Neutrinoless double beta decay searches in KamLAND-Zen and beyond

Patrick Decowski

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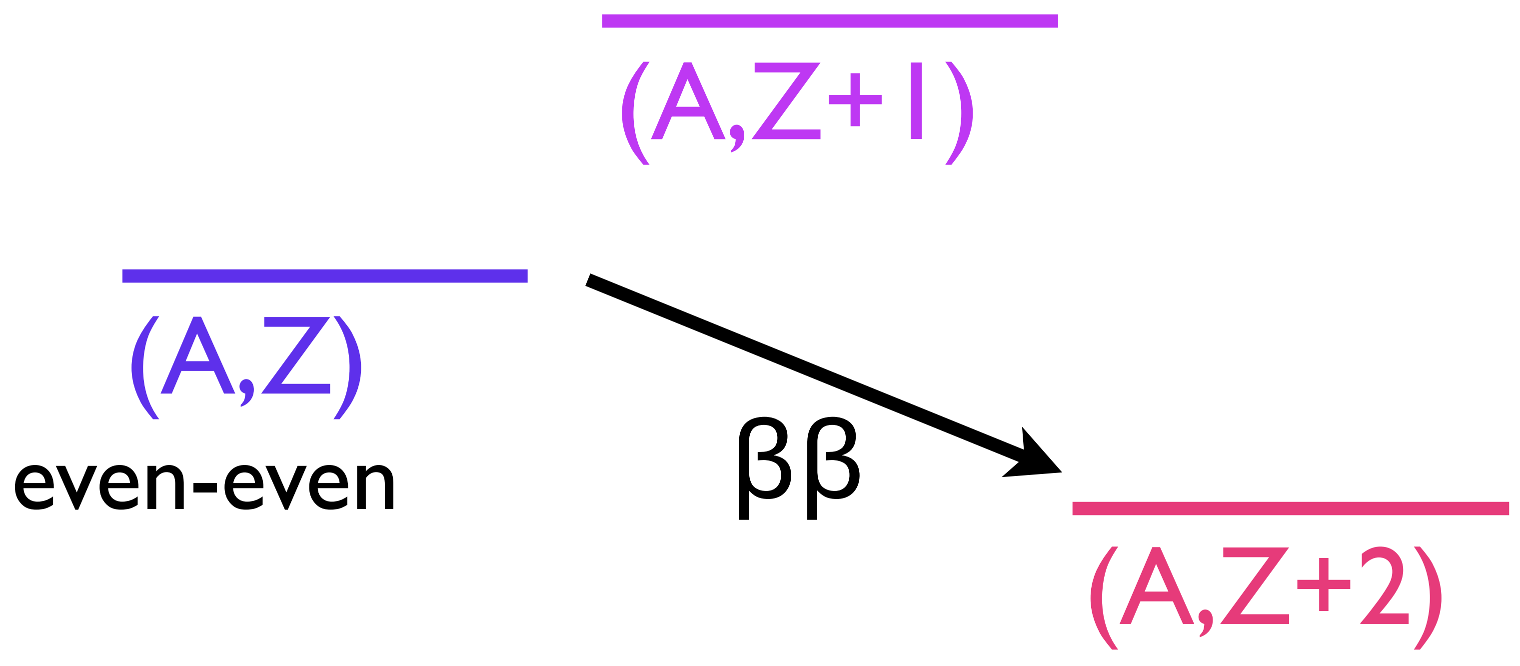
Double Beta Decay



^{136}Xe

^{76}Ge

^{82}Se

^{100}Mo

^{130}Te

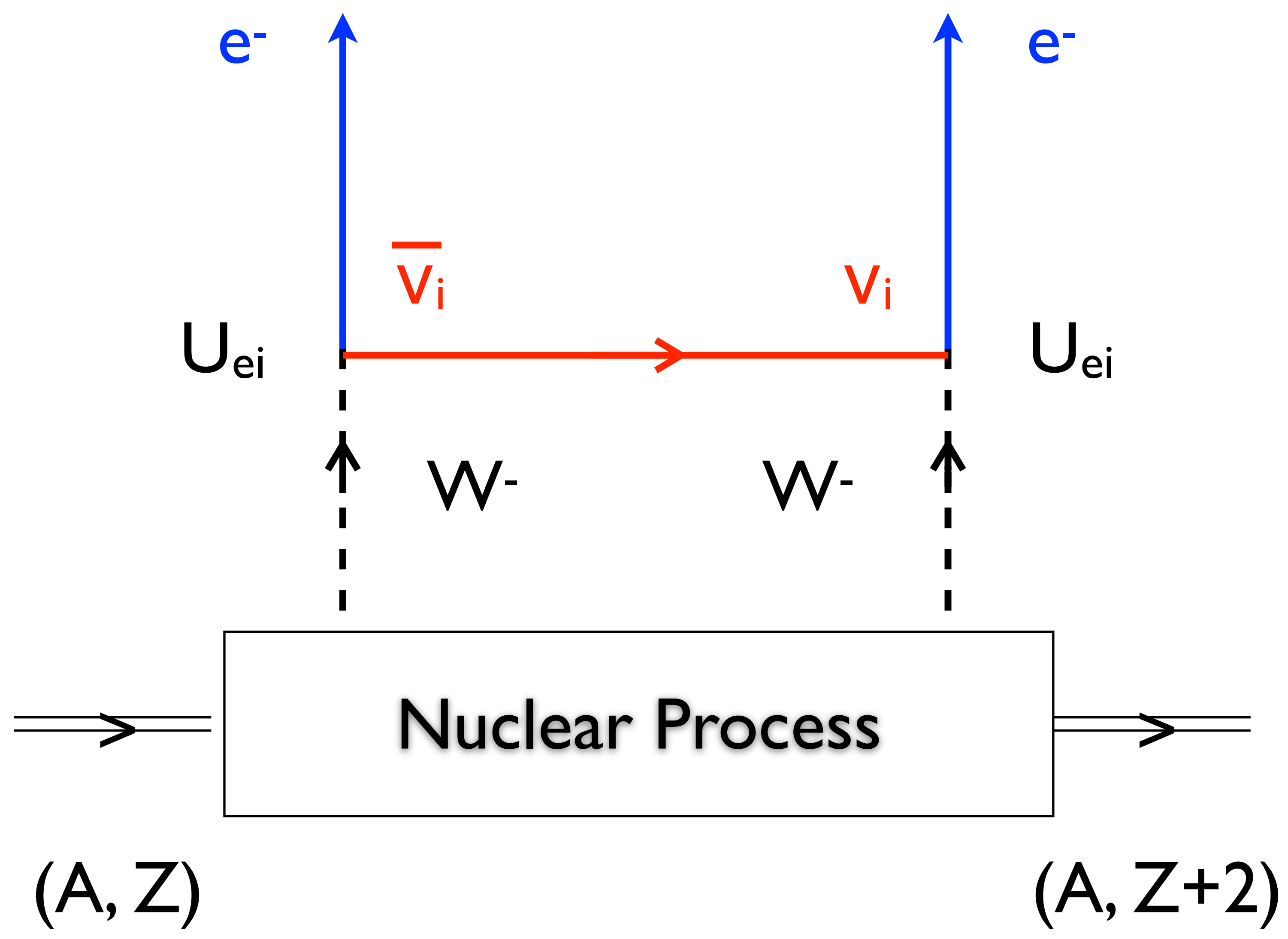
...

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

Rare, but Standard Model Process:

$$2\nu2\beta : (A,Z) \rightarrow (A,Z+2) + e^- + e^- + \overline{\nu}_e + \overline{\nu}_e$$

Neutrinoless Double Beta Decay



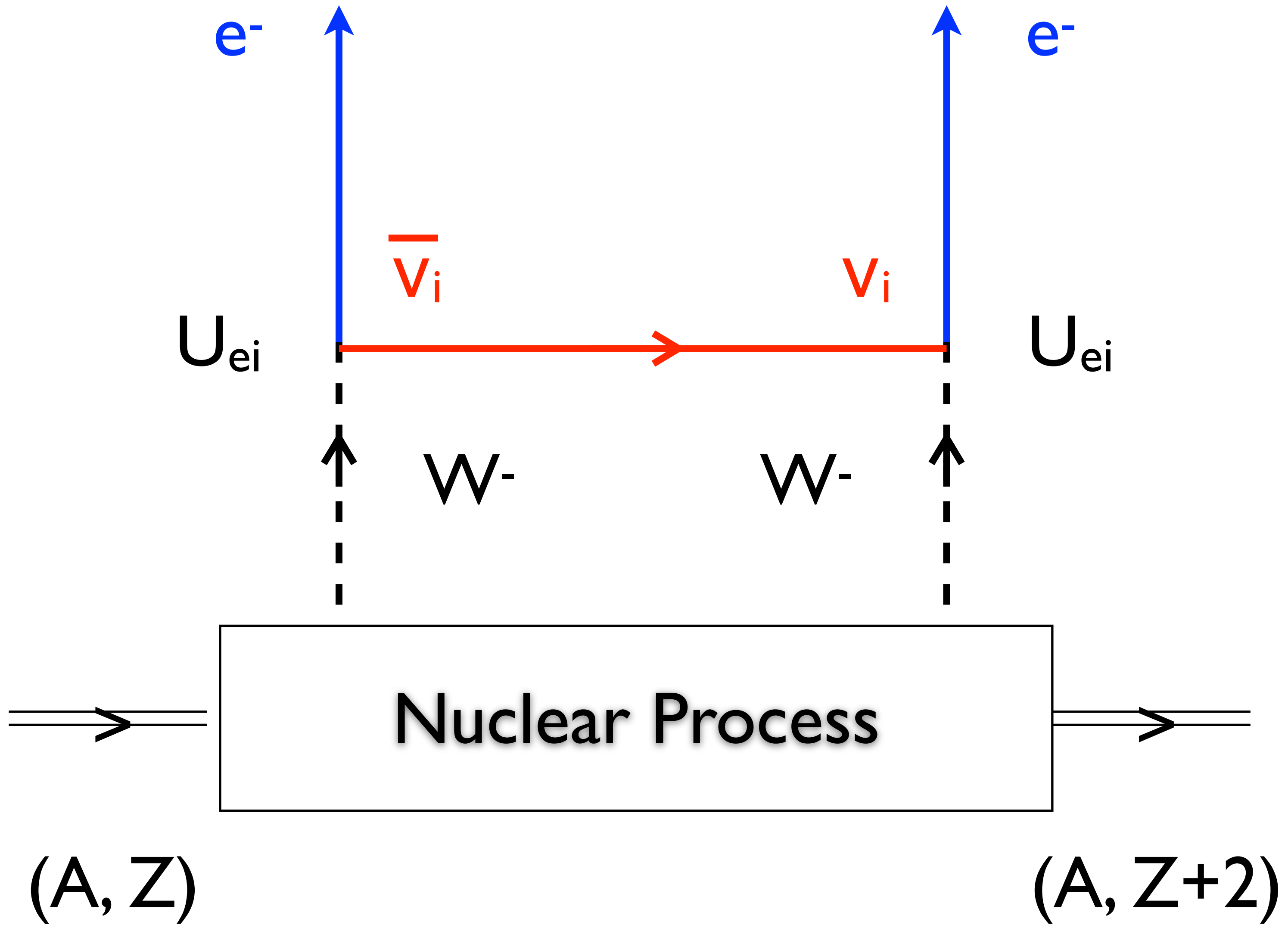
But what if ν is Majorana?

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

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

- Extremely rare process [W.H. Furry (1939): $T_{1/2} > 10^{16}$ yr]
- Requires massive Majorana neutrino
- Lepton Number Violation
  - Model dependent - Standard interpretation: light Majorana ν + SM interactions

Neutrinoless Double Beta Decay



But what if ν is Majorana?

$$M_\nu \neq 0$$
$$|\Delta L| = 2$$

$$0\nu2\beta : (A, Z) \to (A, Z+2) + e^- + e^-$$

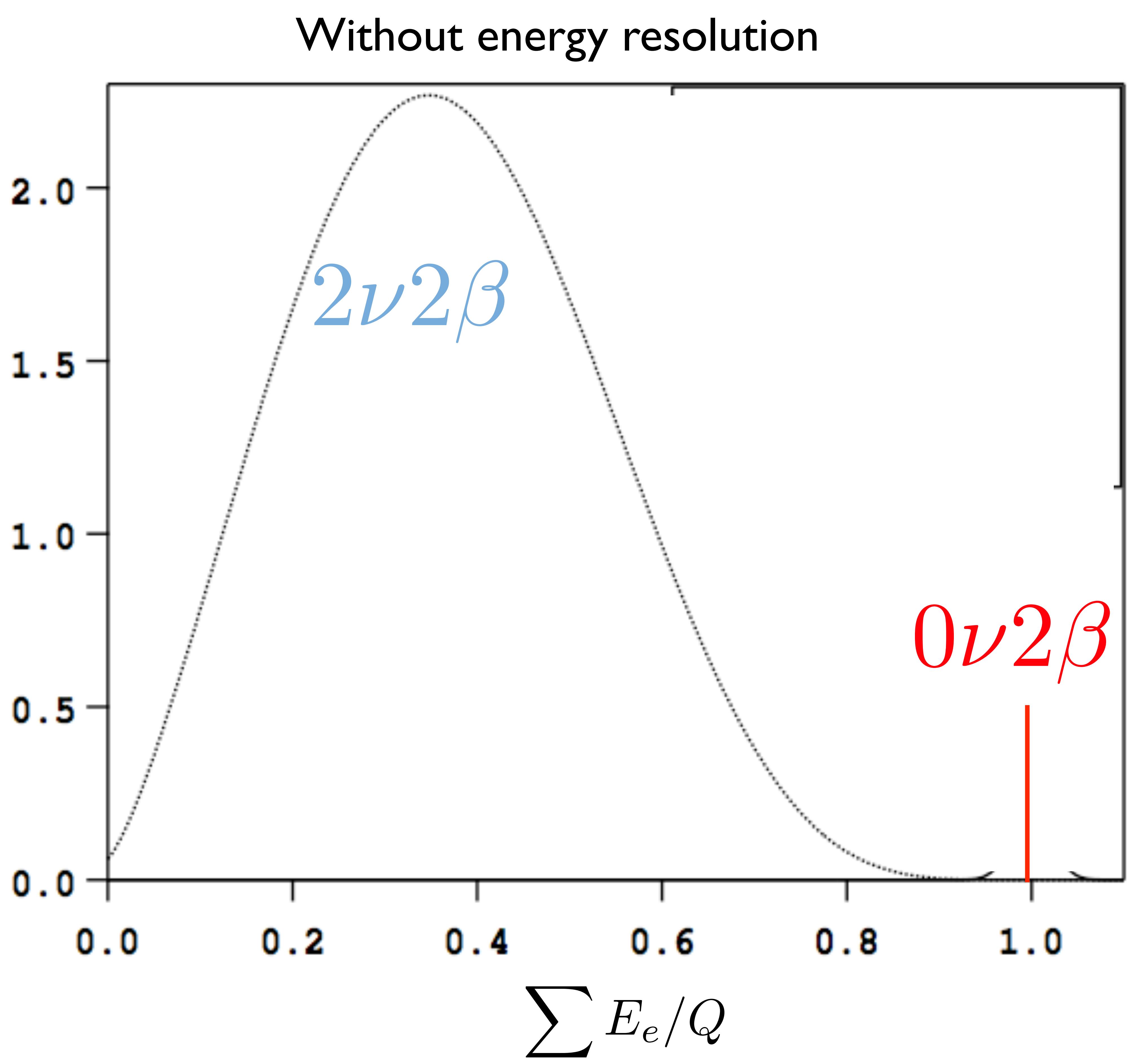
PHYSICAL REVIEW D VOLUME 25, NUMBER 11 1 JUNE 1982

Neutrinoless double-β decay in SU(2)×U(1) theories

J. Schechter and J. W. F. Valle
Department of Physics, Syracuse University, Syracuse, New York 13210
(Received 14 December 1981)

It is shown that gauge theories give contributions to neutrinoless double-β decay [$(\beta\beta)_{0\nu}$] which are not covered by the standard parametrizations. While probably small, their existence raises the question of whether the observation of $(\beta\beta)_{0\nu}$ implies the existence of a Majorana mass term for the neutrino. For a "natural" gauge theory we argue that this is indeed the case.

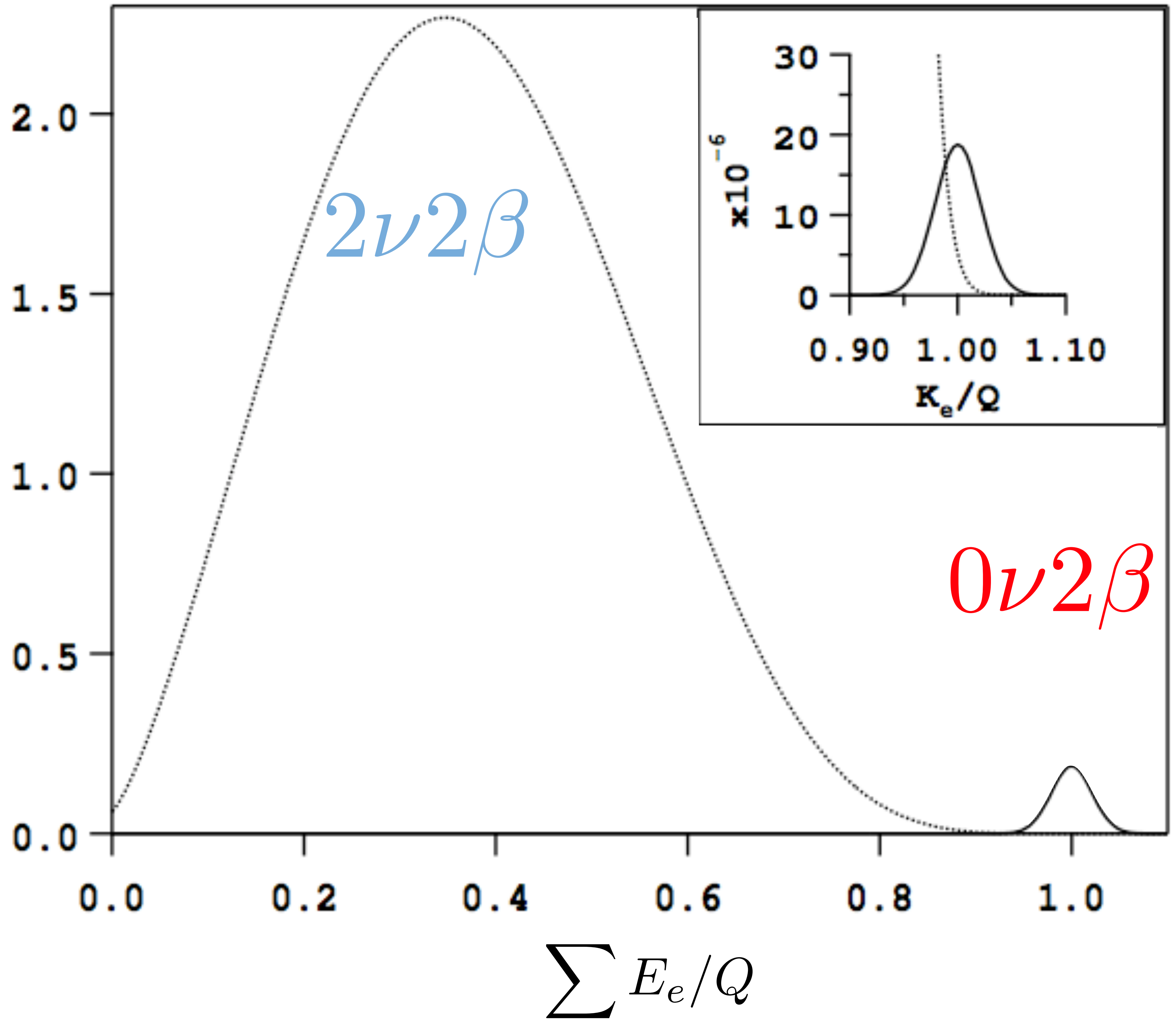
Detecting 0v2β Decay



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

Detecting 0ν2β Decay

With energy resolution



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

What mass does 0v2β measure?

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

Phase Space factor: Calculable

Nuclear Matrix Element: Hard to calculate

What mass does 0v2β measure?

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

Phase Space factor: Calculable

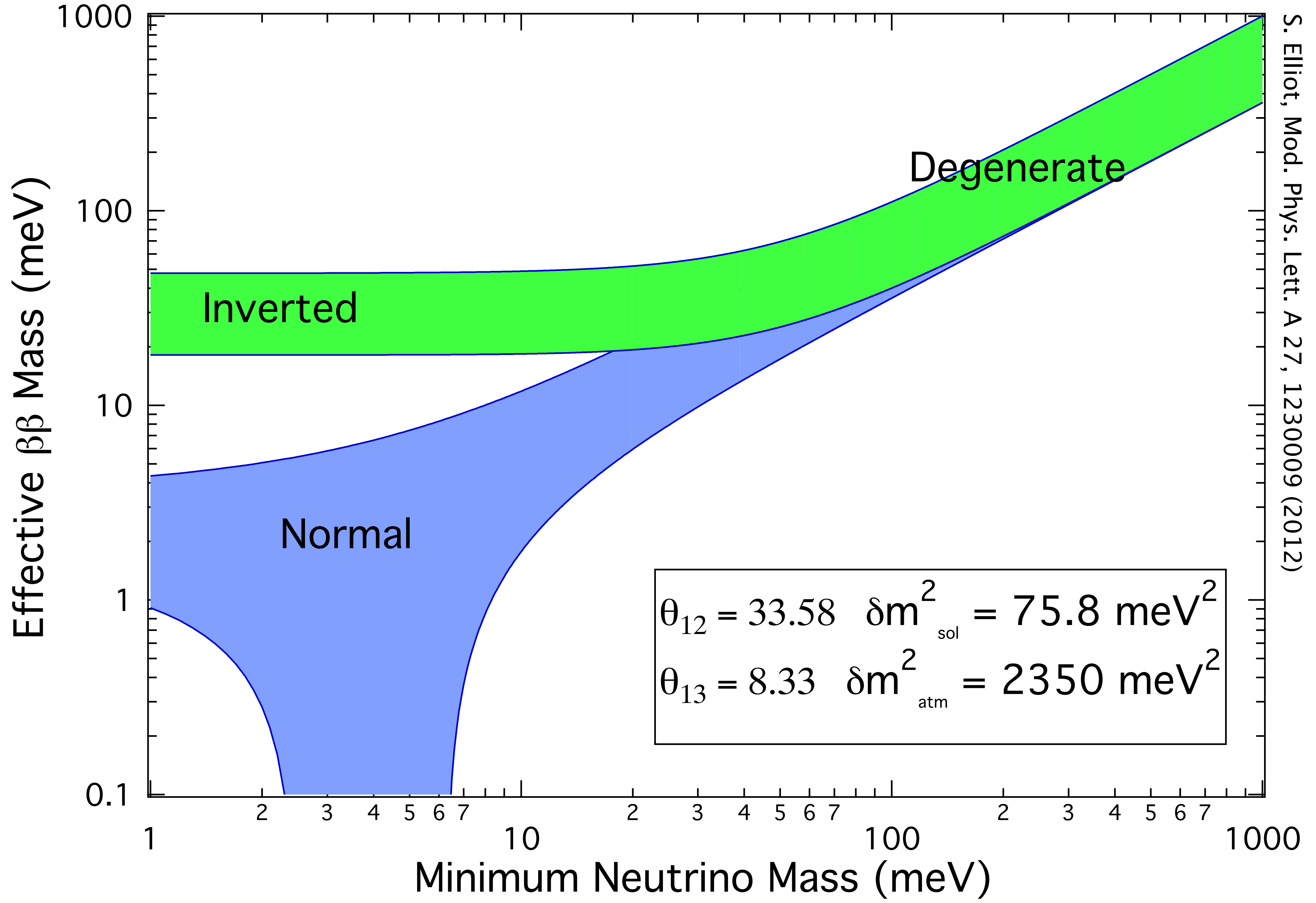
Nuclear Matrix Element: Hard to calculate

Interesting physics

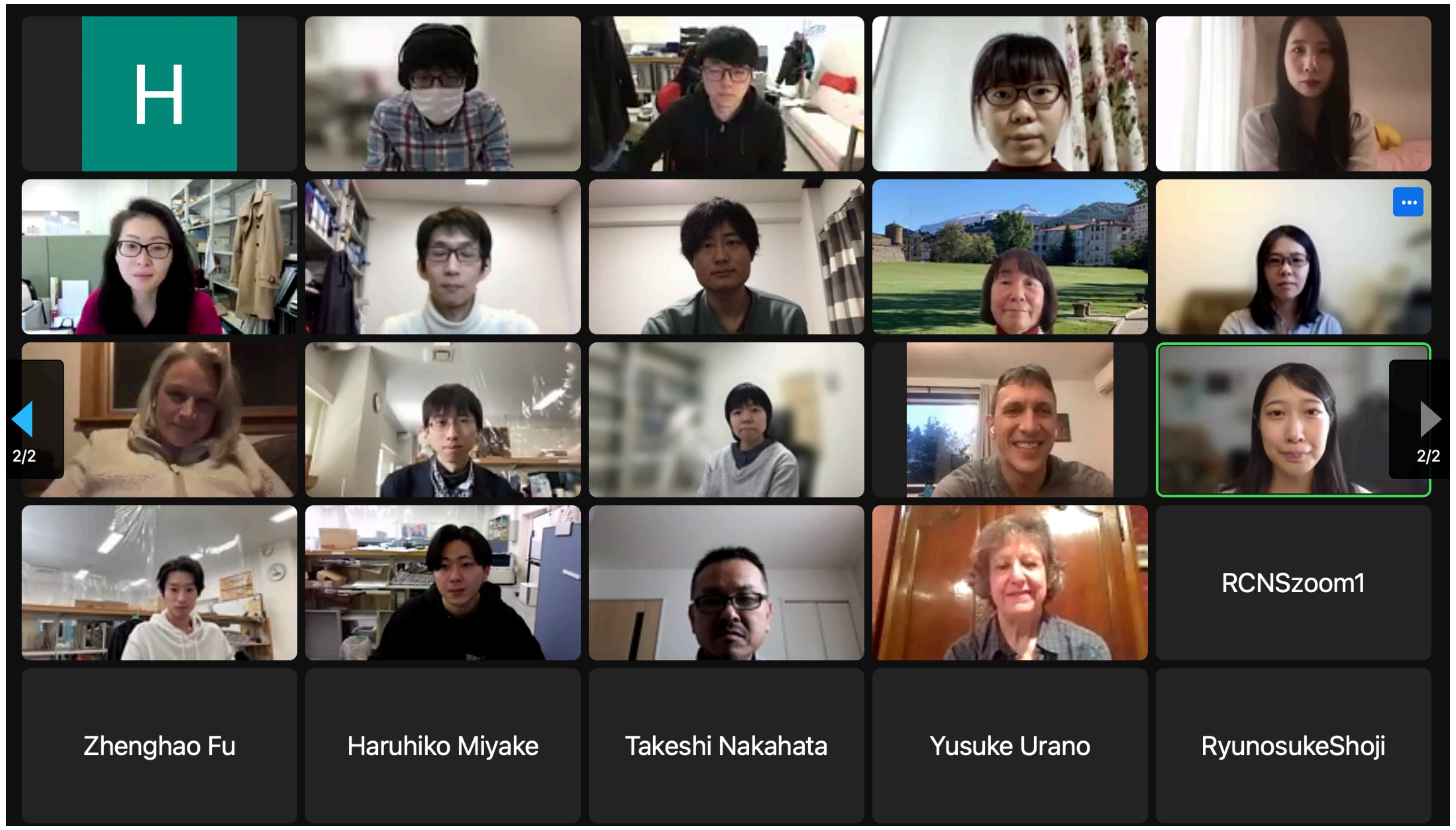
Effective Majorana mass: $\langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$ [coherent sum]

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

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

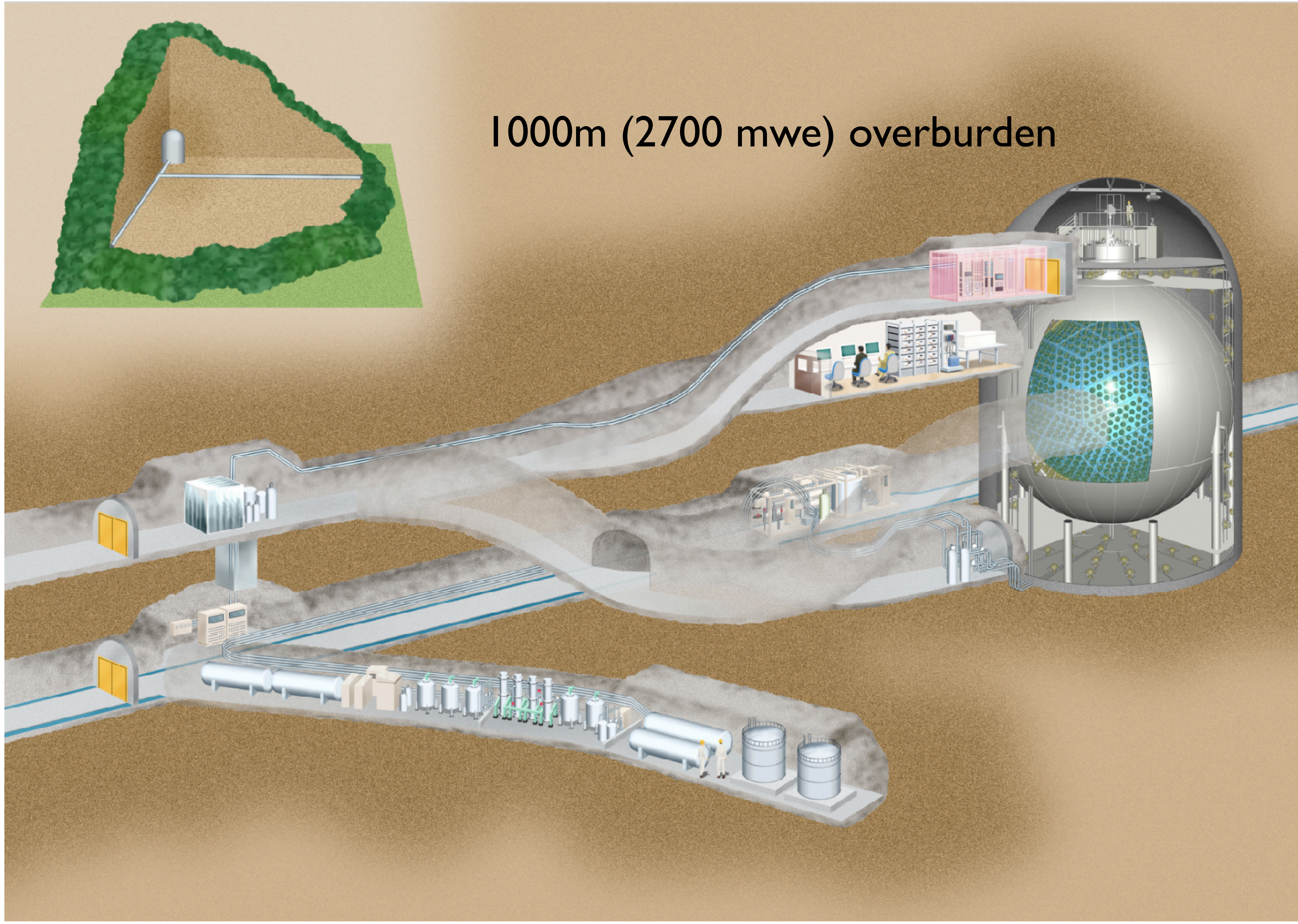


KamLAND-Zen Collaboration



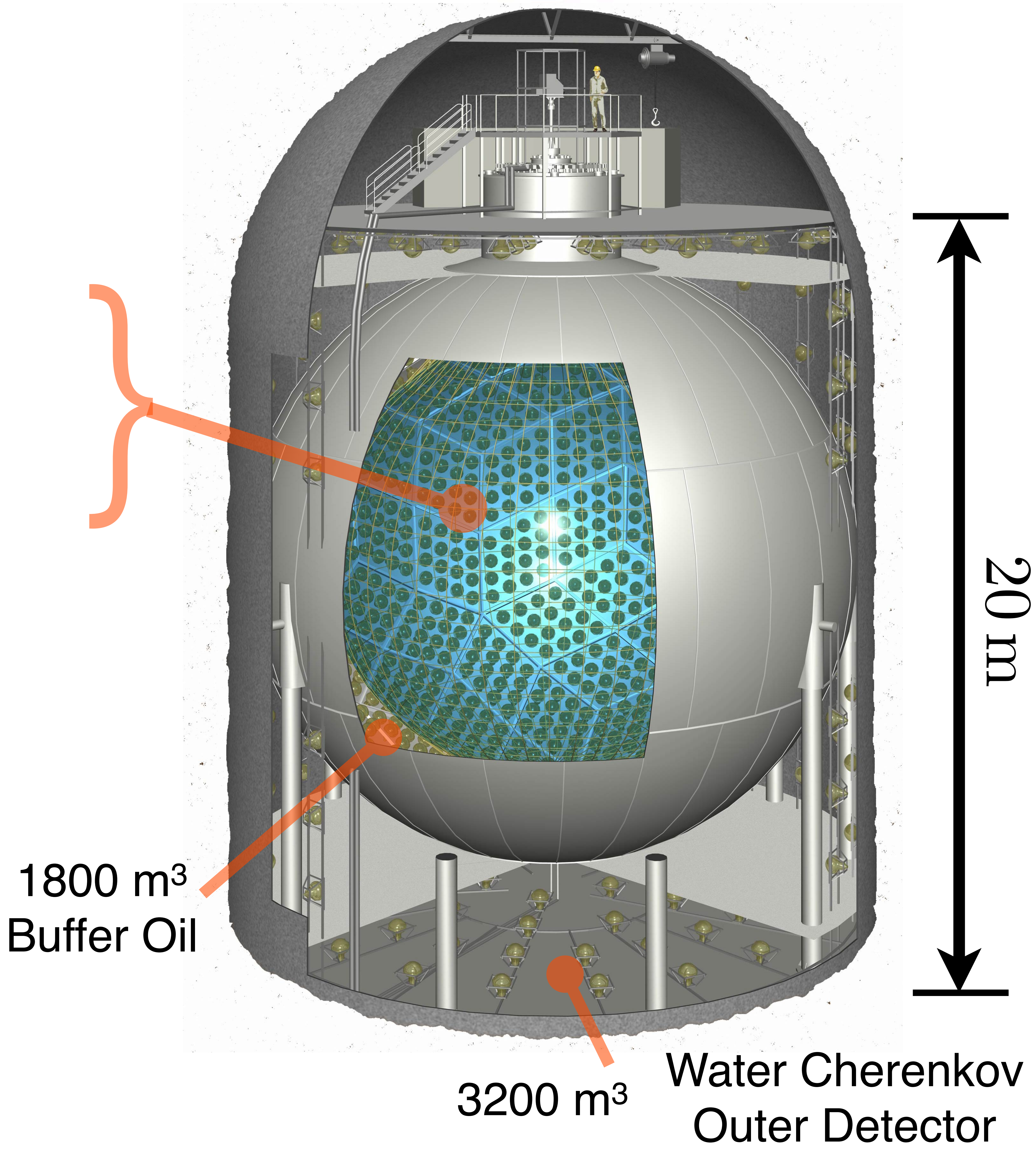
TOHOKU UNIVERSITY · 東京大学 THE UNIVERSITY OF TOKYO · 大阪大学 OSAKA UNIVERSITY · TOKUSHIMA UNIVERSITY · BERKELEY LAB · KYOTO UNIVERSITY · THE UNIVERSITY OF TENNESSEE KNOXVILLE · TUNL · VIRGINIA TECH · MIT · UNIVERSITY of HAWAI'I · BOSTON UNIVERSITY · Nikhef

KamLAND-Zen at Kamioka in Japan



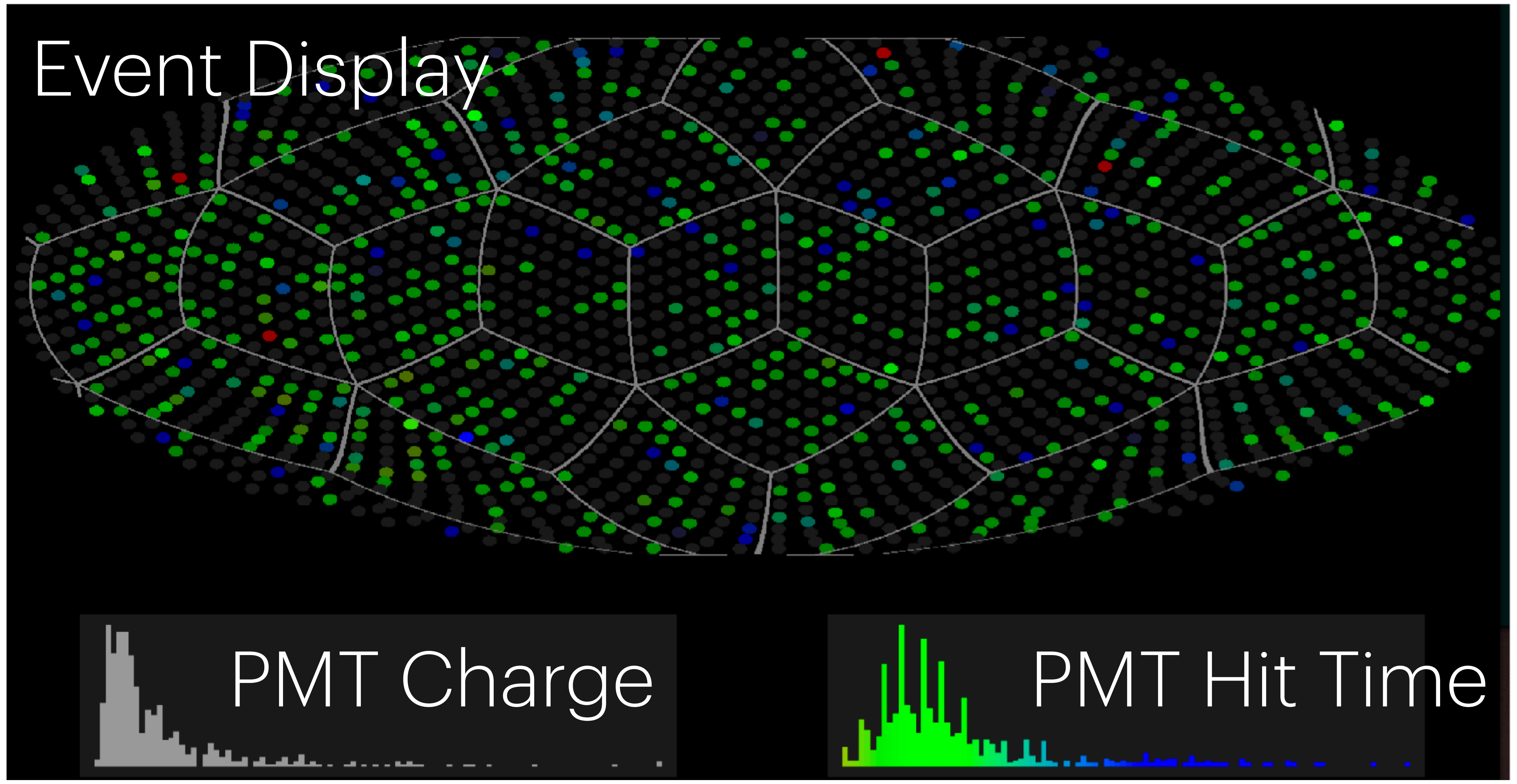
KamLAND(-Zen) detector

- 1 kton Scintillation 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

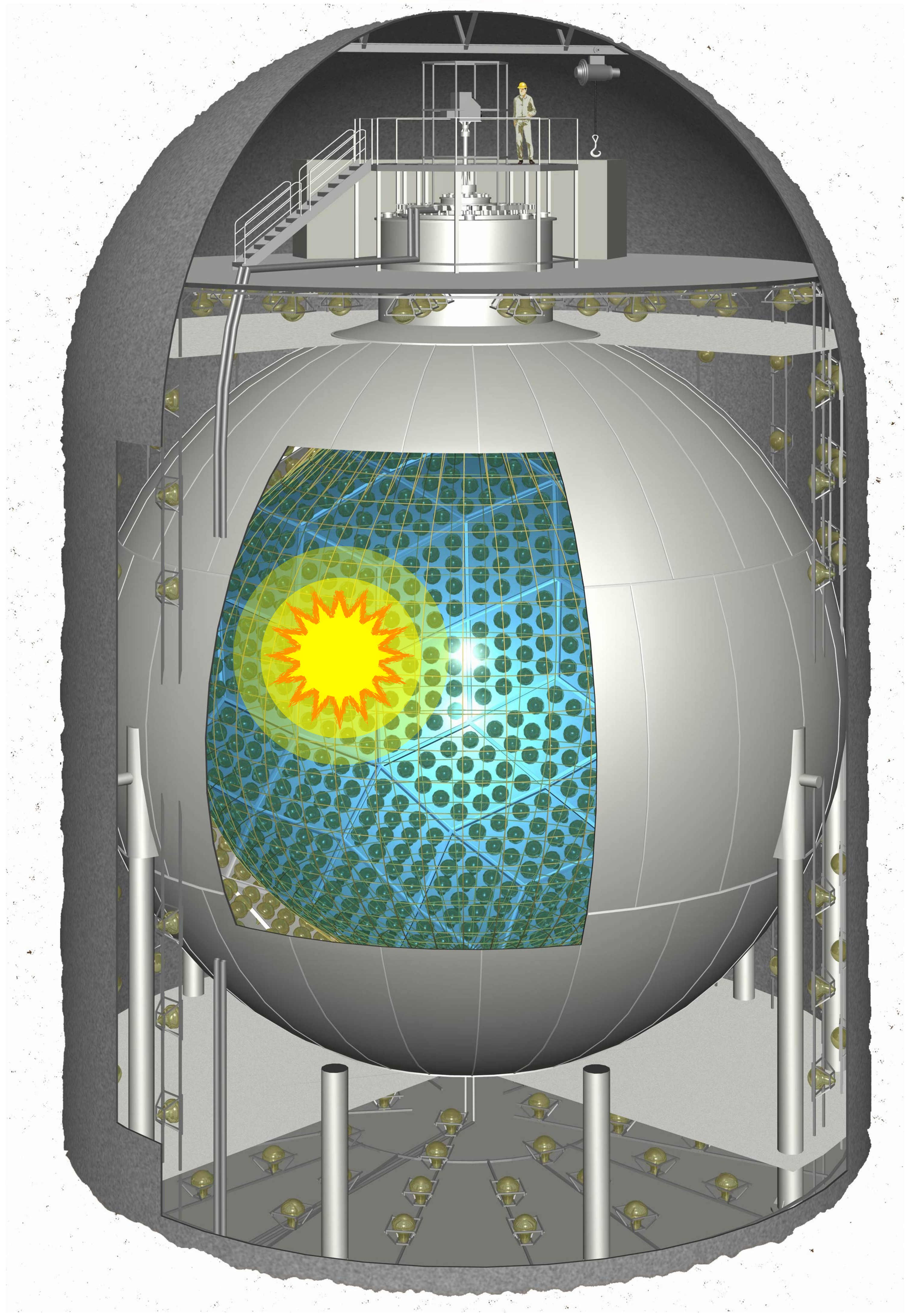


Energy reconstruction

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

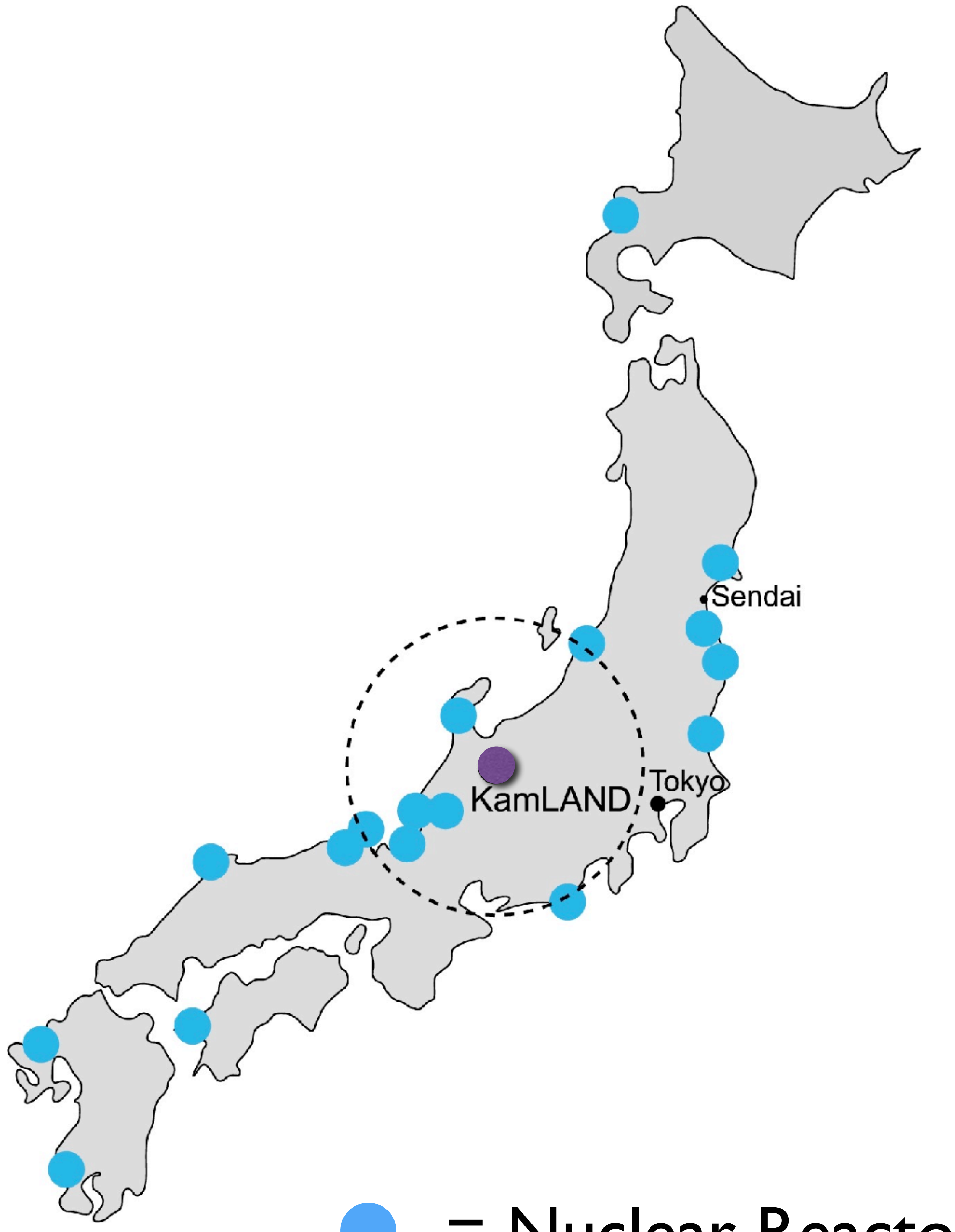
Position reconstruction

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



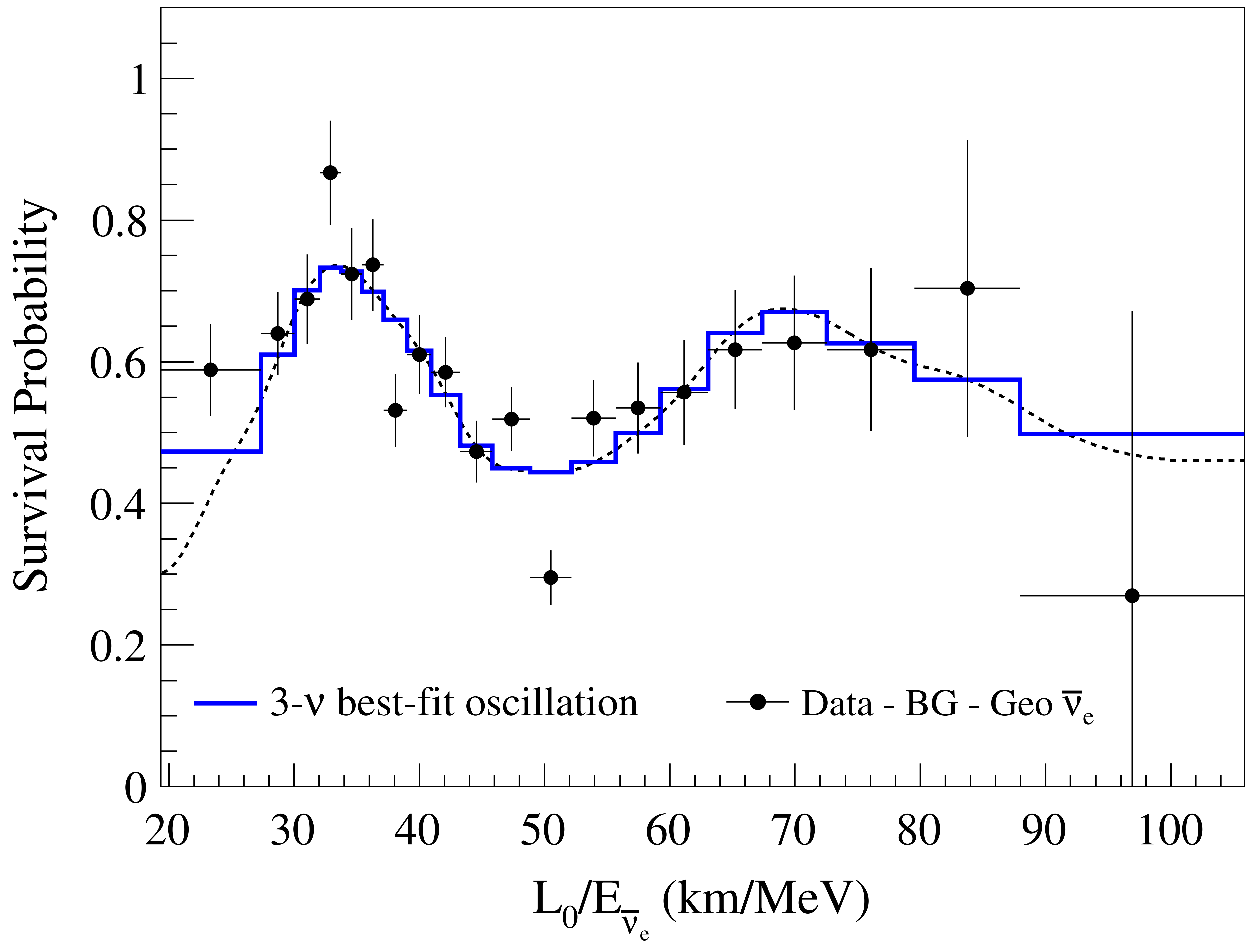
Neutrino Science with KamLAND

- KamLAND started taking data more than 20 years ago!
- Circa 2002, the primary goal was to measure neutrino oscillations using reactor antineutrinos.



= Nuclear Reactor

KamLAND, *Phys.Rev.D* 88 (2013) 3, 033001, arXiv:1303.4667



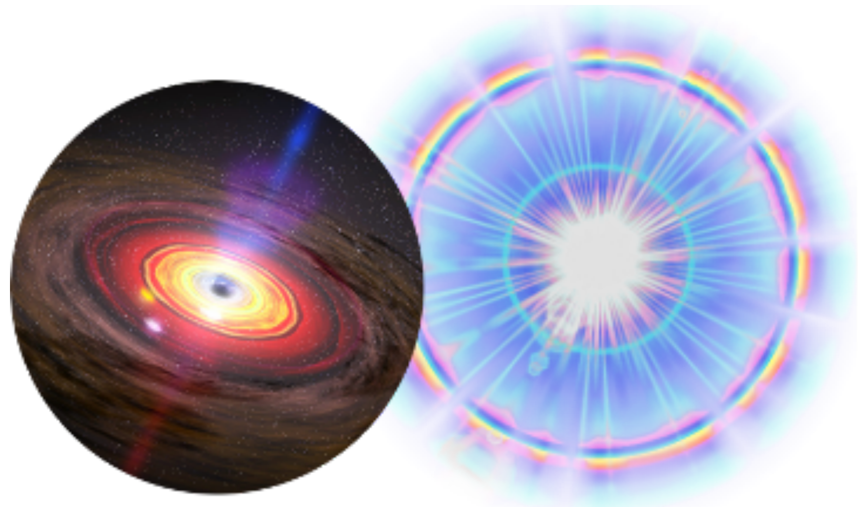
Direct observation of two full oscillation cycles
KamLAND determined that LMA-MSW was the solution to the solar neutrino problem.

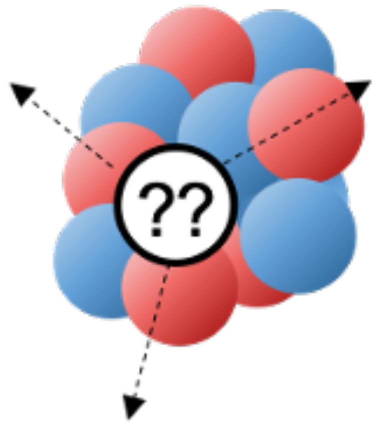
Neutrino Science with KamLAND

Highly versatile KamLAND detector allows for a broad science program…

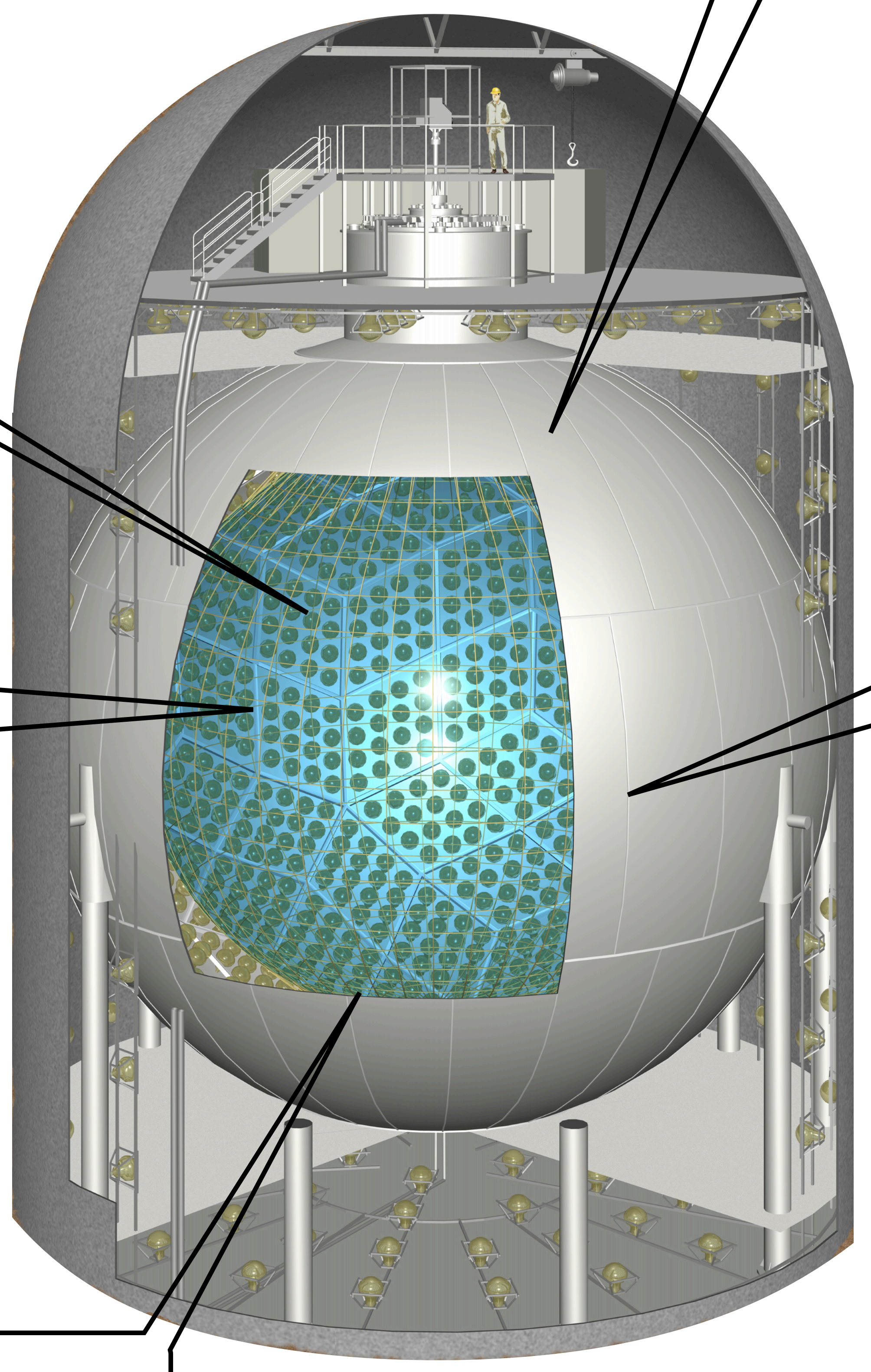
Solar Neutrinos

Astrophysical Neutrinos (Supernovae, GRBs, etc)

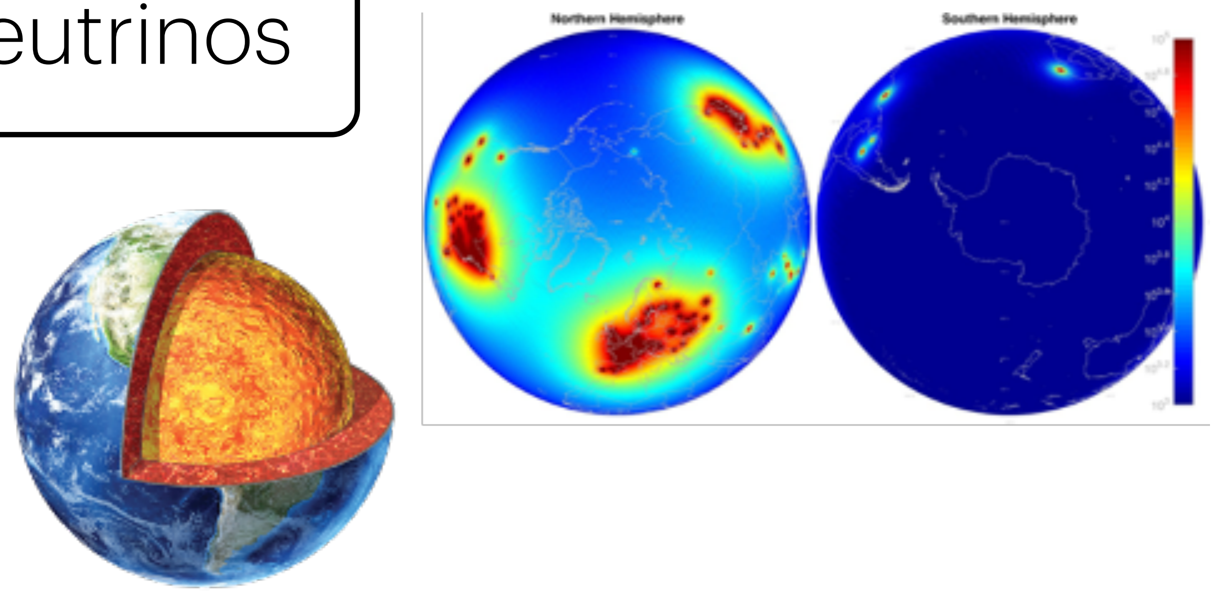




Nucleon Decay



Geo and Reactor Neutrinos



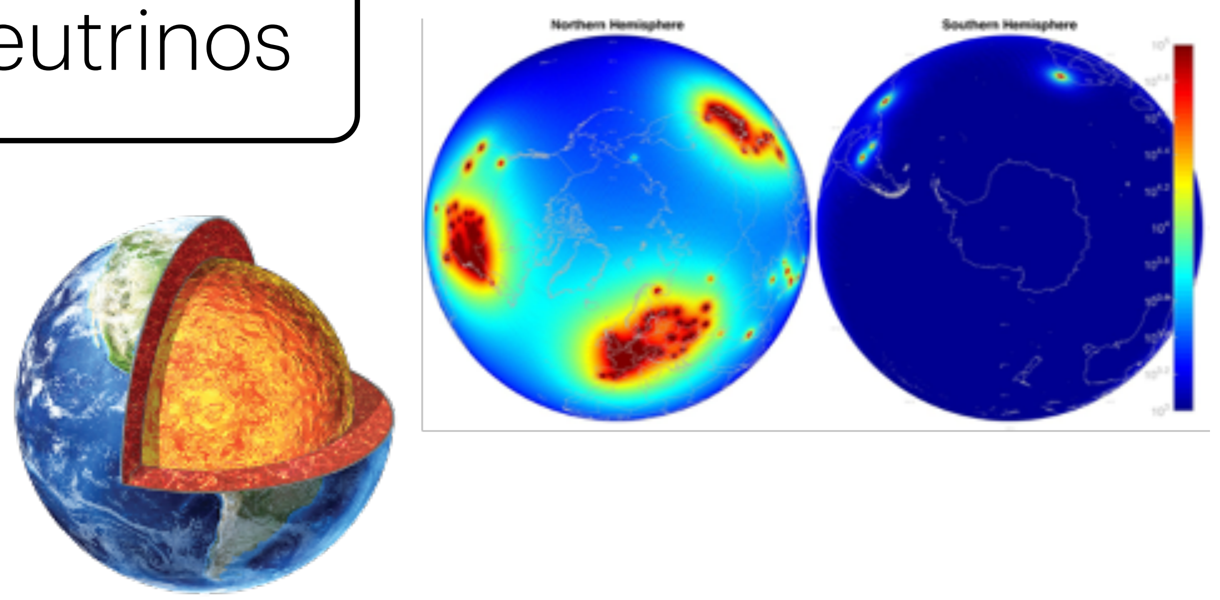
Accelerator Neutrinos

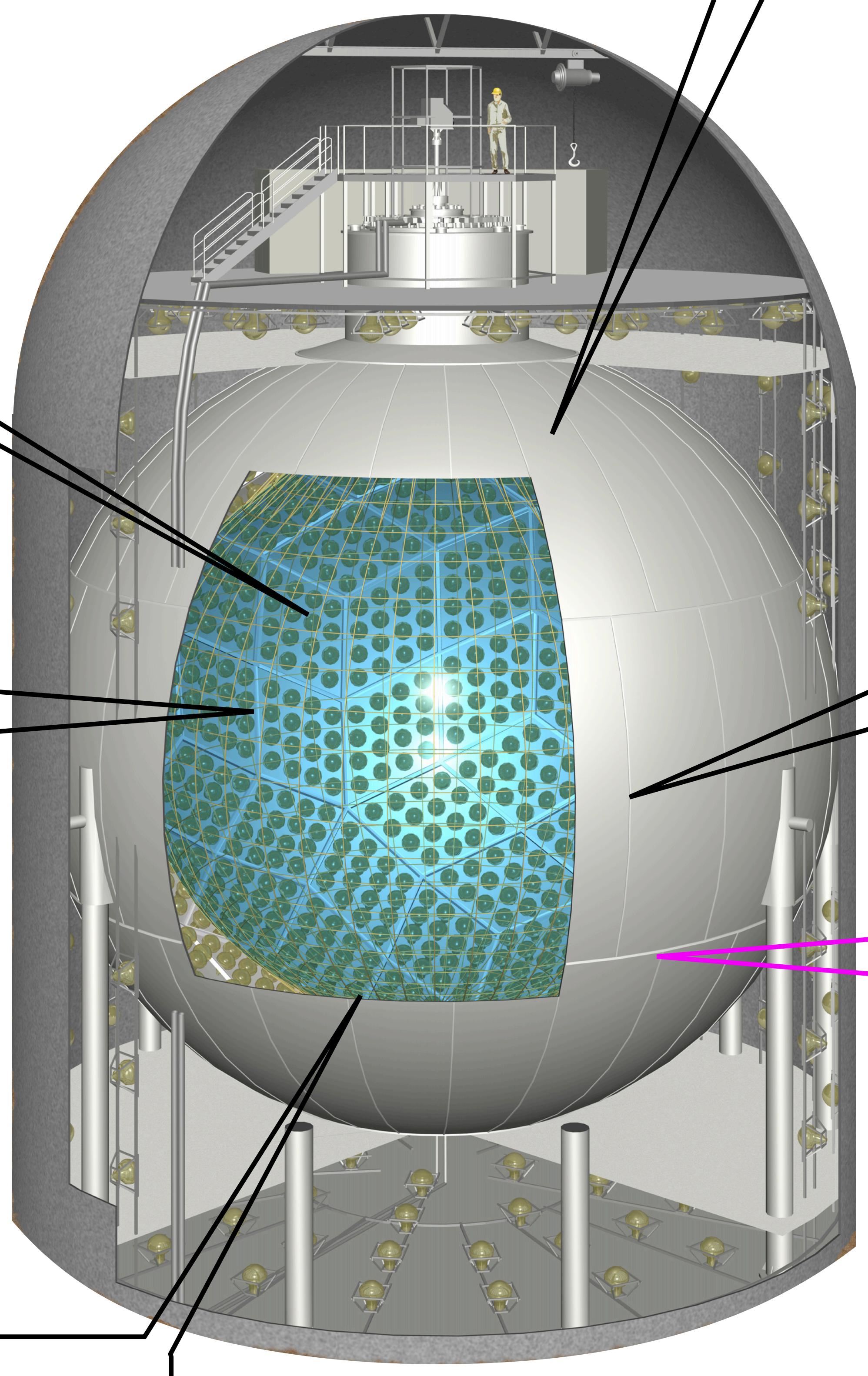
Neutrino Science with KamLAND

Highly versatile KamLAND detector allows for a broad science program…

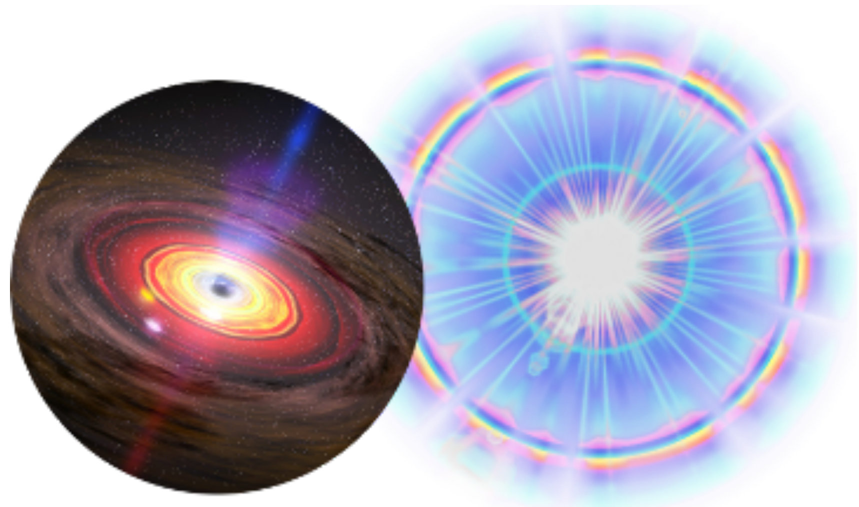
Solar Neutrinos

Geo and Reactor Neutrinos



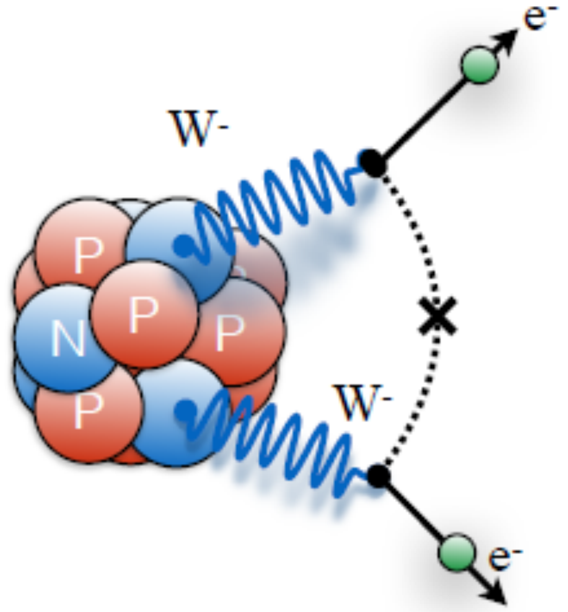


Astrophysical Neutrinos (Supernovae, GRBs, etc)

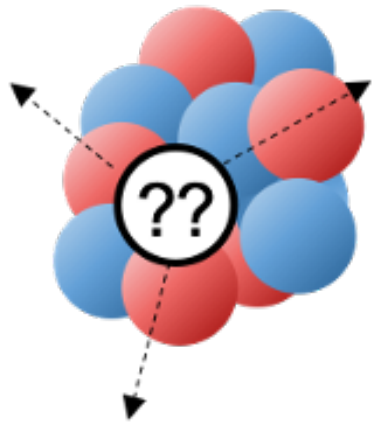


Accelerator Neutrinos

Neutrinoless Double-Beta Decay (0νββ)



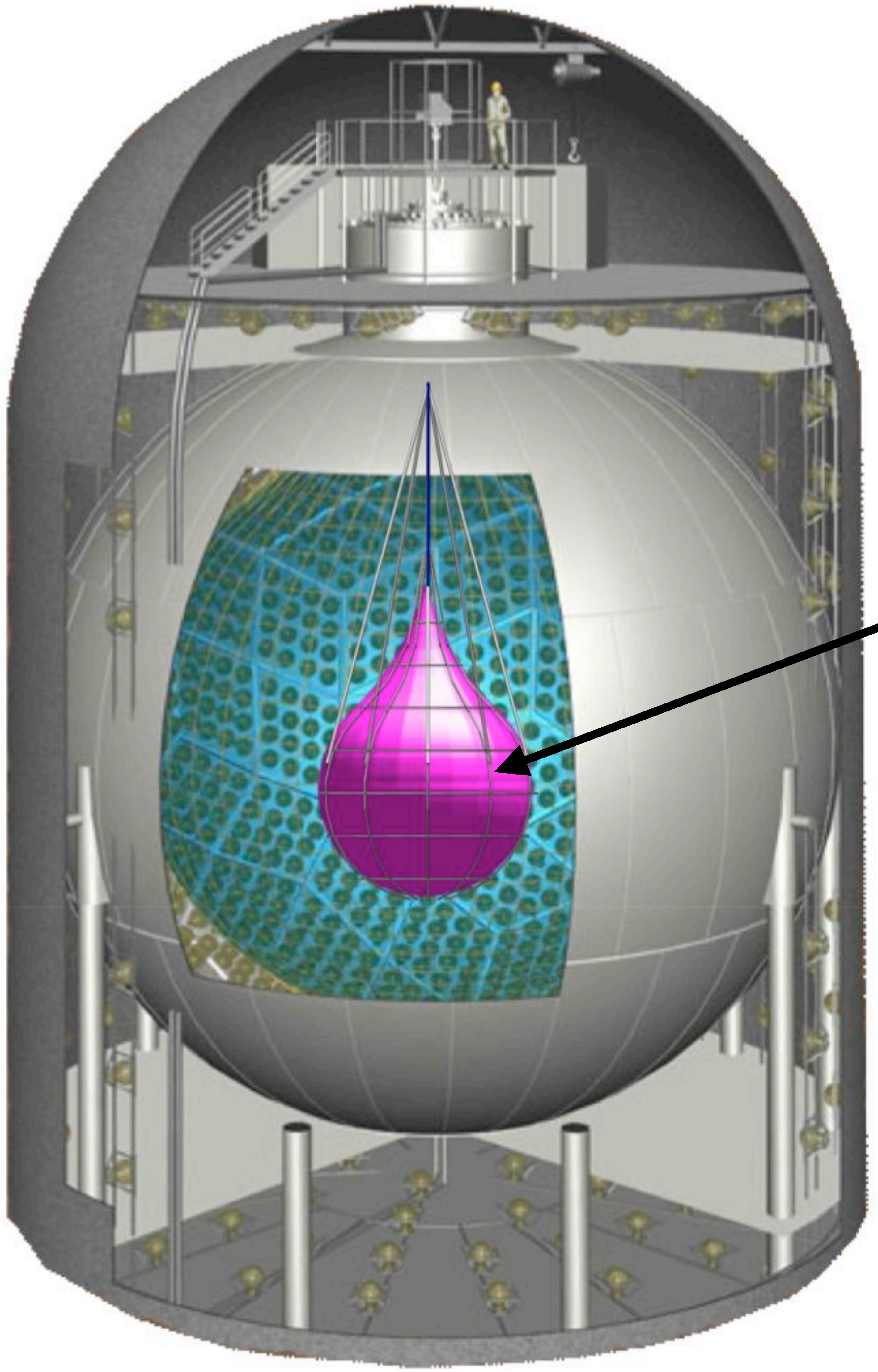
Nucleon Decay



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

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



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

KLZ 400 & KLZ 800

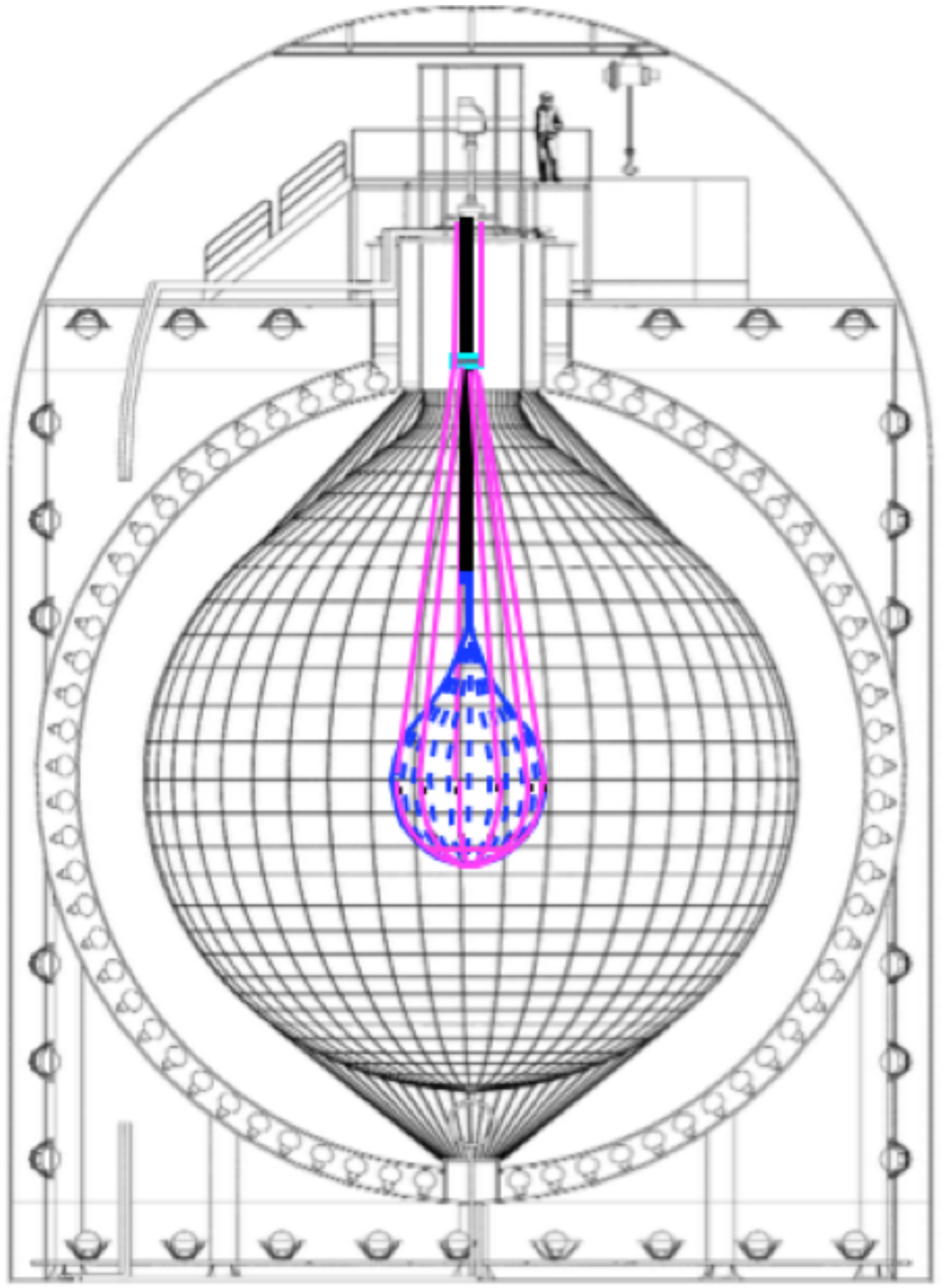
2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021

Phase I	No Xe	KLZ 400 - Phase II	No Xe	~~New balloon~~	No Xe	New balloon	KLZ 800
90 kg-yr	purification	504 kg-yr					Start Jan'19

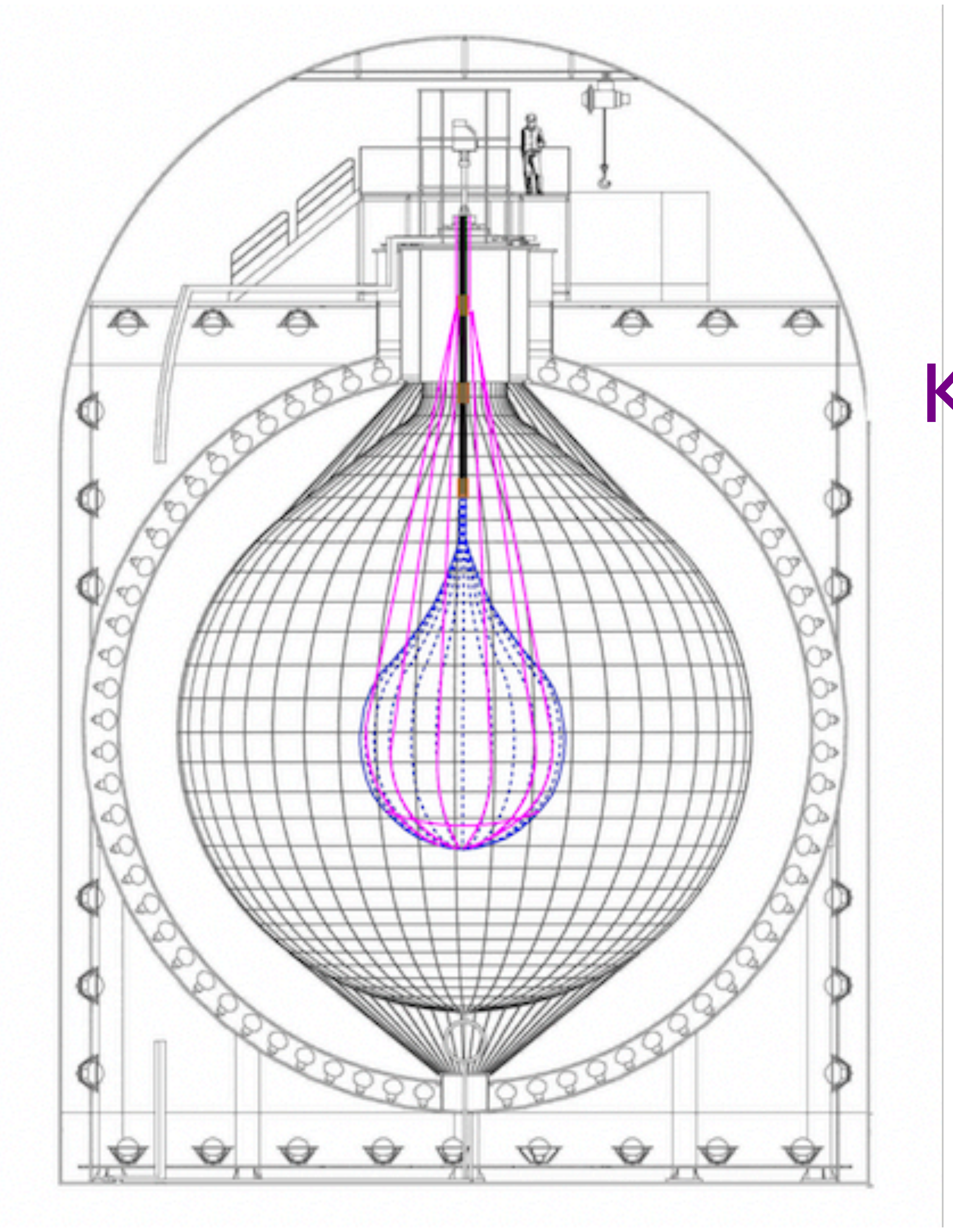
KamLAND-Zen 400

- Mini-balloon radius 1.54m
- 320 - 380kg ^{136}Xe
- 2011 - 2015

$T^{0\nu}_{1/2} > 1.07 \times 10^{26}$ yr



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

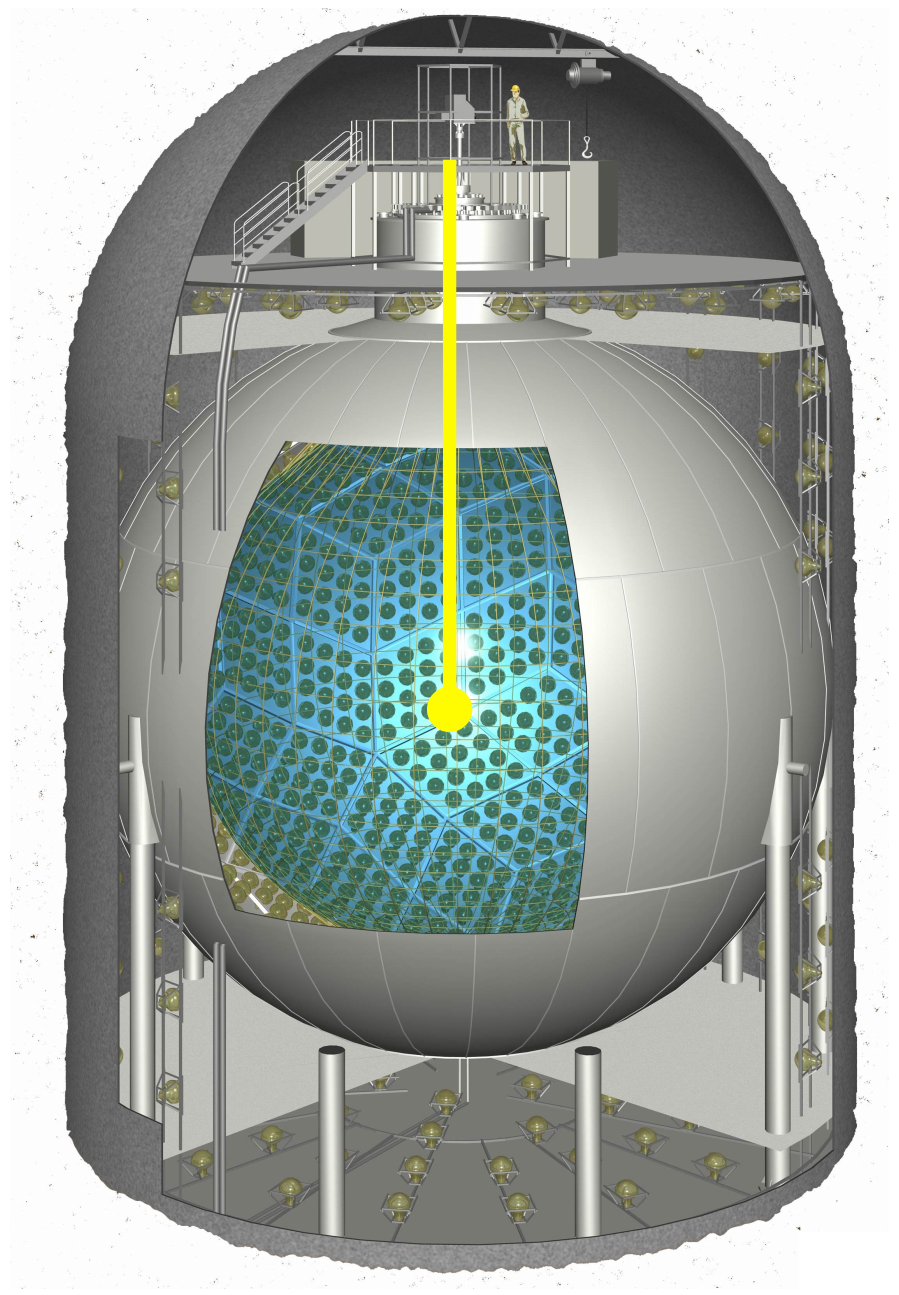


KamLAND-Zen 800

- Mini-balloon radius 1.90m
- 745kg ^{136}Xe
- Start Jan 2, 2019
- Dataset:
  Feb, 2019 - May 8, 2021

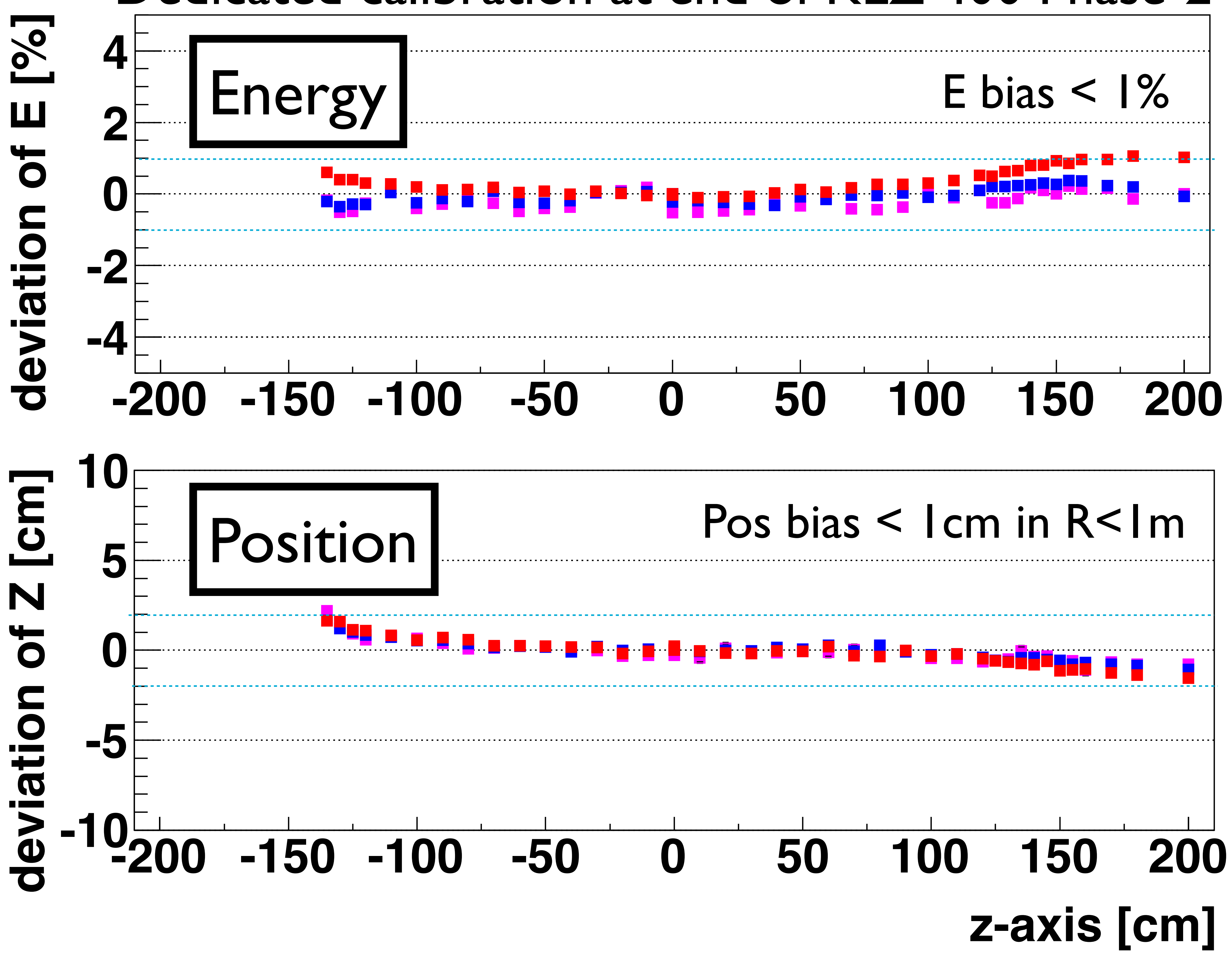
KamLAND-Zen Coll, Phys. Rev. Lett. 130, 051801 (2023), arXiv:2203.02139

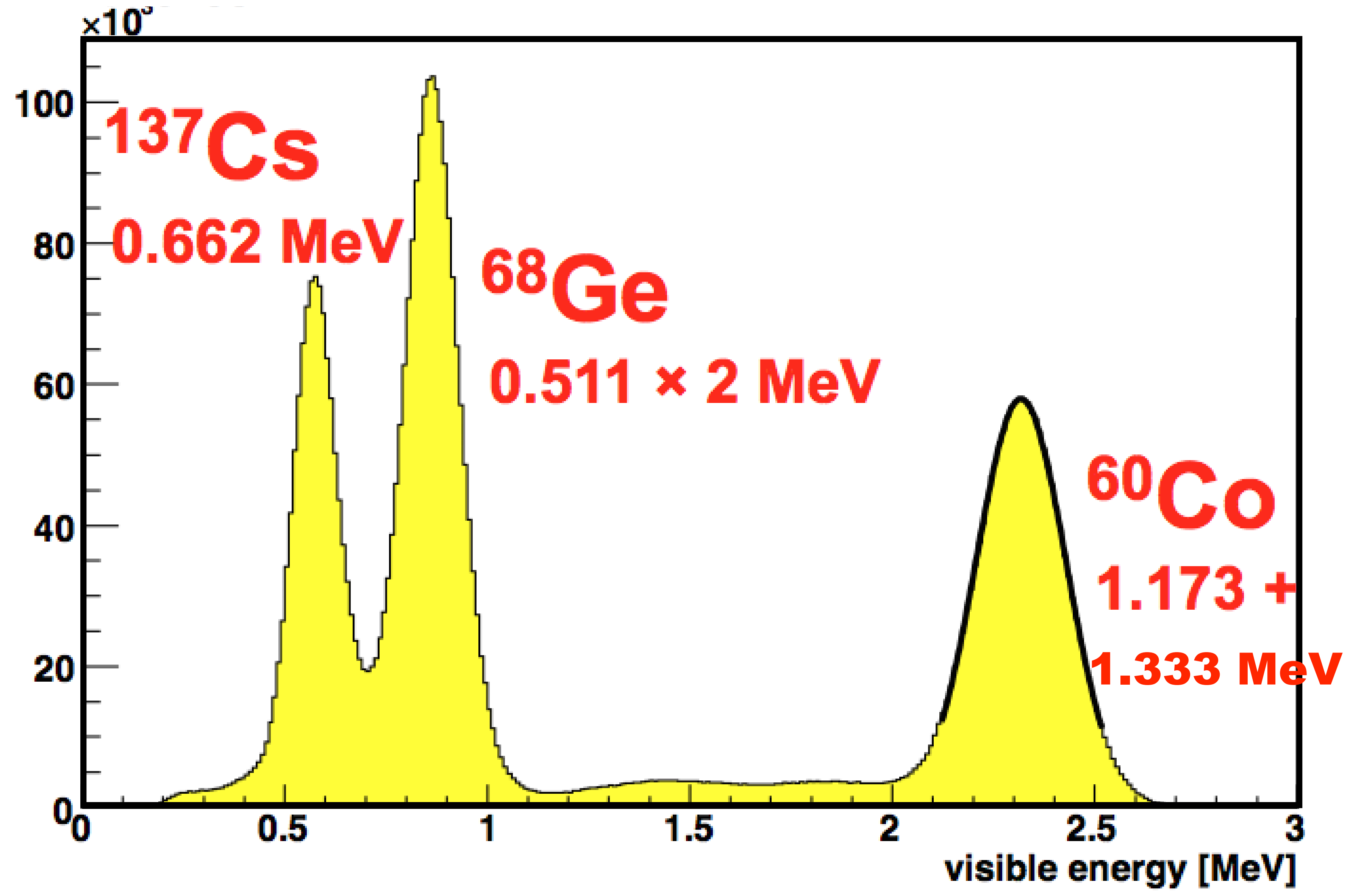
Position & Energy Calibration



KamLAND is well-understood. Previous reconstruction algorithms can be easily adapted

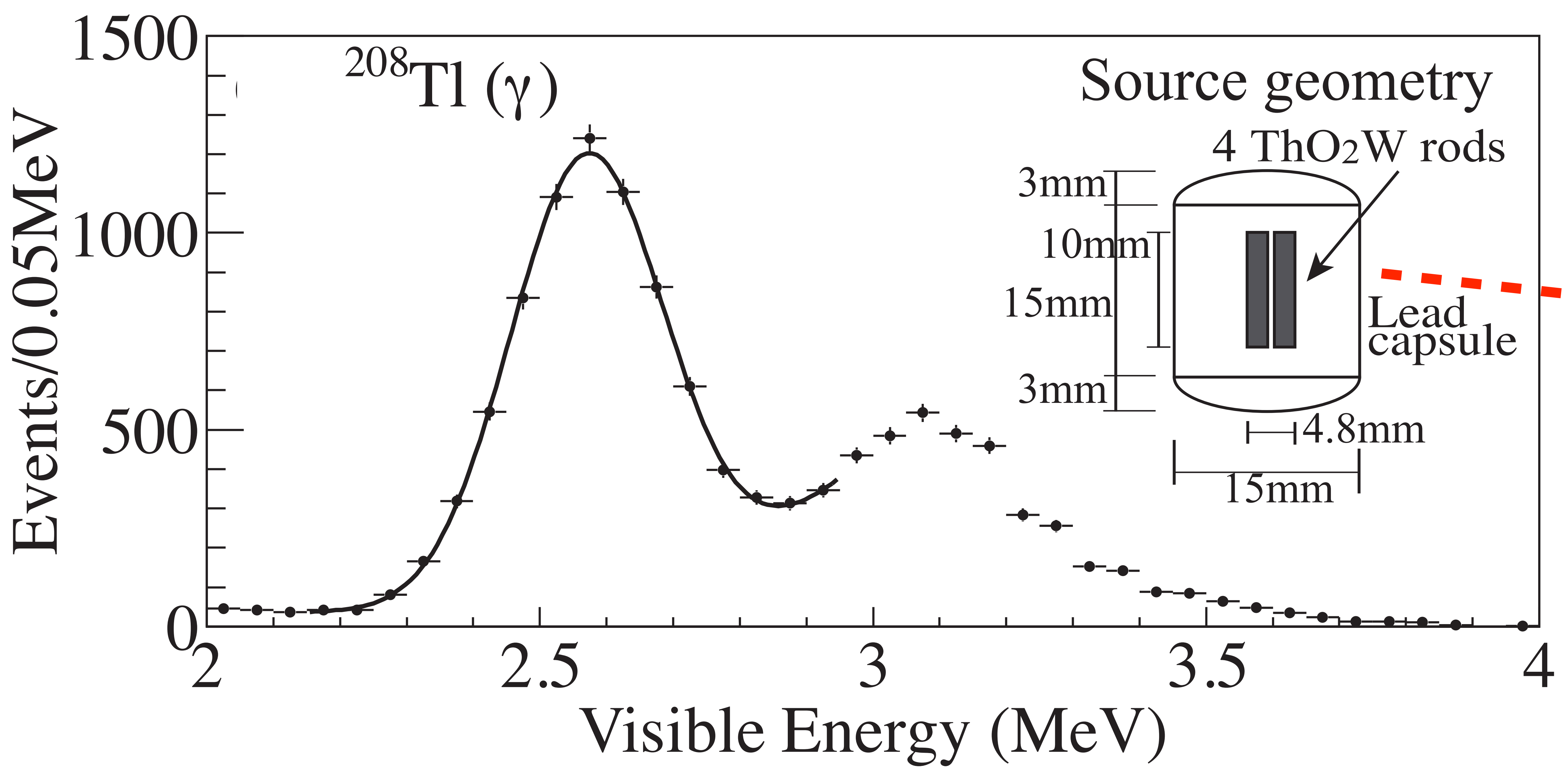
Dedicated calibration at end of KLZ 400 Phase-2

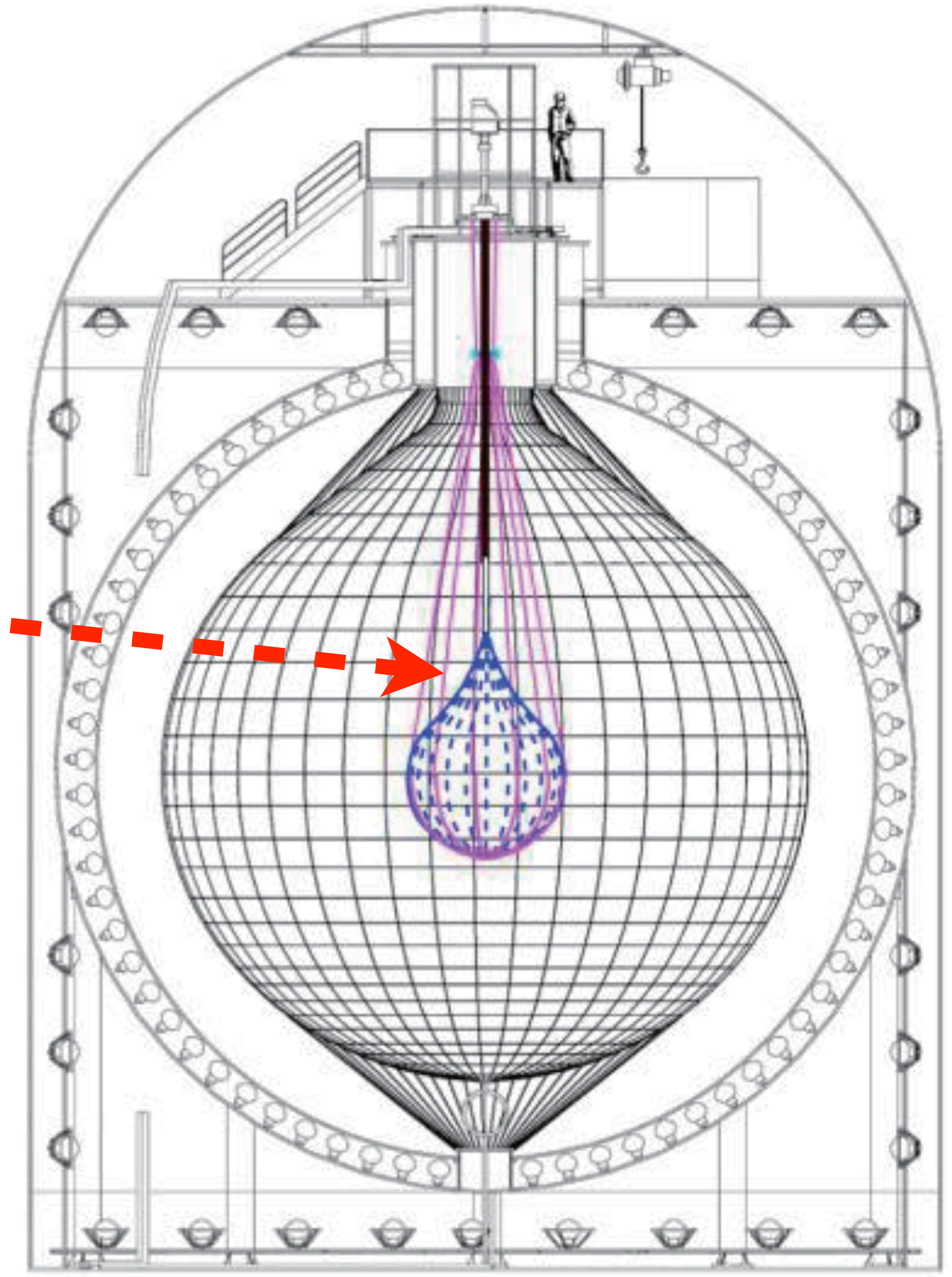




Calibration

External energy calibration





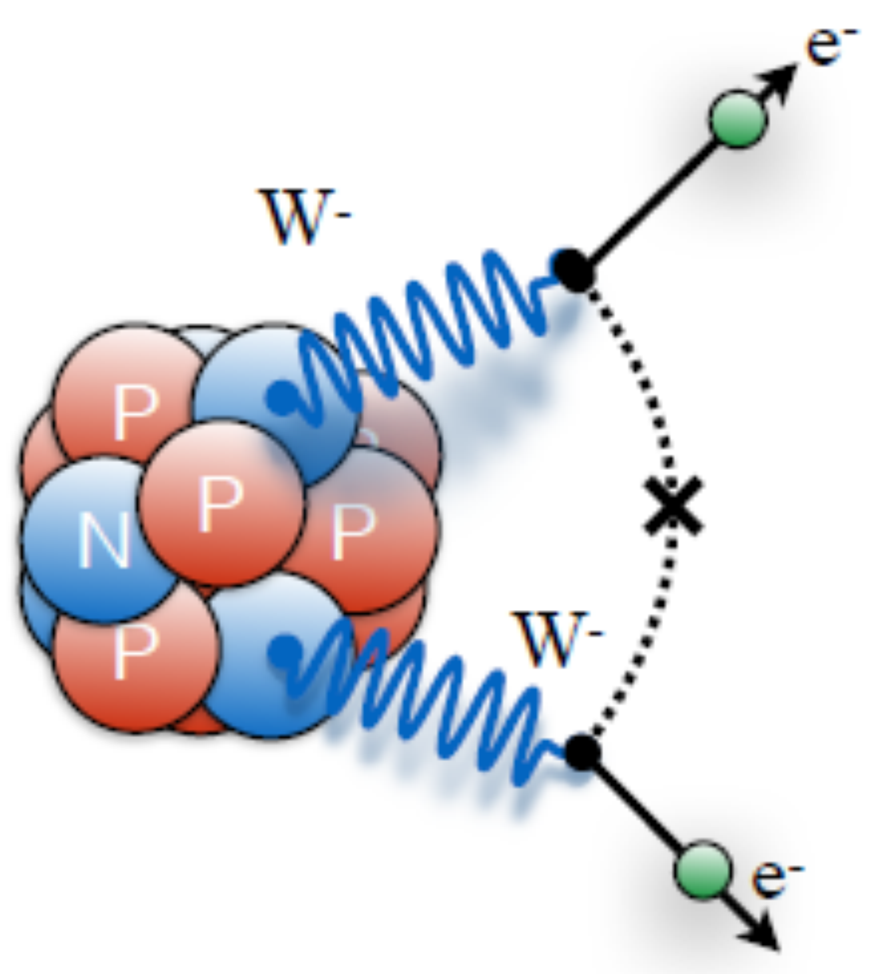
Internal calibration sources:

- 2ν2β
- tagged ^{214}BiPo
- ^{222}Rn during filling
- 2.225 MeV neutron capture γ

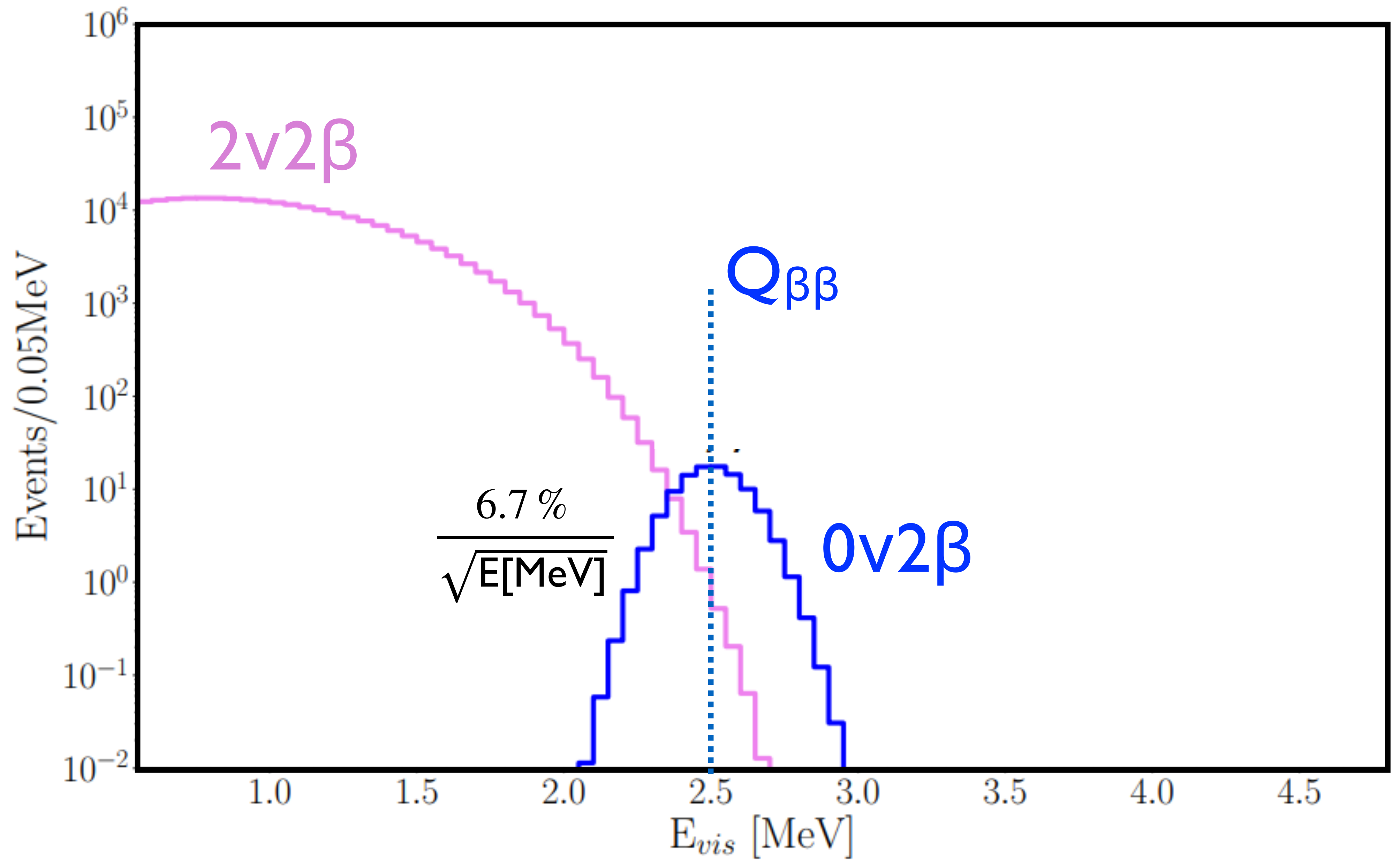
Outer-LS 10% brighter than Xe-LS

σ_P = 13.7cm /√E(MeV)
σ_E = 6.7% / √E(MeV)

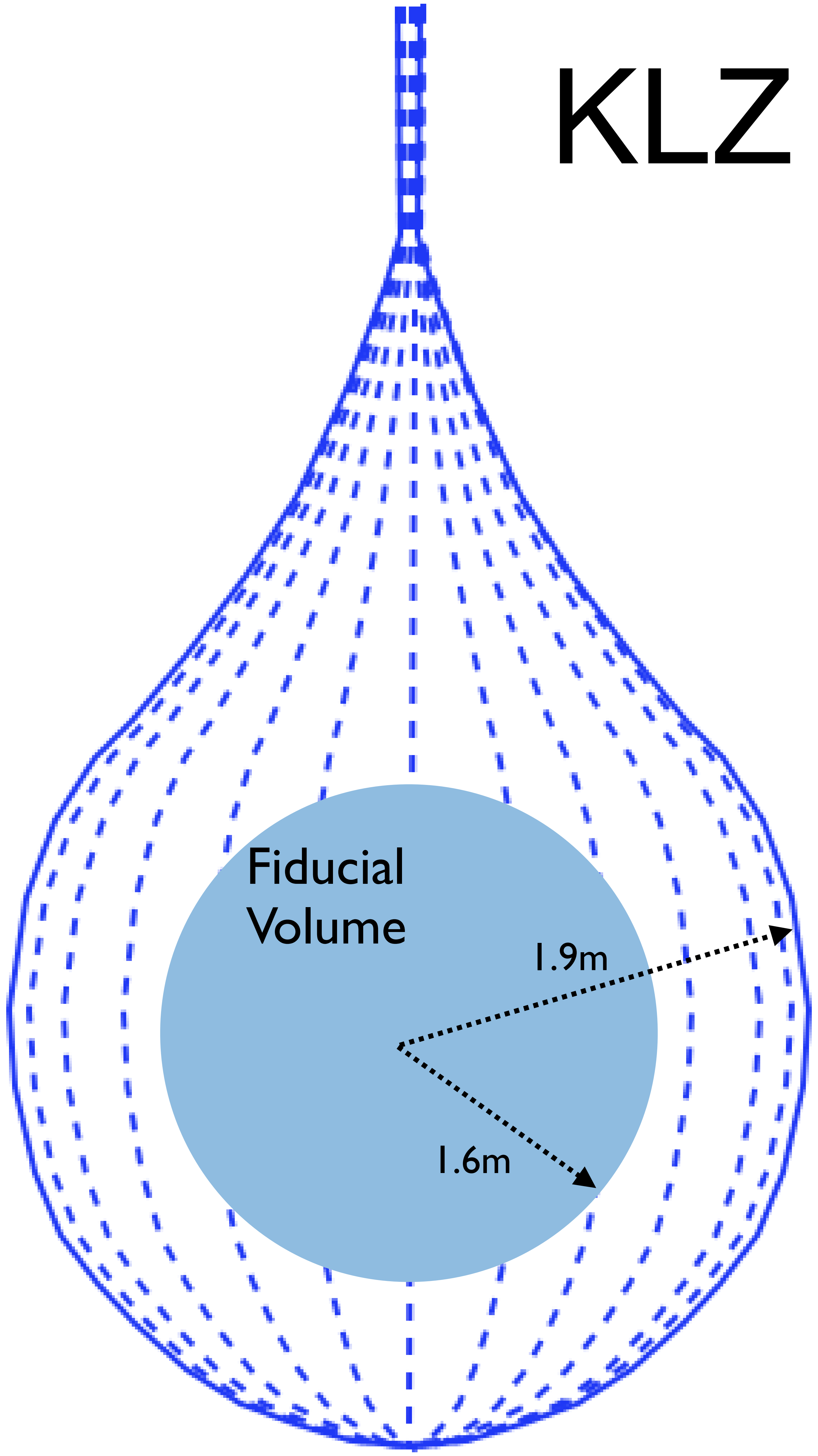
Signals and Backgrounds



- For ^{136}Xe $Q_{\beta\beta}$ = 2.458 MeV
  - Define Region of Interest (ROI) between 2.35-2.70 MeV
- Primary Backgrounds:
  - 2ν2β decays
  - Solar neutrinos
  - Radioactive contamination
  - Cosmic muon spallation
- Also refer backgrounds to their location
  - **Xe-LS background** originates in the Xe loaded LS
  - **Film background** originates on mini-balloon surface

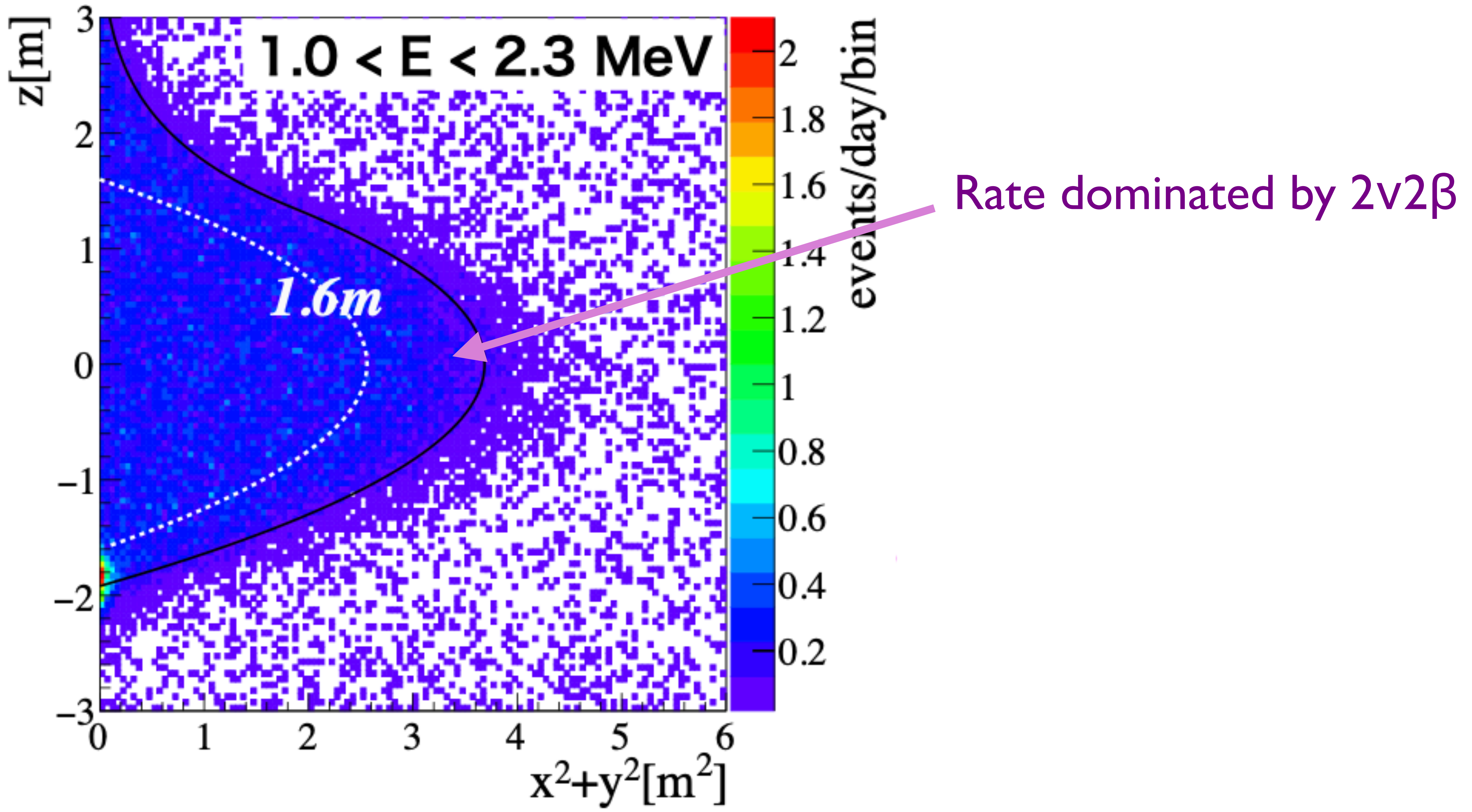


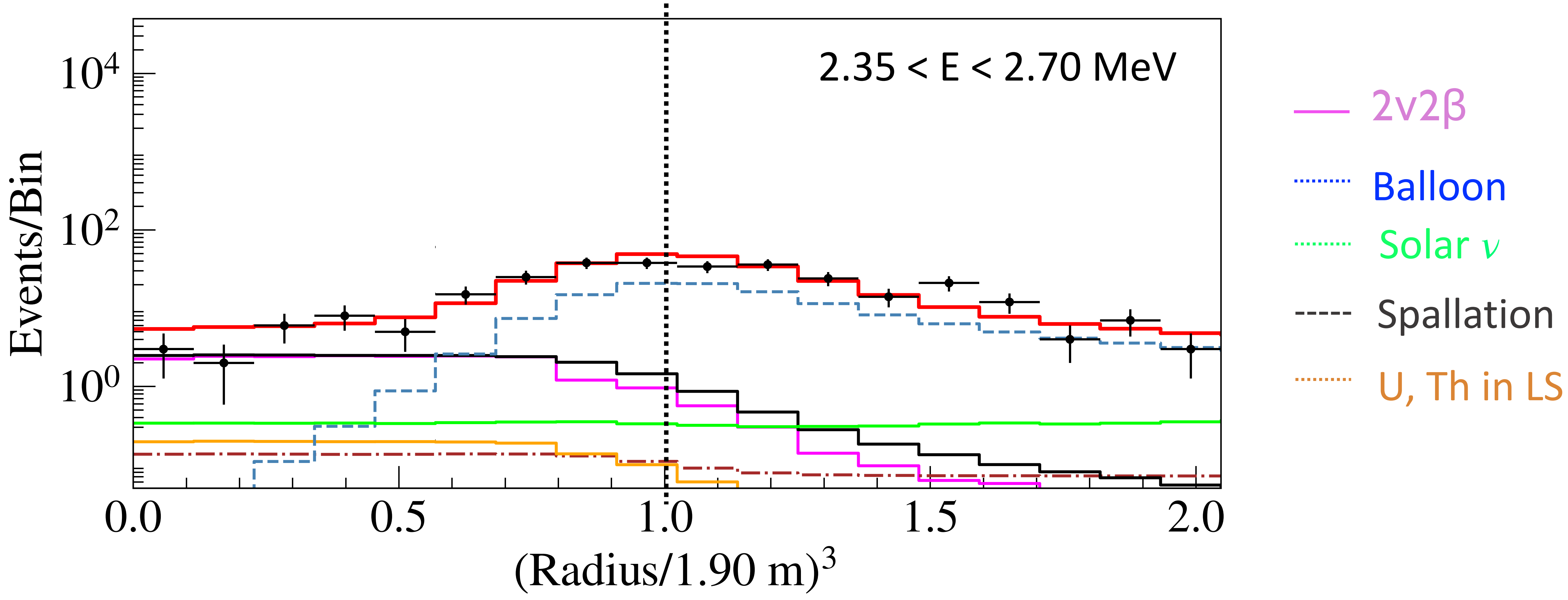
KLZ 800 Mini-Ballon Backgrounds



Balloon film backgrounds:
$^{238}U \sim 3 \times 10^{-12}$ g/g
$^{232}Th \sim 4 \times 10^{-11}$ g/g

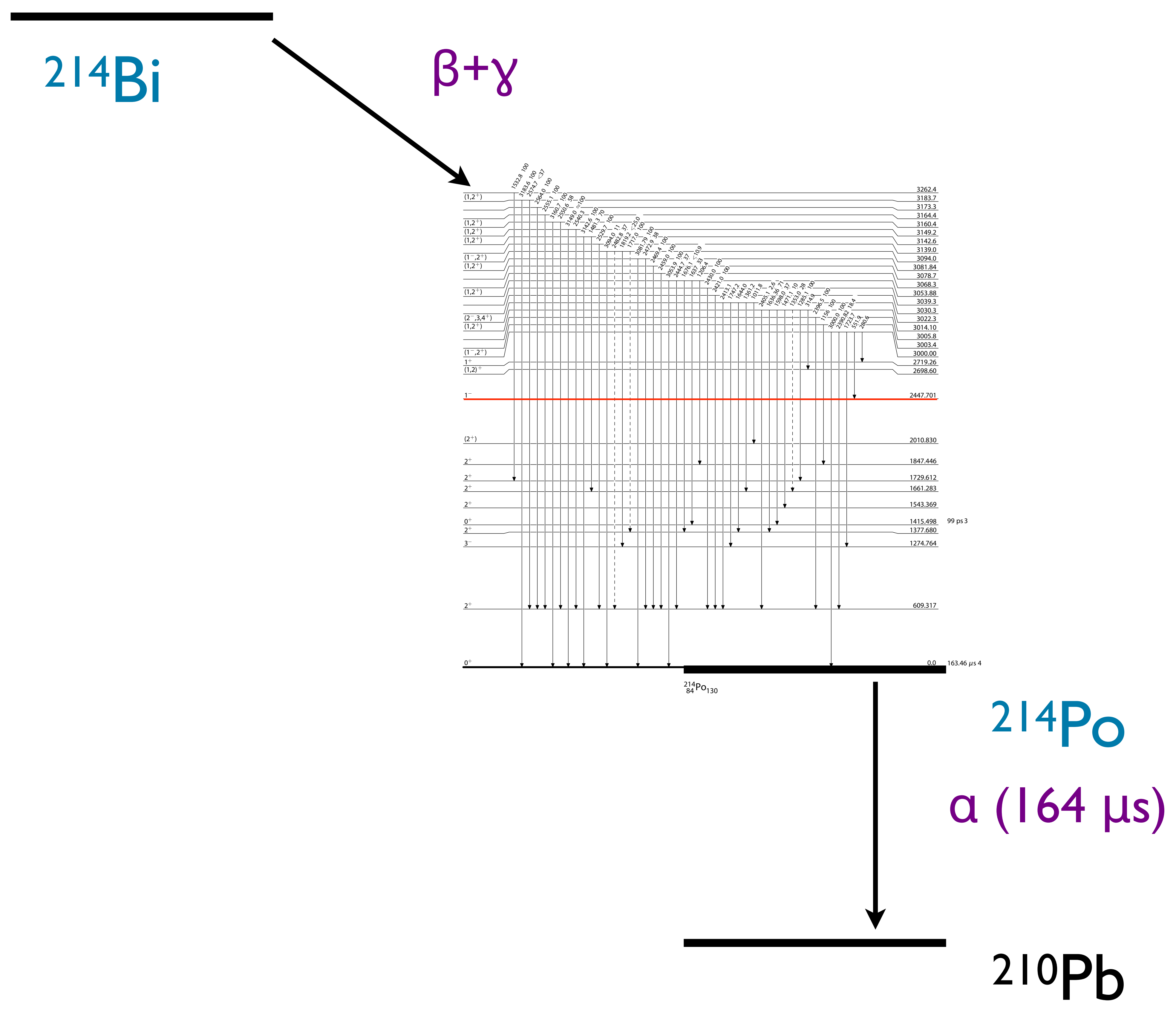
10x reduction compared to KLZ 400 IB





^{214}Bi Background

^{214}Bi is a core BG with a ɣ-line at 2.448 MeV while $Q_{\beta\beta}$ = 2.458 MeV

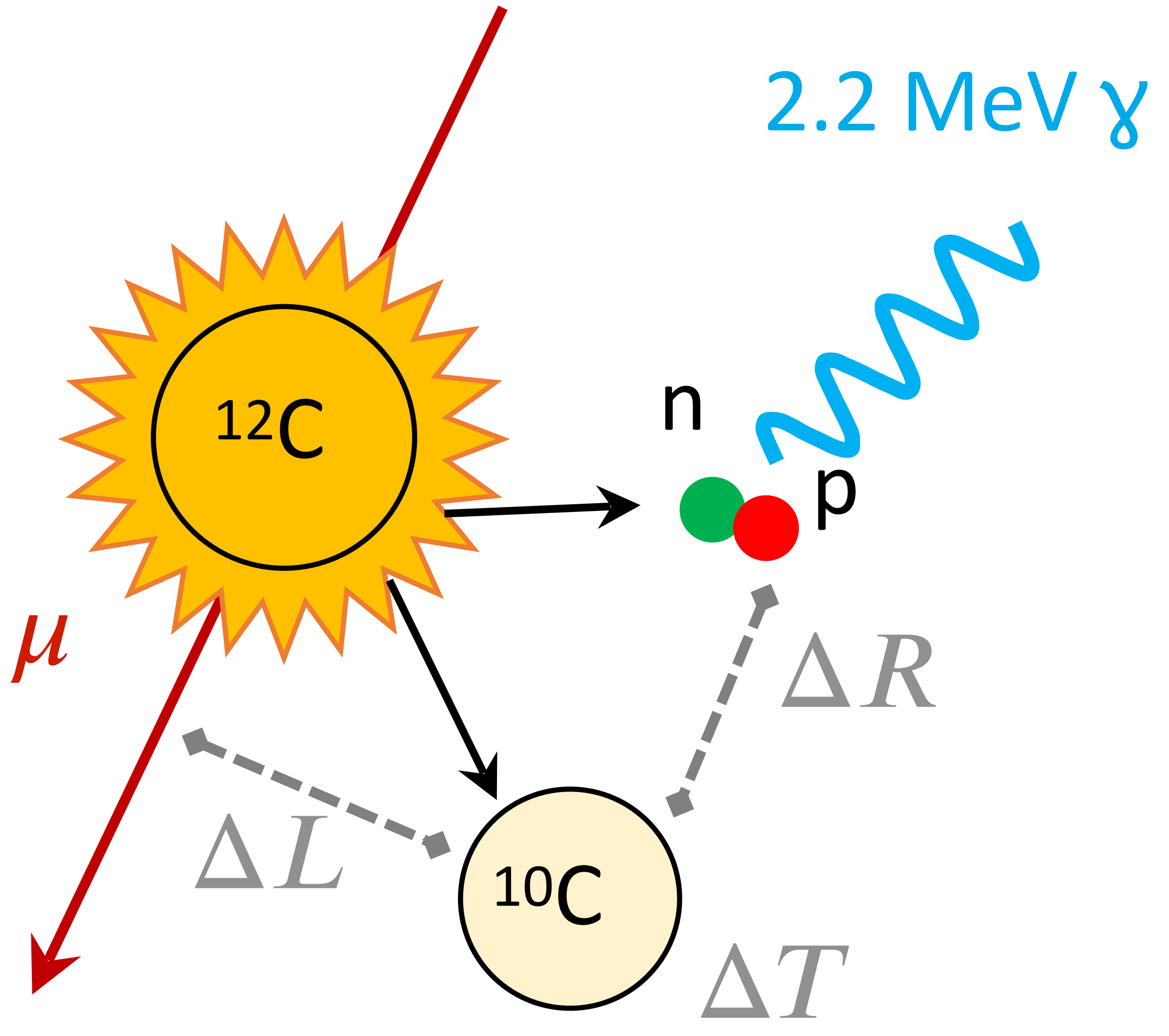


GEANT4 based MC with ^{214}Bi β+ɣ cascade, particle tracking, energy deposit, scintillation photon emission / propagation

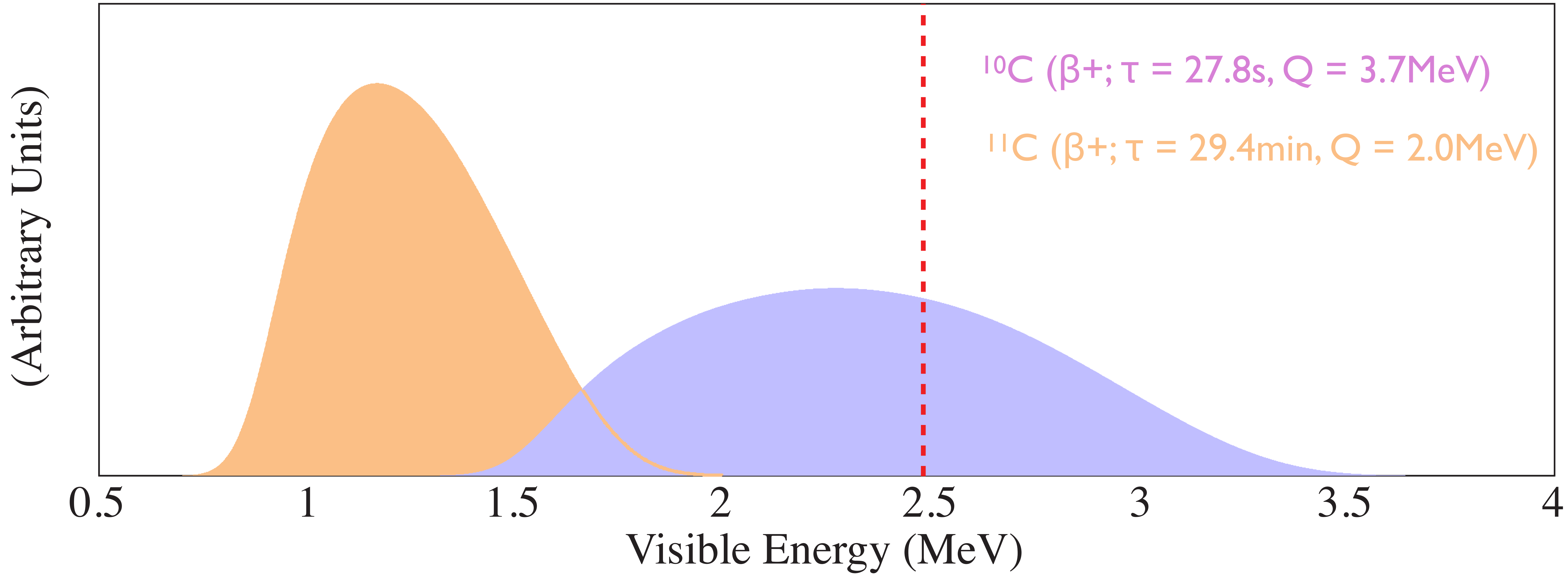
Muon Spallation

Carbon-based liquid scintillator produces muon 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%

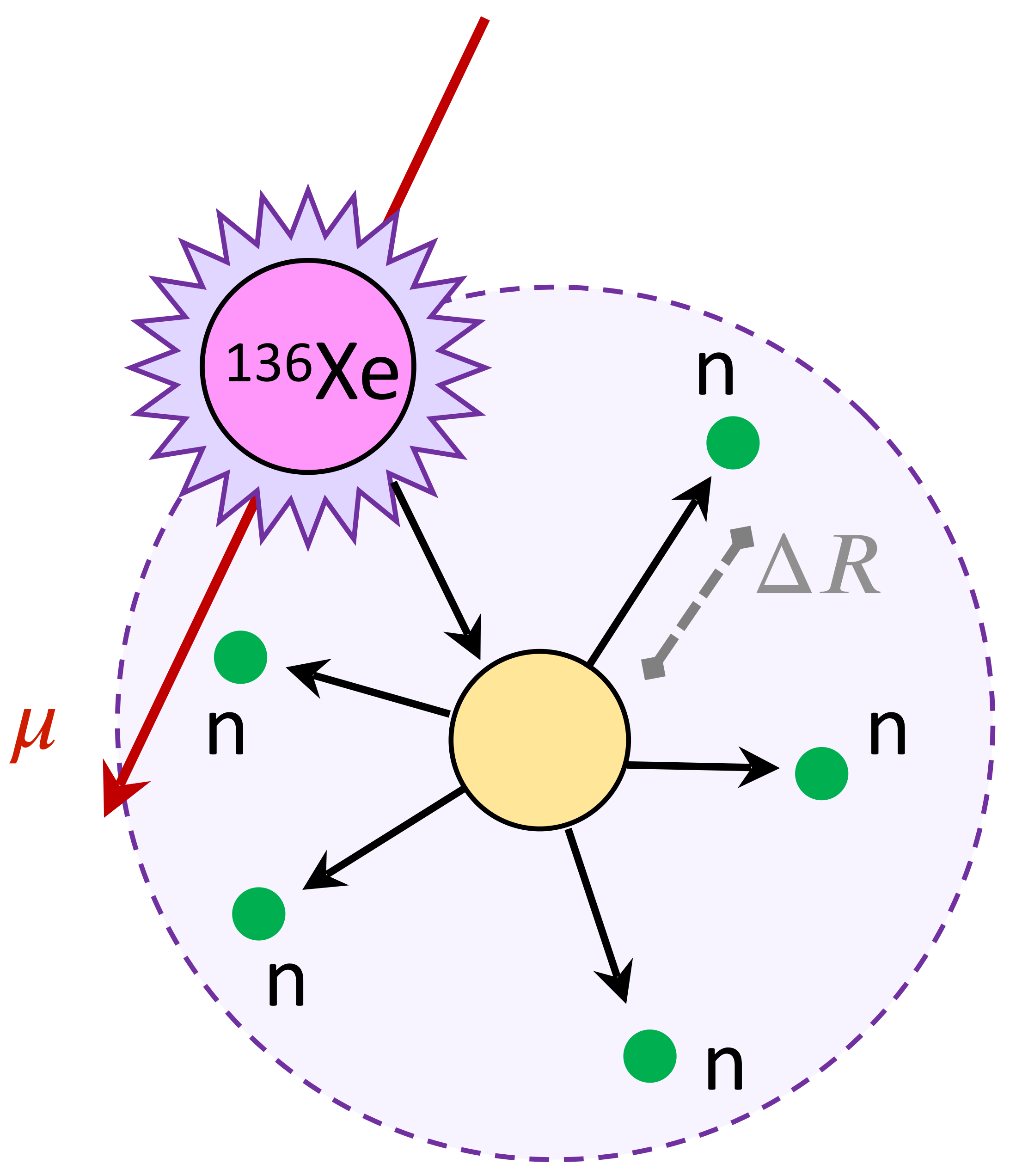
Isotope	τ(s)	Eff (%)
^{10}C	27.8	99.3
^{6}He	1.2	97.6±1.7
^{137}Xe	330	74±7

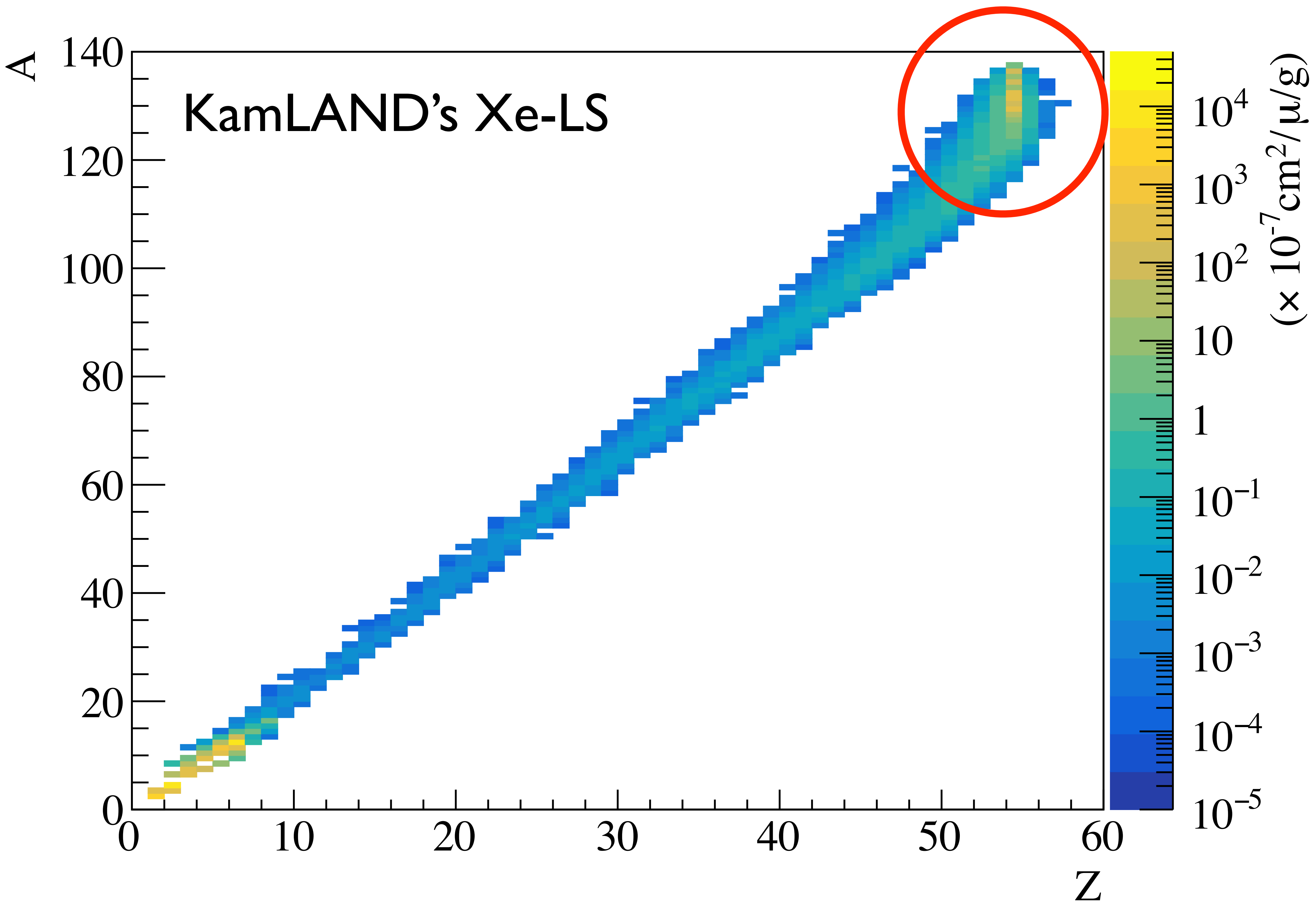
Short-lived spallation products τ < ~5 min

Muon Spallation

μ + ^{136}Xe spallation byproducts from FLUKA simulation

(NEW) Spallation on ^{136}Xe





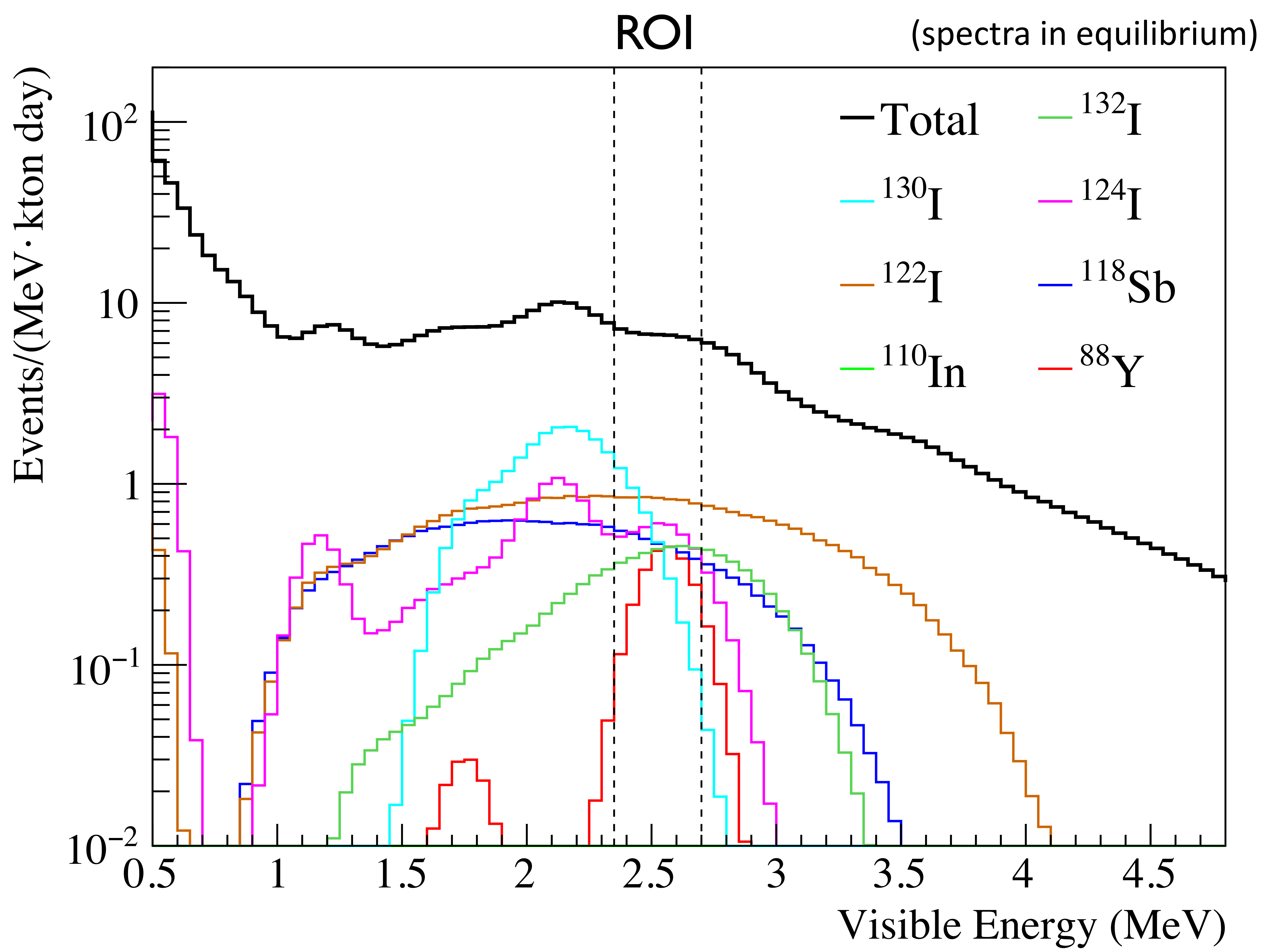
Isotope	$T_{1/2}$ (s)
^{88}Y	9.2×10^6
^{124}I	3.6×10^5
^{130}I	4.5×10^4
^{110}In	1.8×10^4
^{132}I	8.3×10^3
^{118}Sb	2.2×10^2
^{122}I	2.2×10^2

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

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

Muon Spallation Decay Spectrum

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



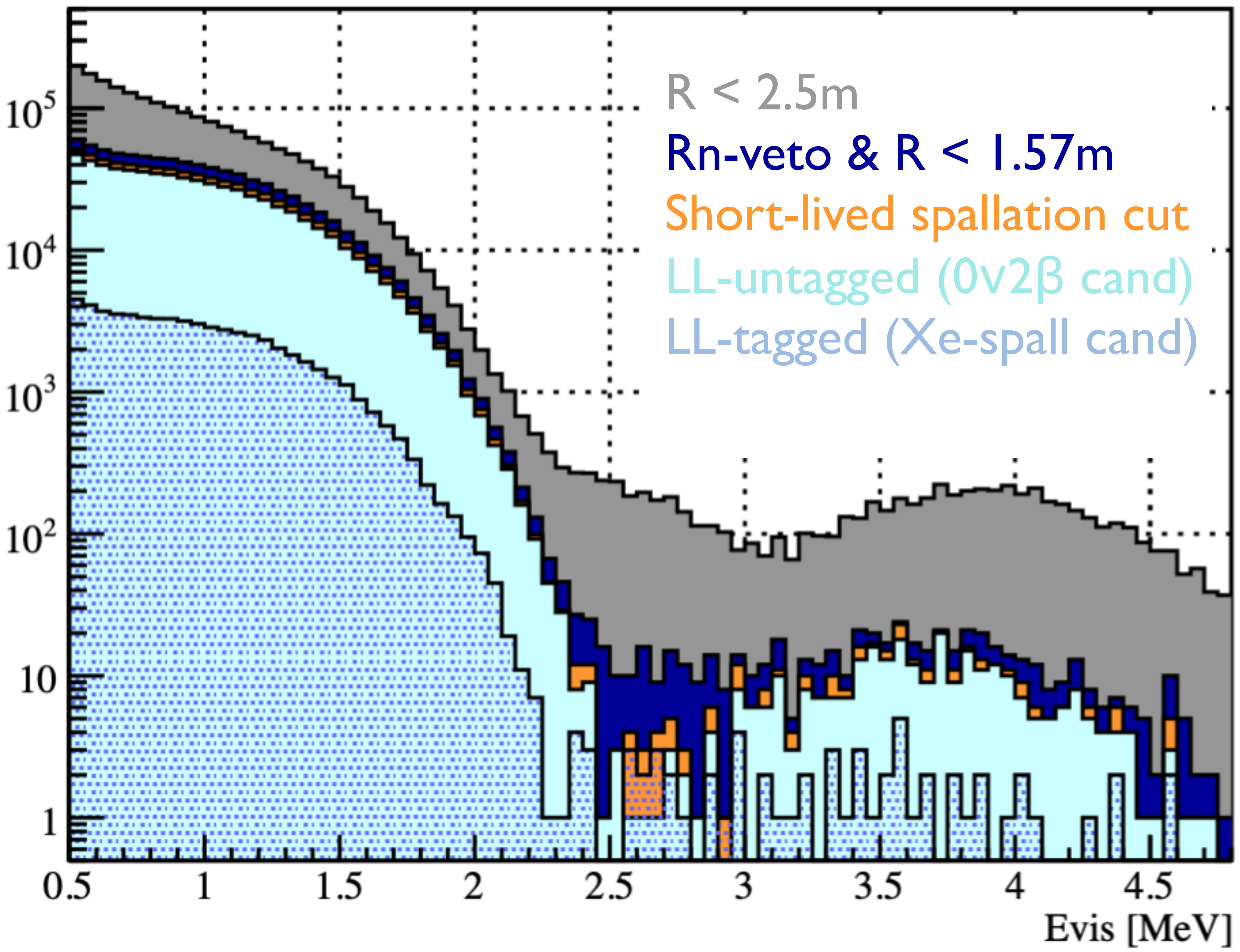
7 spall. isotopes mostly contributing in ROI

Long-lived spallation tag based on neutron-multiplicity, neutron vtx positions and ΔT with (42 ± 9)% tagging eff

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
  - $\bar{\nu}_e$ 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 samples

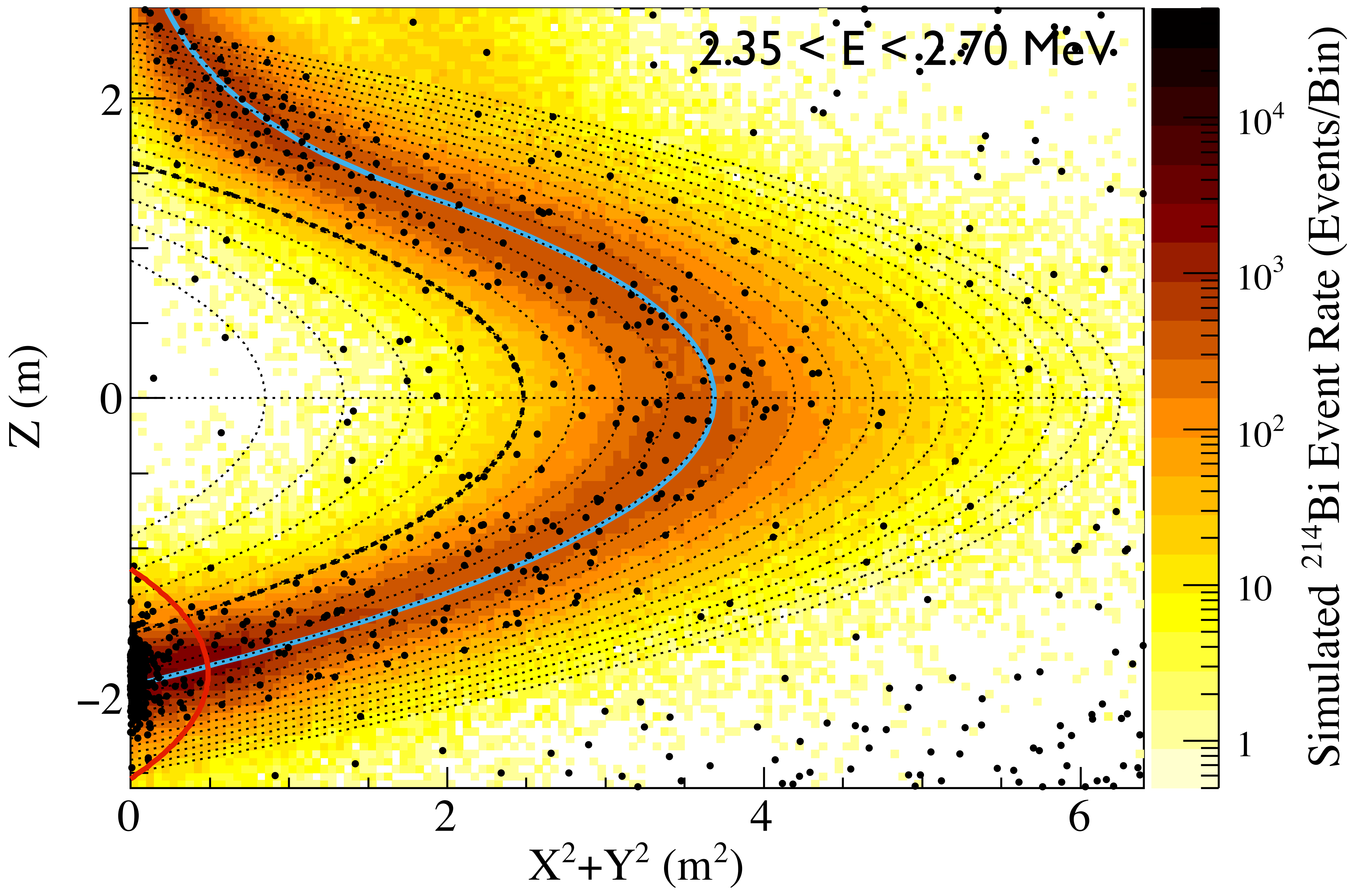
(745 ± 3)kg Xe, 523 day livetime → 970 kg-days



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 mini-balloon film
- All parameters fitted simultaneously

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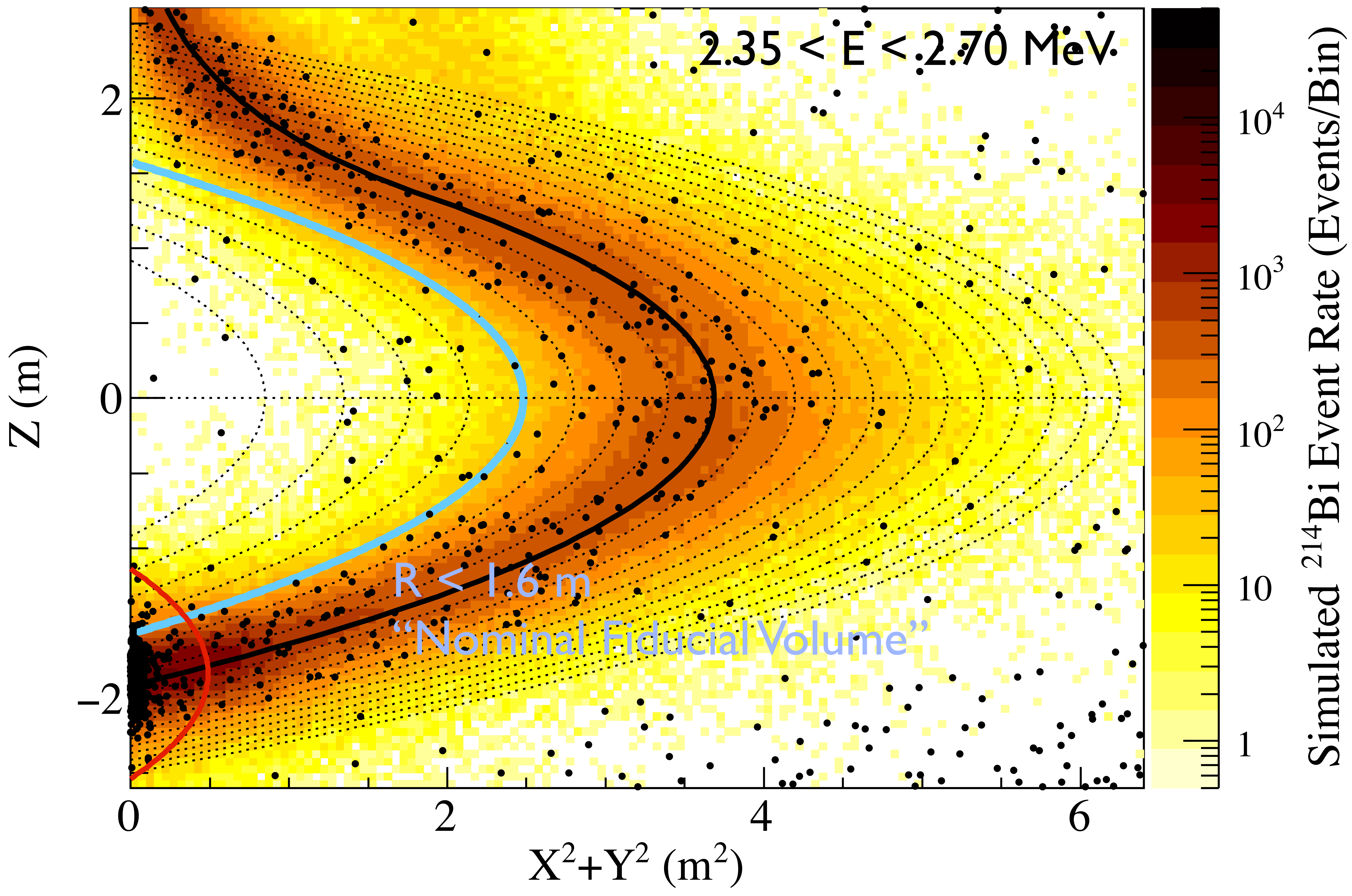

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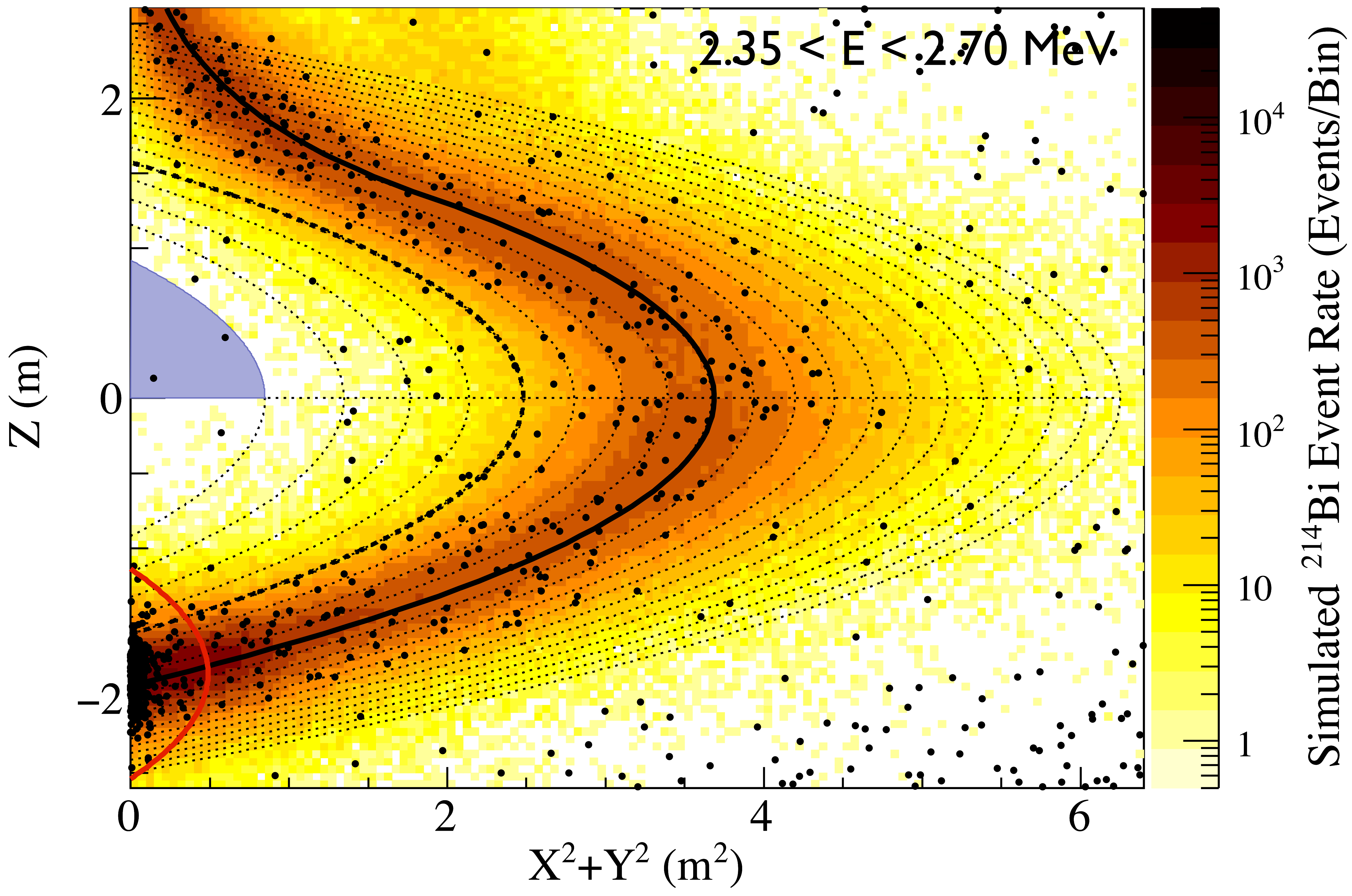

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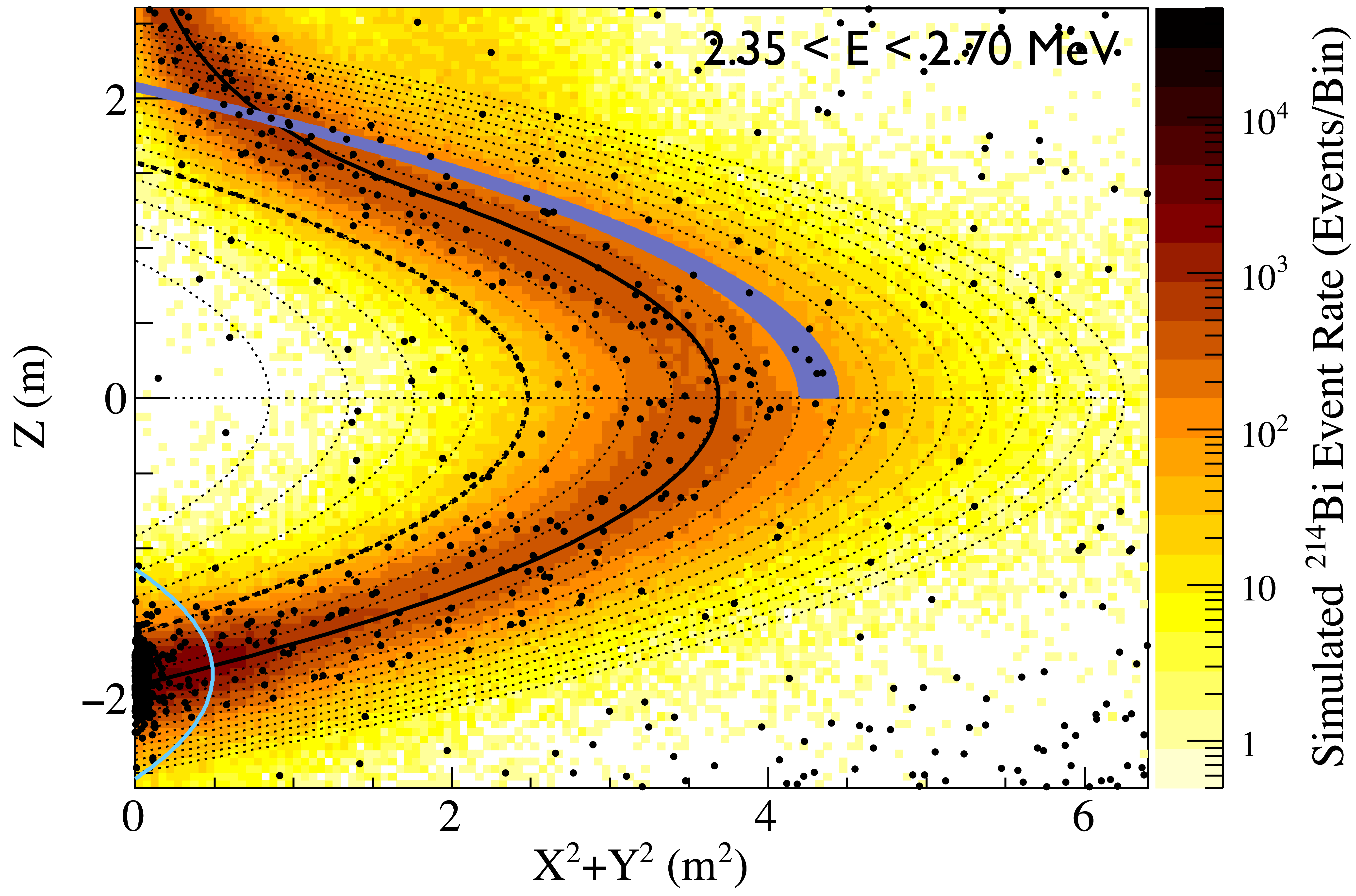
Fitting the Data in Equal Volume Bins

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

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



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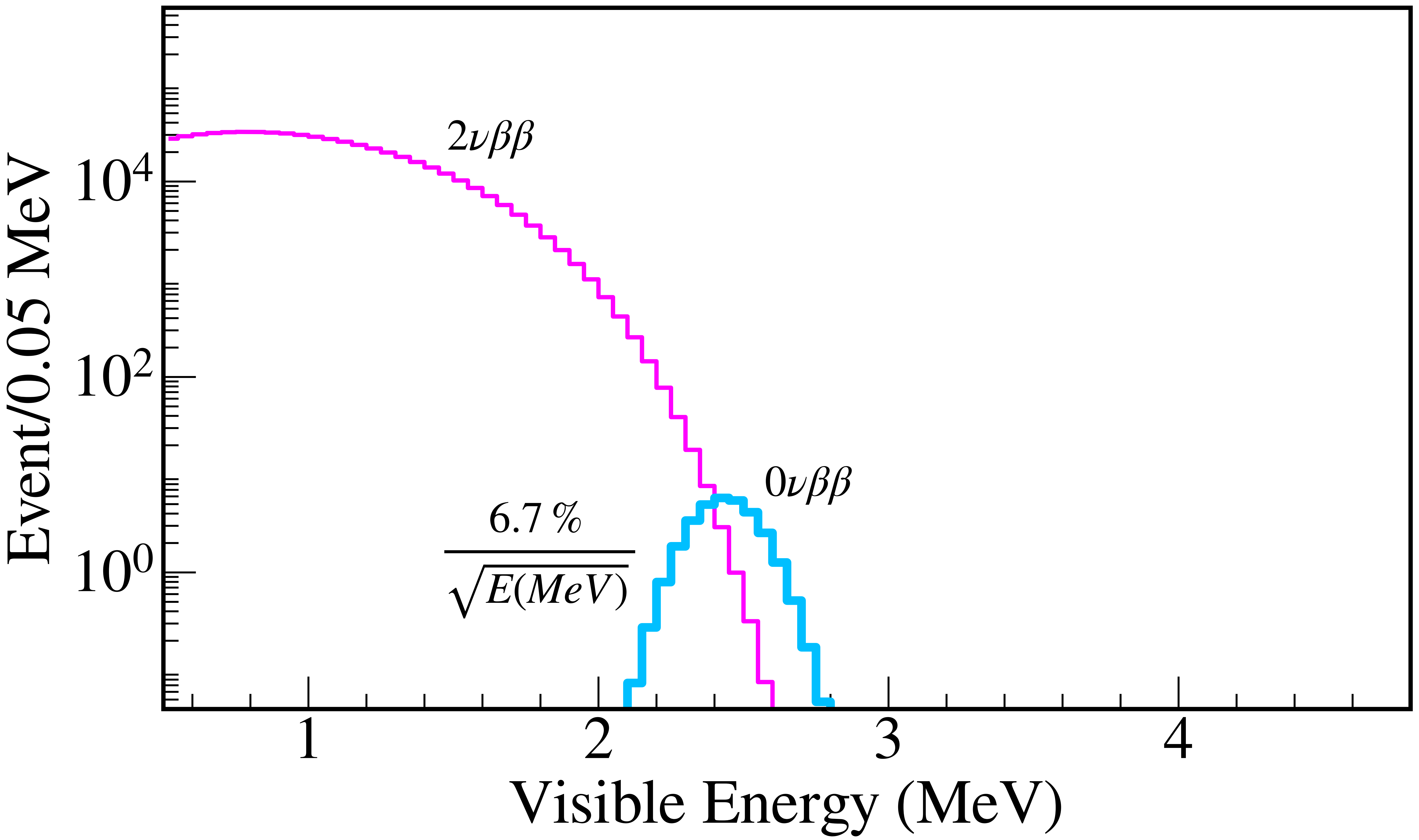
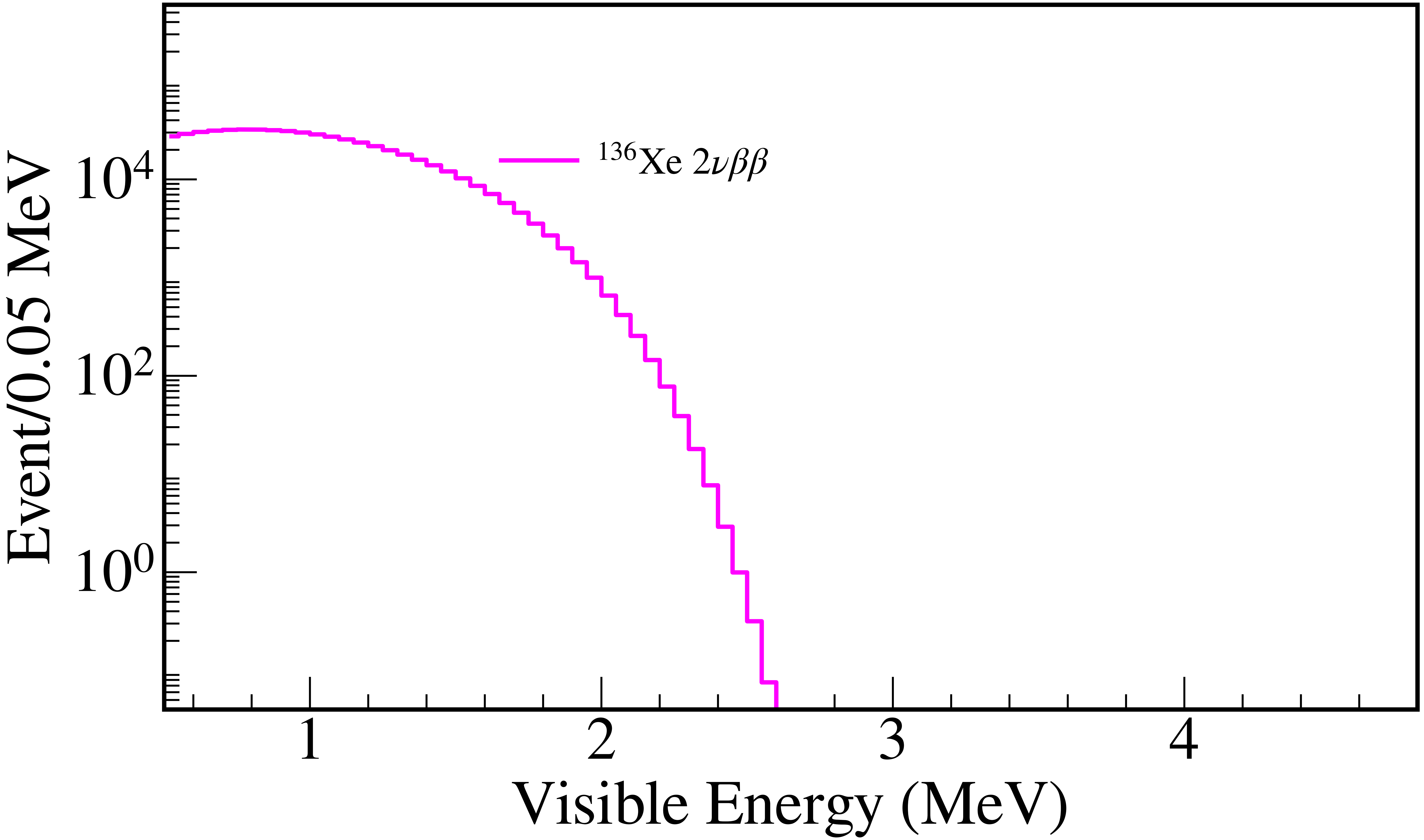
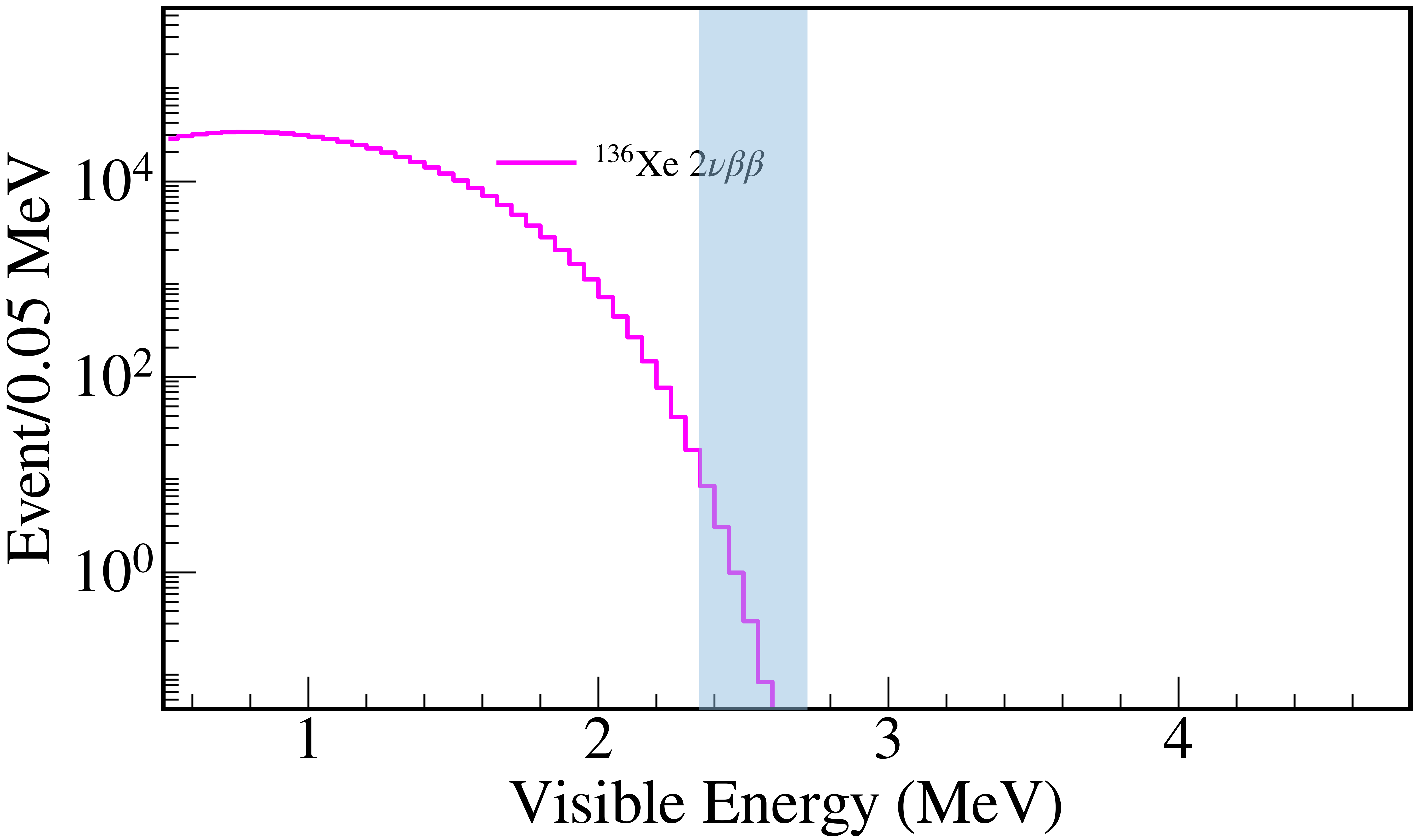
Energy Spectrum



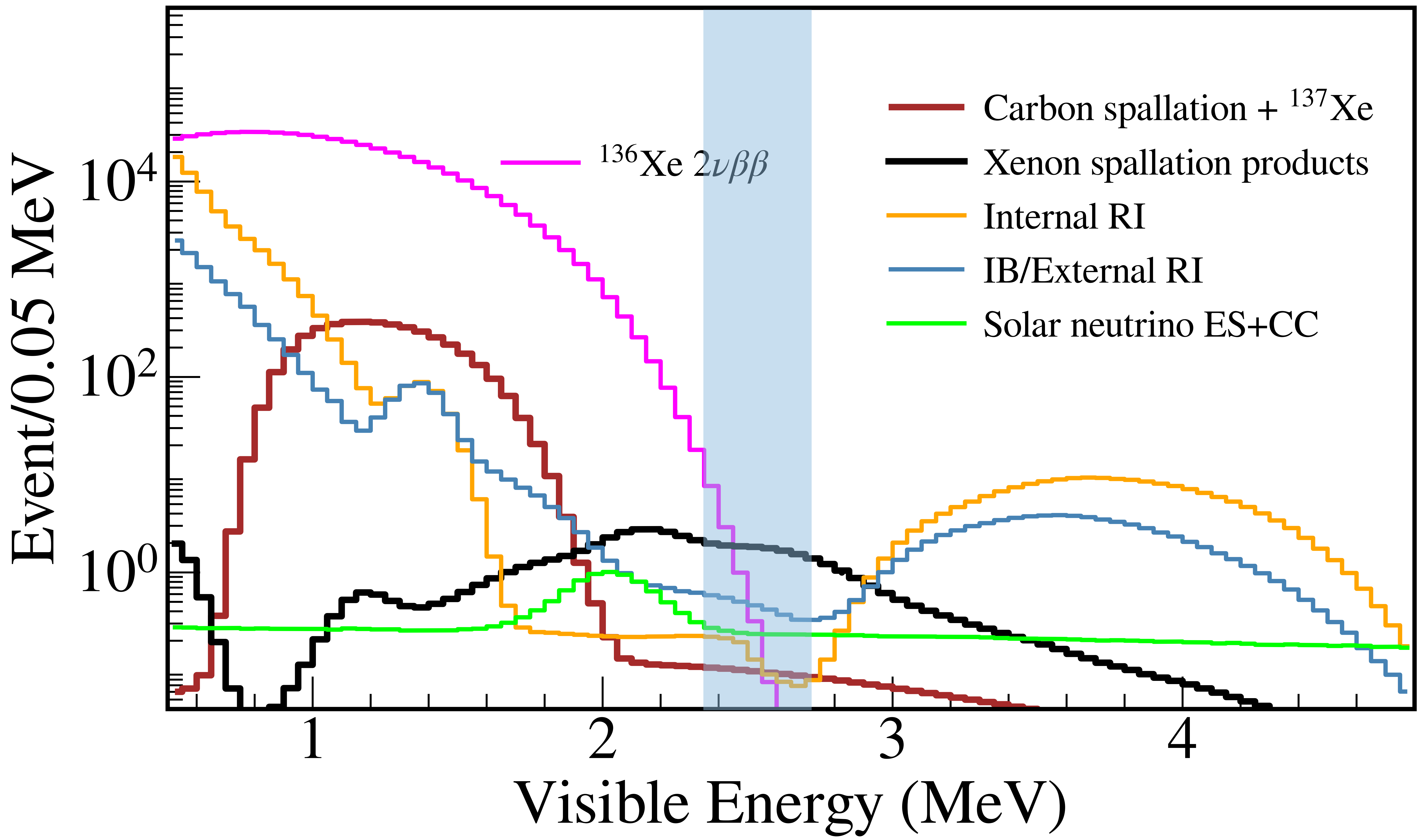
Energy Spectrum



Energy Spectrum

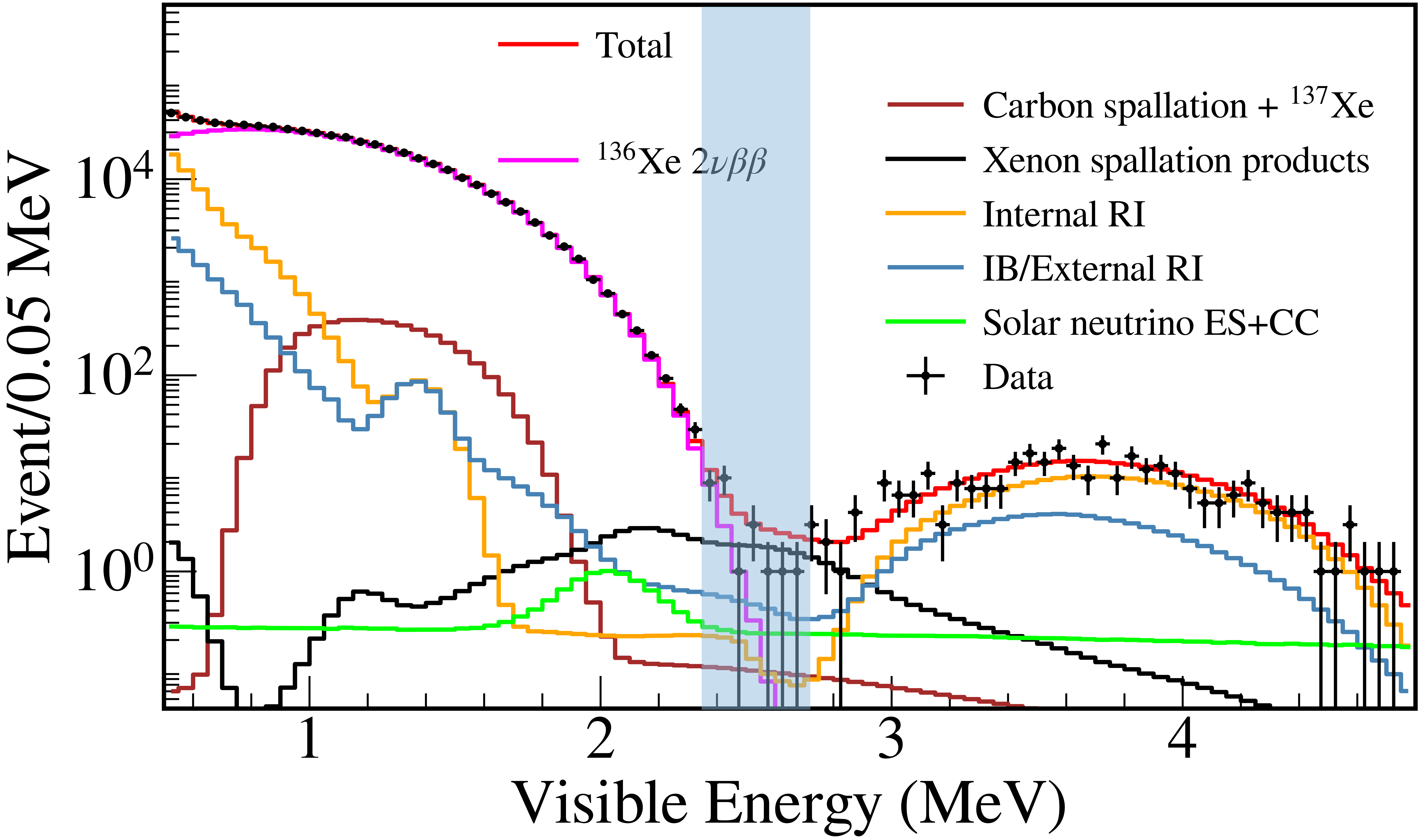


Energy Spectrum

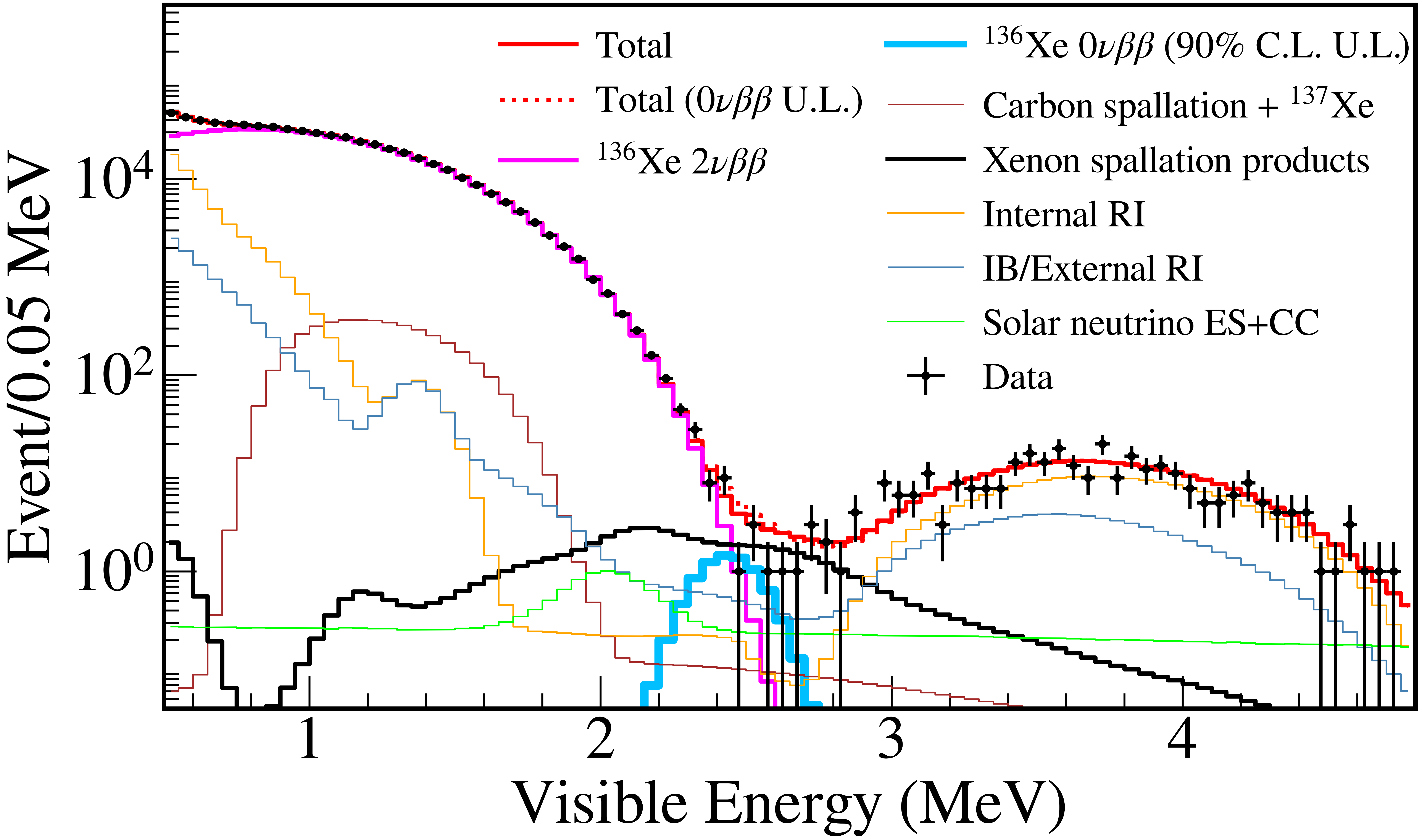


R<1.57m

Energy Spectrum



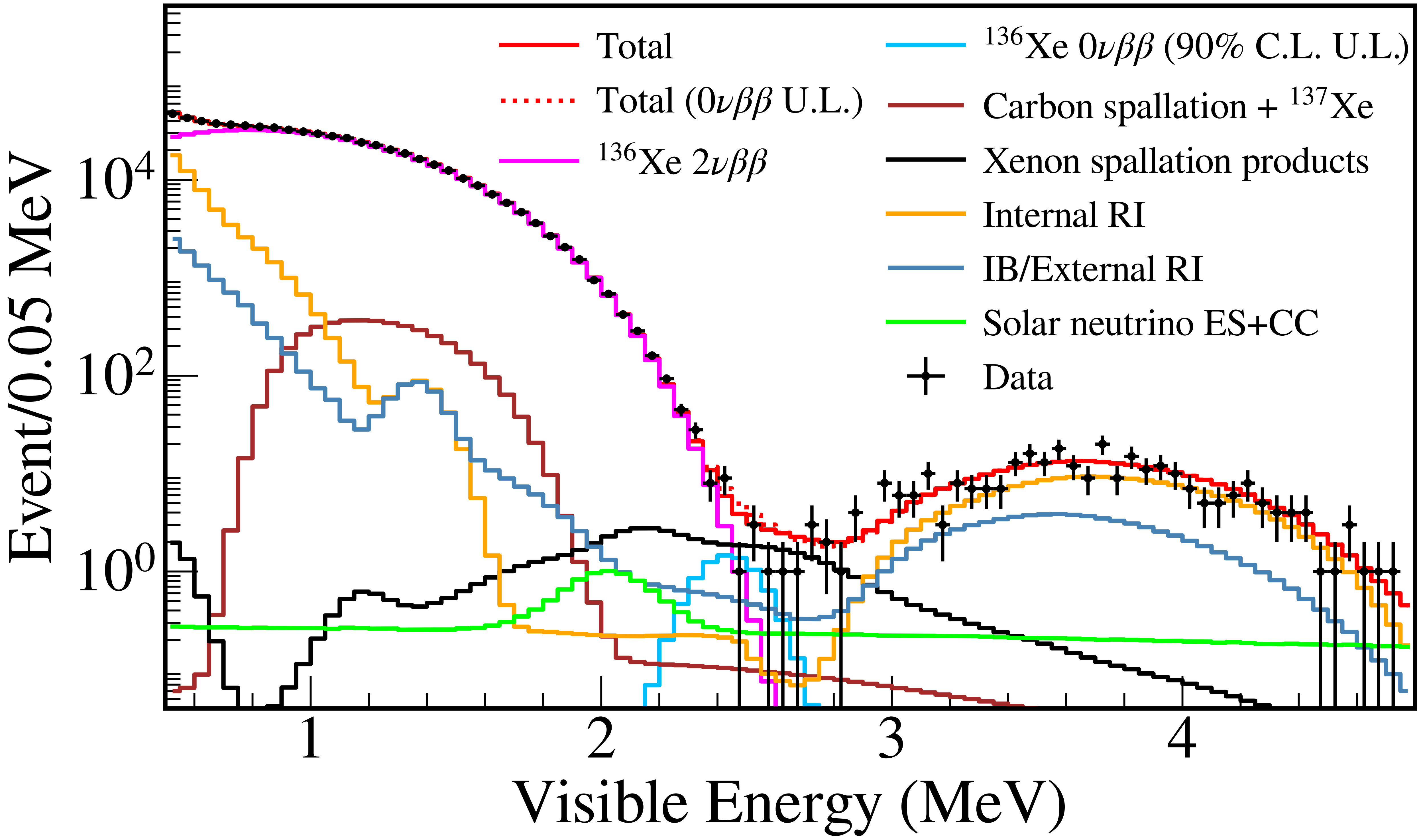
Energy Spectrum



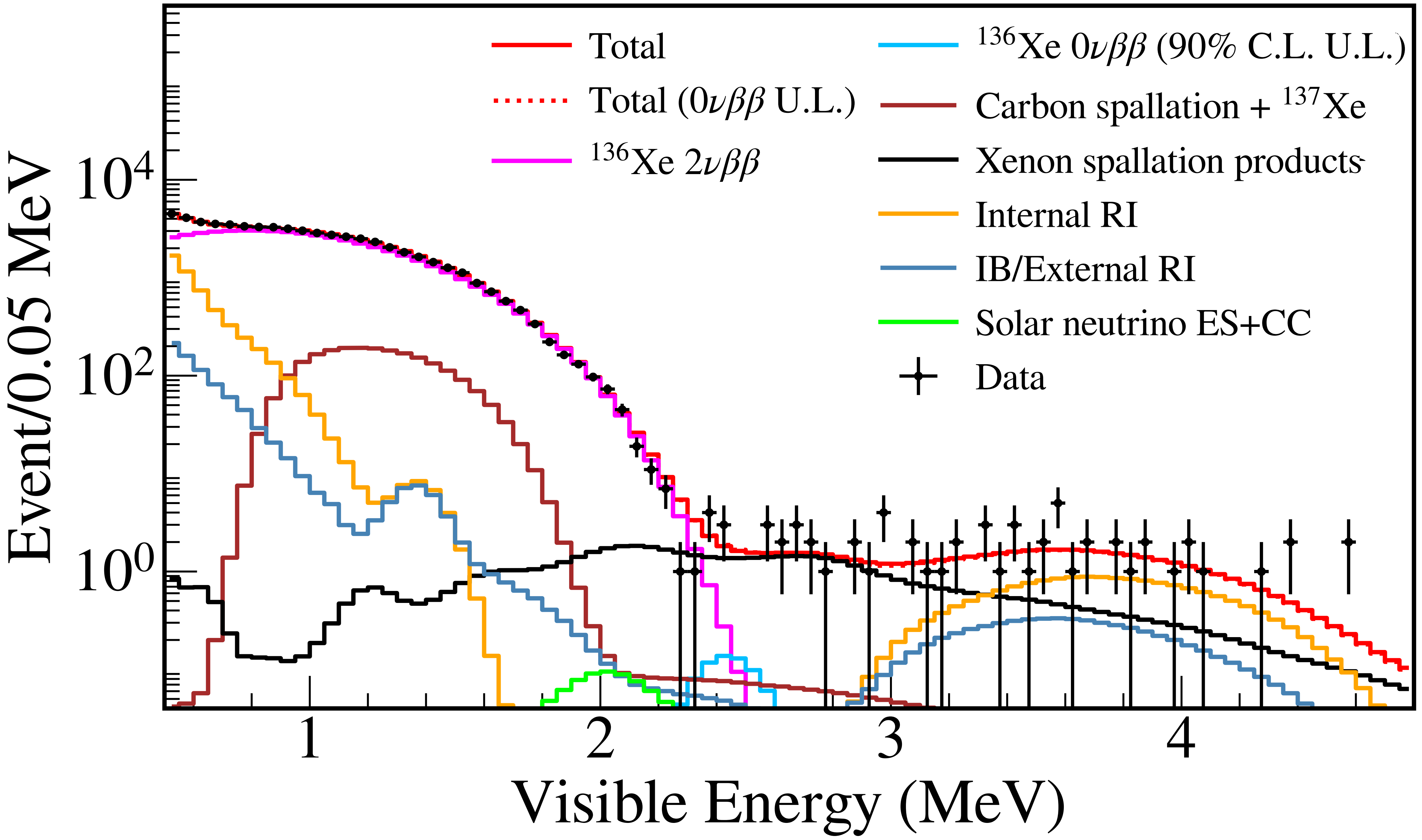
0v2β and long-lived Data

Simultaneous fit of the 0v2β and long-lived spallation spectrum to constrain backgrounds

0v2β candidate dataset, sensitive to 0v2β



Long-lived spallation dataset, constrain LL rate



R<1.57m
KLZ-800 only

Summary of Results

Background	Estimated	Best-fit Frequentist	Best-fit Bayesian
^{136}Xe $2\nu\beta\beta$	-	11.98	11.95
Residual radioactivity in Xe-LS			
^{238}U series	0.14 ± 0.04	0.14	0.09
^{232}Th series	-	0.84	0.87
External (Radioactivity in IB)			
^{238}U series	-	3.05	3.46
^{232}Th series	-	0.01	0.01
Neutrino interactions			
^{8}B solar ν e^- ES	1.65 ± 0.04	1.65	1.65
Spallation products			
Long-lived	7.75 ± 0.57 (MC)	12.52	11.80
^{10}C	0.00 ± 0.05	0.00	0.00
^{6}He	0.20 ± 0.13	0.22	0.21
^{137}Xe	0.33 ± 0.28	0.34	0.34

24 events observed

No excess events found

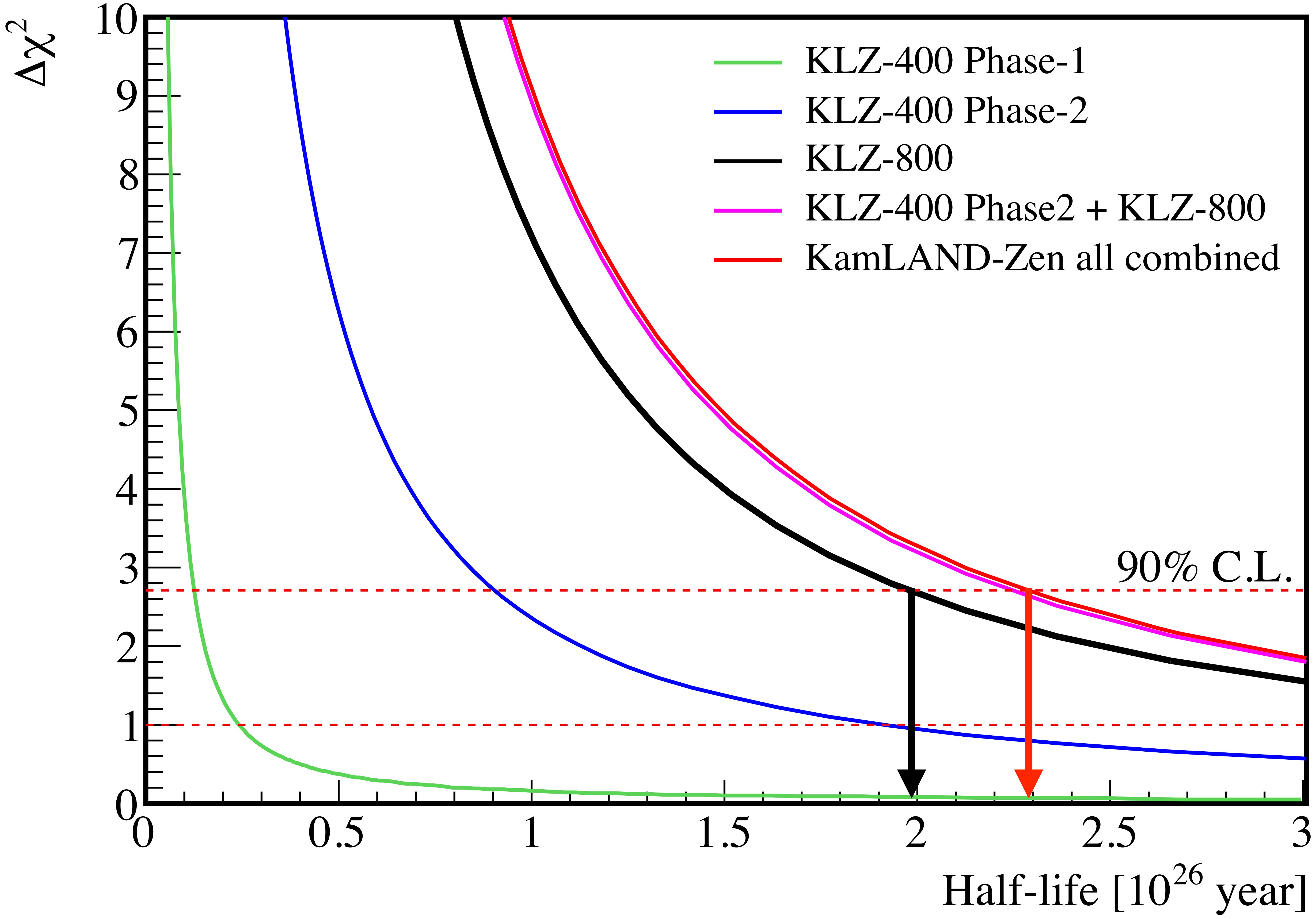
Frequentist result (90% CL):
$T_{1/2} > 2.0 \times 10^{26}$ yr
[sensitivity 1.3×10^{26} yr, 24% prob]

Feldman-Cousins:
$T_{1/2} > 2.3 \times 10^{26}$ yr

Bayesian (flat prior in $1/T_{1/2}$):
$T_{1/2} > 2.1 \times 10^{26}$ yr
[sensitivity 1.5×10^{26} yr]

Combination of all phases of KLZ

Combined frequentist fit, including reanalysis of KLZ-400 data with updated BG rejection techniques and long-lived-spallation



Frequentist result (90% CL):

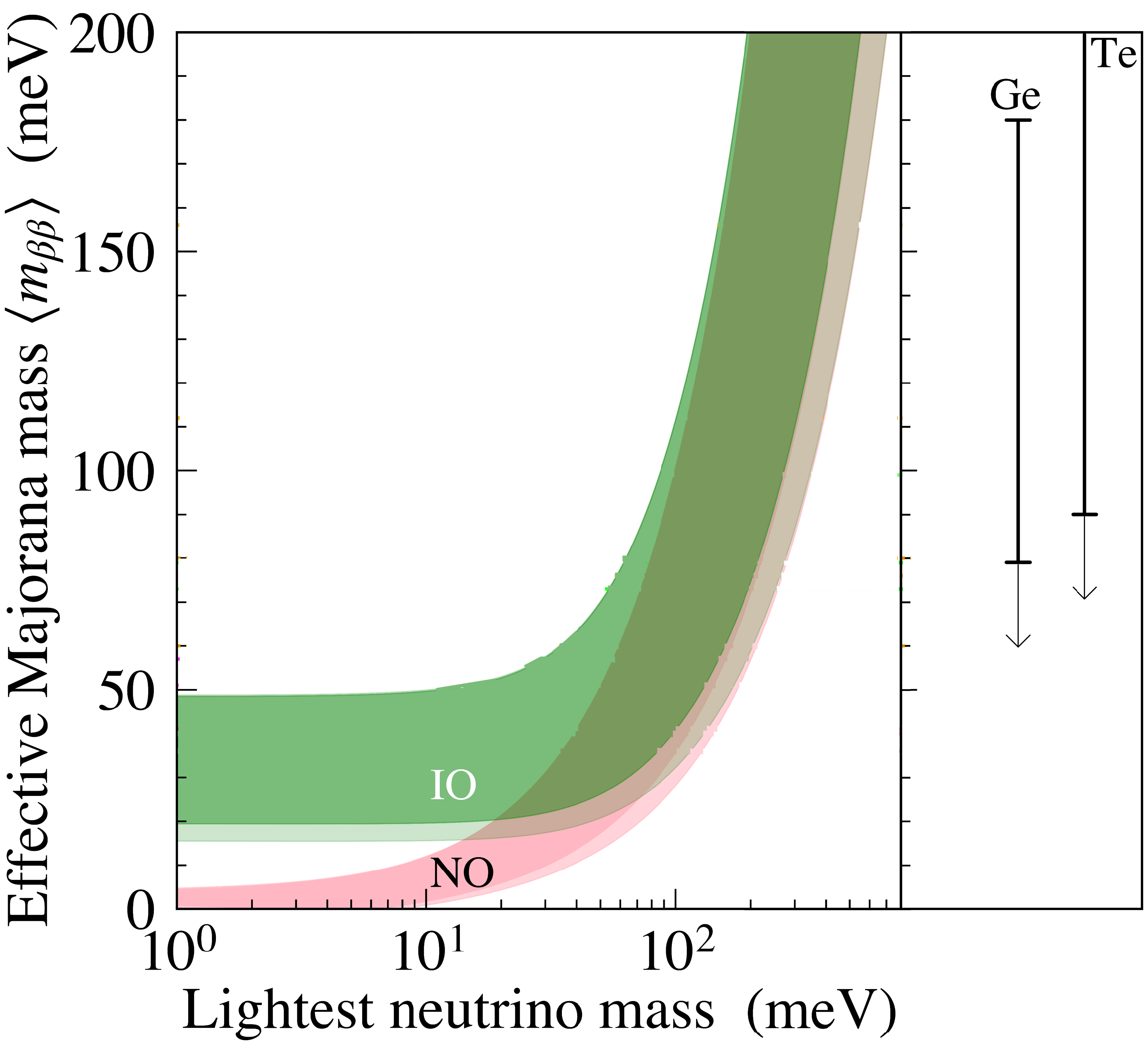
$T_{1/2} > 2.3 \times 10^{26}$ yr

[sensitivity 1.5 x 10^{26} yr]

Effective Majorana Mass

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

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



(Te) CUORE, arxiv: 2104.06906
(Ge) GERDA, PRL 125, 252502

KamLAND-Zen Coll, Phys. Rev. Lett. 130, 051801 (2023), arXiv:2203.02139

Effective Majorana Mass

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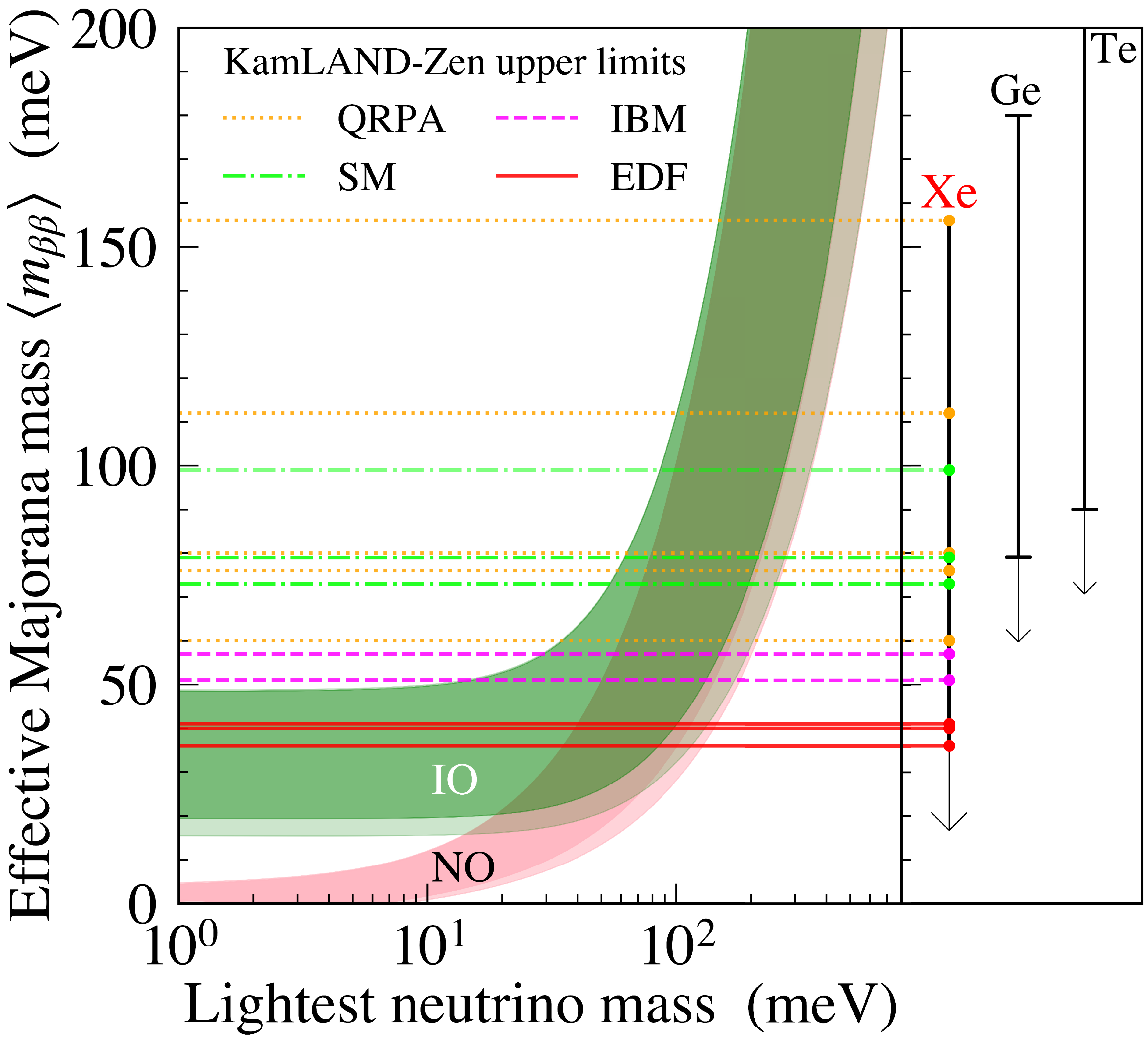

(Te) CUORE, arxiv: 2104.06906
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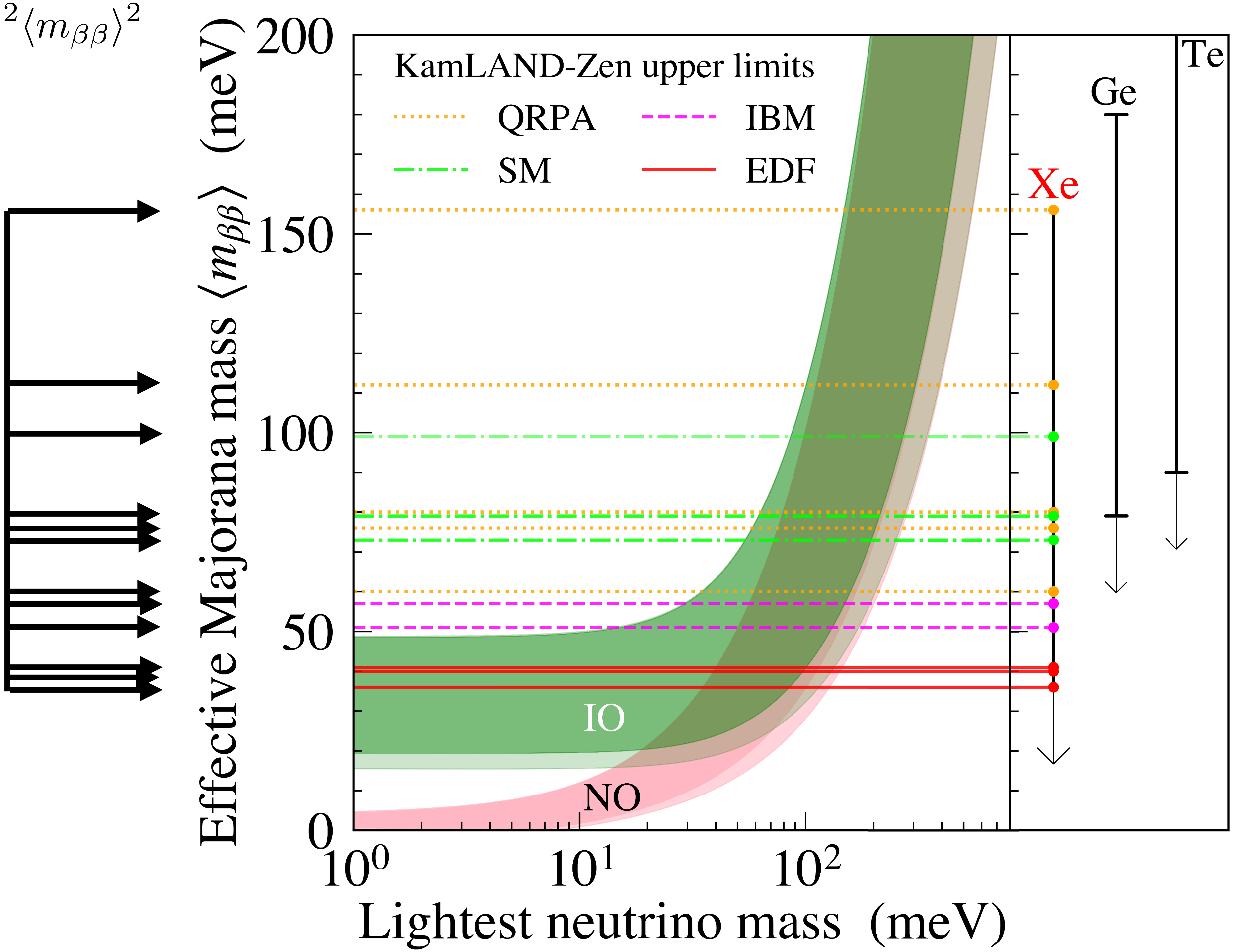
Result dependent on individual NMEs



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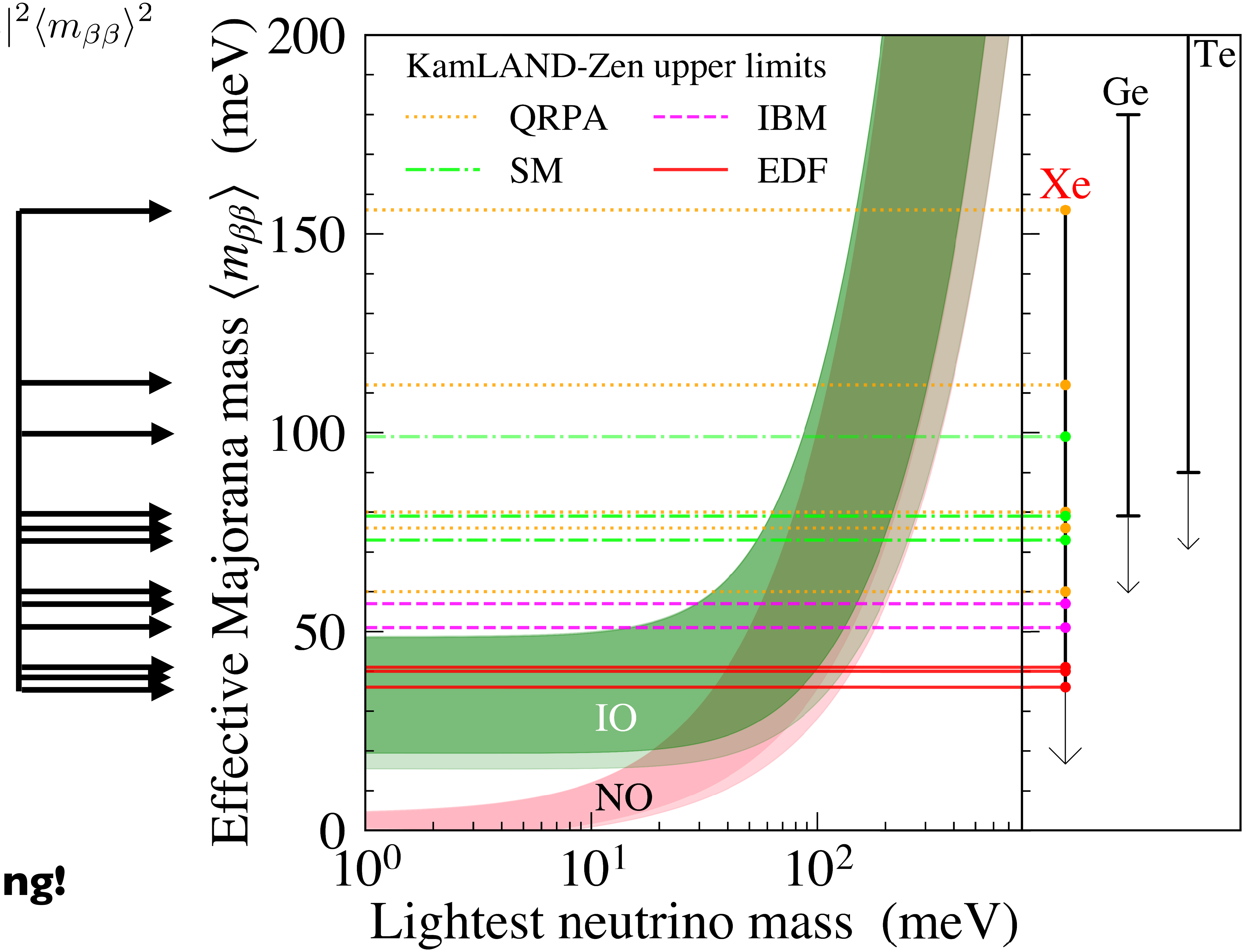
Result dependent on individual NMEs

EDF NME we enter the Inverted Ordering!



(Te) CUORE, arxiv: 2104.06906
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KamLAND-Zen Coll, Phys. Rev. Lett. 130, 051801 (2023), arXiv:2203.02139

Effective Majorana Mass

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

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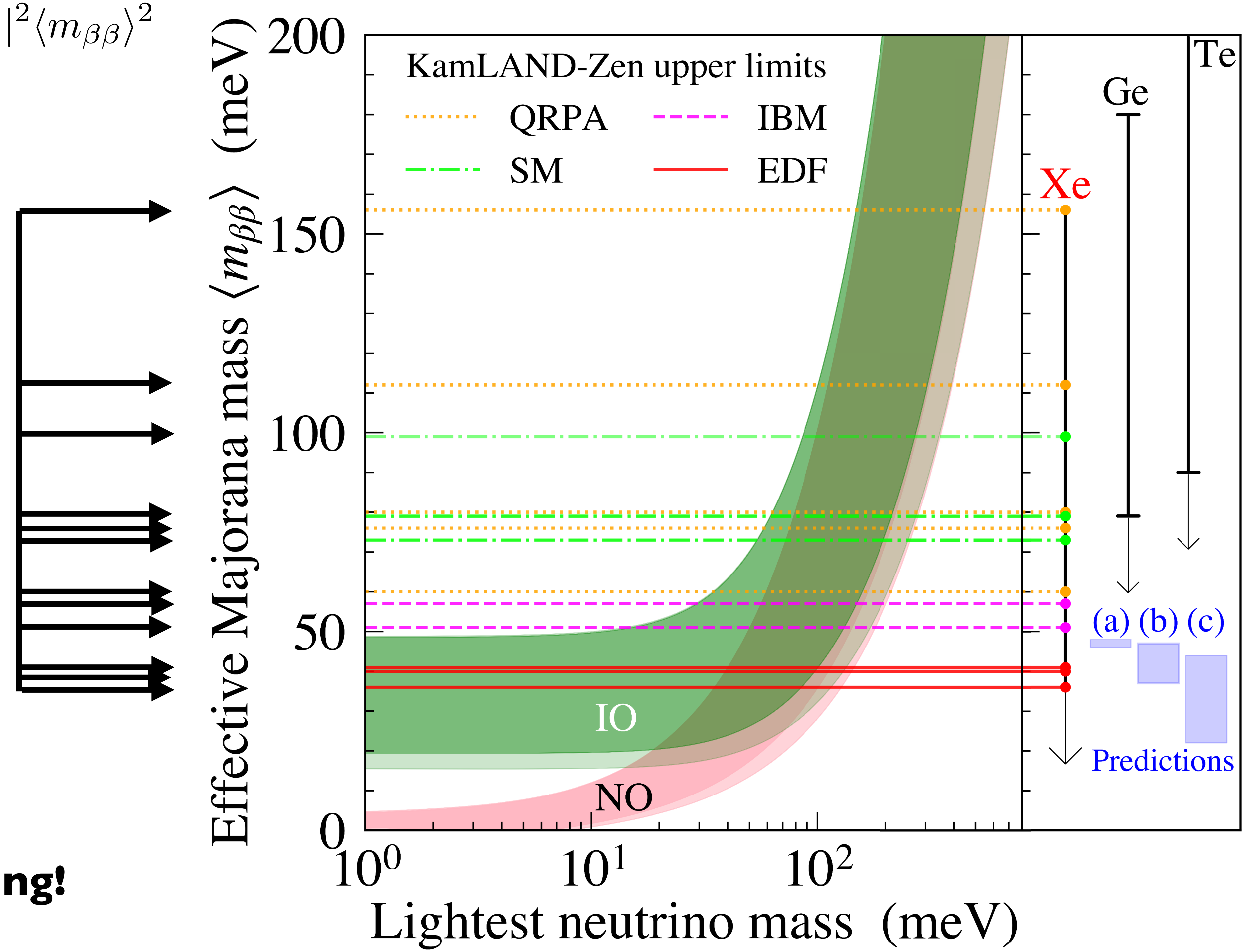


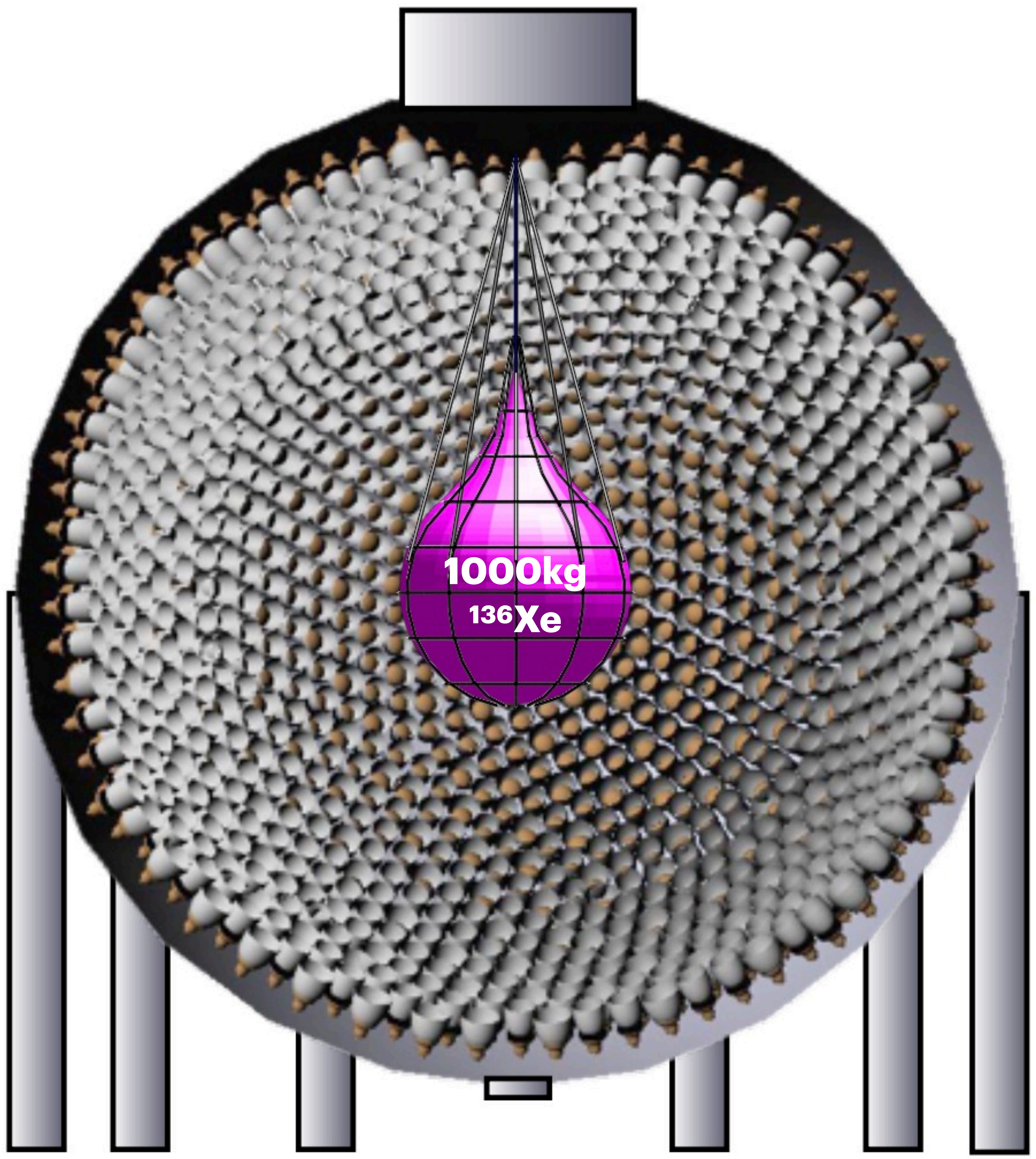
(Te) CUORE, arxiv: 2104.06906
(Ge) GERDA, PRL 125, 252502

First test of theoretical predictions
(a) PRD 86, 013002
(b) PLB 811, 135956
(c) EJPC 80, 76

KamLAND-Zen Coll, Phys. Rev. Lett. 130, 051801 (2023), arXiv:2203.02139

KamLAND2-Zen

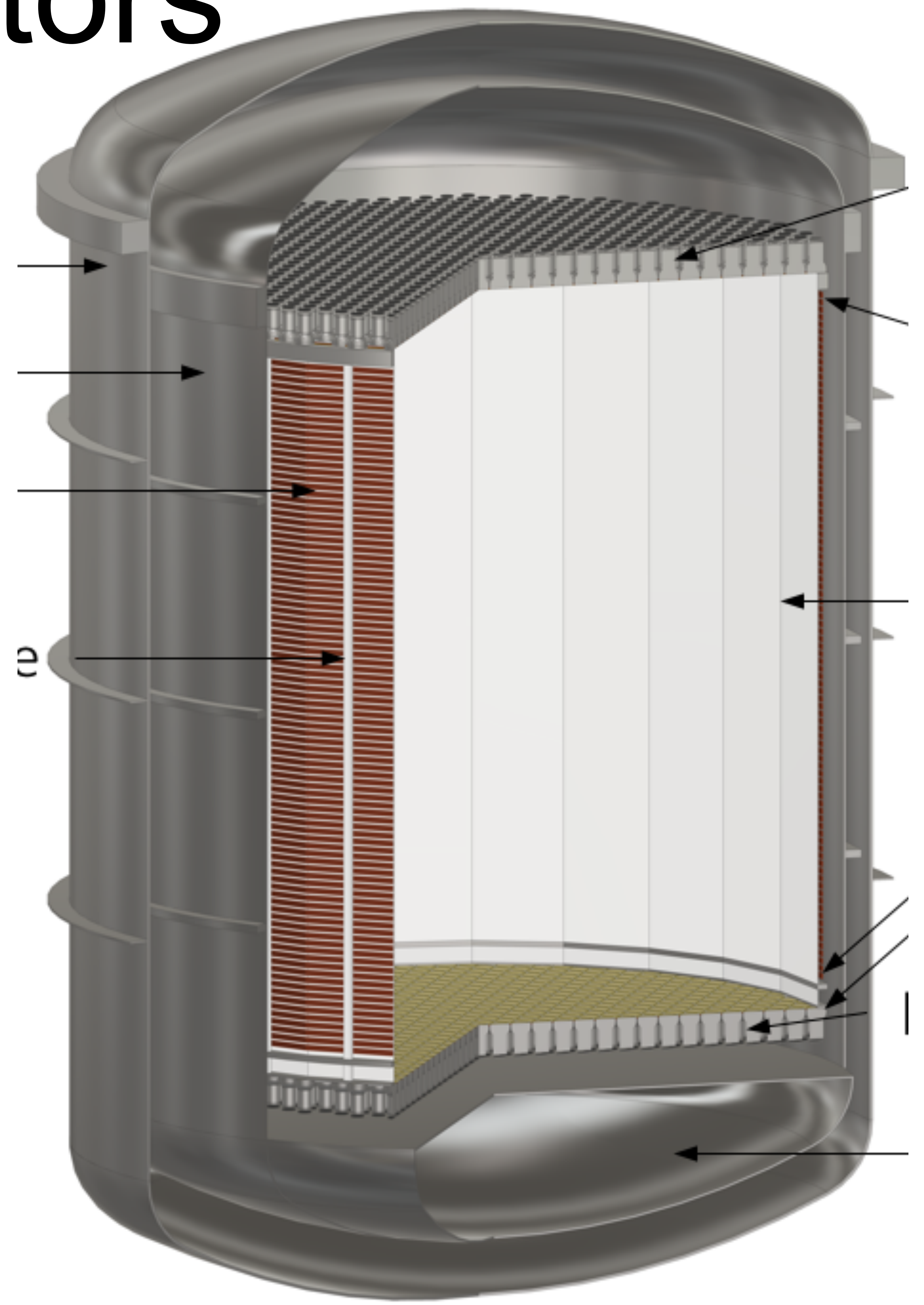
Design sensitivity of $T_{1/2} > 2 \times 10^{27}$ yrs and $\langle m_{\beta\beta} \rangle \sim 20$ meV



- Improved energy resolution: Winston Cones (x1.8), new LS (x1.4), More high-QE PMTs (x1.9)
  - 4% → 2% (x100 reduction in 2ν2β 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

Using Liquid XENON Detectors

Natural xenon has 8.9% ^{136}Xe use it to study 0ν2β !



XENON1T
3.2 tons LXe
2015-2019

XENONnT
8.5 tons LXe
2021-

DARWIN / XLZD
60 tons LXe
2030-

XENON Coll, Phys. Rev. C 106, 024328 (2022); arXiv:2205.04158

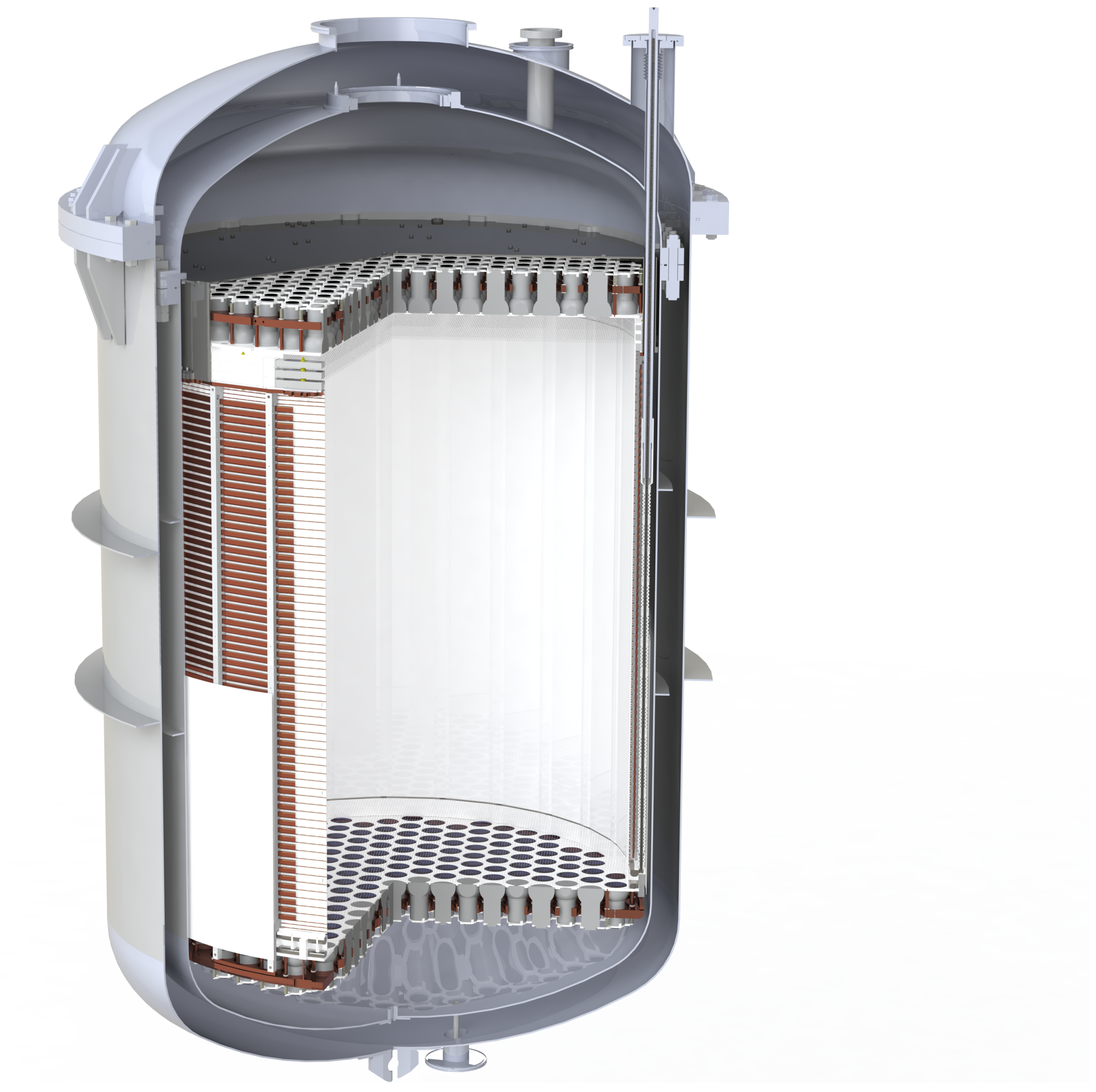
DARWIN Coll, Eur. Phys. J. C 80, 808 (2020); arXiv:2003.13407

XENON

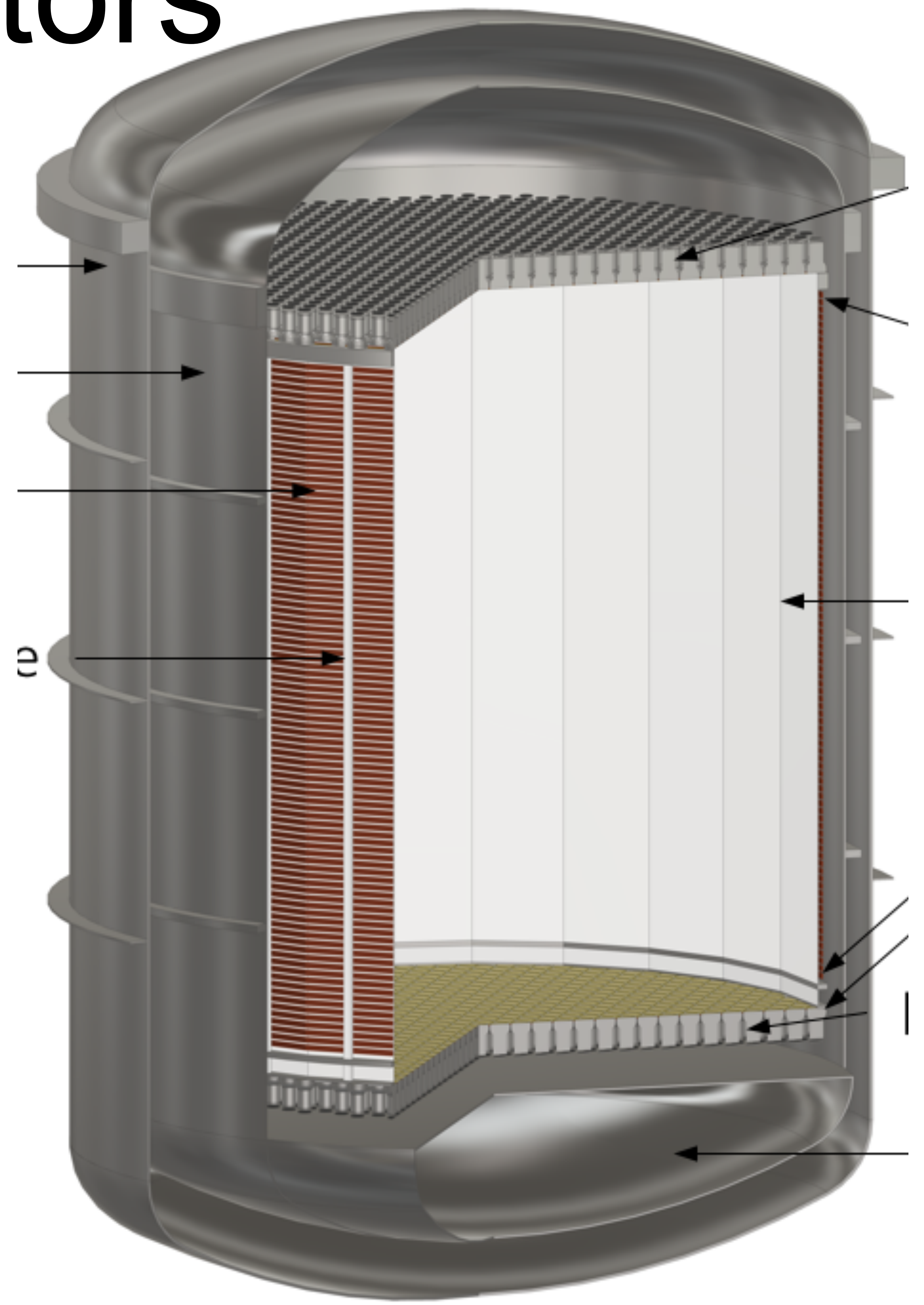
Using Liquid XENON Detectors

Natural xenon has 8.9% ^{136}Xe use it to study $0\nu2\beta$!

XENON1T
3.2 tons LXe
2015-2019



XENONnT
8.5 tons LXe
2021-



DARWIN / XLZD
60 tons LXe
2030-

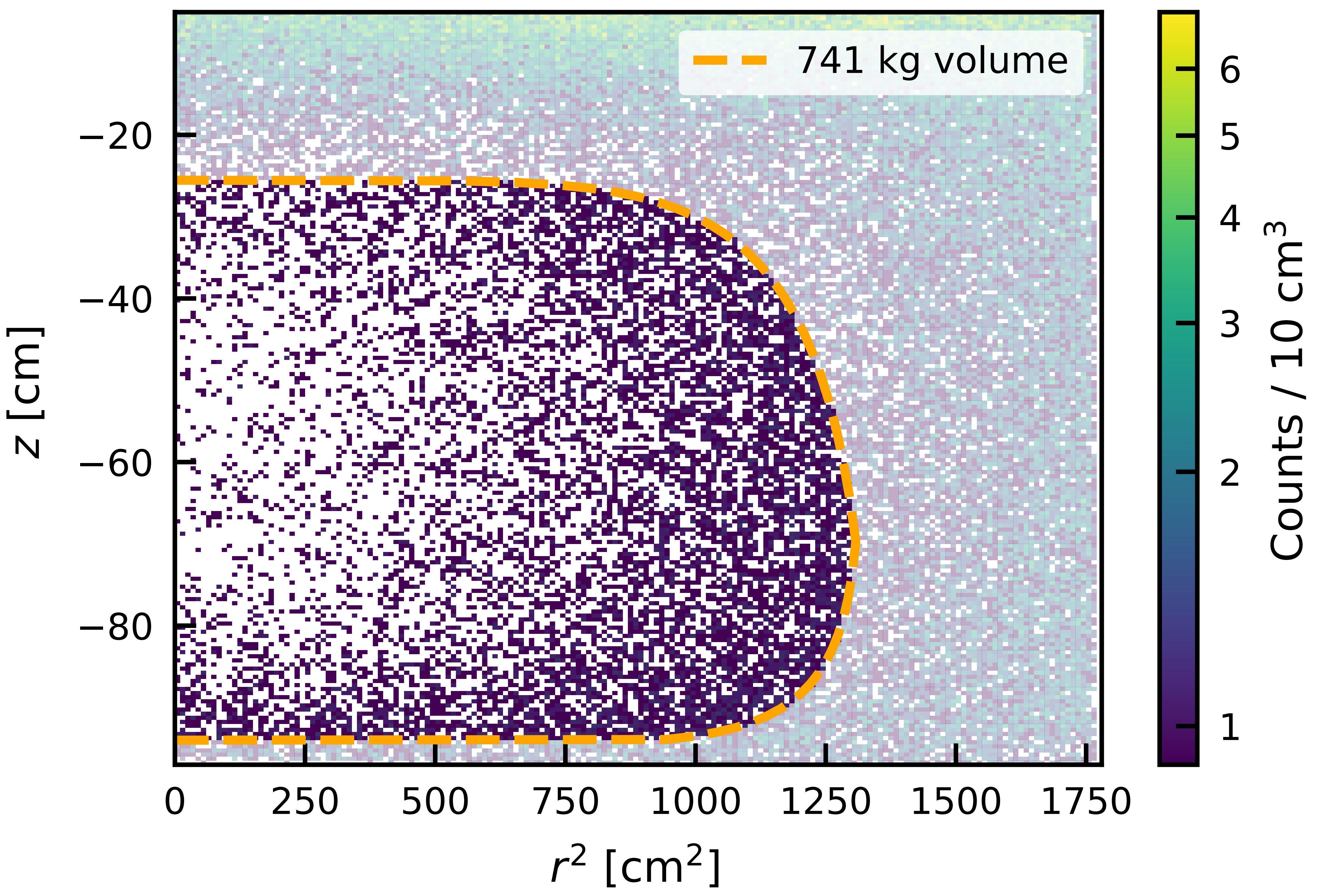
XENON Coll, Phys. Rev. C 106, 024328 (2022); arXiv:2205.04158

DARWIN Coll, Eur. Phys. J. C 80, 808 (2020); arXiv:2003.13407

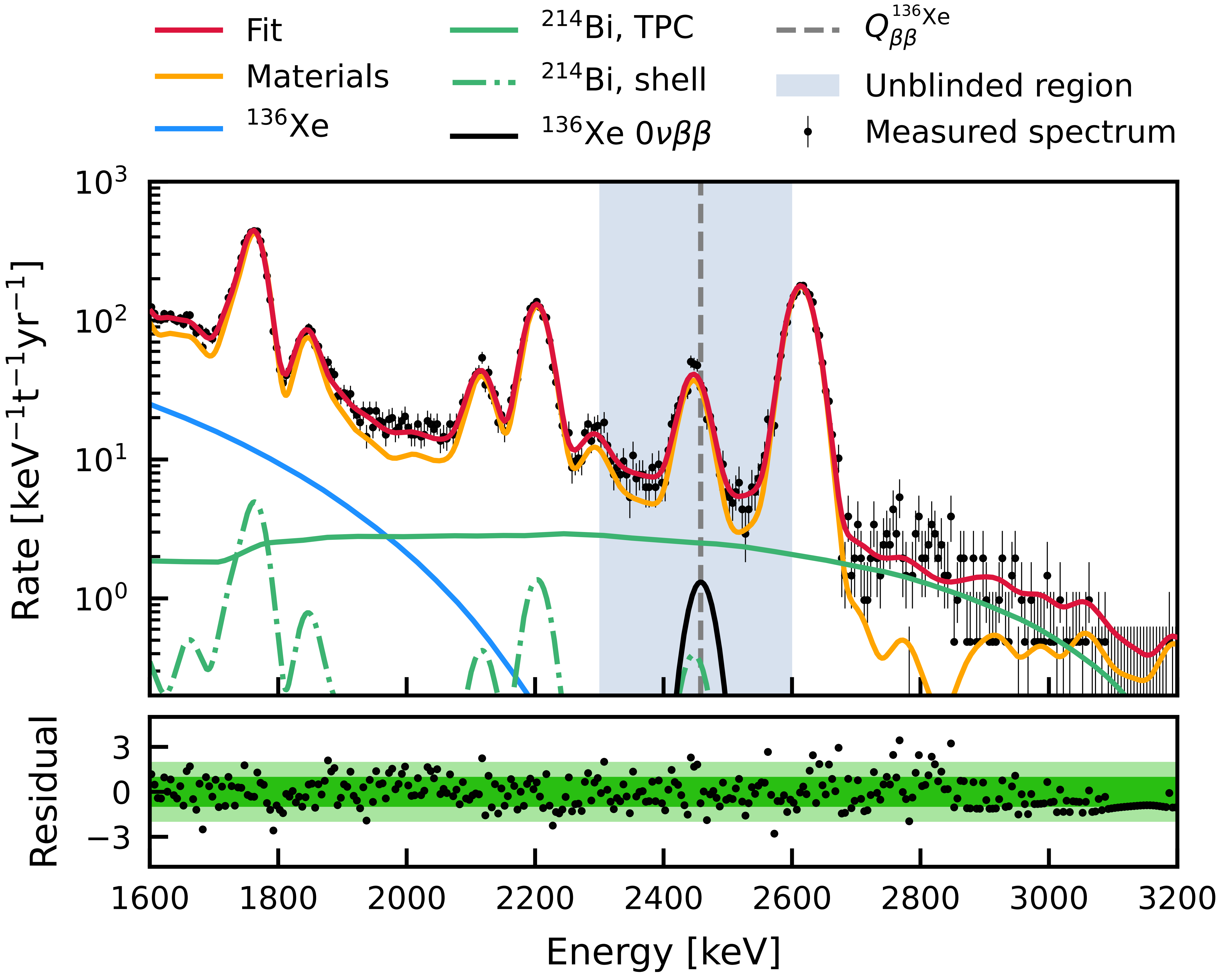
XENON Coll, Phys. Rev. C 106, 024328 (2022); arXiv:2205.04158

XENON1T 0ν2β Analysis

Optimized FV on ^{214}Bi and ^{208}Tl sidebands



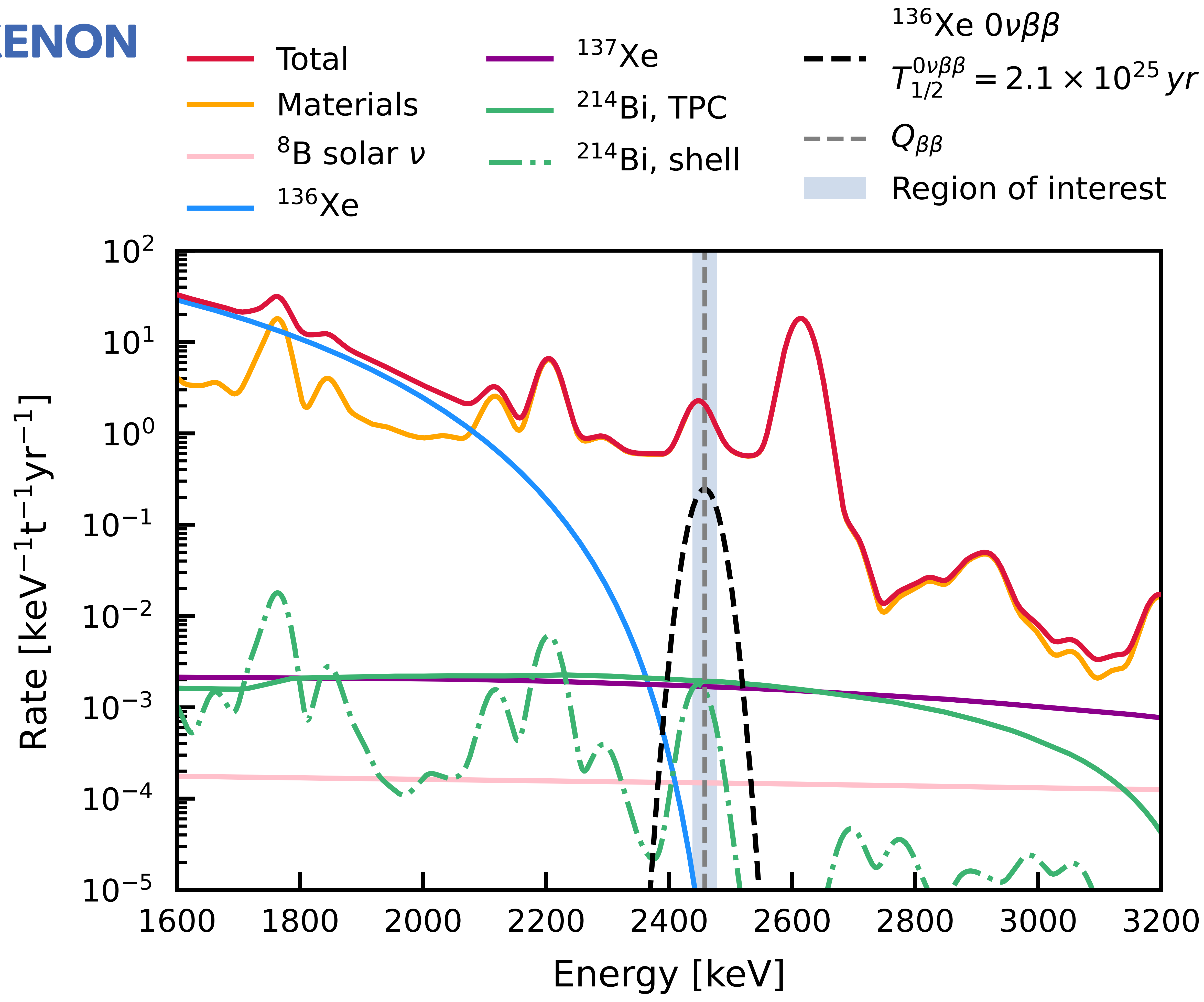
66 kg of ^{136}Xe isotope → 36 kg-yr exposure

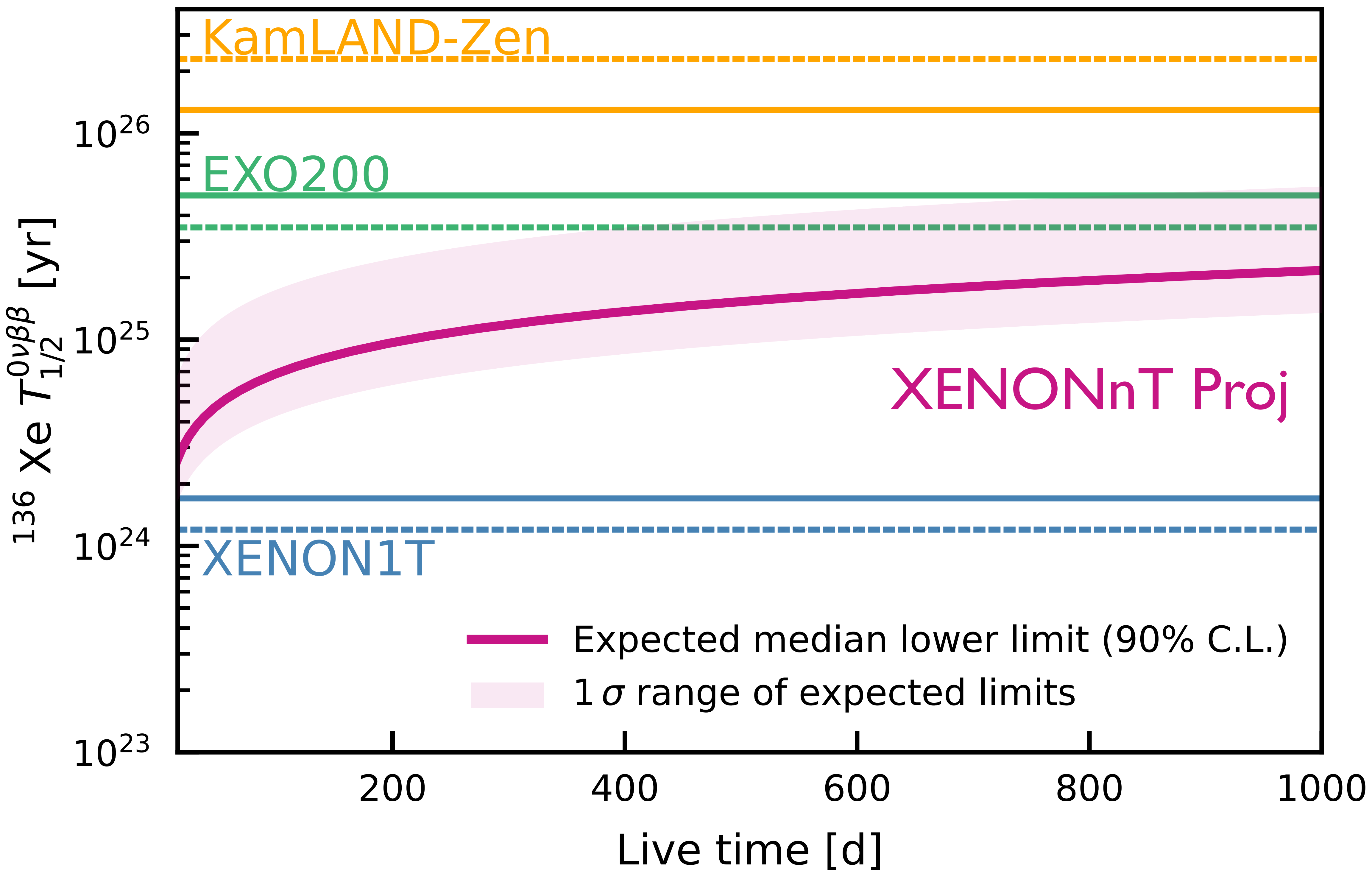


$T_{1/2} > 1.2 \times 10^{24}$ yr

[sensitivity 1.7×10^{24} yr]

XENONnT 0ν2β Projection



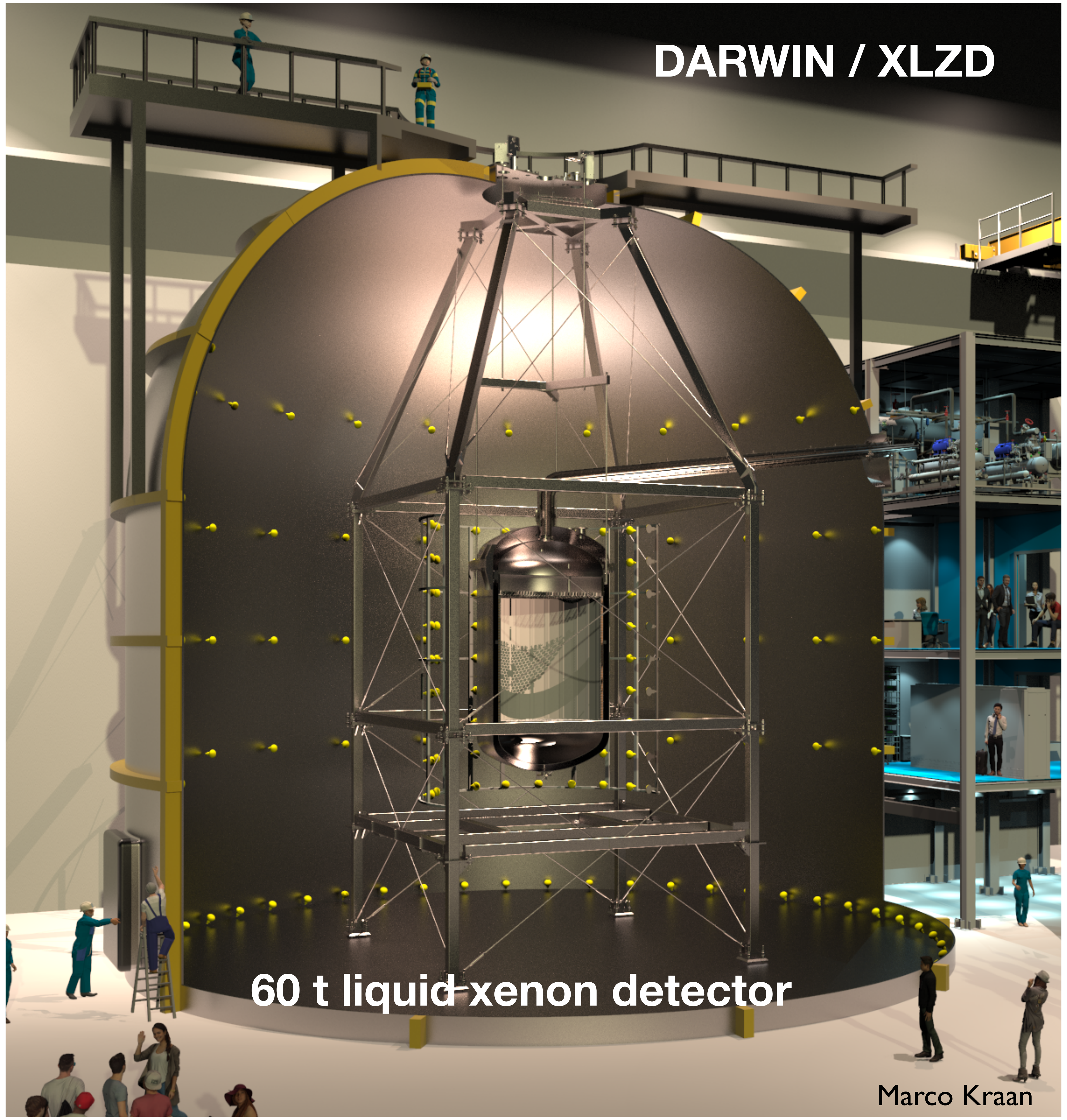


Optimal fiducial mass of 1088 kg LXe
→ 97 kg of ^{136}Xe
Limited by high material background

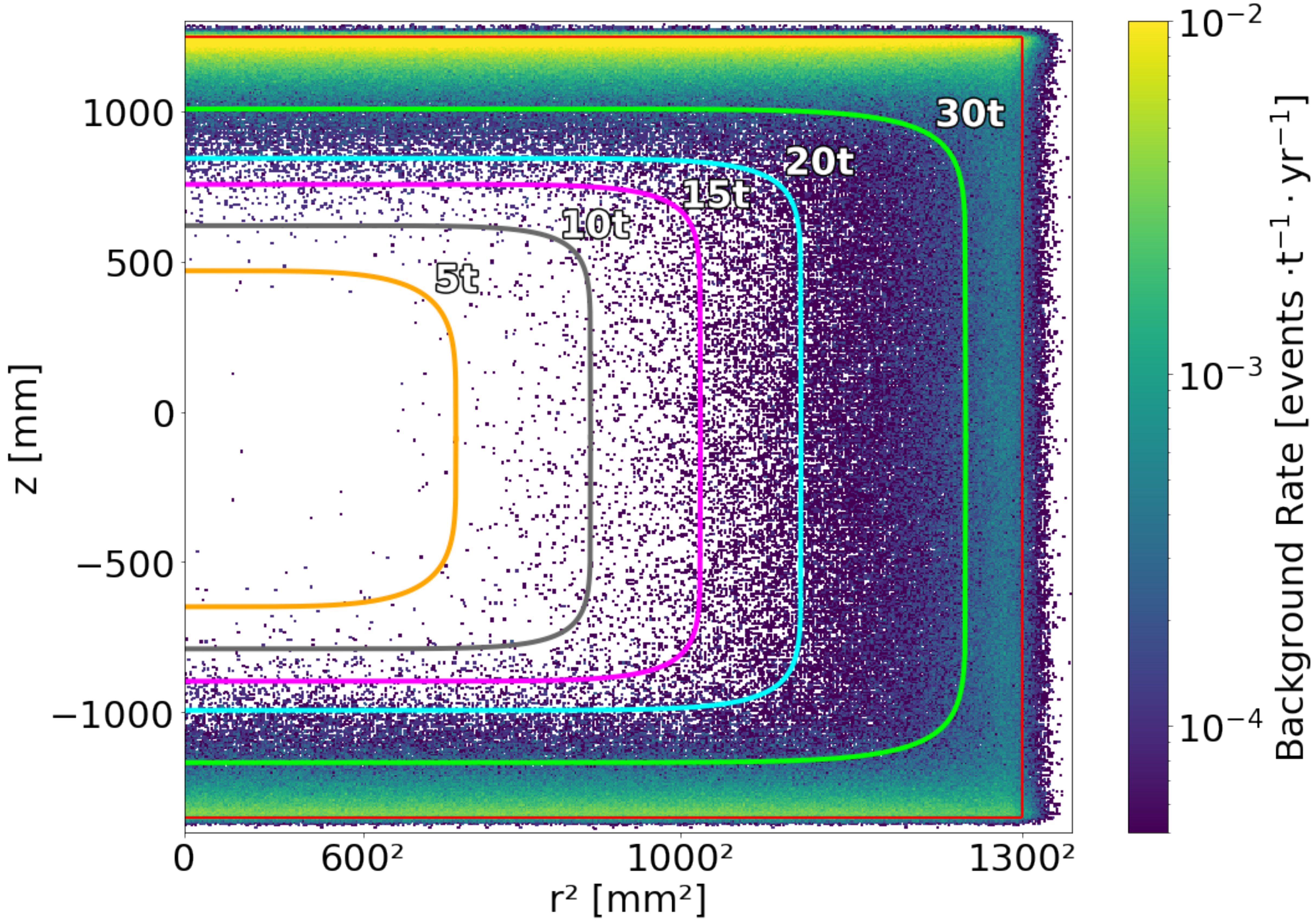
DARWIN Coll, Eur. Phys. J. C 80, 808 (2020); arXiv:2003.13407

DARWIN / XLZD

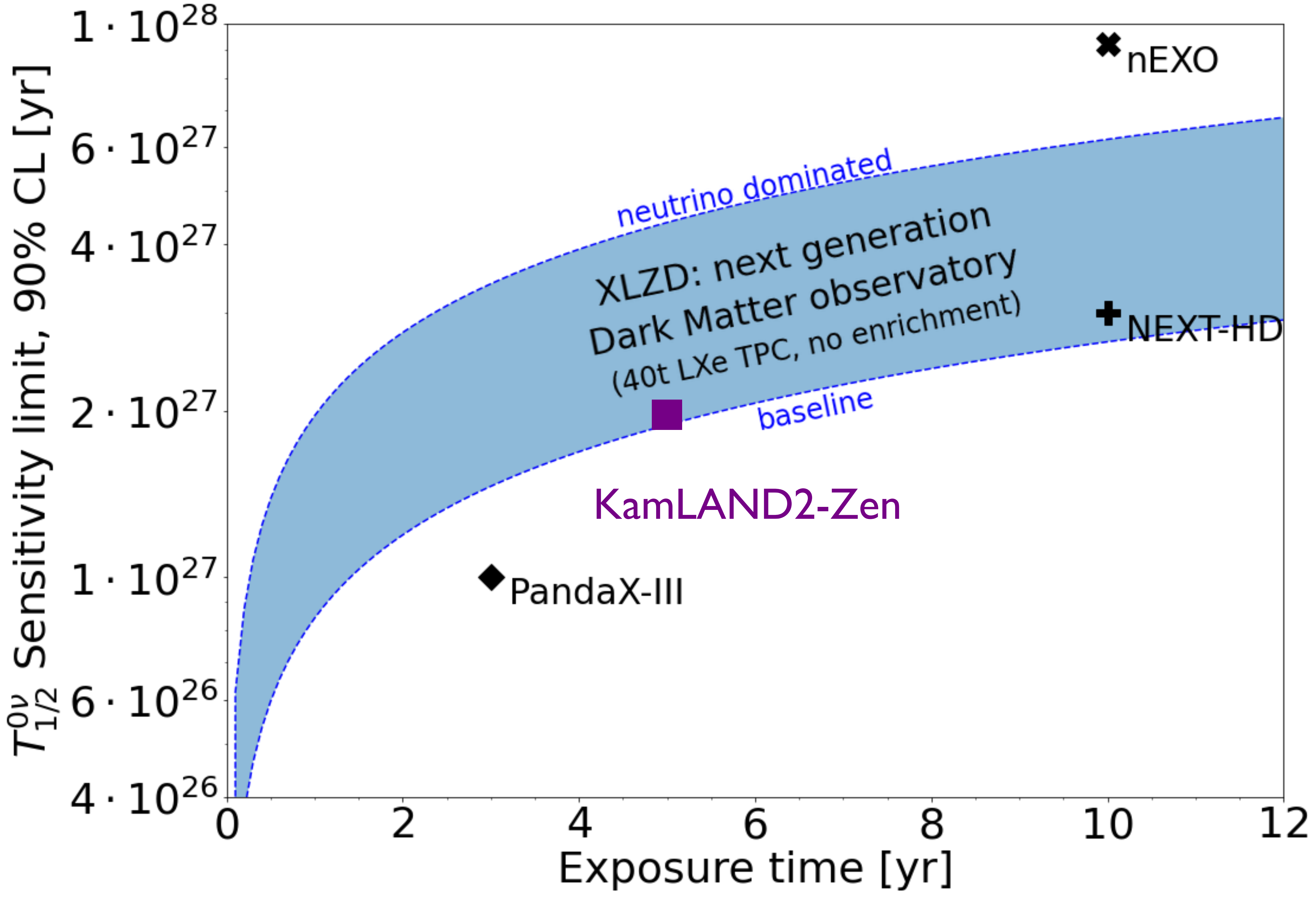
XLZD = XENON **+** LZ **+** DARWIN

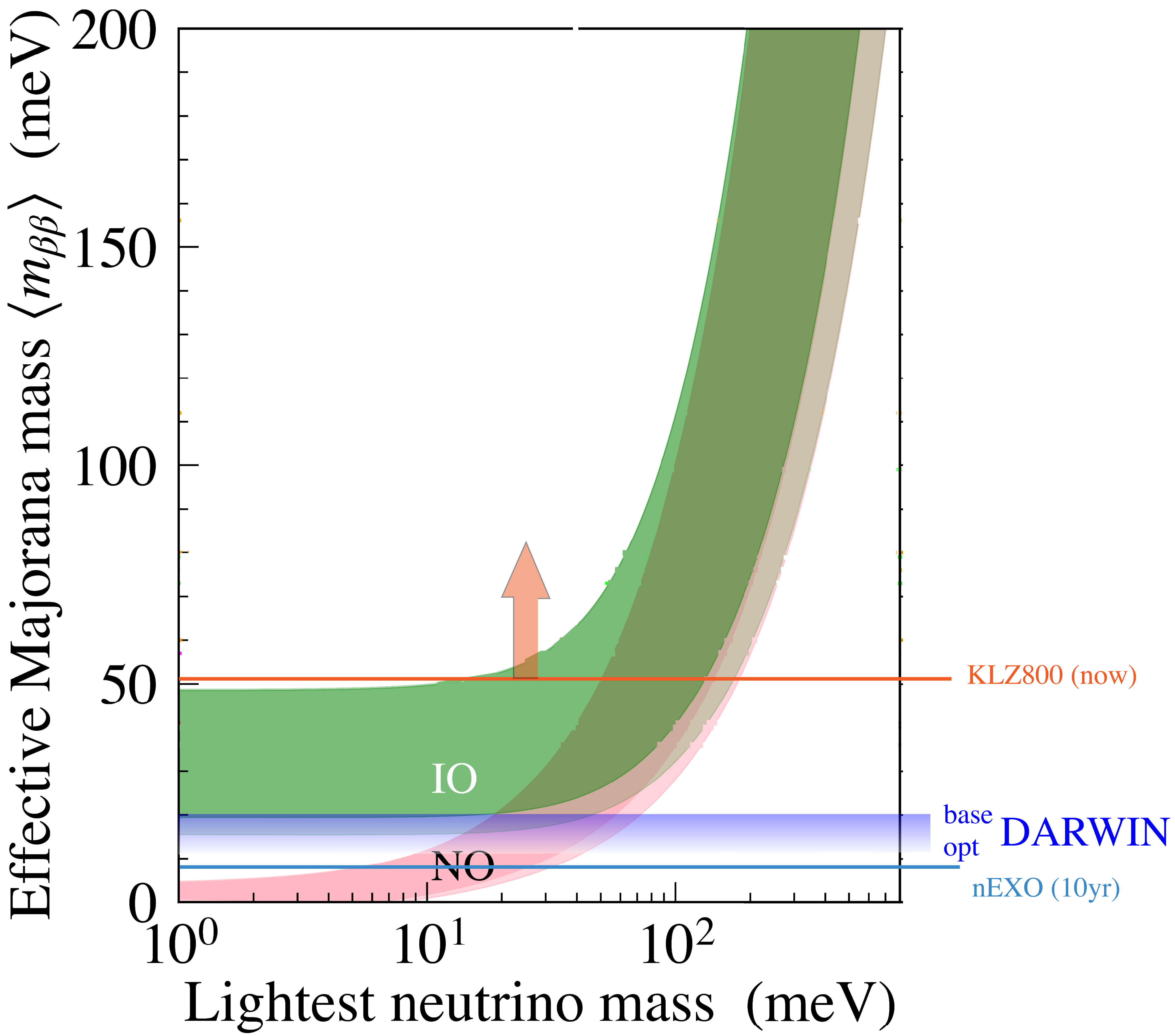


Self shielding of LXe



XLZD Sensitivity





[Assuming QRPA NME]

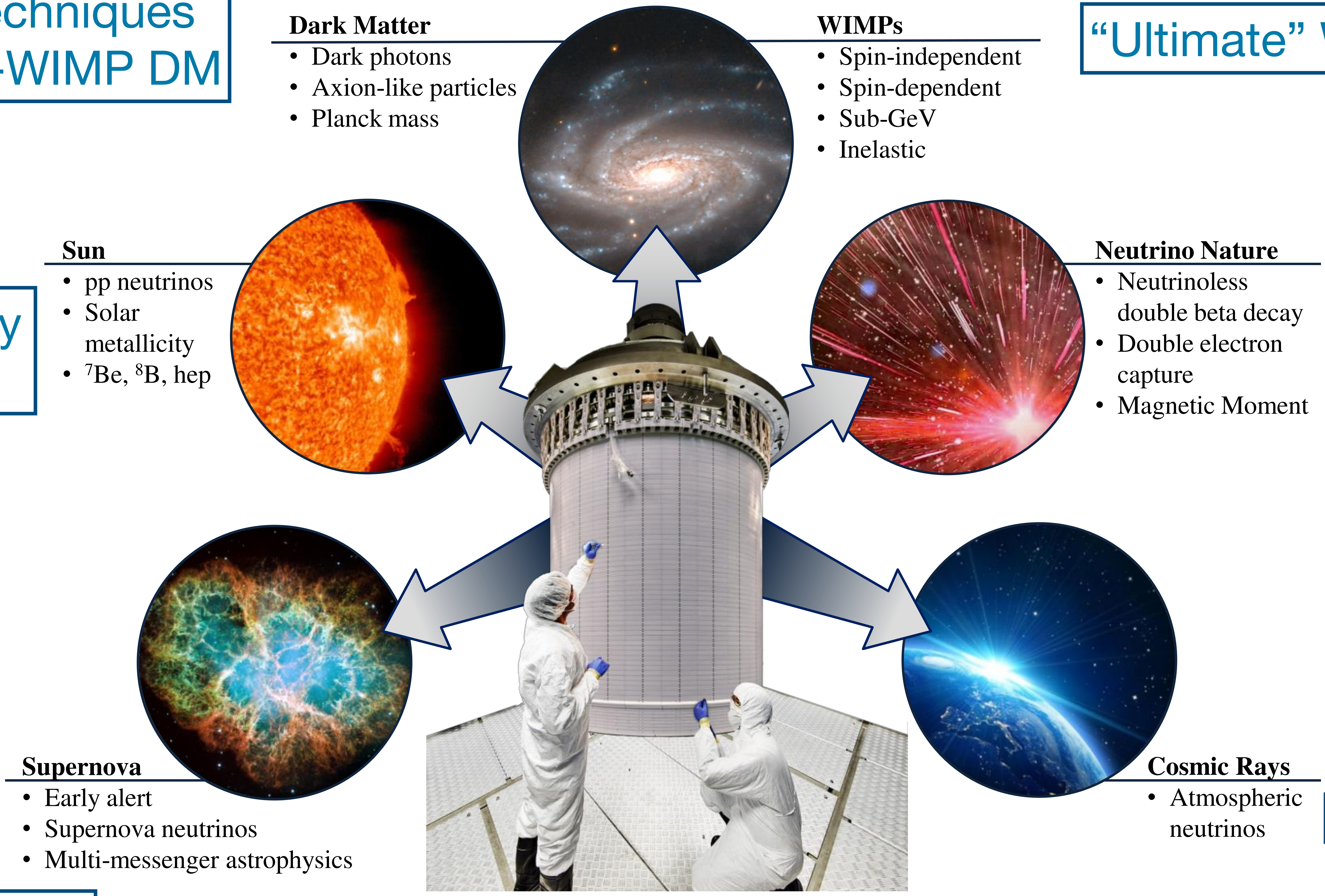
White Paper: J. Phys. G: Nucl. Part. Phys. 50 (2023) 013001, arXiv:2203.02309

Ultra-low BG + new techniques allow to search for non-WIMP DM

“Ultimate” WIMP DM detector

Low-E complementarity with DUNE

Competitive with dedicated 0v2b exp



Atmospheric $E_\nu < 100$ MeV

Detailed measurements if/when galactic SN occurs

Large liquid xenon mass and ultra-low backgrounds expand number of available physics channels

Summary

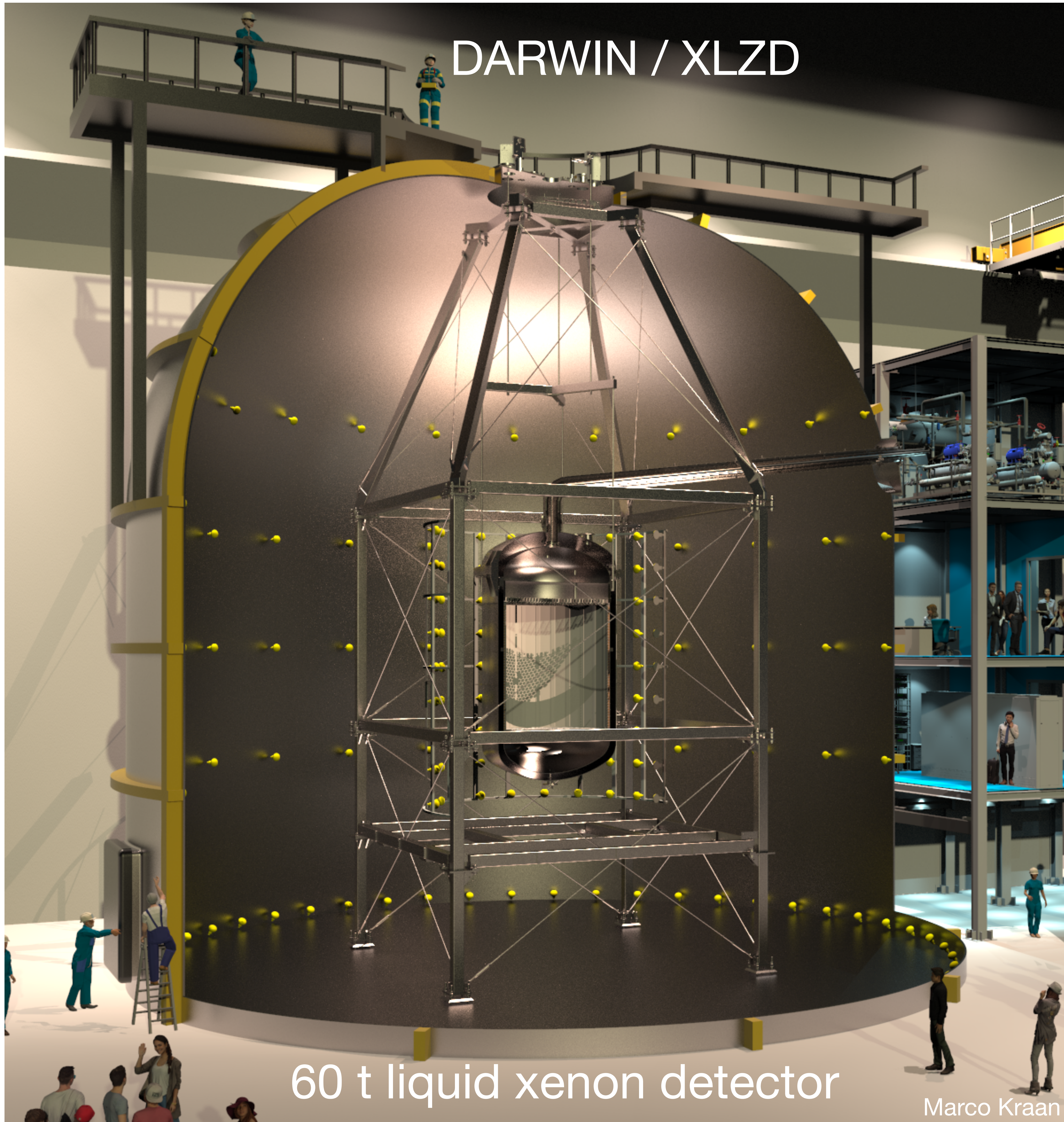
- Neutrinoless double beta decay searches are the only practical method to search for Majorana neutrinos in a model-independent way
- All KamLAND-Zen data
  - $T_{1/2}^{0\nu} > 2.3 \times 10^{26}$ yr (90% C.L.) → $\langle m_{\beta\beta} \rangle < 36 - 156$ meV
  - Best limit in the world - starting to probe Inverted Ordering
  - KamLAND-Zen 800 continues data taking
- KamLAND2-Zen will have sensitivity $\langle m_{\beta\beta} \rangle \sim 20$ meV
- Future LXe Rare Event Observatories like DARWIN/XLZD will become competitive with dedicated $0\nu2\beta$ experiments!

DM → Rare Event Searches & Measurements

XLZD = XENON + LZ + DARWIN

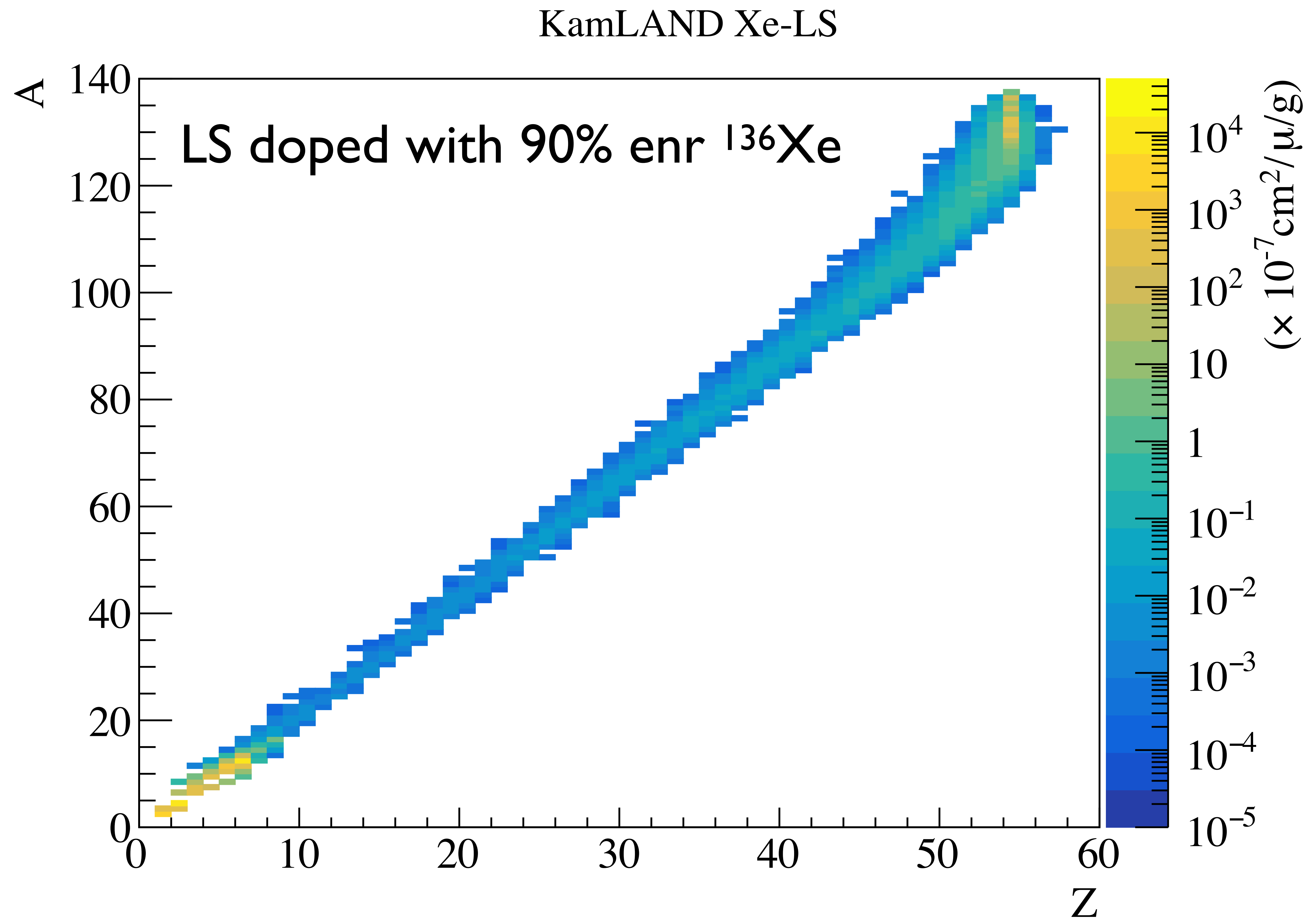
- Joined forces with competing LZ experiment
  - XLZD Consortium
- Ultra-sensitive liquid xenon rare event observatory
- On roadmaps in NL, Germany, Switzerland, US SNOWMASS / P5 process
- 60t LXe mass
- Preparing a Design Book

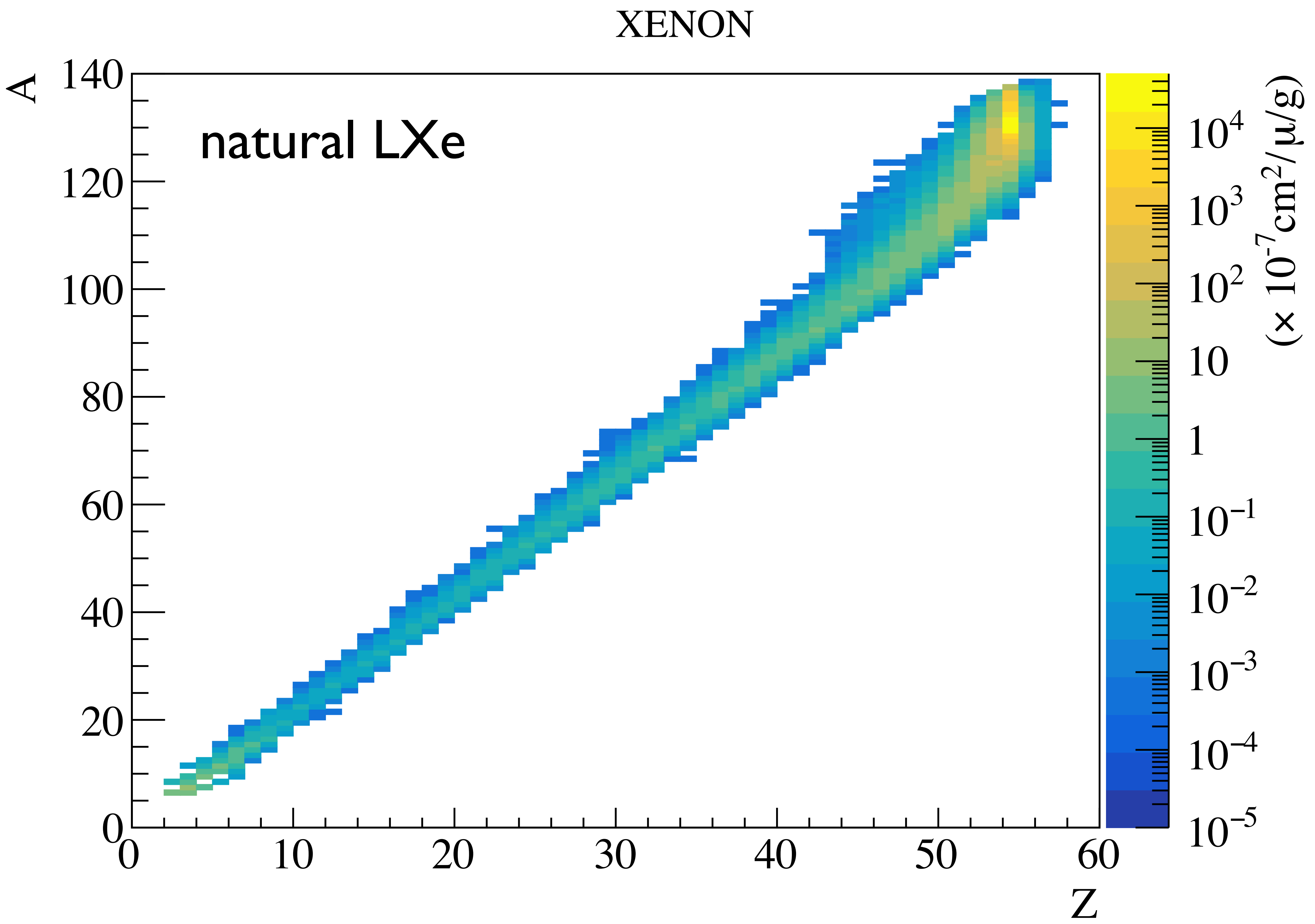
White Paper: J. Phys. G: Nucl. Part. Phys. 50 (2023) 013001, arXiv:2203.02309



Muon Spallation

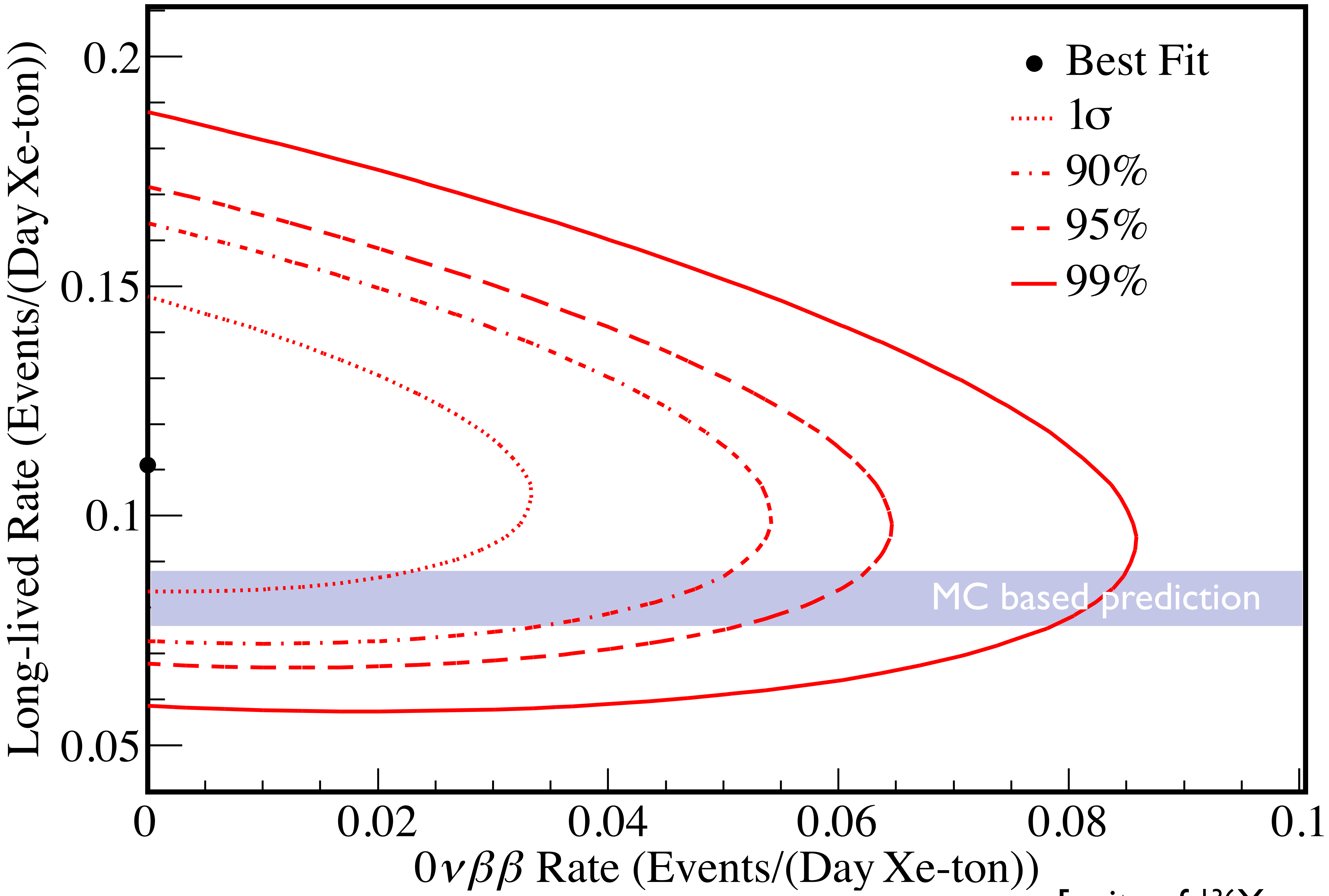
Not just KamLAND-Zen affected by spallation of heavy isotopes





Frequentist Results

Maximum likelihood calculation with raster scan of long-lived spallation rate and 0ν2β rate



[units of ^{136}Xe exposure]

Consistency between spallation FLUKA/G4 prediction and fitted values