Recommended Values for Neutrinoless Double-Beta Decay Nuclear Matrix Elements

Jason Detwiler, UW

INT-26-2a, Seattle, WA

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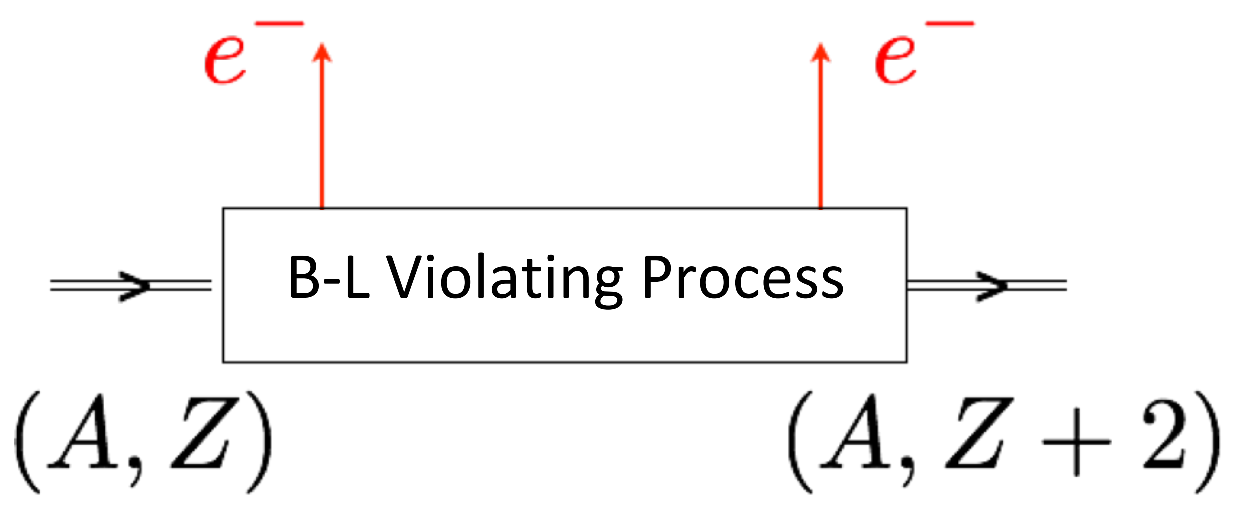
Disclaimer: I'm co-spokesperson of LEGEND and participated in the MAJORANA DEMONSTRATOR and KamLAND-Zen experiments

Neutrinoless Double-Beta Decay

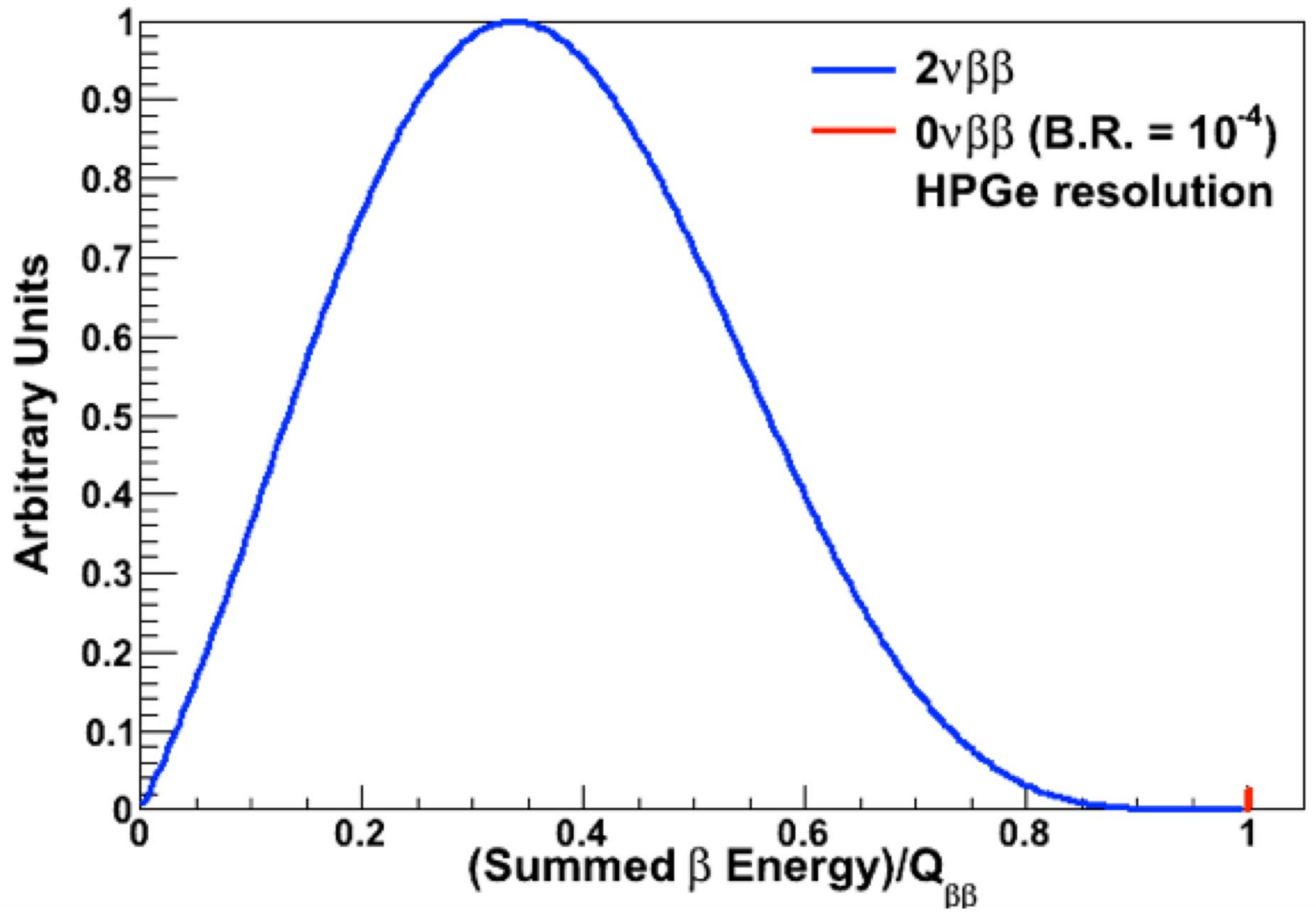
Creates two new particles of matter but no antimatter

- Violates not just *L* but *B-L*: the last accidentally conserved quantity of the SM
  - Other accidental symmetries L_e, L_μ, L_τ all violated by m_ν ...
- An observation of this process would be important regardless of theoretical motivations



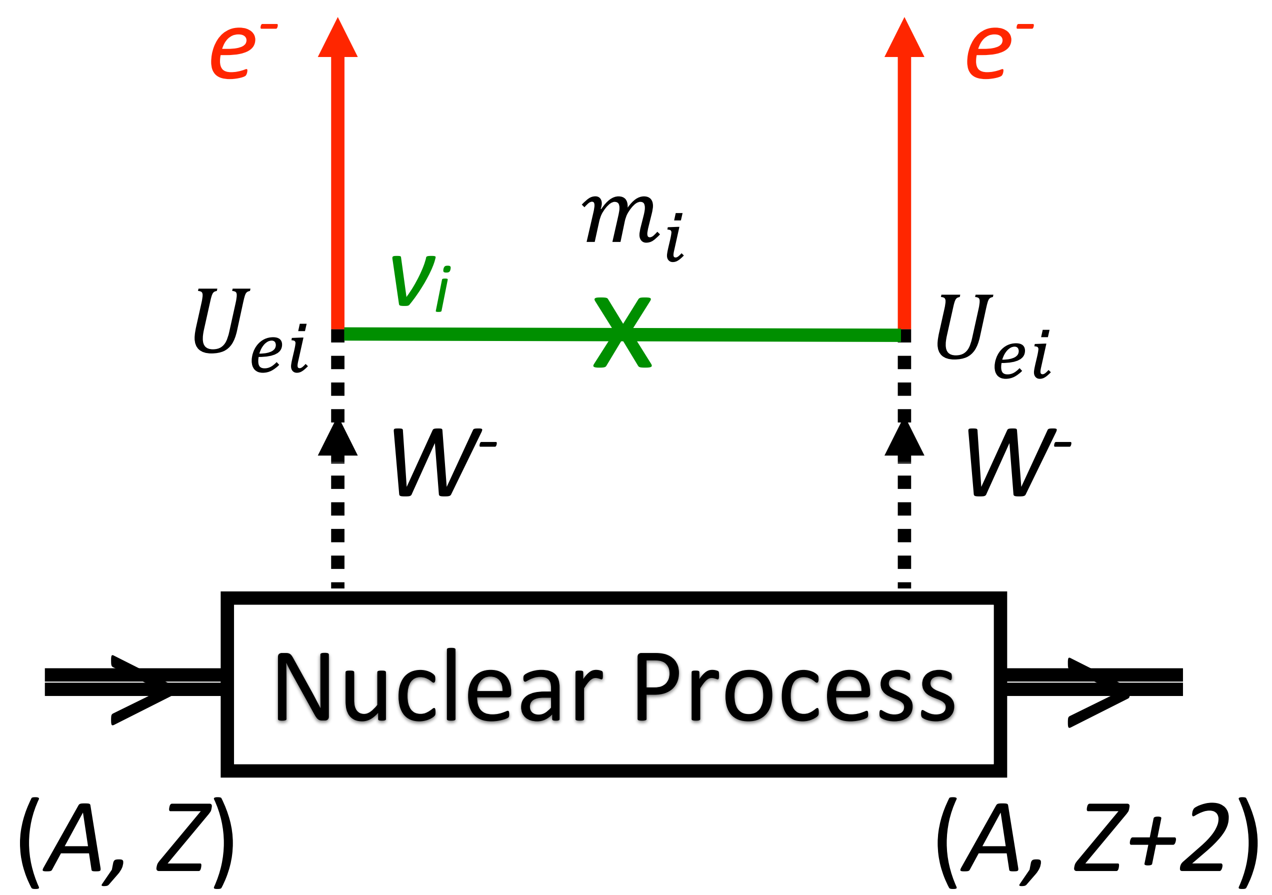
Experimental Signature: δ peak at $Q_{\beta\beta}$

- Necessary and sufficient to measure $\Sigma T_{\beta i}$ (in multiple isotopes)
- Tracking ($\cos\theta$, $T_{\beta 1}$:$T_{\beta 2}$) and isotope dependence probes the decay mechanism
- Additional handles provide background rejection, statistical characterization



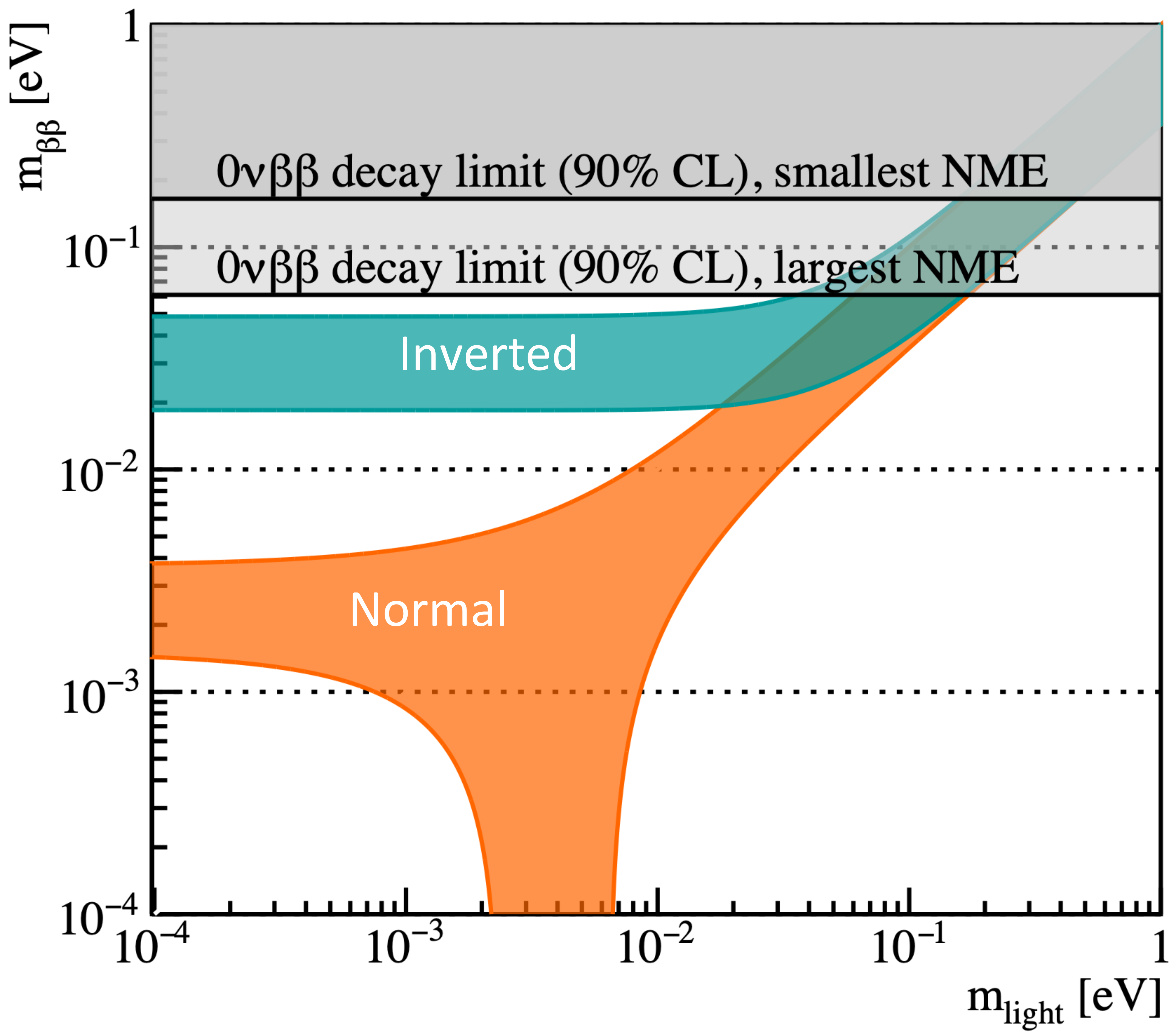
Current Limits and Future Goals

- Light neutrino exchange:



$$\Gamma_{0\nu} = G|M_{0\nu}|^2 m_{\beta\beta}^2$$

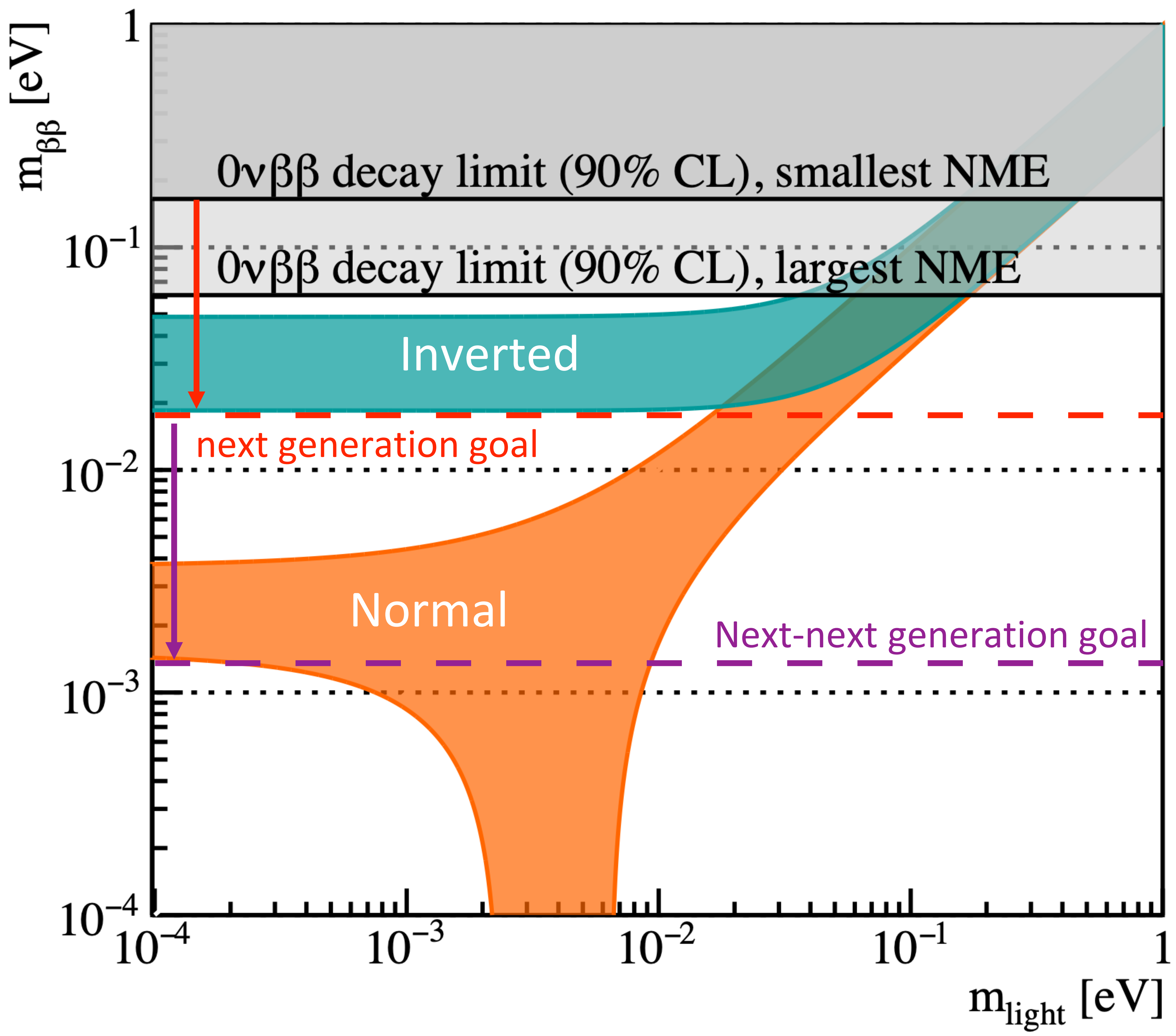
$$m_{\beta\beta} = \left|\sum_i U_{ei}^2\, m_i\right|$$



Agostini, Benato, Detwiler, Menendez, & Vissani, RMP **95**, 025002 (2023)

Current Limits and Future Goals

- Light neutrino exchange is "natural" and "minimalistic", and sets clear experimental goal posts:
  - $T_{1/2} \sim 10^{28}$ years (10^{18} times the age of the universe): fully probe IO and the degenerate NO
  - $T_{1/2} \sim 10^{30}$ years: fully probe the NO (modulo cancellations, flavor symmetries, etc.)



Agostini, Benato, Detwiler, Menendez, & Vissani, RMP **95**, 025002 (2023)

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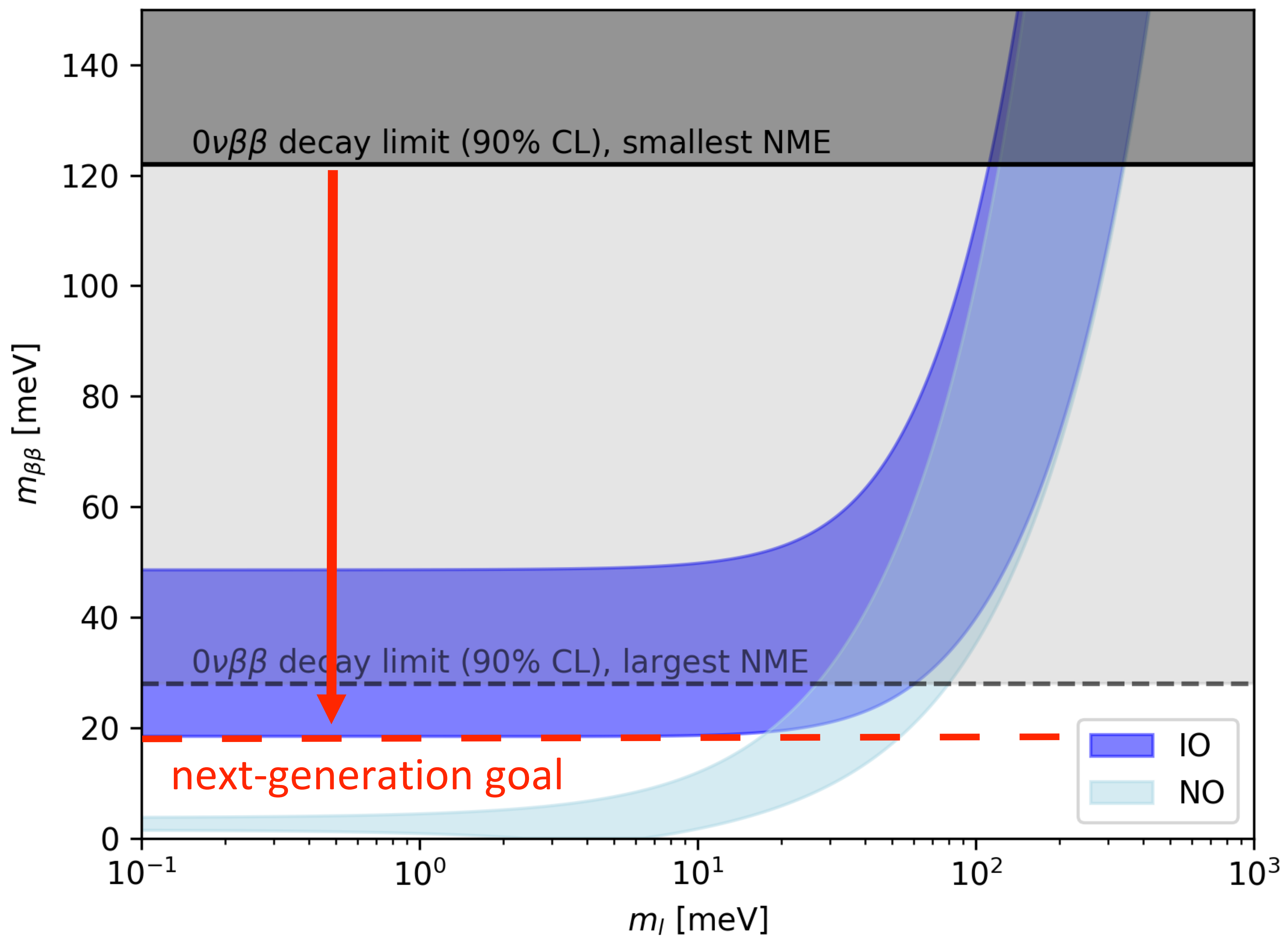

Plot by I. Guinn. Limit by KLZ800, 2406.11438: $T_{1/2} > 4\times10^{26}$ yr

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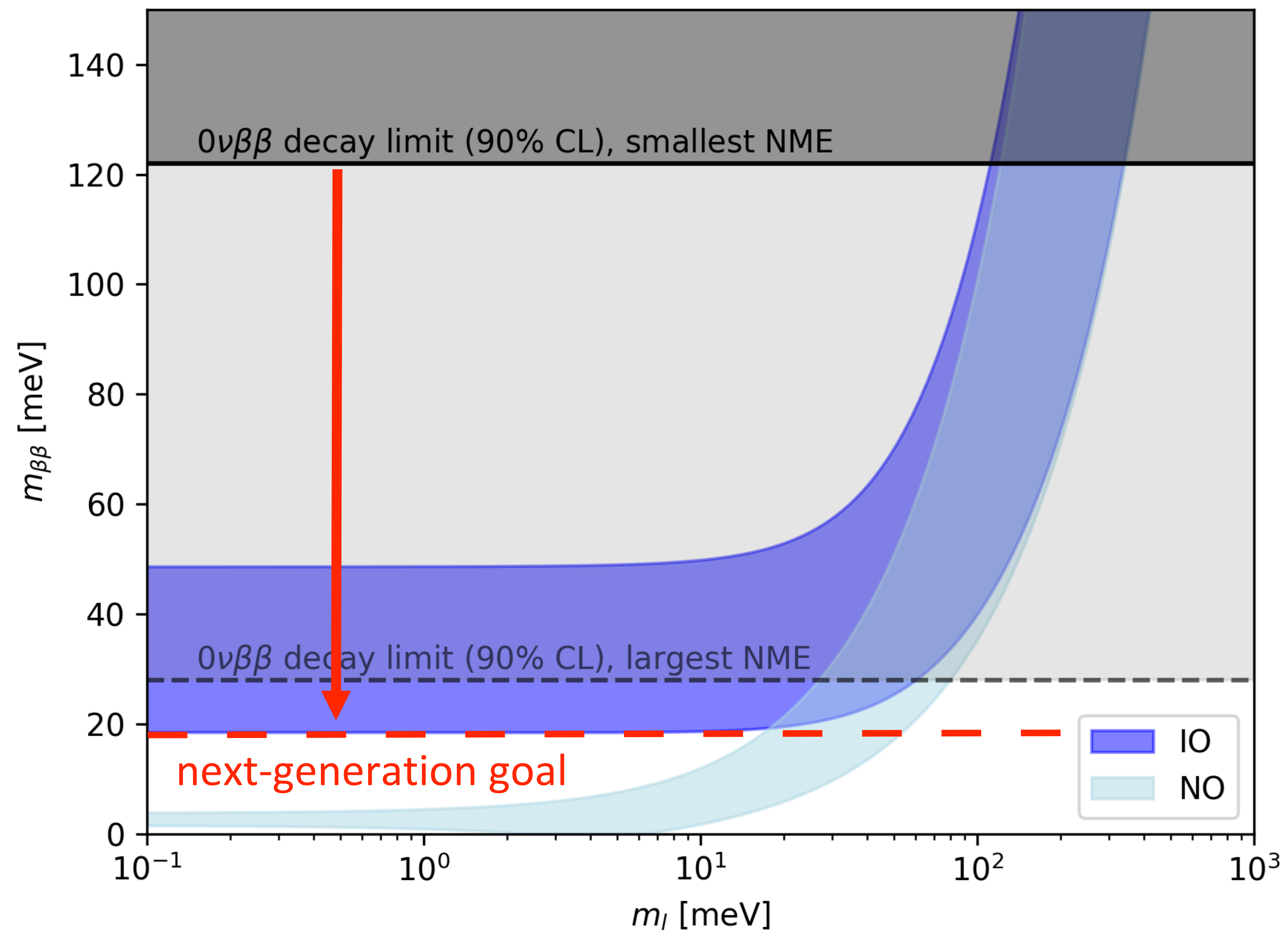
  - $T_{1/2} \sim 10^{28}$ years (10^{18} times the age of the universe): fully probe IO and the degenerate NO
  - $T_{1/2} \sim 10^{30}$ years: fully probe the NO (modulo cancellations, flavor symmetries, etc.)
- Other mechanisms are possible: the whole region is "open"!
  - Dim 5, 7, 9 LNV probed at the GUT, PeV, TeV scales
  - Sterile ν make the IO/NO regions cover the entire plane

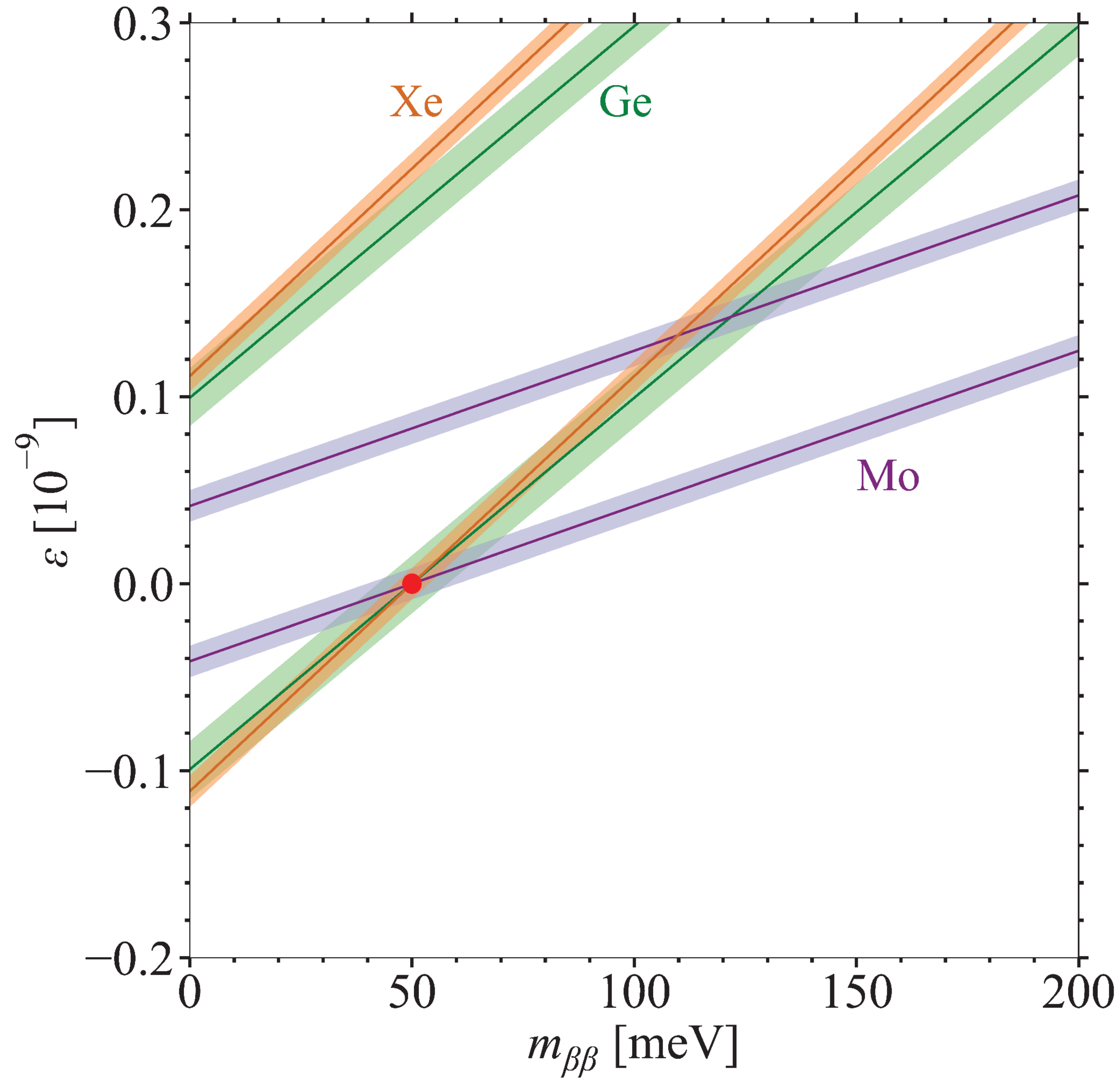


Plot by I. Guinn. Limit by KLZ800, 2406.11438: $T_{1/2}$ > 4x10^{26} yr

Probing the Mechanism with $T_{1/2}^{0\nu}$

$$\text{e.g.}\;\; \Gamma_{1/2}^{0\nu} = G\left|M_\nu m_{\beta\beta} + \epsilon M_{SR}\right|^2$$

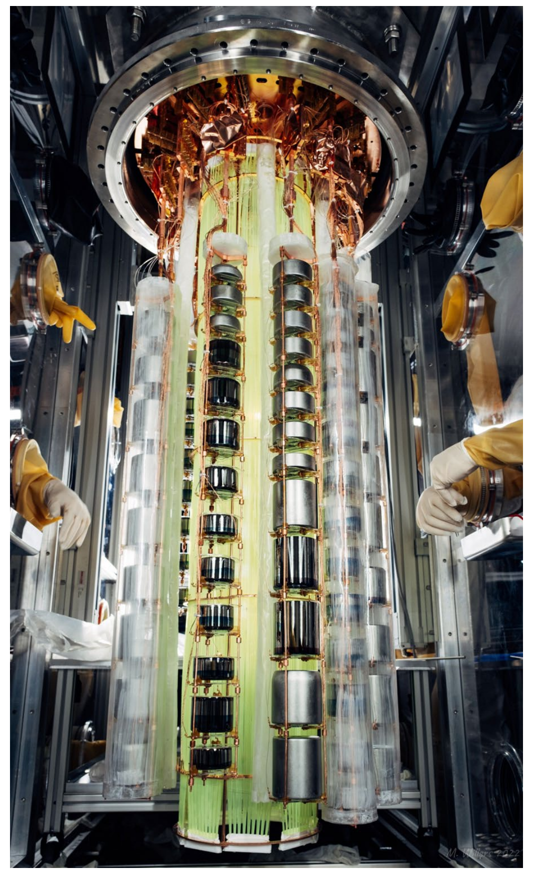
- Different exchange mechanisms predict different NME ratios for different isotopes
- Each observation provides an allowed region in the $\epsilon - m_{\beta\beta}$ plane
- Measurements in multiple isotopes with different ratios will converge on a single point in the plane for viable mechanisms



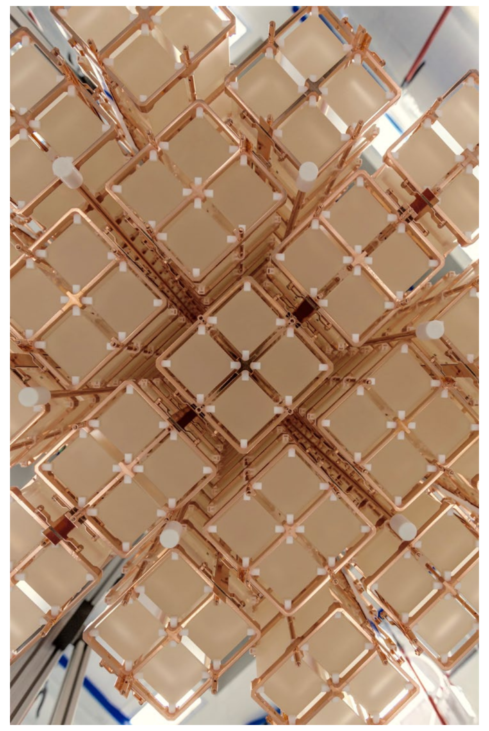
Experimental Techniques

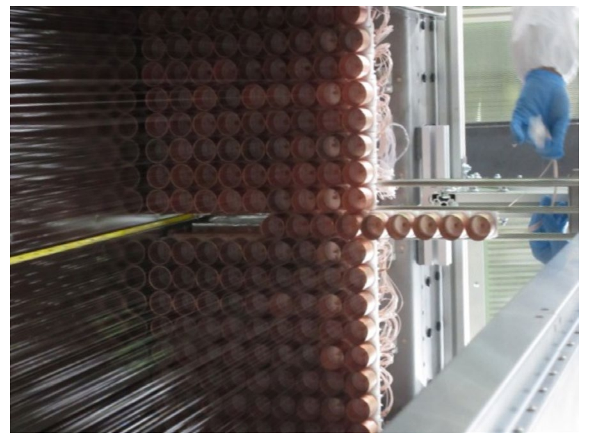
- Cryogenic calorimeters (CUORE/CUPID, AMoRE)
  - Measure *E* (σ ~ 0.1-0.3%) from phonons; granularity gives position info
  - Instrumenting with photon detectors for background rejection
- External trackers (SuperNEMO)
  - Trackers + calorimeters, measure *E* (σ ~ 3-10%) + tracks / positions + PID
- Scintillators (KamLAND-Zen, SNO+, JUNO, Theia)
  - Measure *E* (σ ~ 3-10%) + position from scintillation light; some PID
- Semiconductors (LEGEND, CDEX)
  - Measure *E* (σ ~ 0.05-0.3%) from ionization; some tracking / position sensitivity
- TPCs (nEXO, NEXT, AXEL, PandaX, XENON, LZ, XLVD, R2D2)
  - Collect scintillation + ionization: measure *E* (σ ~0.4-3%) + tracks / position + PID

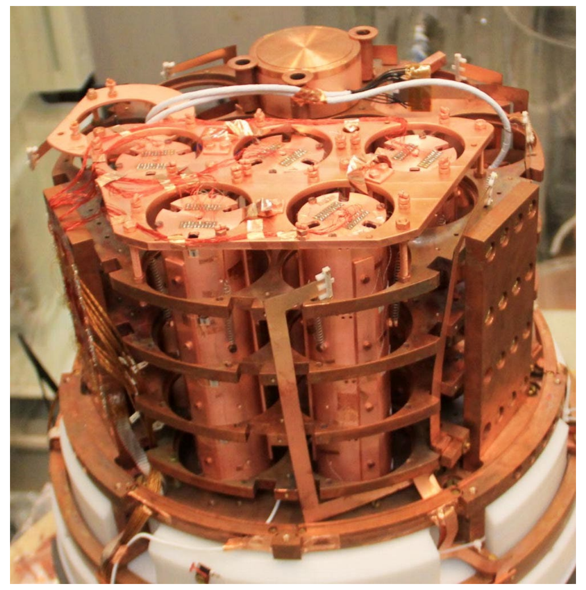

KamLAND-Zen

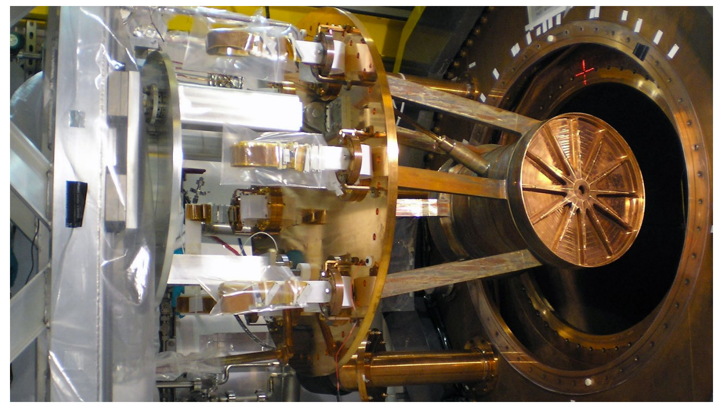

LEGEND-200


NEXT-100


CUORE

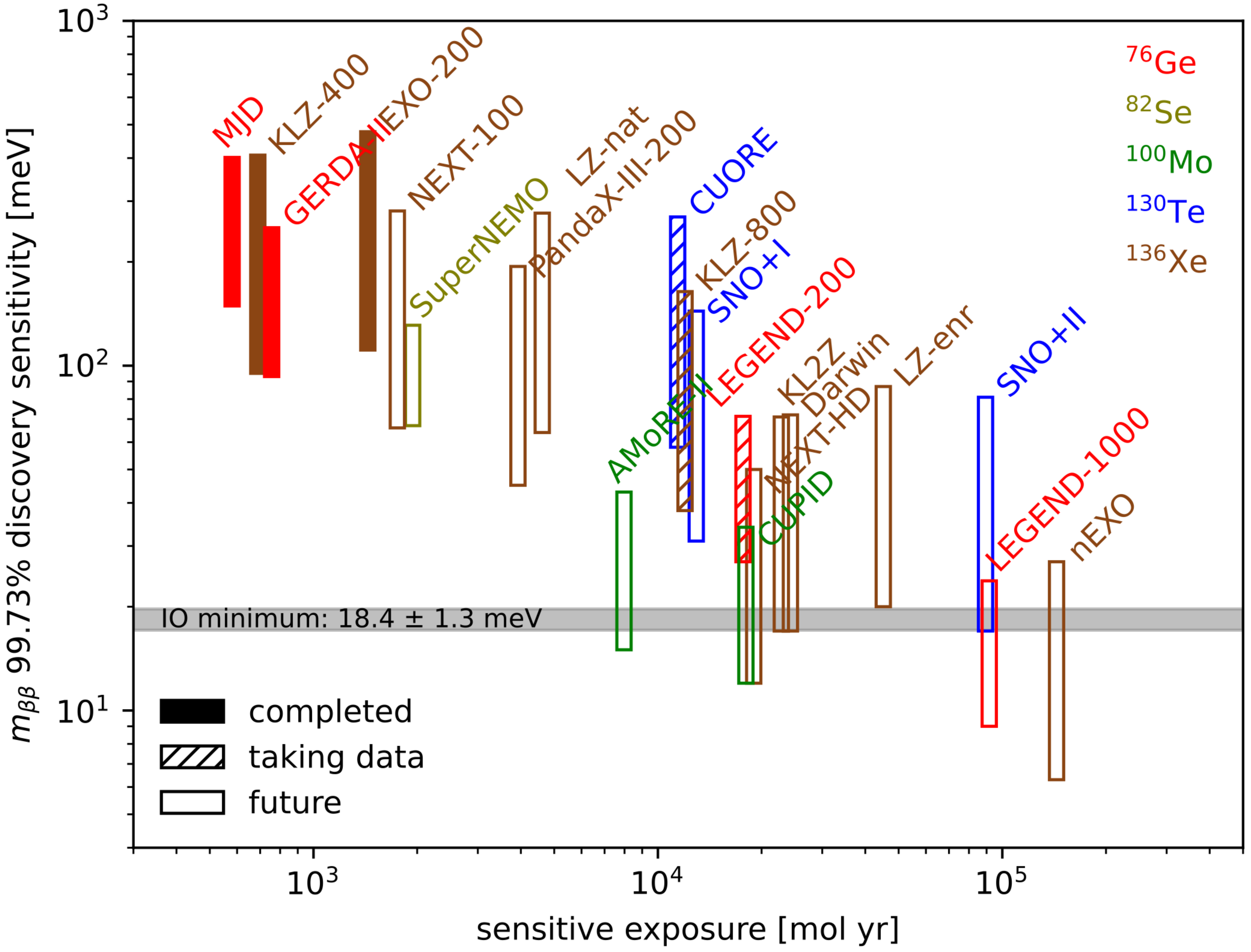

SuperNEMO


CUPID-Mo


EXO-200


PandaX-4T

Current and Future Sensitivities



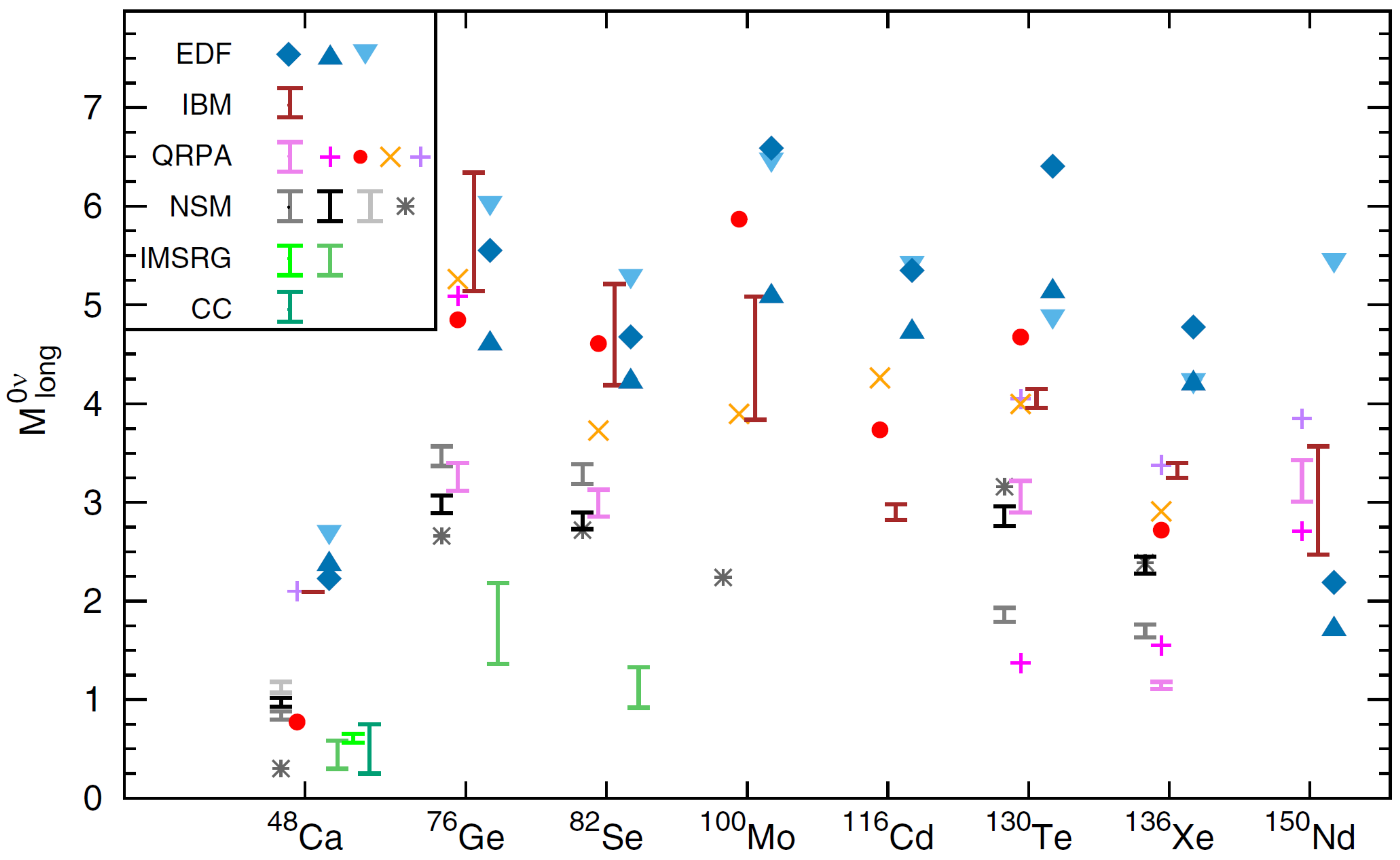
Nuclear Matrix Elements

- NME are the bridge between experimental measurements and the physical parameters of interest:

$$\Gamma^{0\nu}_{1/2} = G\left|M_{\nu} m_{\beta\beta} + \epsilon M_{SR} + \cdots\right|^2$$

- We use them for:
  - Constraining those parameters with experiments
  - Making plans and funding decisions for future experiments

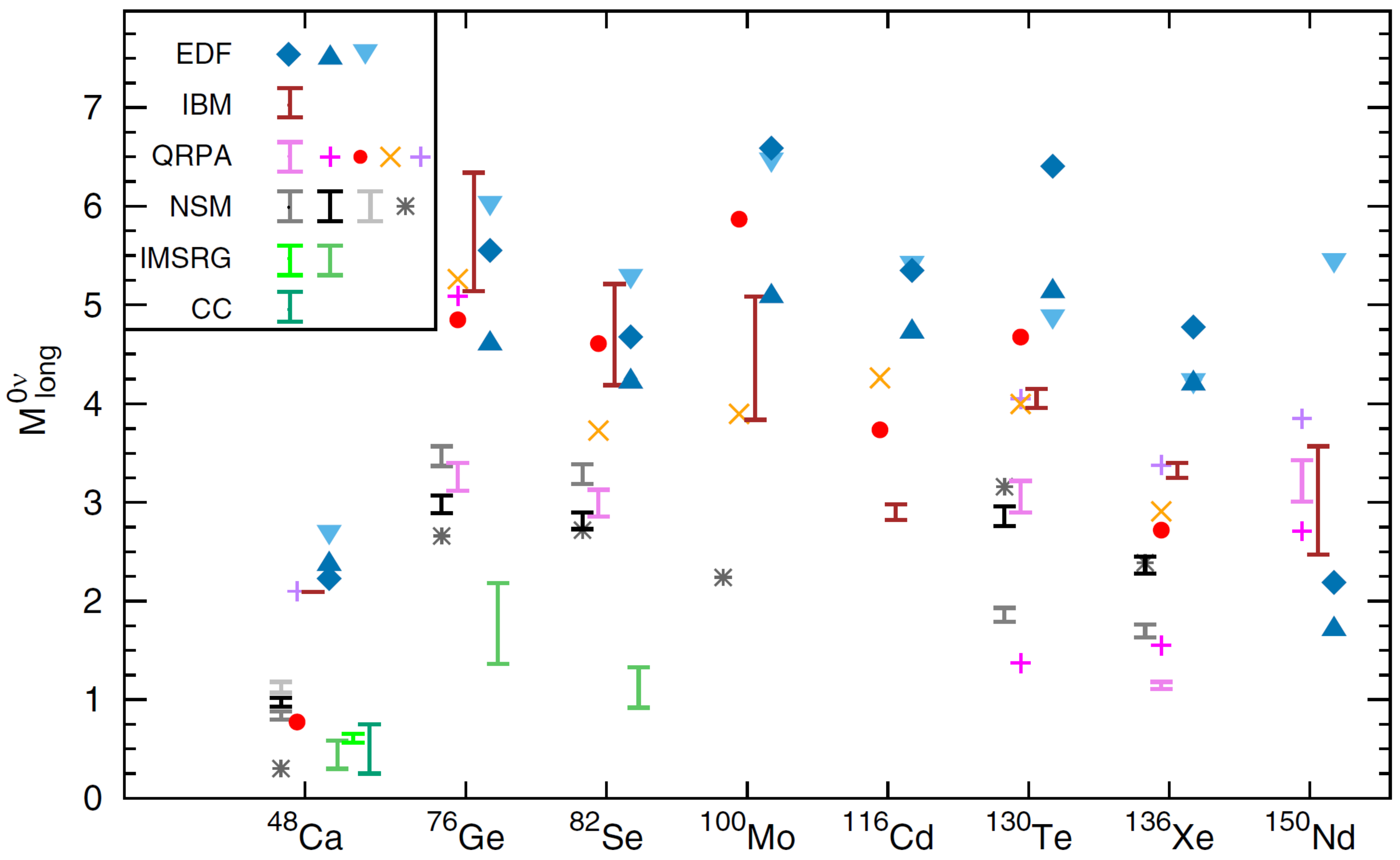
- It's important to have trustworthy values, especially for the isotopes being pursued



Agostini, Benato, Detwiler, Menendez, & Vissani, RMP **95**, 025002 (2023)

Nuclear Matrix Elements

- But they are notoriously difficult to compute:
  - Values have historically varied by factors of 2-3 or more
  - And have been missing physics responsible for the "quenching" of single-beta decay rates
  - And have also been missing $M^{0\nu}_{\text{short}}$
  - And uncertainties have been quantified only for parts of the calculations



Agostini, Benato, Detwiler, Menendez, & Vissani, RMP **95**, 025002 (2023)

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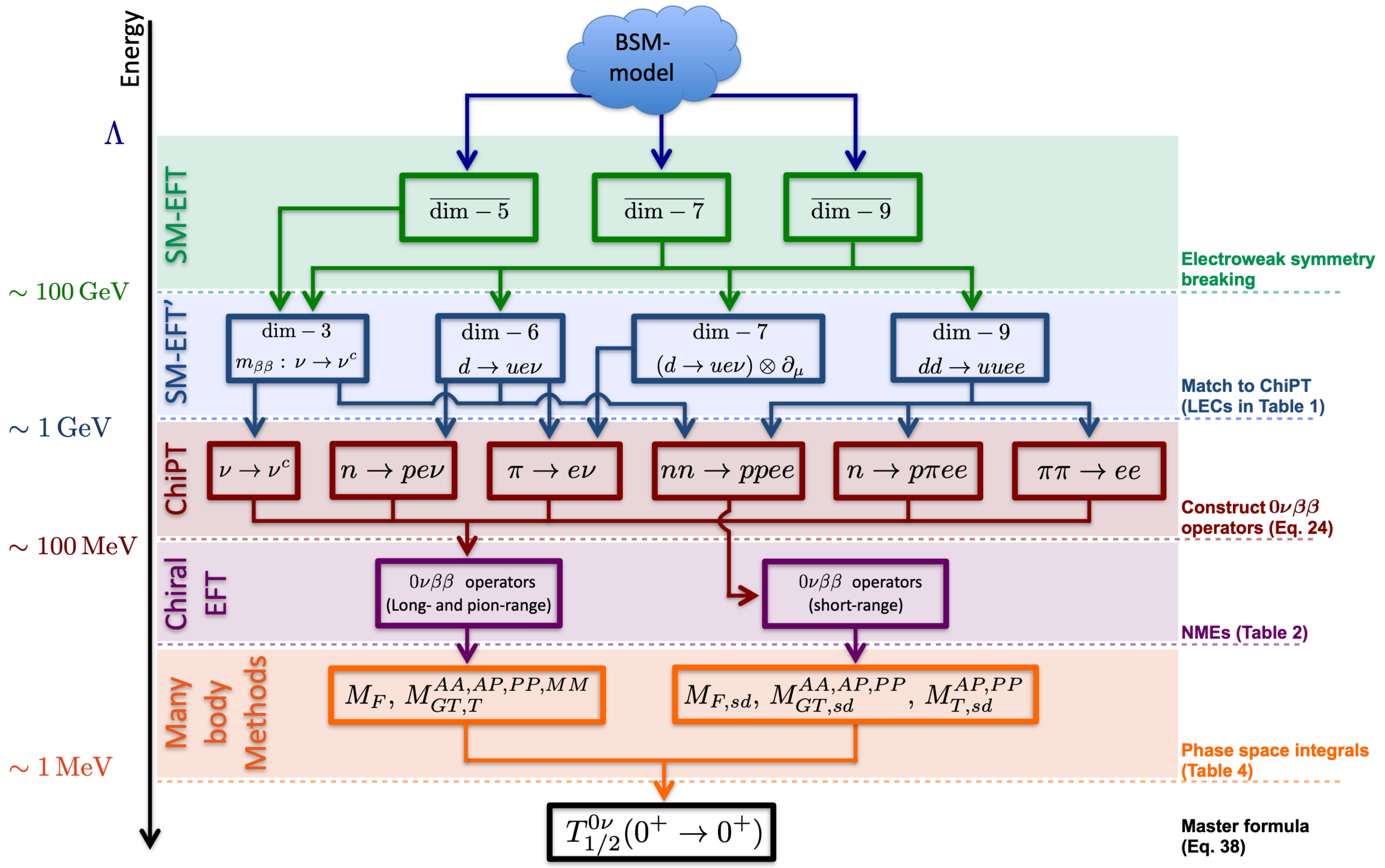

Cirigliano *et al.*, JHEP **12**, 097 (2018)

A New Era for NME

- More sophisticated and higher-fidelity and calculations are now possible
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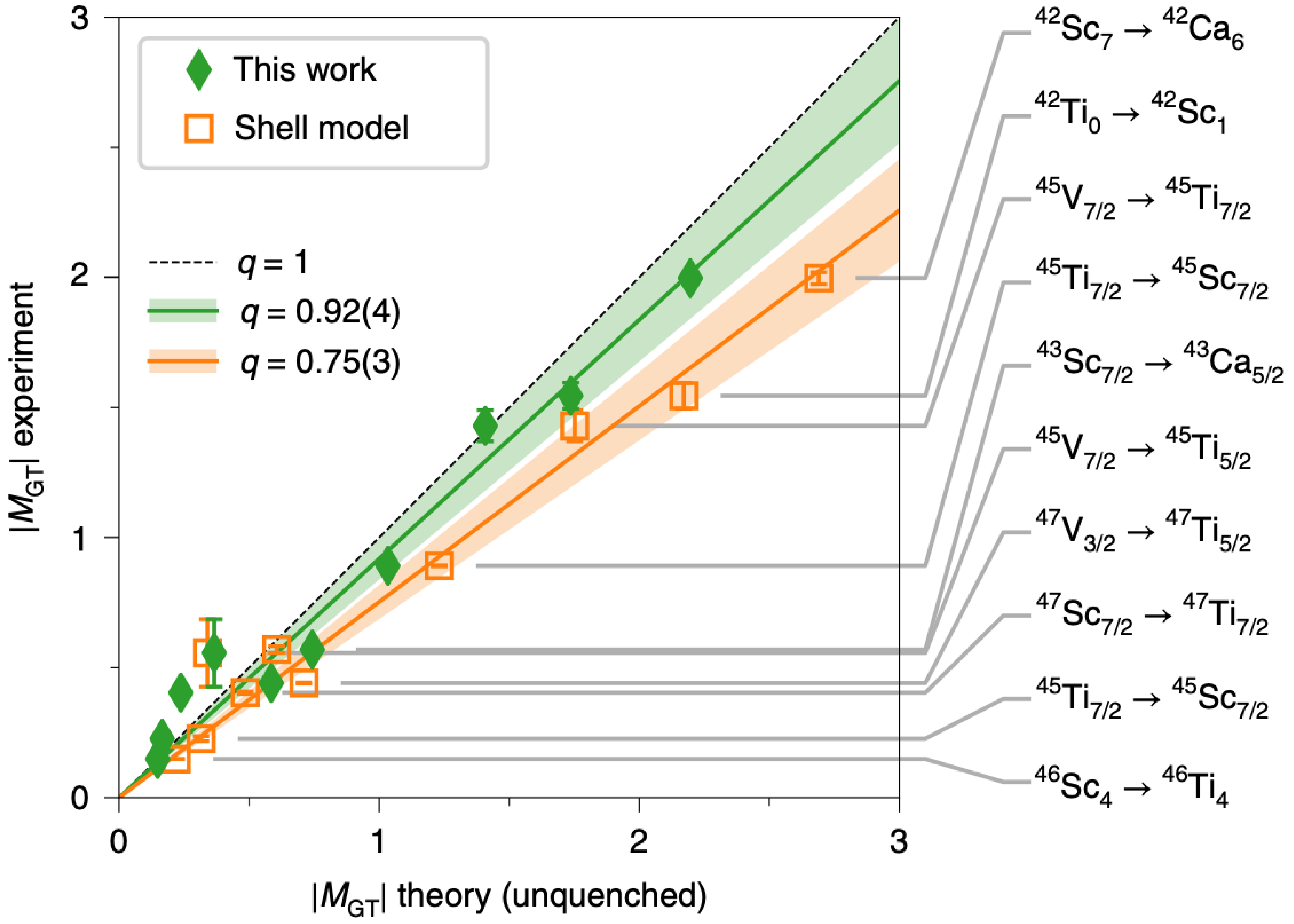

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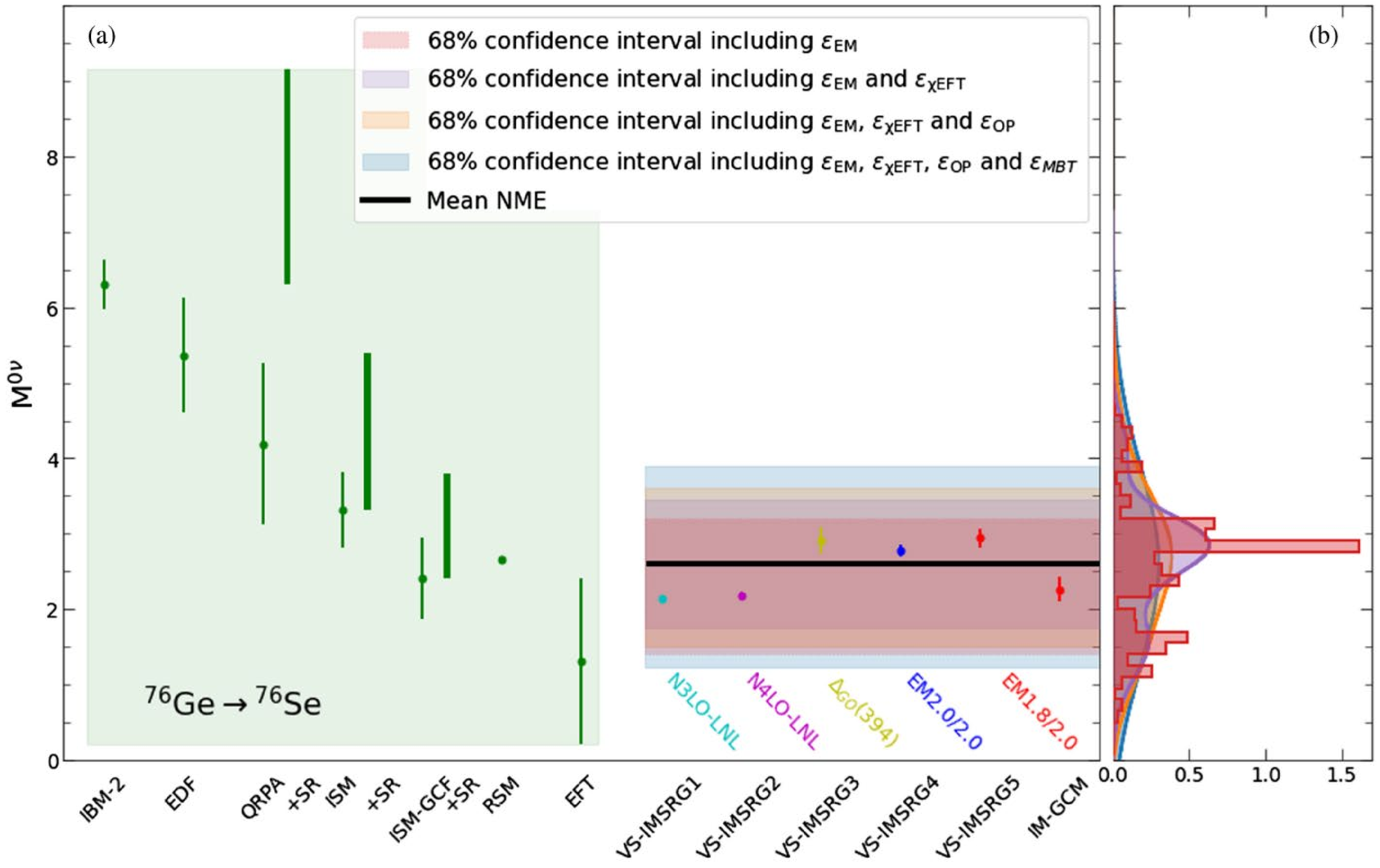
Gysbers *et al.*, Nature Phys. **15**, 428 (2019)

A New Era for NME

- More sophisticated and higher-fidelity and calculations are now possible
- χEFT has provided a systematic approach to NME and identification of the contact term
- Ab-initio methods appear to resolve the quenching problem in ordinary beta decay
- "Full" uncertainty quantification is underway



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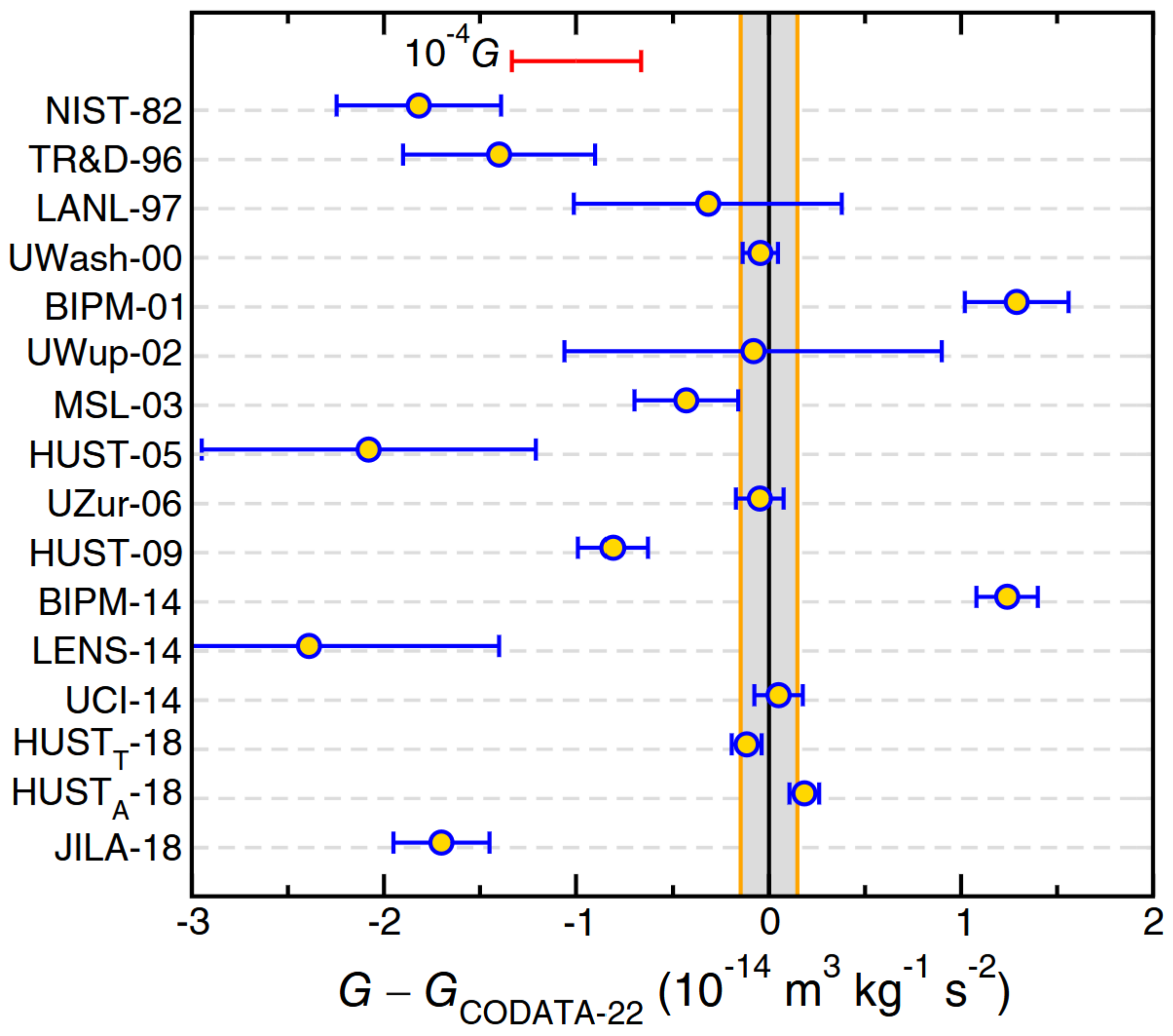
Belley et al., PRL 132, 182502 (2024)

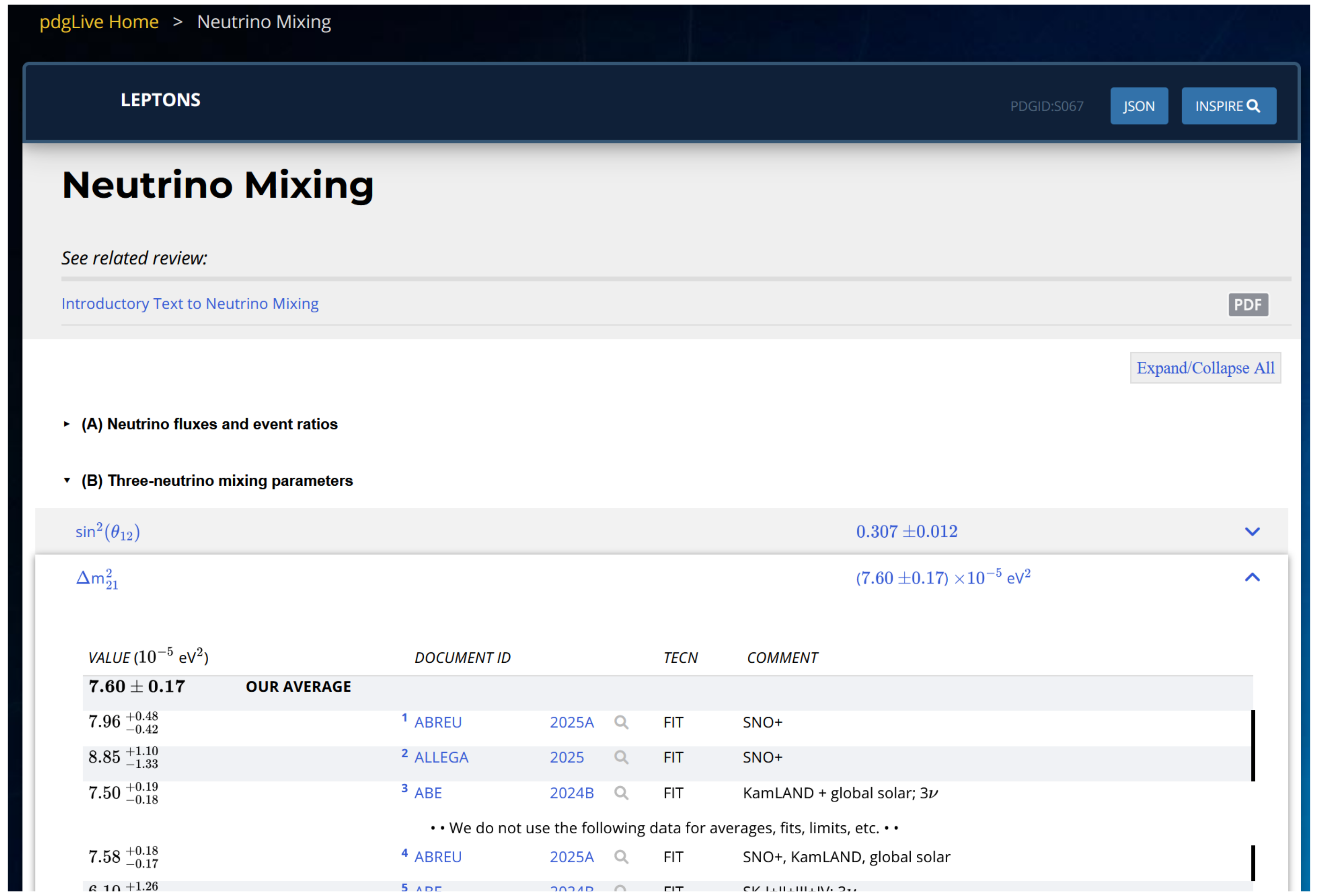
An Experimentalist’s Perspective

- It’s hard to figure out what NME we are supposed to use
  - Usually: start with the last big review and then ask theorist friends if any new ones should be added
- We of course wish they were large, but it’s more important that they be correct
  - We want to use NME that incorporate all known physics, including quenching and the contact term
- We also want to know the full uncertainty
  - Once NME are available with uncertainties, we will start moving away from NME without uncertainties
- We want to make apples-to-apples comparisons across isotopes
  - We don’t want to unfairly advantage or disadvantage ourselves or our colleagues

Examples from other SubFields

Mohr et al., RMP **97**, 025002 (2022)





pdgLive Home > Neutrino Mixing

LEPTONS

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Neutrino Mixing

See related review:

Introductory Text to Neutrino Mixing PDF

Expand/Collapse All

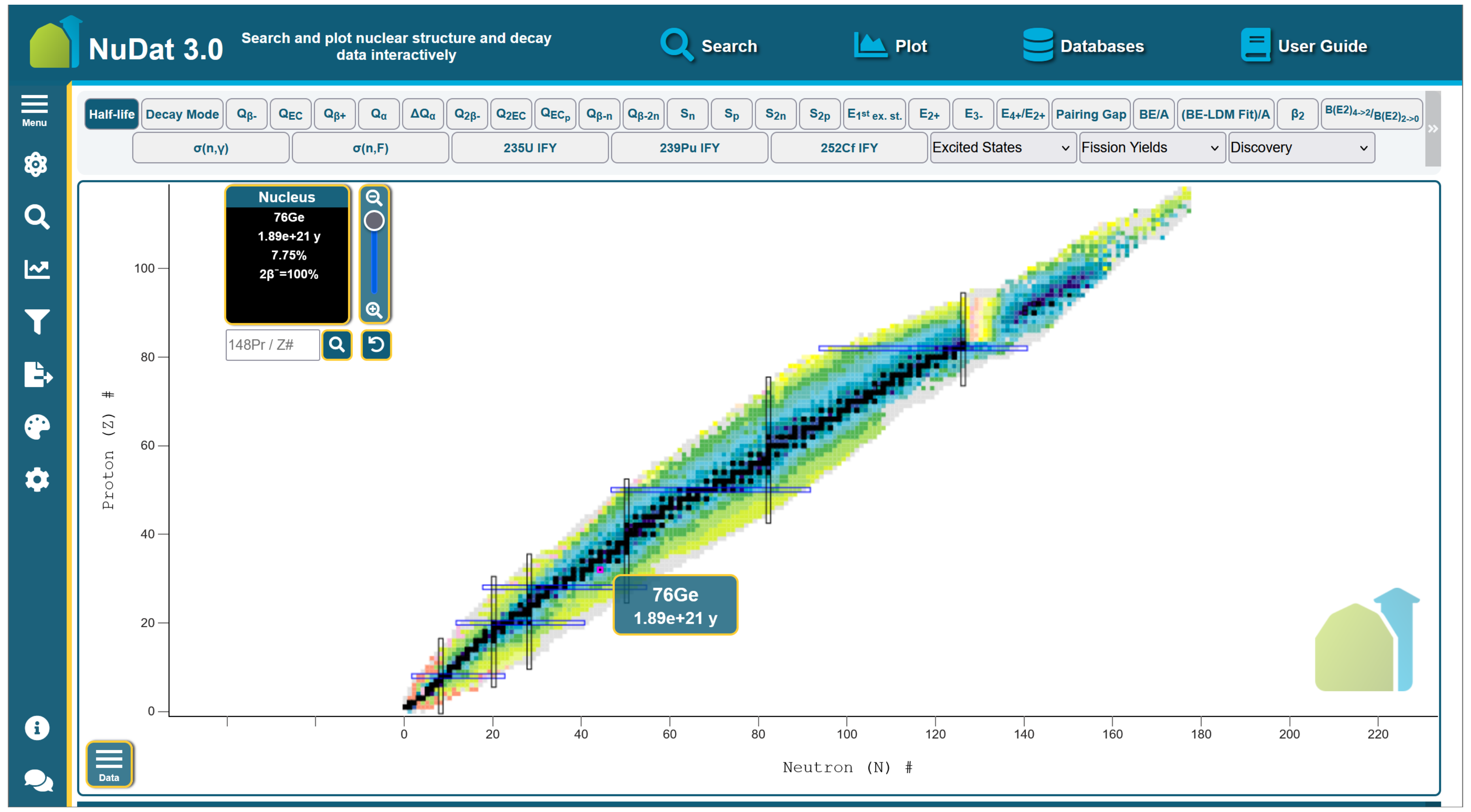
▸ (A) Neutrino fluxes and event ratios

▾ (B) Three-neutrino mixing parameters

$\sin^2(\theta_{12})$ 0.307 ±0.012

Δm^2_{21} $(7.60 \pm 0.17) \times 10^{-5}$ eV^2

VALUE (10^{-5} eV^2)	DOCUMENT ID		TECN	COMMENT
7.60 ± 0.17	OUR AVERAGE			
$7.96^{+0.48}_{-0.42}$	[1] ABREU	2025A	FIT	SNO+
$8.85^{+1.10}_{-1.33}$	[2] ALLEGA	2025	FIT	SNO+
$7.50^{+0.19}_{-0.18}$	[3] ABE	2024B	FIT	KamLAND + global solar; 3ν
• • We do not use the following data for averages, fits, limits, etc. • •				
$7.58^{+0.18}_{-0.17}$	[4] ABREU	2025A	FIT	SNO+, KamLAND, global solar



Physics Reports 1143 (2025) 1–158

Contents lists available at ScienceDirect

Physics Reports

journal homepage: www.elsevier.com/locate/physrep

ELSEVIER

Review article

The anomalous magnetic moment of the muon in the Standard Model: an update

Check for updates

R. Aliberti [1,2], T. Aoyama [3], E. Balzani [4,5], A. Bashir [6,7], G. Benton [8,9], J. Bijnens [10],

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A Future Vision for Recommended NME Values

- NME *evaluations*, with full uncertainties including correlations
- For all 15 long- and short-range NME
- For each nucleus of experimental relevance
- With methods that satisfy a set of benchmarks
  - For example, ability to reproduce other relevant measured observables

How might we get there?

Recommended Values for Neutrinoless Double-Beta Decay Nuclear Matrix Elements

June 29, 2026 - July 24, 2026

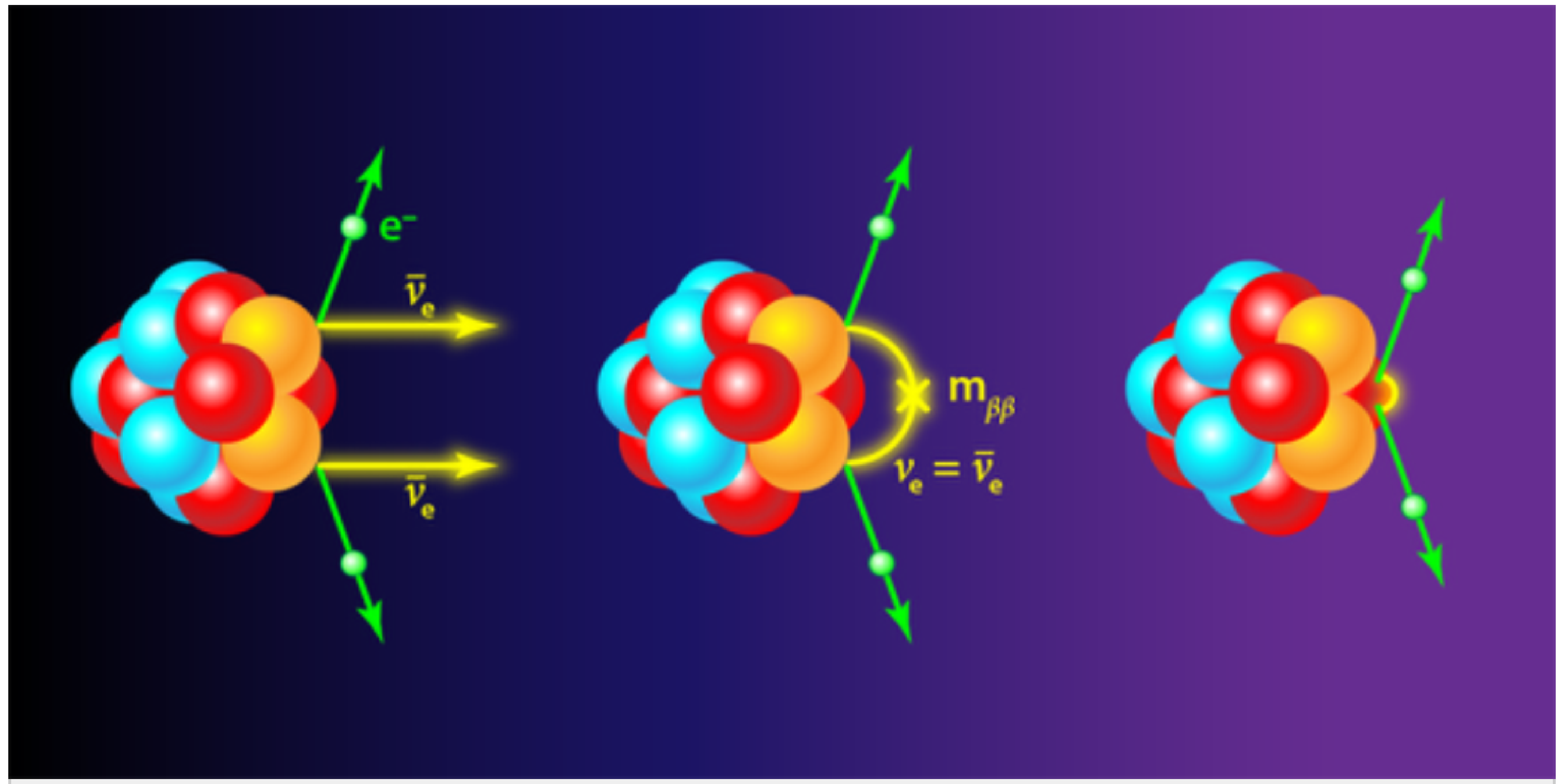
ORGANIZERS

Jason Detwiler
University of Washington
jasondet@uw.edu

Jason Holt
TRIUMF
jholt@triumf.ca

Brian Lenardo
SLAC National Accelerator Laboratory
blenardo@slac.stanford.edu

Javier Menendez
University of Barcelona
menendez@fqa.ub.edu



APS / Alan Stonebraker

VIEW SCHEDULE

PARTICIPANT LIST

The priority application deadline for this program has passed

Week 1: Many-Body Methods – *Ab Initio* and Phenomenological. Discussion of the nuclear structure physics relevant for understanding 0νββ decay.

Week 2: Double Beta Decay Operators and the Contact Term. Discussion of the physics connecting the nuclear decay to lepton-number-violating physics.

Week 3: Uncertainty Quantification. Discussion of sources of uncertainty and error propagation.

Week 4: Workshop and Recommendation Development – "Toward Recommended Values for Neutrinoless Double Beta Decay Nuclear Matrix Elements". Workshop to engage the larger community, including experimentalists, in the process of producing reliable and community-vetted NME values. Will include the drafting of a whitepaper summarizing results from the program to disseminate the first community-vetted NME values, and development of a plan for their stewardship into the future.

Goal: generate a whitepaper with the same title as the program!

INT-26-2a

- We have had 3 weeks of great discussions so far, and have identified and worked on many key sticking points
- It's clear we are still very far from our ultimate goal, but an iterative process could achieve success
- This iteration: inclusive ranges (see next slide)
  - Even a recommendation of "continue using the historical phenomenological ranges" would be valuable, if it comes with a justification / explanation
- Then let's spend our energy developing *goals* for the *next* iteration
  - Proposed time between iterations: ~3 years

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Starting Proposal

- Proposed criteria for inclusion in the recommended values for *this* iteration:
  - The authors stand behind their calculations and argue that they should be included in the "recommended range" at present.
  - The calculations include deformation as well as *consideration* of quenching physics and the contact term
  - The calculations are available at the same level of effort at least for ^{76}Ge, ^{100}Mo, ^{130}Te, and ^{136}Xe, and preferably also for ^{48}Ca and ^{82}Se
- Proposed goals for the next iteration
  - *Inclusion* of correlations / quenching physics, deformation, and the contact term
  - A best-effort assessment of the full theoretical uncertainty at least for light neutrino exchange
  - Available at the same level of effort at least for ^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, and ^{136}Xe
  - The methods should be shown to reproduce some relevant measured / known quantities (to be discussed)
  - We attempt to probe / compare the "anatomy" of the calculations (to be discussed)

Plans for this Week

- Today through Wednesday:
  - Review the discussions held over the past few weeks
  - Hear from experimentalists and from colleagues who could not attend in earlier weeks
  - Discuss the criteria/goals for inclusion in this and the next iteration, and what to do in between
- Thursday and Friday:
  - Outline the whitepaper, break into editing groups, begin outlining and drafting
- After the workshop
  - Flesh out the whitepaper sections
  - Circulate our ideas within the community to solicit feedback and try to build consensus
  - Plan to meet again soon to push the draft forward