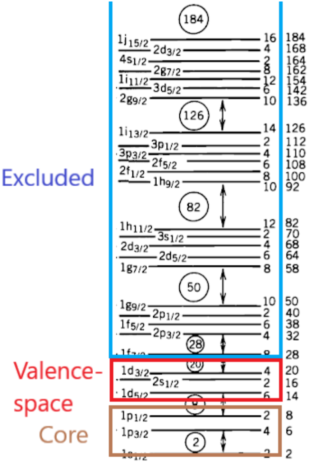
- Add the effect of **two-body currents**

Valence-Space In-Medium Similarity Renormalization Group (VS-IMSRG)

- Hamiltonian based on the chiral EFT with EM 1.8/2.0 interaction (in this case)



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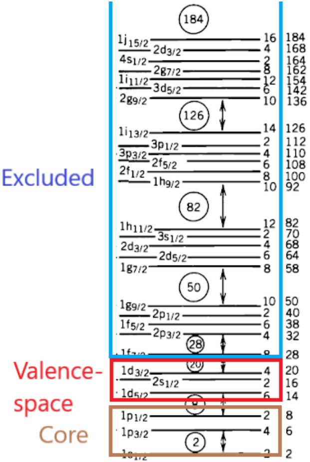

TRIUMF

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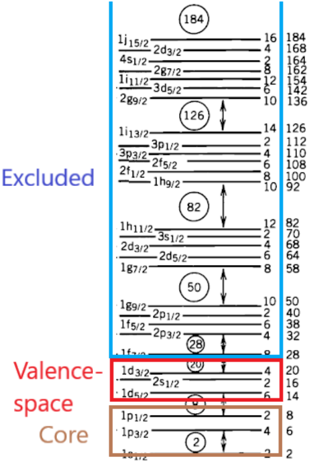
  - **Operators can be made consistent with the Hamiltonian!**



TRIUMF

Capture Rates on Low-Lying States in ^{24}Na

VS-IMSRG + Two-Body Currents + Realistic Muon Wave Function

J_i^π	E_{exp} (MeV)	Rate (10^3 1/s)				
		Exp.[3]	NSM		IMSRG	
			1bc	1bc+2bc	1bc	1bc+2bc
1_1^+	0.472	(21.0 ± 6.6)	4.0	3.0	22.3	15.2
1_2^+	1.347	17.5 ± 2.3	32.7	21.3	7.7	4.9
Sum(1^+)		38.5 ± 8.9	36.7	24.5	30.0	20.0
2_1^+	0.563	17.5 ± 2.1	1.0	0.7	0.5	0.3
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LJ, T. Miyagi, S.R. Stroberg, J.D. Holt, J. Kotila and J. Suhonen, arXiv:2111.12992

[3] P. Gorringe *et al.*, Phys. Rev. C **60**, 055501 (1999)

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Discovery, accelerated

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- **1^+ states mixed**

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LJ, T. Miyagi, S.R. Stroberg, J.D. Holt, J. Kotila and J. Suhonen, arXiv:2111.12992

- **Generally, IMSRG gives smaller capture rates**
- **1^+ states mixed**
- Agreement with experiment hopefully gets better with new data from MONUMENT

[3] P. Gorringe *et al.*, Phys. Rev. C **60**, 055501 (1999)

Discovery, accelerated

No-Core Shell Model (NCSM)

- Basis expansion method

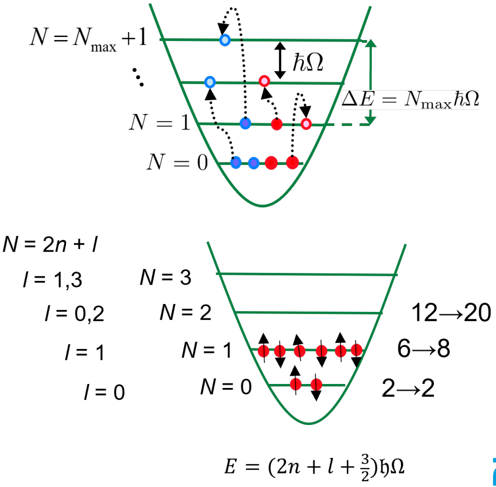
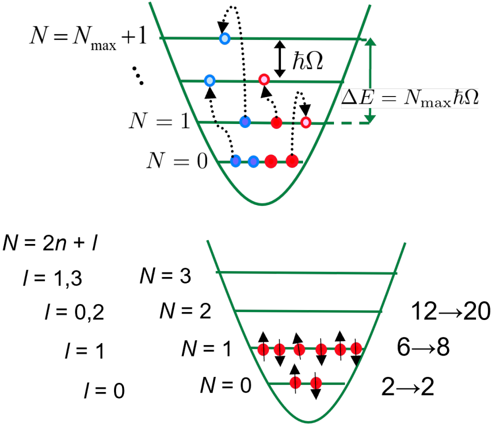


Figure courtesy of P. Navrátil

No-Core Shell Model (NCSM)

- Basis expansion method
  - Harmonic oscillator (HO) basis truncated with $N_{\max}$



$E = (2n + l + \frac{3}{2})\hbar\Omega$

Figure courtesy of P. Navrátil

No-Core Shell Model (NCSM)

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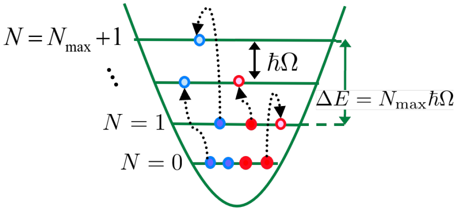
$\rightarrow$ For more details, see P. Gysbers' talk!



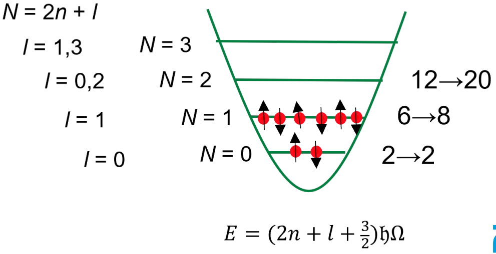


Figure courtesy of P. Navrátil

No-Core Shell Model (NCSM)

- Basis expansion method
  - Harmonic oscillator (HO) basis truncated with $N_{\max}$
  - → For more details, see P. Gysbers' talk!
- Hamiltonian based on the chiral EFT with N4LO EM500 lnl interaction (in this case)

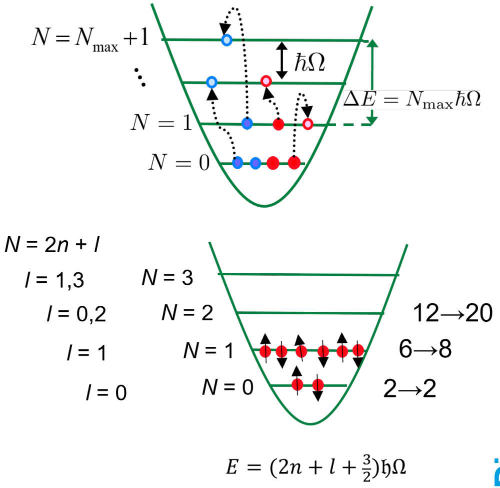
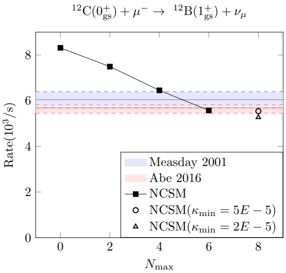
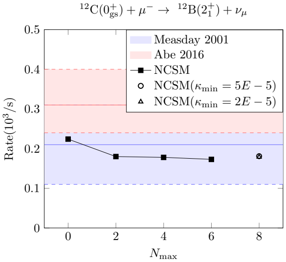


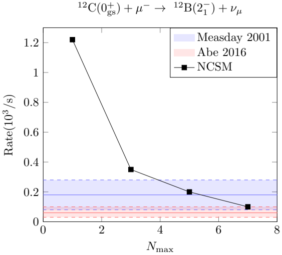
Figure courtesy of P. Navrátil

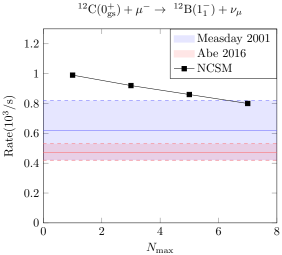
Capture Rates to Low-Lying States in ^{12}B

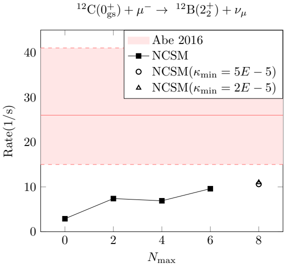
NCSM + Realistic Muon Wave Functions











LJ, P. Navrátil, work in progress

Two-body currents?
Transition invariance?
Continuum?

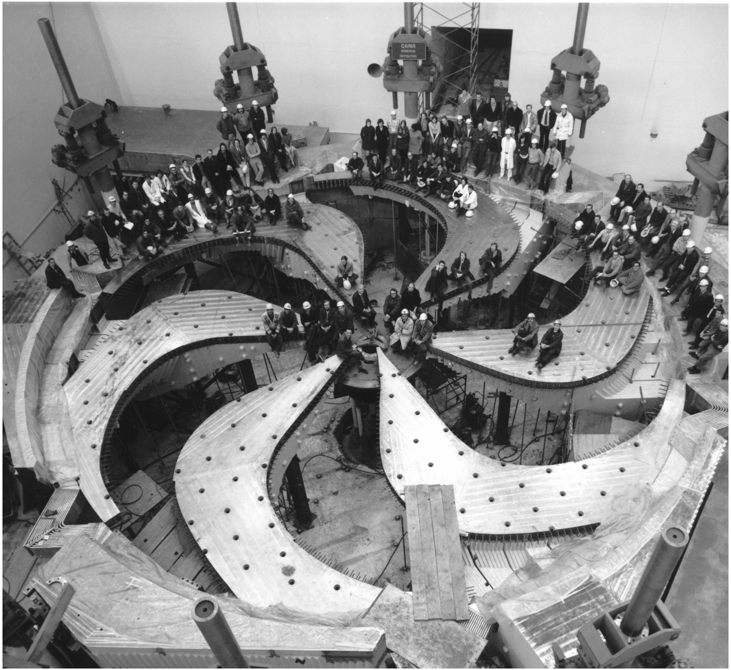
Outline

Summary

- Reliable nuclear matrix elements crucial for $0\nu\beta\beta$ studies
- Adding a new short-range term enhances the NMEs notably
- On the other hand, adding the effect of two-body currents reduce the NMEs
- Related nuclear observables, such charge-exchange reactions, $\gamma\gamma$ decays and $2\nu\beta\beta$ decays, can help constrain the $0\nu\beta\beta$-decay NMEs
- Ab initio muon capture calculations could shed light on g_{A} quenching at finite momentum exchange regime

TRIUMF

Thank you
Merci



Discovery, accelerated

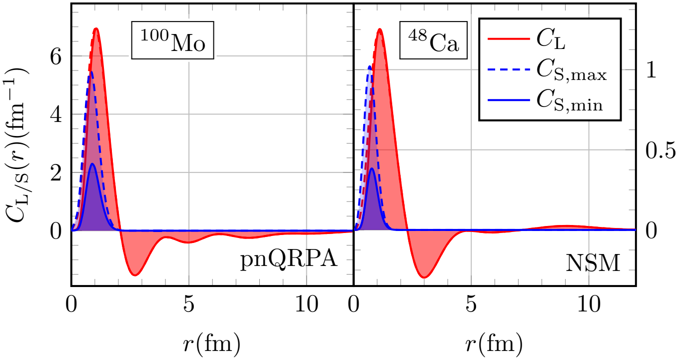
The Extreme Cases: ^{100}Mo and ^{48}Ca

For $^{100}\mathrm{Mo}$:

$M_S/M_L = 49 - 108\%$

For $^{48}\mathrm{Ca}$:

$M_S/M_L = 23 - 62\%$



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

TRIUMF

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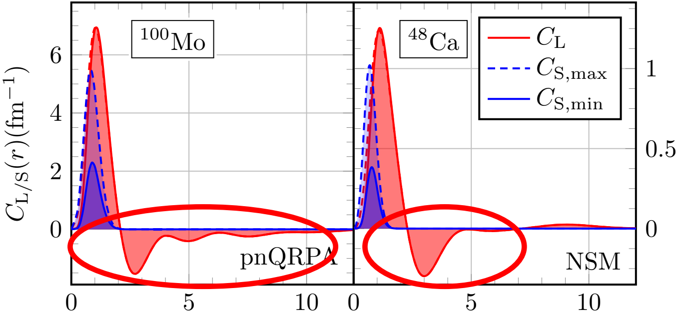
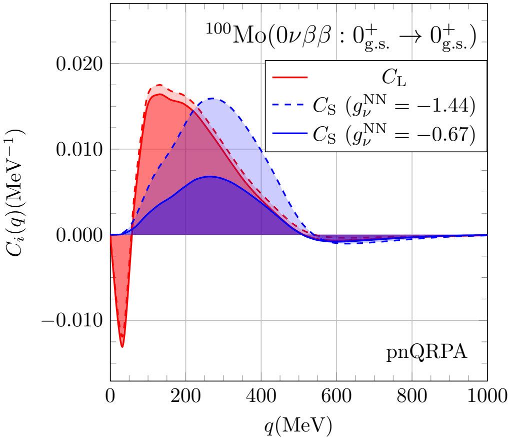


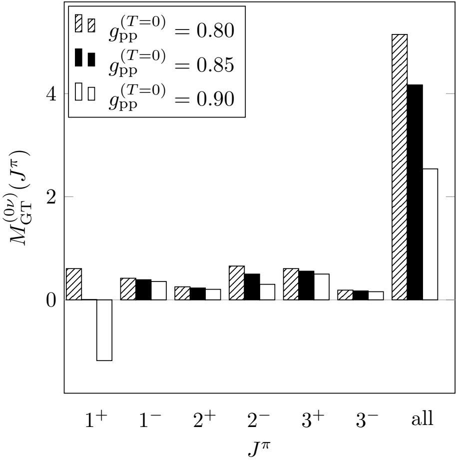
Cancellations at large distances

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

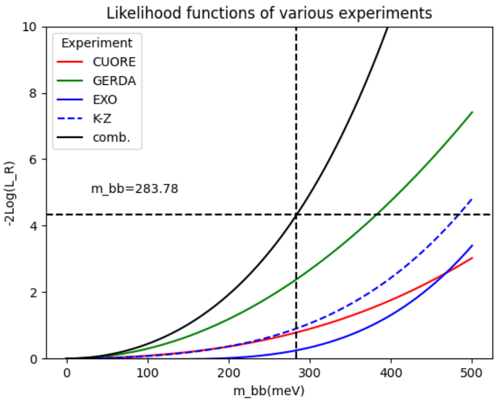
Discovery, accelerated

Unexpectedly Large M_S/M_L in ^{100}Mo





Obtaining Majorana Bound from experiments



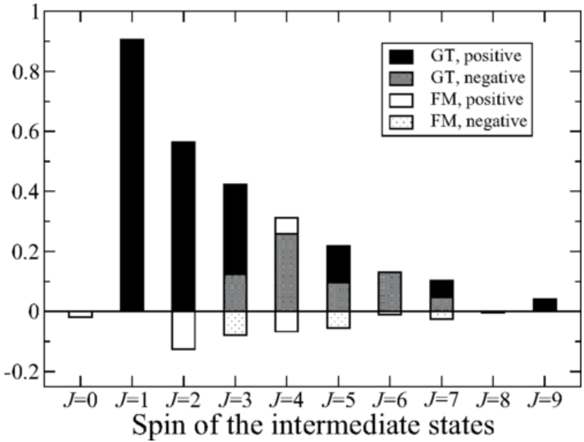
$$\Gamma^{0\nu} = \log(2) g_A^4 G_{0\nu} |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

- Input: log(likelihood) functions from experiments
- $\Gamma^{0\nu} \rightarrow m_{\beta\beta}$ with our NMEs
- 90% CI Bayesian bounds for $m_{\beta\beta}$ from 90% CI upper bounds on combined $\Gamma^{0\nu}$ [20]

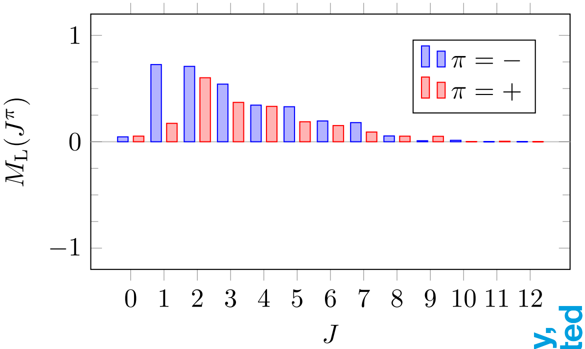
[20] S. D. Biller, PRD **104**, 012002 (2021)

TRIUMF

J^π Decomposition of $M^{0\nu}$ of ^{76}Ge



NSM [21]



pnQRPA

[21] R. A. Sen'kov, M. Horoi, Phys. Rev. C **90**, 051301(R) (2014)

Discovery, accelerated

Technical Note: Spherical pnQRPA

- Excitations $|J_k^\pi M\rangle = \sum_{pn}(X_{pn}^{J_k^\pi} A_{pn}^\dagger(JM) - Y_{pn}^{J_k^\pi} \tilde{A}_{pn}(JM))|\mathrm{QRPA}\rangle$ [9]

[9] J. Suhonen, *From Nucleons to Nucleus: Concepts of Microscopic Nuclear Theory* (2007)

TRIUMF

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- ...obtained from pnQRPA equation:

$$\begin{pmatrix} A & B \\ -B^* & -A^* \end{pmatrix}\begin{pmatrix} X^\omega \\ Y^\omega \end{pmatrix} = E_\omega \begin{pmatrix} X^\omega \\ Y^\omega \end{pmatrix} ,$$

$$\begin{aligned} A_{pn,p'n'}(J) =& (E_p + E_n)\delta_{pp'}\delta_{nn'} \\ &+ (u_p u_n u_{p'} u_{n'} + v_p v_n v_{p'} v_{n'}) \times g_{\mathrm{pp}}\langle pn; J|V|p'n'; J\rangle \\ &+ (u_p v_n u_{p'} v_{n'} + v_p u_n v_{p'} u_{n'}) \times g_{\mathrm{ph}}\langle pn^{-1}; J|V'|p'n'^{-1}; J\rangle , \\ B_{pn,p'n'}(J) =& -(u_p u_n v_{p'} v_{n'} + v_p v_n u_{p'} u_{n'}) \times g_{\mathrm{pp}}\langle pn; J|V|p'n'; J\rangle \\ &+ (u_p v_n v_{p'} u_{n'} + v_p u_n u_{p'} v_{n'}) \times g_{\mathrm{ph}}\langle pn^{-1}; J|V'|p'n'^{-1}; J\rangle \end{aligned}$$

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solved from BCS equations

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solved from BCS equations

adjustable parameters

[9] J. Suhonen, *From Nucleons to Nucleus: Concepts of Microscopic Nuclear Theory* (2007)

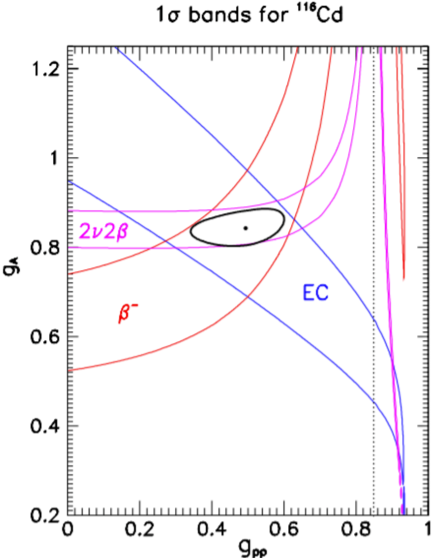
Discovery, accelerated

Technical Note: $g_{\rm pp}$-Problem of pnQRPA

$$[t_{1/2}^{2\nu}]^{-1} = g_{\rm A}^4 G_{2\nu} \, |M^{2\nu}|^2$$

$$\log ft_{{\rm EC}/\beta} = \log_{10}(3\kappa/(g_{\rm A}^2|M_{{\rm EC}/\beta}|^2))$$

- It is hard to simultaneously reproduce experimental $2\nu\beta\beta$, EC and β^- data



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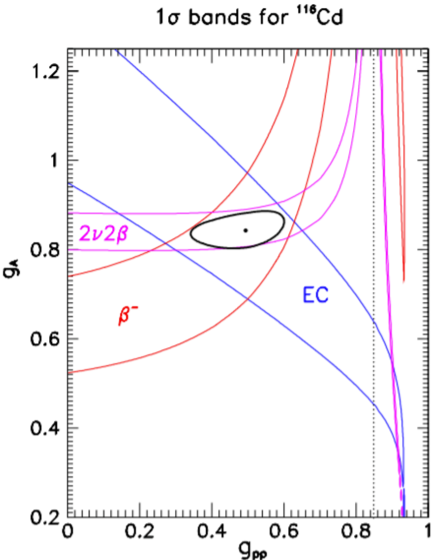

TRIUMF

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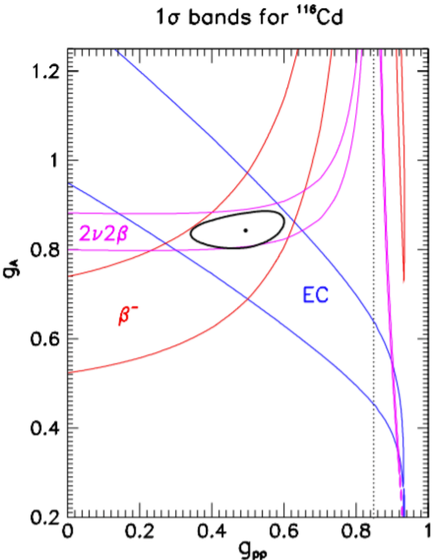
- It is hard to simultaneously reproduce experimental $2\nu\beta\beta$, EC and β^- data
  - Often small values of $g_{\rm pp}$ AND quenched $g_{\rm A}^{\rm eff} \ll 1.27$ needed
- Usually, $g_{\rm pp}$ adjusted to observed $2\nu\beta\beta$ decays with $g_{\rm A}^{\rm free} = 1.27$ or $g_{\rm A}^{\rm eff} = 1.0$



Discovery, accelerated

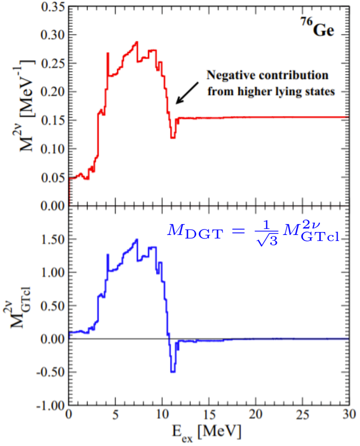
Partial Isospin Restoration Scheme

$$g_{\rm pp}\langle pn;J|V|p'n';J\rangle \to \; g_{\rm pp}^{T=0}\langle pn;J,T=0|V|p'n';J,T=0\rangle + \\ + \, g_{\rm pp}^{T=1}\langle pn;J,T=1|V|p'n';J,T=1\rangle$$

- $g_{\rm pp}^{T=1}$ adjusted to $M_{\rm F}^{2\nu}=0$ to restore isospin
- $g_{\rm pp}^{T=0}$ then usually adjusted to $M_{\rm exp.}^{2\nu}$ with $g_{\rm A}=1.27$ or $g_{\rm A}^{\rm eff}=1.0$

M_{DGT} in pnQRPA

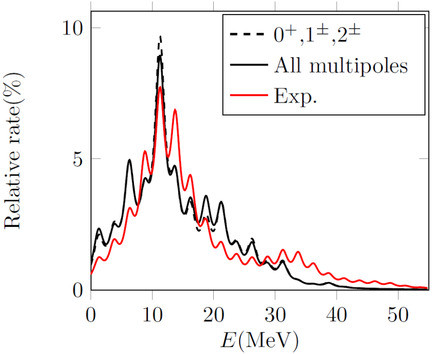
- Negative contributions in pnQRPA can make M_{DGT} small
  - **In NSM, normally no (strong) cancellation**
- It is possible to force $M_{\mathrm{DGT}} = 0$ by adjusting proton-neutron pairing (g_{pp})
  - **What if we free the value of g_{pp}?**



F. Šimkovic, A. Smetana, P. Vogel, Phys. Rev. C ***98****,064325 (2018)*

Muon-Capture Experiments

- Mostly total capture rates measured



*LJ, J. Suhonen, H. Ejiri, I.H. Hashim, Phys. Lett. B **794**, 143 (2019)*

Muon-Capture Experiments

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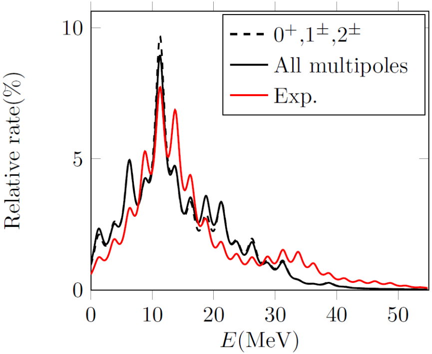
LJ, J. Suhonen, H. Ejiri, I.H. Hashim, Phys. Lett. B **794**, 143 (2019)



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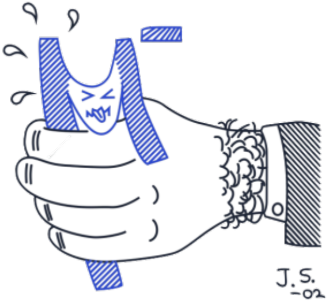
  LJ, J. Suhonen, H. Ejiri, I.H. Hashim, Phys. Lett. B **794**, 143 (2019)

- Experiments extended to **daughter nuclei of $\beta\beta$ triplets** by MONUMENT (a.k.a. OMC4DBD) collaboration at PSI, Switzerland



MONUMENT Collaboration