Impact of different nuclear matrix element calculations on the interpretation of current and future 0νββ experiments

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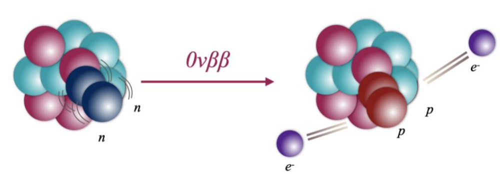
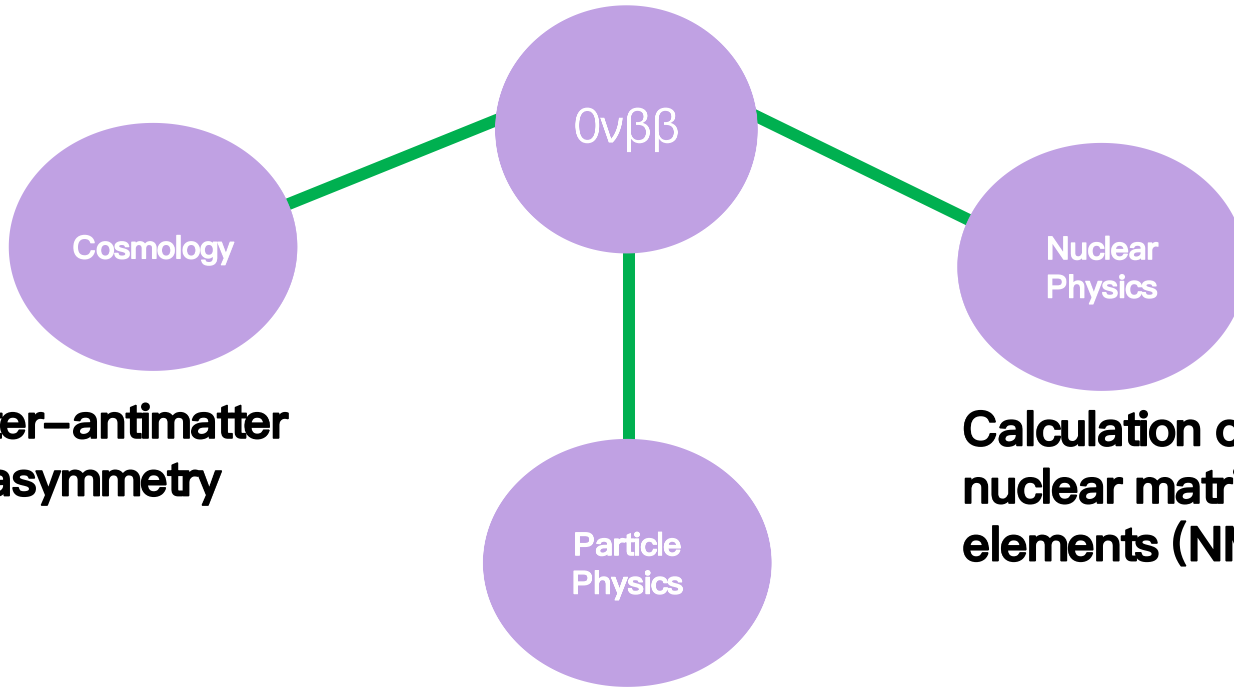
Based on the work with Prof. Thomas Schwetz and Federica Popma,
JHEP 06 (2023) 104



NvDEx-CUPID-CHINA合作组2023年会

Big picture



Matter–antimatter asymmetry

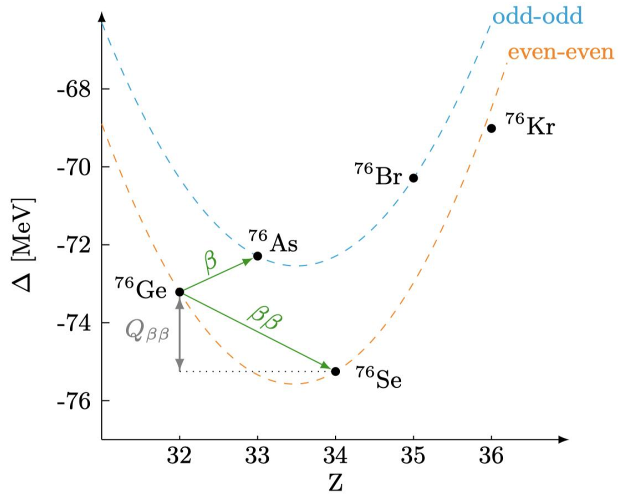
Calculation of nuclear matrix elements (NME)

The production mechanism BSM

Experiments:

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

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_{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	$[9.34 \pm 0.22(\text{stat})^{+0.62}_{-0.60}(\text{syst})] \times 10^{18}$	$> 2.0 \times 10^{22}$

10^{18} yr – 10^{21} yr

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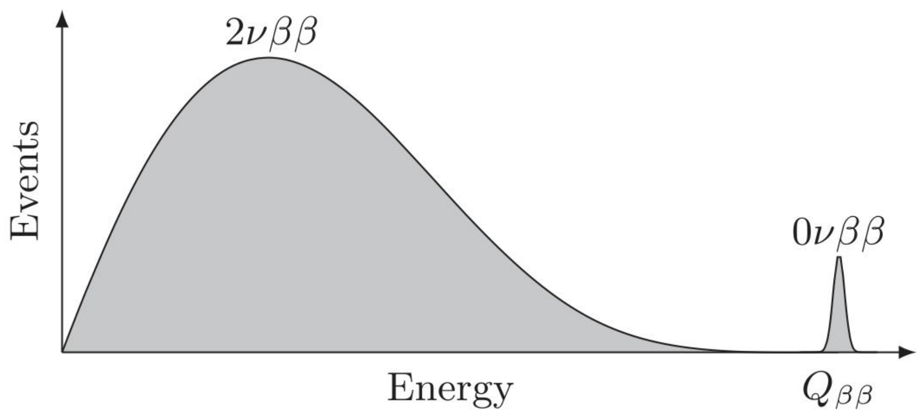
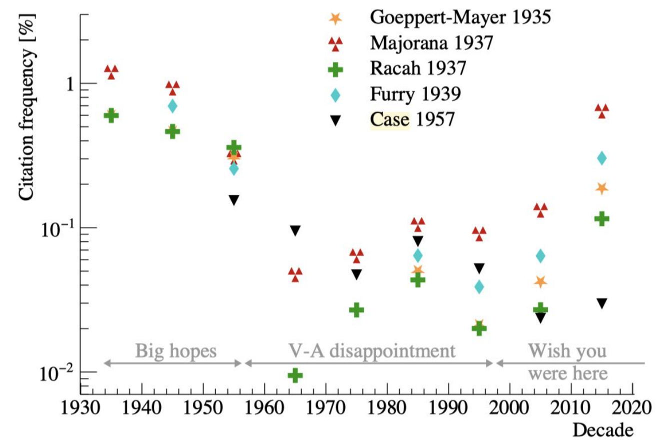
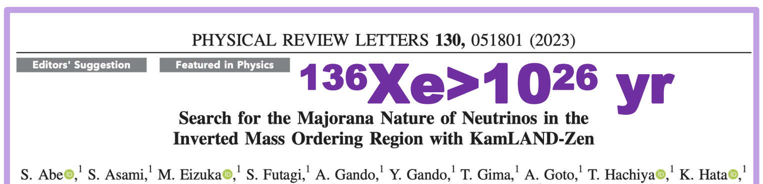
Brief background





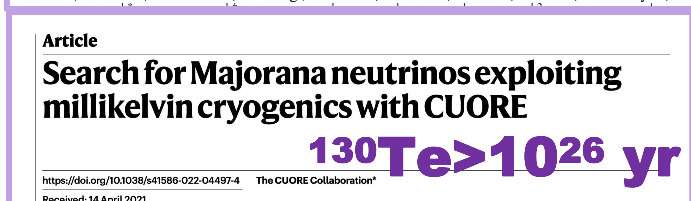

PHYSICAL REVIEW LETTERS 130, 051801 (2023)

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

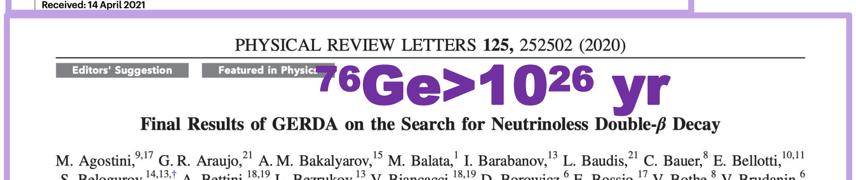

Article

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

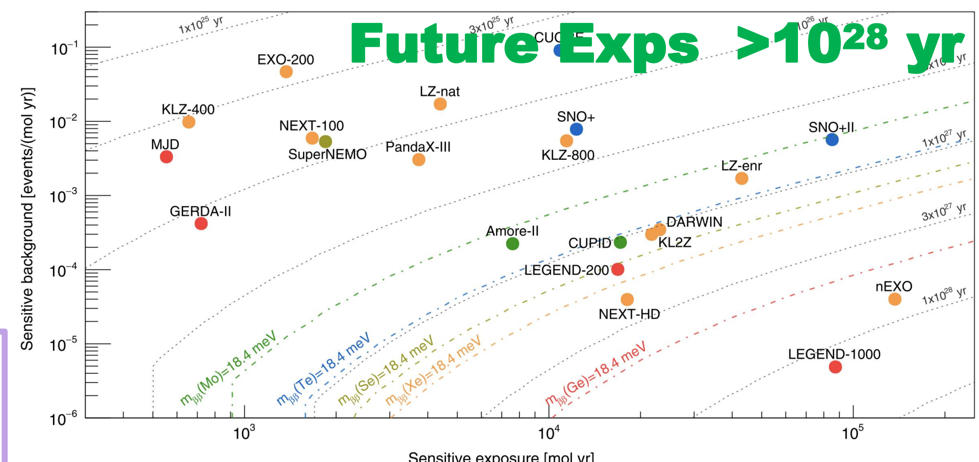

PHYSICAL REVIEW LETTERS 125, 252502 (2020)

Editors' Suggestion | Featured in Physics

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

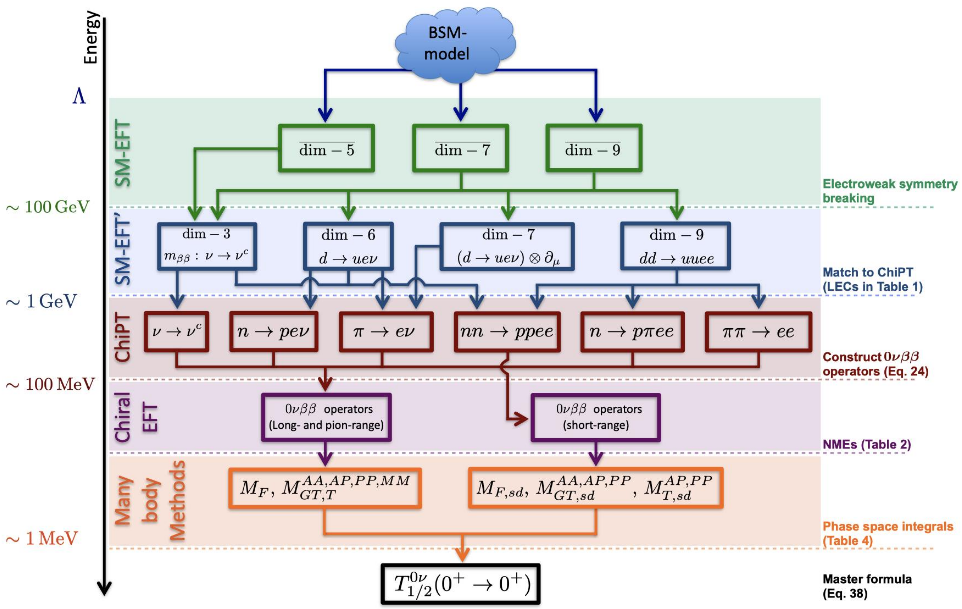
Final Results of GERDA on the Search for Neutrinoless Double-β Decay

M. Agostini, G. R. Araujo, A. M. Bakalyarov, M. Balata, I. Barabanov, L. Baudis, C. Bauer, E. Bellotti, S. Belogurov, A. Bettini, L. Bezrukov, V. Biancacci, D. Borowicz, E. Bossio, V. Bothe, V. Brudanin



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

A general theoretical framework



Cirigliano et al., JHEP 2018

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).

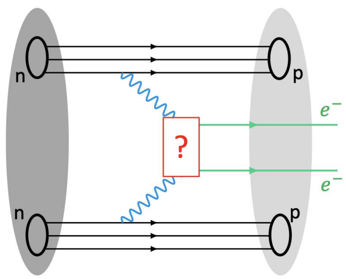
and $F_\pi = 92.2$ MeV is the pion decay constant. However, it is known that Weinberg's power counting leads to inconsistent results in nucleon-nucleon scattering [34–37] and nuclear processes mediated by external currents [38], due to a conflict between naive dimensional analysis and nonperturbative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

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

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	$G_F^2 \left\|\frac{S_{ei}^2}{M_i}\right\|$	2×10^{-8} GeV^{-1}	LFV, collider
heavy neutrino and RHC	$G_F^2\, m_W^4 \left\|\frac{V_{ei}^2}{M_i\, M_{W_R}^4}\right\|$	4×10^{-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
λ-mechanism with RHC	$G_F^2 \frac{m_W^2}{q}\left\|\frac{U_{ei}\,\tilde{S}_{ei}}{M_{W_R}^2}\right\|$	1.4×10^{-10} 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 $\not{R}$	$\frac{\|\lambda_{111}'^2\|}{\Lambda_{\rm SUSY}^5}$ $\Lambda_{\rm SUSY} = f(m_{\tilde{g}}, m_{\tilde{u}_L}, m_{\tilde{d}_R}, m_{\chi_i})$	7×10^{-18} GeV^{-5}	collider, flavor
long-range $\not{R}$	$\frac{G_F}{q}\left\|\sin 2\theta^b\, \lambda_{131}'\, \lambda_{113}' \left(\frac{1}{m_{\tilde{b}_1}^2} - \frac{1}{m_{\tilde{b}_2}^2}\right)\right\|$ $\sim \frac{G_F}{q} m_b \frac{\|\lambda_{131}'\,\lambda_{113}'\|}{\Lambda_{\rm SUSY}^3}$	2×10^{-13} GeV^{-2} 1×10^{-14} GeV^{-3}	flavor, collider
Majorons	$\propto \|\langle g_\chi\rangle\|$ or $\|\langle g_\chi\rangle\|^2$	$10^{-4}\ldots 1$	spectrum, cosmology

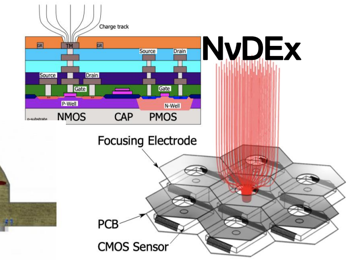
Rodejohann, Int.J.Mod.Phys.E 20 (2011)



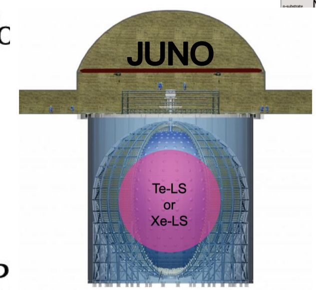
Phase factor + nuclear matrix element ?+ new physics parameter ?(effective neutrino mass)

Experimental techniques @CJPL

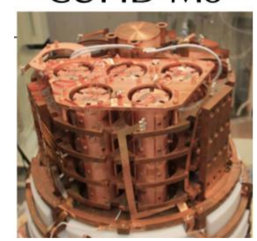
- Bolometers (CUPID, AMoRE, CANDLES IV)
  - Measure E (σ ~ 0.1-0.3%) from phonons; granularity gives position info
  - Instrumenting with photon detectors for background rejection
- External trackers (SuperNEMO)
  - Trackers + calorimeters, measure E (σ ~ 3-10%) + tracks / positions + P
- Scintillators (KamLAND2-Zen, SNO+, Theia, ZICOS)
  - Measure E (σ ~ 3-10%) + position from scintillation light; some PID
- Semiconductors (LEGEND, SELENA) CDEX
  - Measure E (σ ~ 0.05-0.3%) from ionization; some tracking / position sensitivity
- TPCs (nEXO, NEXT, PandaX, AXEL, NvDEx, DARWIN, LZ)
  - Collect scintillation + ionization: measure E (σ ~0.4-3%) + tracks / position + PID

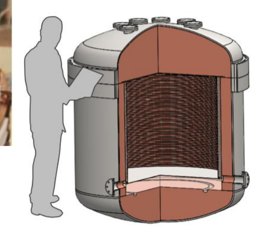


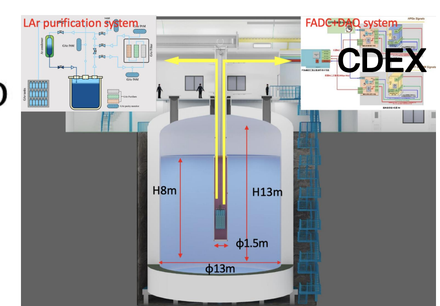
Topmetal CMOS Technology



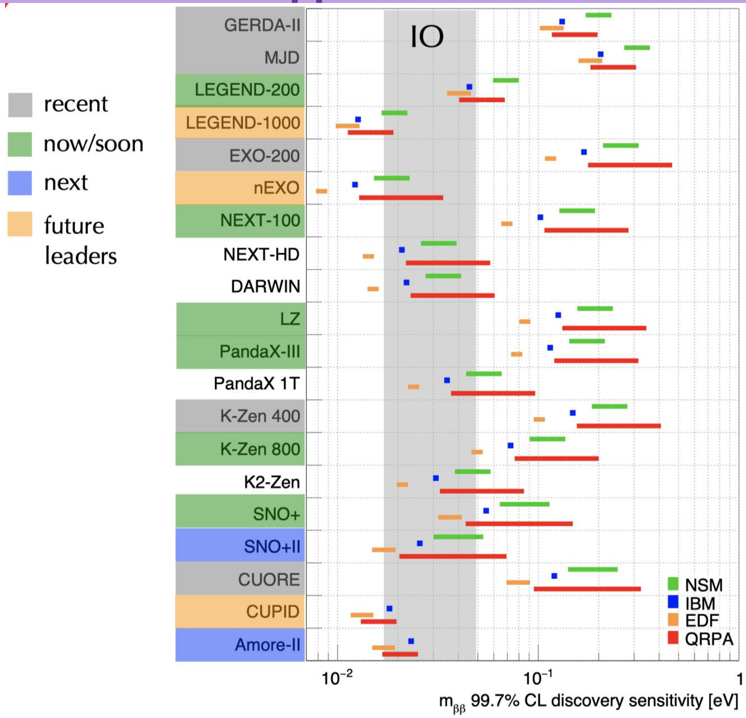

PandaX-4T LXe TPC

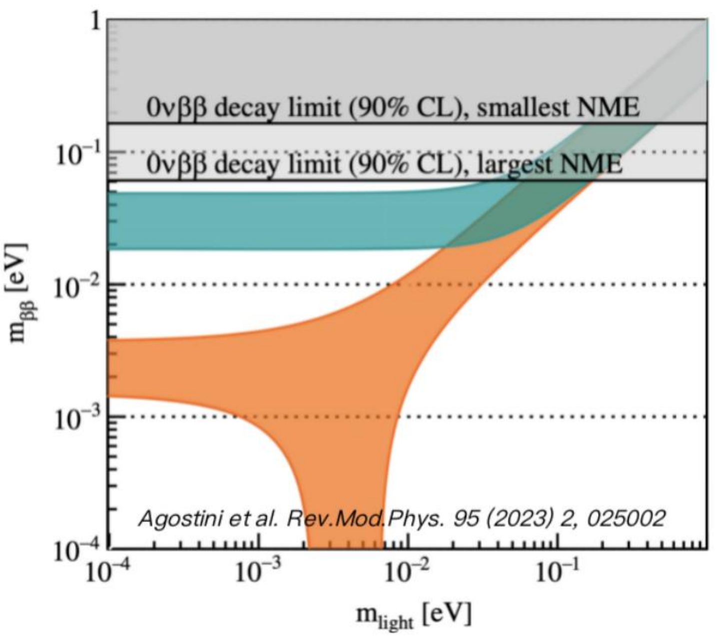
CUPID-Mo



PandaX-III GXe TPC



NME → $m_{\beta\beta}$





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 0νββ experiments
- Checking the possibilities of discriminating NME models in future 0νββ experiments

Formula (light neutrino exchange mechanism)

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

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

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

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

- **Quenching effect: correct the NME by q^2 and the decay rate by q^4**
  (Ab initio many–body theory, see **Yao's talk** later**)**
- 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

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	**Fang, Faessler, Simkovic, PRC2018**
	Q5 [32]	3.40	3.13	-	3.22	1.18	**Fang, Faessler, Simkovic, PRC2018**
	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	**Song, Yao, Ring, Meng, PRC2017**
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	

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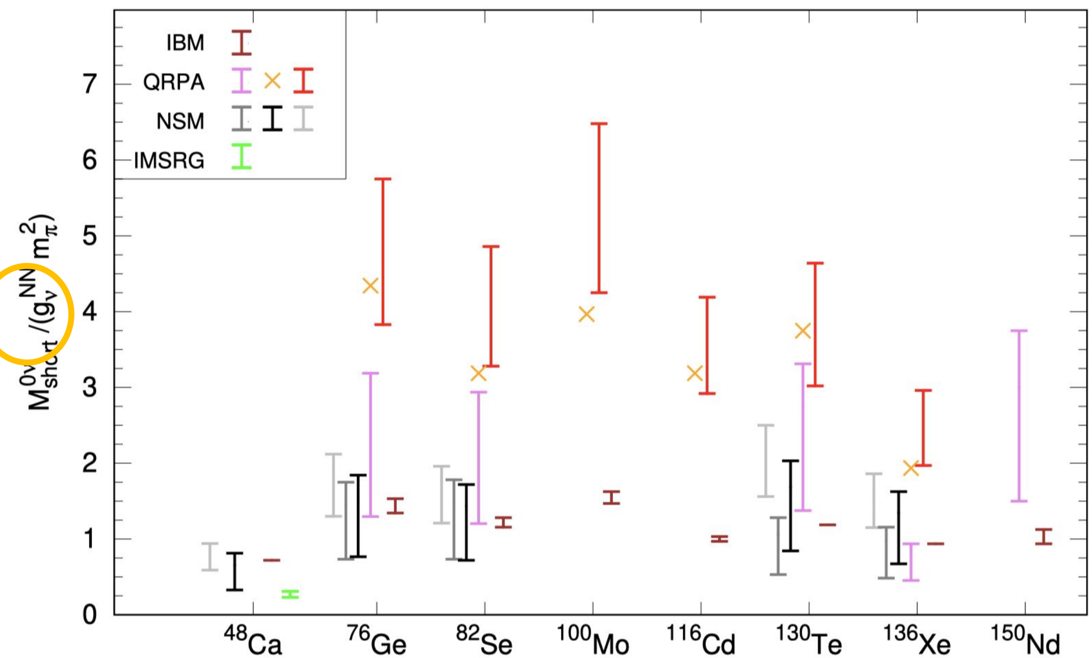
Short-range NME

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

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



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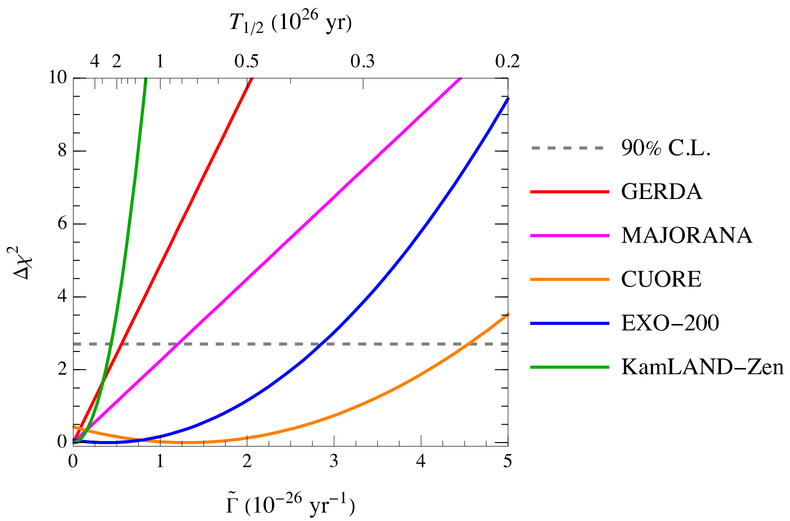
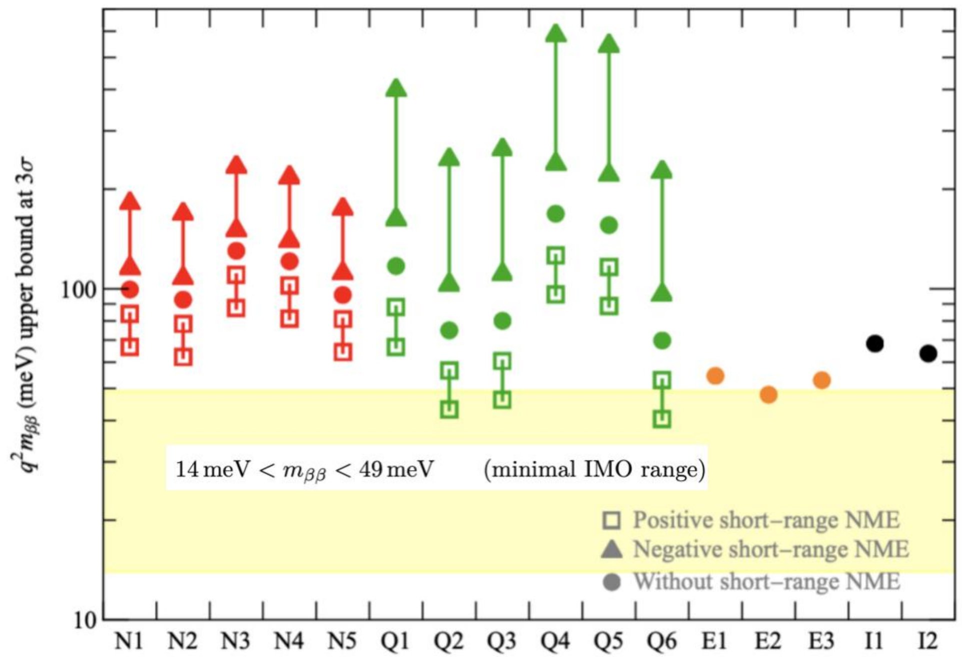
Current constraints

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





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

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

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

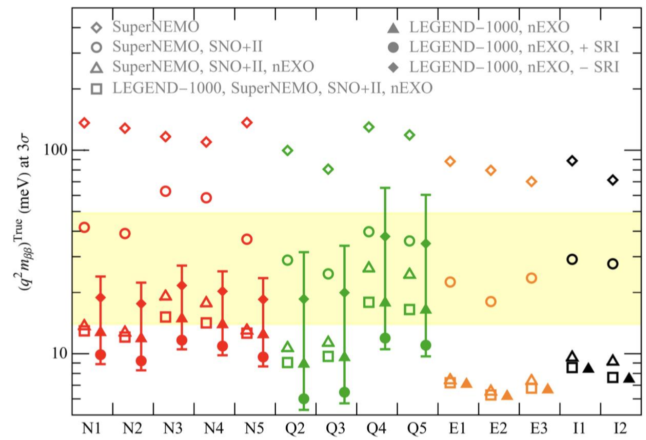
$$N_{\mathrm{SuperNEMO}} = \left\{0.09 \times \left[\frac{(q^2 m_{\beta\beta})^{\mathrm{True}}}{40\ \mathrm{meV}}\right]^2 \left(\frac{M_{\mathrm{Se}}^{\mathrm{long}}}{2.72}\right)^2 + 1.0\right\} \times \frac{T}{1\ \mathrm{yr}}$$

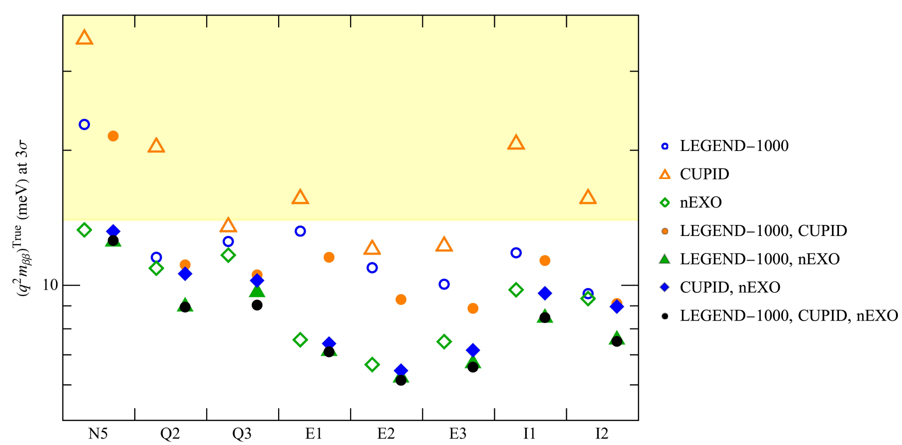
$$N_{\mathrm{nEXO}} = \left\{1.64 \times \left[\frac{(q^2 m_{\beta\beta})^{\mathrm{True}}}{40\ \mathrm{meV}}\right]^2 \left(\frac{M_{\mathrm{Xe}}^{\mathrm{long}}}{1.11}\right)^2 + 0.5\right\} \times \frac{T}{1\ \mathrm{yr}}$$

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

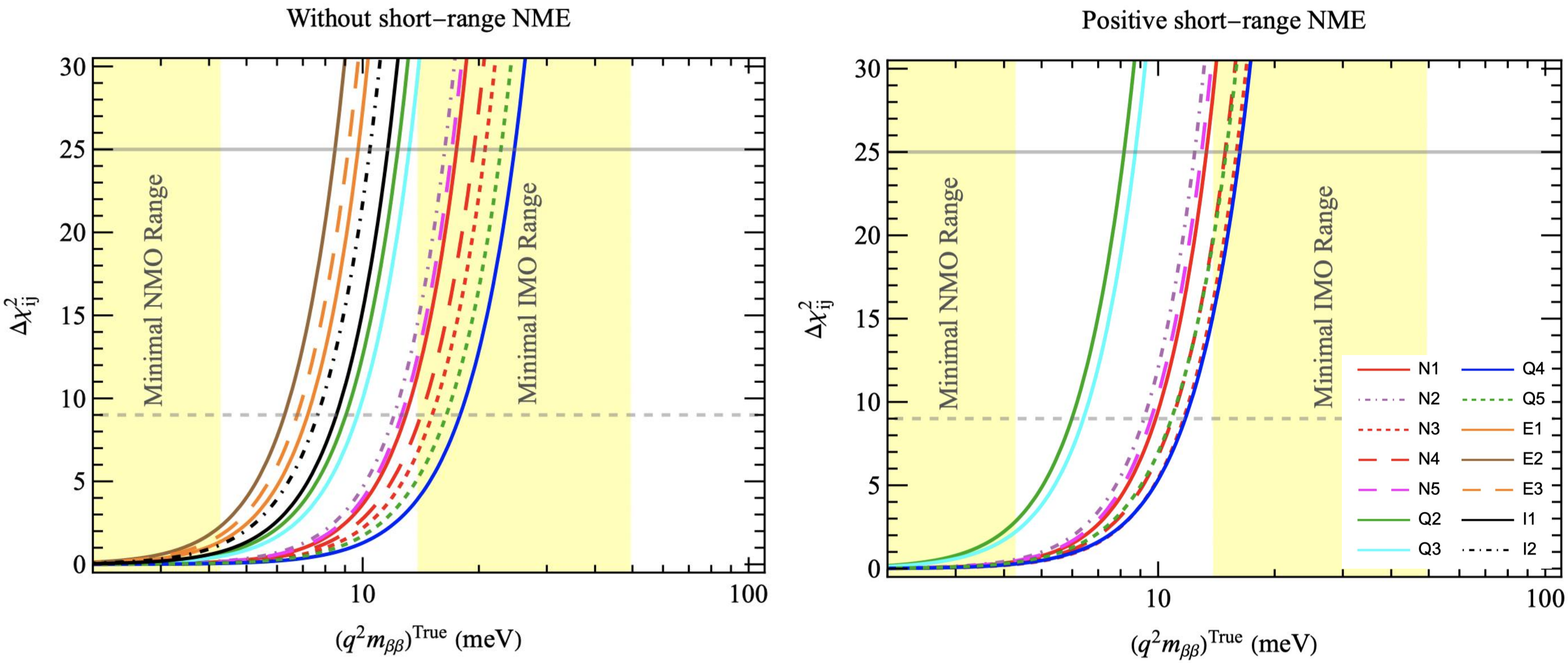
$$S_{\alpha i}(m_{\beta\beta}, M_{\alpha i}) = \ln 2 \cdot N_A \cdot \varepsilon_\alpha \cdot \left(\frac{T}{1\ \mathrm{yr}}\right) \cdot \widetilde{\Gamma}_\alpha(m_{\beta\beta}, M_{\alpha i})$$

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





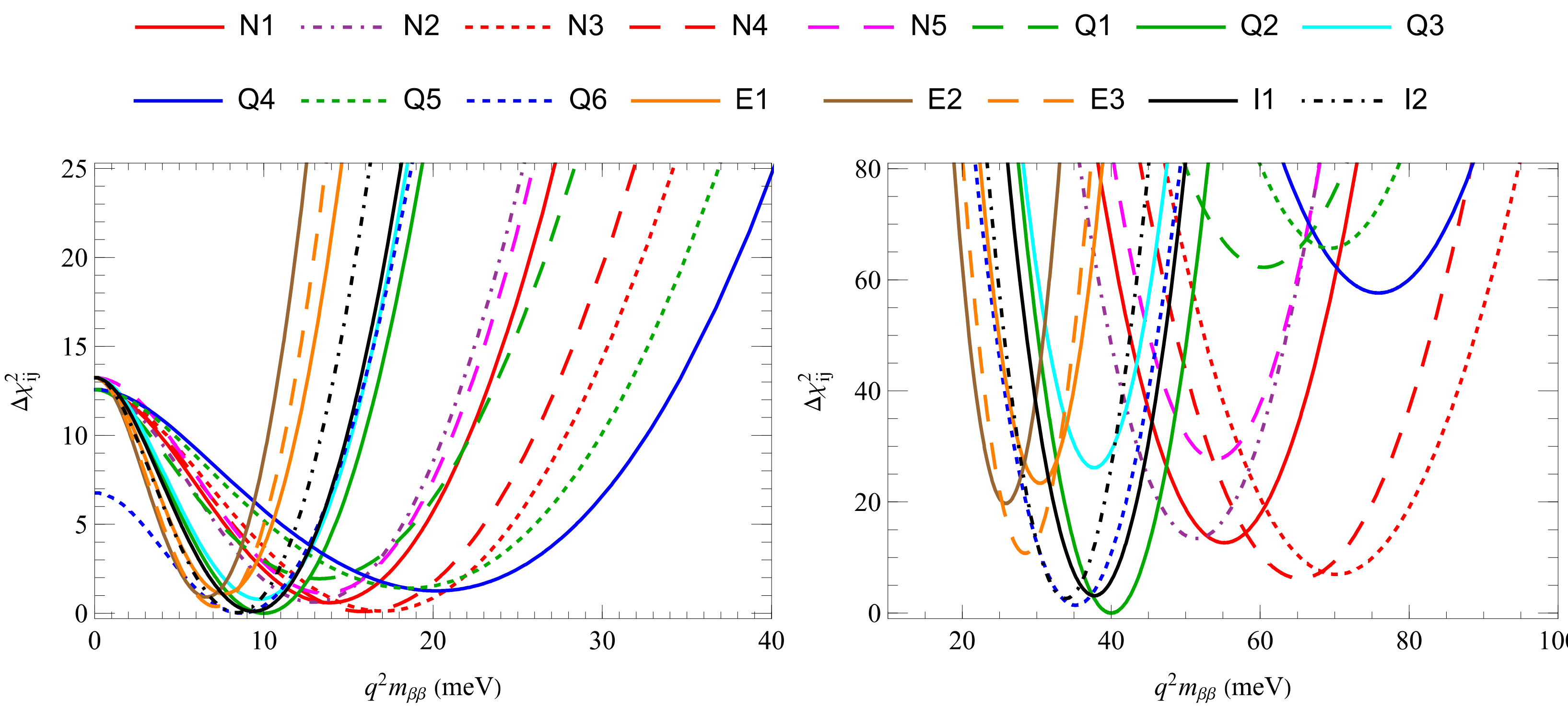
The significance of observing one positive signal:



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

($\Delta\chi^2_{ij}$) as function of $q^2m_{\beta\beta}$

i=Q2



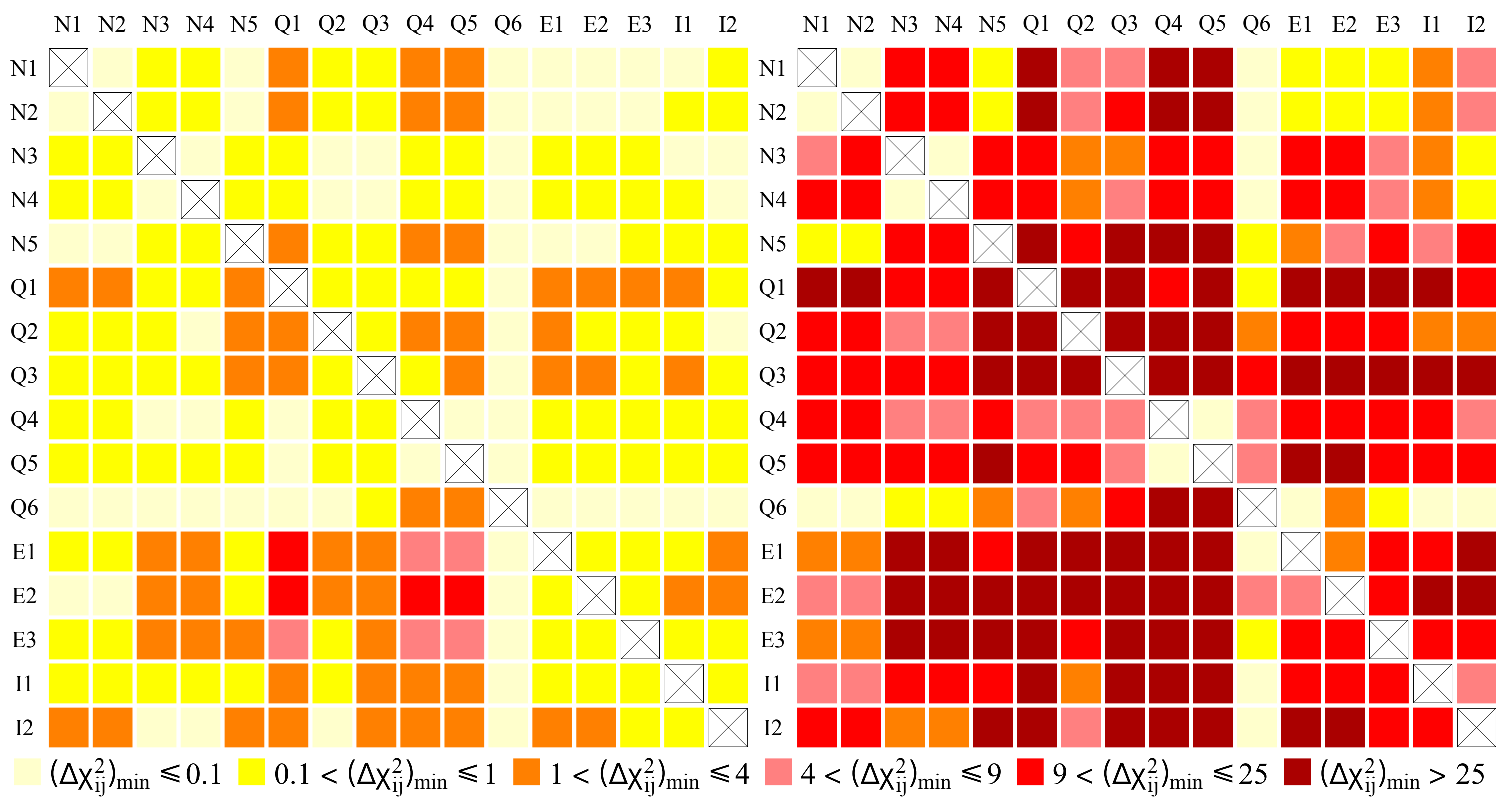
$(q^2m_{\beta\beta})^{True}$=10 meV ***$(q^2m_{\beta\beta})^{True}$=40 meV***

Discrimination without short-range NME

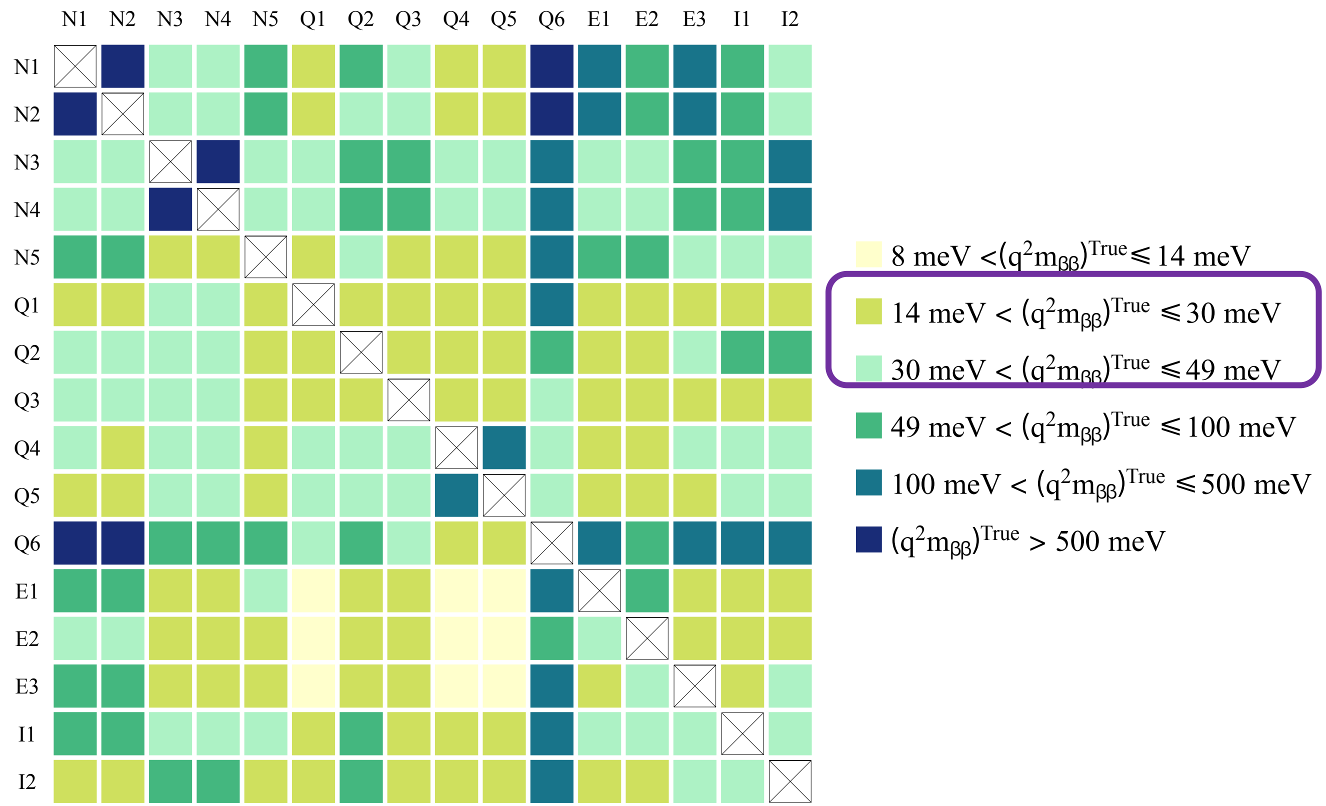
$$(\Delta\chi^2_{ij})_{\min} = \min_{m_{\beta\beta}} \Delta\chi^2_{ij}(m_{\beta\beta}, M_{\alpha j}\,;\,(q^2 m_{\beta\beta})^{\rm True}, M^{\rm True}_{\alpha i})$$

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

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

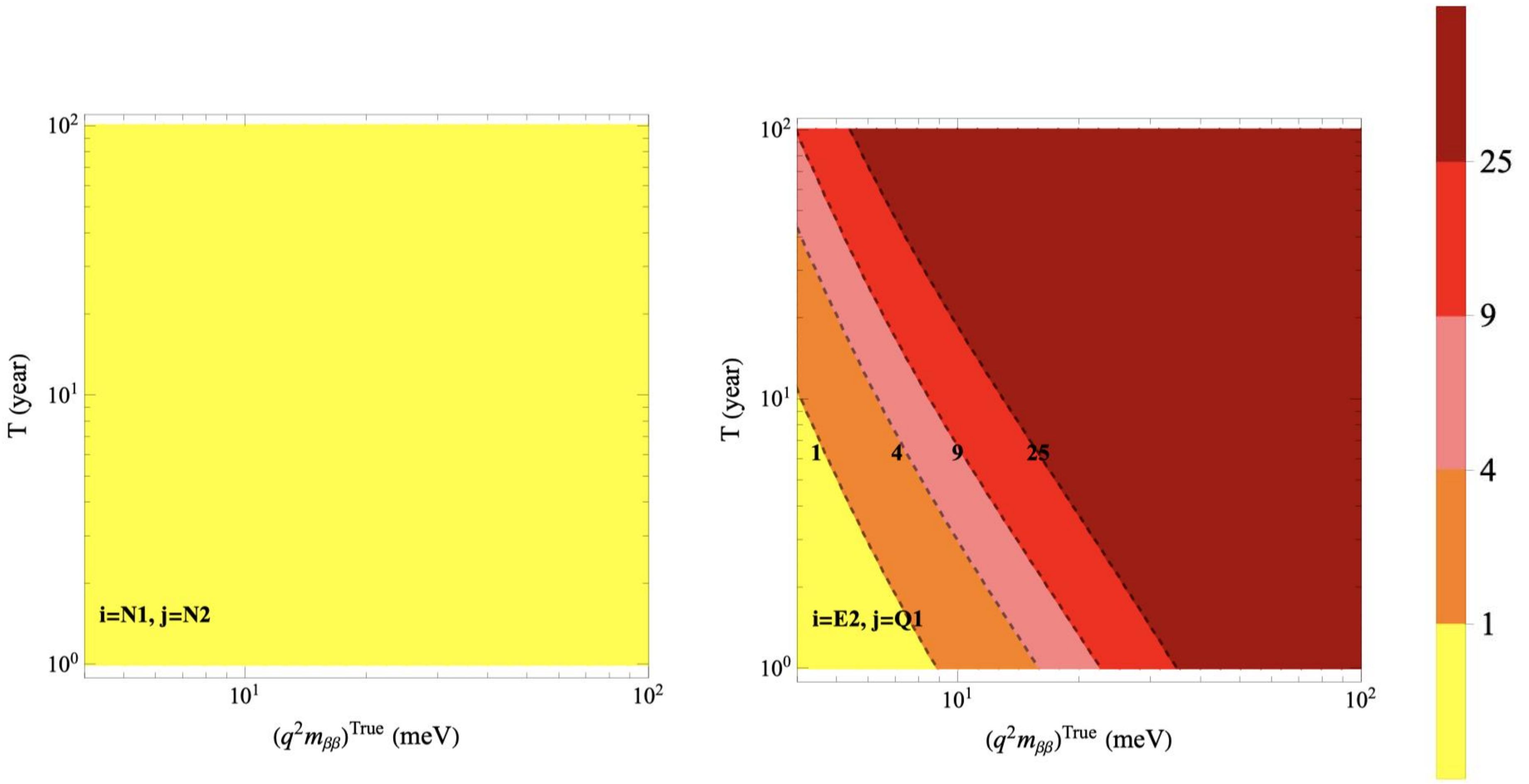


$m_{\beta\beta}^{True}$ corresponding to discrimination at 3σ



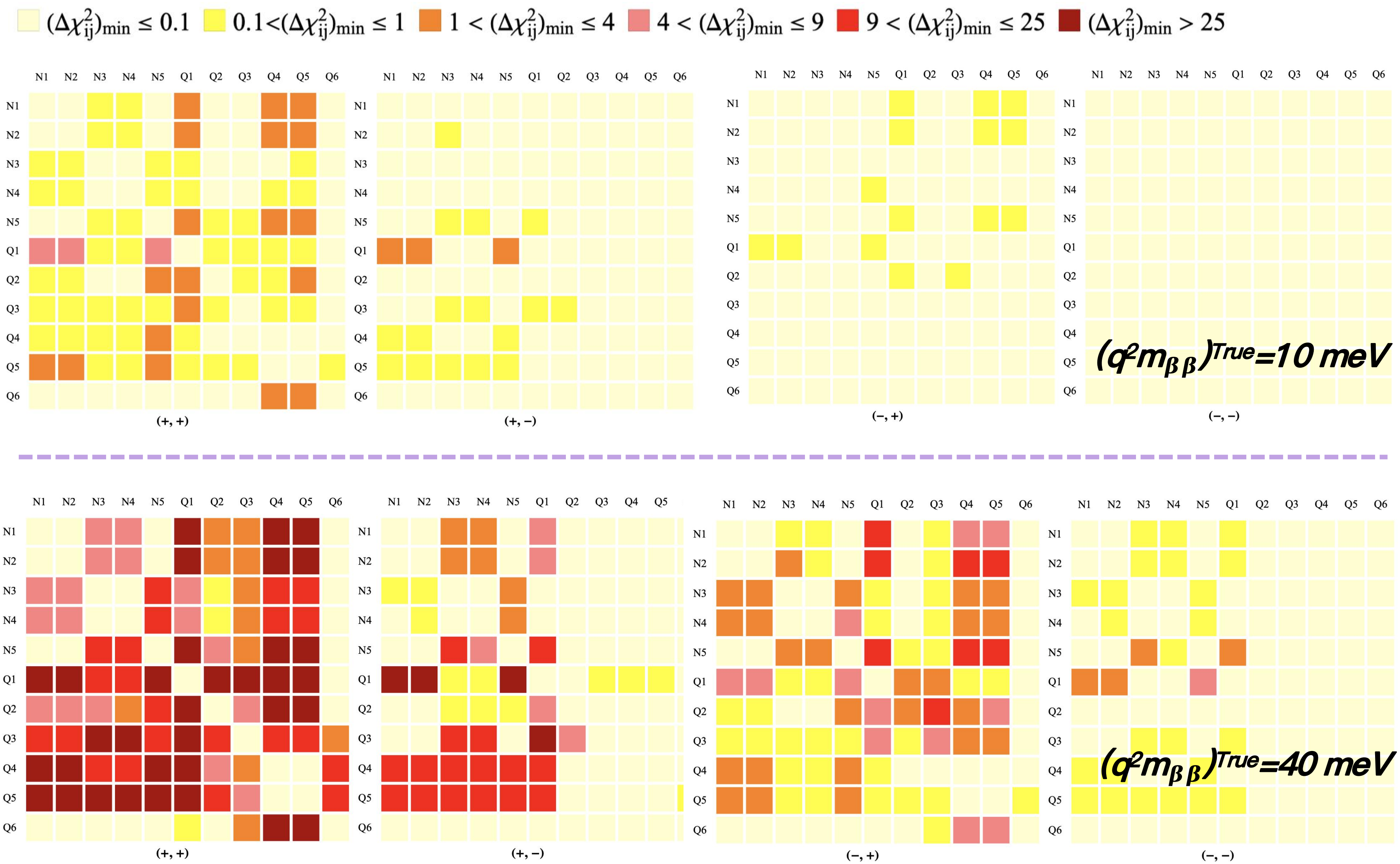
(without short- range NME)

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

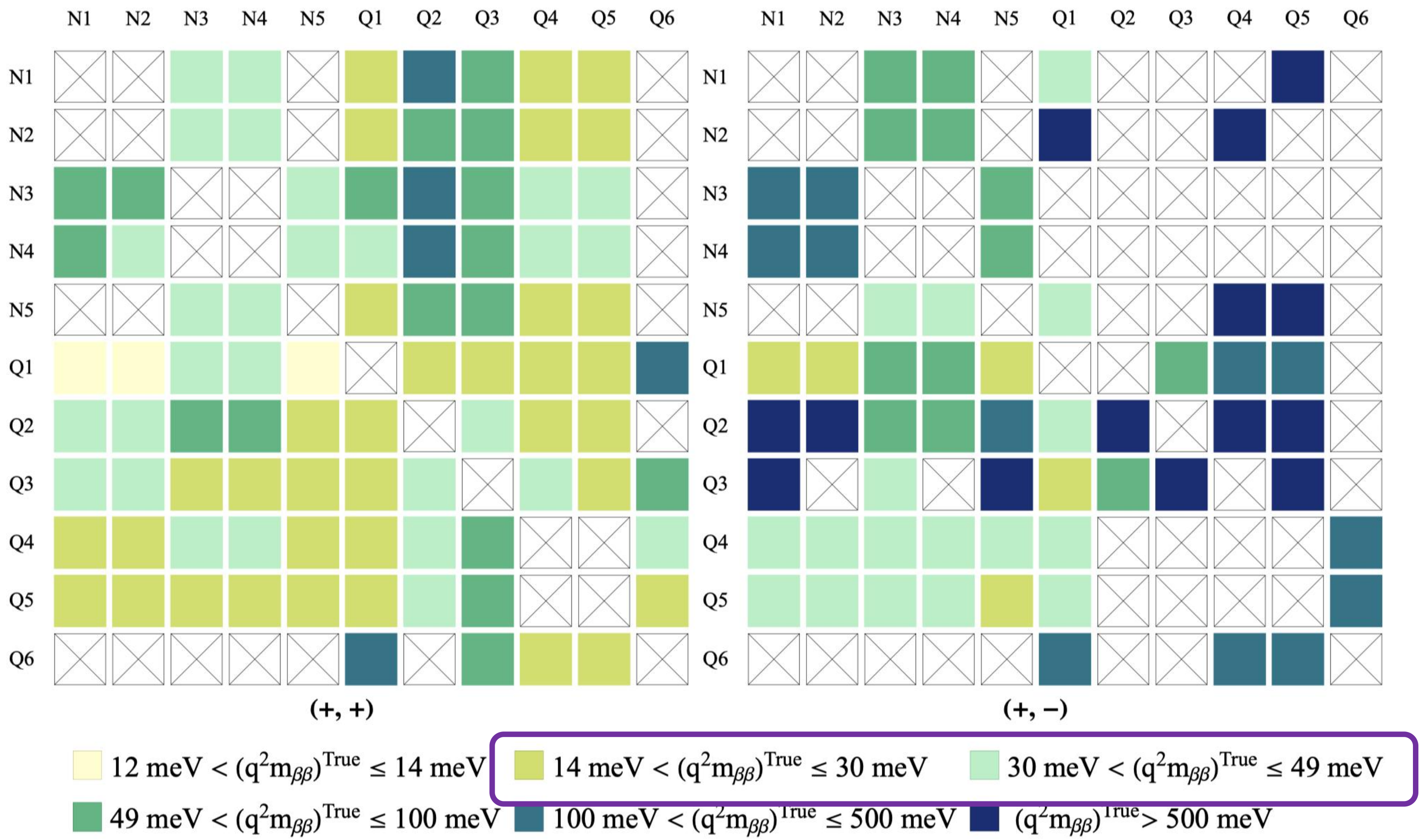


(without short- range NME)

Discrimination with short-range NME, T=10 yr

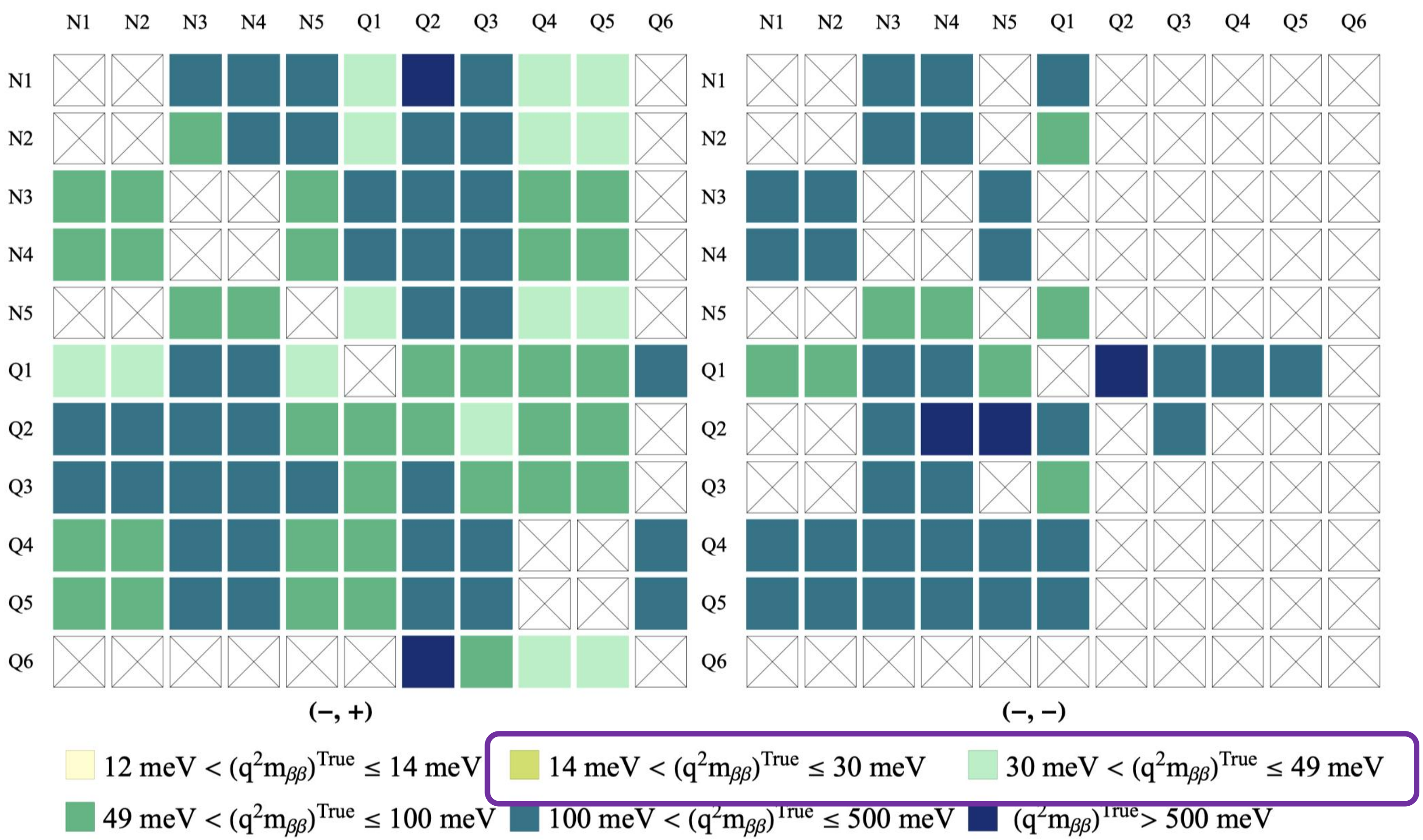


$m_{\beta\beta}^{\text{True}}$ corresponding to discrimination at 3σ



(with short- range NME)

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

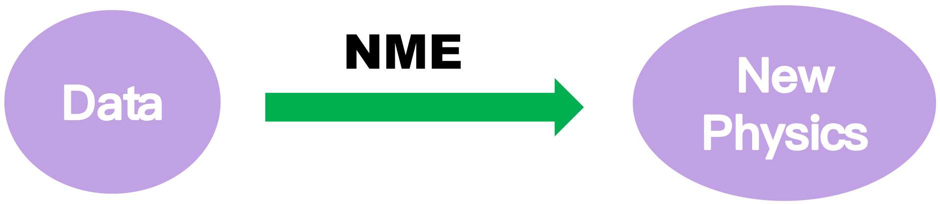


(with short- range NME)

Conclusions

- **NME uncertainties due to the SRI may lead to the bound on $q^2 m_{\beta\beta}$ varying by a factor of order 10**
- **Promising discrimination of different NMEs if $(q^2 m_{\beta\beta})^{True} > 40$ meV, positive SRI and 10 year exposure**
- **Similar analysis can be performed in the case of other 0νββ production mechanism** *(Phys.Rev.D 108 (2023) 5, 055023)*

Outlook

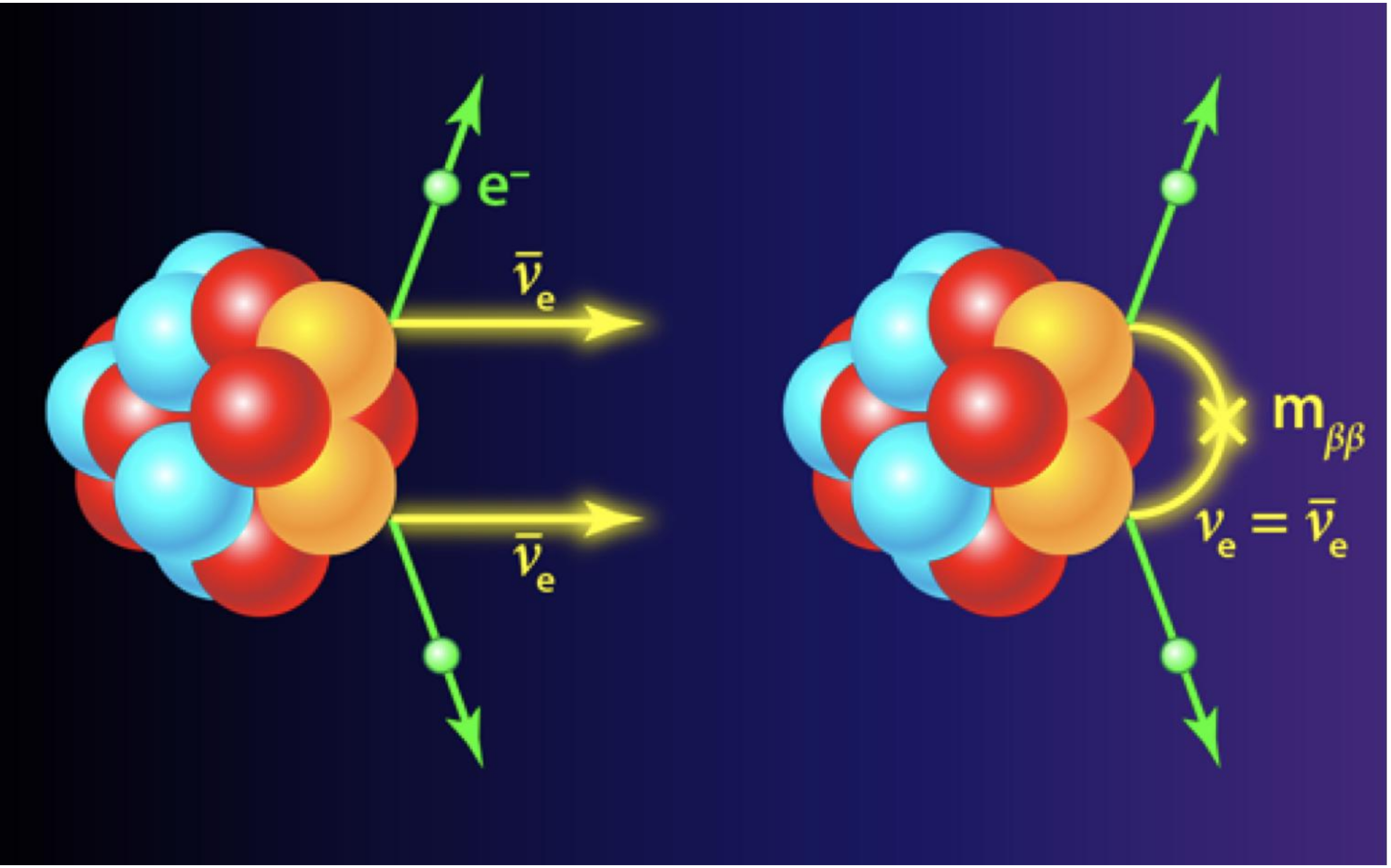


- Better understanding the short-range NME in 0νββ
- Better understanding the nuclear structure
- The quenching problem
- NME statistical uncertainties
- LEC from lattice calculations

More talks on this soon

- From 0νββ to $m_{\beta\beta}$: improving the calculations of NME
- From 0νββ to discriminating NME models: more information on $m_{\beta\beta}$

Which direction do you bet will get through first? (the former one?)

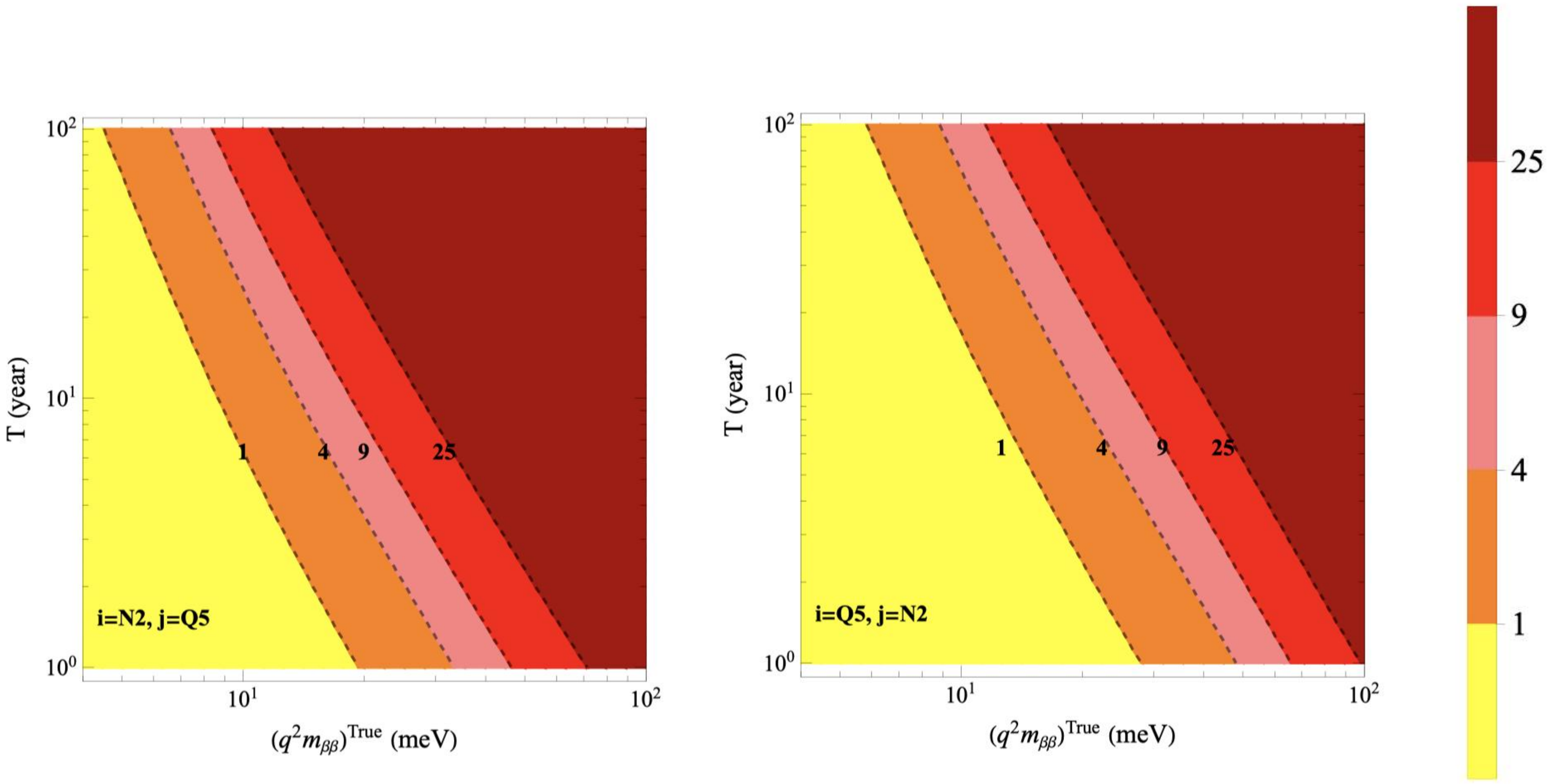


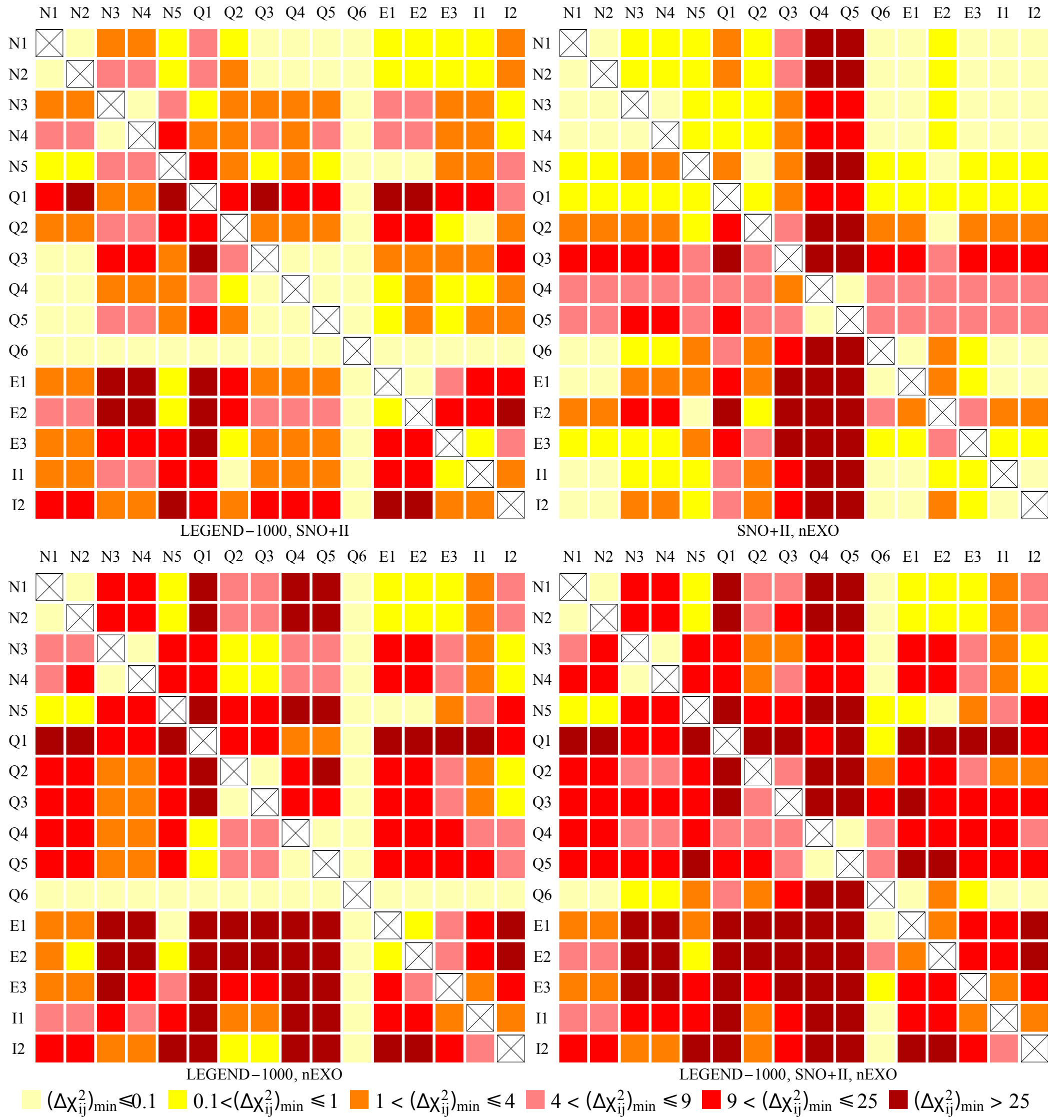
Where are you?

Thank you!

Backups

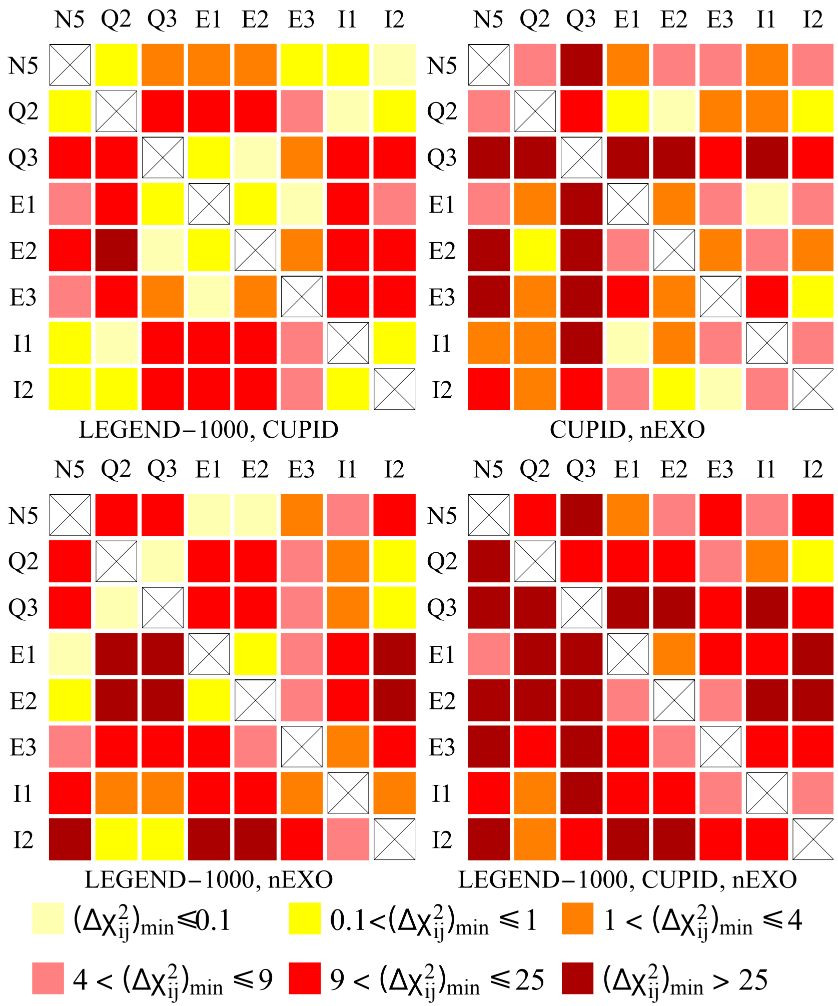
The contours of $(\Delta\chi^2_{ij})_{min}$ as function of the exposure time T and $(q^2 m_{\beta\beta})^{True}$





nEXO and LEGEND−1000 dominate

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



nEXO and LEGEND−1000 dominate

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