HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Future of neutrino-less double beta decay searches: the possibility to discriminate different nuclear models

F.Pompa, T.Schwetz, J.Y.Zhu - JHEP 06 (2023) 104

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Federica Pompa - fpompa@ific.uv.es

In collaboration with:

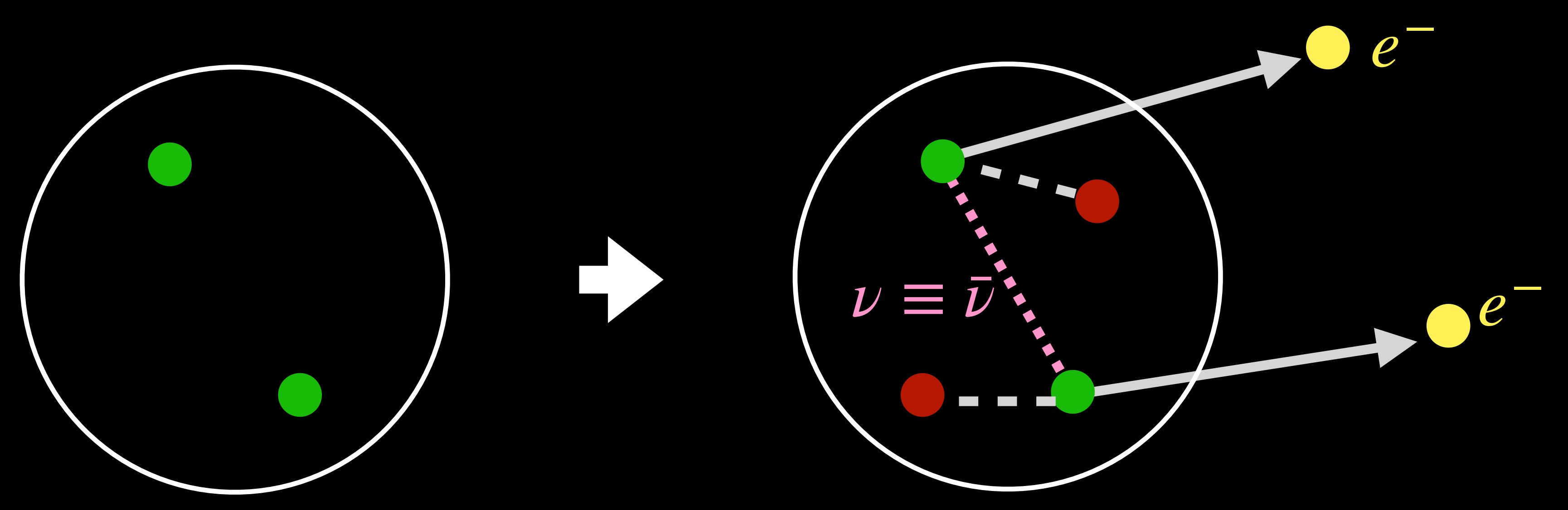
Prof. Thomas Schwetz - schwetz@kit.edu
Dr. Jing-Yu Zhu - zhujingyu@sjtu.edu.cn

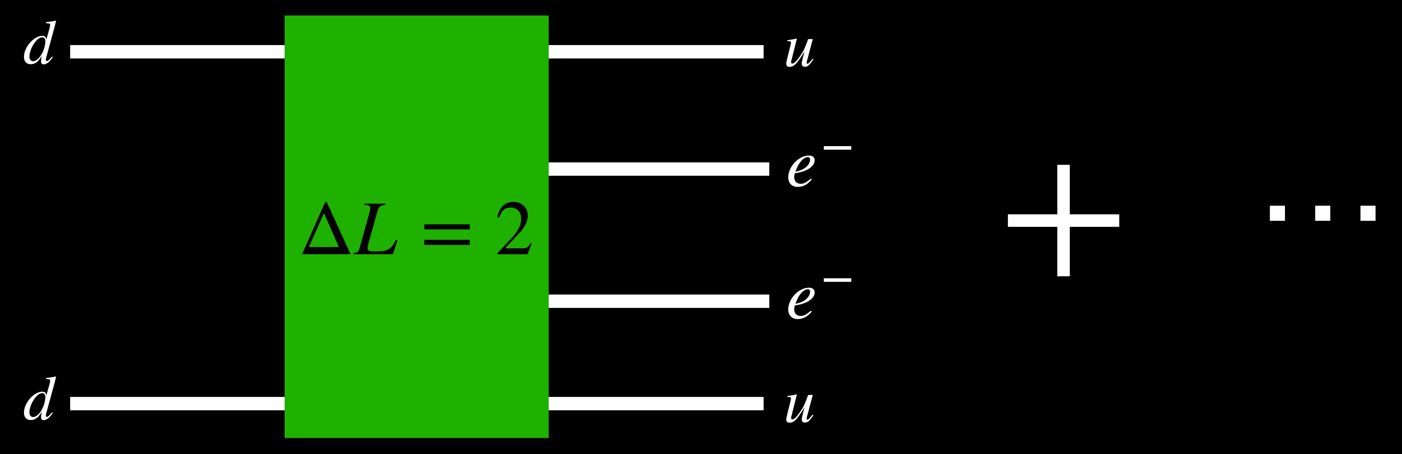
CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

VNIVERSITAT DE VALÈNCIA

IFIC
INSTITUT DE FÍSICA CORPUSCULAR

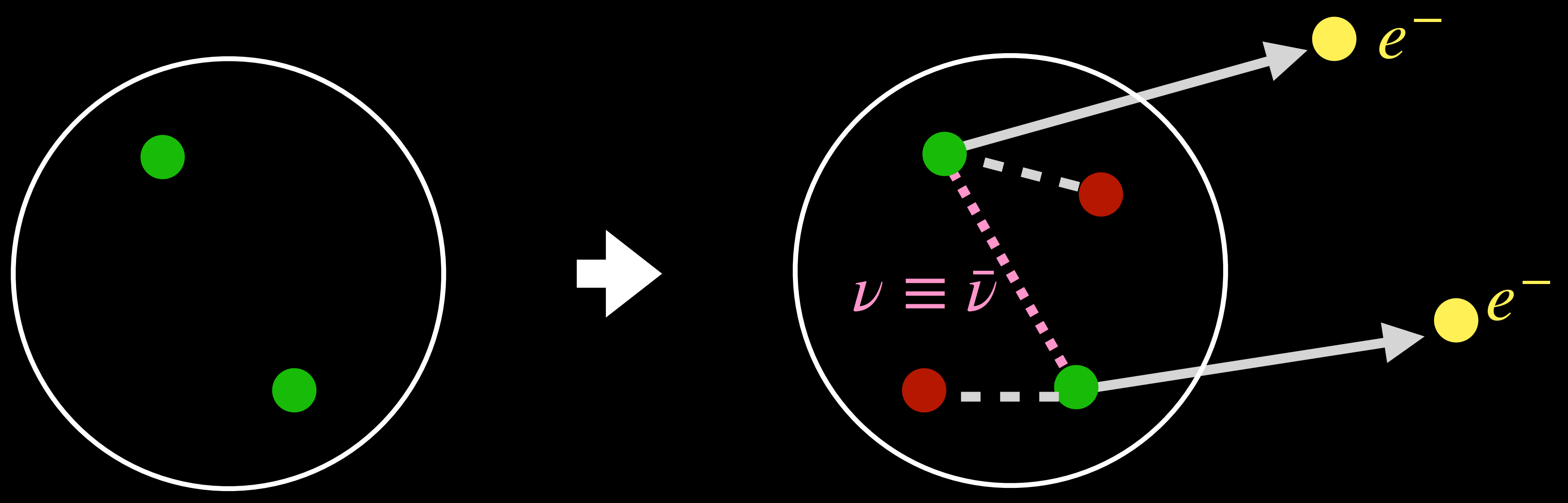
$0\nu\beta\beta$

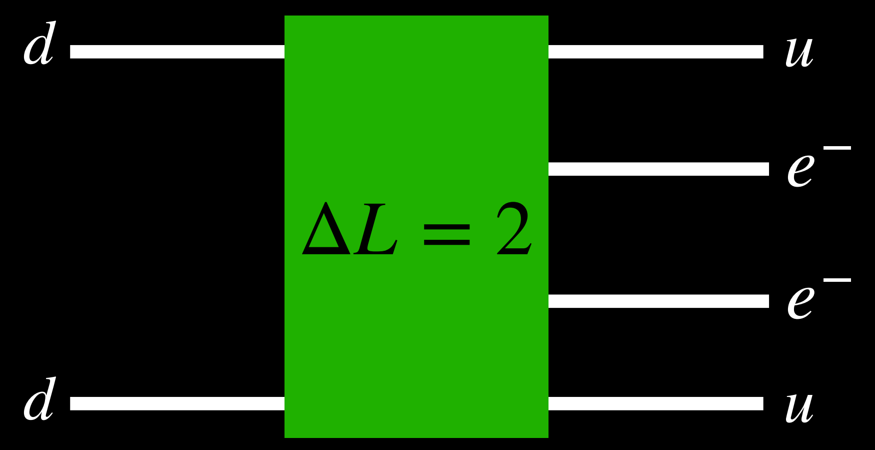




- Hypothetical $(A, Z) \longrightarrow (A, Z+2) + 2e^-$
- Forbidden in the Standard Model : $\Delta L = 2$
- The only known feasible way to prove the Majorana nature of ν

$0\nu\beta\beta$





$+ \cdots$

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Exchange of light Majorana neutrinos

$$\Gamma_\alpha(m_{\beta\beta}, M_{\alpha i}) = G_{0\nu} \times (g_A^2 \, | M_{\alpha i} |)^2 \times m_{\beta\beta}^2$$

Phase Space Factor (PSF) (kinematic)

$M_{\alpha i}$ **Nuclear Matrix Element (NME)**

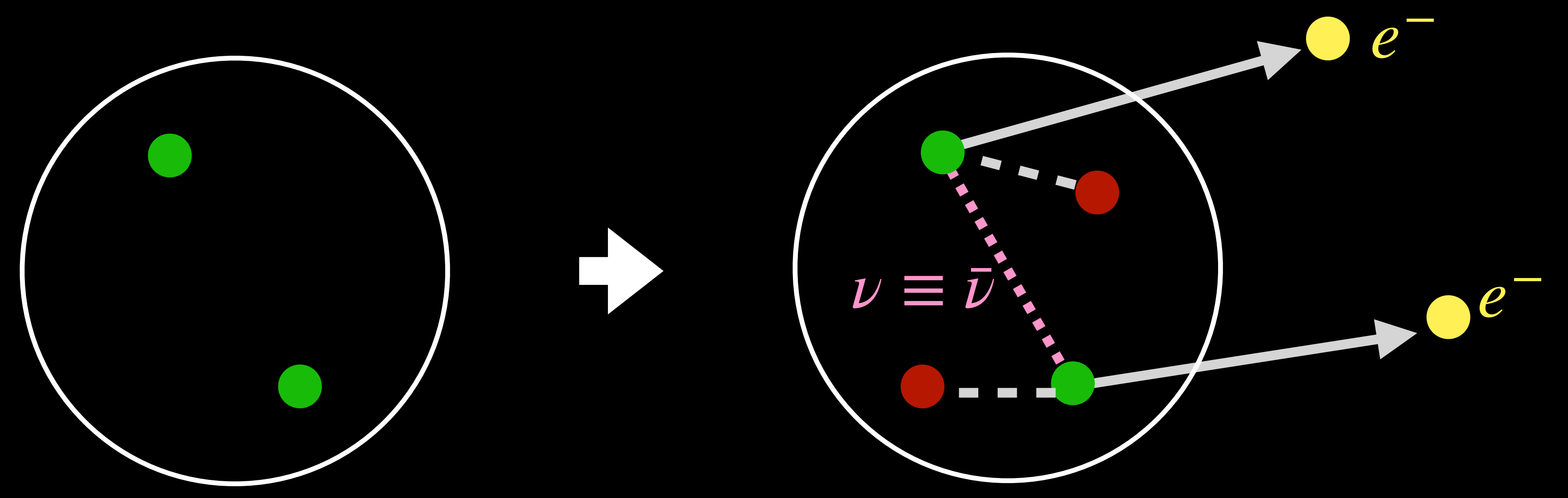
$g_A = q \, g_A^{\rm bare}$

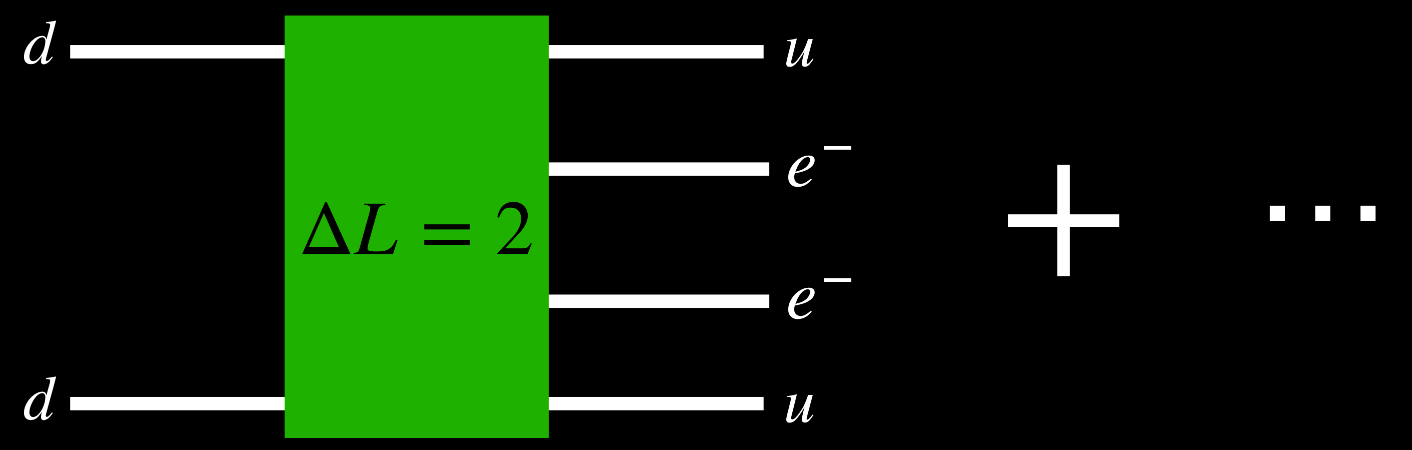
Effective Majorana mass

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

$$M_{\alpha i} = M_{\alpha i}^{\rm long}$$

$0\nu\beta\beta$





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$$M_{\alpha i} = M_{\alpha i}^{\rm long} + M_{\alpha i}^{\rm short} = M_{\alpha i}^{\rm long} \left(1 + \frac{M_{\alpha i}^{\rm short}}{M_{\alpha i}^{\rm long}} \right)$$

Unknown value and sign leading either to an enhancement or suppression of the expected decay rate

$\left\| \frac{M_{\alpha i}^{short}}{M_{\alpha i}^{long}} \right\|$	Nuclear Shell Model %	Quasiparticle Random Phase Approximation %
^{76}Ge	$15 \div 42$	$32 \div 73$
^{82}Se	$15 \div 42$	$30 \div 70$
^{100}Mo	-	$49 \div 108$
^{130}Te	$17 \div 47$	$34 \div 77$
^{136}Xe	$17 \div 47$	$30 \div 70$

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$M_{\alpha i}^{long}$		^{76}Ge	^{82}Se	^{100}Mo	^{130}Te	^{136}Xe
Nuclear Shell Model	N1	2.89	2.73	-	2.76	2.28
	N2	3.07	2.90	-	2.96	2.45
	N3	3.37	3.19	-	1.79	1.63
	N4	3.57	3.39	-	1.93	1.76
	N5	2.66	2.72	-	3.16	2.39
Quasiparticle Random Phase Approximation	Q1	5.09	-	-	1.37	1.55
	Q2	5.26	3.73	3.90	4.00	2.91
	Q3	4.85	4.61	5.87	4.67	2.72
	Q4	3.12	2.86	-	2.90	1.11
	Q5	3.40	3.13	-	3.22	1.18
	Q6	-	-	-	4.05	3.38
Energy-Density Functional theory	E1	4.60	4.22	5.08	5.13	4.20
	E2	5.55	4.67	6.59	6.41	4.77
	E3	6.04	5.30	6.48	4.89	4.24
Interacting Boson Model	I1	5.14	4.19	3.84	3.96	3.25
	I2	6.34	5.21	5.08	4.15	3.40

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$$M_{\alpha i} = M_{\alpha i}^{long} + M_{\alpha i}^{short} = M_{\alpha i}^{long}\left(1 + \frac{M_{\alpha i}^{short}}{M_{\alpha i}^{long}}\right)$$

What is the effect induced by this new short-range contribution?

Unknown value and sign leading either to an enhancement or suppression of the expected decay rate

$\left\vert \frac{M_{\alpha i}^{short}}{M_{\alpha i}^{long}} \right\vert$	Nuclear Shell Model %	Quasiparticle Random Phase Approximation %
^{76}Ge	$15 \div 42$	$32 \div 73$
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^{100}Mo	-	$49 \div 108$
^{130}Te	[illegible]	[illegible]
^{136}Xe	$17 \div 47$	$30 \div 70$

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	Q2	5.26	[illegible]	3.90	[illegible]	2.91
	Q3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Q4	3.12	2.86	-	2.90	1.11
	Q5	3.40	[illegible]	[illegible]	[illegible]	1.18
	Q6	[illegible]	[illegible]	[illegible]	4.05	3.38
Energy-Density Functional theory	E1	4.60	4.22	5.08	5.13	4.20
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$$M_{\alpha i} = M_{\alpha i}^{long} + M_{\alpha i}^{short} = M_{\alpha i}^{long}\left(1 + \frac{M_{\alpha i}^{short}}{M_{\alpha i}^{long}}\right)$$

Future prospect

^{76}Ge	LEGEND-1000
^{136}Xe	nEXO
^{100}Mo	CUPID
^{130}Te	SNO+II
^{82}Se	SuperNEMO

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

$$B_\alpha = b_\alpha \cdot \varepsilon_\alpha \cdot \left(\frac{T}{1\,\mathrm{yr}}\right)$$

$$N_{\alpha i} = S_{\alpha i} + B_\alpha$$

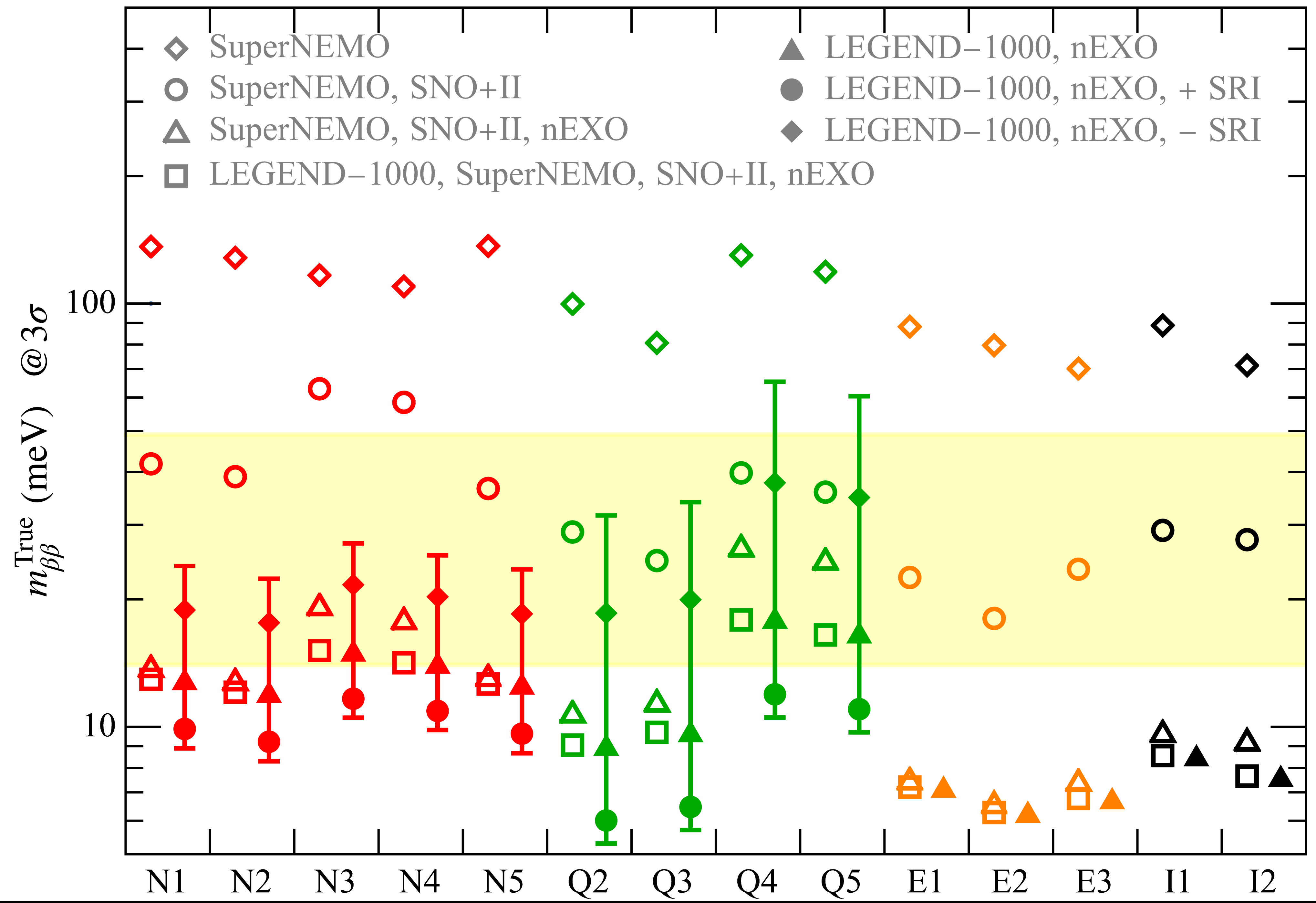
$$[\varepsilon] = \mathrm{mol}\cdot\mathrm{yr} \qquad [b] = \frac{\mathrm{events}}{\mathrm{mol}\cdot\mathrm{yr}}$$

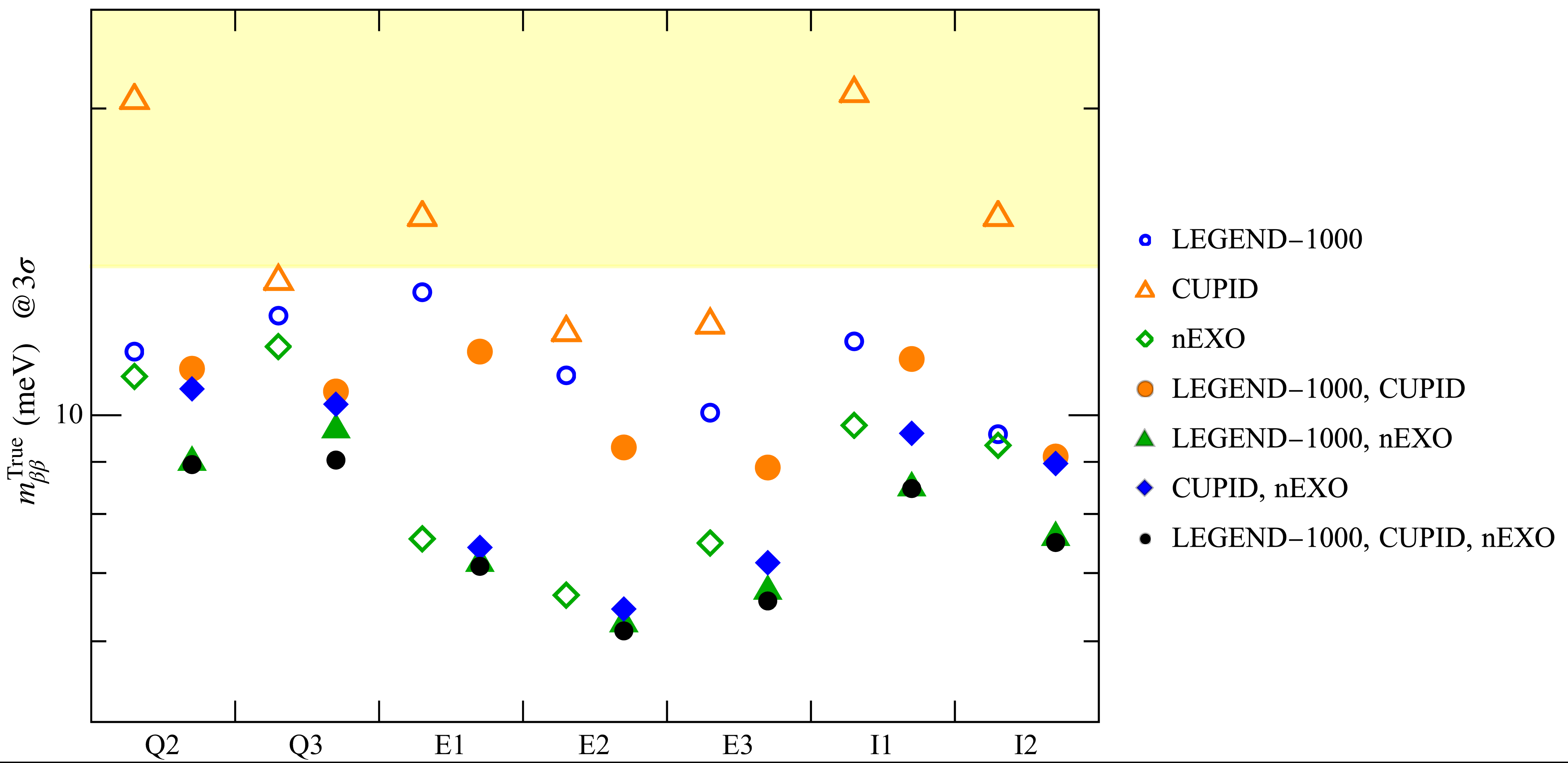
$T = 10\ \mathrm{yr}$ in the following analysis

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

Future prospect

Sensitivity @ 3σ ($\Delta\chi^2_{\text{tot}} = 9$)





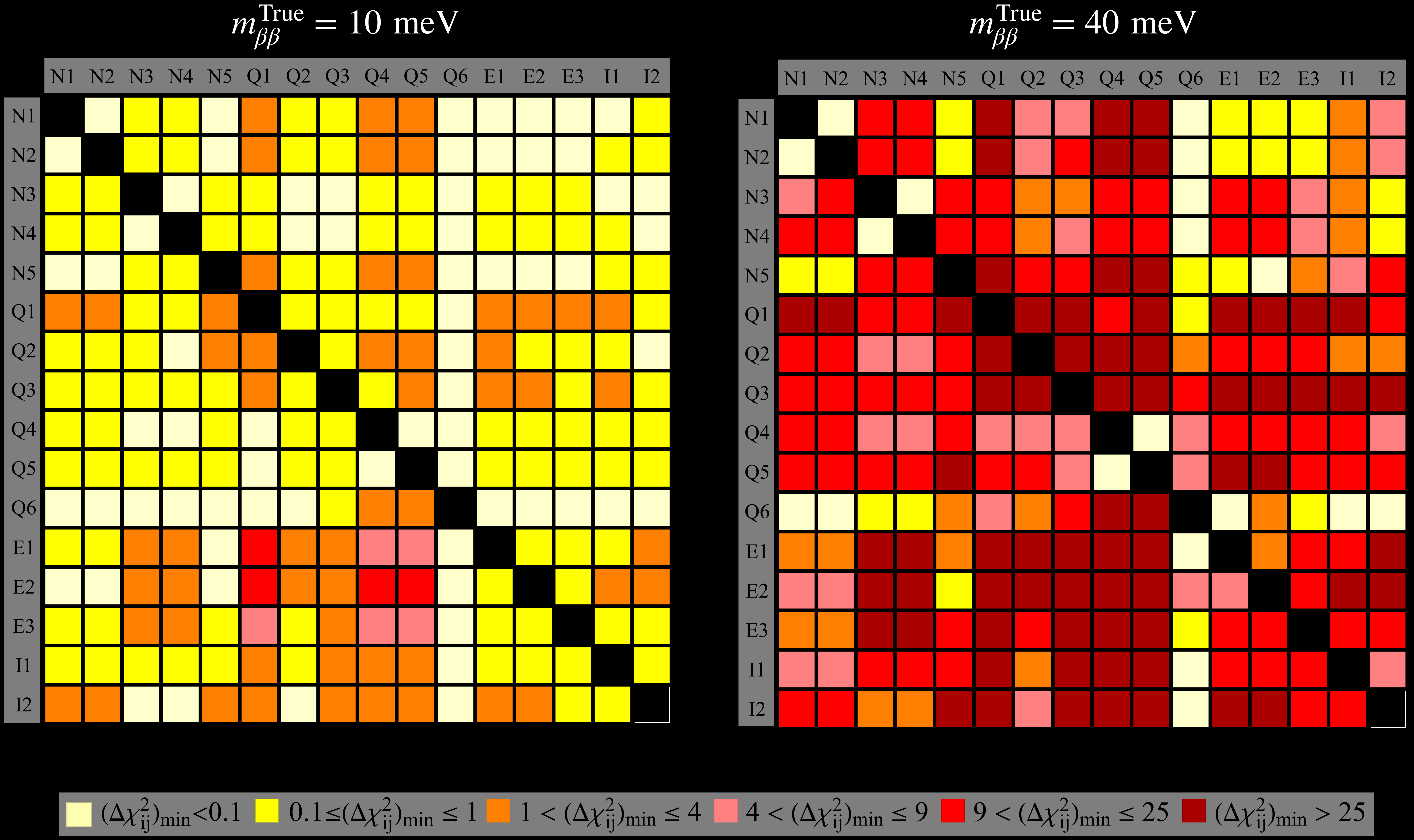
- Big impact of the short-range term
- Uncertainties on both the size and sign of $\left|\frac{M_\alpha^{\text{short}}}{M_\alpha^{\text{long}}}\right|$
- LEGEND-1000 (^{76}Ge) + nEXO (^{136}Xe)

Assuming that future $0\nu\beta\beta$ experiments detect a positive signal, will it be possible, via the combination of several experiments, to discriminate among different nuclear models?

$$M_{\alpha i} = M_{\alpha i}^{\text{long}}$$

$$(\Delta\chi^2_{ij})_{\min} = \min_{m_{\beta\beta}} \Delta\chi^2_{ij}\,(m_{\beta\beta}, M_{\alpha j}\,;\, m_{\beta\beta}^{\text{True}}, M_{\alpha i}^{\text{True}}) \longrightarrow (\Delta\chi^2_{ij})_{\min} \neq 0$$

A large set of (i, j) model combinations allows a 3σ model discrimination in the Inverted Mass Ordering



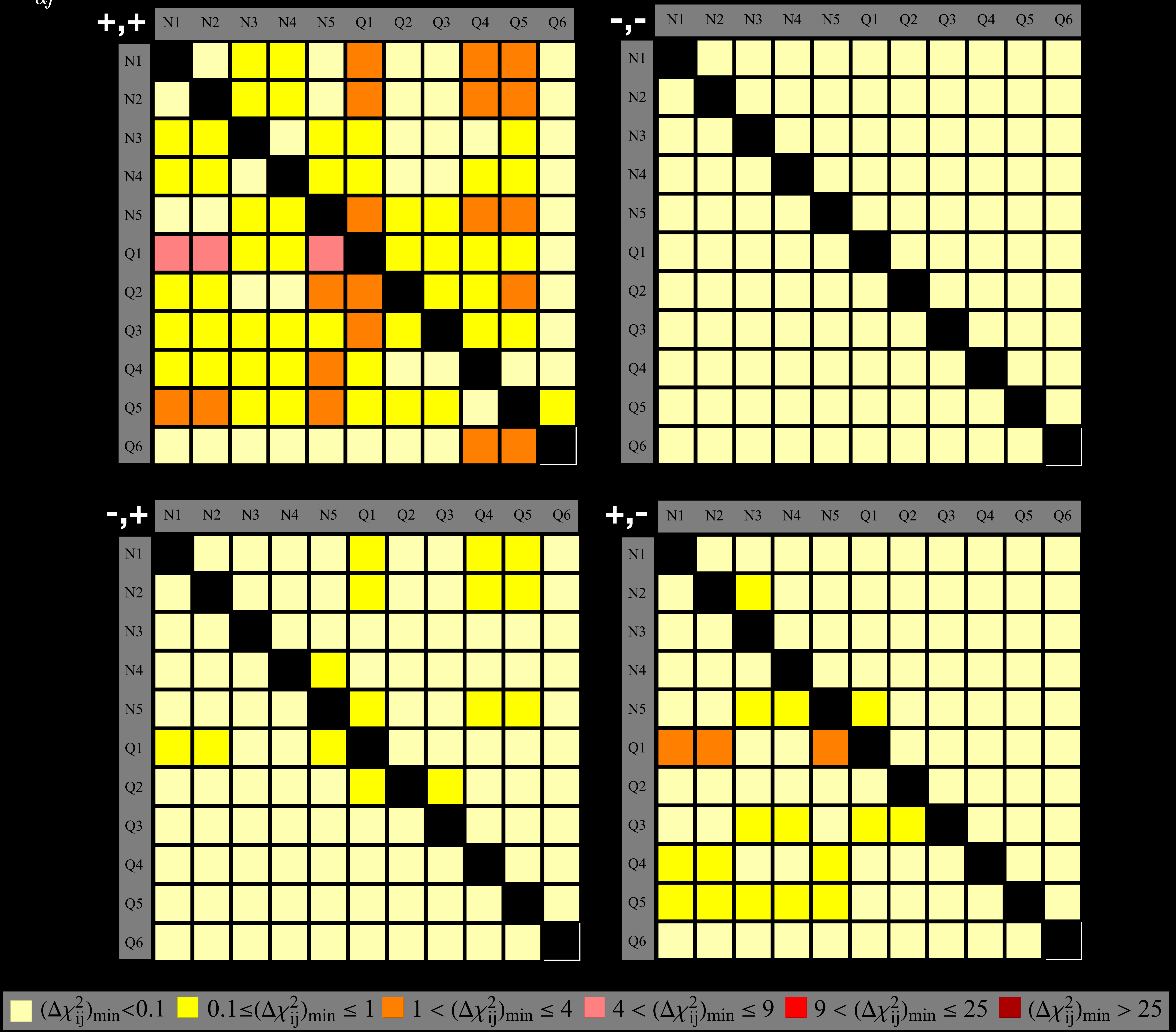
$$\boxed{M_{\alpha i} = M^{\text{long}}_{\alpha i} + M^{\text{short}}_{\alpha i}}$$

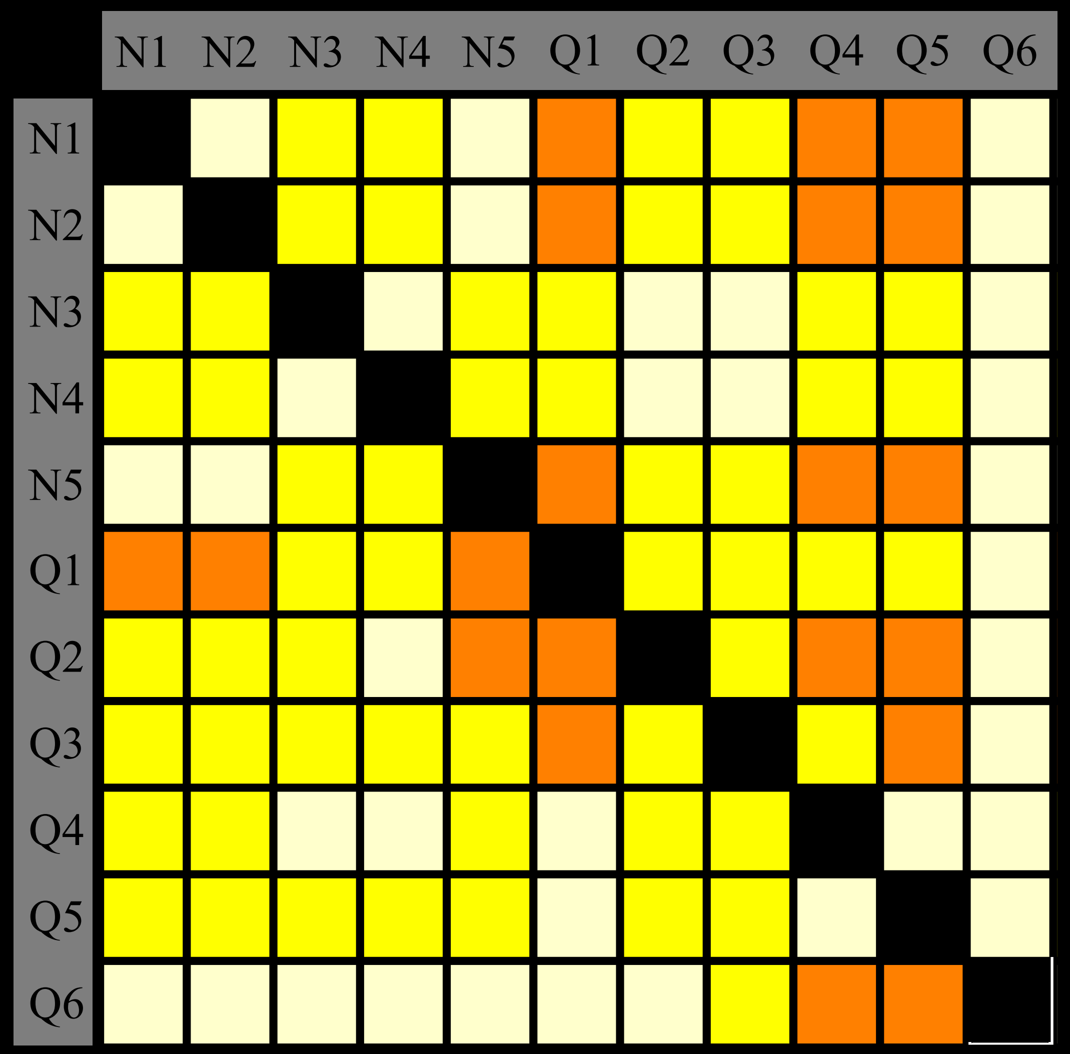
$$(\Delta\chi^2_{ij})_{\min} = \min_{m_{\beta\beta},\, \frac{M^{\text{short}}_{\alpha j}}{M^{\text{long}}_{\alpha j}}} \Delta\chi^2_{ij}\,(m_{\beta\beta}, M_{\alpha j}\,;\, m^{\text{True}}_{\beta\beta}, M^{\text{True}}_{\alpha i}) \longrightarrow (\Delta\chi^2_{ij})_{\min} \neq 0$$

$$m^{\text{True}}_{\beta\beta} = 10 \text{ meV}$$

$\left|\frac{M^{\text{short}}_{\alpha i}}{M^{\text{long}}_{\alpha i}}\right|$ taken as the central value of the allowed range

$\left|\frac{M^{\text{short}}_{\alpha j}}{M^{\text{long}}_{\alpha j}}\right|$ free to vary in the corresponding range





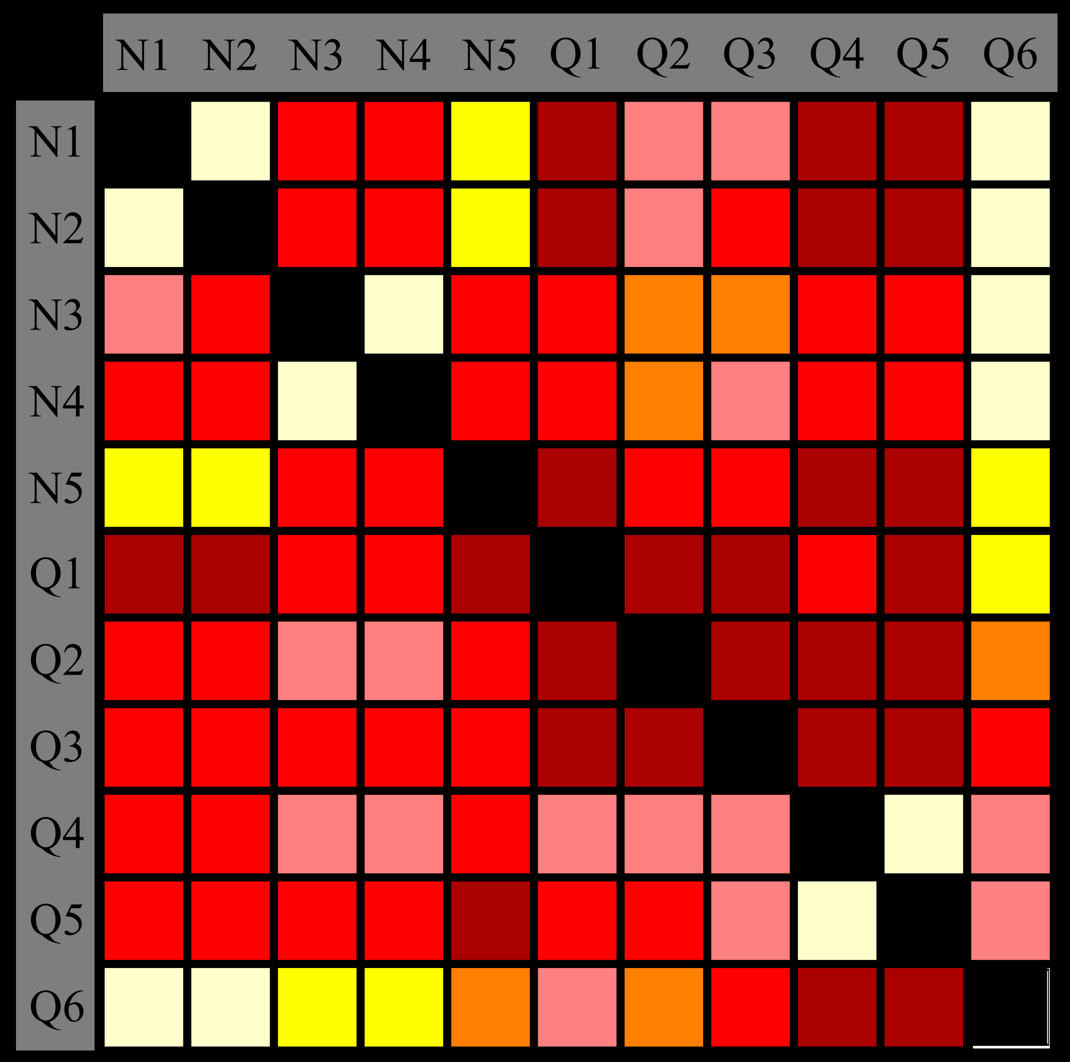
$$\boxed{M_{\alpha i} = M_{\alpha i}^{\rm long} + M_{\alpha i}^{\rm short}}$$

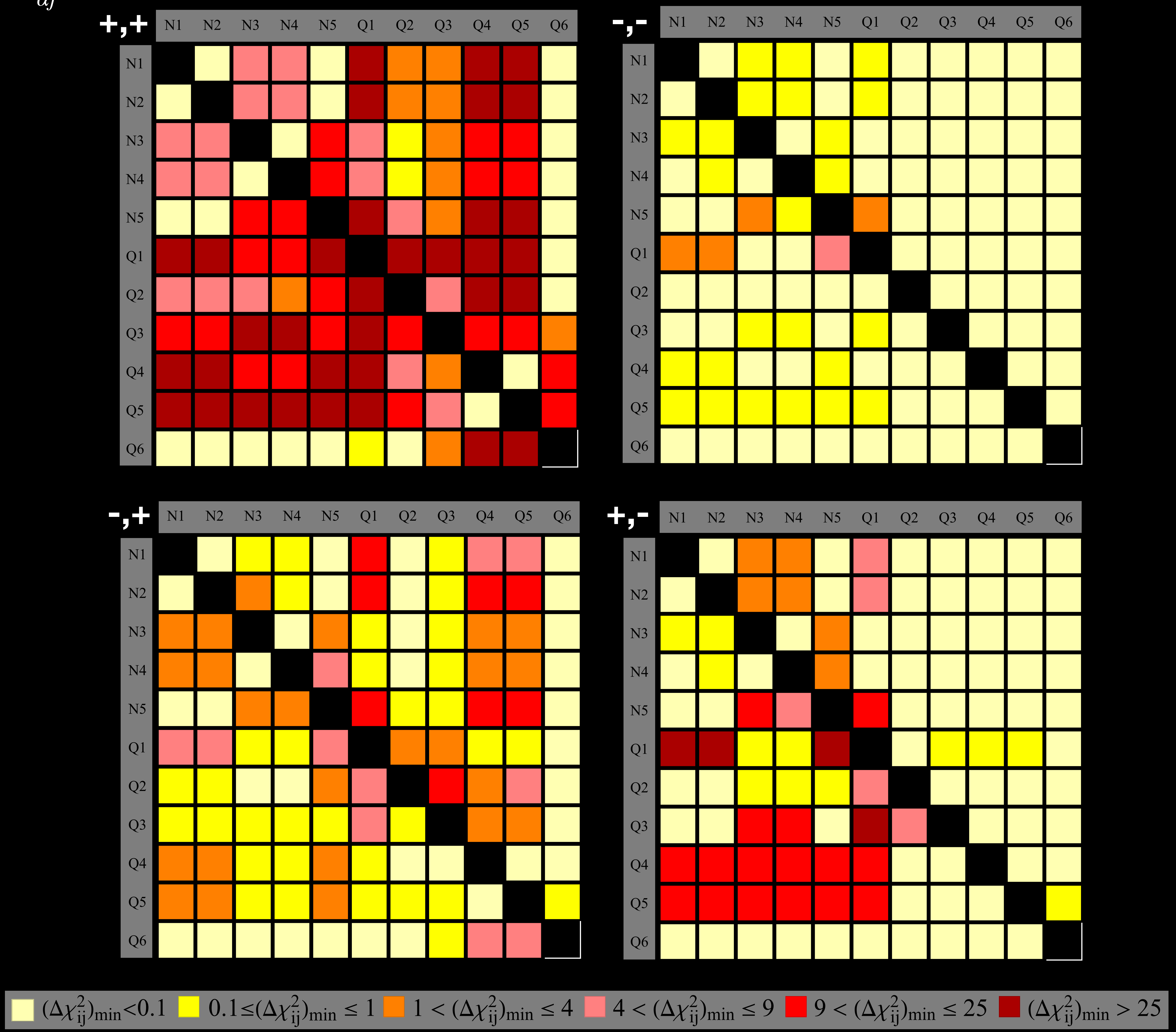
$$(\Delta\chi^2_{ij})_{\rm min} = \min_{m_{\beta\beta},\, \frac{M_{\alpha j}^{\rm short}}{M_{\alpha j}^{\rm long}}} \Delta\chi^2_{ij}\,(m_{\beta\beta}, M_{\alpha j}\,;\, m_{\beta\beta}^{\rm True}, M_{\alpha i}^{\rm True}) \longrightarrow (\Delta\chi^2_{ij})_{\rm min} \neq 0$$

$$m_{\beta\beta}^{\rm True} = 40\ {\rm meV}$$

$\left|\frac{M_{\alpha i}^{\rm short}}{M_{\alpha i}^{\rm long}}\right|$ taken as the central value of the allowed range

$\left|\frac{M_{\alpha j}^{\rm short}}{M_{\alpha j}^{\rm long}}\right|$ free to vary in the corresponding range





In conclusion

Assuming that future $0\nu\beta\beta$ experiments detect a positive signal, will it be possible, via the combination of several experiments, to discriminate among different nuclear models?

This project has received funding and support from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No 860881-HIDDeN

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In conclusion

Assuming that future $0\nu\beta\beta$ experiments detect a positive signal, will it be possible, via the combination of several experiments, to discriminate among different nuclear models?

YES (depending on the value Nature has chosen for $m_{\beta\beta}^{\rm True}$)!

The short-range term could affect considerably both the sensitivities and the nuclear model discrimination power of next-generation $0\nu\beta\beta$ experiments:

- The most sensitive projects are LEGEND-1000 and nEXO, whose sensitivity to $m_{\beta\beta}$ will cover most part of the inverted mass ordering region for many NME models. However, unfortunate short-range interaction interference might prevent these advanced setups to reach this region.
- Discriminating between different NME calculations will be possible for a broad range of NME models, even though the presence of the short-range contribution will essentially destroy this sensitivity, unless its sign is known to be positive.

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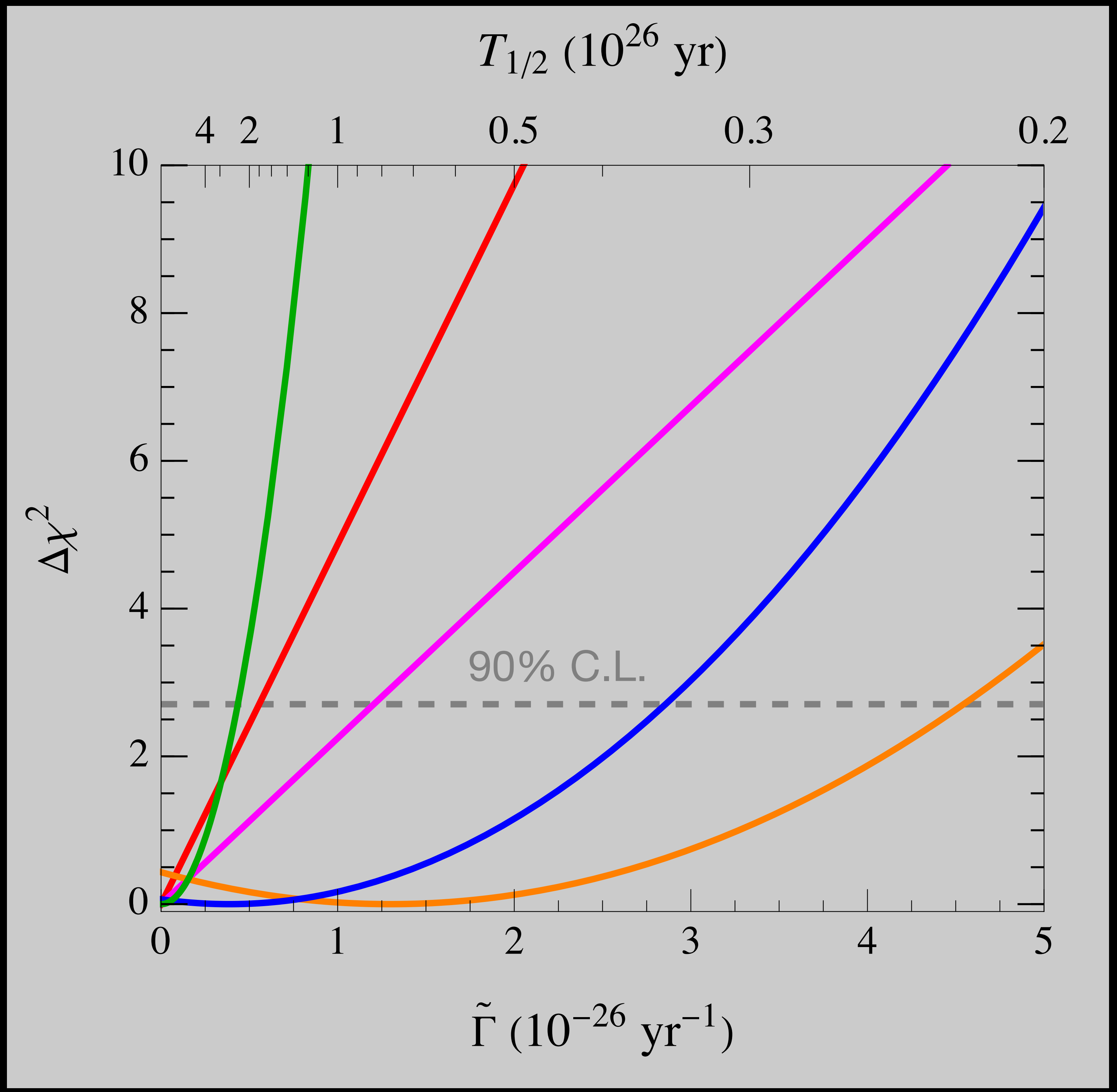
Backup

Current picture

E.Lisi, A.Marrone - Phys.Rev.D 106 (2022) 1, 013009

$$\Delta\chi^2_r(\Gamma_\alpha) = a_r(\Gamma_\alpha)^2 + b_r\Gamma_\alpha + c_r$$



		$\times 10^{26}$ yr	meV
^{76}Ge	GERDA	$T_{1/2} > 1.8$ →	$m_{\beta\beta} \in [79, 180]$
	MAJORANA	$T_{1/2} > 0.83$ →	$m_{\beta\beta} \in [113, 269]$
^{130}Te	CUORE	$T_{1/2} > 0.22$ →	$m_{\beta\beta} \in [90, 305]$
^{136}Xe	EXO-200	$T_{1/2} > 0.35$ →	$m_{\beta\beta} \in [93, 286]$
	KamLAND-Zen	$T_{1/2} > 2.3$ →	$m_{\beta\beta} \in [36, 156]$

Inverted Mass Ordering : $m_{\beta\beta} \in [14, 49]$ meV

Backup

Current picture

E.Lisi, A.Marrone - Phys.Rev.D 106 (2022) 1, 013009

Sensitivity on $m_{\beta\beta}$:

$$\Delta\chi^2_r(\Gamma_\alpha) = a_r(\Gamma_\alpha)^2 + b_r\Gamma_\alpha + c_r$$

$$\Gamma_\alpha(m_{\beta\beta}, M_{\alpha i}) = G_{0\nu}\,(\,g_A^2\,|\,M_{0\nu}\,|\,)^2\, m_{\beta\beta}^2$$

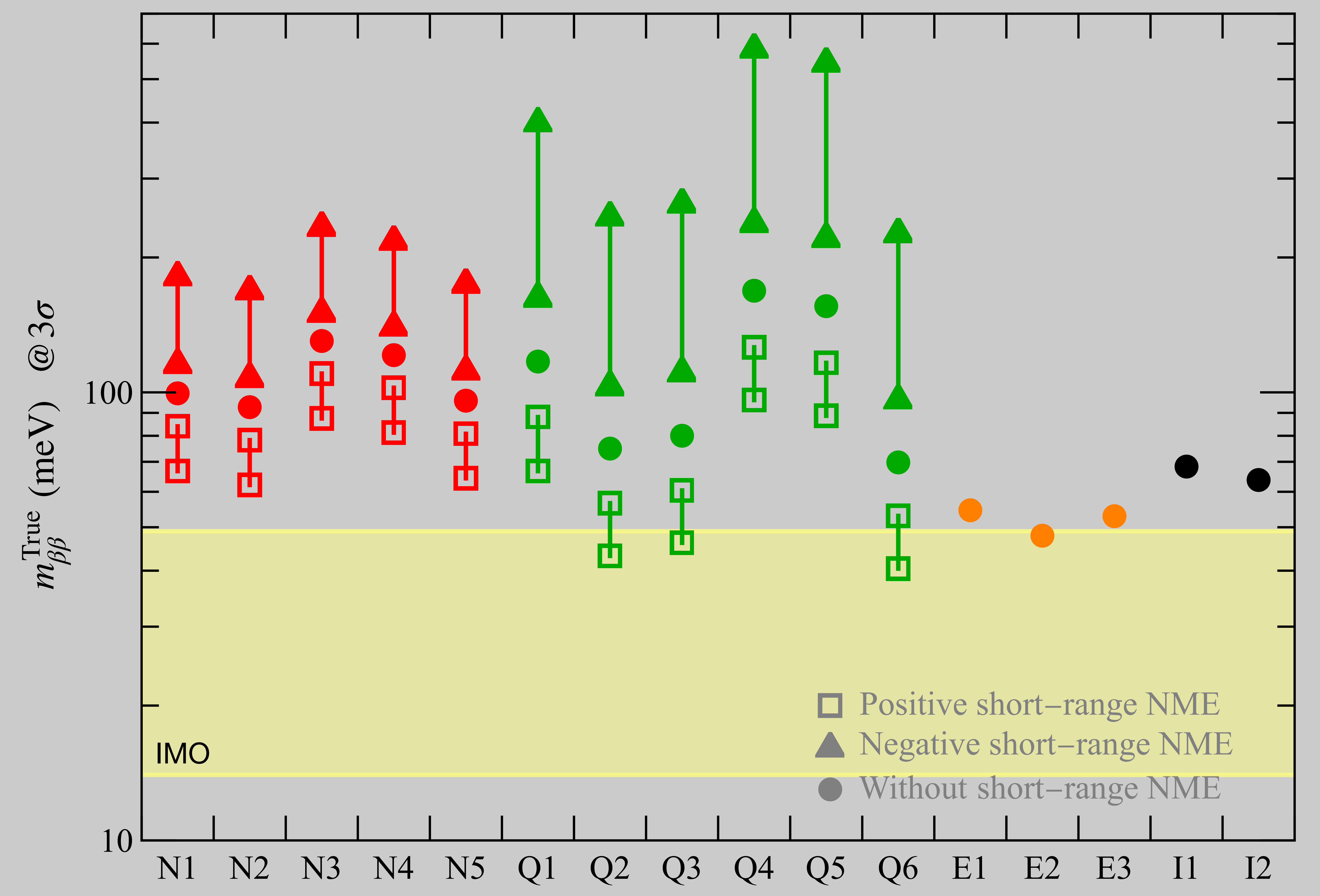
$$\Downarrow$$

$$\chi^2_{\rm tot}(m_{\beta\beta}) = \sum_r \Delta\chi^2_r(m_{\beta\beta})$$

$$\Delta\chi^2_{\rm tot}(m_{\beta\beta}) = \chi^2_{\rm tot}(m_{\beta\beta}) - \chi^2_{\rm tot,min}(m_{\beta\beta})$$

- Impact of the short-range term
- Uncertainties on both the size and sign of $|\,n_{\alpha i}\,|$

@ 3σ $(\Delta\chi^2_{\rm tot} = 9)$



Backup

$$\Delta\chi_r^2(\Gamma_\alpha) = a_r(\Gamma_\alpha)^2 + b_r\Gamma_\alpha + c_r$$

E.Lisi, A.Marrone - Phys.Rev.D 106 (2022) 1, 013009

Nuclide	Experiment	a_r	b_r	c_r	$T_{1/2}^{90}/10^{26}\text{yr}$
^{76}Ge	GERDA	0.000	4.871	0.000	1.8
	MAJORANA	0.000	2.246	0.000	0.83
^{130}Te	CUORE	0.257	−0.667	0.433	0.22
^{136}Xe	KamLAND-Zen	14.315	0.000	0.000	2.3
	EXO-200	0.443	−0.342	0.066	0.35

Updated with recent results

Backup

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

$$B_\alpha = b_\alpha \cdot \varepsilon_\alpha \cdot \left(\frac{T}{1\ \mathrm{yr}}\right)$$

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Experiment	Isotope	ε [mol·yr]	b [events/(mol·y)]	PSF [$\mathrm{yr}^{-1}\ \mathrm{eV}^{-2}$]
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	$4.0 \cdot 10^{-5}$	$14.56 \cdot 10^{-26}$

Backup

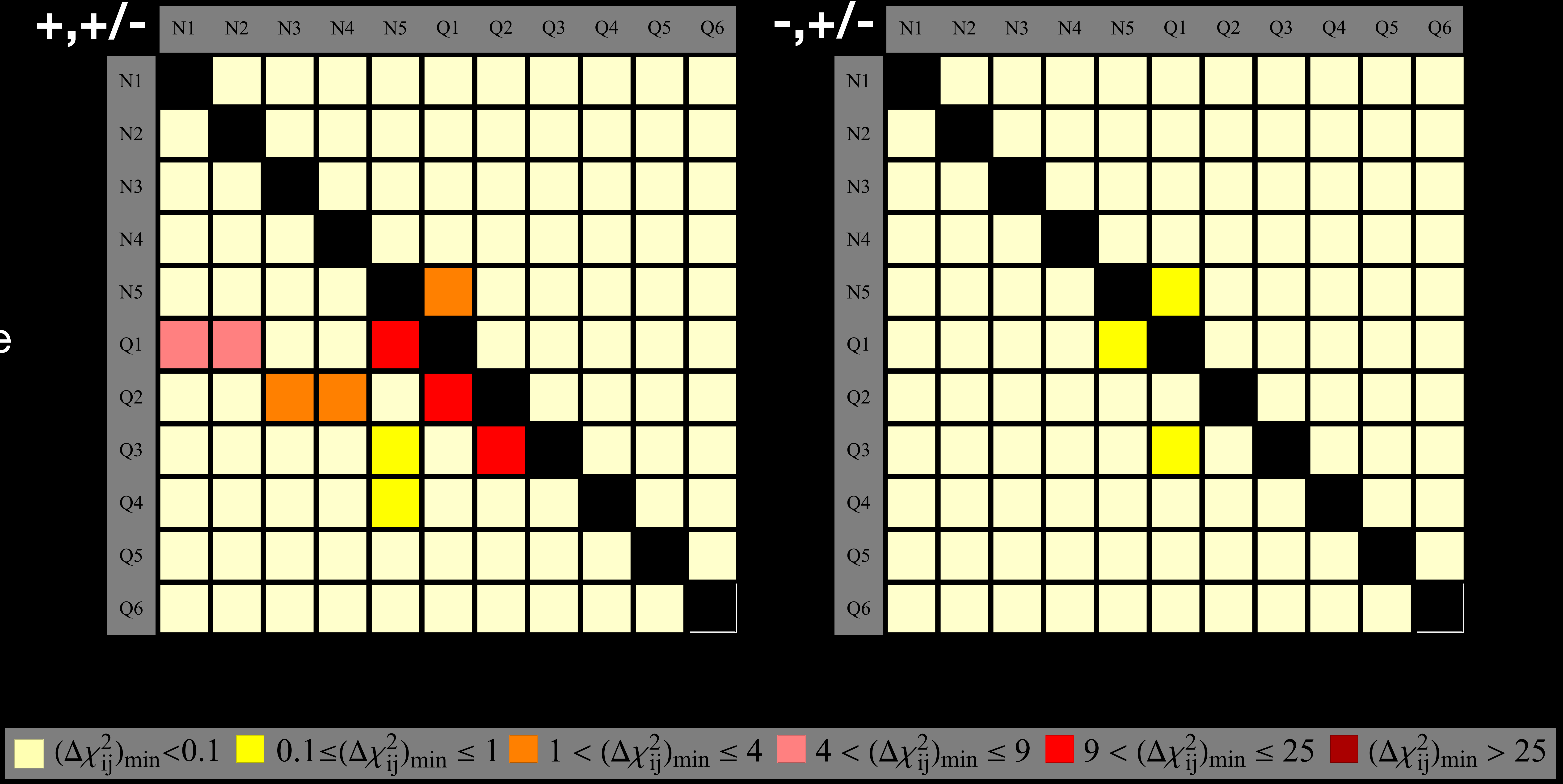
What if sign unknown?

$$m_{\beta\beta}^{\mathrm{True}} = 60\ \mathrm{meV}$$

$\left|\dfrac{M_{\alpha i}^{\mathrm{short}}}{M_{\alpha i}^{\mathrm{long}}}\right|$ taken as the central value of the allowed range

$\left|\dfrac{M_{\alpha j}^{\mathrm{short}}}{M_{\alpha j}^{\mathrm{long}}}\right|$ free to vary in the union of the corresponding positive and negative ranges

Discrimination power gets weaken for smaller $m_{\beta\beta}^{\mathrm{True}}$



Not promising nuclear model discrimination!

Backup

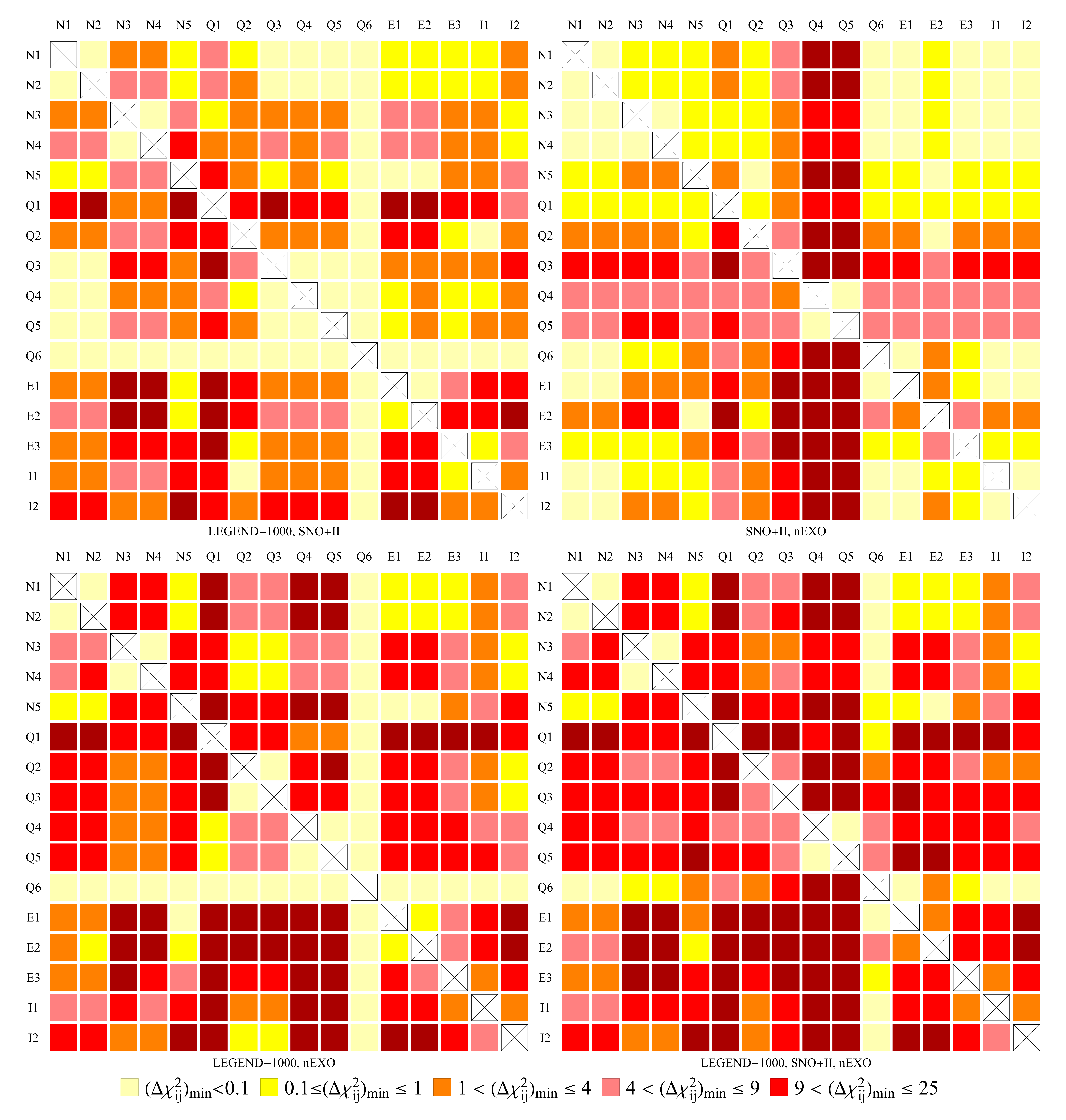
$$M_{\alpha i} = M_{\alpha i}^{\text{long}}$$

$$m_{\beta\beta}^{\text{True}} = 40 \text{ meV}$$

Nuclear model discrimination power for different combinations of future experiments.

All Nuclear models considered.

The involvement of SNO+II significantly improves the discrimination potential and increase the number of distinguishable models.



Backup

$$\boxed{M_{\alpha i} = M_{\alpha i}^{\text{long}}}$$

$$m_{\beta\beta}^{\text{True}} = 40 \text{ meV}$$

Nuclear model discrimination power for different combinations of future experiments.

The involvement of CUPID significantly improves the discrimination potential and increase the number of distinguishable models.