



Manchester 0v2b workshop, September 2026

Towards KamLAND2-Zen

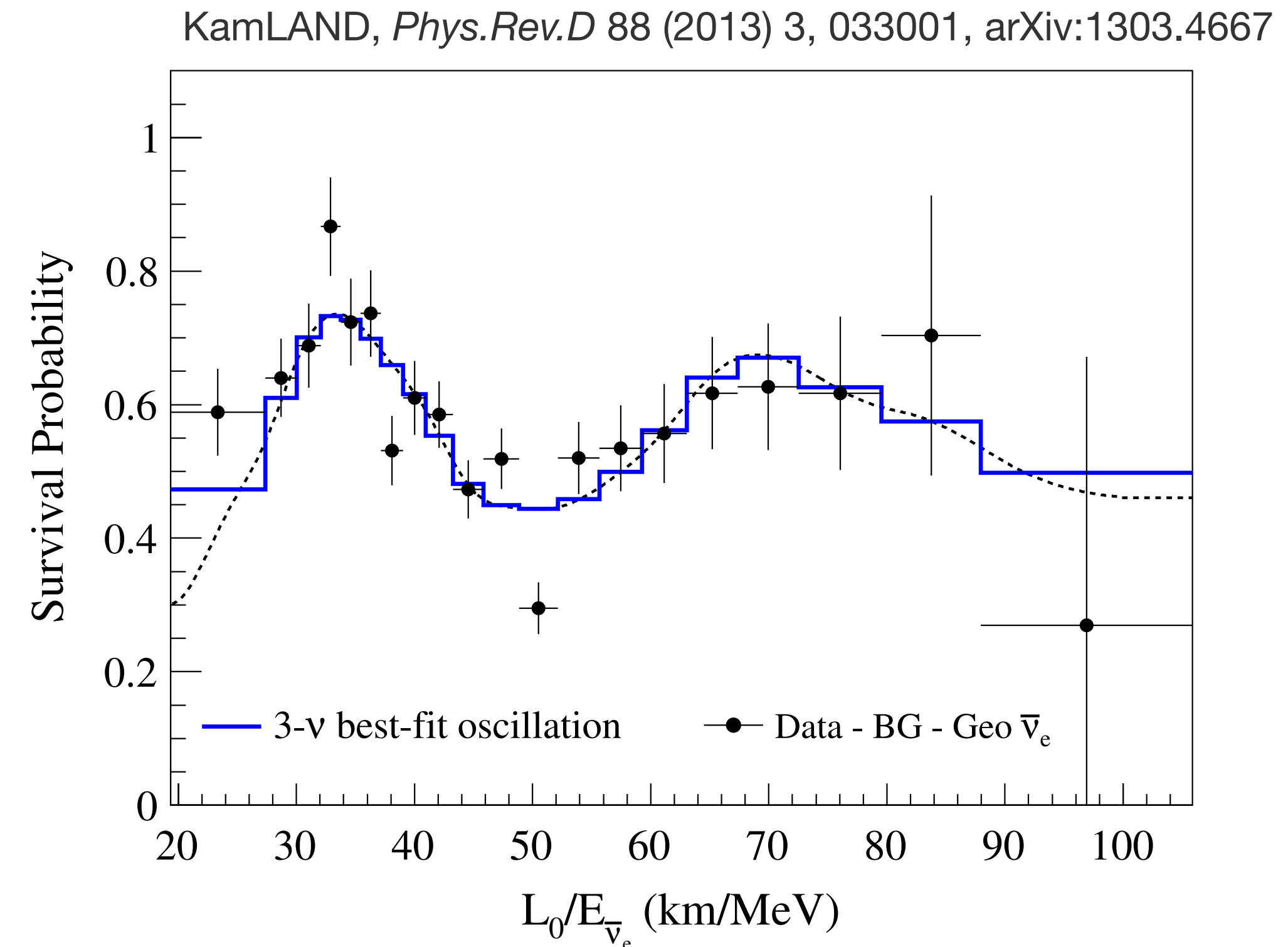
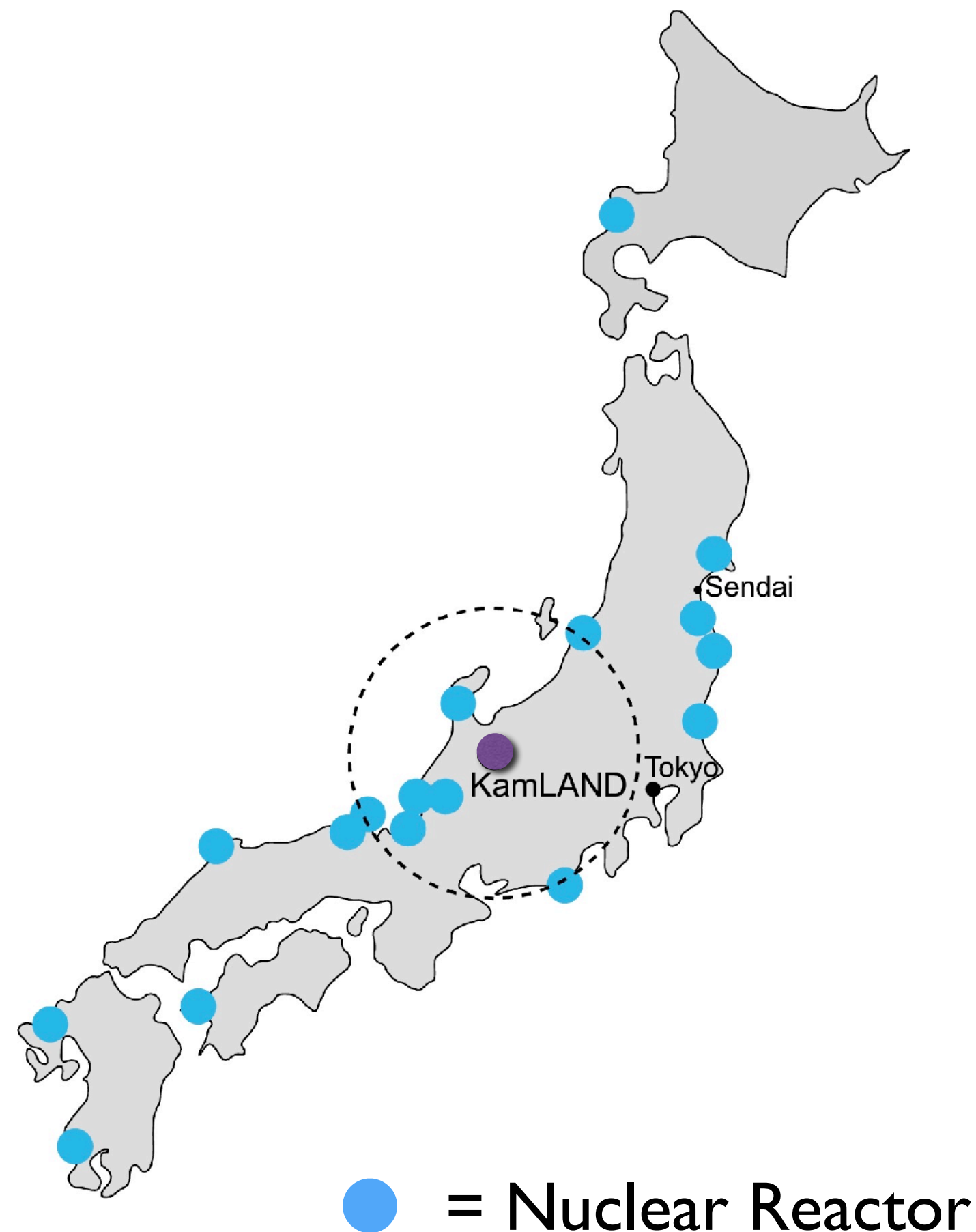
Patrick Decowski
decowski@nikhef.nl



UNIVERSITEIT VAN AMSTERDAM

Neutrino Science with KamLAND

- KamLAND started taking data about 25 years ago!
- Circa 2002, the primary goal was to measure neutrino oscillations using reactor antineutrinos.

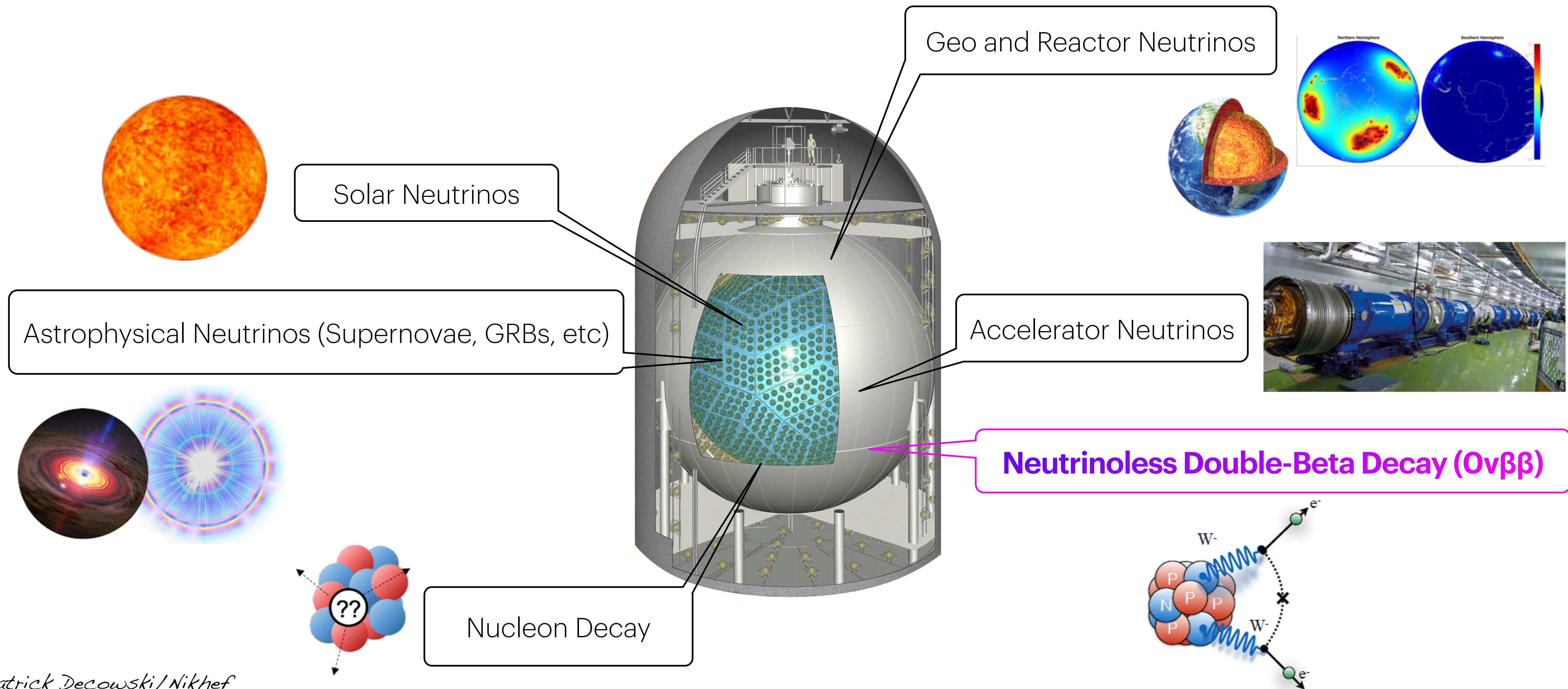


Direct observation of two full oscillation cycles

KamLAND determined that LMA-MSW was the solution to the solar neutrino problem.

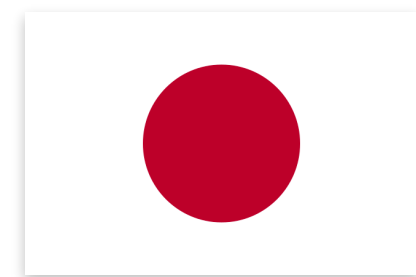
Neutrino Science with KamLAND

Highly versatile KamLAND detector allows for a broad science program...





KamLAND-Zen Collaboration



TOKUSHIMA UNIVERSITY



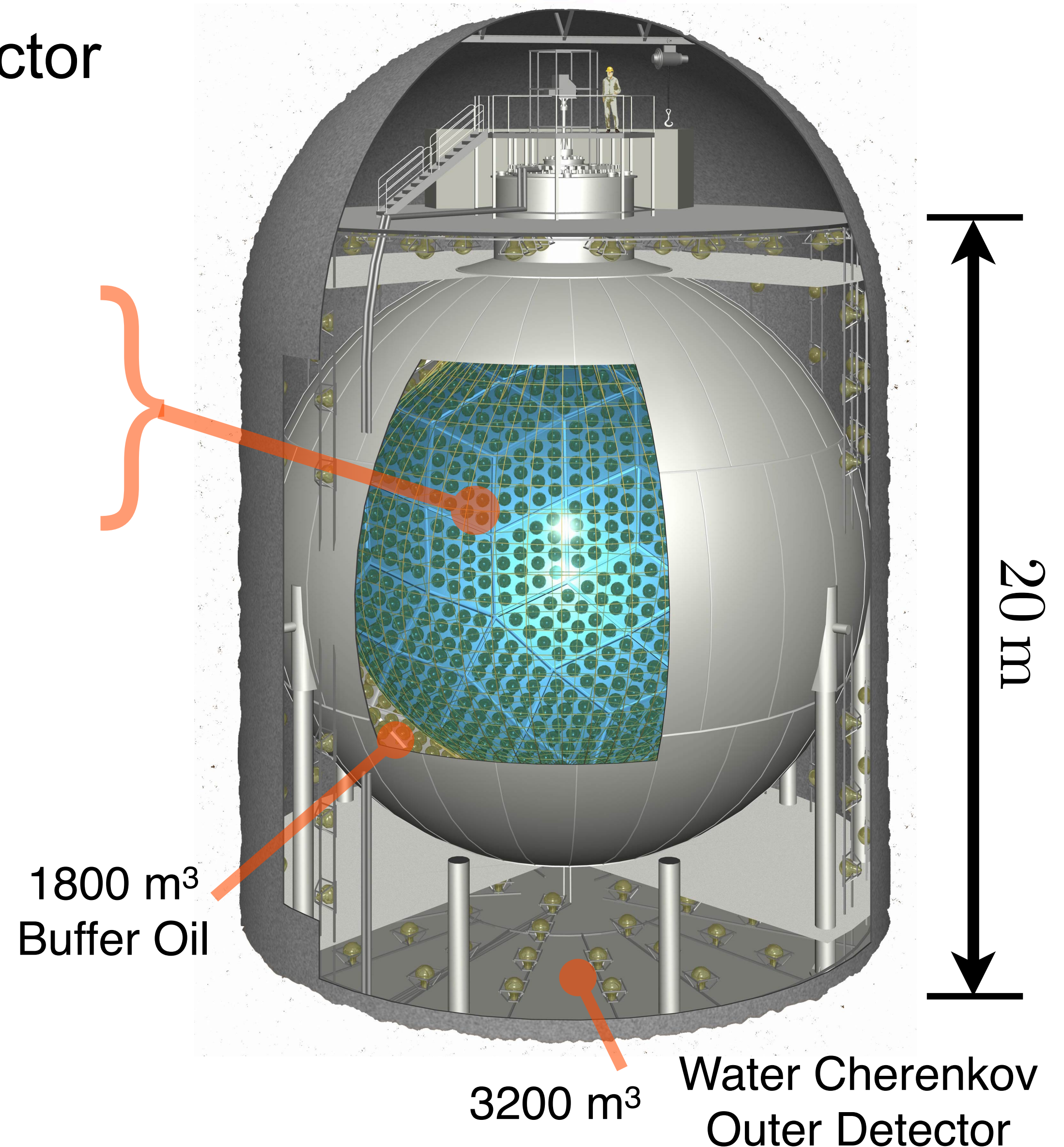
UNIVERSITY of HAWAI'I



KamLAND(-Zen) detector

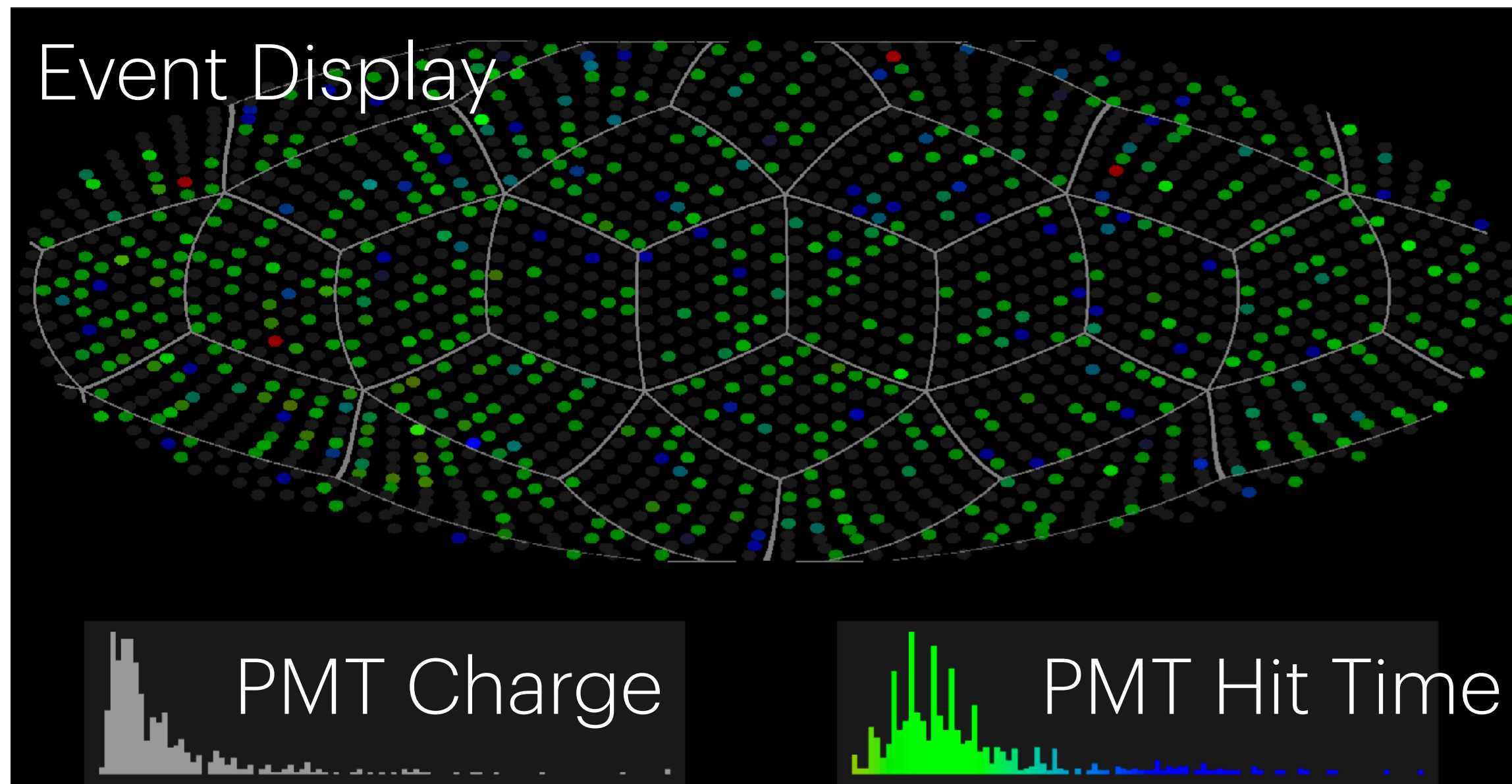
Located in the
Kamioka Mine in Japan
1000m rock = 2700 mwe

- 1 kton Liquid Scintillator Detector
 - 6.5m radius balloon filled with:
 - 20% Pseudocumene (scintillator)
 - 80% Dodecane (oil)
 - PPO
- 34% PMT coverage
 - ~1300 17" fast PMTs
 - ~550 20" large PMTs
- Water Cherenkov veto
- Operational since 2002



KamLAND(-Zen) detector

Particles interact in the LS and deposit energy.
Energy is converted to light and detected by PMTs

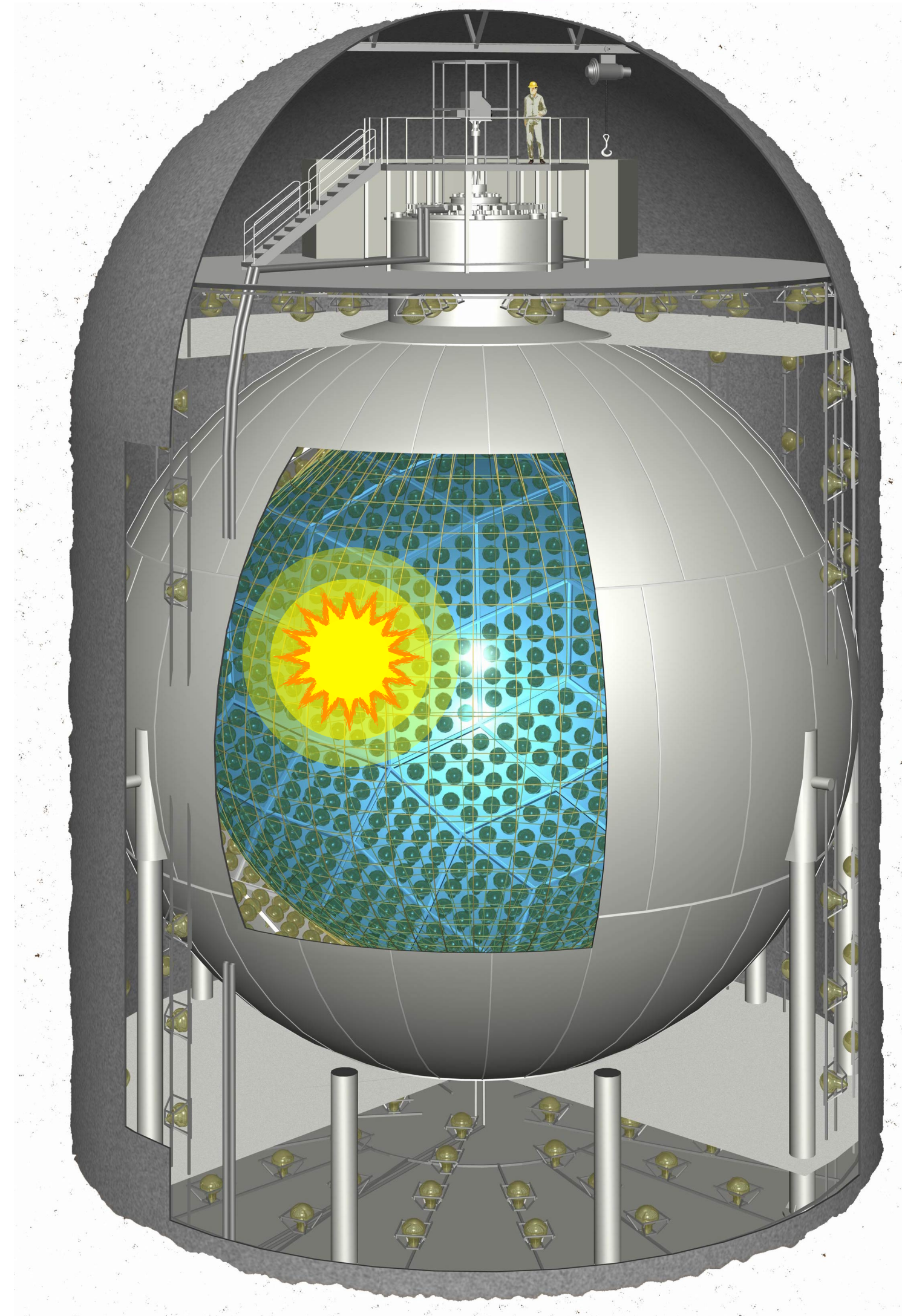


Energy reconstruction

$$\sim \frac{6.7\%}{\sqrt{E(\text{MeV})}}$$

Position reconstruction

$$\sim \frac{13.7 \text{ cm}}{\sqrt{E(\text{MeV})}}$$

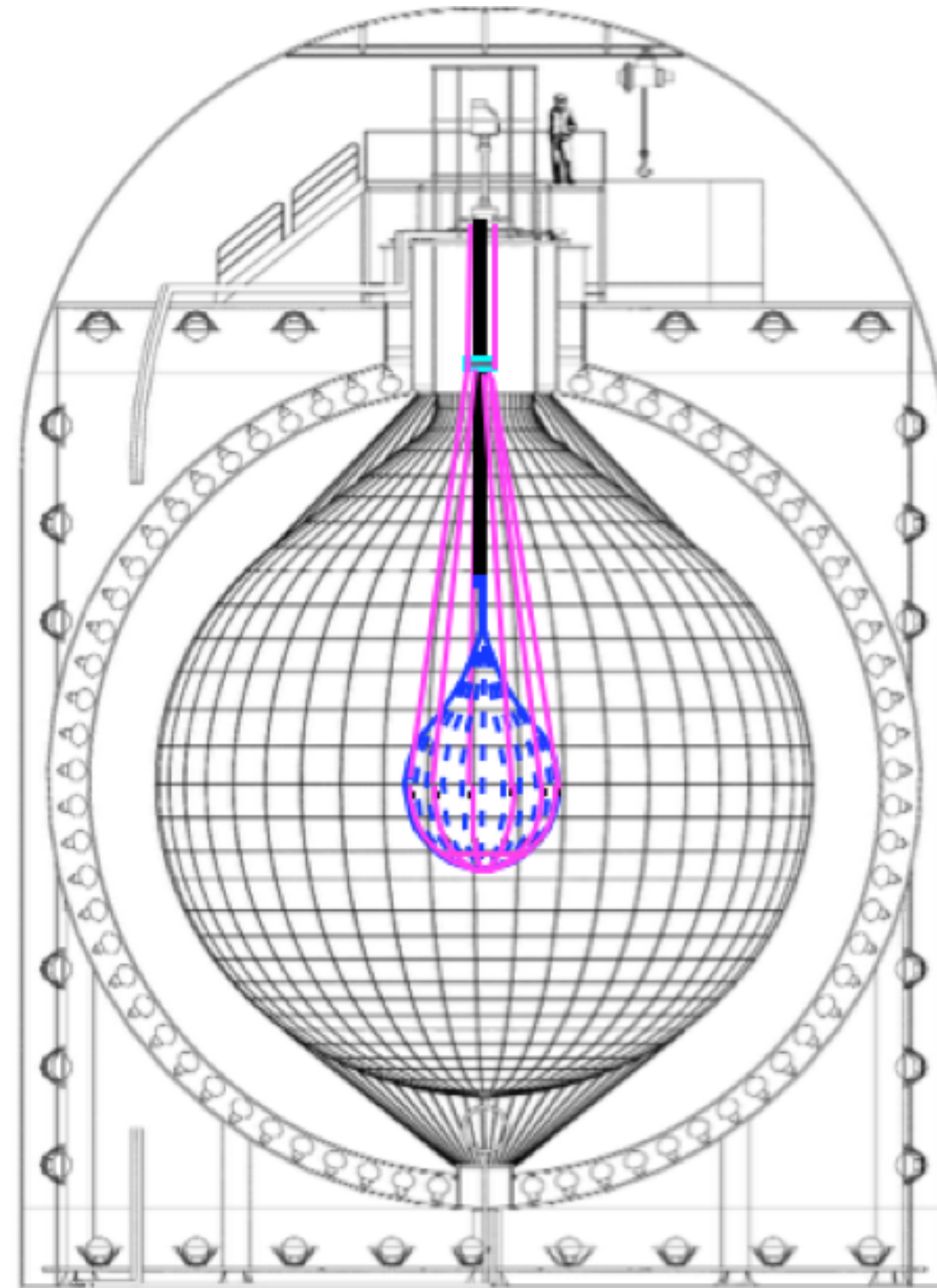


KamLAND-Zen 400

2011 - 2015

- Inner-balloon radius 1.54m
- 320 - 380kg ^{136}Xe
- Exposure 504 kg-yr

$$T^{0\nu}_{1/2} > 1.1 \times 10^{26} \text{ yr}$$



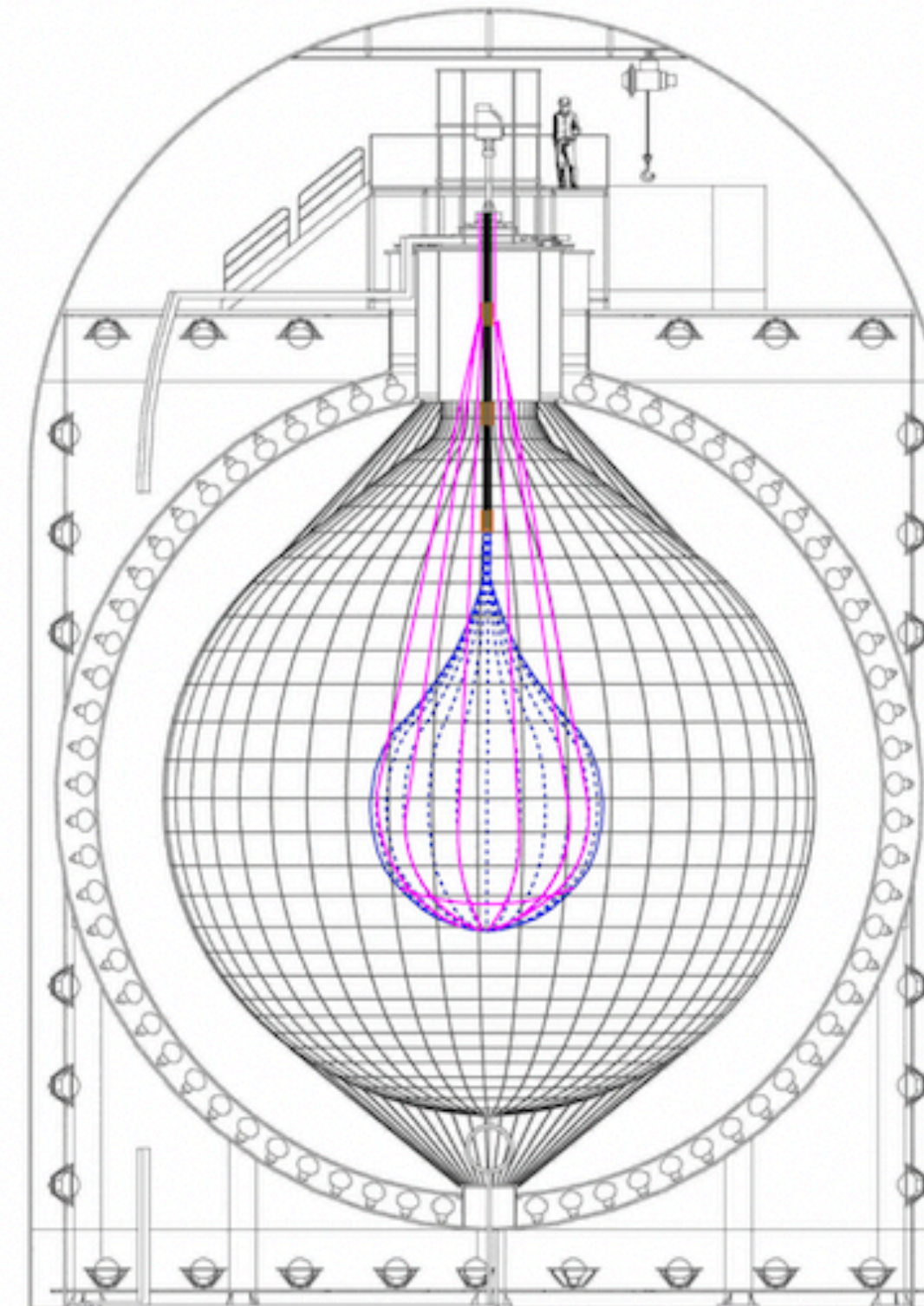
KamLAND-Zen Coll, Phys. Rev. Lett. 117, 082503 (2016); arXiv:1605.02889

KamLAND-Zen 800

2019 - 2024

- Inner-balloon radius 1.90m
- 745kg ^{136}Xe
- Exposure 2100 kg-yr

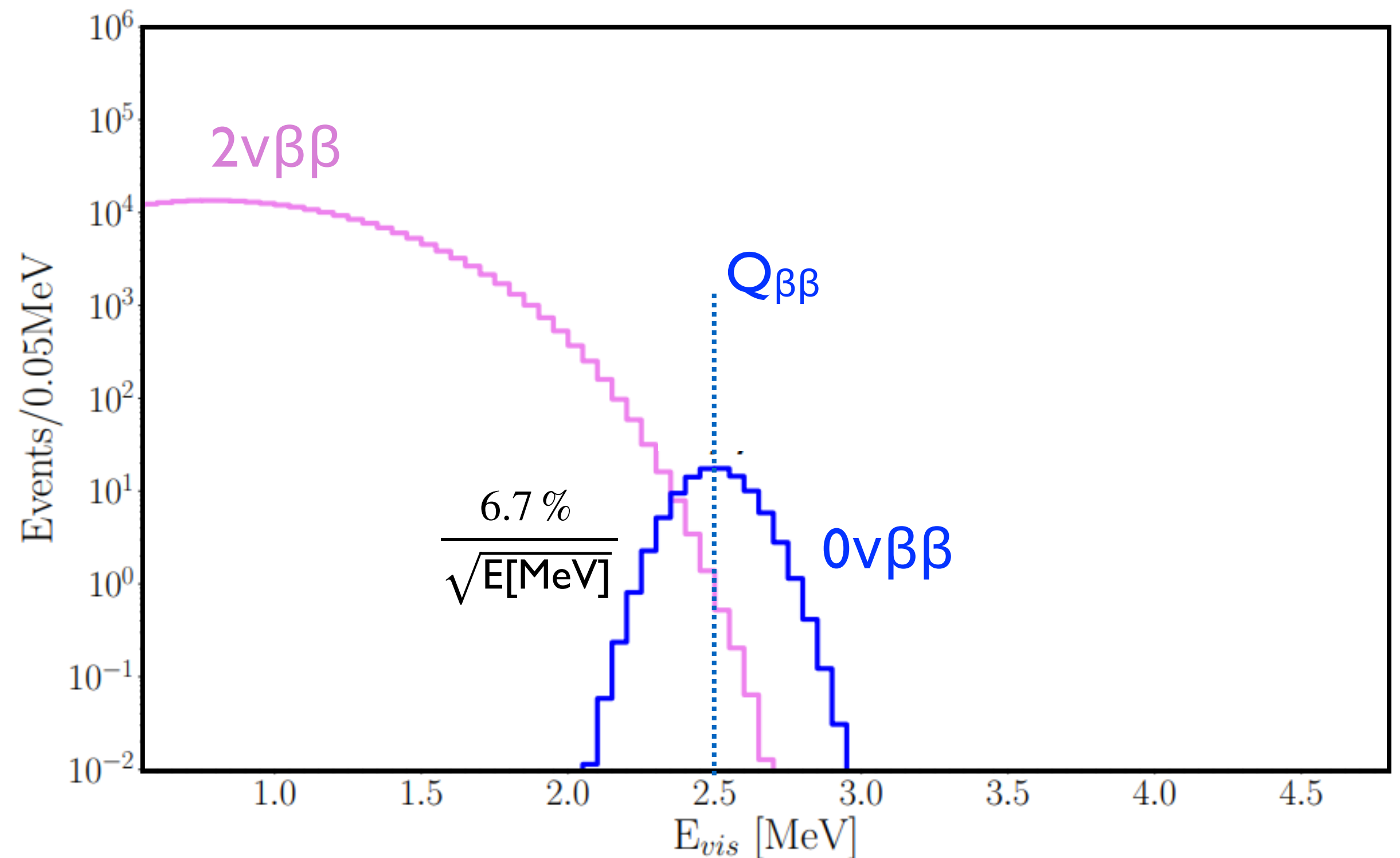
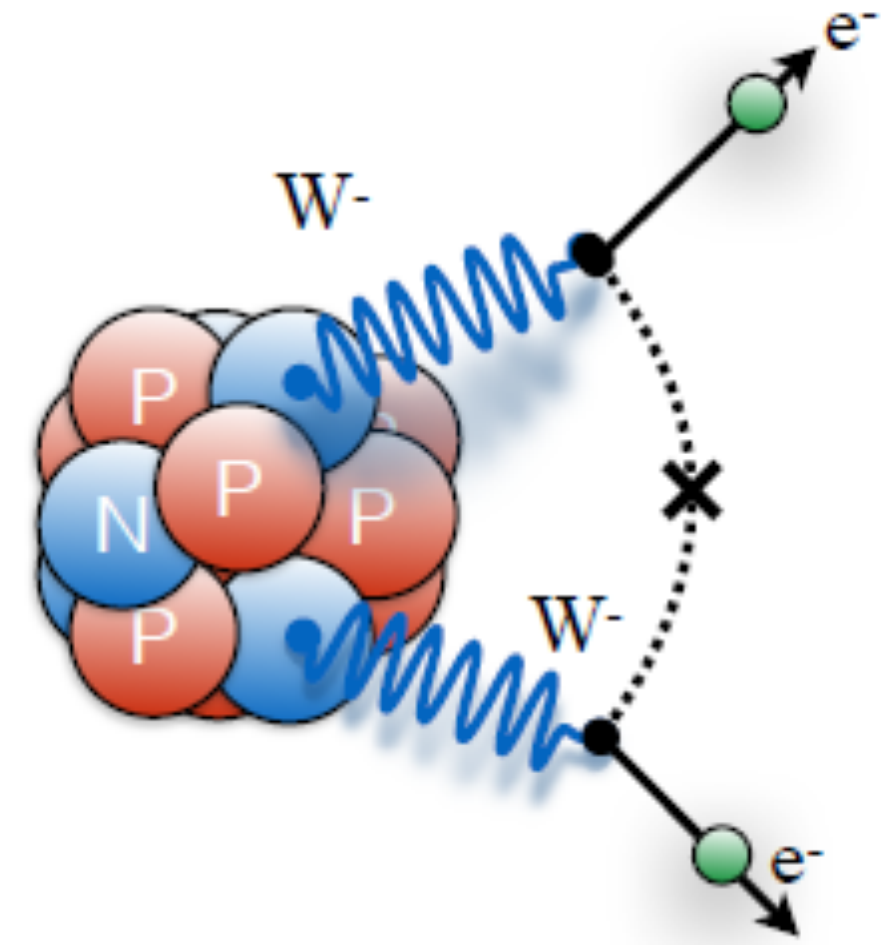
Full dataset



KamLAND-Zen Coll, Phys.Rev. Lett. 135, 262501 (2025); arXiv:2406.11438

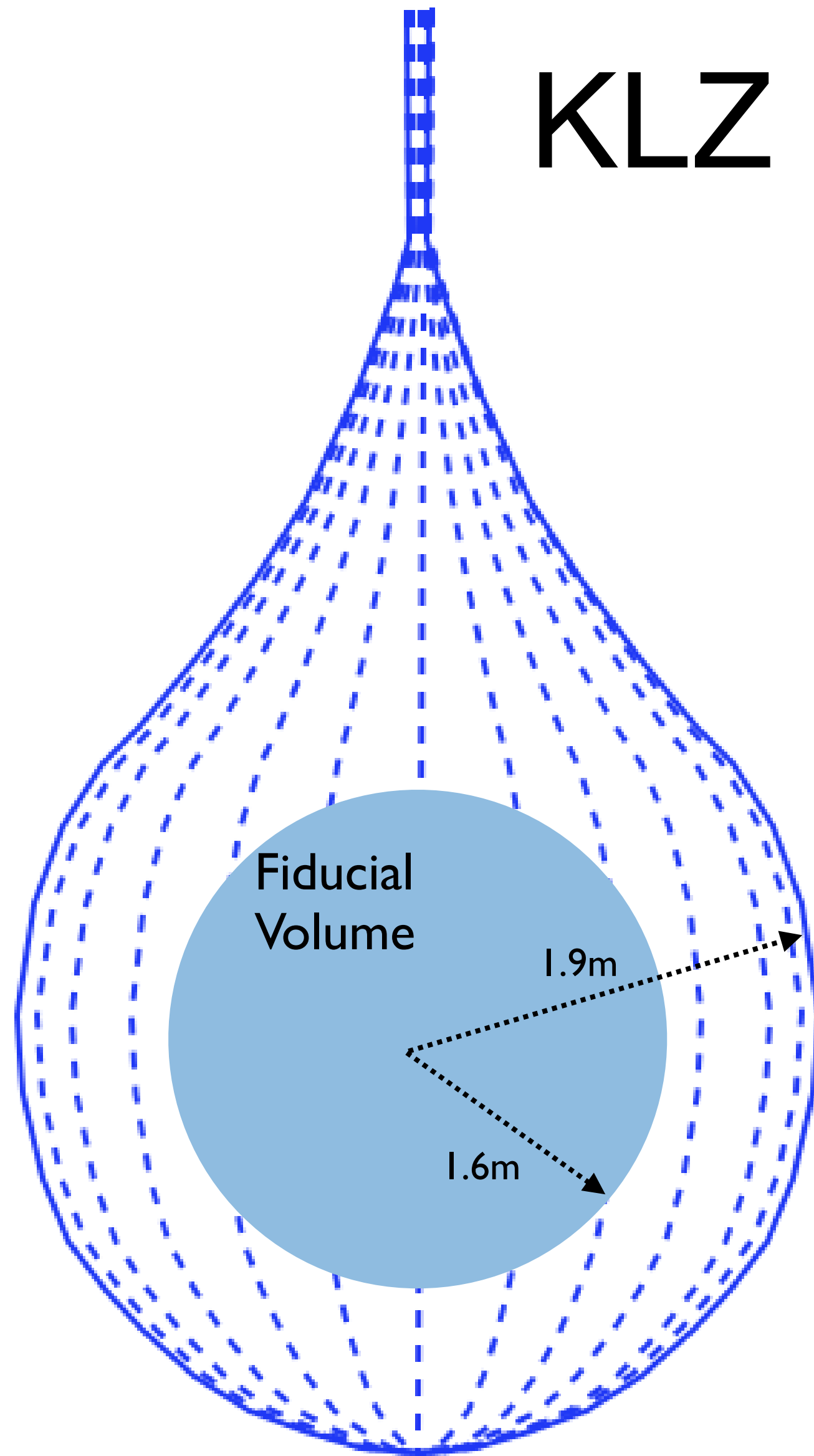
Signals and Backgrounds

- Expected signal: **peak for ^{136}Xe at $Q_{\beta\beta} = 2.458 \text{ MeV}$**
 - Define Region of Interest (ROI) between 2.35-2.70 MeV
- Primary Backgrounds:
 - $2\nu\beta\beta$ decays
 - Cosmic muon spallation
 - Radioactive contamination, e.g. ^{214}Bi
 - Solar neutrinos



KLZ 800 Inner-Ballon Backgrounds

^{214}Bi from radon-chain veto: β delayed coincidence α very effective veto in Xe-LS
But not on the balloon - α may get absorbed by the balloon



Balloon film backgrounds:

$^{238}\text{U} \sim 4 \times 10^{-12} \text{ g/g}$

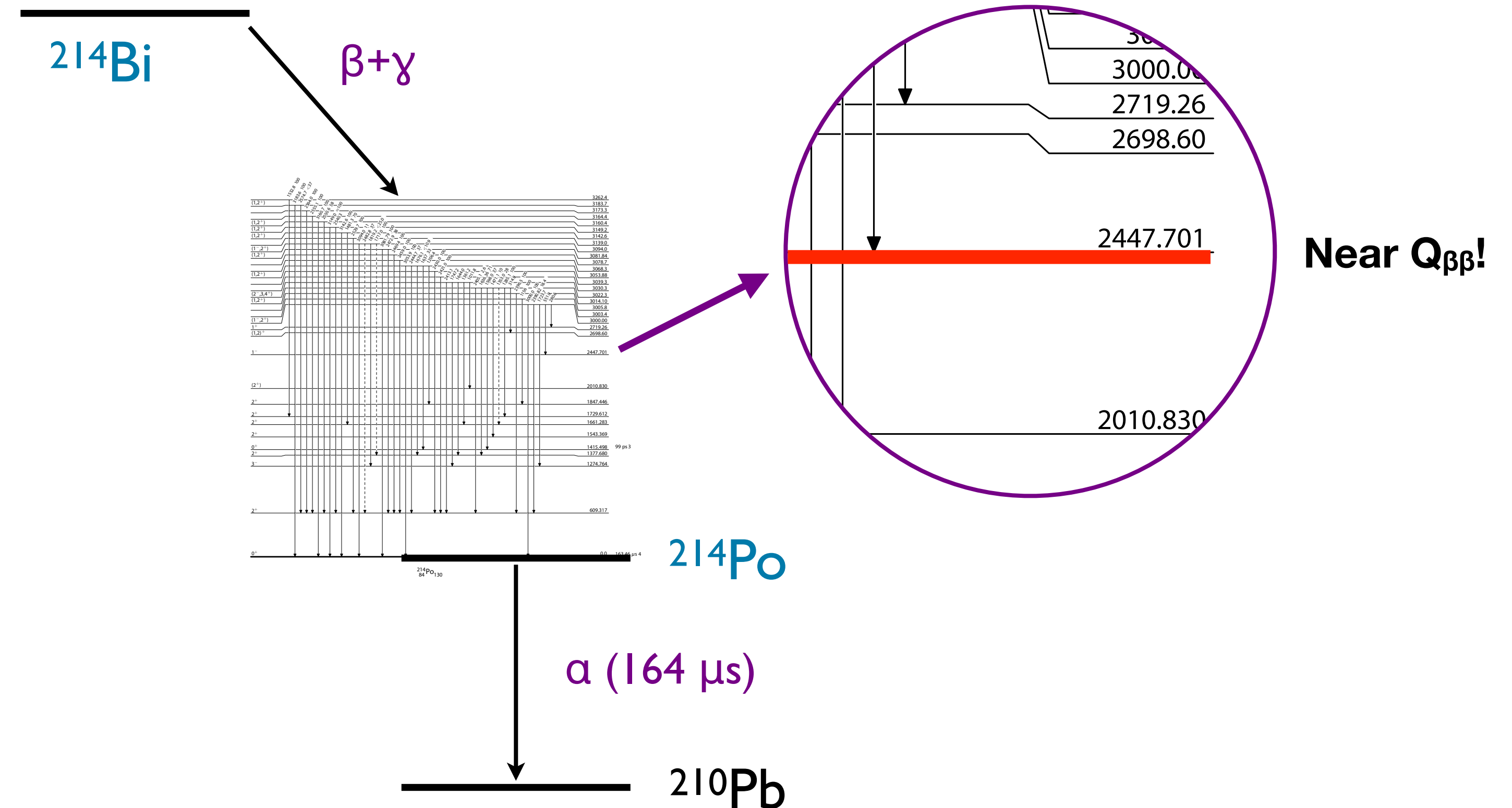
$^{232}\text{Th} \sim 2 \times 10^{-11} \text{ g/g}$

Xe-LS backgrounds:

$^{238}\text{U} \sim 1.5 \pm 0.4 \times 10^{-17} \text{ g/g}$

$^{232}\text{Th} \sim 3.0 \pm 0.4 \times 10^{-16} \text{ g/g}$

10x reduction compared to KLZ 400 IB

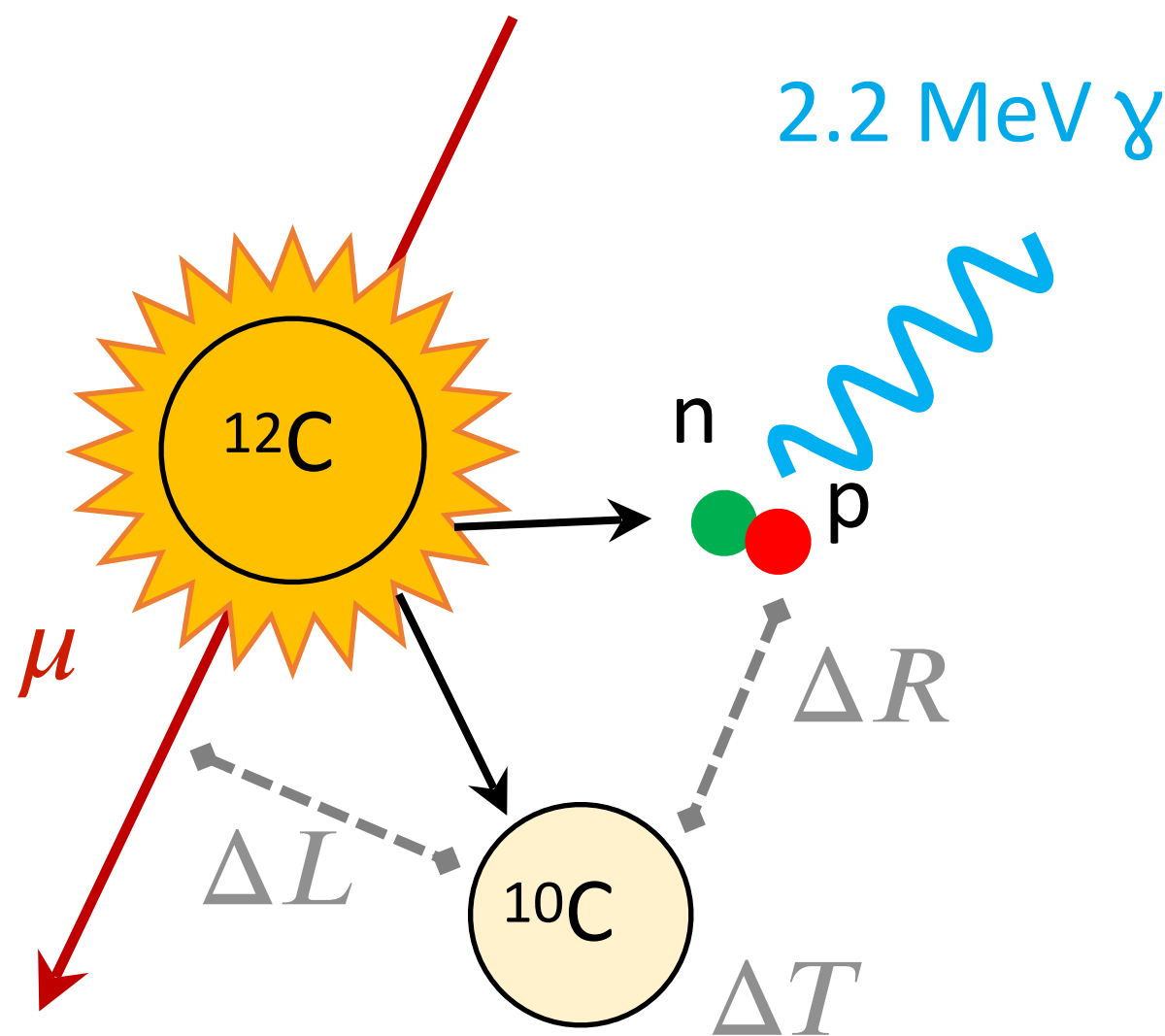


GEANT4 based MC with ^{214}Bi $\beta+\gamma$ cascade, particle tracking, energy deposit, scintillation photon emission / propagation

Muon Spallation

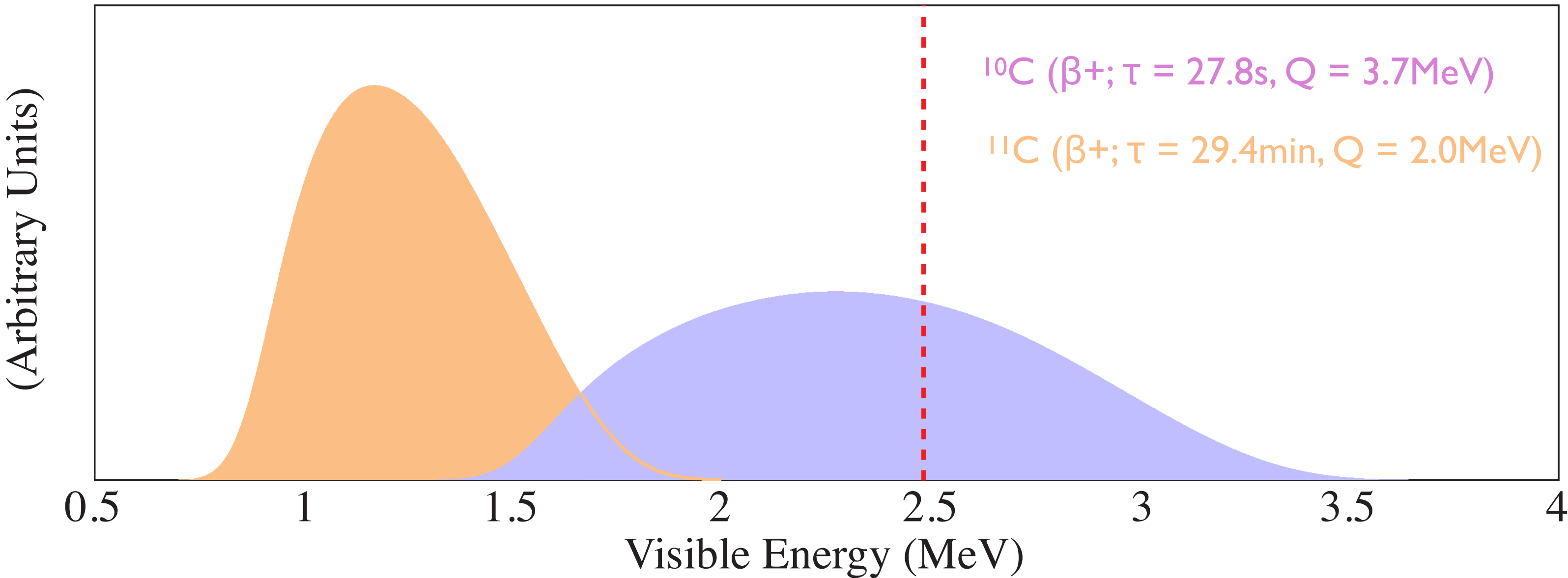
Carbon-based liquid scintillator: $^{12}\text{C} + \mu \rightarrow \text{spallation products}$

Spallation on ^{12}C



(muon time – decay time)

Triple coincidence cut (muon, neutron capture, subsequent ^{10}C decay)
effective veto, tagging efficiency $\sim 99\%$



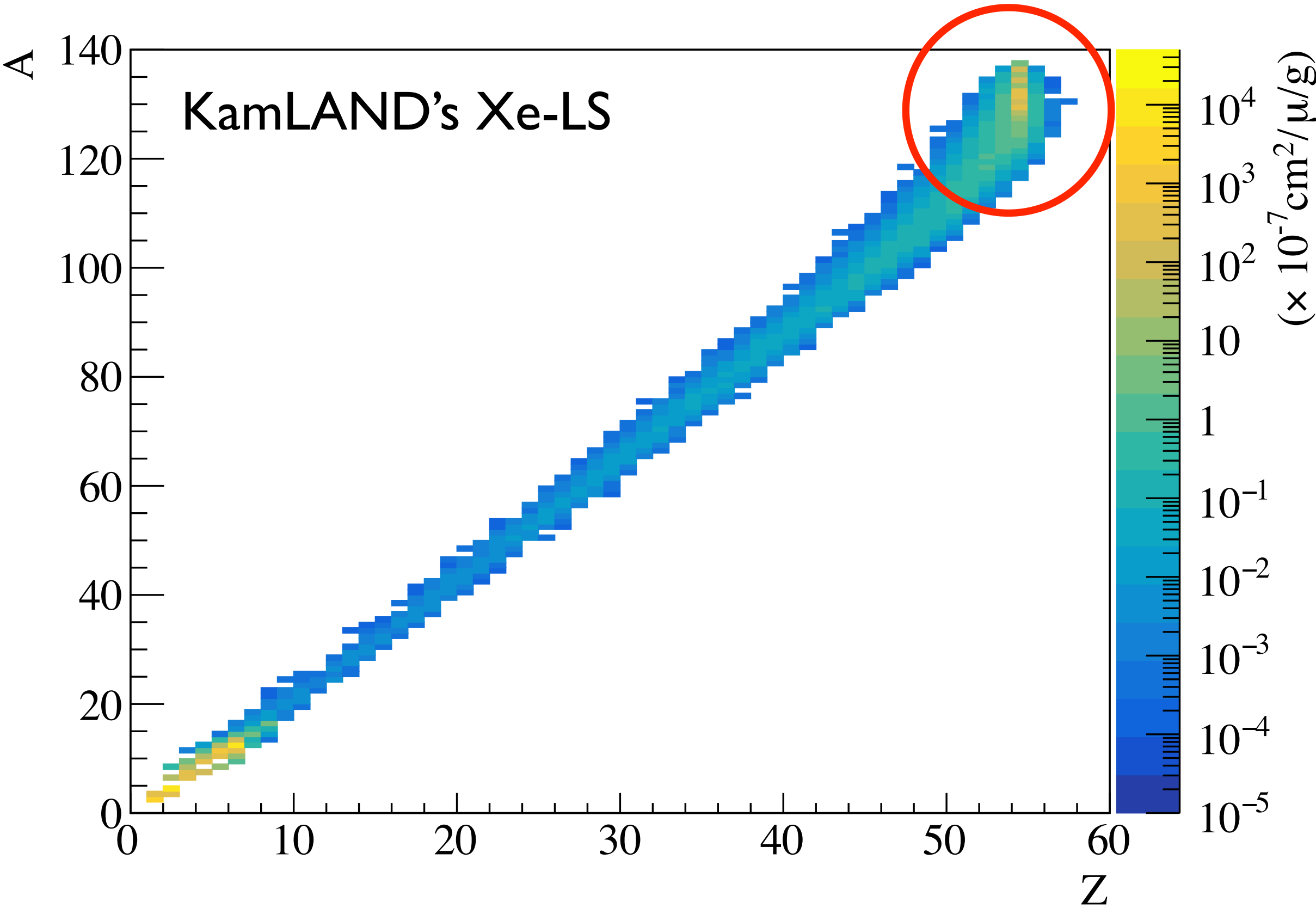
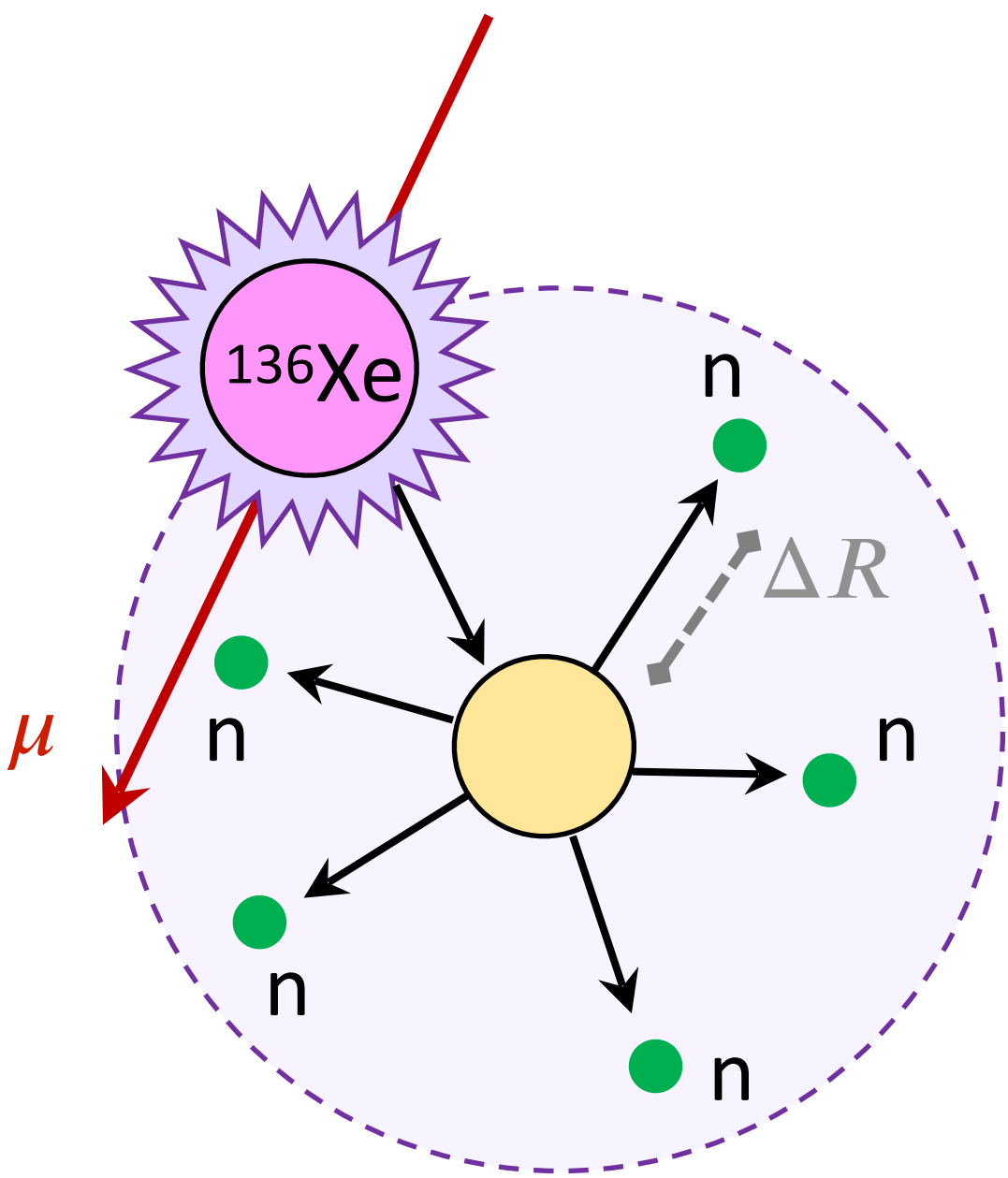
Isotope	$\tau(\text{s})$	Eff (%)
^{10}C	27.8	99.3
^6He	1.2	97.6 ± 1.7
^{137}Xe	330	74 ± 7

Short-lived spallation products $\tau < \sim 5 \text{ min}$

Muon Spallation

$\mu + {}^{136}\text{Xe}$ spallation products from FLUKA simulation

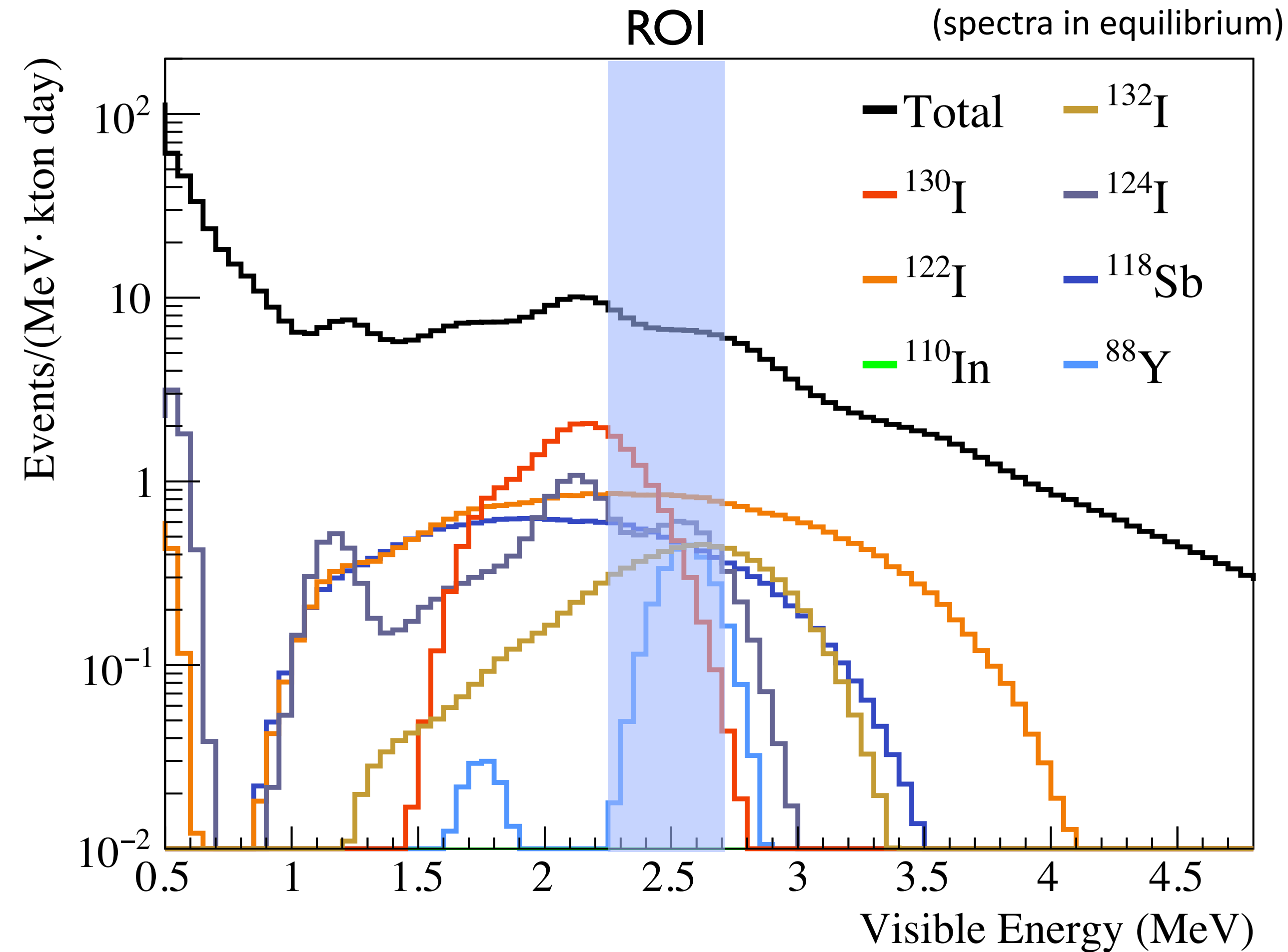
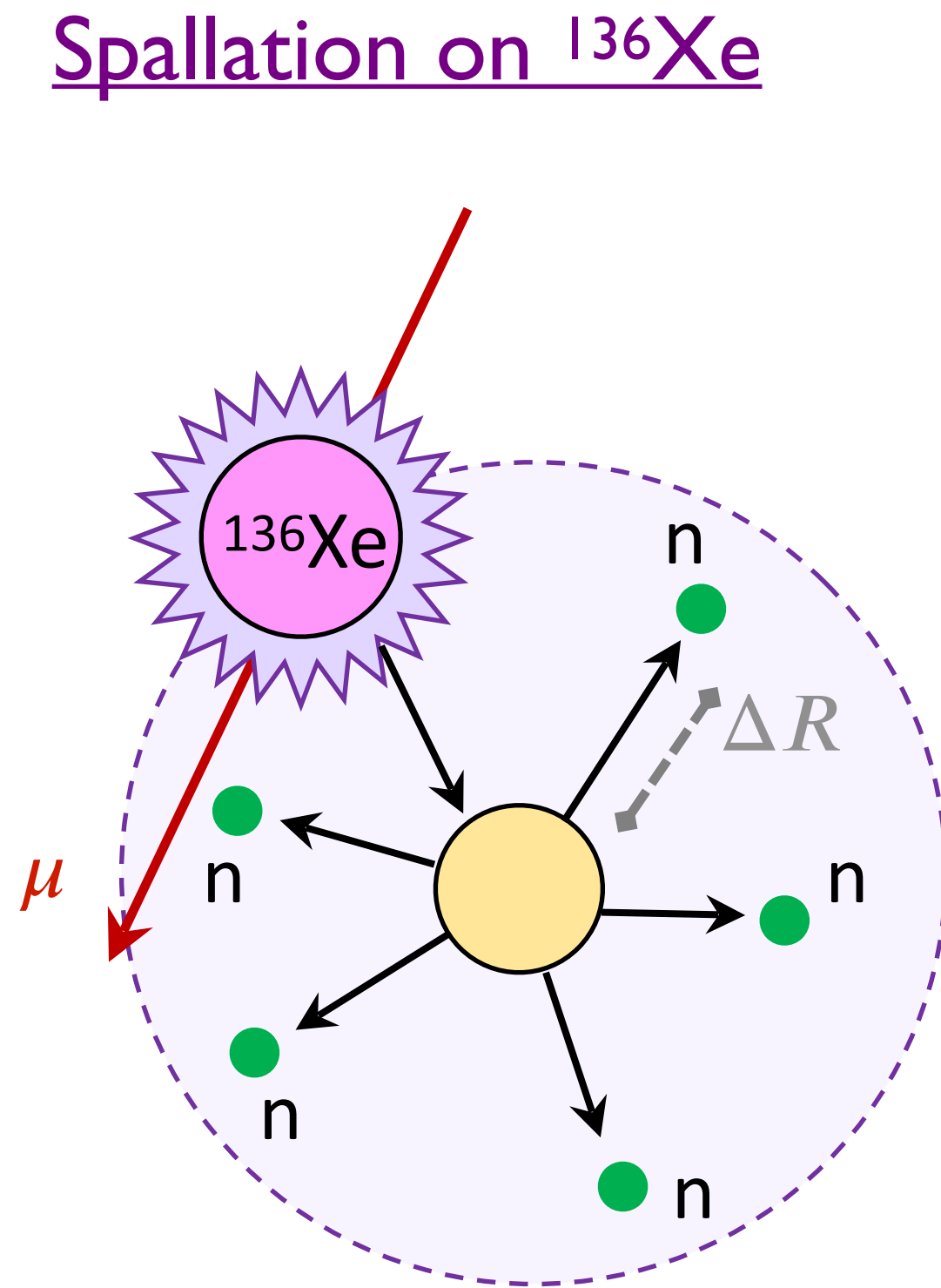
Spallation on ${}^{136}\text{Xe}$



Isotope	$T_{1/2}$ (s)
${}^{88}\text{Y}$	9.2×10^6
${}^{124}\text{I}$	3.6×10^5
${}^{130}\text{I}$	4.5×10^4
${}^{110}\text{In}$	1.8×10^4
${}^{132}\text{I}$	8.3×10^3
${}^{118}\text{Sb}$	2.2×10^2
${}^{122}\text{I}$	2.2×10^2

Muon Spallation

$\mu + {}^{136}\text{Xe}$ spallation products from FLUKA simulation, spectrum after decay



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Long-lived spallation products in the ROI

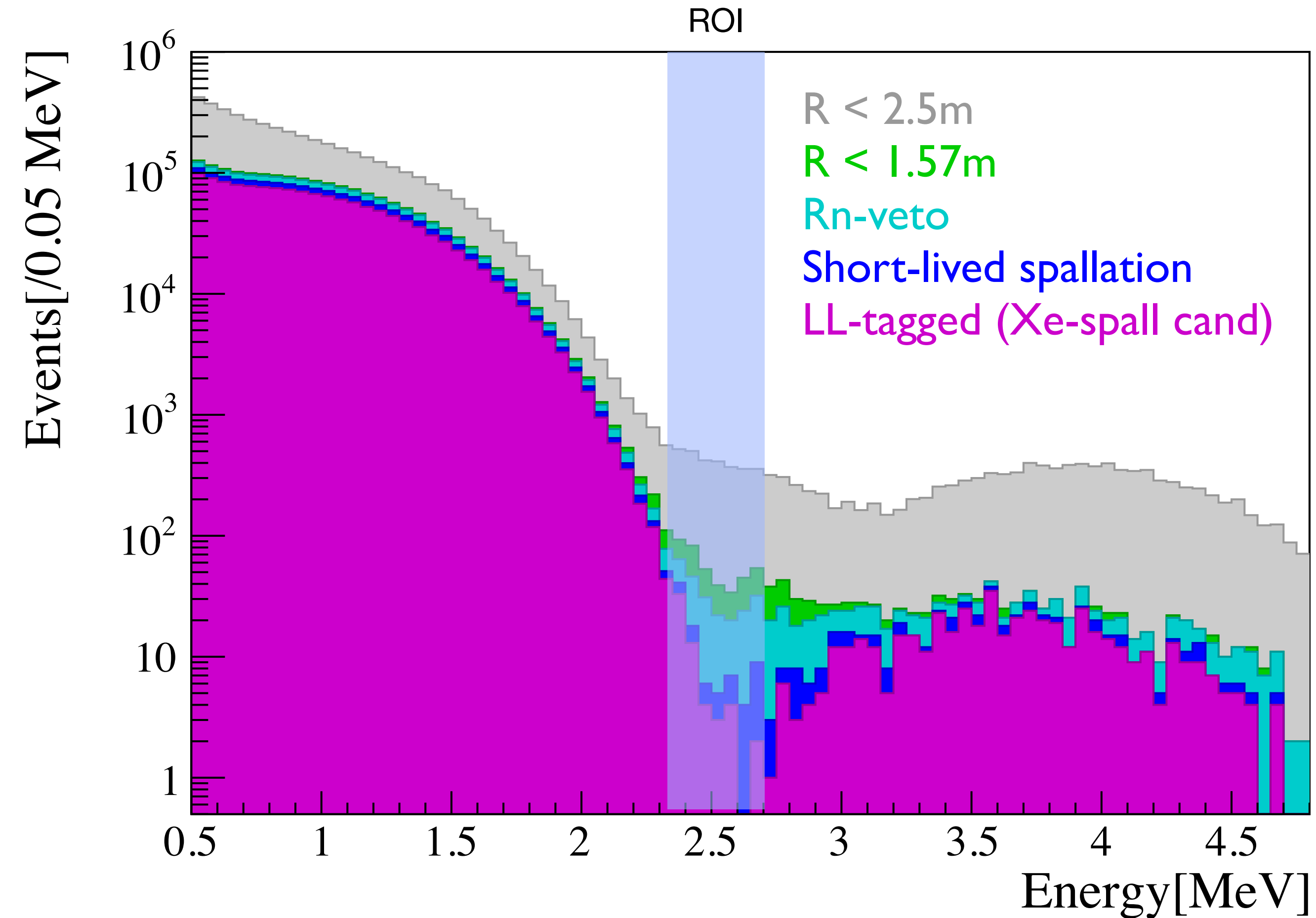
$T_{1/2}$: **several hours to weeks**

Very low rate!

Event Selection

(745 ± 3)kg Xe, 1131 day lifetime → 2100 kg-yr exposure

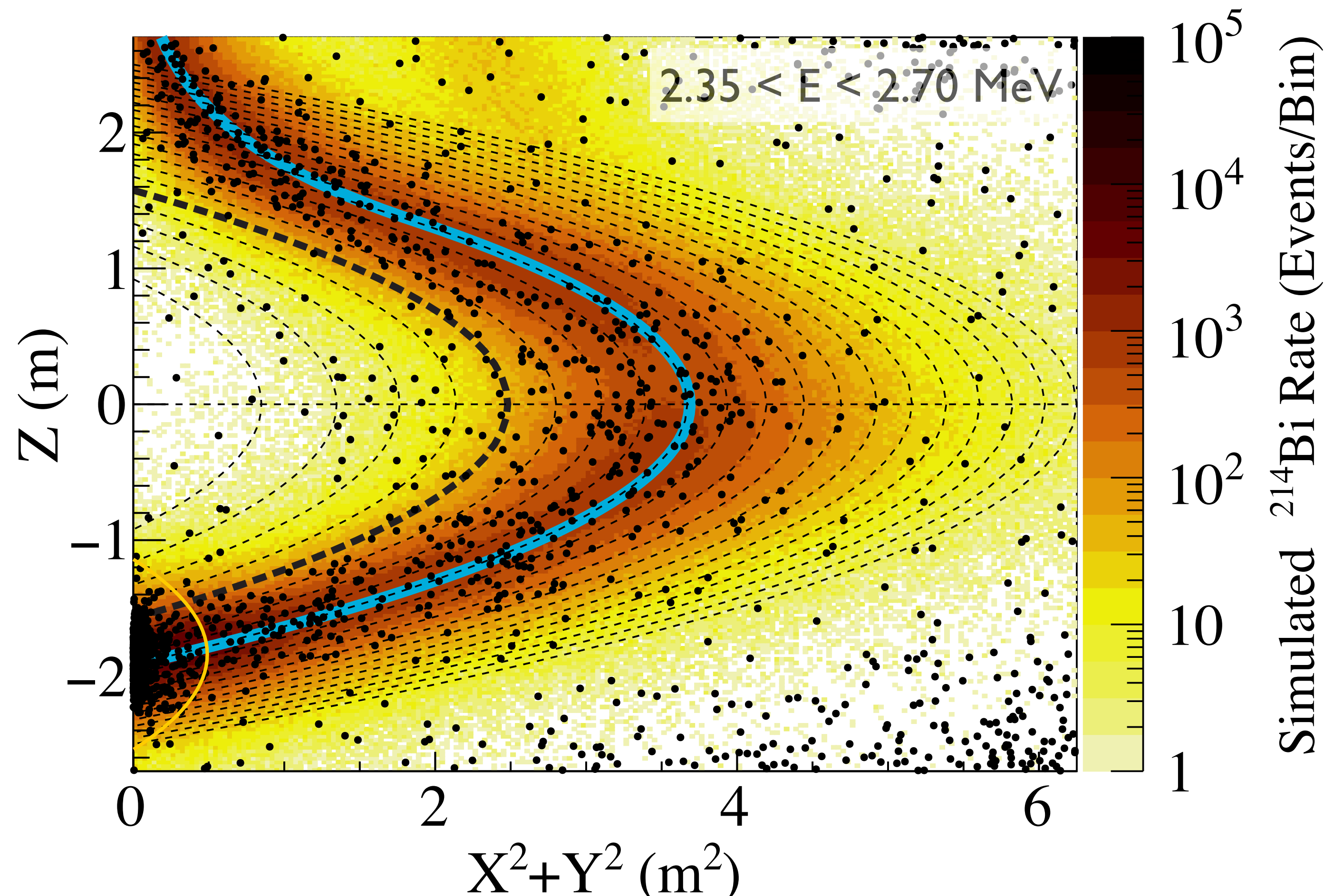
- Event selection cuts:
 - Events < 2.5m from center and > 0.7m away from bottom
 - Events > 150ms after muons
 - Radioactive decays by coincidence cut rejected
 - $\bar{\nu}_e$ identified by coincidence cut rejected
 - Poorly reconstructed events rejected
 - Spallation cuts applied:
 - Short-lived spallation (e.g. ^{10}C) rejected
 - Long-lived (LL) spallation: tagged and untagged sample



Fitting the Data in Equal Volume Bins

Vertex distribution in the ROI overlaid on ^{214}Bi MC

Beta-decay of ^{214}Bi can also include a γ at 2.448 MeV

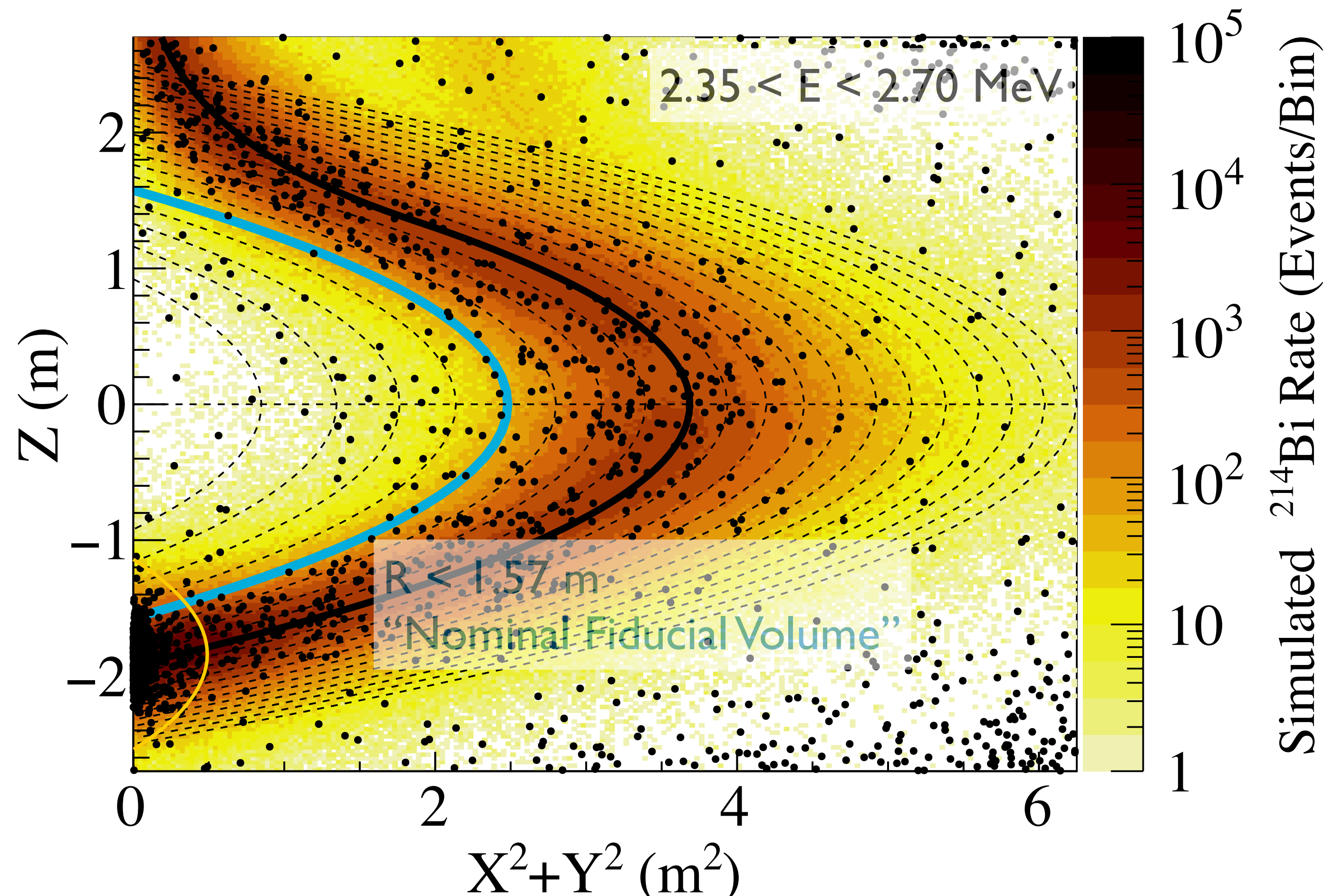


- Simultaneously fit 40 equal volume bins inside of $R < 2.5$ m
- Inner region → more sensitive to $0\nu 2\beta$ decay
- Outer region → more sensitive to backgrounds on inner-balloon film
- All parameters fitted simultaneously

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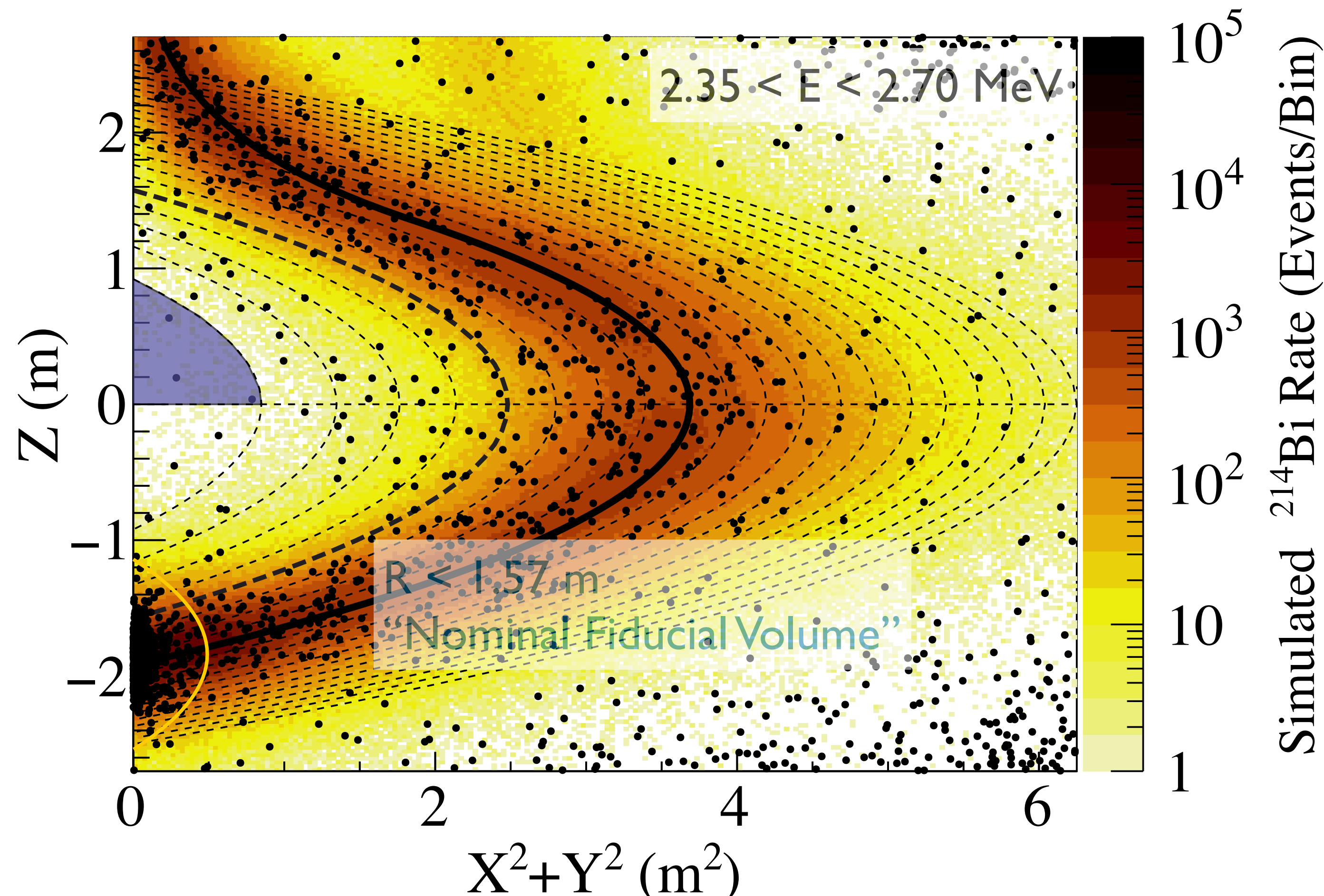


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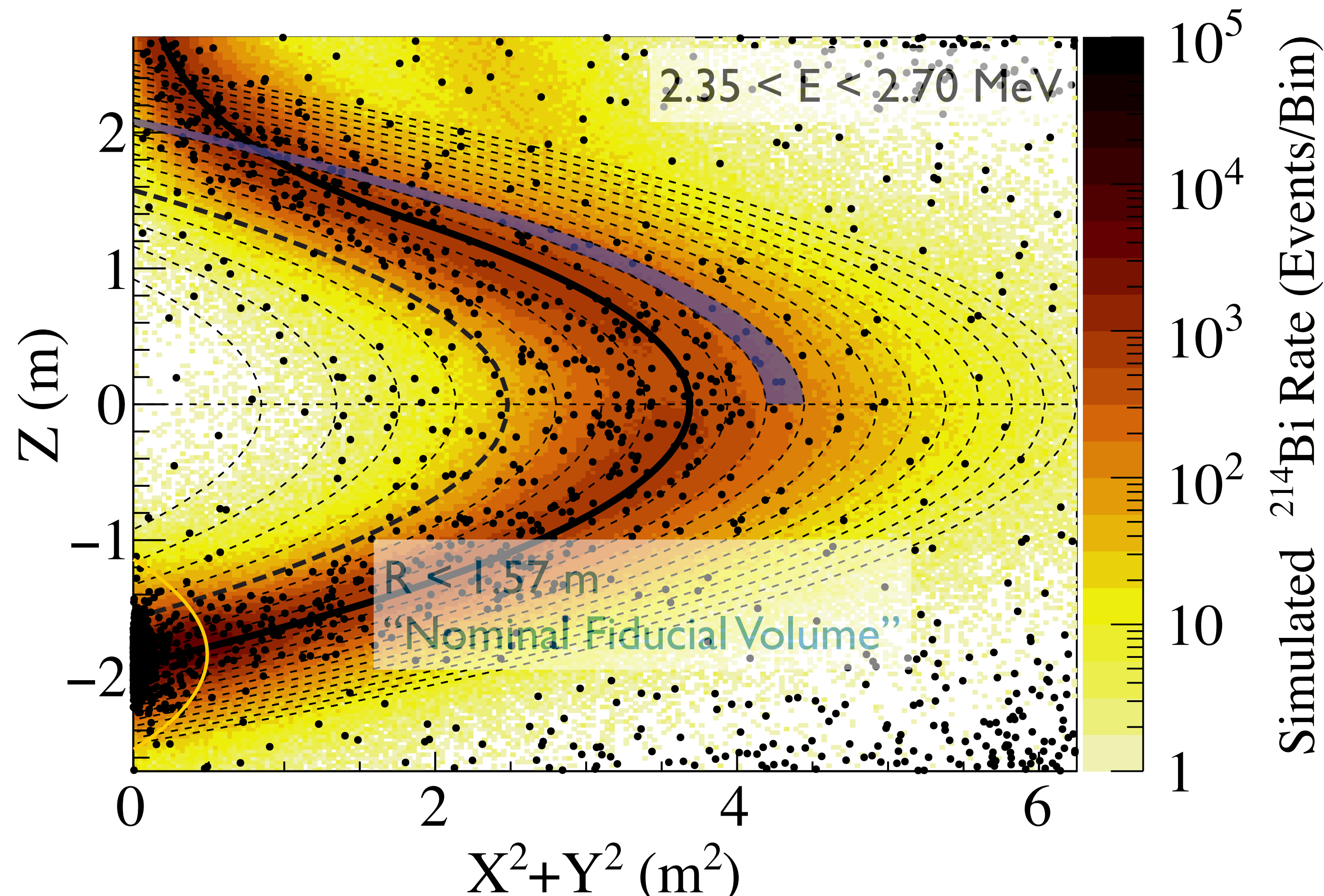


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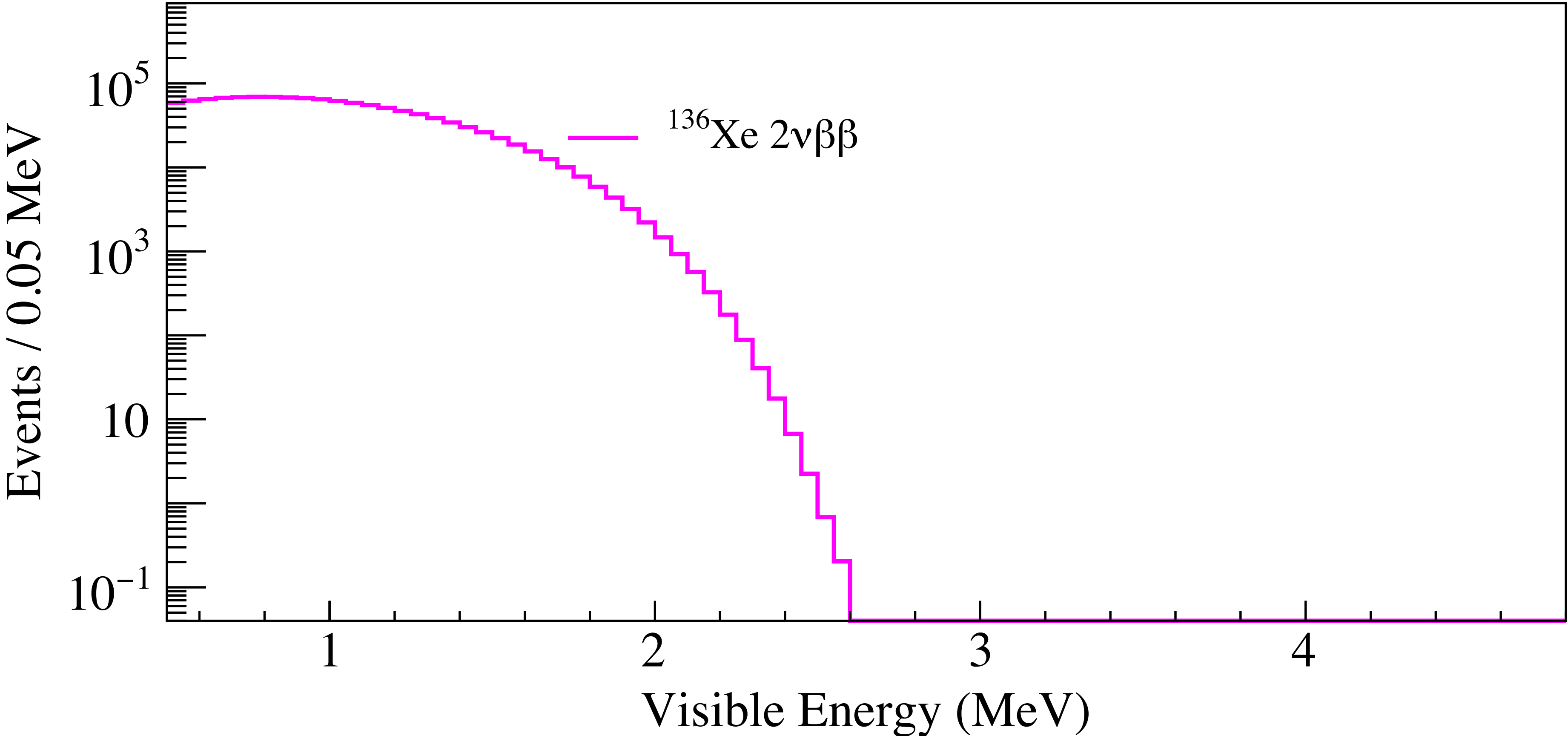
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New KamLAND-Zen 800 Results

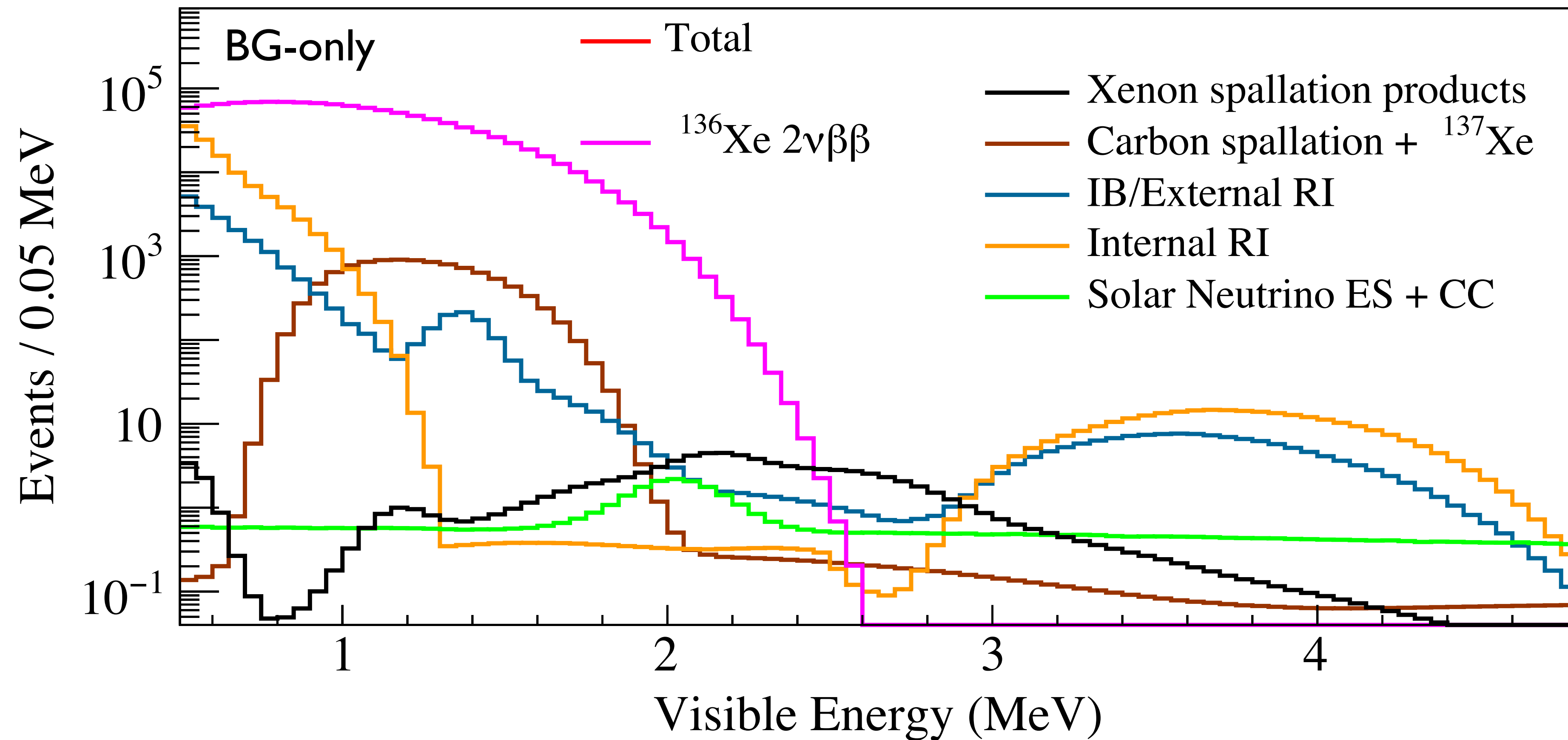
Spectrum inside R<1.57m Fiducial Volume



New KamLAND-Zen 800 Results

arXiv:2406.11438

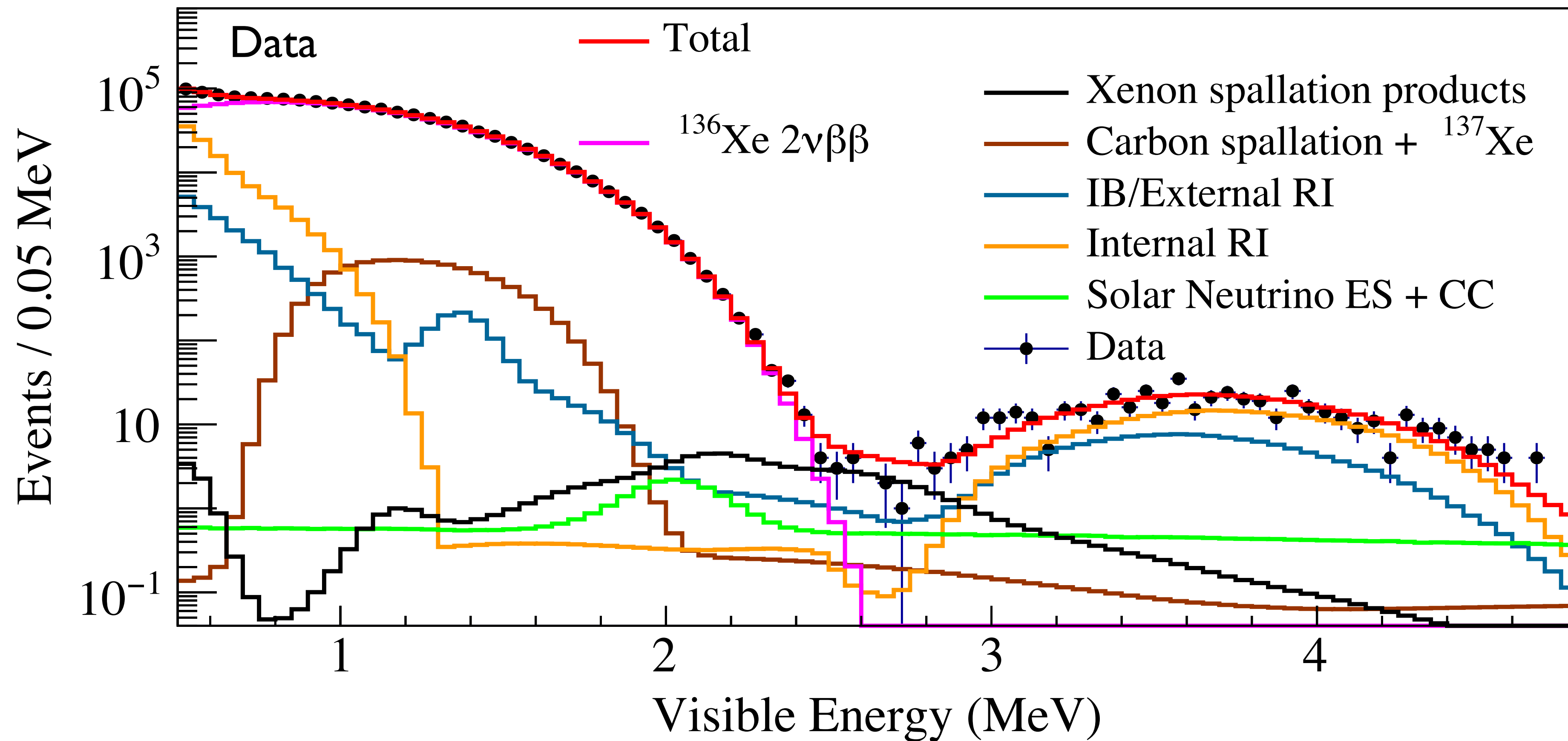
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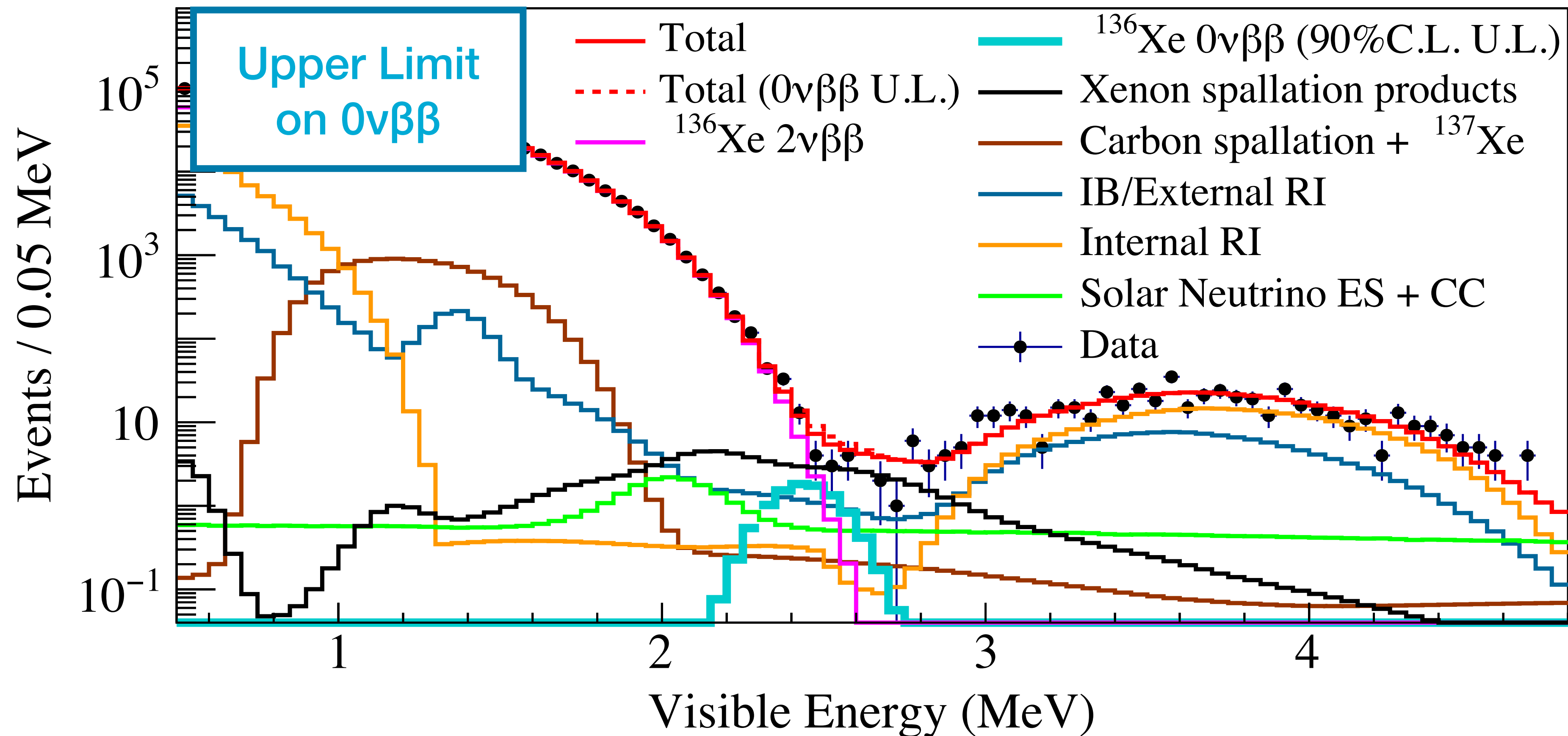
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New KamLAND-Zen 800 Results

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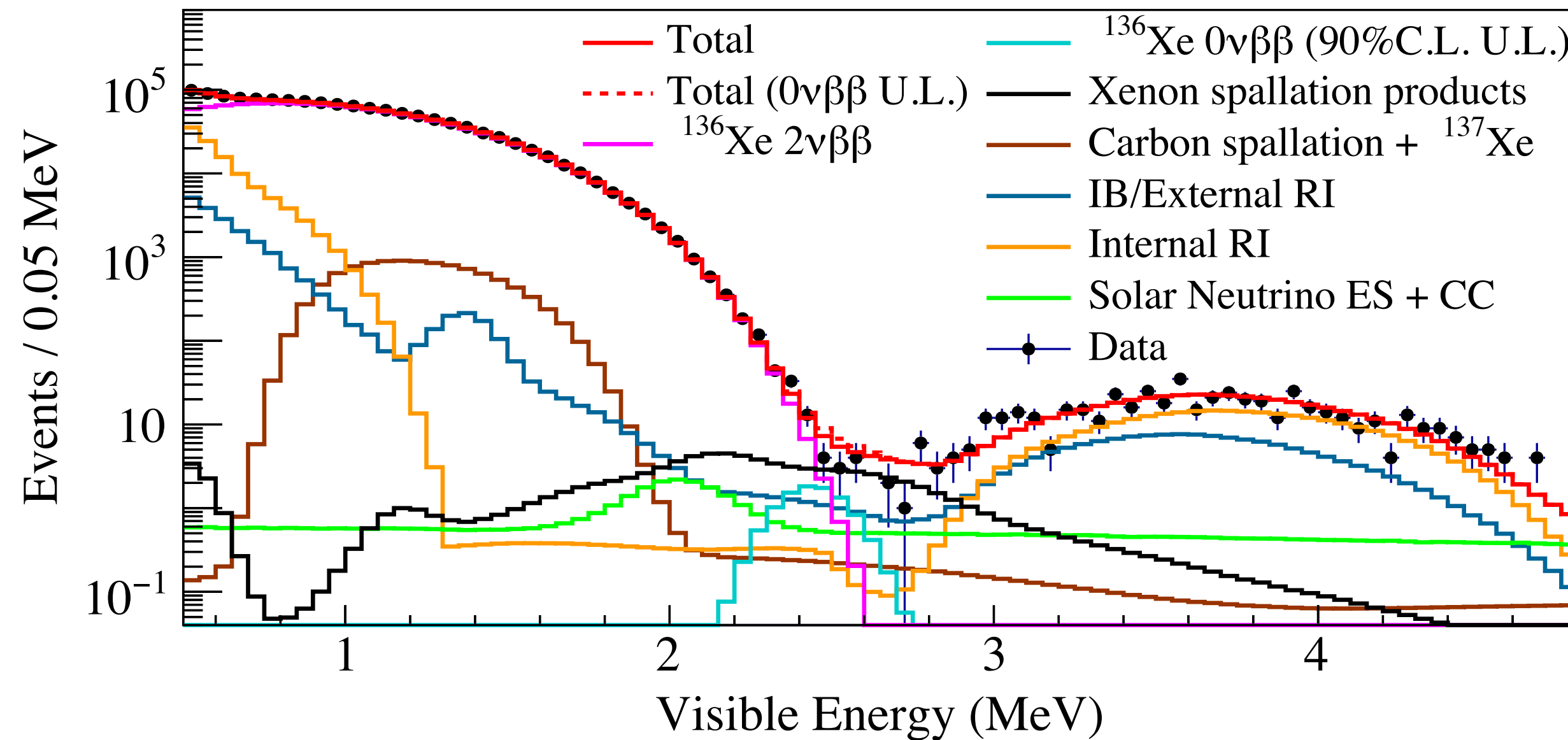


90% C.L. Upper Limit < 10.0 events $\rightarrow T_{1/2} > 3.4 \times 10^{26} \text{ yr}$
 [Sensitivity $T_{1/2} > 2.3 \times 10^{26} \text{ yr}$]

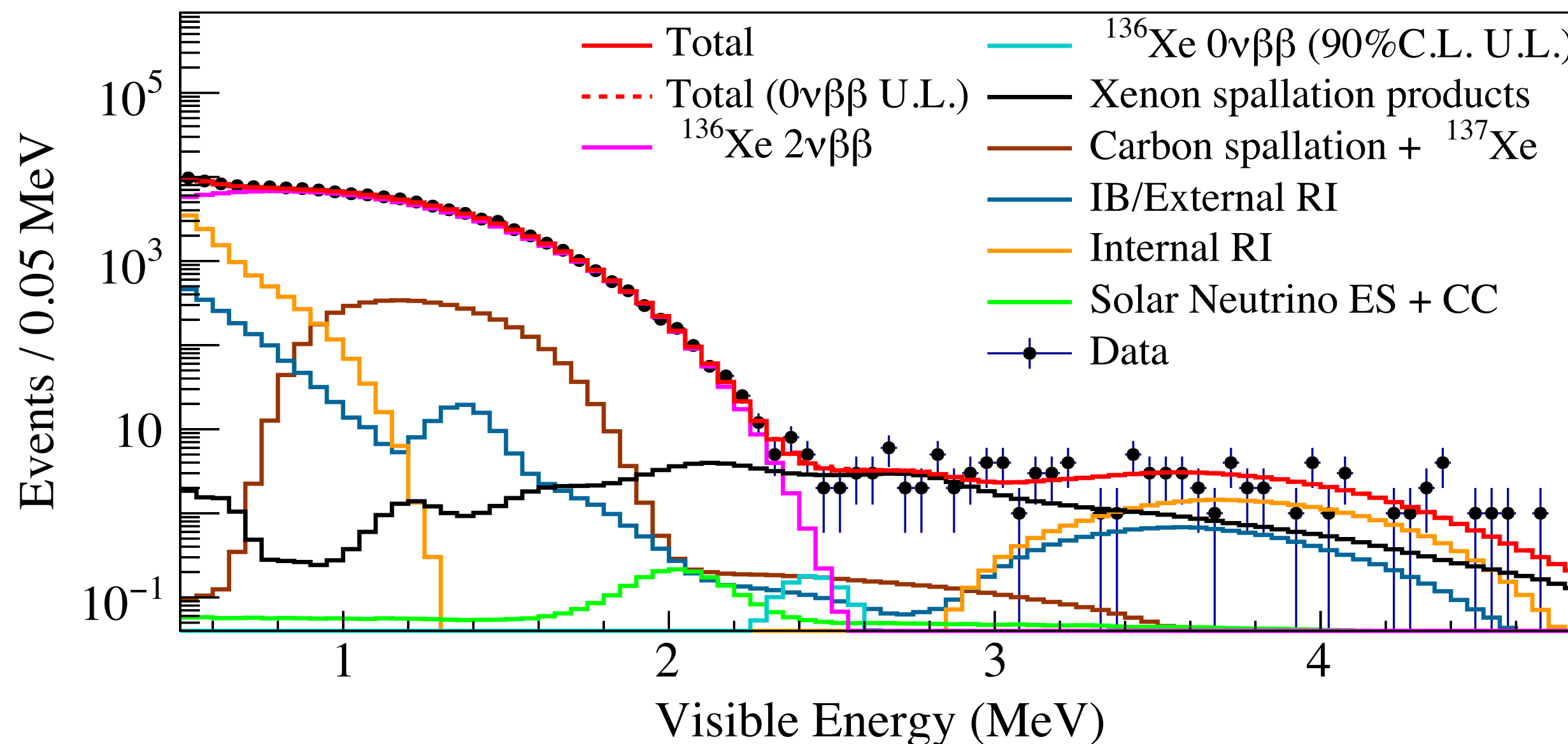
Combined with earlier KamLAND-Zen 400 results: $T_{1/2} > 3.8 \times 10^{26} \text{ years}$

$0\nu2\beta$ and tagged Long-lived spectrum

$0\nu2\beta$ candidates



Xe-spallation candidates



Selection Cuts

Long-lived spallation

untagged

tagged

1131 days

111 days

$0\nu2\beta$ candidates

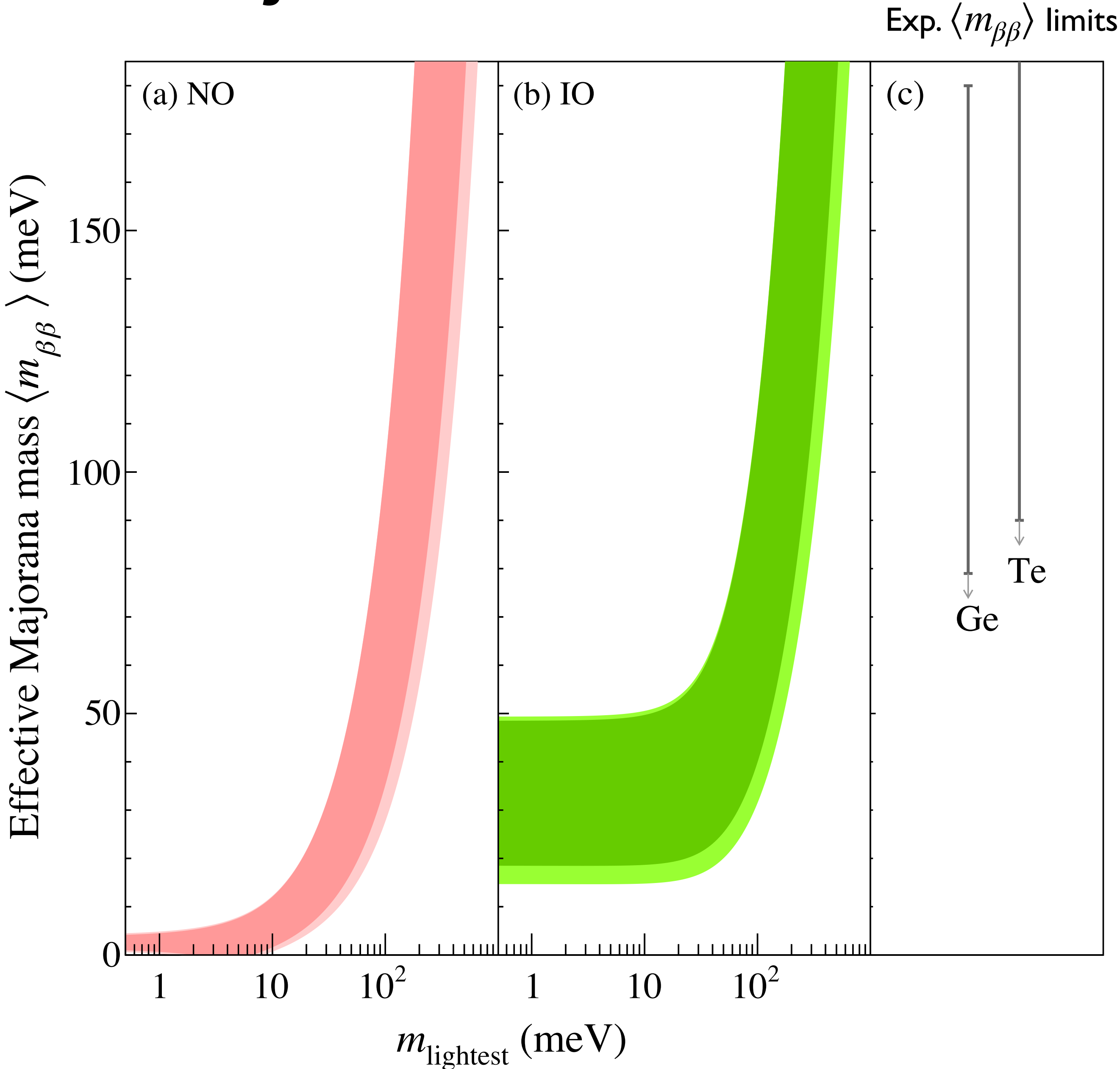
Xe-spallation candidates

The two spectra ($0\nu2\beta$ and Xe-spallation) are fitted simultaneously to constrain the Xe-spallation BG

Effective Majorana Mass

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q, Z)|M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

$T_{1/2} > 3.8 \times 10^{26} \text{ yr}$

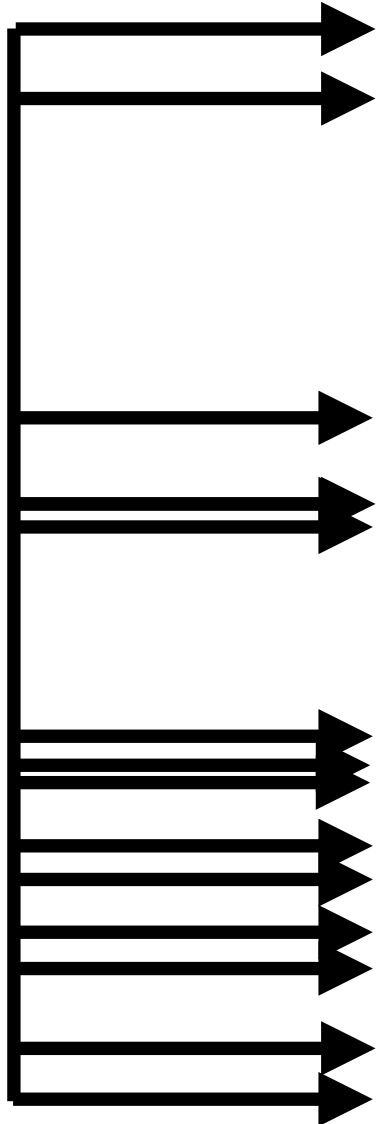


Effective Majorana Mass

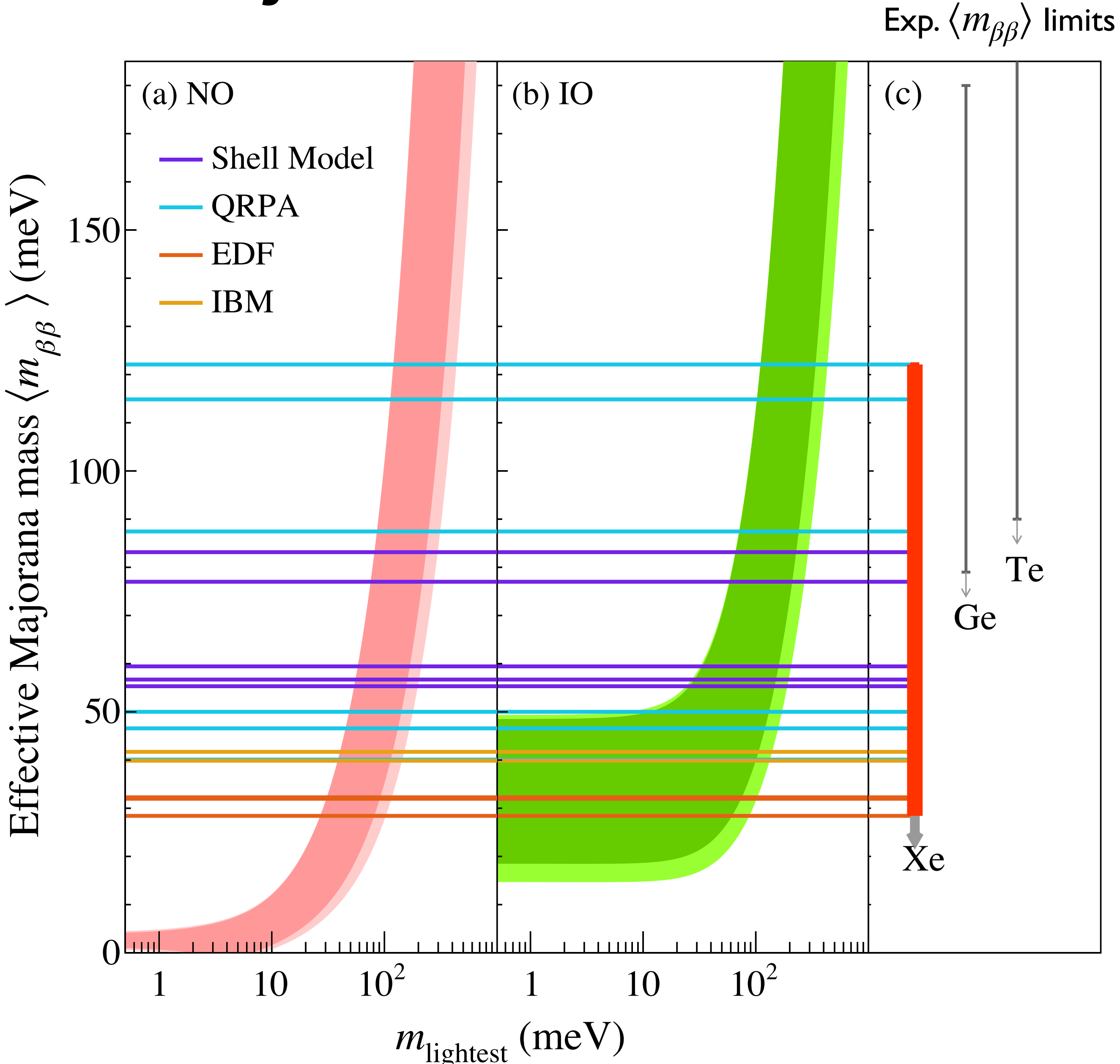
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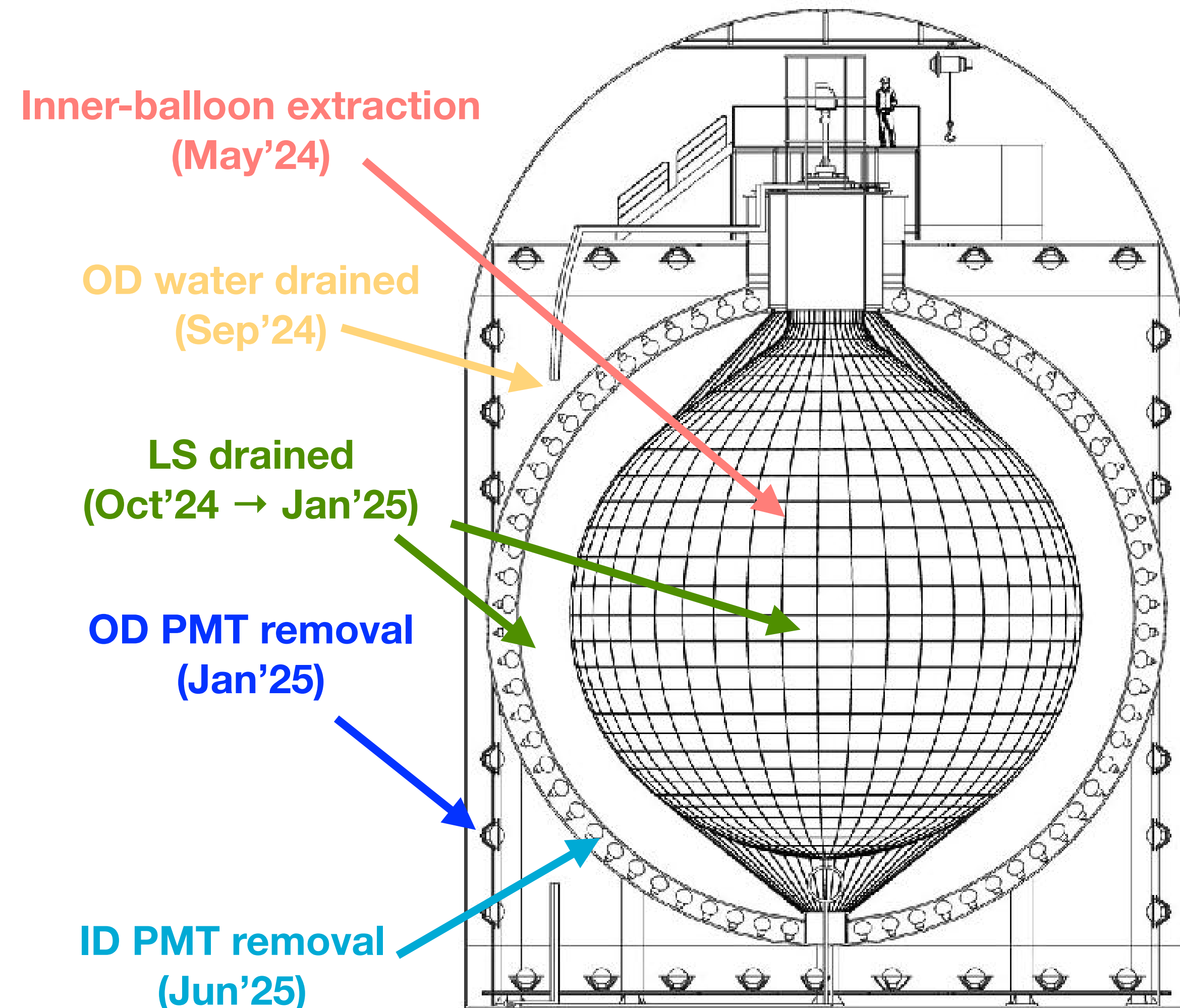
$\langle m_{\beta\beta} \rangle$ excl. limit depends on Nuclear Matrix Elements



Most stringent limit on $\langle m_{\beta\beta} \rangle$
For some NMEs we probe
Inverted Ordering v-mass

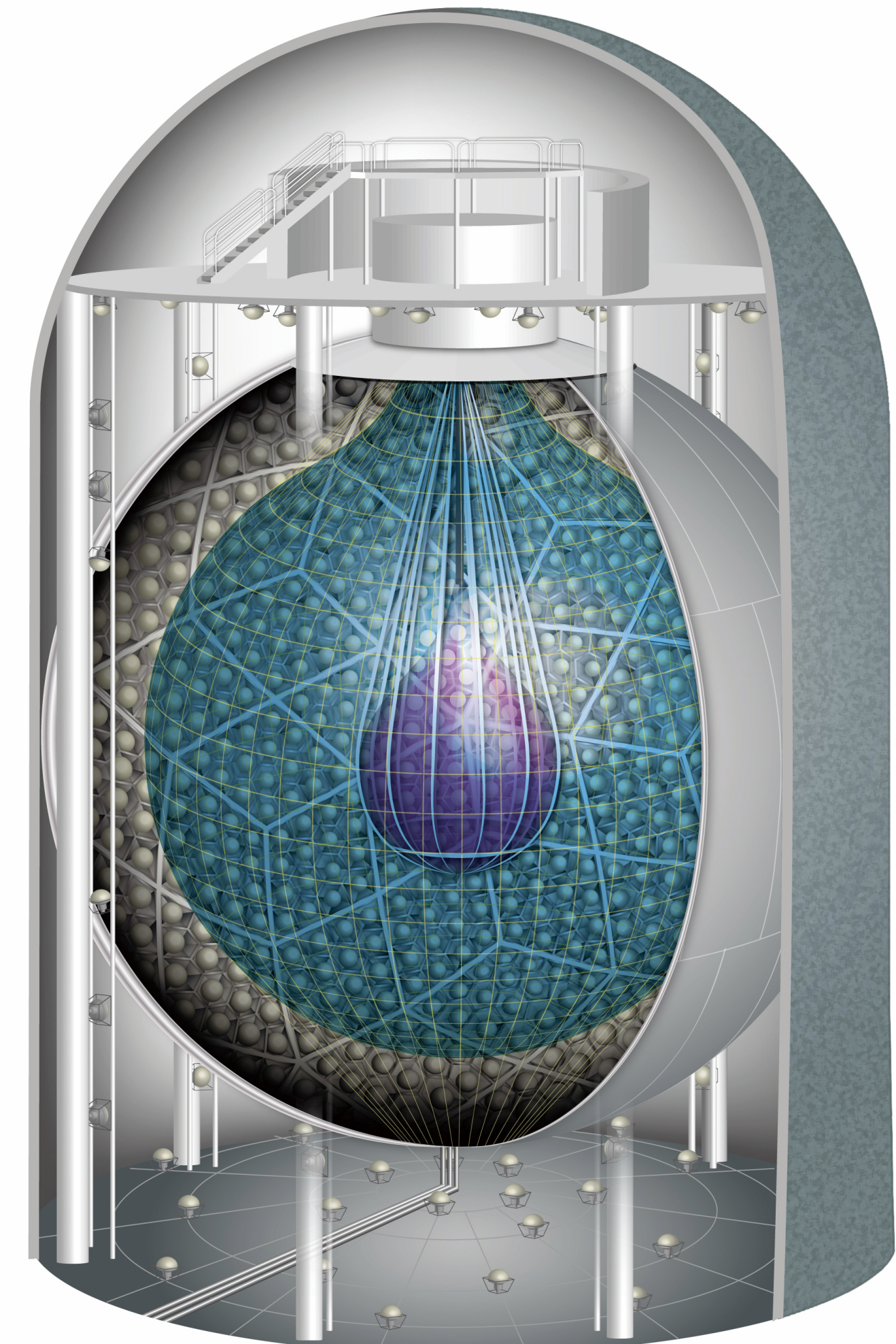


Transition to KamLAND2-Zen in progress!



KamLAND(-Zen)
2002-2024

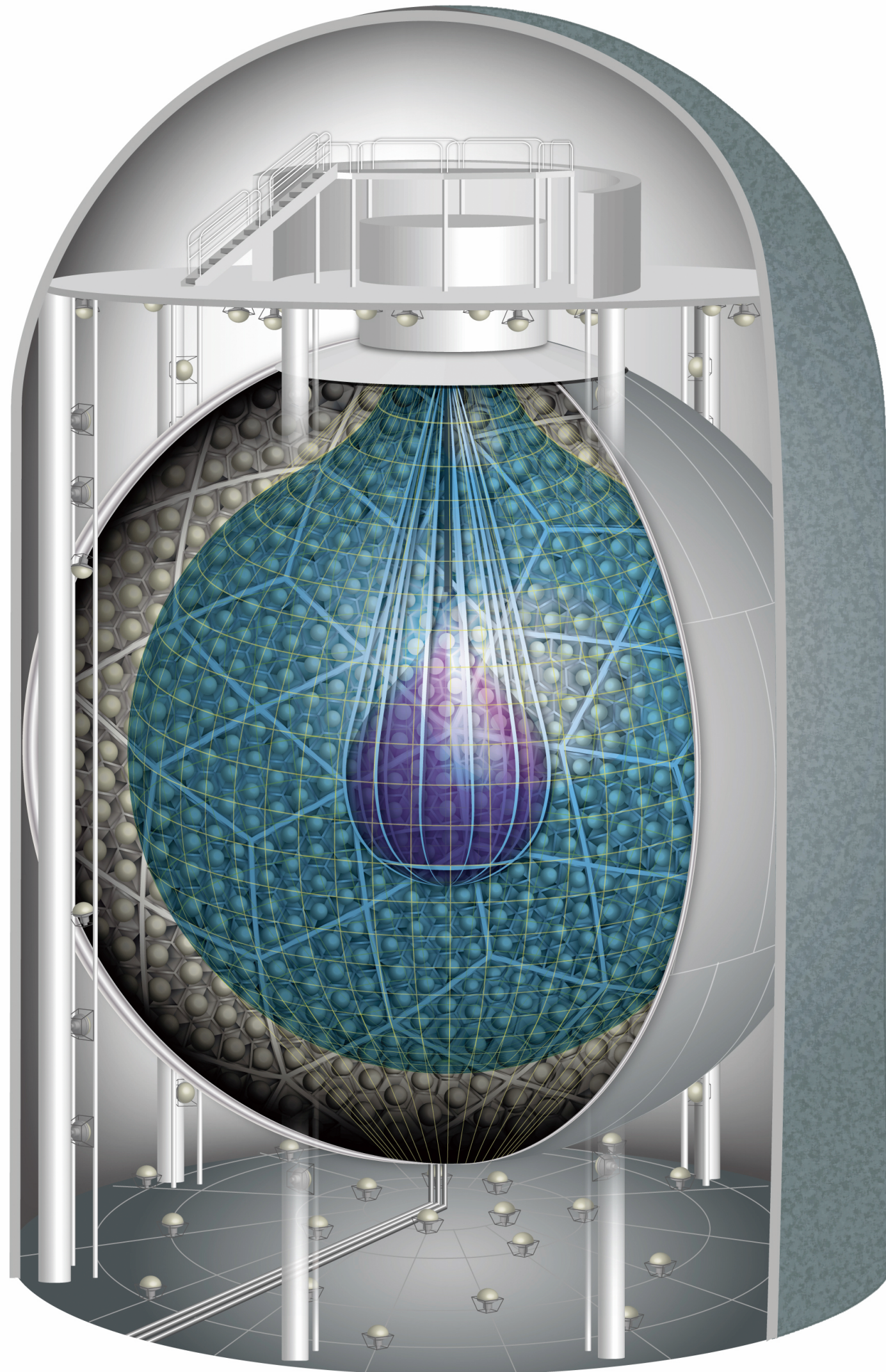
R.I.P.



KamLAND2-Zen

KamLAND2-Zen

Design sensitivity of $T_{1/2} > 2 \times 10^{27}$ yrs and $\langle m_{\beta\beta} \rangle \sim 20$ meV

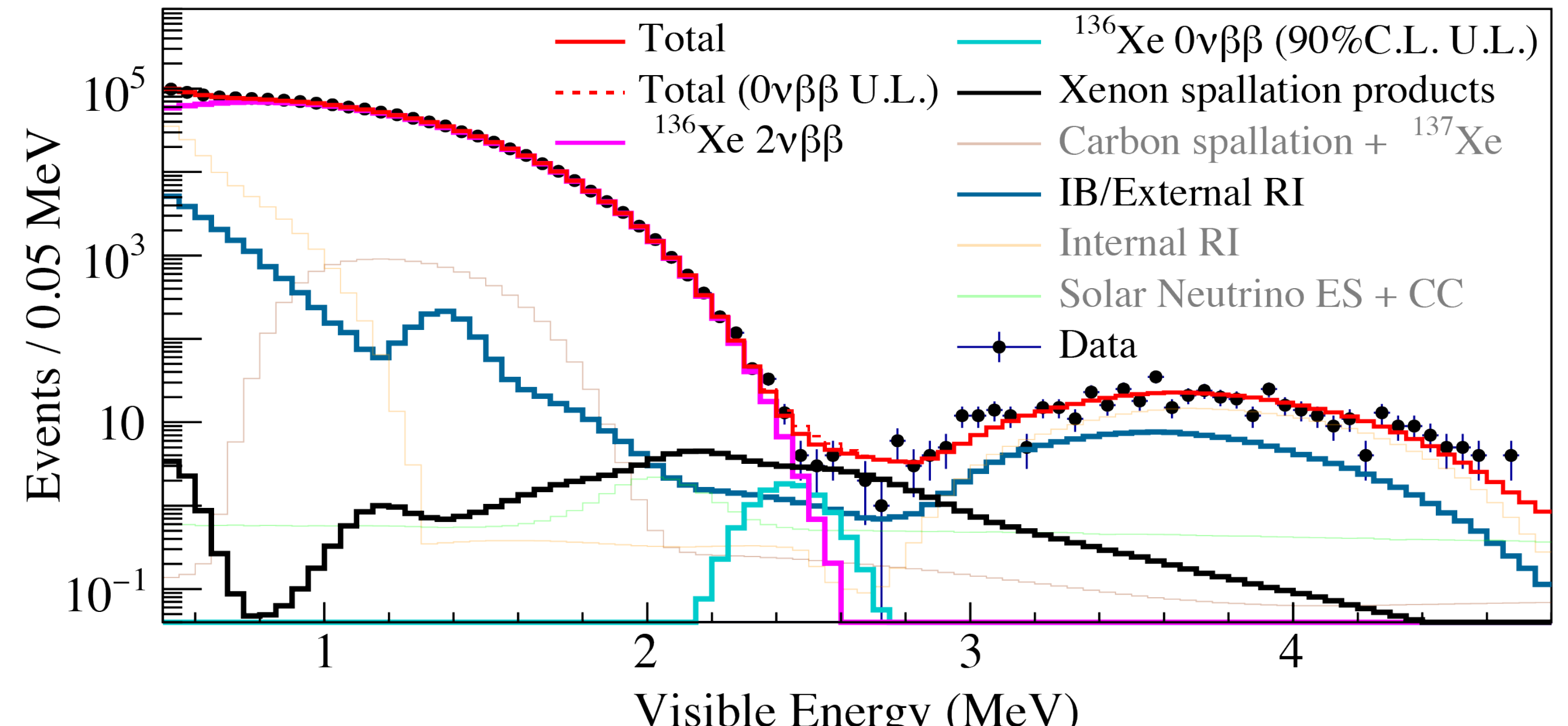
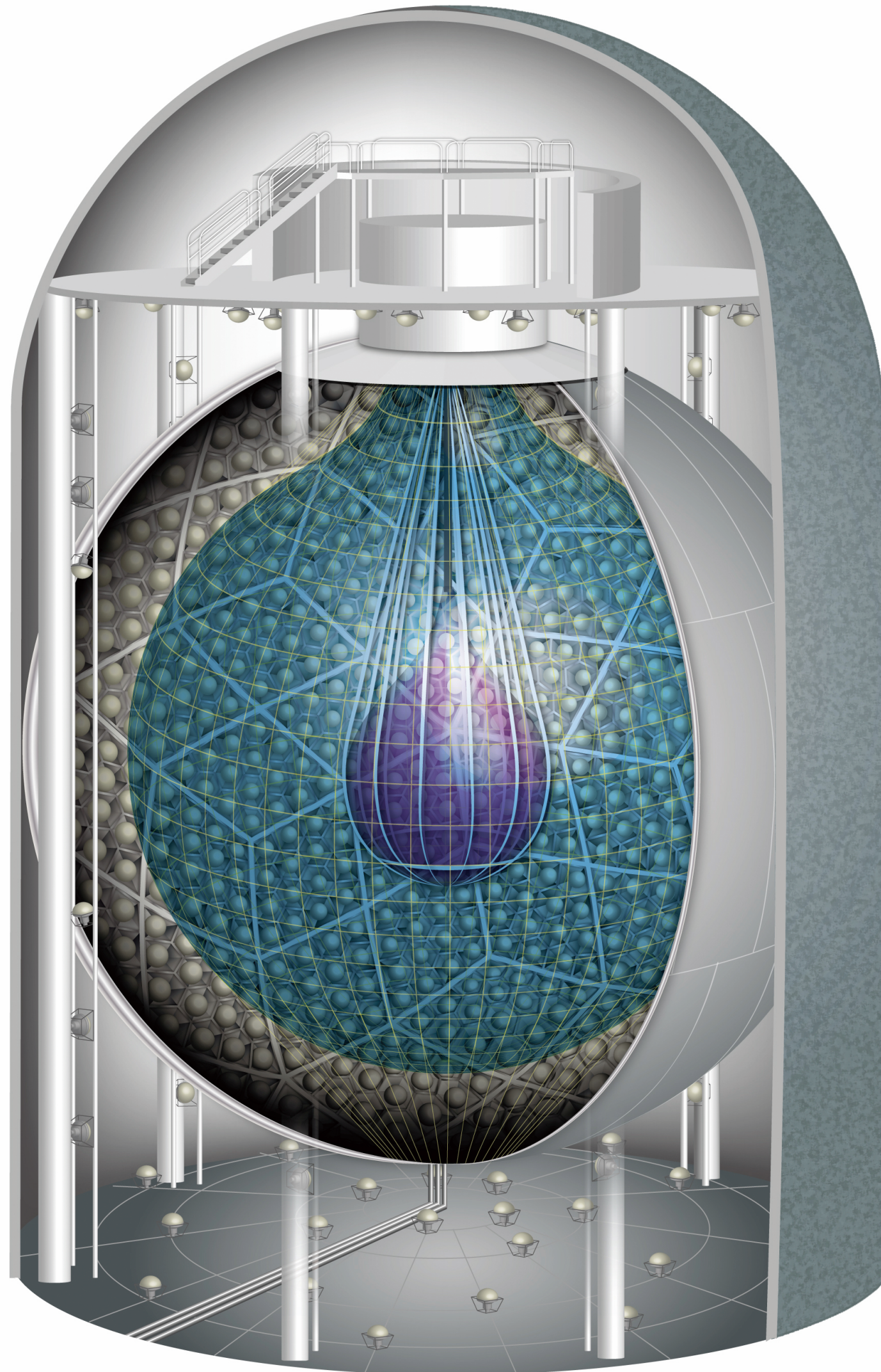


- Improved energy resolution: Winston Cones (x1.8), High-QE PMTs (x1.9)
 - 4% $\rightarrow$ 2% (x100 reduction in $2\nu\beta\beta$ BG rate)
- Better tag long-lived spallation BG: State-of-the-art electronics
- Reduce BG on inner balloon: scintillating balloon

KamLAND2-Zen

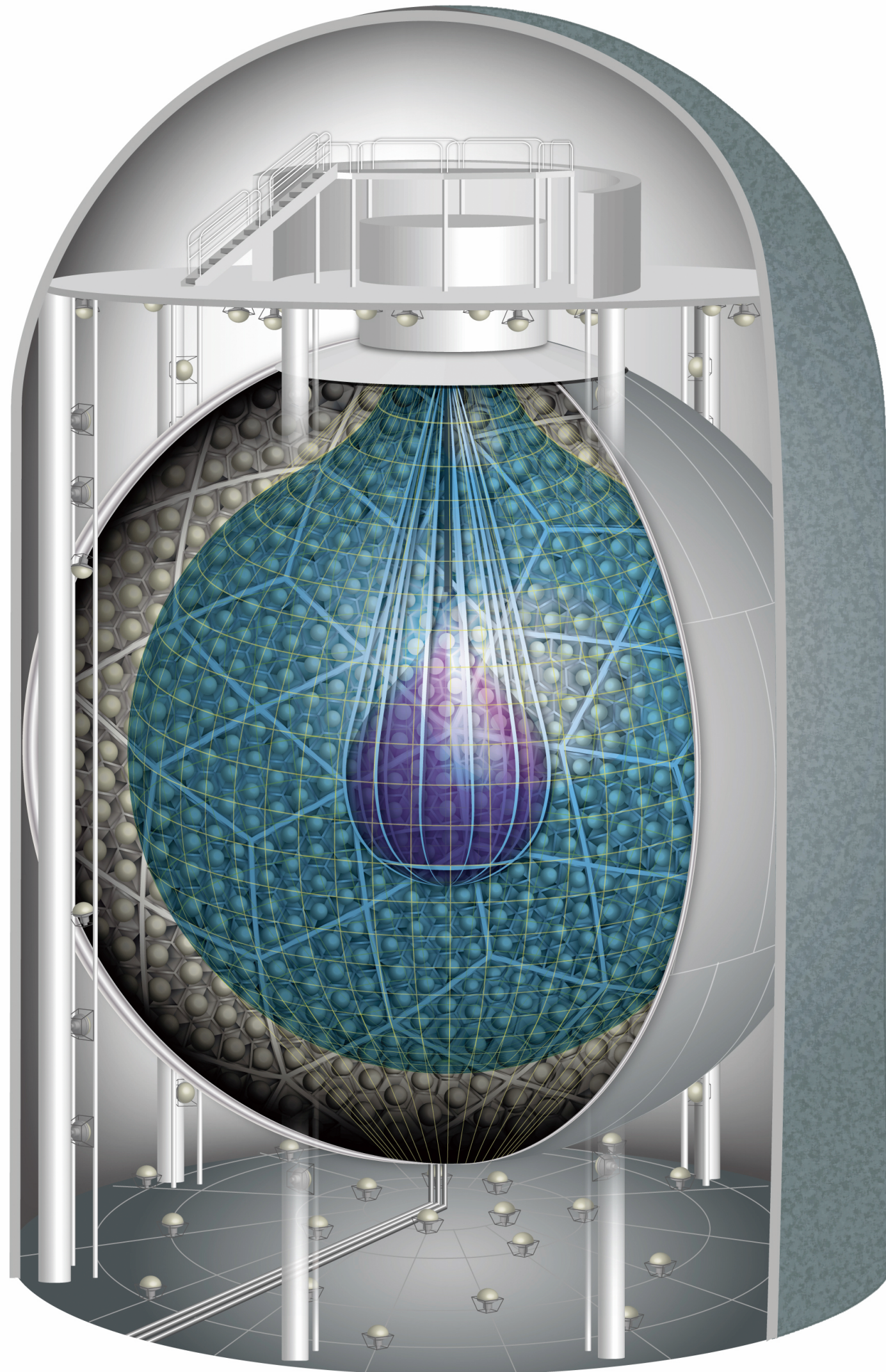
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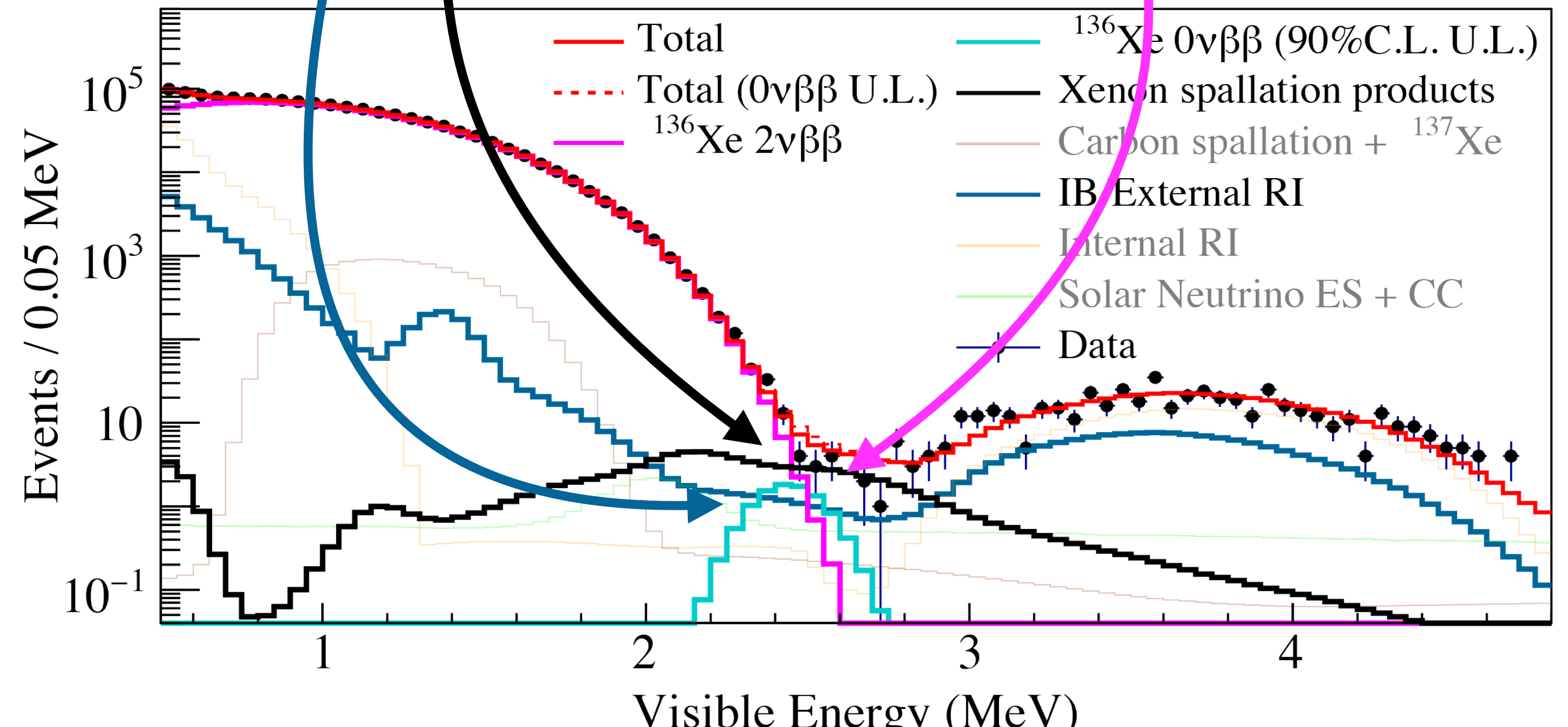


KamLAND2-Zen

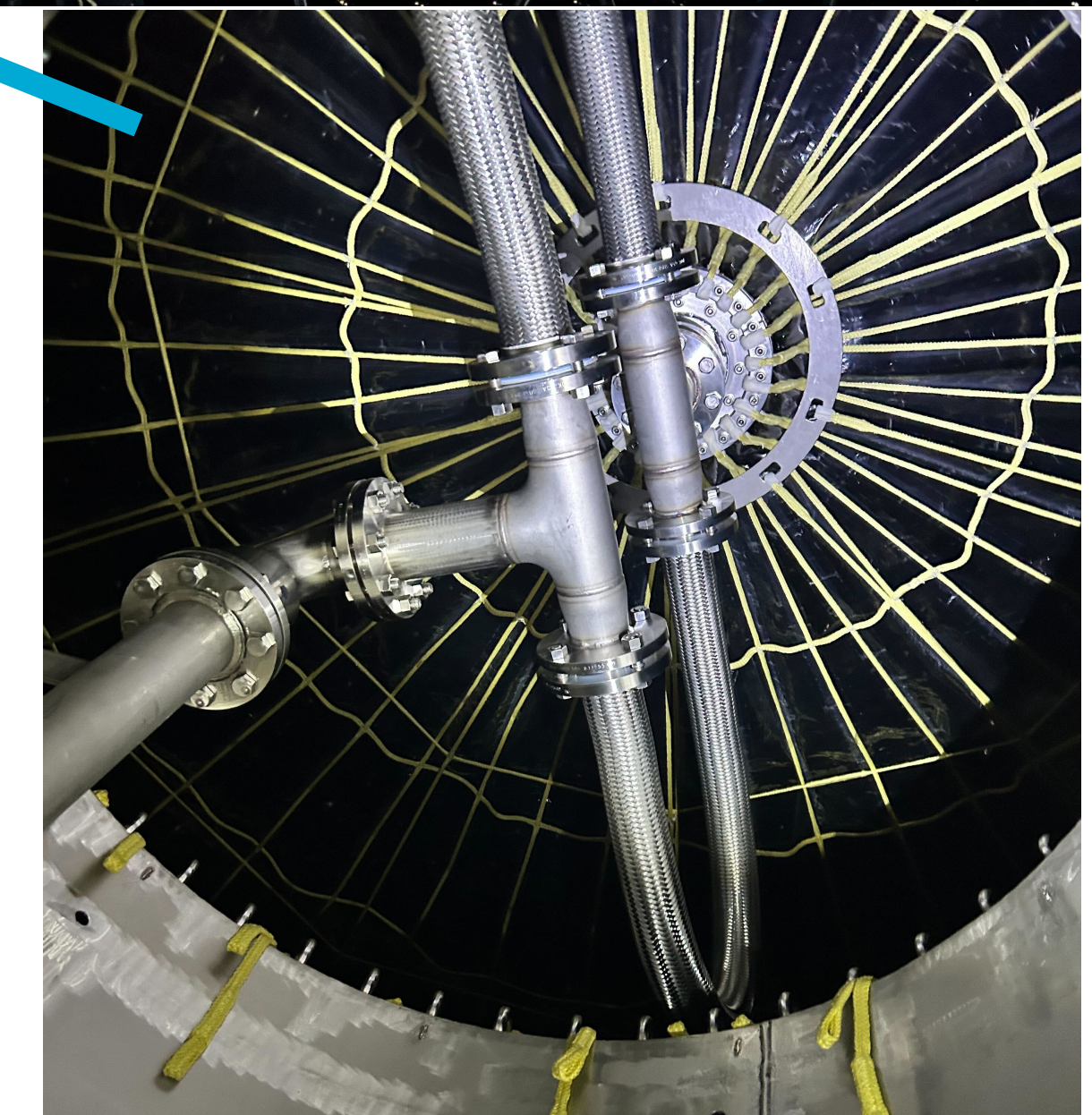
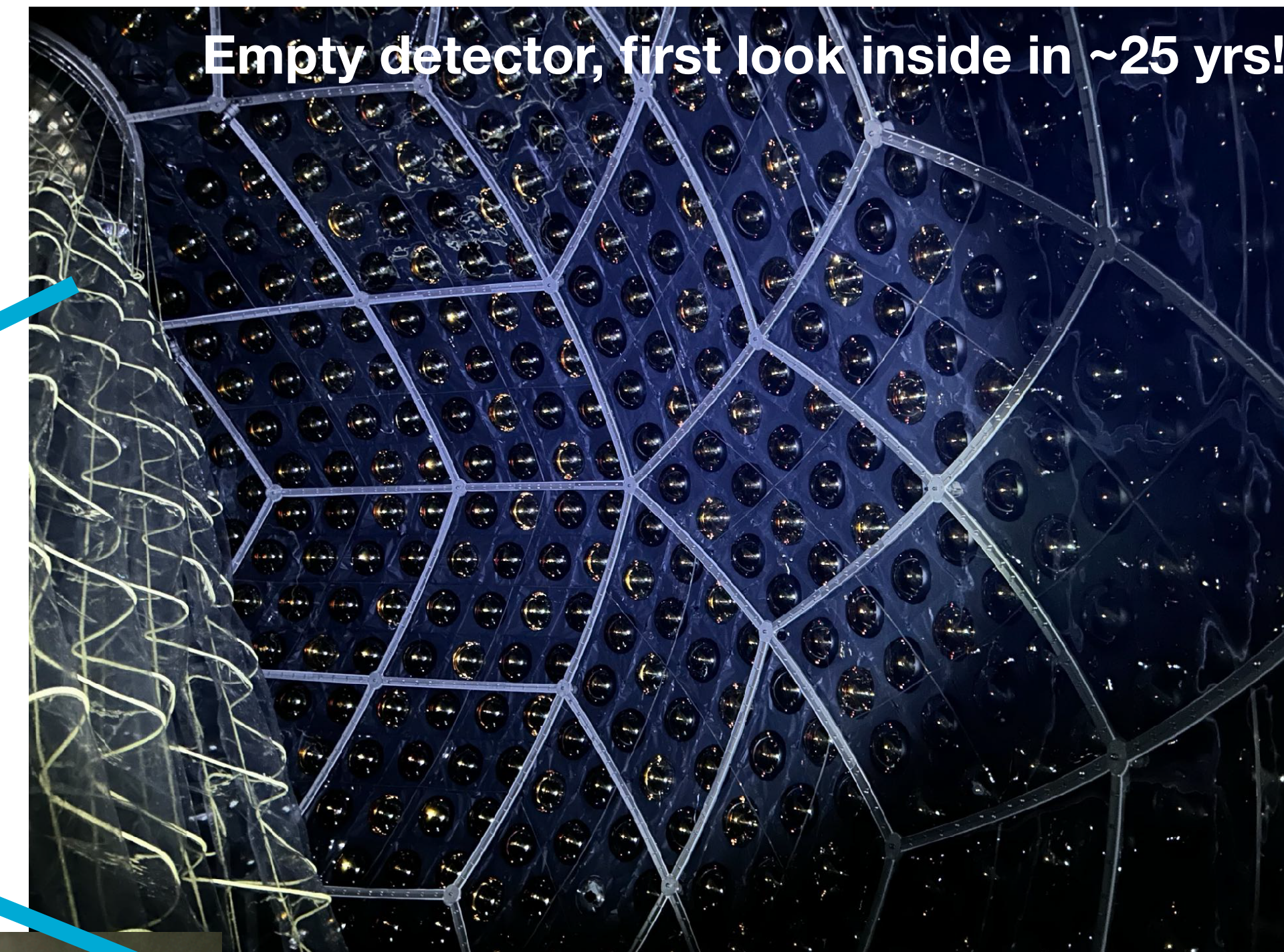
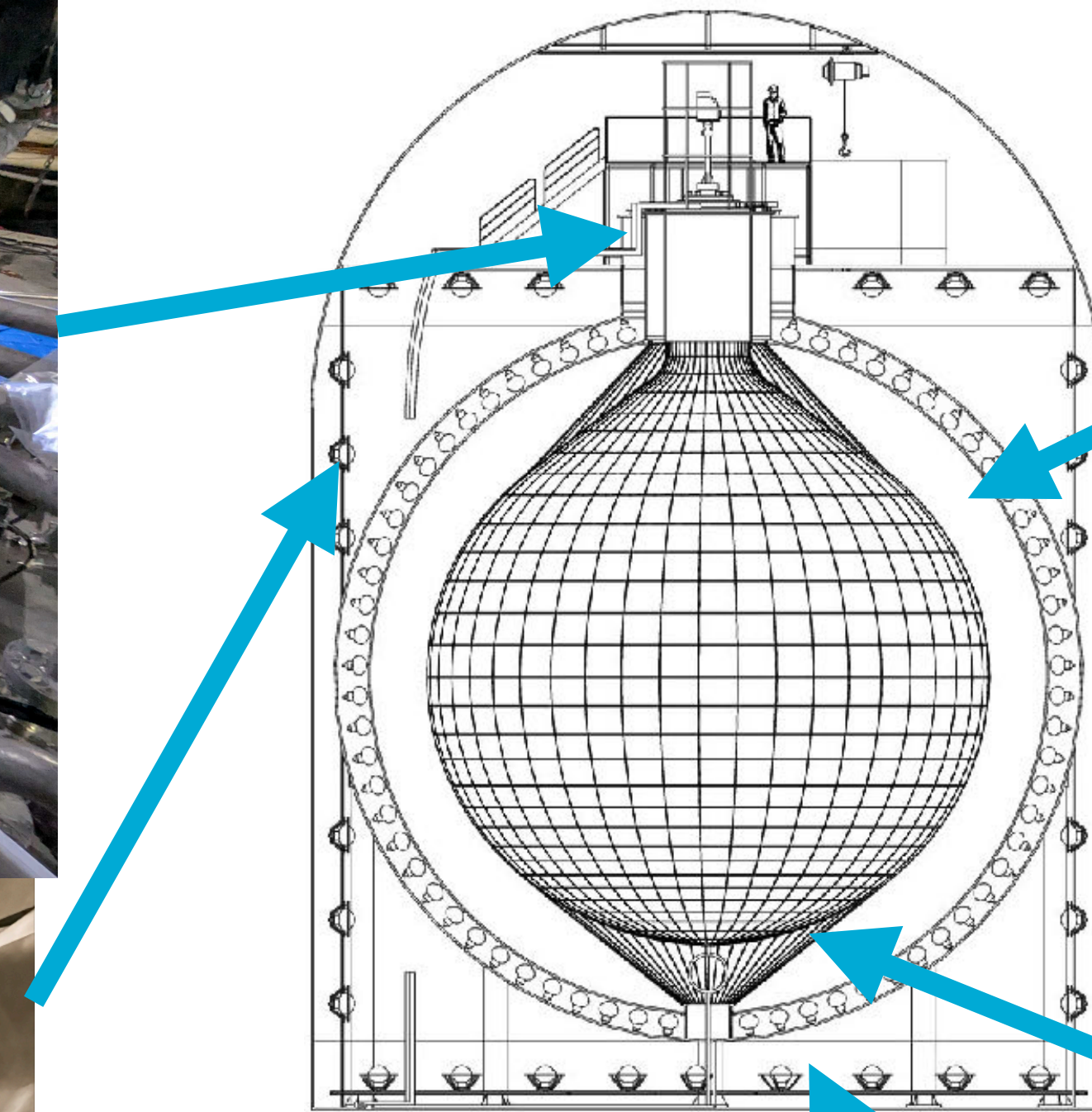
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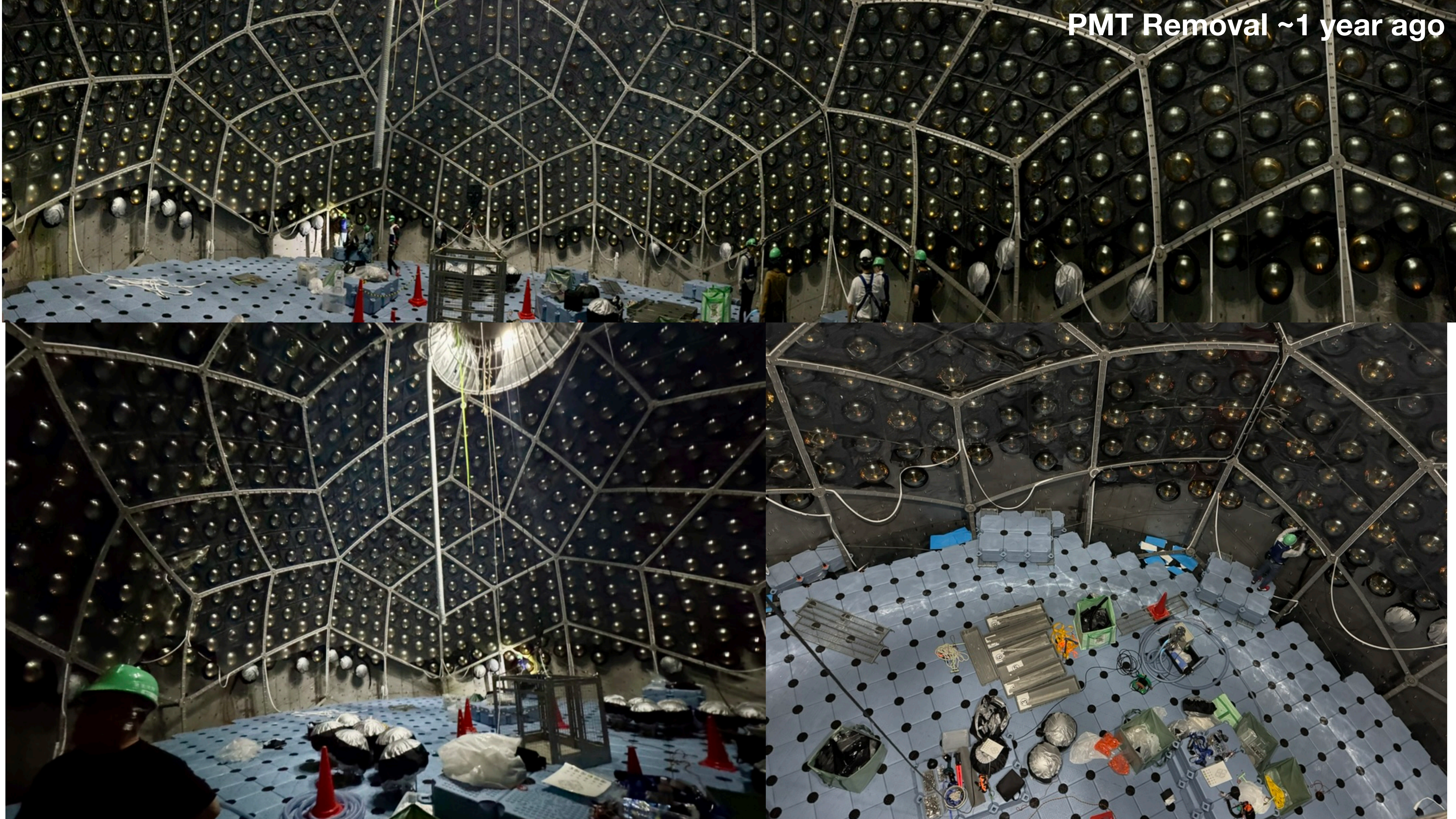
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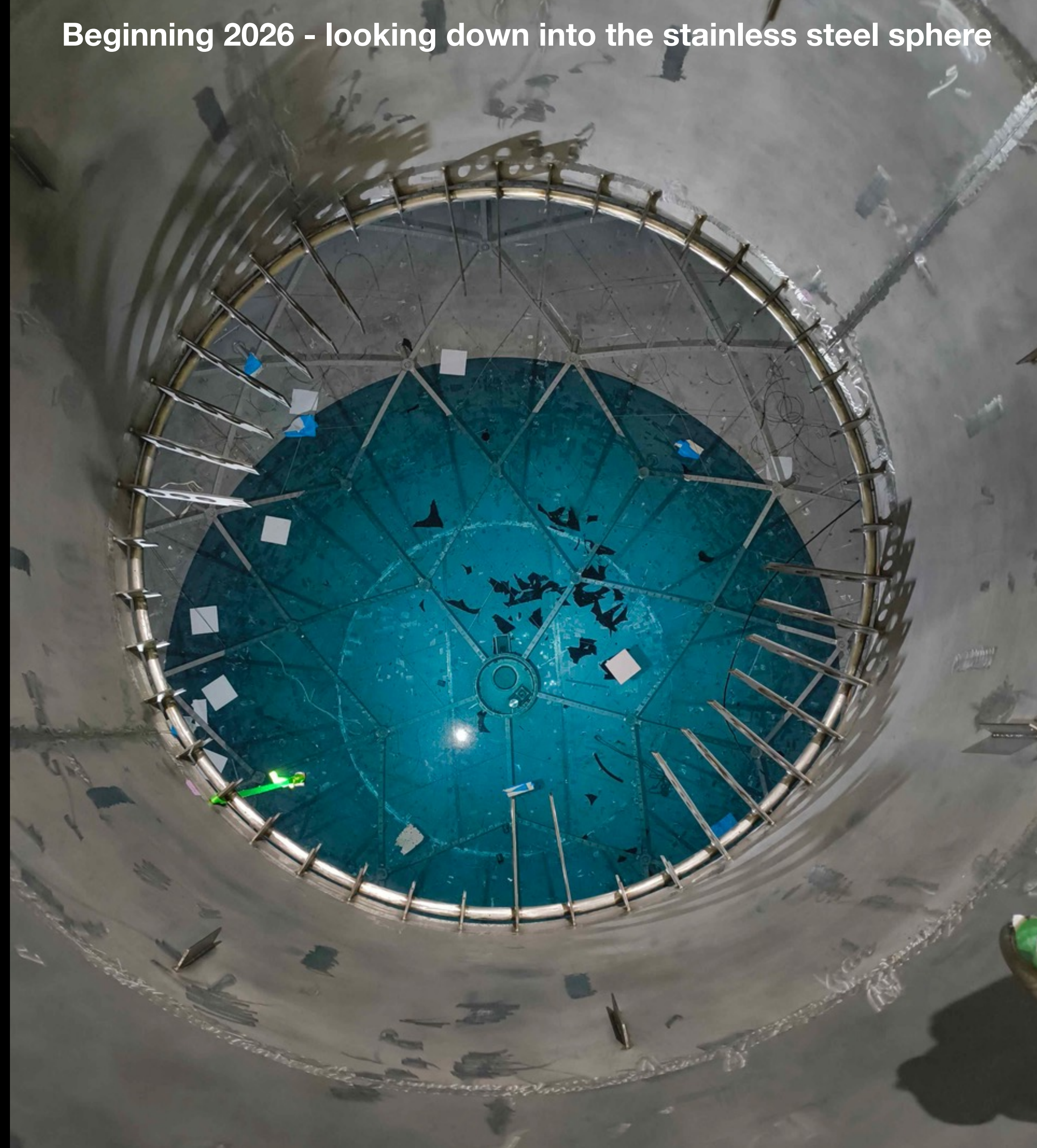
KamLAND-Zen disassembly Fall'24 onwards



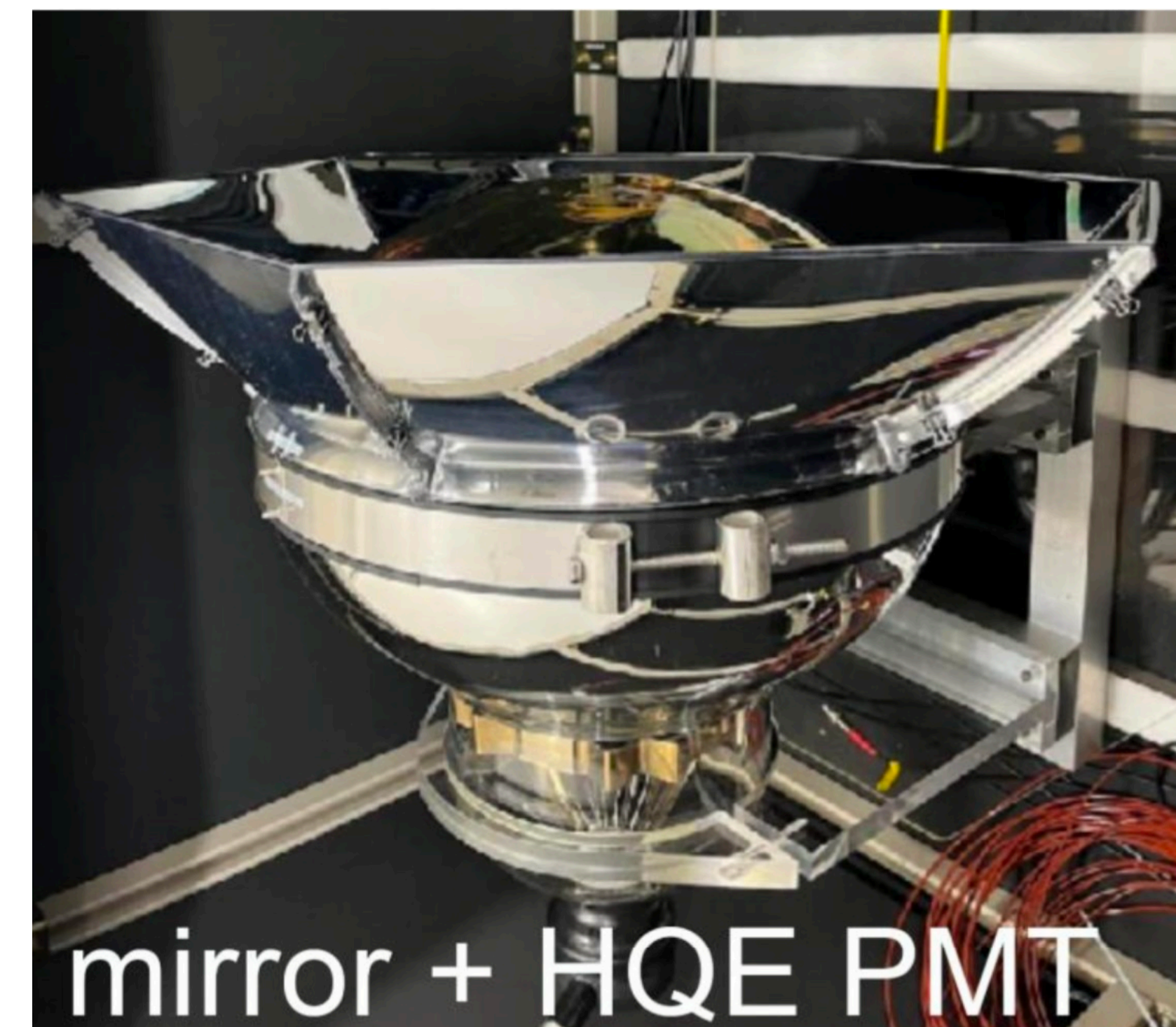
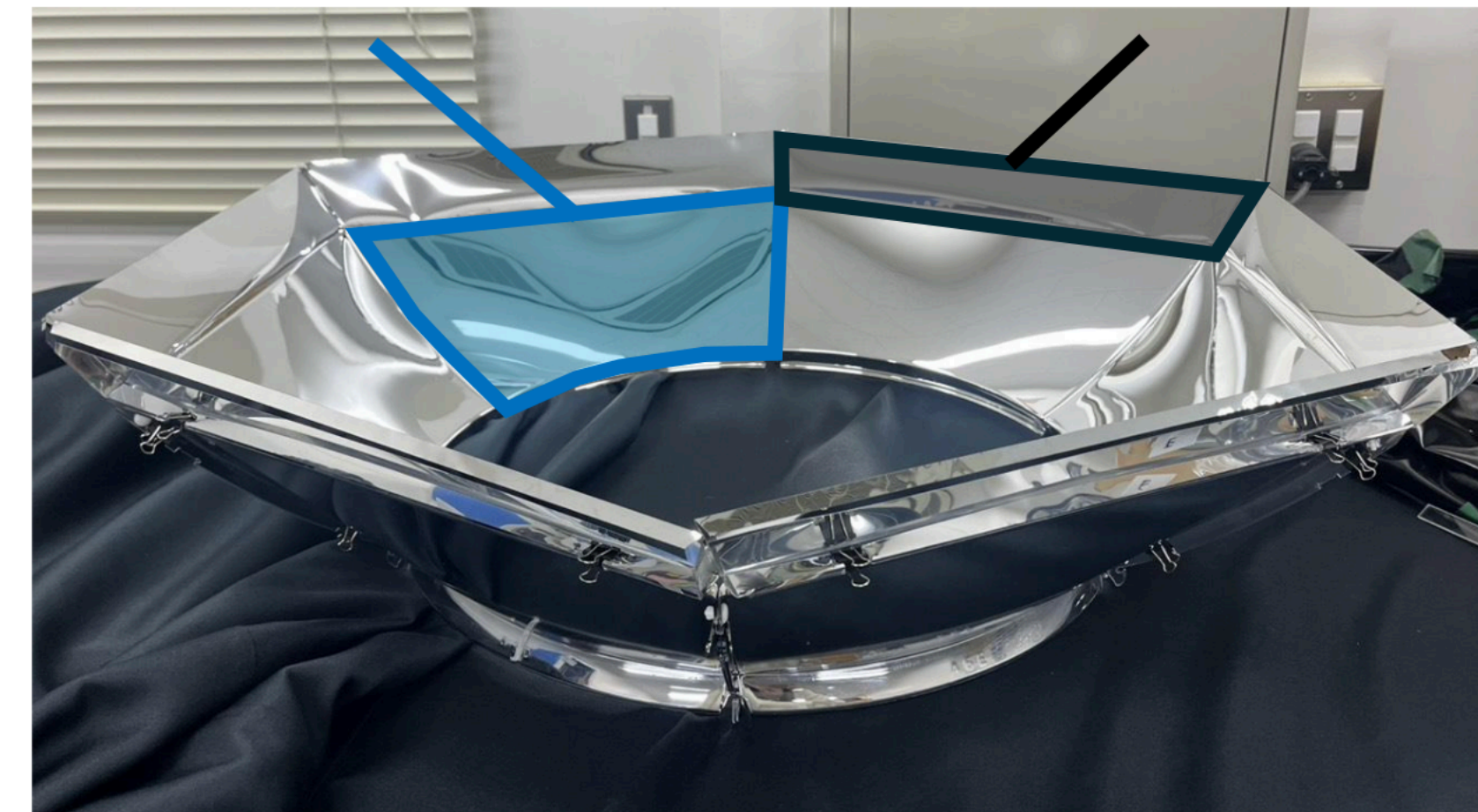
PMT Removal ~1 year ago



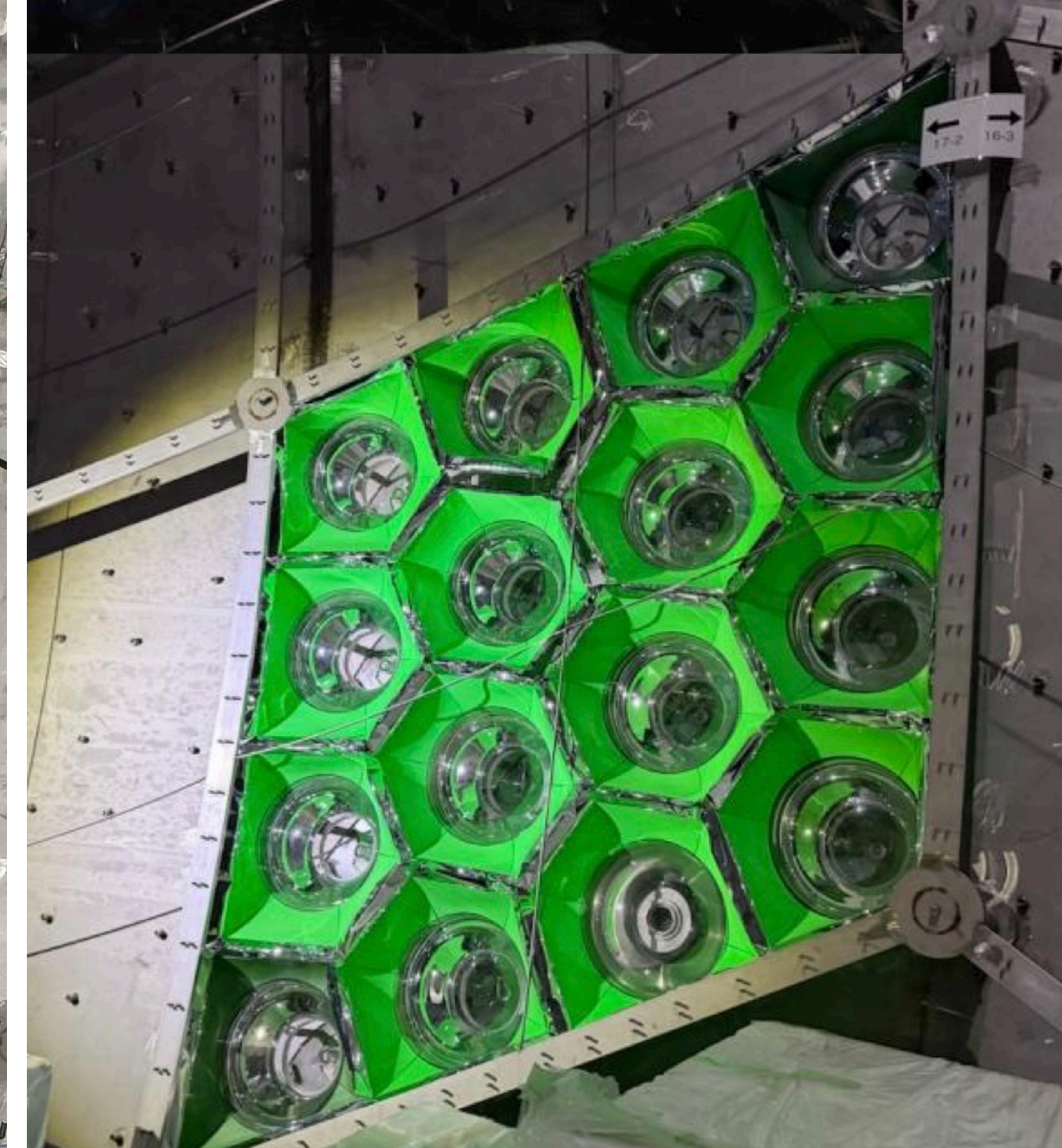
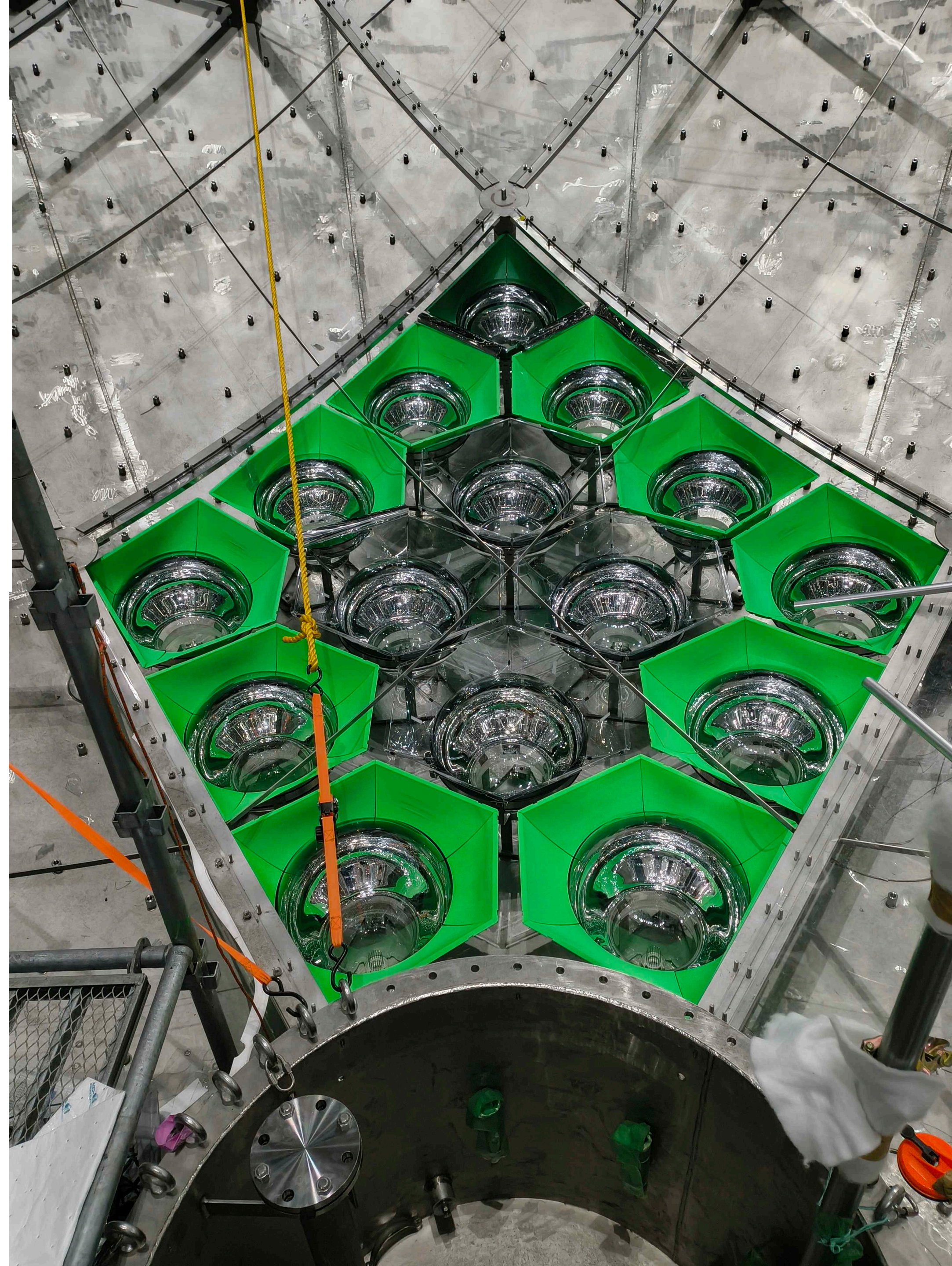
Beginning 2026 - looking down into the stainless steel sphere



PET mirror **sheet mirror**

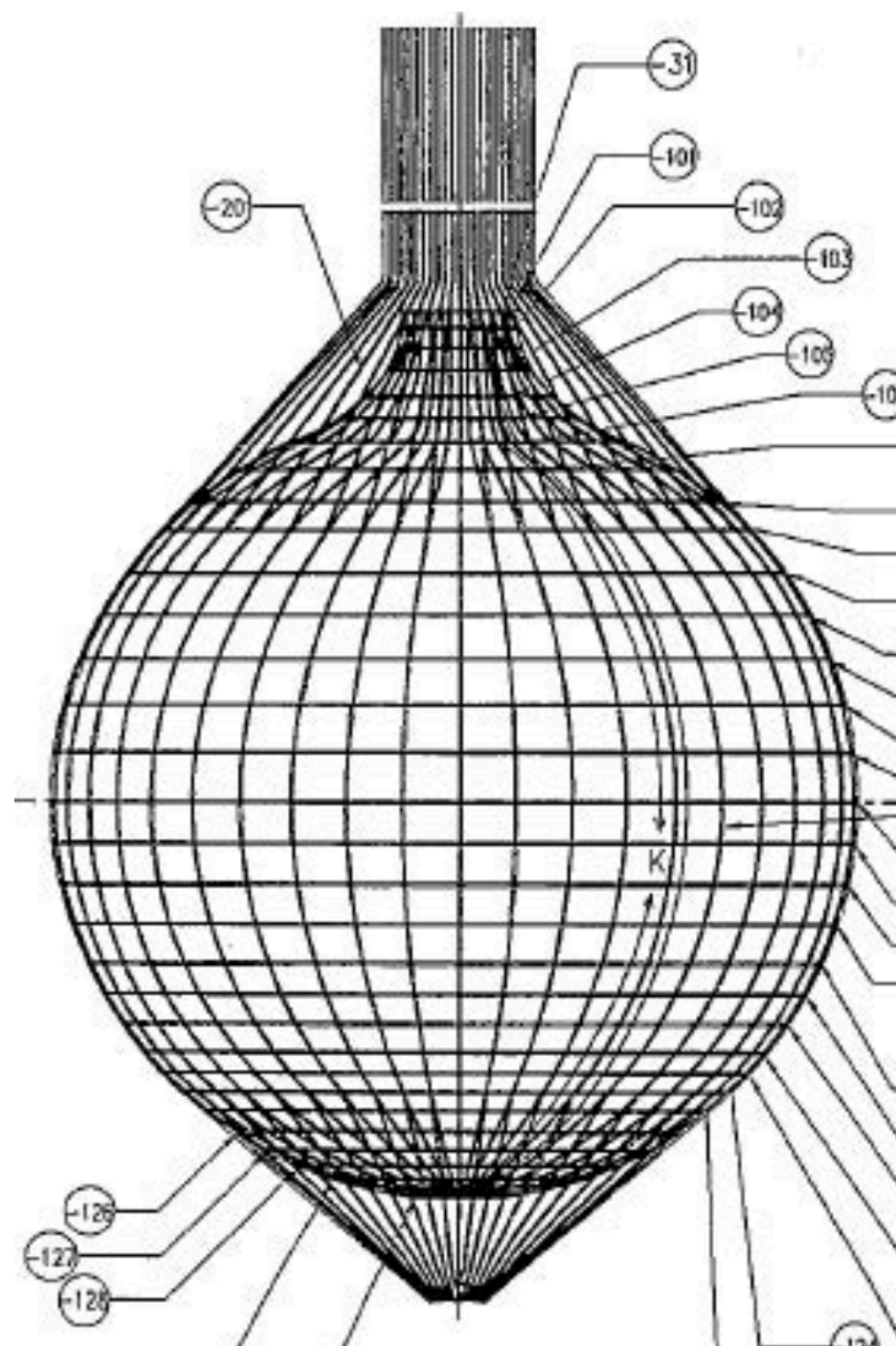
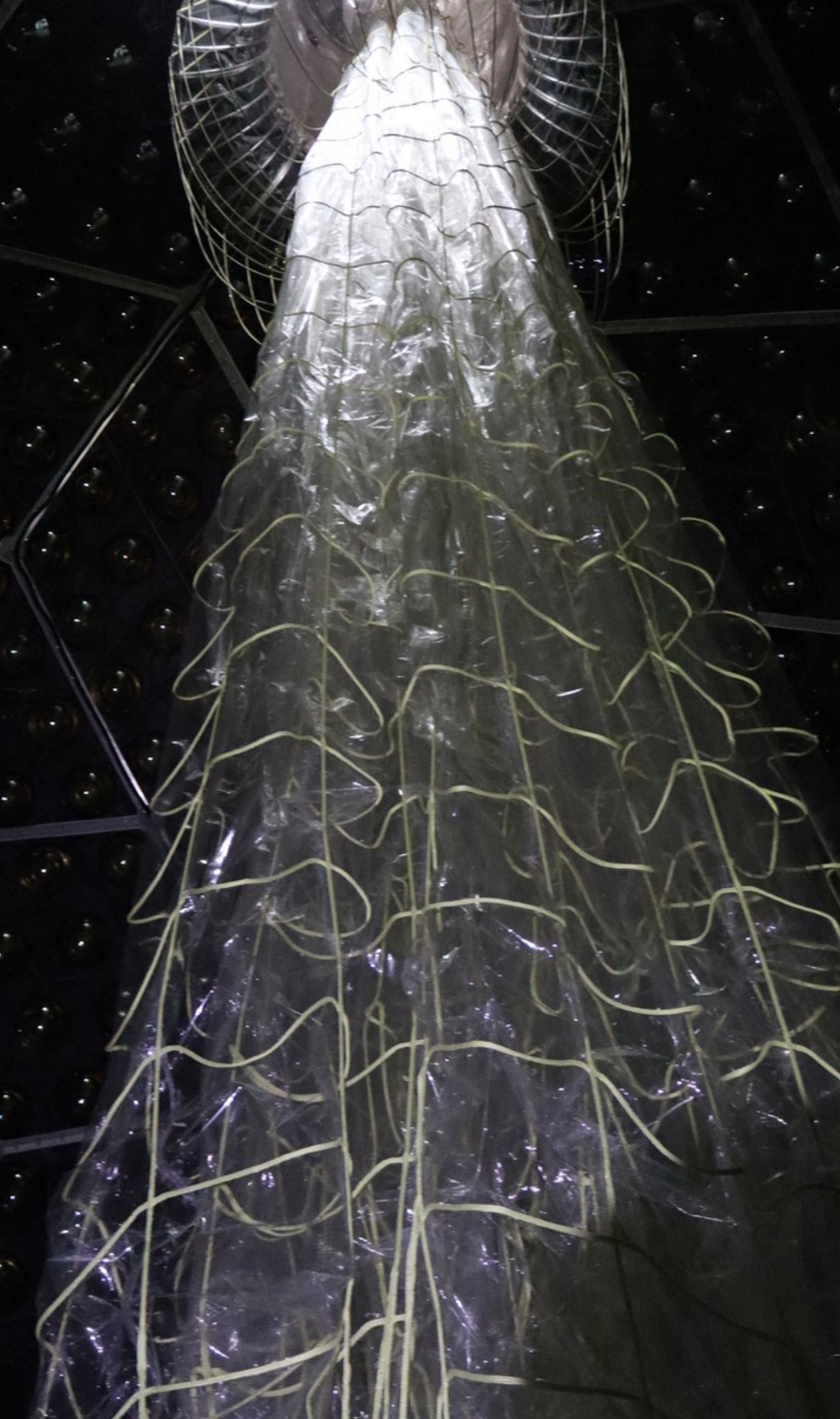


mirror + HQE PMT



More photons collected:

- Mirrors: x1.8
- HQE PMTs: x1.9
- 1900 new PMTs



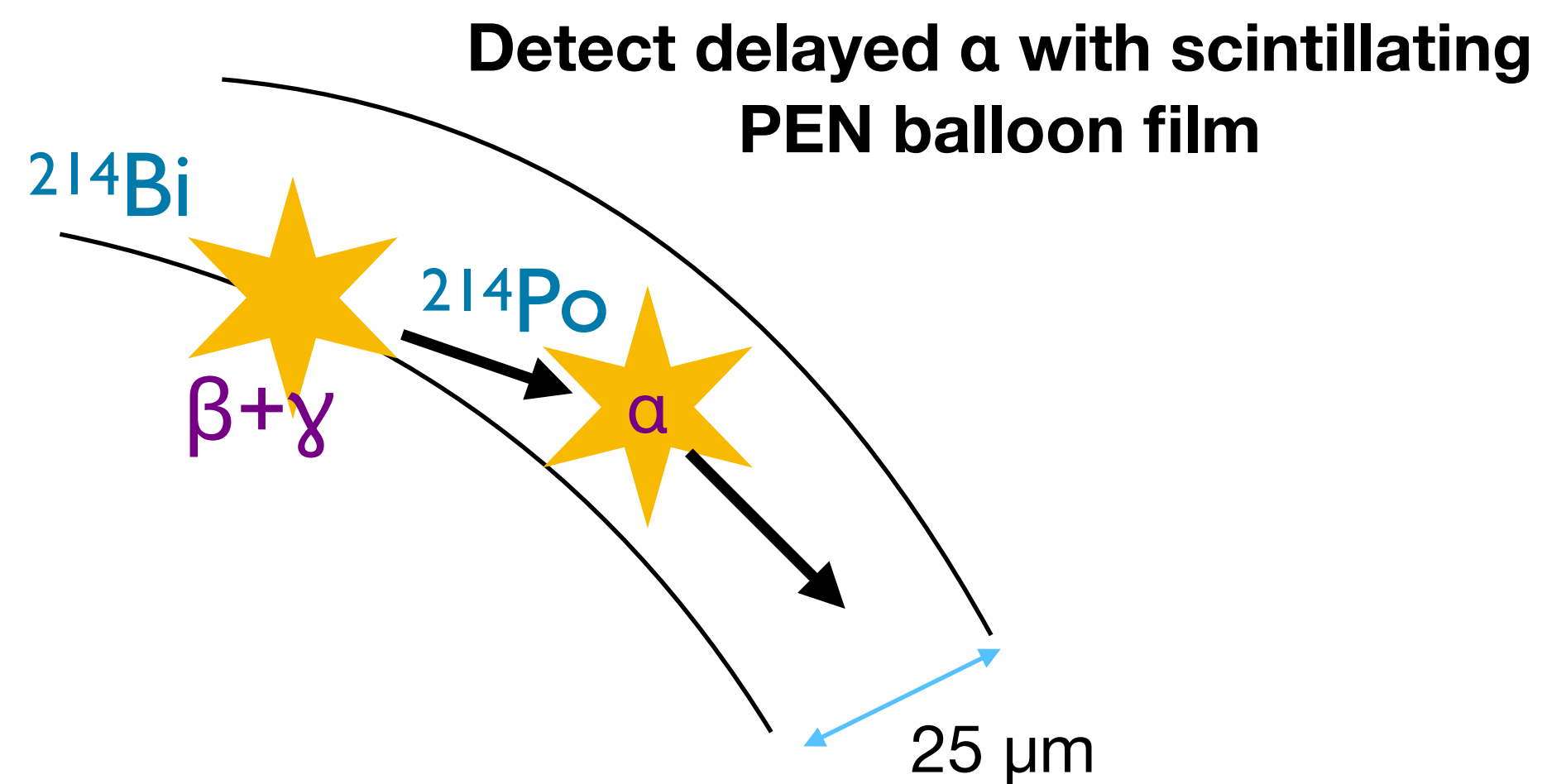
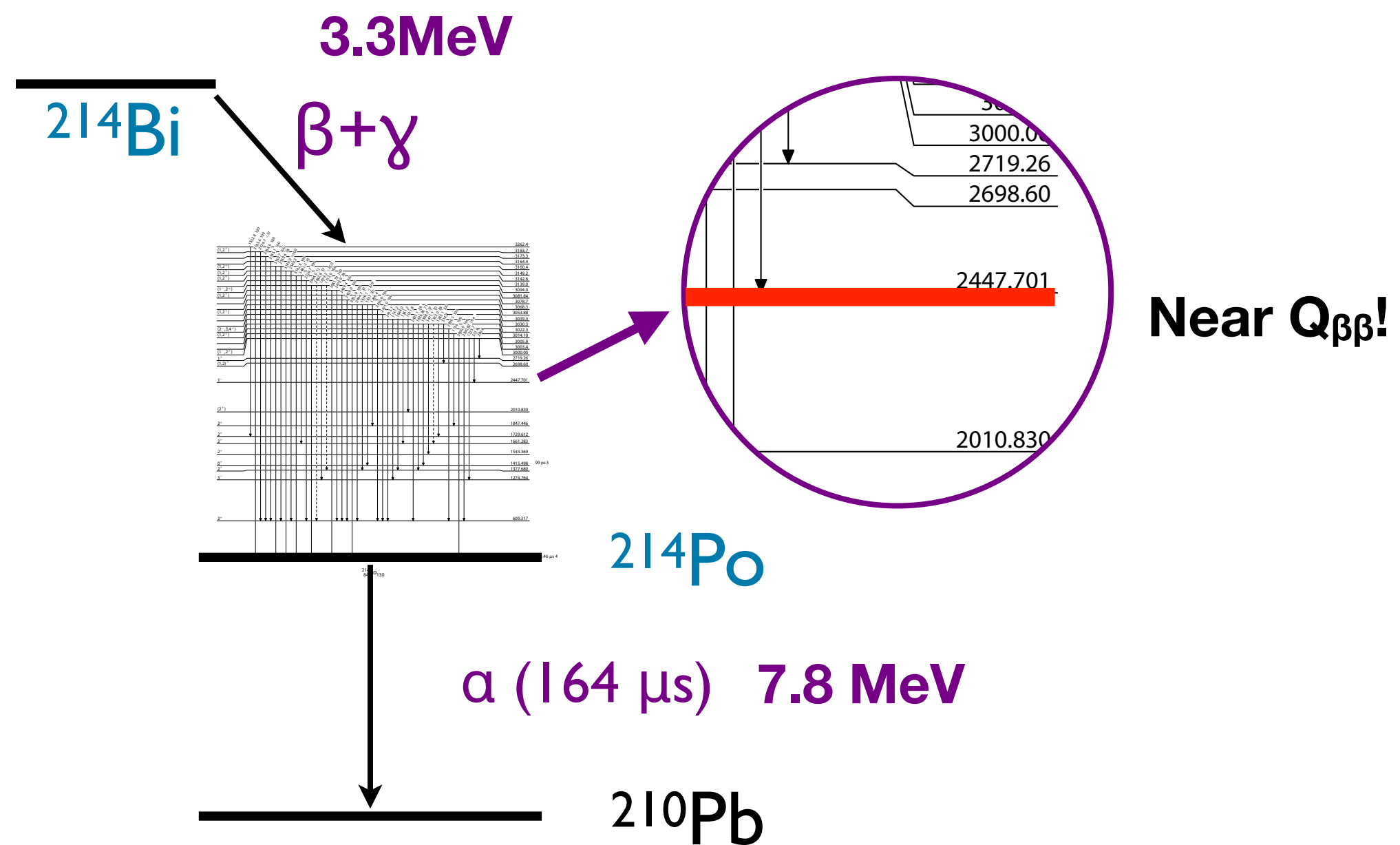
Very similar to original KamLAND balloon:

- 6.5 m radius
- 125 μm five-layer EVOH-nylon film

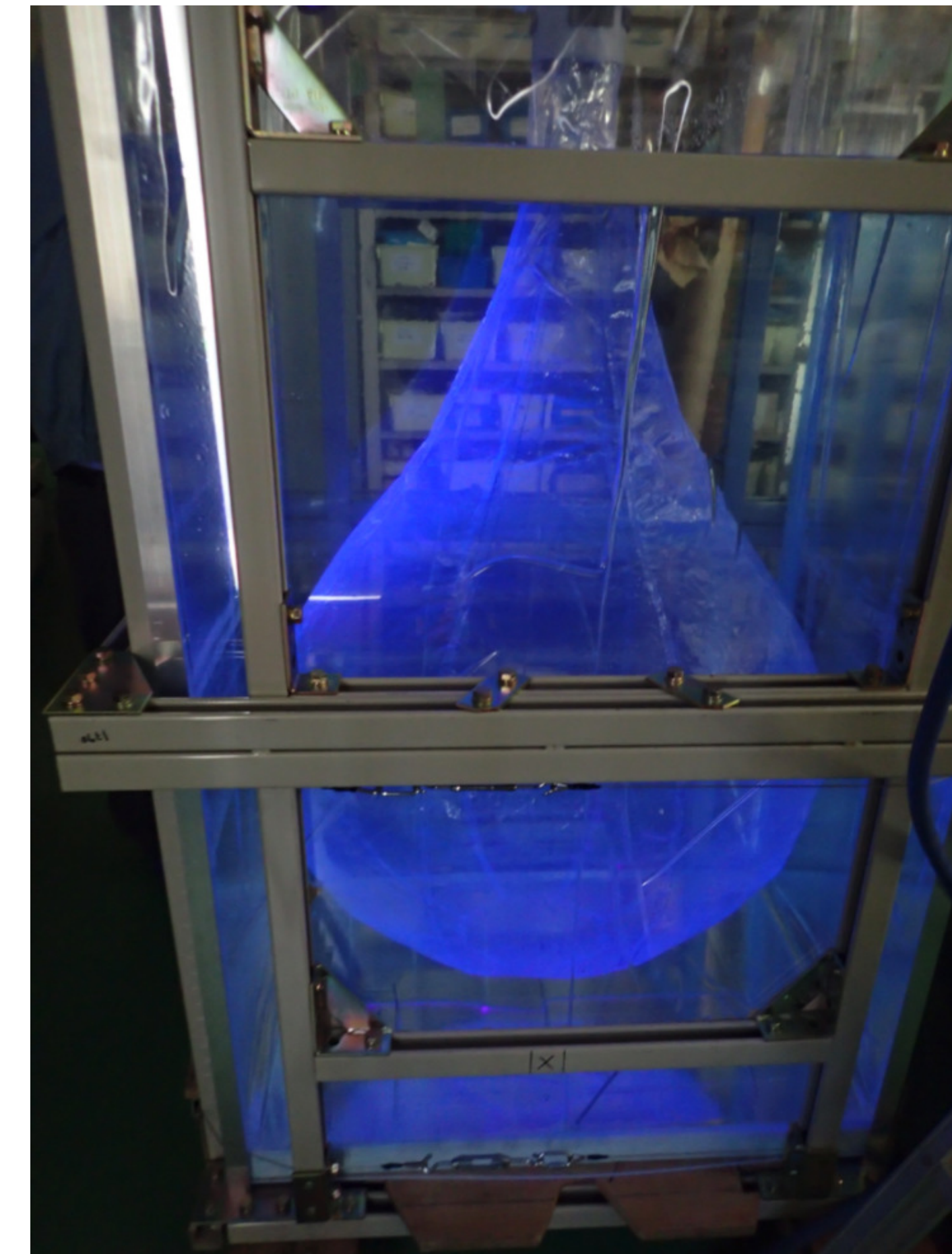
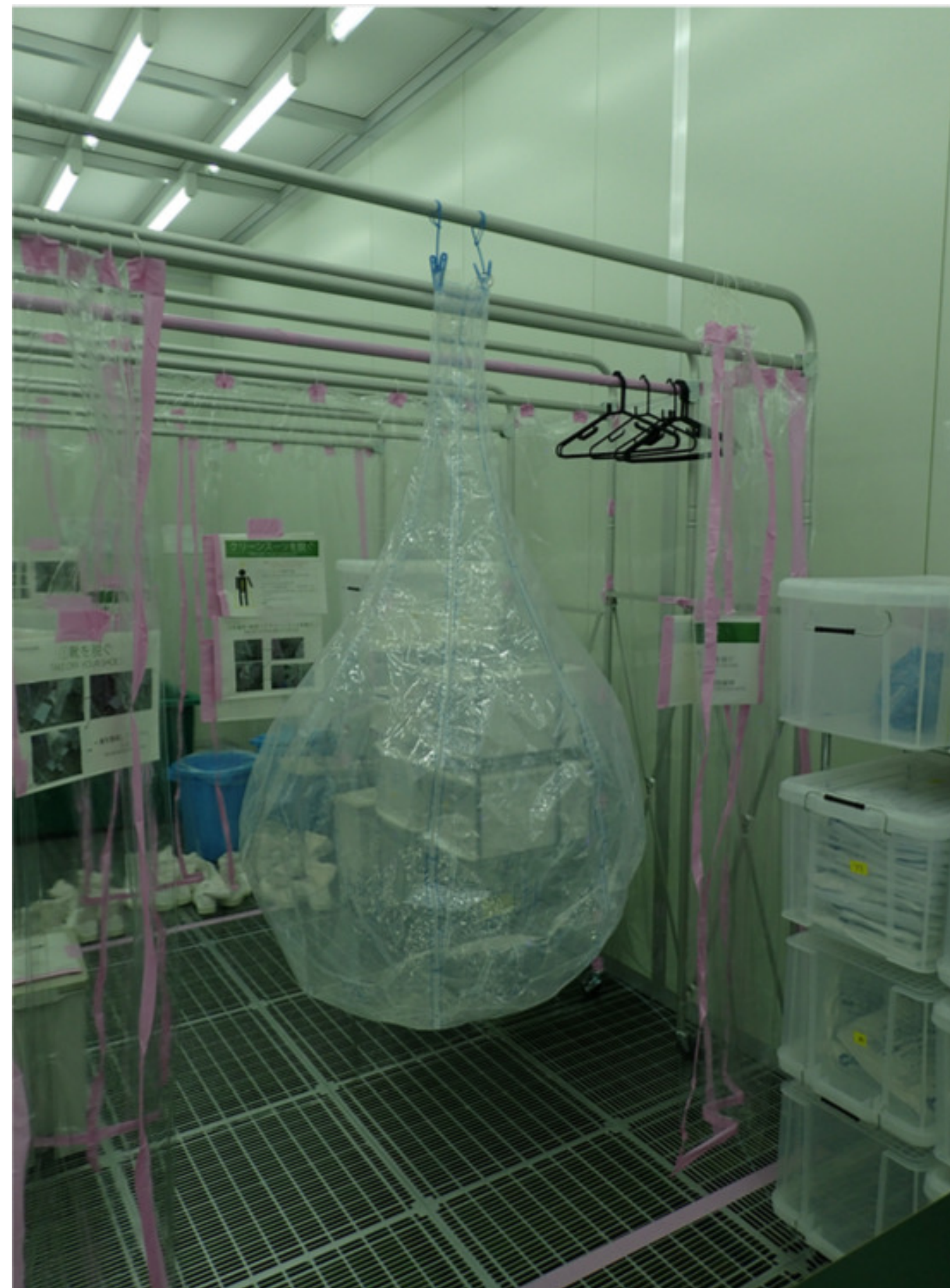
Tests being done on original balloon:

→ 25 years in LS!

Scintillating Inner Balloon

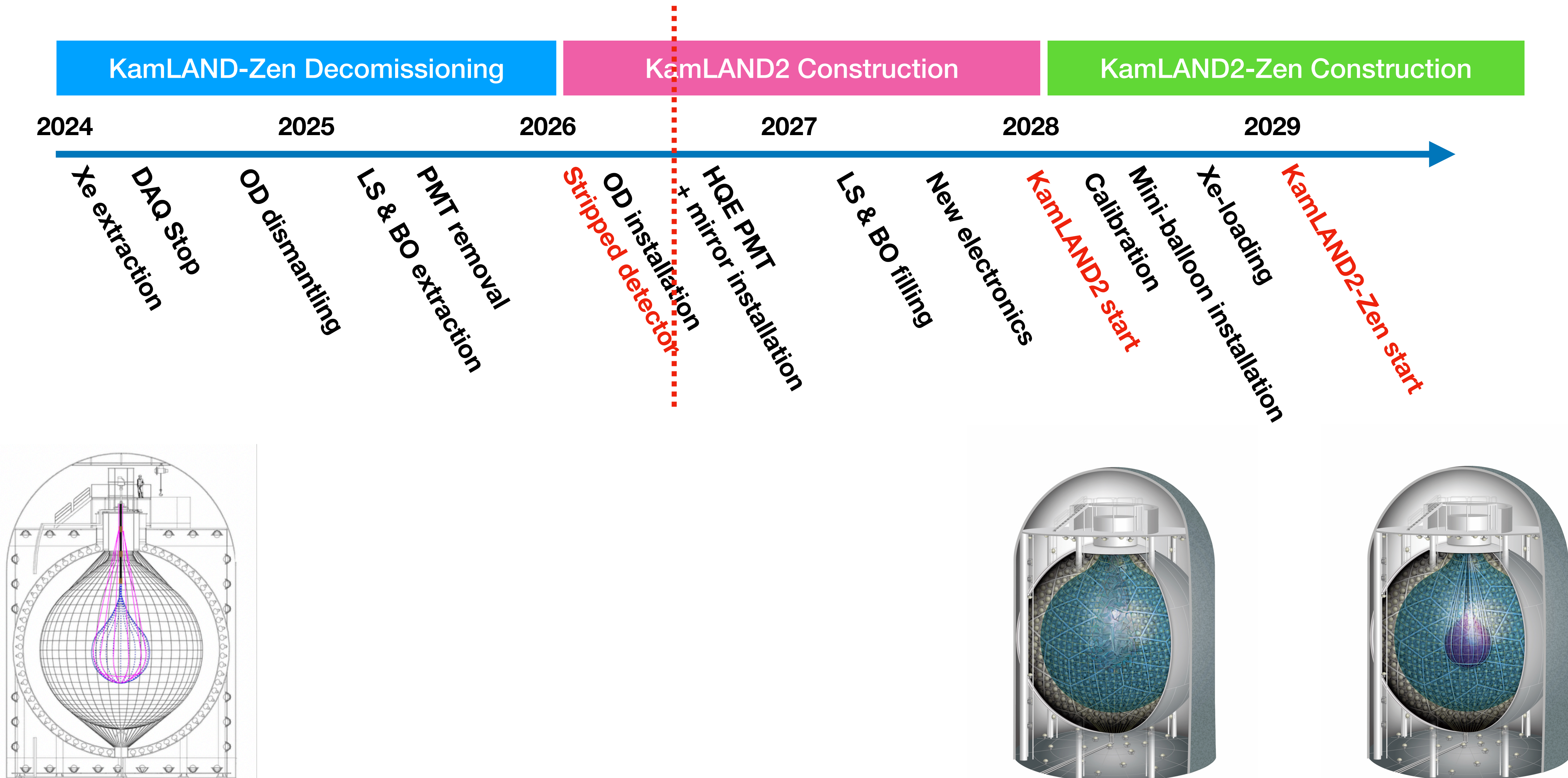


PEN (Polyethylene naphthalate) balloon



In water, with UV light

Timeline to KamLAND2-Zen



Summary



- Neutrinoless double beta decay searches are the only practical method to search for Majorana neutrinos in a model-independent way
- All KamLAND-Zen data, 2.1 ton-year of exposure
- $T_{1/2}^{0\nu} > 3.8 \times 10^{26} \text{ yr (90\% C.L.)} \rightarrow \langle m_{\beta\beta} \rangle < 28 - 122 \text{ meV}$
 - Currently best limit - starting to probe Inverted Ordering
 - KamLAND-Zen 800 stopped operation, being dismantled
 - $\rightarrow$ KamLAND2 (end 2027) $\rightarrow$ KamLAND2-Zen (end 2028)
- KamLAND2-Zen will have sensitivity of $2 \times 10^{27} \text{ years} \rightarrow \langle m_{\beta\beta} \rangle \sim 20 \text{ meV}$

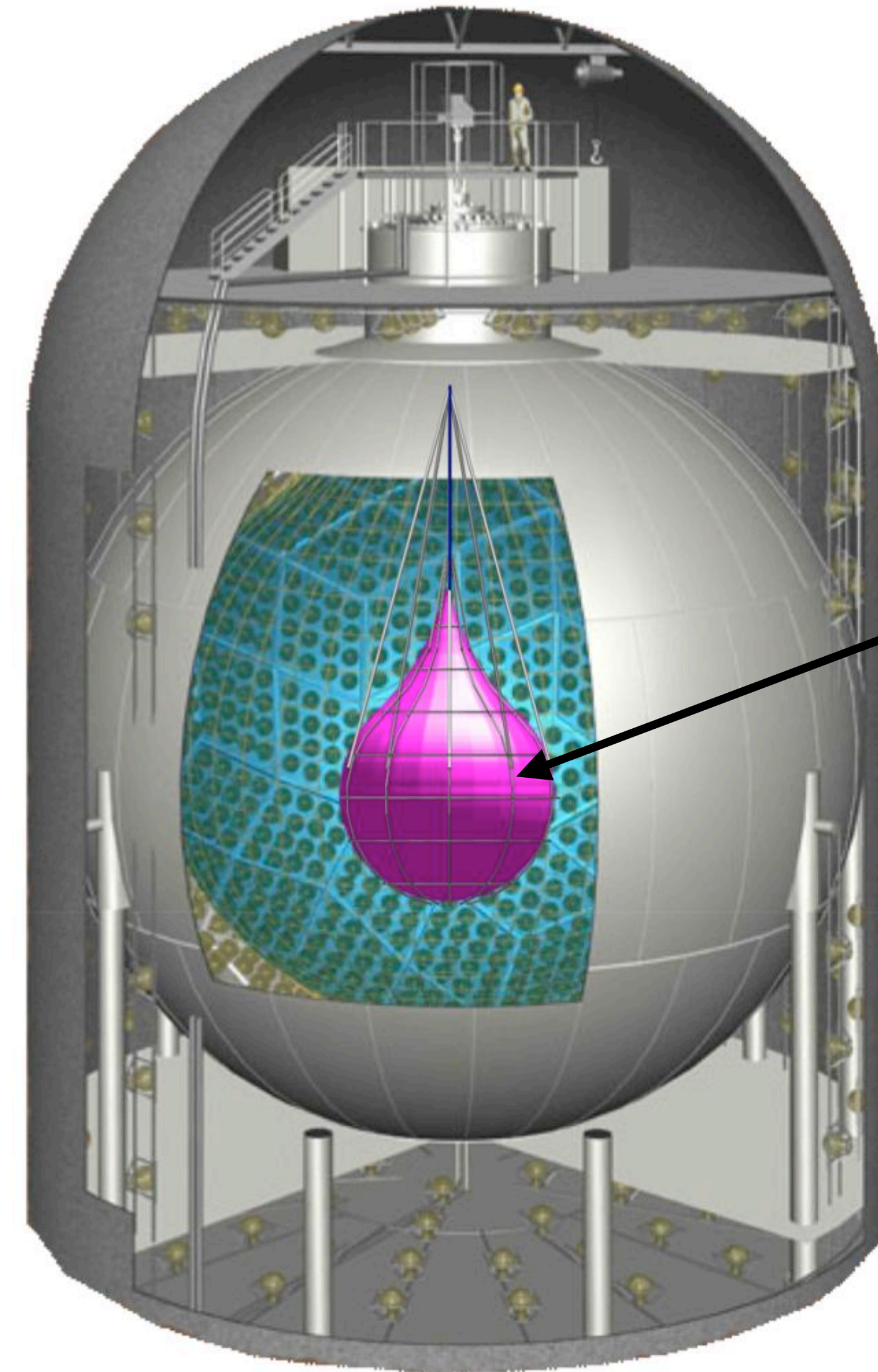
KamLAND-Zen uses Xe-doped LS



- +Well-understood detector
- +Highly pure, self-shielding environment
- +Large $\beta\beta$ source mass, scalable
- -Relatively poor energy resolution
- -No particle identification

$$T_{1/2}^{0\nu} \propto \epsilon \frac{a}{A} \sqrt{\frac{Mt}{b\Delta E}}$$

**Detector Mass,
Exposure, BG and
Energy Resolution**

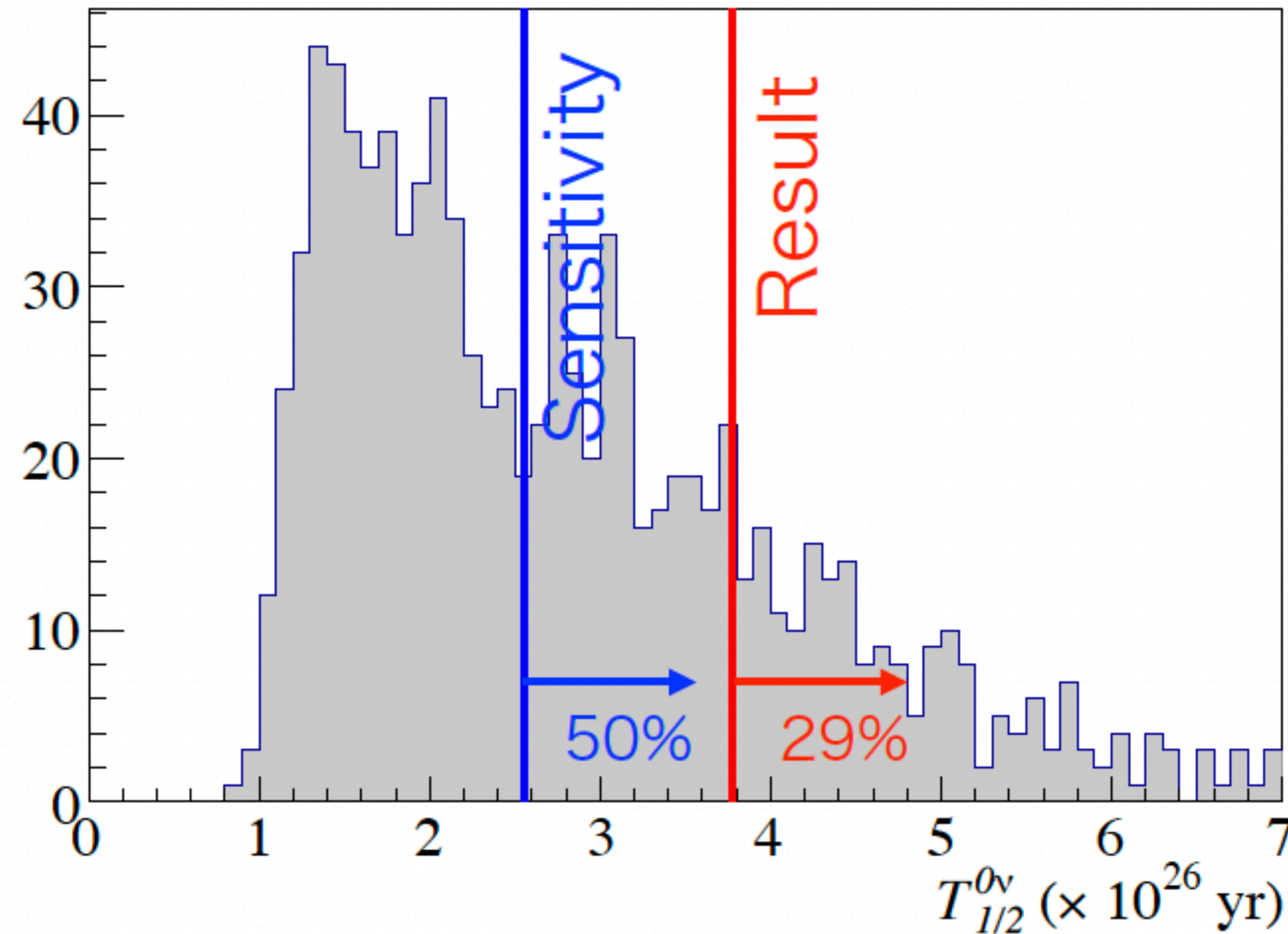


745 kg of ^{136}Xe
dissolved in Liquid
Scintillator

Sensitivity

KamLAND-Zen, 2.1 ton-yr exposure

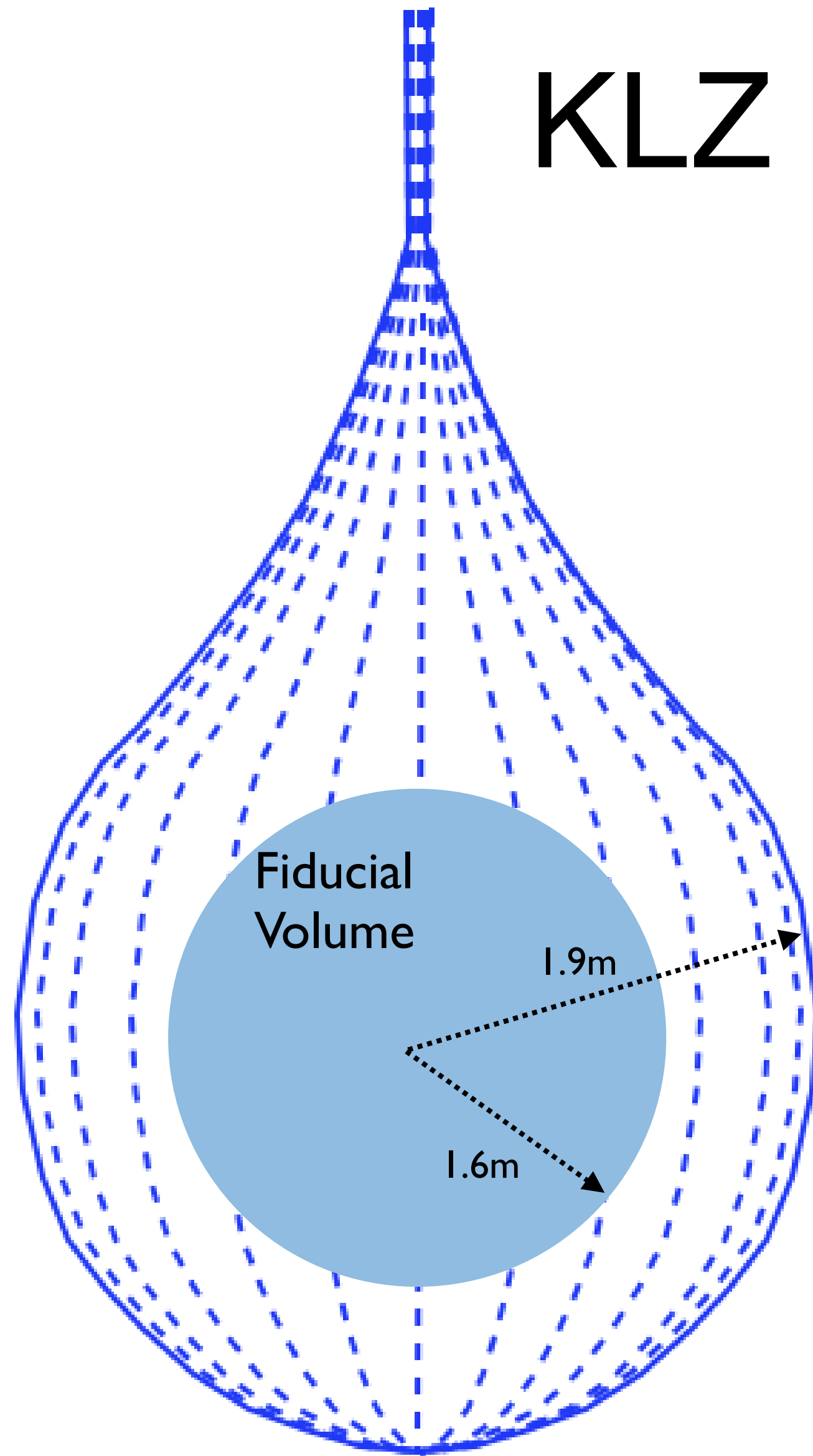
Given the background, what is the expected sensitivity?



Sensitivity: $T_{1/2} > 2.6 \times 10^{26}$ years

Combined limit: $T_{1/2} > 3.8 \times 10^{26}$ years

KLZ 800 Inner-Ballon Backgrounds

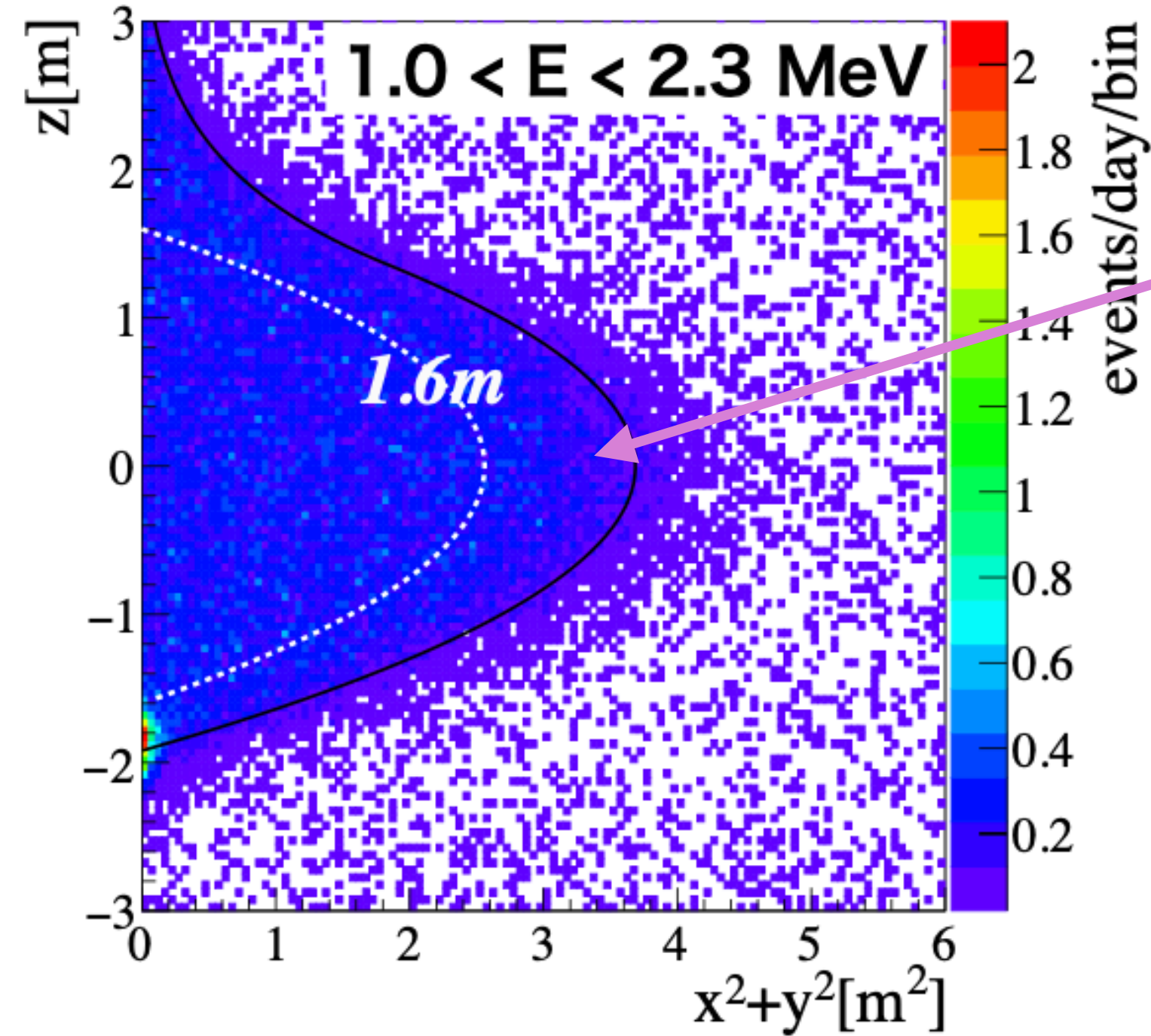


Balloon film backgrounds:

$$^{238}\text{U} \sim 3 \times 10^{-12} \text{ g/g}$$

$$^{232}\text{Th} \sim 4 \times 10^{-11} \text{ g/g}$$

10x reduction compared to KLZ 400 IB



Xe-LS backgrounds:

$$^{238}\text{U} \sim 1.5 \pm 0.4 \times 10^{-17} \text{ g/g}$$

$$^{232}\text{Th} \sim 3.0 \pm 0.4 \times 10^{-16} \text{ g/g}$$

