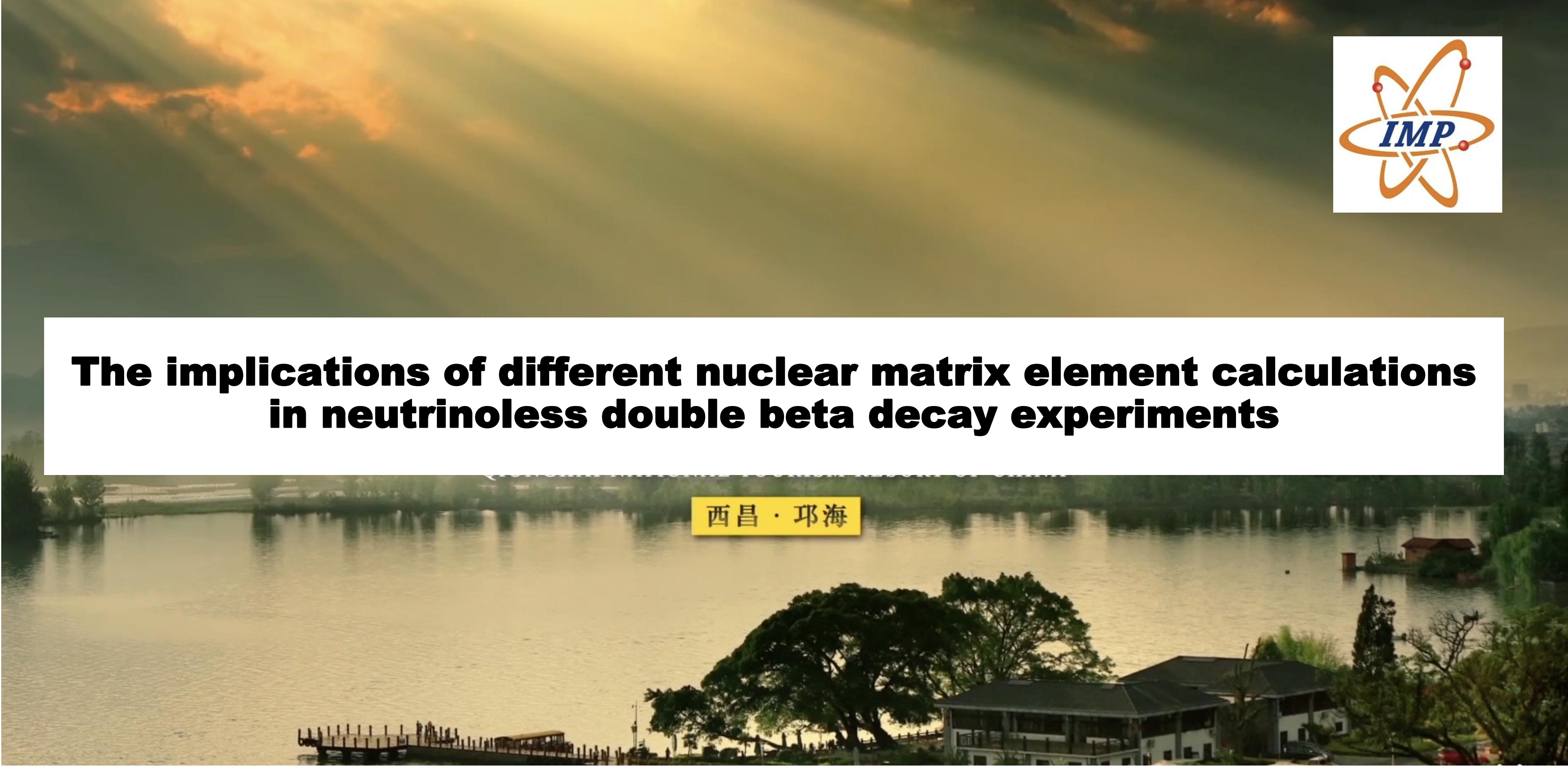
The implications of different nuclear matrix element calculations in neutrinoless double beta decay experiments



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Based on the work with Fang, Li and Zhang,   arXiv:2404.12316

10 May 2024

3rd Conference on frontiers of underground and space particle physics and cosmophysics

Outline

- **Brief background**
- **Theoretical framework**

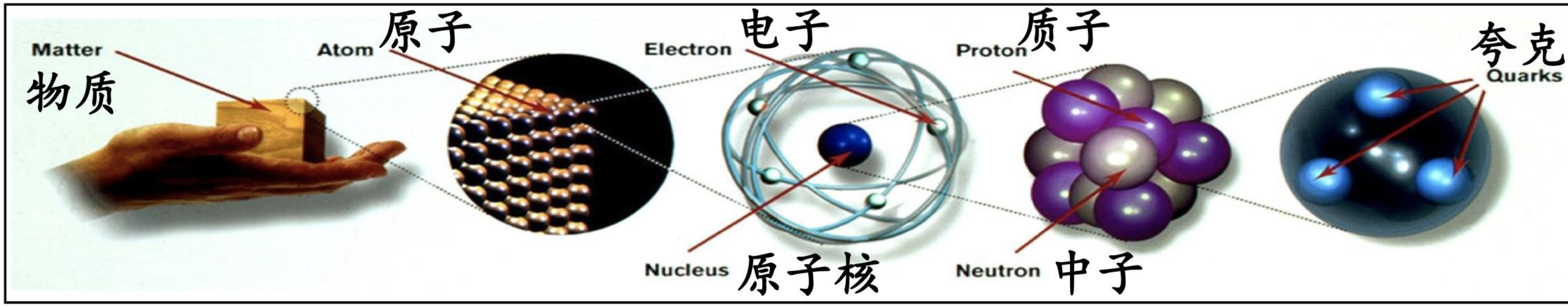
  $0\nu2\beta$ process in minimal Type-I seesaw

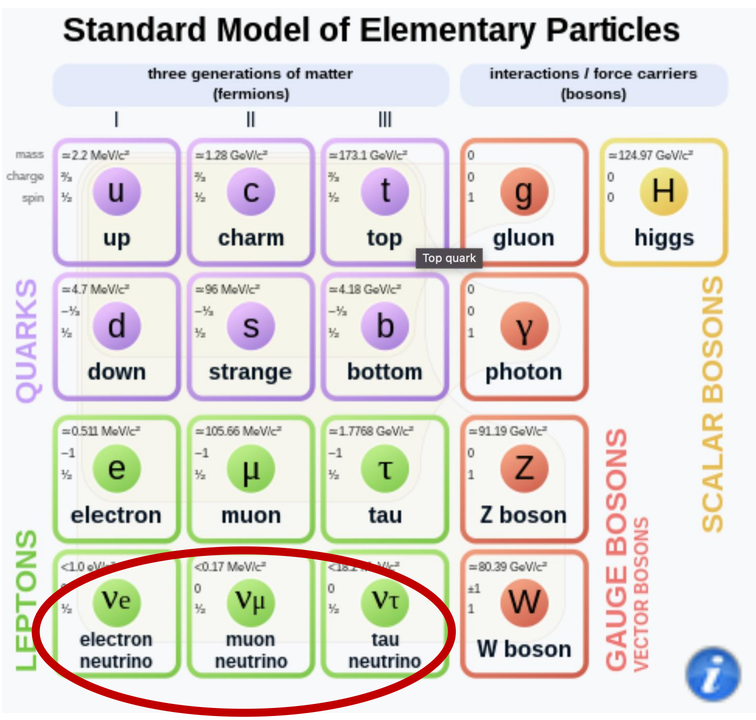
- **Numerical results**

  Constraints of minimal Type-I seesaw from current and future $0\nu2\beta$ experiments

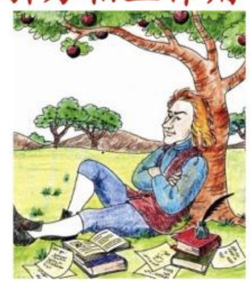
- **Conclusions**

Known basics



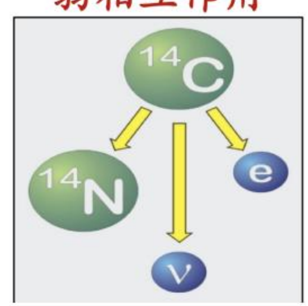


引力相互作用



电磁相互作用

弱相互作用



强相互作用

About neutrinos

Neutrinos oscillate (only proven new physics in particle physics)
1998 (SuperK)

↓

Precise neutrino oscillation parameters?

Absolute neutrino mass?

Neutrino mass origin?

Dirac or Majorana nature?

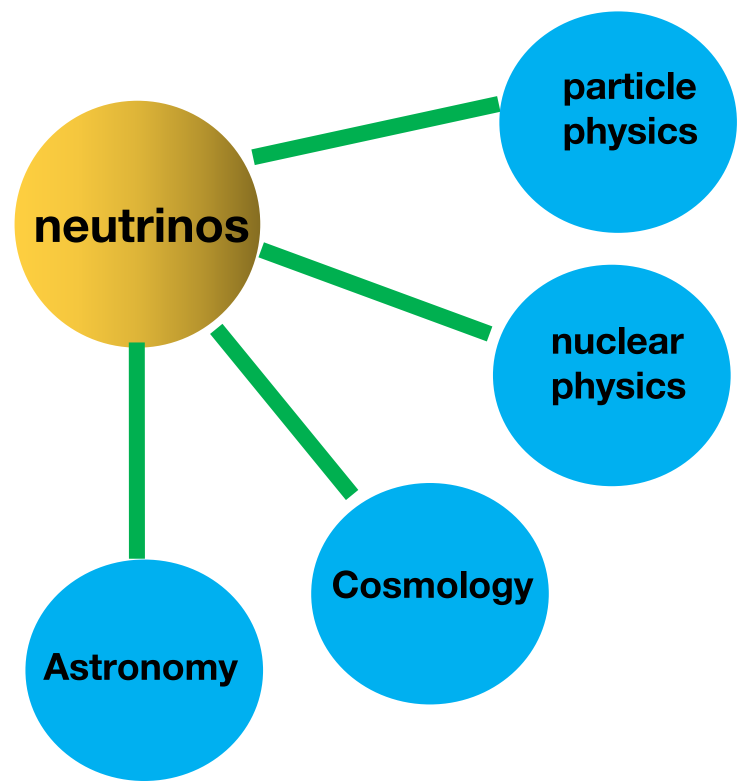
Relation to matter-antimatter asymmetry?

more unknowns...

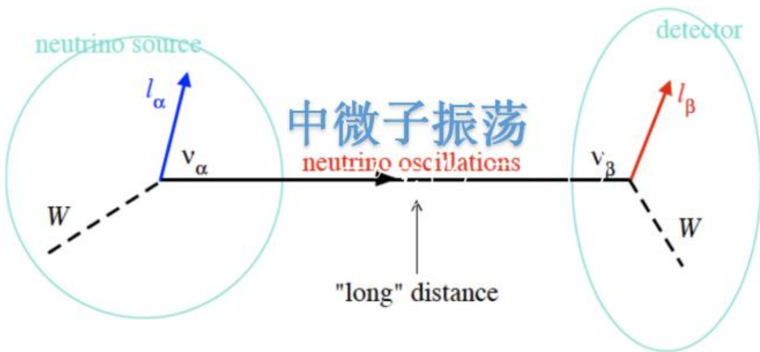
↓

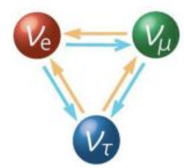
Good portal to more new physics

SM is definitely not the end story



Precise measurement era





$$
\begin{pmatrix}
c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\
-s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\
s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23}
\end{pmatrix}
$$

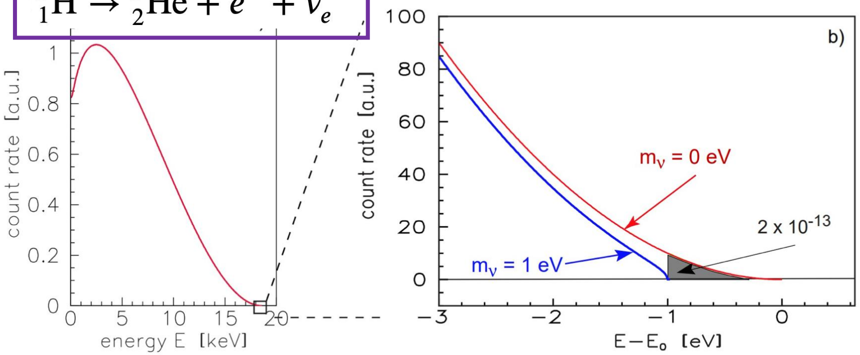
I. Esteban, M. C. Gonzalez-Garcia, A. Hernandez-Cabezudo, et al.,

相对精度 (1σ/bf)		NuFIT 5.2	正质量顺序		? 倒质量顺序 ($\Delta\chi^2 = 6.4$)	
			最佳拟合 $\pm 1\sigma$	3σ 范围	最佳拟合 $\pm 1\sigma$	3σ 范围
2%	✓	$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
2%	✓	$\theta_{23}/^\circ$	$42.2^{+1.1}_{-0.9}$	$39.7 \to 51.0$	$49.0^{+1.0}_{-1.2}$	$39.9 \to 51.5$
1%	✓	$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.94$
13%	?	$\delta/^\circ$	232^{+36}_{-26}	$144 \to 350$	276^{+22}_{-29}	$194 \to 344$
3%	✓	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
1%	✓	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.507^{+0.026}_{-0.027}$	$+2.427 \to +2.590$	$-2.486^{+0.025}_{-0.028}$	$-2.570 \to -2.406$

Not sensitive to absolute neutrino mass

Precise measurement era

$^{3}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + e^{-} + \bar{\nu}_e$



$m_\beta < 0.8$ eV (90% CL)

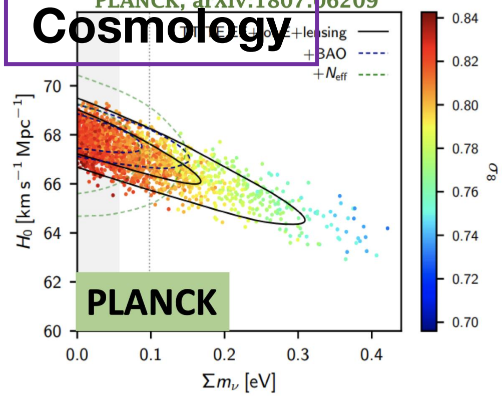
KATRIN 最终的灵敏度

$m_\beta < 0.2$ eV (90% CL)

$m_1 < 0.2$ eV (90% CL)

Cosmology

PLANCK, arXiv:1807.06209



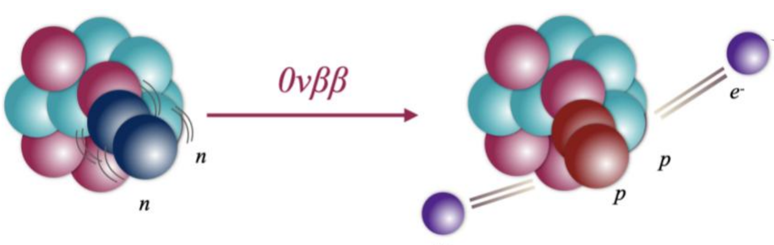
Planck TT, TE, EE + lowE + lensing + BAO

$\Sigma < 0.12$ eV (95% CL)

$m_1 < 0.03$ eV (95% CL, NO)

Future:
JUNO, DUNE
CDEX, PandaX-III,
NνDEx, CUPID,
TRIDENT,
PTOLEMY…

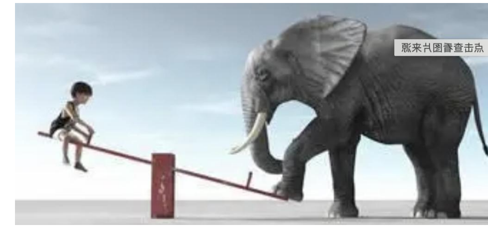
0ν2β



Nuclear physics
Particle physics
Matter antimatter asymmetry

Formulas (minimal type-I seesaw)

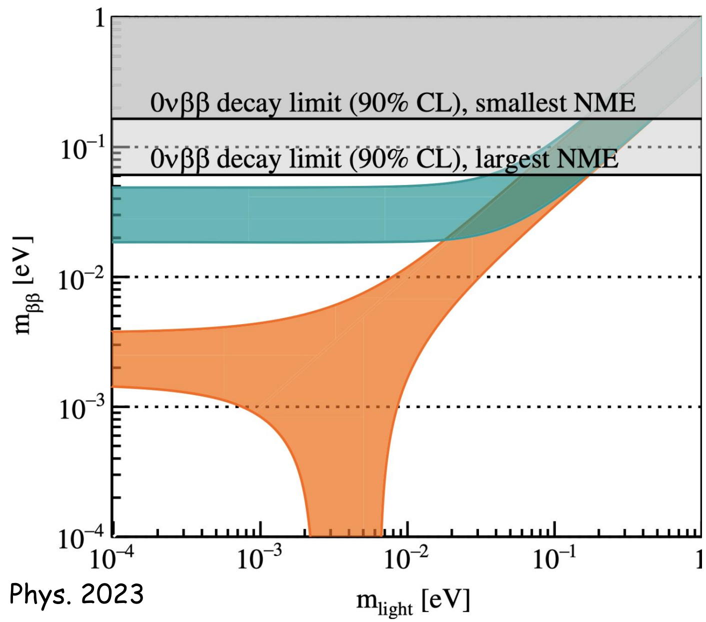
$$\mathcal{L}_{\rm mass} = -\frac{1}{2}\overline{(\nu_{\rm L}, N_{\rm R}^c)} \begin{pmatrix} 0 & M_{\rm D} \\ M_{\rm D}^{\rm T} & M_{\rm R} \end{pmatrix} \begin{pmatrix} \nu_{\rm L}^c \\ N_{\rm R} \end{pmatrix} + {\rm h.c.}$$



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

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

$$f_\beta(M_N) = M_{0\nu}(M_N)/M_{0\nu}(0)$$ **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

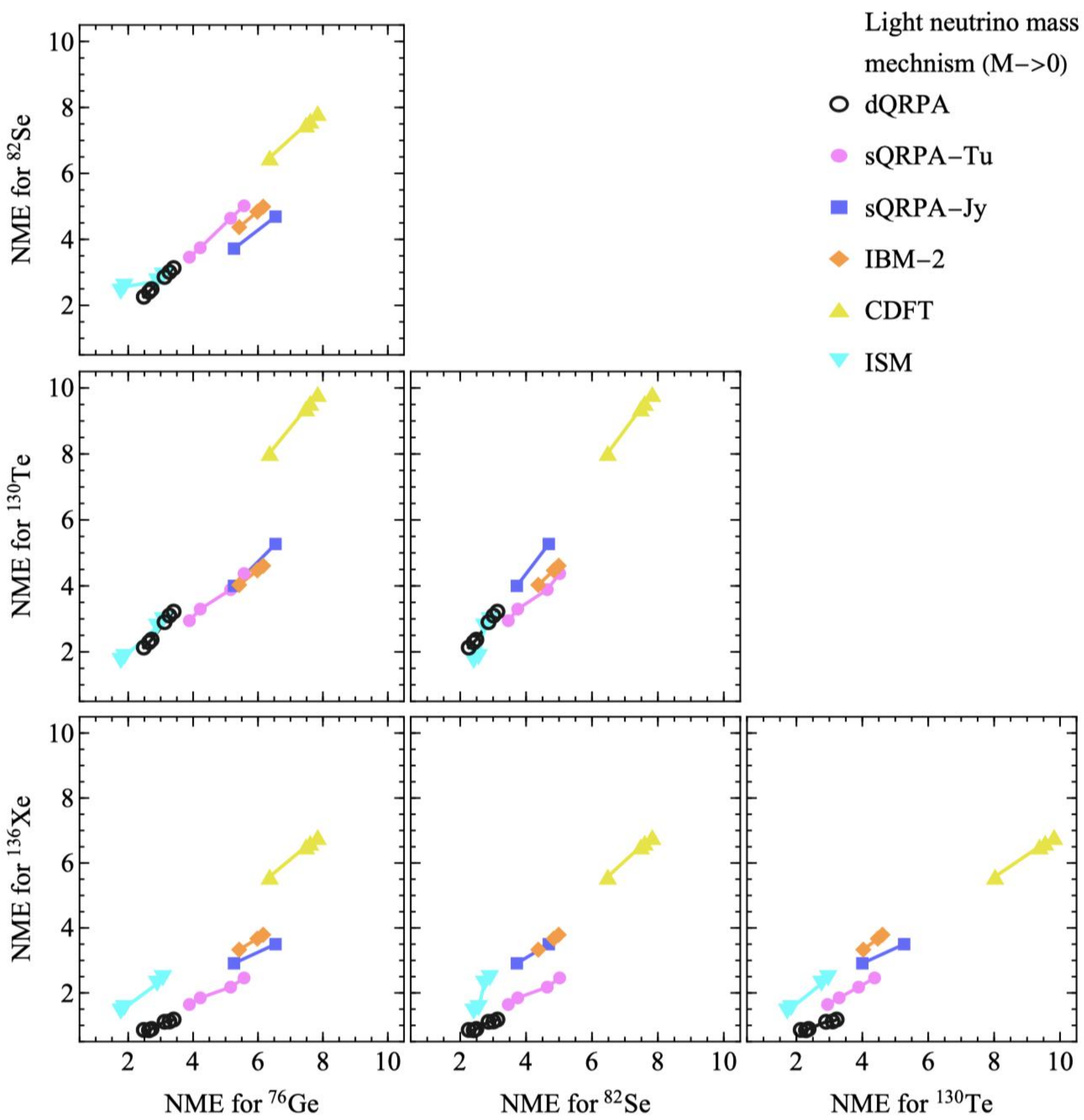
NME of light neutrinos

	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
		CD-Bonn	2.72	4.221	5.26	-	-	1.88
^{82}Se	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	-	-	-	-	-
		Argonne	2.26	3.460	-	-	-	2.41
		CD-Bonn	2.49	3.746	3.73	-	-	2.56
^{130}Te	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	
	1.00	w/o	2.29					
		Argonne	2.13	2.945	-	-	-	1.72
		CD-Bonn	2.37	3.297	4.00	-	-	1.84
^{136}Xe	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
		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

NME of heavy neutrinos

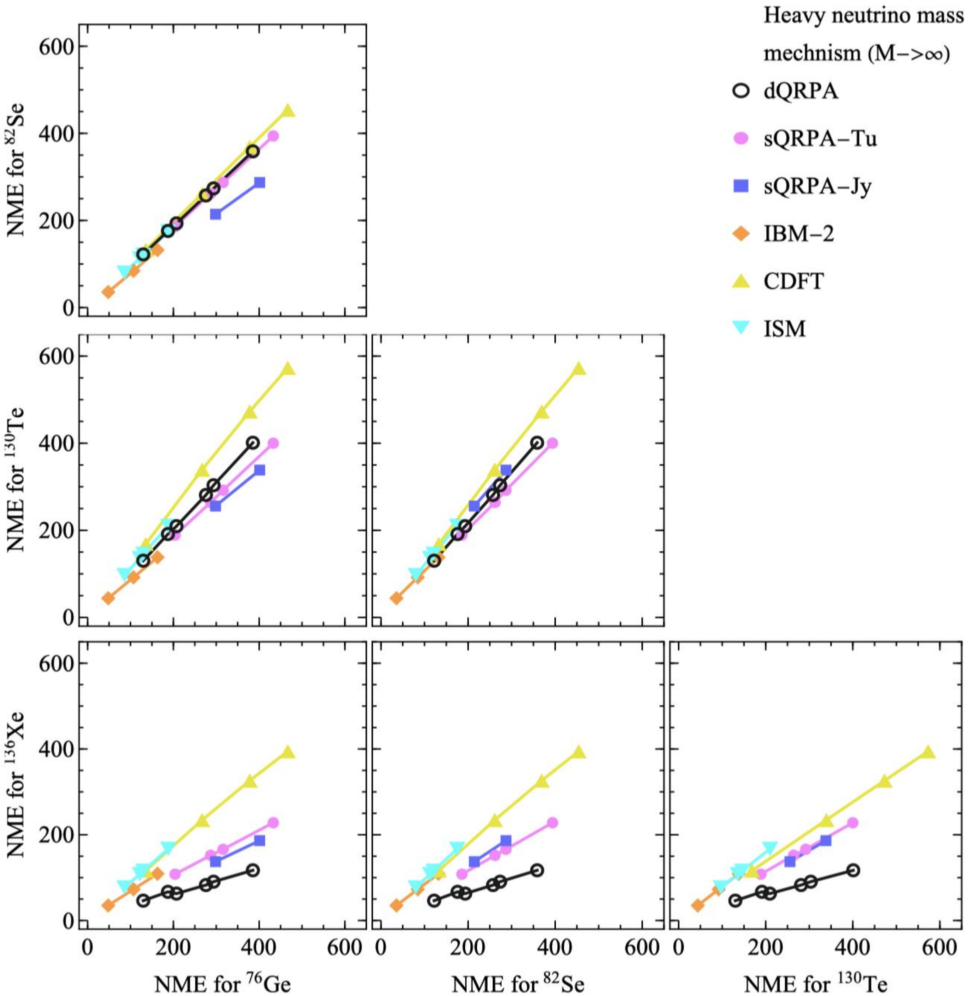
	g_A	src	dQRPA [74]	sQRPA-Tu [75]	sQRPA-Jy [77]	IBM-2 [87]	CDFT [80]	ISM [81]
	1.27	w/o	385.4				466.8	
		Argonne	187.3	316		107	267	130
		CD-Bonn	293.7	433	401.3	163	378.1	188
^{76}Ge		Miller-Spencer				48.1	135.7	
	1.00	w/o	275.9					
		Argonne	129.7	204				86
		CD-Bonn	207.2	287	298.3			122
^{82}Se	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					
		Argonne	122.1	186	-	-	-	80
		CD-Bonn	193.4	262	214.3	-	-	113
^{130}Te	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	
	1.00	w/o	281.2					
		Argonne	130.2	189	-	-	-	97
		CD-Bonn	209.5	264	255.7	-	-	136
^{136}Xe	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
		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

NME of light neutrinos



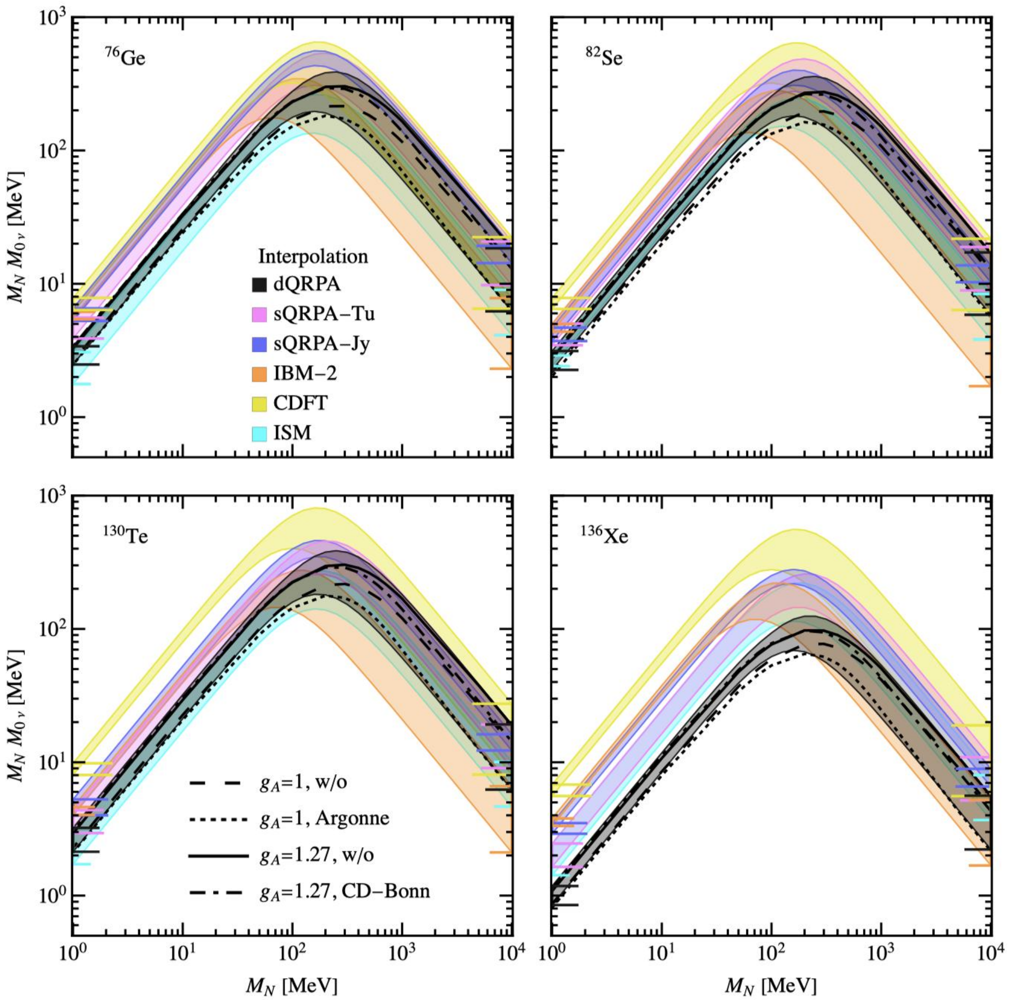
- CDFT biggest
- dQRPA smallest
- different NME ratios between different isotopes

NME of heavy neutrinos



- CDFT/ISM biggest
- IBM-2/dQRPA smallest
- different NME ratios between different isotopes

Mass-dependent NME

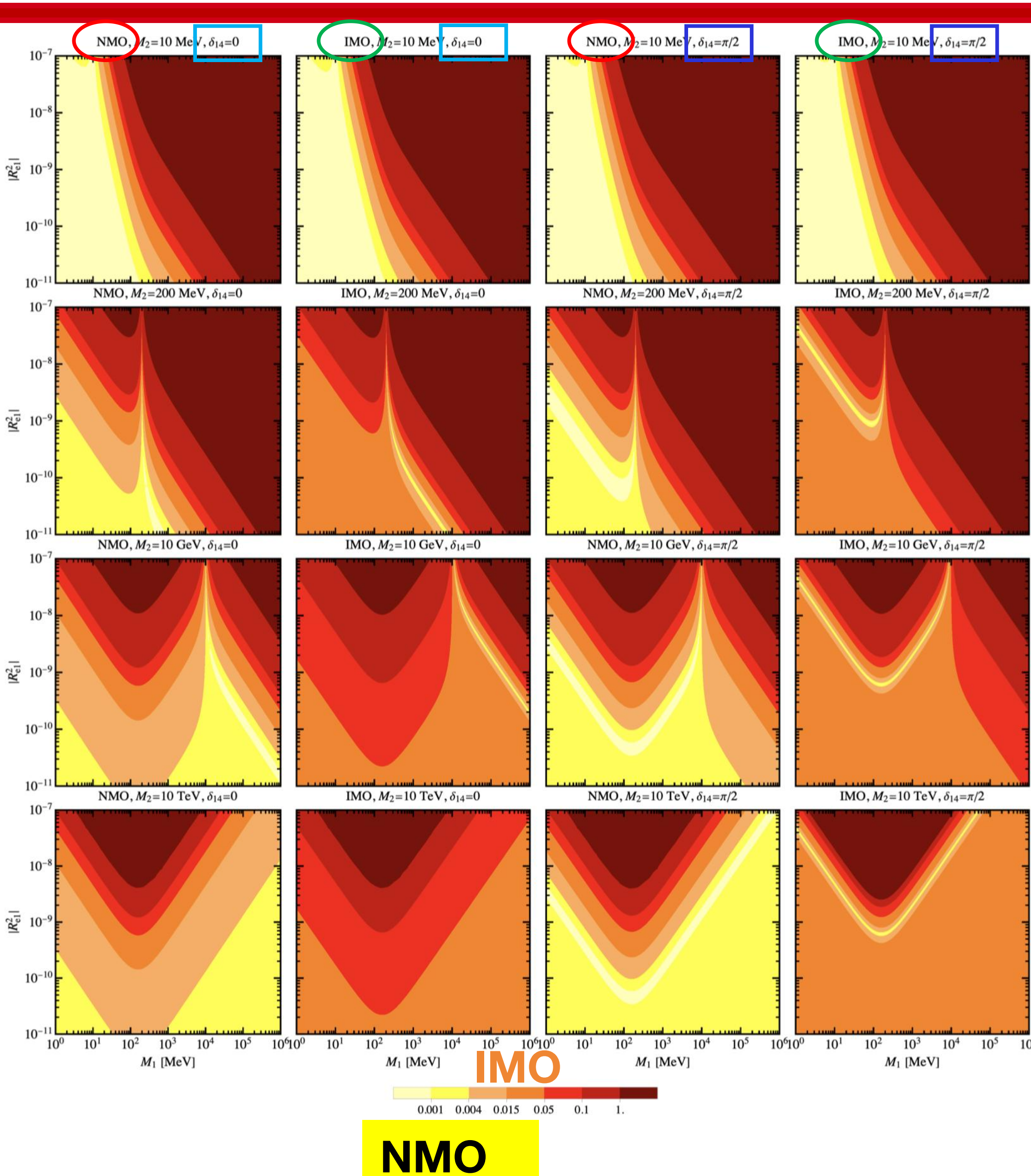


- **dQRPA:** Numerical calculation
- **Others:** interpolation with two extreme values

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

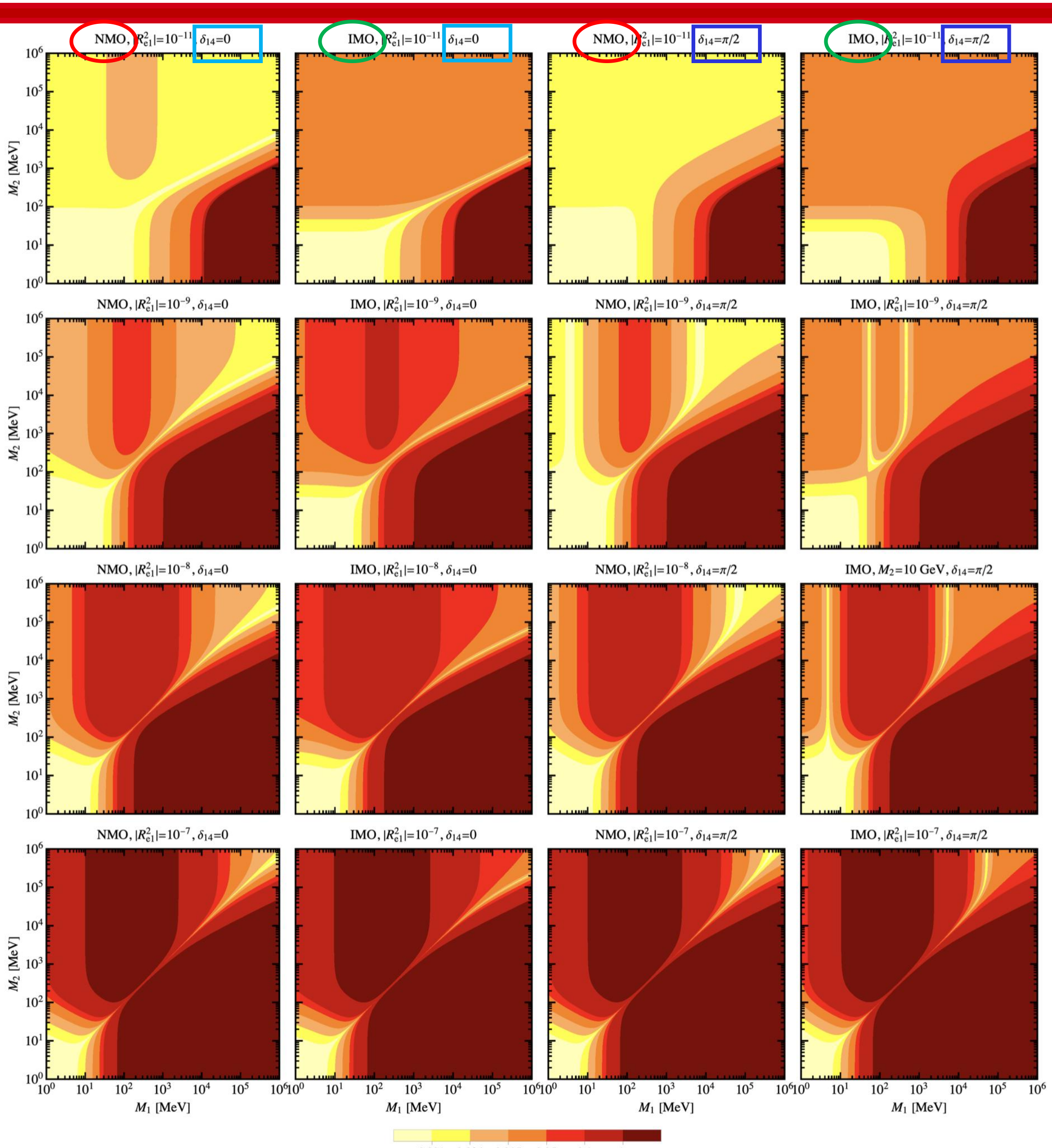
- **dQRPA:** agrees with ISM for light vs and tends to be consistent with CDFT for heavy vs
- **In light neutrino mass** theNME from **dQRPA** model is smaller than that of the **IBM-2** model, and in heavy neutrino mass the reverse applies.

Parameter space of m_{eff}

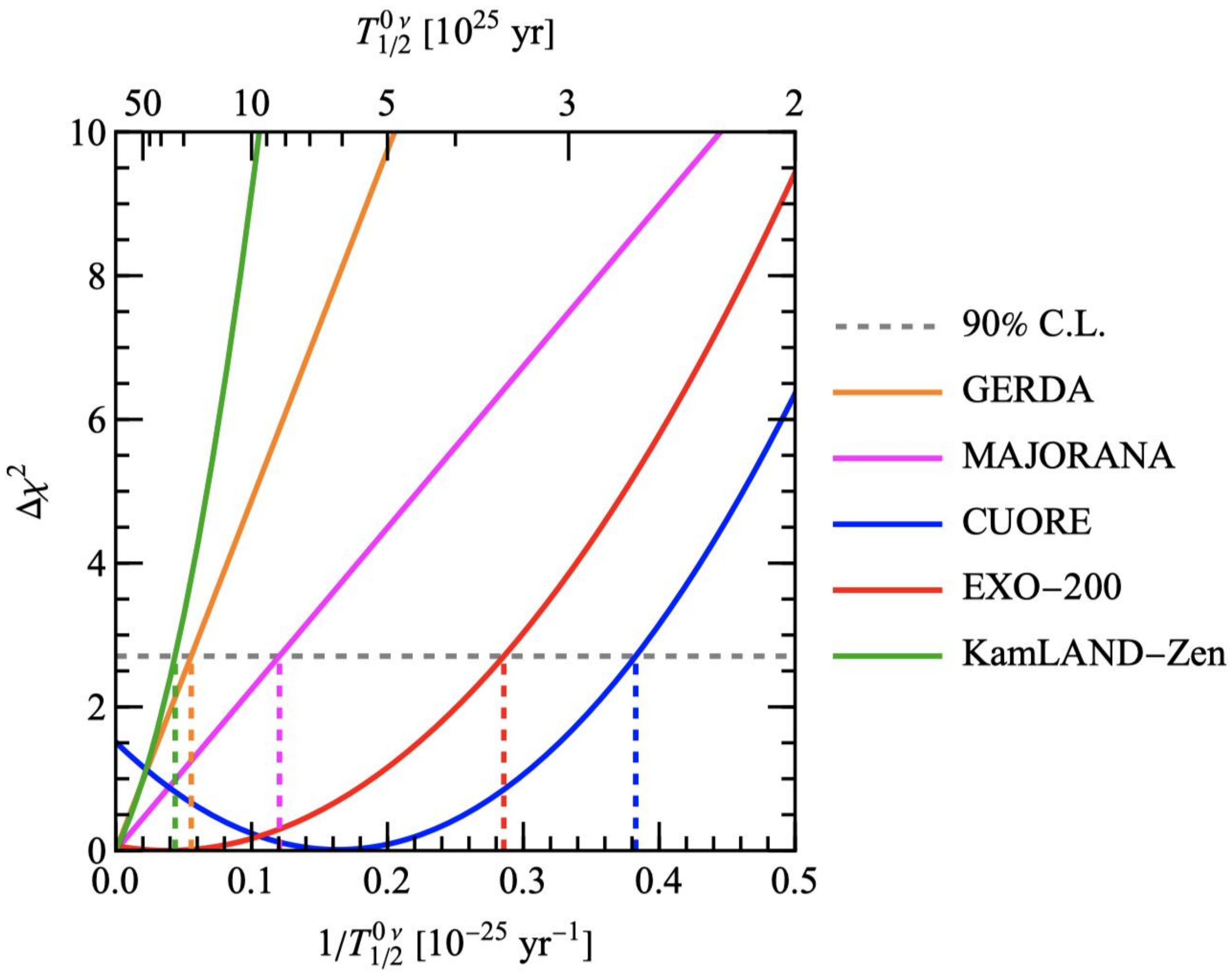


- g_A=1, Argonne src
- Some parameter space can be very easily/hardly excluded by current/future 0ν2β experiments
- The NMO/IMO can be very different and δ_{14} matters

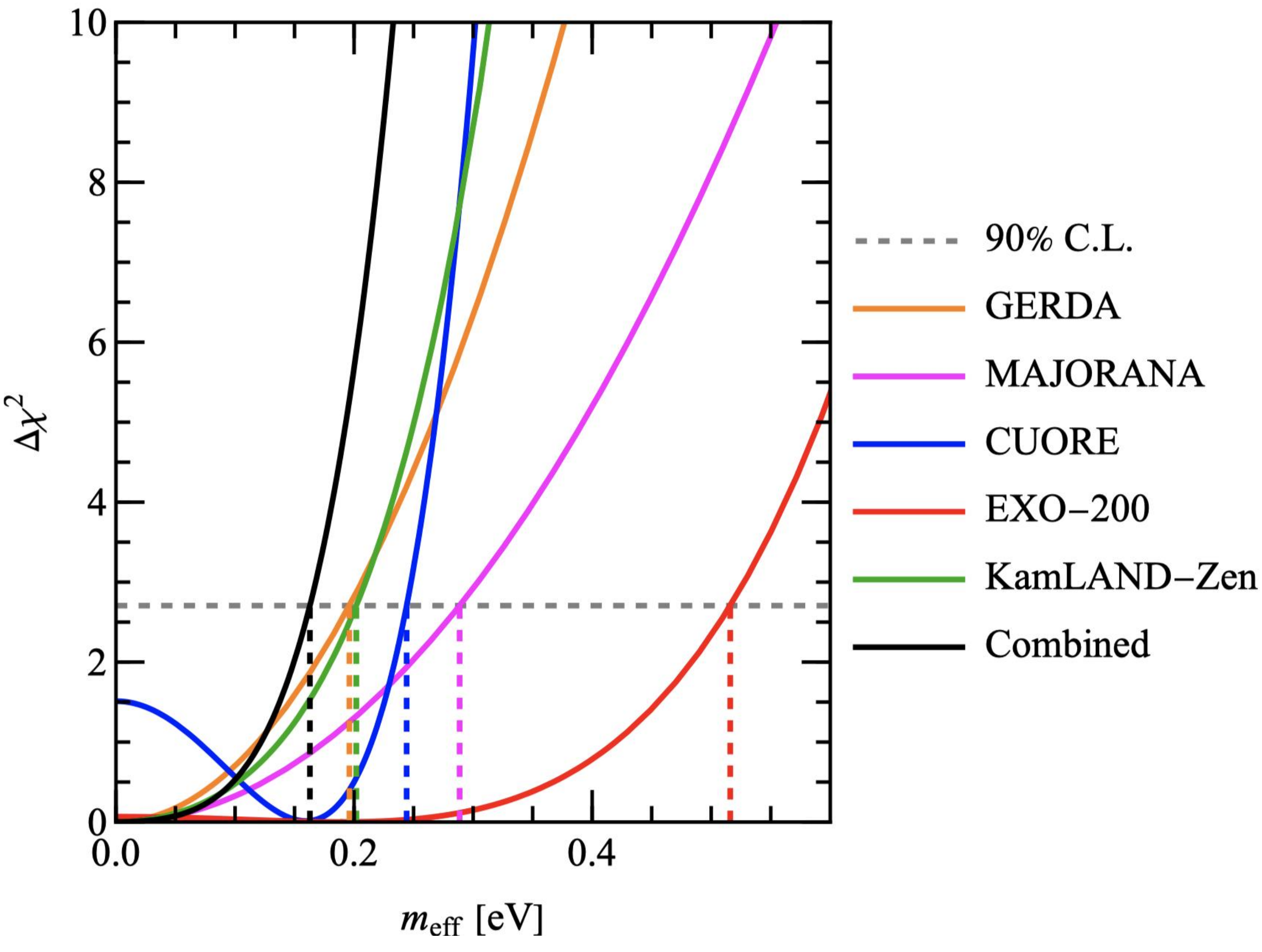
Parameter space of m_{eff}



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

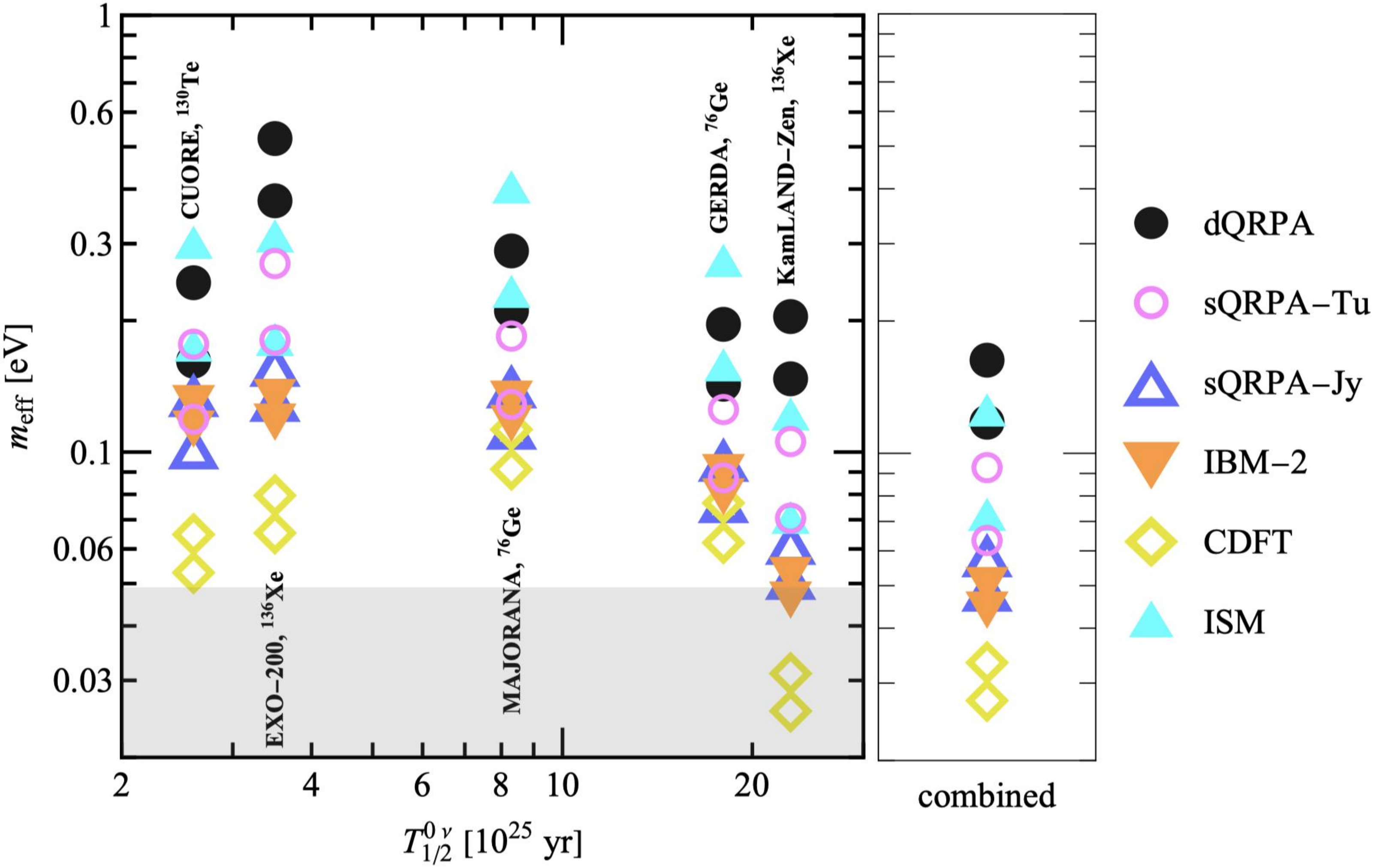


$\Delta\chi^2$ functions of m_{eff}

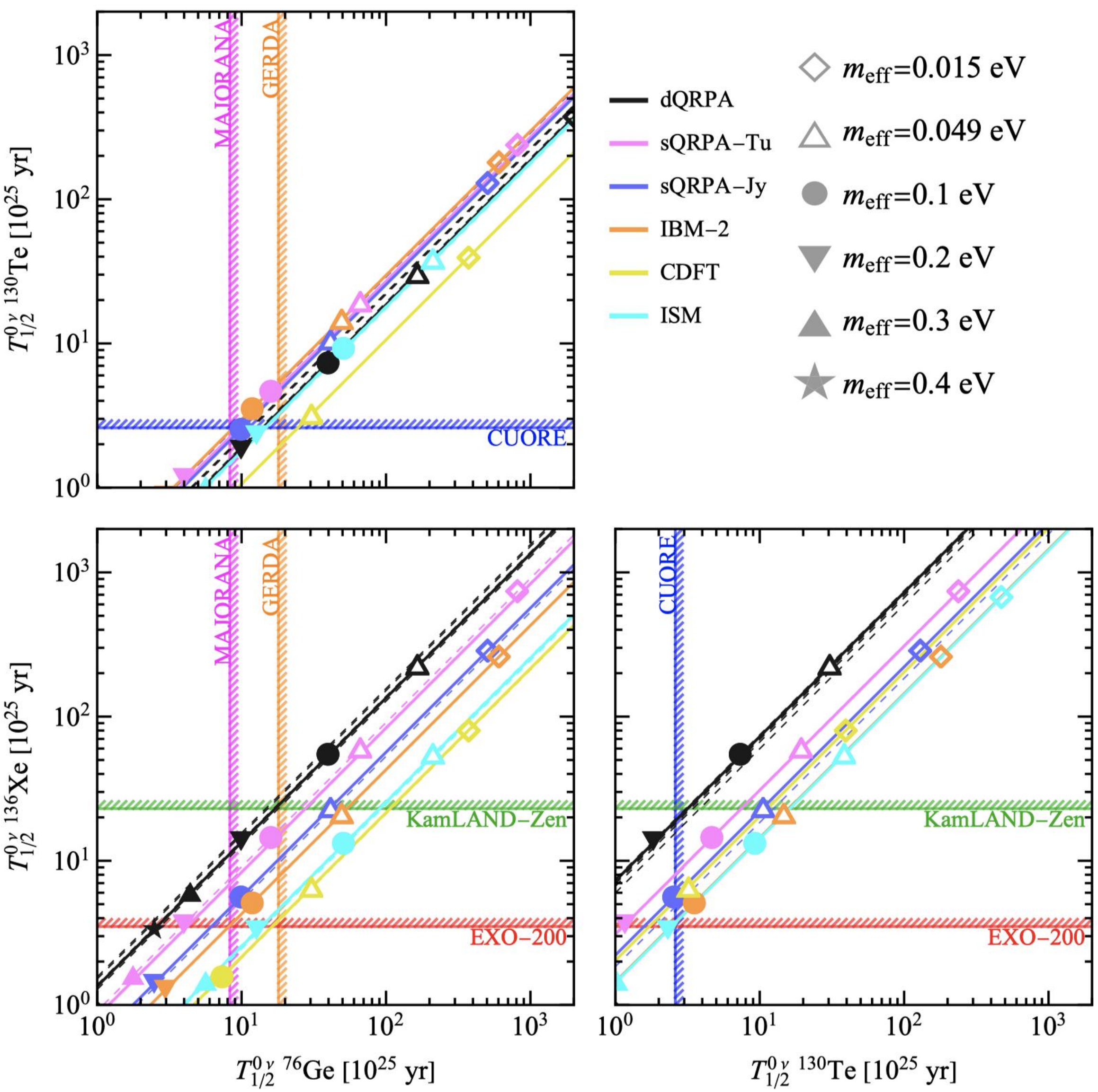


g_A=1, Argonne src

The upper limit of m_{eff}



Half-life relations of different isotopes

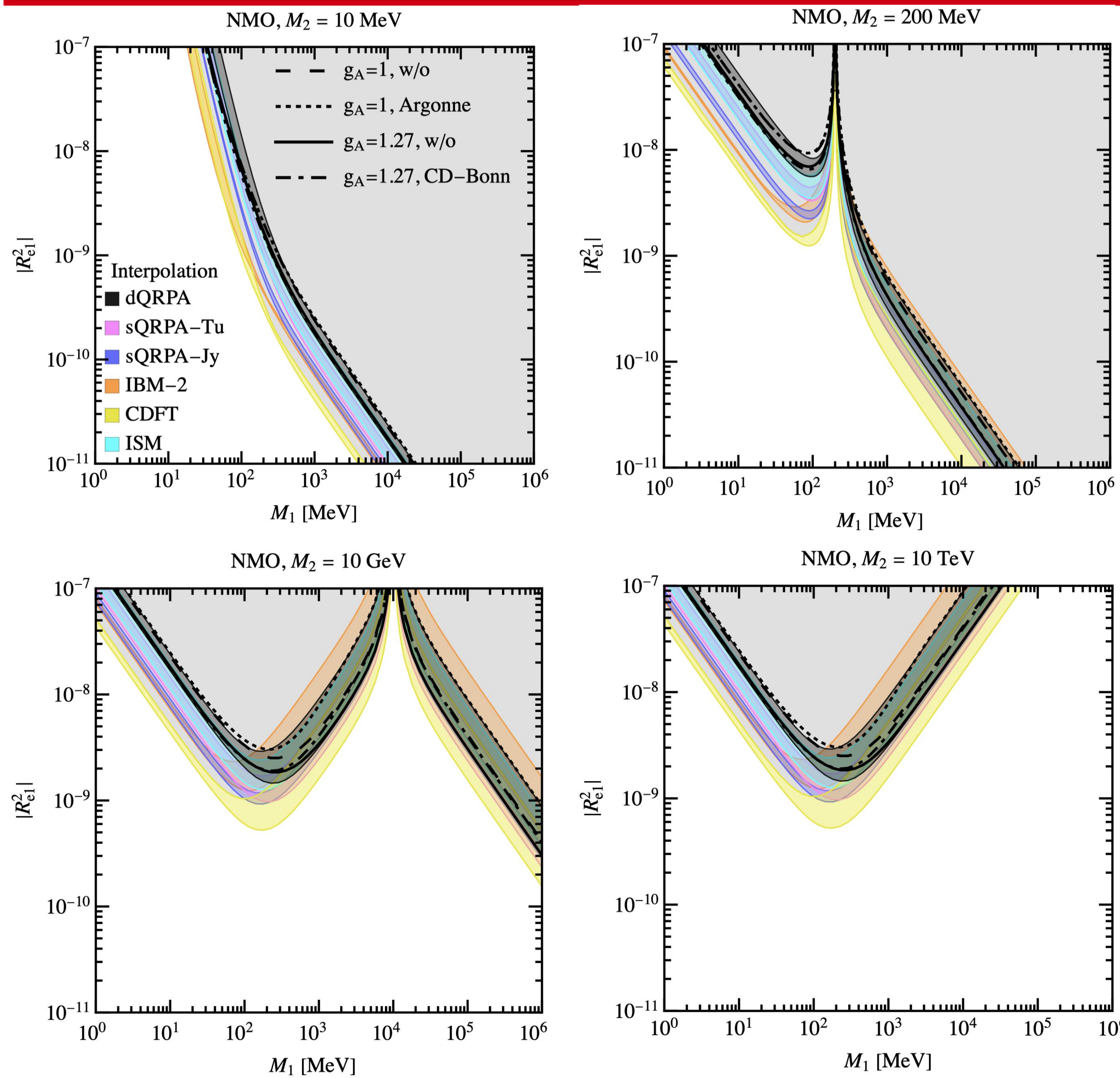


g_A=1.27, CD-bonn src

0ν2β half life

- m_{eff} value
- NME value

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

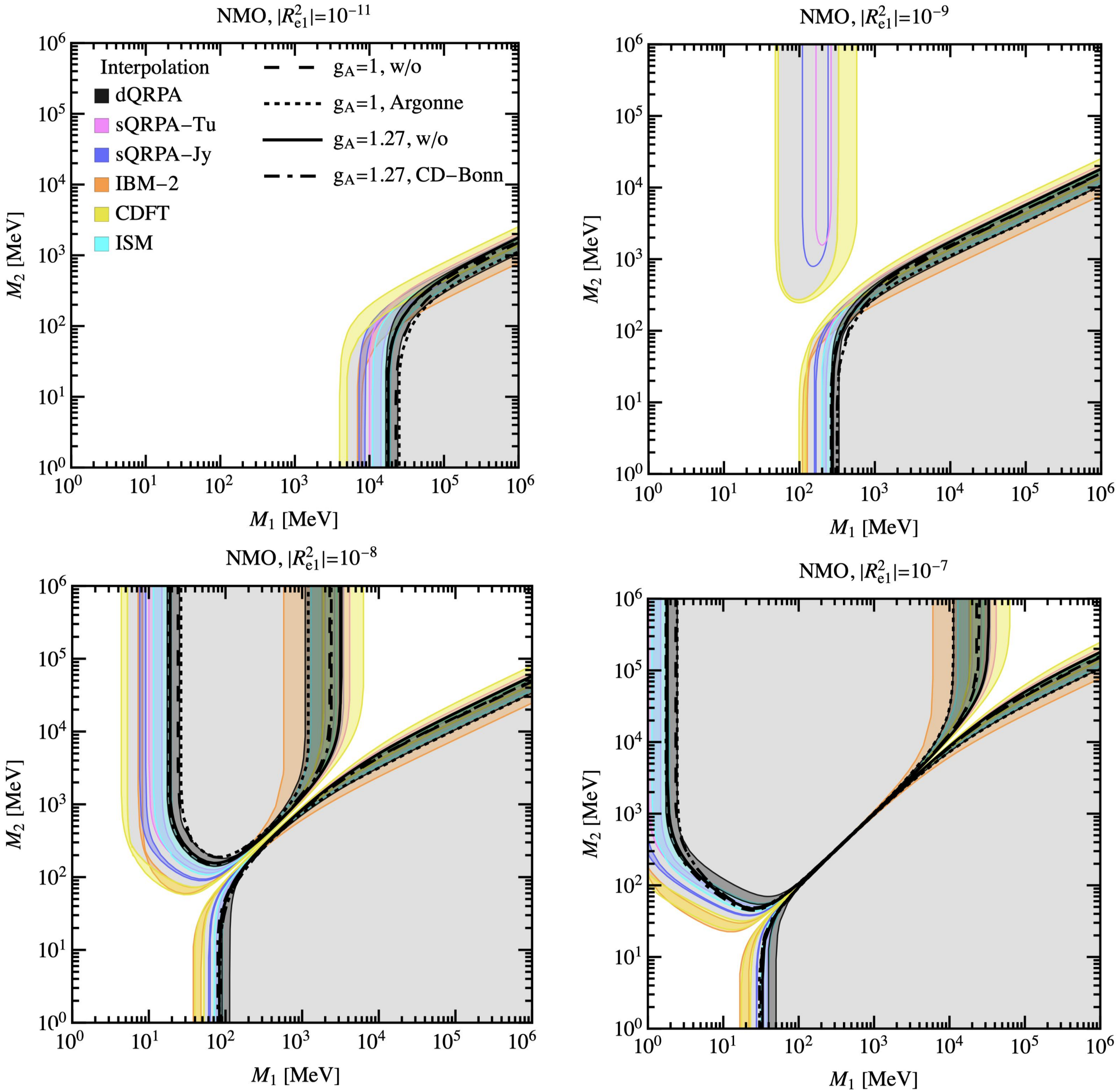


- 3σ C.L
- Gray regions: excluded regions in the case of CDFT model
- Different choices of parameters and models are scanned (not as Guassian)
- Both the **0ν2β-decay** and **oscillation data** are used

- The **IMO** case is similar

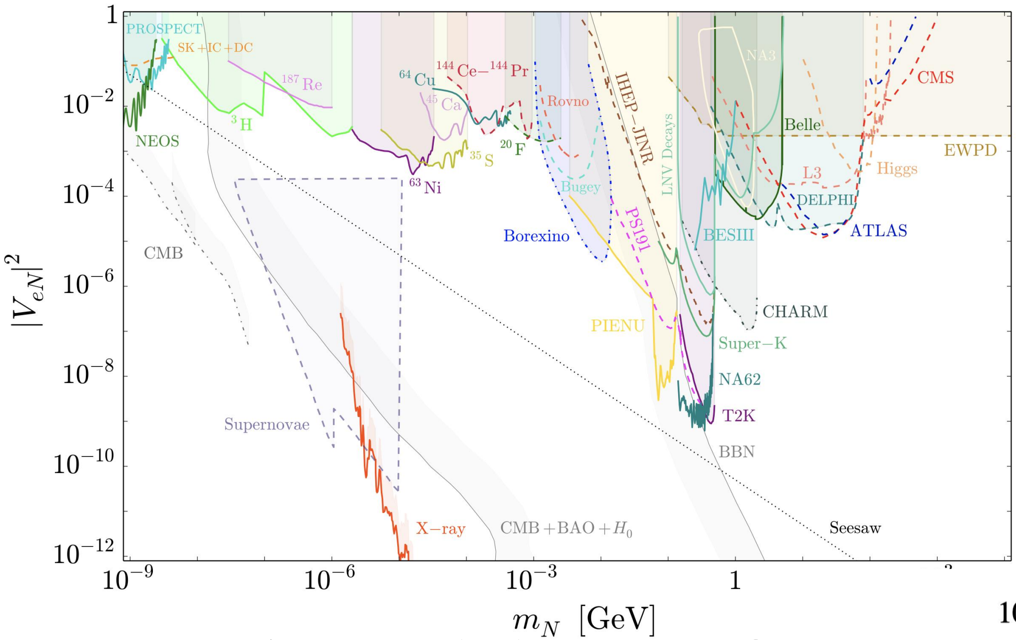
- The peak shape

Current limits (M_1 & M_2)



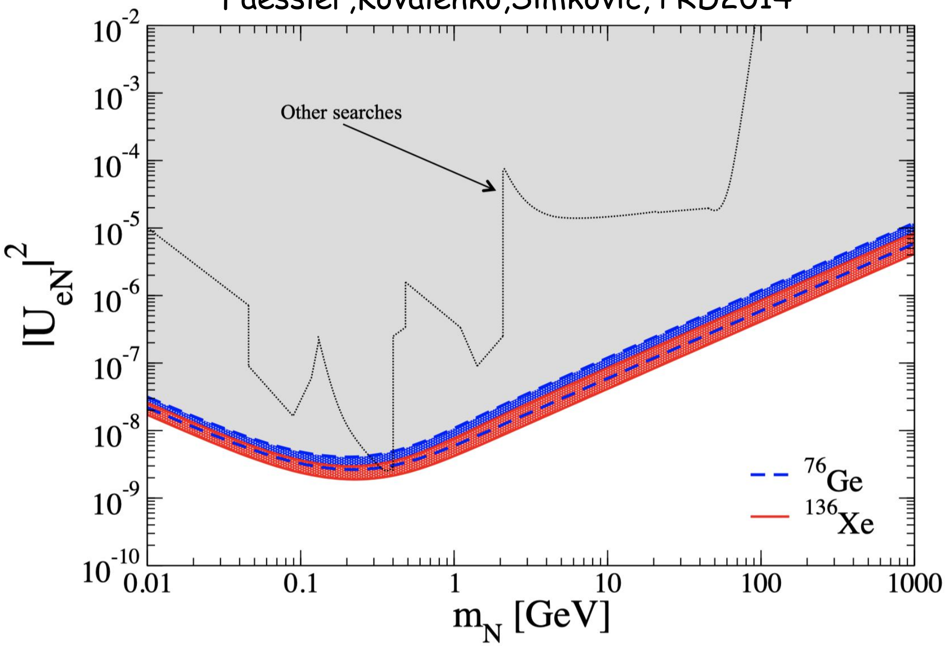
- ➢ The IMO case is similar
- ➢ The NME hierarchy changes with neutrino mass

Constraints from other probes



Bolton, Deppisch, Bhupap Dev, JHEP 2020

Faessler,Kovalenko,Simkovic, PRD2014



- 3+1case: similar to the case $M_2 \gg M_1$
- 0ν2β data provide strongest limits in the mass range considered here

Future sensitivities

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

Assumed number events

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

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

Assuming no positive 0ν2β signal is observed,
Leading to sensitivities independent of true NME model

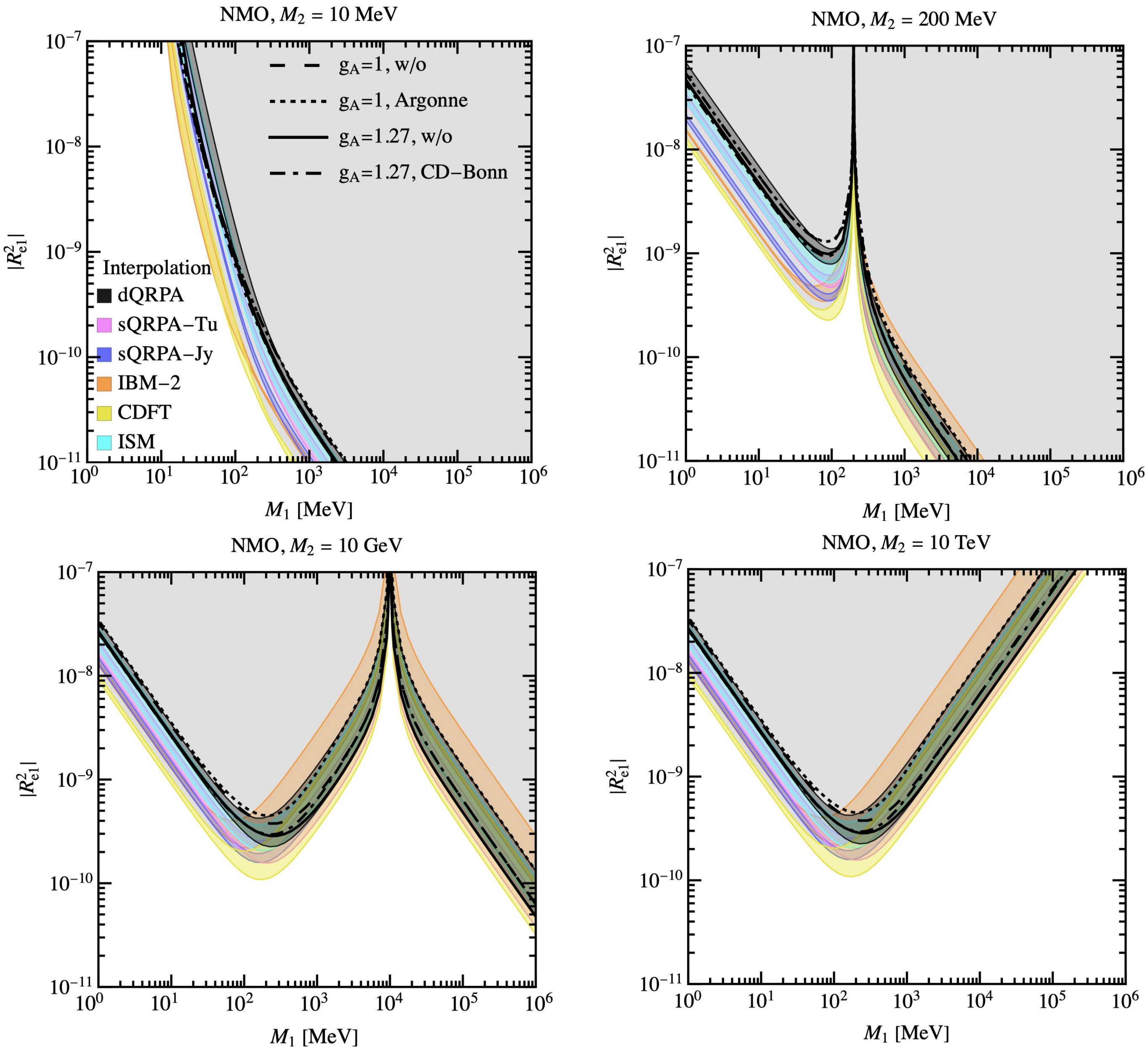
$$S_{\alpha i}(m_{\rm eff},\ M_{\alpha i}) = {\rm In}2\cdot N_A\cdot\varepsilon_\alpha\cdot(T^{0\nu}_{1/2})^{-1}_{\alpha i}\cdot T/(1\ {\rm yr})$$

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

T=10 yr

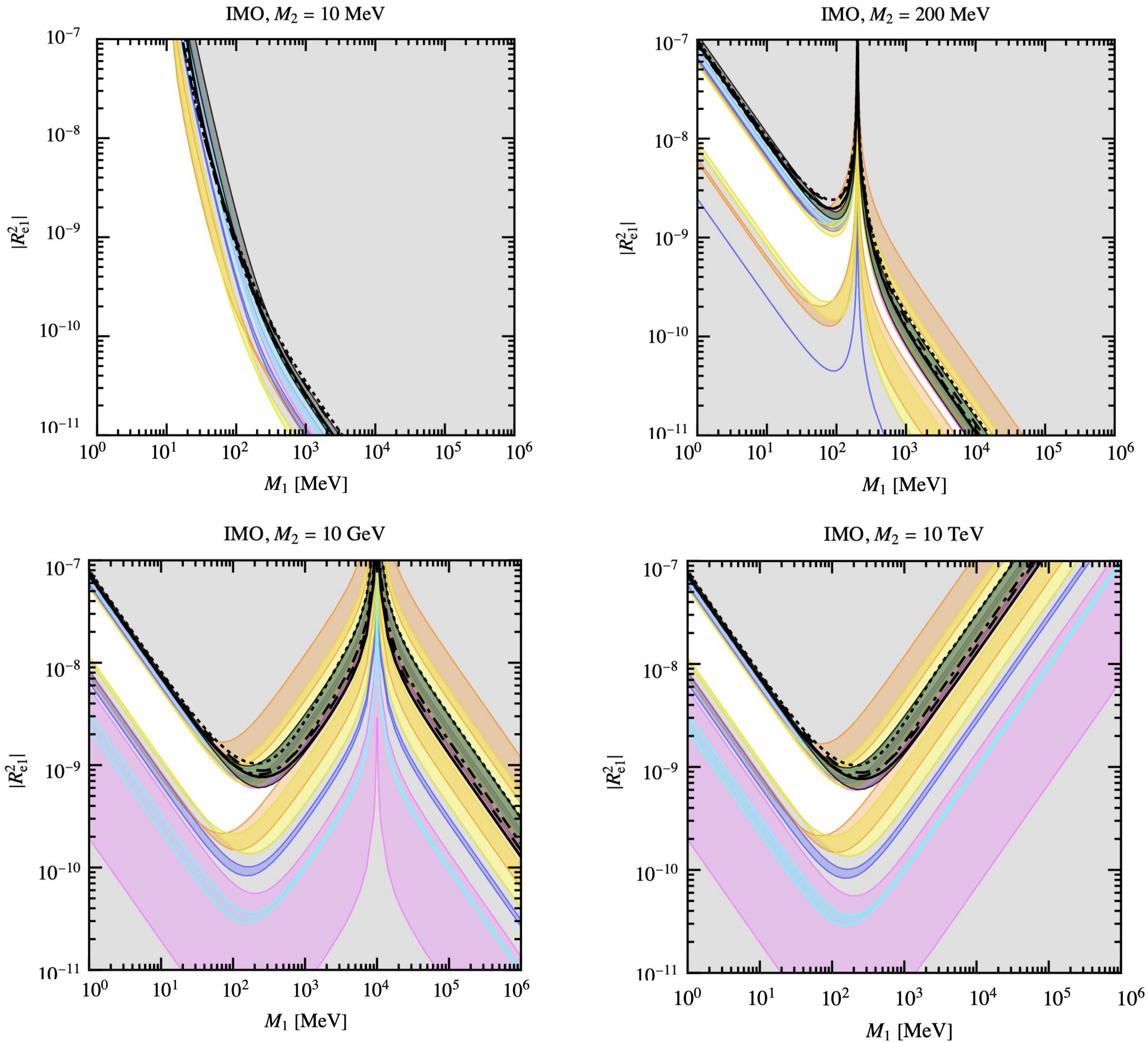
Experiment	Isotope	ε [mol· yr]	b [events/(mol· yr)]
LEGEND-1000	^{76}Ge	8736	$4.9\cdot10^{-6}$
SuperNEMO	^{82}Se	185	$5.4\cdot10^{-3}$
SNO+II	^{130}Te	8521	$5.7\cdot10^{-3}$
nEXO	^{136}Xe	13700	$4.0\cdot10^{-5}$

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



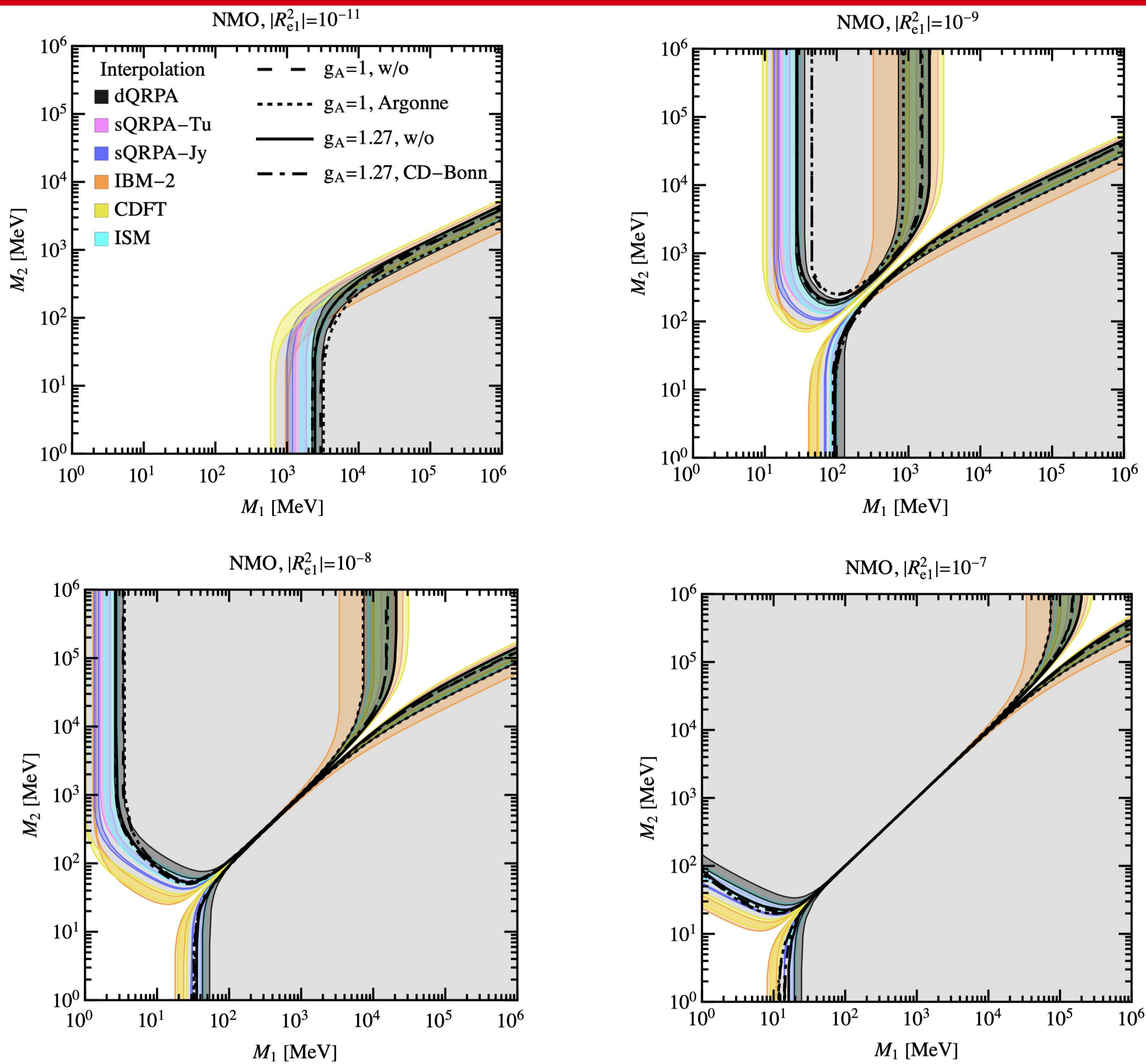
- The NMO case
- More parameter space can be tested compared the current experiments

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



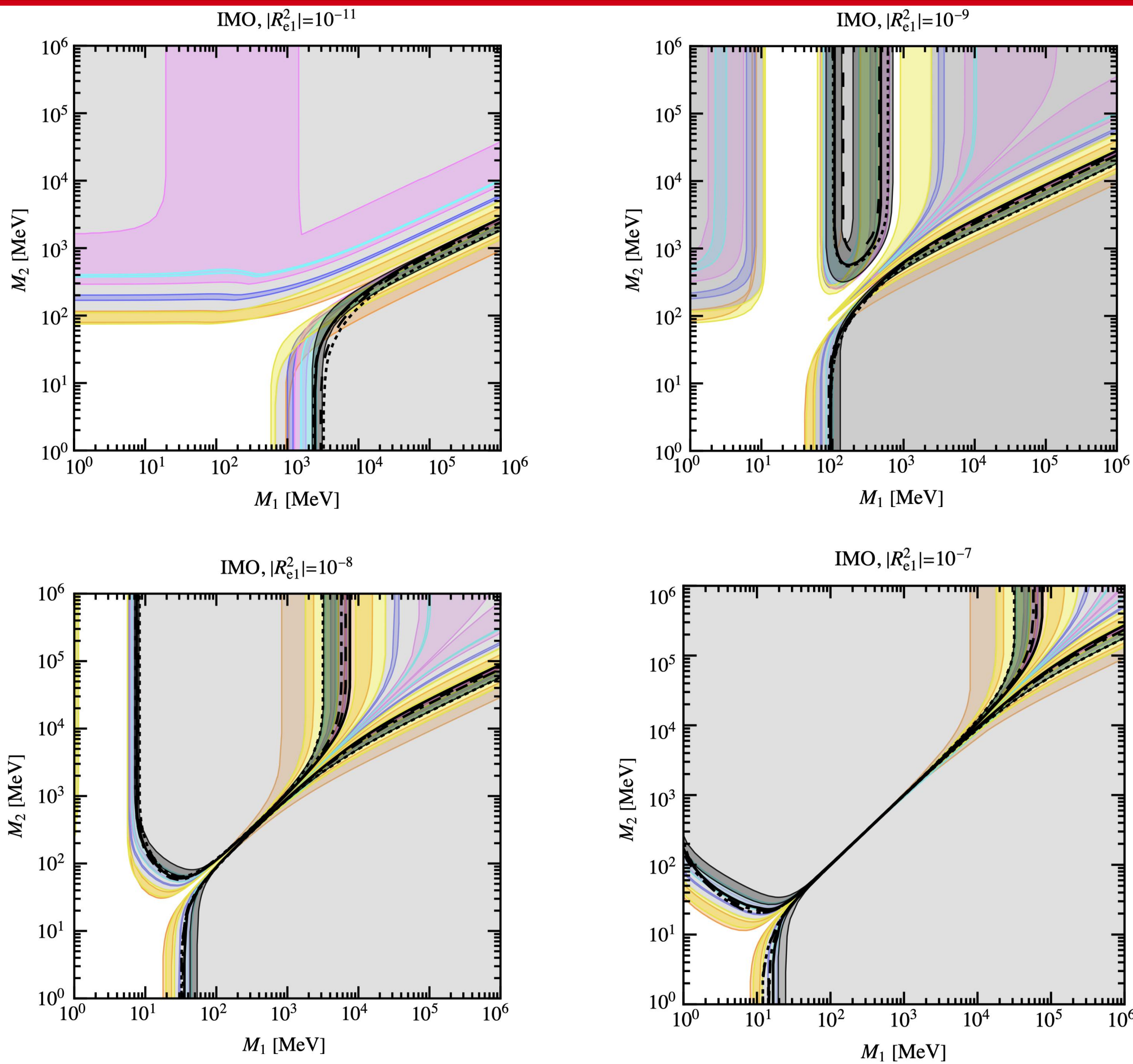
- The IMO case
- Much more parameter space are expected to exclude than NMO case due to zero positive 0ν2β signal assumed
- By assuming **enough positive 0ν2β signal**, possible to **discriminate NME calculations** and more parameter space can be **excluded in the NMO case**

Future sensitivities (M_1 & M_2)



The NMO case

Future sensitivities (M_1 & M_2)



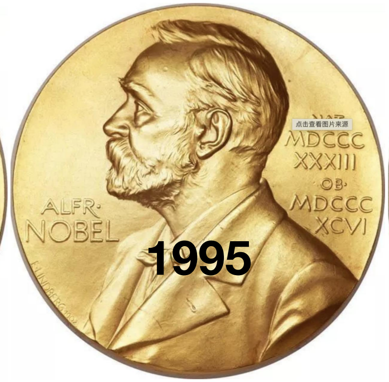
- The IMO case
- The wide pink region in the upper left panel: mainly diffrent δ_{14} values

Conclusions

- 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 $0\nu2\beta$ experiments
- Highlight of the entanglements between new physics exploration and NME calculation
- Possible discrimination of different NME calculations in this framework is on-going.

Thank you for your attention!

Backups



1988:缪子型中微子，Lederman, Schwartz,Steinberger
1995:首次观测到中微子, (Reines)
2002:宇宙中的中微子（太阳、超新星中微子），小柴昌俊
2015:中微子振荡,日本物理学家梶田隆章和加拿大物理学家阿瑟·麦克唐纳(Arthur B. McDonald)