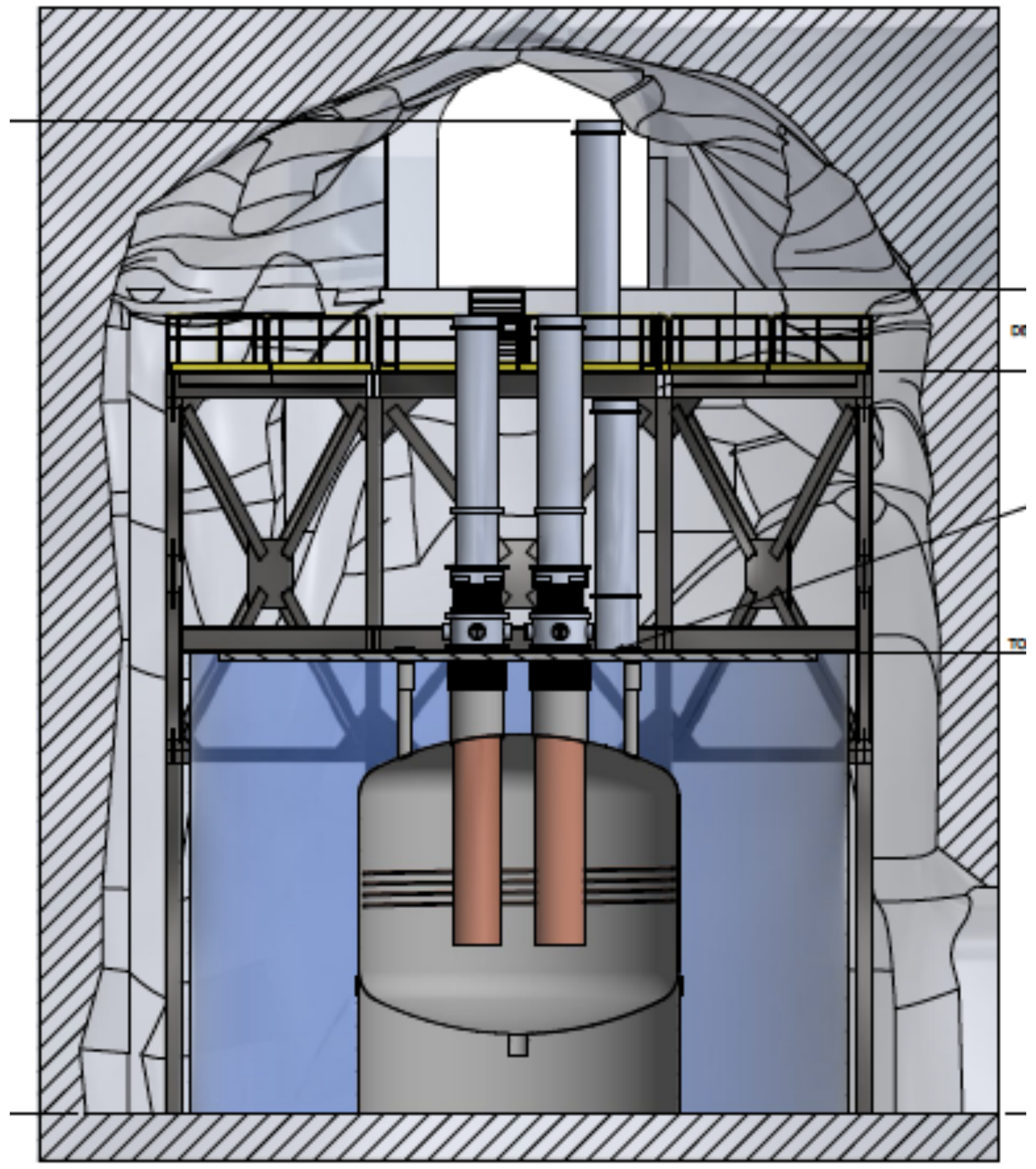
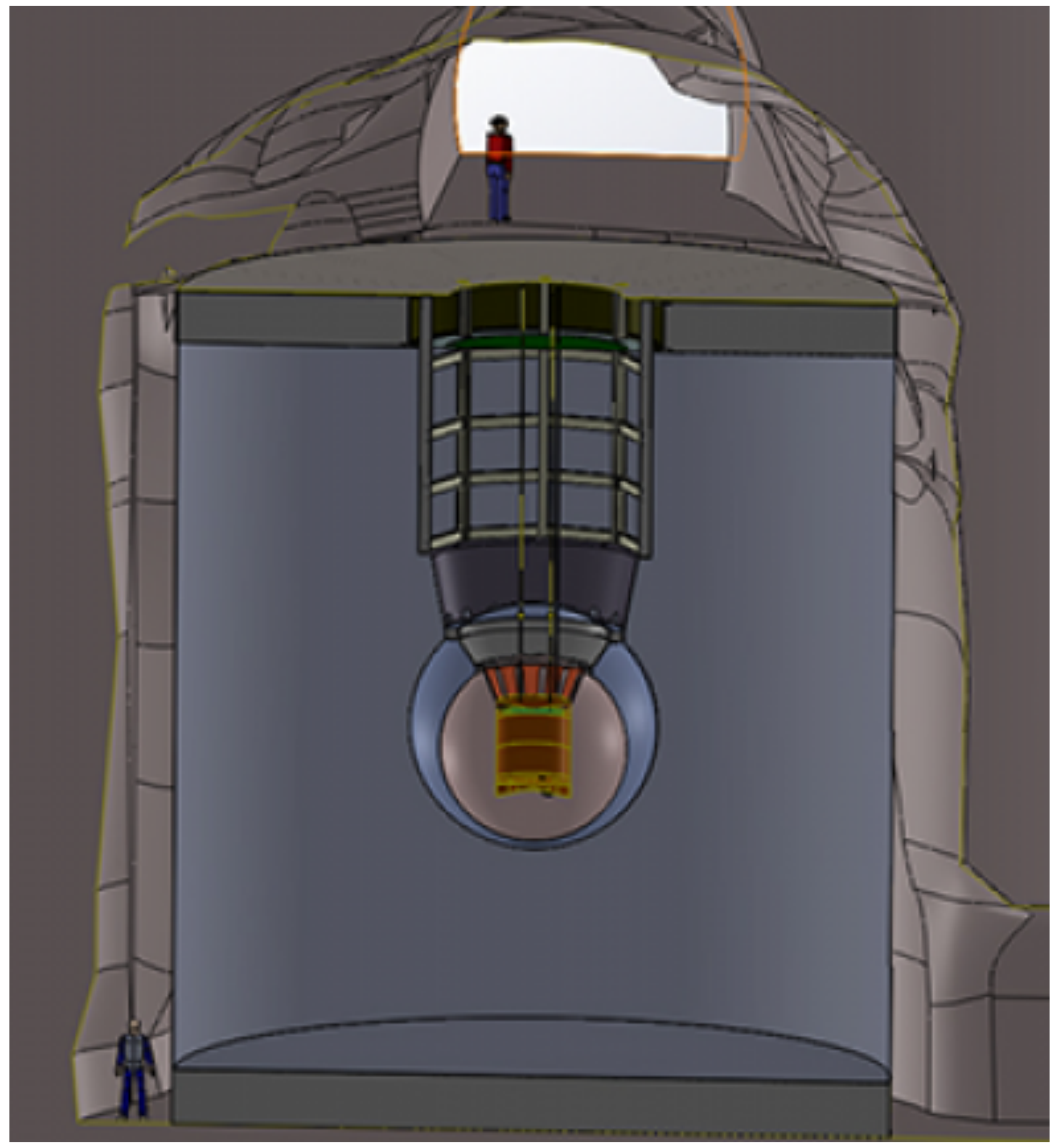
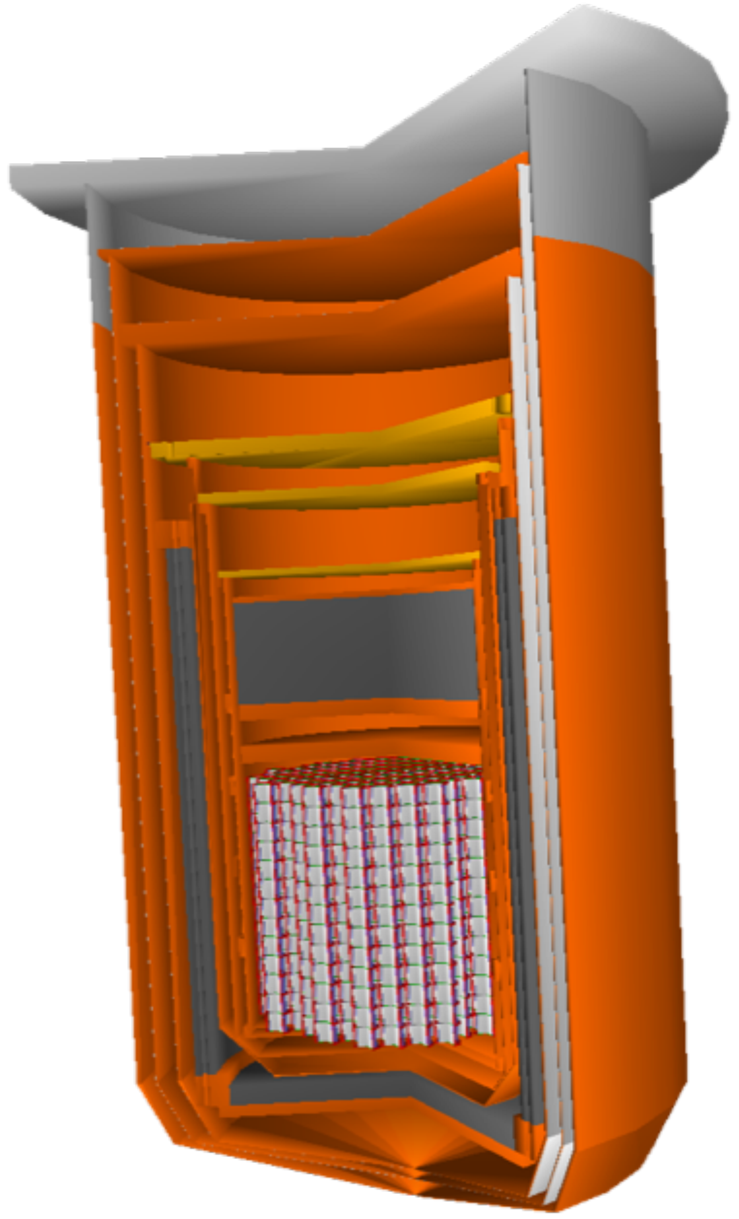
Report from the US: Double-Beta Decay

Jason Detwiler, University of Washington

UGAP 2022, Noda, Chiba, Japan, 13 June 2022



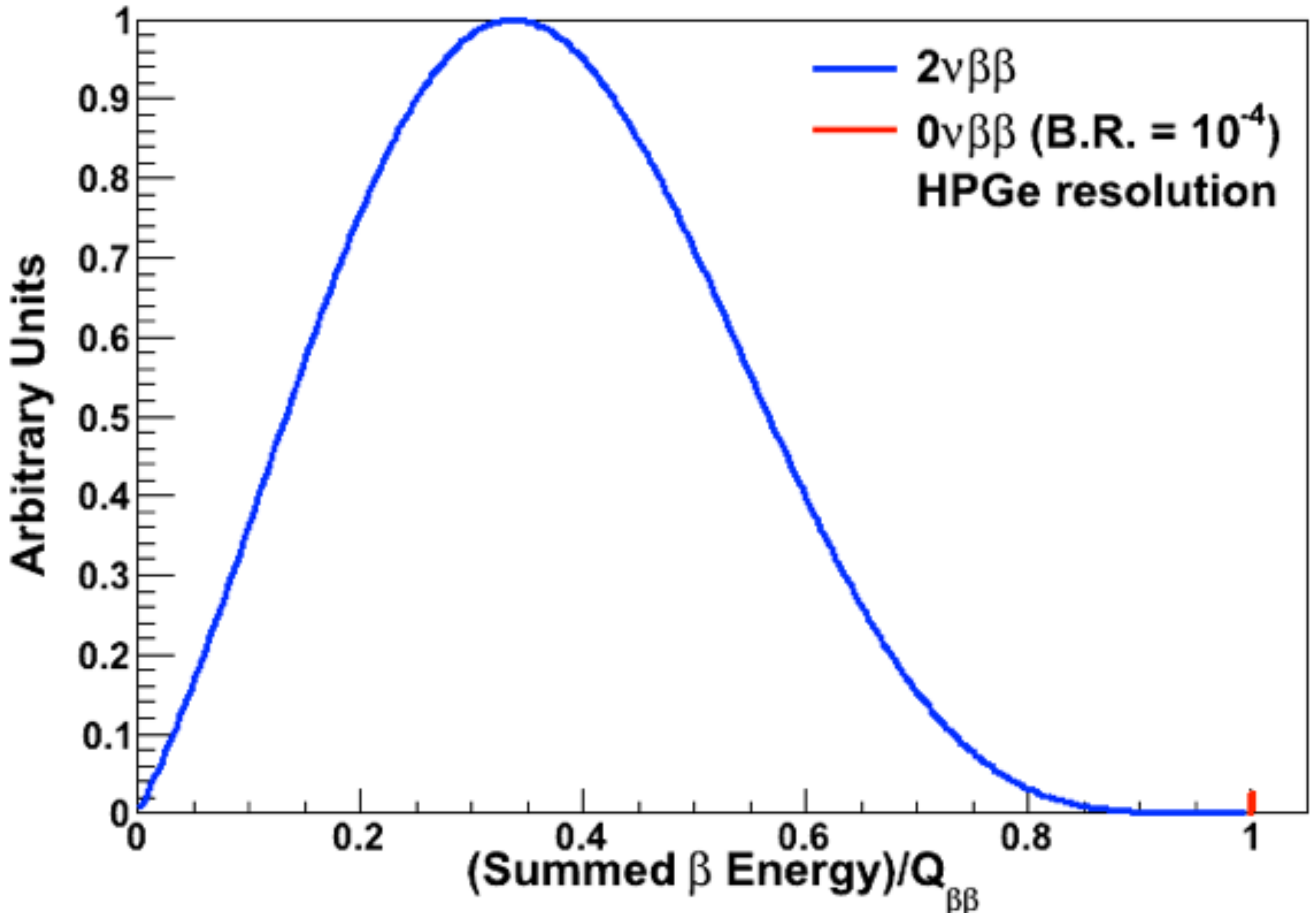




Disclaimer: I'm a member of the MAJORANA, LEGEND, and KamLAND-Zen Collaborations

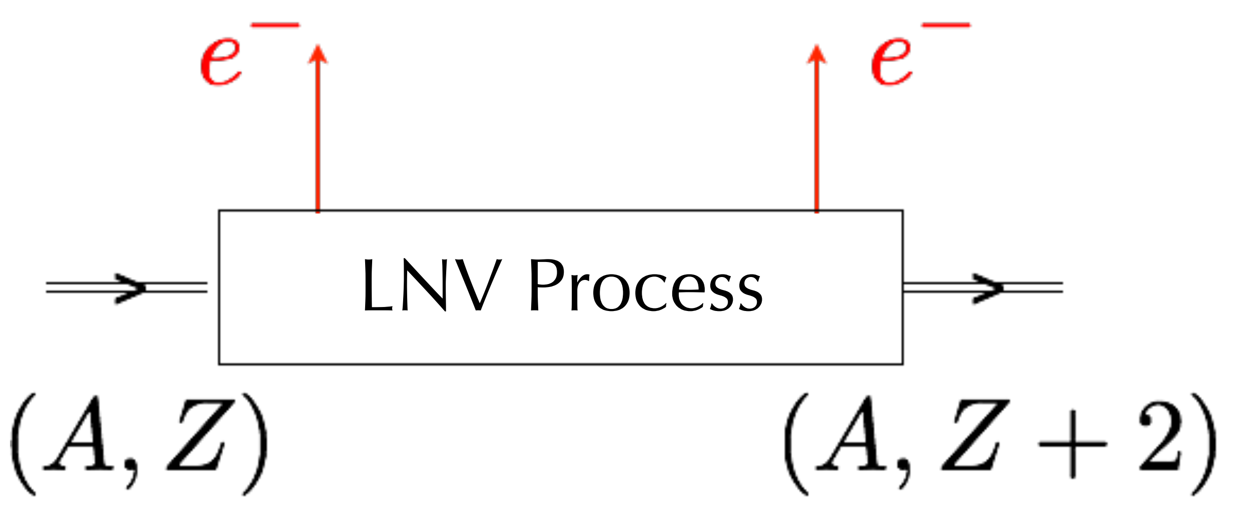
Outline

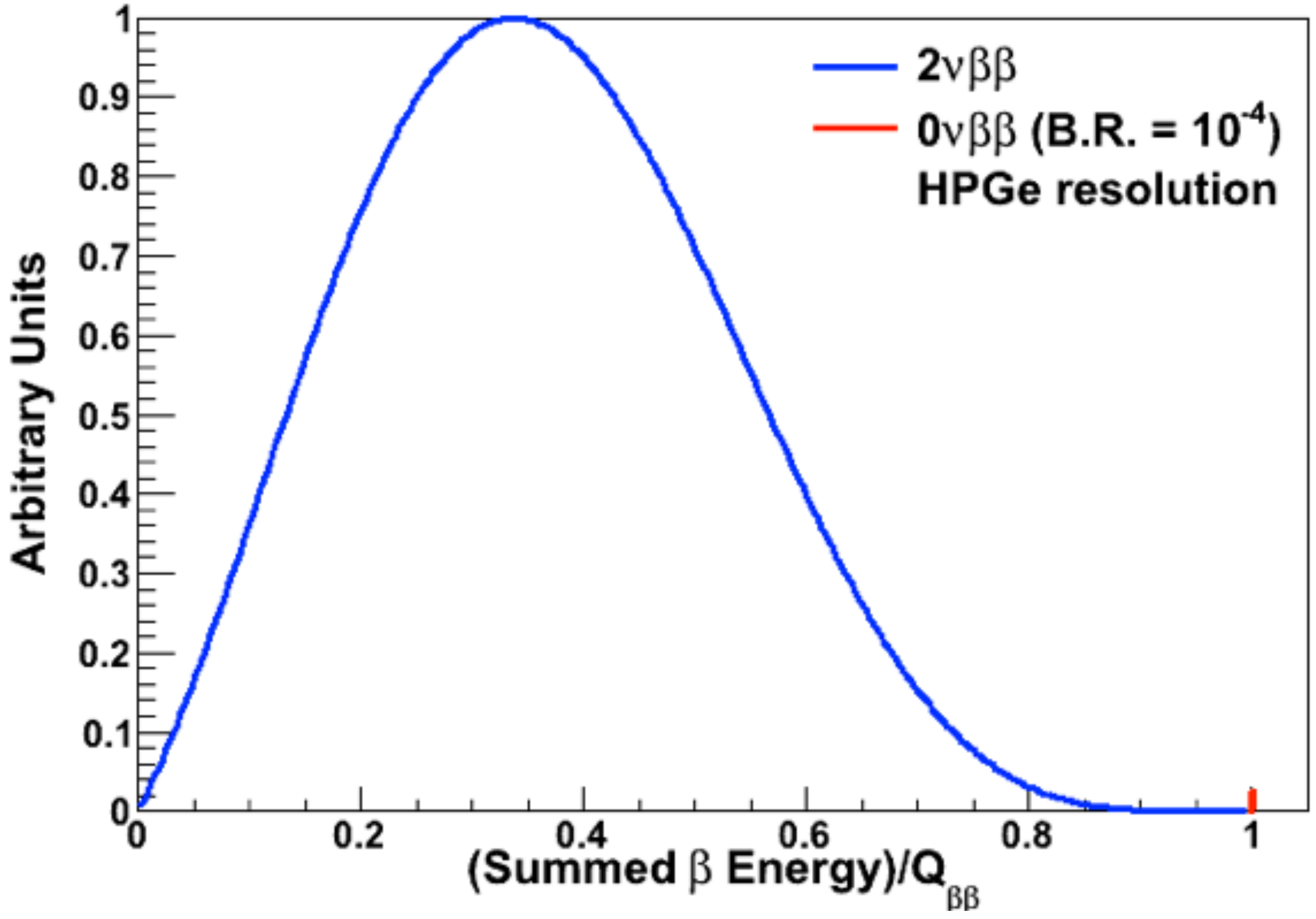
- Introduction
- Experimental Situation
- US Program
- US Planning / Funding Status



0νββ Decay: A "Little Bang"

- (B-L)-violating process that creates two new matter particles! (irrespective of mechanism)
- *Must* measure summed electron kinetic energy to distinguish from Standard-Model 2ν process: ionization, scintillation, and/or heat
- Some experiments can also measure electron momenta (tracking), providing a handle on the Lepton Number Violating (LNV) process
- Additional experimental handles (position, pulse shape / topology, daughter nucleus ID...) reject background
- The peak in the plot exceeds current limits by ~1 order of magnitude





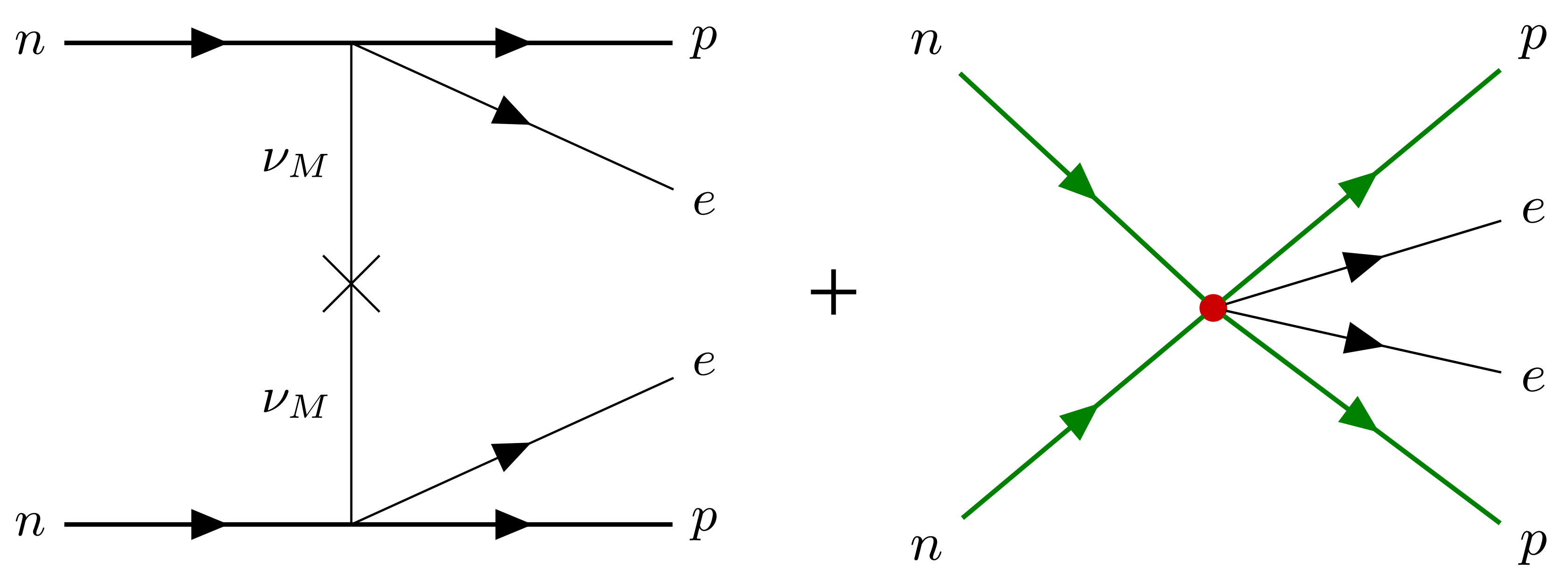
Mediating Processes

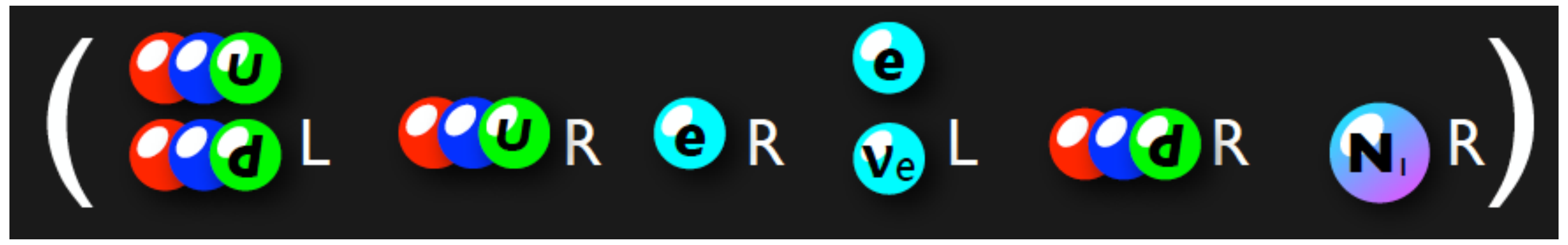
- EFT: LNV appears in L terms of dimension 5, 7, 9… and in general gives halflives like:

$$T_{1/2}^{-1} = G_{01}\, g_A^4 \,\left(M_{\text{light}}^{0\nu}\right)^2 \frac{m_{\beta\beta}^2}{m_e^2} + \frac{m_N^2}{m_e^2} \tilde{G}\, \tilde{g}^4\, \tilde{M}^2 \left(\frac{v}{\tilde{\Lambda}}\right)^6 + \ \ldots$$

  - $d = 5$ operator is unique (Weinberg operator): Light left-handed neutrino exchange, accompanied by a recently-recognized "contact term"

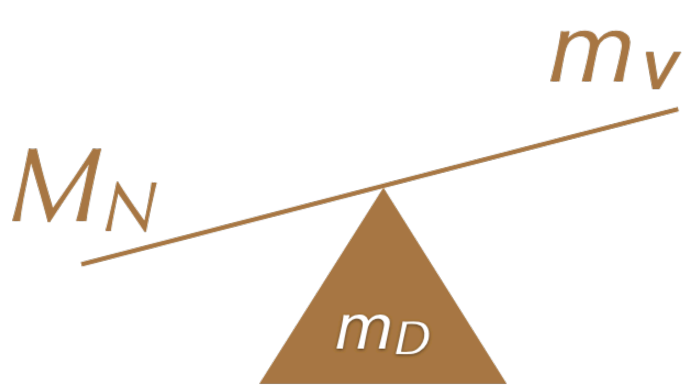
$$T_{1/2}^{-1} = G_{01}\, g_A^4 \,\left|M_{\text{long}}^{0\nu} + M_{\text{short}}^{0\nu}\right|^2 \frac{m_{\beta\beta}^2}{m_e^2} \qquad m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$$

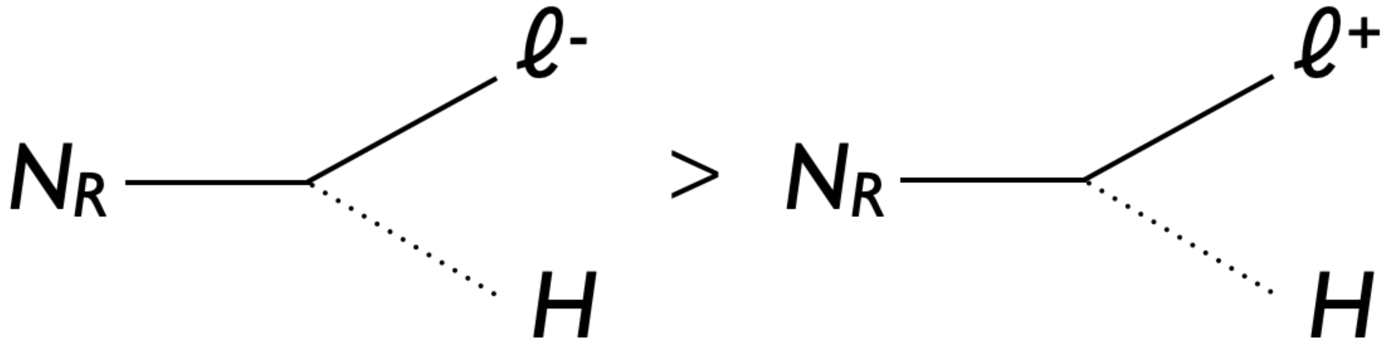




- Motivating example: SO(10) GUT
  - SO(10) requires one new right-handed singlet N_R
  - N_R generates Majorana neutrino masses via the seesaw mechanism
  - CPV N_R decays immediately after the Big Bang generate the cosmic matter asymmetry (leptogenesis)

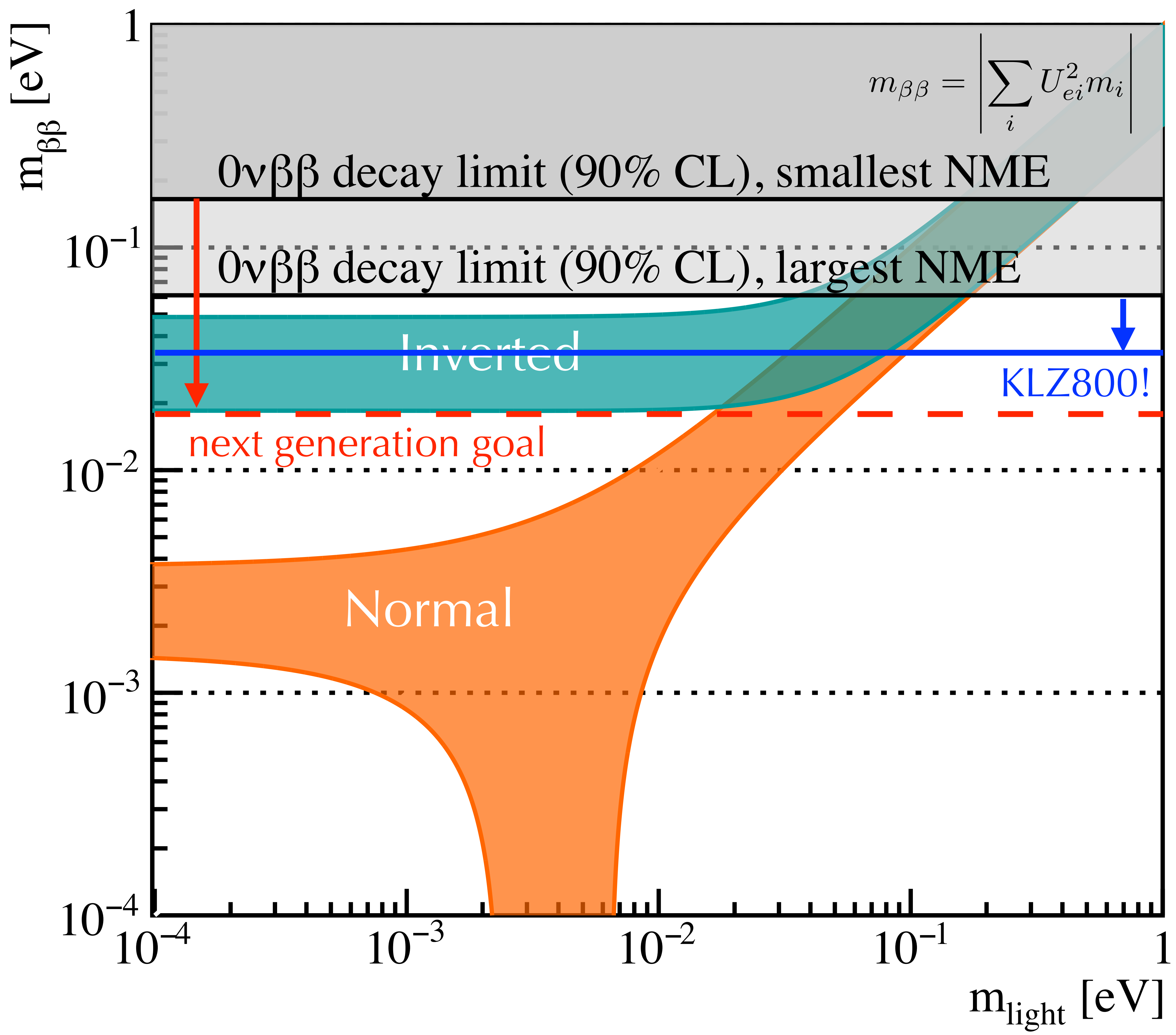
$$m_\nu = \frac{m_D^2}{M_N}$$





Current Limits and Future Goals

- Present best limits:
  - ^{136}Xe (KamLAND-Zen): $T_{1/2} > 2.3\text{x}10^{26}$ yr
    arXiv:2203.02139 [hep-ex] (2022)
  - ^{76}Ge (GERDA): $T_{1/2} > 1.8\text{x}10^{26}$ yr
    PRL **125**, 252502 (2020)
  - ^{130}Te (CUORE): $T_{1/2} > 2.2\text{x}10^{25}$ yr
    Nature **604**, 53 (2022)
- Future goal: O(100x) further in $T_{1/2}$
  - Covers IO
  - Up to 50% of NO
  - Factor of ~few in Λ
  - An aggressive experimental goal



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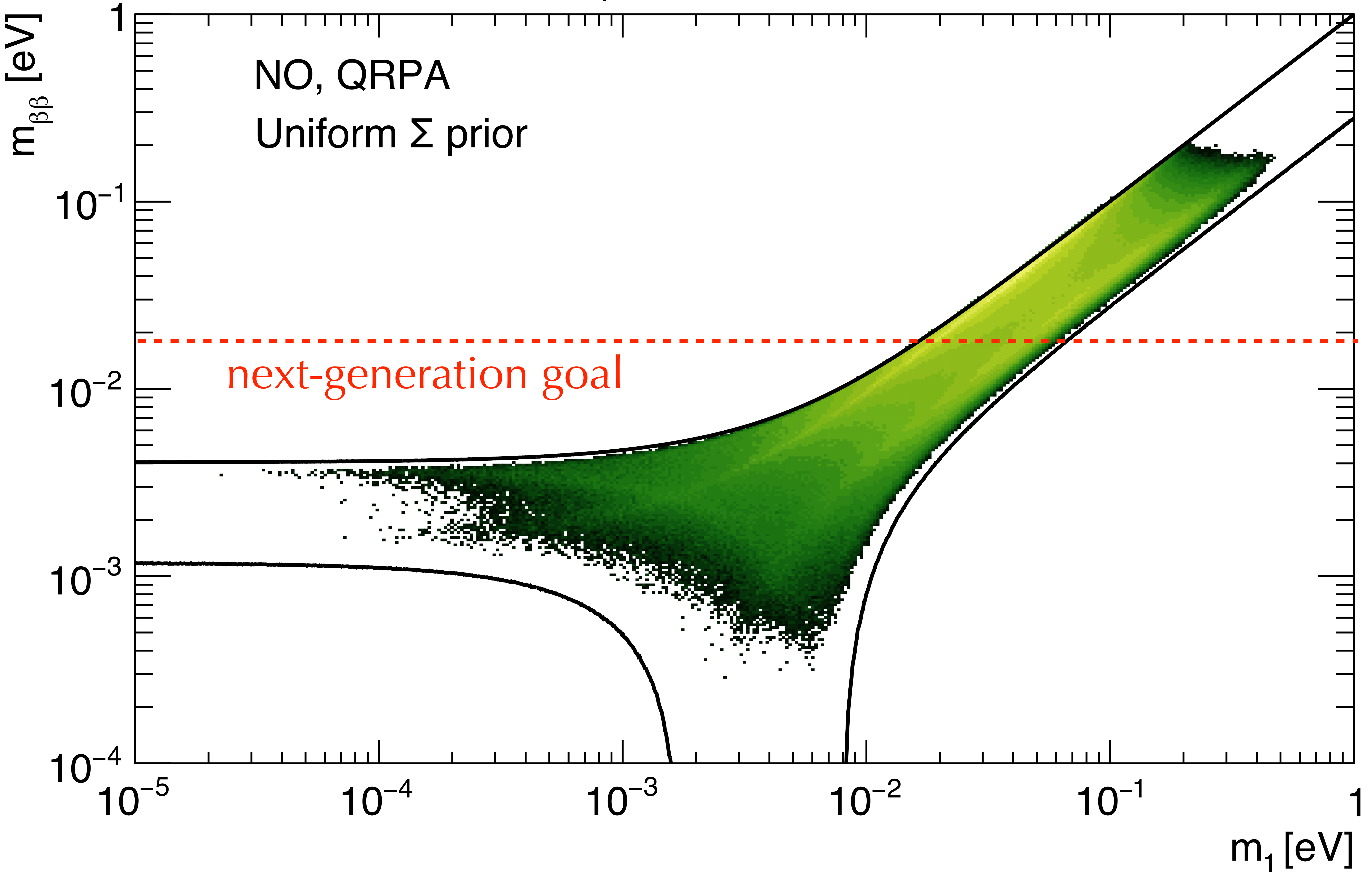
Bayesian Posterior



PRD **96**, 053001 (2017)

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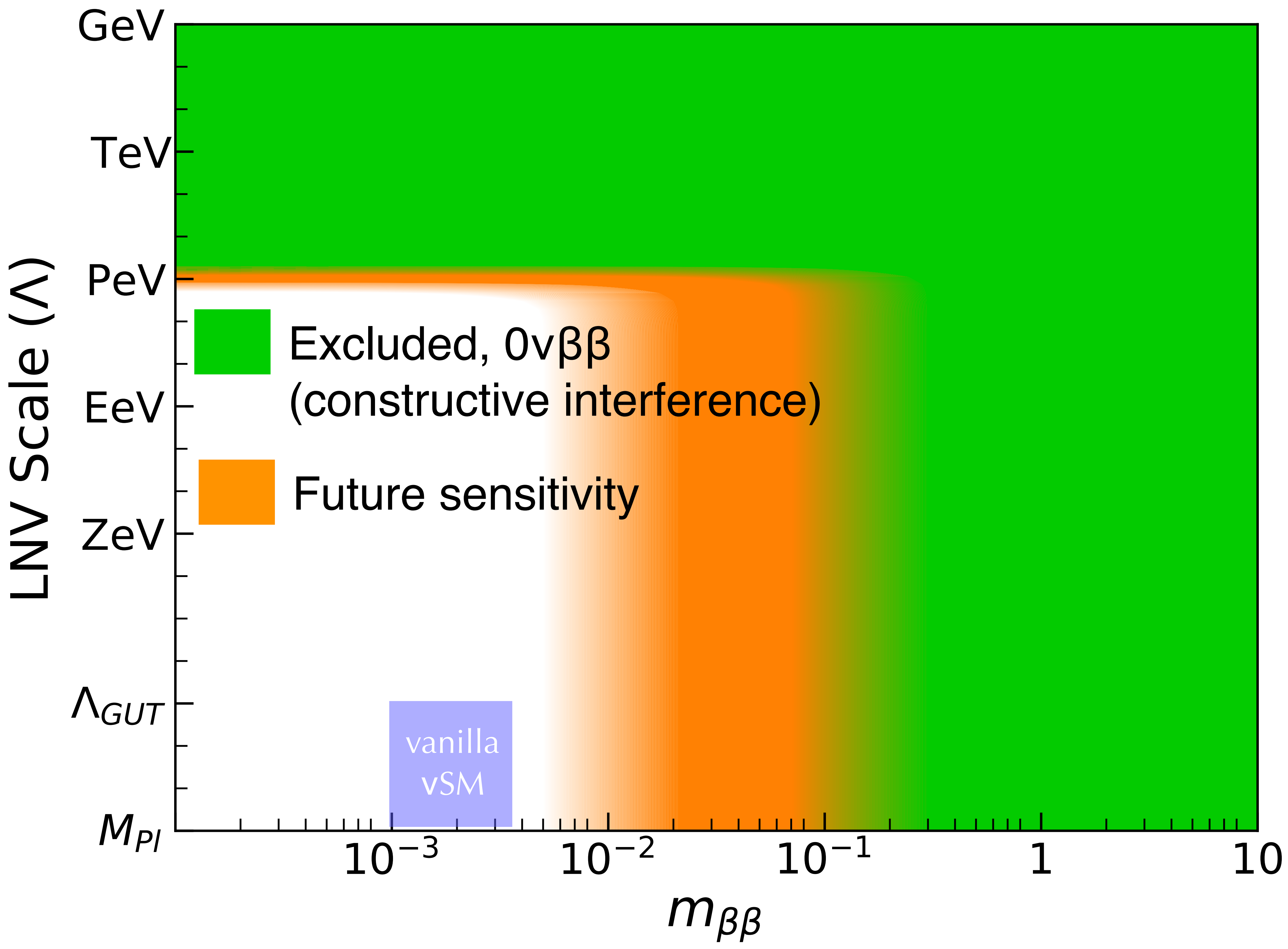

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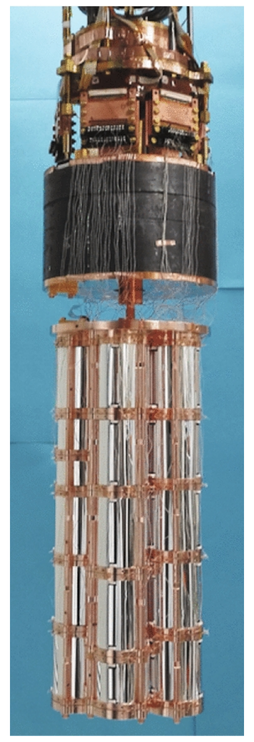
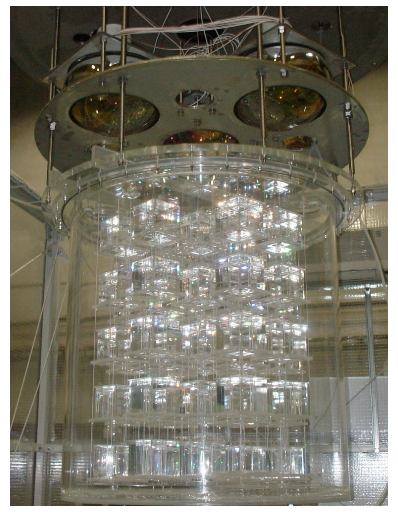
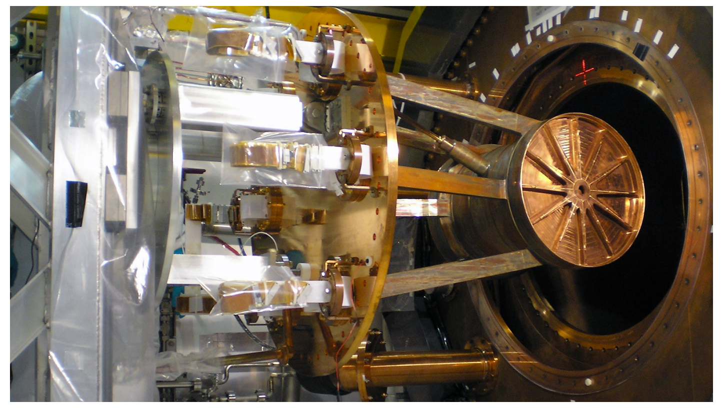
KamLAND-Zen

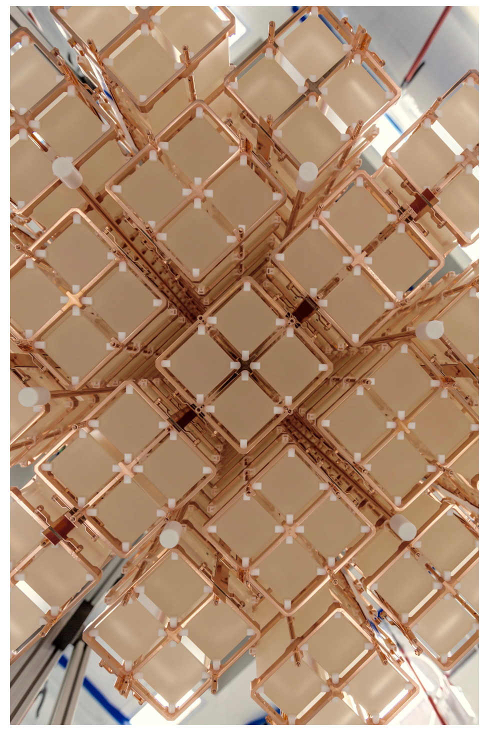

CUPID-0

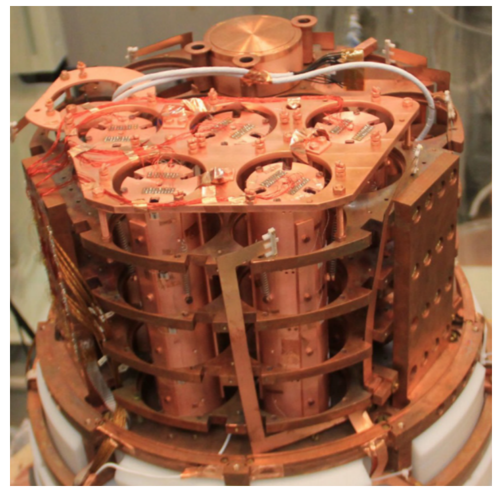

AMORE

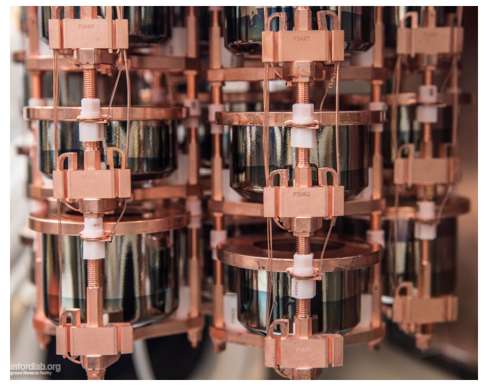

CANDLES

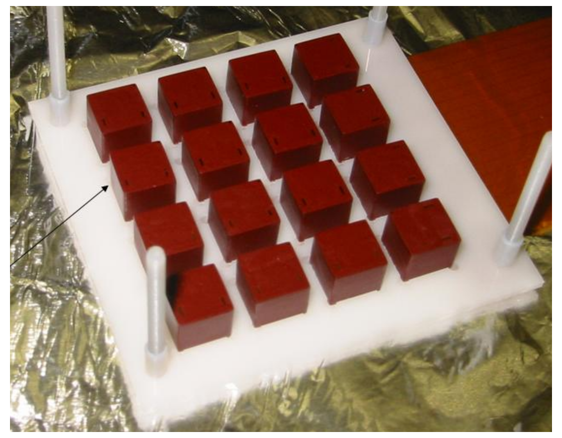

EXO-200


NEXT-100

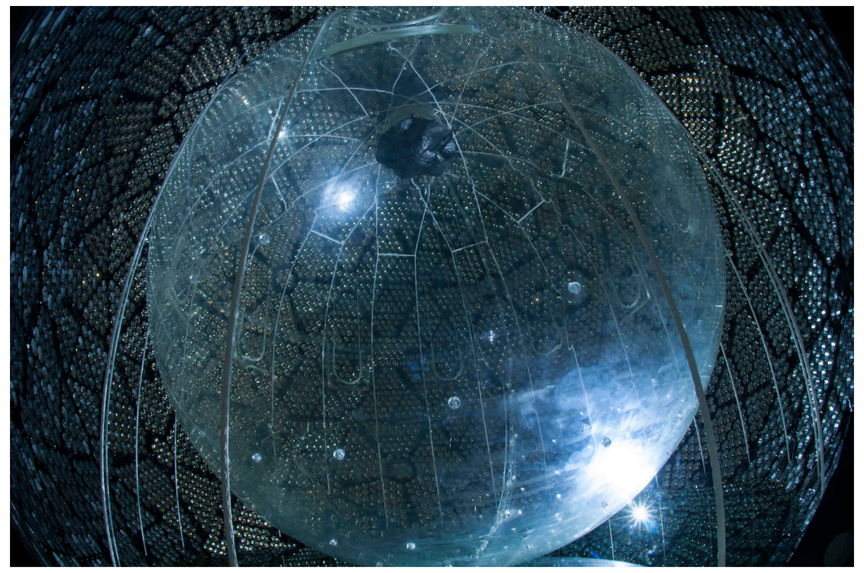

CUORE


CUPID-Mo

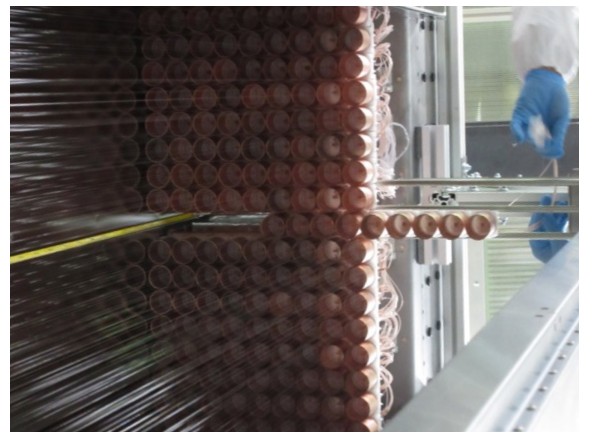

MAJORANA


COBRA


LEGEND-200


SNO+


GERDA

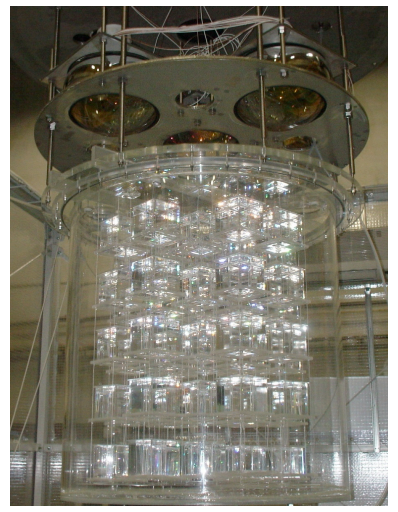

SuperNEMO

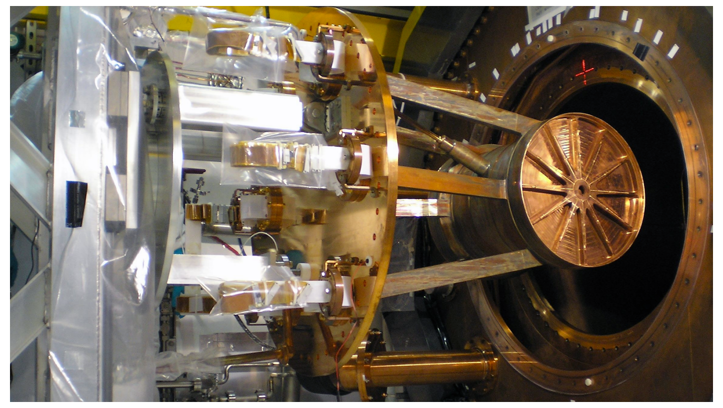

NEMO3

Experimental Techniques

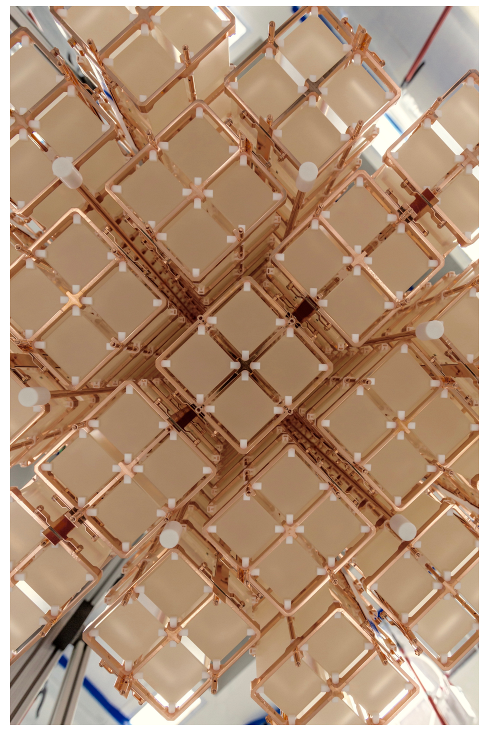
- Bolometers (CUORE/CUPID, AMoRE, CANDLES IV)
  - Measure *E* (σ ~ 0.1-0.3%) from phonons; granularity gives position info
  - Instrumenting with photon detectors for background rejection
- External trackers (NEMO3, SuperNEMO)
  - Trackers + calorimeters, measure *E* (σ ~ 3-10%) + tracks / positions + PID
- Scintillators (KamLAND-Zen, SNO+, CANDLES-III, Theia, ZICOS)
  - Measure *E* (σ ~ 3-10%) + position from scintillation light; some PID
- Semiconductors (COBRA, MAJORANA, GERDA, LEGEND)
  - Measure *E* (σ ~ 0.05-0.3%) from ionization; some tracking / position sensitivity
- TPCs (EXO, NEXT, PandaX, AXEL, NvDEx, DARWIN, LZ)
  - Collect scintillation + ionization: measure *E* (σ ~0.4-3%) + tracks / position + PID

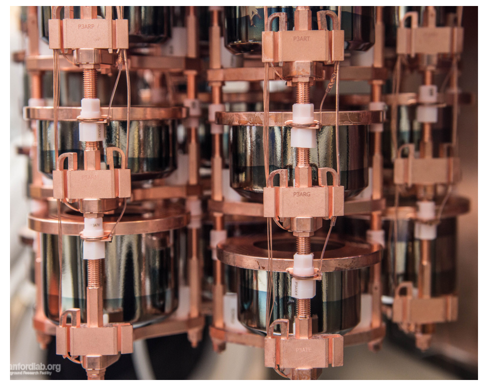

KamLAND-Zen

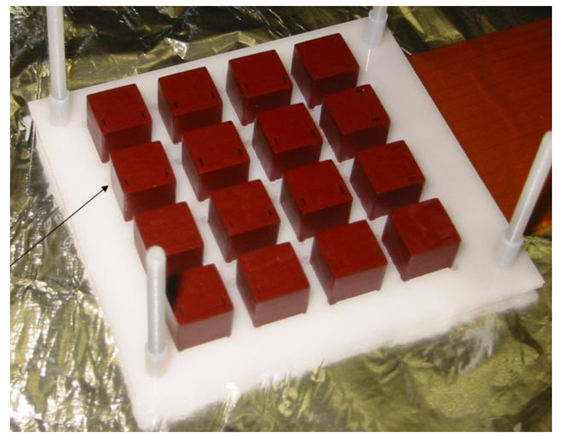

CANDLES

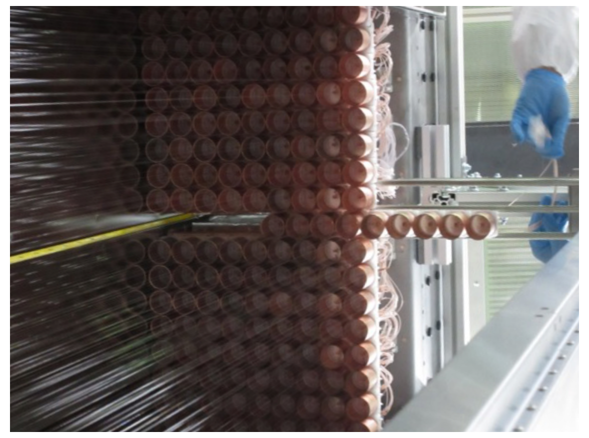

EXO-200


NEXT-100


CUORE


MAJORANA


COBRA


SuperNEMO


NEMO3

Experimental Focus: Discovery

- Energy is the only observable that is both necessary and sufficient for discovery of 0νββ decay: effectively a Poisson counting experiment

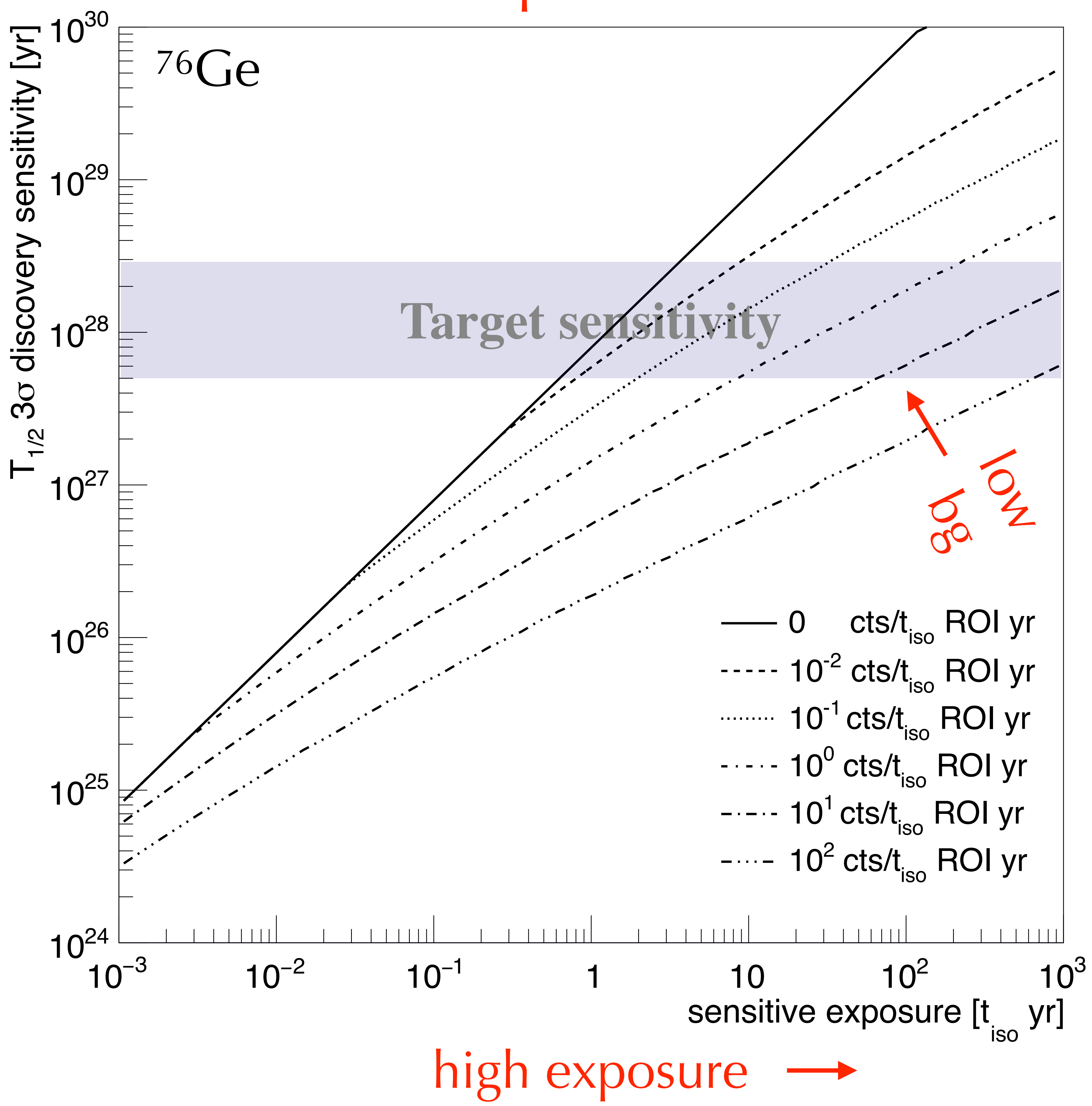
- Relevant parameters: sensitive exposure and sensitive background

$$\mathcal{E} = \epsilon \, m_{iso}^{FV} t \qquad \mathcal{B} = N_{bg}/\mathcal{E}$$

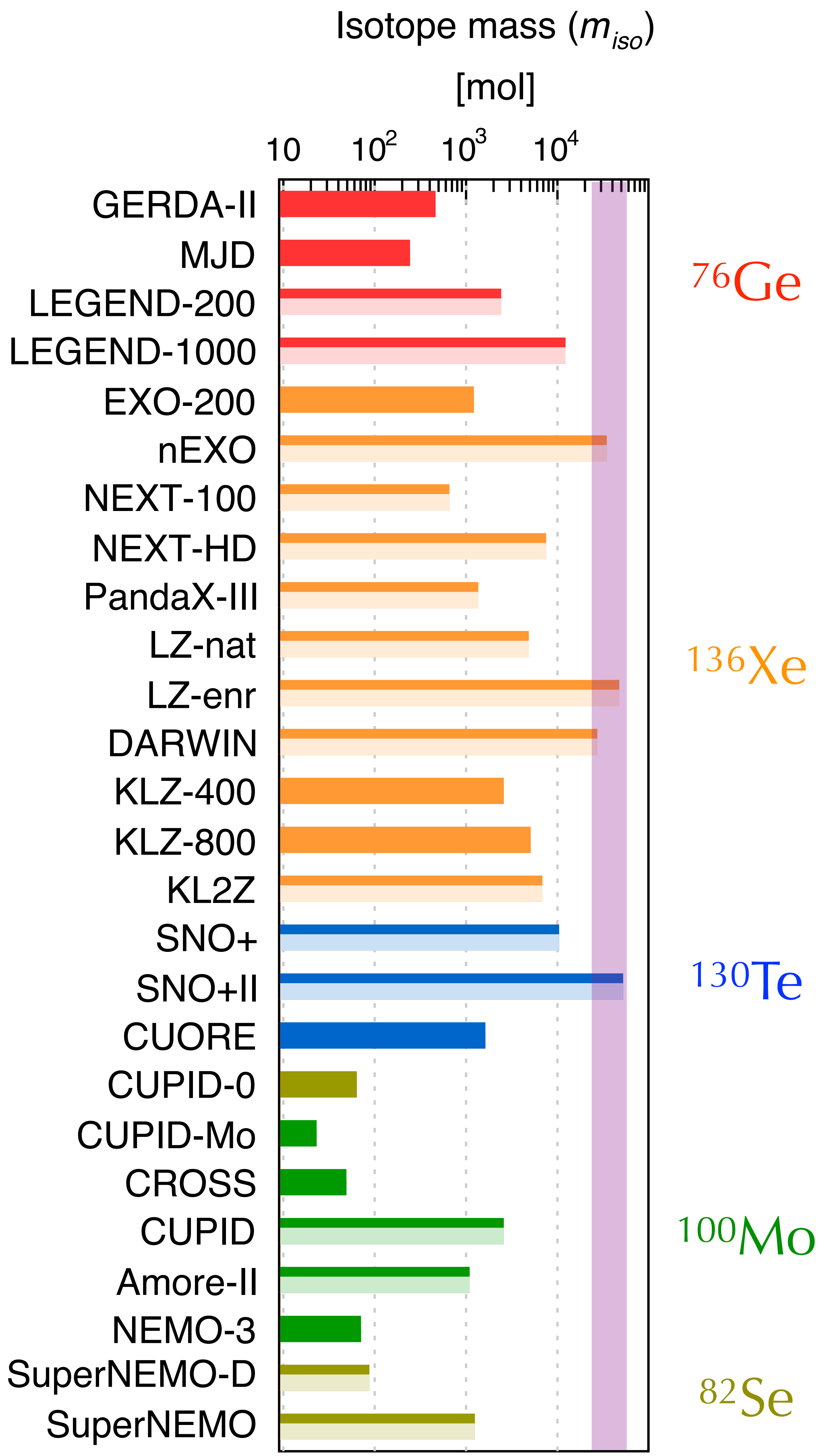
- Discovery sensitivity: the value of $T_{1/2}$ for which an experiment has a 50% chance to observe a signal above background with 3σ significance:

$$T_{1/2}^{3\sigma} = \ln 2 \frac{N_A \mathcal{E}}{m_a S_{3\sigma}(\mathcal{B}\mathcal{E})}$$

Requirements:



PRD **96**, 053001 (2017)



semiconductors

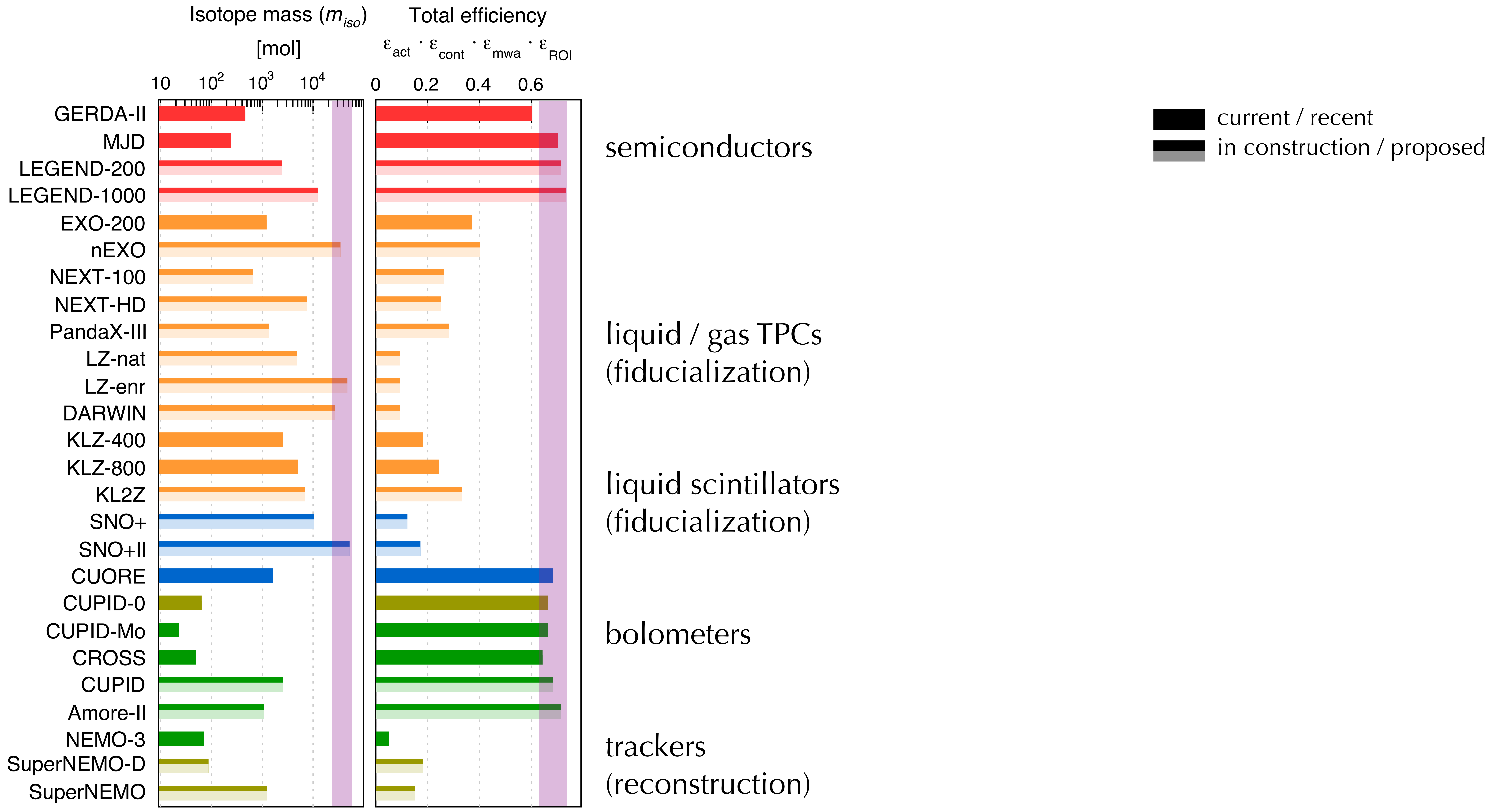
liquid / gas TPCs

liquid scintillators

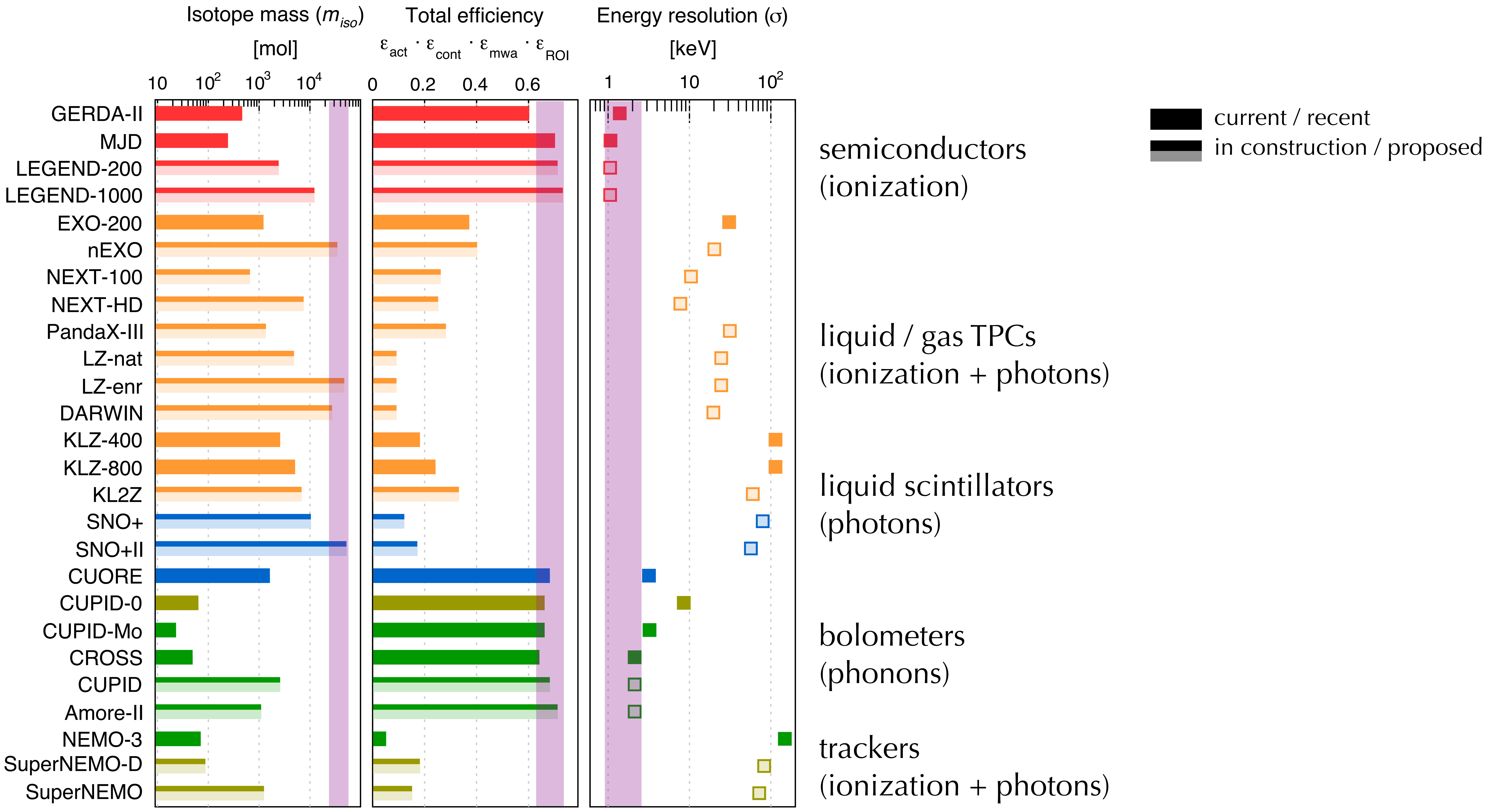
bolometers

trackers

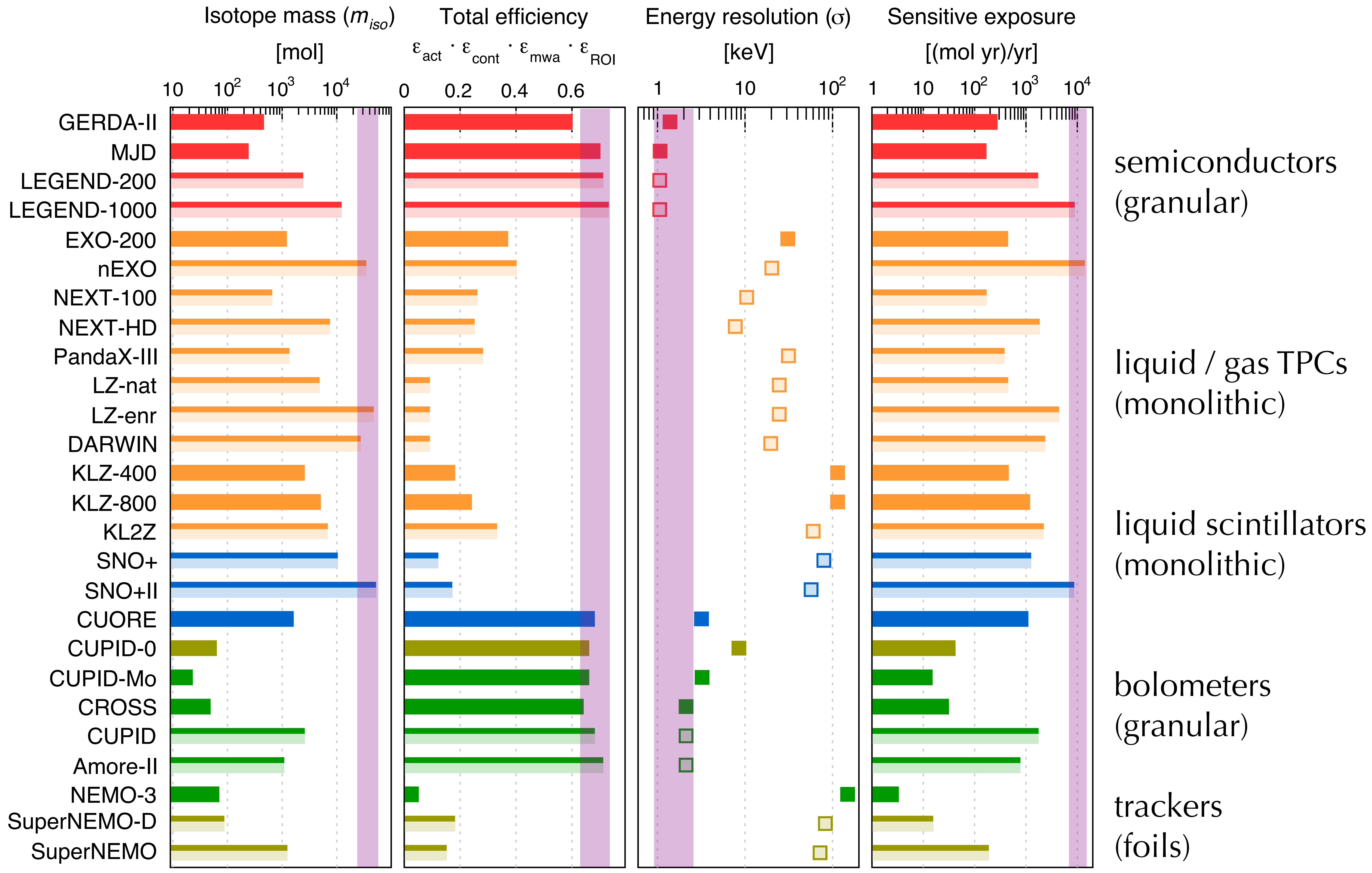
current / recent
in construction / proposed



Isotope mass (m_{iso}) [mol]
10
10^2
10^3
10^4
Total efficiency
$\varepsilon_{act} \cdot \varepsilon_{cont} \cdot \varepsilon_{mwa} \cdot \varepsilon_{ROI}$
0
0.2
0.4
0.6
GERDA-II
MJD
LEGEND-200
LEGEND-1000
EXO-200
nEXO
NEXT-100
NEXT-HD
PandaX-III
LZ-nat
LZ-enr
DARWIN
KLZ-400
KLZ-800
KL2Z
SNO+
SNO+II
CUORE
CUPID-0
CUPID-Mo
CROSS
CUPID
Amore-II
NEMO-3
SuperNEMO-D
SuperNEMO
semiconductors
liquid / gas TPCs
(fiducialization)
liquid scintillators
(fiducialization)
bolometers
trackers
(reconstruction)
current / recent
in construction / proposed



Isotope mass (m_{iso}) [mol]
10
10^2
10^3
10^4
Total efficiency
$\varepsilon_{act} \cdot \varepsilon_{cont} \cdot \varepsilon_{mwa} \cdot \varepsilon_{ROI}$
0
0.2
0.4
0.6
Energy resolution (σ) [keV]
1
10
10^2
GERDA-II
MJD
LEGEND-200
LEGEND-1000
EXO-200
nEXO
NEXT-100
NEXT-HD
PandaX-III
LZ-nat
LZ-enr
DARWIN
KLZ-400
KLZ-800
KL2Z
SNO+
SNO+II
CUORE
CUPID-0
CUPID-Mo
CROSS
CUPID
Amore-II
NEMO-3
SuperNEMO-D
SuperNEMO
current / recent
in construction / proposed
semiconductors
(ionization)
liquid / gas TPCs
(ionization + photons)
liquid scintillators
(photons)
bolometers
(phonons)
trackers
(ionization + photons)


Isotope mass (m_{iso}) [mol]
Total efficiency
$\varepsilon_{act} \cdot \varepsilon_{cont} \cdot \varepsilon_{mwa} \cdot \varepsilon_{ROI}$
Energy resolution (σ) [keV]
Sensitive exposure [(mol yr)/yr]
10
10^2
10^3
10^4
0
0.2
0.4
0.6
1
10
10^2
1
10
10^2
10^3
10^4
GERDA-II
MJD
LEGEND-200
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EXO-200
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CUORE
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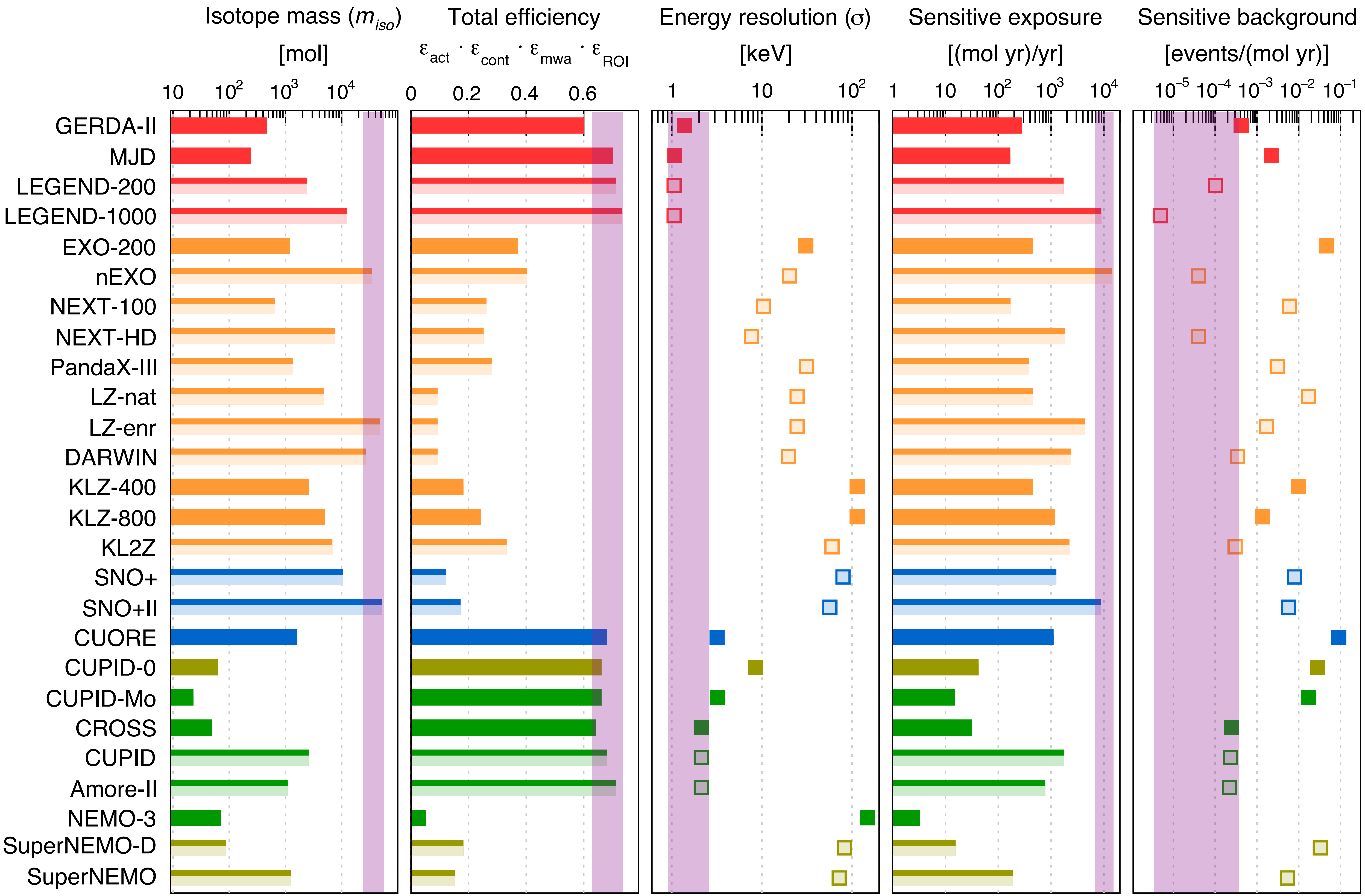
semiconductors
(granular)
liquid / gas TPCs
(monolithic)
liquid scintillators
(monolithic)
bolometers
(granular)
trackers
(foils)



Isotope mass (m_{iso}) [mol]
Total efficiency $\varepsilon_{act} \cdot \varepsilon_{cont} \cdot \varepsilon_{mwa} \cdot \varepsilon_{ROI}$
Energy resolution (σ) [keV]
Sensitive exposure [(mol yr)/yr]
Sensitive background [events/(mol yr)]
10 10^2 10^3 10^4
0 0.2 0.4 0.6
1 10 10^2
1 10 10^2 10^3 10^4
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1}
GERDA-II
MJD
LEGEND-200
LEGEND-1000
EXO-200
nEXO
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SNO+
SNO+II
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CUPID-Mo
CROSS
CUPID
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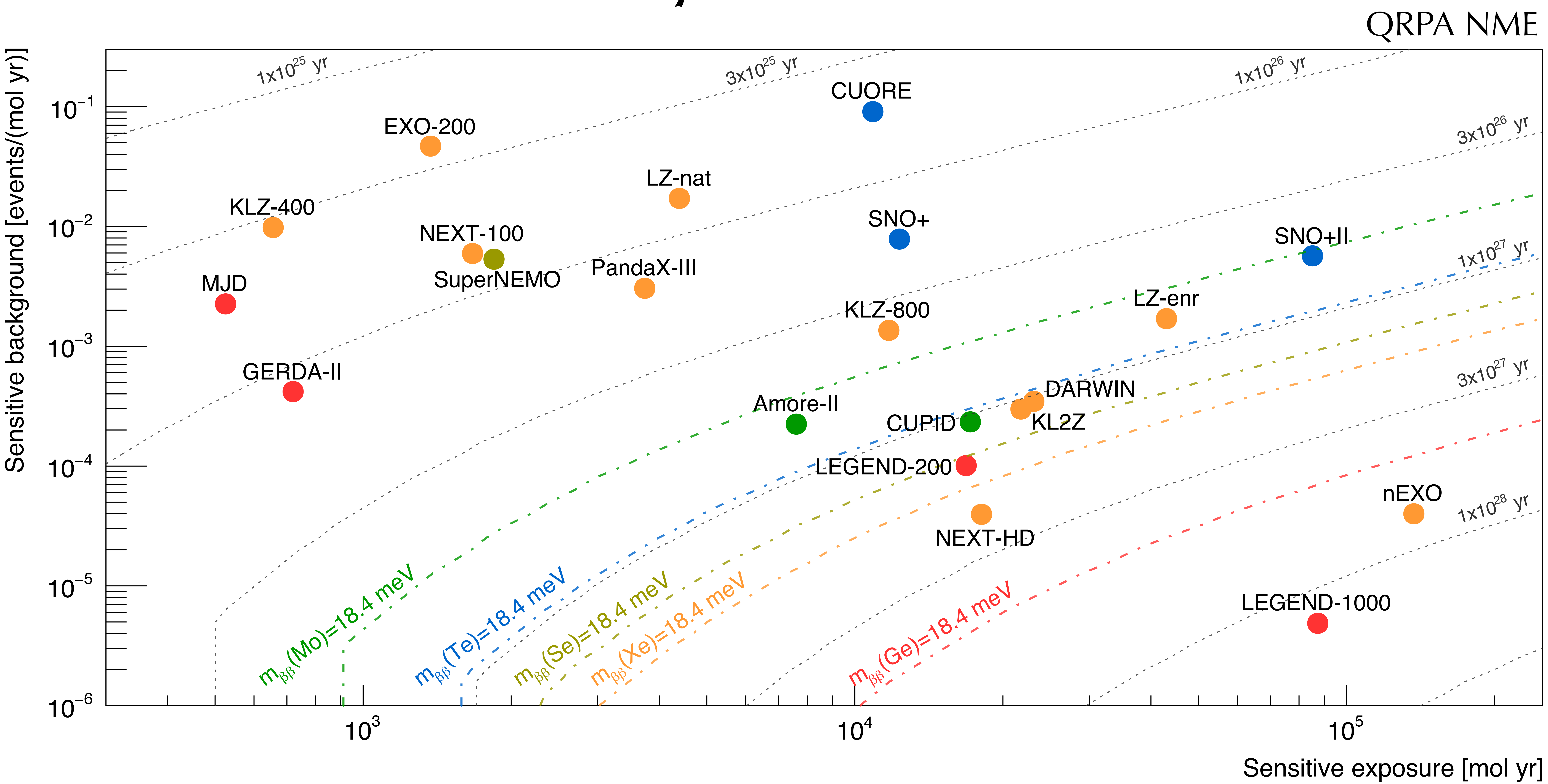
NEMO-3
SuperNEMO-D
SuperNEMO

Discovery Sensitivities



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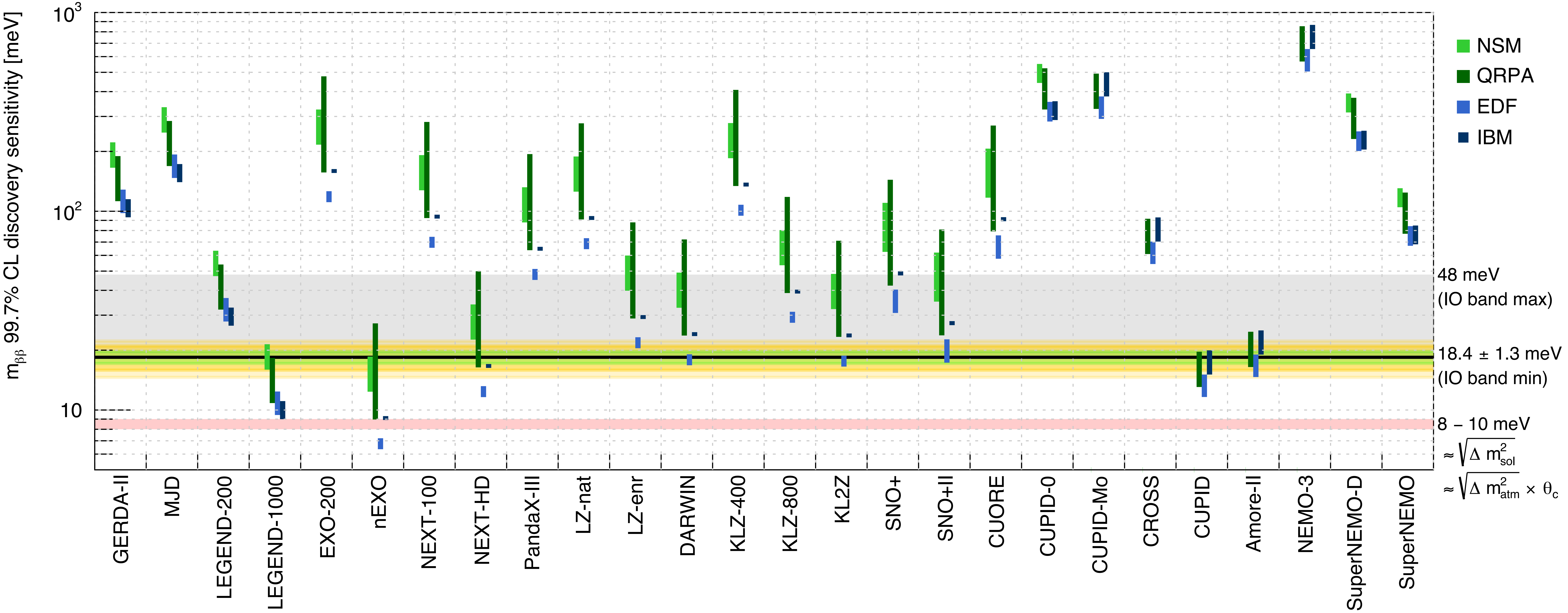

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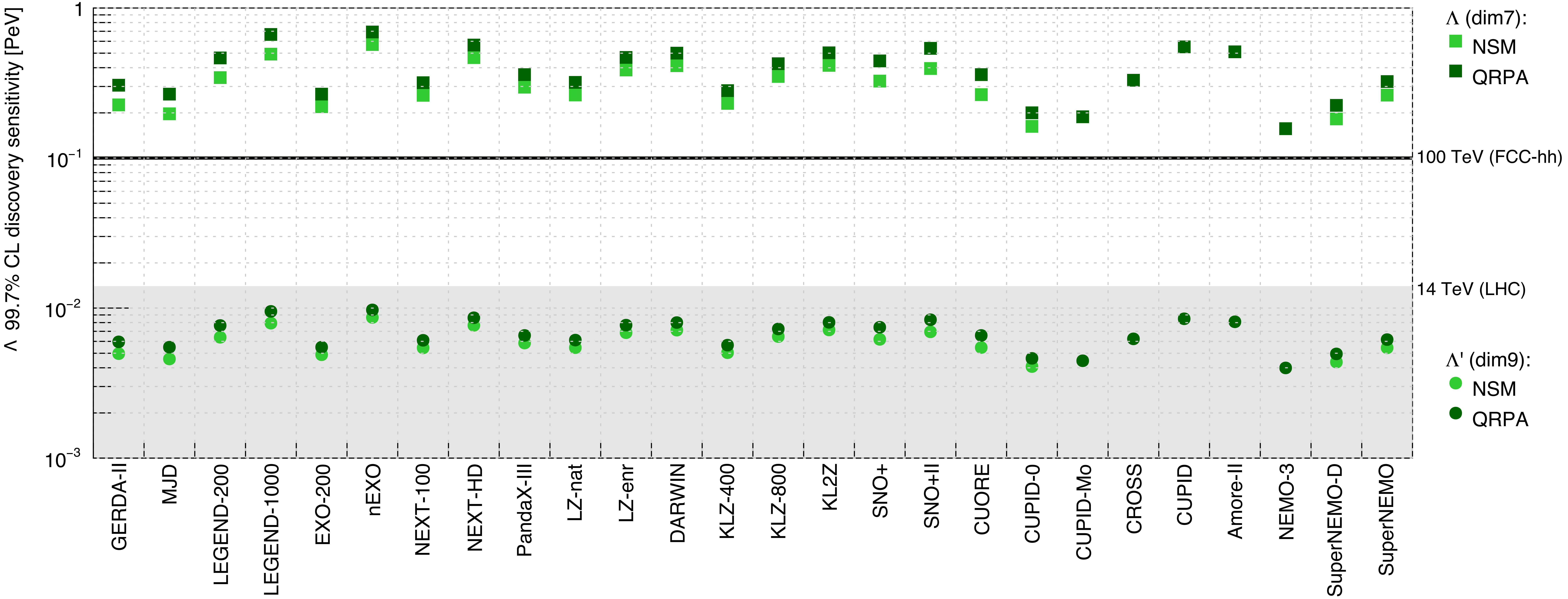
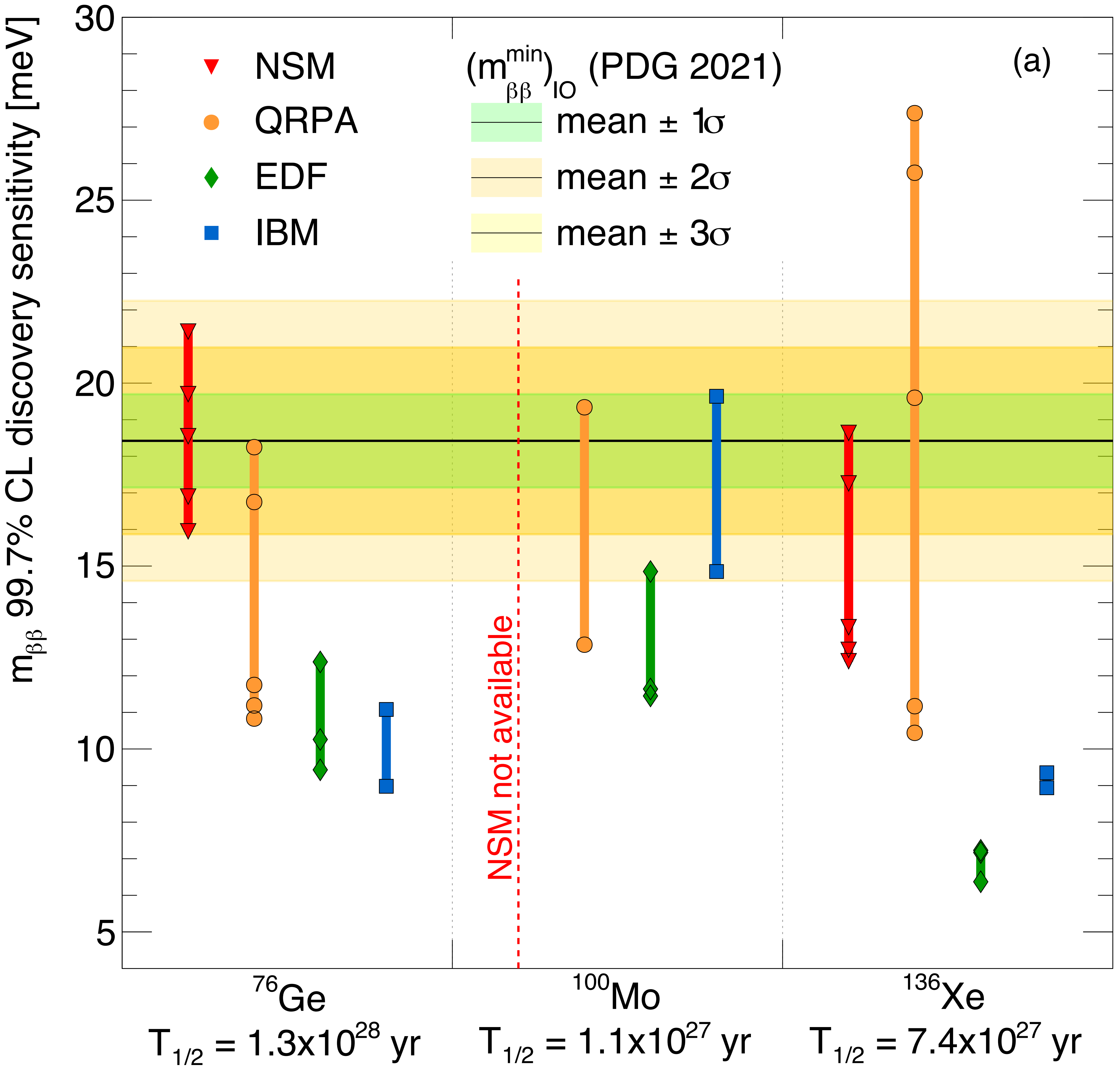


Next-Generation Reach

- Next generation experiments seem poised to reach the IO minimum:
  - for most NME calculations
  - in multiple isotopes
  - With very different experimental techniques
- Some NME reach deep into the NO region
- Experiments are being designed with upgrade capability to push even further into the NO



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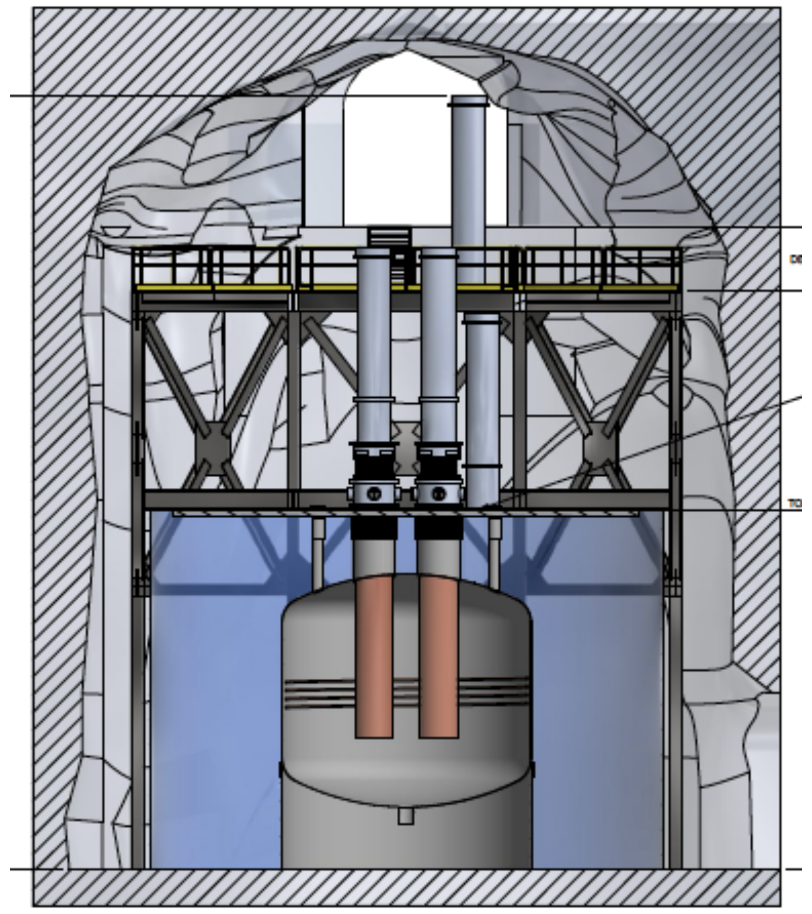
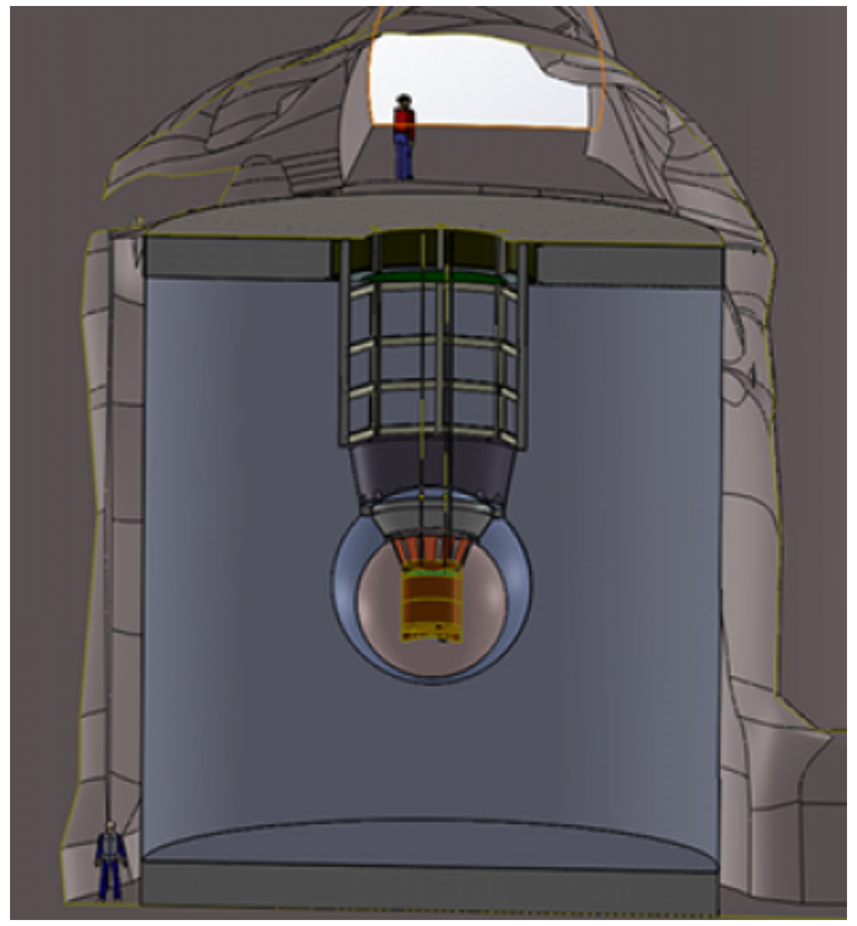
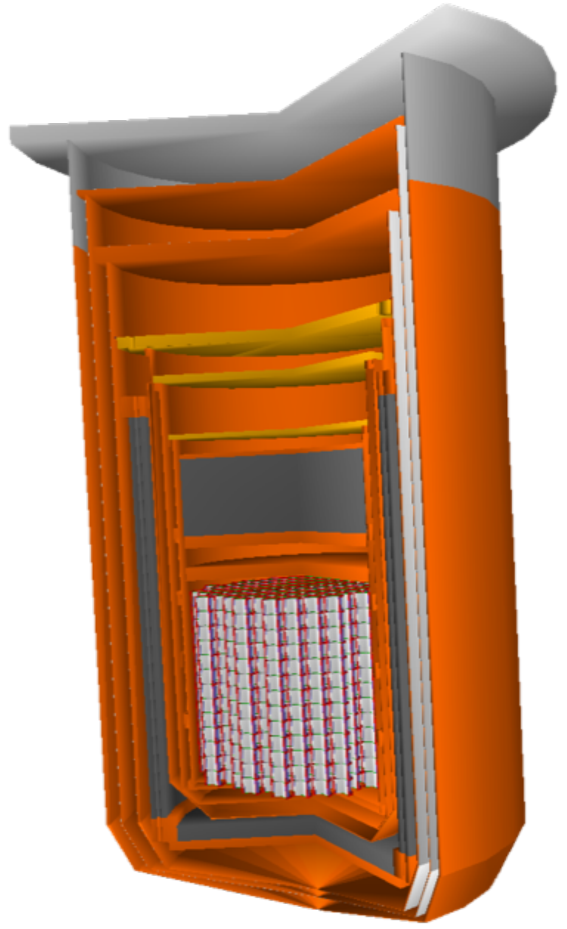


LEGEND



nEXO



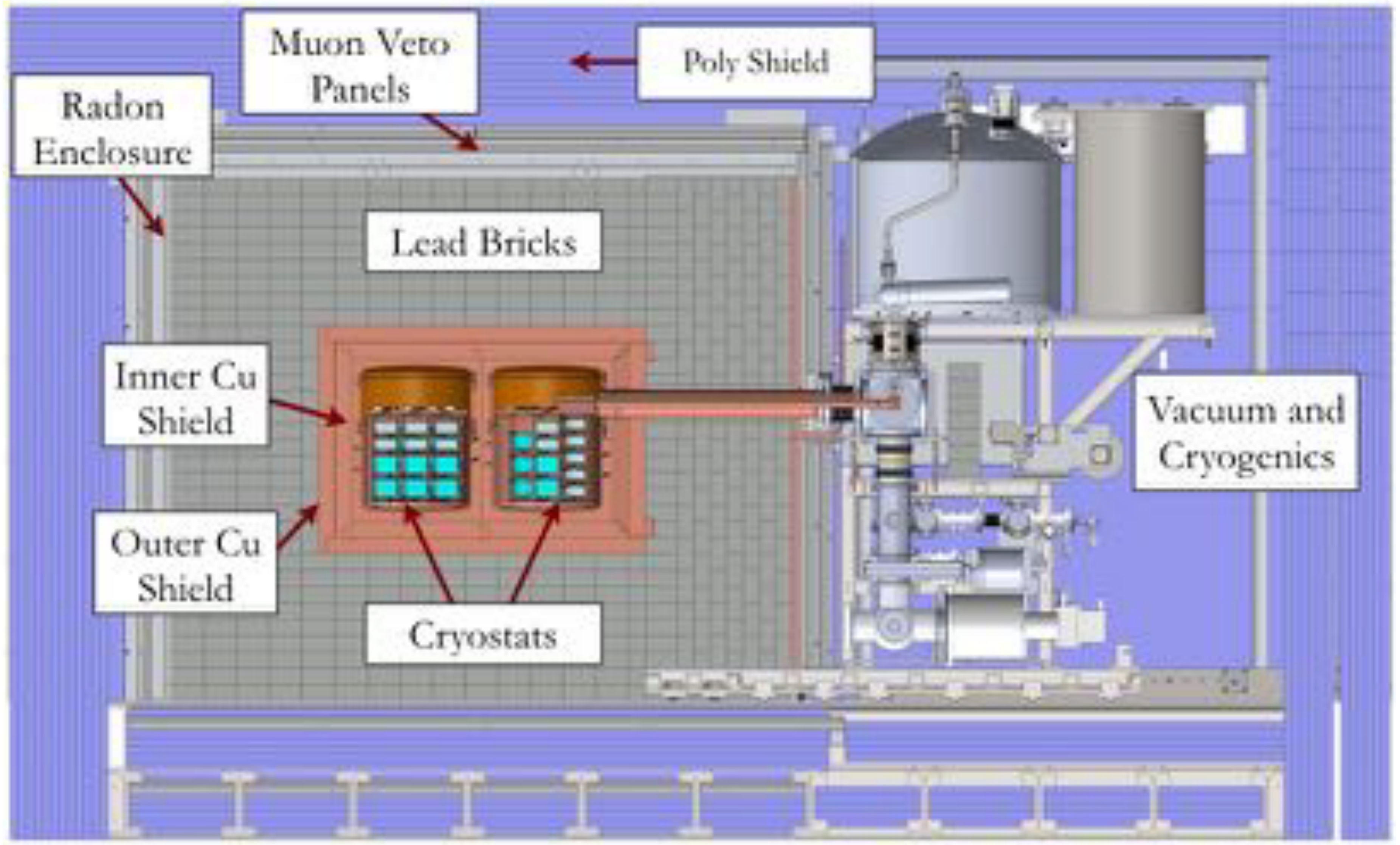
CUPID

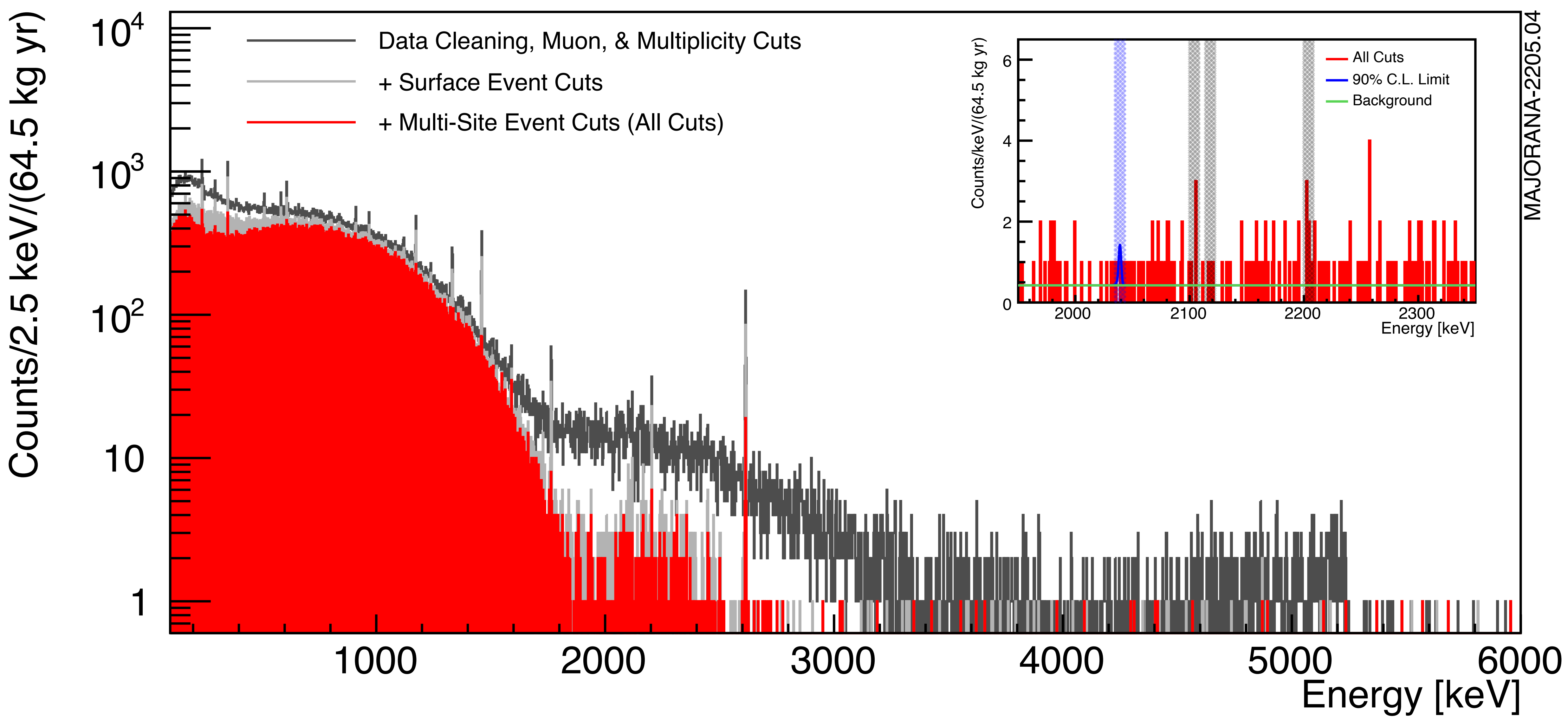
US DBD Community

- Majorana / LEGEND
- EXO-200 / nEXO
- CUORE / CUPID
- Also: KamLAND-Zen, SNO+, NEXT, SuperNEMO, Theia…
- Funded primarily by DOE Office of Nuclear Physics, and also the NSF

MAJORANA

- 30 kg of 87% enriched HPGe crystals deployed in electroformed Cu cryostats in a passive Cu and Pb shield at SURF (Lead, SD)
- Best FWHM at $Q_{\beta\beta}$: 2.5 keV at 2039 keV
- 2nd-lowest background rate at $Q_{\beta\beta}$: 16 cts/(FWHM t yr), dominated by Th
- Collected 65 kg-years, final results presented at Neutrino 2022: $T_{1/2} > 8.3 \times 10^{25}$ yr

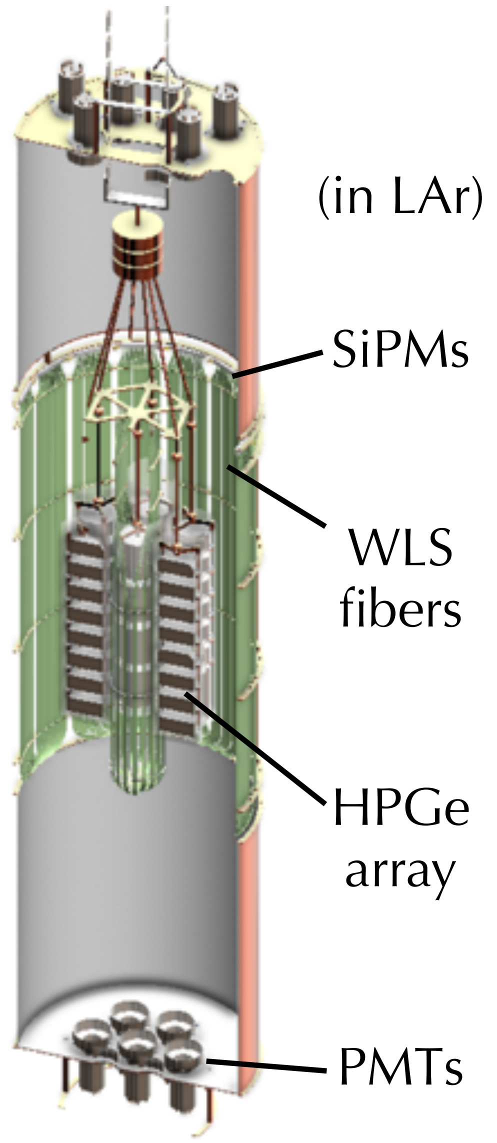


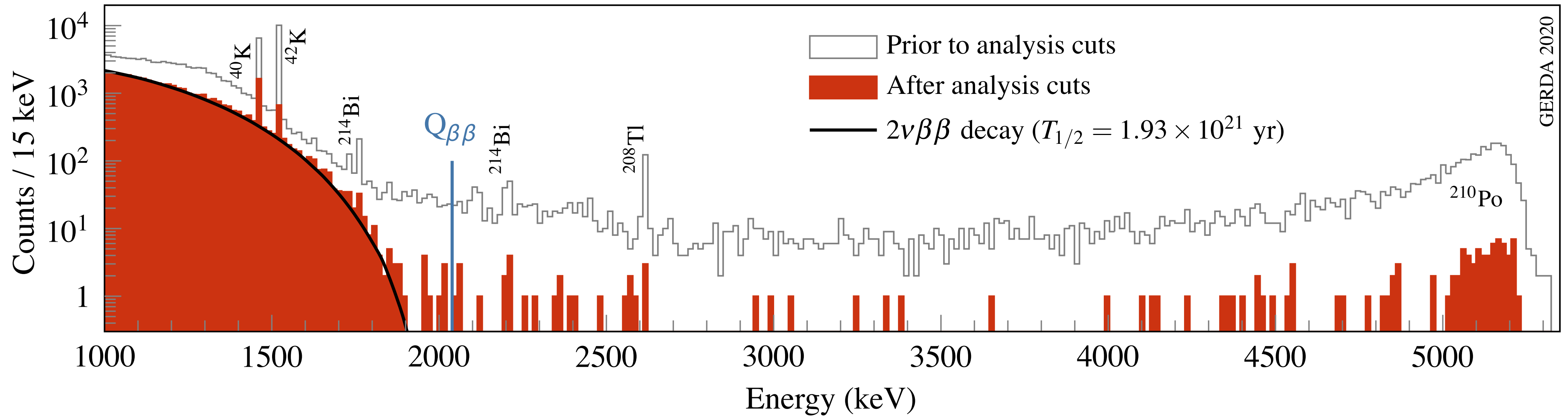


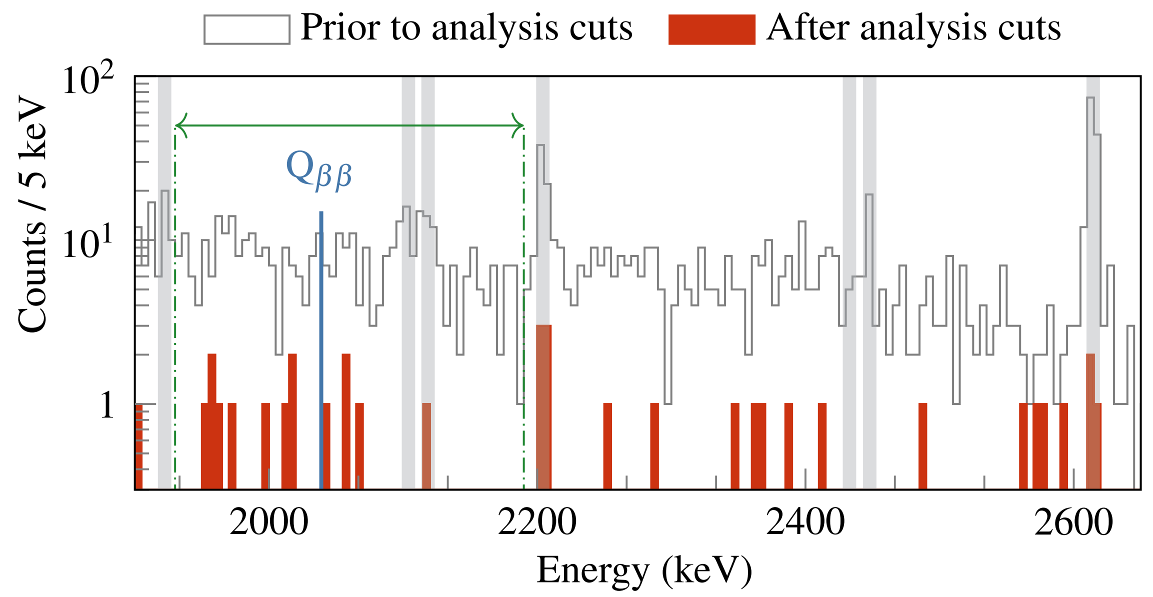
Gruszko, Neutrino 2022

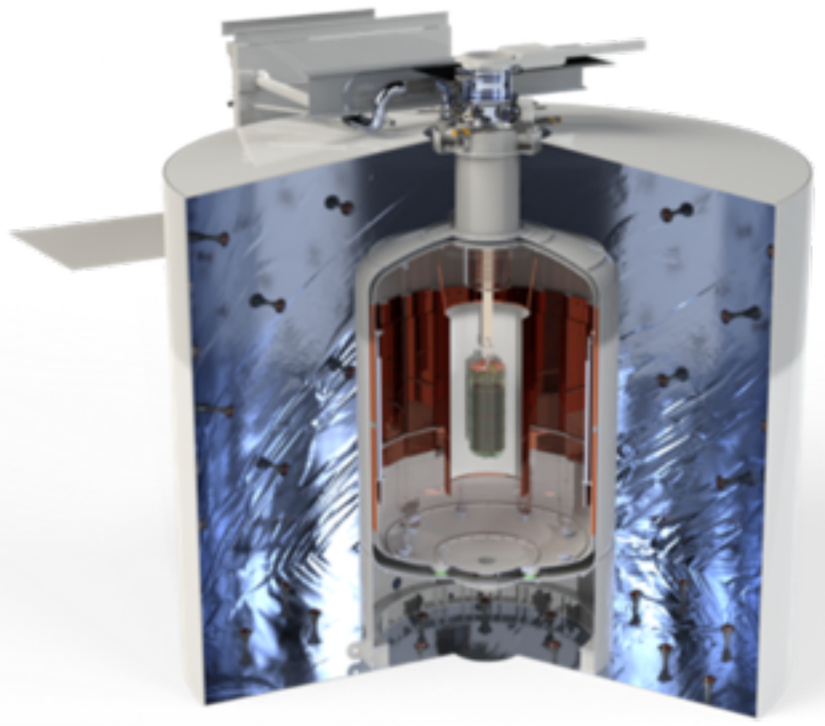
GERDA and LEGEND-200

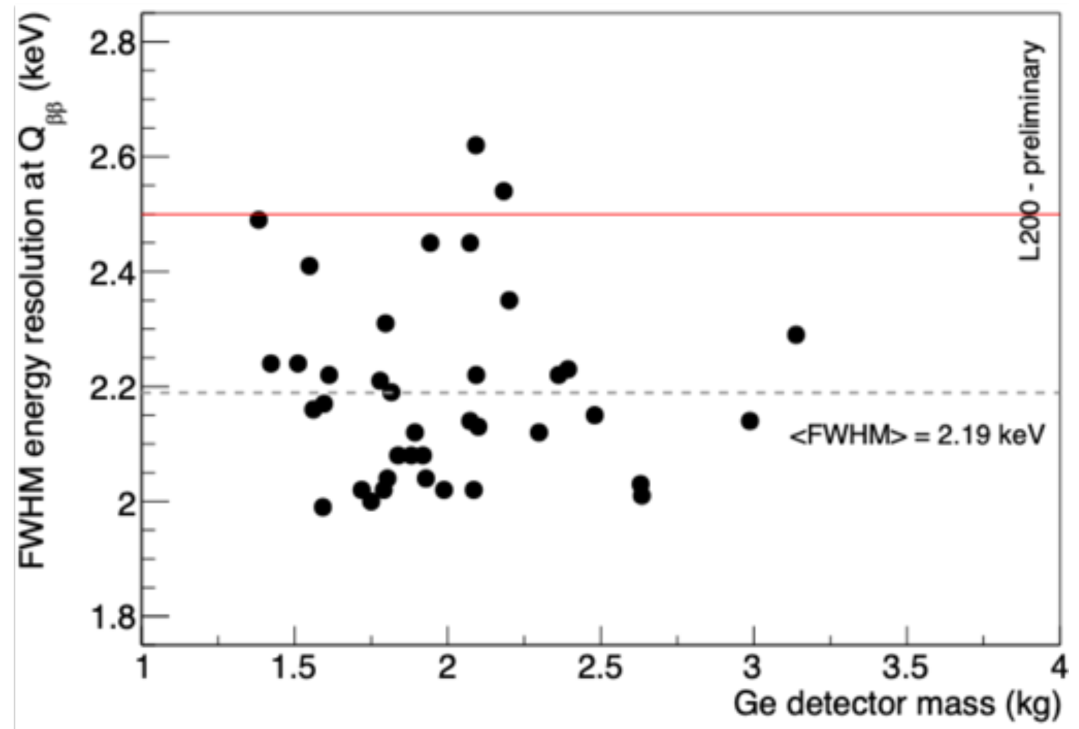
- GERDA
  - 34 kg of 87% enr HPGe detectors immersed in LAr with SiPM+WLS readout at LNGS (Italy)
  - 100 kg yr exposure with lowest background at $Q_{\beta\beta}$: ~1.5 cts/(FWHM t yr)
  - Final result: $T_{1/2}$ > 1.8 x 10^{26} yr
- LEGEND-200
  - 200 kg enr HPGe detectors (including GERDA's and MAJORANA's) in upgraded GERDA LAr cryostat with MAJORANA materials and electronics
  - Background goal: factor ~3 improvement over GERDA
  - Discovery sensitivity (5 yr): $T_{1/2}$ > 10^{27} yr
  - Currently in commissioning at LNGS, data taking commencing soon









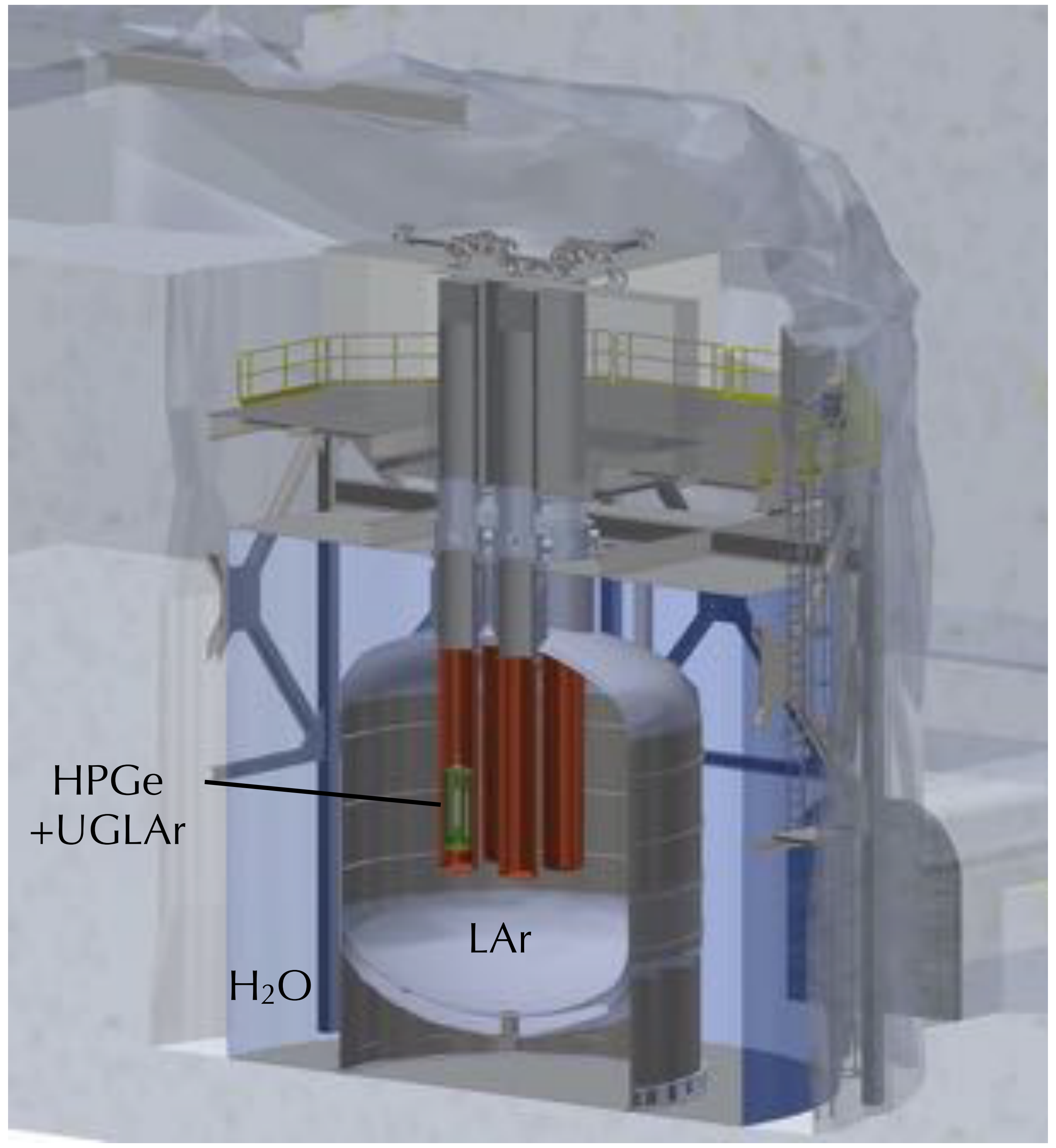


PRL **125**, 252502 (2020); Gruszko, Neutrino 2022

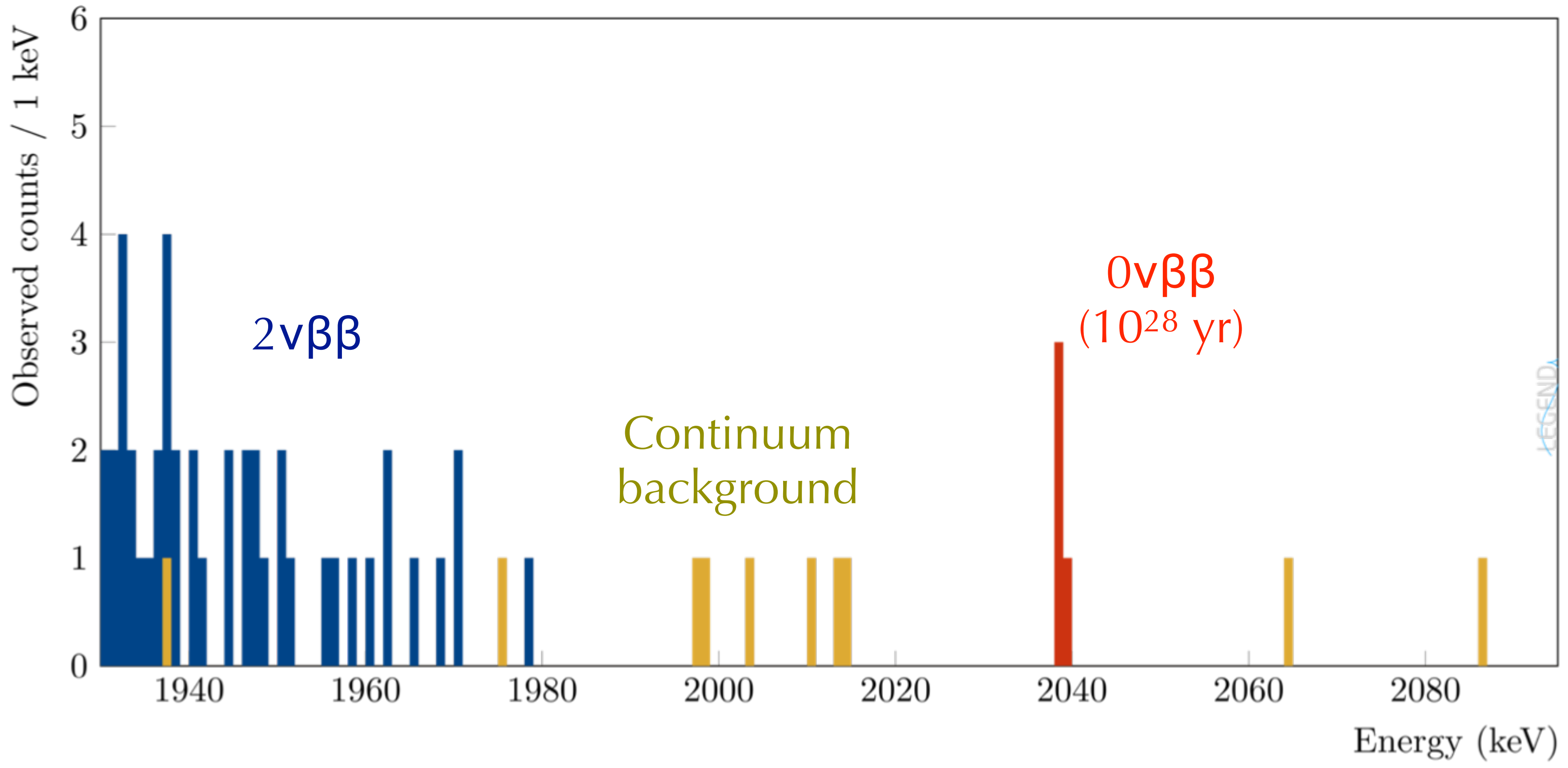
LEGEND-1000

- 1 ton array of 90% enr HPGe crystals in LAr, location TBD (SNOLAB, LNGS)
  - Larger 3+ kg crystals with ASIC readout
  - Underground LAr in immediate vicinity of HPGe arrays to remove ^{42}K background
  - Improved SiPM + WLS fiber based readout
- Background dominated by ^{42}K, goal: <0.025 cts/(FWHM t yr)
- Discovery sensitivity (10 yr): $T_{1/2} > 10^{28}$ yr

LEGEND-1000 Concept



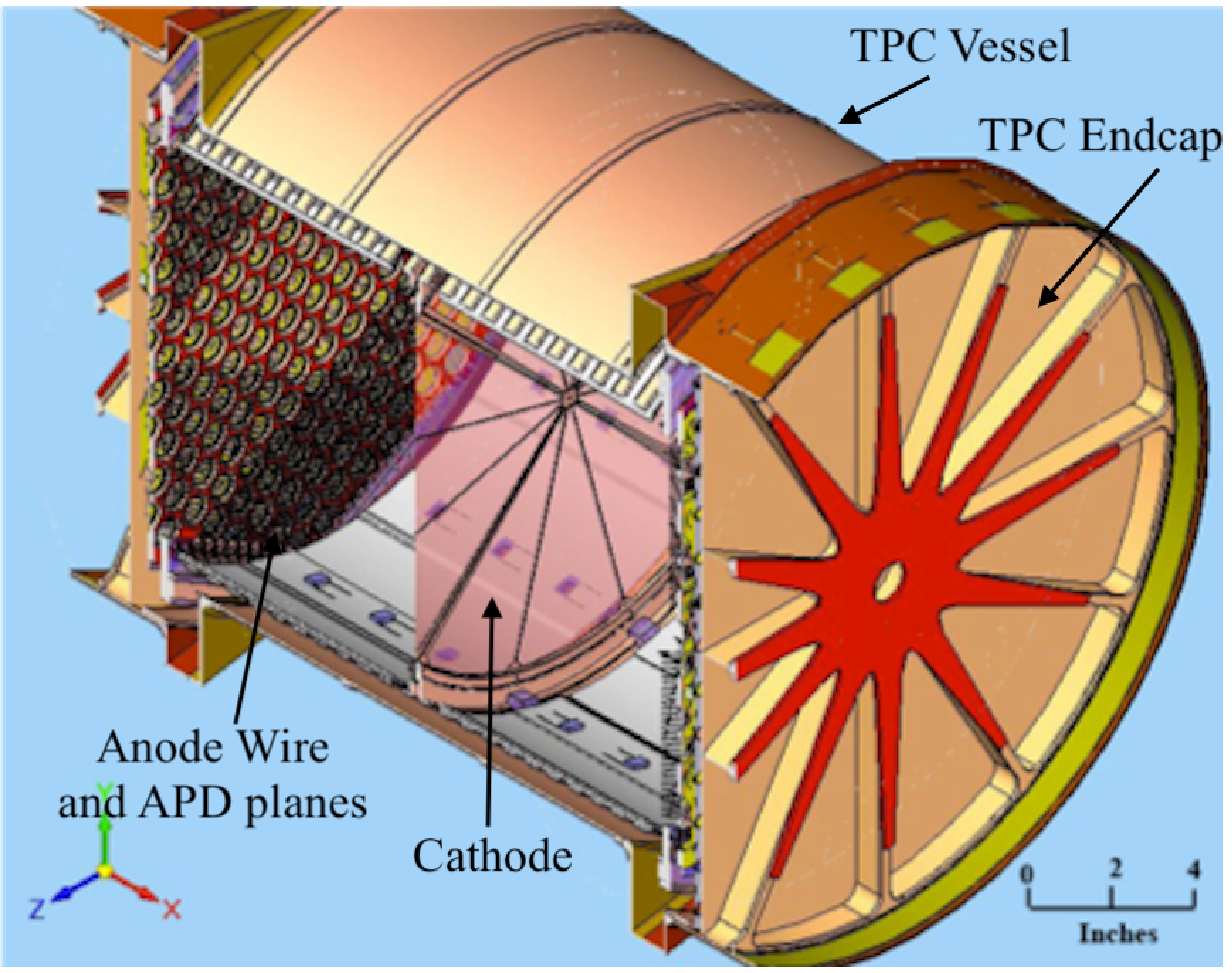
Simulated 10 t y LEGEND-1000 spectrum for $T_{1/2} = 10^{28}$ yr

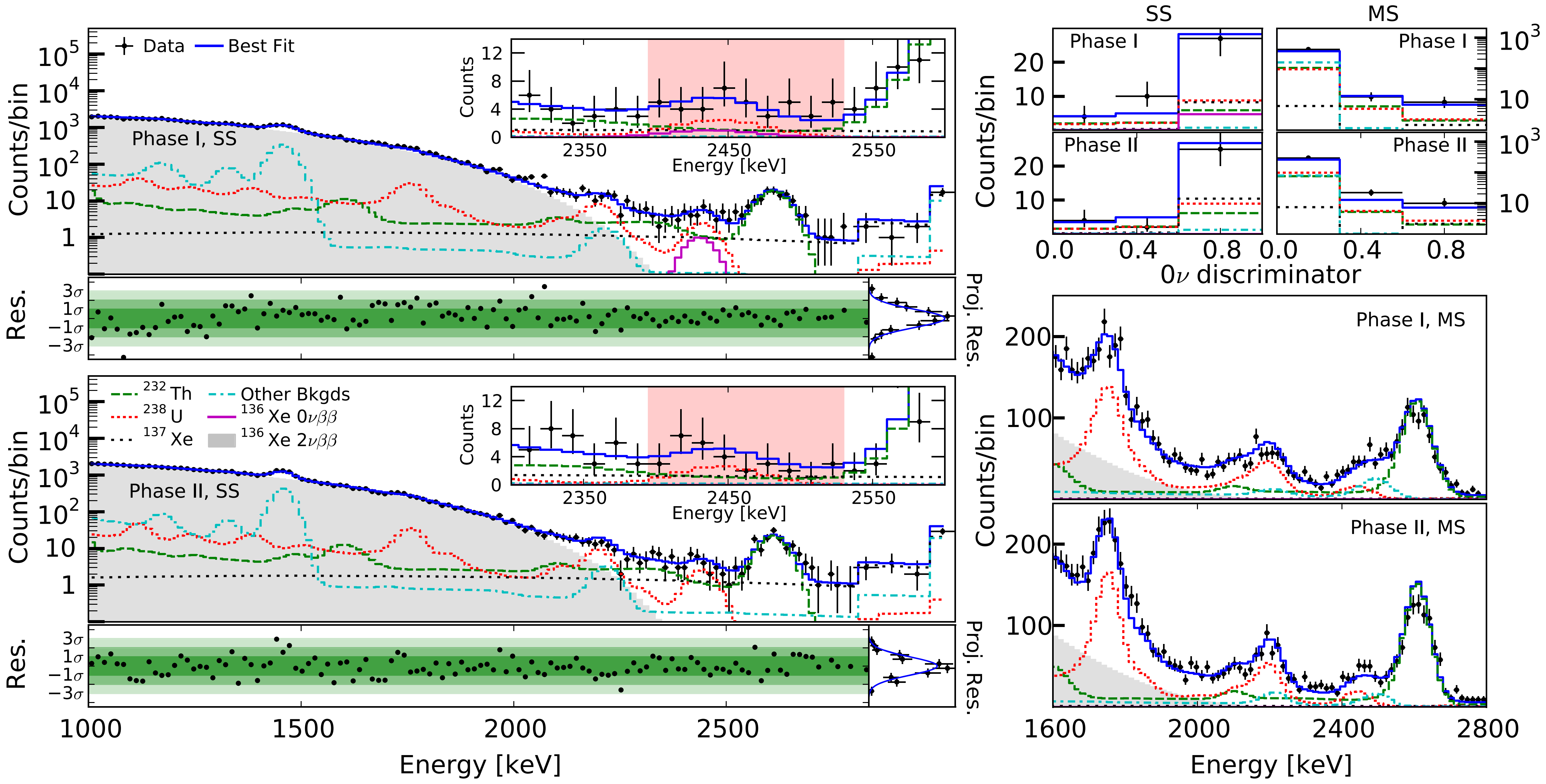


arXiv: 2107.11462, Gruszko, Neutrino 2022

EXO-200

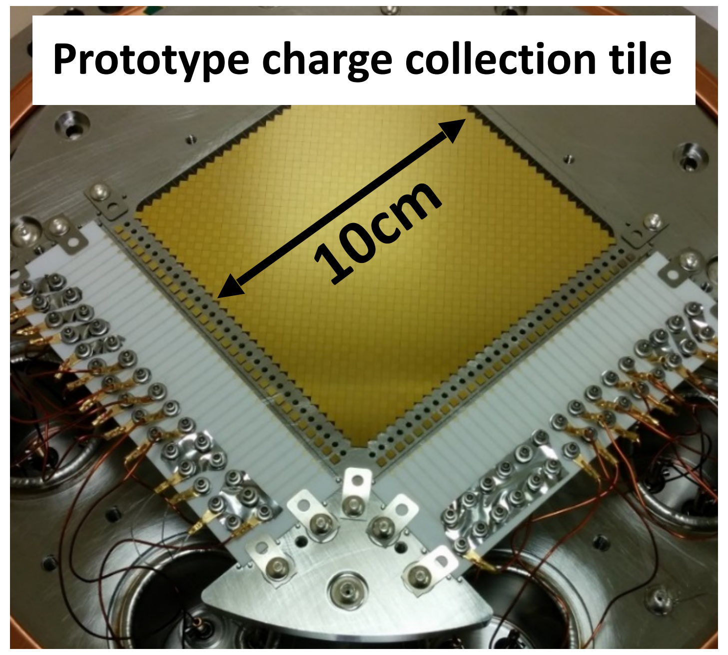
- 161 kg of 90% enr ^{136}Xe in LXe TPC at WIPP (Carlsbad, NM)
  - Ionization and scintillation both contribute to *E* reconstruction
  - Also: tracking / topology / position reconstruction
- Background rate at $Q_{\beta\beta}$, averaged over FV: 120 cts/(FWHM t yr), dominated by ^{214}Bi line
- Final result for 230 kg yr exposure: $T_{1/2}$ > 3.5 x 10^{25} yr

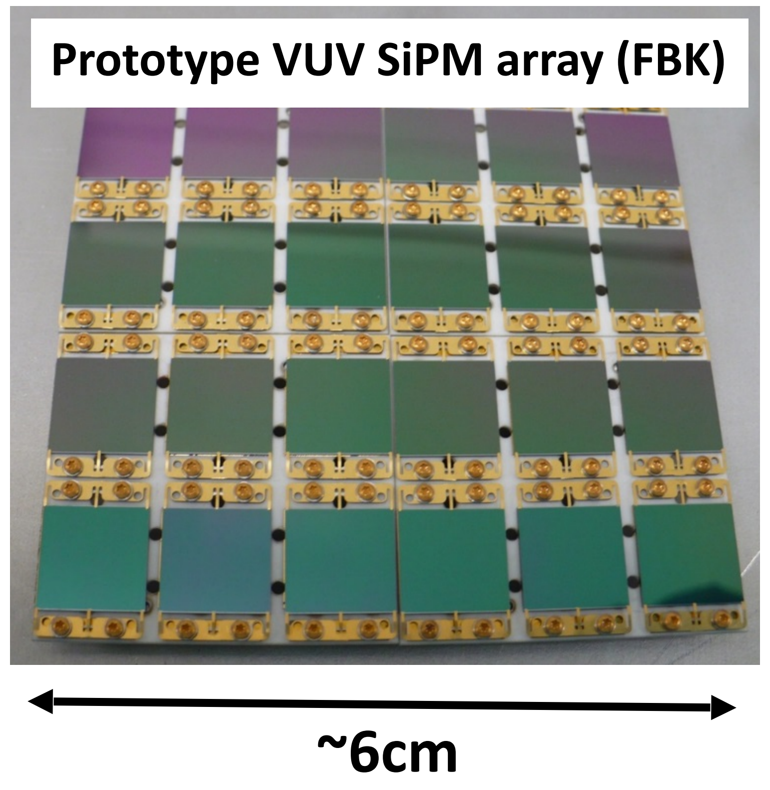


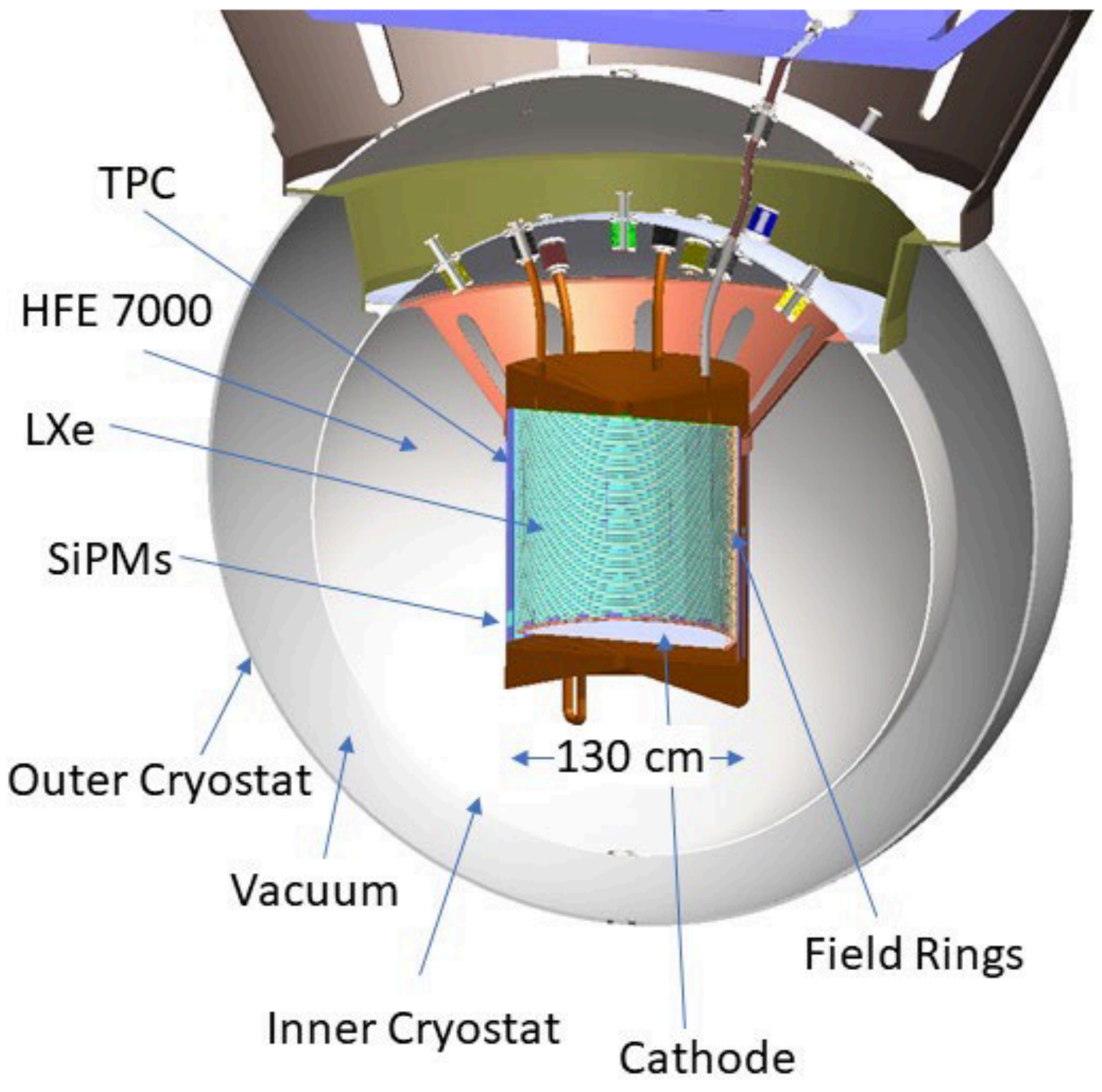


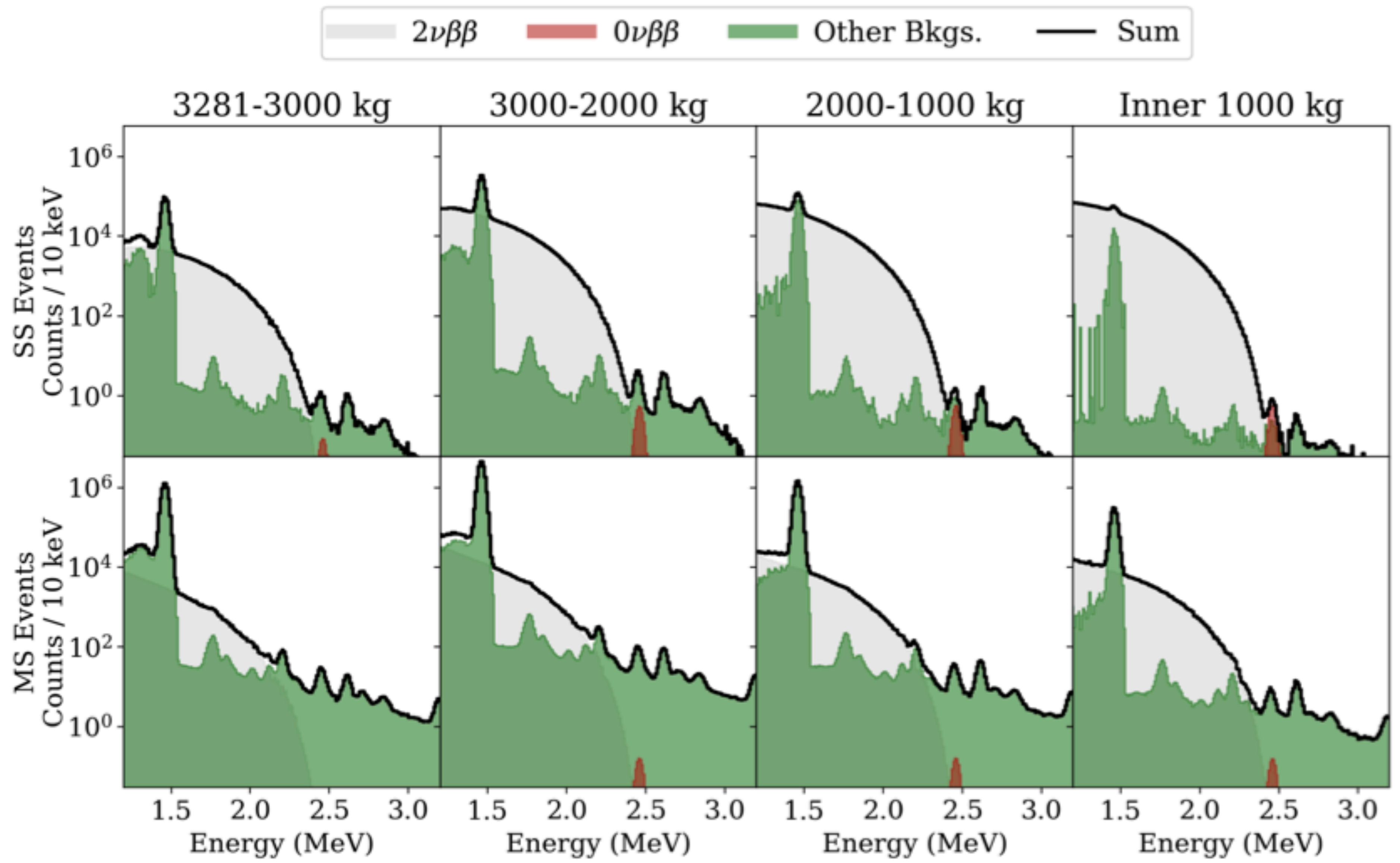
nEXO

- 5 tons of 90% enr ^{136}Xe in LXe TPC at SNOLAB
- Upgrade of EXO-200 design
  - Improved light and charge collection
  - Self-shielding, only one drift volume
  - R&D for Ba tagging
- Background goal: ~0.07 cts/(FWHM t y) in sensitive region, dominated by natural radioactivity
- Discovery sensitivity (10 yr): $T_{1/2}$ > 7.5 x 10^{27} yr





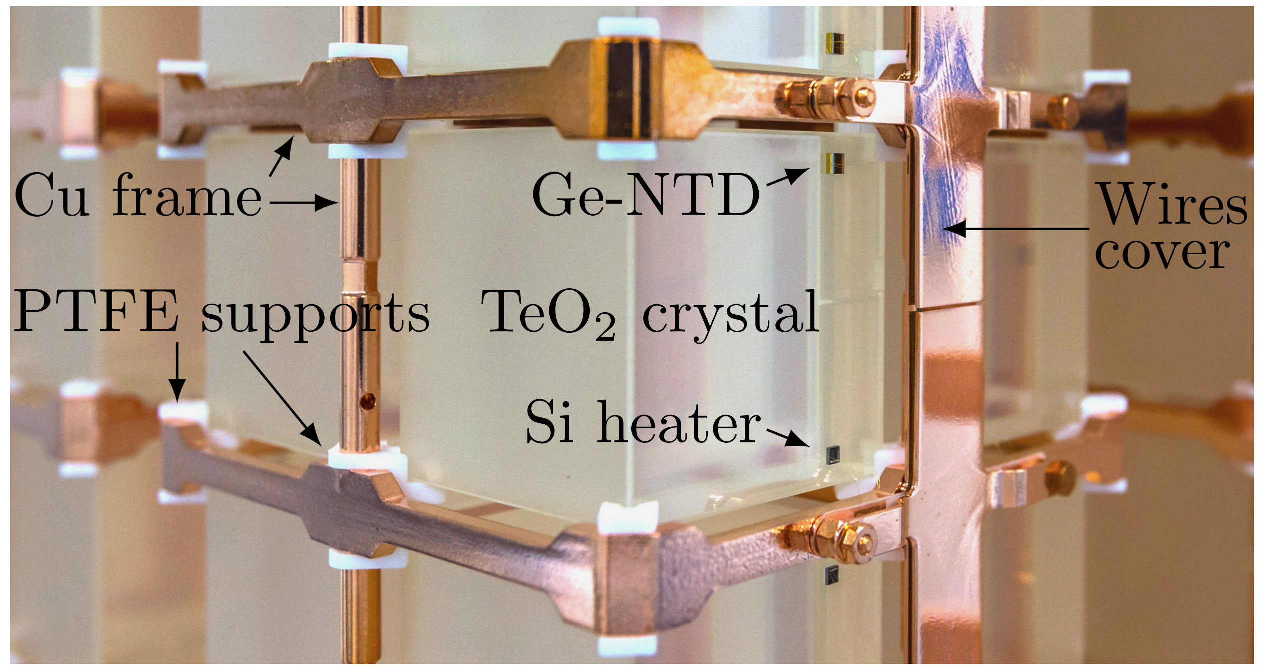


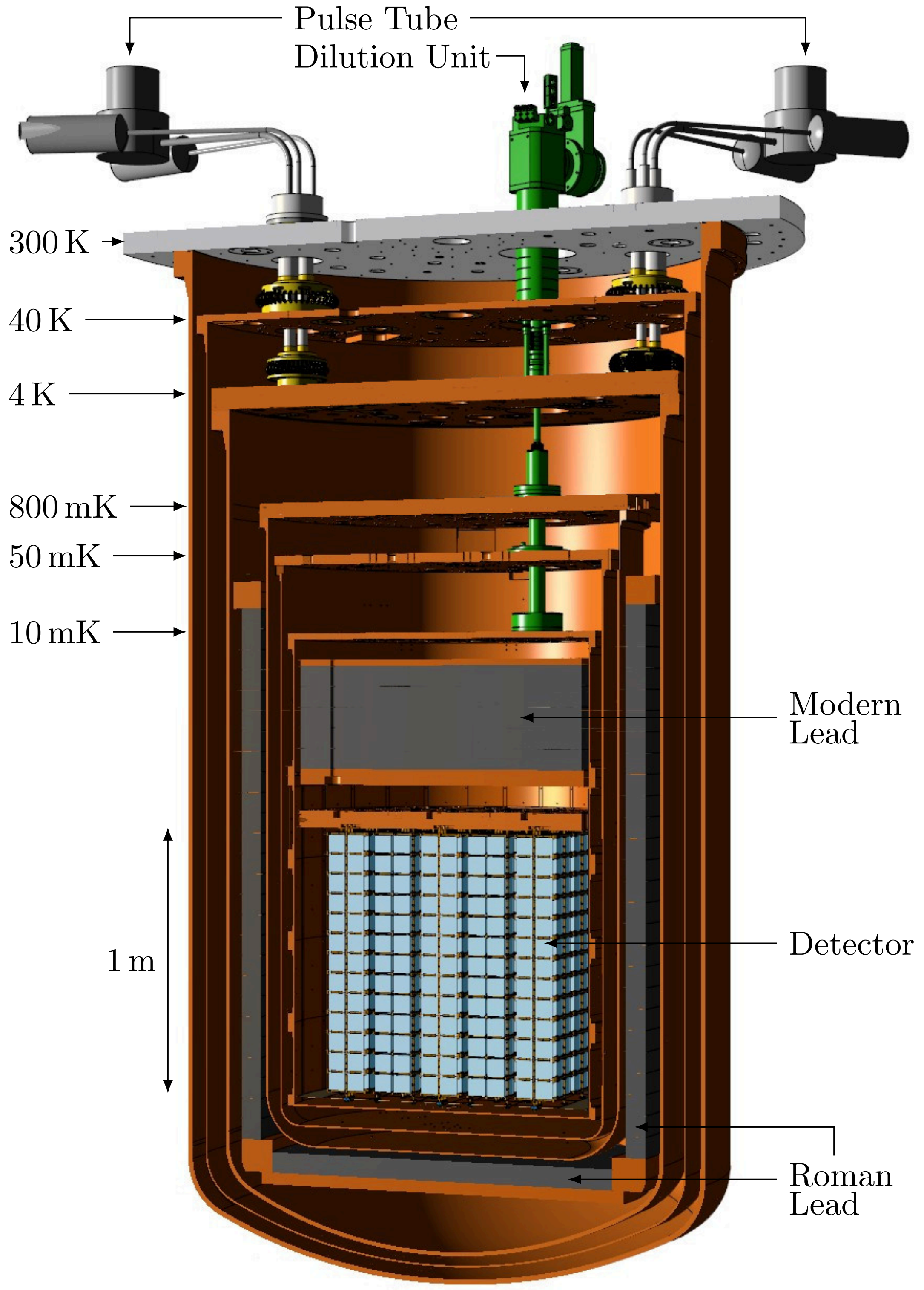


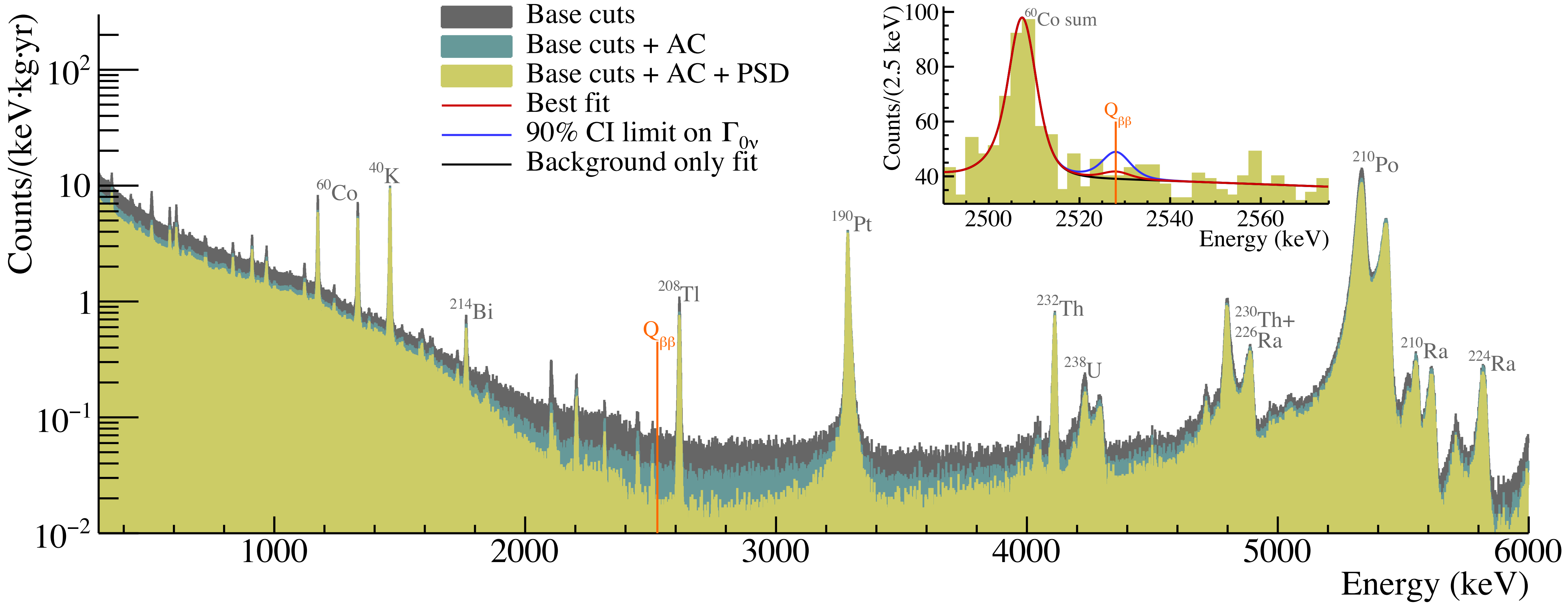
arXiv:1805.11142, PRC **97** 0655034 (2018), arXiv:2106.16243, and G. Gratta

CUORE

- 750 kg of natural TeO_2 cryogenic crystals (200 kg ^{130}Te)
  - Ge-NTD readout
  - Cu and Pb shielding
  - Located at LNGS
- Background: 110 cts/(FWHM t yr), dominated by surface alphas
- Result for 1 t y: $T_{1/2} > 2.2 \times 10^{25}$ yr
- Will take 3 t y of data

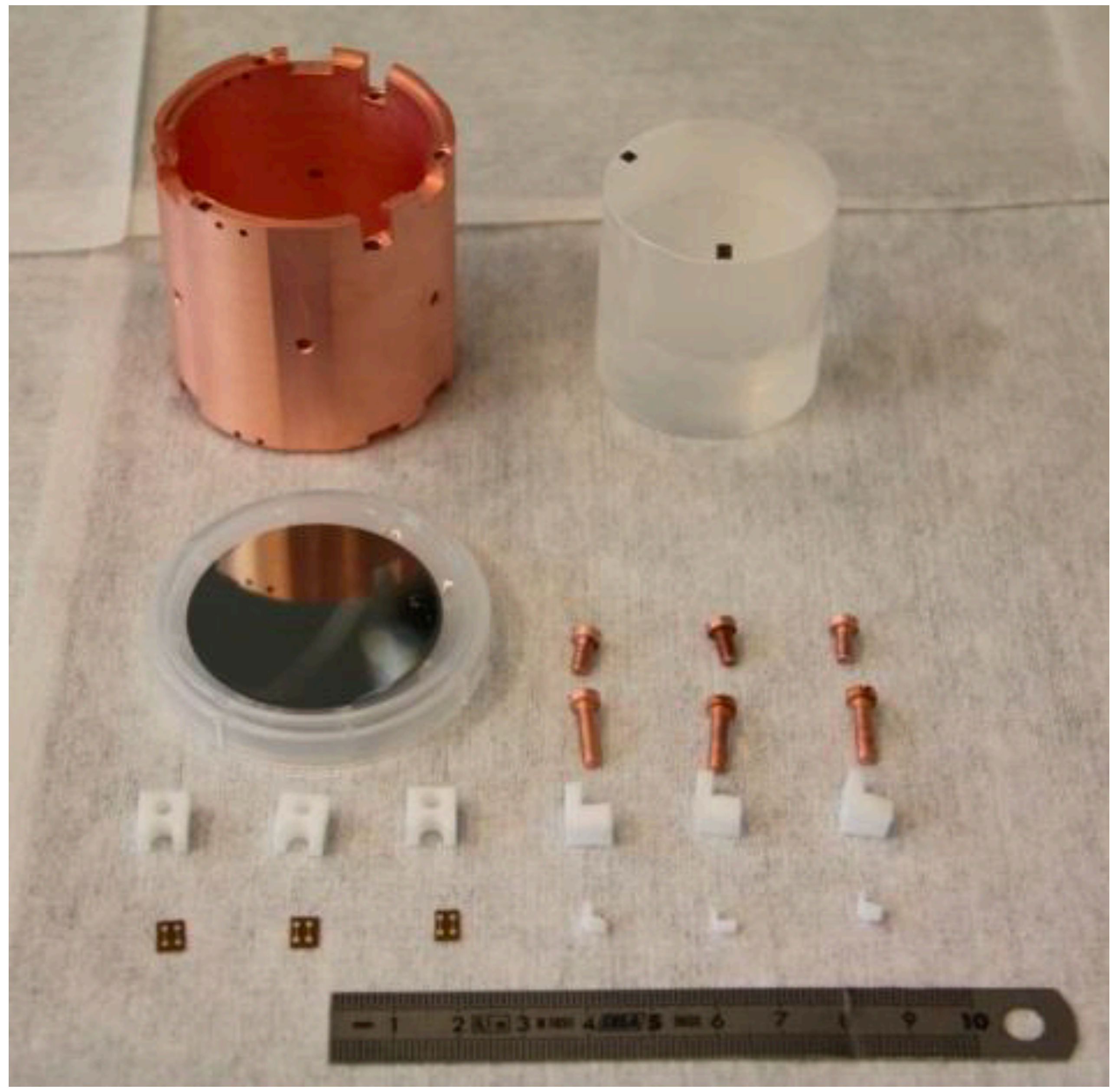


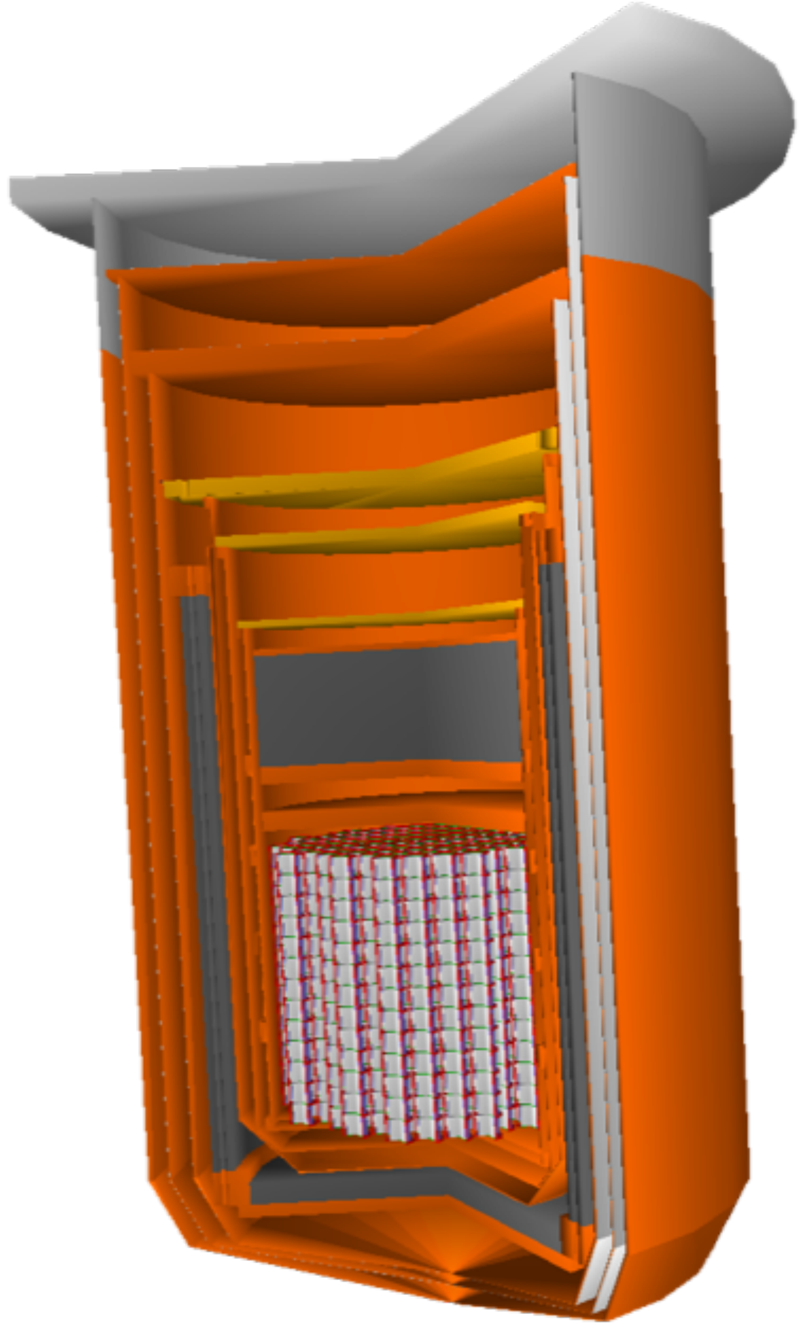




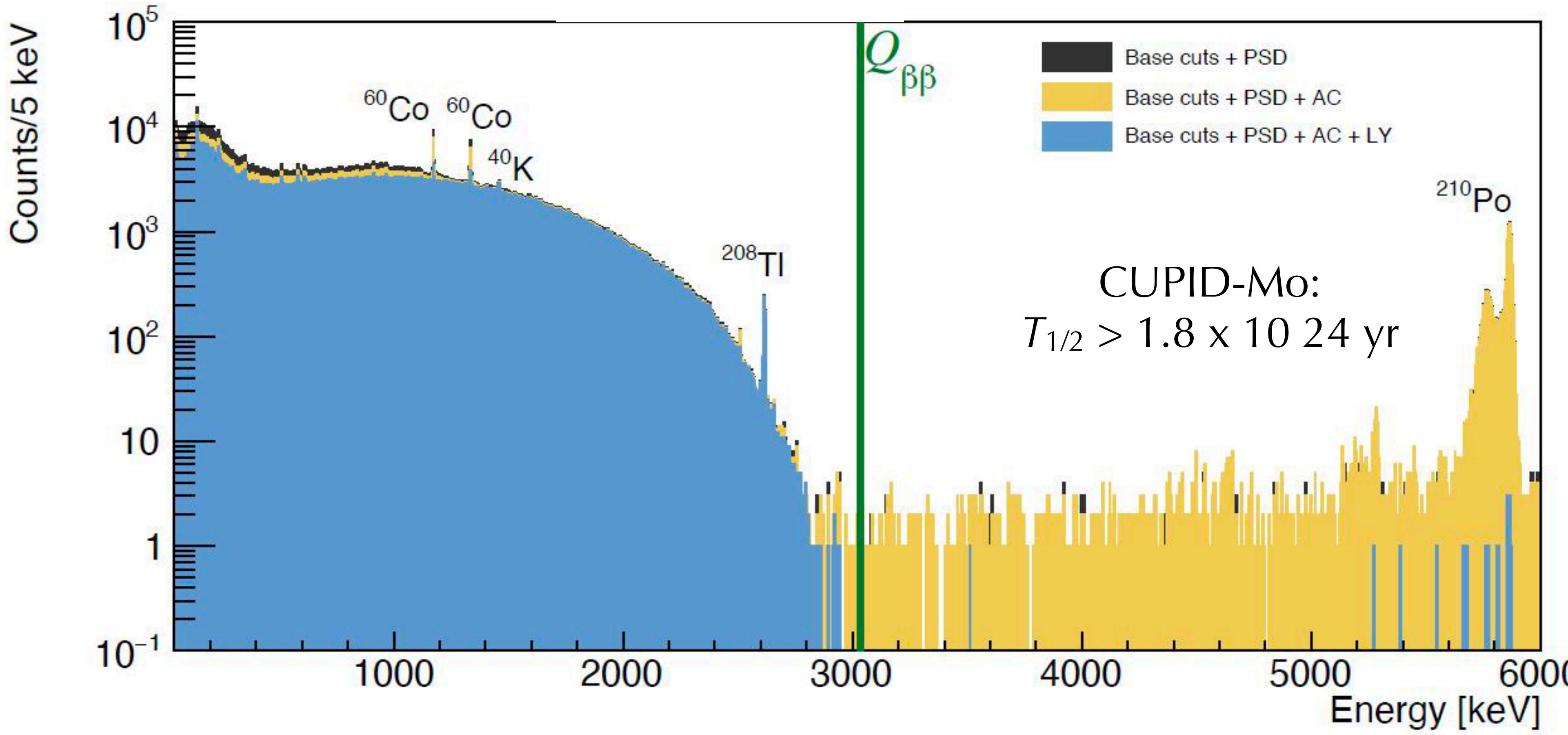
CUPID

- 240 kg of ^{100}Mo in 1600 Li_2MoO_4 scintillating crystals (>95% enrichment) in CUORE cryostat
  - Good *E* resolution from phonons: FWHM <10 keV at $Q_{\beta\beta}$
  - Ge-based scintillation readout rejects primary CUORE background
- Particle ID technique robustly demonstrated by CUPID-0 and CUPID-Mo
  - >99.9% α rejection, >99.9% β/γ acceptance
  - Single-tower measurement underway at LNGS
- Background goal: 0.5 c/(FWHM t y) dominated by 2νββ pile-up and U/Th γ summing
- Discovery sensitivity (10 yr): $T_{1/2}$ > 1.1 x 10^{27} yr





PRL **126**, 181892 (2021)



arXiv:1907.09376, Zolotarova, Neutrino 2022

Outline

- Introduction
- Experimental Situation
- US Program
- US Planning / Funding Status

NSAC Subcommittee Guidance

- 2014-2015: Nuclear Science Advisory Committee's 0νββ Decay Subcommittee recommended guidelines for US investment (experimental aspects):
  - **Discovery Potential**: 3σ discovery sensitivity covering the IO for 10 years of counting assuming the most pessimistic NME (neglecting quenching and the contact term)
  - **Staging**: favor concepts that provide a phased approach
  - **Standard of Proof**: favor techniques for which a positive result is unambiguous
  - **Continuing R&D**: recommended funding for modest scope demonstration projects for background suppression or sensitivity enhancement
  - **International Collaboration**: recommended coordinating with international funding agencies to establish a global program in multiple isotopes
  - **Timeliness**: results are needed on a time scale competitive with international efforts

US Long Range Plan

- 2015 Long Range Plan
  - Recommendation I: "The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made." (**CEBAF, FRIB, RHIC upgrade**…)
  - Recommendation II: "**We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment**."
  - Recommendation III: "We recommend a high-energy high-luminosity polarized **EIC** as the highest priority for new facility construction following the completion of FRIB."
  - Recommendation IV: "We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories."

US “Downselect”

- DOE began planning for a “Downselect”
  - Approved “CD0”
  - No clear leader, no strong international pressure to act fast, budgets remained tight
  - MJD / CUORE still just starting to take data
  - Unique opportunity arose to fund EIC first
- DOE opted to then pursue a “Portfolio Review”

DOE Order 413.3B

Process for projects requiring >$50M

- **CD0**: Mission Need
- **CD1**: Alternate Selection and Cost Range
- **CD2**: Performance Baseline
- **CD3**: Start of Construction
  - **CD3a**: Long-Lead Item Procurement
- **CD4**: Start of Operations

2021 Portfolio Review

- Review of nEXO, CUPID, and LEGEND in July 2021
- Review Criteria
  - **Scientific Merit**: sensitivity, credibility, robustness of the overall approach
  - **Global Context**: US scope and leadership
  - **Technical Maturity**: feasibility, robustness, and completeness of the technical design
  - **Cost Competitiveness and Timeliness**: cost, schedule, required international contributions
  - **Assurance of Successful Project Delivery**: project management
- Close-out report has not yet been made public

Recent Developments

- Announcement at APS Division of Nuclear Physics Meeting, Oct 2021
    - LEGEND and nEXO preparing for "CD1" in Spring 2022
- US 2022 Budget: continuing resolution through March 2022
- Announcement at APS Meeting, April 2022
    - No significant $0\nu\beta\beta$ funding in 2022 or 2023
    - LEGEND / nEXO preparing for CD1 in 2023

DOE Order 413.3B

Process for projects requiring >$50M

- **CD0**: Mission Need
- **CD1**: Alternate Selection and Cost Range
- **CD2**: Performance Baseline
- **CD3**: Start of Construction
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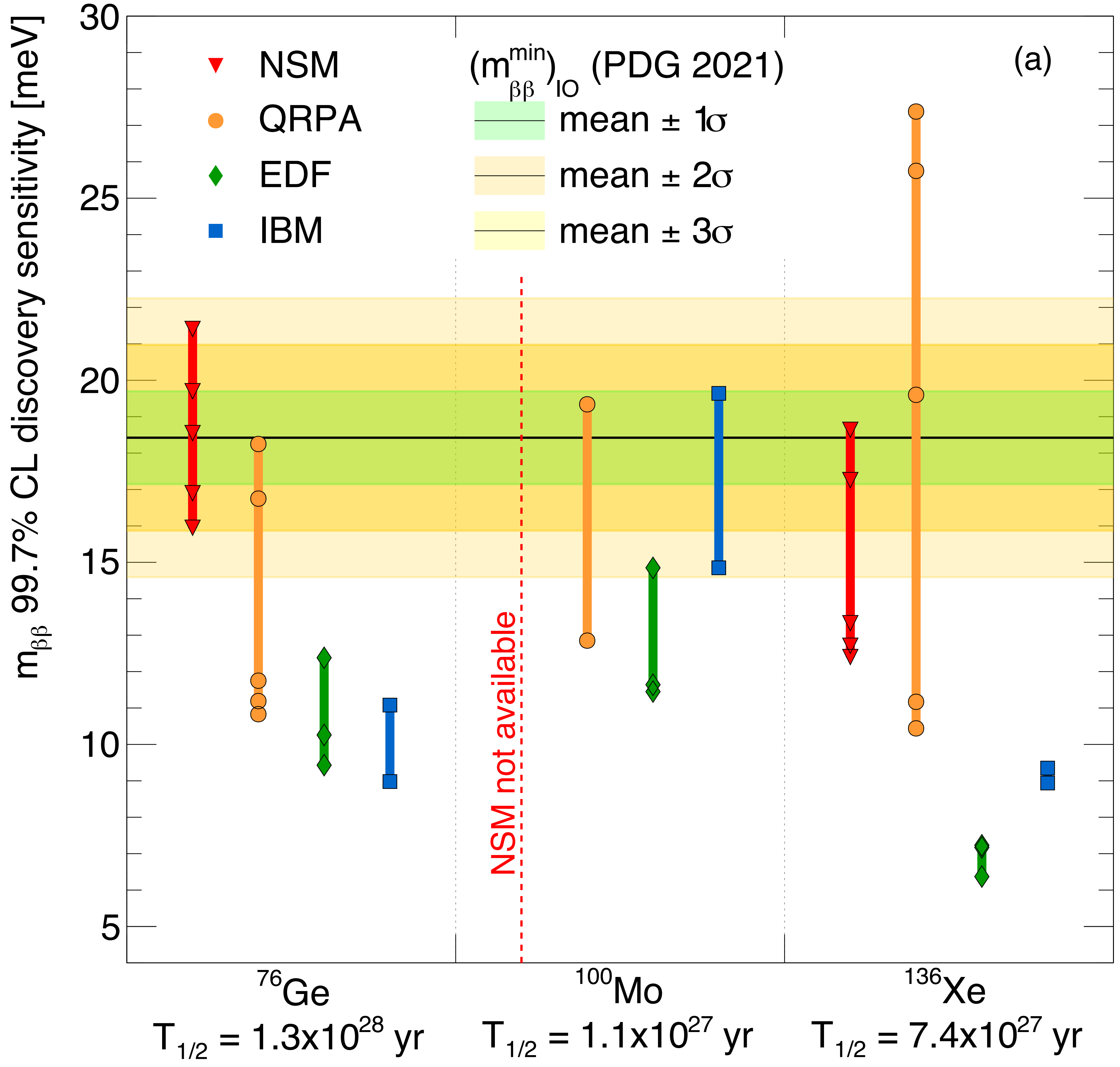
- **CD4**: Start of Operations

Summary

- The international experimental program to search for 0νββ decay is robust and aggressive
  - Kamioka and US experiments have been among the leaders this program over the last decade
- The US aims to play a leading role in next-generation experiments that cover the IO
- A steady march in sensitivity improvement is expected for at least a decade in multiple isotopes

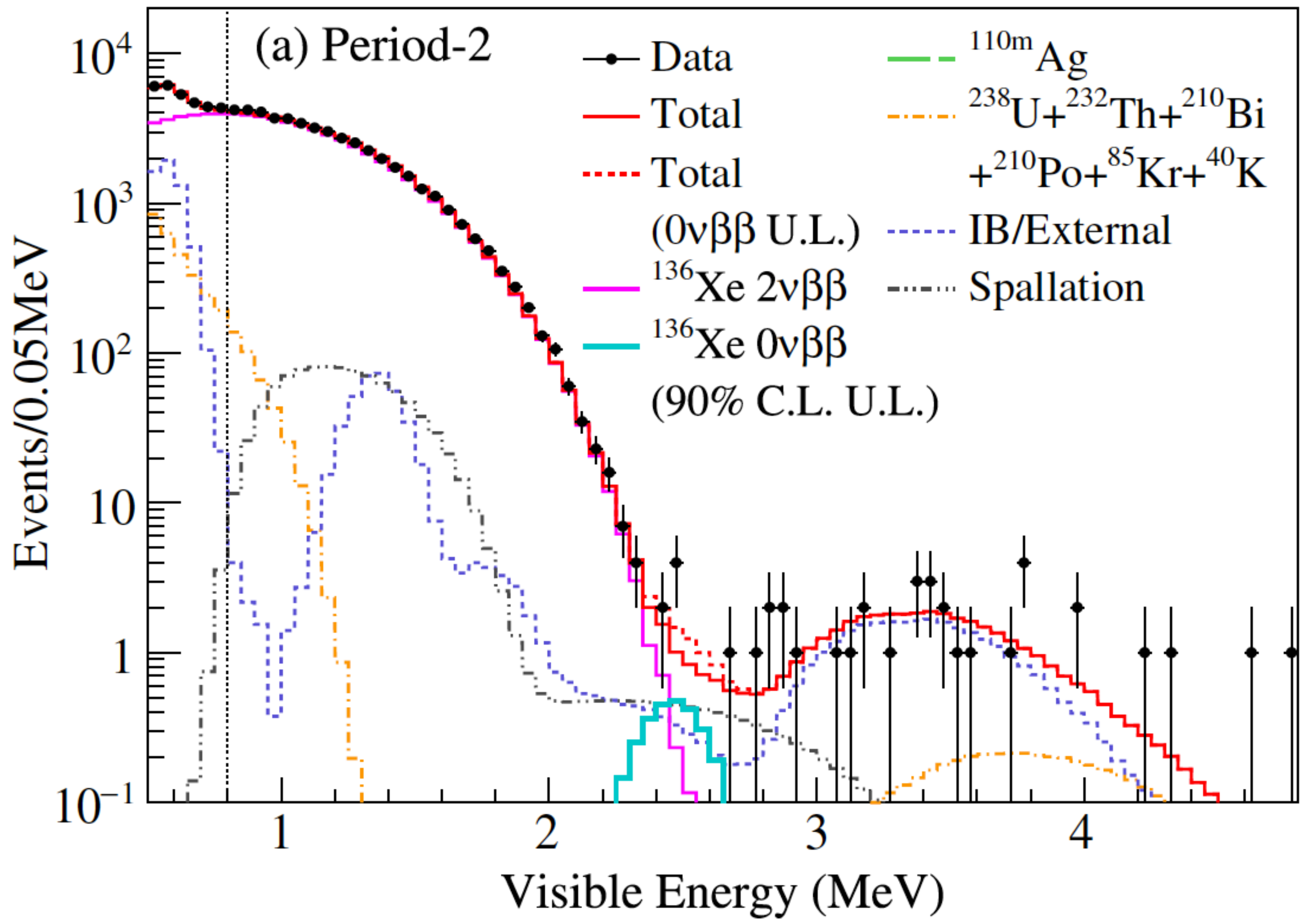


Backup

Background Shape and Model Selection

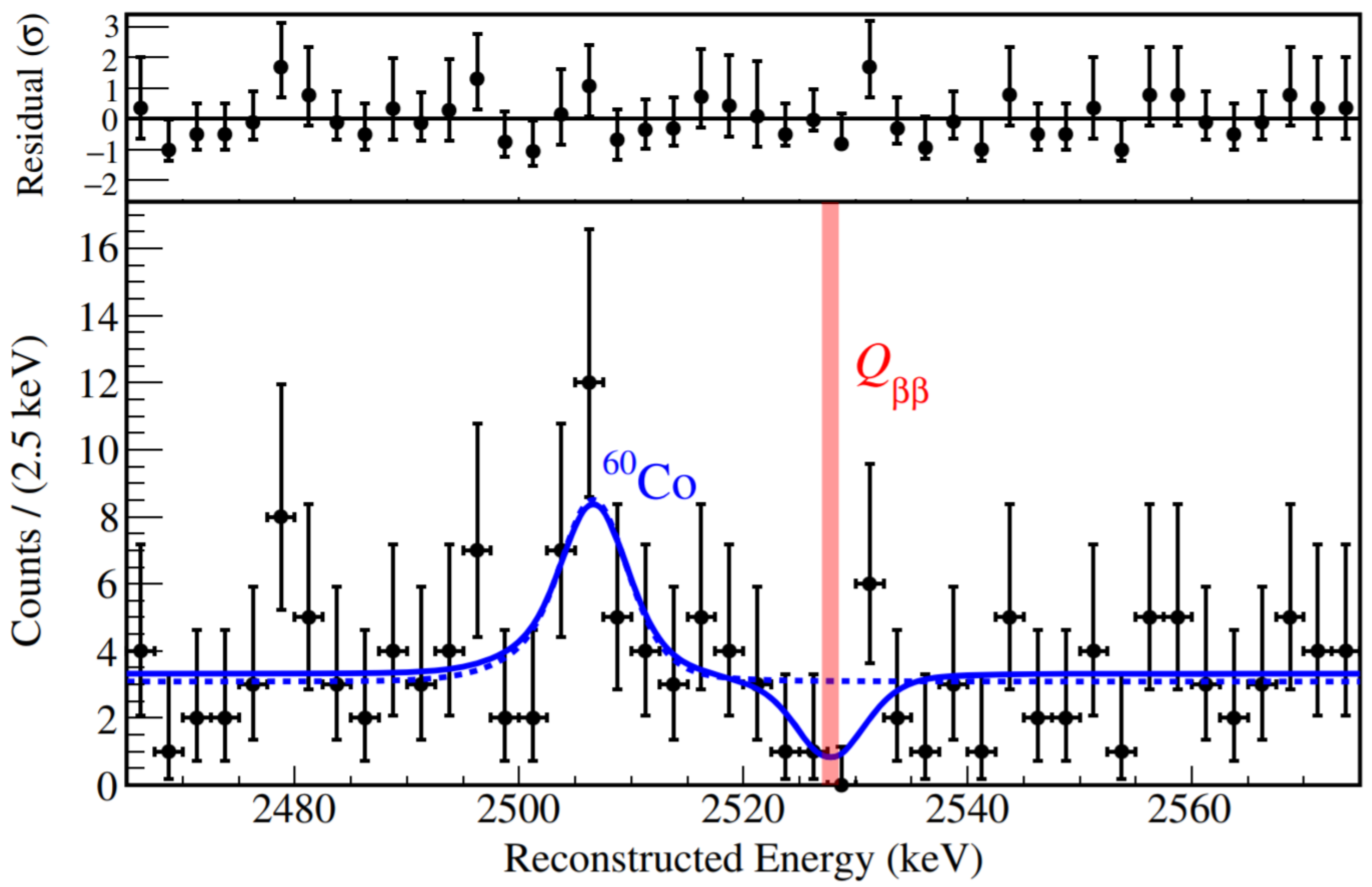
- Sensitivity degrades when there are systematic background shape uncertainties
    - But not until those uncertainties become very large
- Model selection becomes critical when the background shape is non-trivial
    - CLs are relevant only within the framework of the chosen background model
    - When important: vary the model, be conservative

KamLAND-Zen: O(10) c/ROI, complex shape



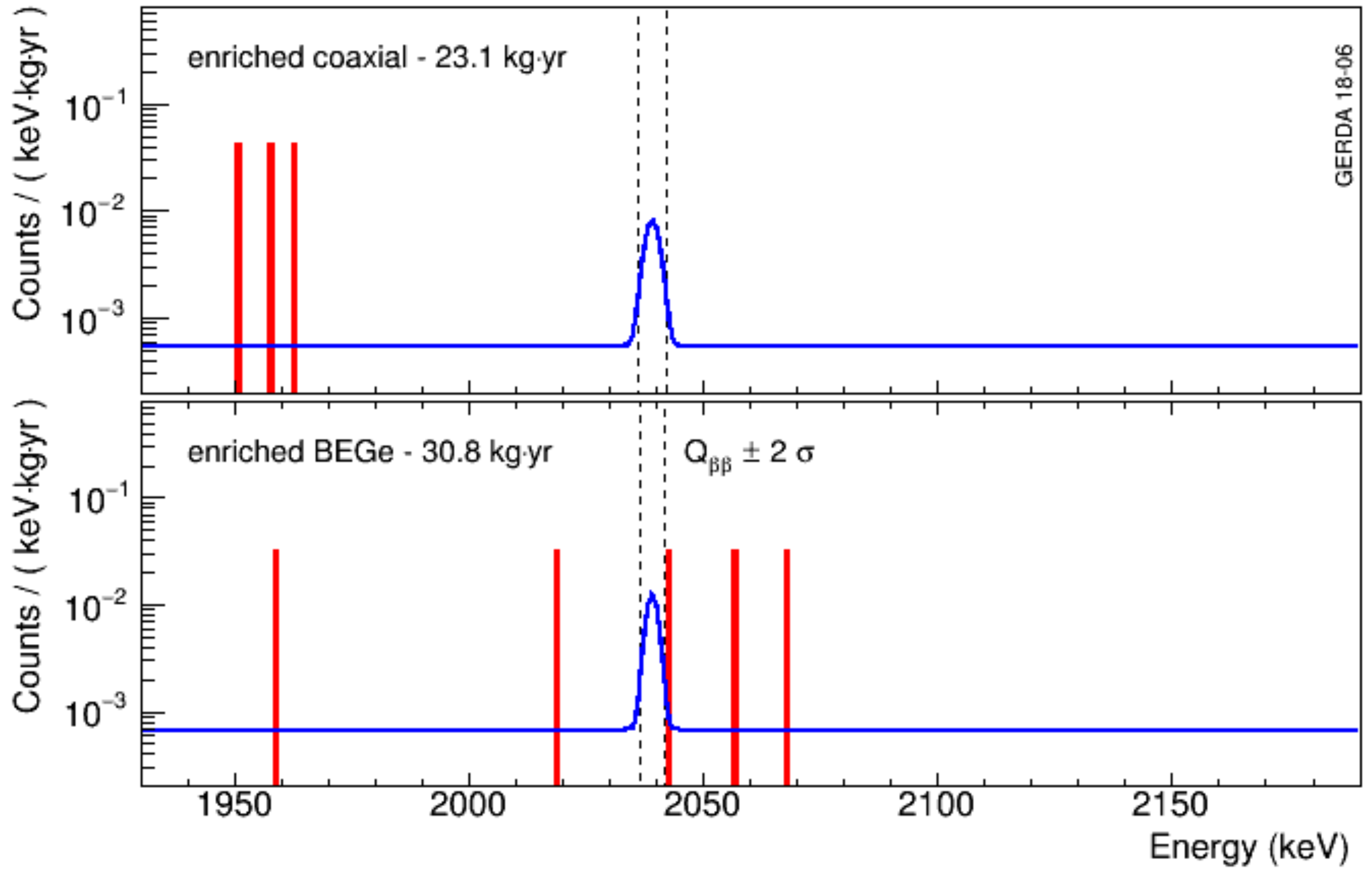
PRL **117**, 109903 (2016)

CUORE: O(10) c/ROI, simple shape



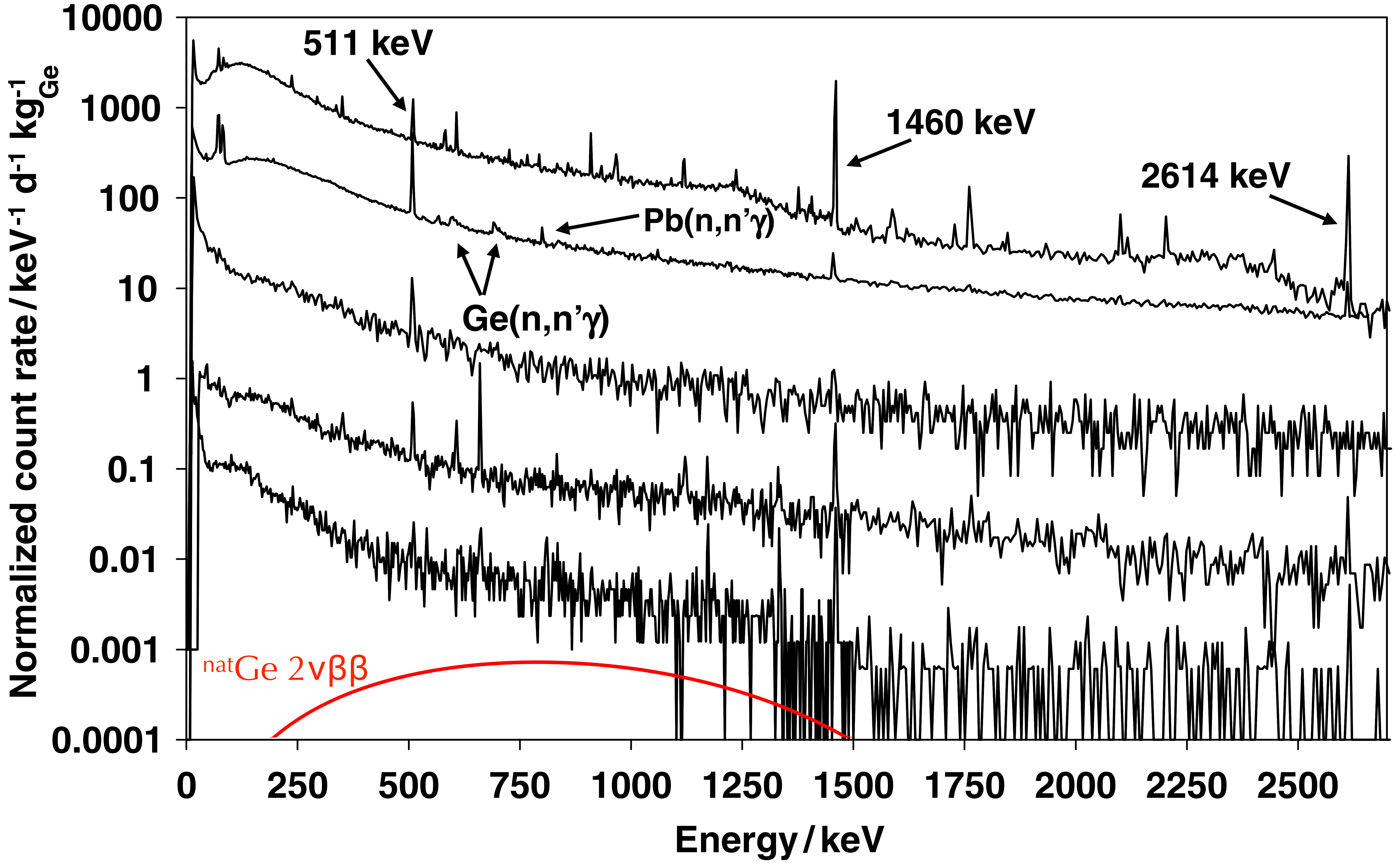
Nu18

GERDA: O(0.1) c/ROI, simple shape



Nu18

The Background Problem



Typical surface detector (HPGe): natural radioactivity dominates

Low-bg surface detector: muon and primary n cosmic rays

Low-bg detector, 125 mwe: muons

Low-bg detector, 500 mwe: muons + natural radioacitivity

Ultra-low-bg detector, 3400 mwe: natural radioacitivity

Need an underground detector made of pure materials, and typically need enrichment.