59th Recontres de Moriond, La Thuile 2025

Neutrinoless double beta decay search in KamLAND-Zen

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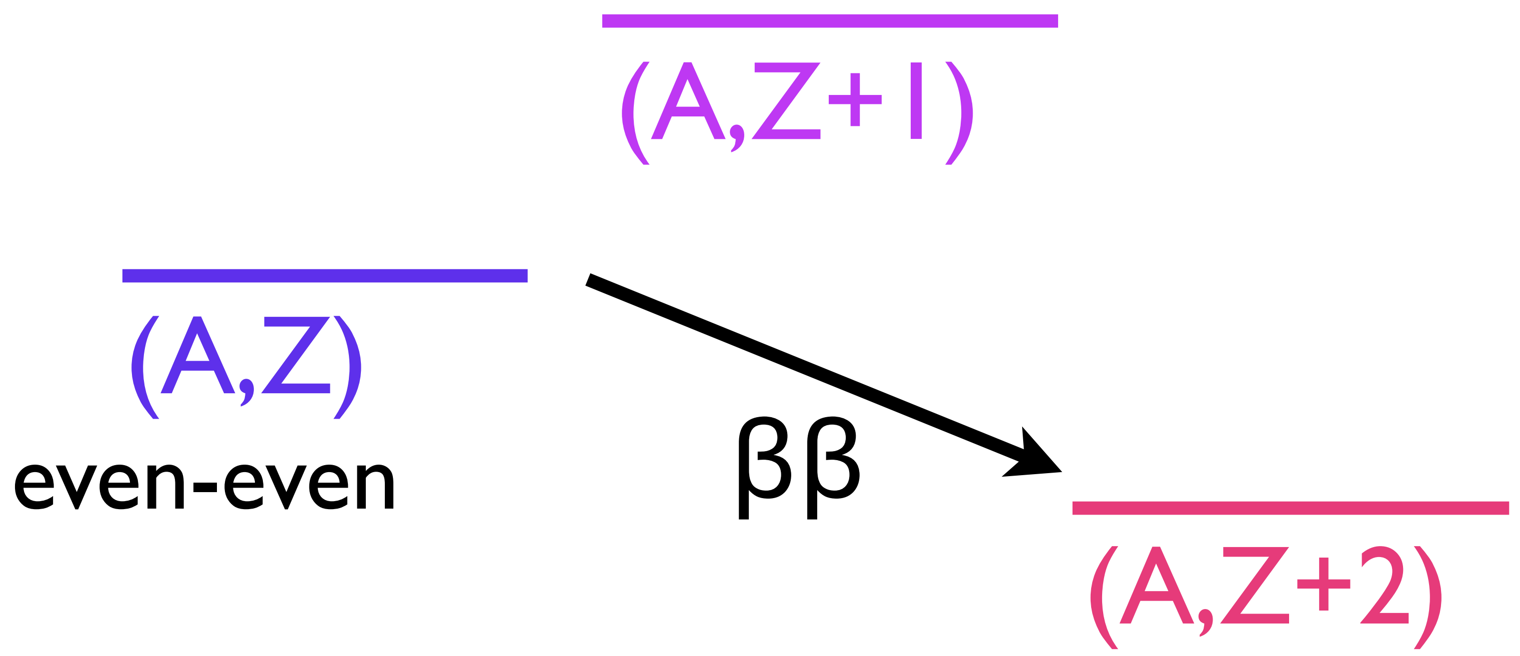
Double Beta Decay



A second-order process only detectable if first-order beta decay is energetically forbidden

Rare, but Standard Model Process:

$$2\nu\beta\beta: (A,Z) \rightarrow (A,Z+2) + e^- + e^- + \overline{\nu}_e + \overline{\nu}_e$$

^{136}Xe

^{76}Ge

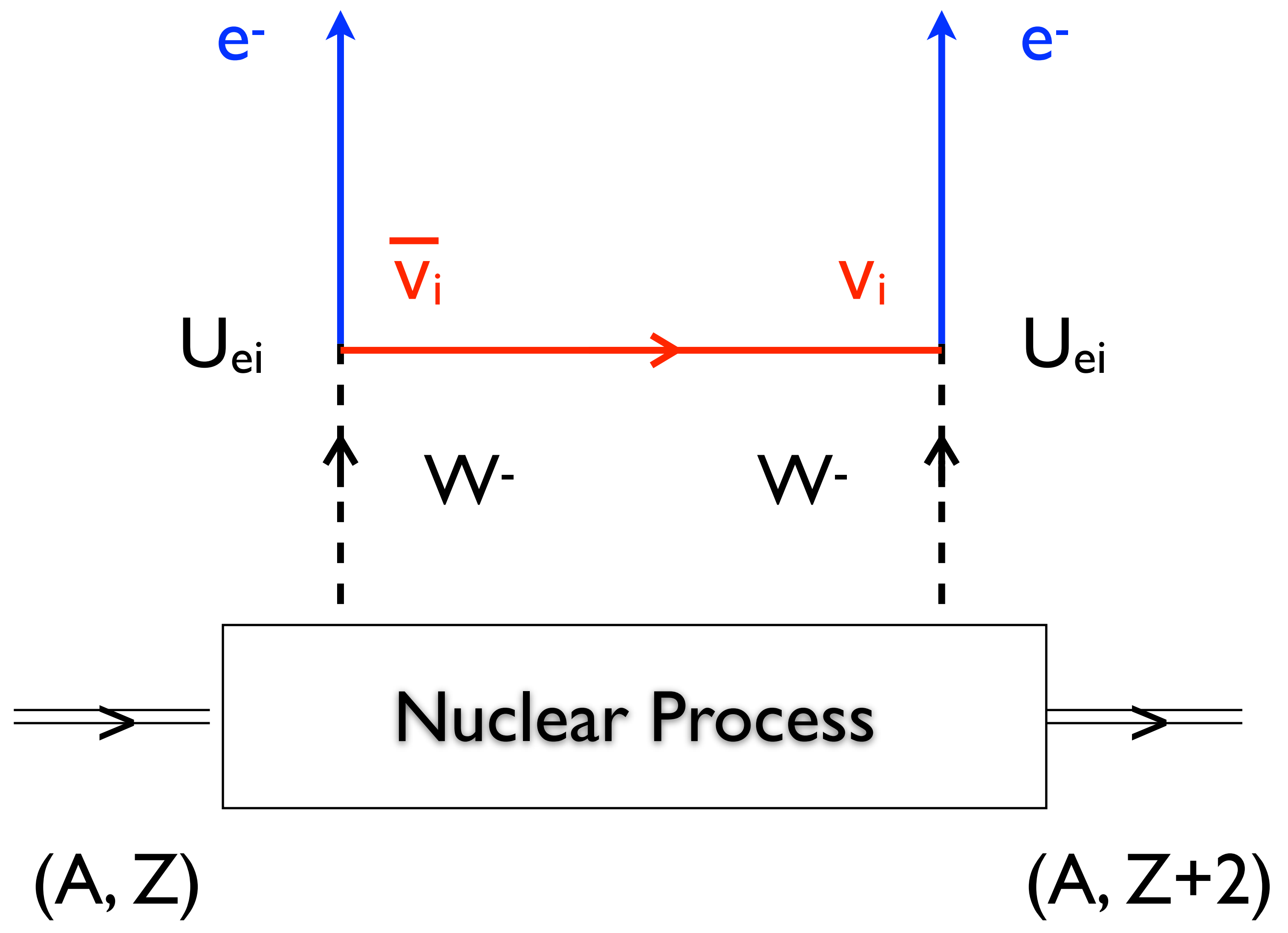
^{82}Se

^{100}Mo

^{130}Te

...

Neutrinoless Double Beta Decay



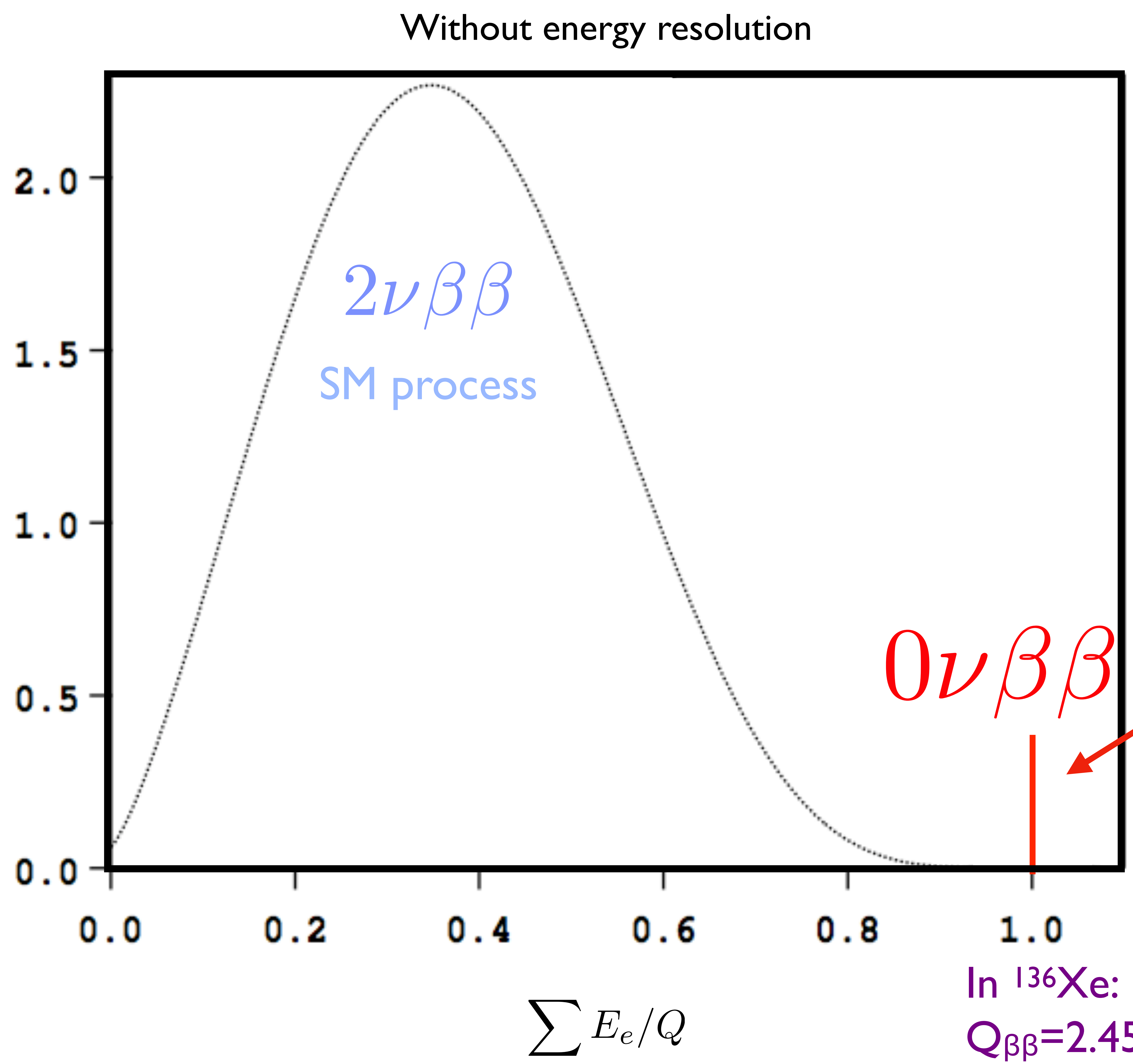
Is ν Majorana?

$$\begin{aligned} M_\nu &\neq 0 \\ |\Delta L| &= 2 \end{aligned}$$

$$0\nu\beta\beta : (A, Z) \rightarrow (A, Z+2) + e^- + e^-$$

- Extremely rare radioactive process
- Requires massive Majorana neutrino
- Lepton Number Violation
- Model dependent - Standard interpretation: light Majorana ν + SM interactions
  - Measure of neutrino mass scale → effective Majorana mass $\langle m_{\beta\beta} \rangle$

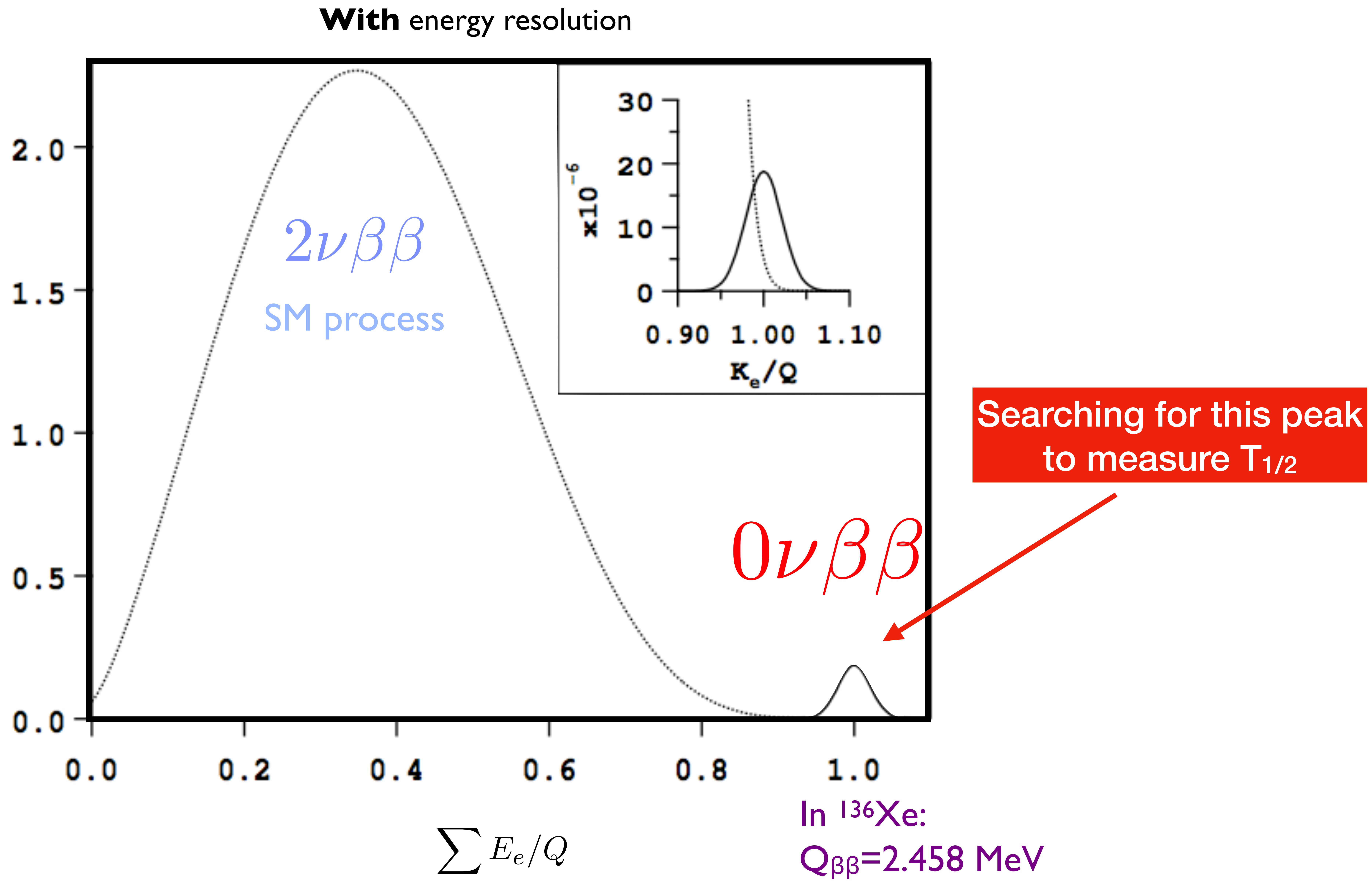
Detecting 0v2β Decay



Searching for this peak to measure $T_{1/2}$

In ^{136}Xe:
$Q_{\beta\beta}$=2.458 MeV

Detecting 0ν2β Decay



What mass does 0νββ measure?

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

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Phase Space factor: Calculable

Nuclear Matrix Element: Hard to calculate

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Phase Space factor: Calculable

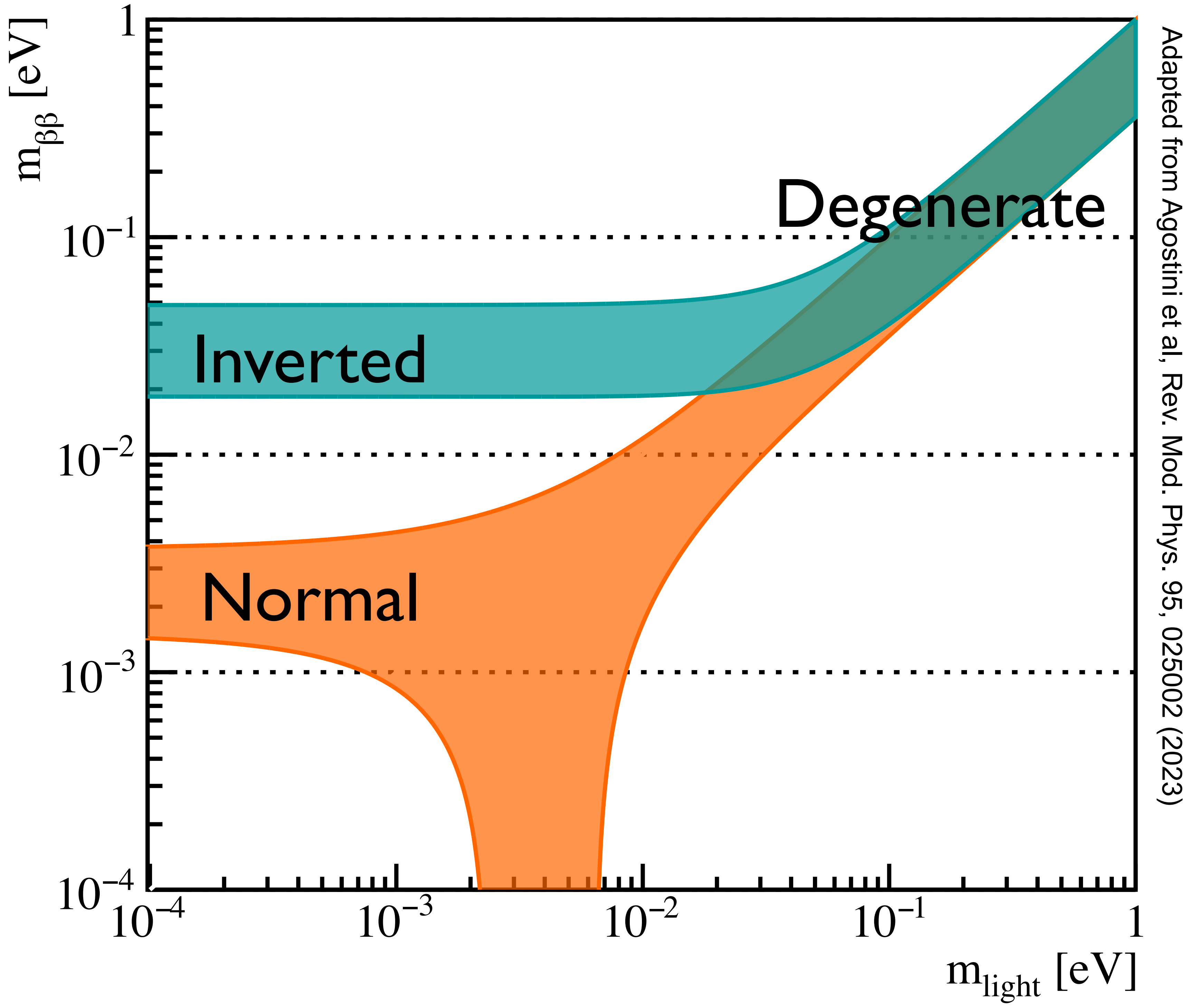
Nuclear Matrix Element: Hard to calculate

Interesting physics

Effective Majorana mass: $\langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$ [coherent sum]

"Inverted Ordering" : $m_{\nu_1} > m_{\nu_3}$

"Normal Ordering" : $m_{\nu_3} > m_{\nu_1}$



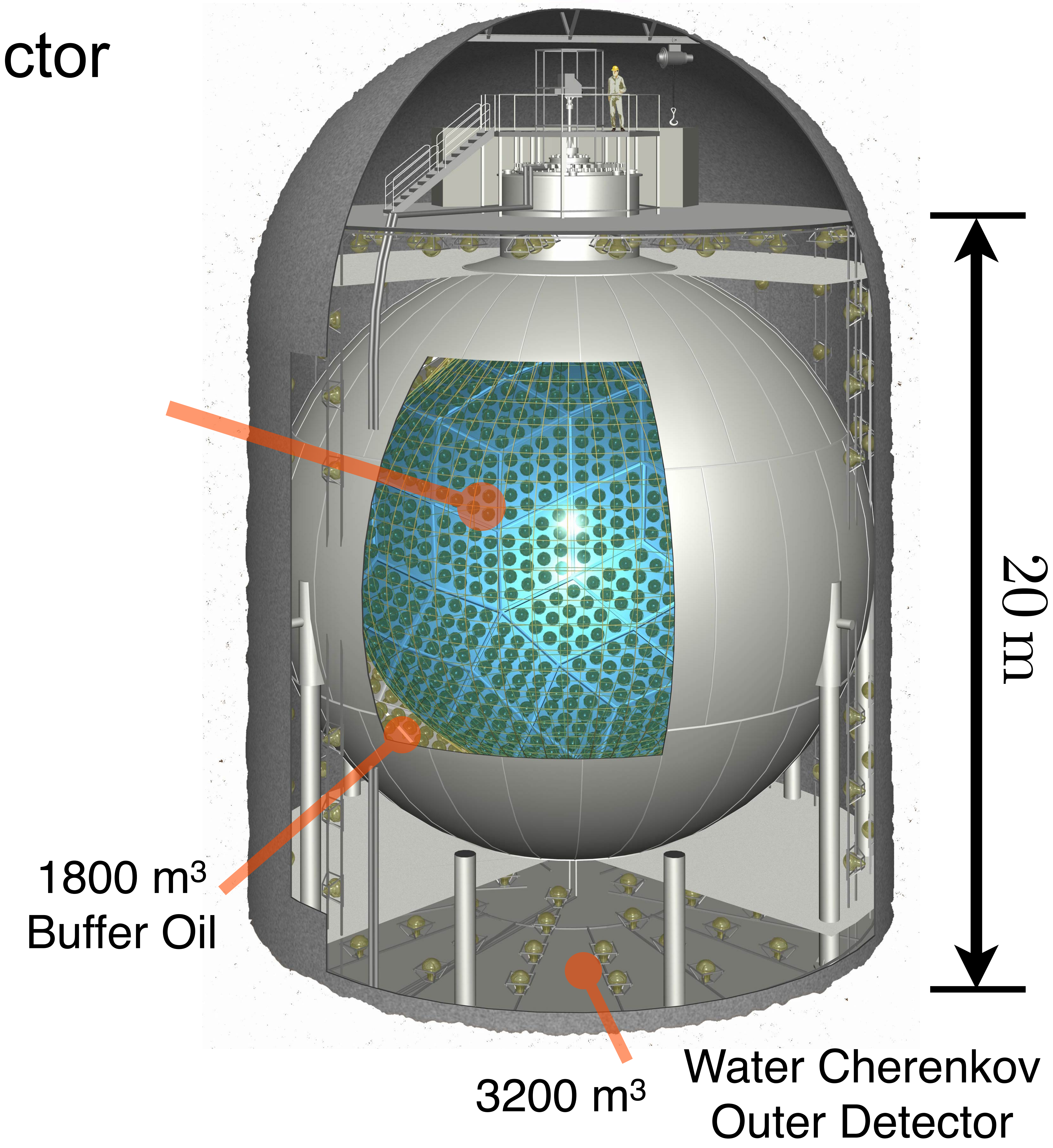
KamLAND-Zen Collaboration

TOHOKU UNIVERSITY · 東京大学 THE UNIVERSITY OF TOKYO · 大阪大学 OSAKA UNIVERSITY · TOKUSHIMA UNIVERSITY · BERKELEY LAB · KYOTO UNIVERSITY · THE UNIVERSITY OF TENNESSEE KNOXVILLE · TUNL · MIT · VIRGINIA TECH · UNIVERSITY of HAWAI'I · BOSTON UNIVERSITY · Nikhef

KamLAND(-Zen) detector

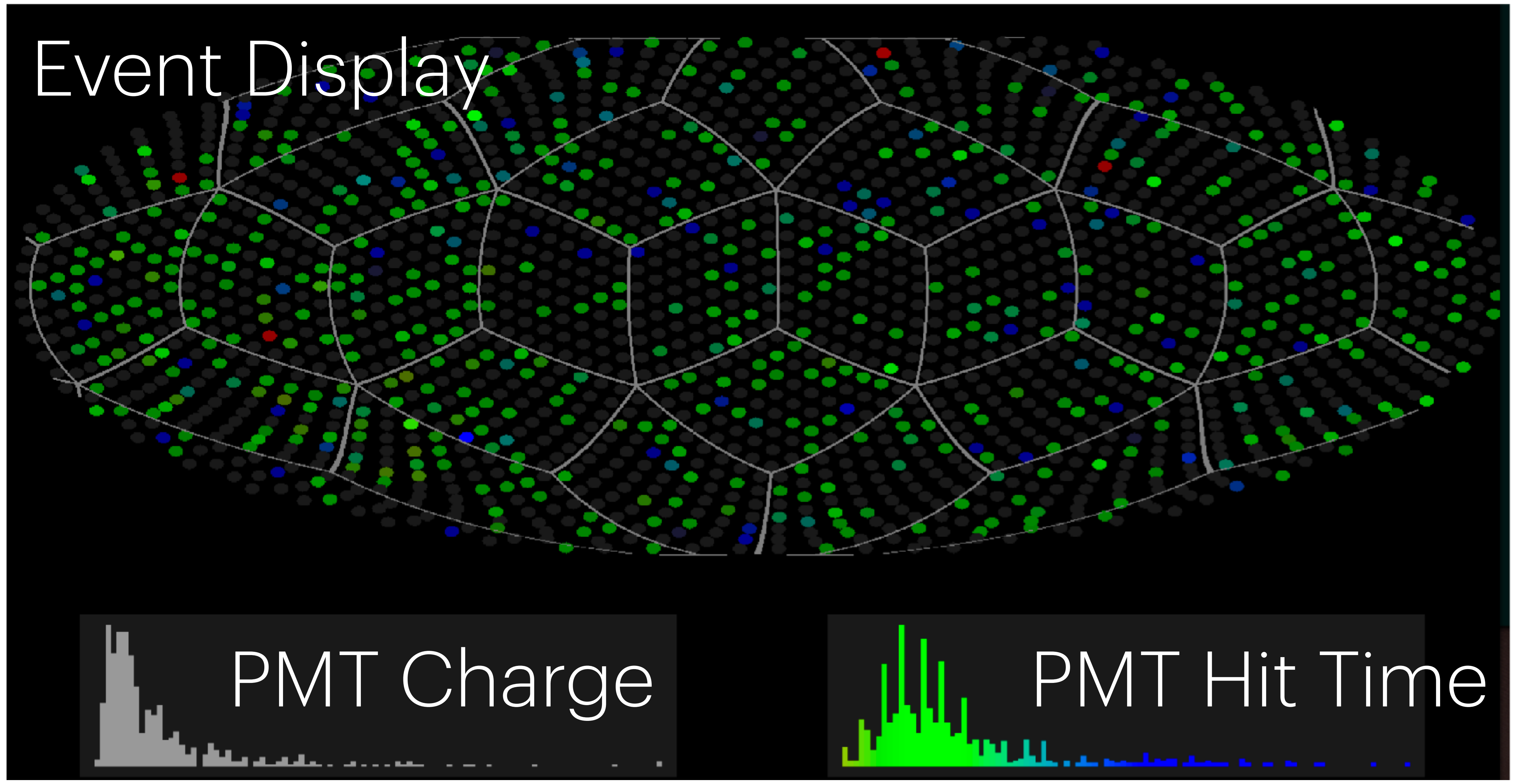
Located in the Kamioka Mine in Japan 1000m rock = 2700 mwe

- 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

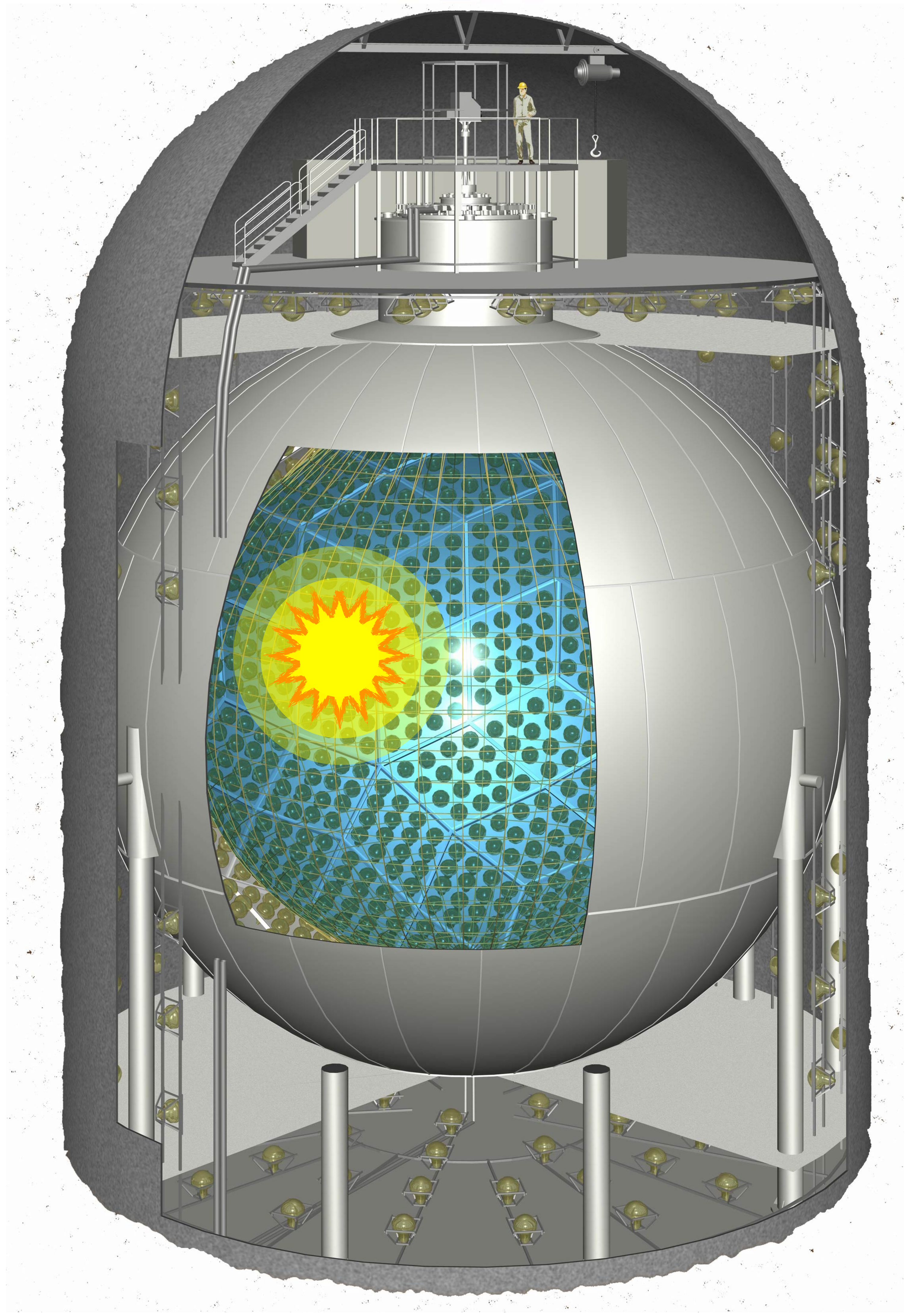


Energy reconstruction

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

Position reconstruction

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

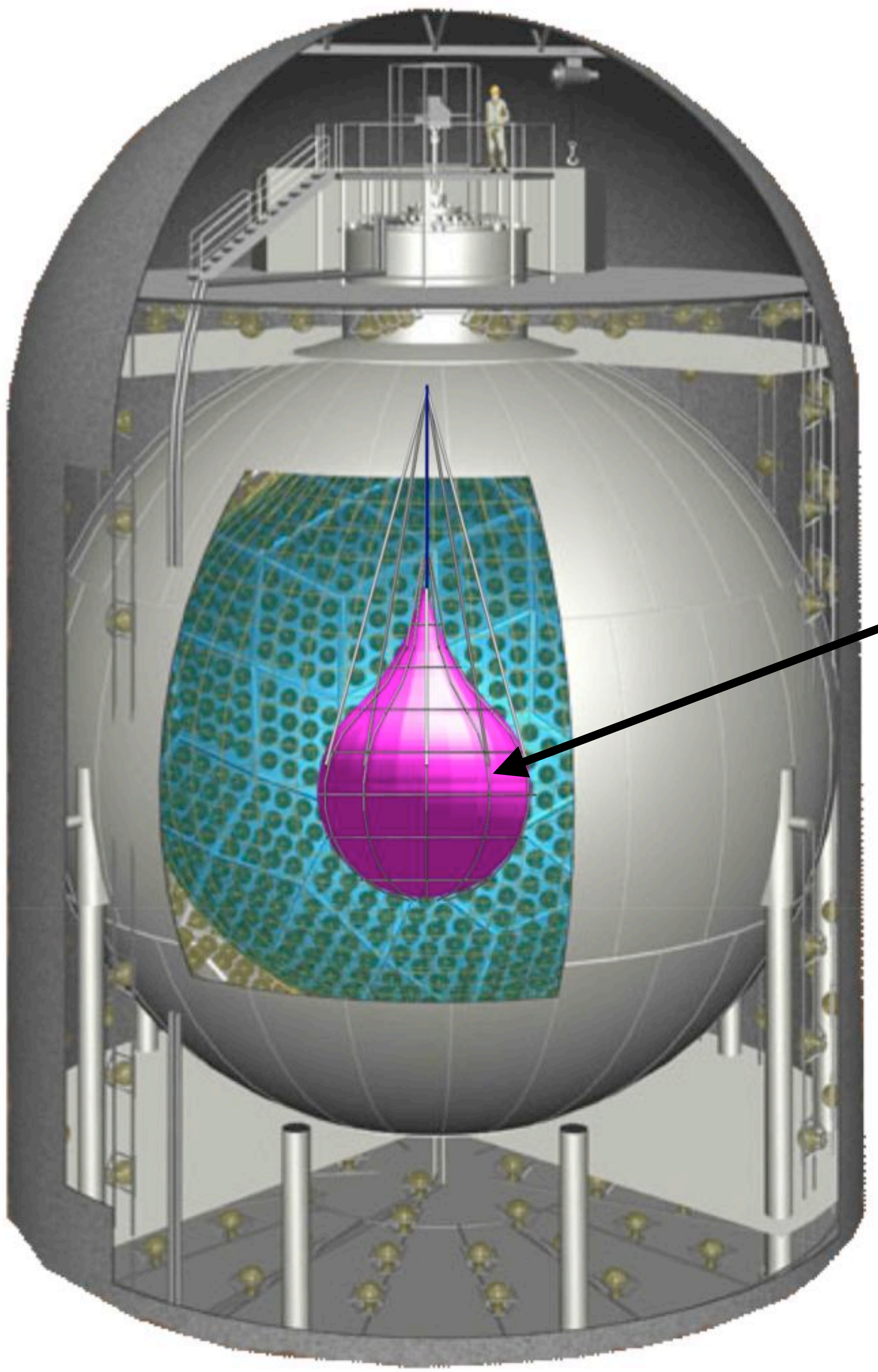


KamLAND-Zen uses Xe-doped LS

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

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

Detector Mass, Exposure, BG and Energy Resolution

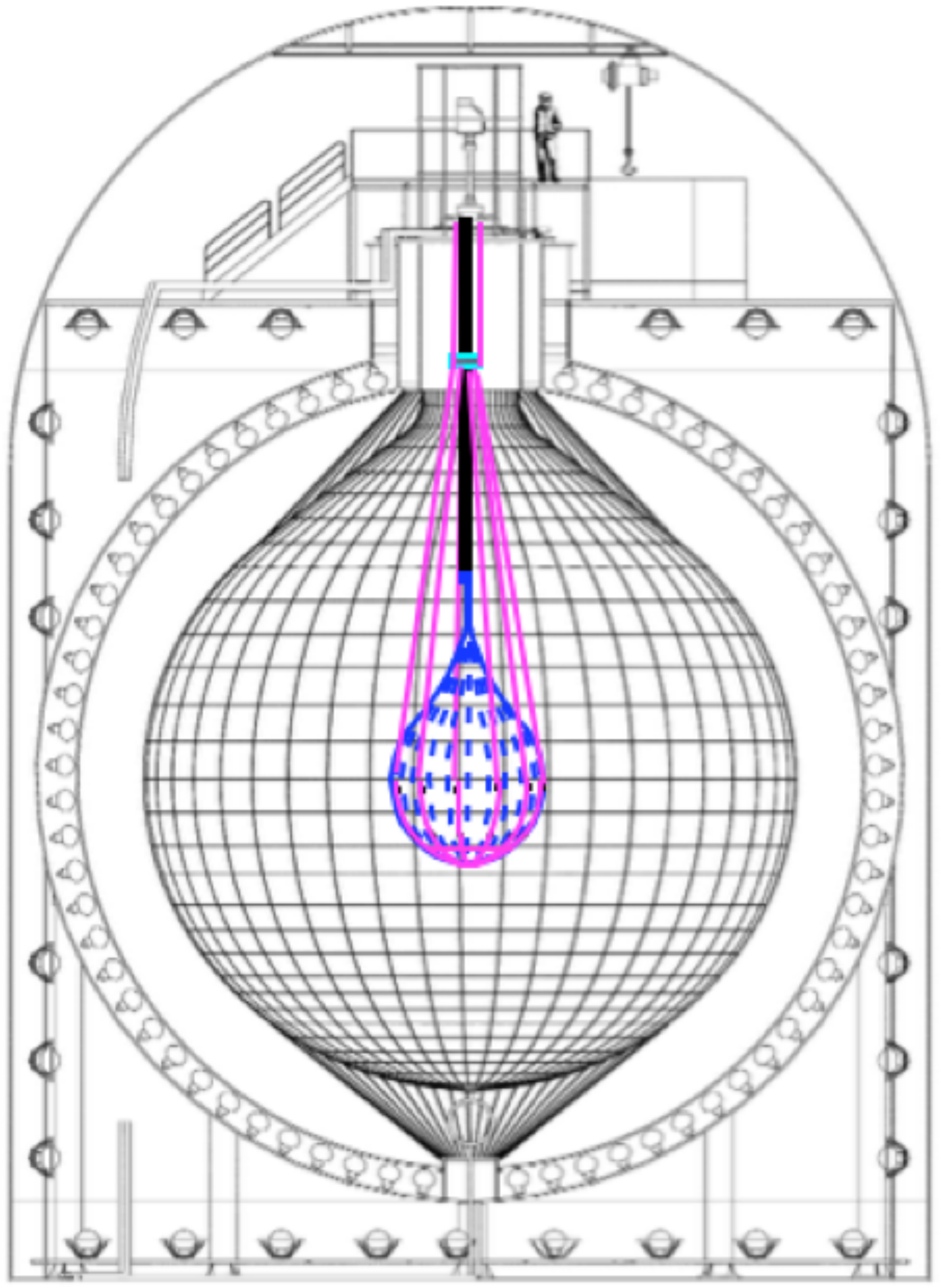


KamLAND-Zen 400

2011 - 2015

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

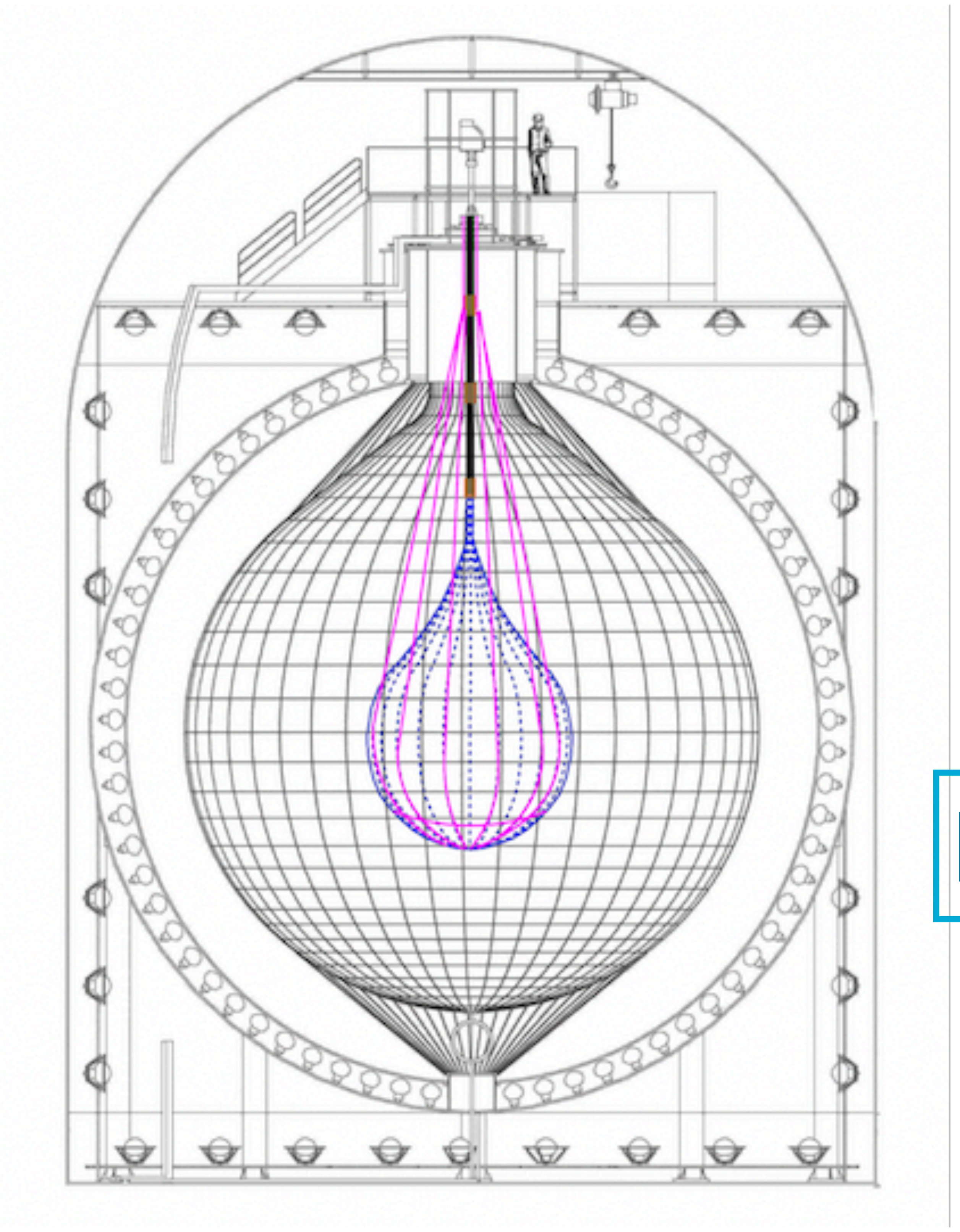
$T^{0\nu}_{1/2} > 1.1 \times 10^{26}$ yr



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

KamLAND-Zen 800

2019 - 2024

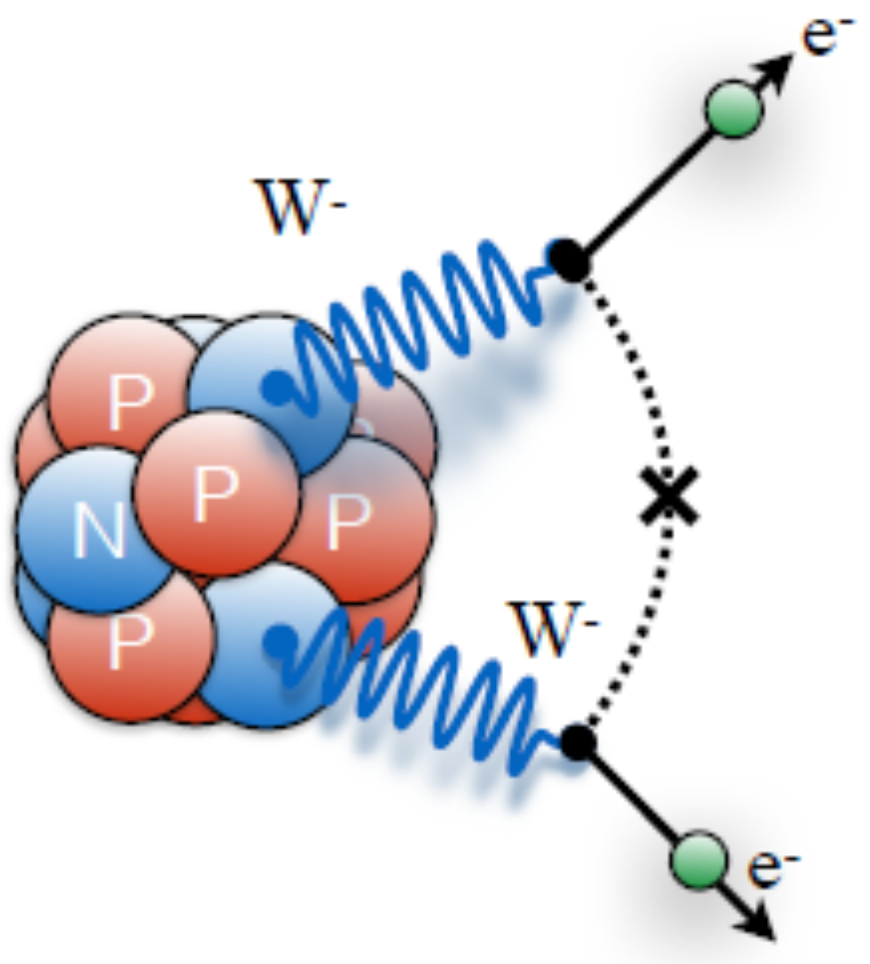


- Inner-balloon radius 1.90m
- 745kg ^{136}Xe
- Exposure 2100 kg-yr

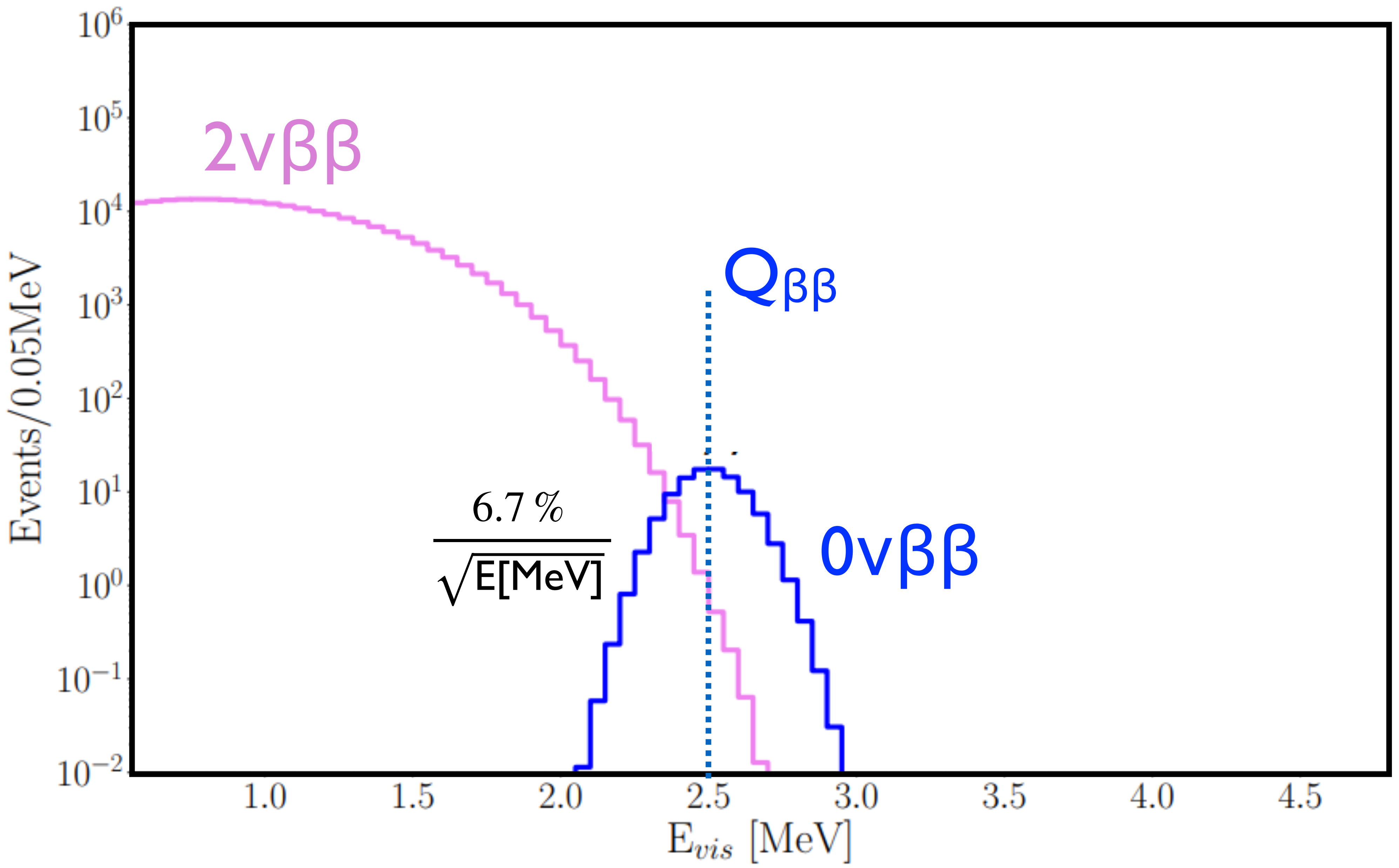
Full dataset - this talk

KamLAND-Zen Coll, arXiv:2406.11438

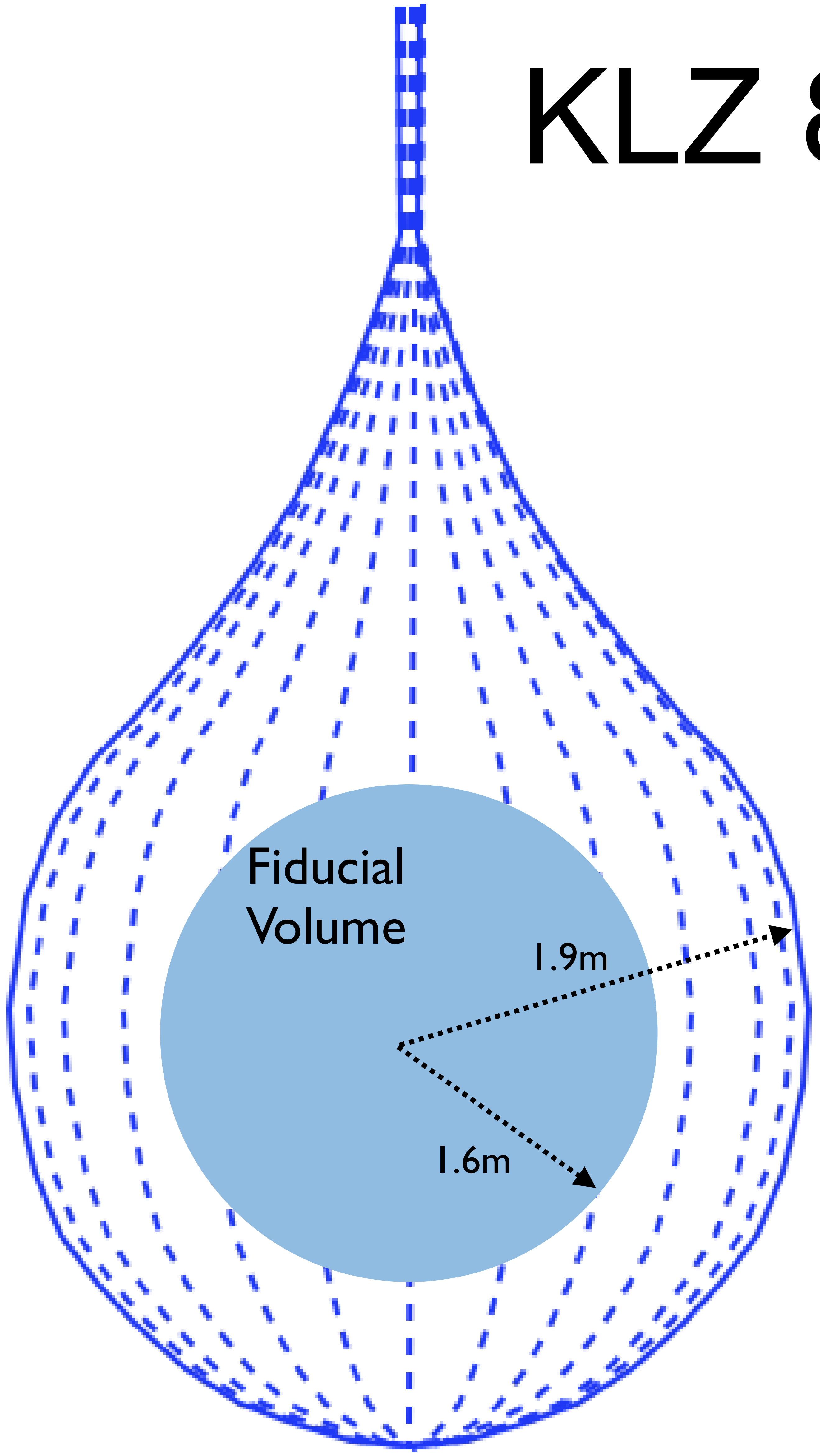
Signals and Backgrounds



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



KLZ 800 Inner-Ballon Backgrounds

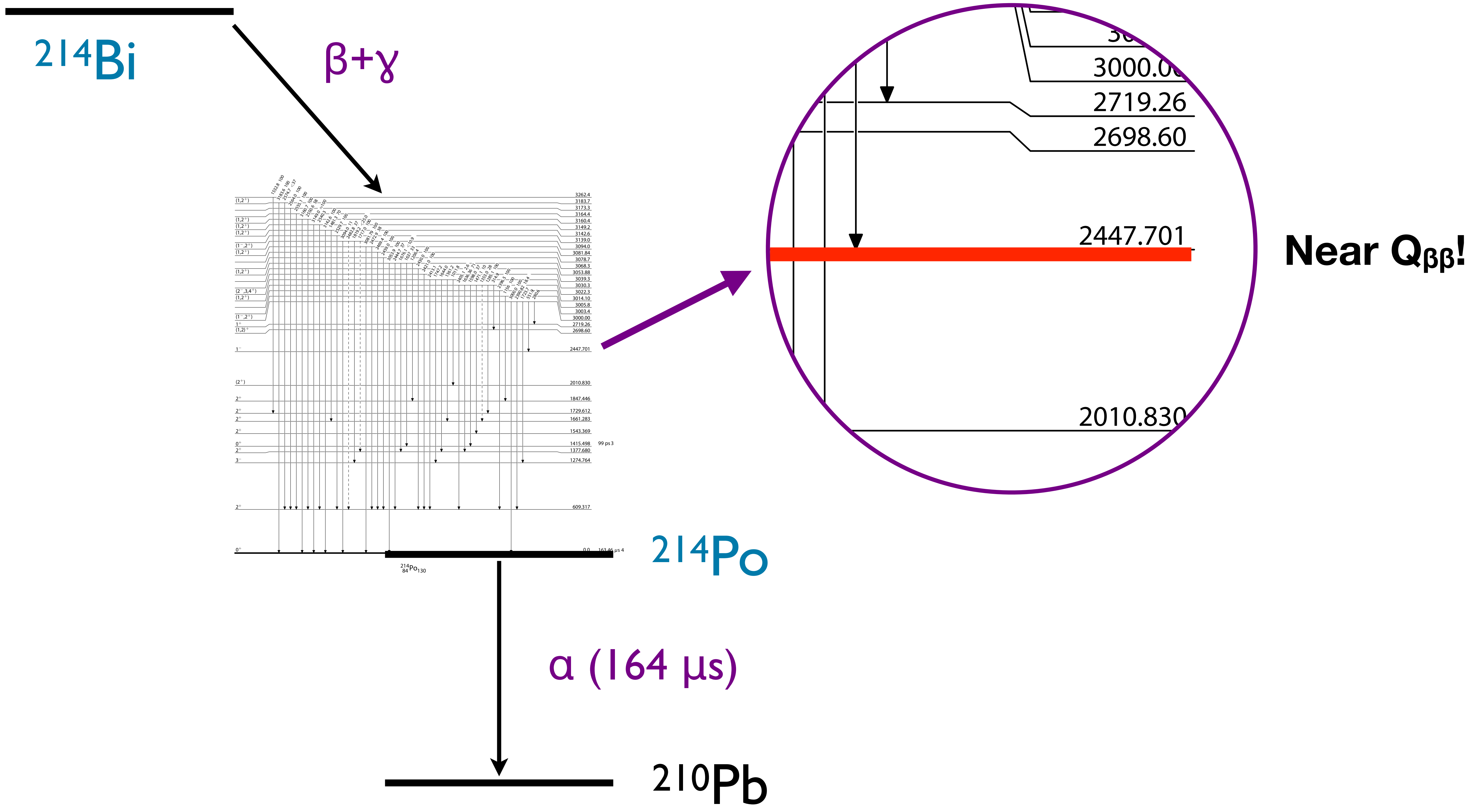


Balloon film backgrounds:
^{238}U ~4 x 10^{-12} g/g
^{232}Th ~2 x 10^{-11} g/g

Xe-LS backgrounds:
^{238}U ~ 1.5±0.4 x 10^{-17} g/g
^{232}Th ~ 3.0±0.4 x 10^{-16} g/g

10x reduction compared to KLZ 400 IB

^{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

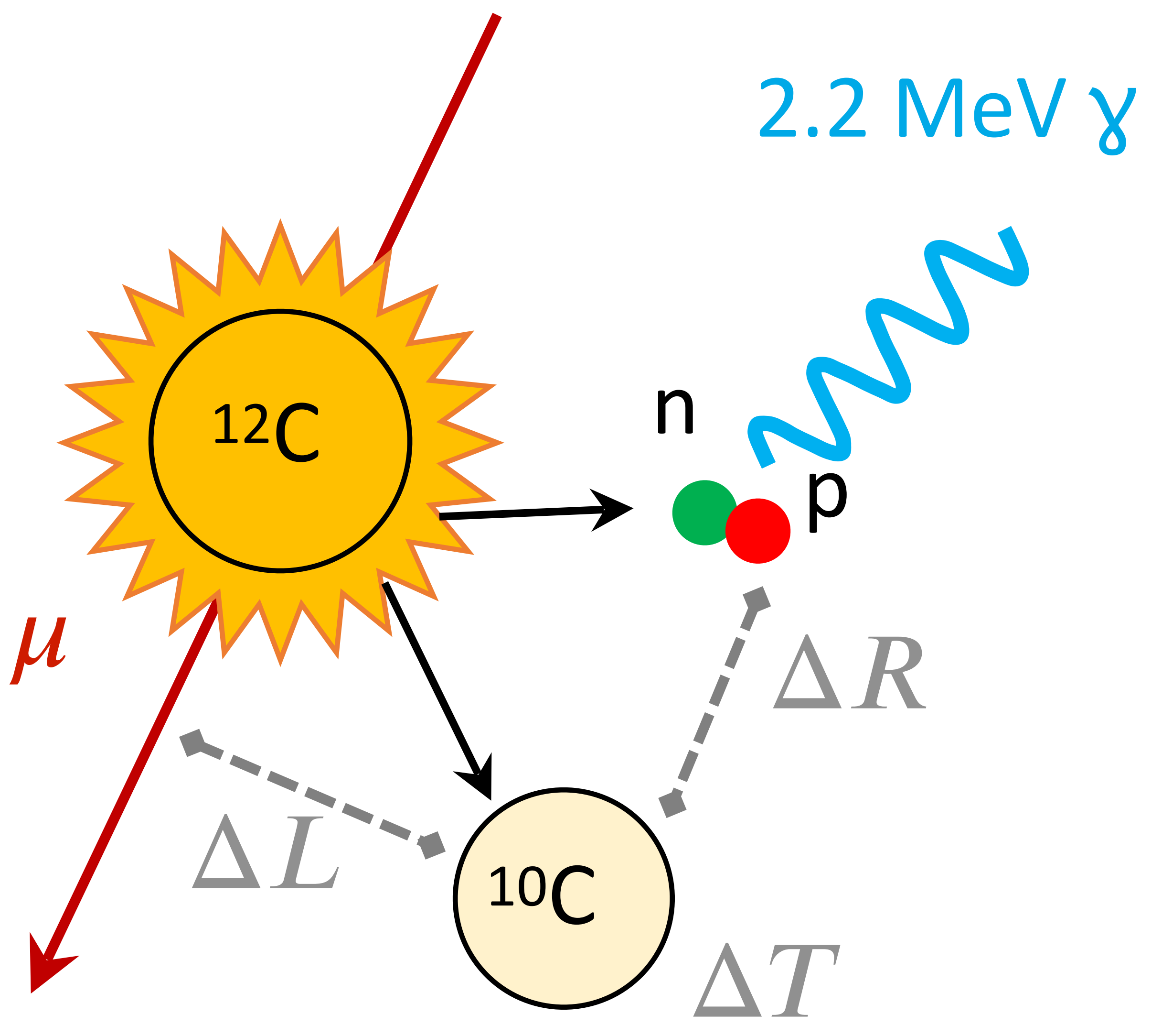


GEANT4 based MC with ^{214}Bi β+γ cascade, particle tracking, energy deposit, scintillation photon emission / propagation

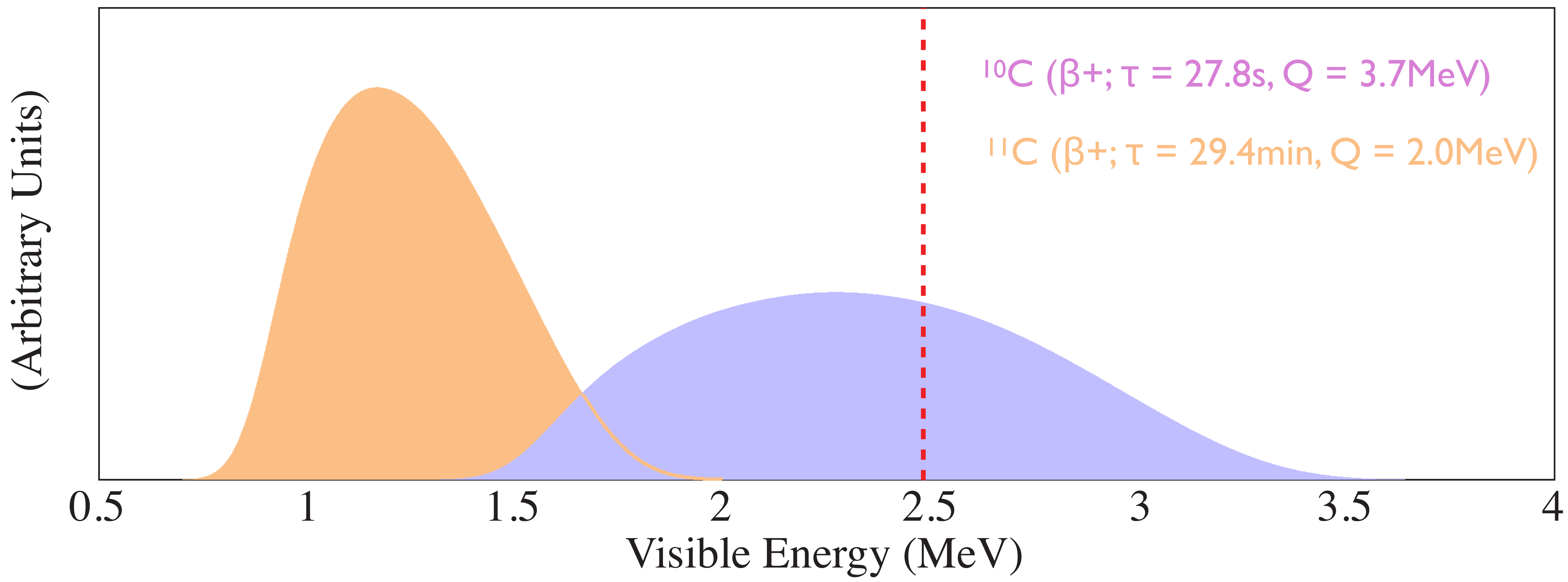
Muon Spallation

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

Spallation on ^{12}C



(muon time – decay time)



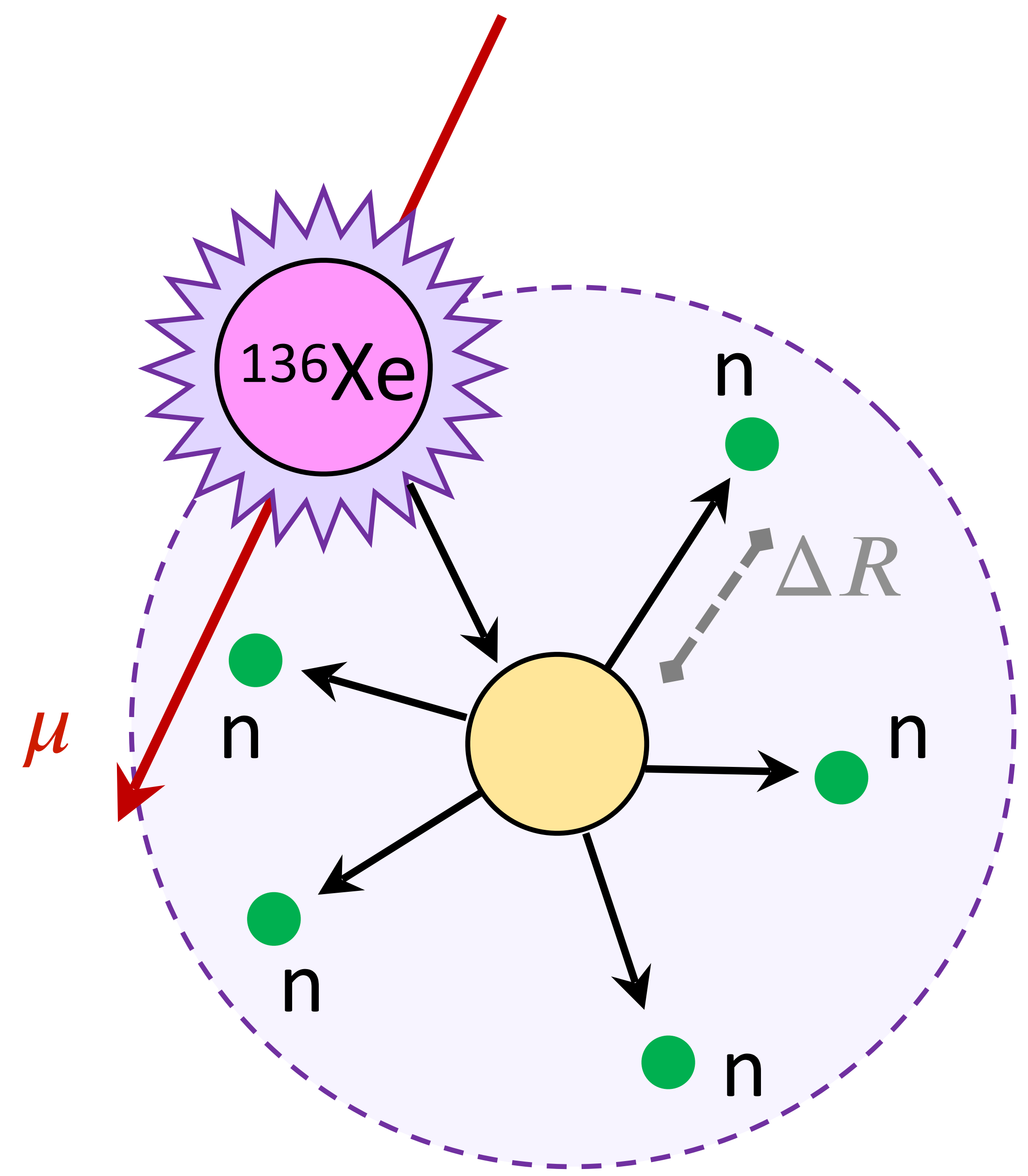
Triple coincidence cut (muon, neutron capture, subsequent ^{10}C decay)
effective veto, tagging efficiency ~99%

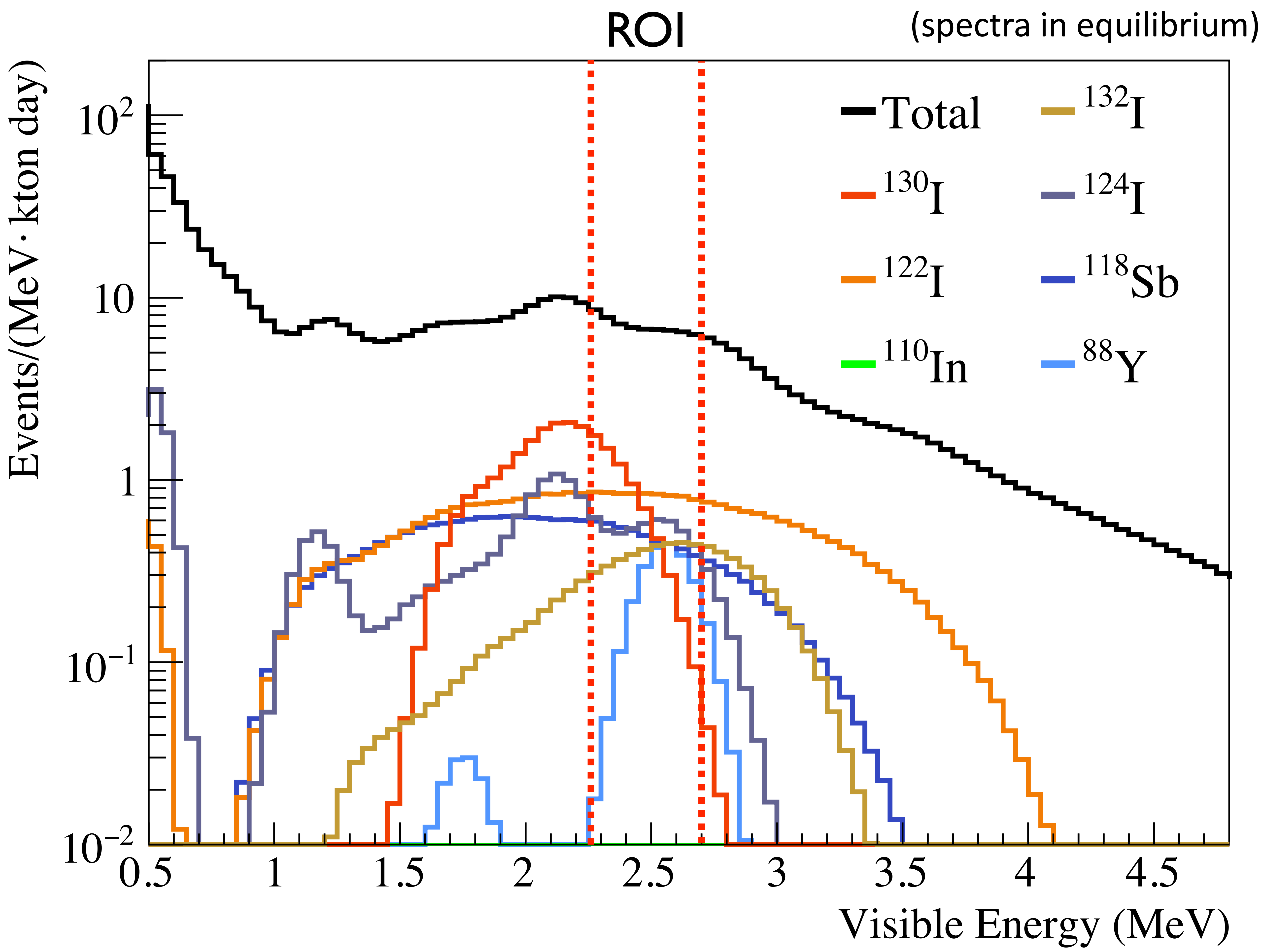
Short-lived spallation products τ < ~5 min

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

Muon Spallation

μ + ^{136}Xe spallation products from FLUKA simulation, spectrum after decay





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

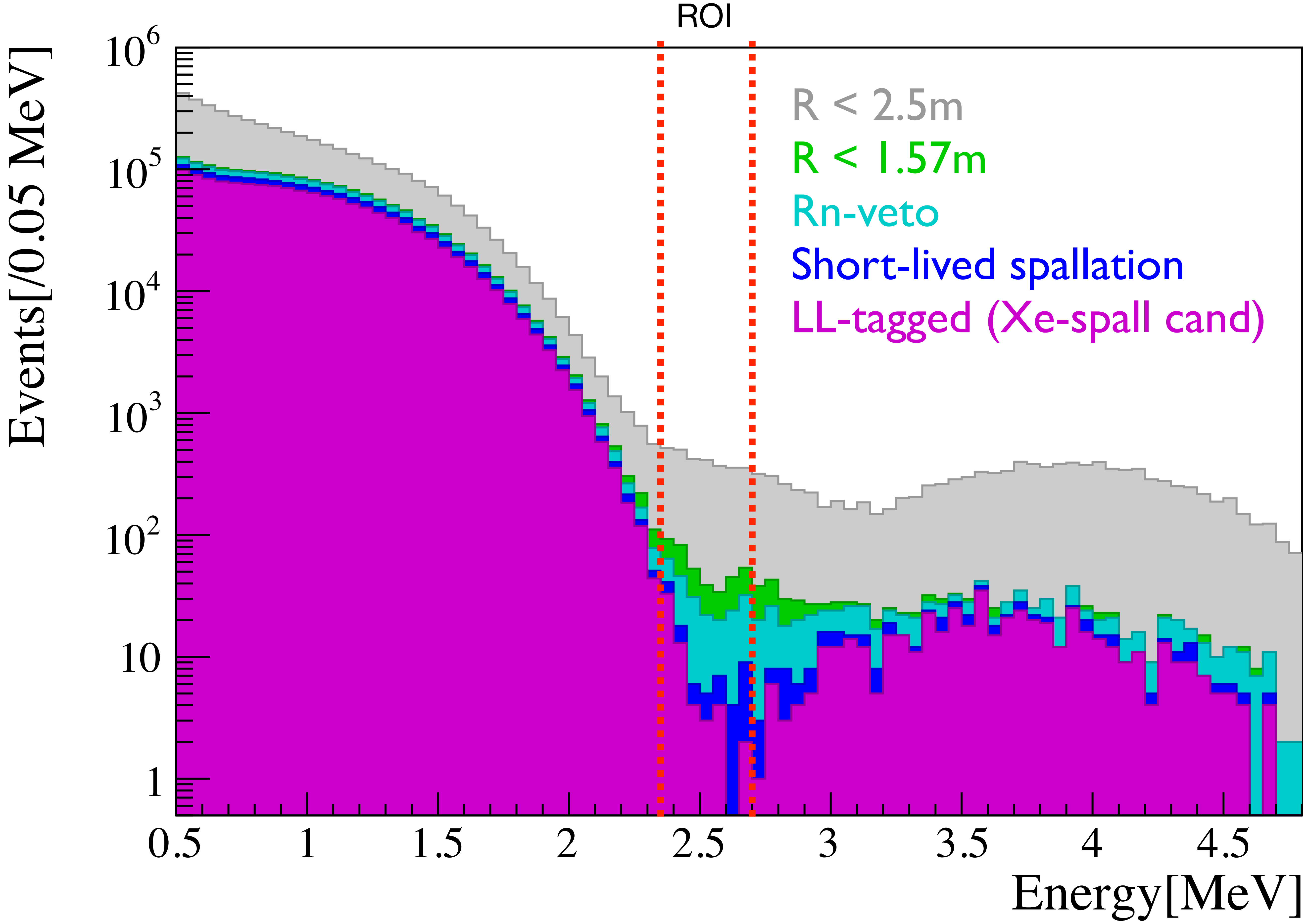
Long-lived spallation products in the ROI
$T_{1/2}$: **several hours to weeks**
Very low rate!

KamLAND-Zen, *Phys.Rev.C* 107 (2023) 5, 054612, arXiv:2301.09307

Event Selection

- Event selection cuts:
  - Events < 2.5m from center and > 0.7m away from bottom
  - Events > 150ms after muons
  - Radioactive decays by coincidence cut rejected
  - $\overline{\nu}_e$ 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

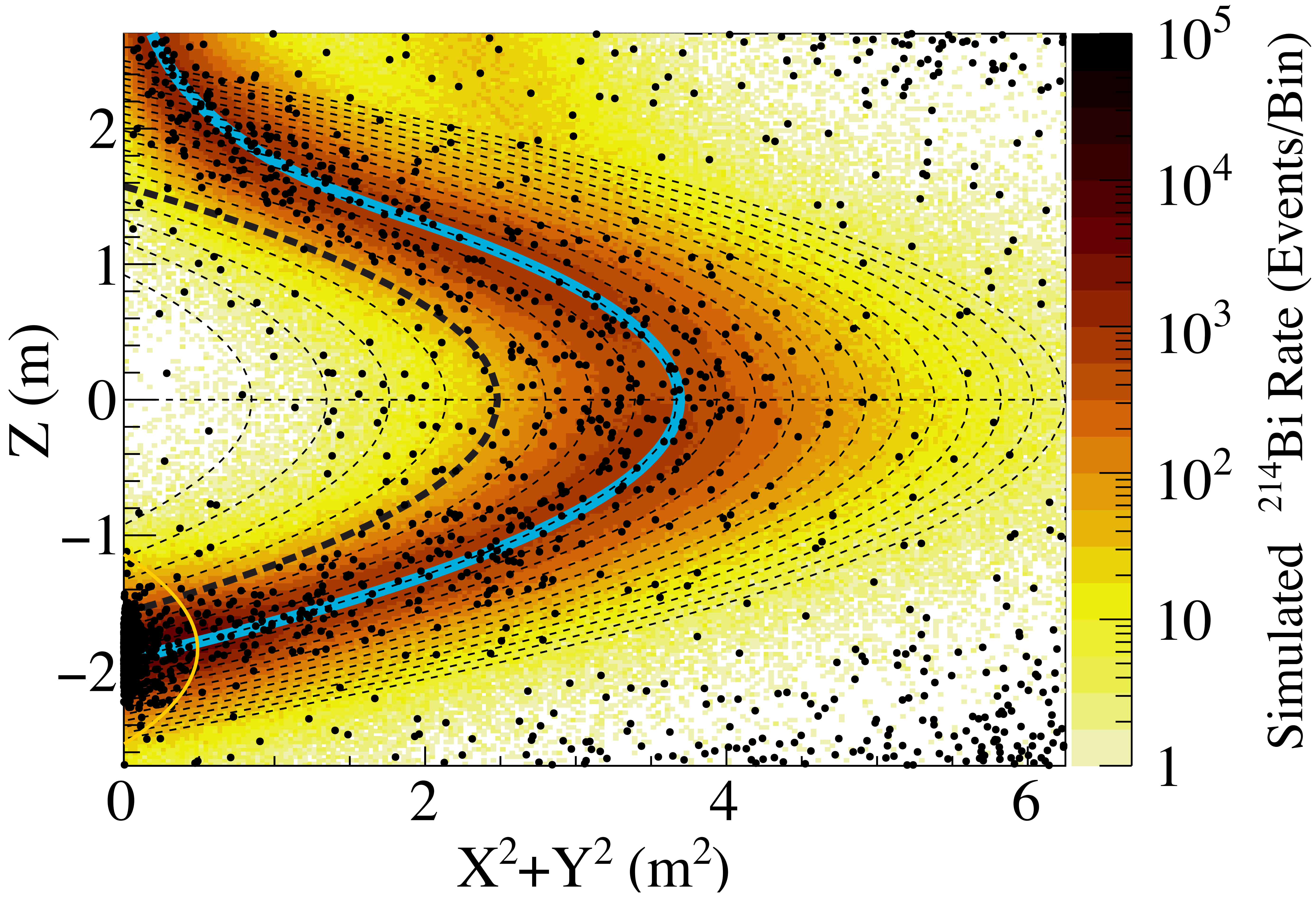
(745 ± 3)kg Xe, 1131 day lifetime → 2100 kg-yr exposure



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 0ν2β decay
  - Outer region → more sensitive to backgrounds on inner-balloon film
- All parameters fitted simultaneously

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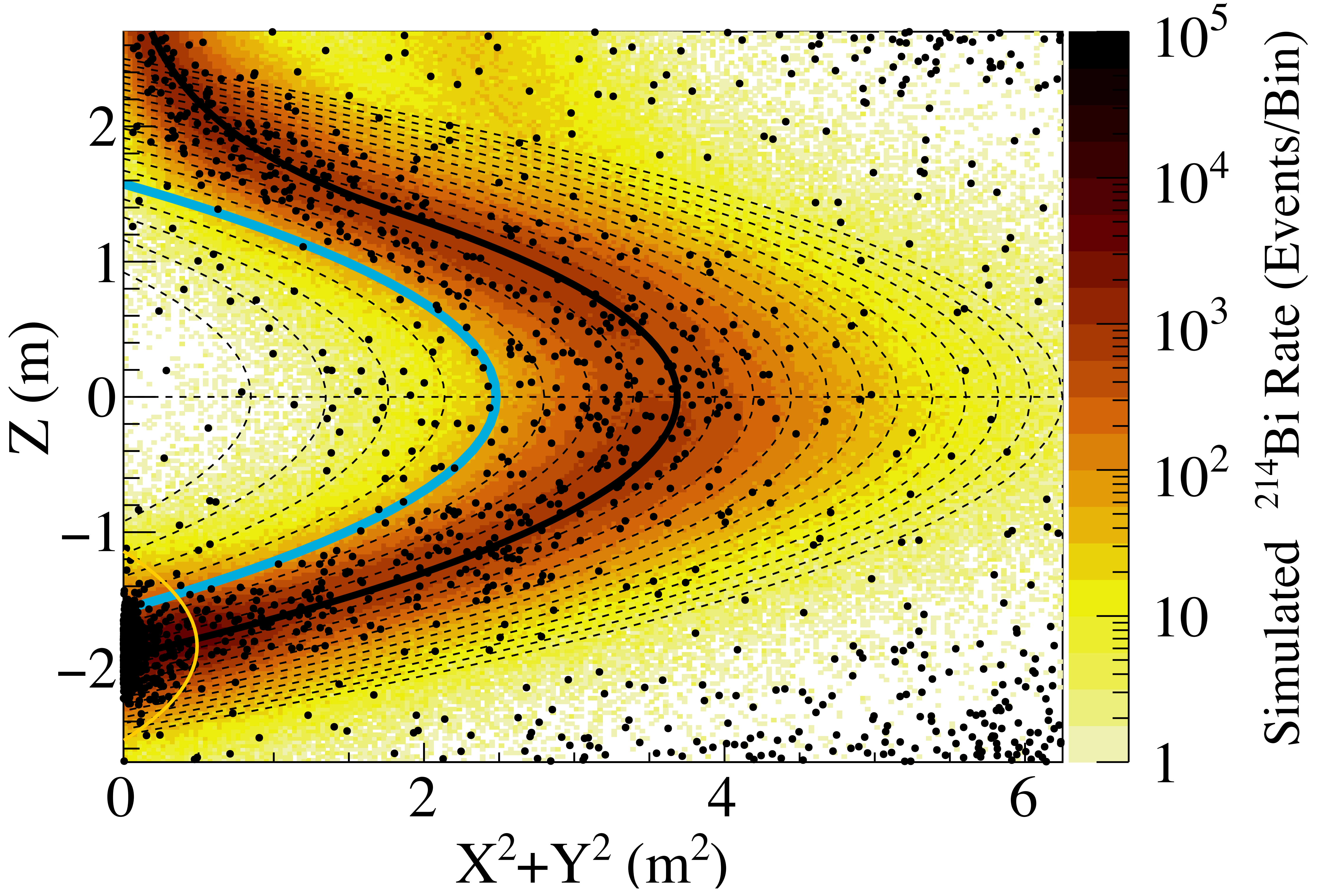

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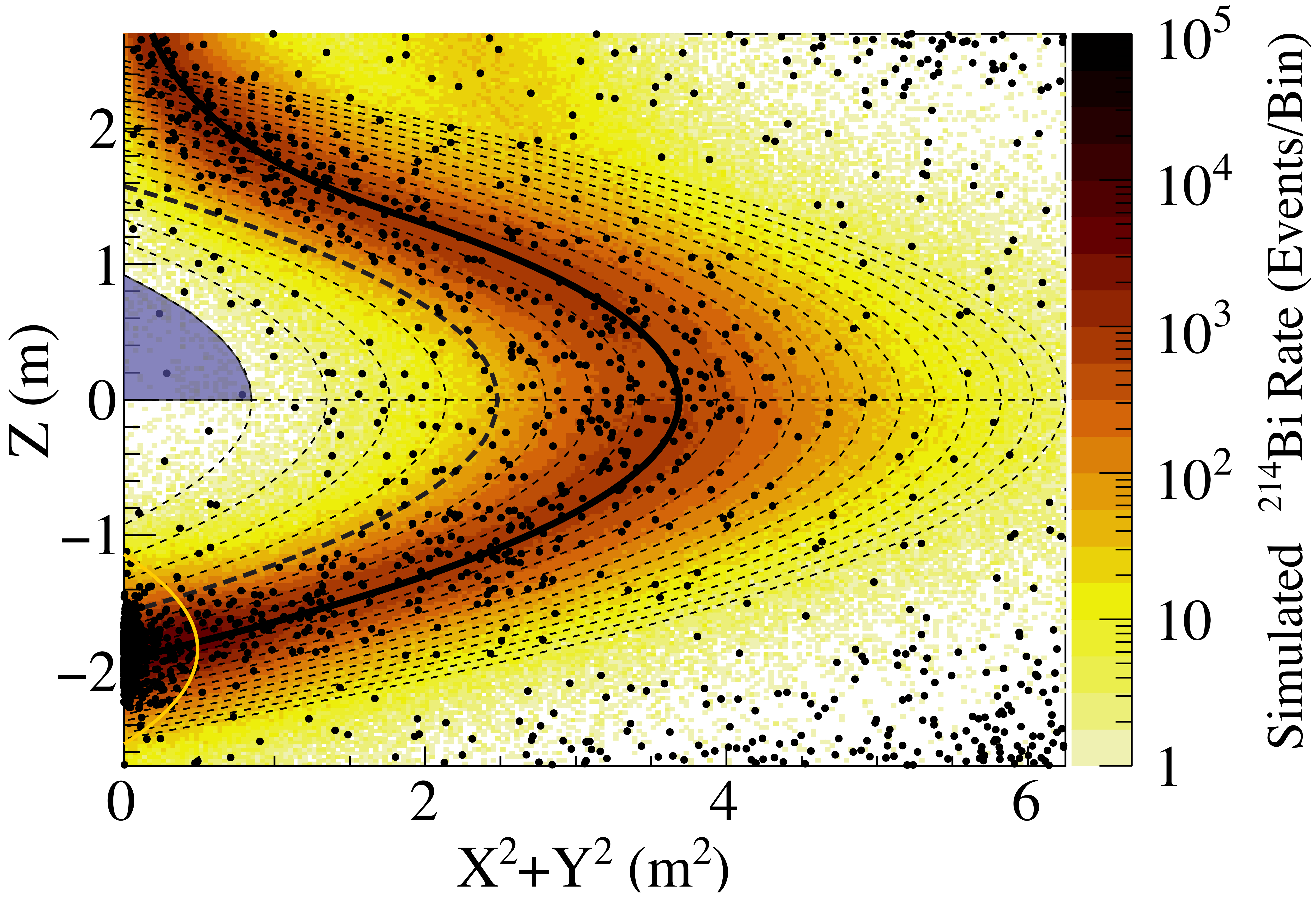

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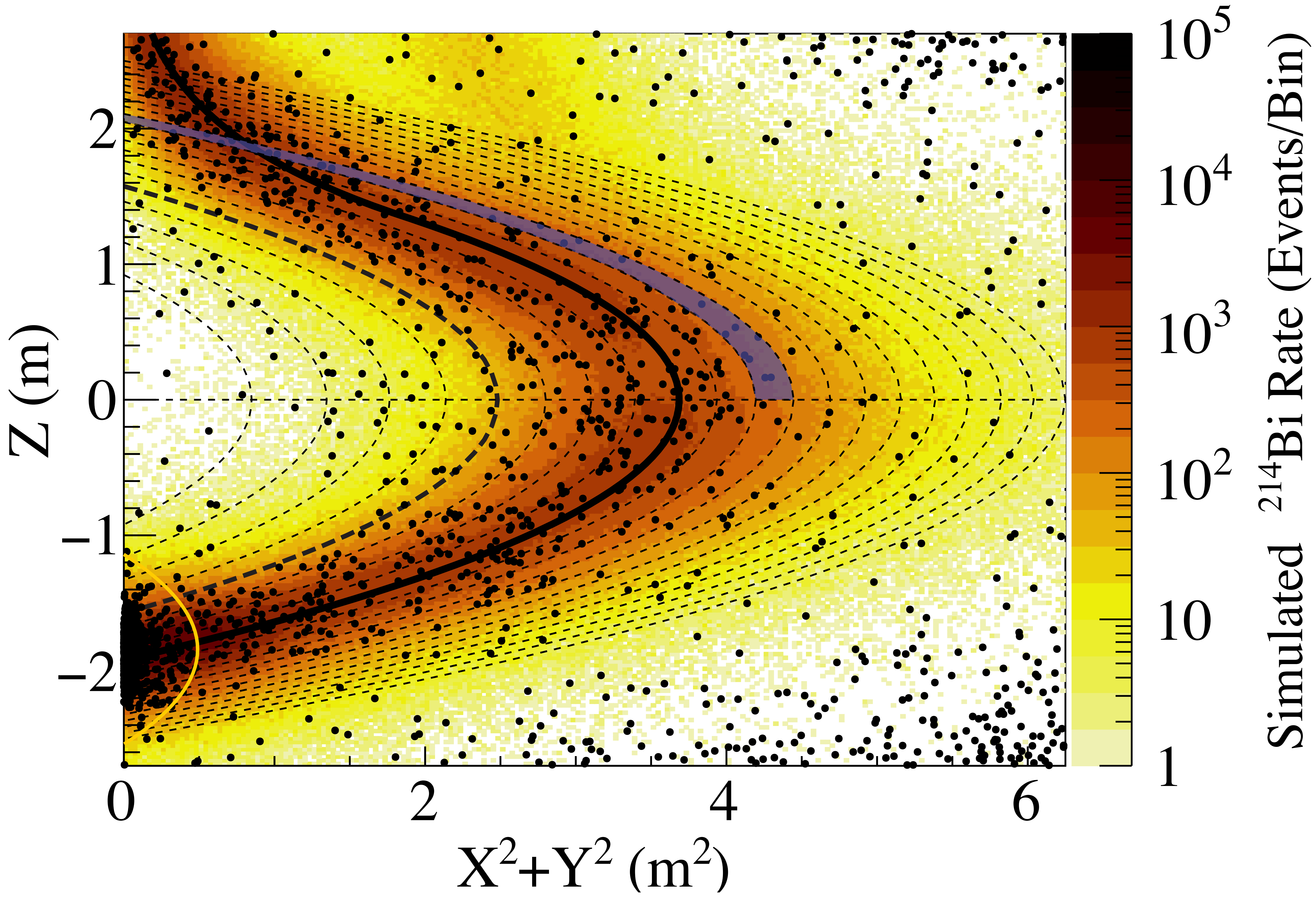

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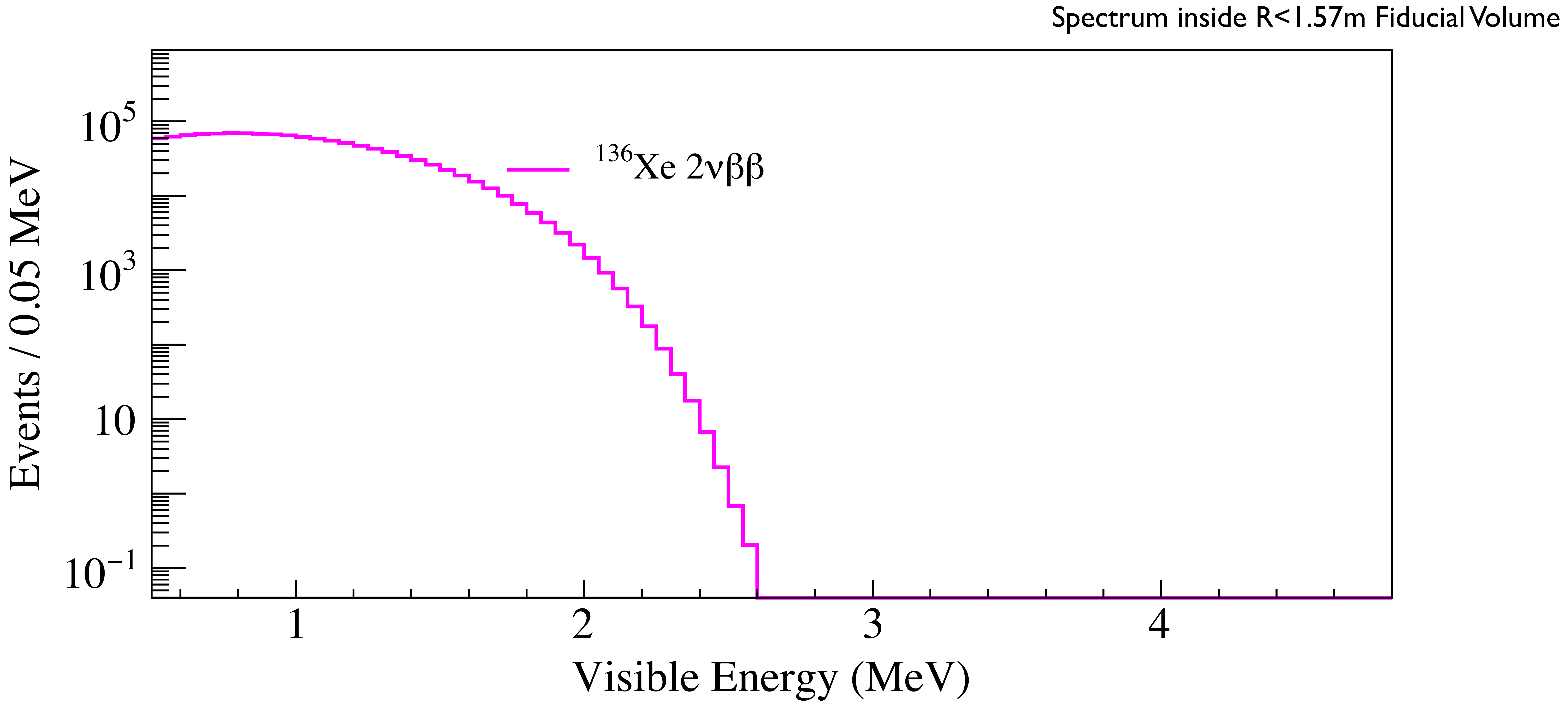
New KamLAND-Zen 800 Results

arXiv:2406.11438



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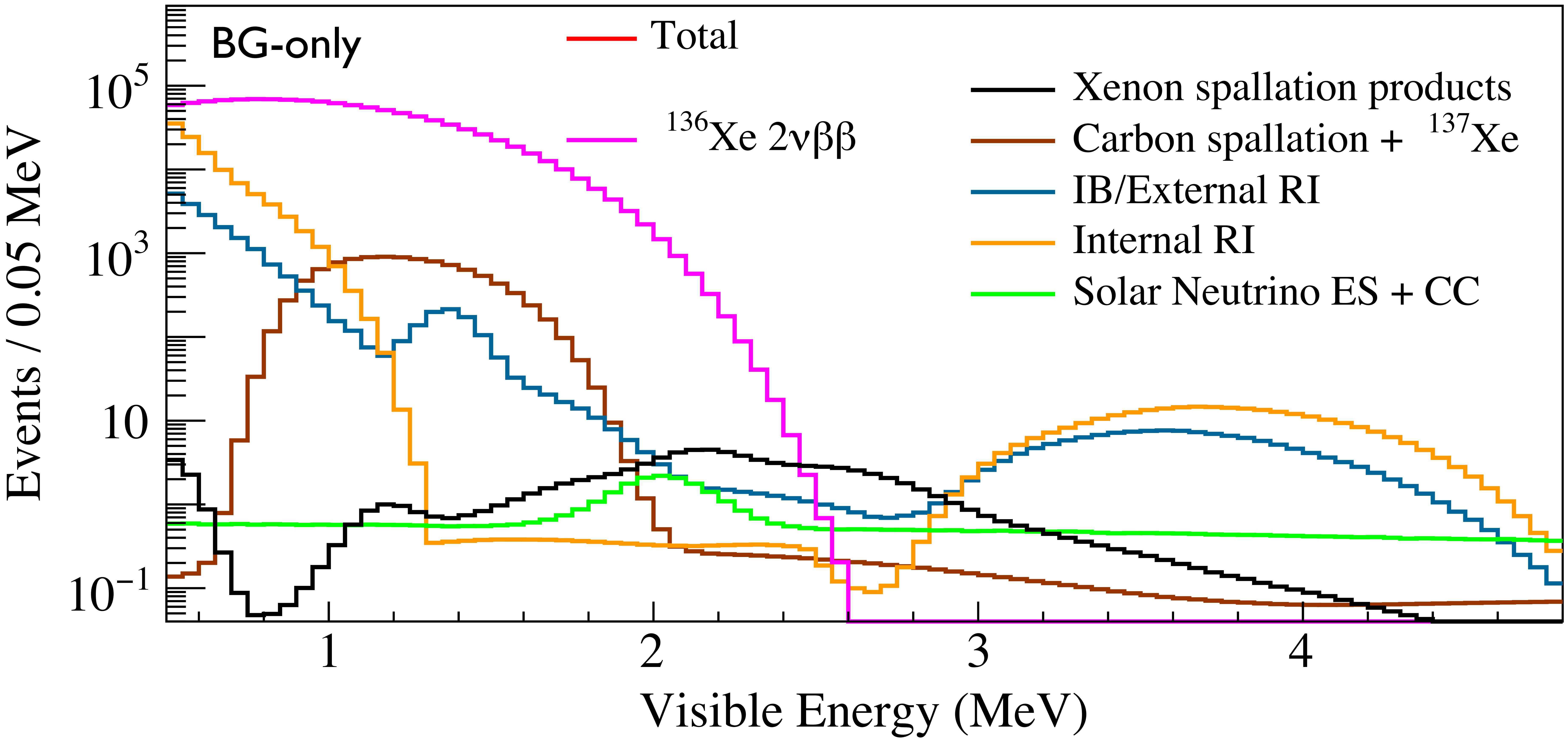
Spectrum inside R<1.57m Fiducial Volume



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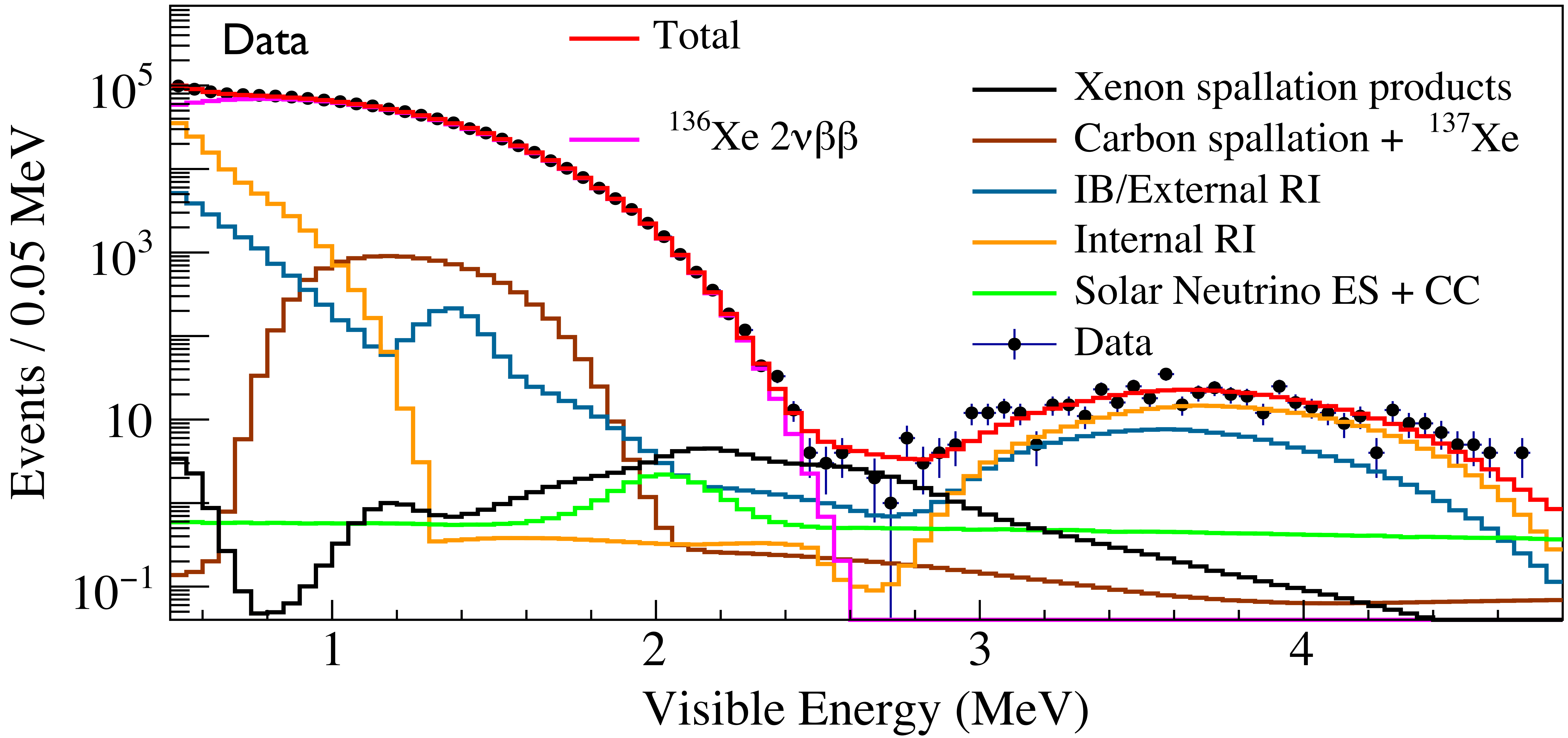

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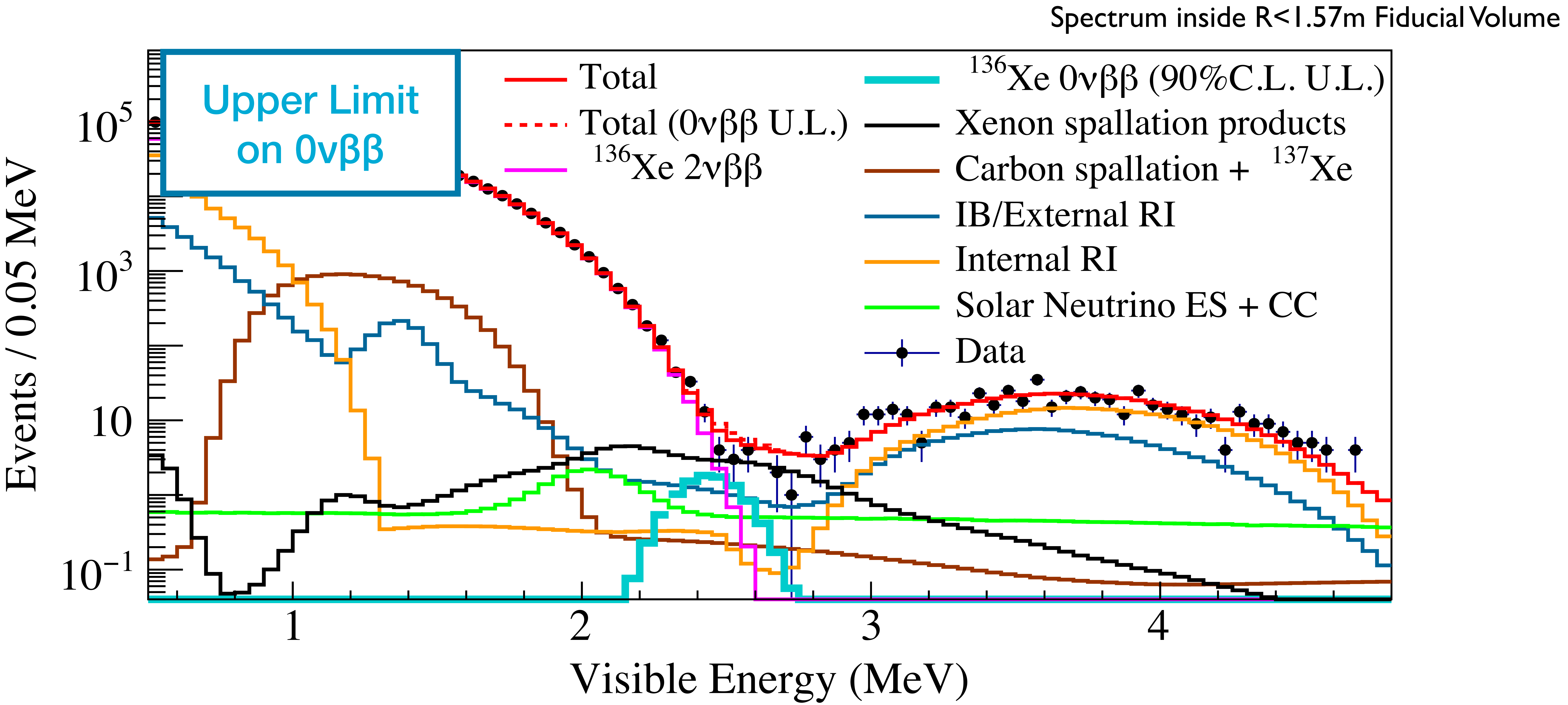


90% C.L. Upper Limit < 10.0 events → $T_{1/2} > 3.4 \times 10^{26}$ yr

[Sensitivity $T_{1/2} > 2.3 \times 10^{26}$ yr]

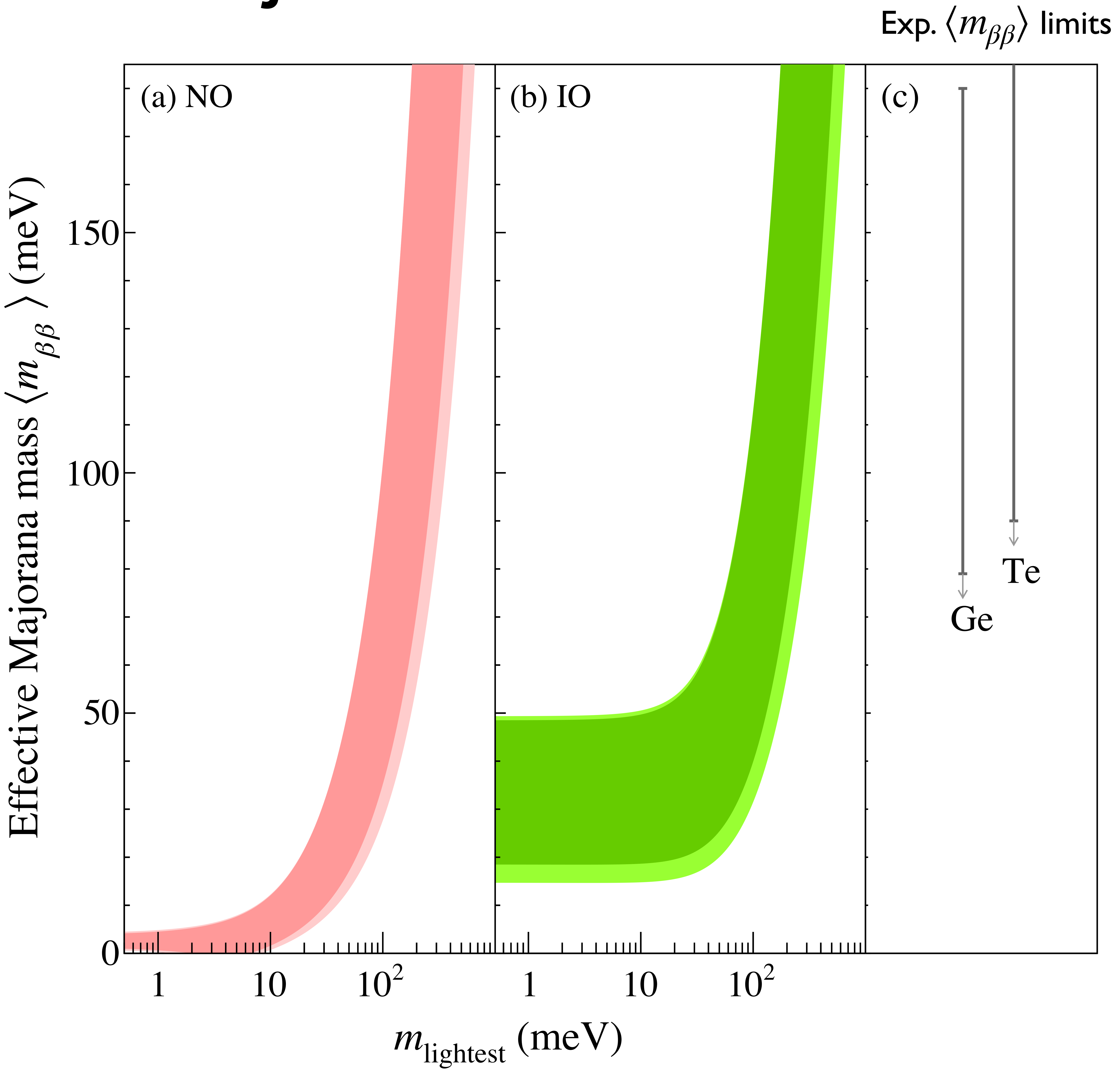
Combined with earlier KamLAND-Zen 400 results: $T_{1/2} > 3.8 \times 10^{26}$ years

arXiv:2406.11438

Effective Majorana Mass

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

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



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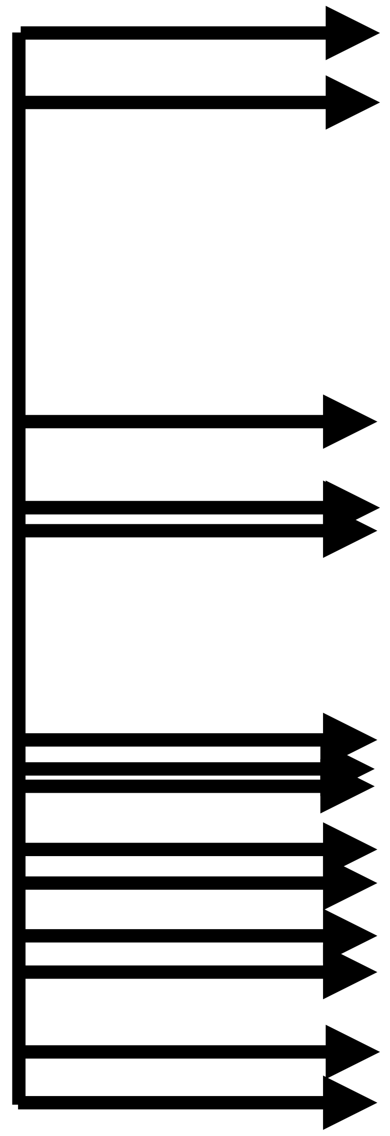
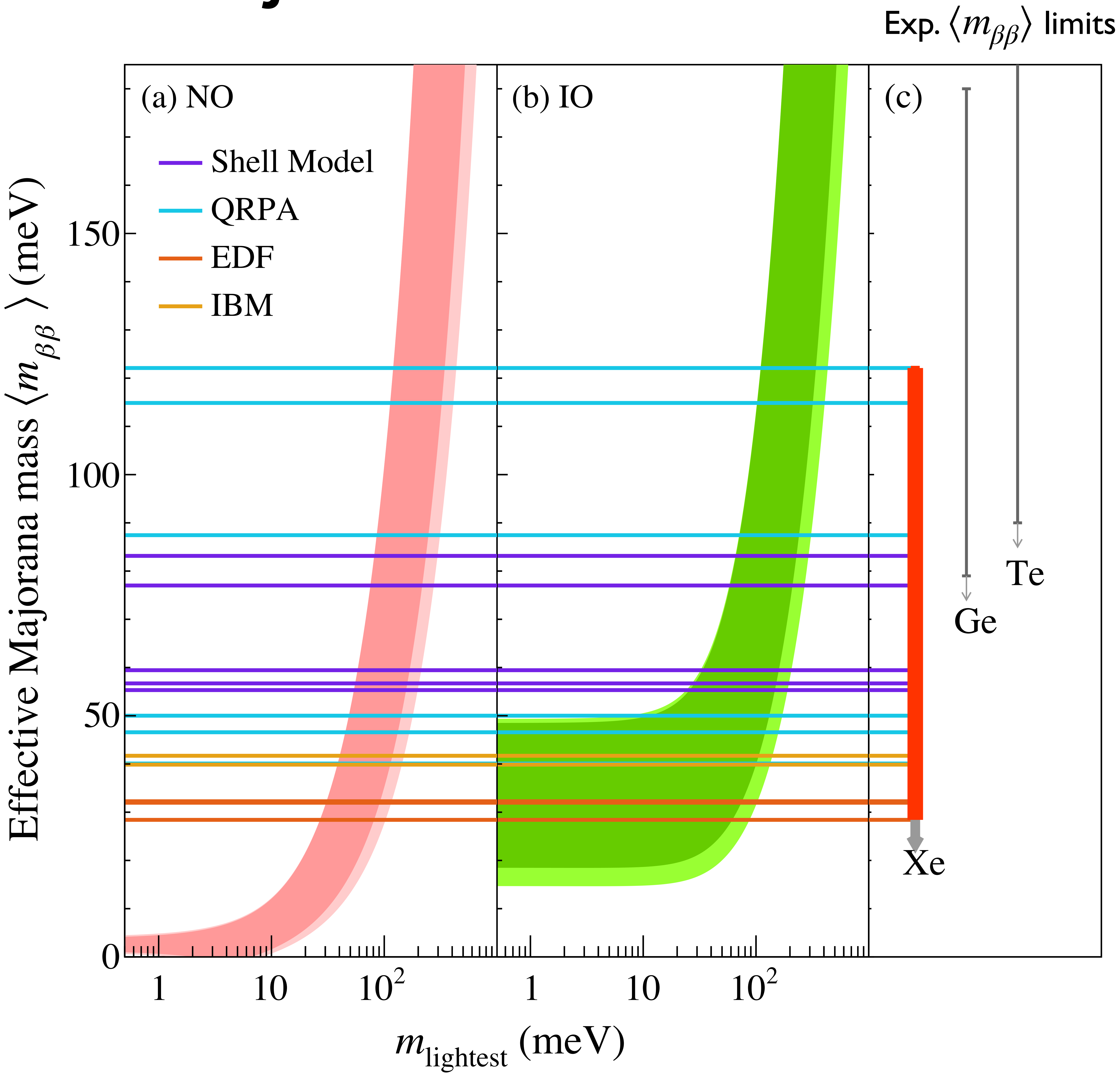
$T_{1/2} > 3.8 \times 10^{26}$ yr

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

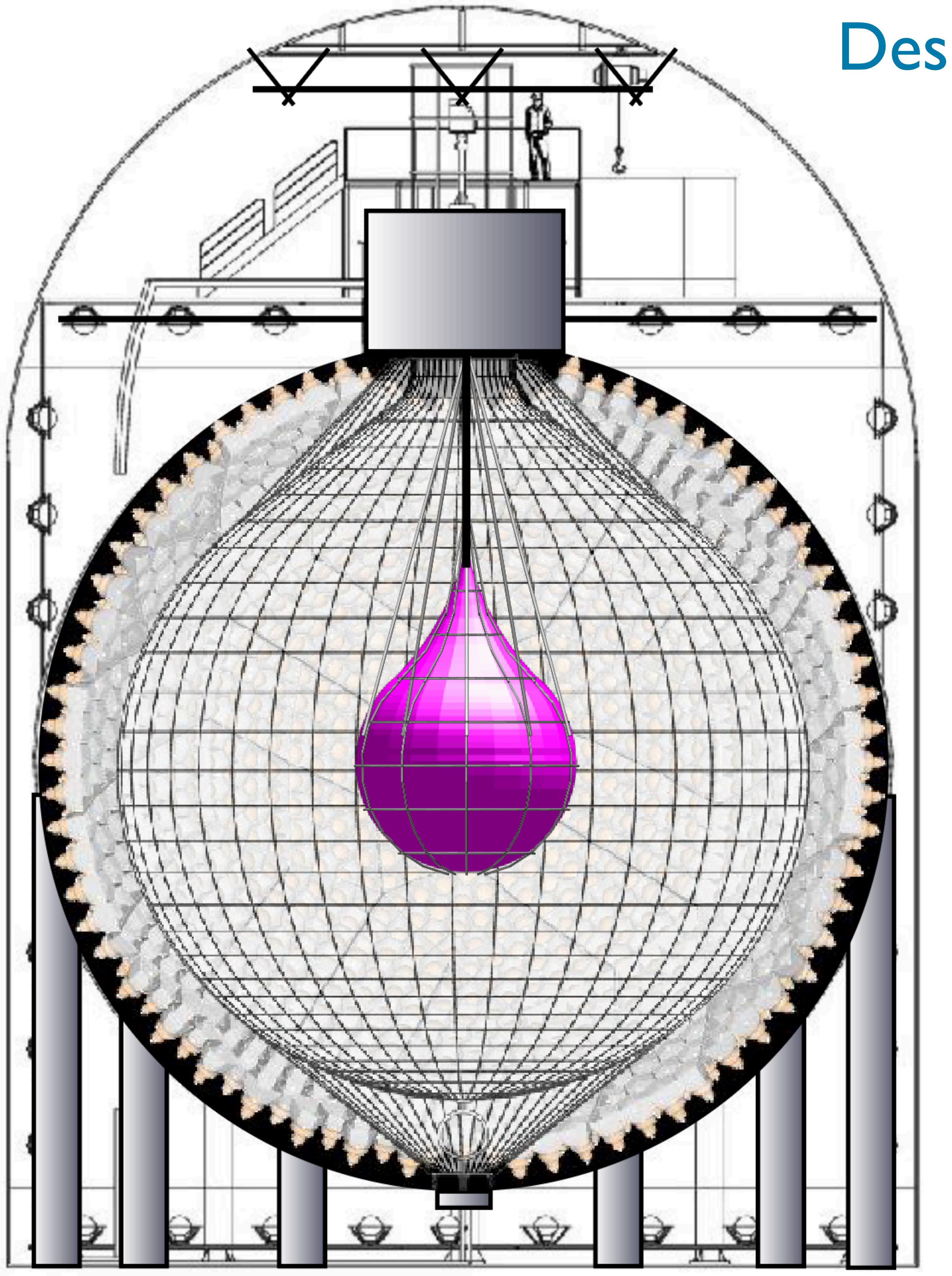




Most stringent limit on $\langle m_{\beta\beta}\rangle$

For some NMEs we probe Inverted Ordering ν-mass

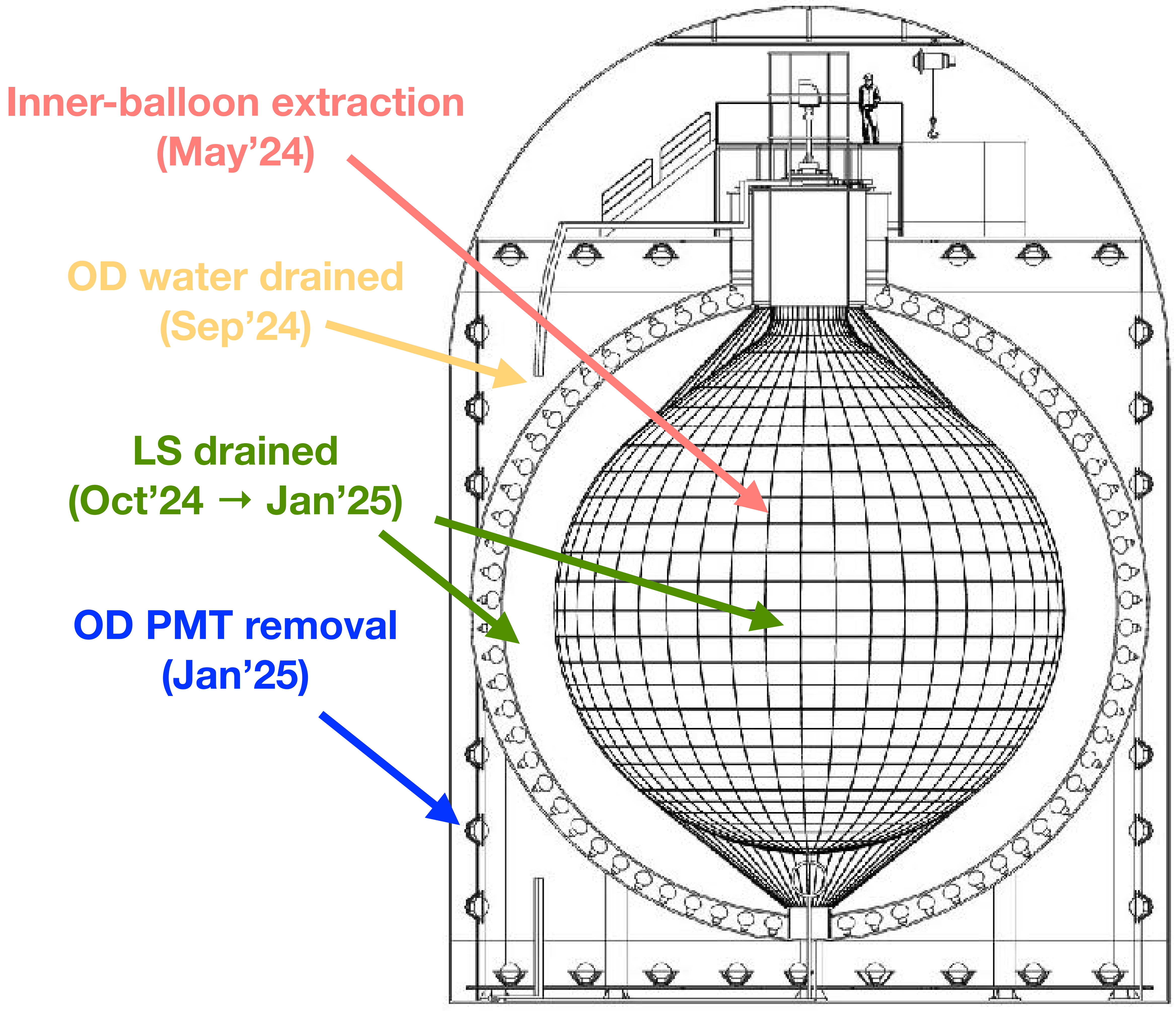
KamLAND2-Zen



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

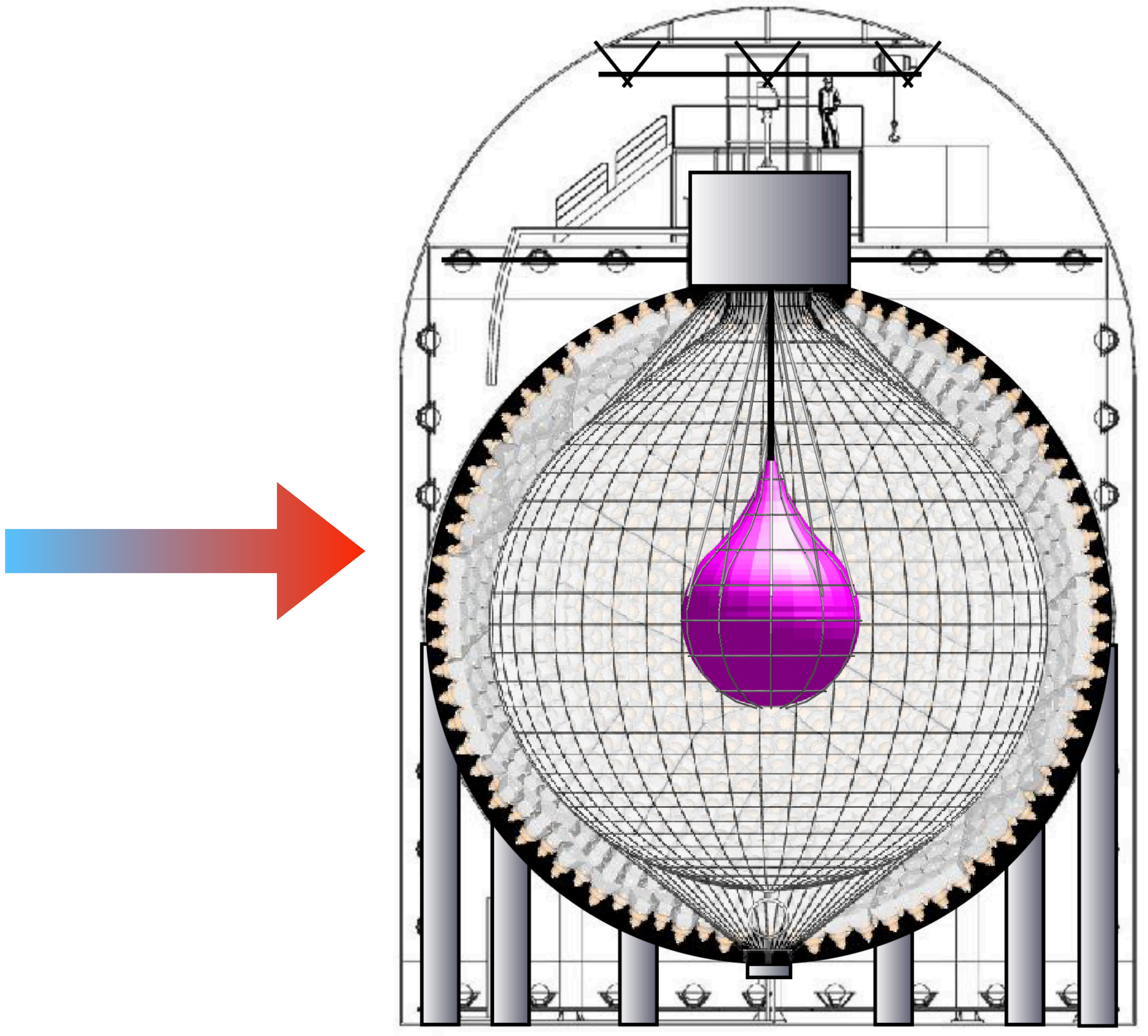
- Improved energy resolution: Winston Cones (x1.8), High-QE PMTs (x1.9)
  - 4% → 2% (x100 reduction in 2νββ BG rate)
- State-of-the-art electronics
  - Improve BG suppression, better tag long-lived spallation
- Improved inner balloon: scintillating balloon
  - Reduce BG originating from balloon

Transition to KamLAND2-Zen in progress!



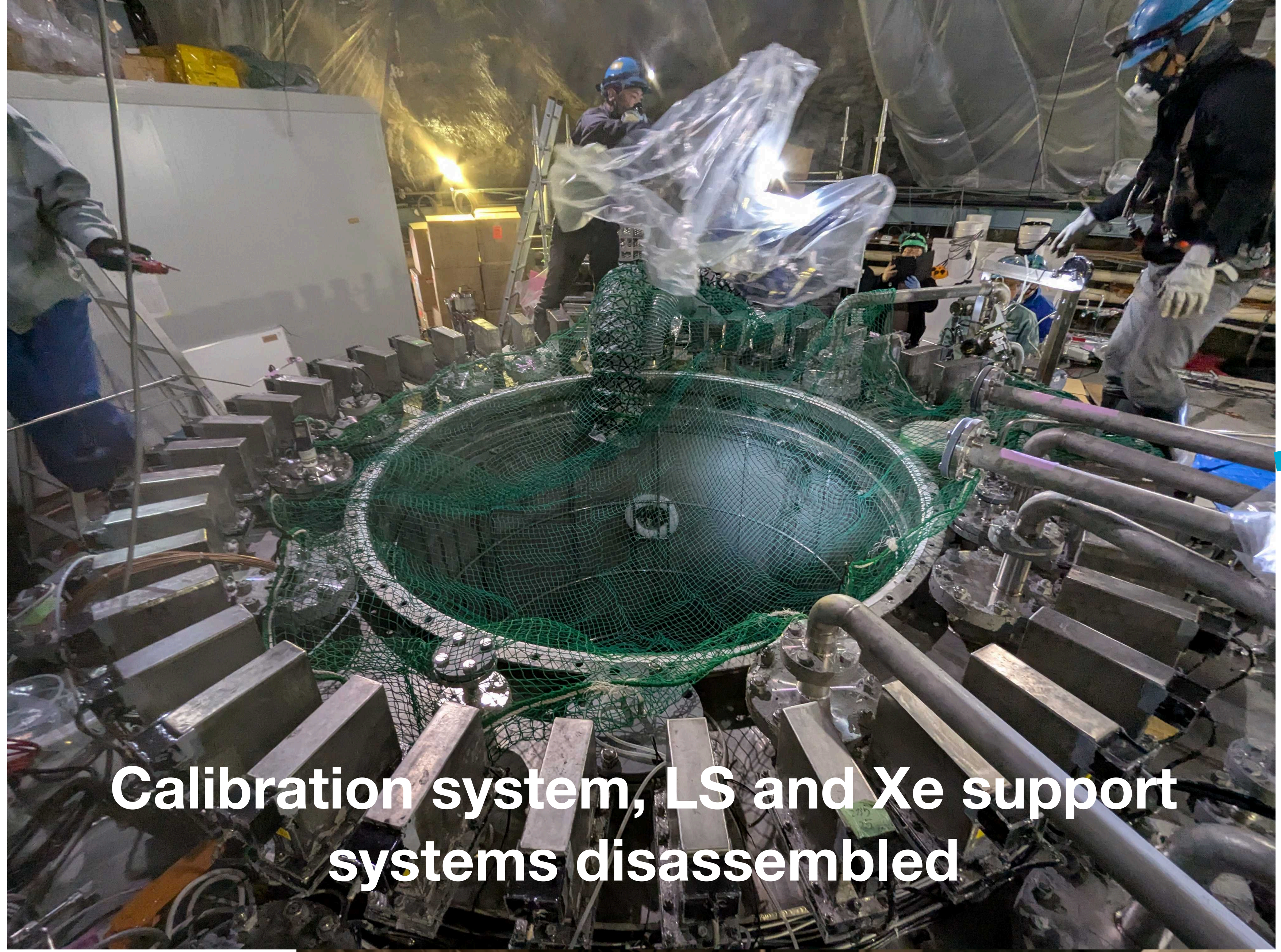
KamLAND(-Zen)
2002-2024

R.I.P.

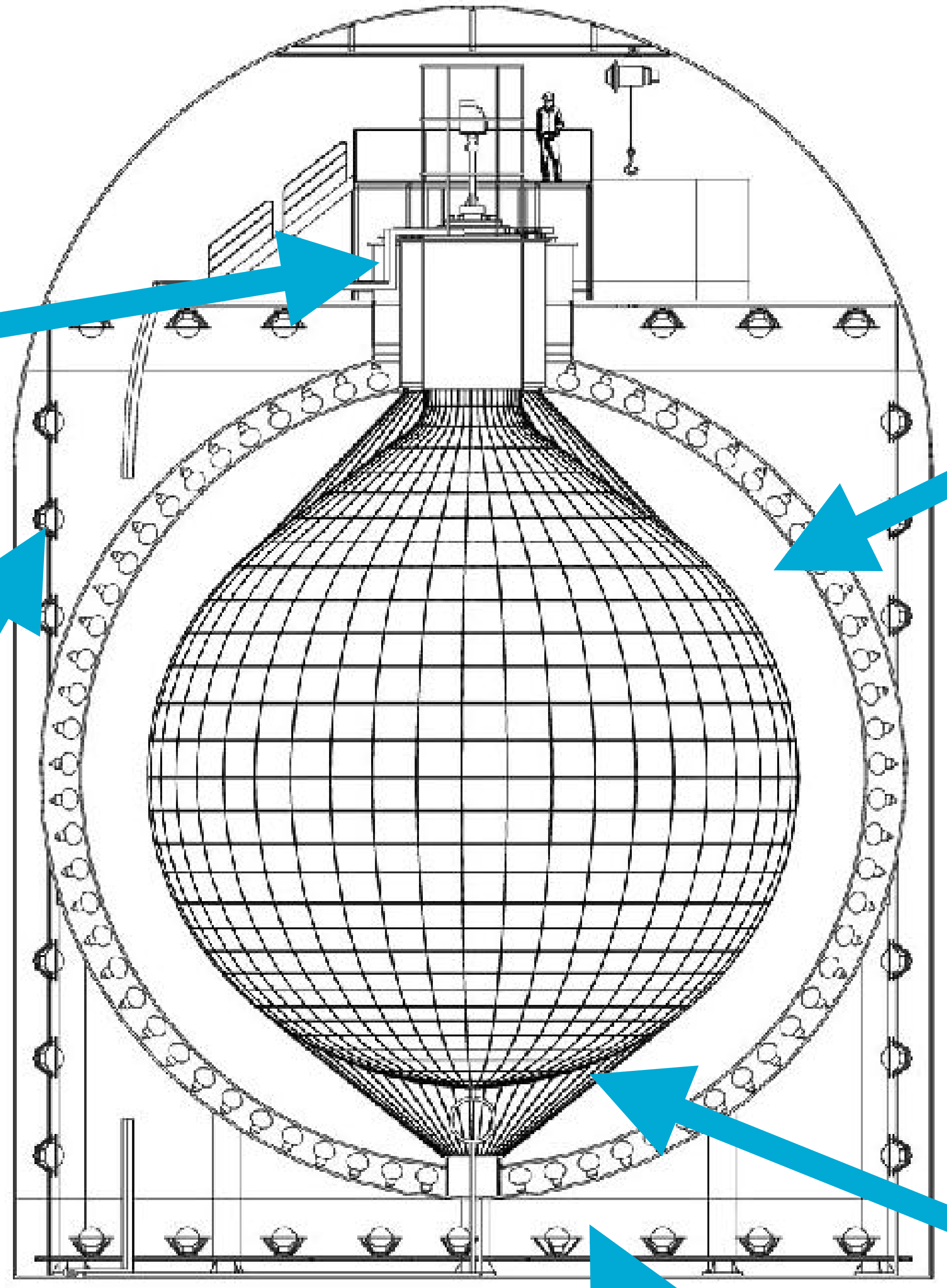


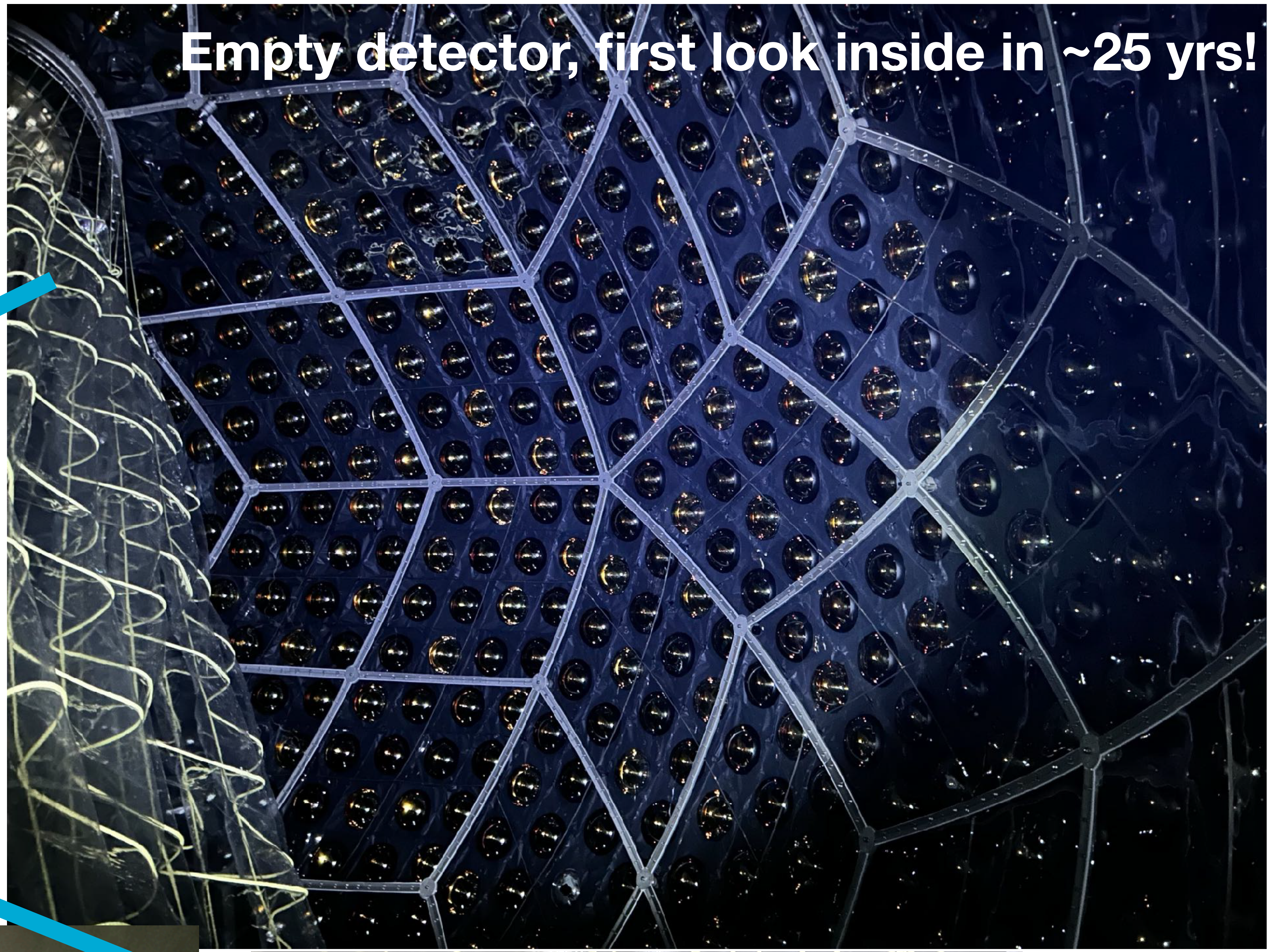
KamLAND2-Zen
Start in 2028

KamLAND-Zen disassembly Fall’24 onwards



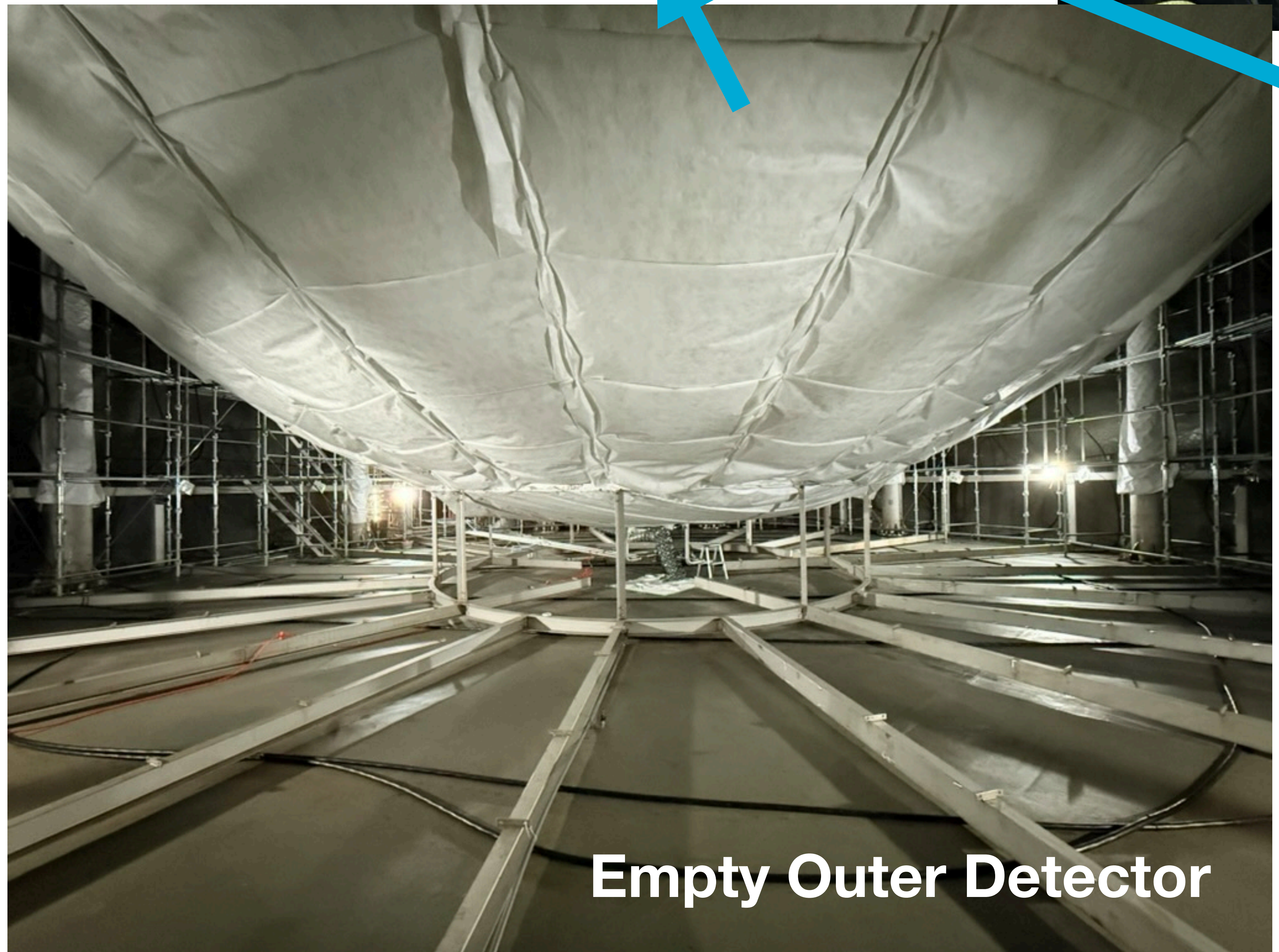
Calibration system, LS and Xe support systems disassembled



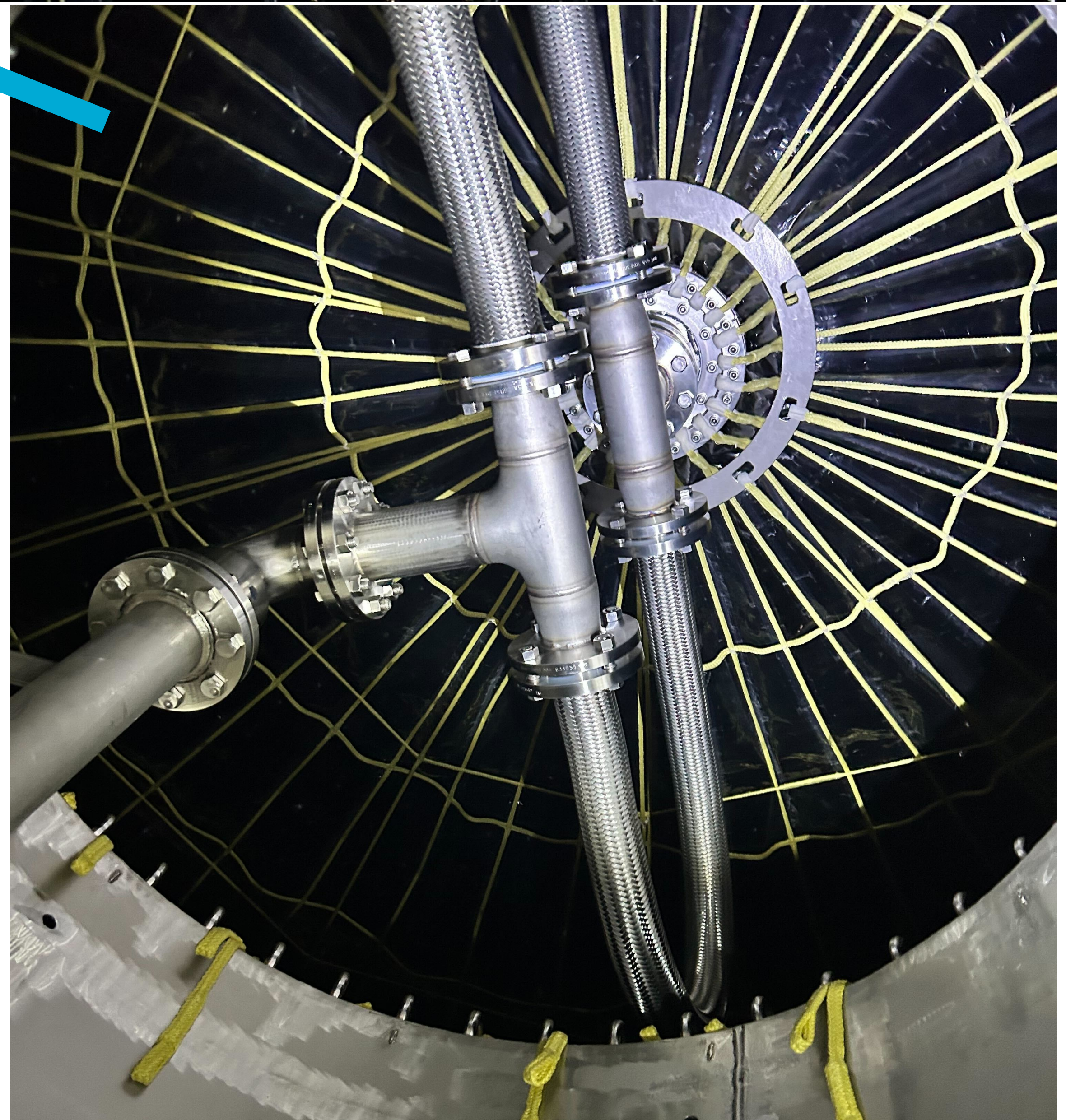


Empty detector, first look inside in ~25 yrs!

Outer Detector PMT disassembly



Empty Outer Detector



Summary

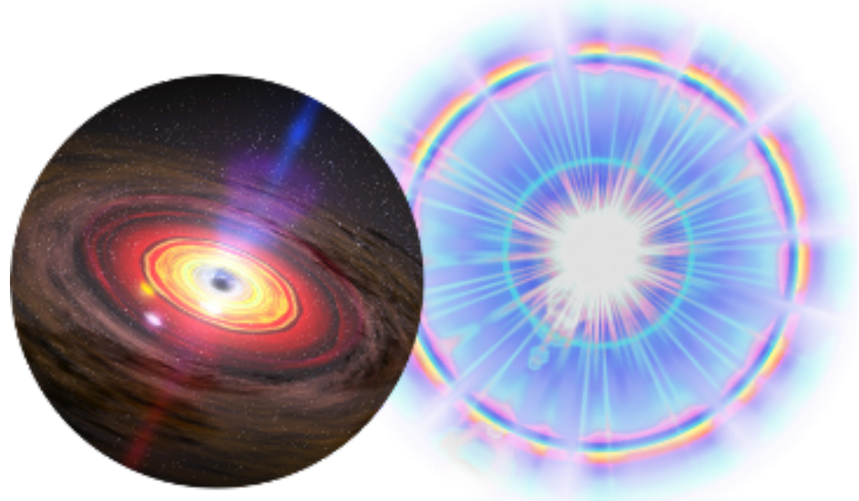
- Neutrinoless double beta decay searches are the only practical method to search for Majorana neutrinos in a model-independent way
- All KamLAND-Zen data, 2.1 ton-year of exposure
- $T_{1/2}^{0\nu} > 3.8 \times 10^{26}$ yr (90% C.L.) → $\langle m_{\beta\beta} \rangle < 28 - 122$ meV
  - Currently best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

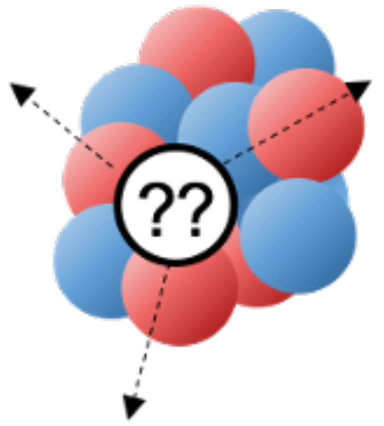
Neutrino Science with KamLAND

Highly versatile KamLAND detector allows
for a broad science program…

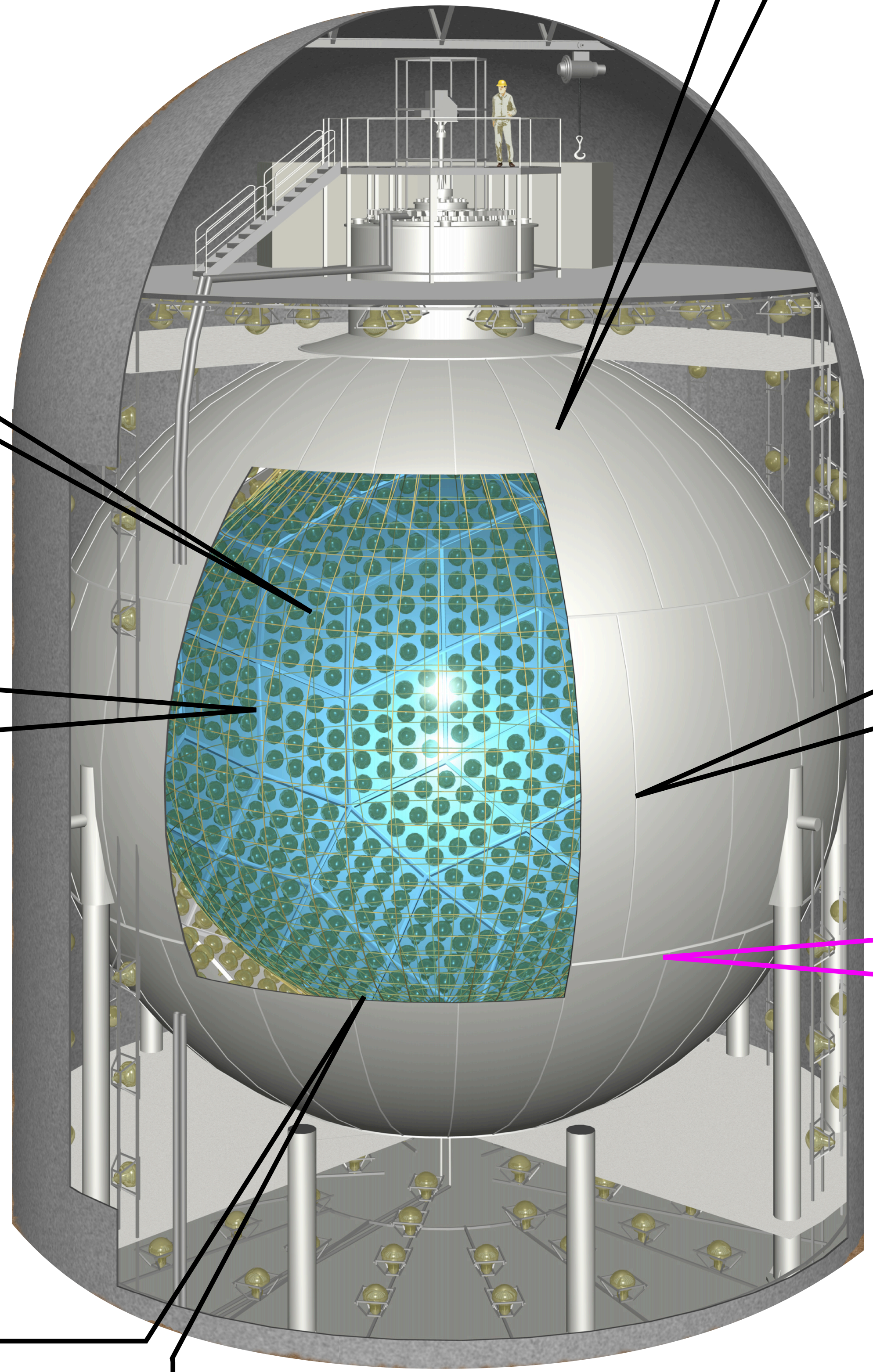
Solar Neutrinos

Astrophysical Neutrinos (Supernovae, GRBs, etc)

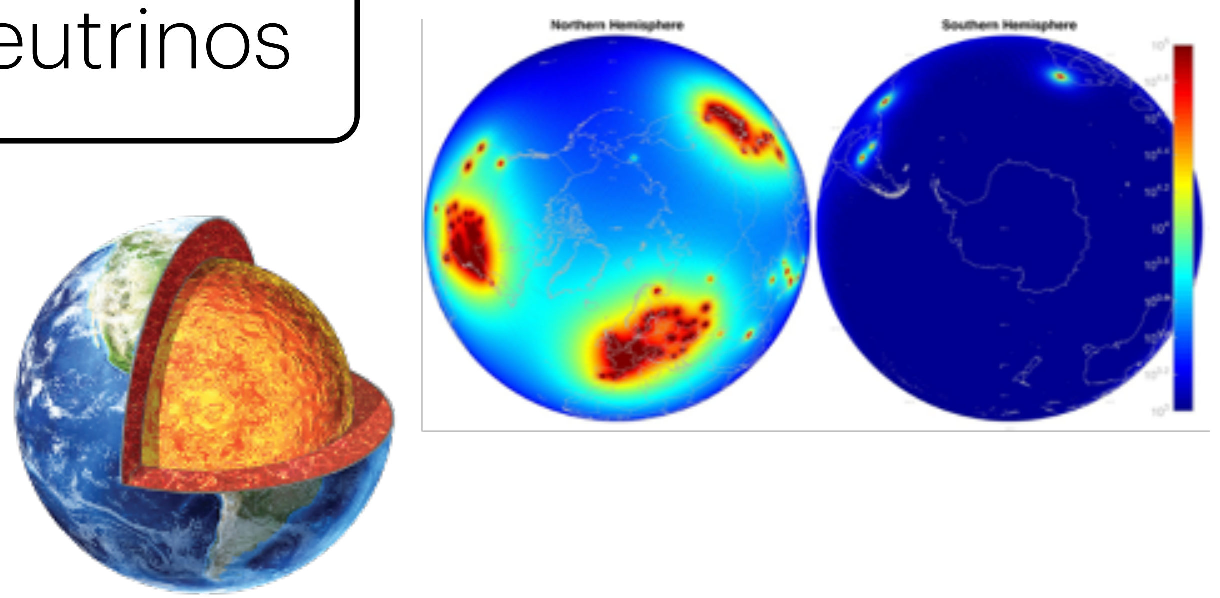




Nucleon Decay

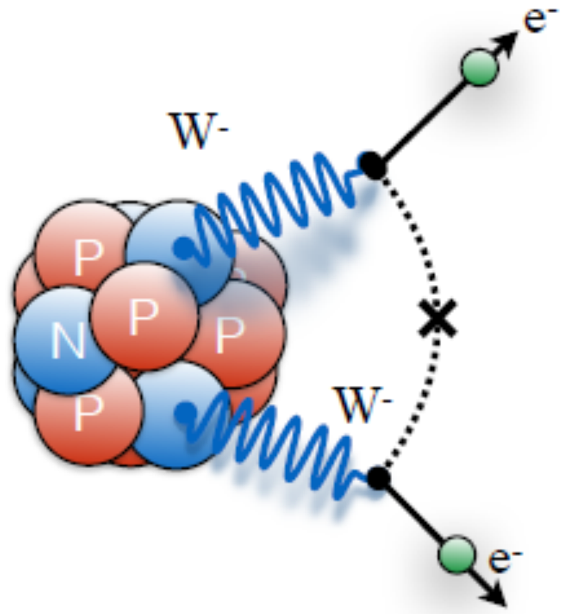


Geo and Reactor Neutrinos



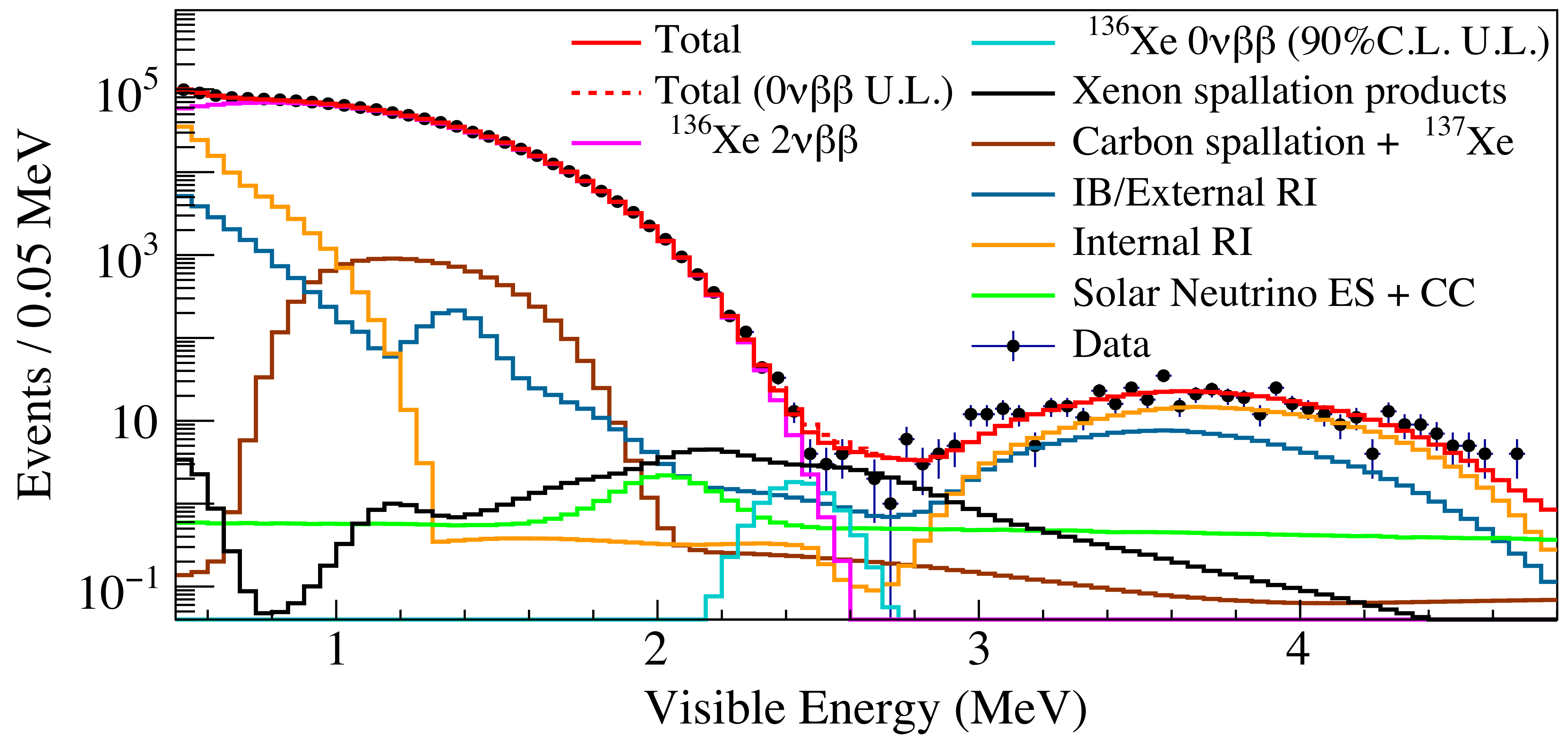
Accelerator Neutrinos

Neutrinoless Double-Beta Decay (0νββ)

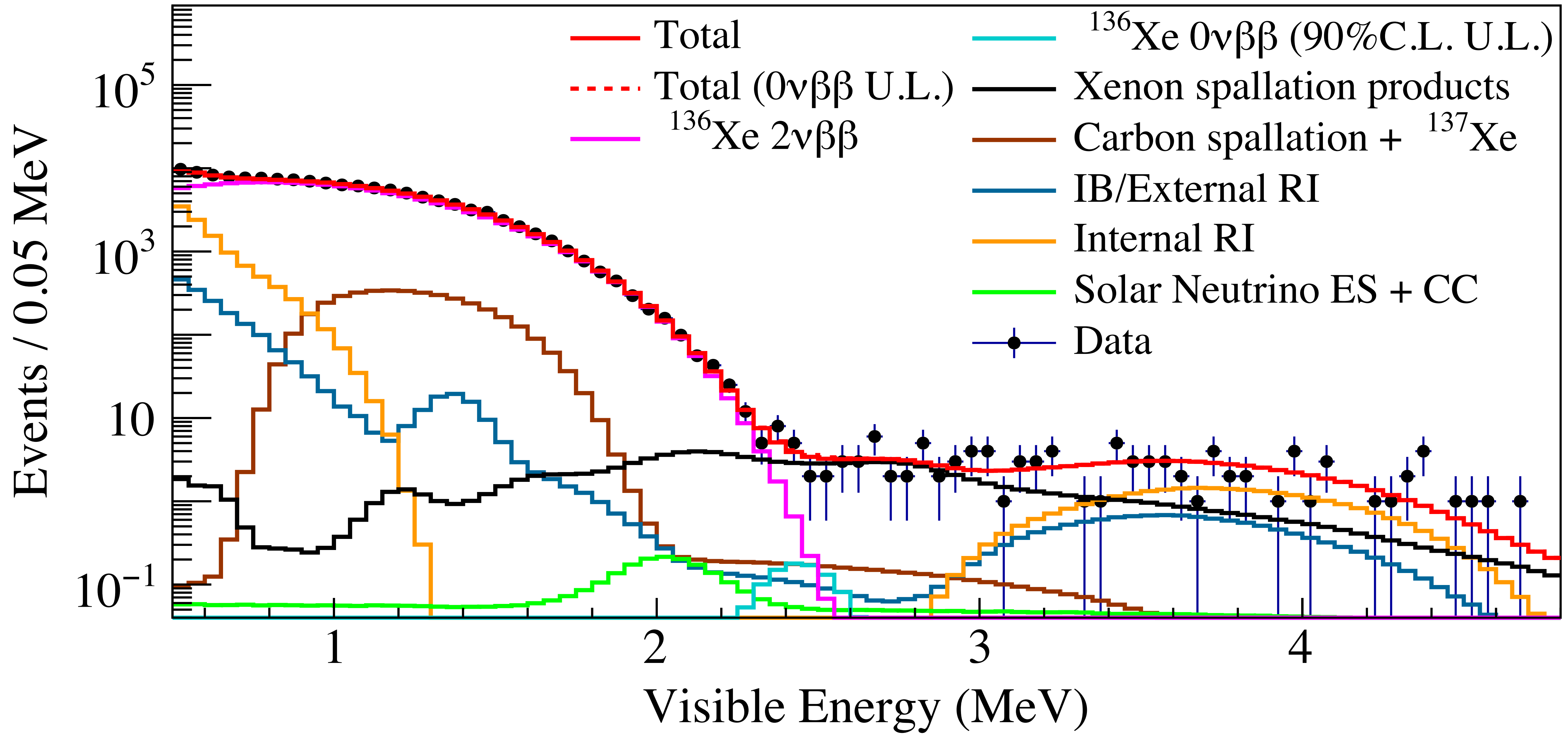


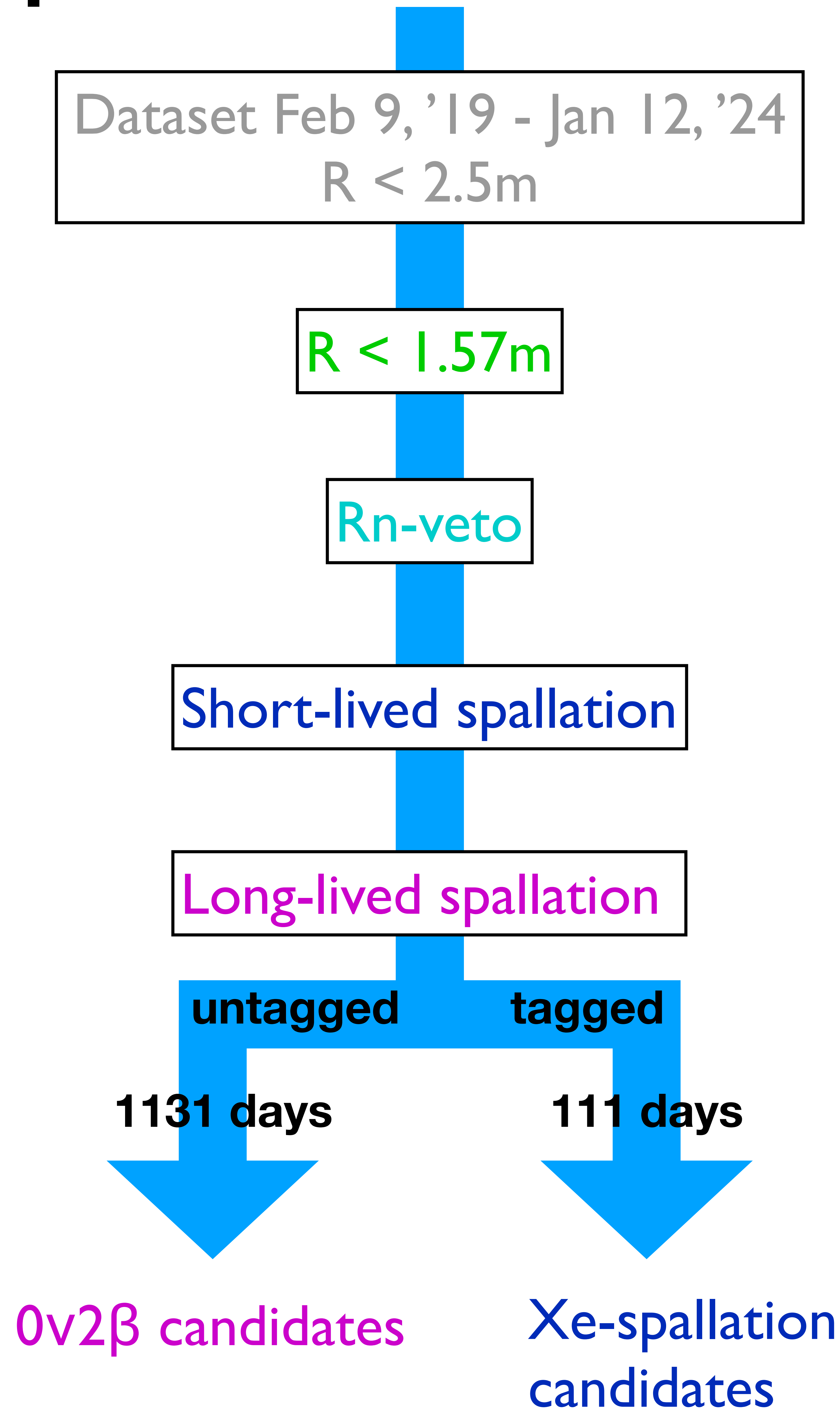
0ν2β and tagged Long-lived spectrum

0ν2β candidates



Xe-spallation candidates



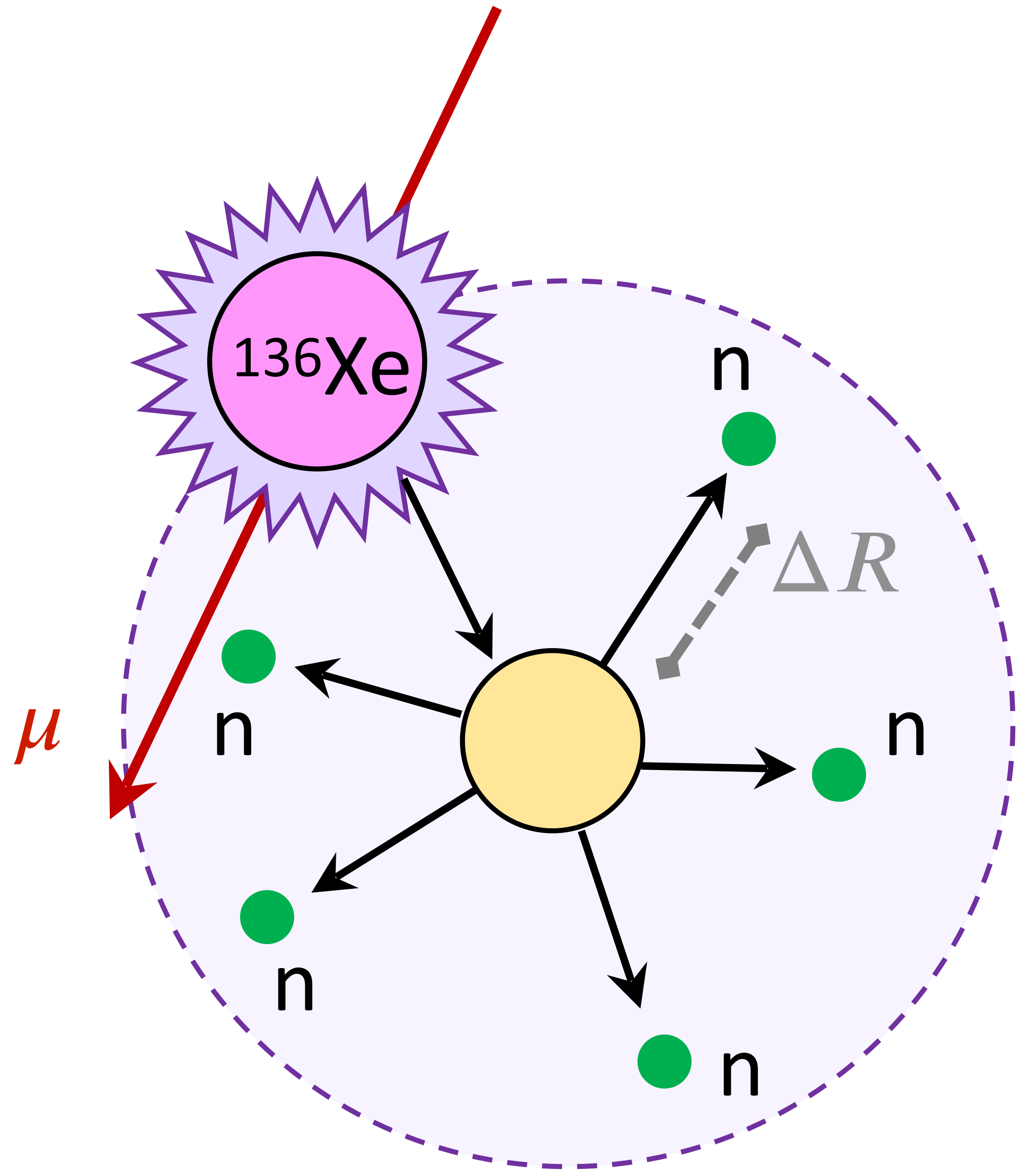


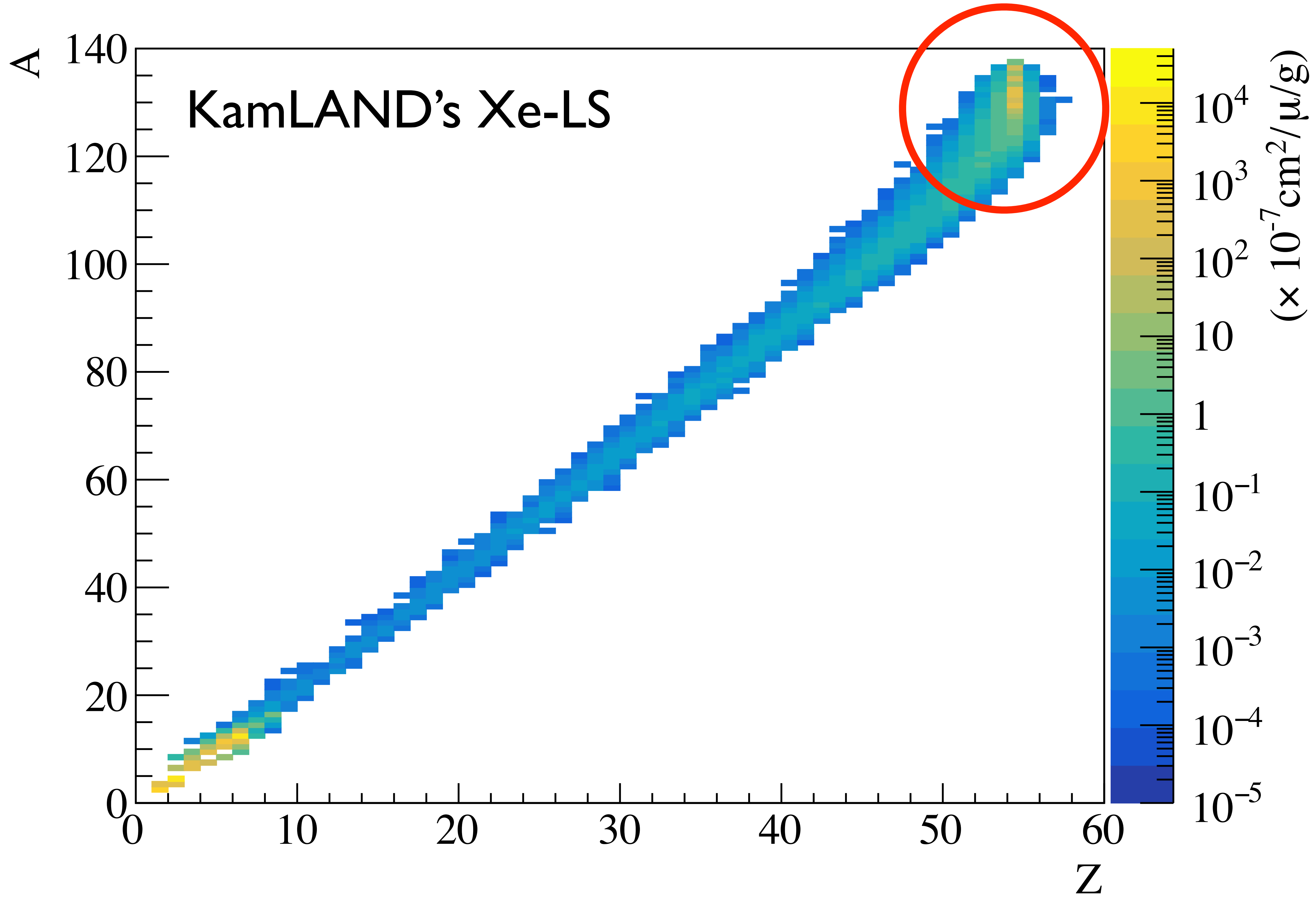
The two spectra (0ν2β and Xe-spallation) are fitted simultaneously to constrain the Xe-spallation BG

Muon Spallation

μ + ¹³⁶Xe spallation products from FLUKA simulation

Spallation on ¹³⁶Xe





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

KamLAND-Zen, *Phys.Rev.C* 107 (2023) 5, 054612, arXiv:2301.09307