Searching for Neutrinoless Double-Beta Decay with KamLAND-Zen and LEGEND

Jason Detwiler, UW

MAYORANA Workshop

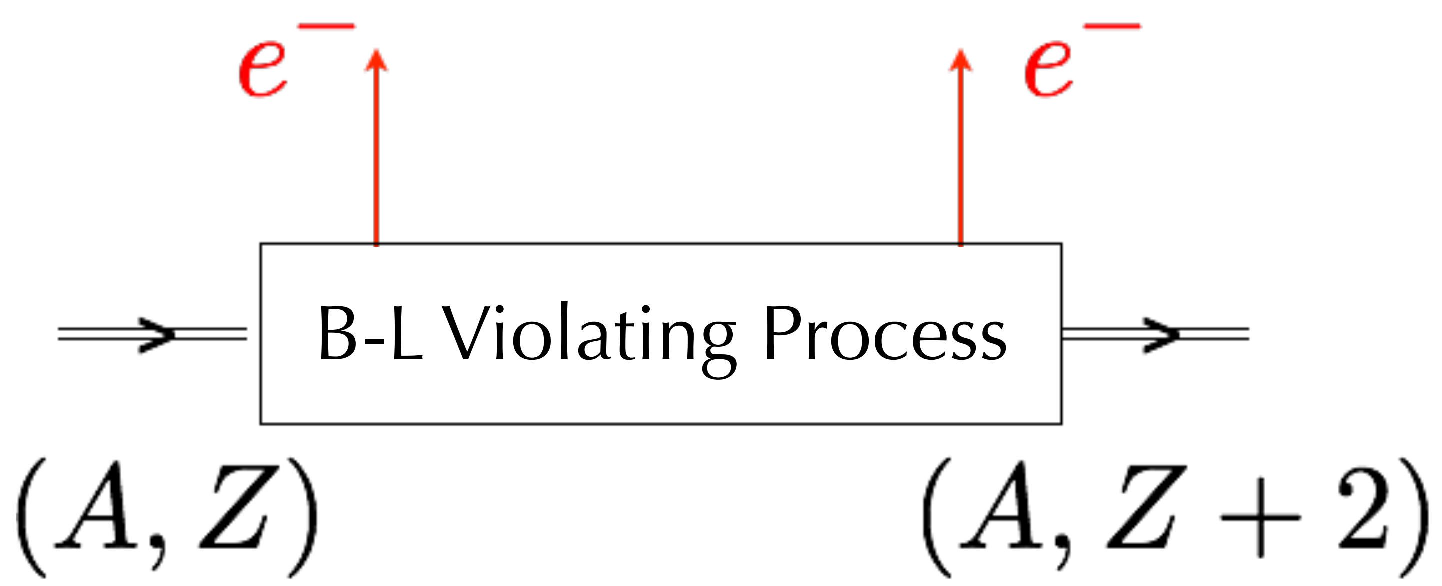
July 12, 2023

Outline

- Introduction: strategies for detecting 0νββ decay
- High-exposure: KamLAND-Zen
- Low-background: LEGEND

0νββ Decay

- The creation of matter without antimatter, which has never been observed (since the Big Bang)
- Violates not just *L* but *B*-*L*: the last accidentally conserved quantity in the SM
- Generically predicted by GUTs that also explain the cosmic matter asymmetry and the smallness of the neutrino mass



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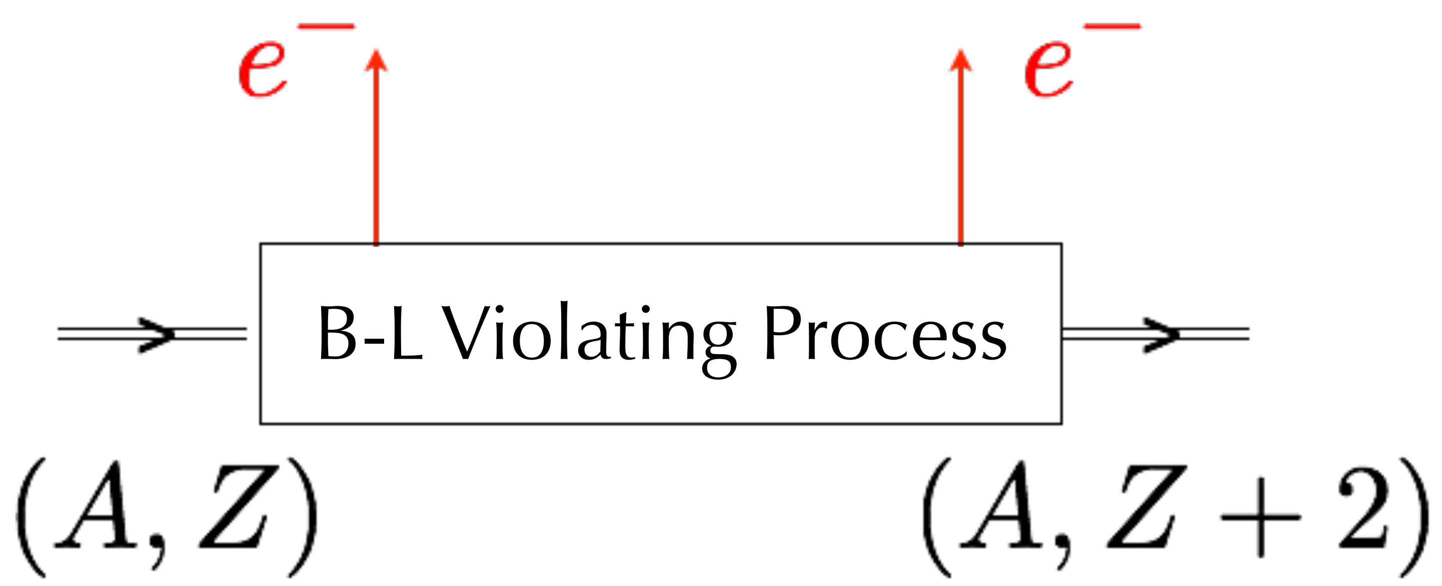
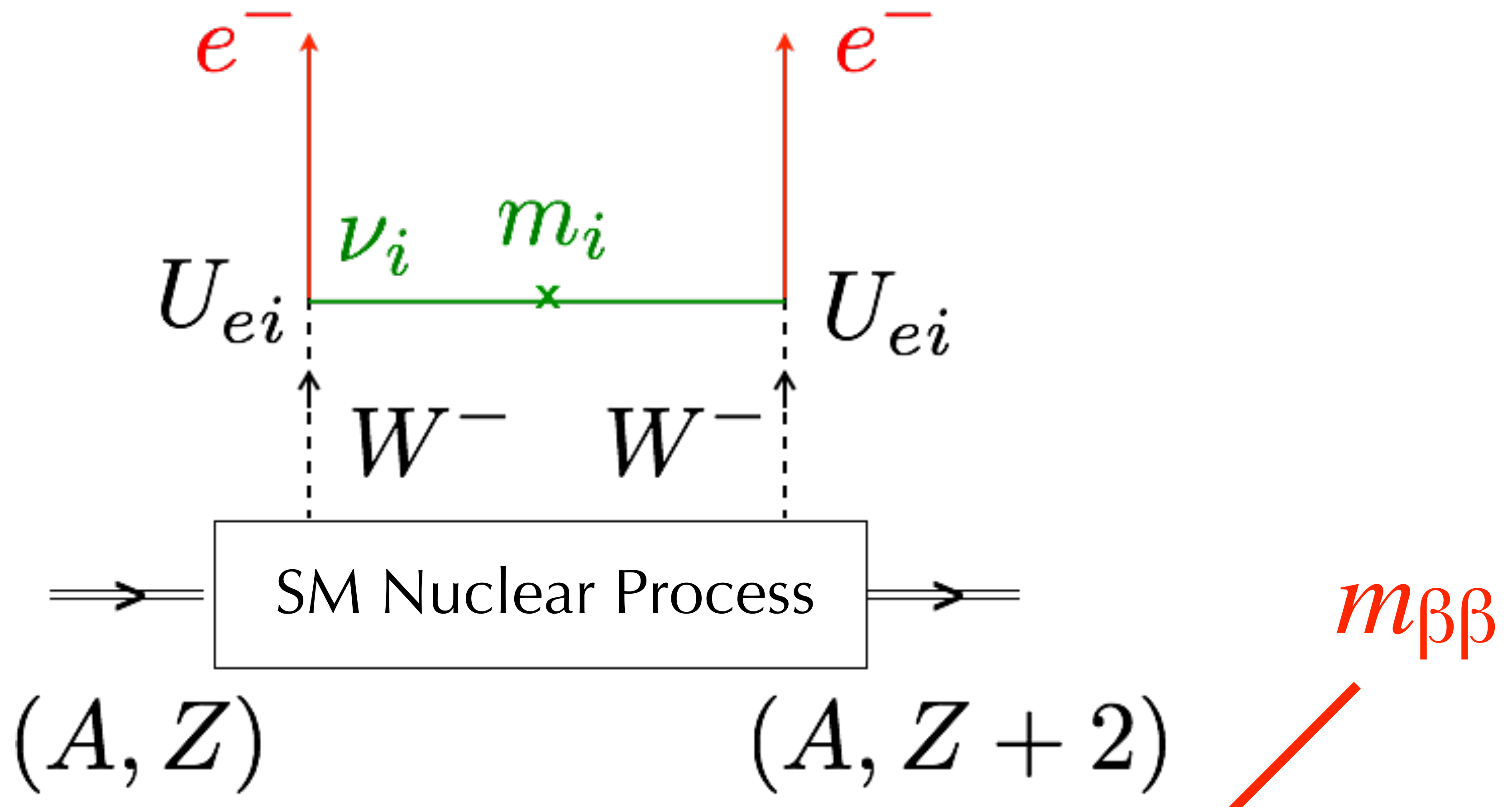
- Generically predicted by GUTs that also explain the cosmic matter asymmetry and the smallness of the neutrino mass
- Lowest-order LNV operator is at dim 5: a Majorana neutrino mass

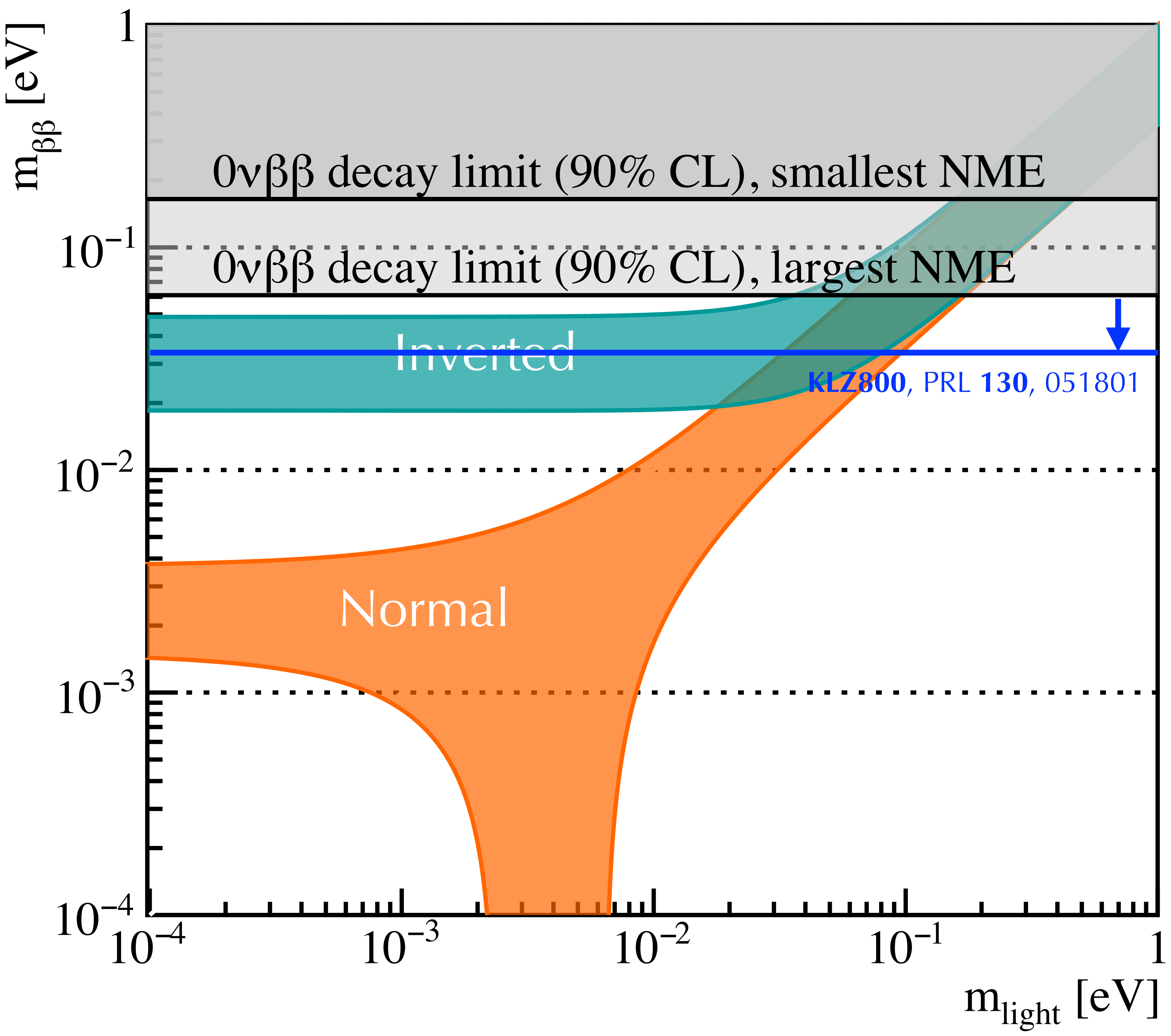




$$\Gamma^{0\nu}_{1/2} = G^{0\nu}|M^{0\nu}|^2 \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|^2$$

Light Neutrino Exchange

- Light neutrino exchange is "natural" and "minimalistic", and sets clear experimental goal posts:
  - IO: $T_{1/2} \lesssim 10^{28}$ years (10^{18} times the age of the universe)
  - NO: $T_{1/2} \lesssim 10^{30}$ years, modulo cancellations, flavor symmetries, etc.
- Other mechanisms are possible: the whole region is "open"!
  - Dim 7 (9) LNV is probed at the PeV (TeV) scale
  - Sterile ν make the IO/NO regions cover the entire plane



 Agostini, Benato, Detwiler, Menendez, and Vissani, RMP **95**, 025002

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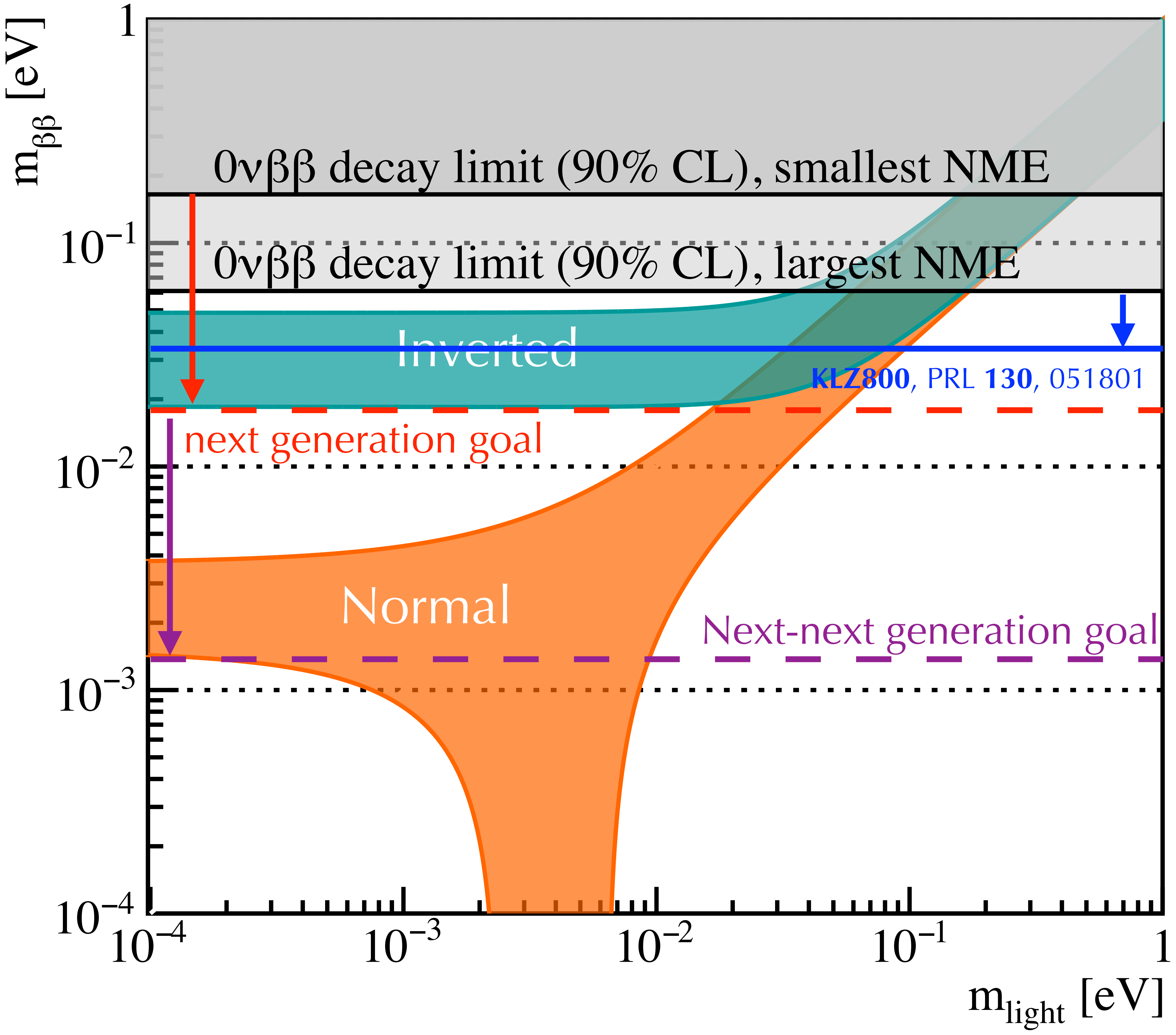
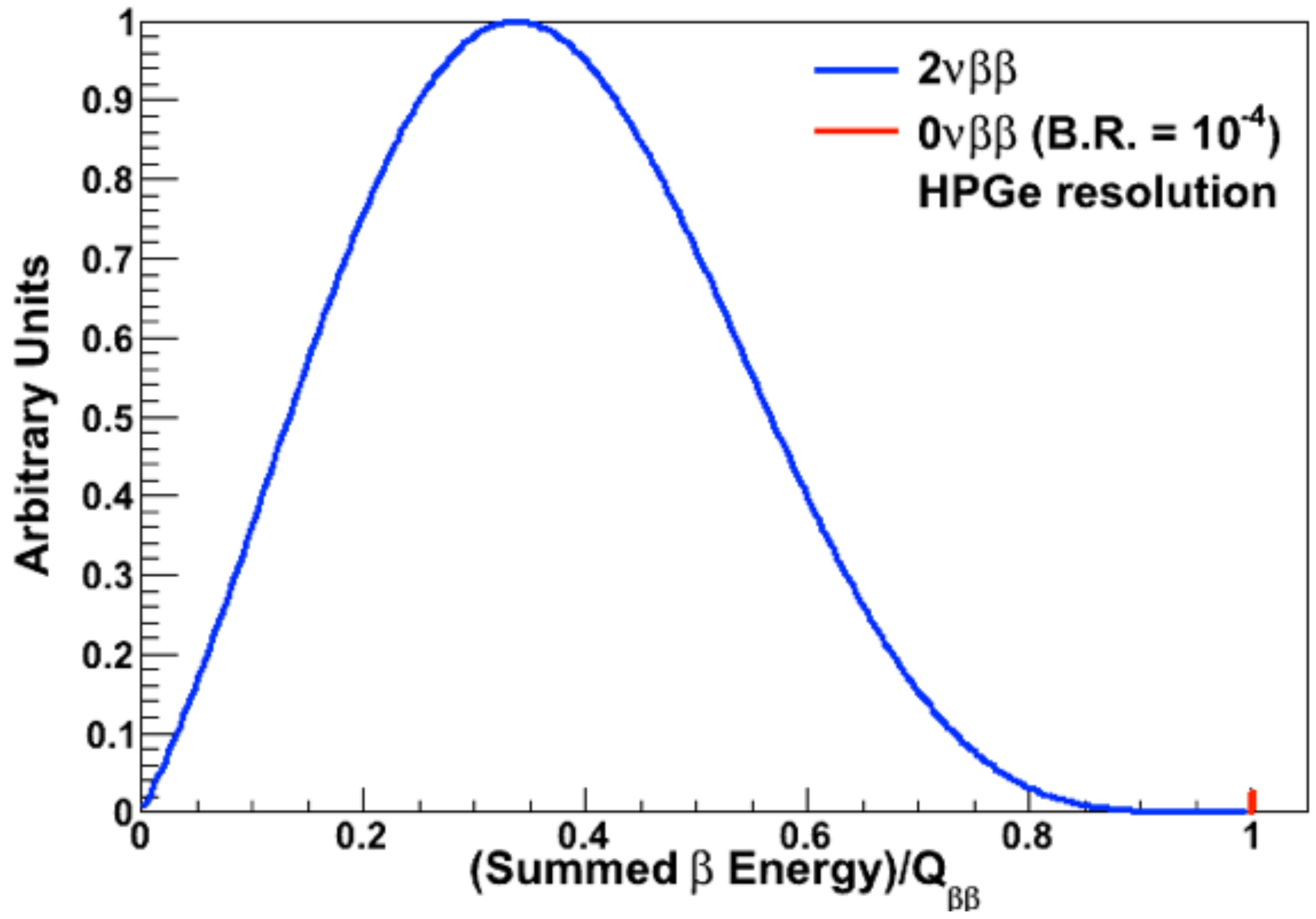


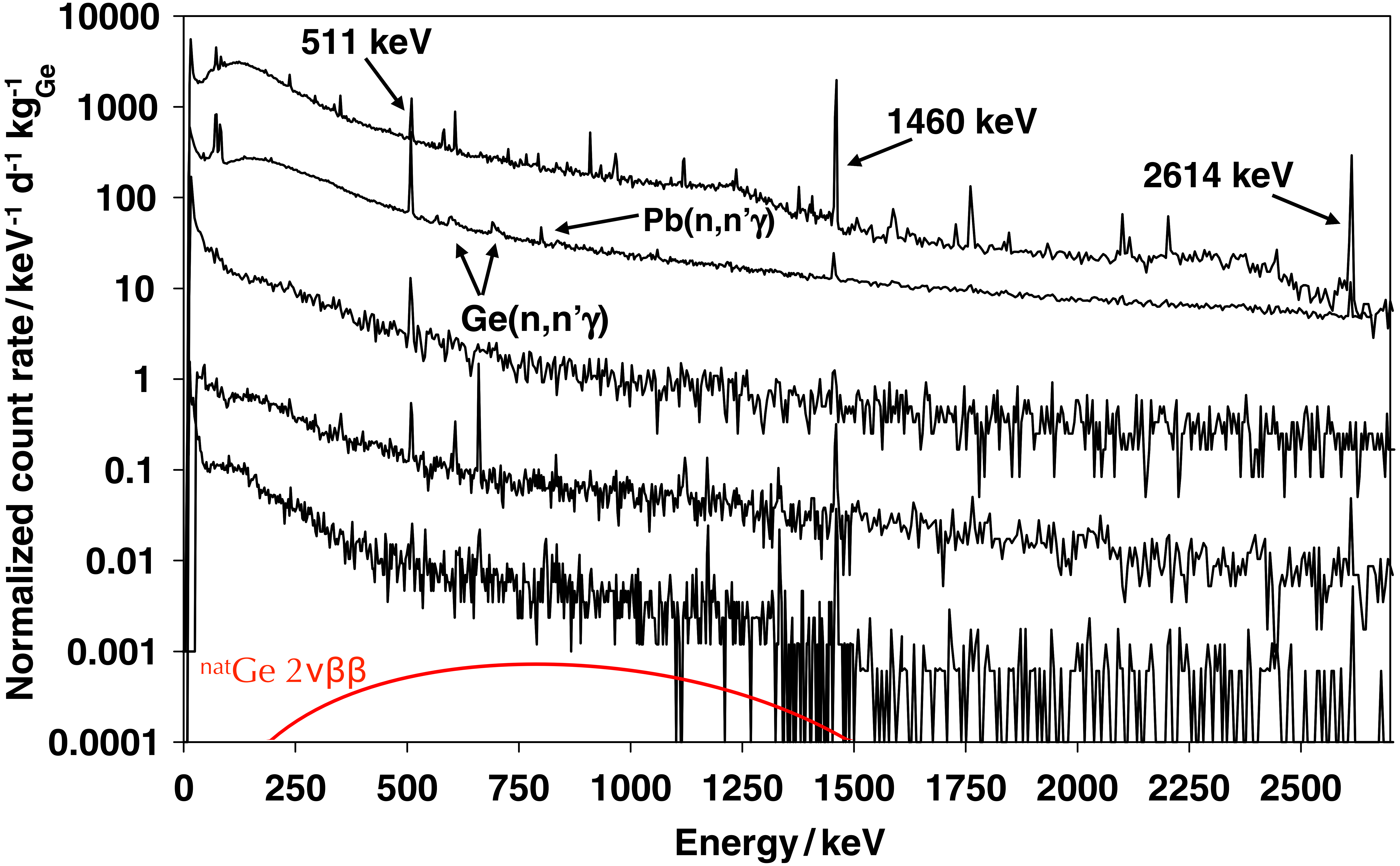
Agostini, Benato, Detwiler, Menendez, and Vissani, RMP **95**, 025002

Neutrinoless Double-Beta Decay

- *Must* measure summed electron kinetic energy to distinguish 0νββ from the Standard-Model 2νββ process: search for a peak at $Q_{\beta\beta}$
- The peak in the plot exceeds current limits by >1 order of magnitude



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.

Experimental Sensitivity

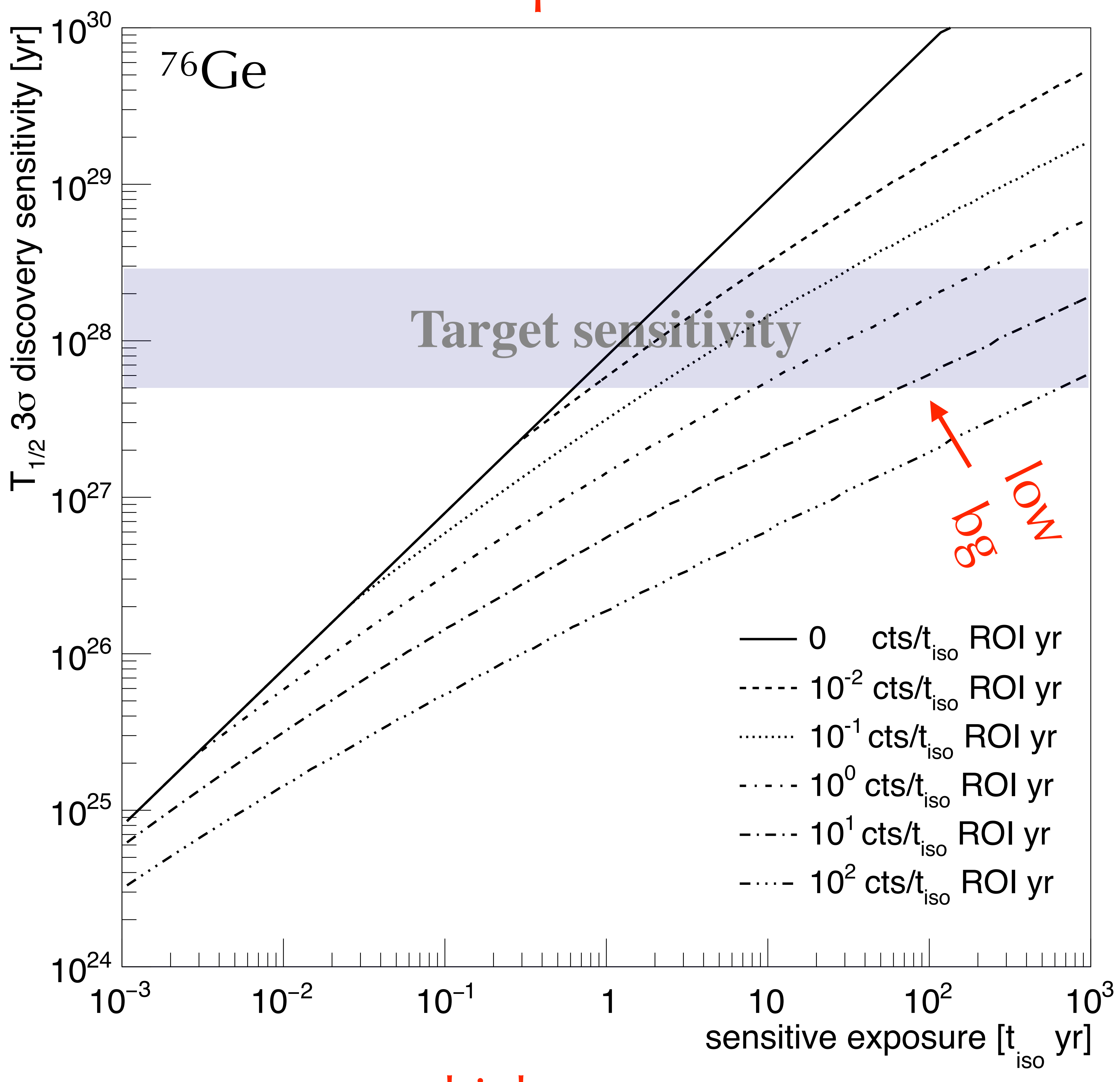
- Effectively a Poisson counting experiment near $Q_{\beta\beta}$
- Relevant parameters: sensitive exposure and sensitive background

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

- Discovery sensitivity: the minimum signal strength for which an experiment has a ≥50% chance to observe a signal above background with significance ≥3σ:

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

Requirements:



high exposure →

Agostini, Benato, Detwiler, PRD **96**, 053001 (2017)

Tutorial for observing a 10^{28} yr half-life

- Get O(tons) of ββ isotope 🤑
- Instrument it so that it can detect 0νββ decay with high efficiency 🧙
- Eliminate ~all random events that can mimic 0νββ 🤫
- Wait ~10 years 😑

Tutorial for observing a 10^{28} yr half-life

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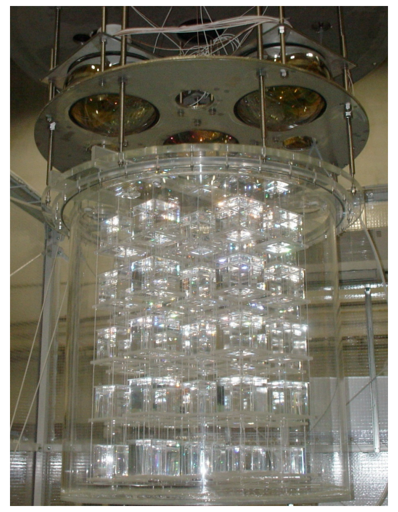
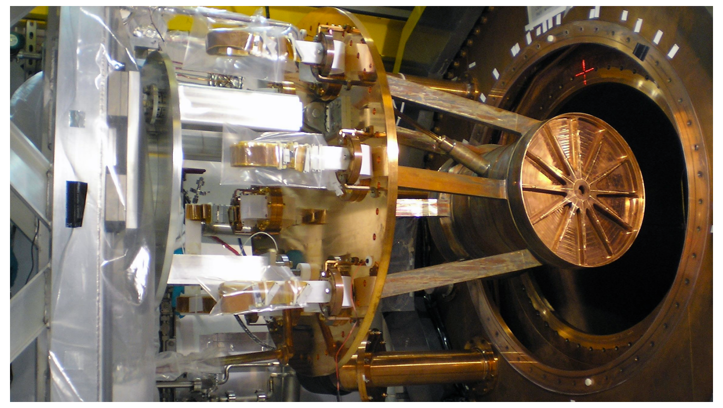
- However: if 0νββ decay is just beyond current limits, these same ton-scale experiments will observe O(100) events!

Experimental Techniques

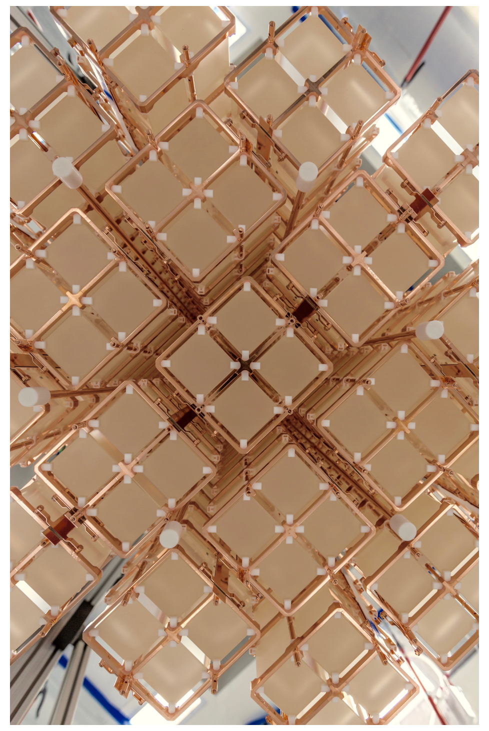
- Bolometers (CUORE/CUPID, AMoRE, CANDLES IV)
  - Measure *E* (σ ~ 0.1-0.3%) from phonons; granularity gives position info
  - Instrumenting with photon detectors for background rejection
- External trackers (NEMO3, SuperNEMO)
  - Trackers + calorimeters, measure *E* (σ ~ 3-10%) + tracks / positions + 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 (nEXO, NEXT, PandaX, AXEL, NvDEx, DARWIN, LZ)
  - Collect scintillation + ionization: measure *E* (σ ~0.4-3%) + tracks / position + PID

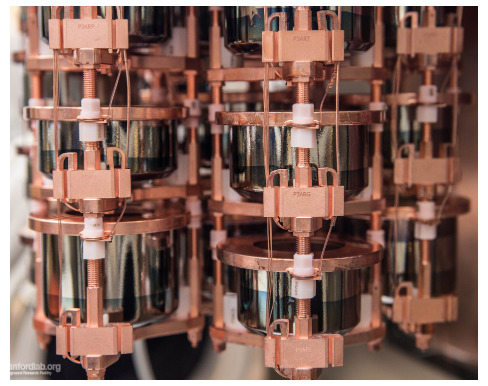

KamLAND-Zen

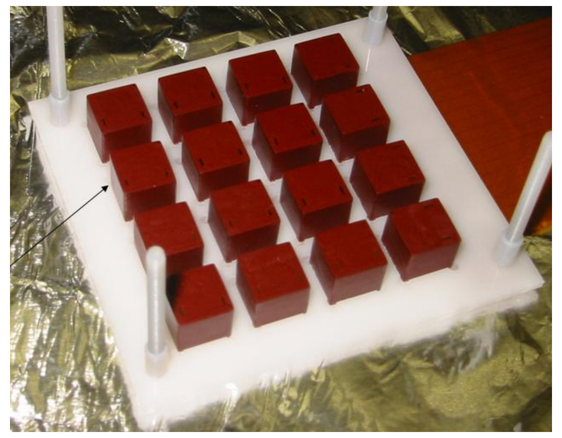

CANDLES

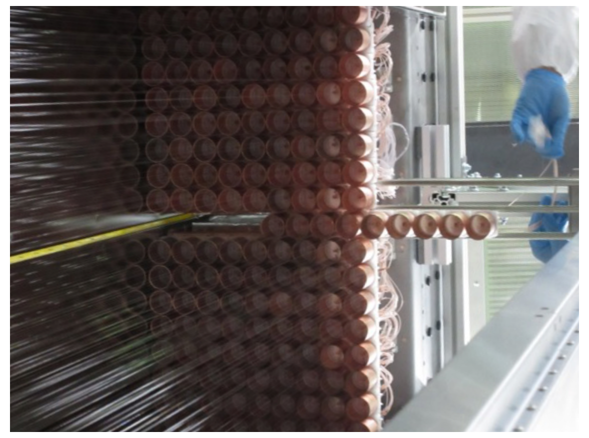

EXO-200


NEXT-100


CUORE


MAJORANA


COBRA


SuperNEMO


NEMO3

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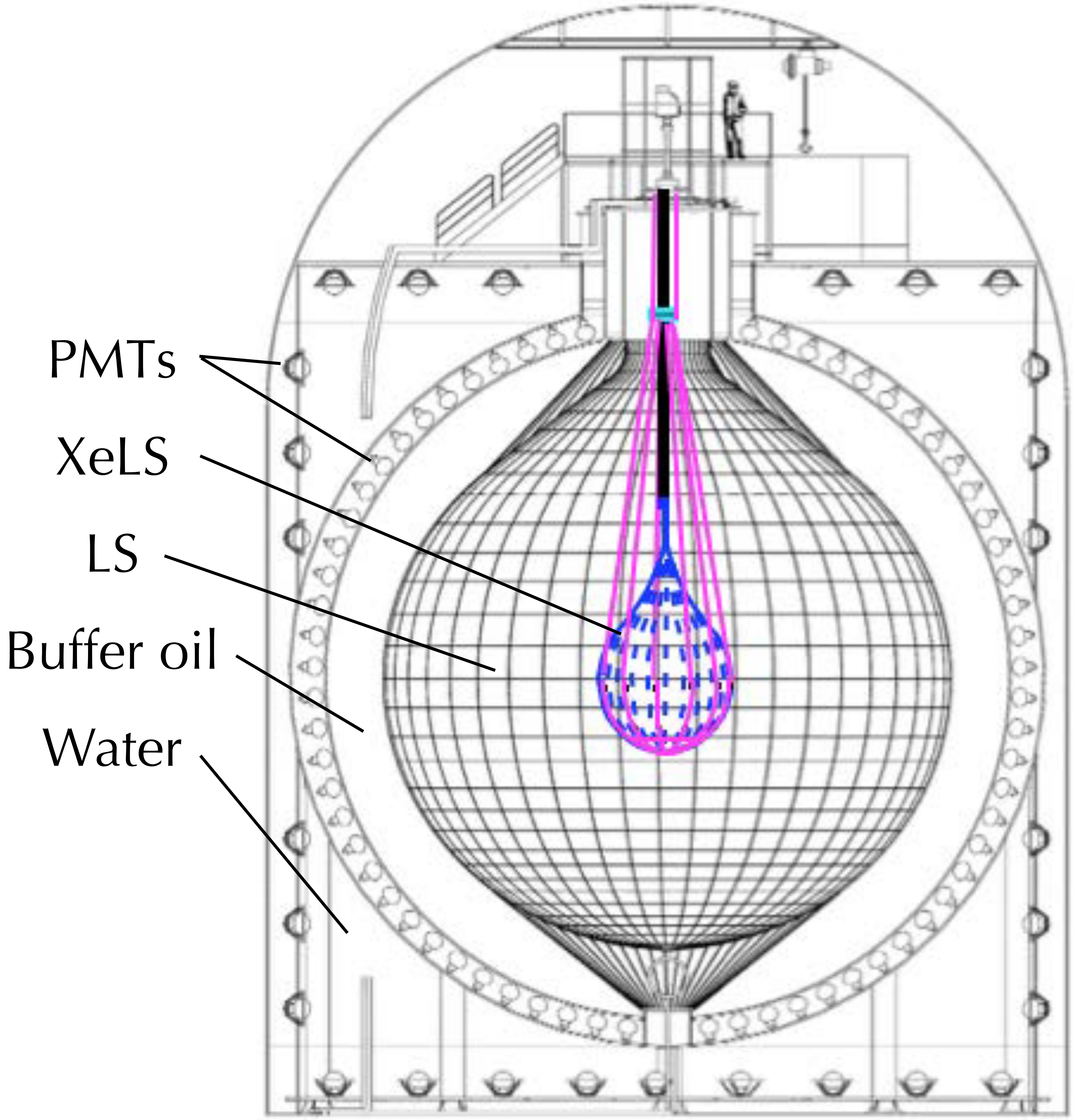
KamLAND-Zen

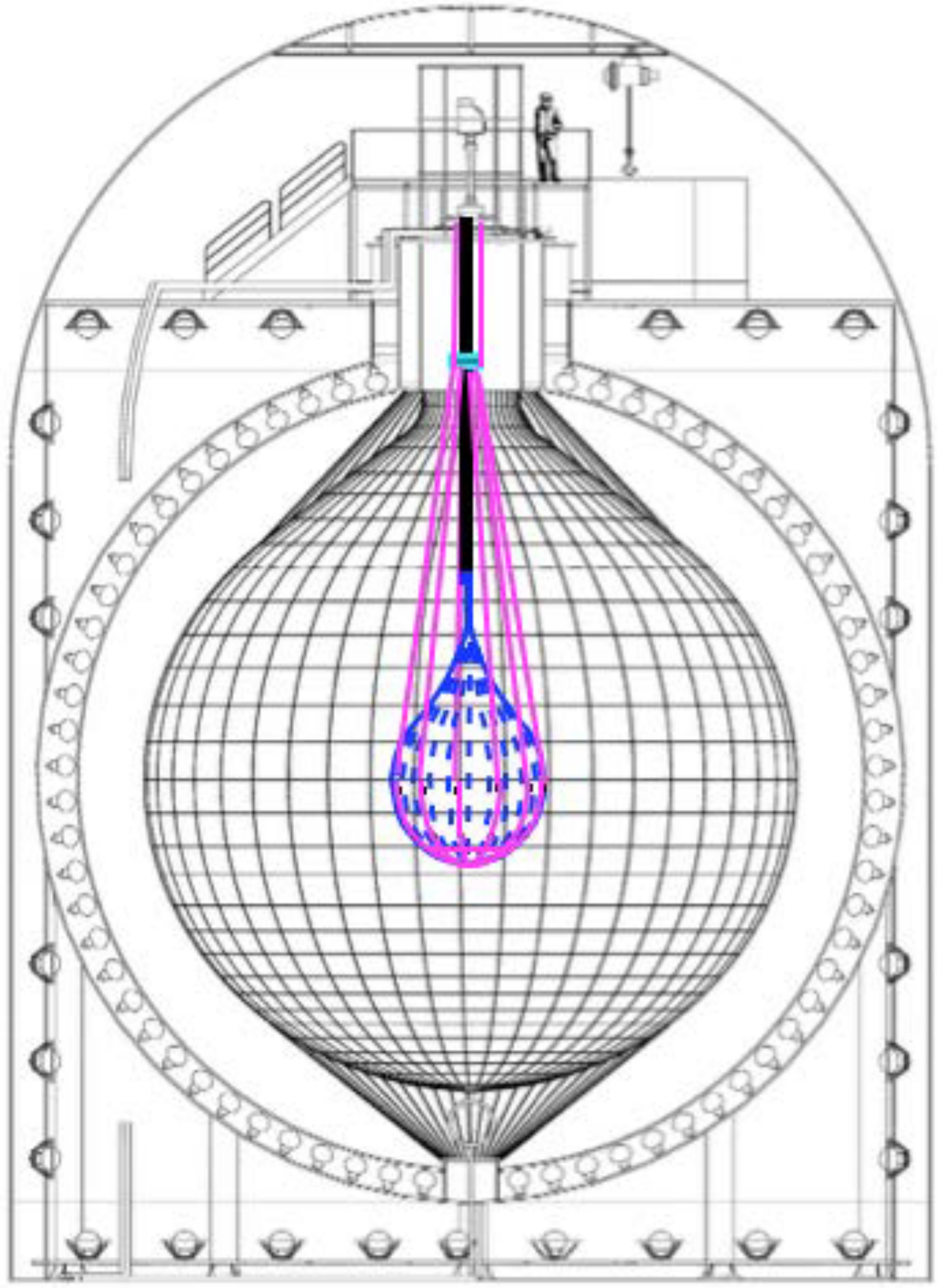


>50 researchers from Japan, the US, and the Netherlands

Measures light: *E*, ***r***, and *t* (+ μ veto)

KamLAND-Zen Timeline

2011-2015: KLZ-400

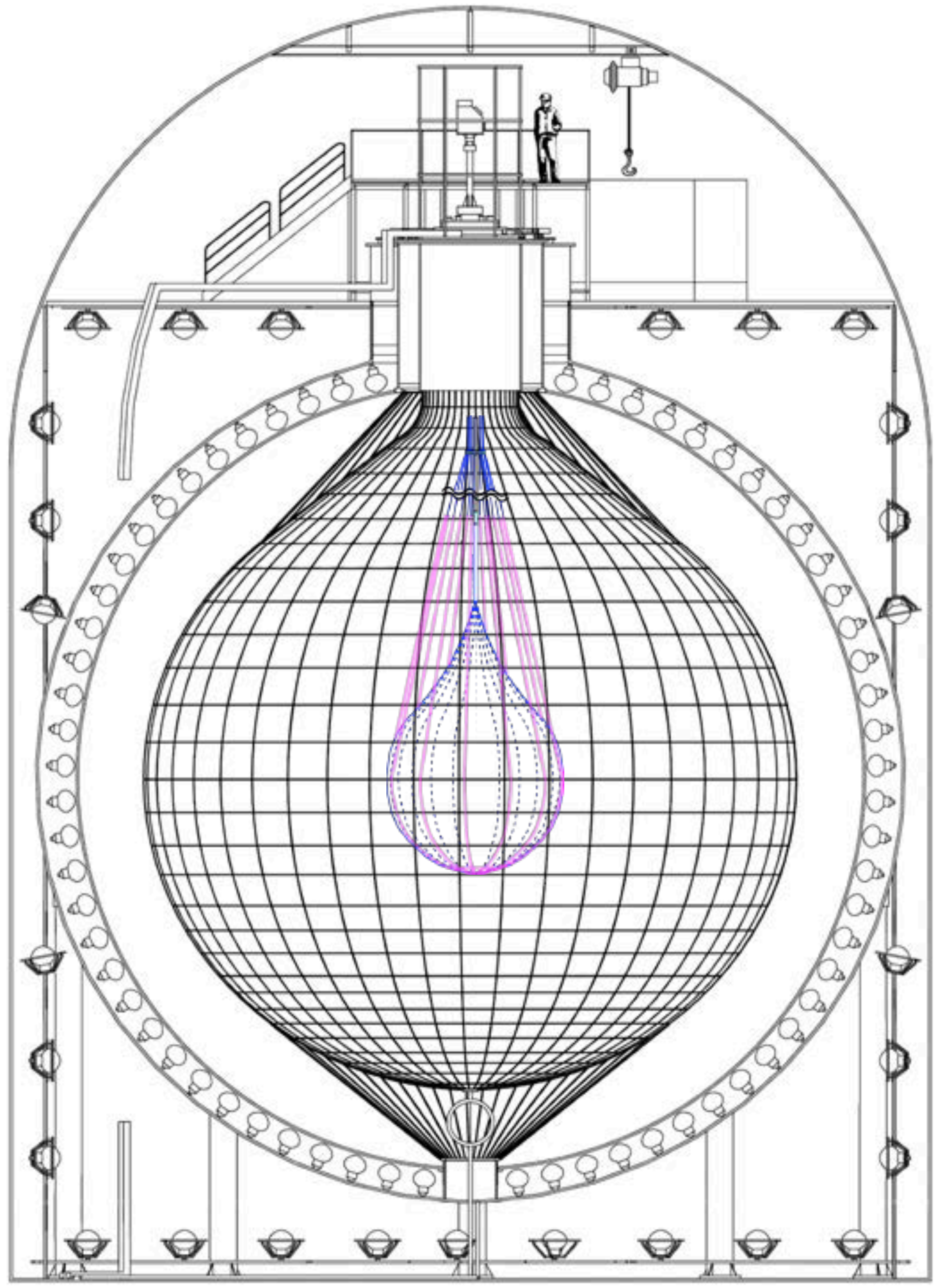


380 kg Xe

$T_{1/2} > 1.07 \times 10^{26}$ yr

PRL **117**, 082503 (2016)

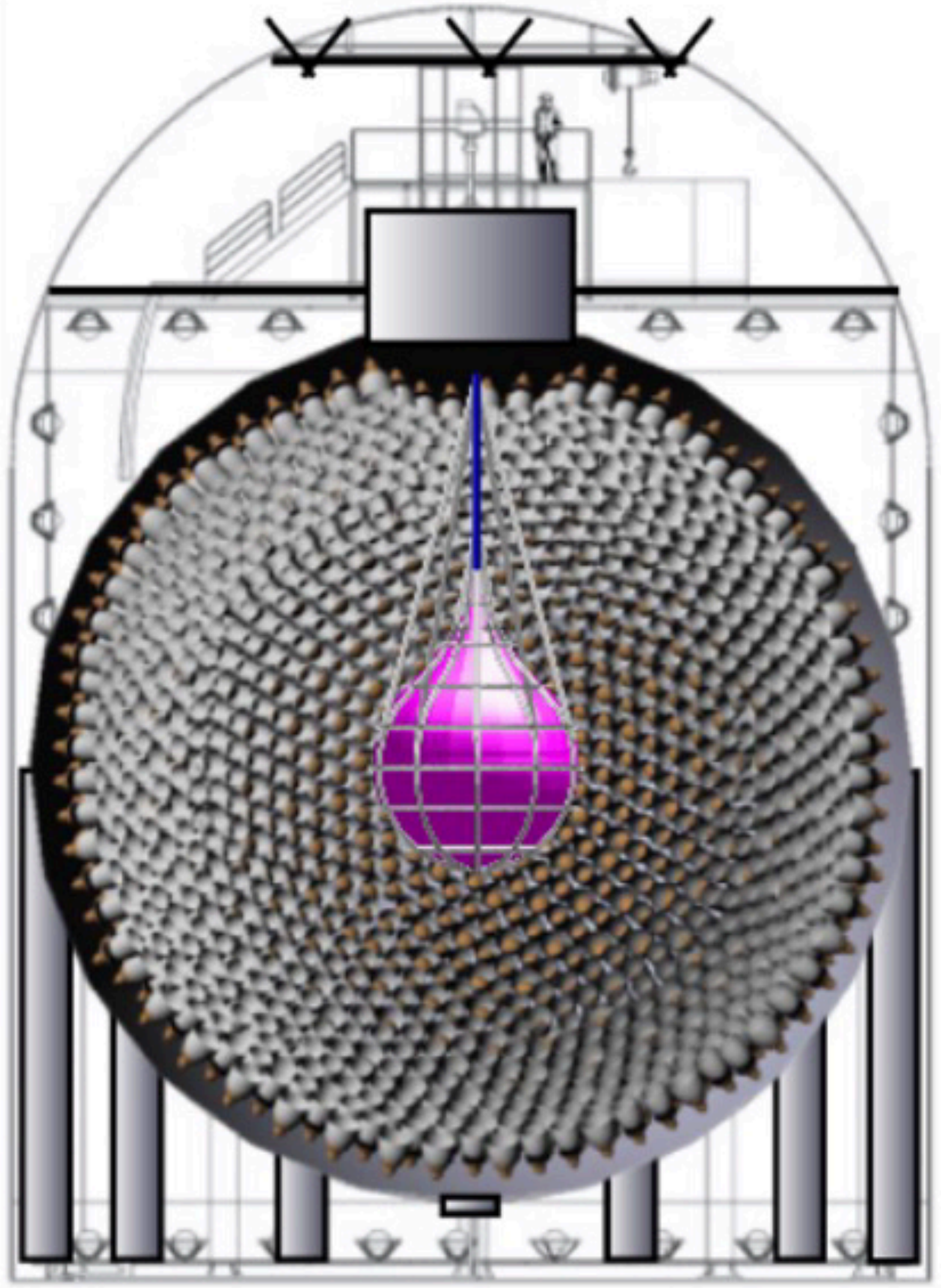
2019-present: KLZ-800



750 kg Xe

Cleaner, larger balloon

Future: KamLAND2-Zen

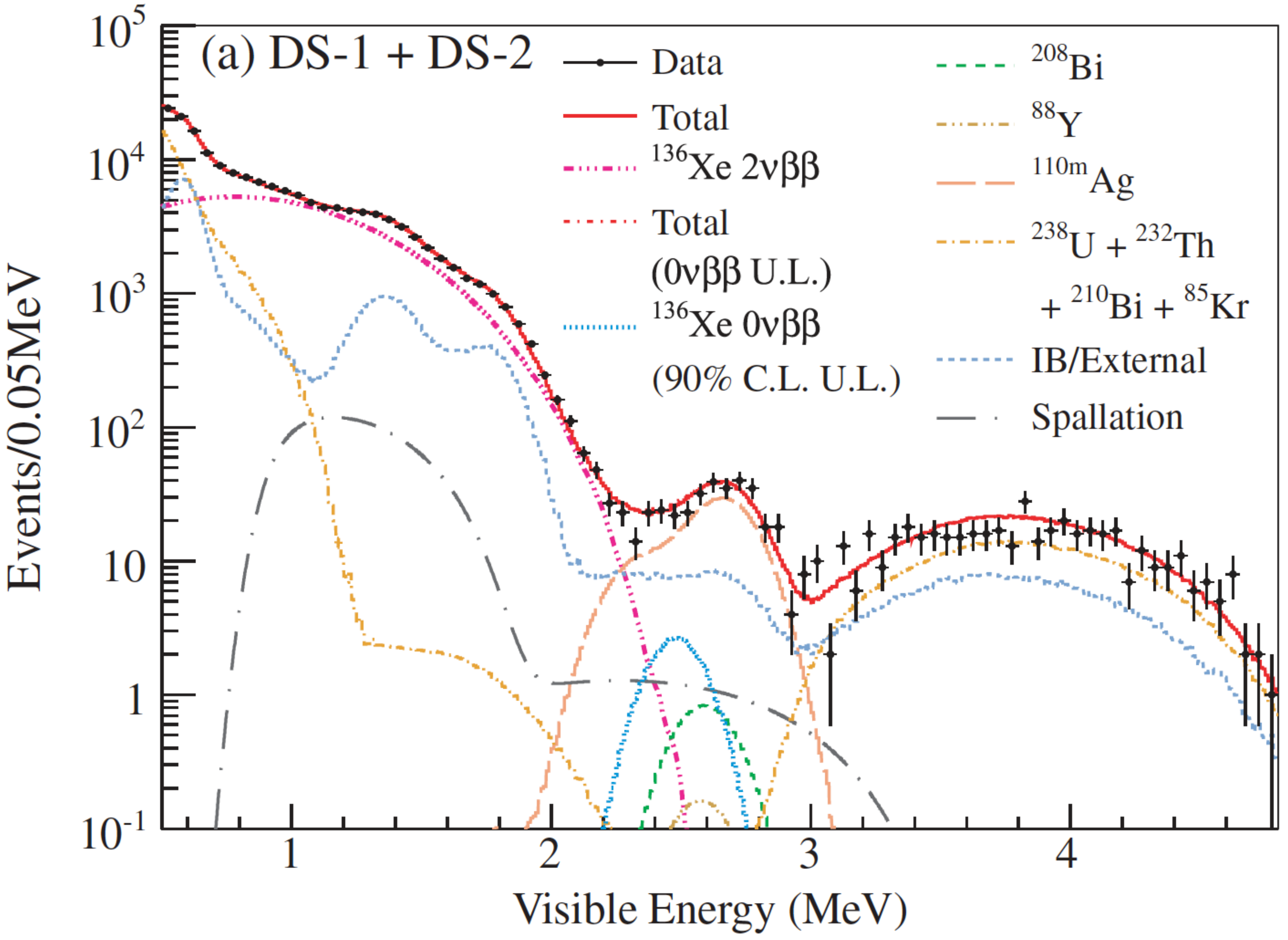


1 t Xe

Improved light collection and background rejection

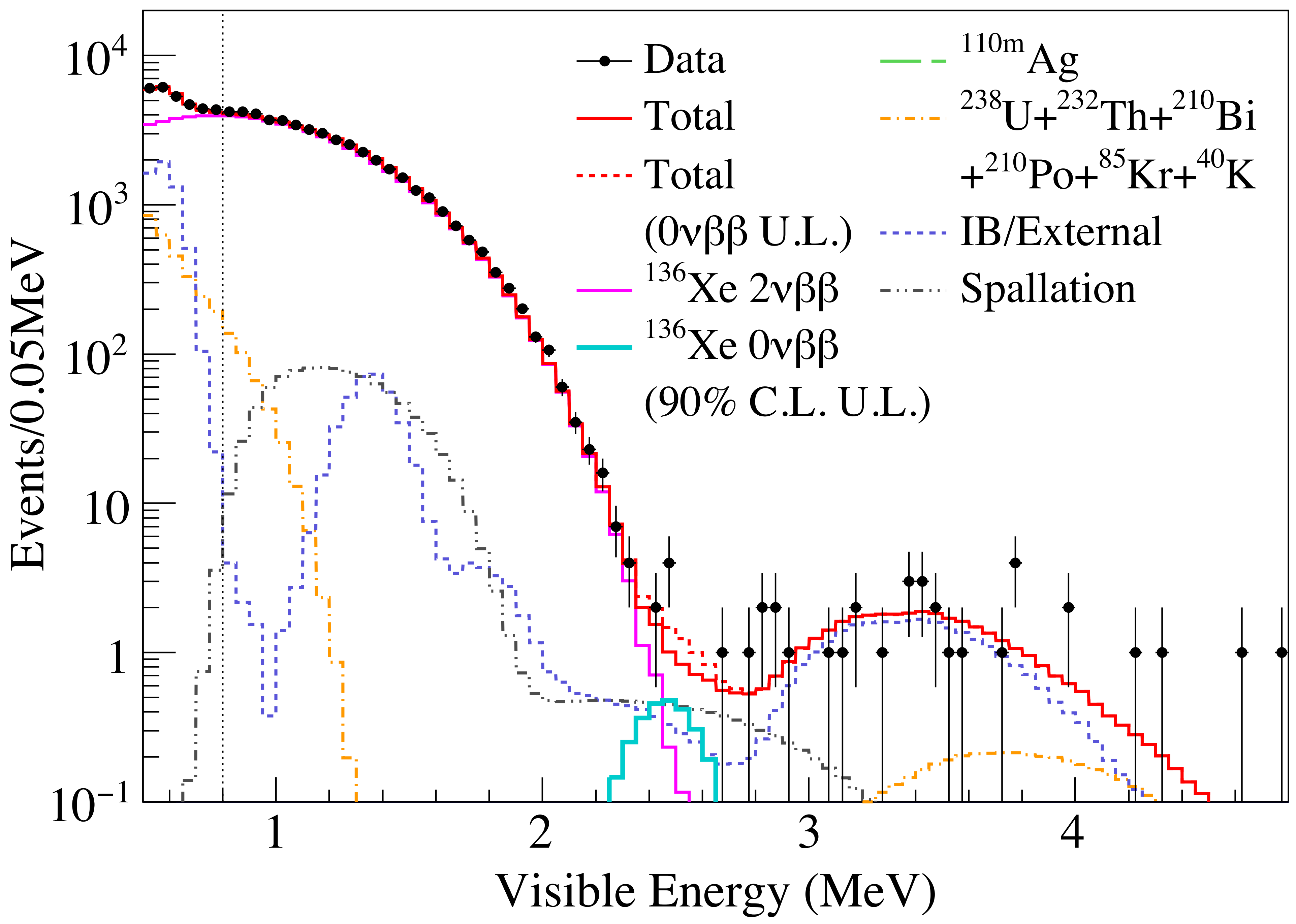
KamLAND-Zen 400 Backgrounds

Phase I spectrum: Fukushima Fallout

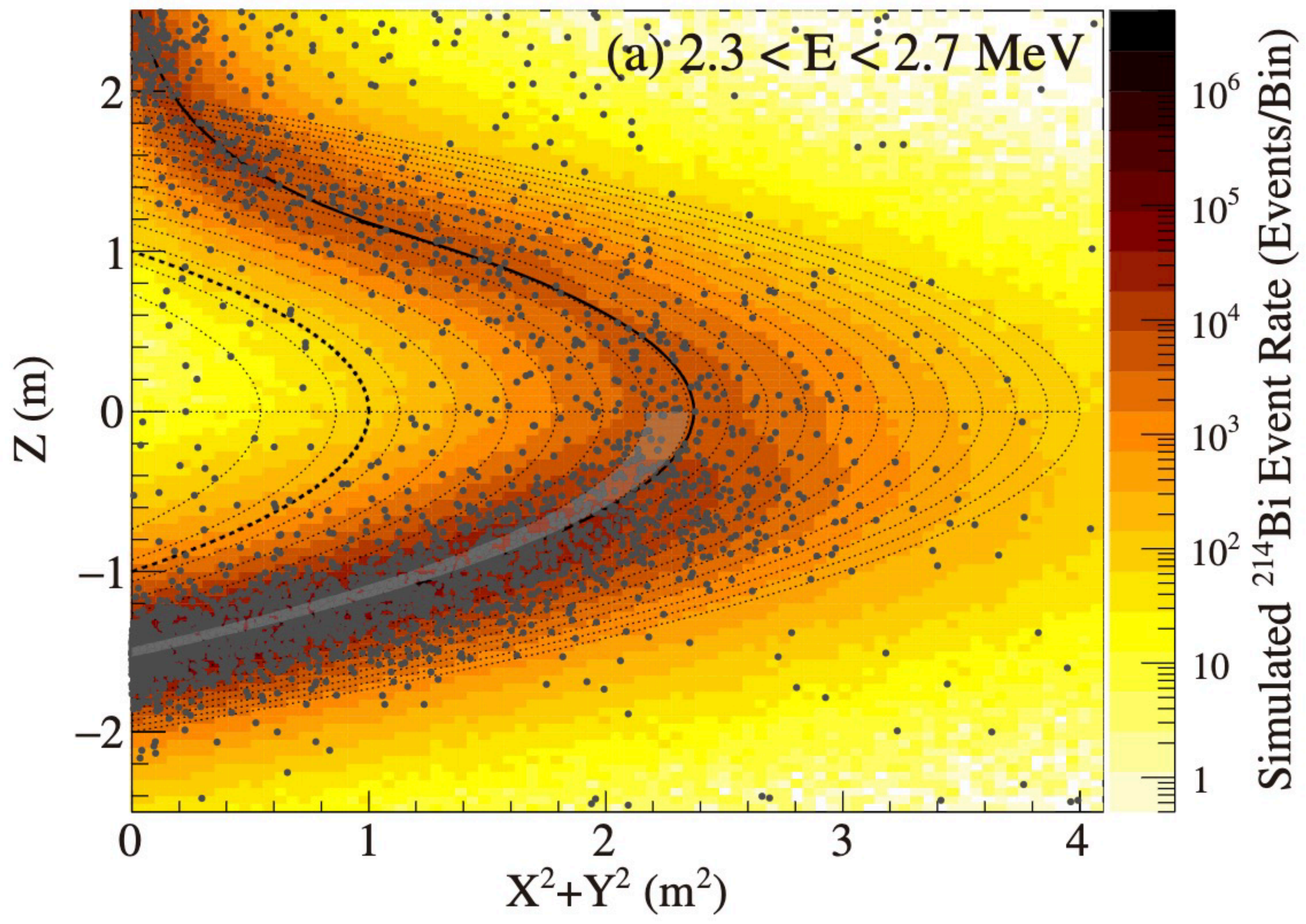


purification

Phase II spectrum

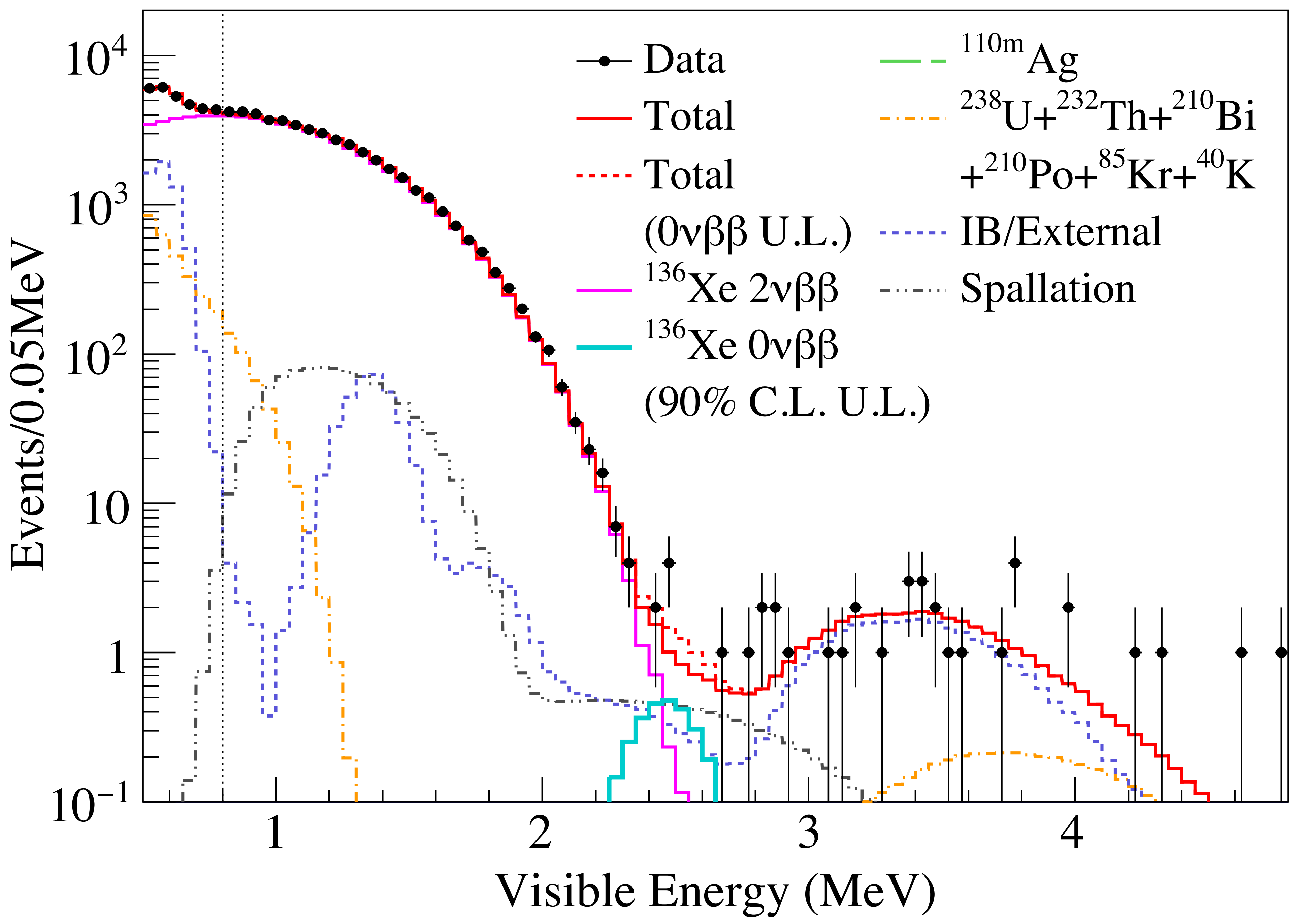


KamLAND-Zen 400 Backgrounds



Fiducial volume limited by balloon backgrounds

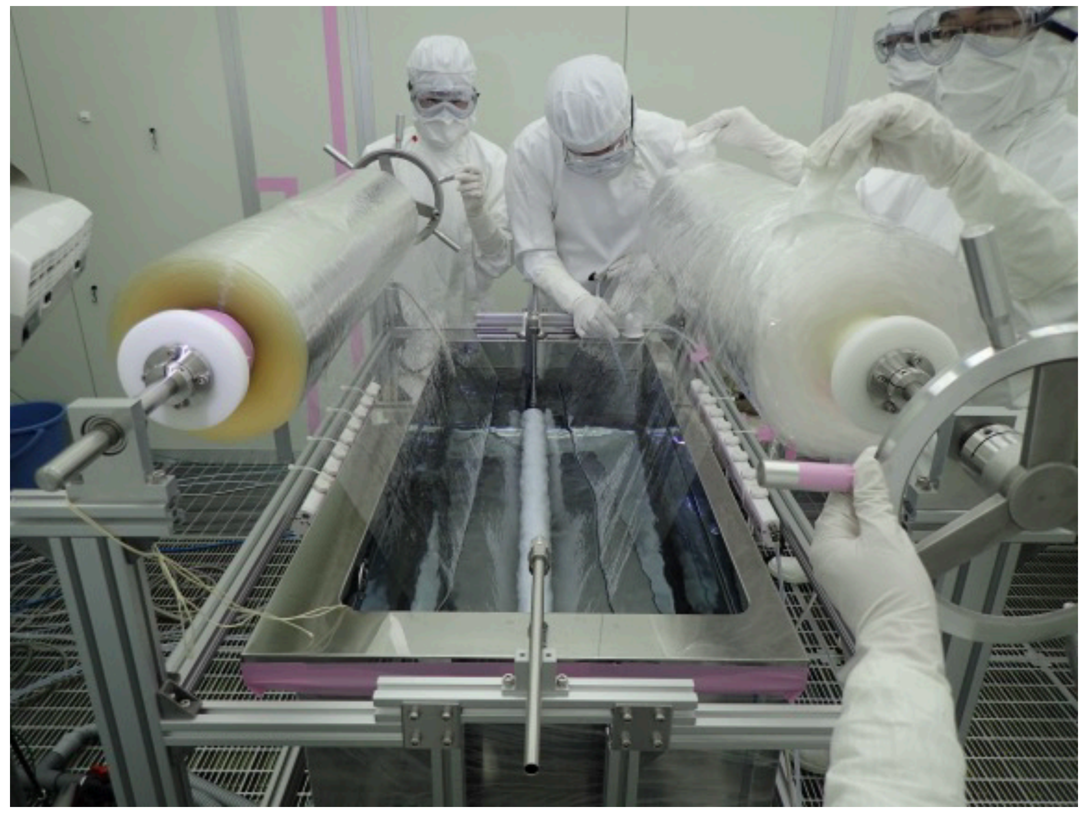
Phase II spectrum



New Balloon Fabrication

- Performed in a class 1 cleanroom
- Full body covering, laundered after each use
- All materials/tools cleaned with ethanol and pure H_2O
- 1.5 years, 20+ researchers

1. Washing



2. Cutting

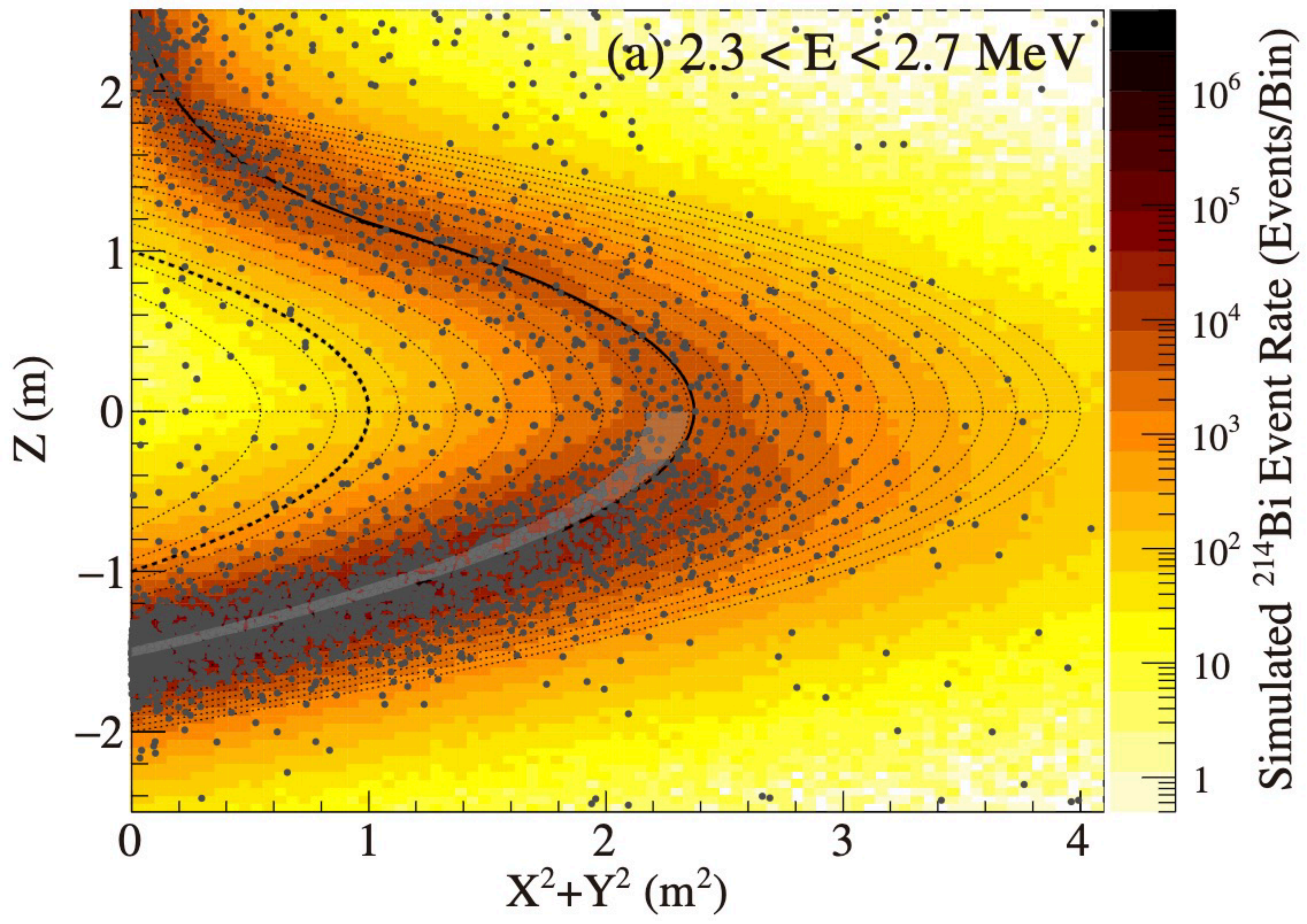
3. Welding

4. Leak tests / repairs

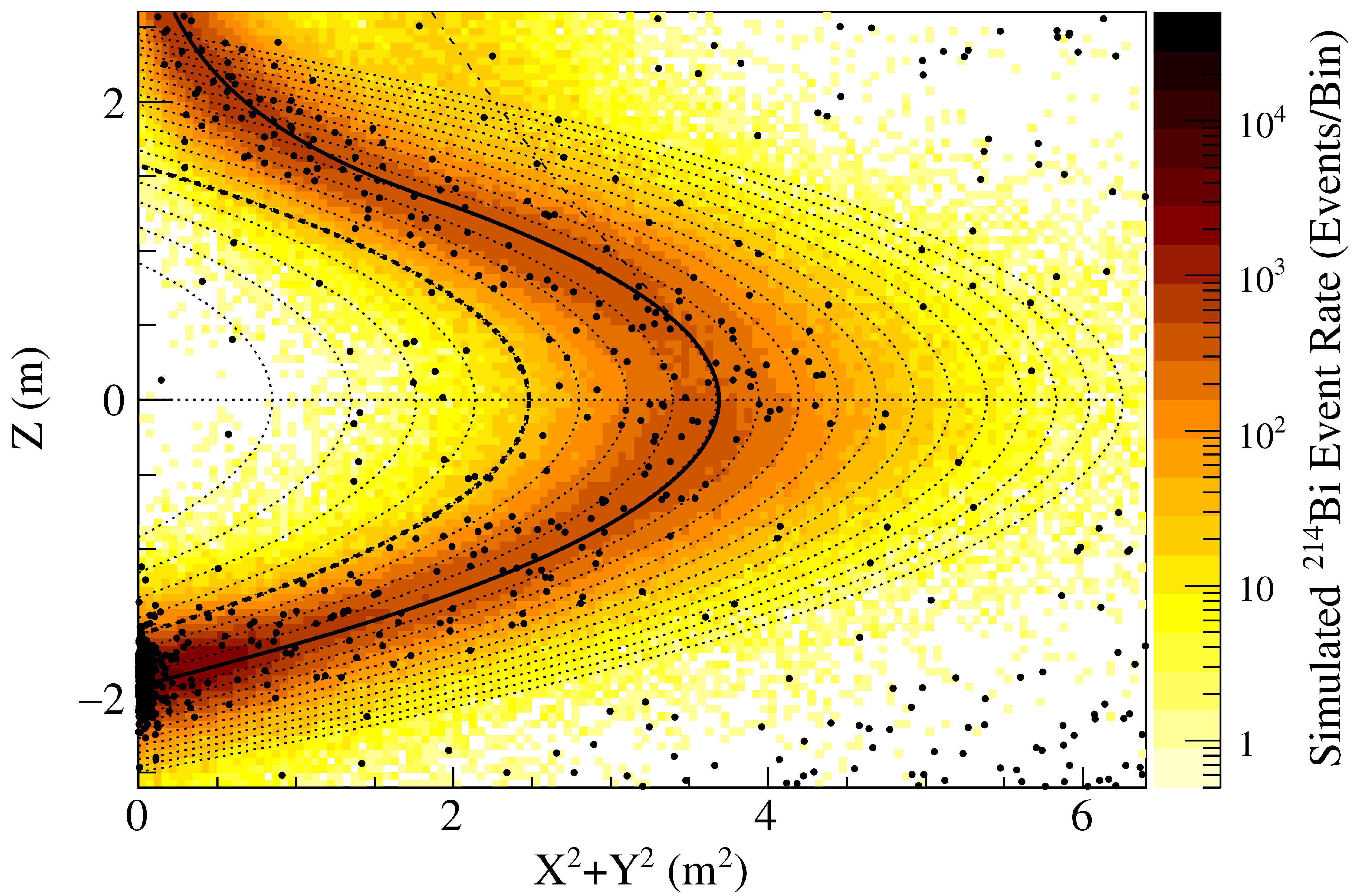
5. Deployment

Balloon Backgrounds

KamLAND-Zen 400 (530 days)



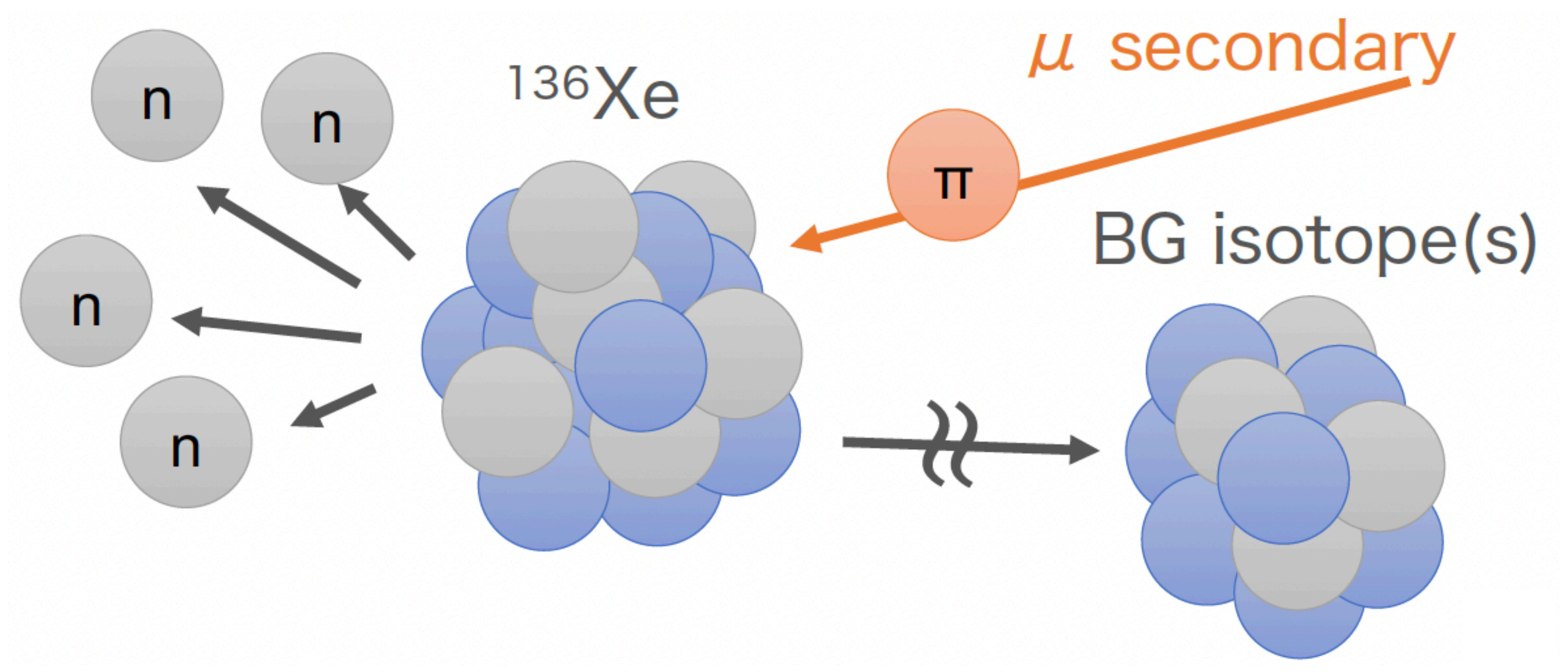
KamLAND-Zen 800 (520 days)

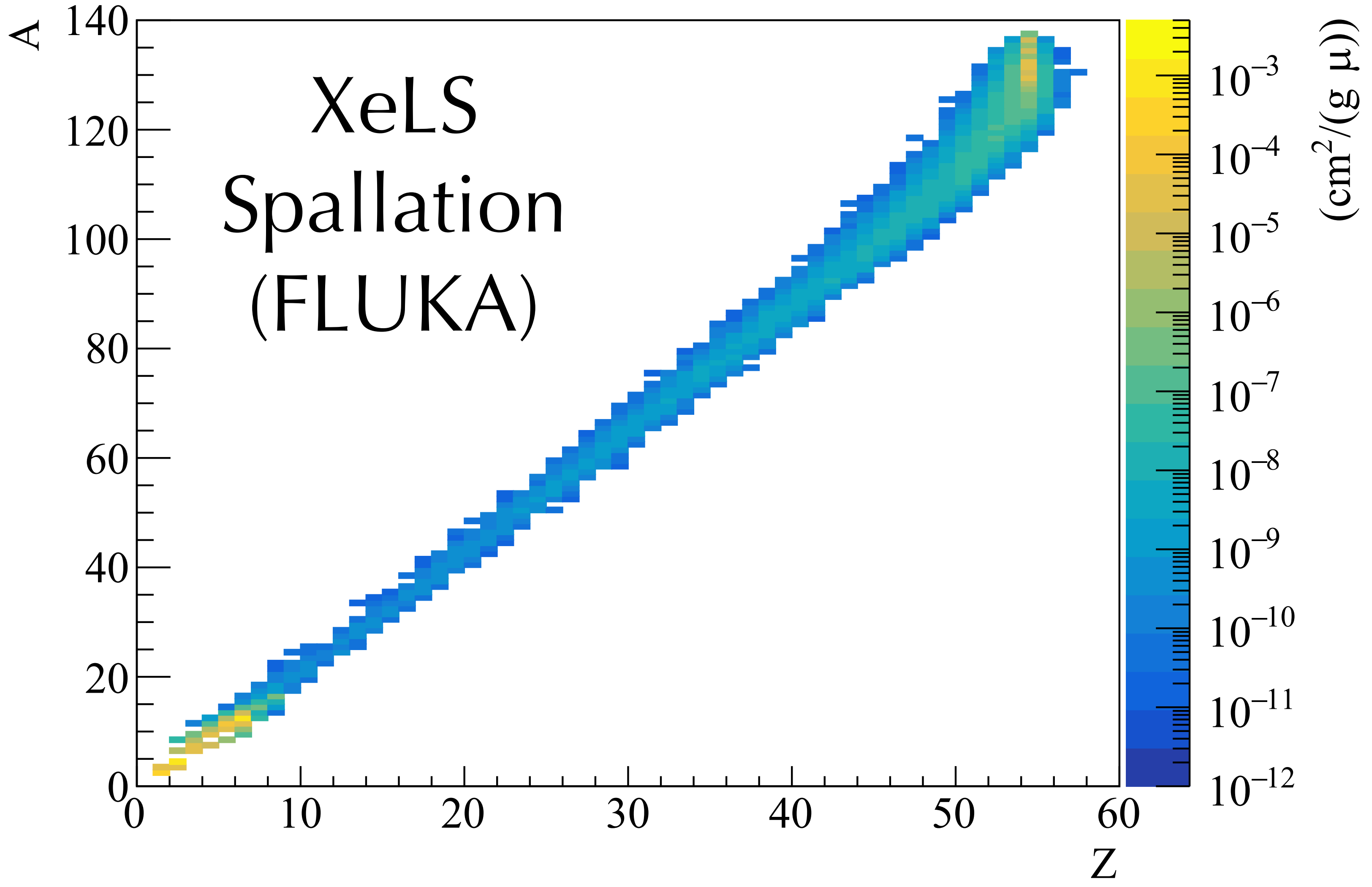


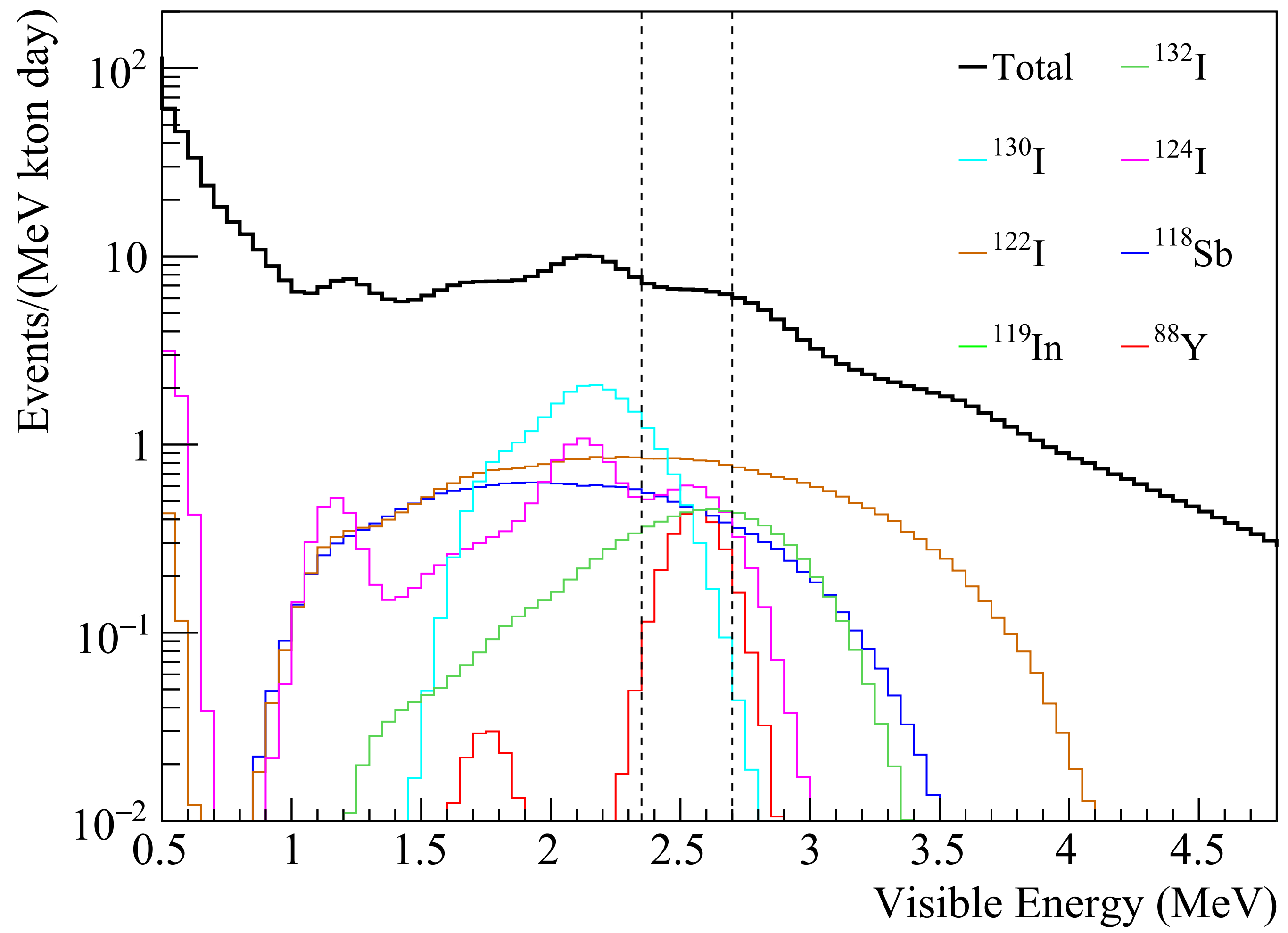
- U/Th reduced by factor of 10
- Fiducial volume increased by factor of 2.5!

Spallation Backgrounds

- Long-lived Xe spallation products are the dominant background in KLZ-800!
- Tag with 3-fold spatial / temporal coincidence
  - 42% rejection with 8.6% sacrifice

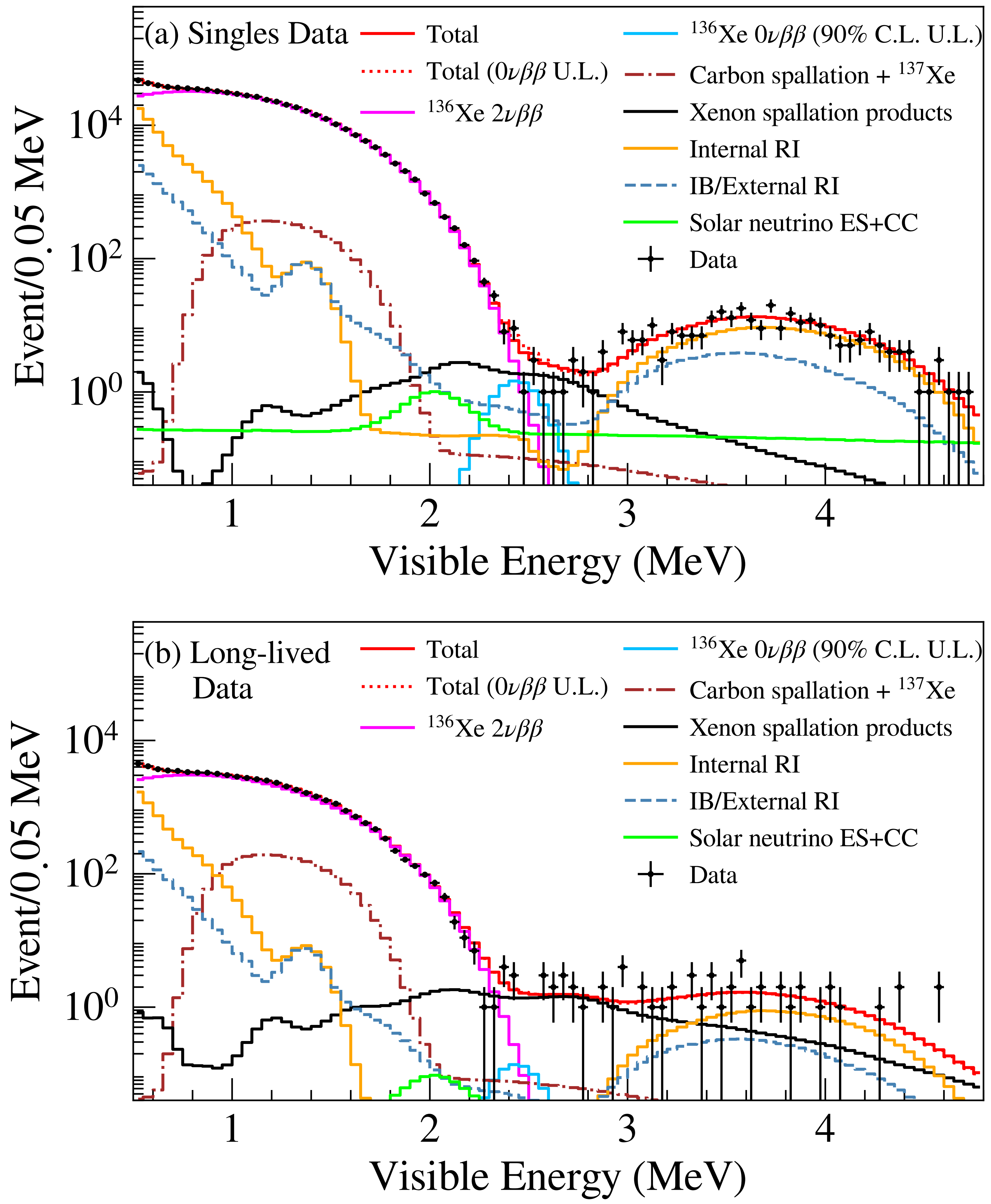


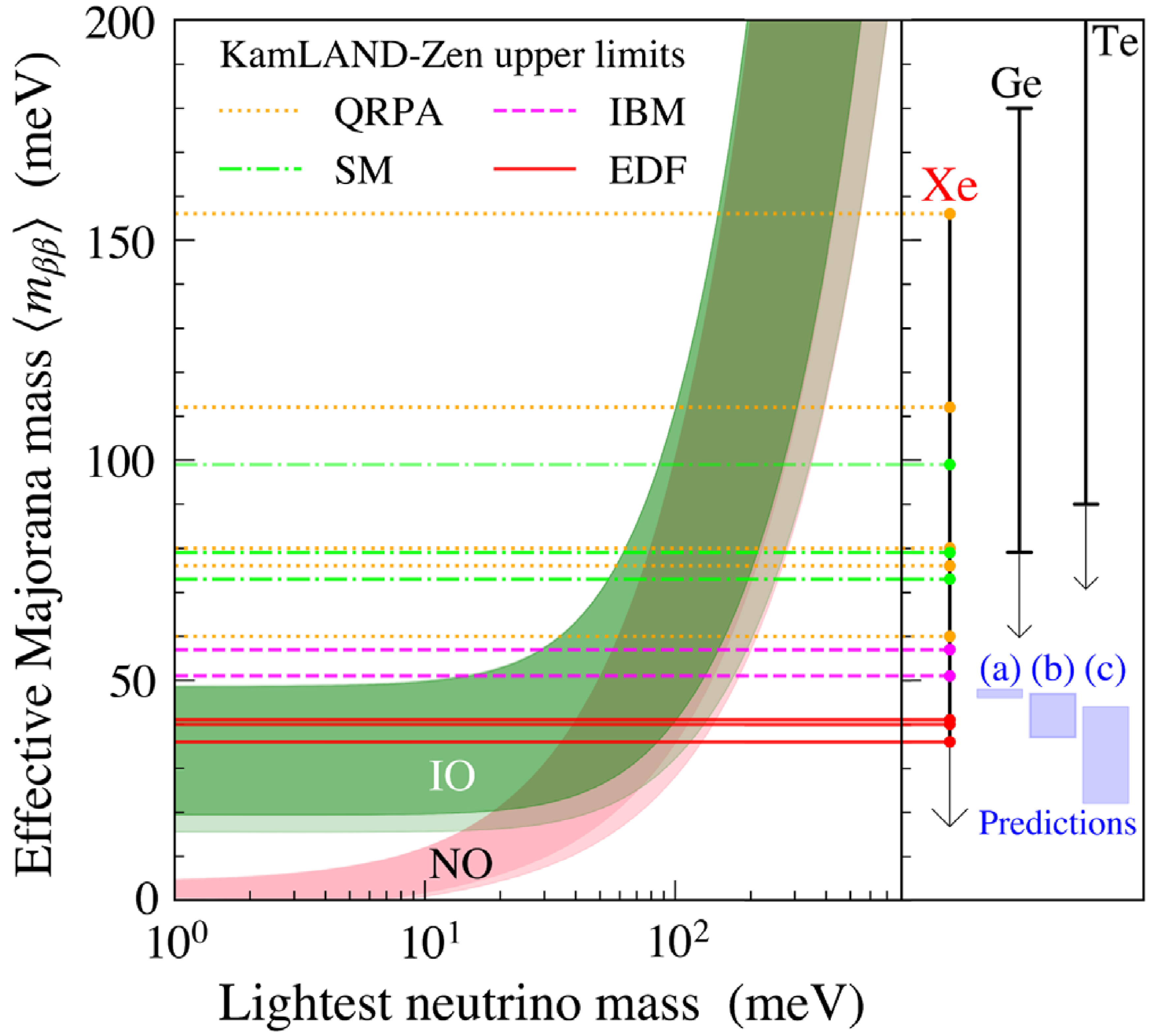




PRC **107**, 054612 (2023)

KamLAND-Zen 800 Results

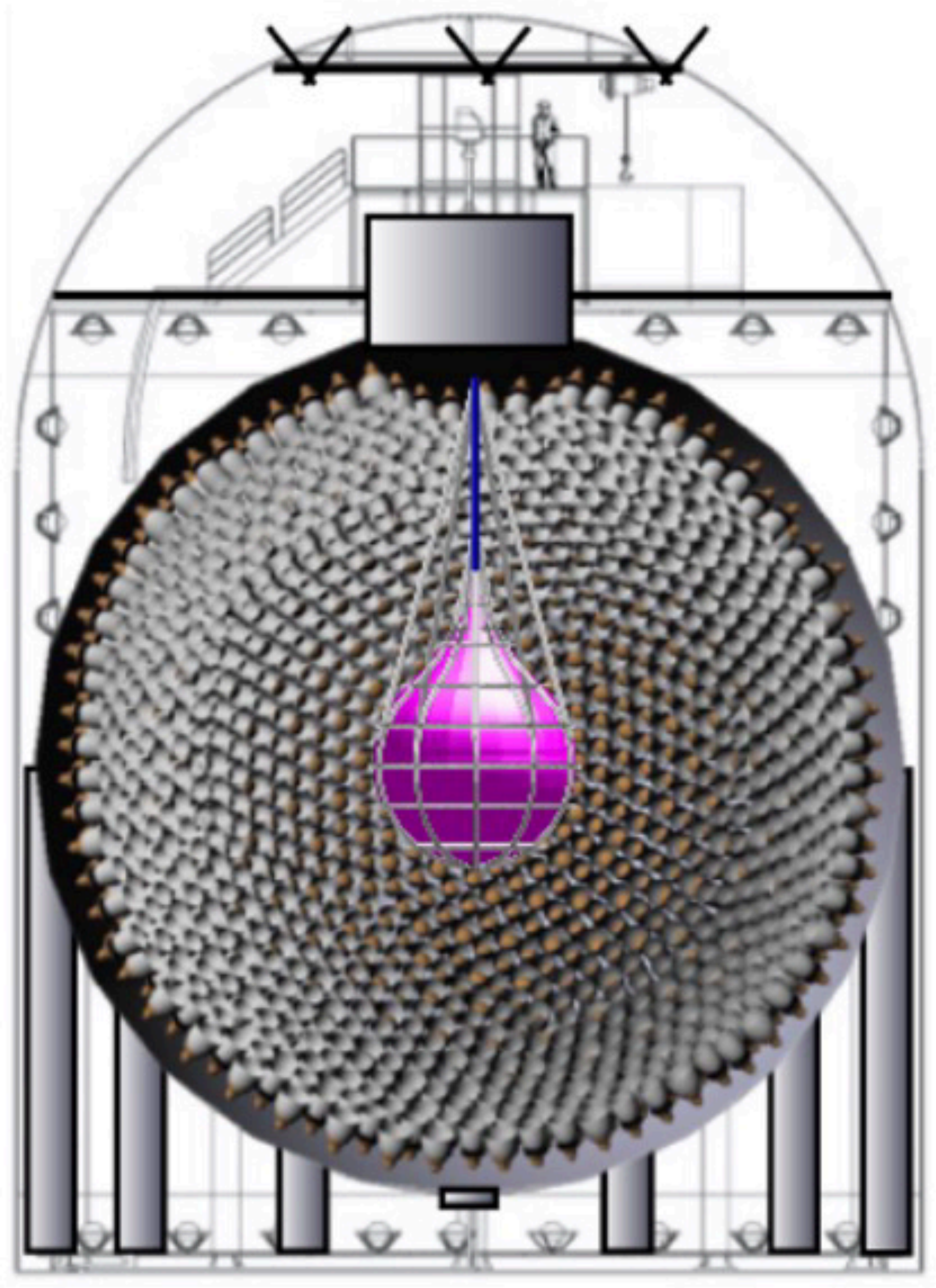




970 kg yr exposure
Combined with KLZ-400
$T_{1/2} > 2.3 \times 10^{26}$ yr

Future: KamLAND2-Zen

- Improved energy resolution (x5 increased light collection)
  - Higher light yield LS (x1.4)
  - New high-quantum-efficiency PMTs (x1.9)
  - Light-collecting Winston cones (x1.8)
- Improved background rejection
  - New scintillating mini-balloon
  - Upgraded electronics (~100% spallation *n* detection)
- More xenon (→ 1 ton)
- Target half-life sensitivity: 2 x 10^{27} yr ($m_{\beta\beta}$ ~ 20 meV)



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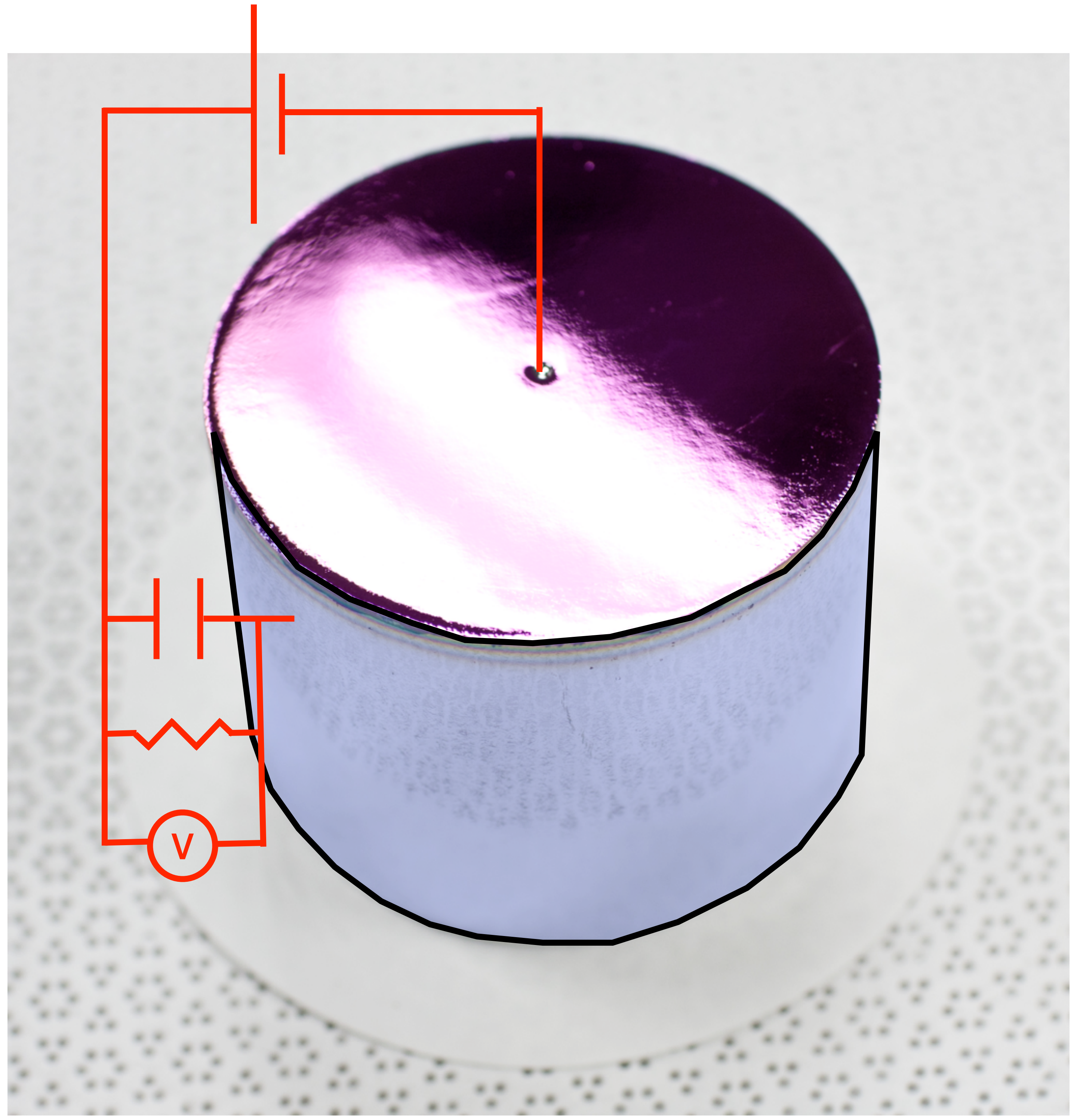
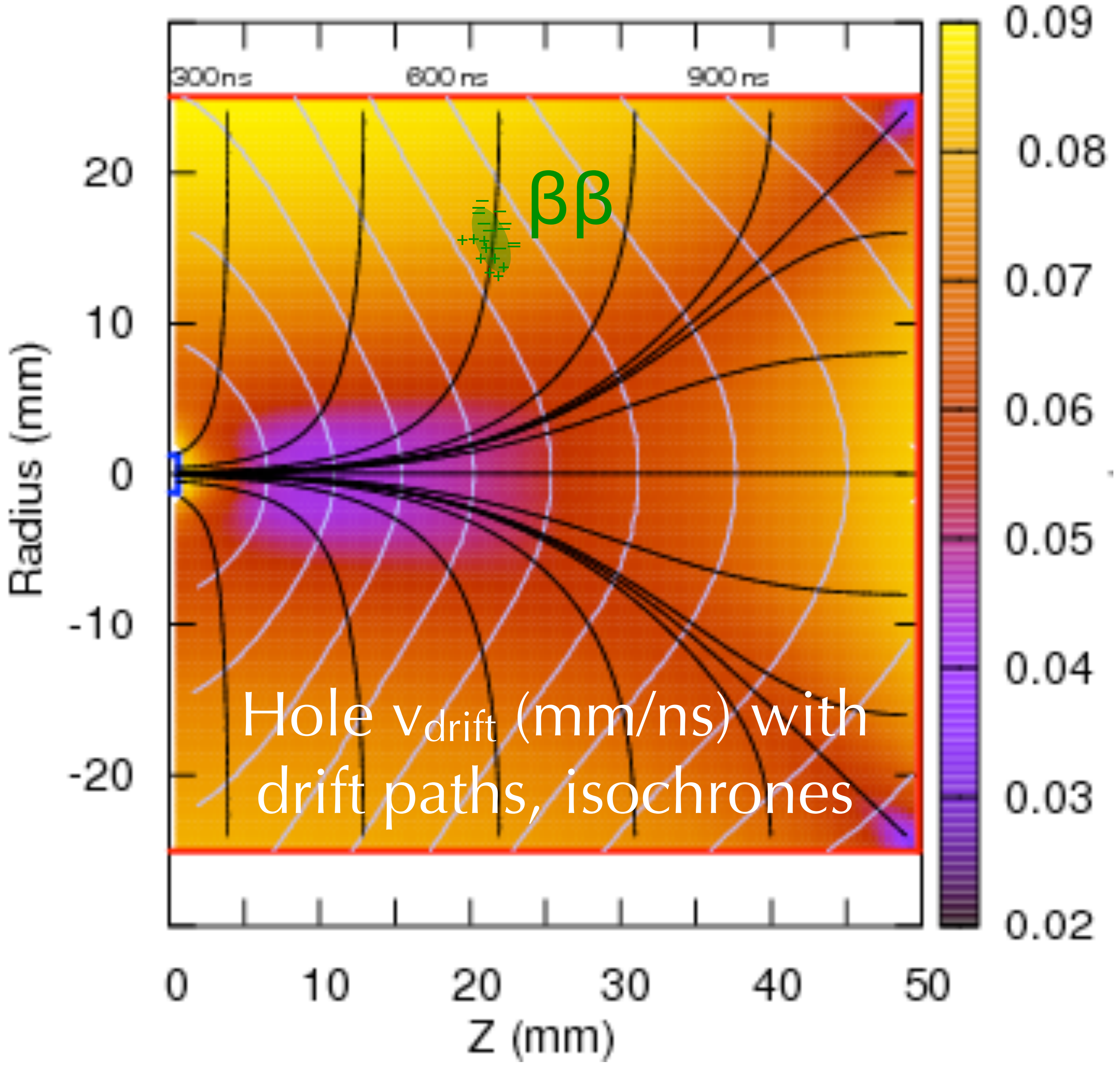
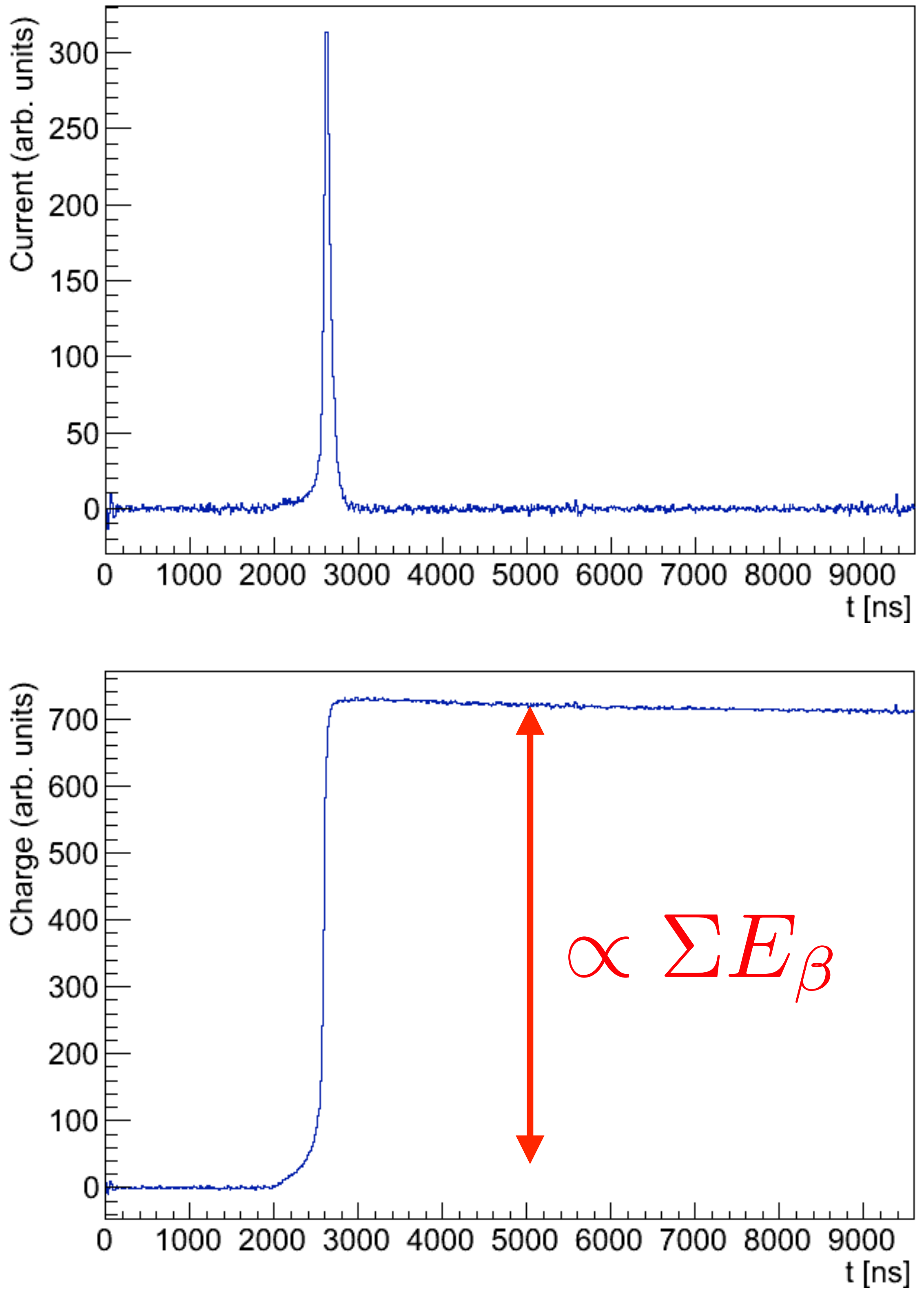
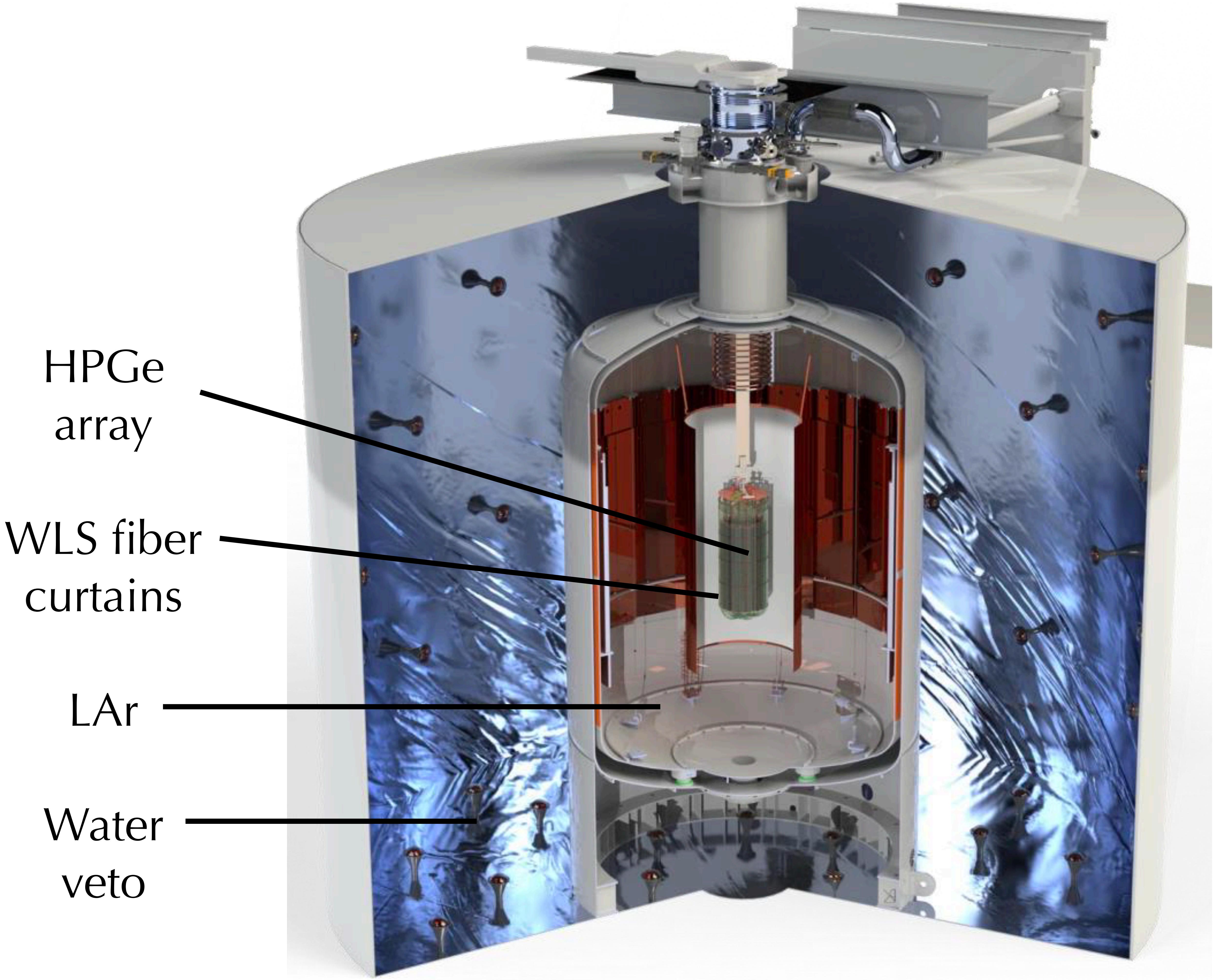
Germanium Detectors







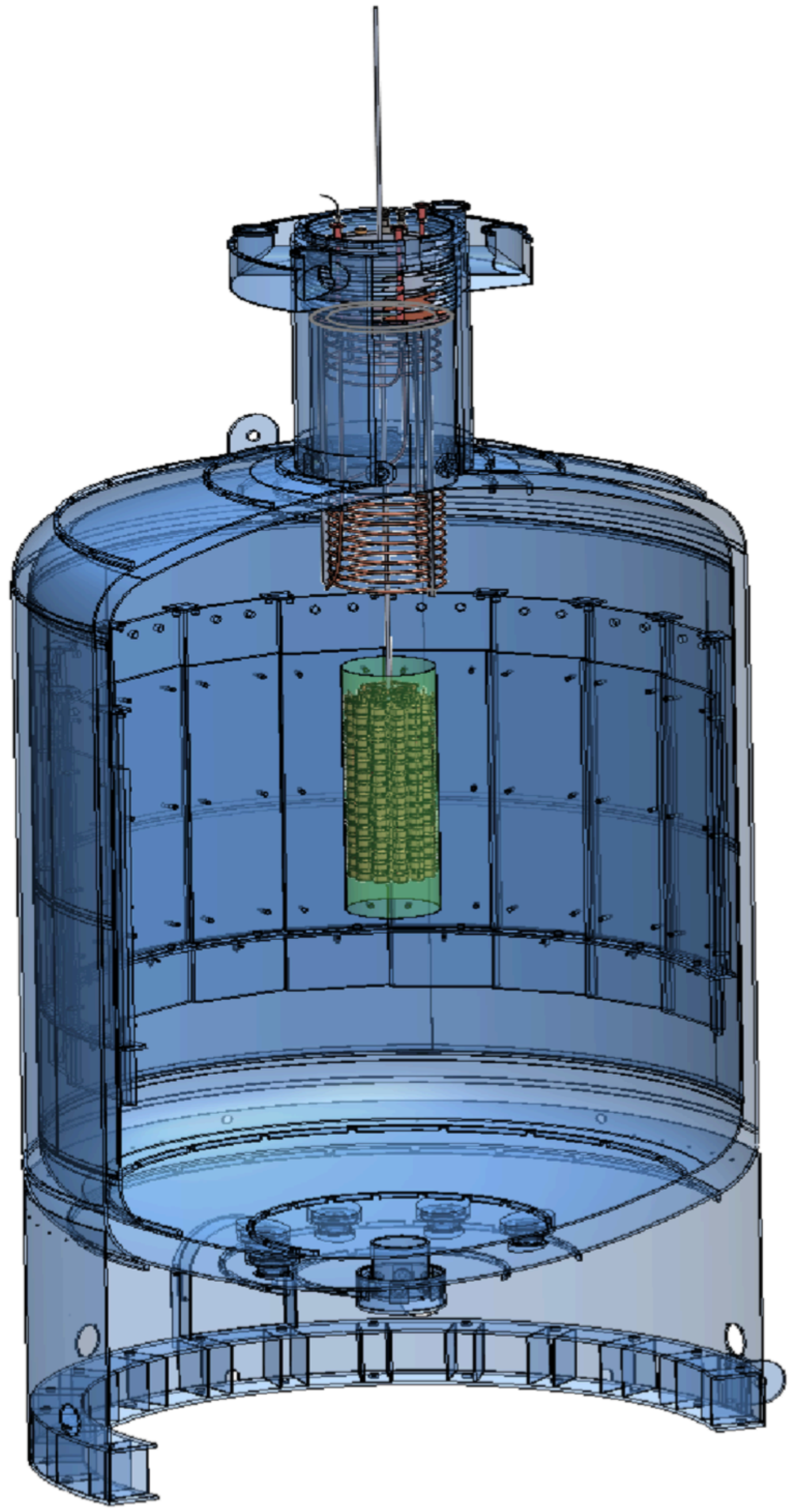
LEGEND



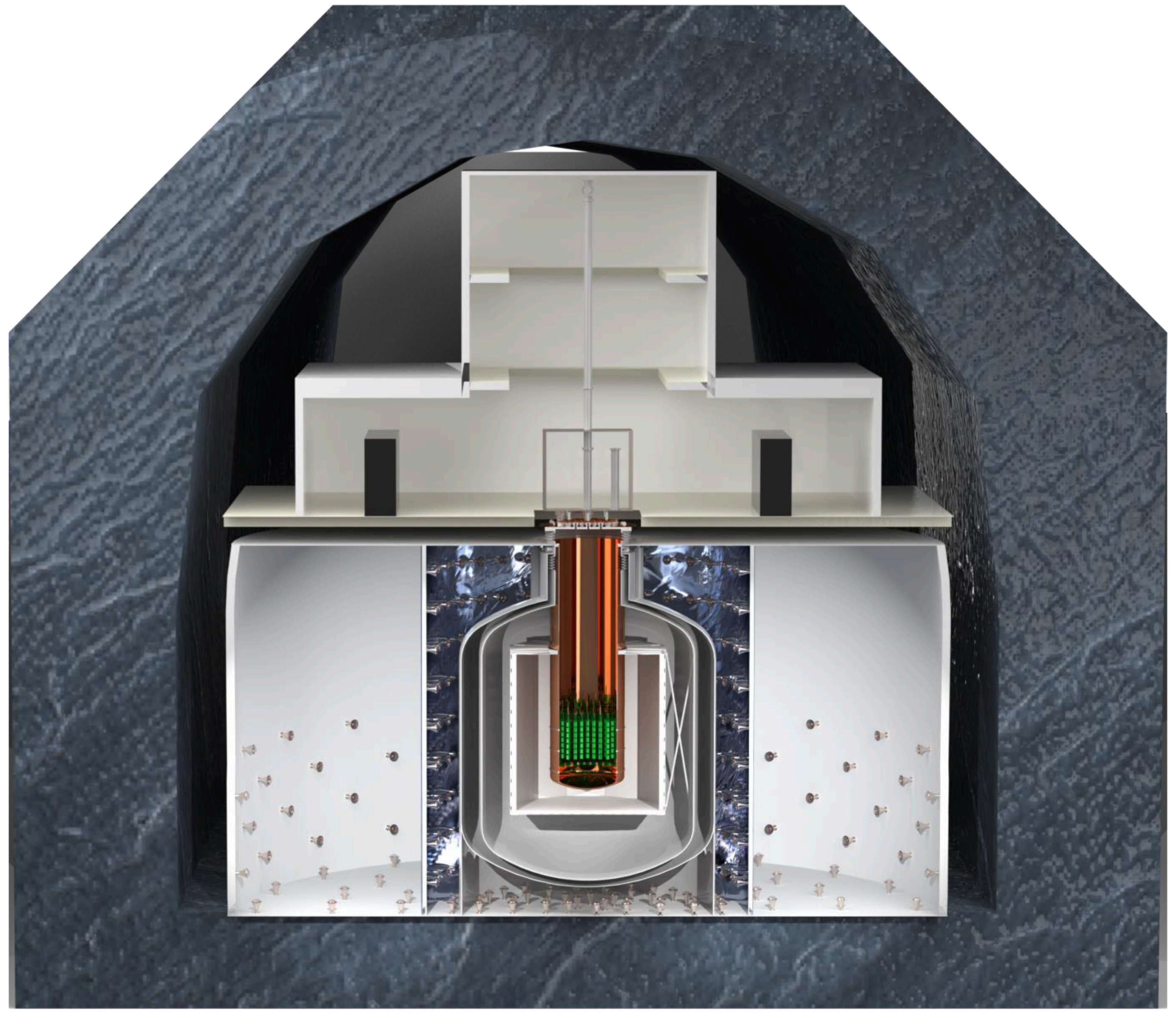
~60 Institutions, ~300 Scientists

LEGEND Stages

- LEGEND 200
  - 200 kg in upgrade of existing GERDA infrastructure at LNGS
  - Reuses GERDA and MAJORANA enriched detectors (~60 kg) and adds new detectors (~140 kg)
  - Background goal: 0.6 cts/(FWHM t yr)
  - Data taking is underway
- LEGEND 1000
  - 1000 kg (staged in ~250 kg payloads)
  - Uses underground argon (eliminate ^{42}Ar and ^{39}Ar)
  - Background goal: <0.1 cts/(FWHM t yr)
  - Location: SNOLAB or LNGS



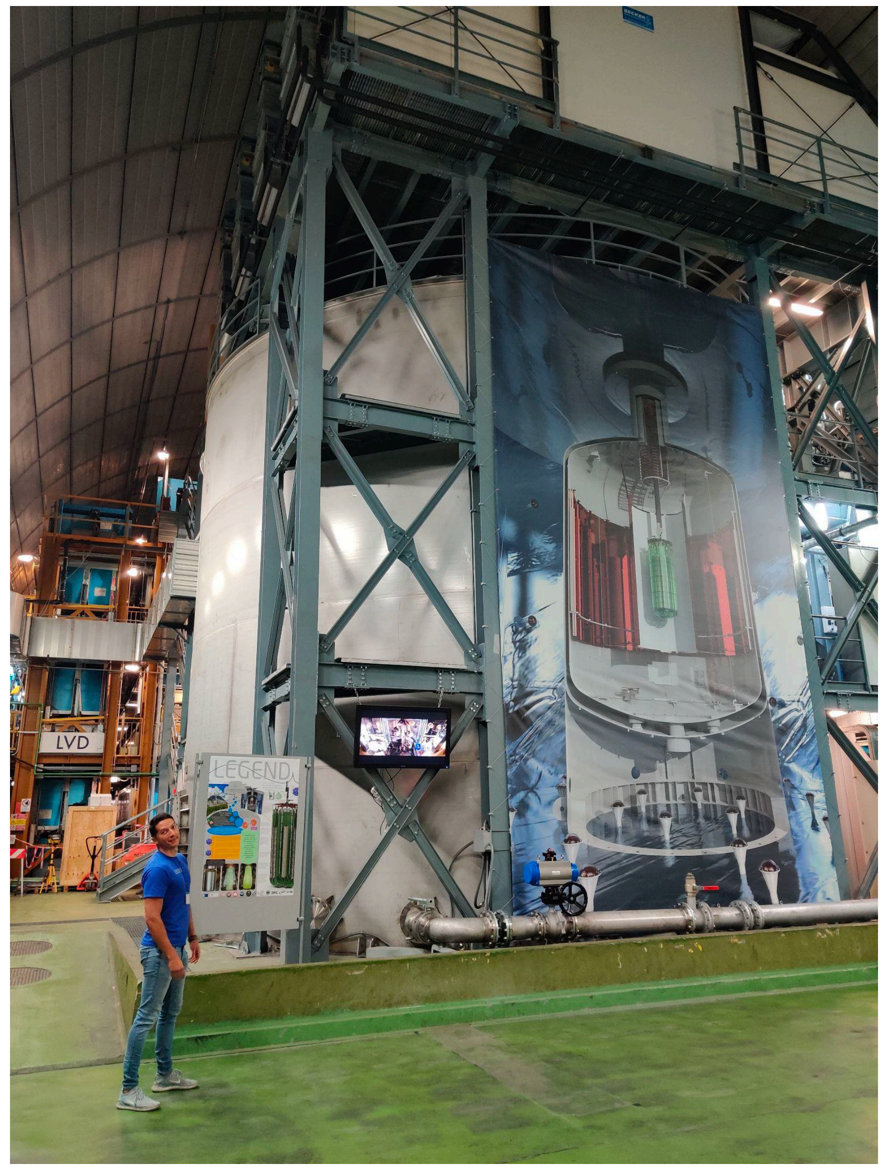
LEGEND 200



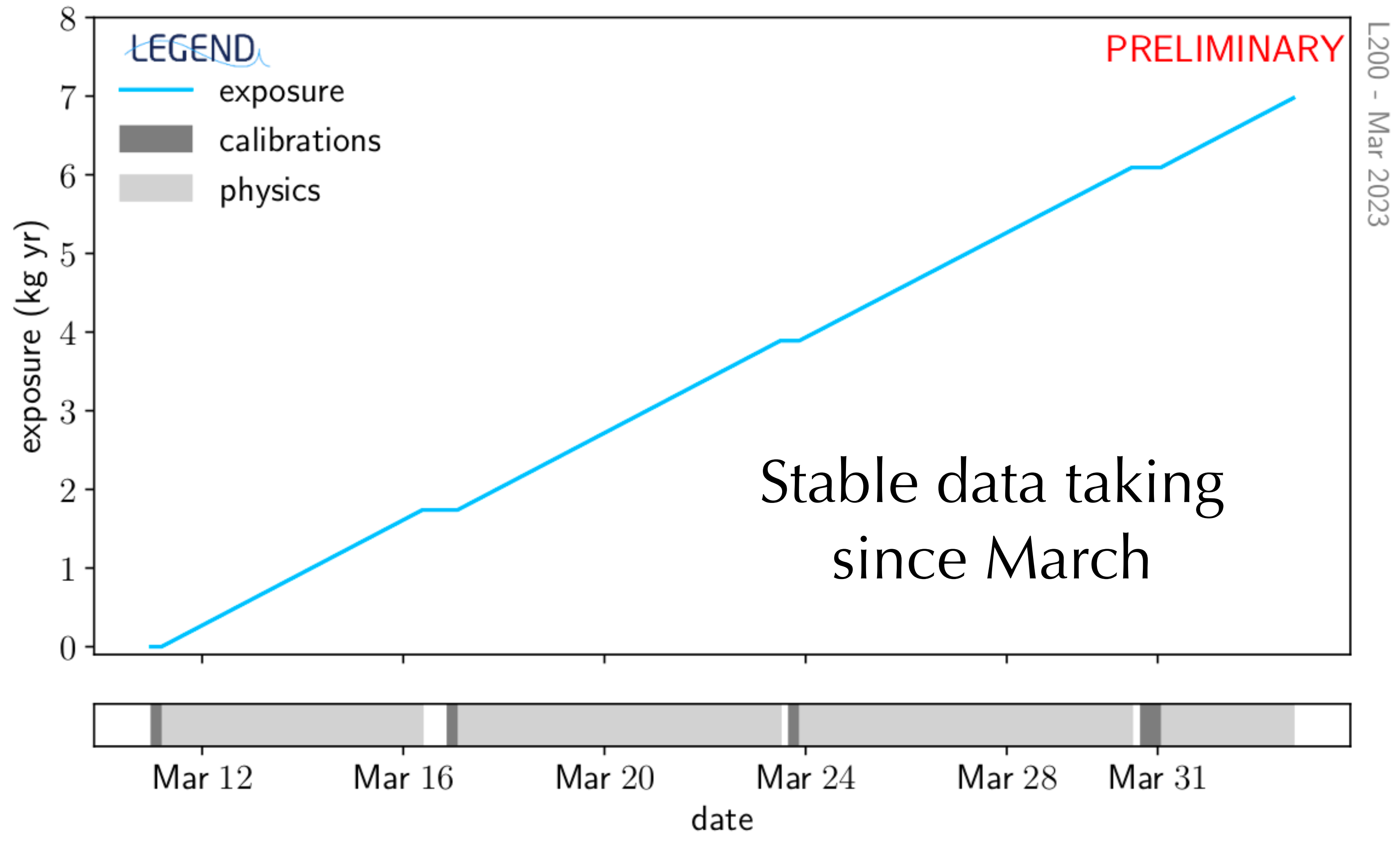
LEGEND 1000

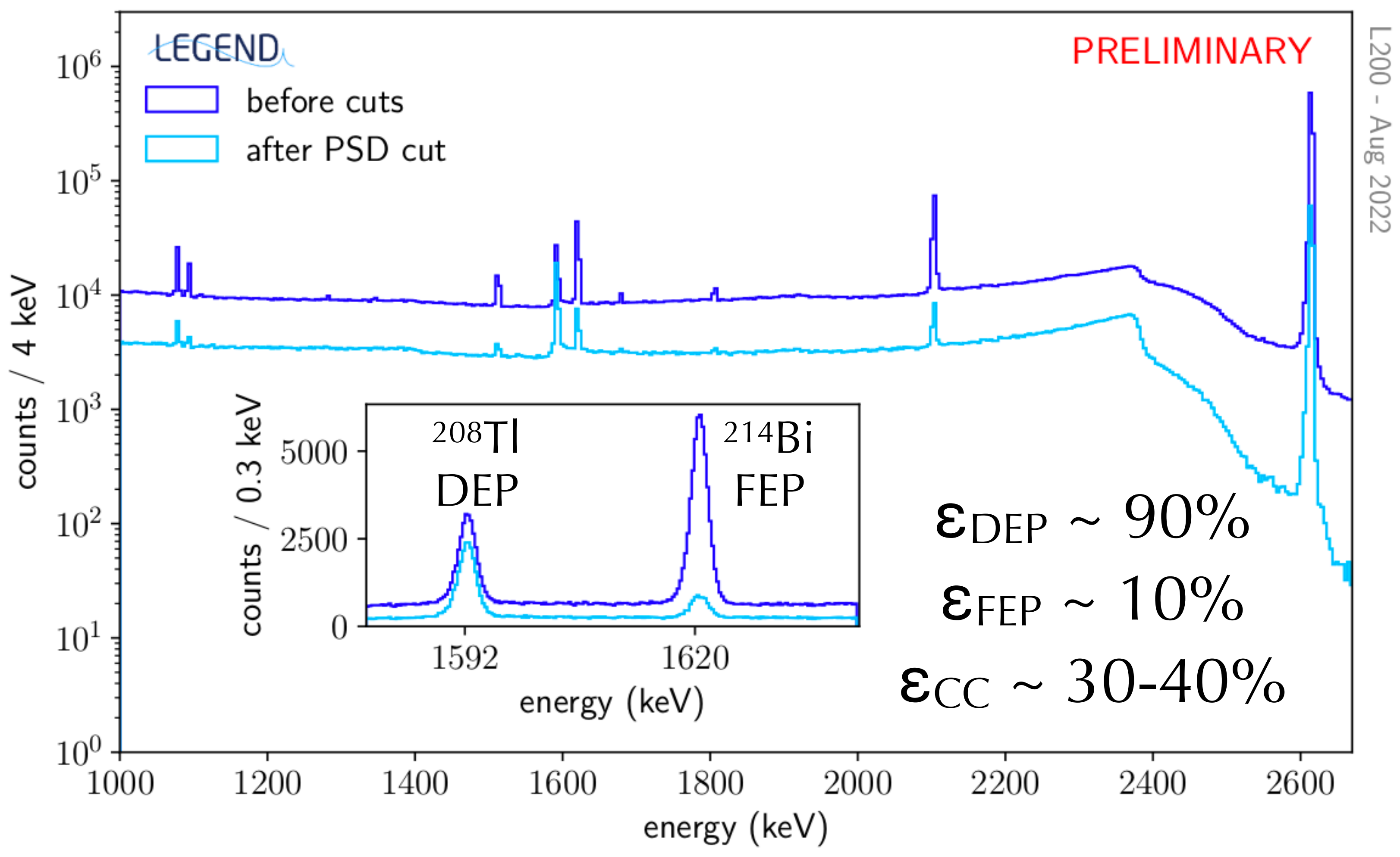
LEGEND-200 Status

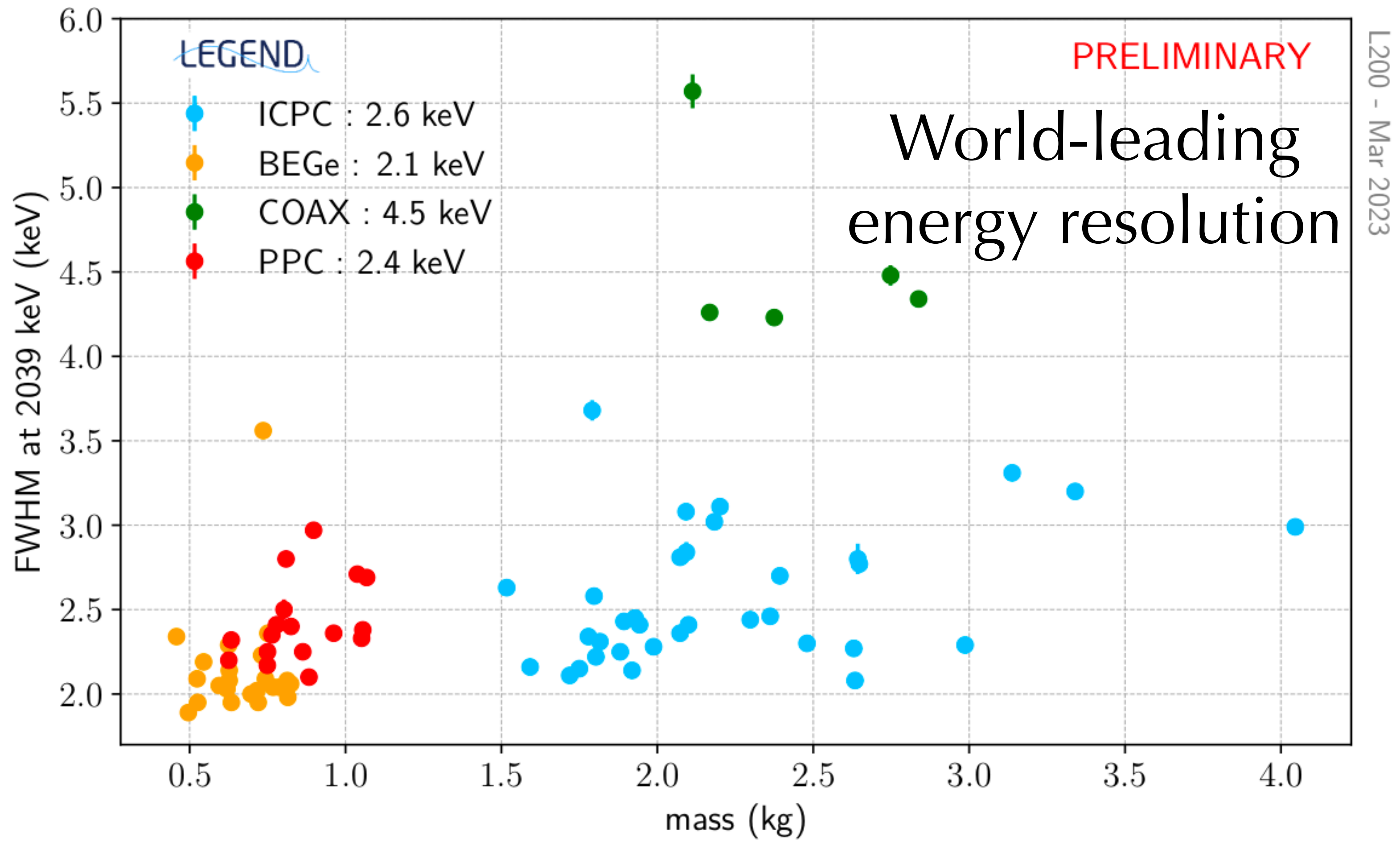
- Cryostat upgrade completed, LAr filling in 2021
- LAr instrumentation, Ge readout implementation, deployment of “the lock” in early 2022
- “L60” commissioning runs taken over summer 2022
- First 140 kg of L200 installed last fall
- Physics data taking in progress!

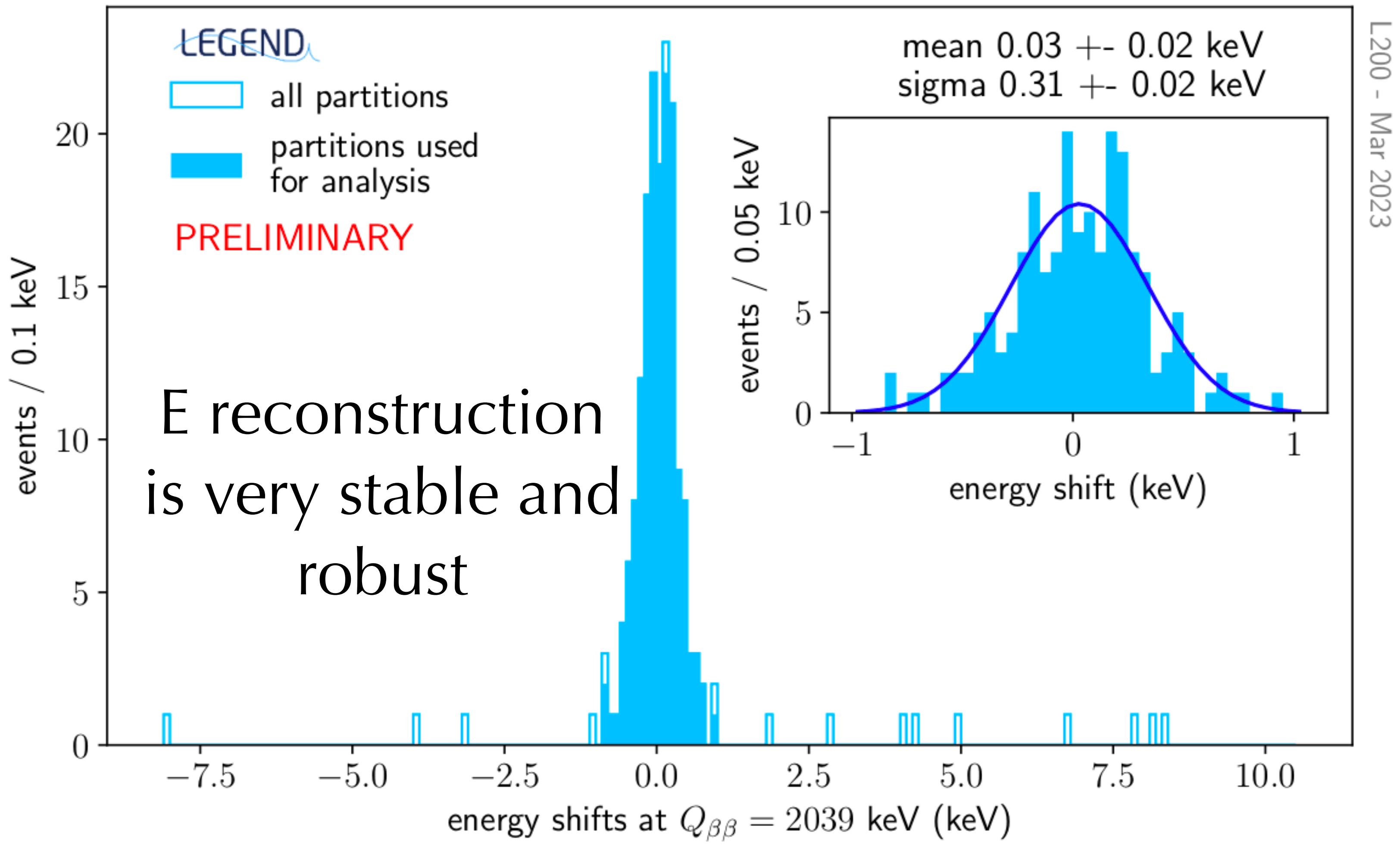


L200 Preliminary Data





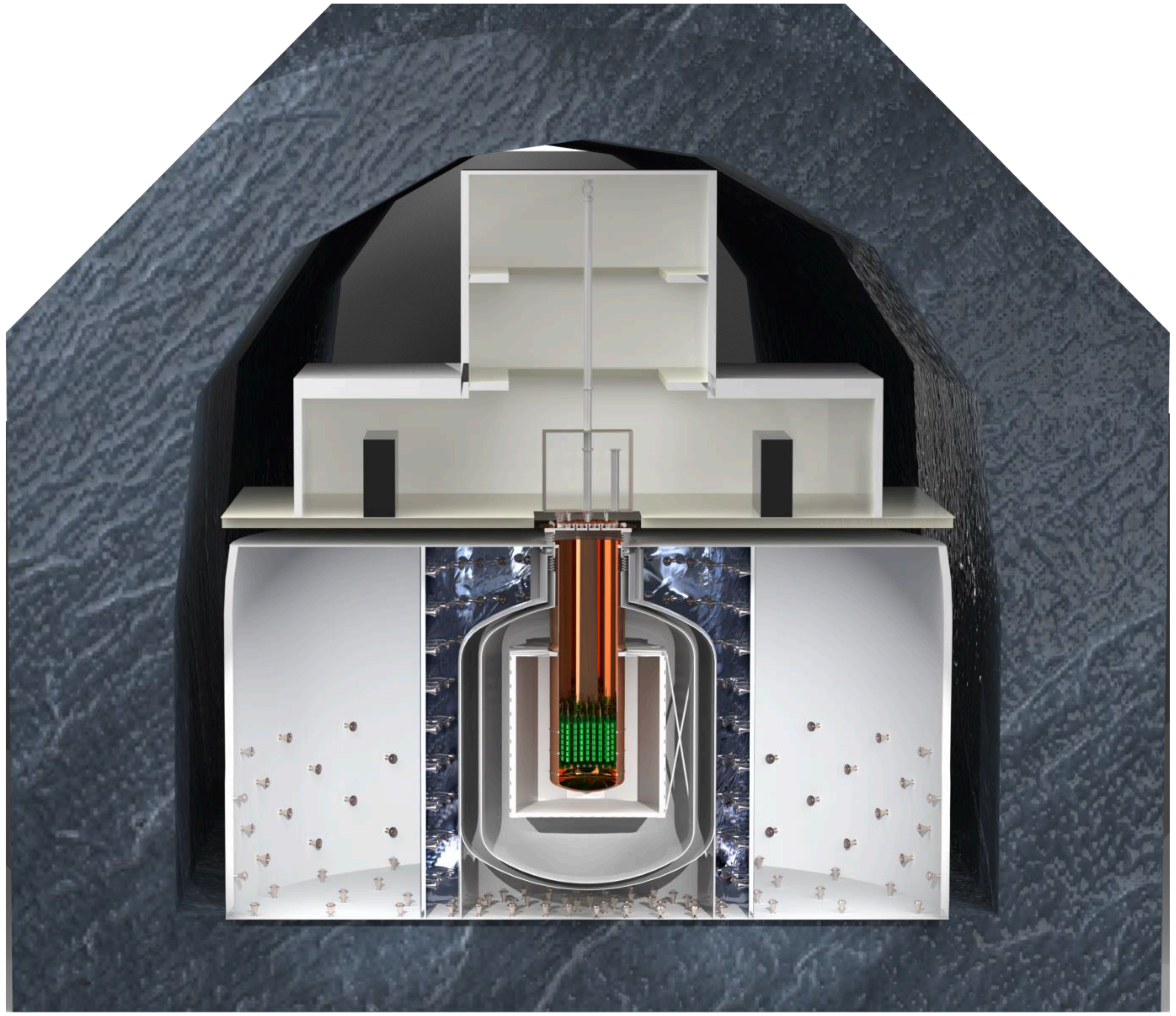




Stay tuned!

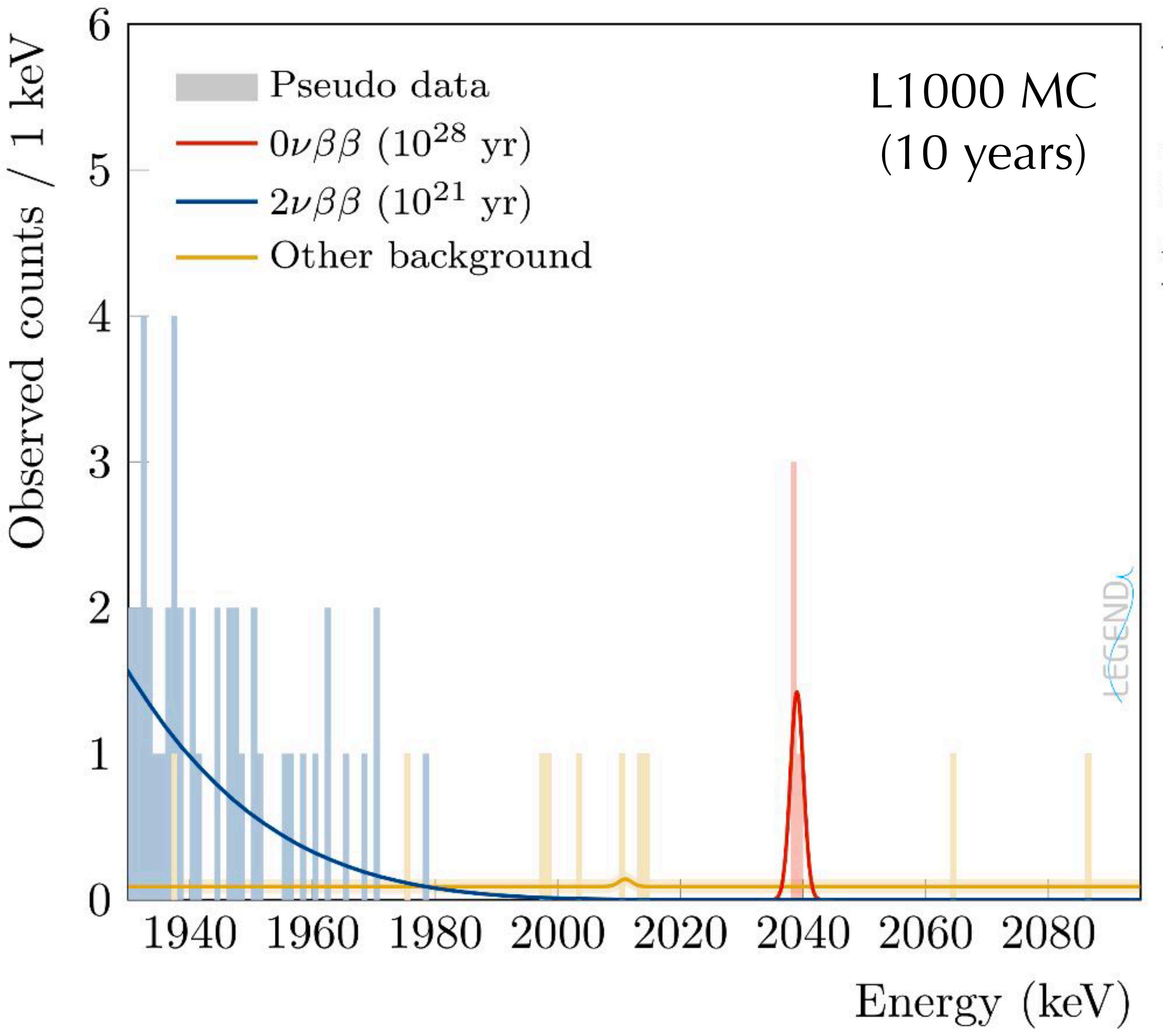
LEGEND-1000 Status

- Preliminary conceptual design: arXiv:2107.11462
- Successful performance at 2021 DOE "Portfolio Review"
- Site selection underway (in conjunction with DOE "Analysis of Alternatives" process)
- Preparing for "CD1" Conceptual Design Review this Winter



LEGEND Sensitivity

- Expect a clear peak over a quasi-background-free continuum near $Q_{\beta\beta}$
- LEGEND 200: $T_{1/2} > 10^{27}$ yr
- LEGEND 1000: $T_{1/2} > 10^{28}$ yr
  - 3σ discovery sensitivity covers the inverted ordering



Summary

- Discovery of neutrinoless double beta decay would be the first observation of matter creation (without antimatter) by humans, and is deeply important.
- KamLAND-Zen's high-exposure strategy has produced leading half-life limits; KamLAND2-Zen will push this technology further.
- LEGEND's low-background approach is poised to lead the field in the coming years. LEGEND-200 is taking data, and LEGEND-1000 is in preparation.
- The international experimental program in both experiment and theory is robust and aggressive. A steady march in sensitivity improvement is expected for at least a decade. Discovery could come at any time!