

New physics constraints from $0\nu\beta\beta$

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

Collaborators: Federica Pompa, Thomas Schwetz; Dong-Liang Fang, Yu-Feng Li, Yi-Yu Zhang

ν NN2025, Lanzhou

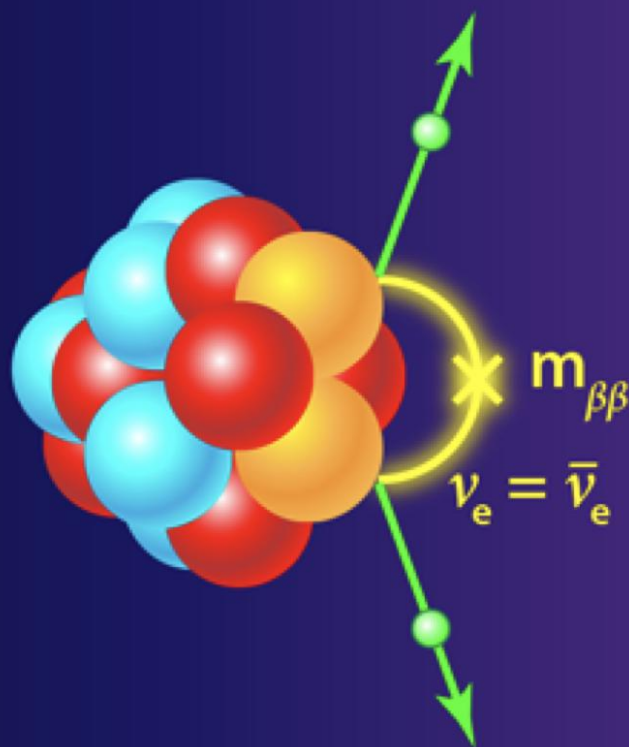
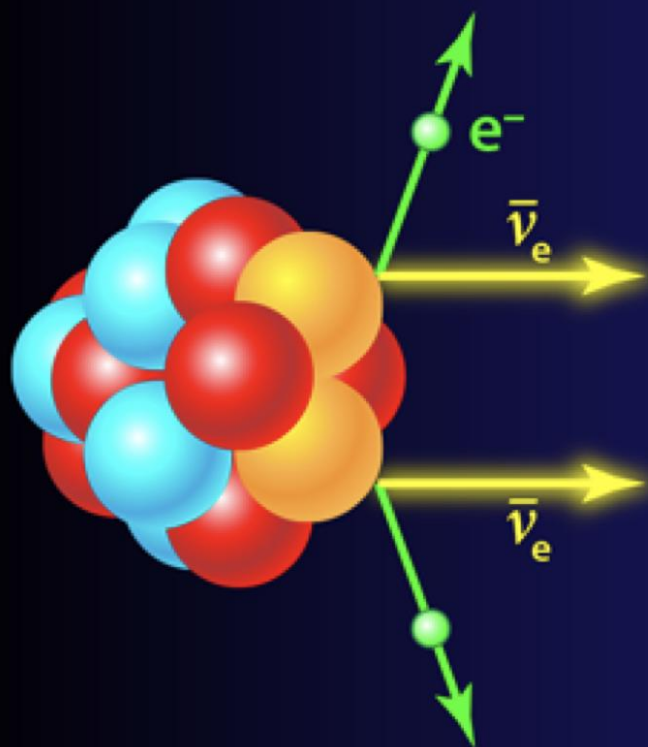
- **Brief introduction**
- **Neutrinoless double beta decay ($0\nu\beta\beta$) in light neutrino exchange mechanism**

Different upper limits of $m_{\beta\beta}$ due to NME uncertainties (short-range contact term)

- **$0\nu\beta\beta$ process in minimal Type-I seesaw**

Constraints of minimal Type-I seesaw from current and future $0\nu\beta\beta$ experiments

- **Summary**

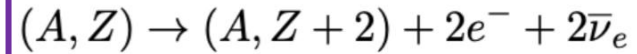
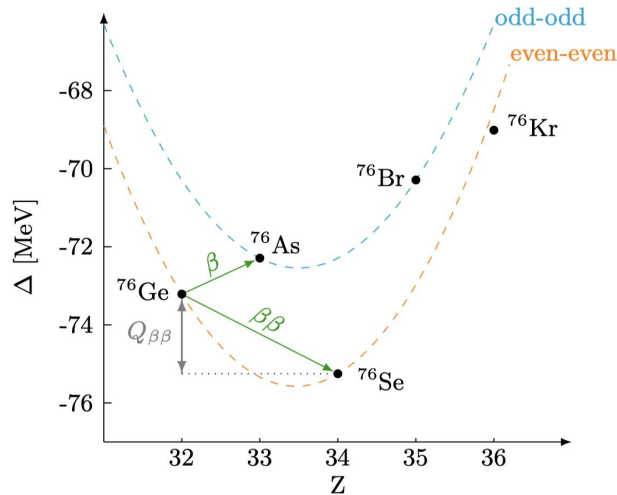


**Where
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you?**



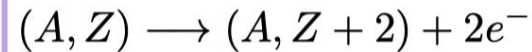
Brief background

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Mayer, 1935; first detected in 1987 by Moe

$$\nu_i^c = \nu_i \quad \text{Majorana, 1937}$$



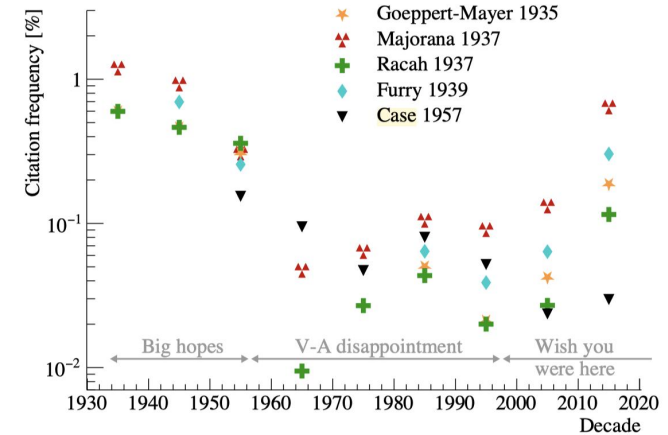
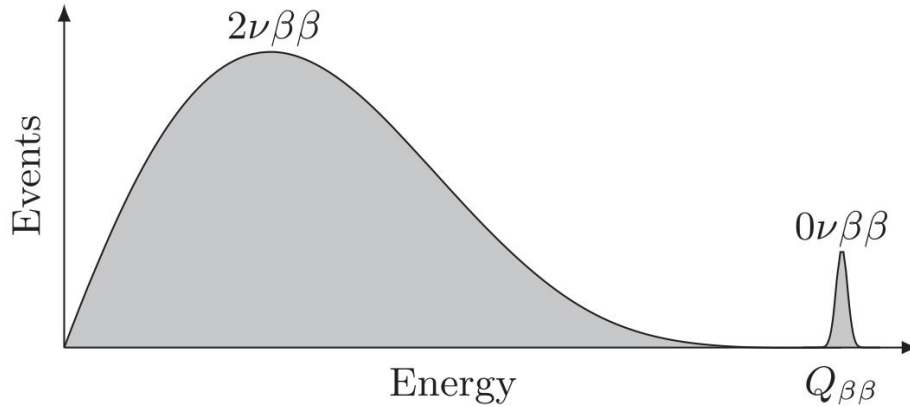
Furry, 1939

Isotope	Daughter	$Q_{\beta\beta}$ (keV) ^a	f_{nat} (%) ^b	f_{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	$[9.34 \pm 0.22(\text{stat})^{+0.62}_{-0.60}(\text{syst})] \times 10^{18}$	$> 2.0 \times 10^{22}$

10¹⁸ yr – 10²¹ yr

Experimental results and future proposals

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PHYSICAL REVIEW LETTERS 130, 051801 (2023)

Editors' Suggestion Featured in Physics

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

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

S. Abe¹, S. Asami¹, M. Eizuka¹, S. Futagi¹, A. Gando¹, Y. Gando¹, T. Gima¹, A. Goto¹, T. Hachiya¹, K. Hata¹

Article

Search for Majorana neutrinos exploiting millikelvin cryogenics with CUORE

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

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

Received: 14 April 2021

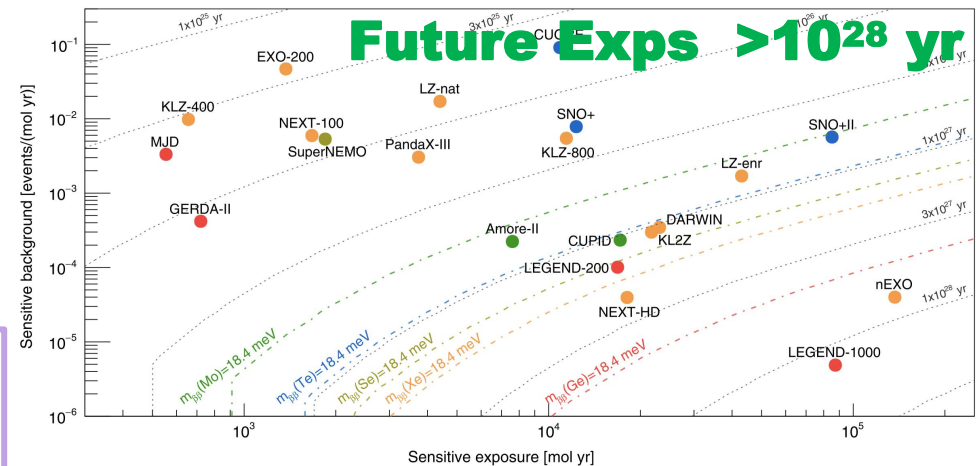
PHYSICAL REVIEW LETTERS 125, 252502 (2020)

Editors' Suggestion Featured in Physics

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

Final Results of GERDA on the Search for Neutrinoless Double- β Decay

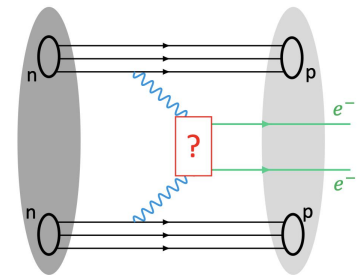
M. Agostini^{9,17}, G. R. Araujo²¹, A. M. Bakalyarov¹⁵, M. Balata¹, I. Barabanov¹³, L. Baudis²¹, C. Bauer⁸, E. Bellotti^{10,11}, S. Belogurov^{14,13,†}, A. Bettini^{18,19}, L. Bezukov¹³, V. Biancacci^{18,19}, D. Borowicz⁶, E. Bossio¹⁷, V. Bothe⁸, V. Brudanin⁶



Theoretical mechanism → which one dominates?

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mechanism	amplitude and particle physics parameter	current limit	test
light neutrino exchange	$\frac{G_F^2}{q^2} U_{ei}^2 m_i $	0.5 eV	oscillations, cosmology, neutrino mass
heavy neutrino exchange	$G_F^2 \frac{S_{ei}^2}{M_i^2}$	$2 \times 10^{-8} \text{ GeV}^{-1}$	LFV, collider
heavy neutrino and RHC	$G_F^2 m_W^4 \frac{V_{ei}^2}{M_i M_{WR}^4}$	$4 \times 10^{-16} \text{ GeV}^{-5}$	flavor, collider
Higgs triplet and RHC	$G_F^2 m_W^4 \left \frac{(M_R)_{ee}}{m_{\Delta_R}^2 M_{WR}^4} \right $	$10^{-15} \text{ GeV}^{-1}$	flavor, collider e^- distribution
λ -mechanism with RHC	$G_F^2 \frac{m_W^2}{q} \left \frac{U_{ei} \tilde{S}_{ei}}{M_{WR}^2} \right $	$1.4 \times 10^{-10} \text{ GeV}^{-2}$	flavor, collider, e^- distribution
η -mechanism with RHC	$G_F^2 \frac{1}{q} \tan \zeta \left U_{ei} \tilde{S}_{ei} \right $	6×10^{-9}	flavor, collider, e^- distribution
short-range $\cancel{R}$	$\frac{ \lambda_{111}^2 }{\Lambda_{\text{SUSY}}^5}$ $\Lambda_{\text{SUSY}} = f(m_{\tilde{g}}, m_{\tilde{u}_L}, m_{\tilde{d}_R}, m_{\chi_i})$	$7 \times 10^{-18} \text{ GeV}^{-5}$	collider, flavor
long-range $\cancel{R}$	$\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 $ $\sim \frac{G_F}{q} m_b \frac{ \lambda'_{131} \lambda'_{113} }{\Lambda_{\text{SUSY}}^3}$	$2 \times 10^{-13} \text{ GeV}^{-2}$ $1 \times 10^{-14} \text{ GeV}^{-3}$	flavor, collider
Majorons	$\propto \langle g_\chi \rangle \text{ or } \langle g_\chi \rangle ^2$	$10^{-4} \dots 1$	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)

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

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

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

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

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

- 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_{ν}^{NN} , to be determined experimentally or Lattice QCD calculations

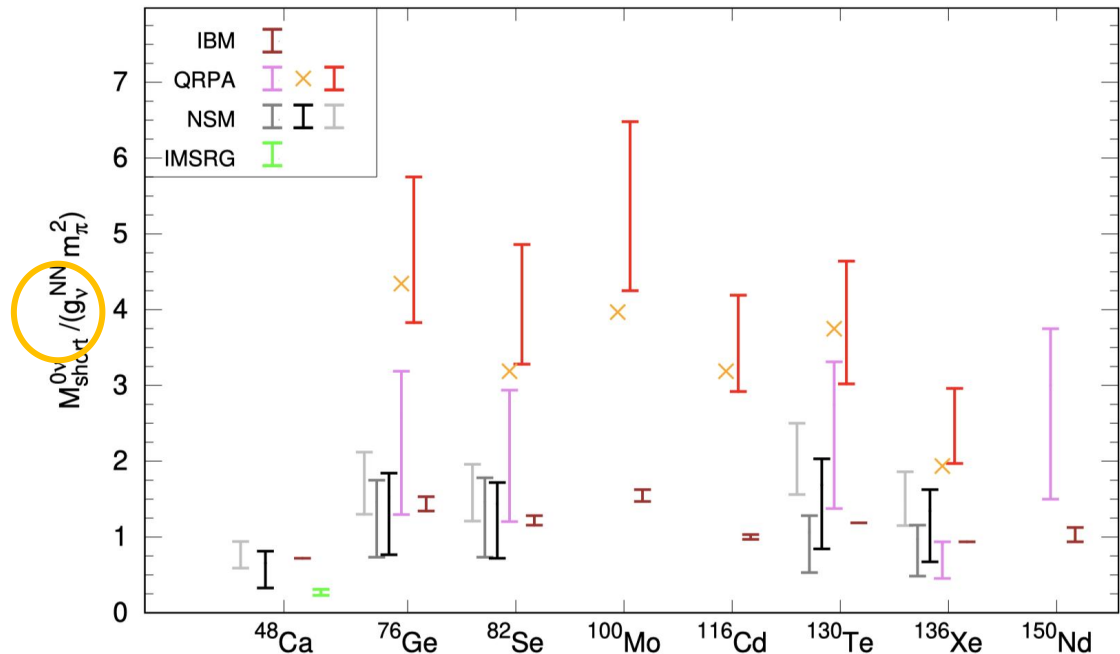
Nuclear Model	Index [Ref.]	^{76}Ge	^{82}Se	^{100}Mo	^{130}Te	^{136}Xe
NSM	N1 [25]	2.89	2.73	-	2.76	2.28
	N2 [25]	3.07	2.90	-	2.96	2.45
	N3 [26]	3.37	3.19	-	1.79	1.63
	N4 [26]	3.57	3.39	-	1.93	1.76
	N5 [27, 28]	2.66	2.72	2.24	3.16	2.39
QRPA	Q1 [29]	5.09	-	-	1.37	1.55
	Q2 [30]	5.26	3.73	3.90	4.00	2.91
	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

Short-range NME (contact term)

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

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



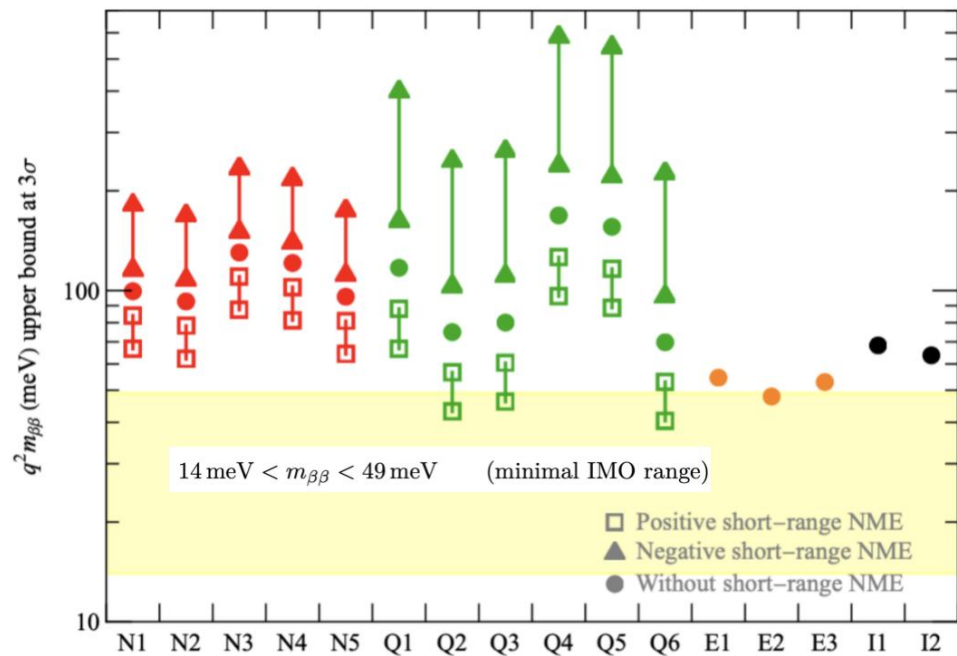
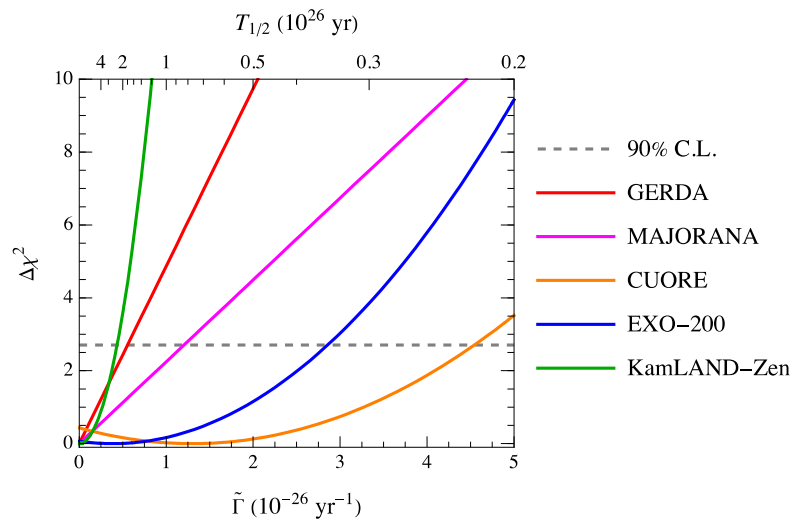
Phys. Lett. B 823 (2021) 136720

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

Recent discussion: Pengwei Zhao's talk

Liu, Huang, Fang arXiv:2405.10503

$$\Delta\chi_r^2(\tilde{\Gamma}_\alpha) = a_r (\tilde{\Gamma}_\alpha)^2 + b_r \tilde{\Gamma}_\alpha + c_r$$



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

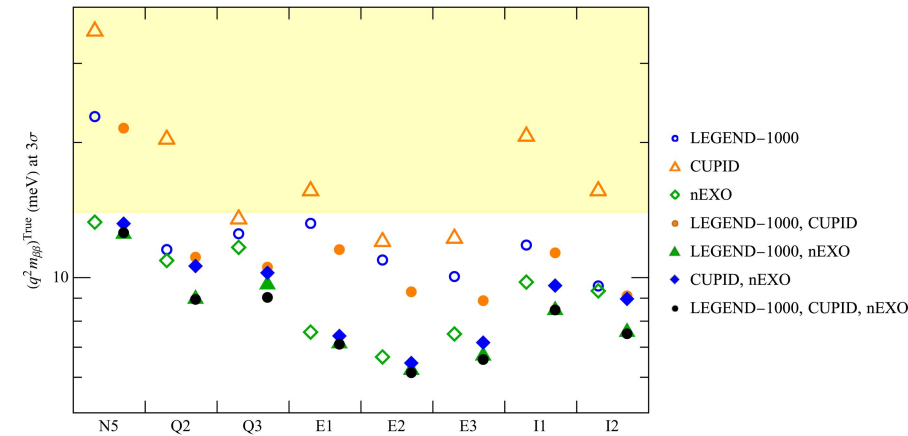
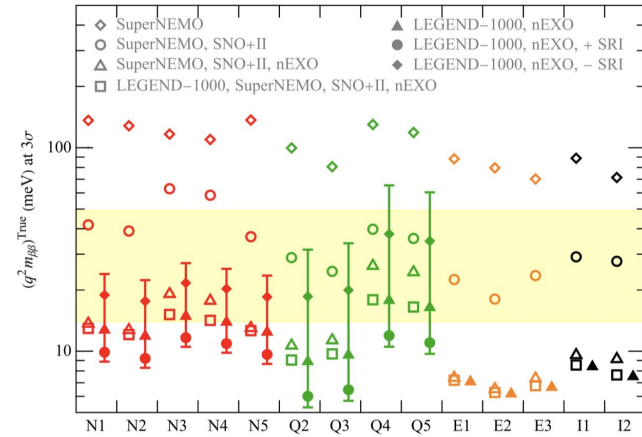
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Experiment	Isotope	ε [mol·yr]	b [events/(mol·y)]	PSF [yr ⁻¹ eV ⁻²]
LEGEND-1000	⁷⁶ Ge	8736	$4.9 \cdot 10^{-6}$	$2.36 \cdot 10^{-26}$
SuperNEMO	⁸² Se	185	$5.4 \cdot 10^{-3}$	$10.19 \cdot 10^{-26}$
CUPID	¹⁰⁰ Mo	1717	$2.3 \cdot 10^{-4}$	$15.91 \cdot 10^{-26}$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

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

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

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



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

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

$$\Delta\chi_{ij}^2(m_{\beta\beta}, M_{\alpha j}; m_{\beta\beta}^{\text{True}}, M_{\alpha i}^{\text{True}}) = 2 \sum_{\alpha} \left(N_{\alpha j} - N_{\alpha i}^{\text{True}} + N_{\alpha i}^{\text{True}} \ln \frac{N_{\alpha i}^{\text{True}}}{N_{\alpha j}} \right)$$

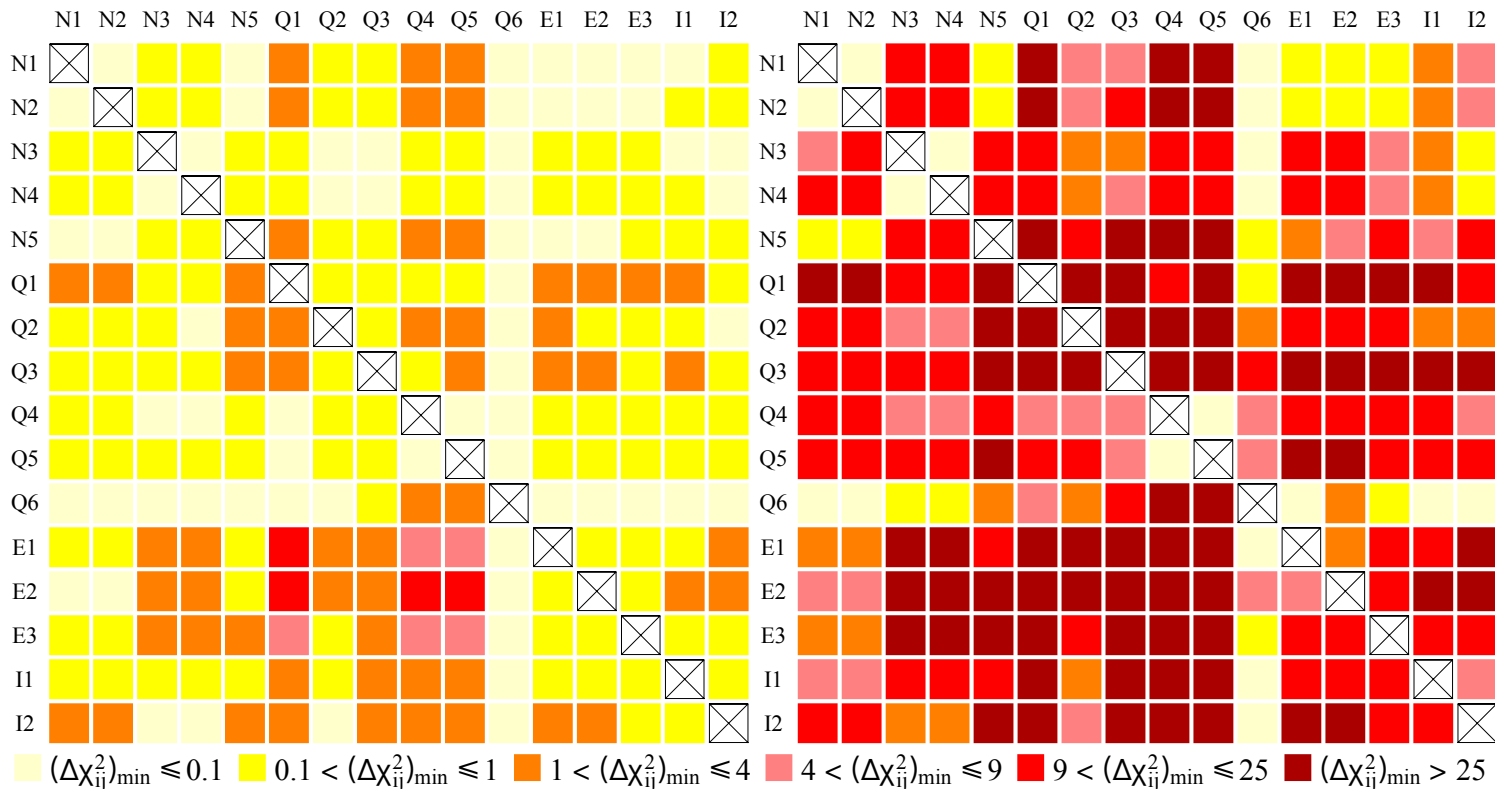
Discrimination without short-range NME

$$(\Delta\chi_{ij}^2)_{\min} = \min_{m_{\beta\beta}} \Delta\chi_{ij}^2(m_{\beta\beta}, M_{\alpha j}; (q^2 m_{\beta\beta})^{\text{True}}, M_{\alpha i}^{\text{True}})$$

Indices i (true model) and j (fitted model) run over the vertical and horizontal axes, respectively

$(q^2 m_{\beta\beta})^{\text{True}} = 10 \text{ meV}$

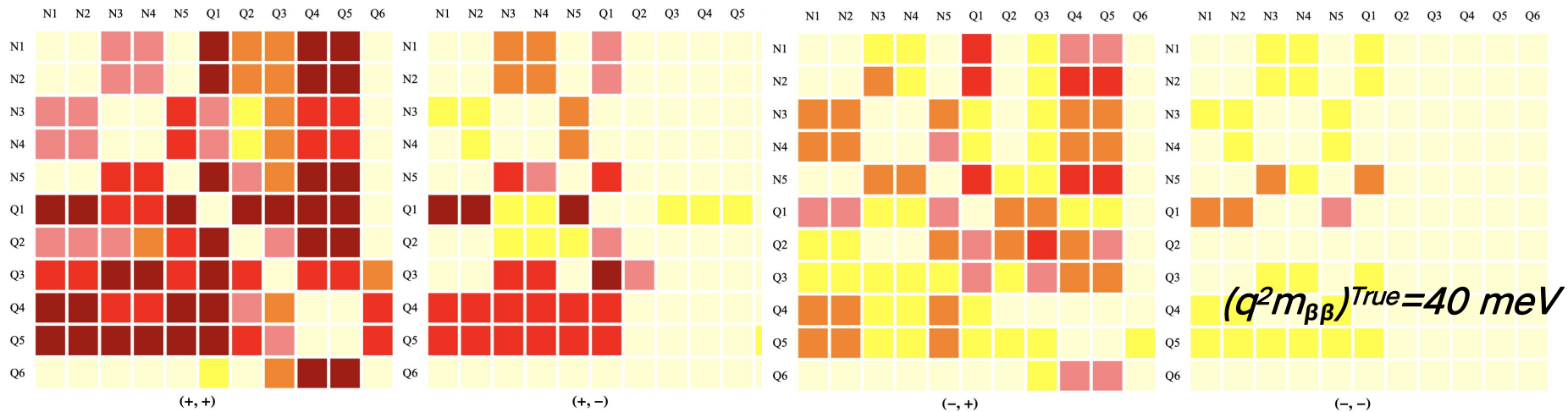
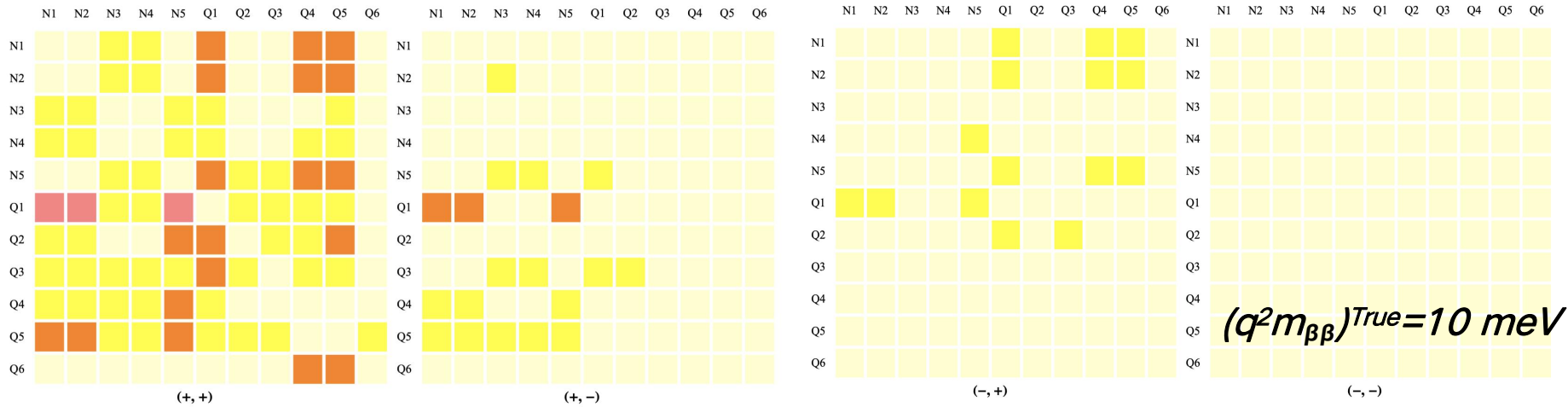
$(q^2 m_{\beta\beta})^{\text{True}} = 40 \text{ meV}$



Discrimination with short-range NME, T=10 yr

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$(\Delta\chi_{ij}^2)_{\min} \leq 0.1$
 $0.1 < (\Delta\chi_{ij}^2)_{\min} \leq 1$
 $1 < (\Delta\chi_{ij}^2)_{\min} \leq 4$
 $4 < (\Delta\chi_{ij}^2)_{\min} \leq 9$
 $9 < (\Delta\chi_{ij}^2)_{\min} \leq 25$
 $(\Delta\chi_{ij}^2)_{\min} > 25$



Formulas (minimal type-I seesaw)

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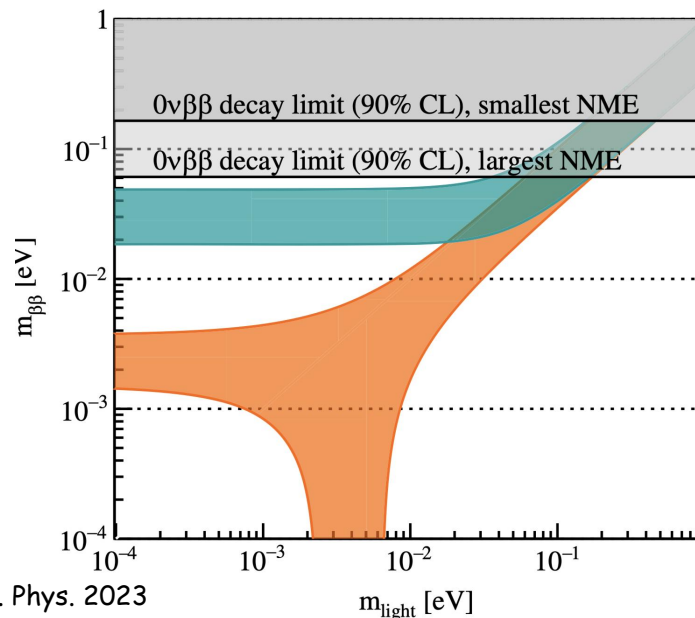
$$\mathcal{L}_{\text{mass}} = -\frac{1}{2} \overline{(\nu_L, N_R^c)} \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix} + \text{h.c.}$$



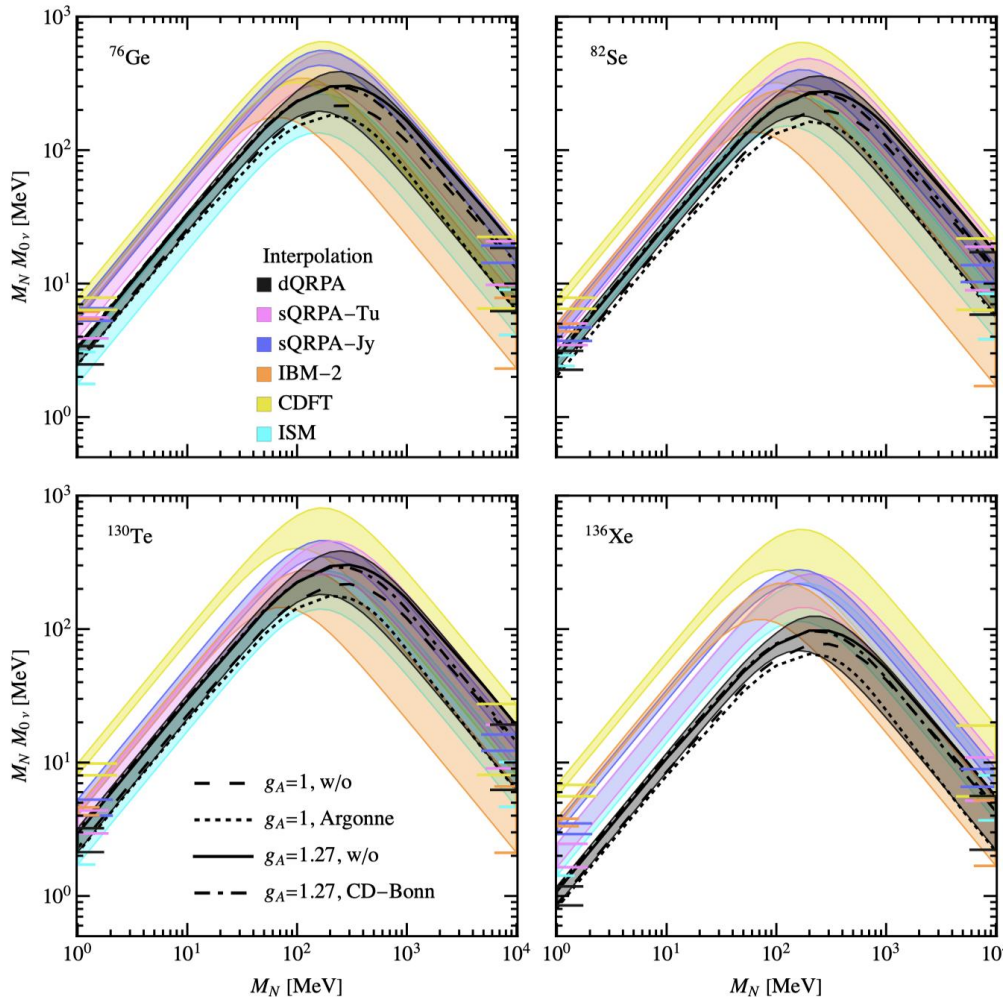
$$1/T_{1/2}^{0\nu} = G |M_{0\nu}(0) \cdot m_{\text{eff}}|^2$$

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

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



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



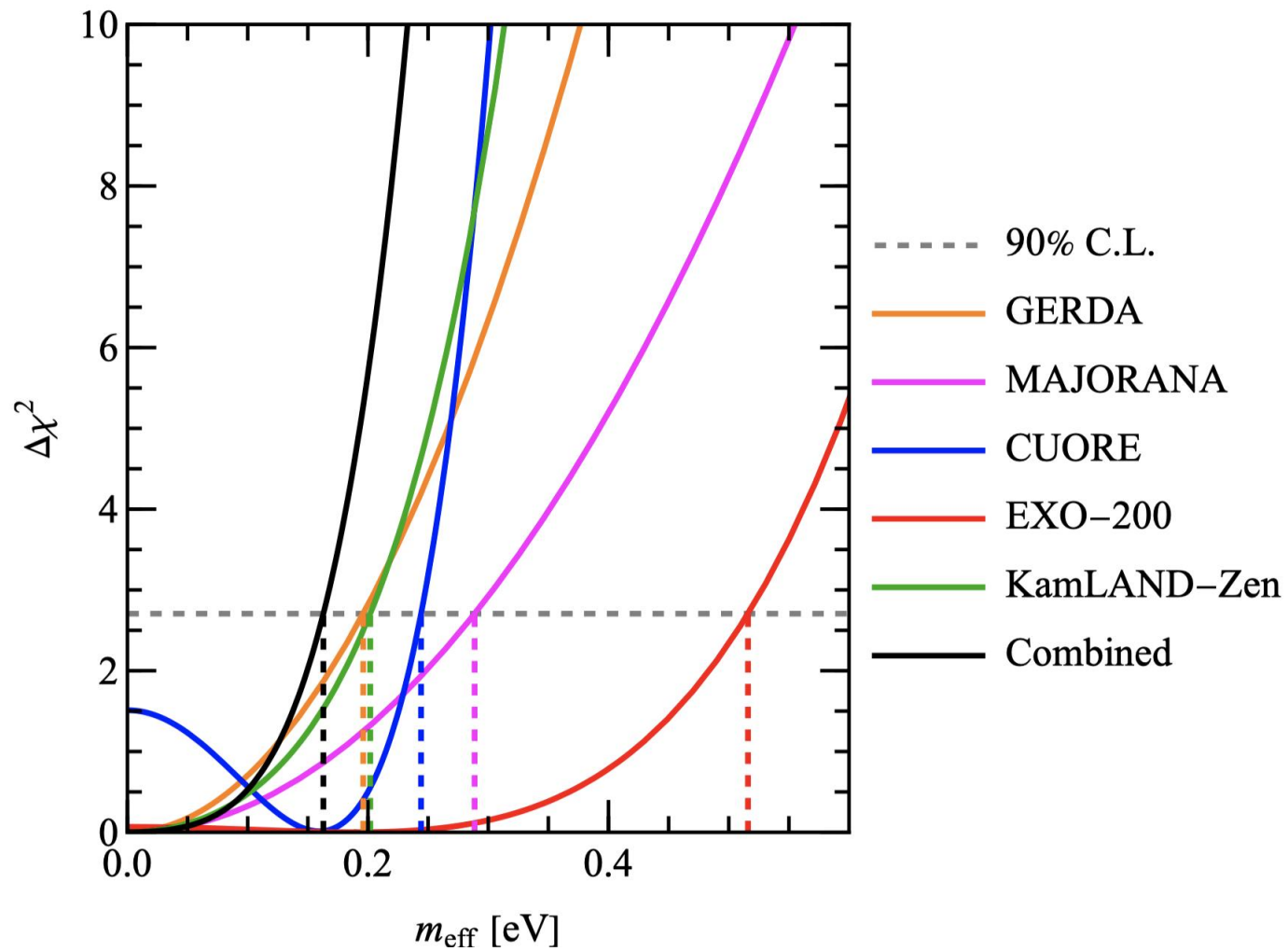
- **dQRPA:** Numerical calculation
- **Others:** interpolation with two extreme values

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

- **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}

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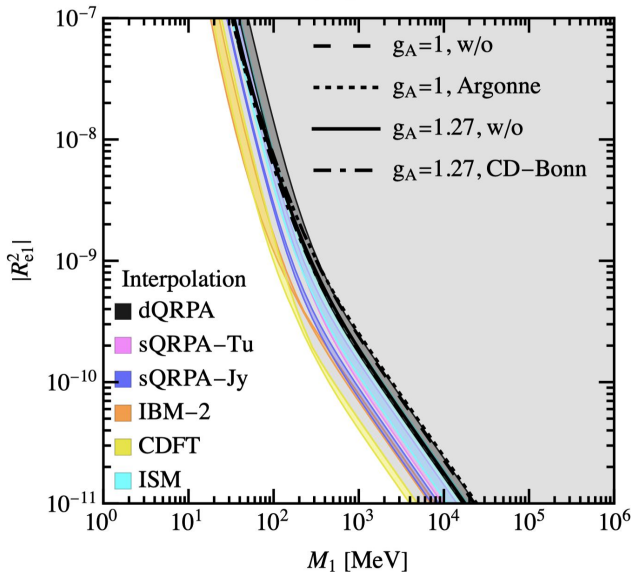


$g_A=1$, Argonne src

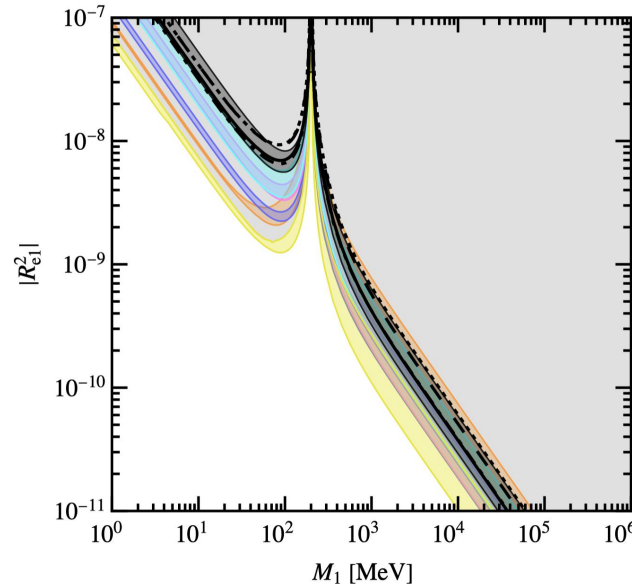
Current limits (M_1 & $|R_{e1}|^2$)

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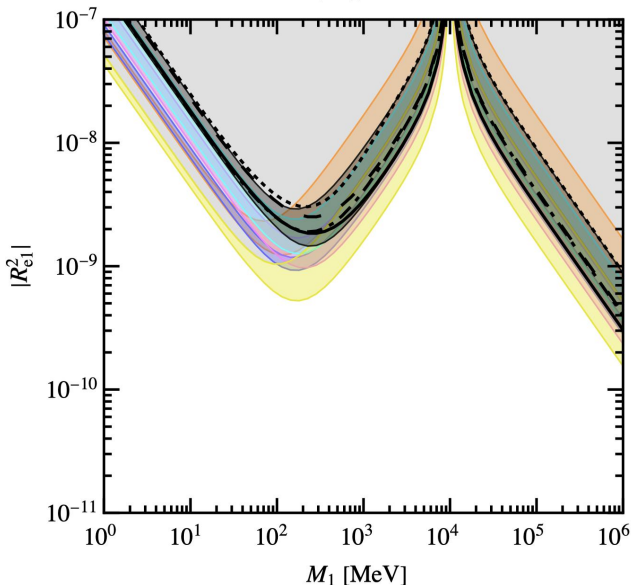
NMO, $M_2 = 10$ MeV



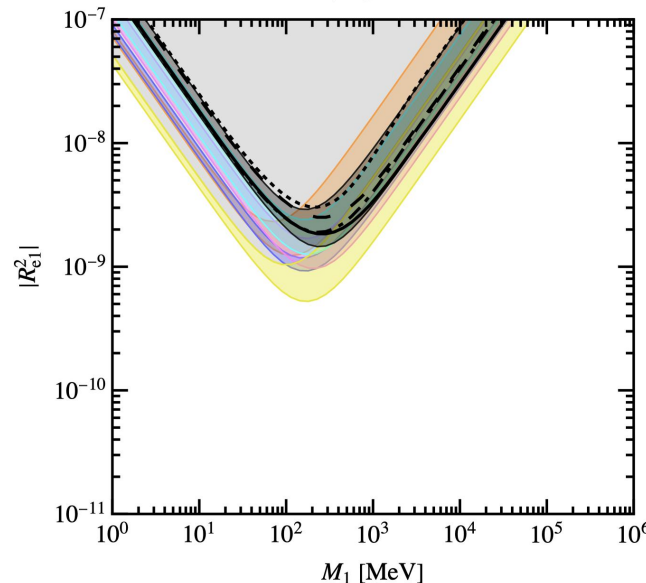
NMO, $M_2 = 200$ MeV



NMO, $M_2 = 10$ GeV



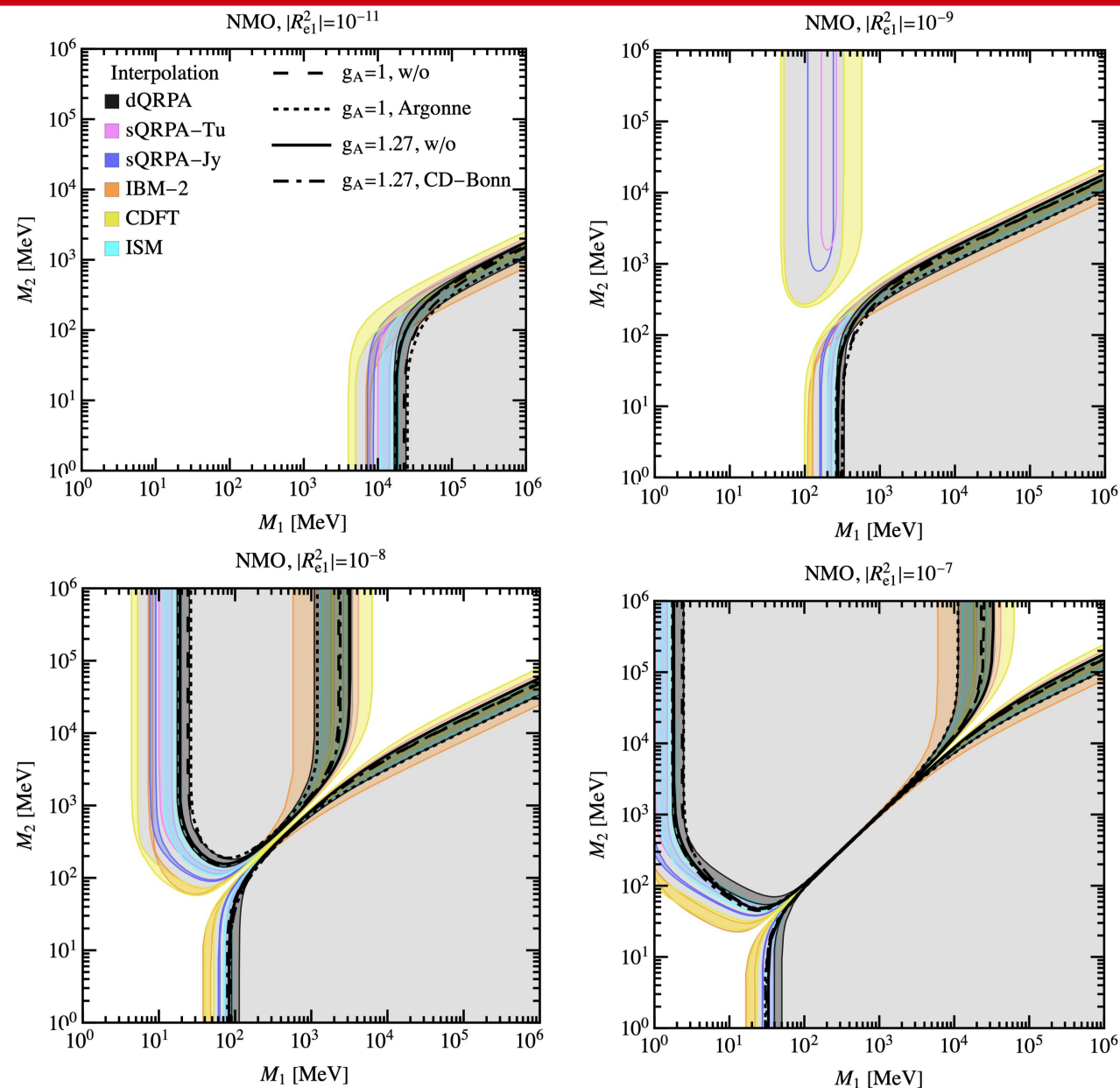
NMO, $M_2 = 10$ TeV



- 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 **$0\nu\beta\beta$ -decay** and **oscillation data** are used
- The **IMO** case is similar
- The peak shape

Current limits (M_1 & M_2)

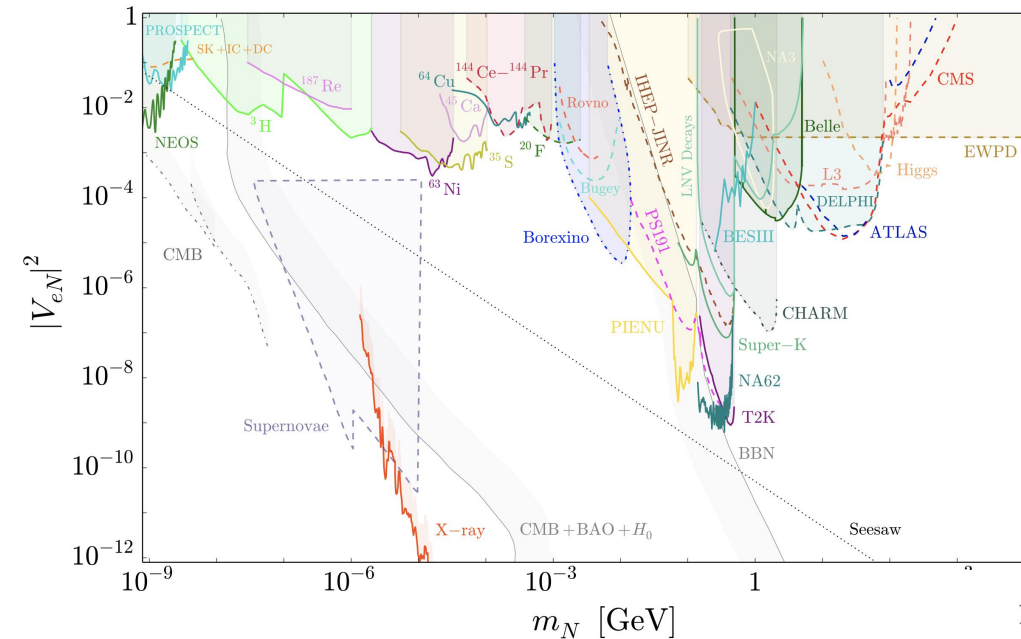
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- The IMO case is similar
- The NME hierarchy changes with neutrino mass

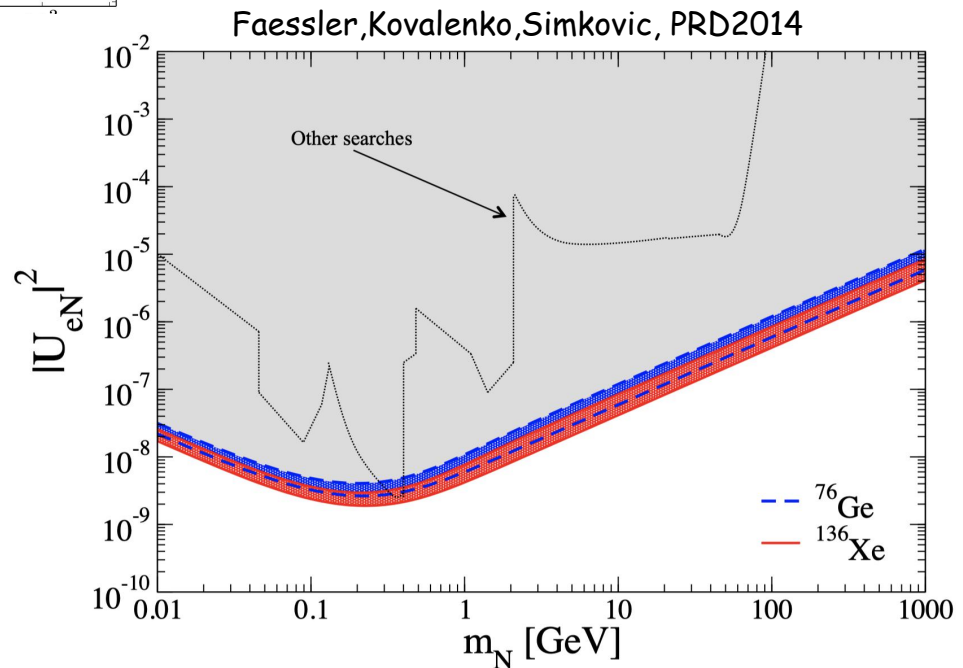
Constraints from other probes

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Bolton, Deppisch, Bhupap Dev, JHEP 2020

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



$$\Delta\chi_{ij}^2(m_{\text{eff}}, (M_{0\nu})_{\alpha j}; m_{\text{eff}}^{\text{True}}, (M_{0\nu})_{\alpha i}^{\text{True}}) = 2 \sum_{\alpha} (N_{\alpha j} - N_{\alpha i}^{\text{True}} + N_{\alpha i}^{\text{True}} \ln \frac{N_{\alpha i}^{\text{True}}}{N_{\alpha j}})$$

Assumed number events

$$N_{\alpha i}^{\text{True}} = B_{\alpha i} + S_{\alpha i}(m_{\text{eff}}^{\text{True}}, (M_{0\nu})_{\alpha i}^{\text{True}})$$

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

Assuming no positive $0\nu\beta\beta$ signal is observed,
Leading to sensitivities independent of true NME model

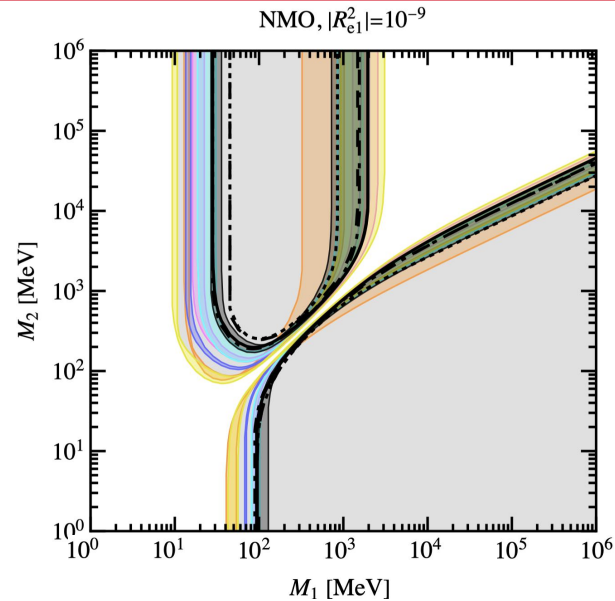
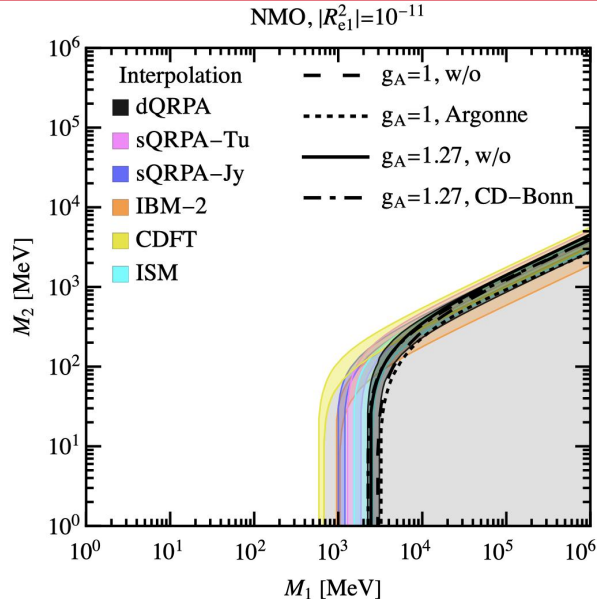
$$S_{\alpha i}(m_{\text{eff}}, M_{\alpha i}) = \ln 2 \cdot N_A \cdot \varepsilon_{\alpha} \cdot (T_{1/2}^{0\nu})_{\alpha i}^{-1} \cdot T / (1 \text{ yr})$$

$$B_{\alpha} = b_{\alpha} \cdot \varepsilon_{\alpha} \cdot T / (1 \text{ yr}) \quad \mathbf{T=10 \text{ yr}}$$

Experiment	Isotope	ε [mol· yr]	b [events/(mol· yr)]
LEGEND-1000	^{76}Ge	8736	$4.9 \cdot 10^{-6}$
SuperNEMO	^{82}Se	185	$5.4 \cdot 10^{-3}$
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nEXO	^{136}Xe	13700	$4.0 \cdot 10^{-5}$

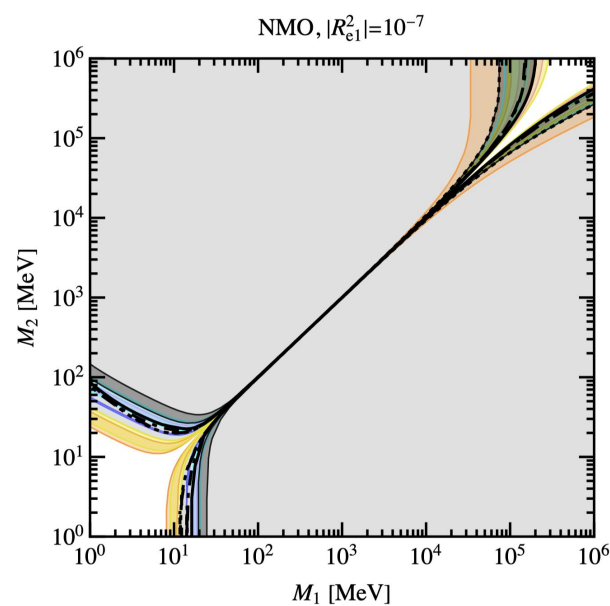
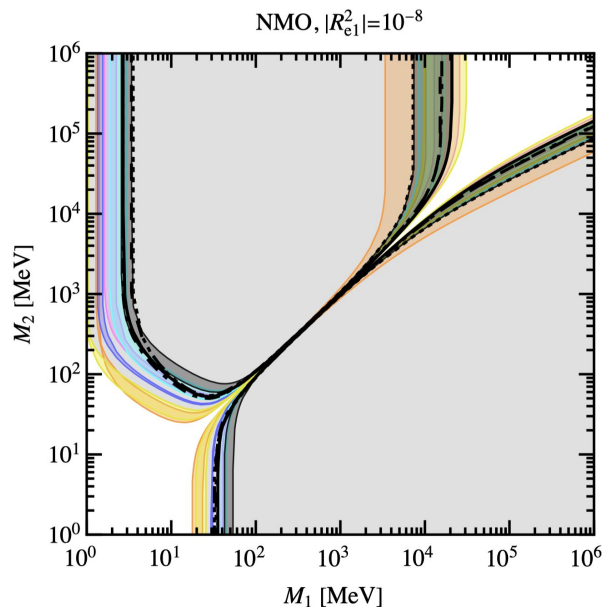
Future sensitivities (M_1 & M_2)

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The NMO case

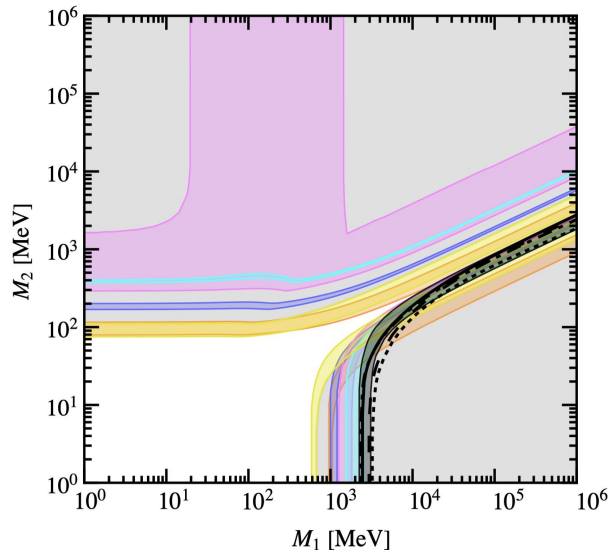
More parameter space can be tested compared the current experiments



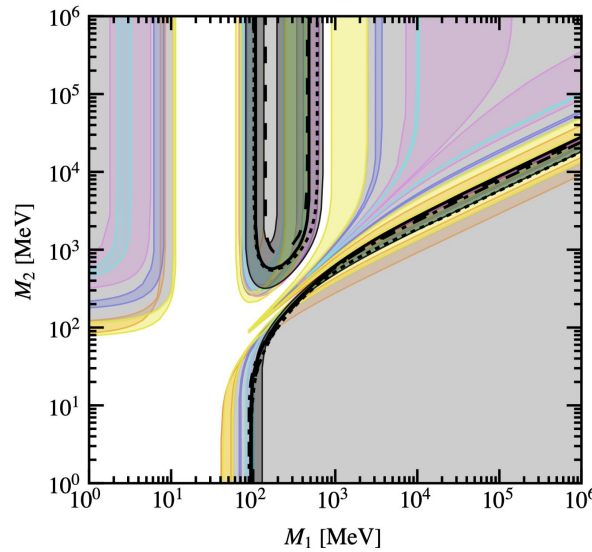
Future sensitivities (M_1 & M_2)

22

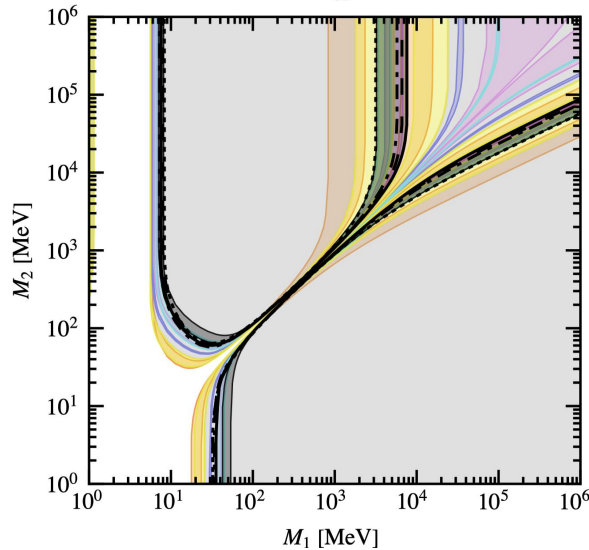
IMO, $|R_{e1}^2|=10^{-11}$



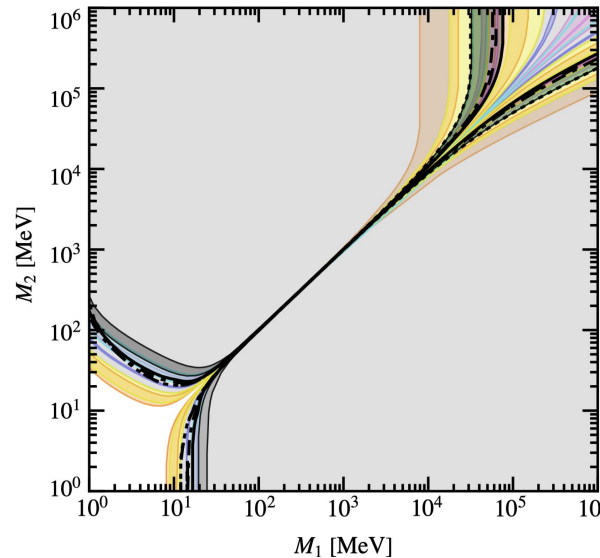
IMO, $|R_{e1}^2|=10^{-9}$



IMO, $|R_{e1}^2|=10^{-8}$

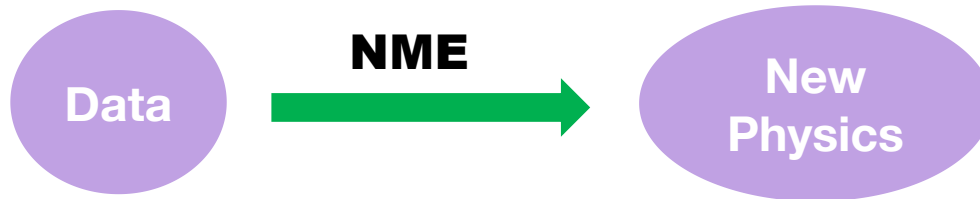


IMO, $|R_{e1}^2|=10^{-7}$



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

- **NME uncertainties due to the SRI may lead to the bound on $q^2 m_{\beta\beta}$ varying by a factor of order 5**
- **Promising discrimination of different NMEs if $(q^2 m_{\beta\beta})_{\text{True}} > 40 \text{ meV}$, positive SRI and 10 year exposure**
- 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



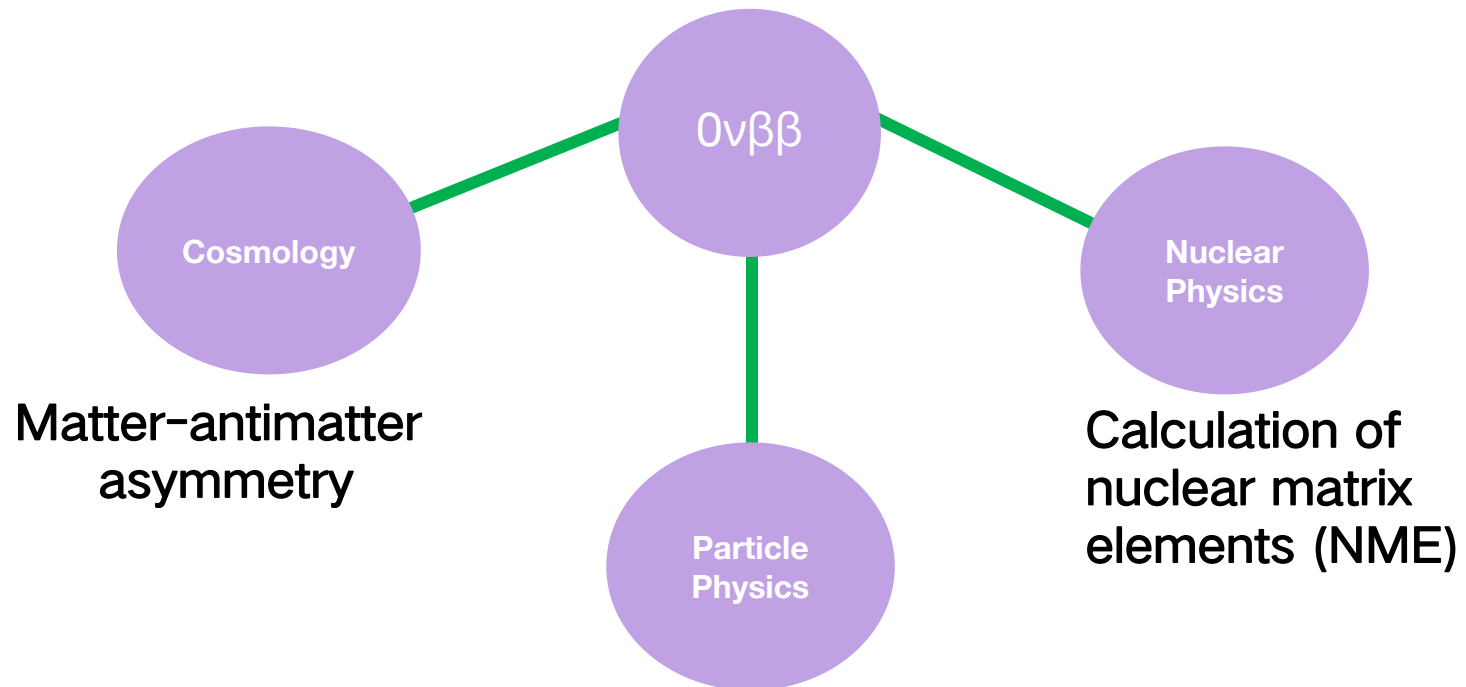
- **Better understanding the short-range NME in $0\nu\beta\beta$**
- **Better understanding the nuclear structure**
- **The quenching problem**
- **NME statistical uncertainties**
- **LEC from lattice calculations**
- **Sensitivities to different particle physics mechanisms and how to distinguish them**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



**Majorana neutrino,
to be or not to be
This is a question!**

Thank you!

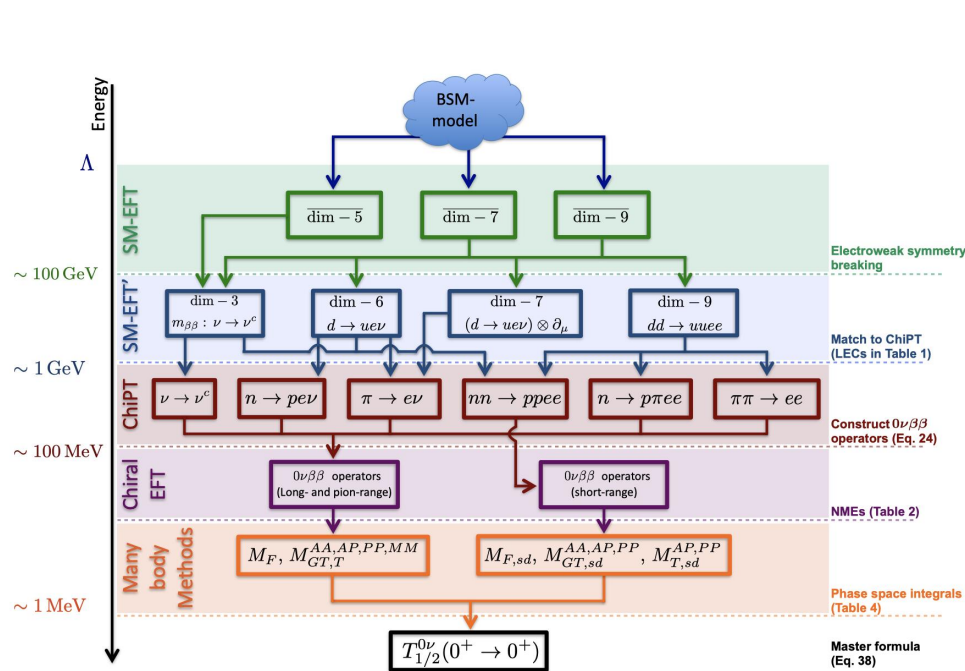
Backups



The production mechanism BSM

Experiments:

- Find compromises between nature abundance, Q-value, enrichment and detector techniques
- Key parameter: background ratio, energy resolution, exposure



Naive Dimensional Analysis(NDA) problem

- D. B. Kaplan, M. J. Savage, and M. B. Wise, *Nucl. Phys.* **B478**, 629 (1996).
- S. R. Beane, P. F. Bedaque, M. J. Savage, and U. van Kolck, *Nucl. Phys.* **A700**, 377 (2002).
- A. Nogga, R. G. E. Timmermans, and U. van Kolck, *Phys. Rev. C* **72**, 054006 (2005).
- B. Long and C.-J. Yang, *Phys. Rev. C* **86**, 024001 (2012).
- M. Pavón Valderrama and D. R. Phillips, *Phys. Rev. Lett.* **114**, 082502 (2015).

and $F_\pi = 92.2$ MeV is the pion decay constant. However, it is known that Weinberg's power counting leads to inconsistent results in nucleon-nucleon scattering [34–37] and nuclear processes mediated by external currents [38], due to a conflict between naive dimensional analysis and nonperturbative renormalization. We therefore investigate the scaling of g_ν^{NN} by studying the amplitude $\mathcal{A}(nn \rightarrow ppee) \equiv \mathcal{A}_{\Delta L=2}$ with strong interactions H_{strong} included nonperturbatively.

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

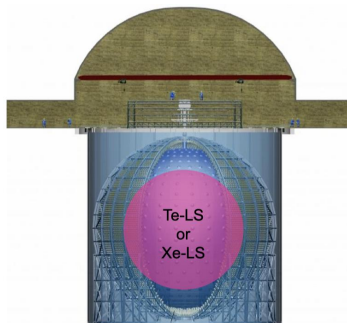
Experimental techniques

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CUPID-Mo



JUNO



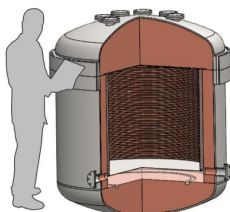
CANDLE CaF scintillating crystal



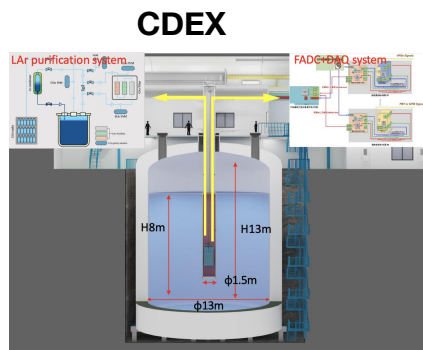
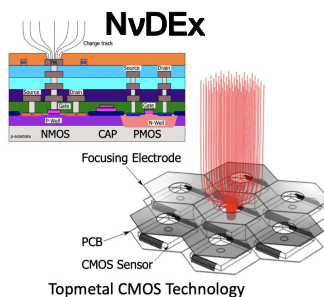
EXO, KamLAND-Zen Liquid Xe



PandaX-4T LXe TPC



PandaX-III GXe TPC

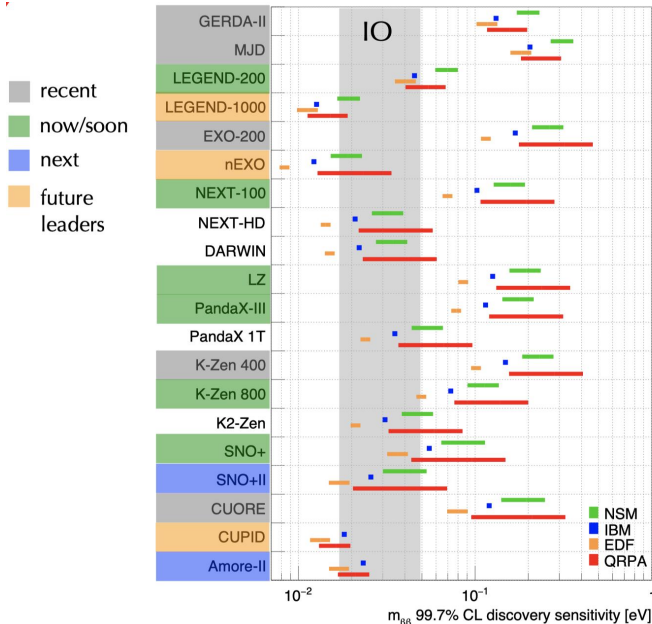


CDEX

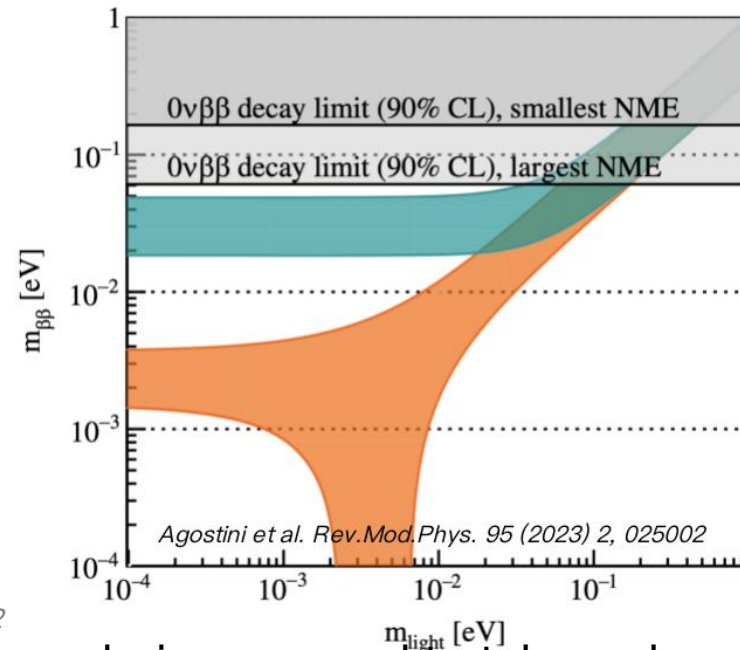
GERDA, MAJORANA Ge crystal



etc.



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



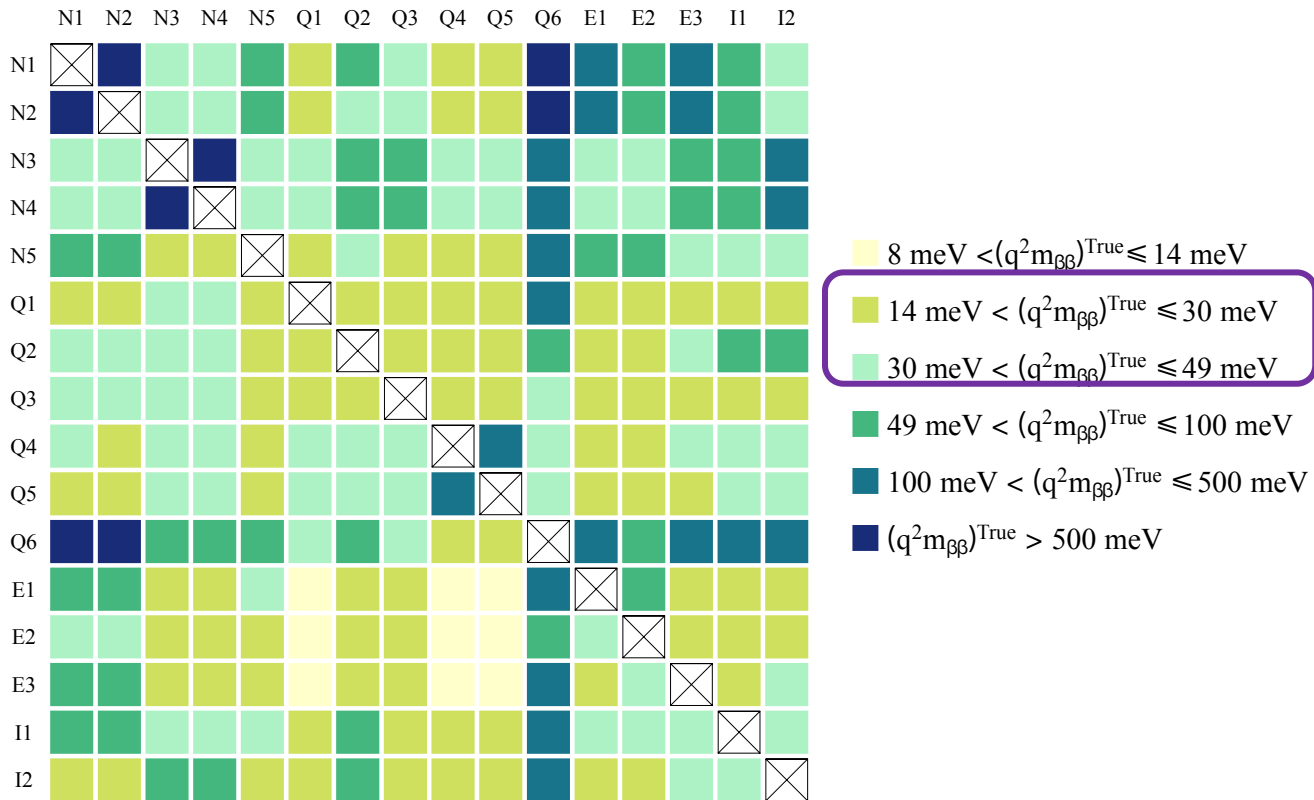
New techniques and more exposure are being pursued to take us beyond the IO. Discovery could come at any time!

Motivations: Schwetz, Popma, Zhu, JHEP 06 (2023) 104

- Interpreting the constraints/sensitivities on $m_{\beta\beta}$ of current/future $0\nu\beta\beta$ experiments
- Checking the possibilities of discriminating NME models in future $0\nu\beta\beta$ experiments

$m_{\beta\beta}^{\text{True}}$ corresponding to discrimination at 3σ

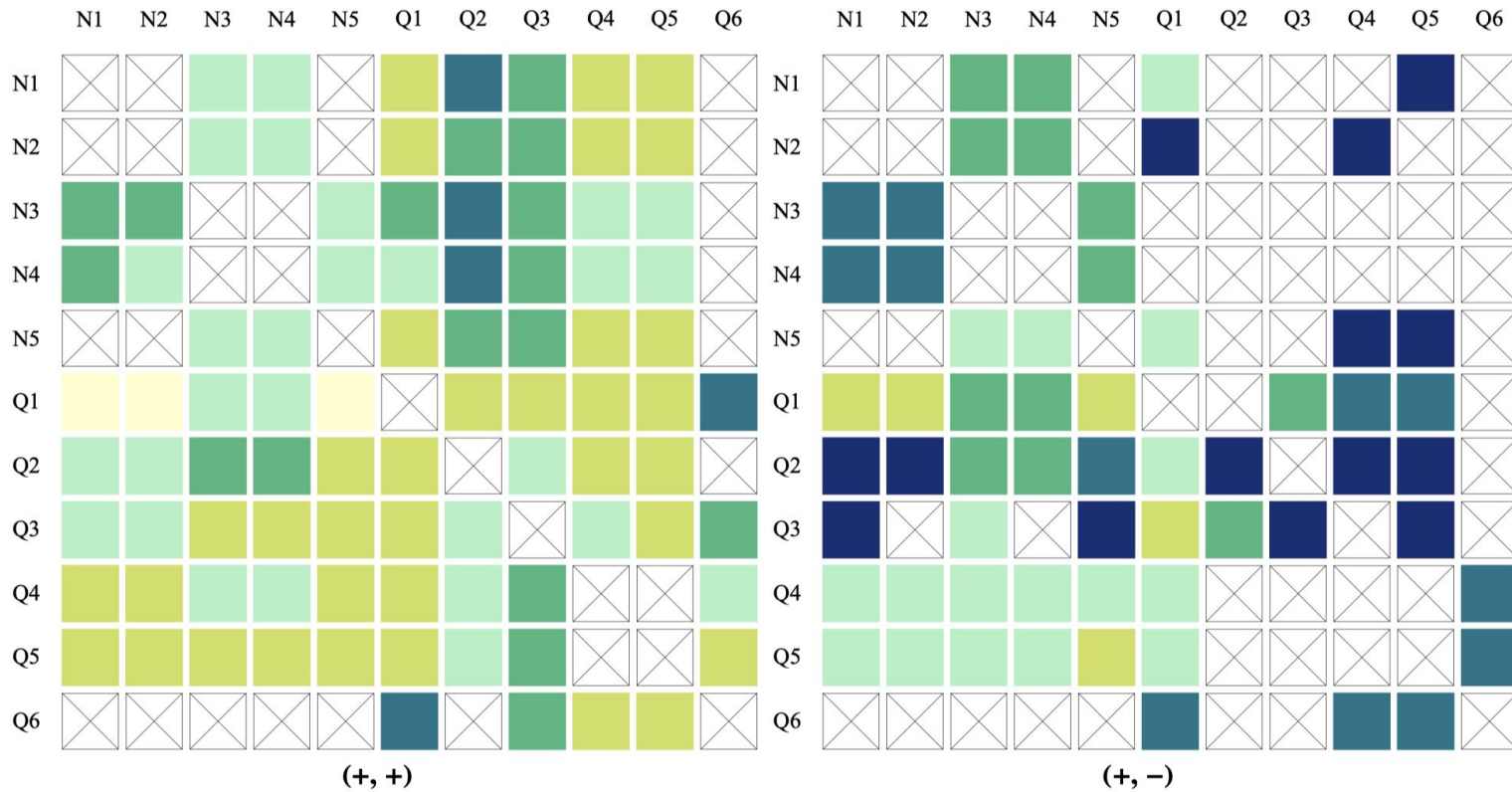
31



(without short- range NME)

$m_{\beta\beta}^{\text{True}}$ corresponding to discrimination at 3σ

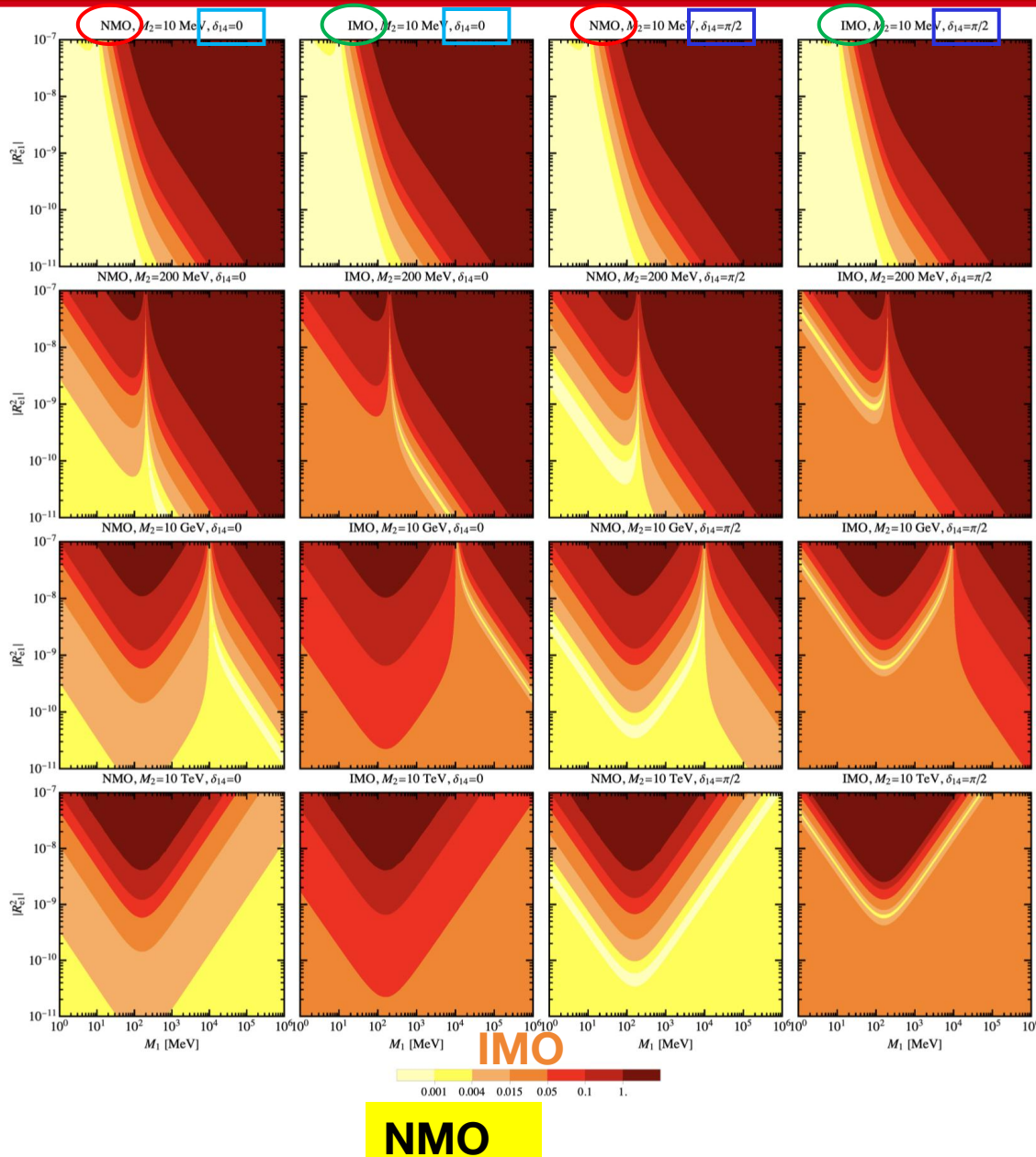
32



(with short- range NME)

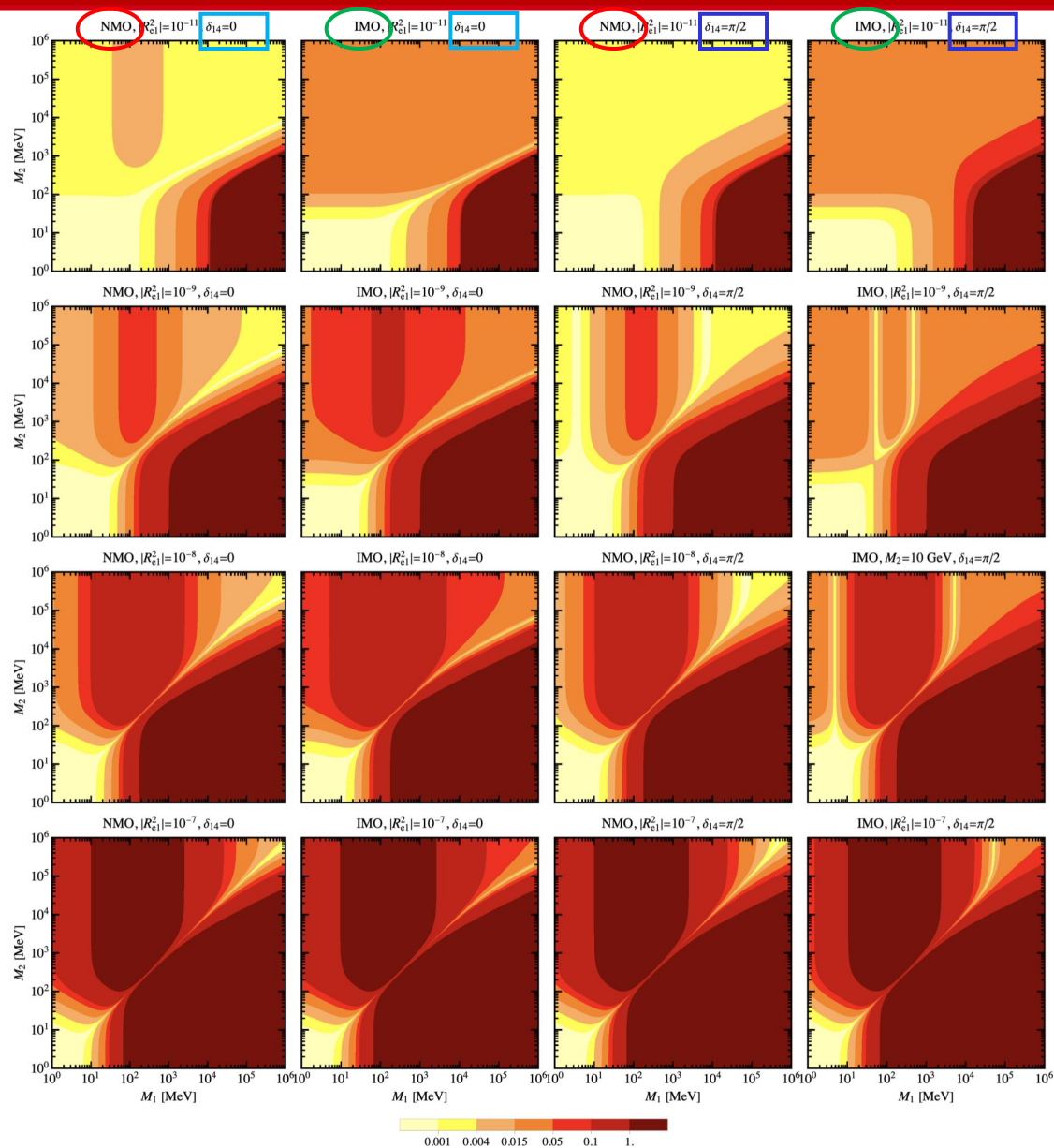
Parameter space of m_{eff}

33



- $g_A=1$, Argonne src
- Some parameter space can be very easily/hardly excluded by current/future $0\nu\beta\beta$ experiments
- The NMO/IMO can be very different and δ_{14} matters

Parameter space of m_{eff}



NME of light neutrinos

	g_A	src	dQRPA [74]	sQRPA-Tu [75]	sQRPA-Jy [77]	IBM-2 [87]	CDFT [80]	ISM [81]
^{76}Ge	1.27	w/o	3.27	-	-	-	7.61	-
		Argonne	3.12	5.157	-	5.98	7.48	2.89
		CD-Bonn	3.40	5.571	6.54	6.16	7.84	3.07
		Miller-Spencer	-	-	-	5.42	6.36	-
	1.00	w/o	2.64	-	-	-	-	-
		Argonne	2.48	3.886	-	-	-	1.77
^{82}Se		CD-Bonn	2.72	4.221	5.26	-	-	1.88
	1.27	w/o	3.01	-	-	-	7.60	-
		Argonne	2.86	4.642	-	4.84	7.48	2.73
		CD-Bonn	3.13	5.018	4.69	4.99	7.83	2.90
		Miller-Spencer	-	-	-	4.37	6.48	-
	1.00	w/o	2.41	-	-	-	-	-
^{130}Te		Argonne	2.26	3.460	-	-	-	2.41
		CD-Bonn	2.49	3.746	3.73	-	-	2.56
	1.27	w/o	3.10	-	-	-	9.55	-
		Argonne	2.90	3.888	-	4.47	9.38	2.76
		CD-Bonn	3.22	4.373	5.27	4.61	9.82	2.96
		Miller-Spencer	-	-	-	4.03	8.03	-
^{136}Xe	1.00	w/o	2.29	-	-	-	-	-
		Argonne	2.13	2.945	-	-	-	1.72
		CD-Bonn	2.37	3.297	4.00	-	-	1.84
	1.27	w/o	1.12	-	-	-	6.62	-
		Argonne	1.11	2.177	-	3.67	6.51	2.28
		CD-Bonn	1.18	2.460	3.50	3.79	6.80	2.45
^{136}Xe		Miller-Spencer	-	-	-	3.33	5.58	-
	1.00	w/o	0.85	-	-	-	-	-
		Argonne	0.86	1.643	-	-	-	1.42
		CD-Bonn	0.89	1.847	2.91	-	-	1.53

- CDFT biggest
- ISM/dQRPA smallest
- different NME ratios between different isotopes

NME of heavy neutrinos

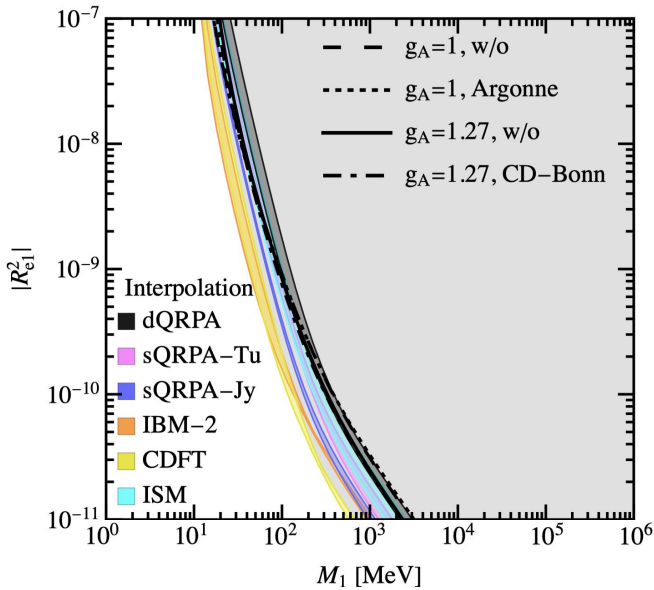
	g_A	src	dQRPA [74]	sQRPA-Tu [75]	sQRPA-Jy [77]	IBM-2 [87]	CDFT [80]	ISM [81]
^{76}Ge	1.27	w/o	385.4				466.8	
		Argonne	187.3	316		107	267	130
		CD-Bonn	293.7	433	401.3	163	378.1	188
		Miller-Spencer				48.1	135.7	
	1.00	w/o	275.9					
		Argonne	129.7	204				86
^{82}Se		CD-Bonn	207.2	287	298.3			122
	1.27	w/o	358.7				454	
		Argonne	175.9	287		84.4	261.4	121
		CD-Bonn	273.6	394	287.1	132	369	175
		Miller-Spencer				35.6	132.7	
	1.00	w/o	257.4					
^{130}Te		Argonne	122.1	186	-	-	-	80
		CD-Bonn	193.4	262	214.3	-	-	113
	1.27	w/o	401.1				573	
		Argonne	191.4	292		92	339.2	146
		CD-Bonn	303.5	400	338.3	138	472.8	210
		Miller-Spencer				44	168.5	
^{136}Xe	1.00	w/o	281.2					
		Argonne	130.2	189	-	-	-	97
		CD-Bonn	209.5	264	255.7	-	-	136
	1.27	w/o	117.1				394.5	
		Argonne	66.9	166		72.8	234.3	116
		CD-Bonn	90.5	228	186.3	109	326.2	167
^{136}Xe		Miller-Spencer	-	-	-	35.1	116.3	
	1.00	w/o	82.7					
		Argonne	46.3	108	-	-	-	77
		CD-Bonn	62.8	152	137.3	-	-	108

- CDFT biggest
- IBM-2 smallest
- different NME ratios between different isotopes

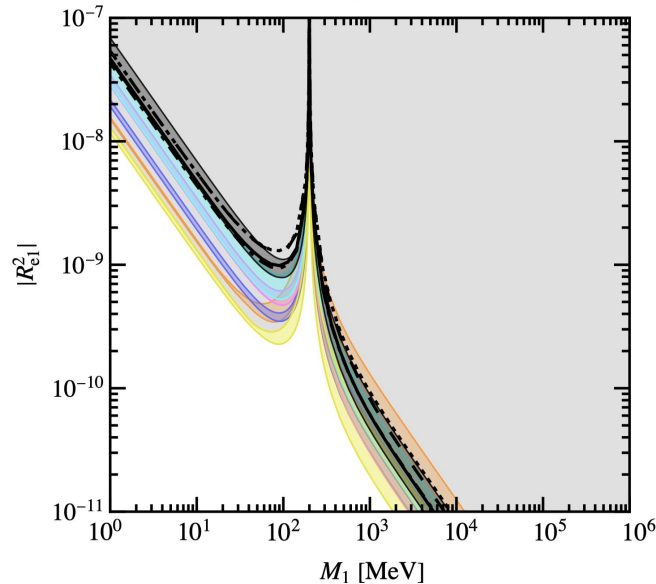
Future sensitivities (M_1 & $|R_{e1}|^2$)

37

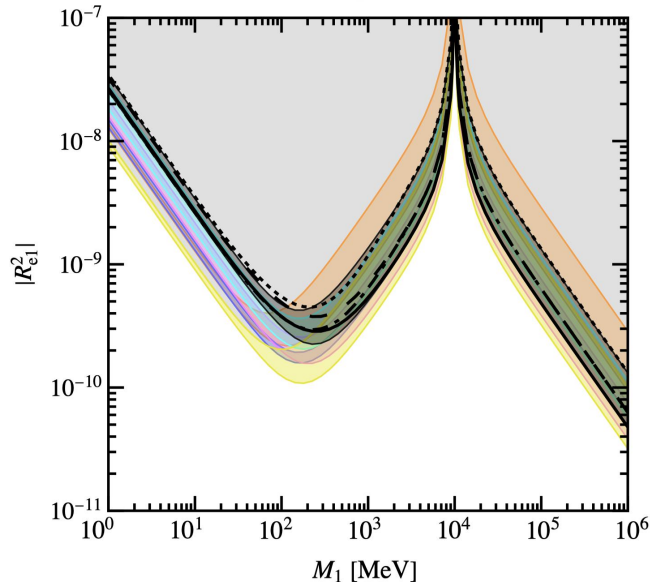
NMO, $M_2 = 10$ MeV



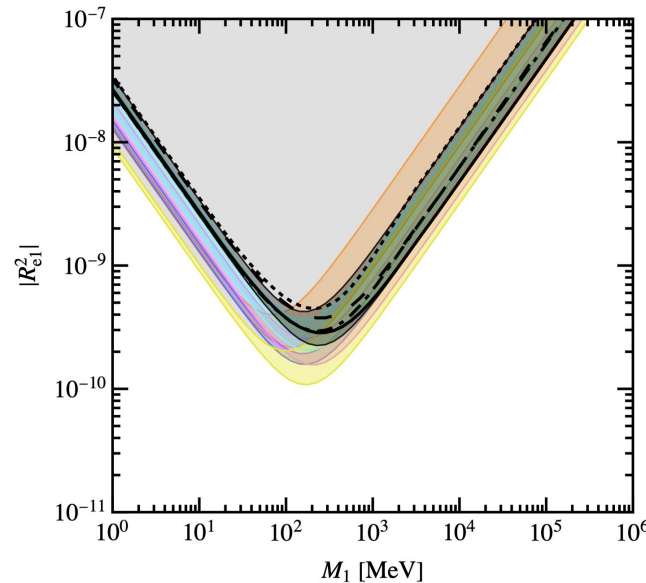
NMO, $M_2 = 200$ MeV



NMO, $M_2 = 10$ GeV



NMO, $M_2 = 10$ TeV

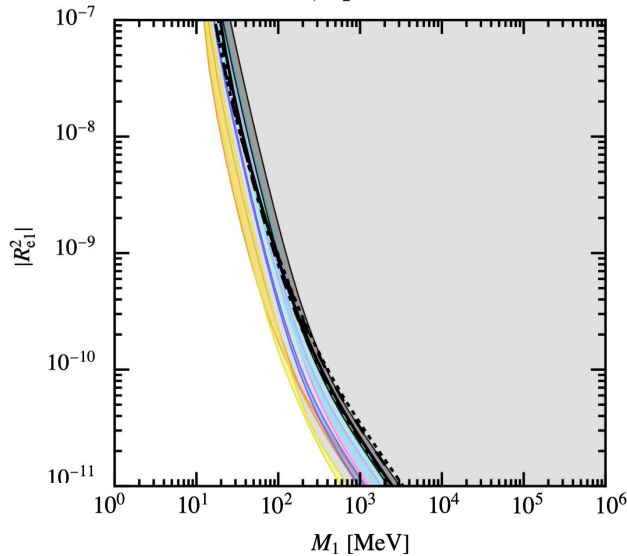


- The NMO case
- More parameter space can be tested compared the current experiments

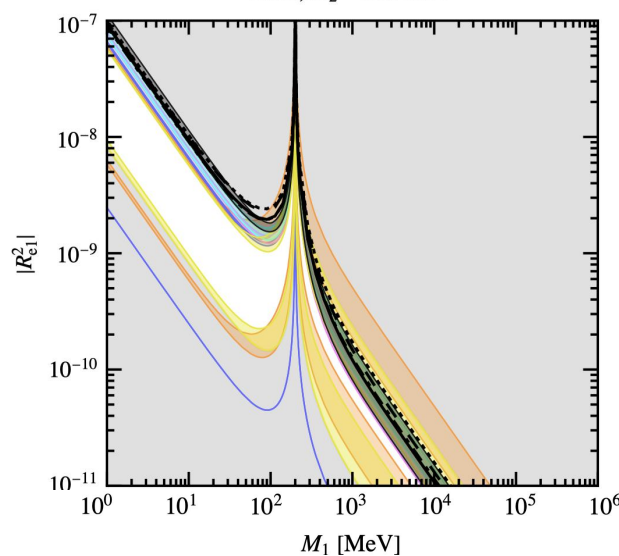
Future sensitivities (M_1 & $|R_{e1}|^2$)

38

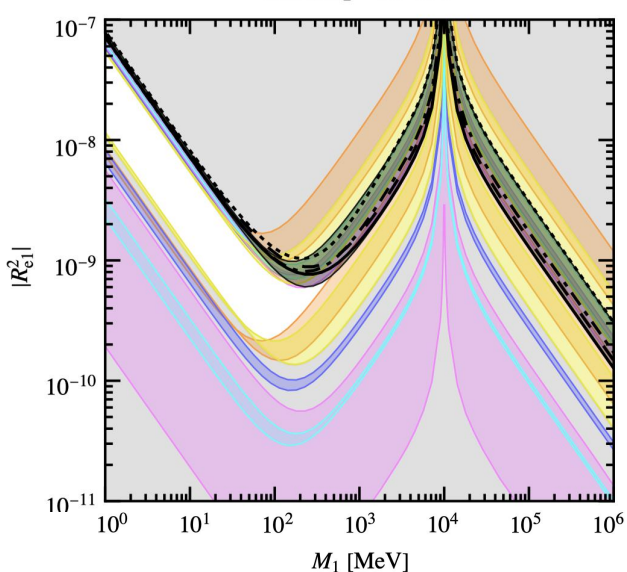
IMO, $M_2 = 10$ MeV



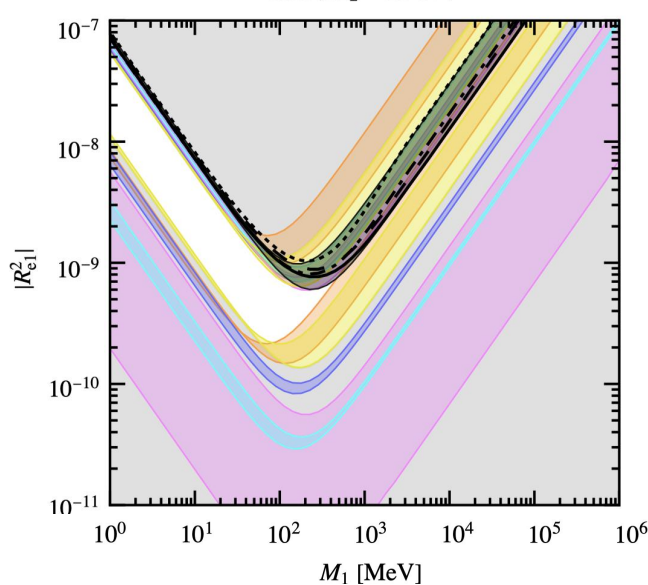
IMO, $M_2 = 200$ MeV



IMO, $M_2 = 10$ GeV



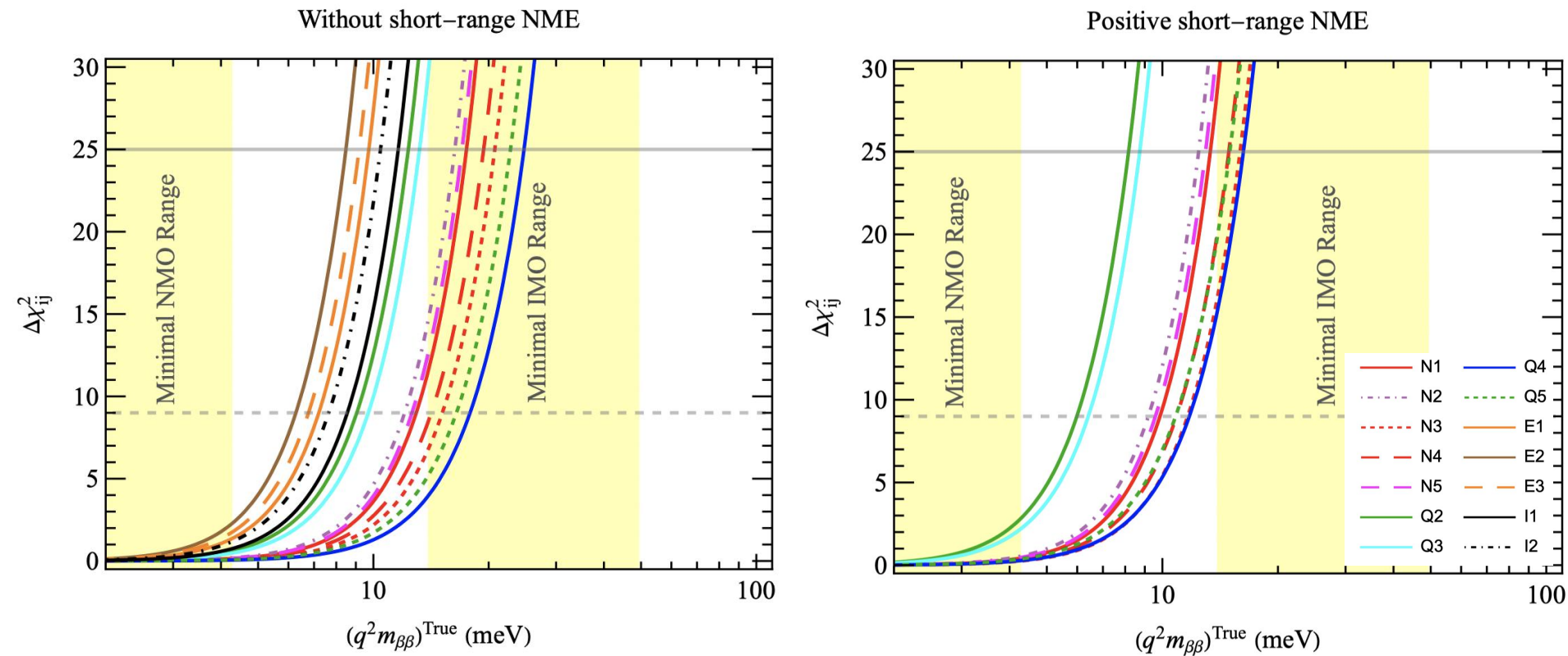
IMO, $M_2 = 10$ TeV



- The IMO case
- Much more parameter space are expected to exclude than NMO case due to zero positive $0\nu\beta\beta$ signal assumed
- By assuming **enough positive $0\nu\beta\beta$ signal**, possible to **discriminate NME calculations** and more parameter space can be **excluded in the NMO case**

The significance of observing one positive signal:

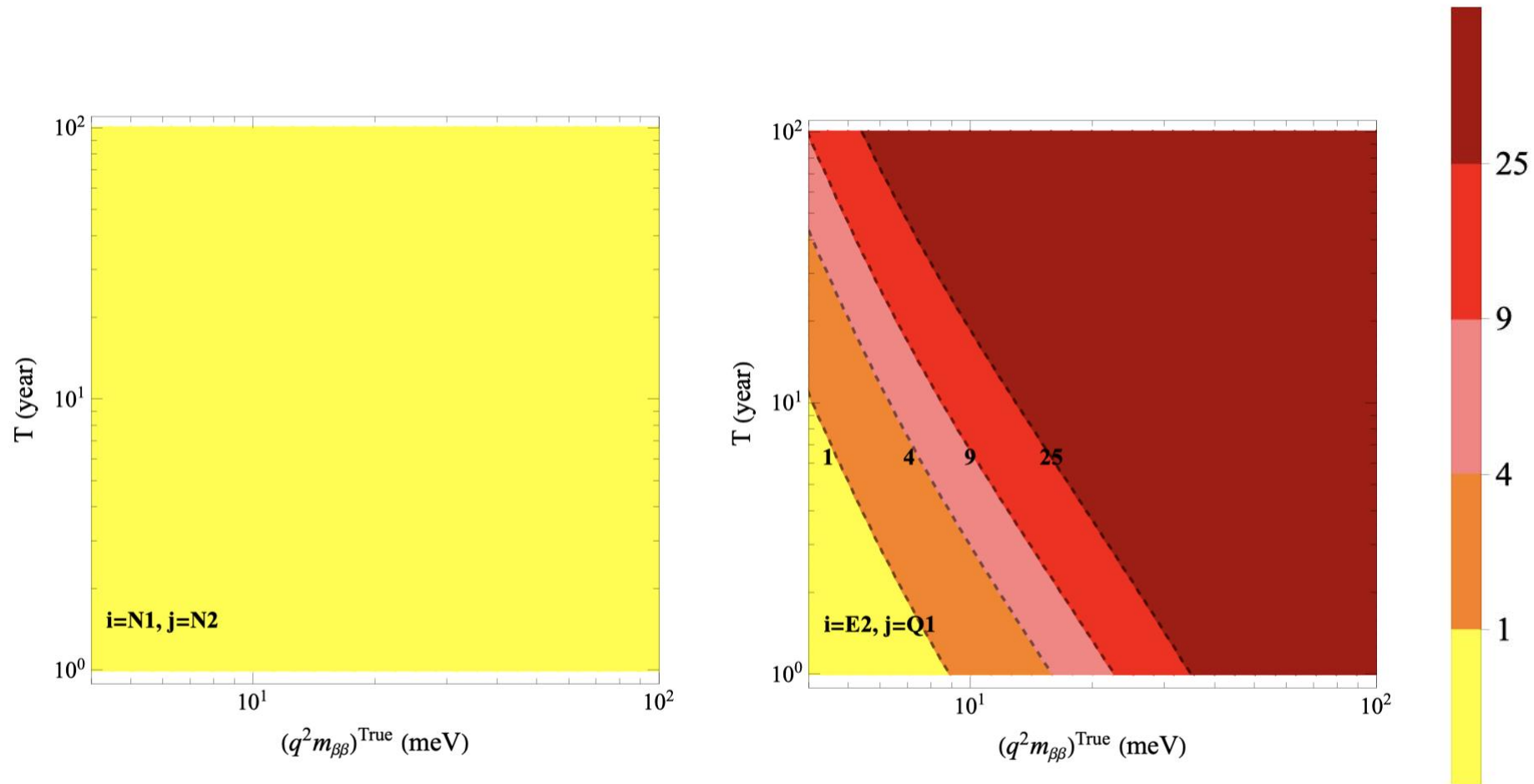
39



$$m_{\beta\beta}=0, T=10 \text{ yr}$$

Contours of $(\Delta\chi_{ij}^2)_{\min}$ as function of T and $(q^2m_{\beta\beta})^{\text{True}}$

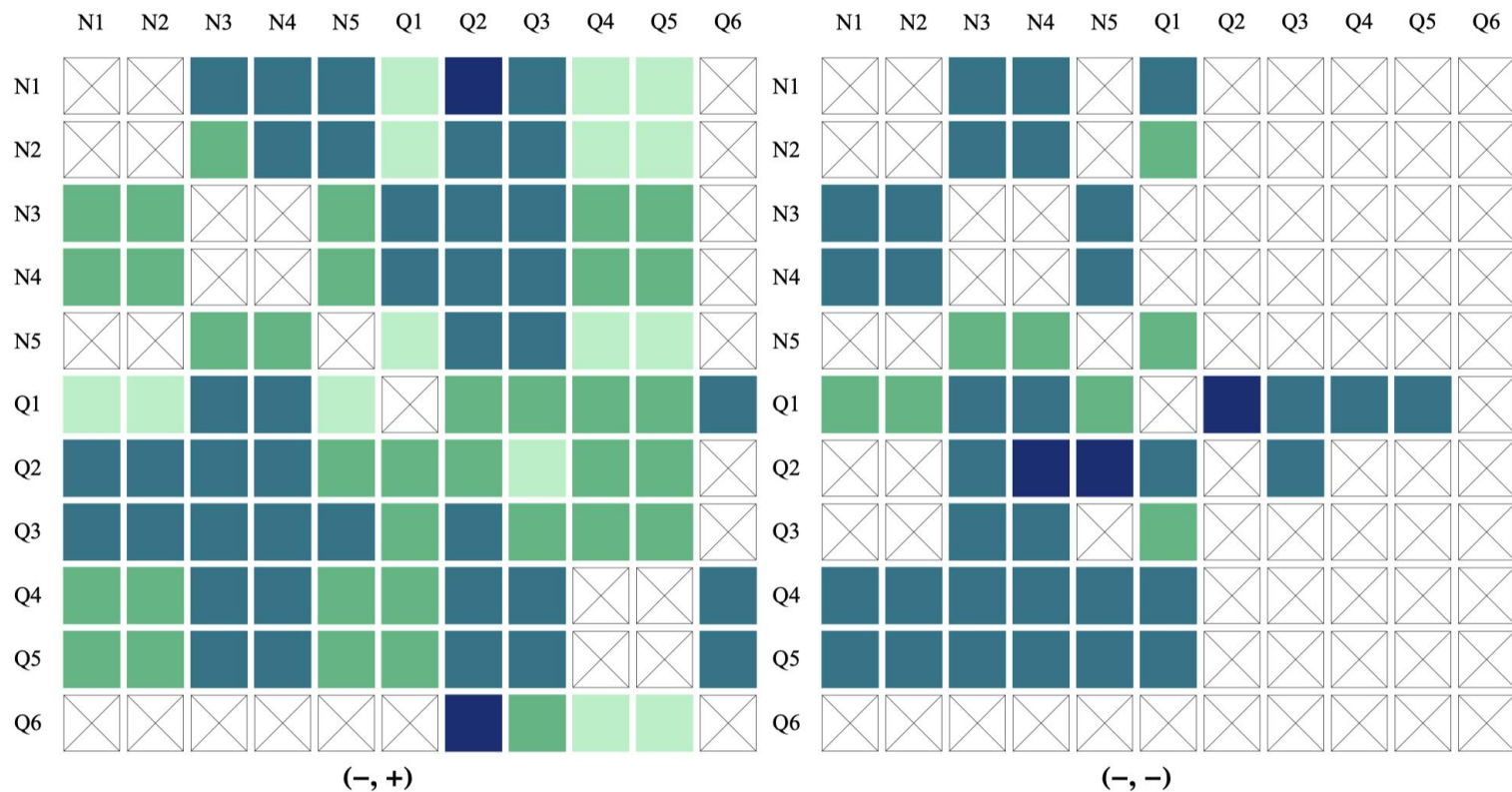
40



(without short- range NME)

$m_{\beta\beta}^{\text{True}}$ corresponding to discrimination at 3σ

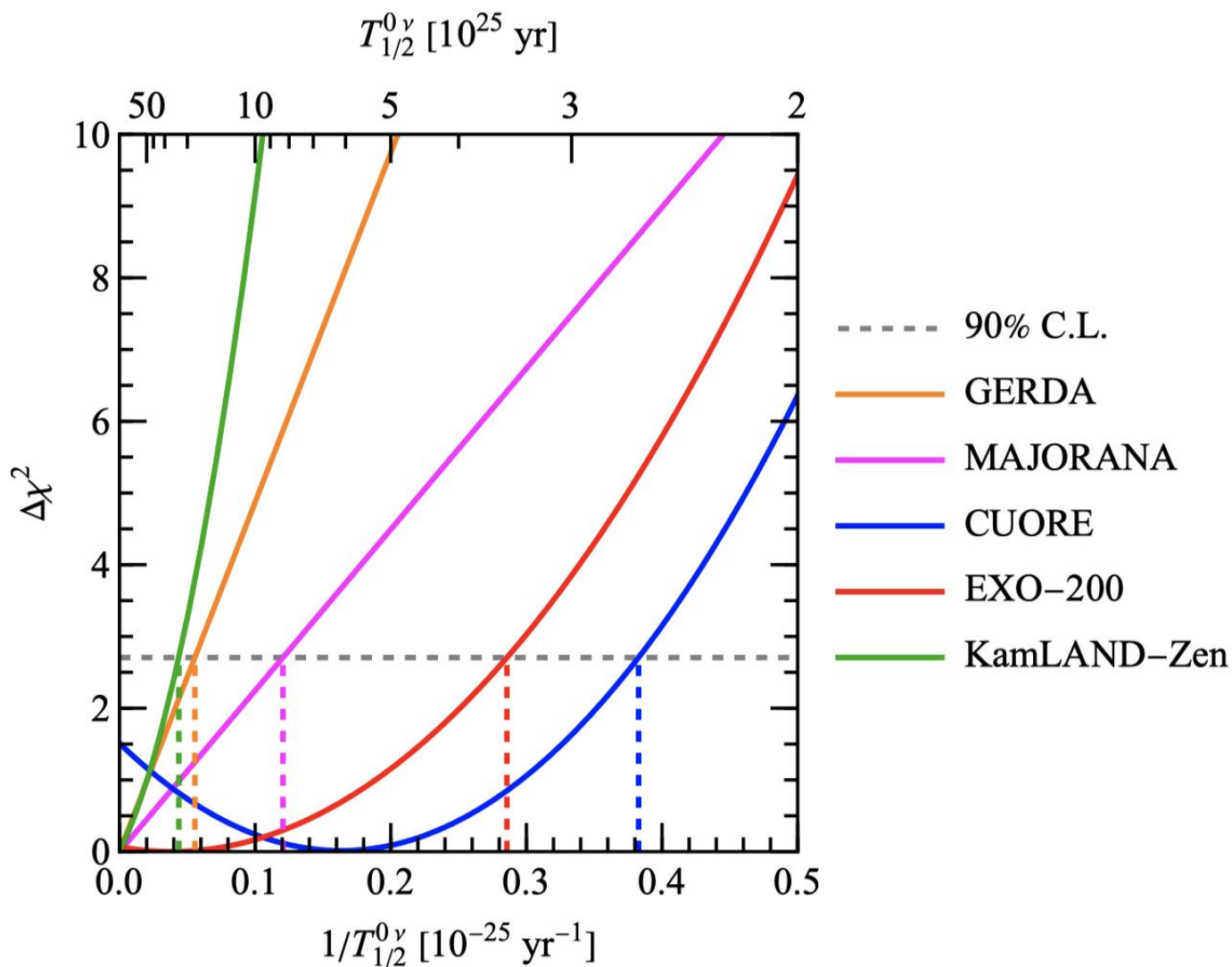
41



(with short- range NME)

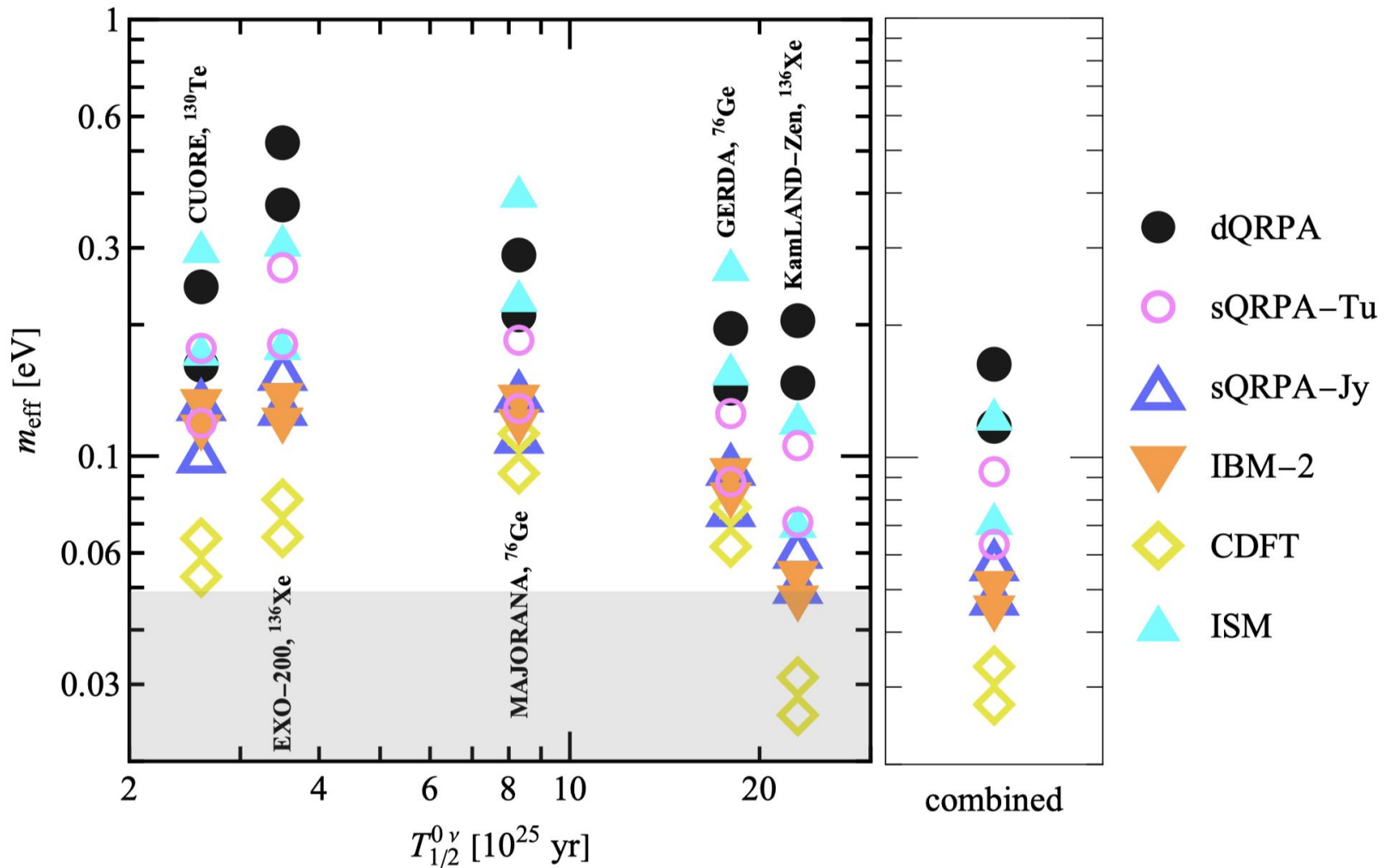
$\Delta\chi^2$ functions of inverse half-life

42



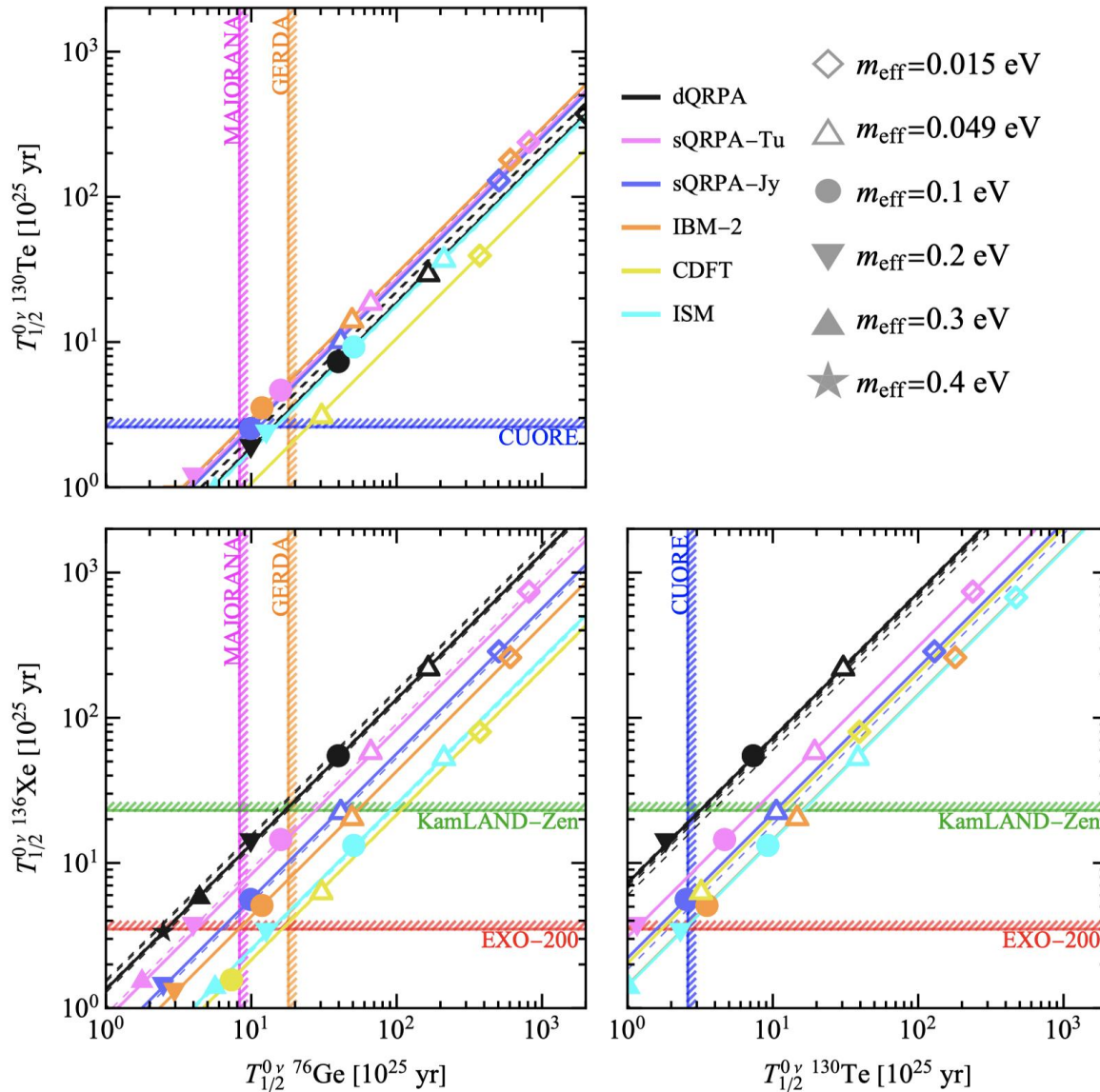
The upper limit of m_{eff}

43



Half-life relations of different isotopes

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$g_A=1.27$, CD-bonn src

$0\nu\beta\beta$ half life

- m_{eff} value
- NME value