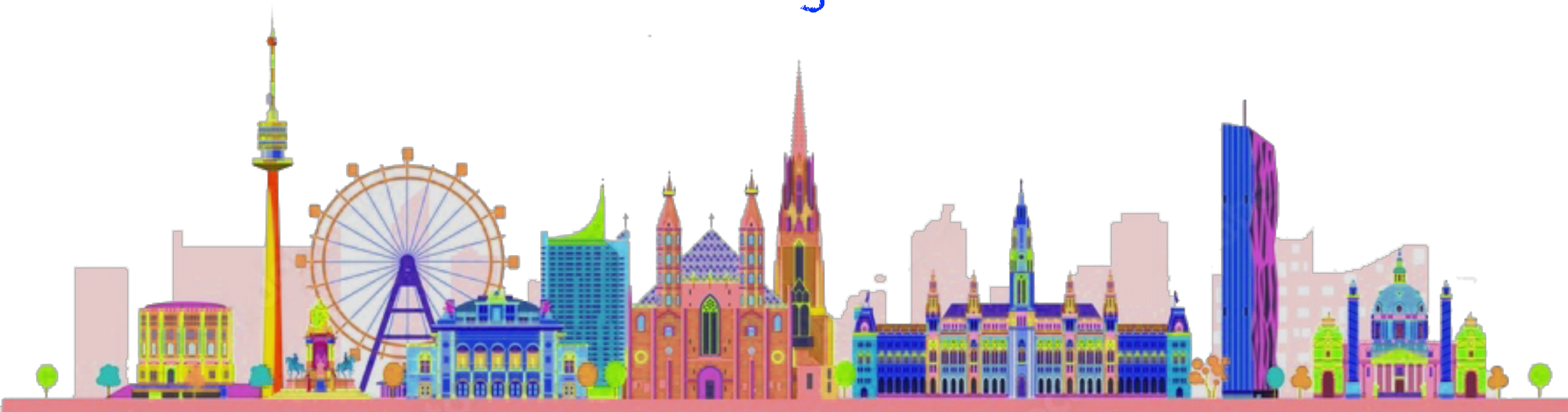


Neutrinoless double beta decay: interplay between nuclear matrix elements and neutrino exchange mechanisms



Antonio Marrone
University of Bari - INFN

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Starting viewpoint: Standard Model + three massive mixed neutrinos

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Second possibility, ν as Majorana particles \rightarrow Majorana mass term $m_L \overline{(\nu_L)^c} \nu_L$ or $m_R \overline{(\nu_R)^c} \nu_R$ Lepton Number violated by 2 units

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Black box theorem: ν masses radiatively generated (but too small to explain observed neutrino mass differences)

While other mechanism could contribute, we assume neutrino mass as the exclusive contributing process to $0\nu\beta\beta$, but consider here the possibility of exchange of both light (ν) and heavy (N) neutrinos in the non-interfering case

What experiments measure $(T_i)^{-1} = S_i = G_i (M_{\nu,i}^2 m_\nu^2 + M_{N,i}^2 m_N^2)$

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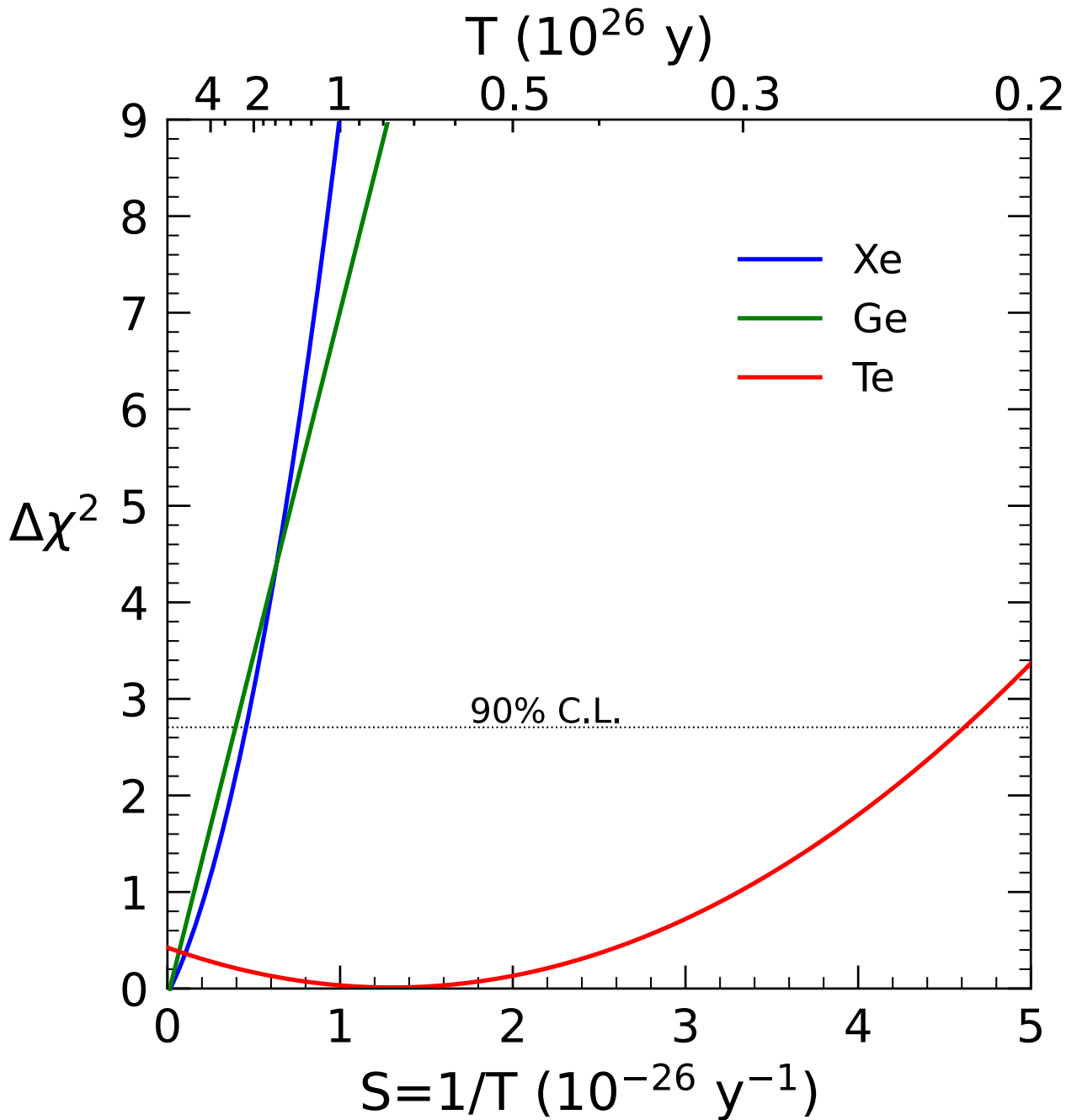
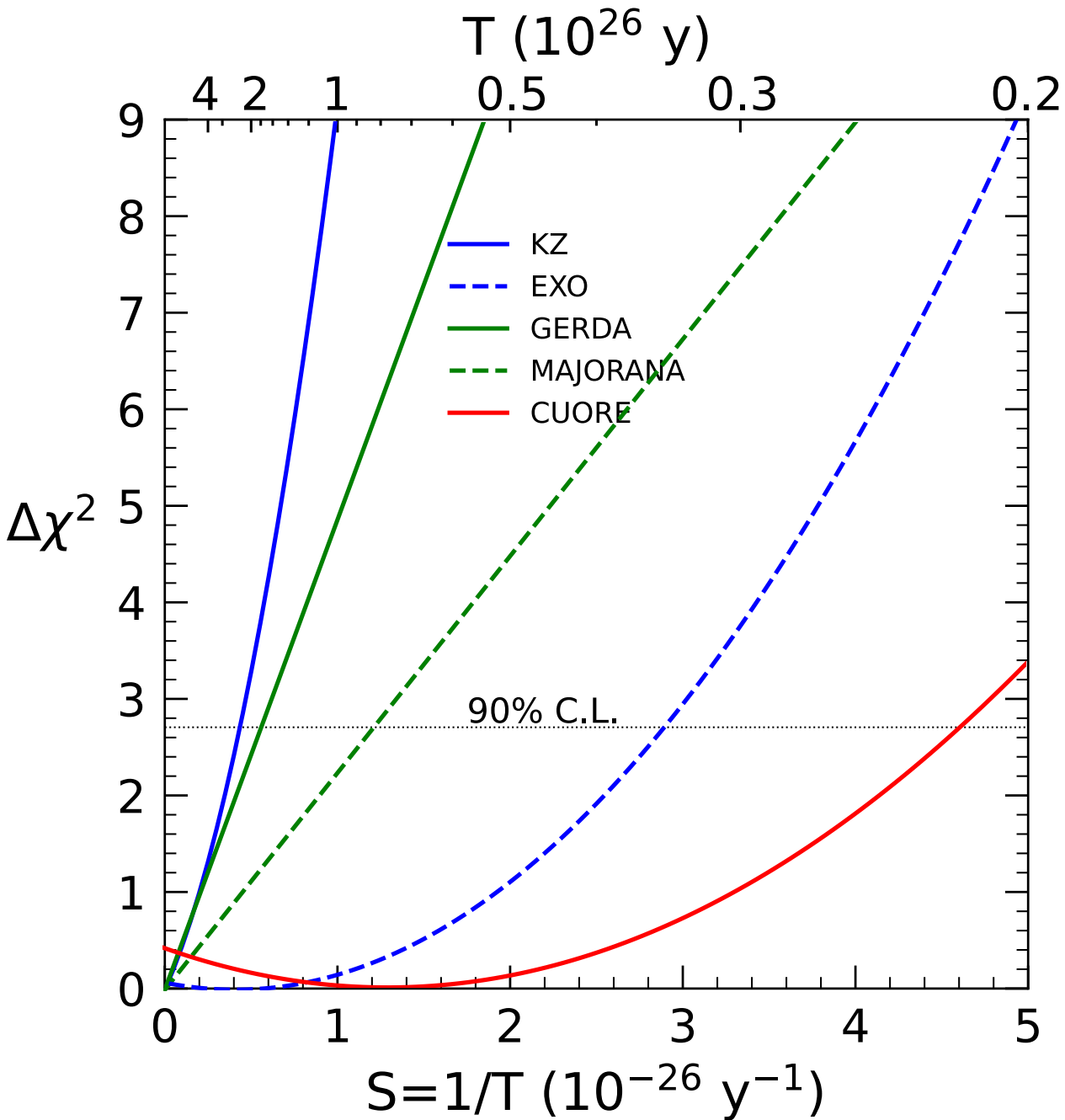
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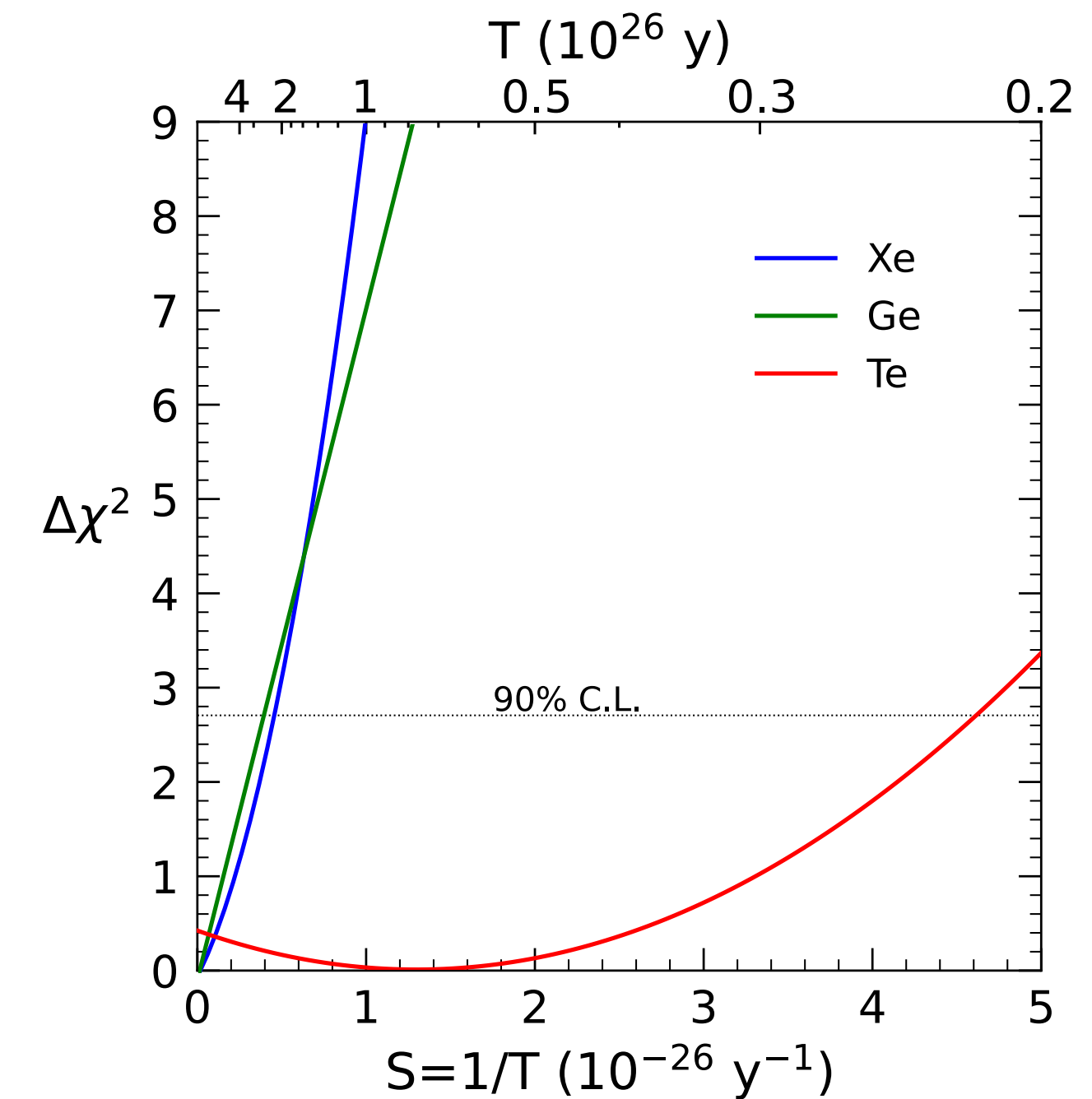
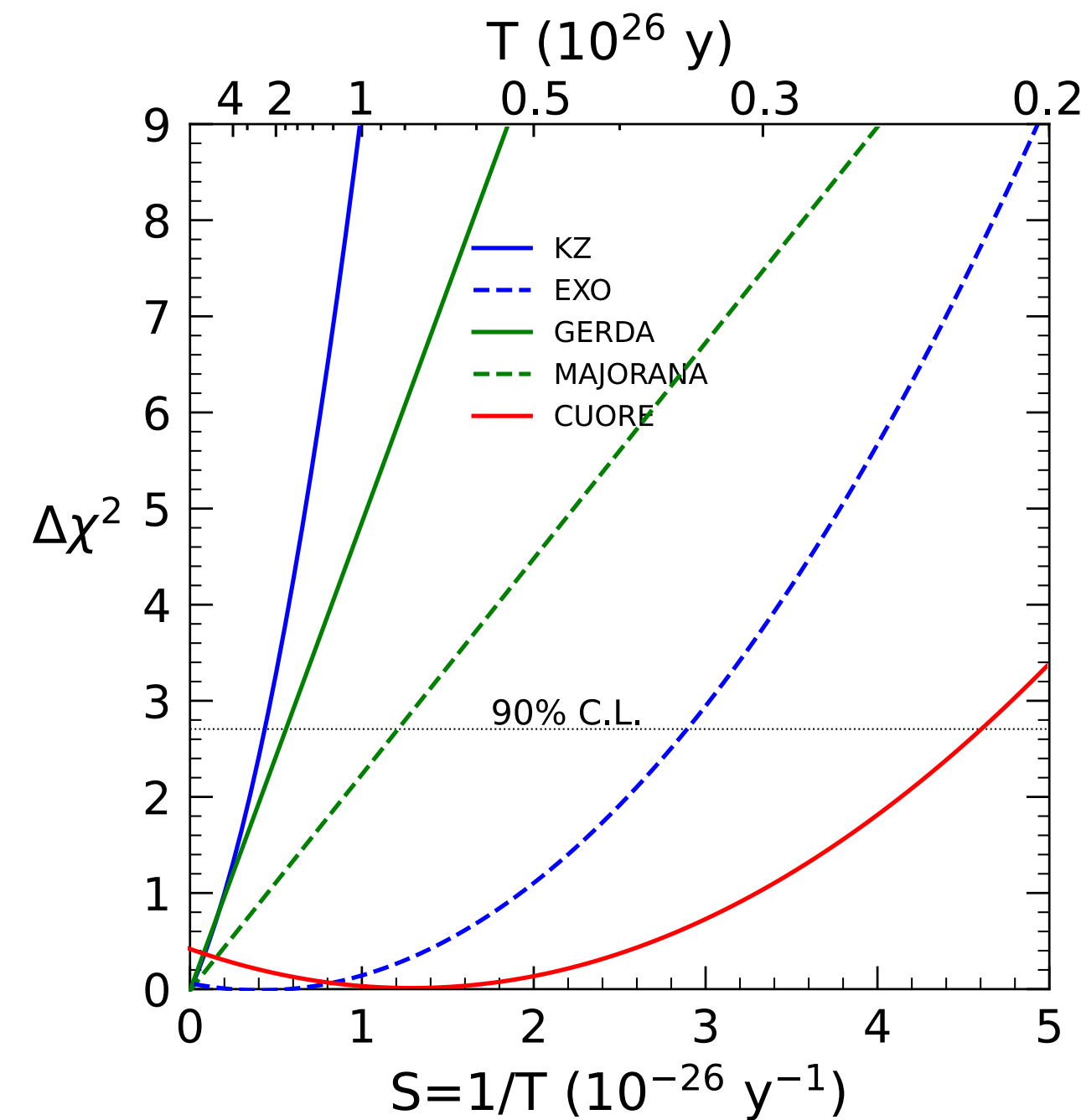
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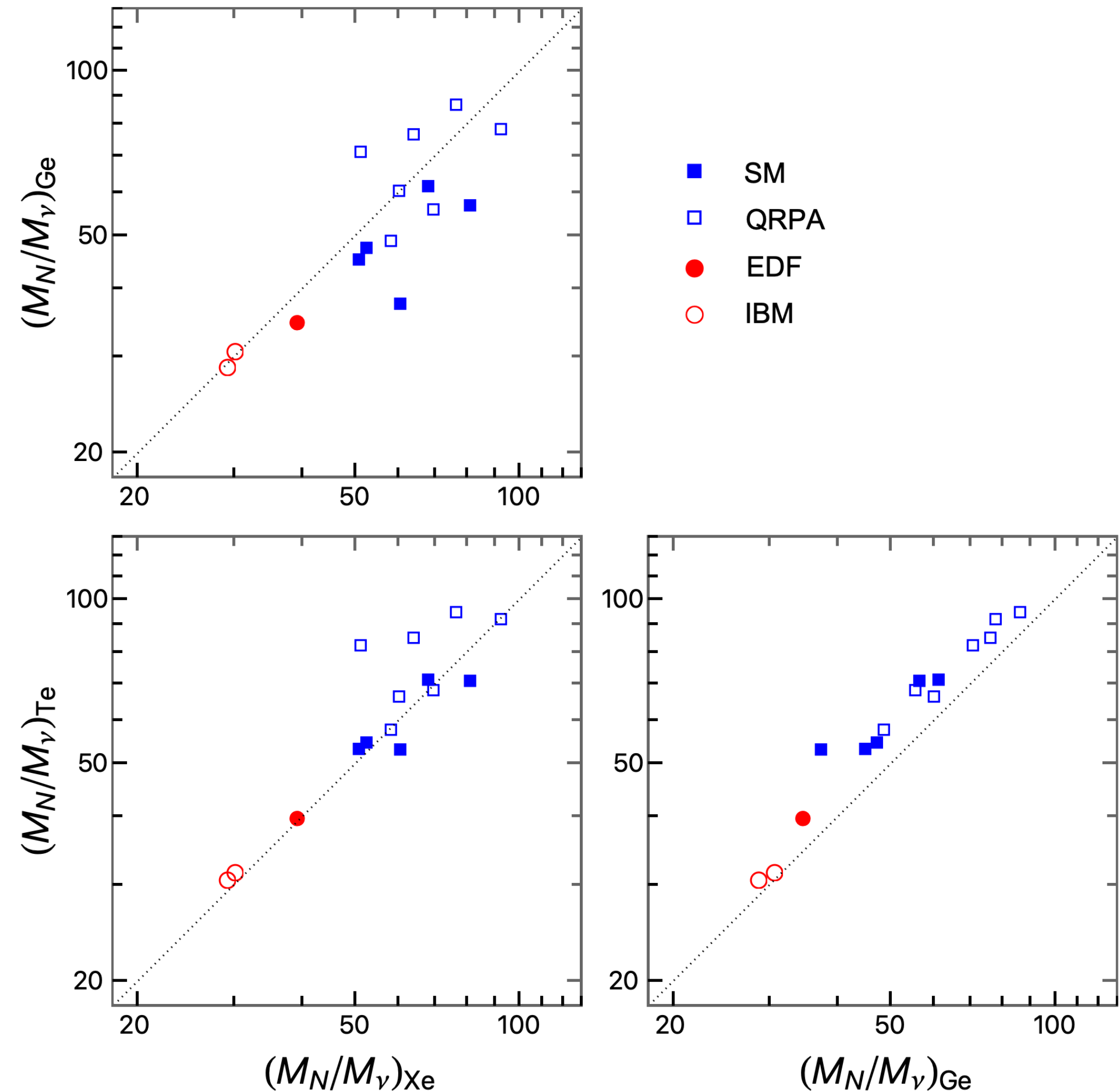
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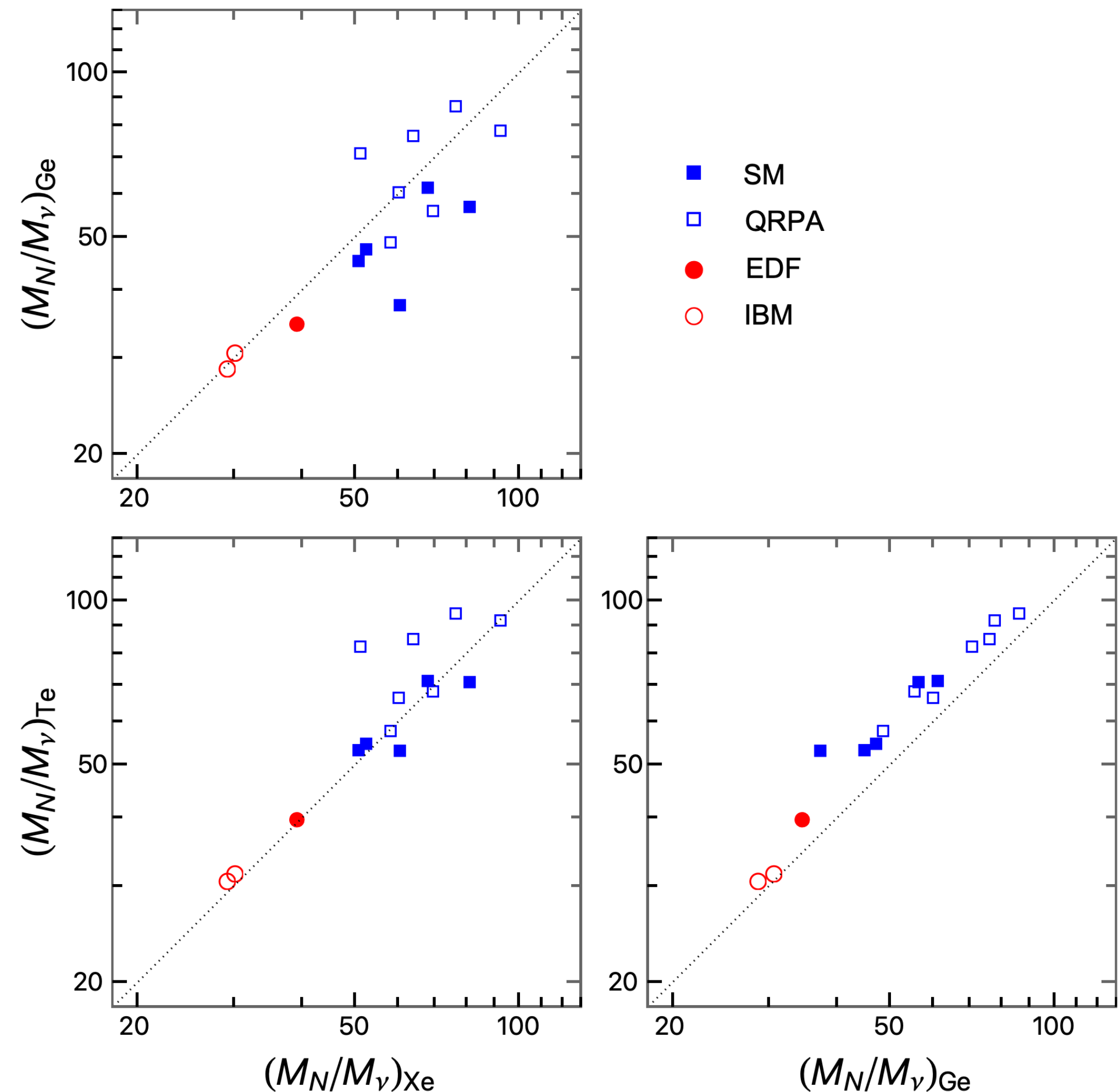
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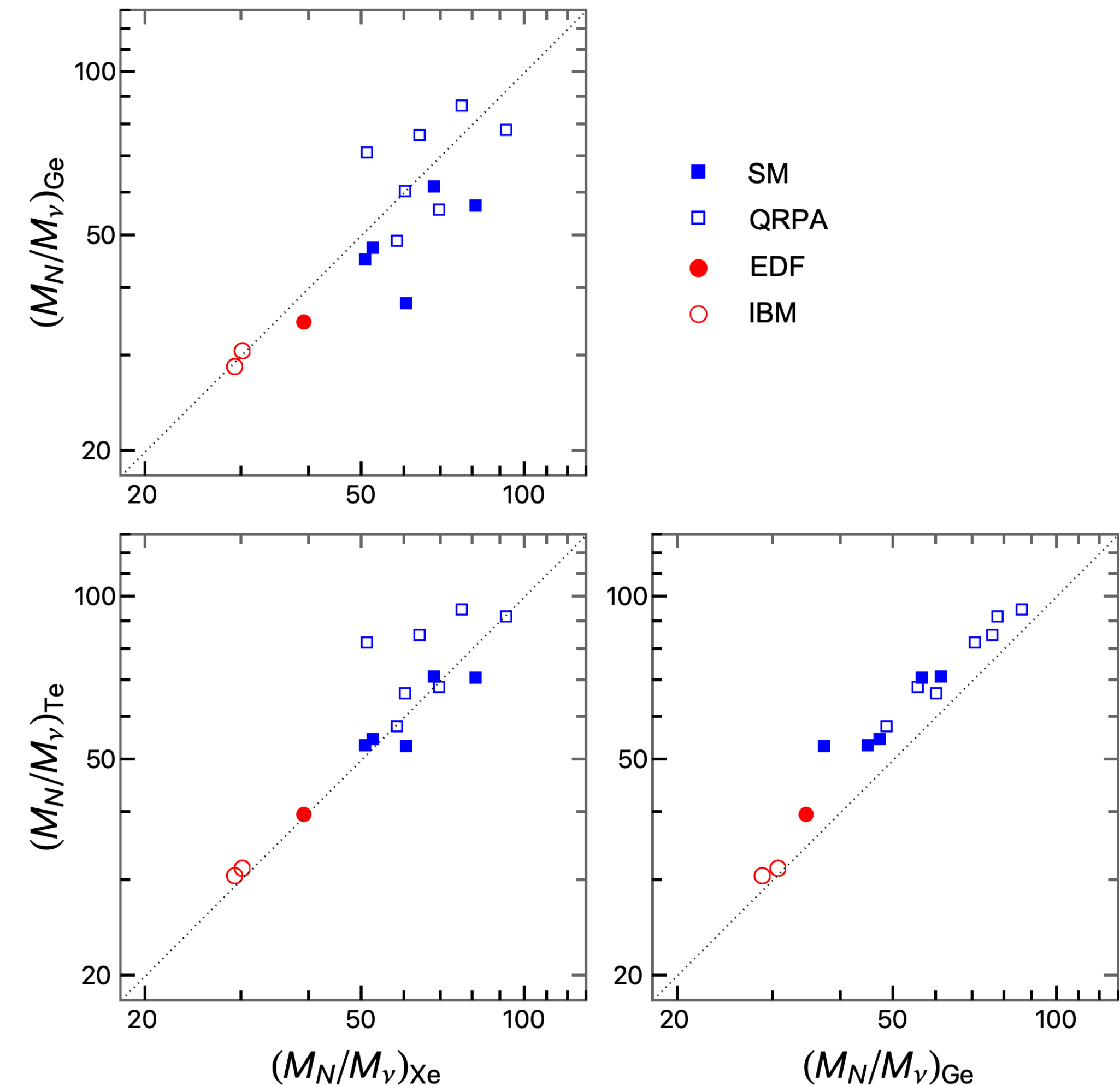
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Strictly true only if the ratio of heavy-to-light NME for the different isotopes (i and j) are not equal

$$\frac{M_{N,i}}{M_{\nu,i}} \neq \frac{M_{N,j}}{M_{\nu,j}}$$



Current experiments give only upper bounds on m_ν and m_N when only one exchange mechanism is present or when the two are both present in the non-interfering case

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Generate a fake true signal with a given set of NME and analyse the data with the same NME set: this corresponds to the assumption of negligible errors on the theoretical NME calculations

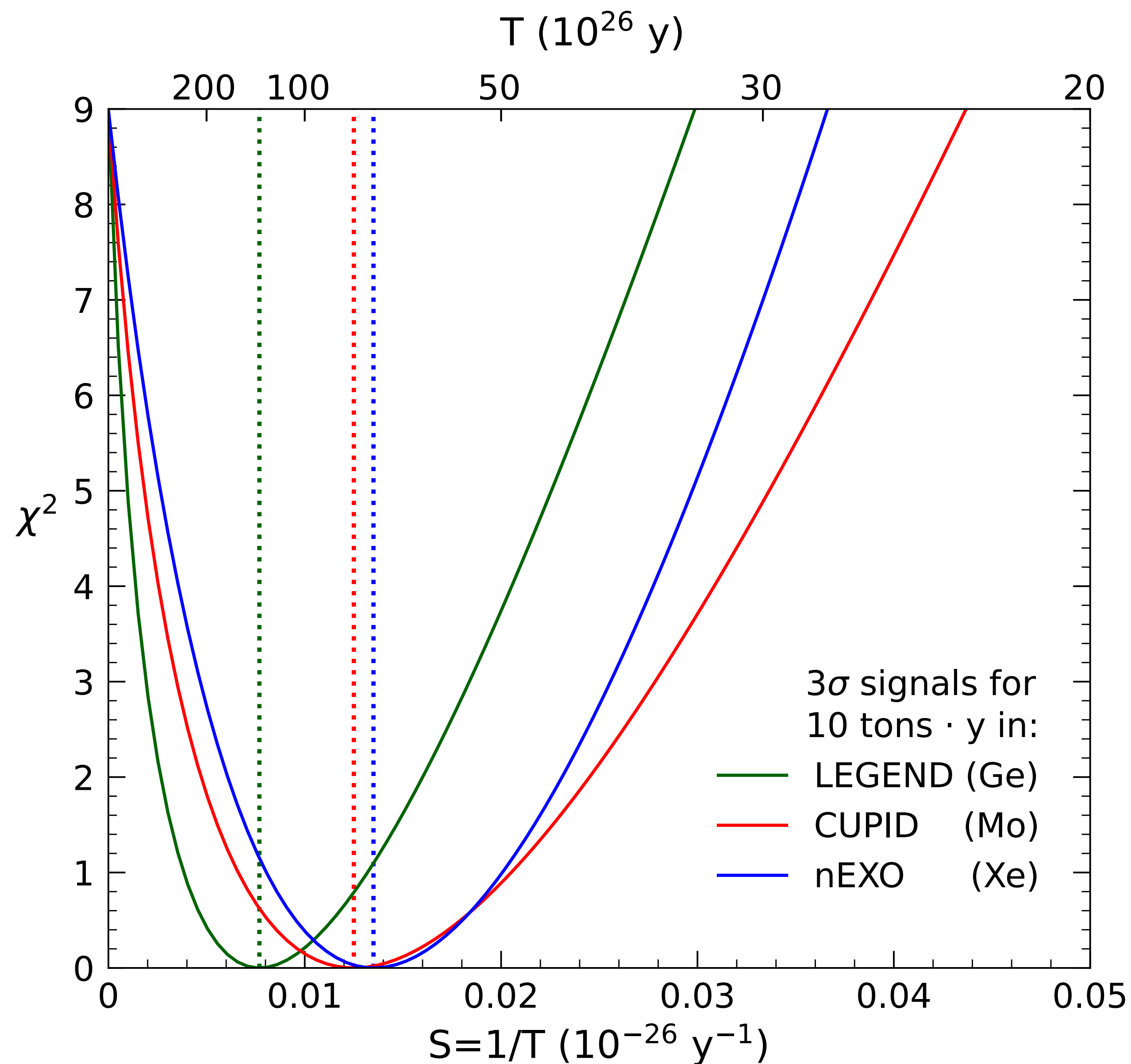
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Generate a fake true signal with a given set of NME and analyse the data with another NME set: this is the actual case, in which the spread between different theoretical calculations is still large and cannot be neglected



Prospective $0\nu\beta\beta$ decay signals (at $> 3\sigma$) in future ton-scale projects, with reference to nEXO (Xe), LEGEND (Ge) and CUPID (Mo)

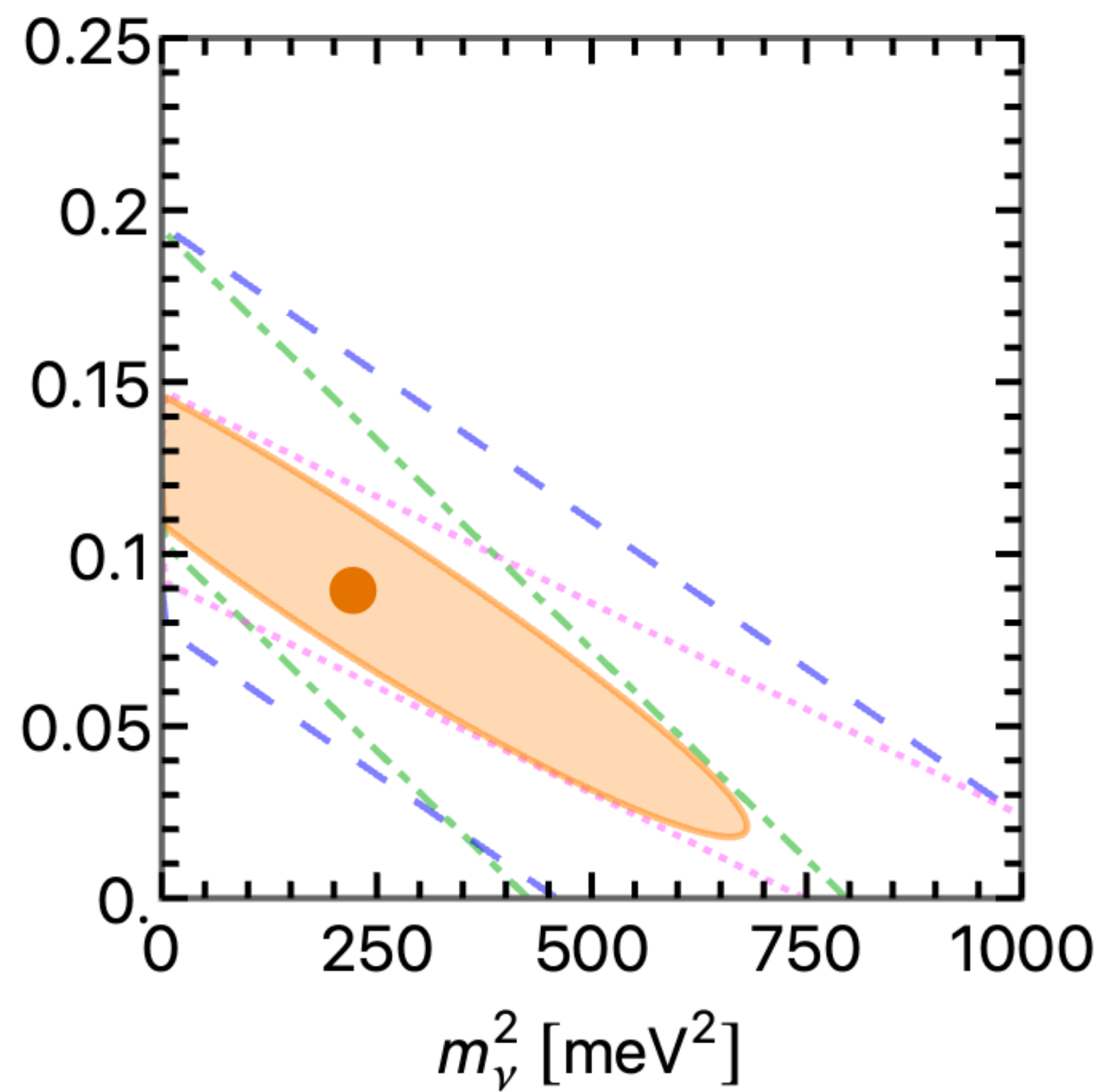
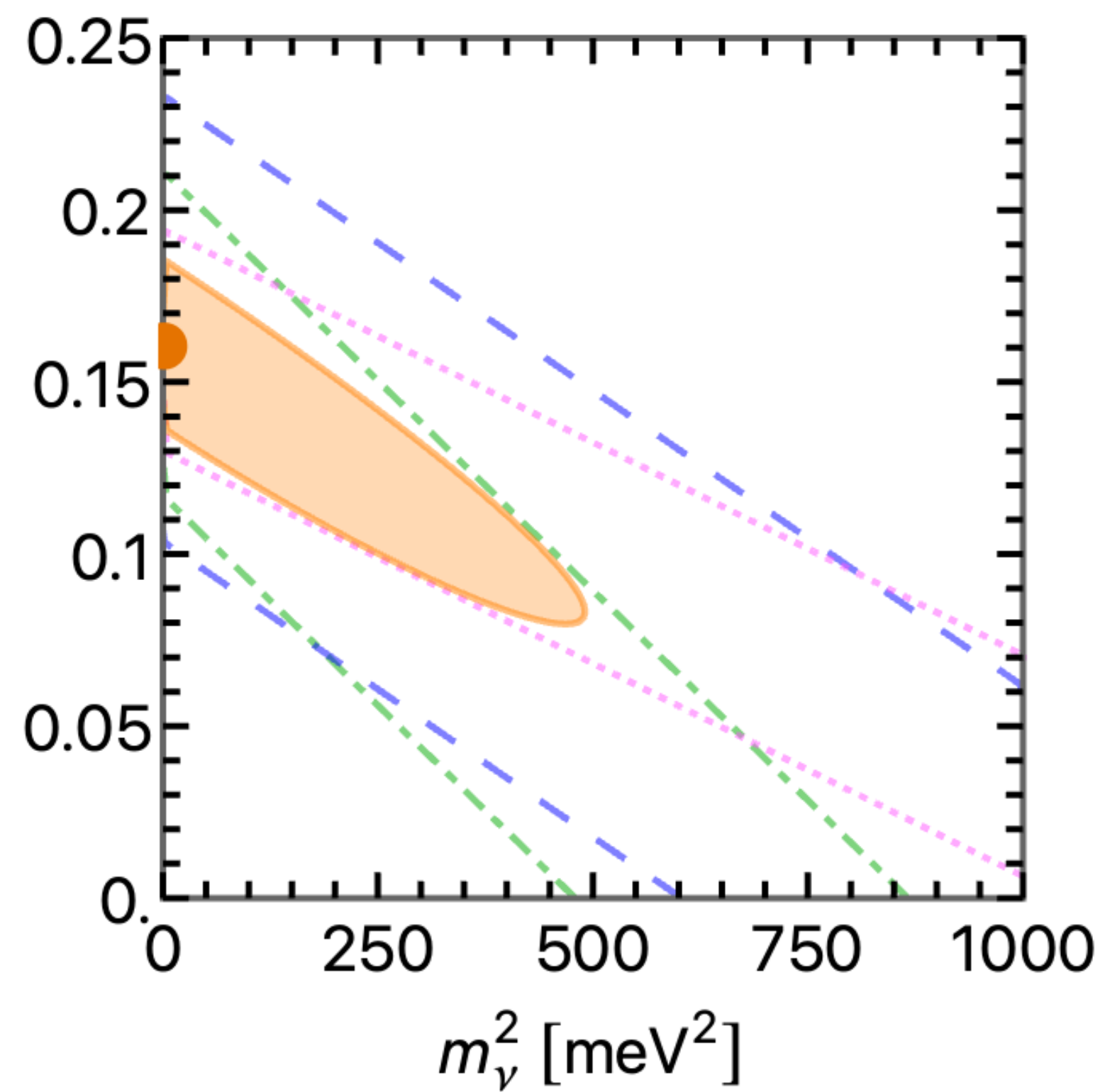
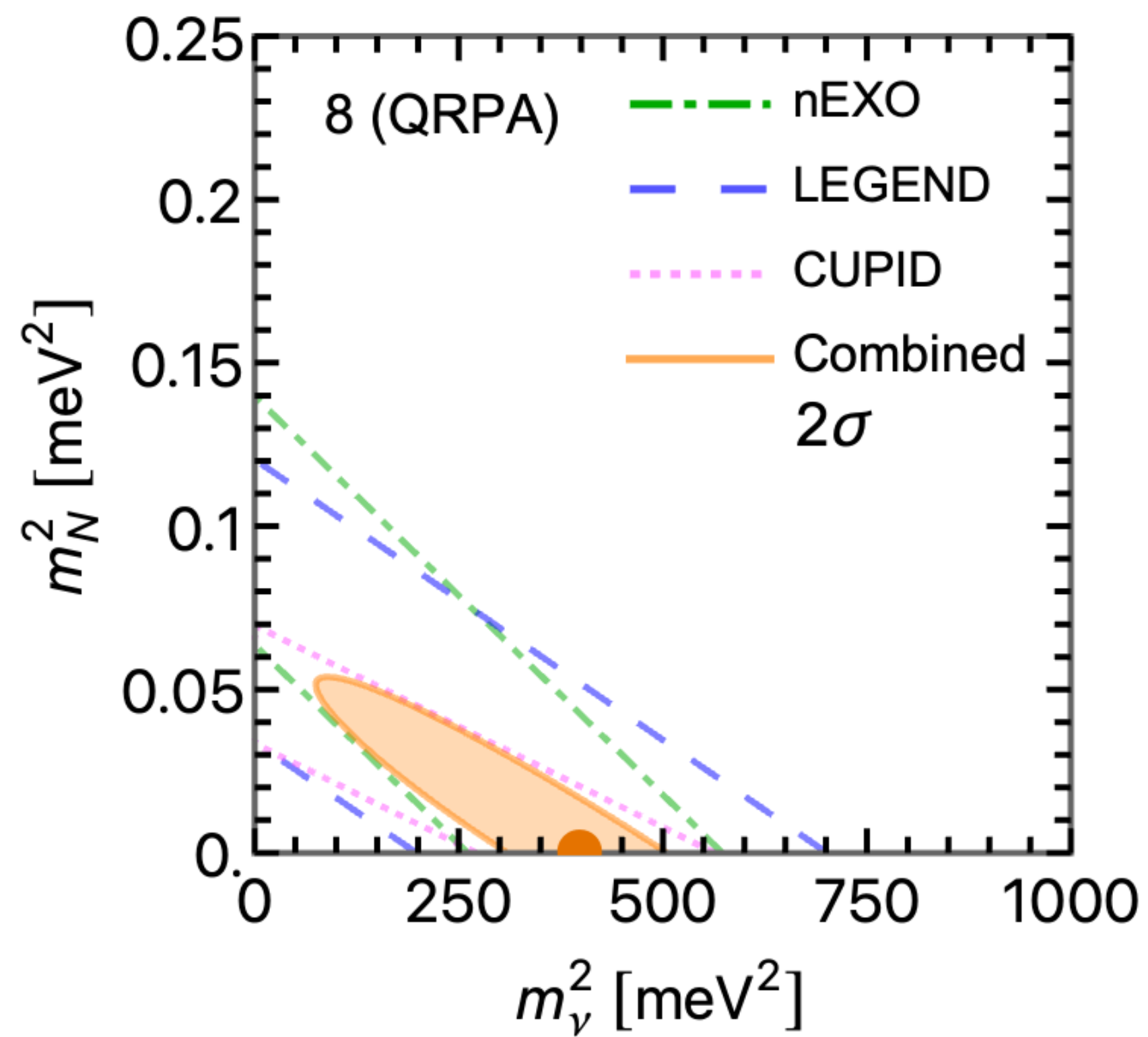
Reconstruction of hypothetical signals for fixed NME sets

Exposure of 1 ton \times 10 years

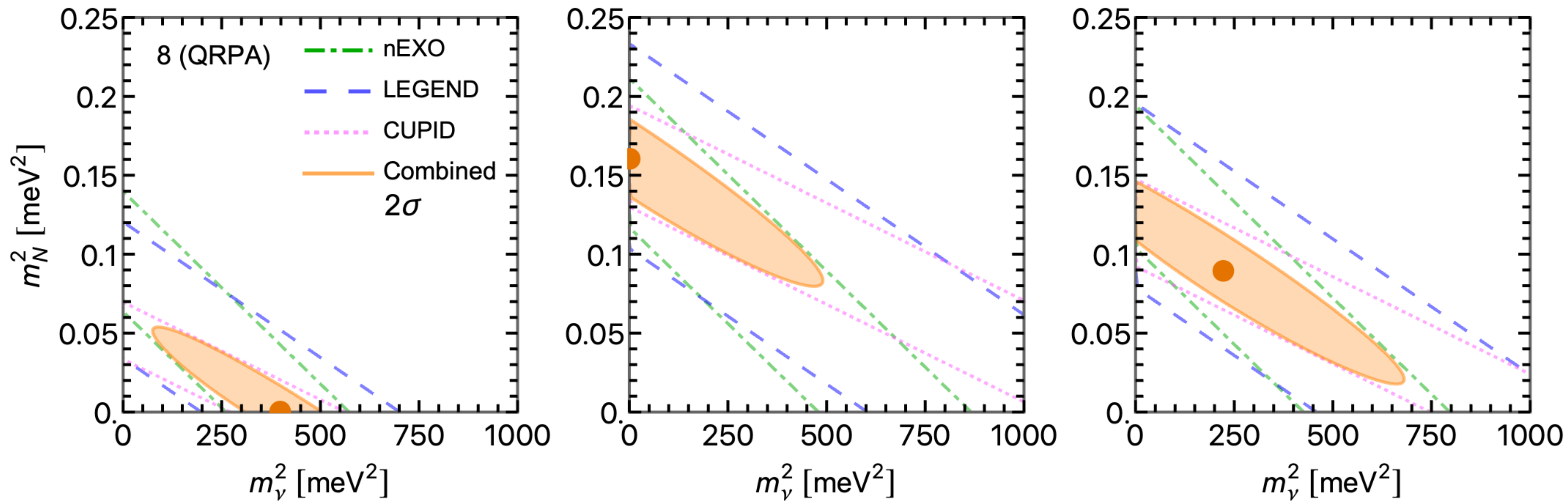
The assumption of a 3σ discovery signal $\bar{S}_i = S_i^{3\sigma}$ corresponds to have $\chi_i^2 = 9$ for $S_i = 0$ and $\chi_i^2 = 0$ for $S_i = S_i^{3\sigma}$

The analysis uses parameters proposed in Rev. Mod. Phys. 95 no.2, 025002 (2023), reproducing the discovery sensitivity presented for various exposures in nEXO (J. Phys. G49, no.1, 015104 (2022) LEGEND (arXiv:2107.11462 [physics.ins-det]) and CUPID (arXiv:2203.08386 [nucl-ex])

Assume no uncertainty on the theoretical calculations: the true and test NME are the same



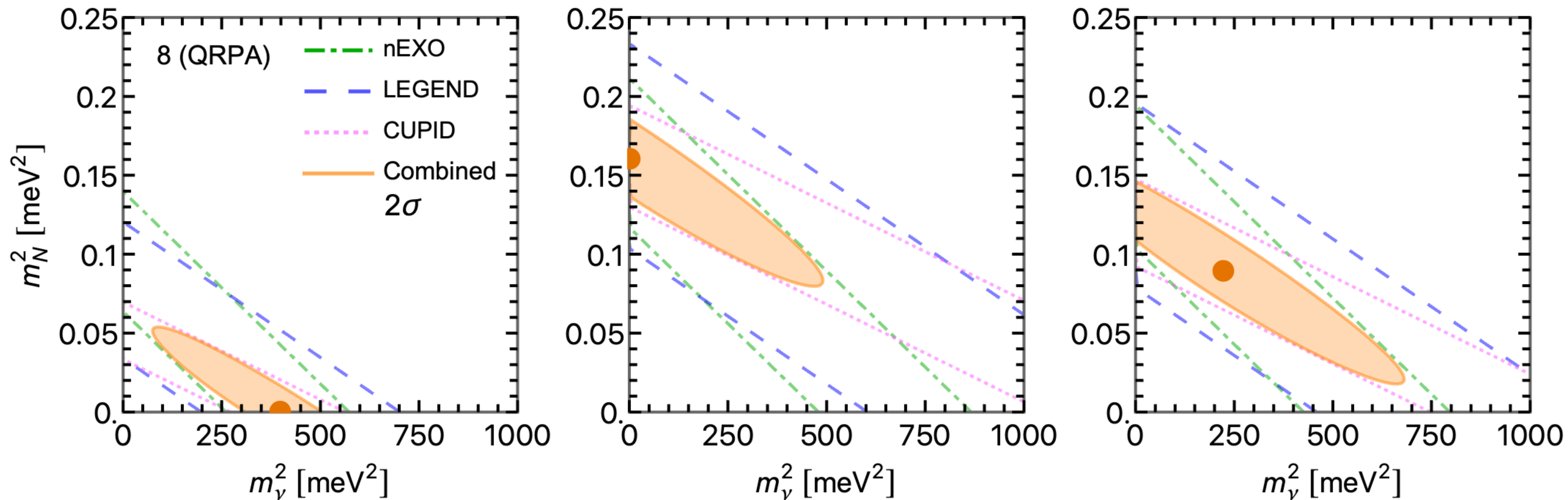
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$$(\bar{m}_\nu, \bar{m}_N) = \begin{bmatrix} (20, 0) \\ (0, 0.4) \\ (15, 0.3) \end{bmatrix} \text{ meV}$$

The slopes of the bands are governed by the $M_{N,i}/M_{\nu,i}$ ratios: the smaller the differences, the closer the slopes, the larger the overlap, the higher the degeneracy between the two $0\nu\beta\beta$ mechanisms

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Three representative pairs for the effective Majorana masses

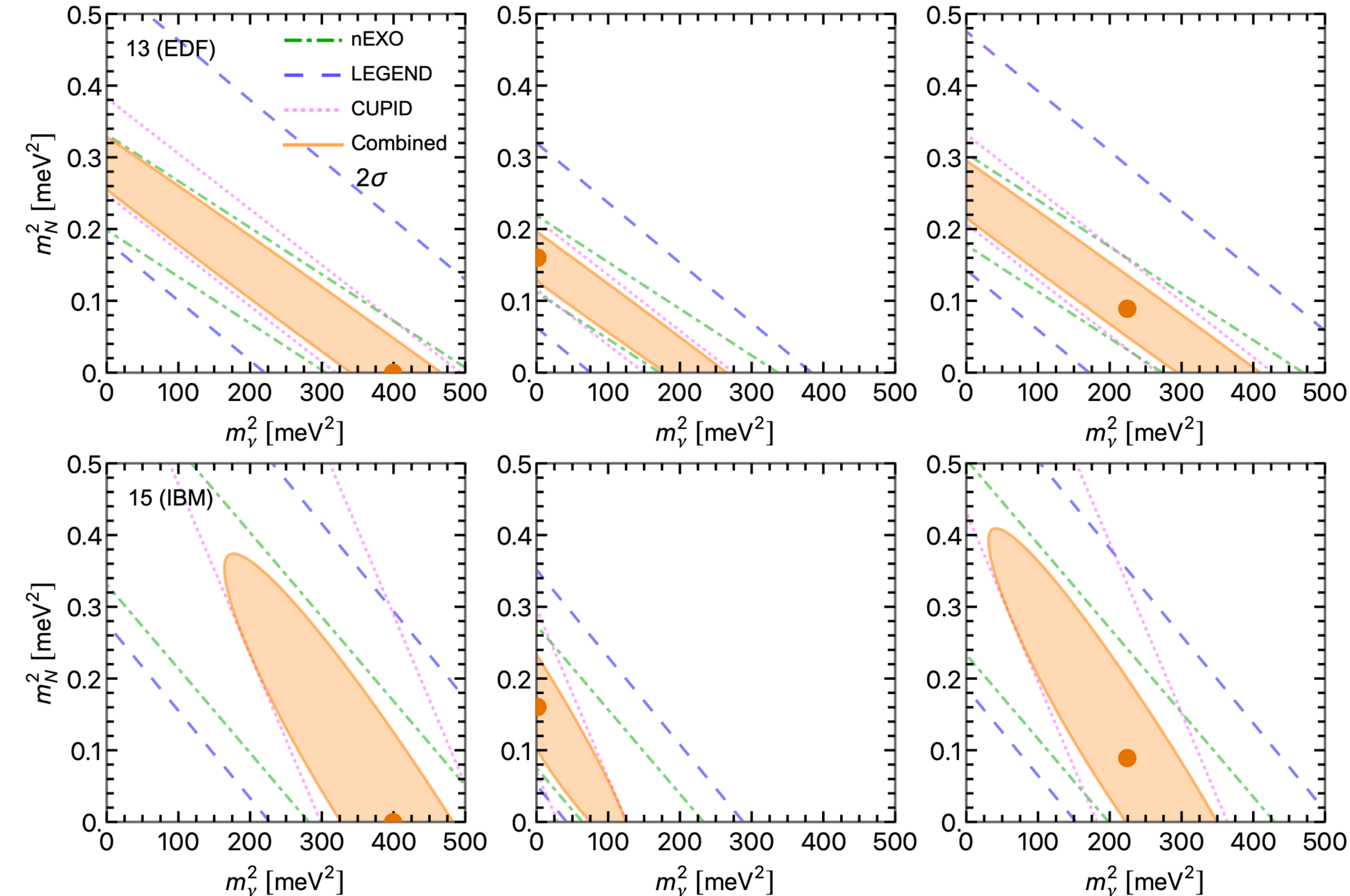
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Separate bands have quite different slopes, and their combination allows to distinguish the extreme cases

For the true cases of only light (or heavy) neutrinos, the opposite test cases of only heavy (or light) neutrinos are rejected at $> 2\sigma$. With both mechanisms at the same time, the limit $m_N = 0$ is rejected, while $m_\nu = 0$ is allowed, as a result of the relatively high ratio $M_{N,i}/M_{\nu,i}$ in all isotopes.

EDF set 13 (upper panels) and the IBM set 15 (lower panels)



These NME sets are characterized by relatively low ratios $M_{N,i}/M_{\nu,i}$

Provide weaker (stronger) constraints on m_ν (m_N) → note the change of scale

In the upper panels, the band slopes are very similar to each other, leading to an almost complete degeneracy of the two mechanisms

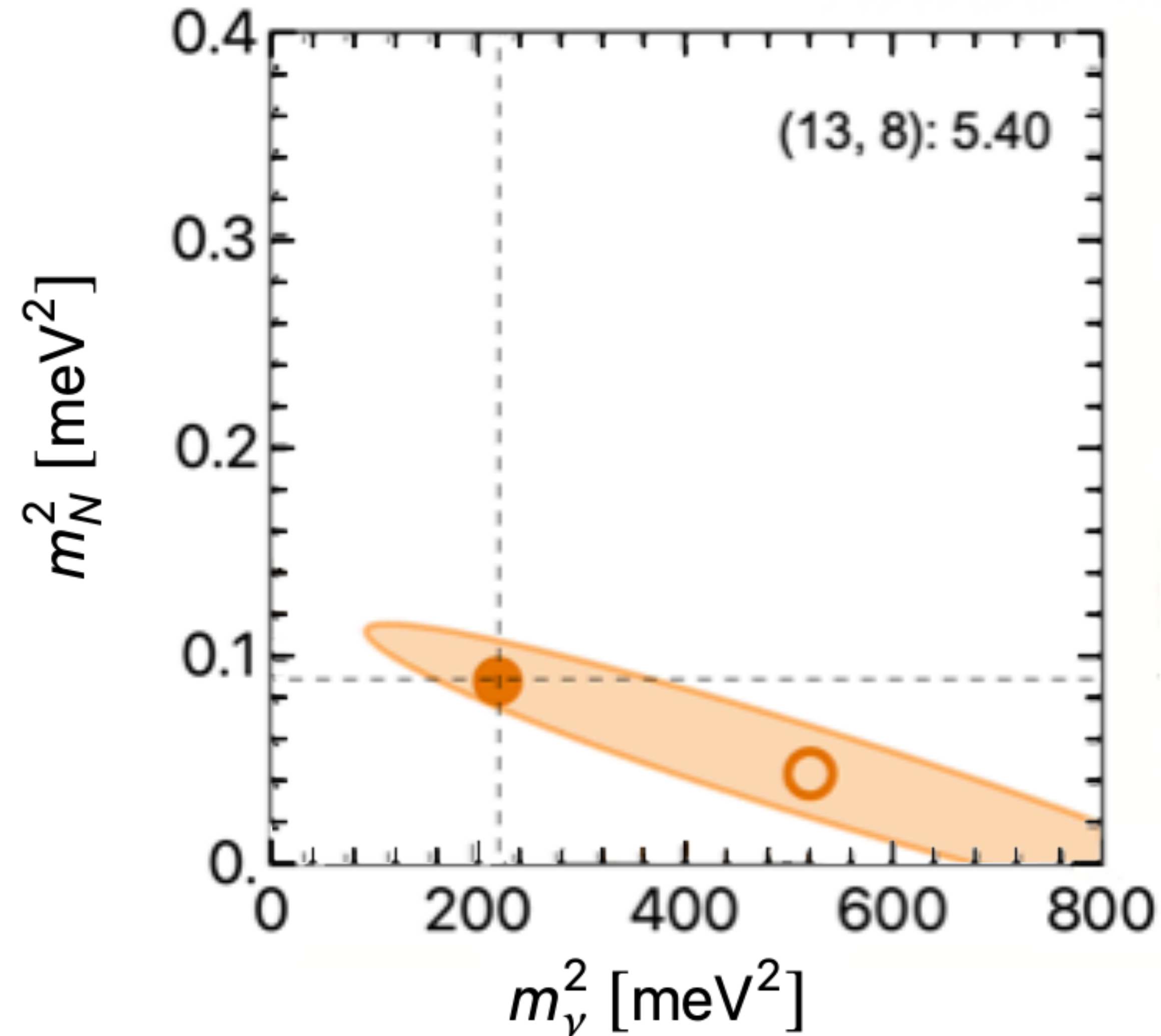
In the lower panels, the degeneracy is partly broken, and some limiting cases can be excluded in the 2σ combination.

Potential to statistically discriminate non-interfering mechanisms, if NME relatively well known for rather different ratios, in at least a couple of isotopes.

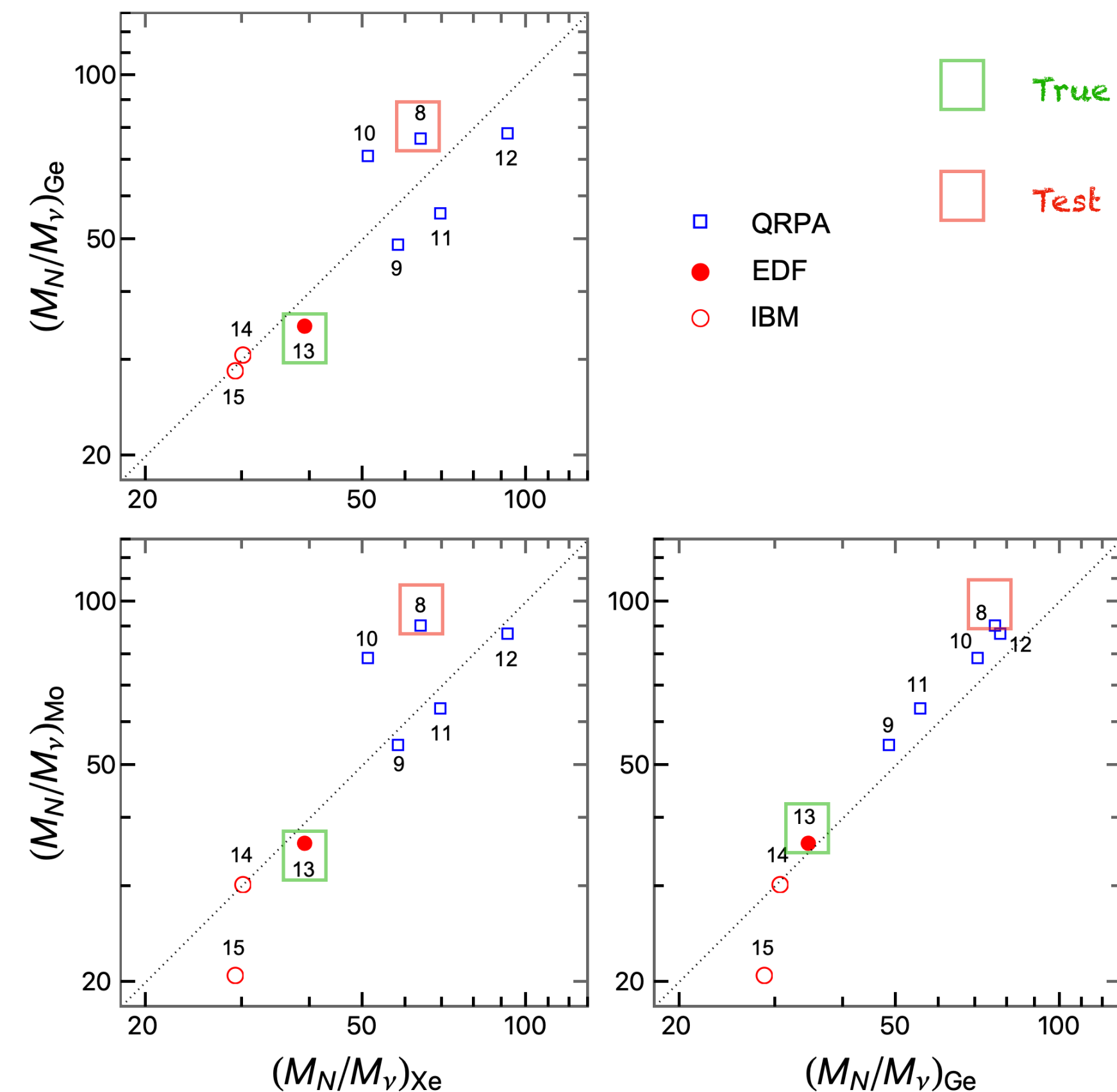
For very similar NME ratios, the mechanisms are instead degenerate

The future will tell us which conditions are met by more accurate NME calculations

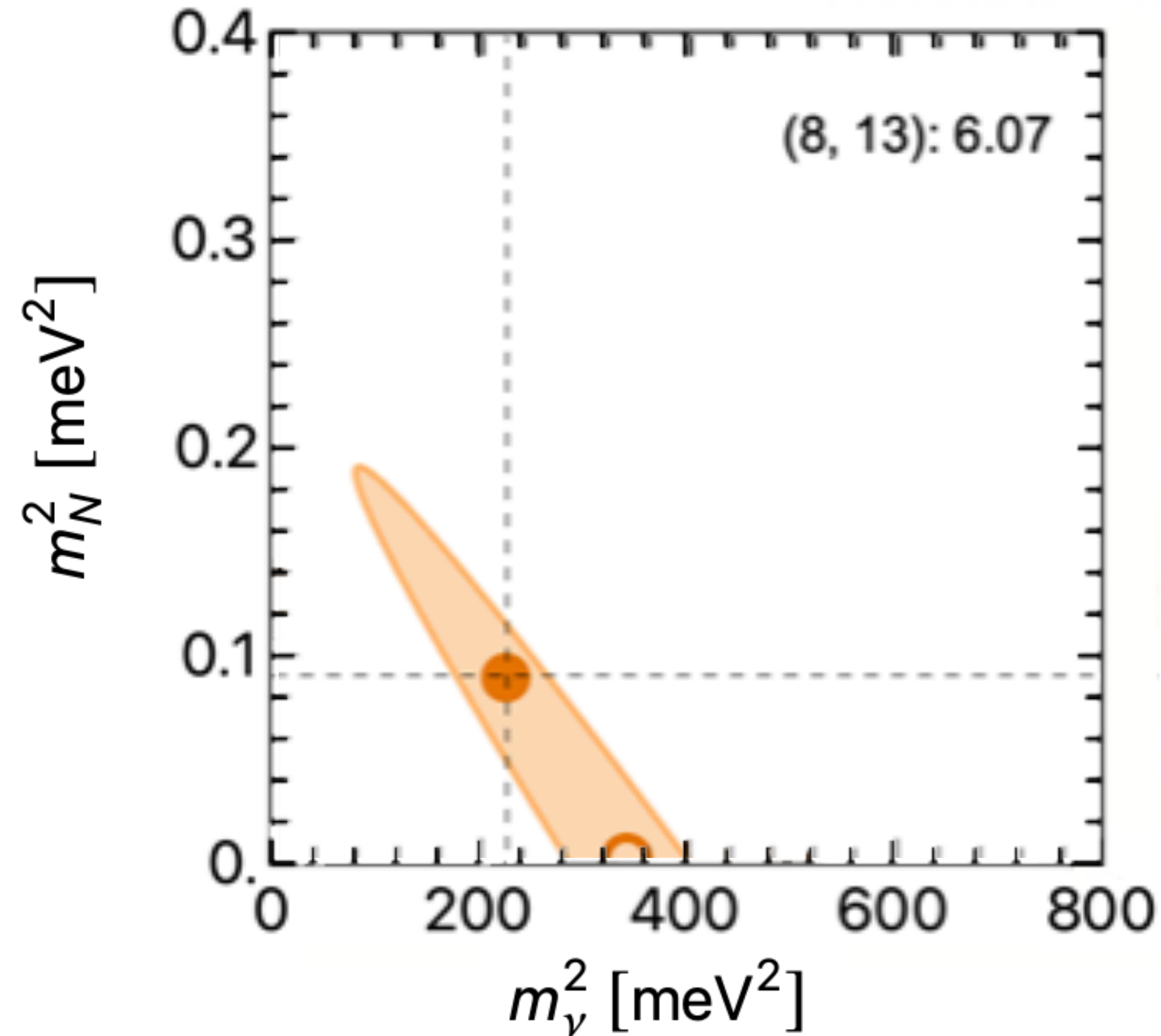
When the **true** and **test** NME sets are different, there are many possible outcomes concerning the relative positions of the true and test minima and the value of the χ^2_{\min}



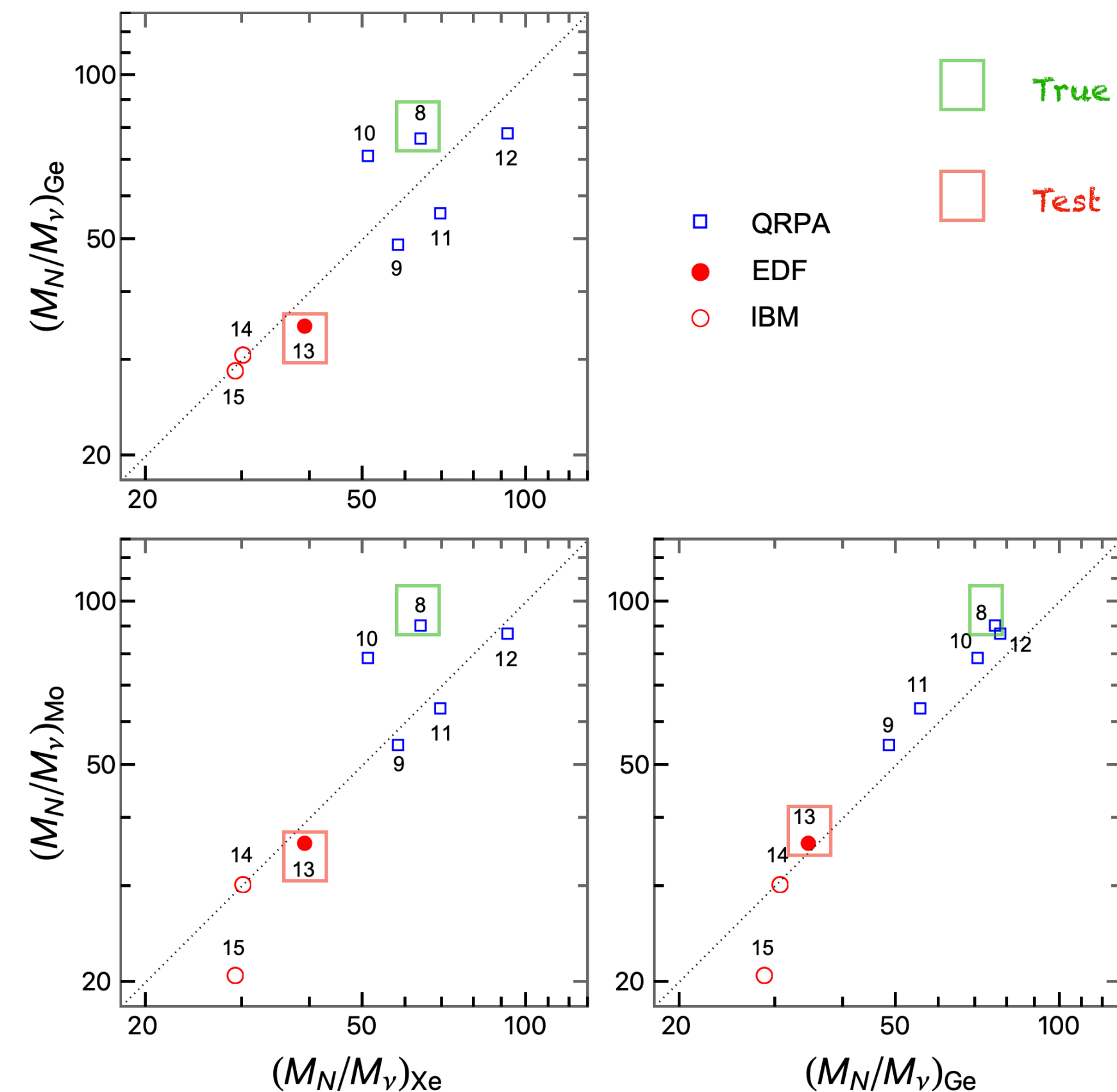
The true minimum is inside the test 2σ region with a χ^2_{\min} marginally acceptable corresponding to $p \sim 0.07$



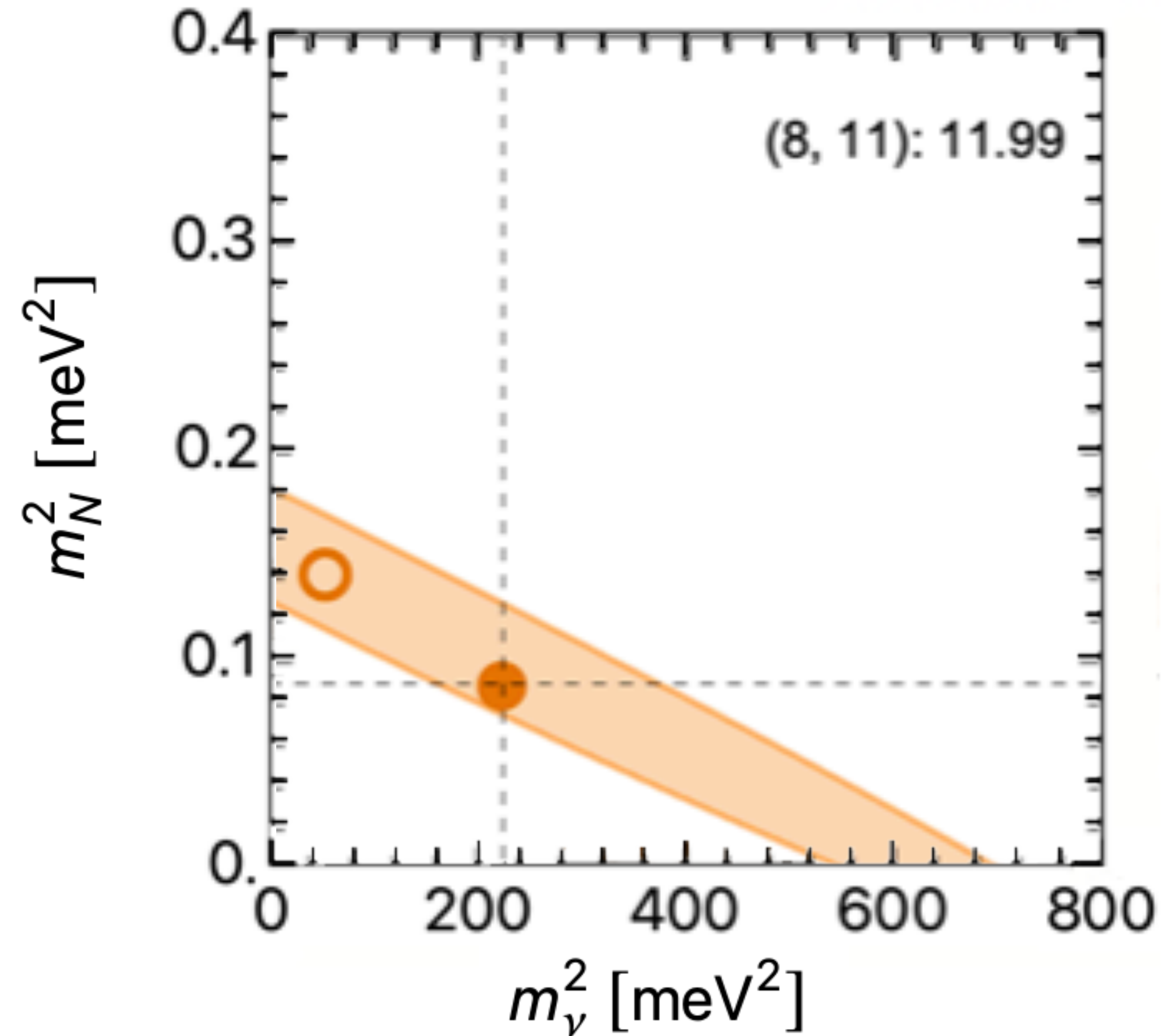
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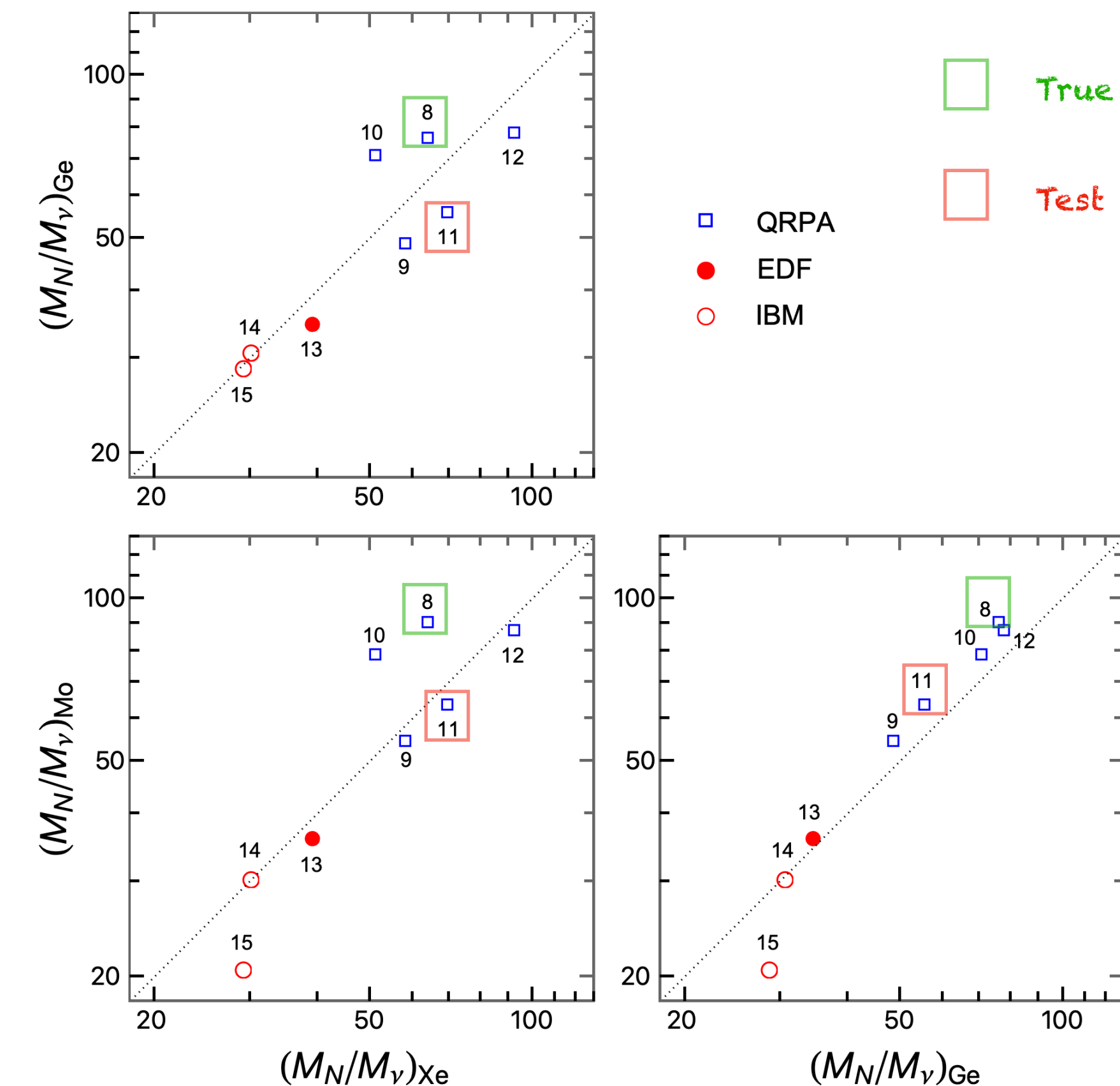
The true minimum is inside the test 2σ region with a χ^2_{\min} marginally acceptable corresponding to $p \sim 0.05$



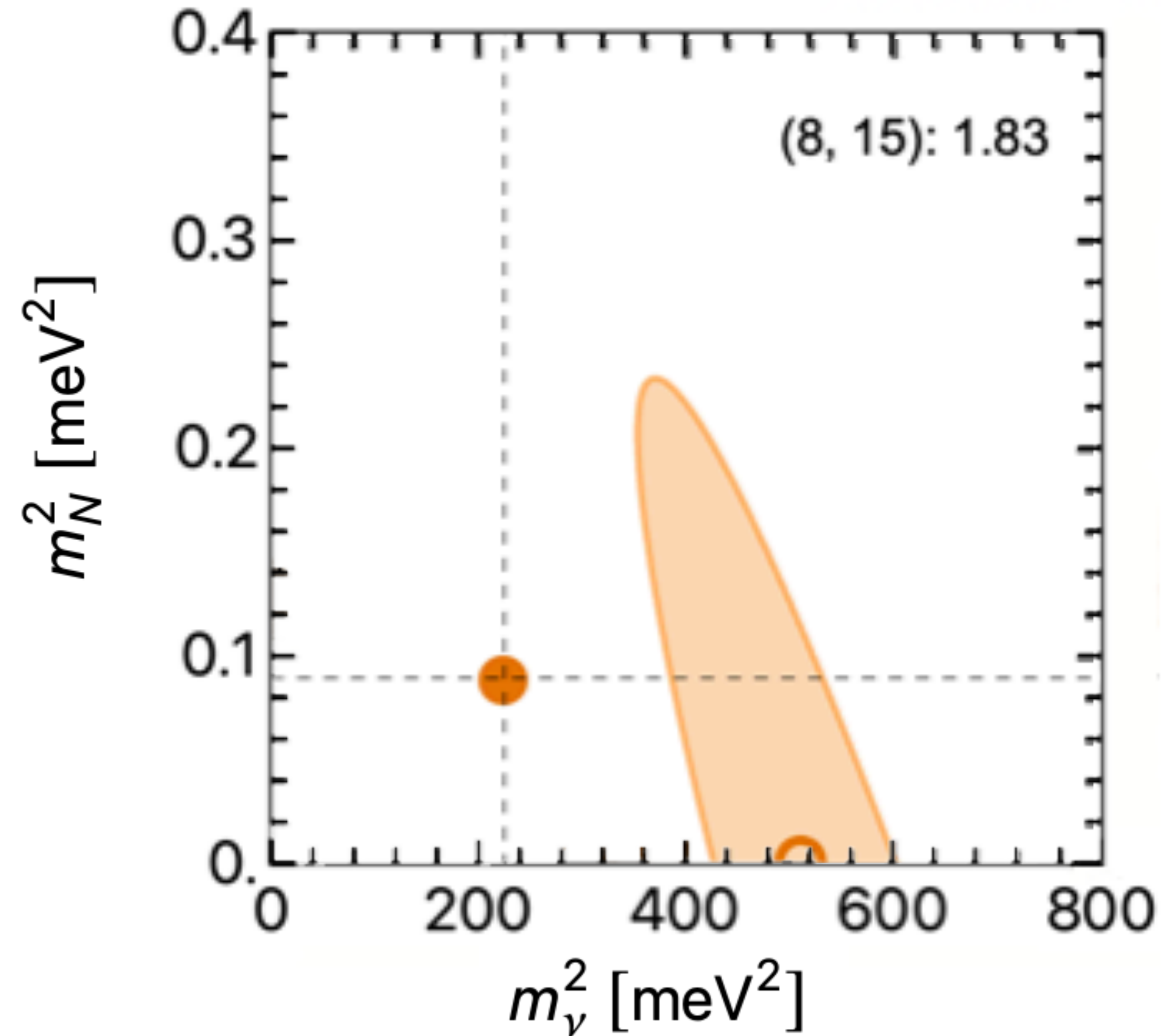
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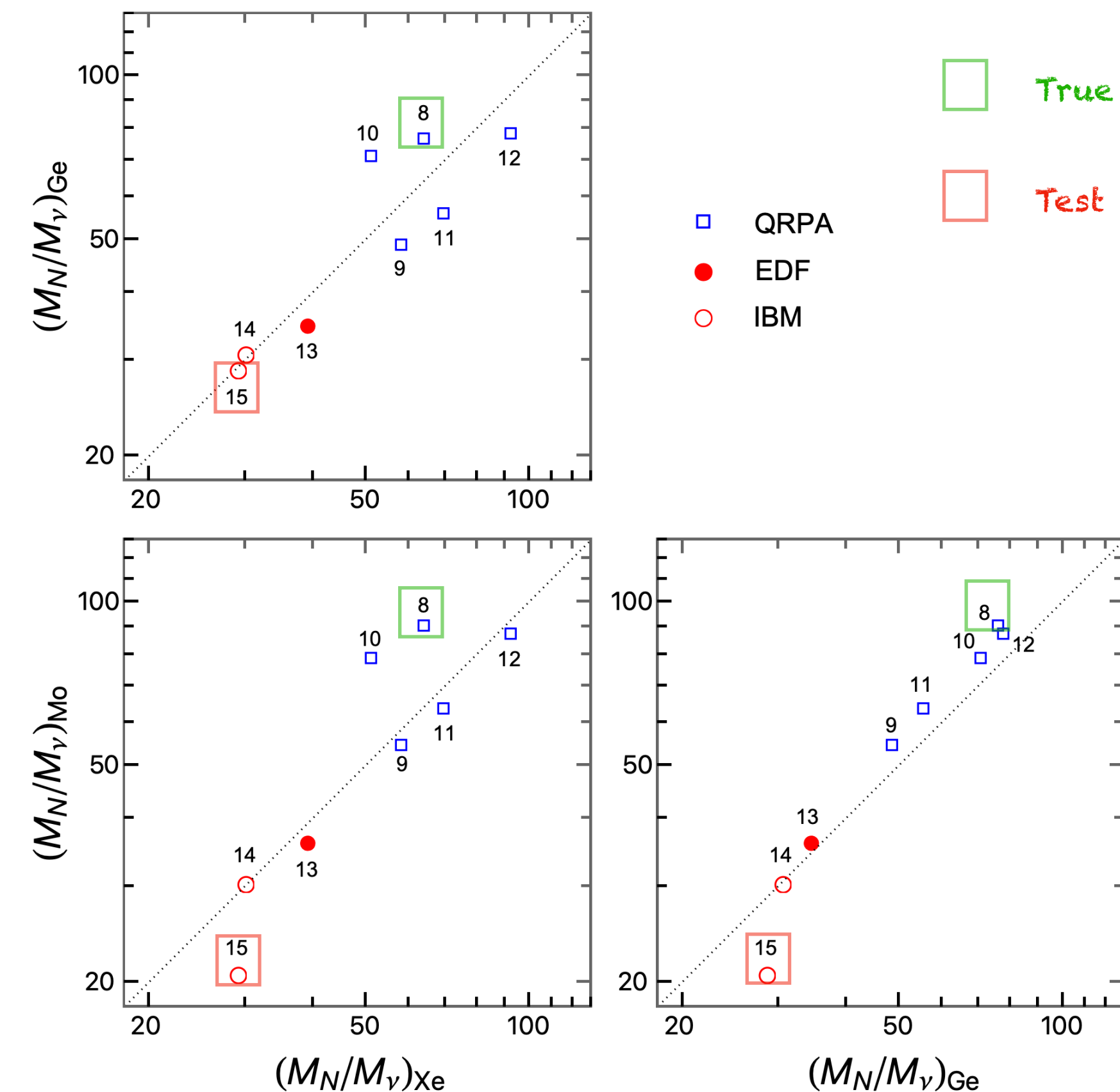
In other cases, the true minimum can be inside the test 2σ region but with a large χ^2_{\min} ($p \sim 5 \times 10^{-4}$)



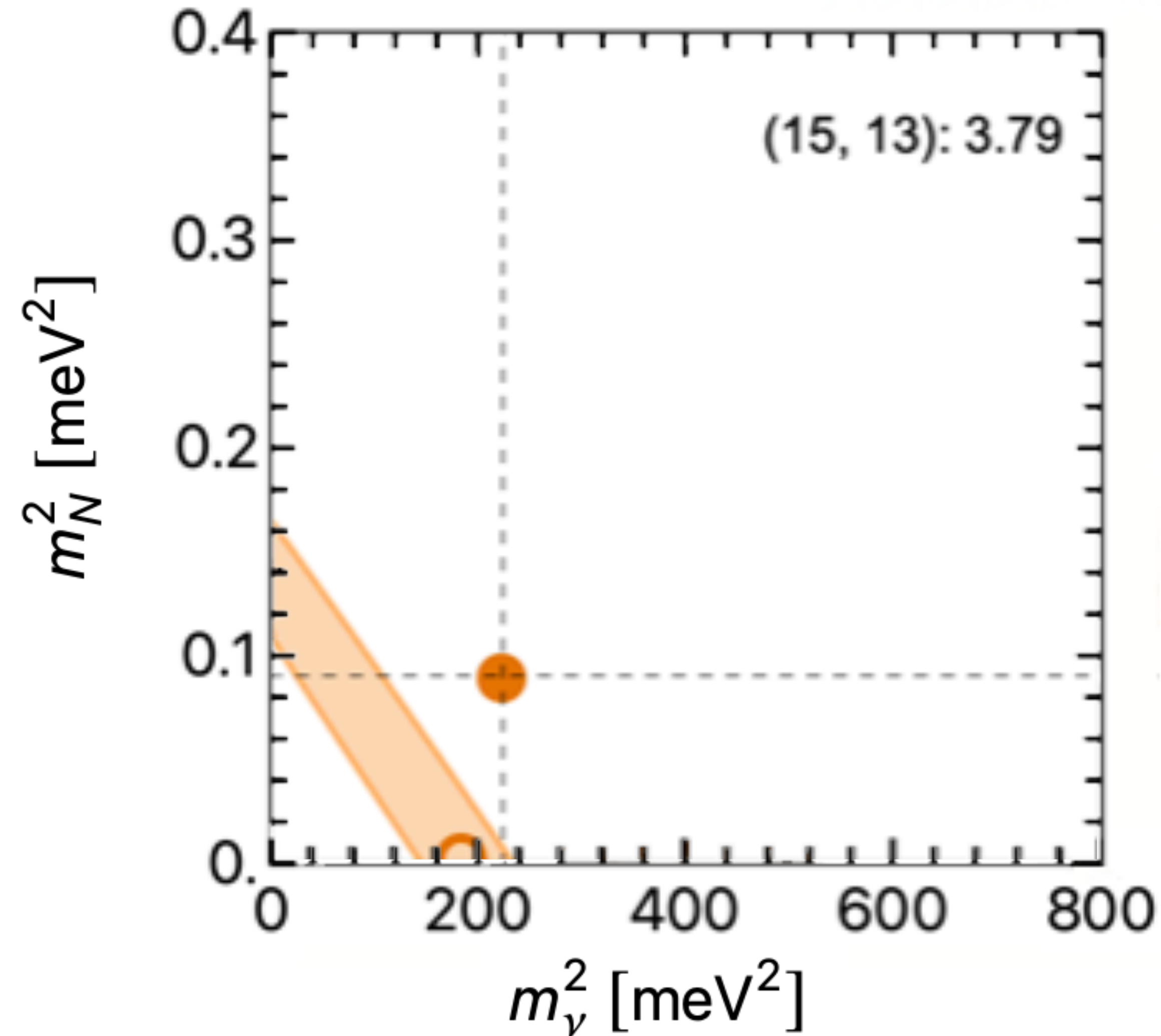
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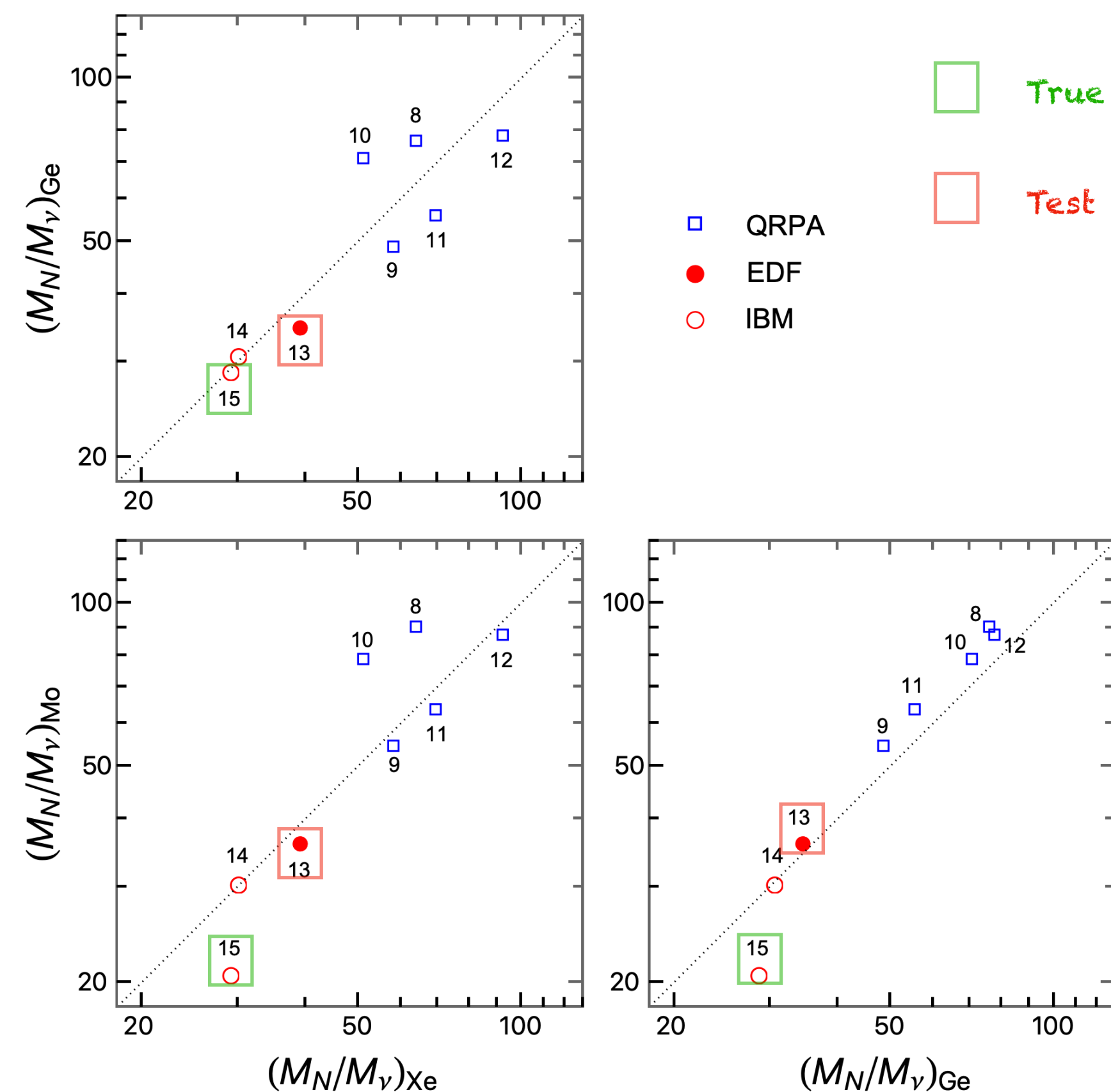
It can also happen that the true minimum is well outside the 2σ allowed test region with a perfectly good χ^2_{\min}



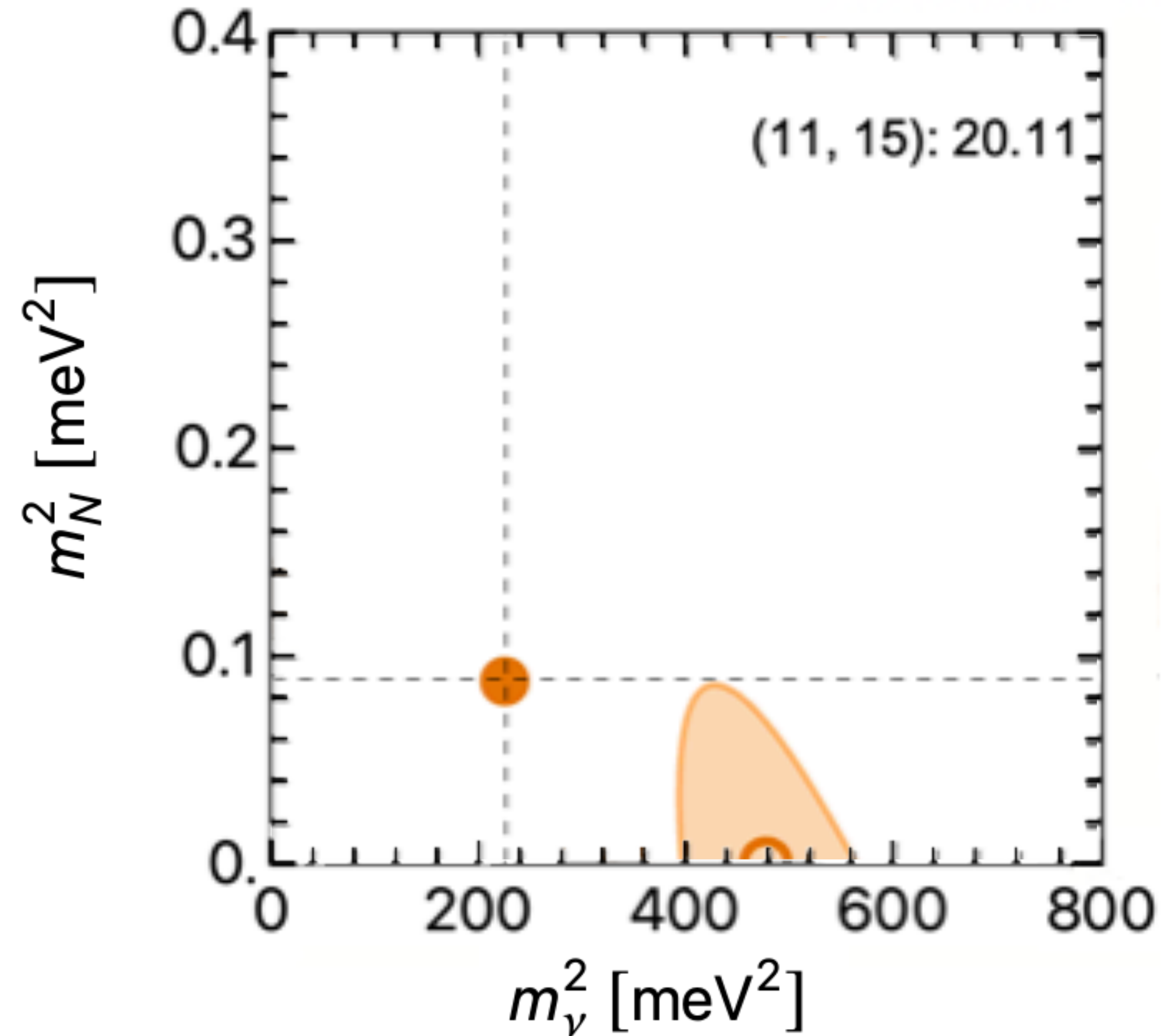
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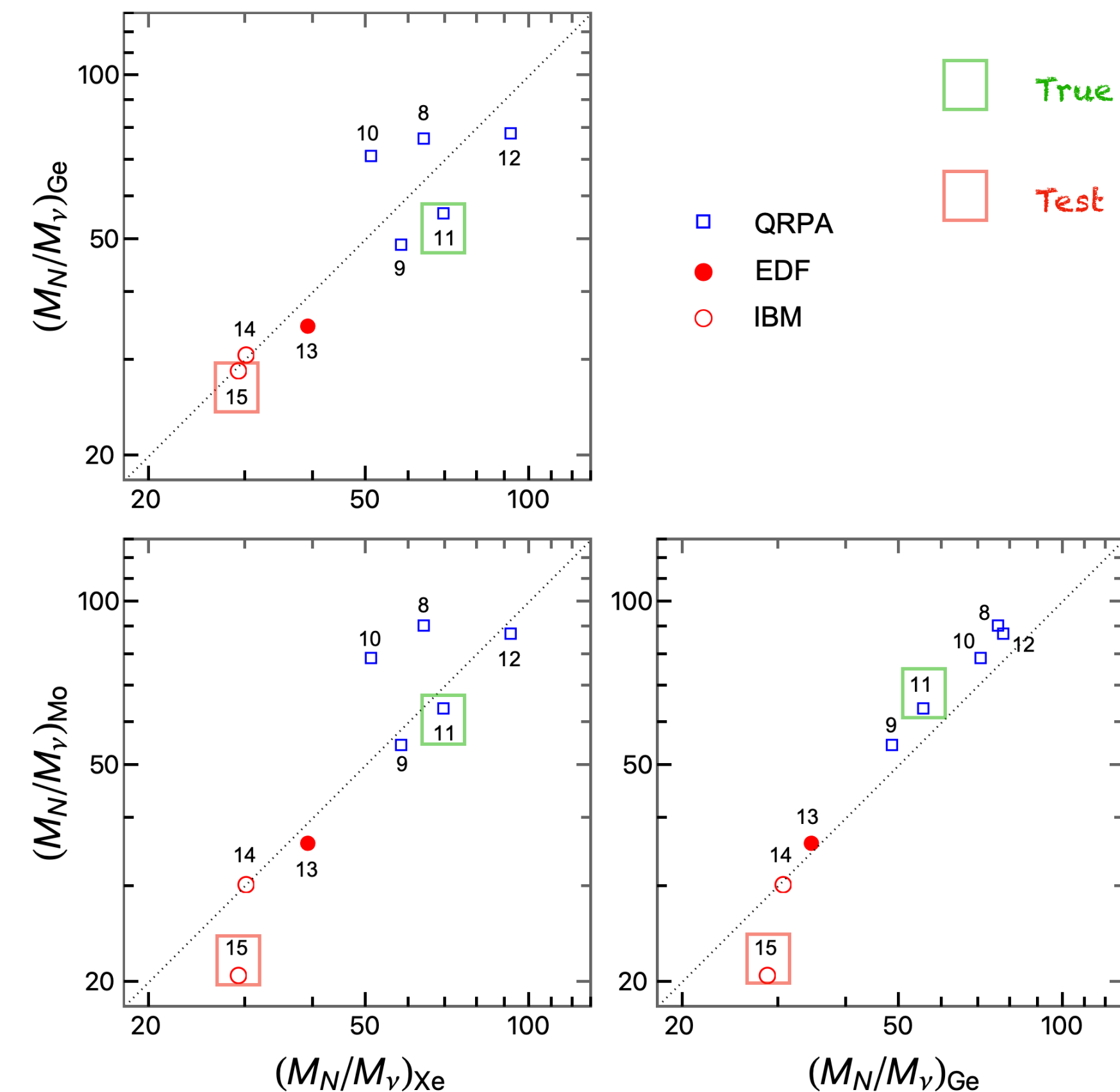
The true minimum is inside the test 2σ region with a χ^2_{\min} acceptable corresponding to $p \sim 0.15$

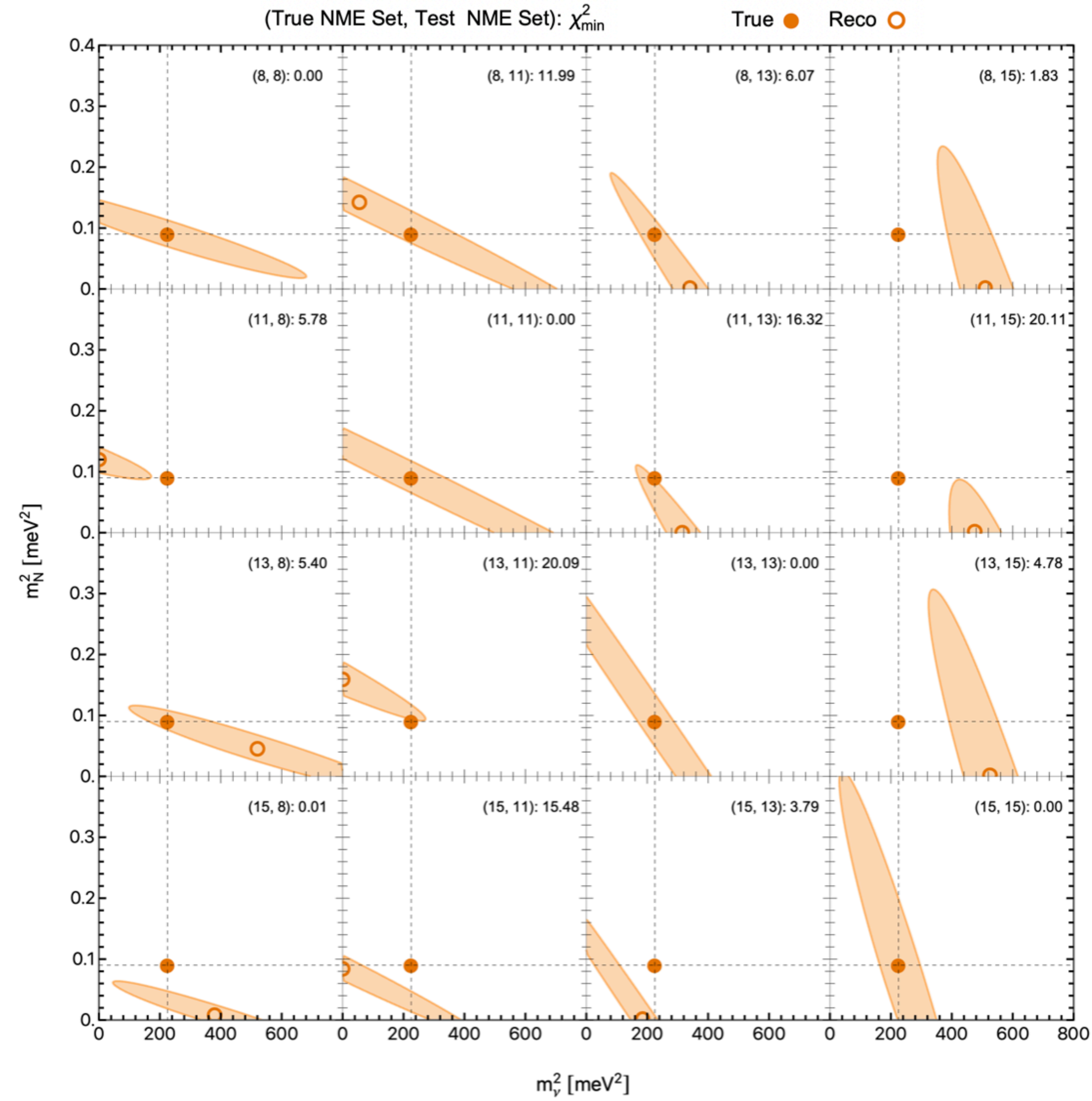


When the **true** and **test** NME sets are different, there are many possible outcomes concerning the relative positions of the true and test minima and the value of the χ^2_{\min}



Finally, there is the possible case of the true minimum outside of the 2σ allowed test region with a very bad χ^2_{\min}





Analysis with different (true and test) NME sets

Each panel is identified by a pair of (true, test) NME sets (χ^2_{\min} in parentheses)

The true values of Majorana mass parameters marked by a solid circle, reconstructed best-fit marked by hollow circles, surrounded by the 2-sigma allowed region. Solid and hollow circles coincide in the diagonal plots

Four panels correspond to moderately high values $4 < \chi^2_{\min} < 9$, for the NME pairs (8, 13), (11, 8), (13, 8) and (13, 15), that provide borderline fits to the prospective data. For the first three of these pairs, the reconstructed mass are within or very close to the 2-sigma allowed region, while for the latter pair the reconstruction bias is quite strong.

For the pair (15, 13) the allowed region interpolates smoothly between the limits of only light or heavy neutrino exchanges, but misses the true values for the mass parameters.

Five panels correspond to high values $\chi^2_{\min} > 9$, for the NME pairs (8, 11), (11, 13), (11, 15), (13, 11) and (15, 11). In such cases, the test NME sets are unable to provide a reasonable description of the data \rightarrow having an extra constraint (three isotopic data versus two free parameters) is crucial to allow a test of the NME

For the pair (15, 8), despite the significant differences between the true and test NME sets, a very good fit ($\chi^2_{\min} \sim 0$) is accidentally obtained

Conclusions

The path to the new BSM-Physics through the neutrino gate is a combined effort of the experimental and theoretical neutrino community that is producing a lot of experimental and theoretical results and progresses that could shed light on what is beyond the limit of our current knowledge, like the sun above the horizon

A handle for the neutrino gate is certainly the $0\nu\beta\beta$, for which the non-interfering exchange of light and heavy neutrinos has been considered

While current (Xe, Ge, Te) data (KamLAND-Zen, EXO, GERDA, MAJORANA, and CUORE) put upper bounds on the effective mass parameters m_ν and m_N , prospective (Xe, Ge, Mo) signals in the upcoming ton-scale nEXO, LEGEND, and CUPID projects could substantially reduce the allowed region in the (m_ν, m_N) plane

The ratios $M_{N,i}/M_{\nu,i}$ in various isotopes for different nuclear models are crucial to disentangle light/heavy contributions to $0\nu\beta\beta$ (degeneracy/ non-degeneracy)

A more accurate determination of the NME is fundamental to avoid any possible bias in the reconstruction of the true values of m_ν and m_N

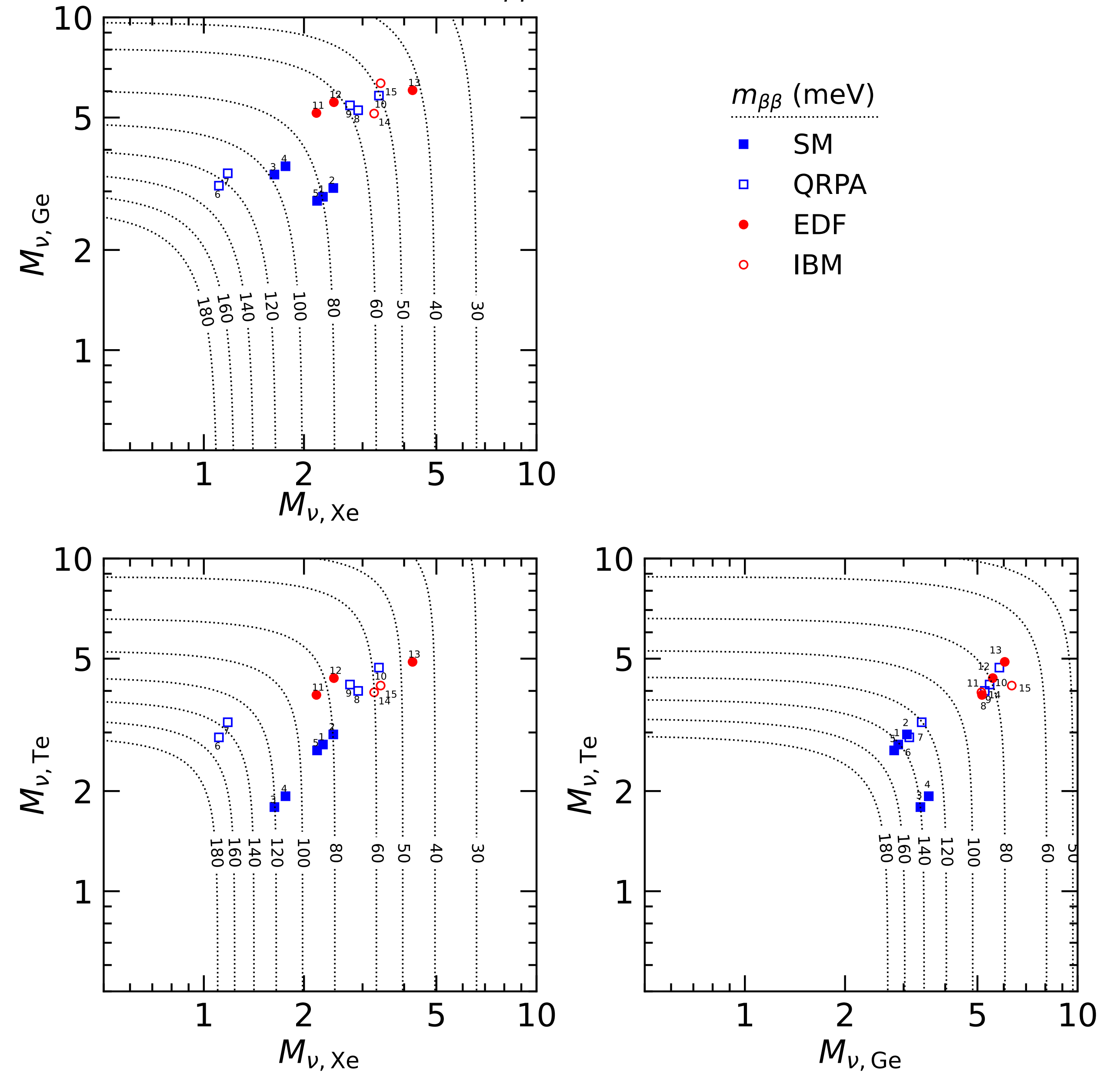
Egon Schiele, Four Trees
Oberes Belvedere, Vienna

Extras

Light neutrino exchange only

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2σ bounds on $m_{\beta\beta}$ from Xe, Ge, Te pairs



Light neutrino exchange only

In most cases, (Xe) sets the most stringent bounds, followed by (Ge) and (Te)

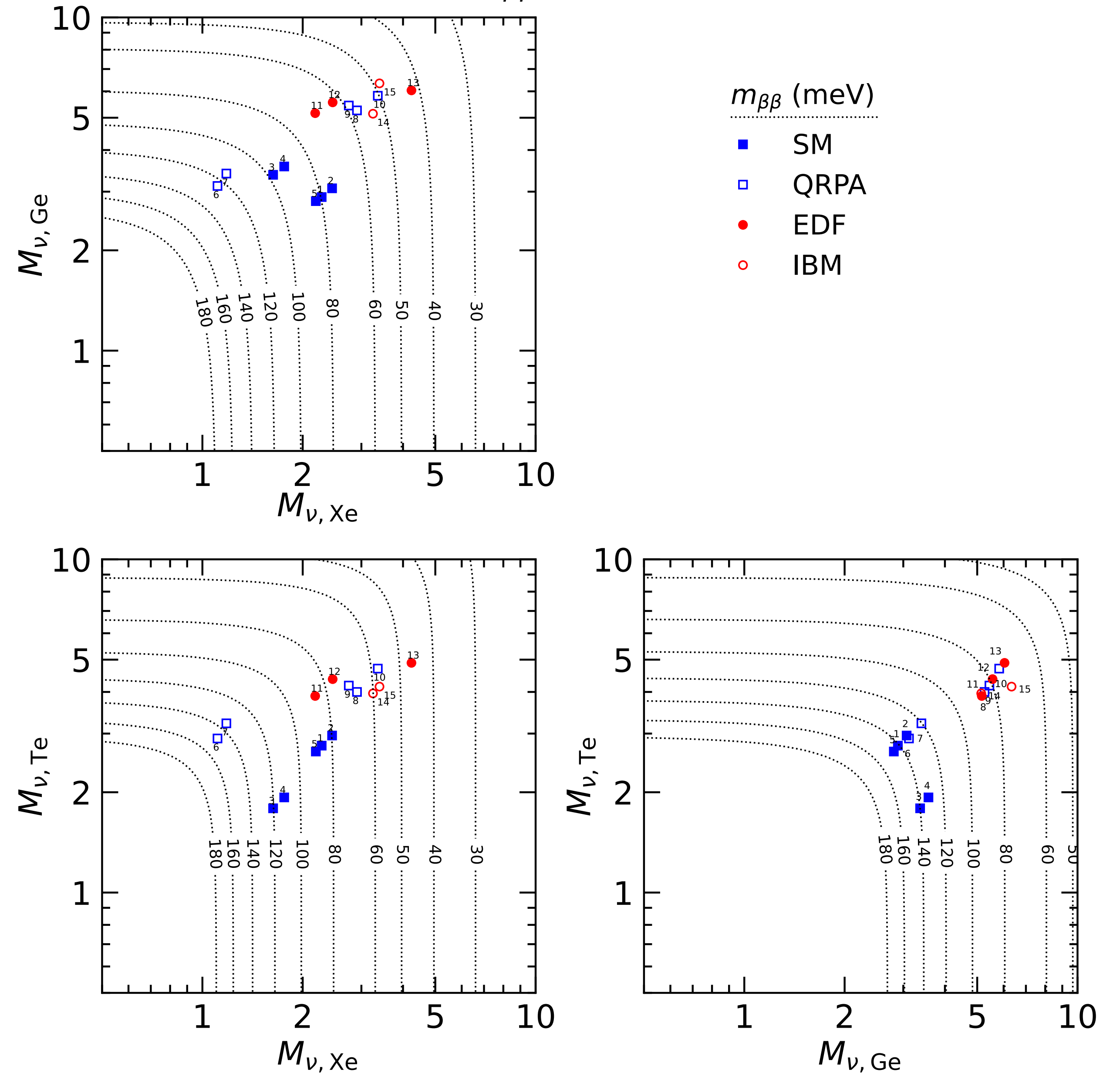
Two QRPA cases (6,7) \rightarrow (Ge) more constraining

In general, the combination of two isotopes gives stronger bounds, with some exception for the cases with (Te) and large NME (not easy to appreciate on the plots)

Best fit for m_ν is always 0, with the exception of (Te) alone and (Xe) + (Te) for cases (6,7)

At 2σ $m_\nu \leq m_{\nu,2\sigma} \in [43.1, 127.9]$ meV for the combination of (Xe)+(Ge)+(Te)

2σ bounds on $m_{\beta\beta}$ from Xe, Ge, Te pairs



Light neutrino exchange only

In most cases, (Xe) sets the most stringent bounds, followed by (Ge) and (Te)

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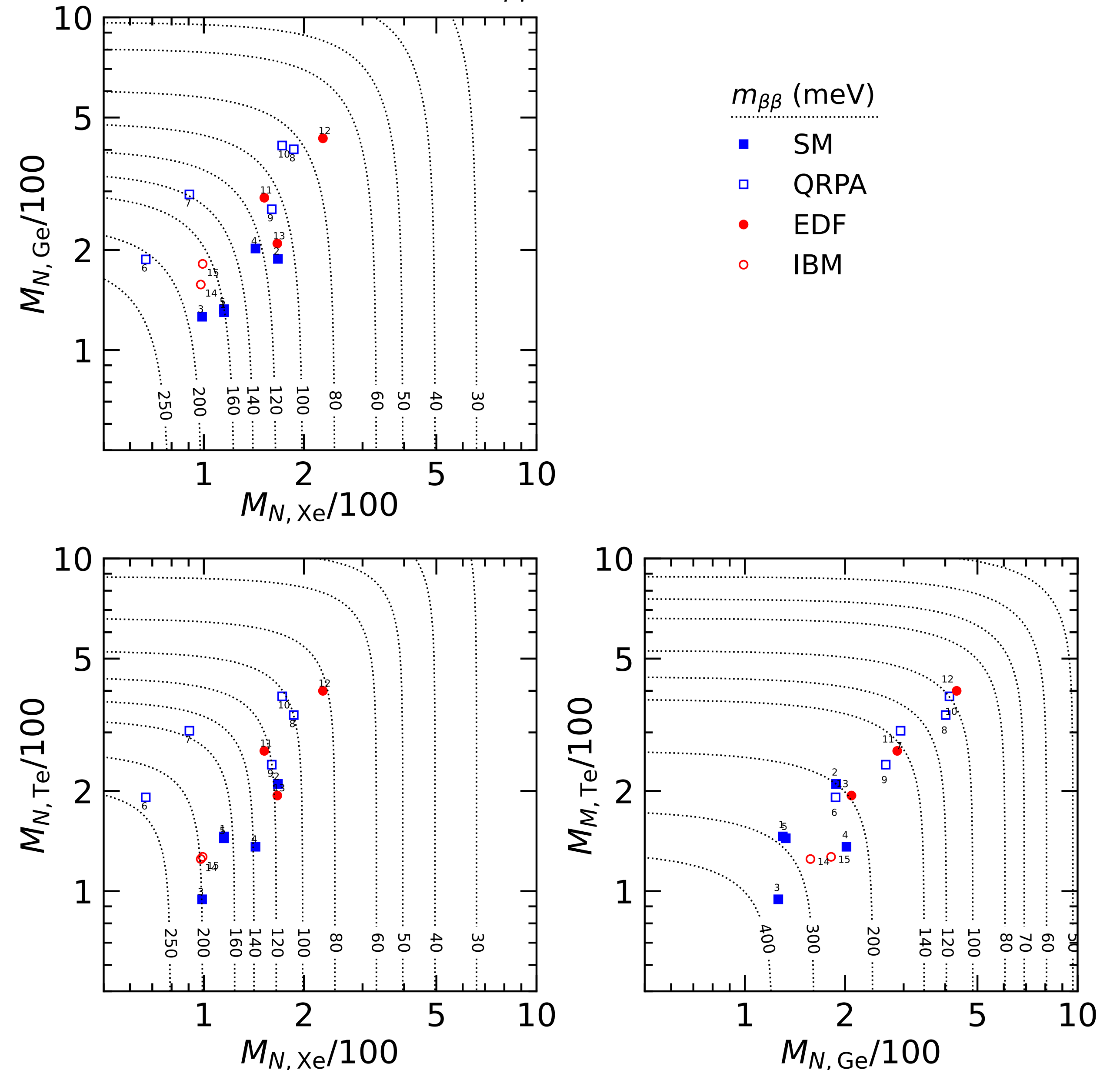
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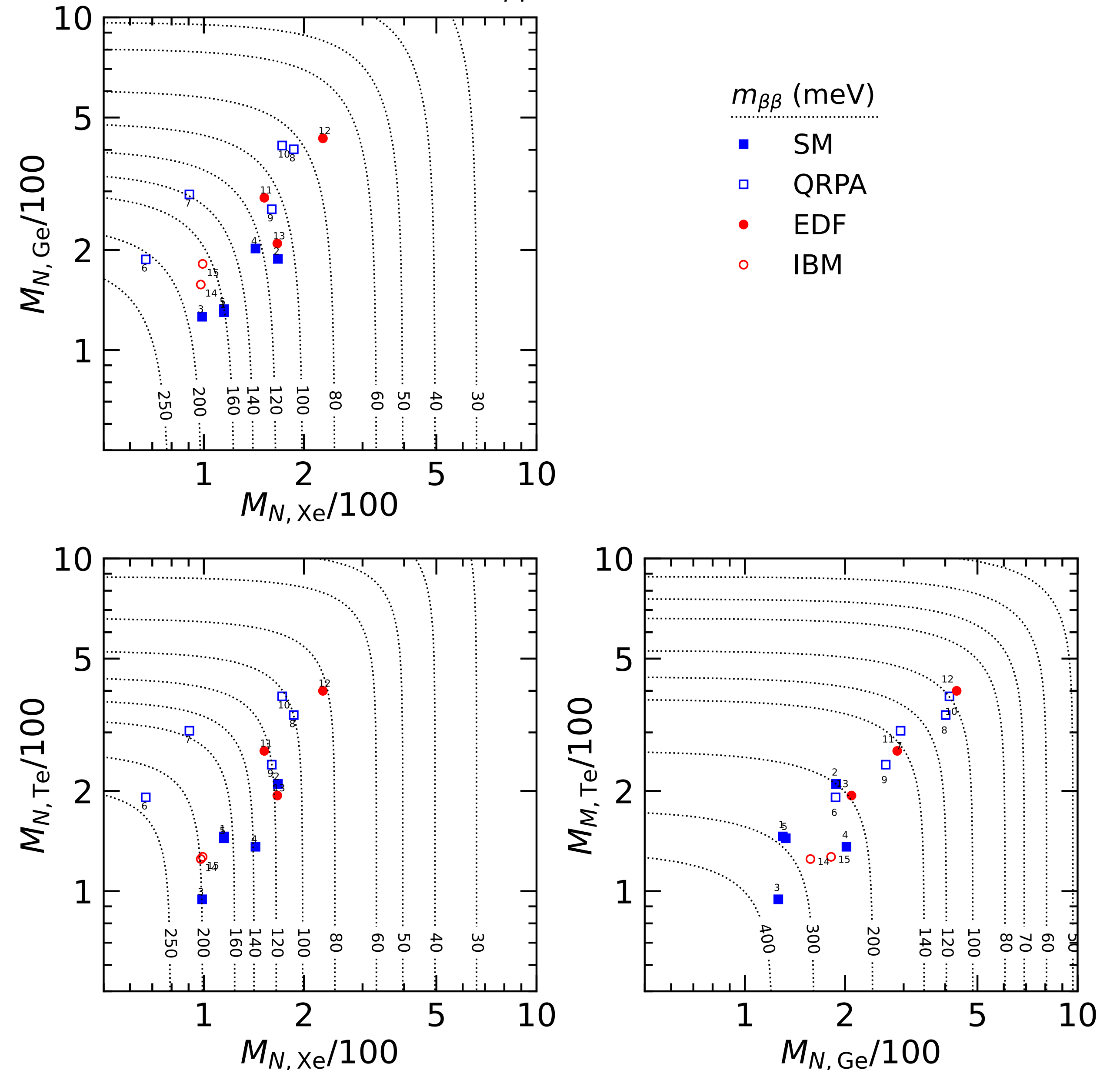
This mechanism can be dominant if $m_\nu \sim 0$ (possible in Normal Ordering)

Bounds on m_N expect to be regulated by the ratio $M_N/M_\nu \sim 30 \div 90$

At 2σ $m_N \leq m_{N,2\sigma} \in [0.75, 2.1]$ meV for the combination of (Xe)+(Ge)+(Te)

(the larger the NME, the smaller the upper bounds on the effective mass)

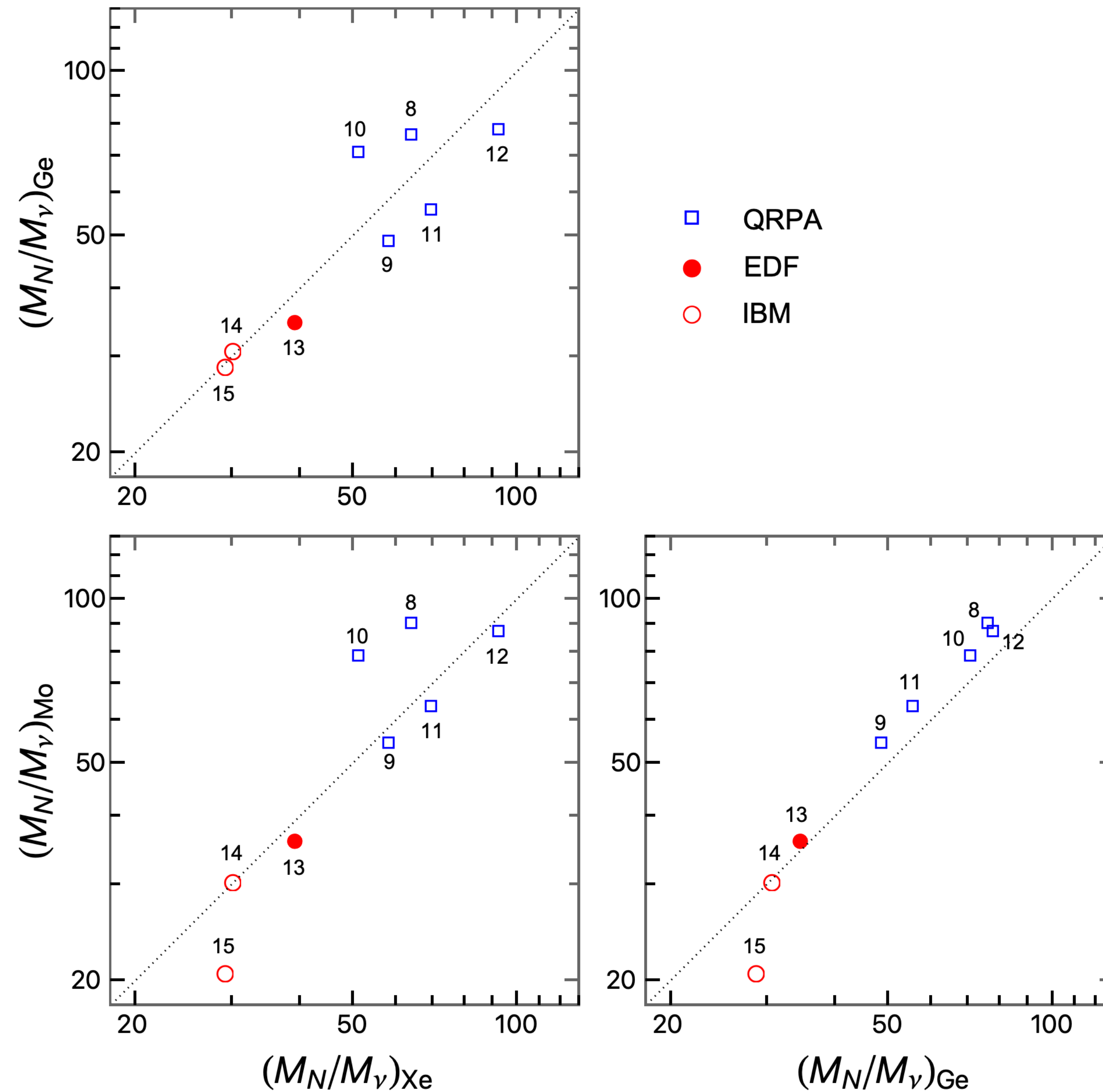
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Heavy-to-light NME ratios for future ton-scale projects

nEXO (Xe), LEGEND (Ge), CUPID (Mo)

In particular in the following we will discuss cases



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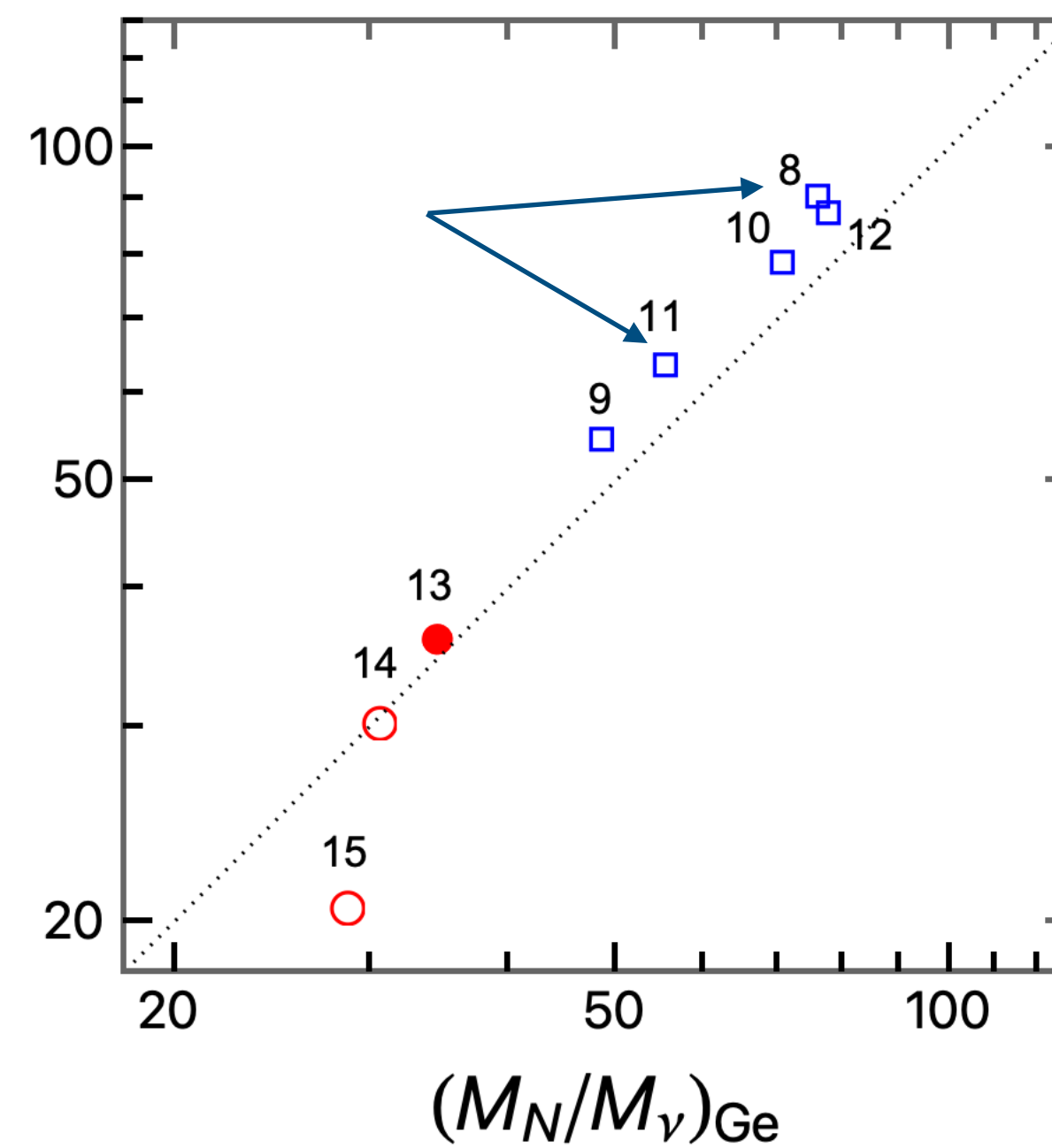
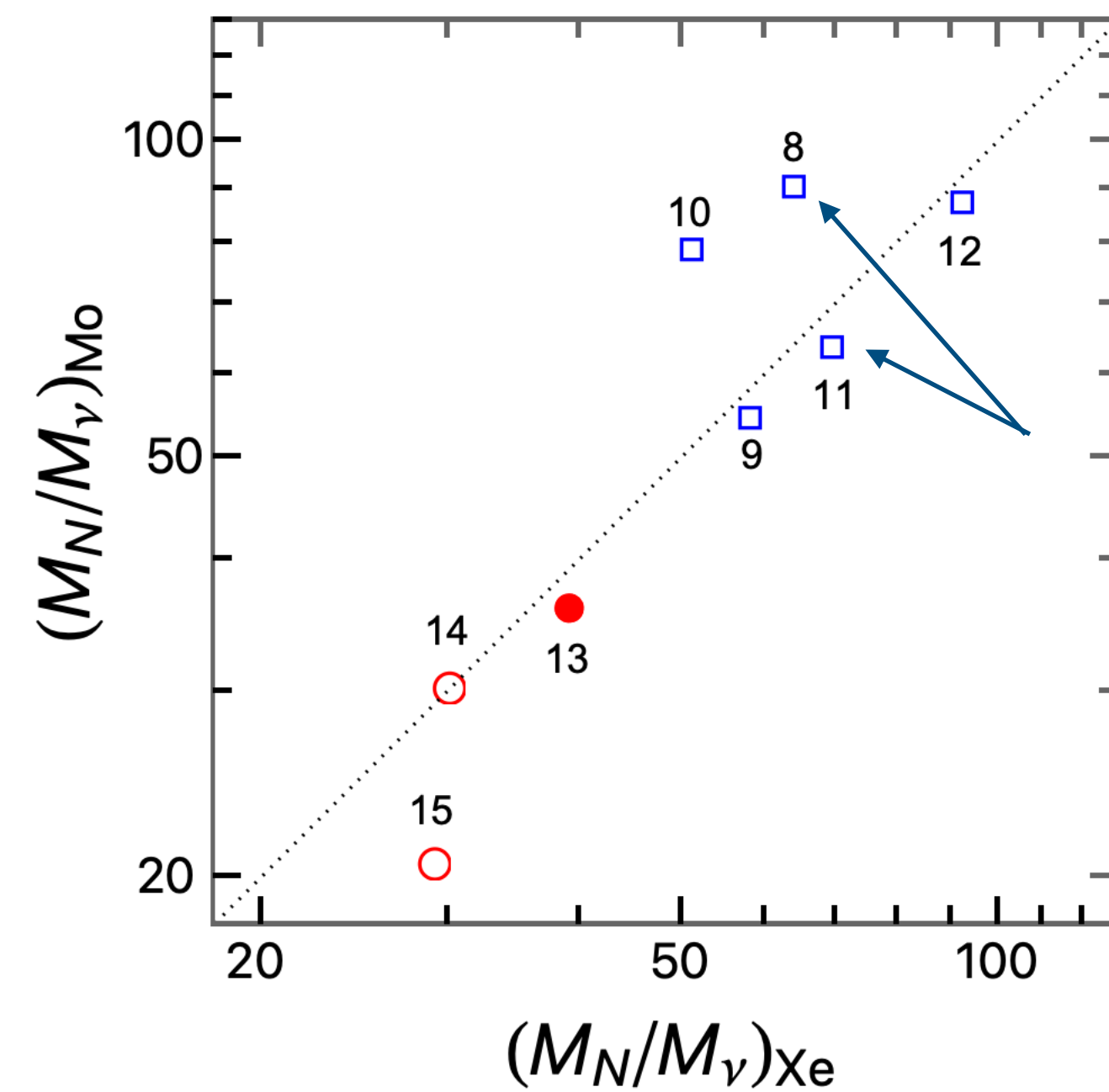
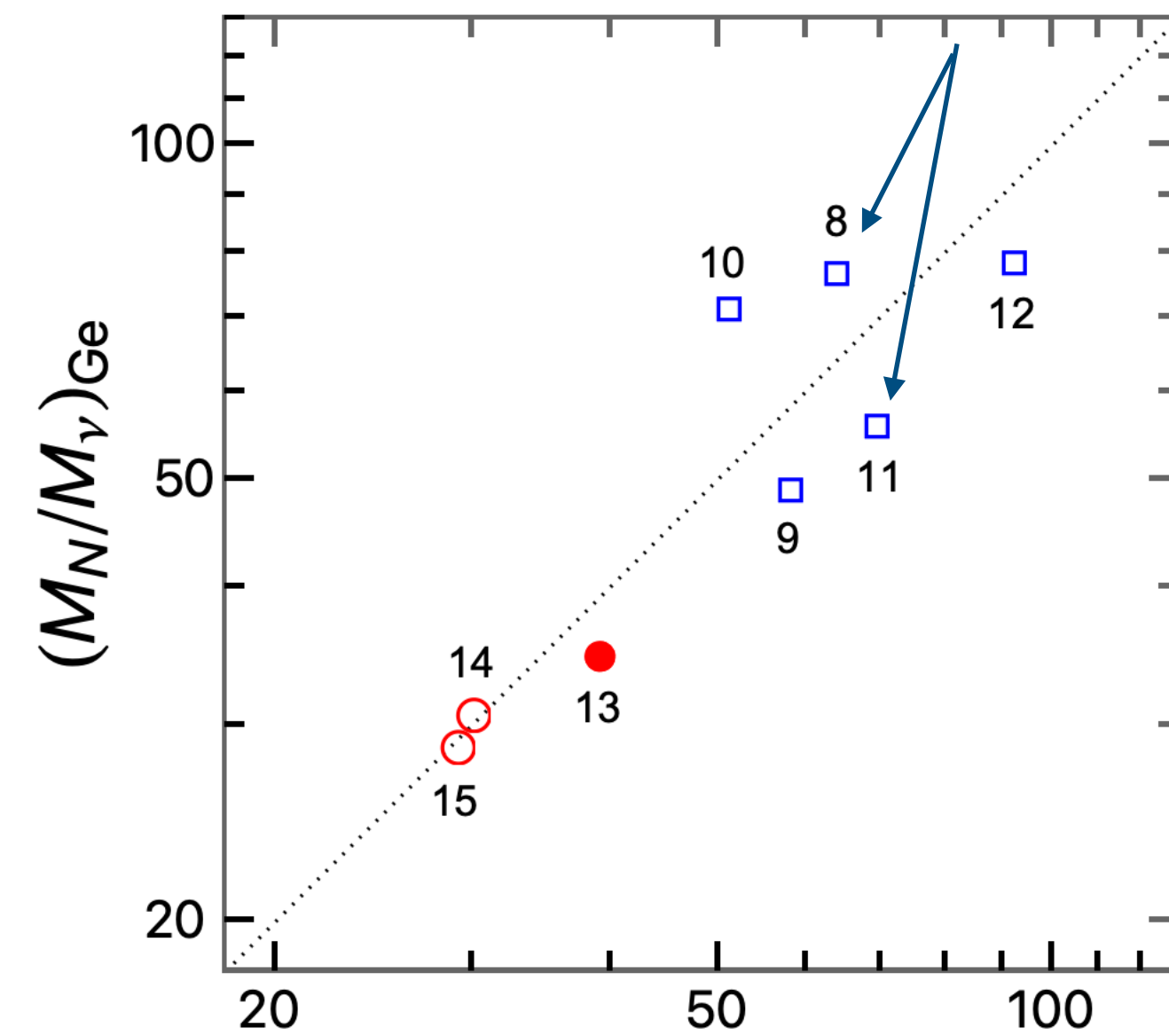
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QRPA cases (8,11): relative high ratios $M_{N,i}/M_{\nu,i}$

non degenerate

on the opposite sides of the diagonal in two planes



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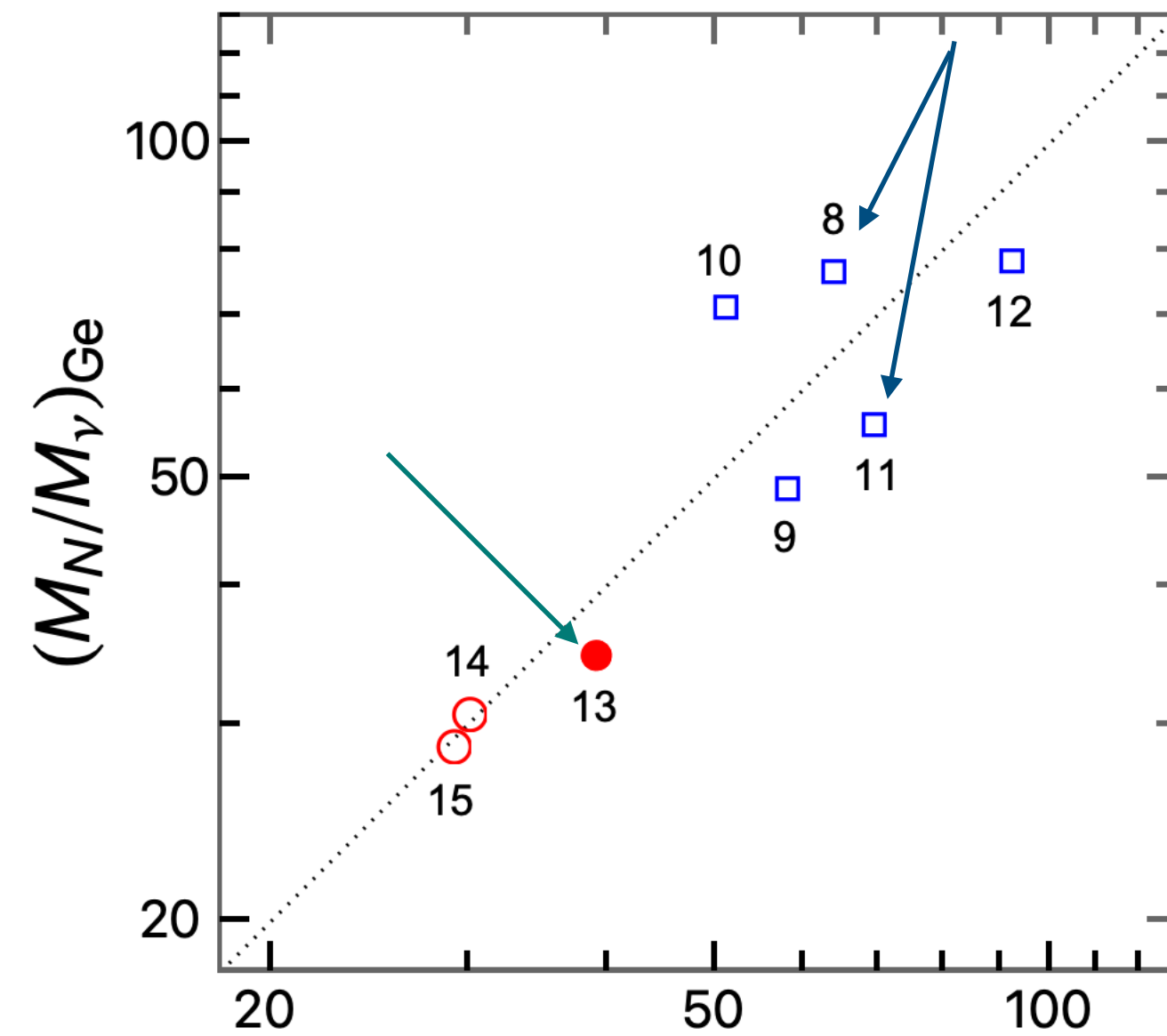
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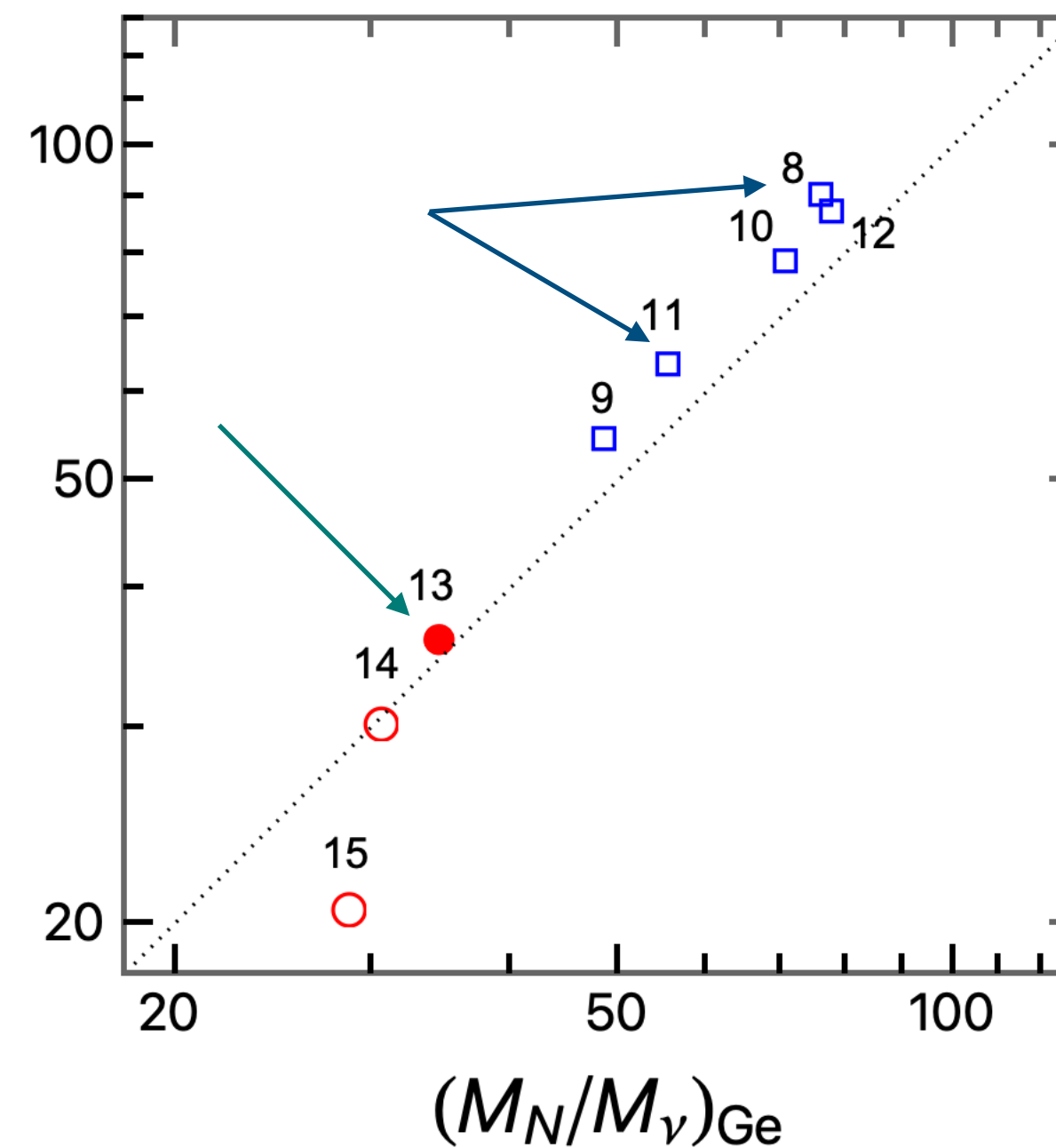
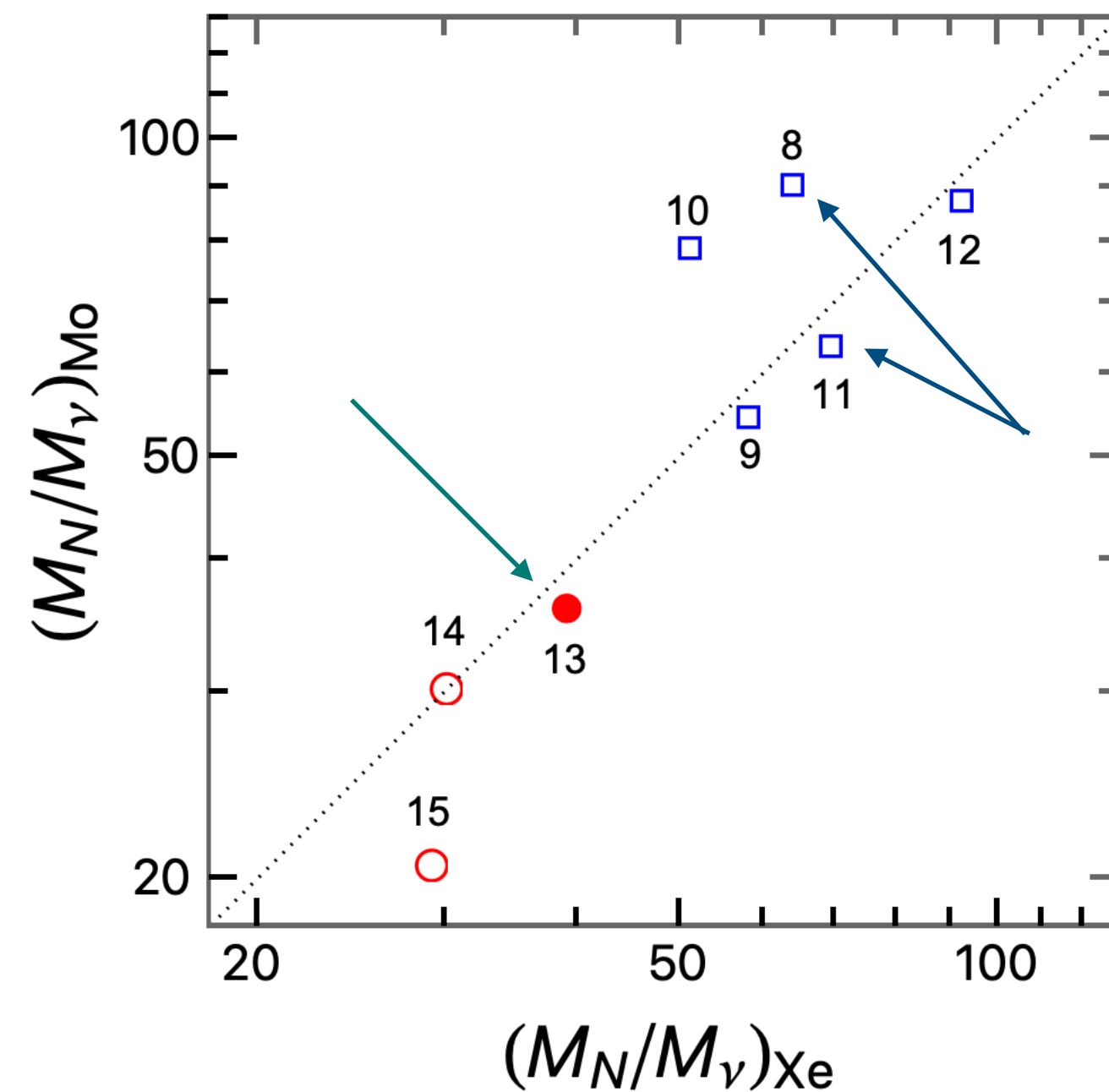
EDF case (13): intermediate values of $M_{N,i}/M_{\nu,i}$

nearly degenerate

close to the diagonal



□ QRPA
● EDF
○ IBM



Heavy-to-Light NME ratios for future ton-scale projects

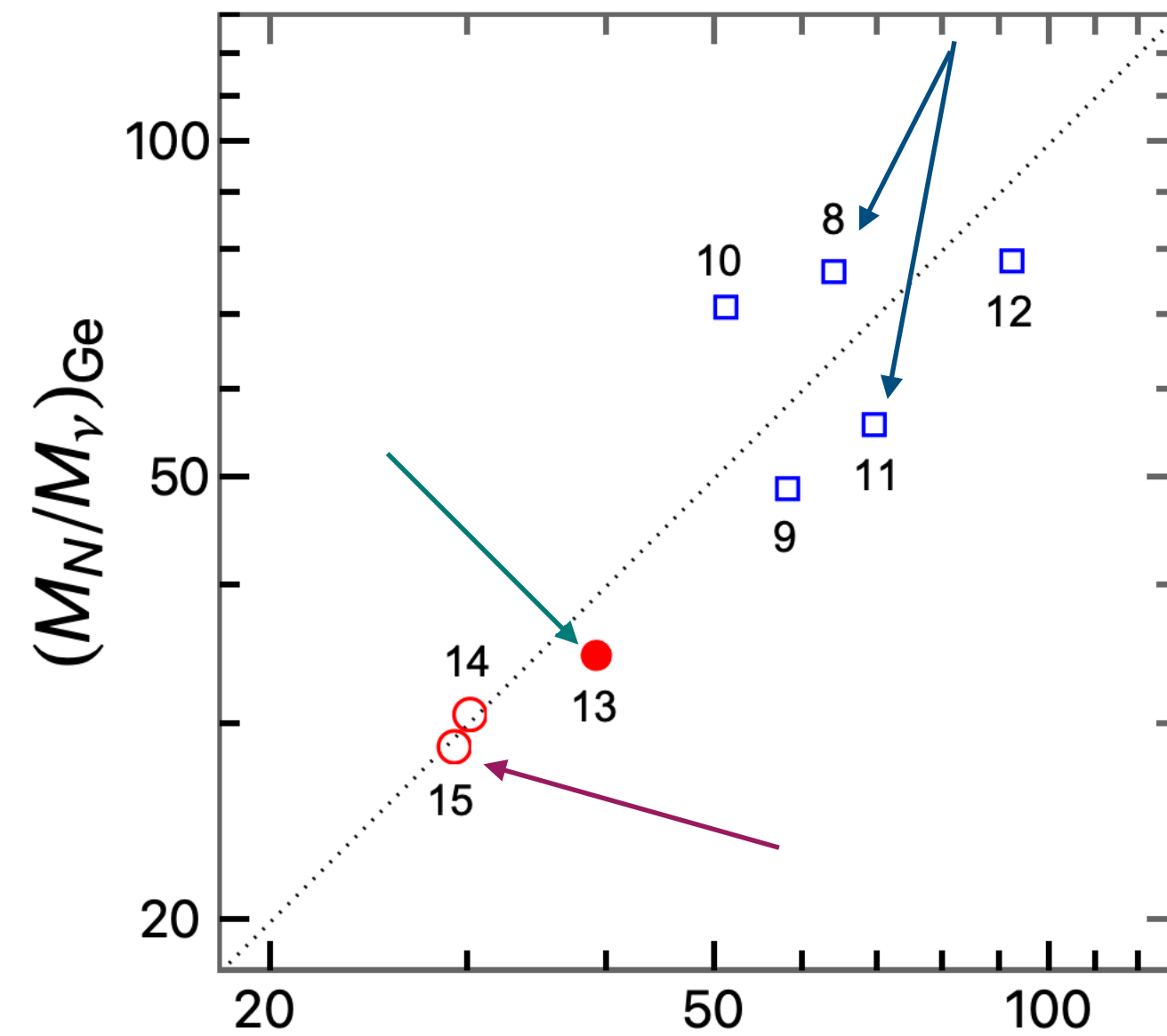
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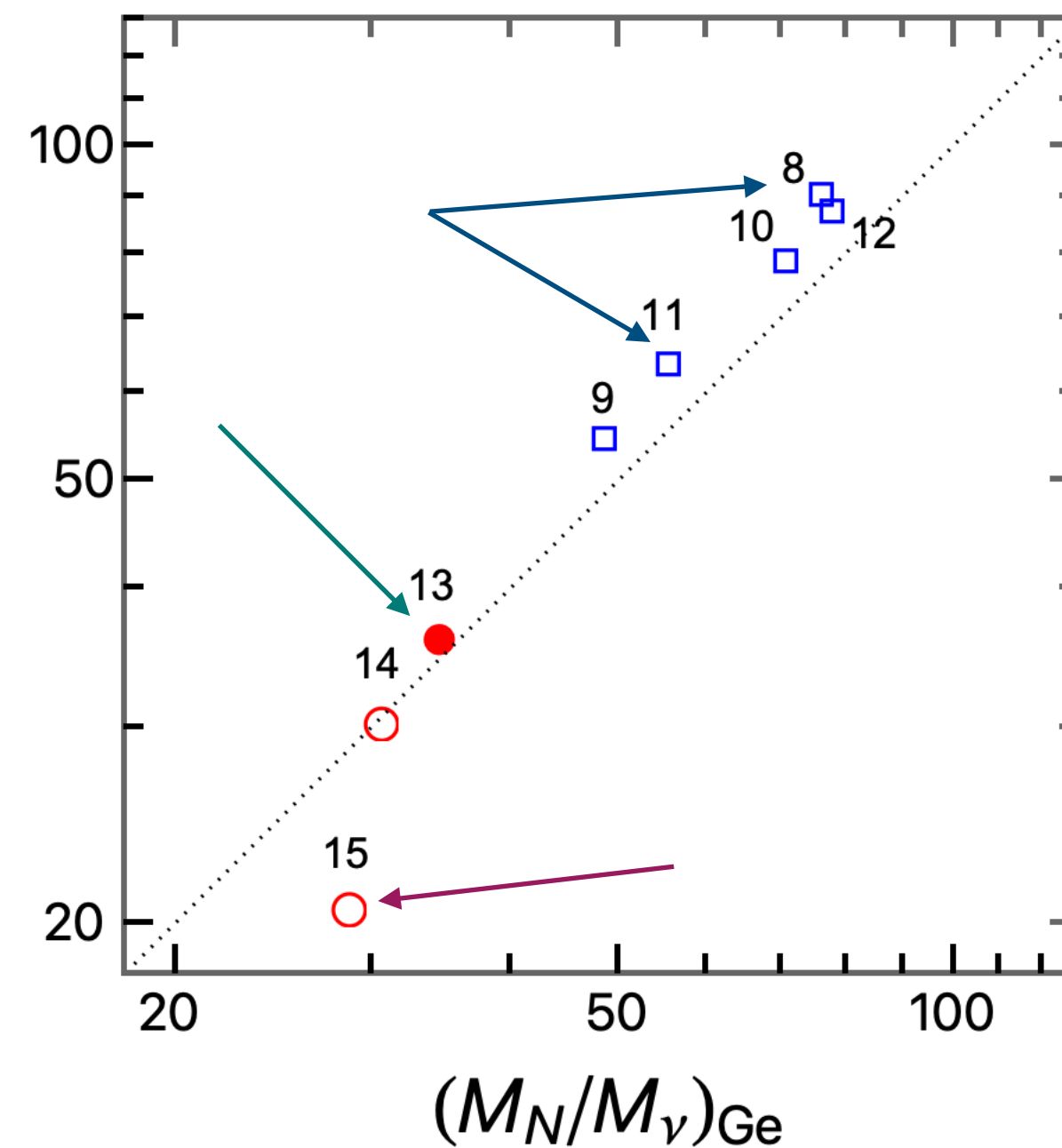
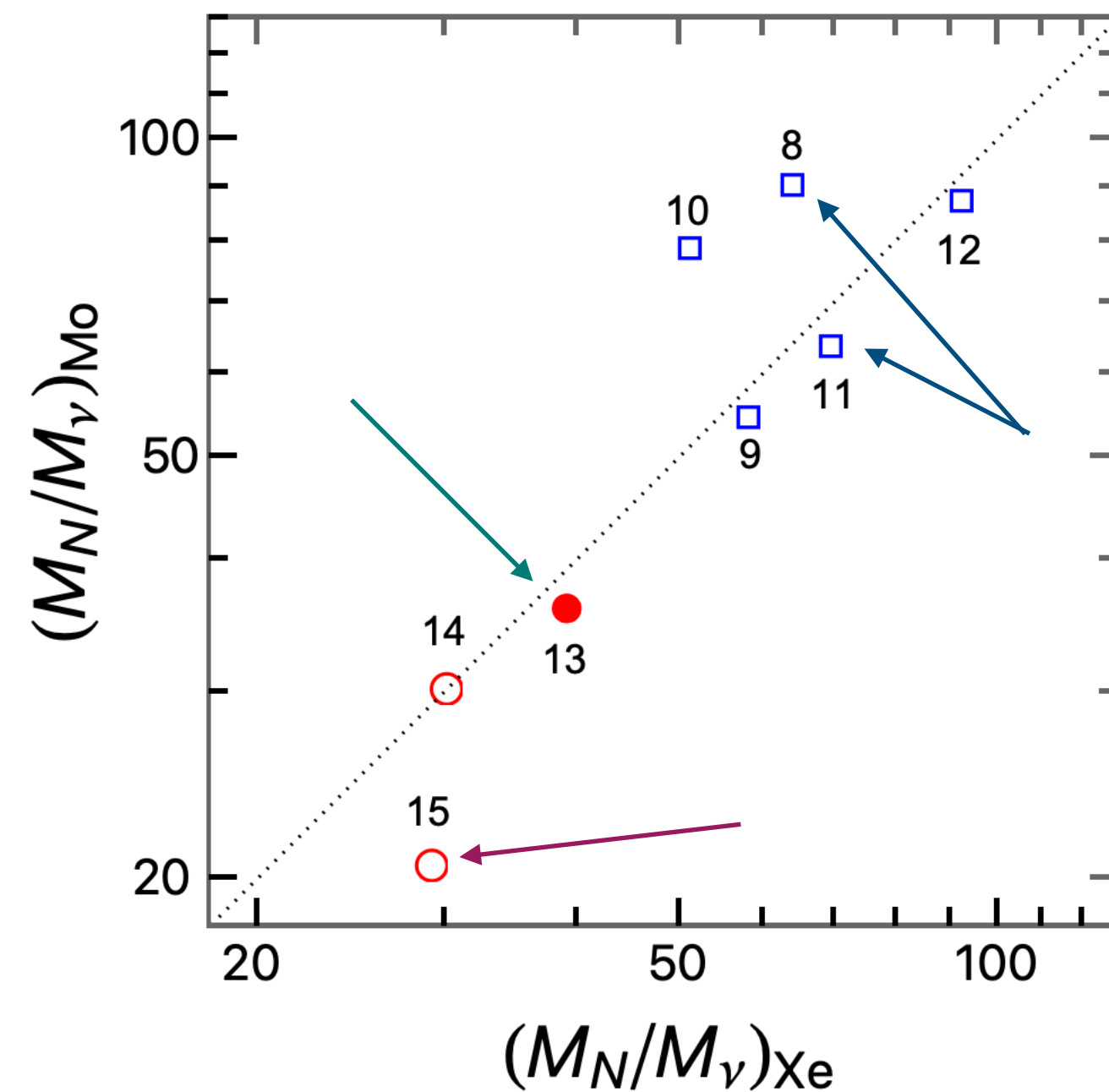
QRPA cases (8,11): relative high ratios $M_{N,i}/M_{\nu,i}$
non degenerate
on the opposite sides of the diagonal
in two planes

EDF case (13): intermediate values of $M_{N,i}/M_{\nu,i}$
nearly degenerate
close to the diagonal

IBM case (15): lower values of $M_{N,i}/M_{\nu,i}$
off-diagonal in two planes



□ QRPA
● EDF
○ IBM



An example relative to a specific L-R model

S. Patra, S. T. Petcov, P. Pritimita and P. Sahu, "Neutrinoless double beta decay in a left-right symmetric model with a double seesaw mechanism," Phys. Rev. D 107, no.7, 075037 (2023)

The model particle content

Two Higgs doublets H_L, H_R and a bidoublet Φ (double seesaw mechanism). The fermion sector has the usual for the L-R symmetric models quarks and leptons, along with three $SU(2)$ singlet fermion $S_{\gamma L}$

The choice of bare Majorana mass term for these sterile fermions $S_{\gamma L}$ induces large Majorana masses for the heavy RH neutrinos leading to two sets of heavy Majorana particles N_j and S_k with $j, k = 1, 2, 3$, with masses $m_{N_j} \ll m_{S_k}$. Dirac mass terms for $\nu_{\alpha L} - N_{\beta R}$ and $N_{\beta R} - S_{\gamma L}$ are chosen to be diagonal

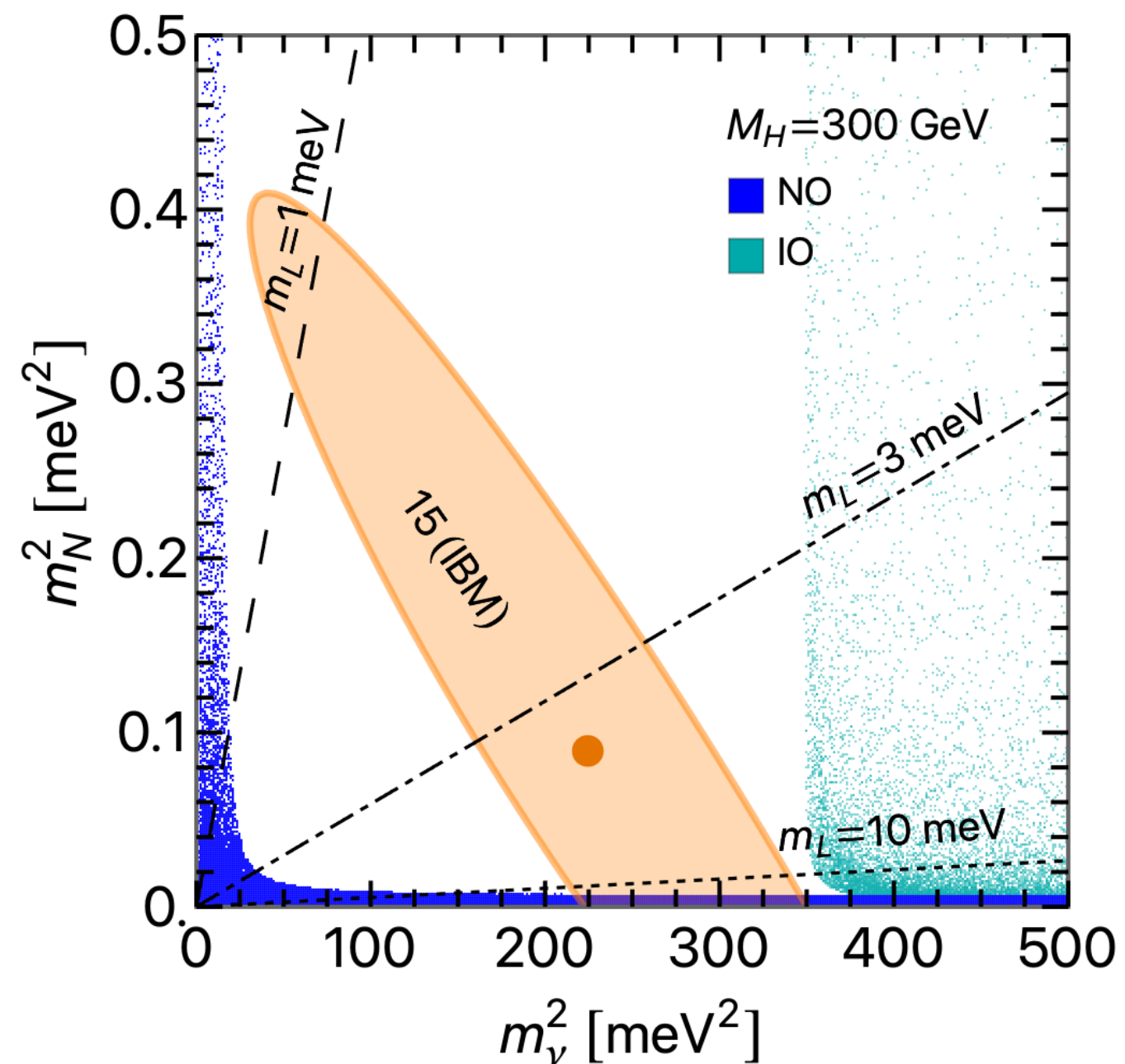
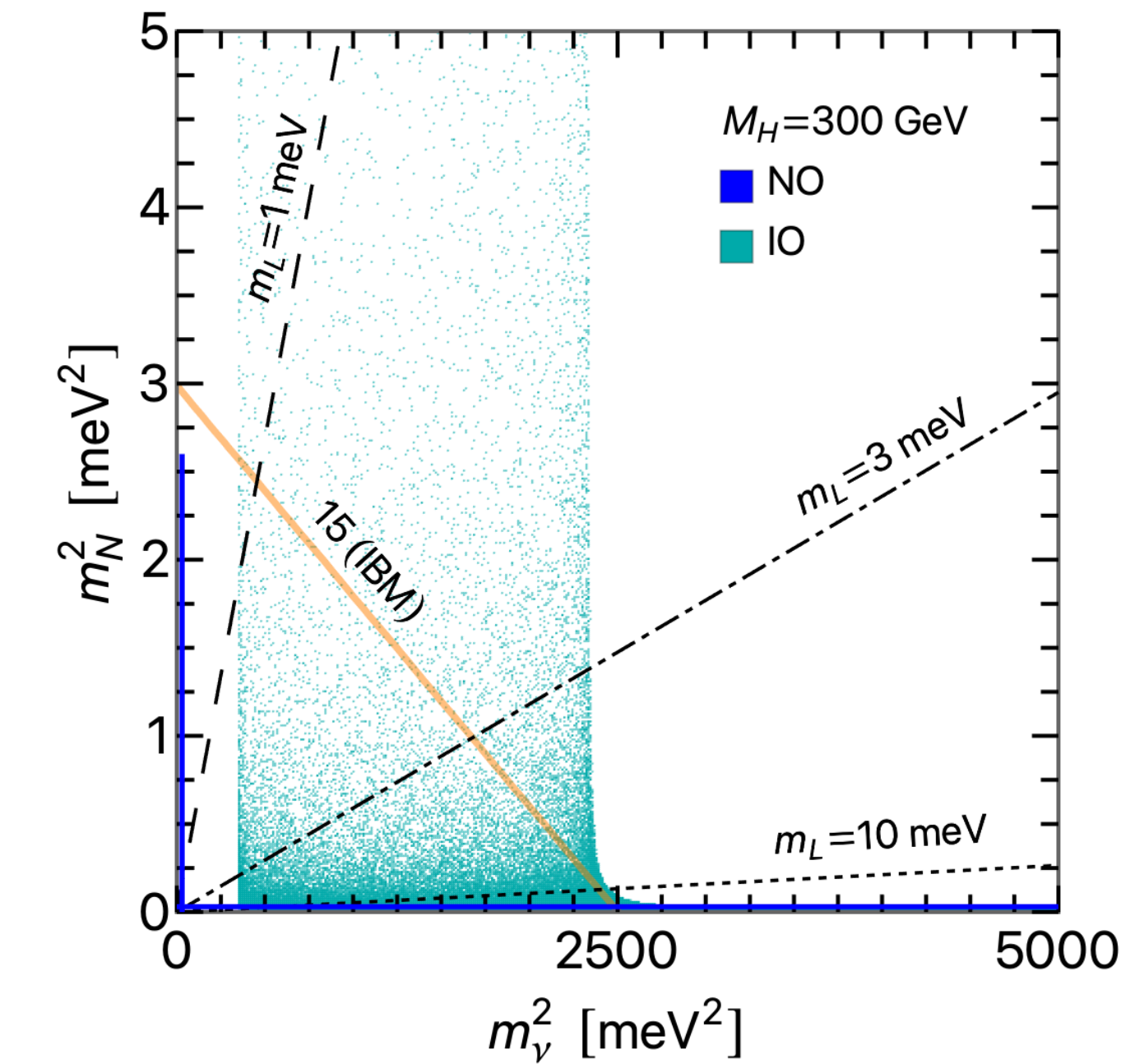
Denoted with m_L the lightest neutrino mass and M_H the heaviest mass of the heavy neutrinos the model satisfies the relation

$$m_N = \frac{m_e m_p}{m_L M_H} \left(\frac{m_W}{m_{W_R}} \right)^4 m_\nu \longrightarrow \text{rays in the } (m_\nu^2, m_N^2) \text{ plane}$$

Upper panel: points above the orange line disfavoured

Lower panel: future results tend to disfavor the IO scenario, not only in the limit of light neutrino exchange (i.e, of vanishing m_N), but also for sizeable contributions of heavy neutrinos. They also disfavor NO cases with small m_ν , while allowing NO cases with vanishing m_N

the lesson is that by considering specific models constraints are introduced in the (m_ν^2, m_N^2) plane



Summary for $0\nu\beta\beta$ searches

Quintessential to probe the Majorana nature of neutrinos

Experiments now probing the region of non-degenerate masses

Next-generation experiments will explore and possibly exclude all the region of Inverted Mass ordering (if neutrino masses are the exclusive mechanism for $0\nu\beta\beta$)

Starting to be sensitive to Majorana phases, if Mass Ordering is known

Important to have experiments with different nuclei to check the consistency of the theoretical calculations (the combination can be tricky and also correlations, if known, should be taken into account)

