HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Unveiling the mysteries of neutrinoless double beta decay: exploring Nuclear Matrix Elements and their impact on Majorana mass sensitivities

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

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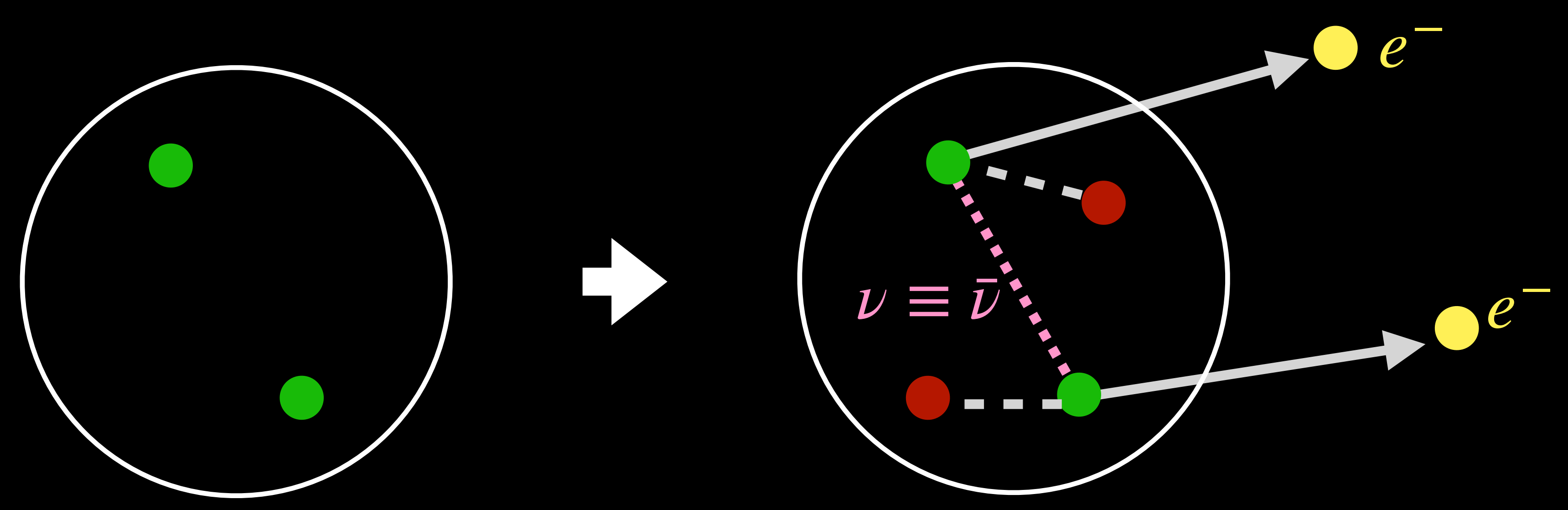
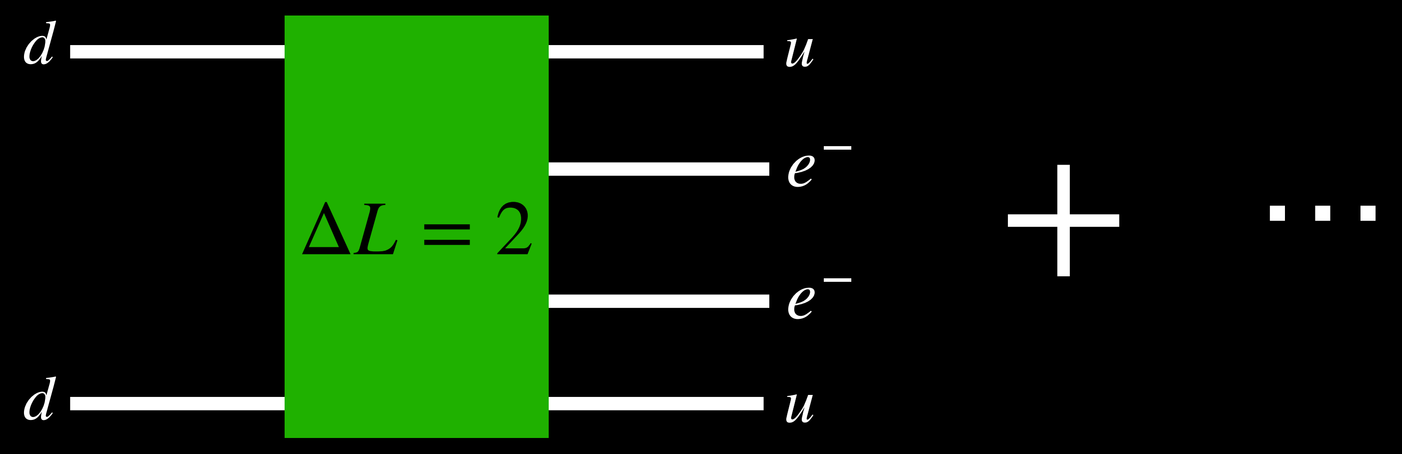
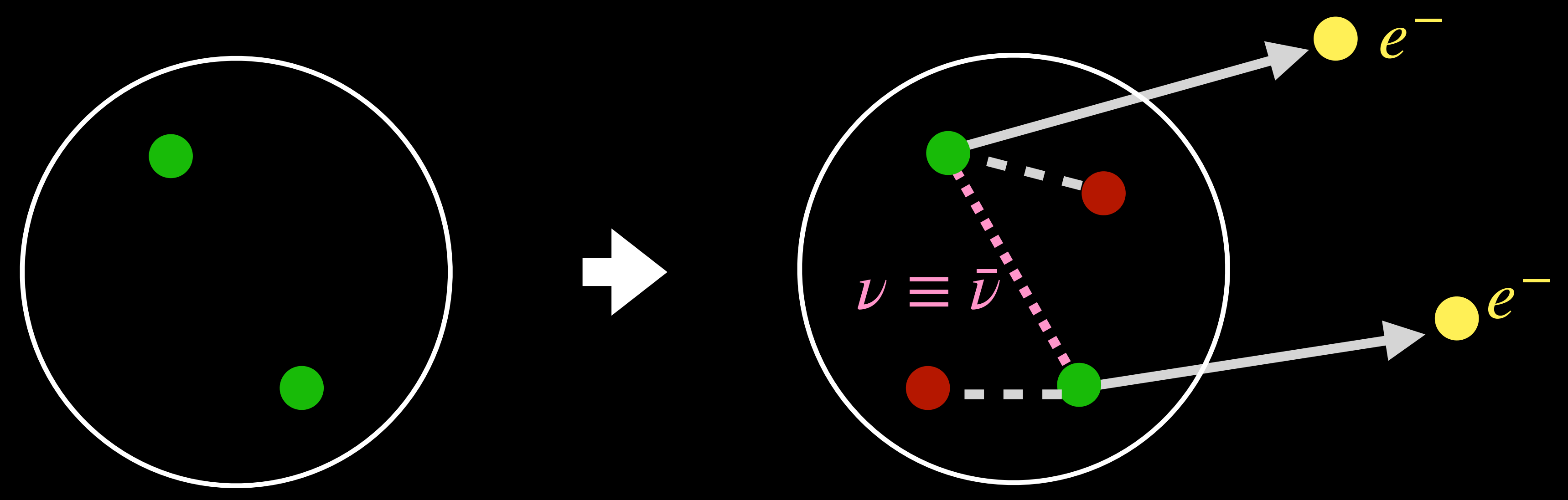
$0\nu\beta\beta$

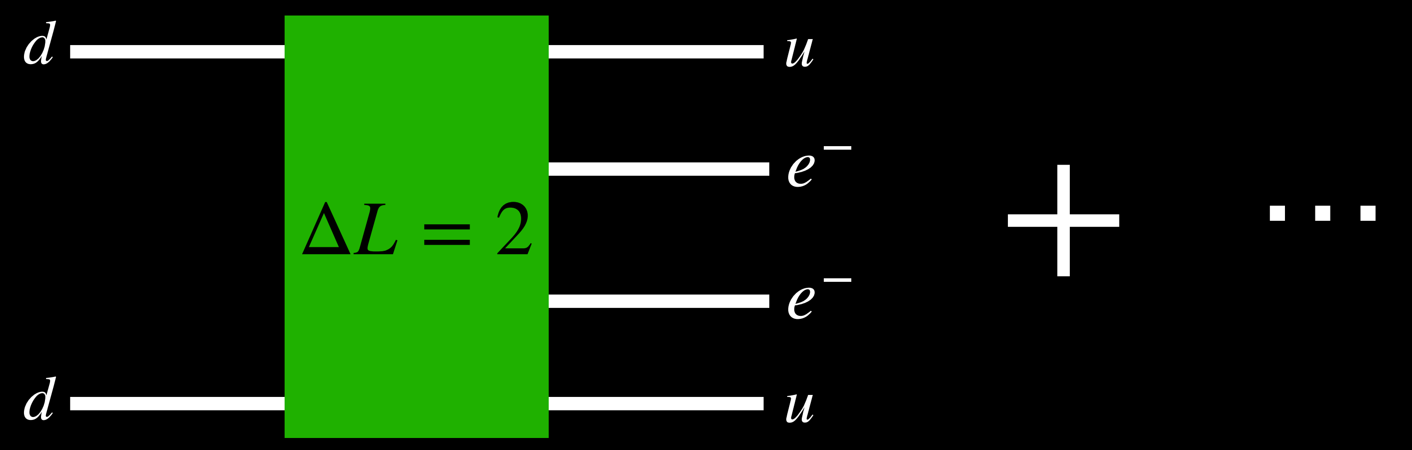




- Hypothetical $(A, Z) \longrightarrow (A, Z+2) + 2e^-$
- Forbidden in the Standard Model : $\Delta L = 2$
- The only known feasible way to prove the Majorana nature of ν

$0\nu\beta\beta$





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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)**

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

Effective Majorana mass

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

Nuclear Models and Nuclear Matrix Elements

M.Agostini et all. - Rev.Mod.Phys. 95 (2023) 2, 025002

$M_{0\nu} = M_{0\nu}^{\text{long}}$ Long-range contribution to the decay rate induced by the exchange of light Majorana ν

- Calculations performed by different groups by assuming $g_A^{\text{bare}} = 1.27$
- Data not available for all the isotopes
- Variation in $M_{0\nu}^{\text{long}}$ of a factor ~ 3

		^{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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	N4	3.57	3.39	-	[illegible]	1.76
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Large theoretical uncertainties!

Short-range contribution

V.Cirigliano et al, Phys.Rev.Lett.120,202001

To renormalize the $0\nu\beta\beta$ amplitude due to light Majorana ν exchange

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

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To renormalize the $0\nu\beta\beta$ amplitude due to light Majorana ν exchange

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

↓

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

Short-range contribution

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

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

$$|n_{\alpha i}| \in$$

	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	$17 \div 47$	$30 \div 70$

L.Jokiniemi et all. - Phys.Lett.B 823 (2021) 136720

Short-range contribution

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To renormalize the $0\nu\beta\beta$ amplitude due to light Majorana ν exchange

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

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 ← $n_{\alpha i} = \dfrac{M^{\text{short}}_{\alpha i}}{M^{\text{long}}_{\alpha i}}$ → $|n_{\alpha i}| \in$

	Nuclear Shell Model %	Quasiparticle Random Phase Approximation %
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Future prospect

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

M.Agostini et all. - Rev.Mod.Phys. 95 (2023) 2, 025002

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

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

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

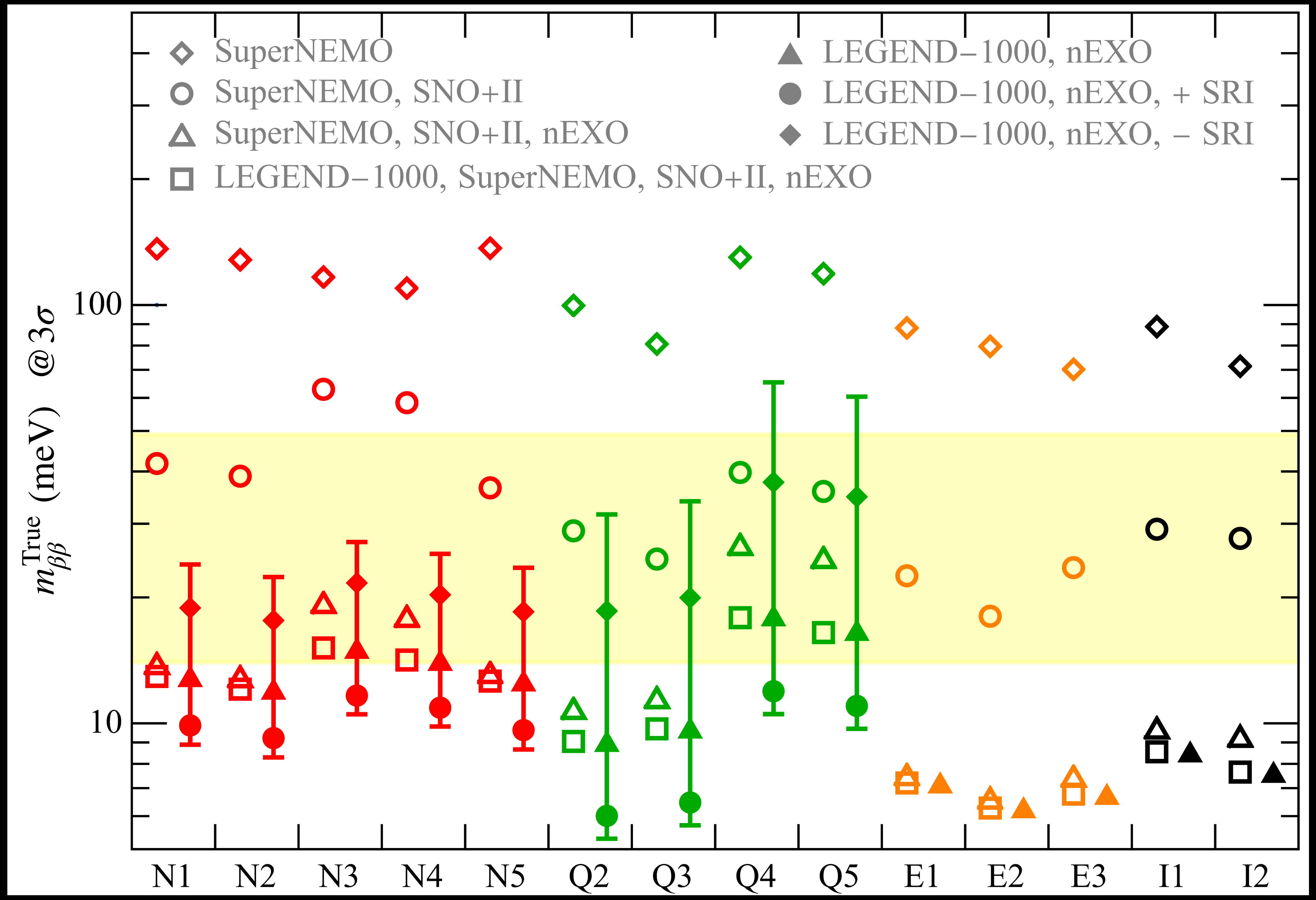
$$[\varepsilon] = \mathrm{mol} \cdot \mathrm{yr} \qquad [b] = \frac{\mathrm{events}}{\mathrm{mol} \cdot \mathrm{yr}}$$

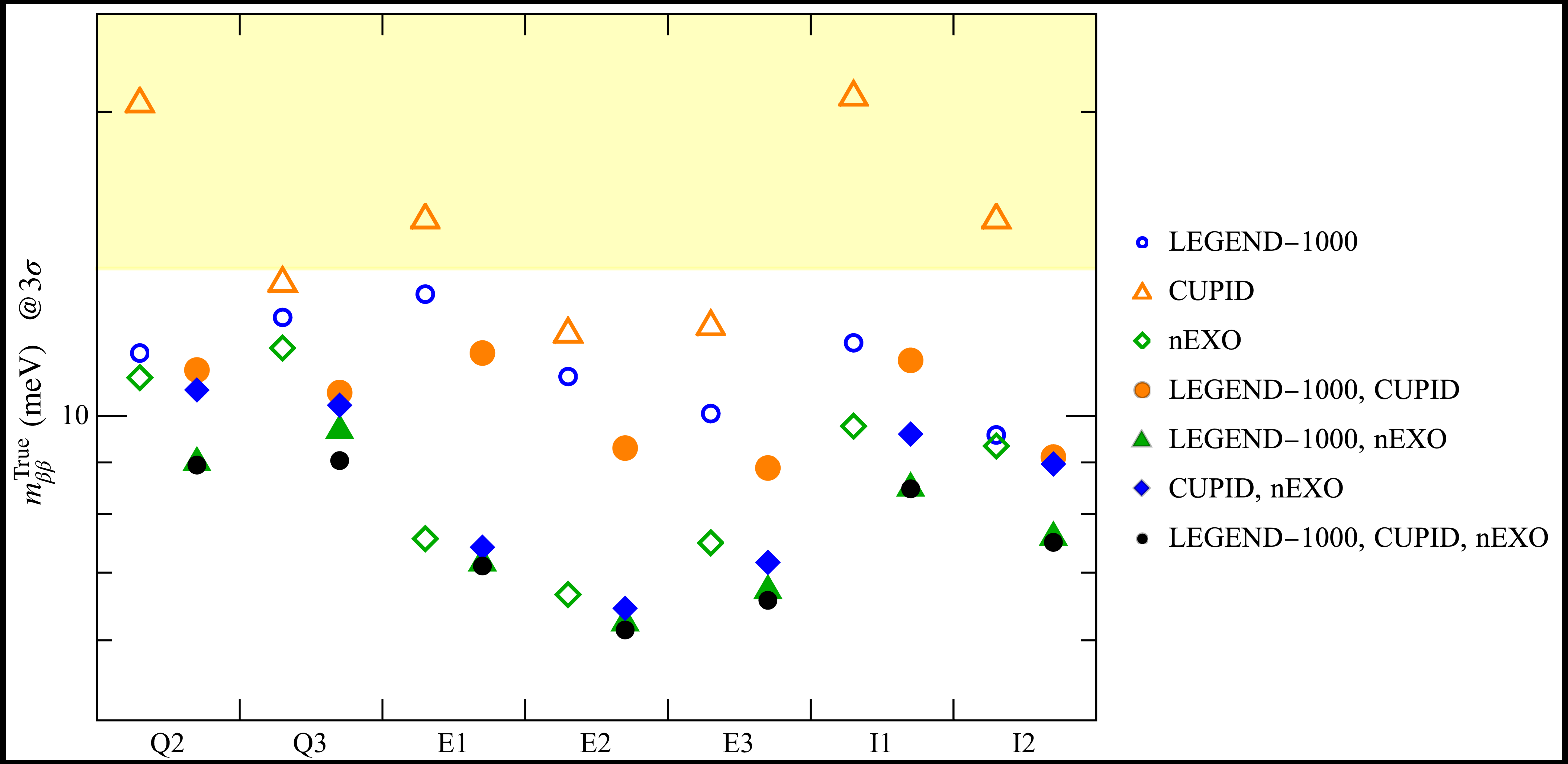
$T = 10\ \mathrm{yr}$ in the following analysis

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

Future prospect

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





- Big impact of the short-range term
- Uncertainties on both the size and sign of $|n_{\alpha i}|$
- LEGEND-1000 (^{76}Ge) + nEXO (^{136}Xe)

Nuclear model discrimination

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

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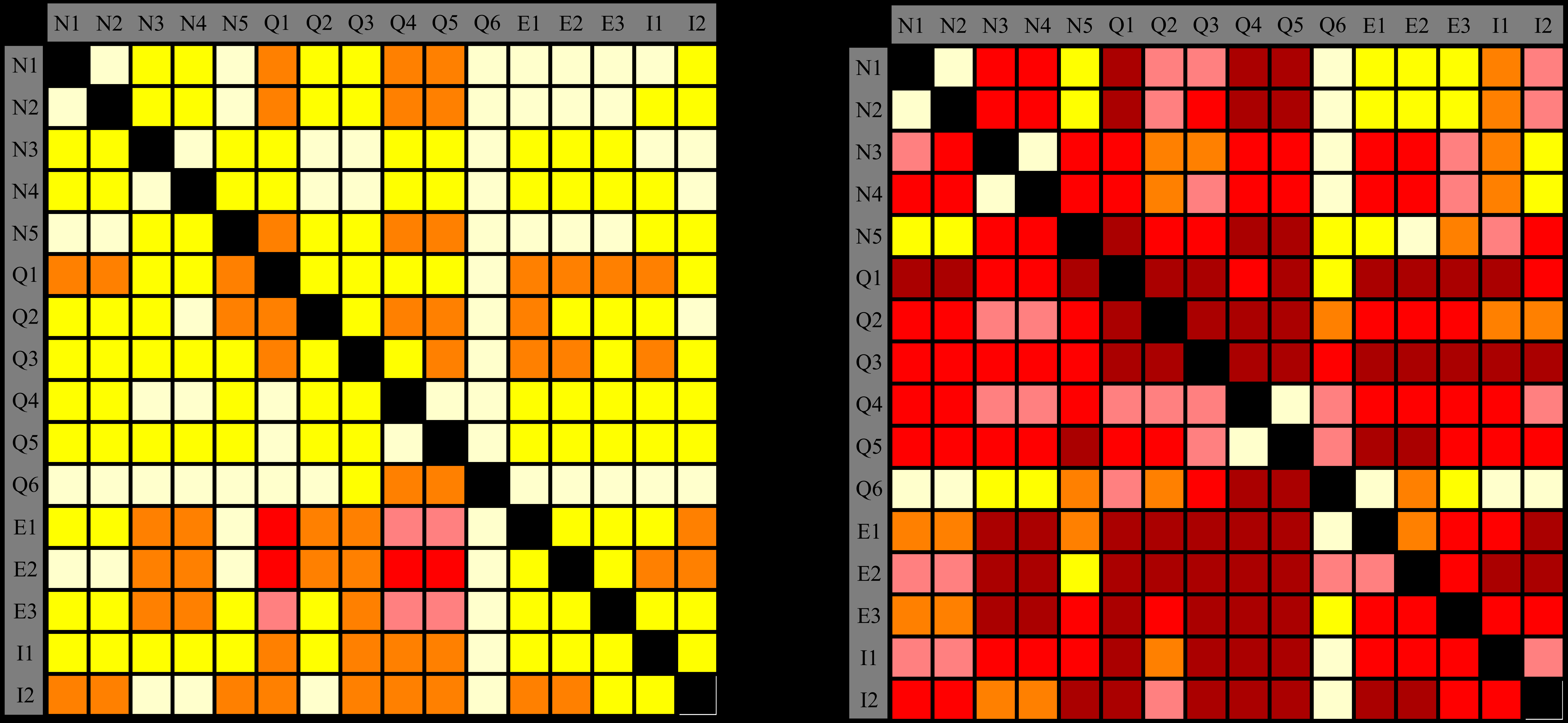
$$\boxed{M_{\alpha i} = M_{\alpha i}^{\text{long}}}$$

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

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

$m_{\beta\beta}^{\text{True}} = 10$ meV

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

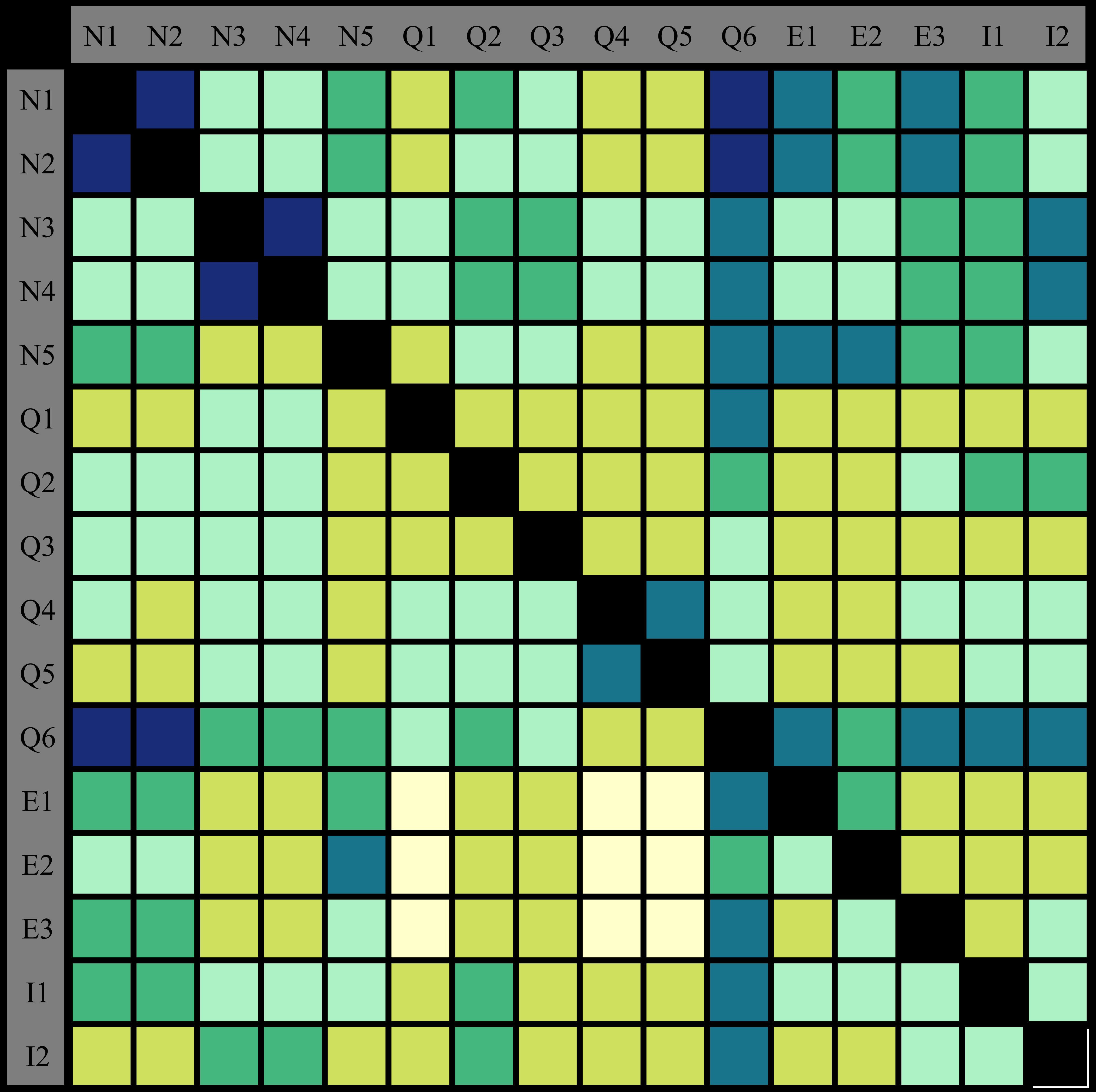


$(\Delta\chi^2_{ij})_{\min} < 0.1$ $\quad 0.1 \le (\Delta\chi^2_{ij})_{\min} \le 1$ $\quad 1 < (\Delta\chi^2_{ij})_{\min} \le 4$ $\quad 4 < (\Delta\chi^2_{ij})_{\min} \le 9$ $\quad 9 < (\Delta\chi^2_{ij})_{\min} \le 25$ $\quad (\Delta\chi^2_{ij})_{\min} > 25$

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

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

- A large set of (i, j) model combinations allows a 3σ model discrimination in the Inverted Mass Ordering
- Nuclear model discrimination assuming $m_{\beta\beta}^{\text{True}} \leq 14$ meV is only possible when $i = \{\text{E1,E2,E3}\}, j = \{\text{Q1,Q4,Q5}\}$



$8 < m_{\beta\beta}^{\text{True}} \leq 14$ meV; $14 \text{ meV} < m_{\beta\beta}^{\text{True}} \leq 30$ meV; $30 \text{ meV} < m_{\beta\beta}^{\text{True}} \leq 49$ meV; $49 \text{ meV} < m_{\beta\beta}^{\text{True}} \leq 100$ meV; $100 \text{ meV} < m_{\beta\beta}^{\text{True}} \leq 500$ meV; $m_{\beta\beta}^{\text{True}} > 500$ meV

Nuclear model discrimination

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

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

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

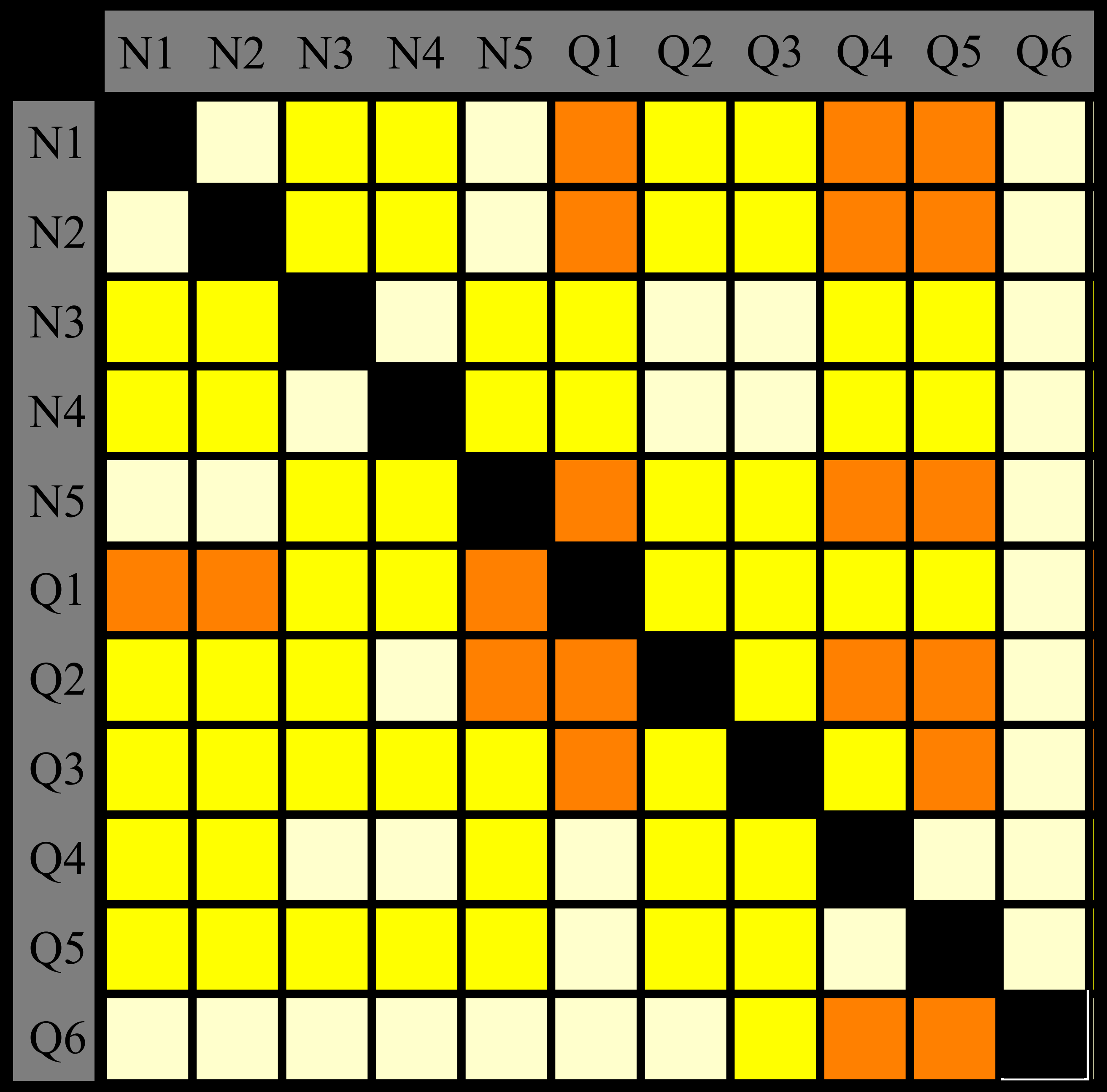
$$n_{\alpha j} = \frac{M_{\alpha j}^{\text{short}}}{M_{\alpha j}^{\text{long}}}$$

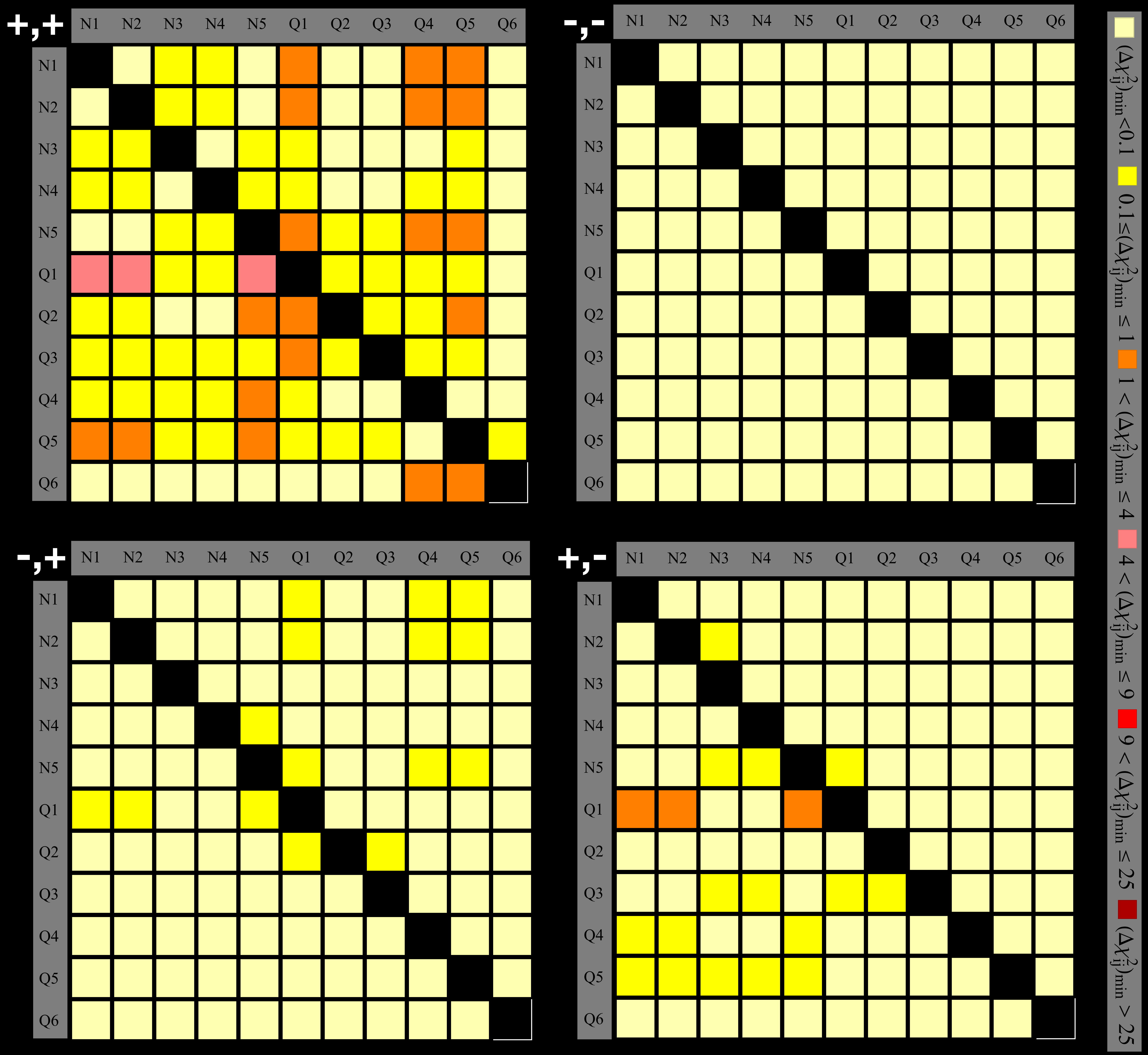
$$M_{\alpha i} = M_{\alpha i}^{\text{long}} + M_{\alpha i}^{\text{short}}$$

$$m_{\beta\beta}^{\text{True}} = 10\ \text{meV}$$

$|n_{\alpha i}|$ taken as the central value of the allowed range

$|n_{\alpha j}|$ free to vary in the corresponding range



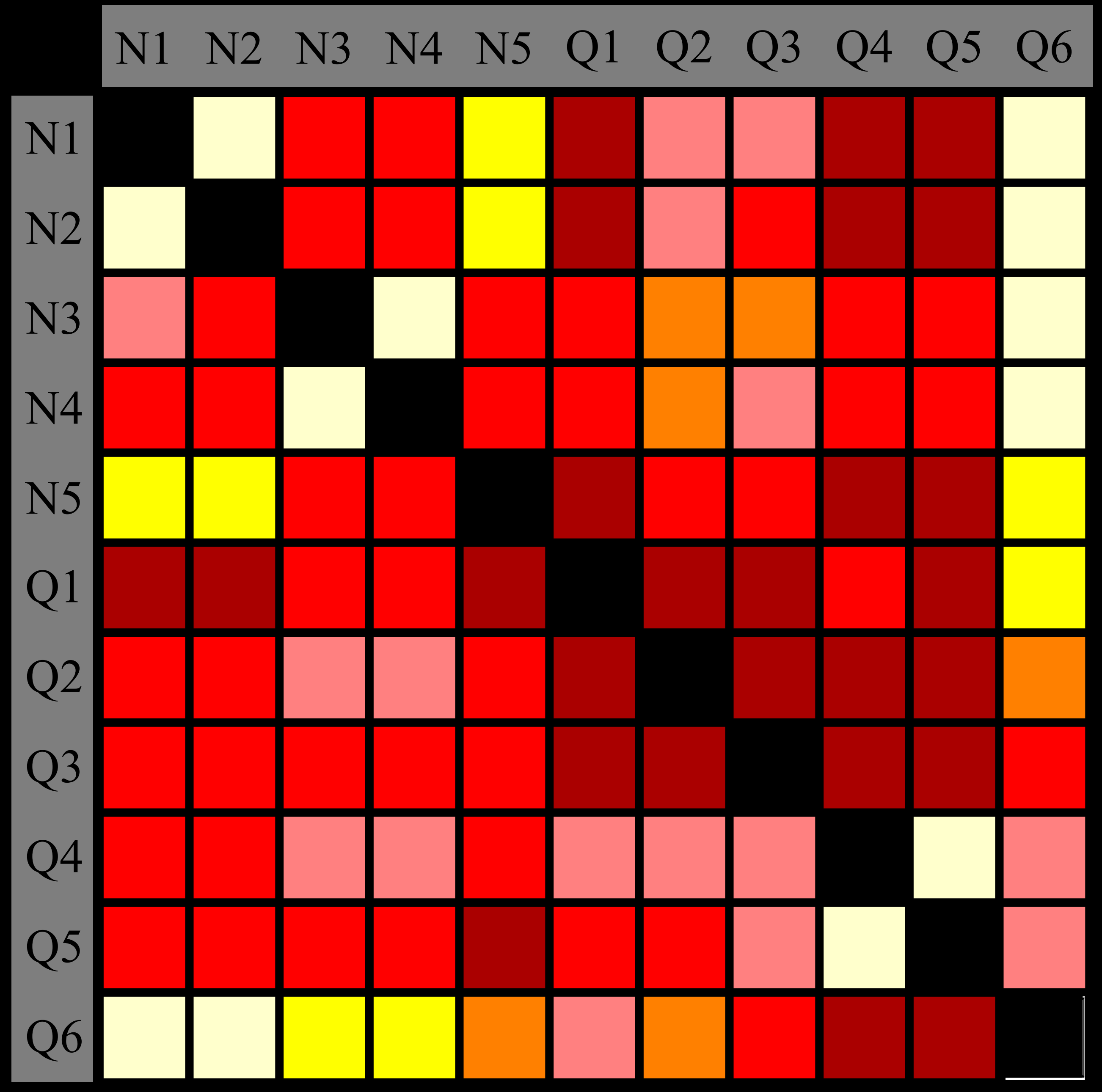


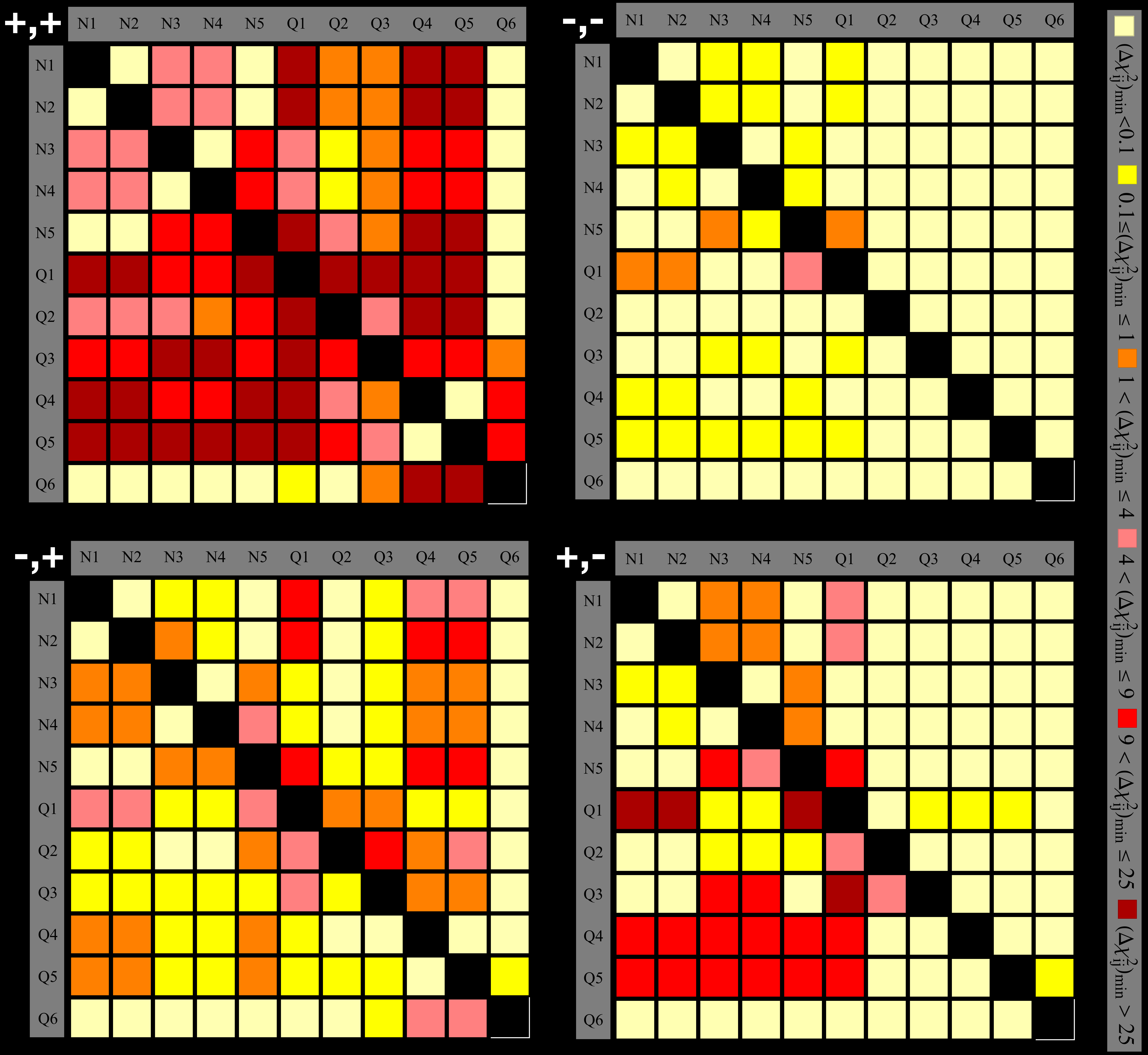
$$M_{\alpha i} = M_{\alpha i}^{\rm long} + M_{\alpha i}^{\rm short}$$

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

$|n_{\alpha i}|$ taken as the central value of the allowed range

$|n_{\alpha j}|$ free to vary in the corresponding range

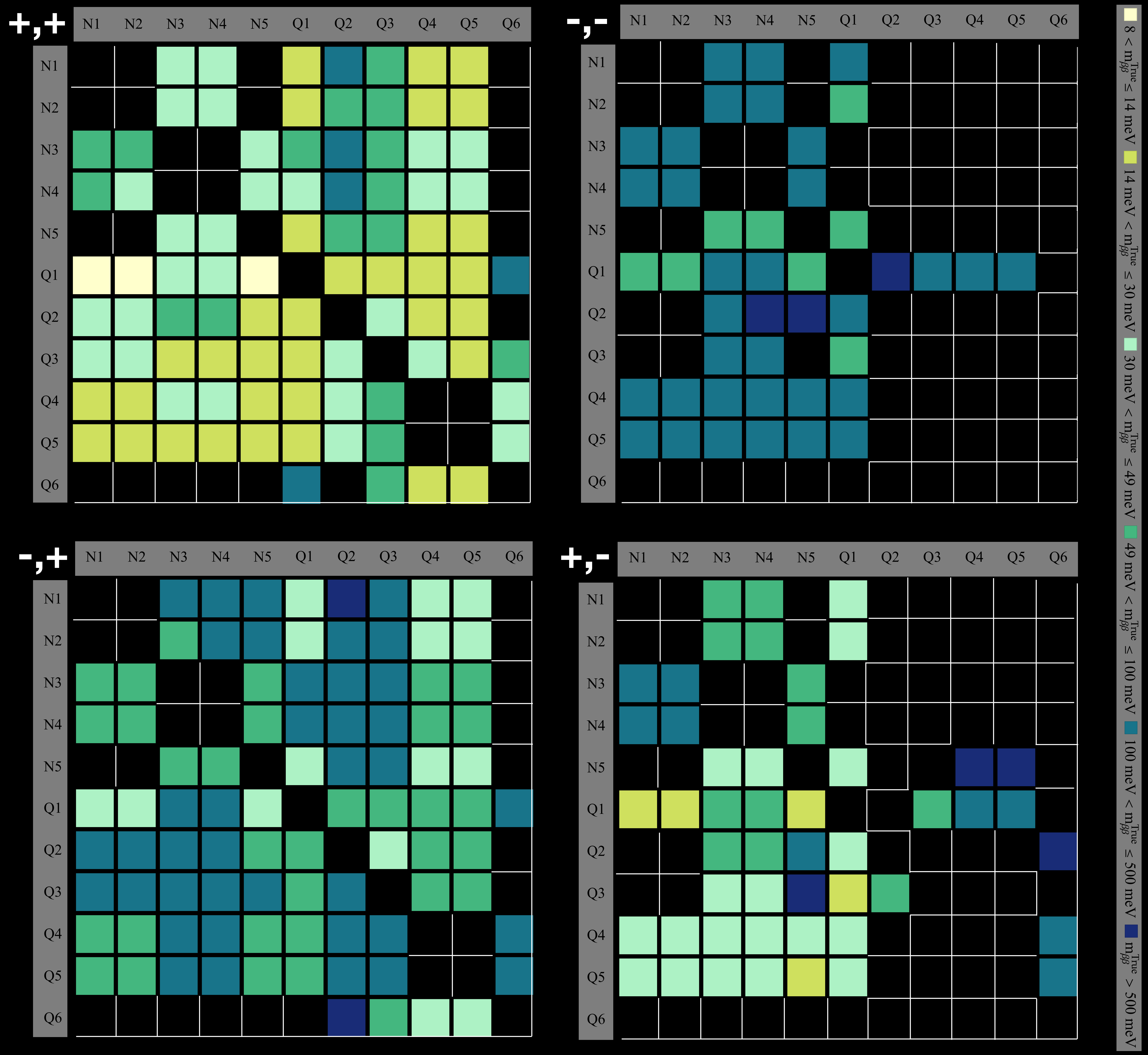




$$M_{\alpha i} = M_{\alpha i}^{\text{long}} + M_{\alpha i}^{\text{short}}$$

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

Black squares indicate the cases where discrimination at 3σ is not possible for realistic values of $m_{\beta\beta}^{\text{True}}$ and exposure times T



In conclusion

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

This project has received funding and support from the European Union's Horizon 2020 research and innovation programme 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 using different isotopes, to discriminate among the various NME models?

YES (depending on the value of $m_{\beta\beta}^{\rm True}$)!

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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HIDDeN
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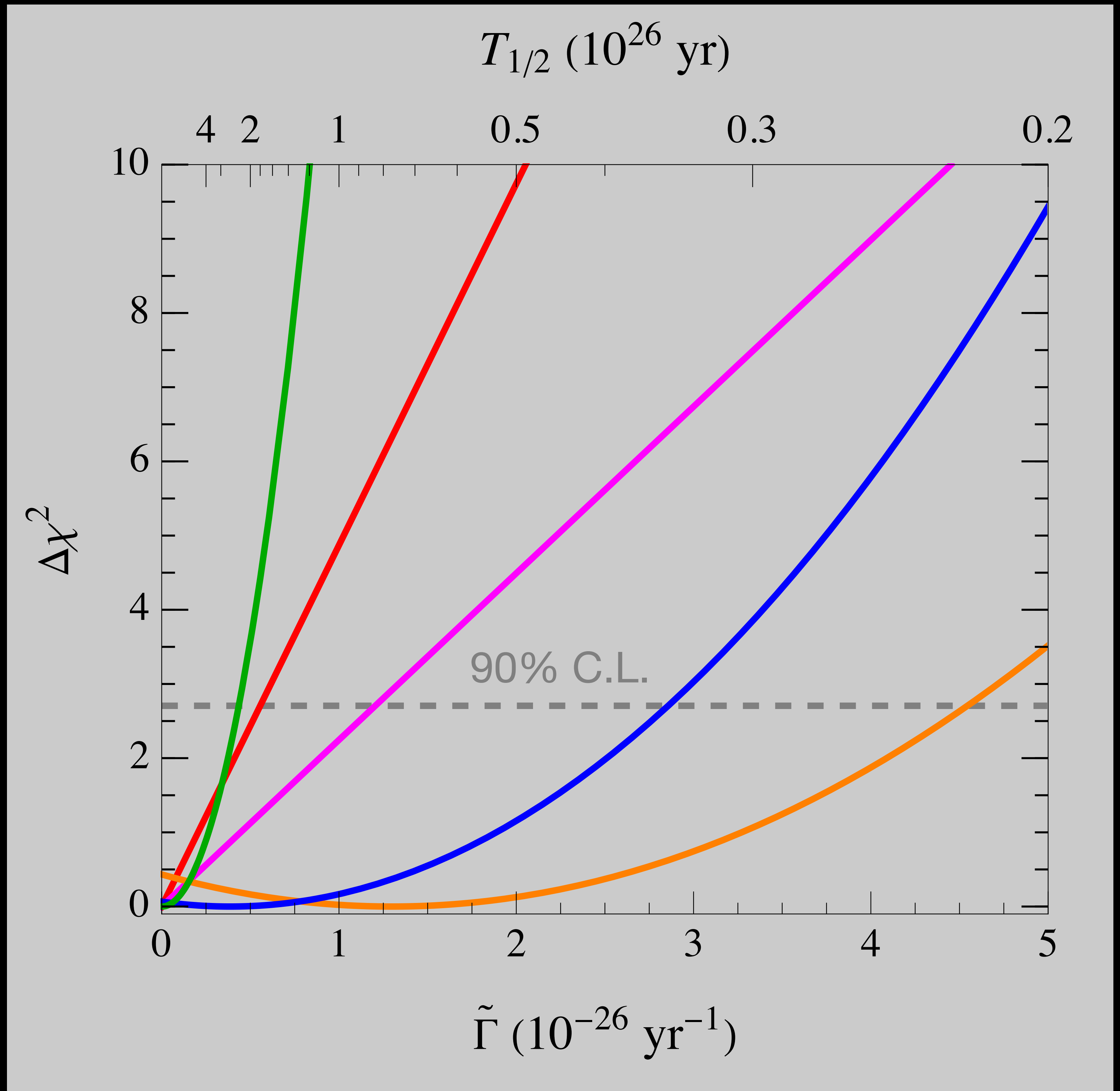
Backup

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 $T_{1/2} > 1.8 \rightarrow m_{\beta\beta} \in [79, 180]$
- MAJORANA $T_{1/2} > 0.83 \rightarrow m_{\beta\beta} \in [113, 269]$

^{130}Te
- CUORE $T_{1/2} > 0.22 \rightarrow m_{\beta\beta} \in [90, 305]$

^{136}Xe
- EXO-200 $T_{1/2} > 0.35 \rightarrow m_{\beta\beta} \in [93, 286]$
- KamLAND-Zen $T_{1/2} > 2.3 \rightarrow m_{\beta\beta} \in [36, 156]$

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 $m_{\beta\beta}$:

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

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

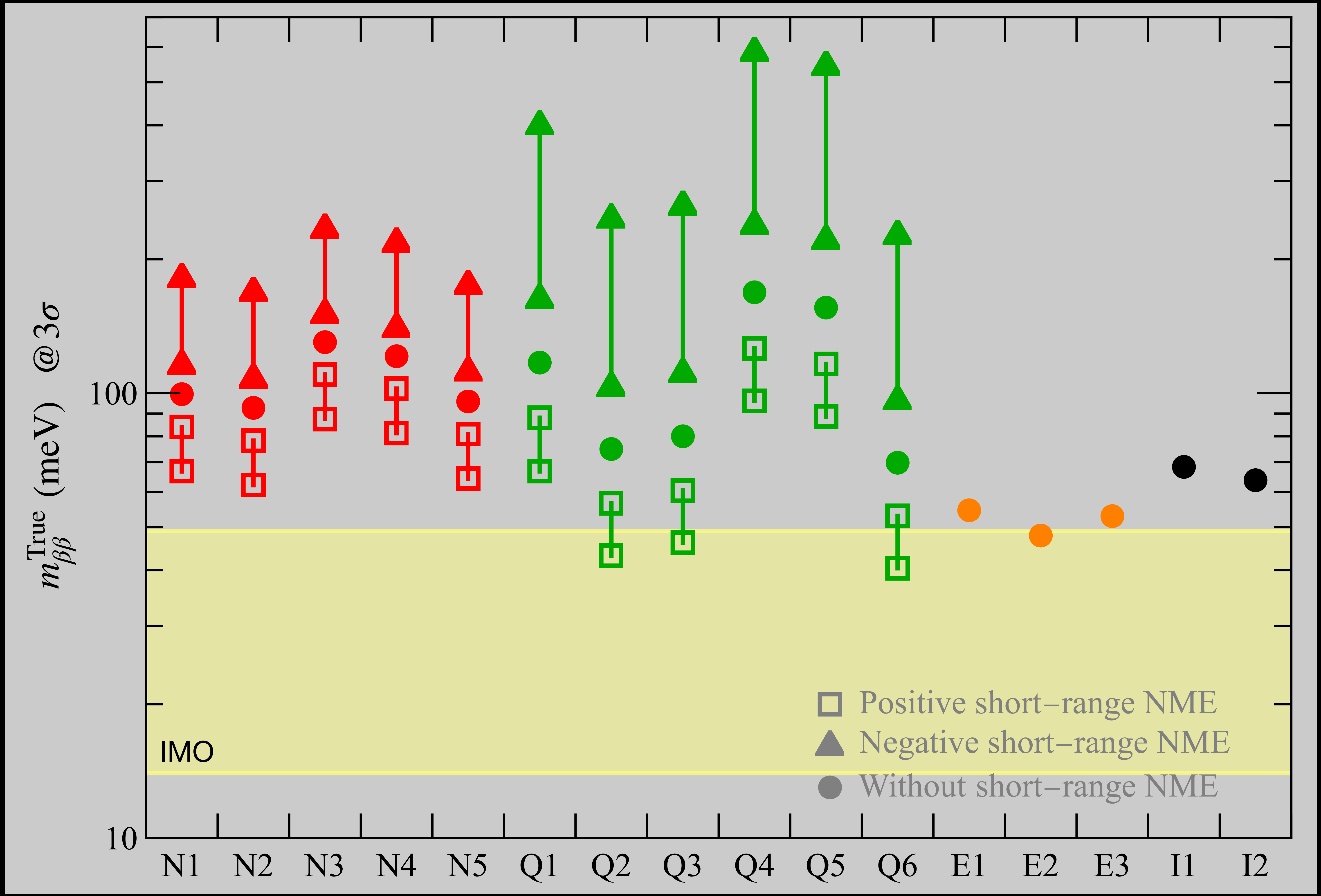
↓

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

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

- 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

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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

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

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

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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	$4.0 \cdot 10^{-5}$	$14.56 \cdot 10^{-26}$

Backup

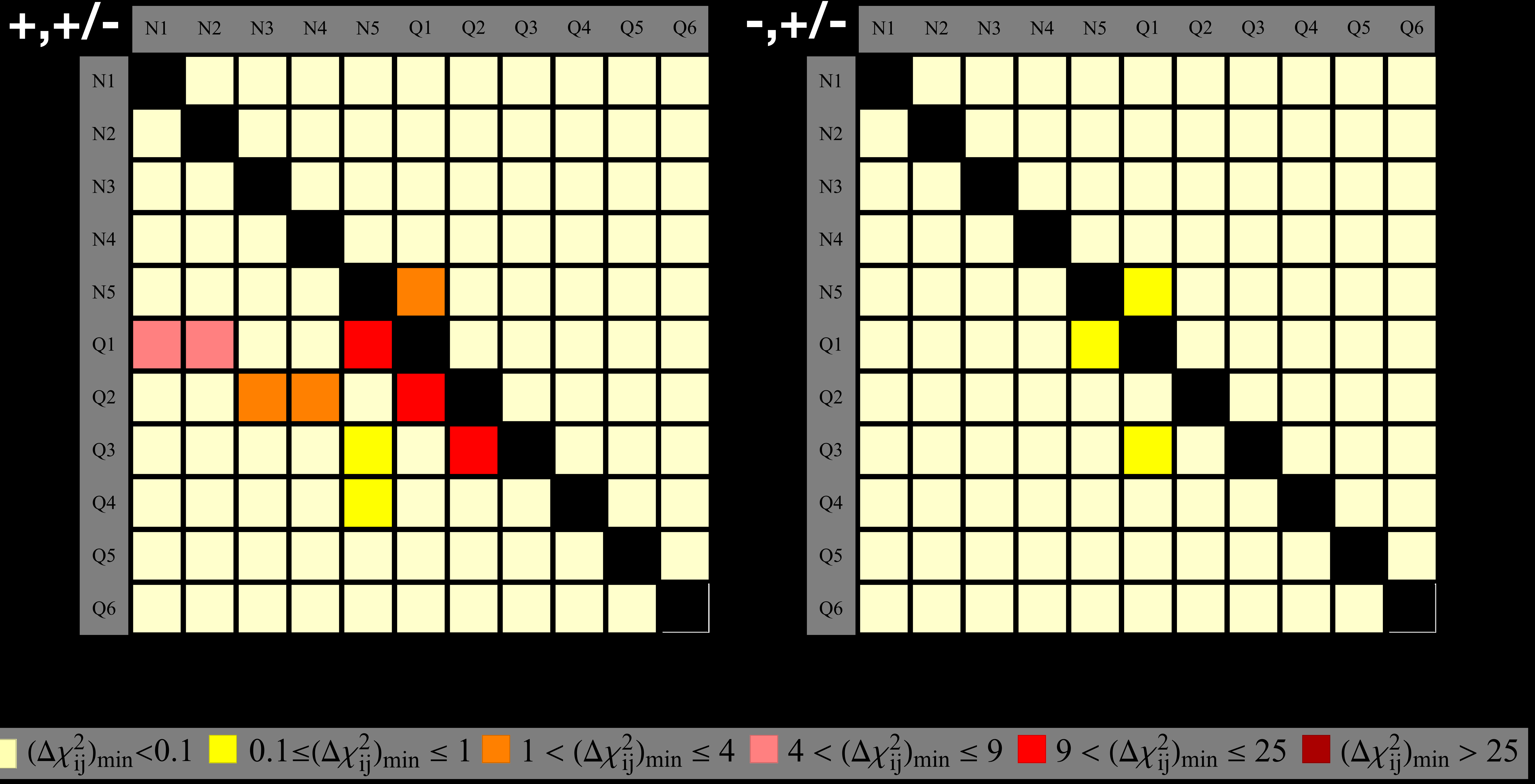
What if sign unknown?

$$m_{\beta\beta}^{\rm True} = 60 \text{ meV}$$

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

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

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



Not promising nuclear model discrimination!

Backup

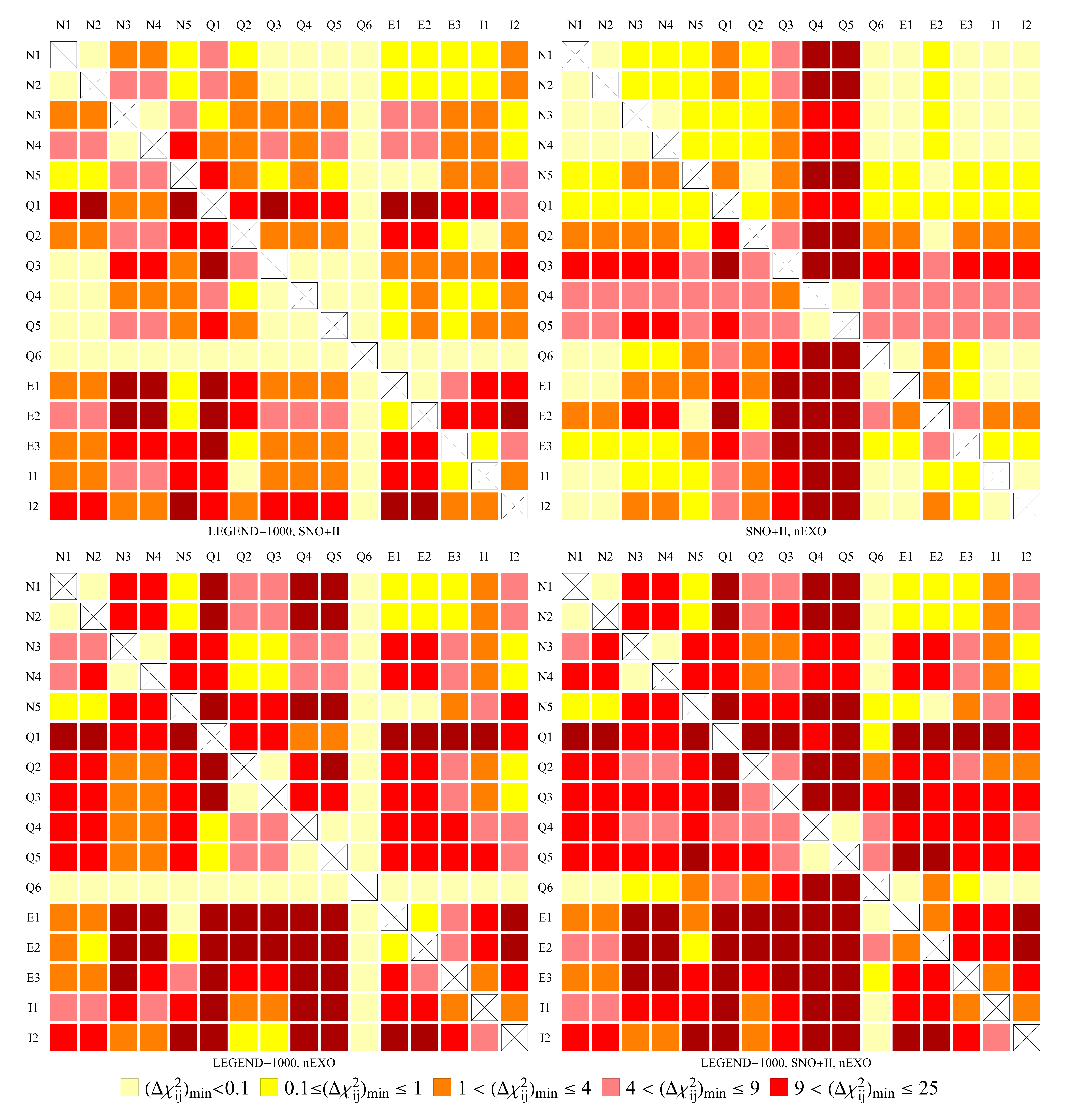
$$M_{\alpha i} = M_{\alpha i}^{\text{long}}$$

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

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

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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.