# New physics in $0\nu\beta\beta$

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*Based on the works JHEP 06 (2023) 104,JHEP 08 (2024) 217*

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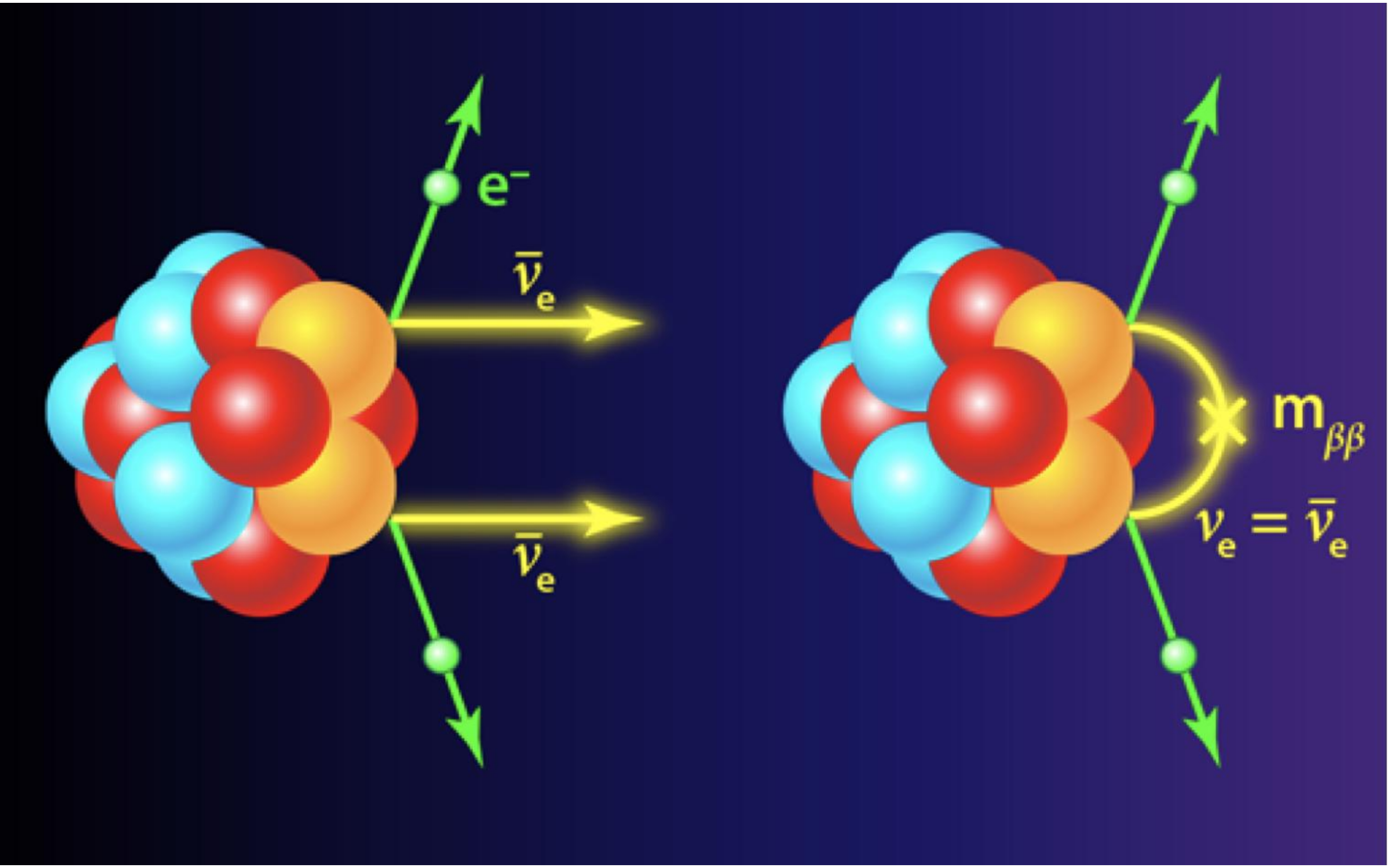
TAUP, XICHANG, 2025.8.25

# Outline

- **Brief introduction**
- **Neutrinoless double data decay (0νββ) in light neutrino exchange mechanism**

  **Different upper limits of $m_{\beta\beta}$ due to NME uncertainties (short-range contact term)**
- **0νββ process in minimal Type-I seesaw**

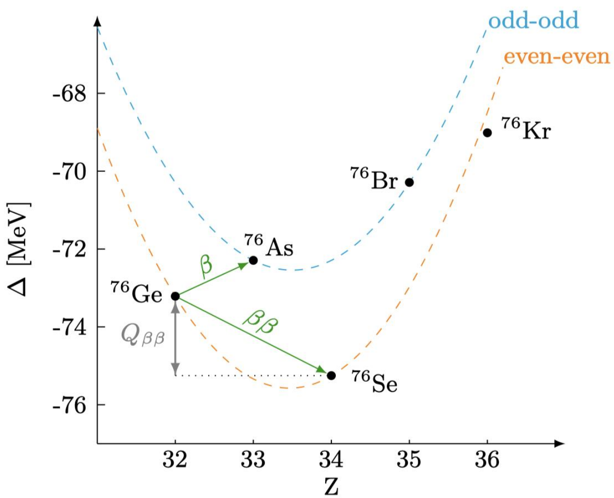
  **Constraints of minimal Type-I seesaw from current and future 0νββ experiments**
- **Summary**




# Where are you?

# Brief background






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

Mayer, 1935; first detected in 1987 by Moe

$\nu_i^c = \nu_i$ Majorana, 1937

$$(A,Z) \longrightarrow (A,Z+2) + 2e^-$$

Furry, 1939

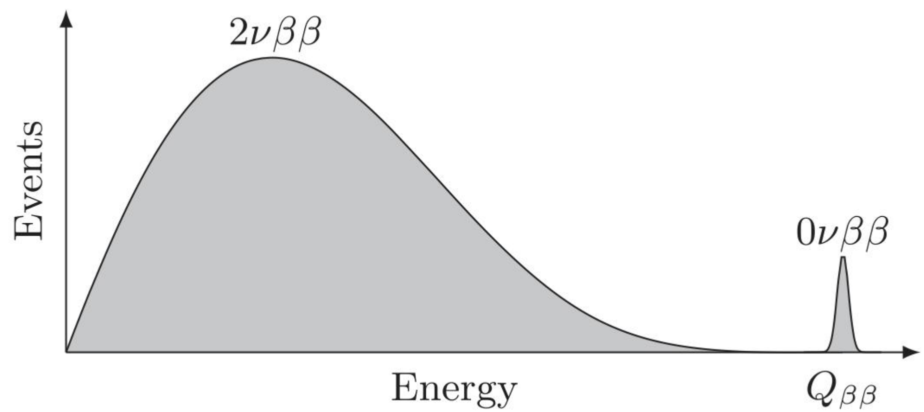
| Isotope | Daughter | $Q_{\beta\beta}$ (keV)[a] | $f_{\mathrm{nat}}$ (%)[b] | $f_{\mathrm{enr}}$ (%)[c] | $T_{1/2}^{2\nu\beta\beta}$ (yr)[d] | $T_{1/2}^{0\nu\beta\beta}$ (yr)[e] |
|---|---|---|---|---|---|---|
| $^{48}$Ca | $^{48}$Ti | 4267.98(32) | 30.187(21) | 16 | $[6.4^{+0.7}_{-0.6}(\text{stat})^{+1.2}_{-0.9}(\text{syst})] \times 10^{19}$ | $> 5.8 \times 10^{22}$ |
| $^{76}$Ge | $^{76}$Se | 2039.061(7) | 37.75(12) | 92 | $(1.926 \pm 94) \times 10^{21}$ | $> 1.8 \times 10^{26}$ |
| $^{82}$Se | $^{82}$Kr | 2997.9(3) | 38.82(15) | 96.3 | $[8.60 \pm 0.03(\text{stat})^{+0.19}_{-0.13}(\text{syst})] \times 10^{19}$ | $> 3.5 \times 10^{24}$ |
| $^{96}$Zr | $^{96}$Mo | 3356.097(86) | 32.80(2) | 86 | $[2.35 \pm 0.14(\text{stat}) \pm 0.16(\text{syst})] \times 10^{19}$ | $> 9.2 \times 10^{21}$ |
| $^{100}$Mo | $^{100}$Ru | 3034.40(17) | 39.744(65) | 99.5 | $[7.12^{+0.18}_{-0.14}(\text{stat}) \pm 0.10(\text{syst})] \times 10^{18}$ | $> 1.5 \times 10^{24}$ |
| $^{116}$Cd | $^{116}$Sn | 2813.50(13) | 37.512(54) | 82 | $2.63^{+0.11}_{-0.12} \times 10^{19}$ | $> 2.2 \times 10^{23}$ |
| $^{130}$Te | $^{130}$Xe | 2527.518(13) | 34.08(62) | 92 | $[7.71^{+0.08}_{-0.06}(\text{stat})^{+0.12}_{0.15}(\text{syst})] \times 10^{20}$ | $> 2.2 \times 10^{25}$ |
| $^{136}$Xe | $^{136}$Ba | 2457.83(37) | 38.857(72) | 90 | $[2.165 \pm 0.016(\text{stat}) \pm 0.059(\text{syst})] \times 10^{21}$ | $> 1.1 \times 10^{26}$ |
| $^{150}$Nd | $^{150}$Sm | 3371.38(20) | 35.638(28) | 91 | $[9.34 \pm 0.22(\text{stat})^{+0.62}_{-0.60}(\text{syst})] \times 10^{18}$ | $> 2.0 \times 10^{22}$ |

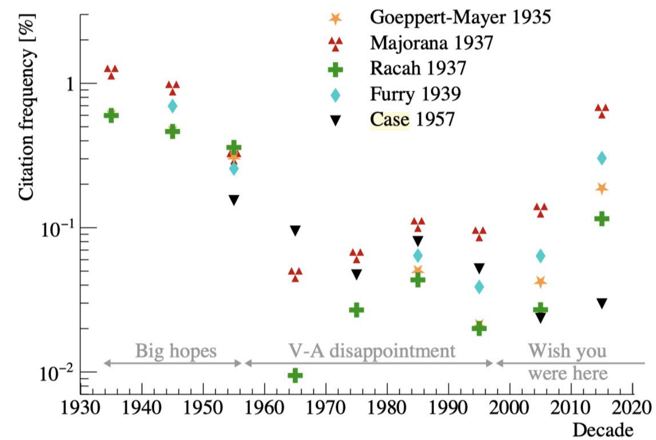
**$10^{18}$ yr – $10^{21}$ yr**

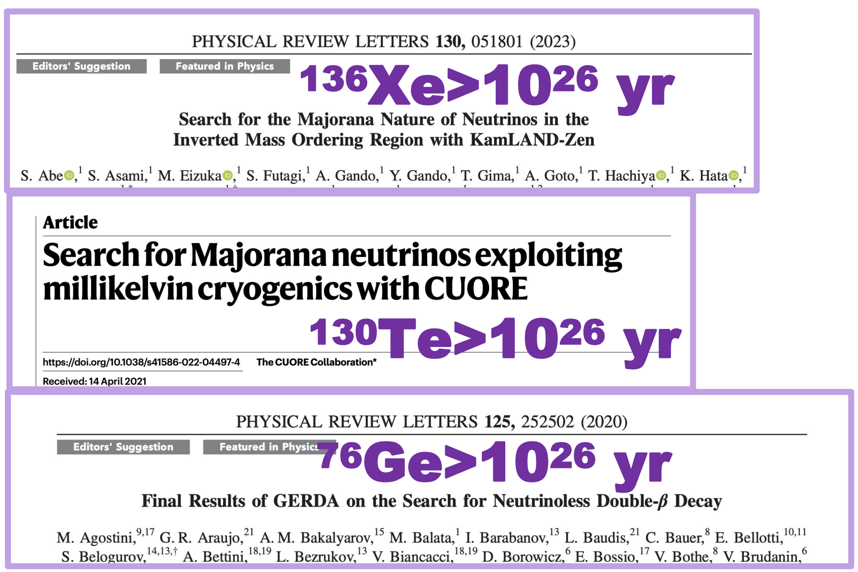
*Agostini et al. Rev.Mod.Phys. 95 (2023) 2, 025002*

# Experimental results and future proposals







PHYSICAL REVIEW LETTERS 130, 051801 (2023)

Editors' Suggestion | Featured in Physics

$^{136}$Xe>10$^{26}$ yr

**Search for the Majorana Nature of Neutrinos in the Inverted Mass Ordering Region with KamLAND-Zen**

S. Abe,[1] S. Asami,[1] M. Eizuka,[1] S. Futagi,[1] A. Gando,[1] Y. Gando,[1] T. Gima,[1] A. Goto,[1] T. Hachiya,[1] K. Hata,[1]

**Article**

**Search for Majorana neutrinos exploiting millikelvin cryogenics with CUORE**

$^{130}$Te>10$^{26}$ yr

https://doi.org/10.1038/s41586-022-04497-4 The CUORE Collaboration*

Received: 14 April 2021

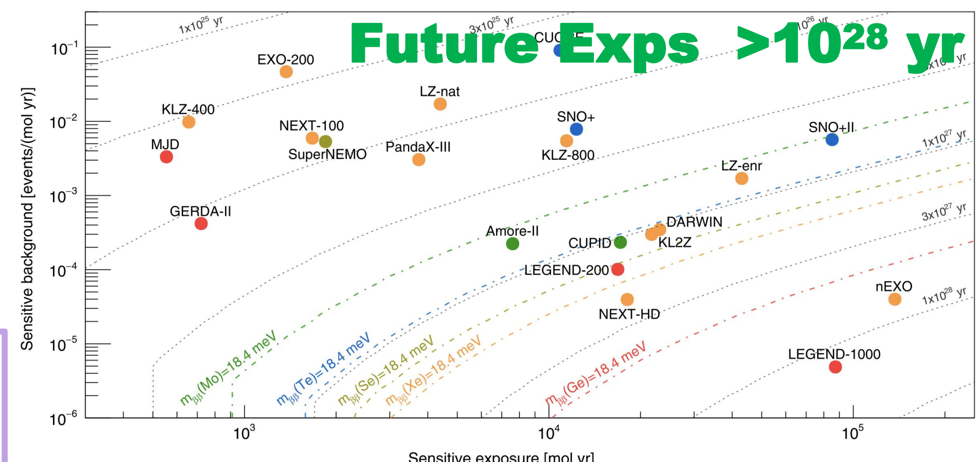
PHYSICAL REVIEW LETTERS 125, 252502 (2020)

Editors' Suggestion | Featured in Physics

$^{76}$Ge>10$^{26}$ yr

**Final Results of GERDA on the Search for Neutrinoless Double-$\beta$ Decay**

M. Agostini,[9,17] G. R. Araujo,[21] A. M. Bakalyarov,[15] M. Balata,[1] I. Barabanov,[13] L. Baudis,[21] C. Bauer,[8] E. Bellotti,[10,11] S. Belogurov,[14,13,†] A. Bettini,[18,19] L. Bezrukov,[13] V. Biancacci,[18,19] D. Borowicz,[6] E. Bossio,[17] V. Bothe,[8] V. Brudanin,[6]

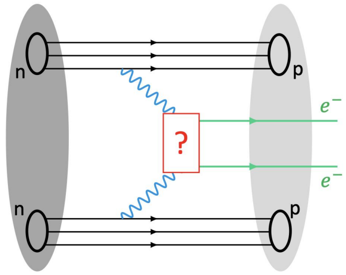



*Agostini et al. Rev.Mod.Phys. 95 (2023) 2, 025002*

# Theoretical mechanism→which one dominates?



| mechanism | amplitude and particle physics parameter | current limit | test |
|---|---|---|---|
| light neutrino exchange | $\frac{G_F^2}{q^2}\left\|U_{ei}^2\, m_i\right\|$ | 0.5 eV | oscillations, cosmology, neutrino mass |
| heavy neutrino exchange | $G_F^2\left\|\frac{S_{ei}^2}{M_i}\right\|$ | $2\times 10^{-8}$ GeV$^{-1}$ | LFV, collider |
| heavy neutrino and RHC | $G_F^2\, m_W^4\left\|\frac{V_{ei}^2}{M_i\, M_{W_R}^4}\right\|$ | $4\times 10^{-16}$ GeV$^{-5}$ | flavor, collider |
| Higgs triplet and RHC | $G_F^2\, m_W^4\left\|\frac{(M_R)_{ee}}{m_{\Delta_R}^2\, M_{W_R}^4}\right\|$ | $10^{-15}$ GeV$^{-1}$ | flavor, collider $e^-$ distribution |
| $\lambda$-mechanism with RHC | $G_F^2\,\frac{m_W^2}{q}\left\|\frac{U_{ei}\,\tilde{S}_{ei}}{M_{W_R}^2}\right\|$ | $1.4\times 10^{-10}$ GeV$^{-2}$ | flavor, collider, $e^-$ distribution |
| $\eta$-mechanism with RHC | $G_F^2\,\frac{1}{q}\,\tan\zeta\,\left\|U_{ei}\,\tilde{S}_{ei}\right\|$ | $6\times 10^{-9}$ | flavor, collider, $e^-$ distribution |
| short-range $\not{R}$ | $\frac{\|\lambda_{111}'^2\|}{\Lambda_{SUSY}^5}$ $\Lambda_{SUSY}=f(m_{\tilde{g}}, m_{\tilde{u}_L}, m_{\tilde{d}_R}, m_{\chi_i})$ | $7\times 10^{-18}$ GeV$^{-5}$ | collider, flavor |
| long-range $\not{R}$ | $\frac{G_F}{q}\left\|\sin 2\theta^b\,\lambda_{131}'\,\lambda_{113}'\left(\frac{1}{m_{\tilde{b}_1}^2}-\frac{1}{m_{\tilde{b}_2}^2}\right)\right\|$ $\sim\frac{G_F}{q}\,m_b\,\frac{\|\lambda_{131}'\,\lambda_{113}'\|}{\Lambda_{SUSY}^3}$ | $2\times 10^{-13}$ GeV$^{-2}$ $1\times 10^{-14}$ GeV$^{-3}$ | flavor, collider |
| Majorons | $\propto\|\langle g_\chi\rangle\|$ or $\|\langle g_\chi\rangle\|^2$ | $10^{-4}\ldots 1$ | spectrum, cosmology |




*Rodejohann, Int.J.Mod.Phys.E 20 (2011)*

Phase space factor + nuclear matrix element (NME) ?+ new physics parameter ?(effective neutrino mass)

# Formula (light neutrino exchange mechanism)



$$(T_{1/2}^{-1})_\alpha = \widetilde{\Gamma}_\alpha(m_{\beta\beta}, M_{\alpha i}) = \frac{\Gamma_\alpha(m_{\beta\beta}, M_{\alpha i})}{\ln 2} = G_\alpha \left|M_{\alpha i}\right|^2 m_{\beta\beta}^2$$

$$m_{\beta\beta} = \left|\sum_j U_{ej}^2 m_j\right|$$

*Cirigliano et al , Phys.Rev.Lett. 120 (2018) 20, 202001*

$$M_{\alpha i} = M_{\alpha i}^{\text{long}} + M_{\alpha i}^{\text{short}} = M_{\alpha i}^{\text{long}}(1 + n_{\alpha i}) \qquad n_{\alpha i} = \frac{M_{\alpha i}^{\text{short}}}{M_{\alpha i}^{\text{long}}}$$

$$g_A^{\text{eff}} = q\, g_A^{\text{free}} \qquad g_A^{\text{free}} = 1.27$$

- **Quenching effect: correct the NME by $q^2$ and the decay rate by $q^4$**
  **(**Ab initio many- body theory**)**
- Short- range NME: Contact operator suggested to contribute to light- neutrino exchange, *Cirigliano et al. PRL2018*
- We do not know neither the value or the sign of short- range NME well.
- Unknown value of the hadronic coupling $g_\nu^{\text{NN}}$, to be determined experimentally or Lattice QCD calculations

# Long-range NME



| Nuclear Model | Index [Ref.] | $^{76}$Ge | $^{82}$Se | $^{100}$Mo | $^{130}$Te | $^{136}$Xe |
|---|---|---|---|---|---|---|
| NSM | N1 [25] | 2.89 | 2.73 | - | 2.76 | 2.28 |
| | N2 [25] | 3.07 | 2.90 | - | 2.96 | 2.45 |
| | N3 [26] | 3.37 | 3.19 | - | 1.79 | 1.63 |
| | N4 [26] | 3.57 | 3.39 | - | 1.93 | 1.76 |
| | N5 [27, 28] | 2.66 | 2.72 | 2.24 | 3.16 | 2.39 |
| QRPA | Q1 [29] | 5.09 | - | - | 1.37 | 1.55 |
| | Q2 [30] | 5.26 | 3.73 | 3.90 | 4.00 | 2.91 |
| | Q3 [31] | 4.85 | 4.61 | 5.87 | 4.67 | 2.72 |
| | Q4 [32] | 3.12 | 2.86 | - | 2.90 | 1.11 |
| | Q5 [32] | 3.40 | 3.13 | - | 3.22 | 1.18 |
| | Q6 [33] | - | - | - | 4.05 | 3.38 |
| EDF | E1 [34] | 4.60 | 4.22 | 5.08 | 5.13 | 4.20 |
| | E2 [35] | 5.55 | 4.67 | 6.59 | 6.41 | 4.77 |
| | E3 [36] | 6.04 | 5.30 | 6.48 | 4.89 | 4.24 |
| IBM | I1 [37] | 5.14 | 4.19 | 3.84 | 3.96 | 3.25 |
| | I2 [13] | 6.34 | 5.21 | 5.08 | 4.15 | 3.40 |

*Agostini et al. Rev.Mod.Phys. 95 (2023) 2, 025002*

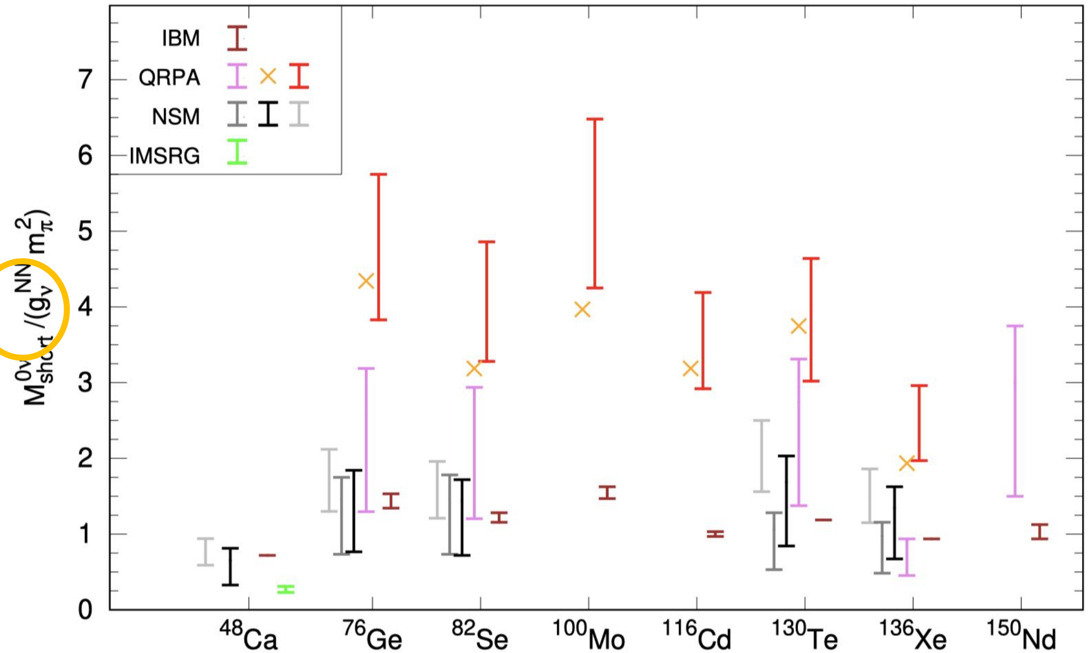
# Short-range NME (contact term)



$$n_{\alpha i} = \frac{M_{\alpha i}^{\text{short}}}{M_{\alpha i}^{\text{long}}}$$

| Isotope | NSM % | QRPA % |
|---|---|---|
| $^{76}$Ge | 15–42 | 32–73 |
| $^{82}$Se | 15–41 | 30–70 |
| $^{100}$Mo | - | 49–108 |
| $^{130}$Te | 17–47 | 34–77 |
| $^{136}$Xe | 17–47 | 30–70 |

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



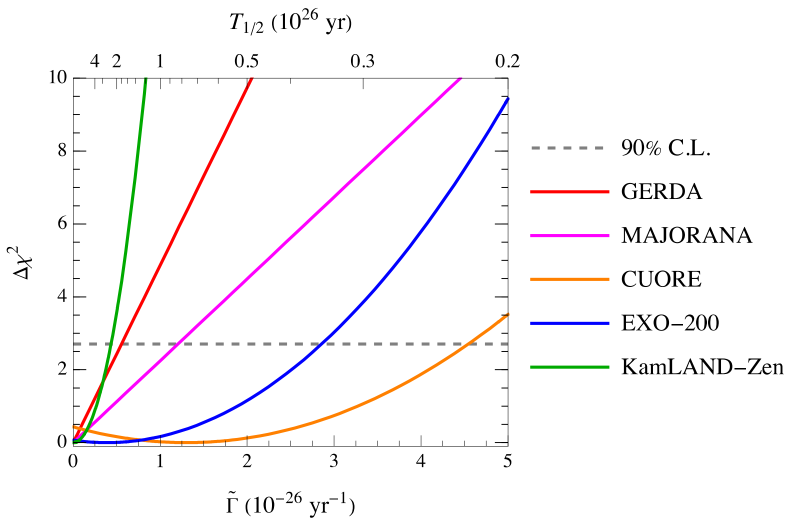

*Agostini et al. Rev.Mod.Phys. 95 (2023) 2, 025002*

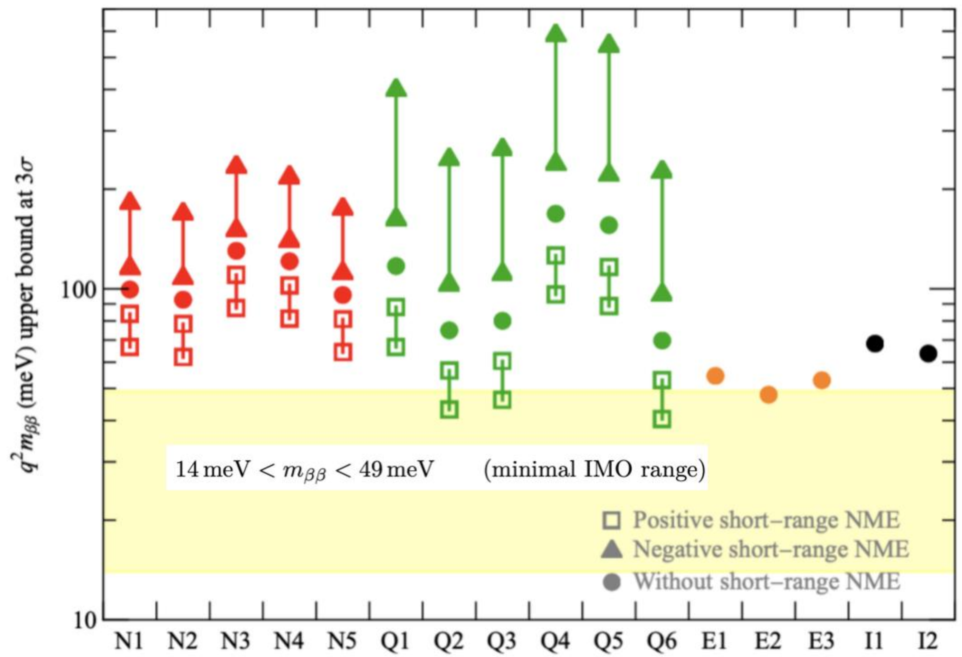
More recent discussion: Cirigliano et al, PRL2021; Yang and Zhao, PLB2024;
Liu, Huang, Fang arXiv:2405.10503

# Current constraints



$$\Delta\chi^2_r(\widetilde{\Gamma}_\alpha) = a_r\,(\widetilde{\Gamma}_\alpha)^2 + b_r\,\widetilde{\Gamma}_\alpha + c_r$$



# Sensitivities to $(q^2 m_{\beta\beta})^{True}$ at $3\sigma$



| Experiment | Isotope | $\varepsilon$ [mol·yr] | $b$ [events/(mol·y)] | PSF [$yr^{-1}$ $eV^{-2}$] |
| --- | --- | --- | --- | --- |
| LEGEND-1000 | $^{76}$Ge | 8736 | $4.9 \cdot 10^{-6}$ | $2.36 \cdot 10^{-26}$ |
| SuperNEMO | $^{82}$Se | 185 | $5.4 \cdot 10^{-3}$ | $10.19 \cdot 10^{-26}$ |
| CUPID | $^{100}$Mo | 1717 | $2.3 \cdot 10^{-4}$ | $15.91 \cdot 10^{-26}$ |
| SNO+II | $^{130}$Te | 8521 | $5.7 \cdot 10^{-3}$ | $14.2 \cdot 10^{-26}$ |
| nEXO | $^{136}$Xe | 13700 | $4.0 \cdot 10^{-5}$ | $14.56 \cdot 10^{-26}$ |

$$N_{\mathrm{LEGEND-1000}} = \left\{0.97 \times \left[\frac{(q^2 m_{\beta\beta})^{\mathrm{True}}}{40\ \mathrm{meV}}\right]^2 \left(\frac{M^{\mathrm{long}}_{\mathrm{Ge}}}{2.66}\right)^2 + 0.04\right\} \times \frac{T}{1\ \mathrm{yr}}$$

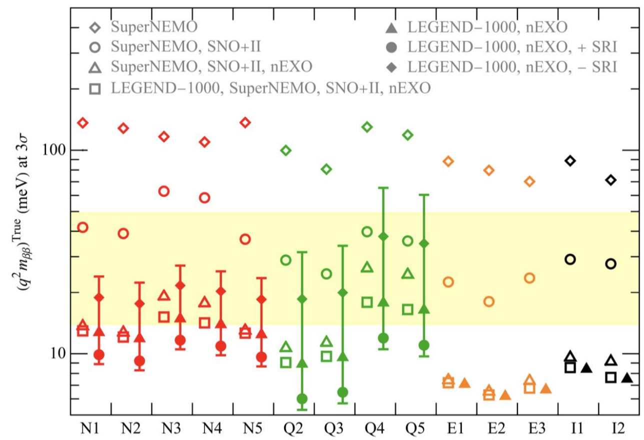
$$N_{\mathrm{SuperNEMO}} = \left\{0.09 \times \left[\frac{(q^2 m_{\beta\beta})^{\mathrm{True}}}{40\ \mathrm{meV}}\right]^2 \left(\frac{M^{\mathrm{long}}_{\mathrm{Se}}}{2.72}\right)^2 + 1.0\right\} \times \frac{T}{1\ \mathrm{yr}}$$

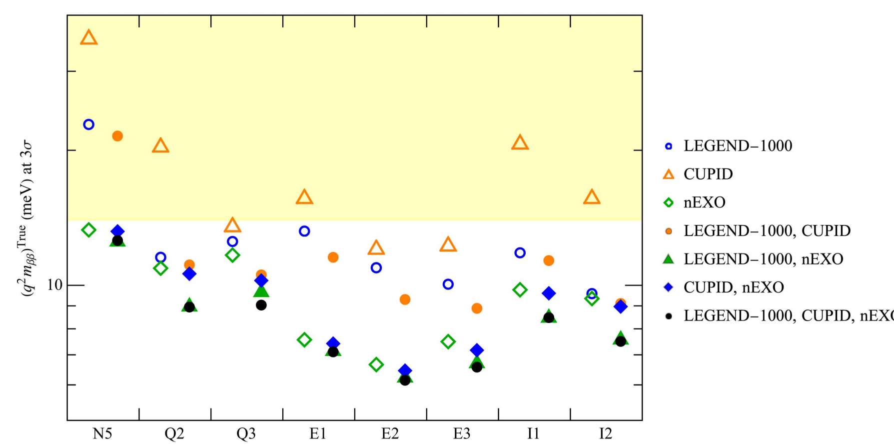
$$N_{\mathrm{nEXO}} = \left\{1.64 \times \left[\frac{(q^2 m_{\beta\beta})^{\mathrm{True}}}{40\ \mathrm{meV}}\right]^2 \left(\frac{M^{\mathrm{long}}_{\mathrm{Xe}}}{1.11}\right)^2 + 0.5\right\} \times \frac{T}{1\ \mathrm{yr}}$$

$$N_{\alpha i} = S_{\alpha i} + B_\alpha \qquad B_\alpha = b_\alpha \cdot \varepsilon_\alpha \cdot \left(\frac{T}{1\ \mathrm{yr}}\right)$$

$$S_{\alpha i}(m_{\beta\beta}, M_{\alpha i}) = \ln 2 \cdot N_A \cdot \varepsilon_\alpha \cdot \left(\frac{T}{1\ \mathrm{yr}}\right) \cdot \widetilde{\Gamma}_\alpha(m_{\beta\beta}, M_{\alpha i})$$

$$\Delta\chi^2_{ij}(m_{\beta\beta}, M_{\alpha j}\,;\, m^{\mathrm{True}}_{\beta\beta}, M^{\mathrm{True}}_{\alpha i}) = 2\sum_\alpha \left(N_{\alpha j} - N^{\mathrm{True}}_{\alpha i} + N^{\mathrm{True}}_{\alpha i} \ln \frac{N^{\mathrm{True}}_{\alpha i}}{N_{\alpha j}}\right)$$



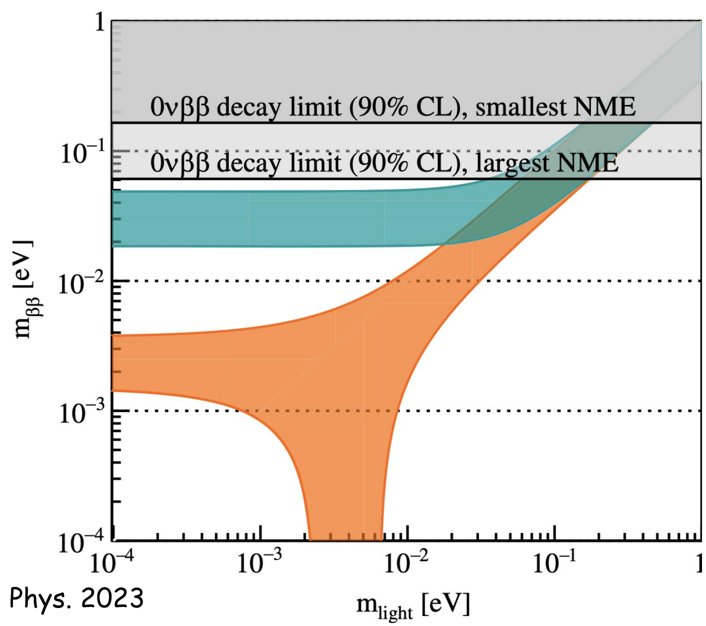
# Formulas (minimal type-I seesaw)

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2}\overline{(\nu_{\text{L}}, N_{\text{R}}^c)} \begin{pmatrix} 0 & M_{\text{D}} \\ M_{\text{D}}^{\text{T}} & M_{\text{R}} \end{pmatrix} \begin{pmatrix} \nu_{\text{L}}^c \\ N_{\text{R}} \end{pmatrix} + \text{h.c.}$$

$$1/T_{1/2}^{0\nu} = G|M_{0\nu}(0) \cdot m_{\text{eff}}|^2$$

$$|m_{\text{eff}}| = \left| |m_{\text{eff}}^{\nu}| - |m_{\text{eff}}^{\nu}| f_\beta(M_2) + |R_{e1}^2| e^{2i\delta_{14}} M_1 \left[f_\beta(M_1) - f_\beta(M_2)\right] \right|$$

$$f_\beta(M_N) = M_{0\nu}(M_N)/M_{0\nu}(0)$$ **Mass dependent nuclear matrix element (NME)**

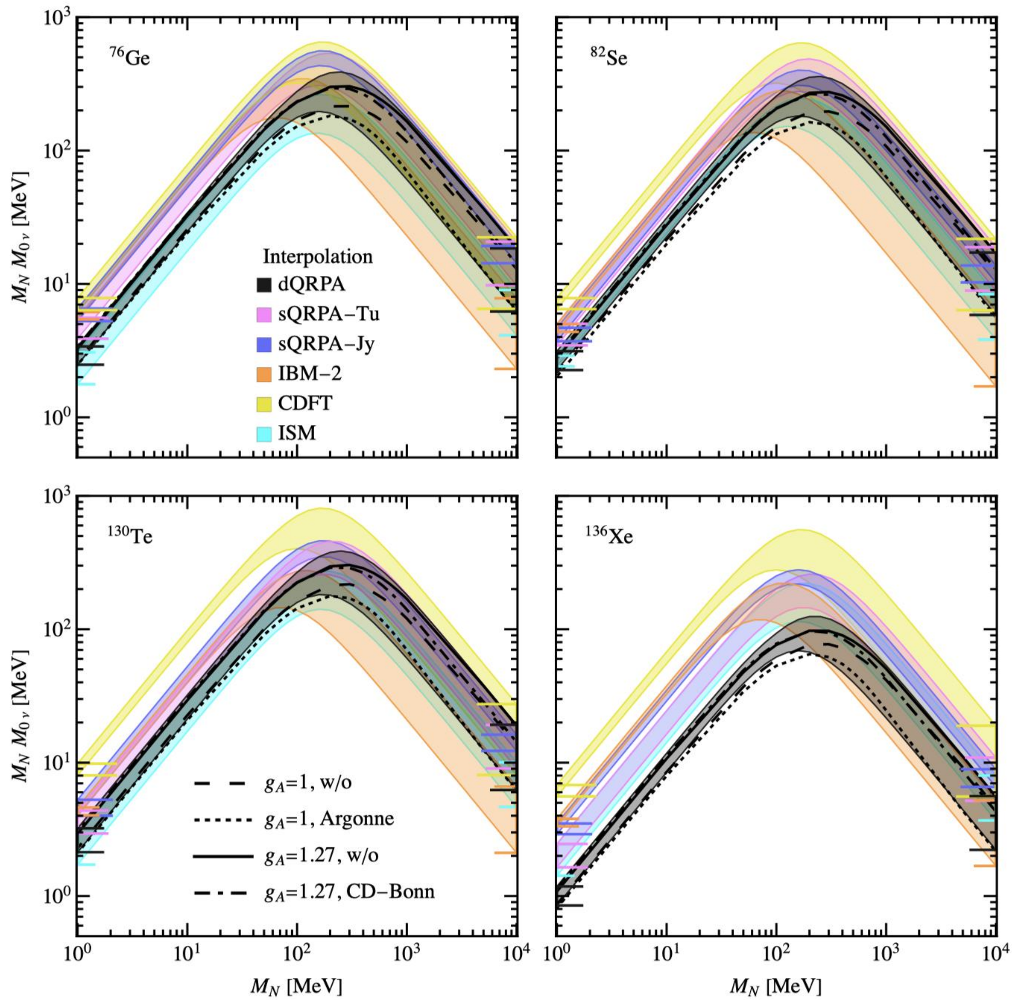



Agostini et al., Rev. Mod. Phys. 2023

minimal Type-I seesaw
NMO, [1,4] meV
IMO, [15, 50] meV

# Mass-dependent NME





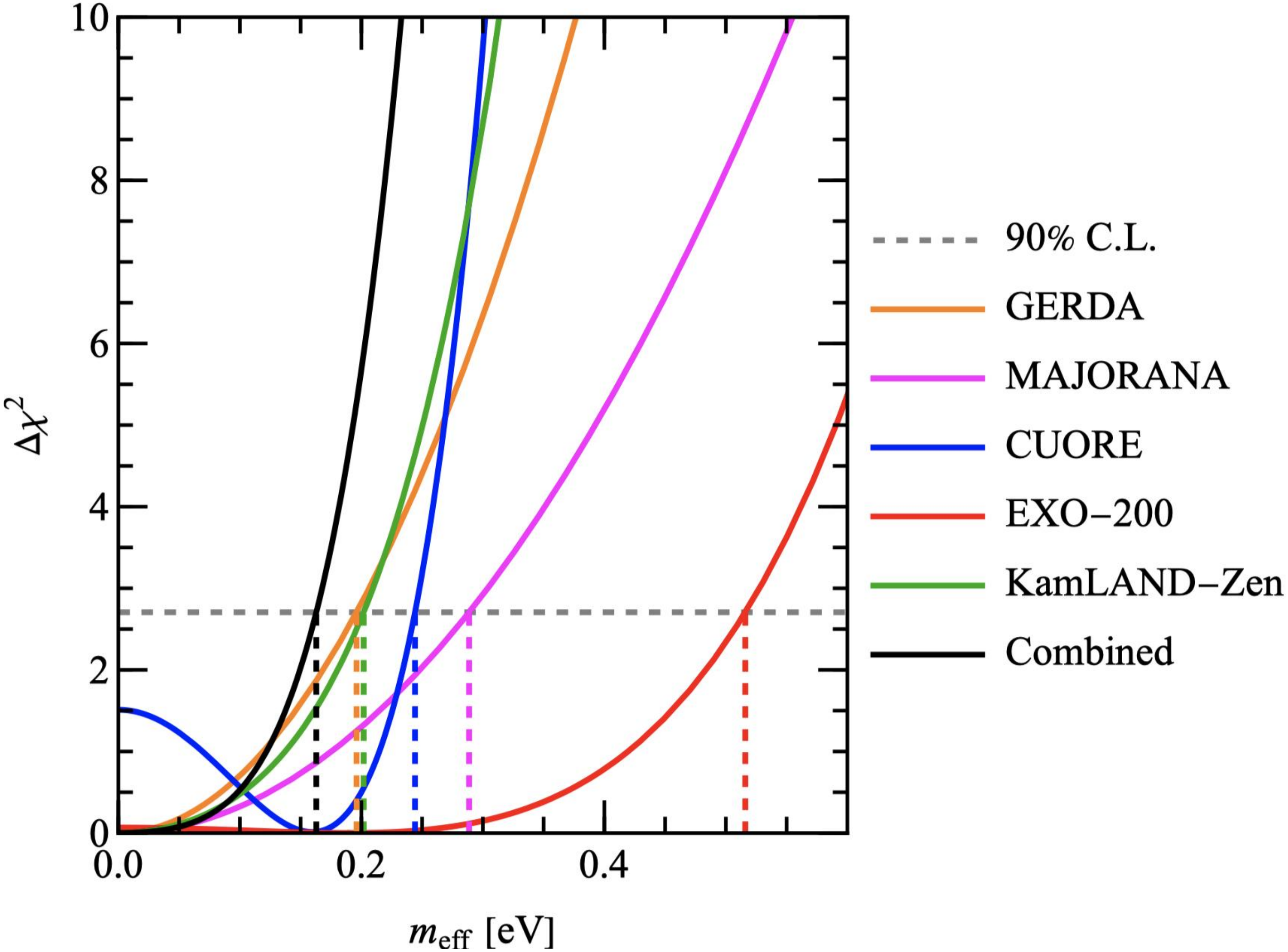

- **dQRPA:** Numerical calculation
- **Others:** interpolation with two extreme values

$$M_{0\nu}(m_j) = \frac{m_p m_e}{\langle p^2 \rangle + m_j^2} M_{\mathrm{H}}$$

- **dQRPA:** agrees with ISM for light neutrinos and tends to be consistent with CDFT for heavy neutrinos
- **In light neutrino mass** the NME from **dQRPA** model is smaller than that of the **IBM-2** model, and in heavy neutrino mass the reverse applies.

# $\Delta\chi^2$ functions of $m_{eff}$

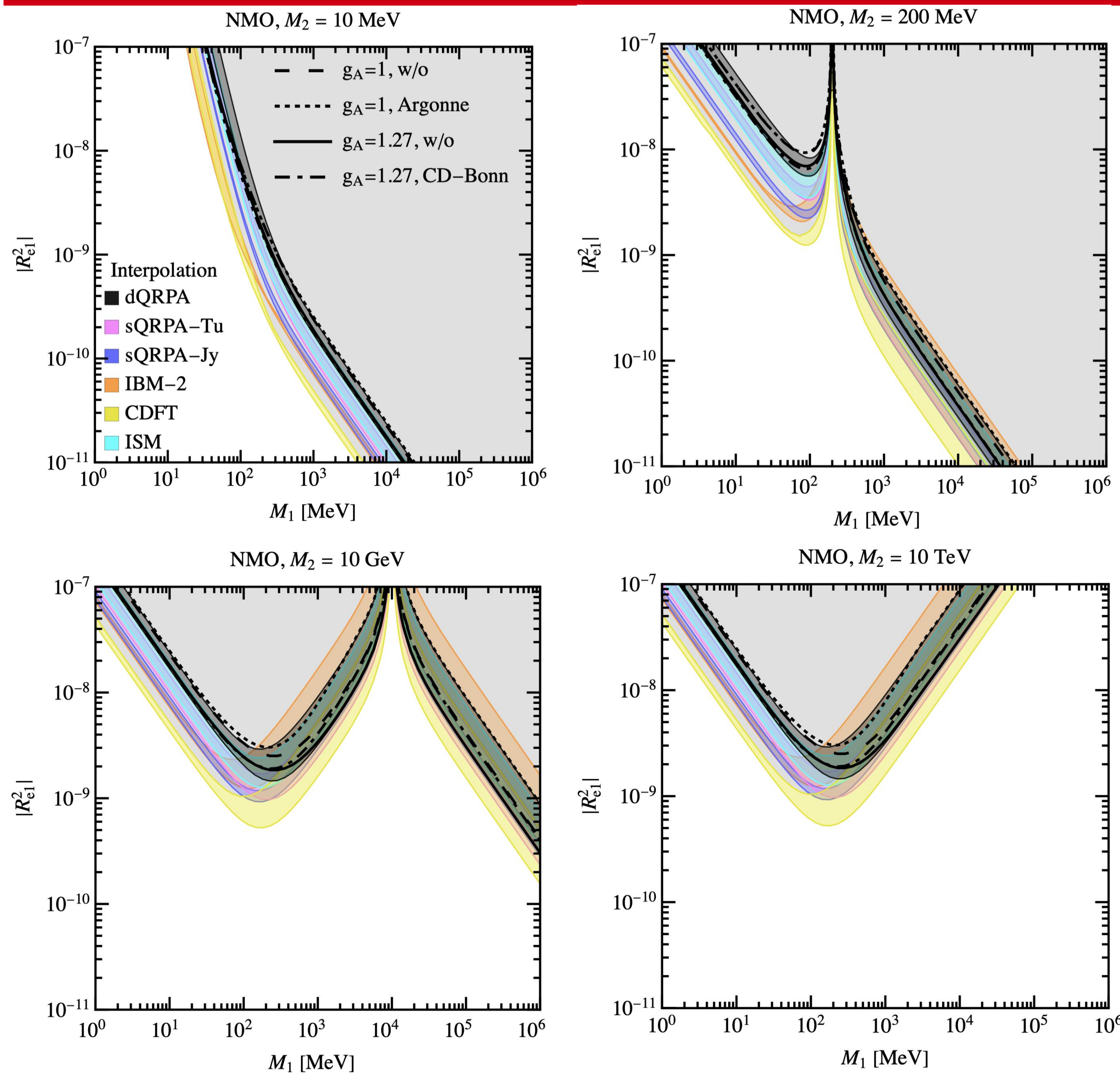





$g_A$=1, Argonne src

# Current limits ($M_1$ & $|R_{e1}|^2$)

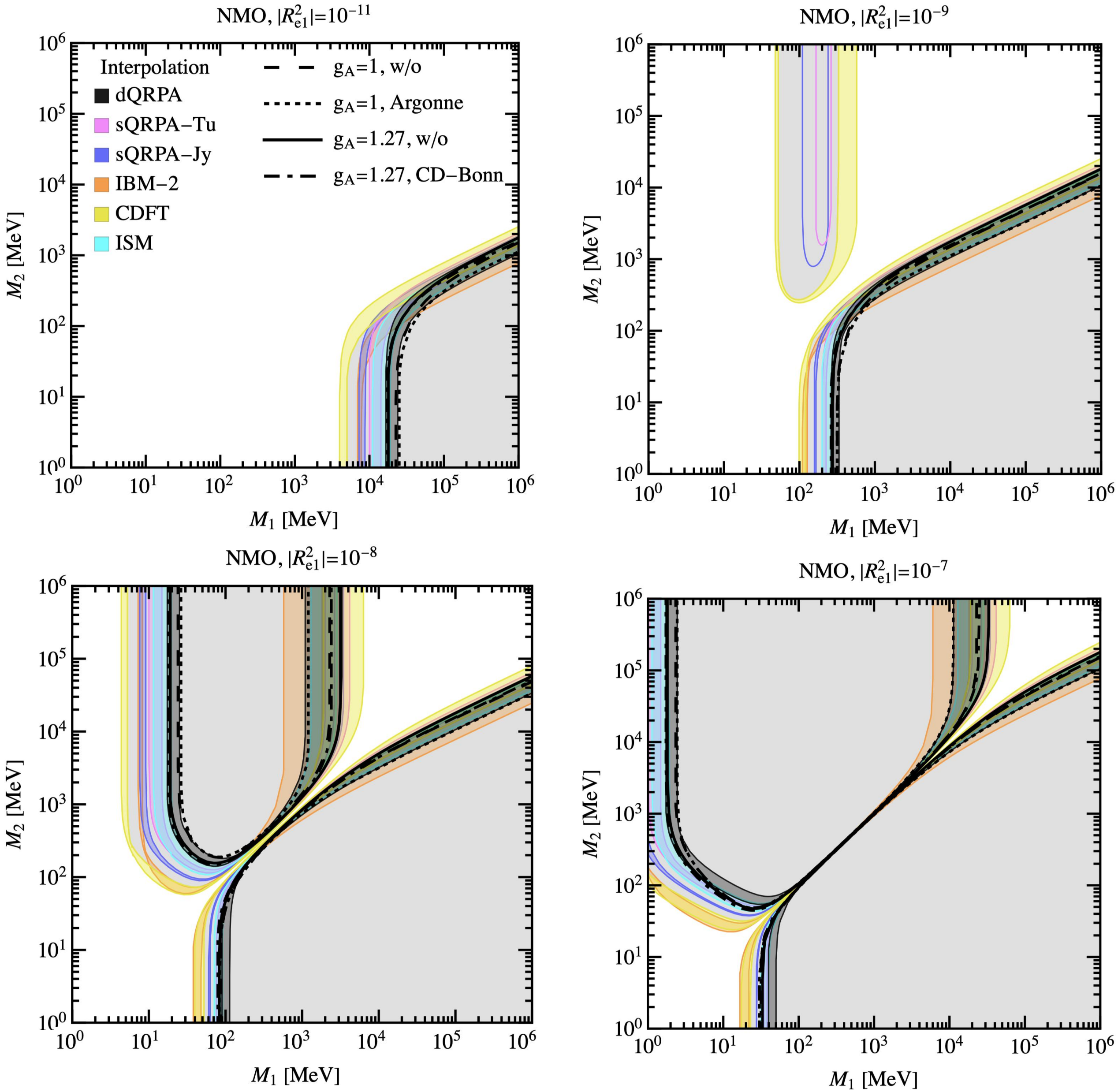





- 3σ C.L
- Gray regions: excluded regions in the case of CDFT model
- Different choices of parameters and models are scanned (not as Gaussian)
- Both the **0νββ-decay** and **oscillation data** are used
- The **IMO** case is similar
- The peak shape

# Current limits ($M_1$ & $M_2$)

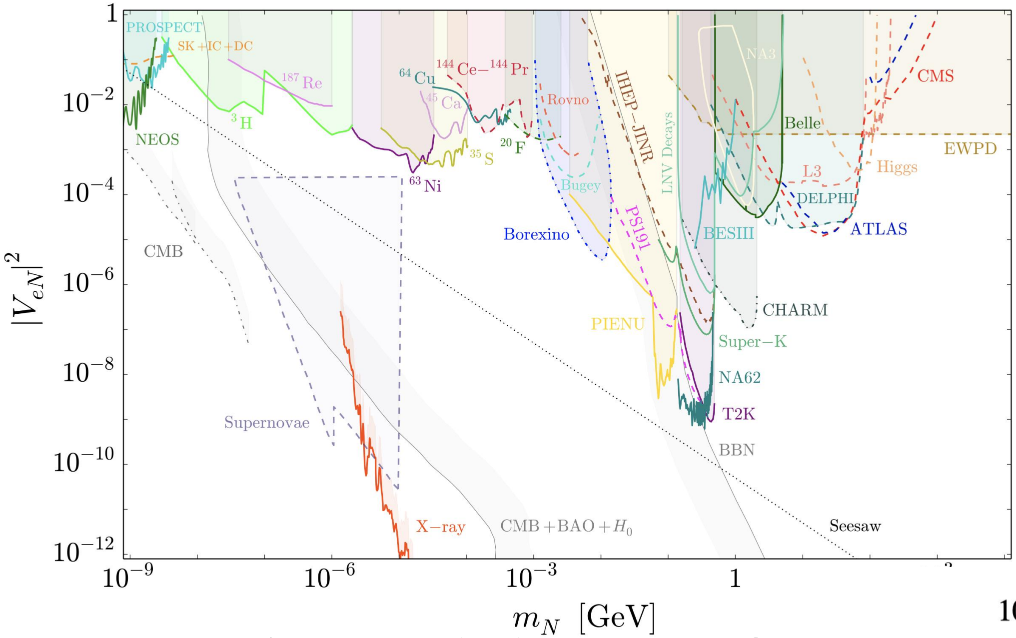





- The IMO case is similar
- The NME hierarchy changes with neutrino mass

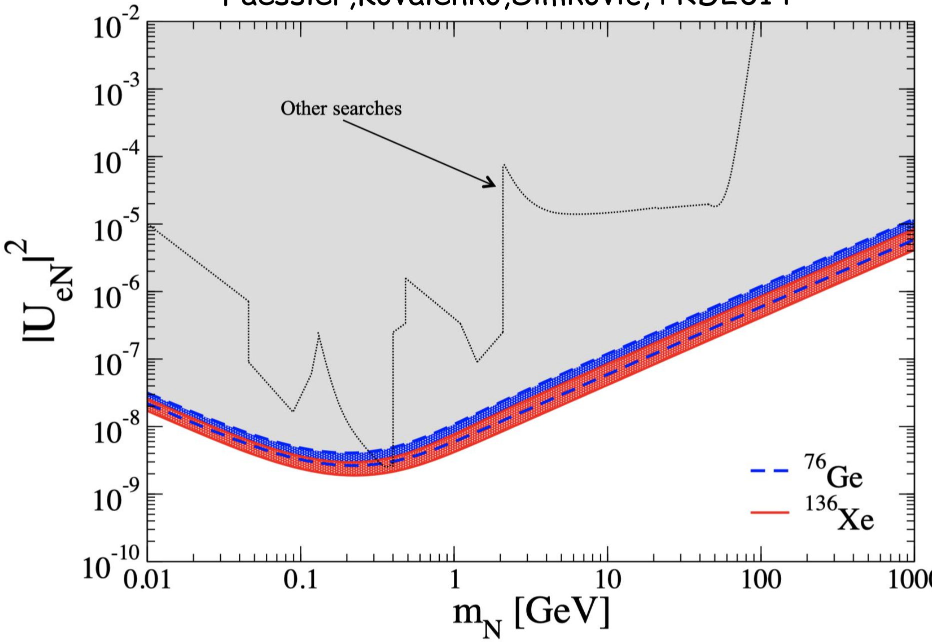
# Constraints from other probes






Bolton, Deppisch, Bhupap Dev, JHEP 2020

Faessler,Kovalenko,Simkovic, PRD2014




- 3+1case: similar to the case ***$M_2 \gg M_1$***
- 0νββ data provide strongest limits in the mass range considered here

# Future sensitivities

$$\Delta\chi^2_{ij}(m_{\rm eff},(M_{0\nu})_{\alpha j};m^{\rm True}_{\rm eff},(M_{0\nu})^{\rm True}_{\alpha i}) = 2\sum_{\alpha}(N_{\alpha j} - N^{\rm True}_{\alpha i} + N^{\rm True}_{\alpha i}{\rm In}\frac{N^{\rm True}_{\alpha i}}{N_{\alpha j}})$$

Assumed number events

$$N^{\rm True}_{\alpha i} = B_{\alpha i} + S_{\alpha i}(m^{\rm True}_{\rm eff},(M_{0\nu})^{\rm True}_{\alpha i})$$

$$N_{\alpha j} = B_{\alpha j} + S_{\alpha j}(m_{\rm eff}, M_{\alpha j})$$

Assuming no positive 0νββ signal is observed,
Leading to sensitivities independent of true NME model

$$S_{\alpha i}(m_{\rm eff},\ M_{\alpha i}) = {\rm In}2\cdot N_A\cdot\varepsilon_\alpha\cdot(T^{0\nu}_{1/2})^{-1}_{\alpha i}\cdot T/(1\ {\rm yr})$$

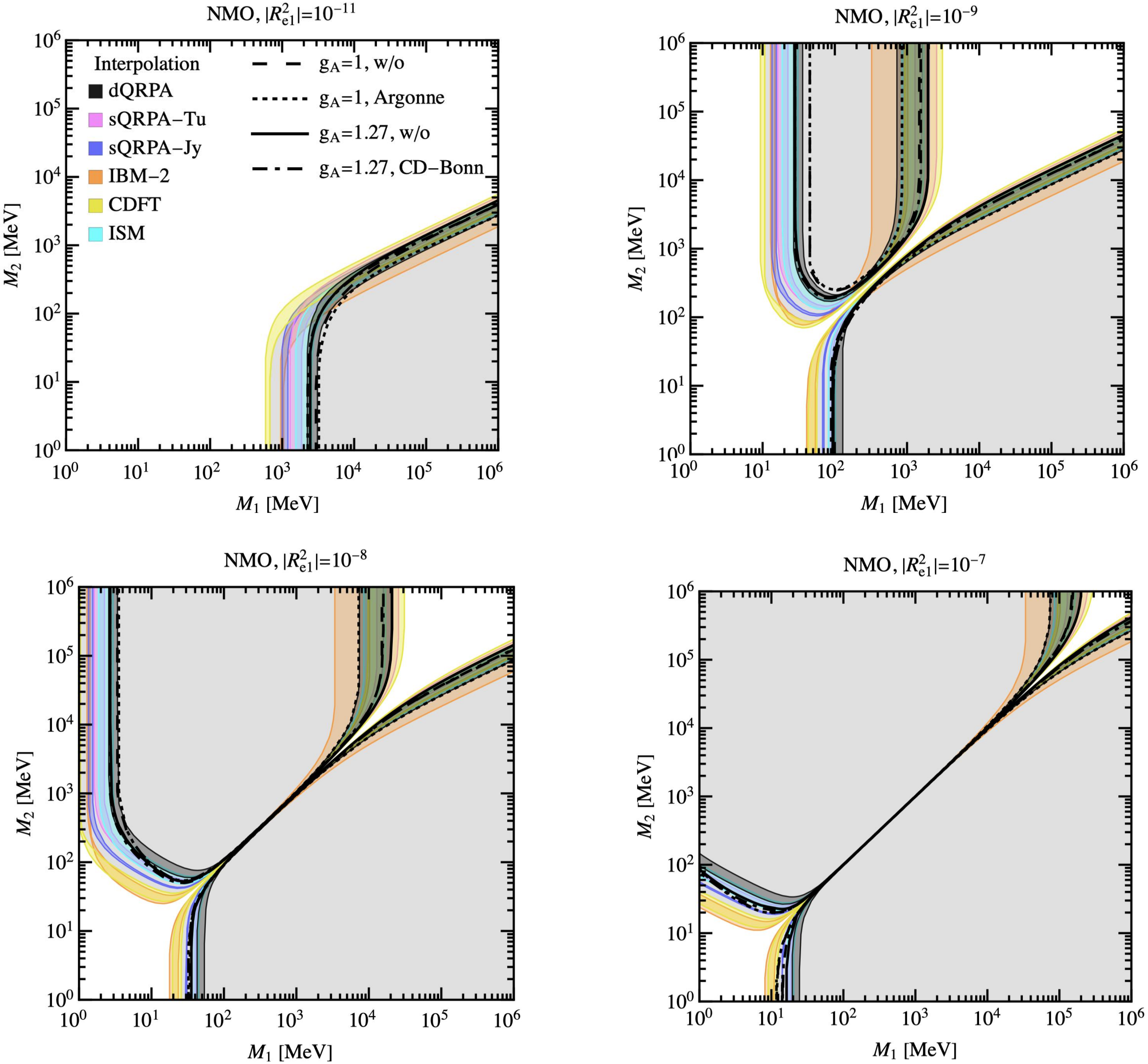
$$B_\alpha = b_\alpha\cdot\varepsilon_\alpha\cdot T/(1\ {\rm yr})$$

**T=10 yr**

| Experiment | Isotope | $\varepsilon$ [mol· yr] | $b$ [events/(mol· yr)] |
|---|---|---|---|
| LEGEND-1000 | $^{76}$Ge | 8736 | $4.9\cdot10^{-6}$ |
| SuperNEMO | $^{82}$Se | 185 | $5.4\cdot10^{-3}$ |
| SNO+II | $^{130}$Te | 8521 | $5.7\cdot10^{-3}$ |
| nEXO | $^{136}$Xe | 13700 | $4.0\cdot10^{-5}$ |

# Future sensitivities ($M_1$ & $M_2$)

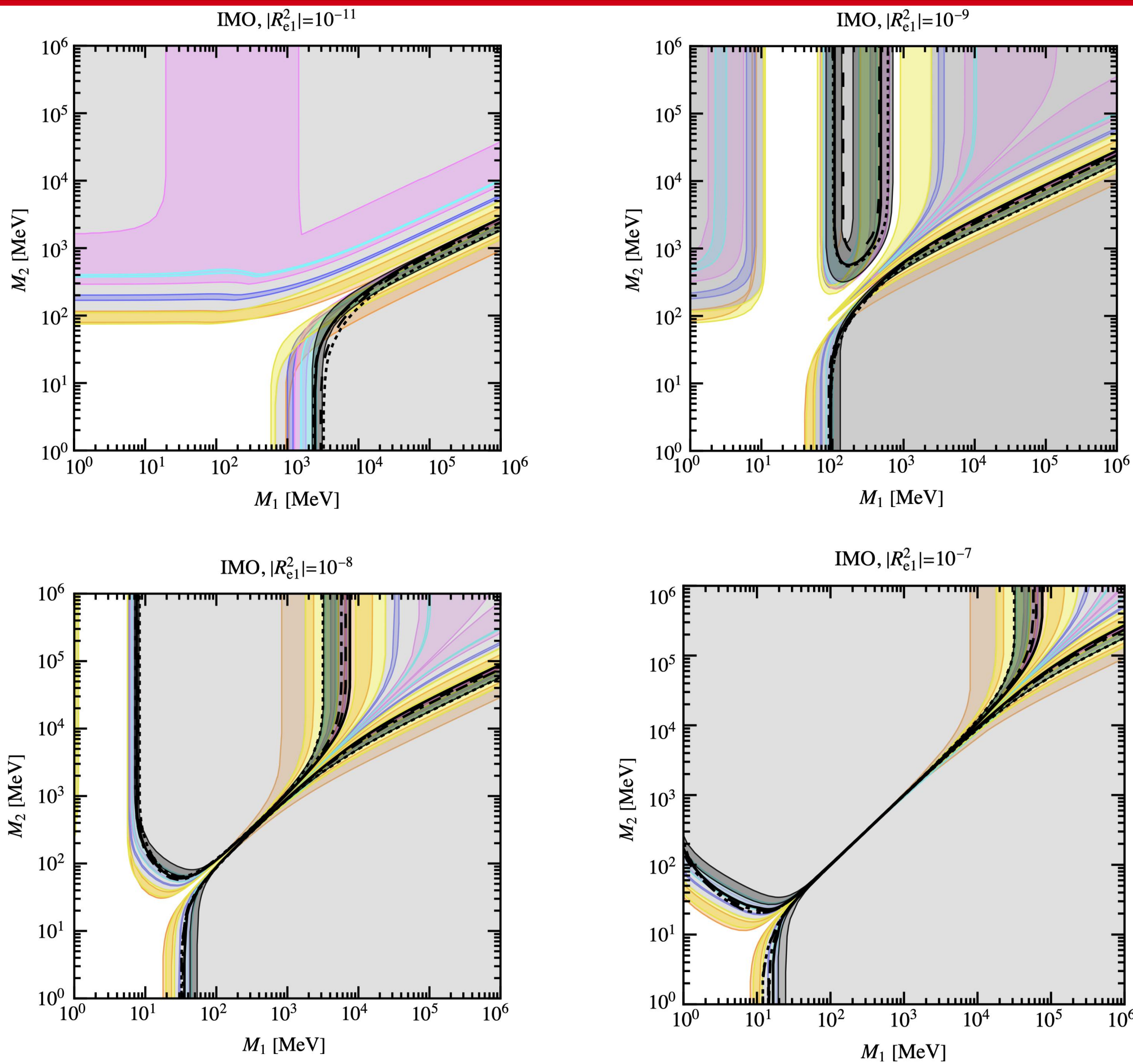





The NMO case

More parameter space can be tested compared the current experiments

# Future sensitivities ($M_1$ & $M_2$)




- The IMO case
- The wide pink region in the upper left panel: mainly different $\delta_{14}$ values
- Much more parameter space are expected to exclude than NMO case due to zero positive 0νββ signal assumed
- By assuming **enough positive 0νββ signal**, possible to **discriminate NME calculations** and more parameter space can be **excluded in the NMO case**

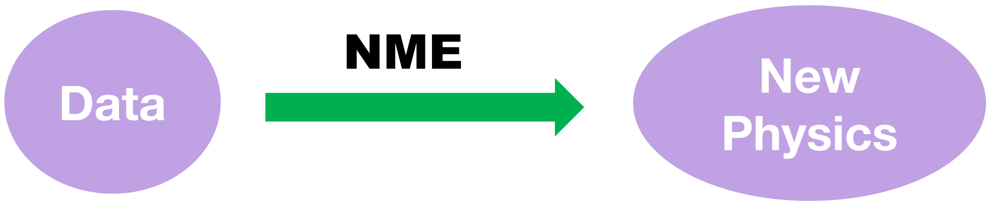
# Summary



- **NME uncertainties due to the SRI may lead to the bound on $q^2 m_{\beta\beta}$ varying by a factor of order 5**
- Comparison of mass dependent NMEs in different nuclear models
- Derivation of limits and sensitivities on the parameter space of minimal type-I seesaw from current and future $0\nu\beta\beta$ experiments

# Outlook






- Better understanding the short-range NME in 0νββ
- Better understanding the nuclear structure
- The quenching problem
- NME statistical uncertainties
- LEC from lattice calculations
- Sensitivities to different particle physics mechanisms and how to distinguish them
- ...
- From 0νββ to $m_{\beta\beta}$: improving the calculations of NME
- From 0νββ to discriminating NME models: more information on $m_{\beta\beta}$


# Thank you!