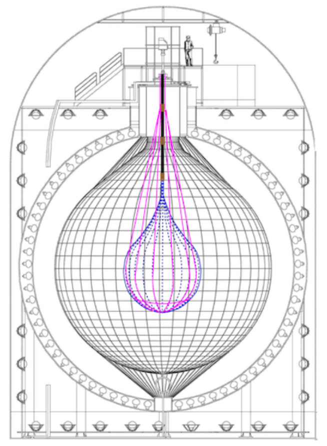
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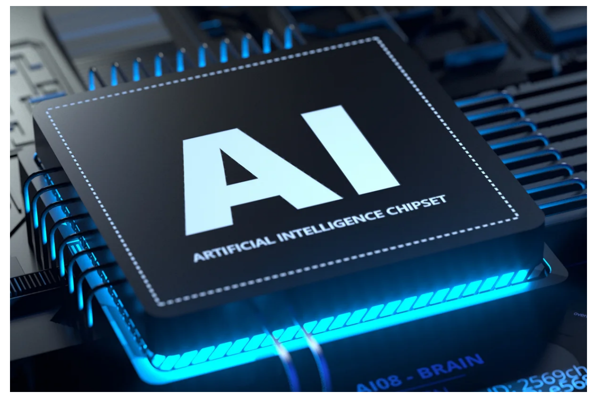

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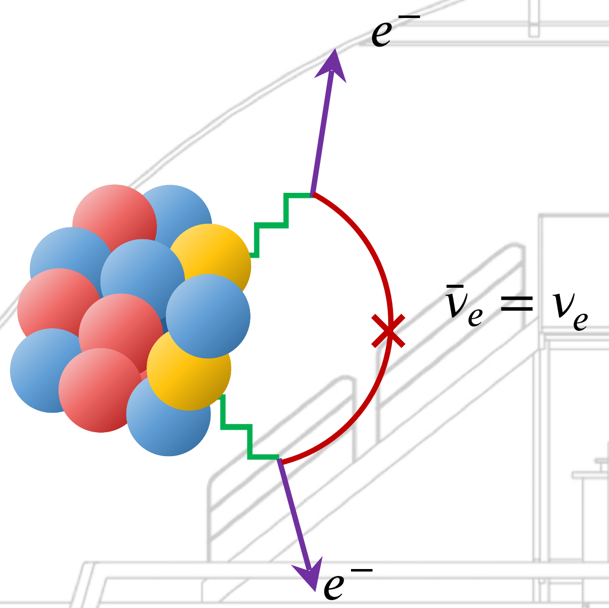


First Search For Majorana Neutrino at the Inverted Mass Ordering Region with KamLAND-Zen

Aobo Li
On Behalf of KamLAND-Zen Collaboration

CONFERENCE ON SCIENCE AT THE SANFORD UNDERGROUND RESEARCH FACILITY
South Dakota Mines campus, May 11-13, 2022

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

KamLAND — Zero neutrino double beta decay search — KamLAND-Zen

TUNL — Triangle Universities Nuclear Laboratory

CoSSURF 2022, 04/07/2022

Neutrinoless Double Beta Decay

Double Beta Decay ($2\nu\beta\beta$)

2nd order weak interaction in SM
Half-life ~ $10^{14\text{-}24}$ years

Neutrinoless Double-Beta Decay ($0\nu\beta\beta$)

Monoenergetic peak at the Q-value of $2\nu\beta\beta$ isotope

BSM Lepton Number Violation ($\Delta L=2$)

Directly imply neutrino is Majorana

Explain matter-antimatter asymmetry

Measuring Majorana Neutrino

If neutrino is Majorana, its mass scale can be described by effective Majorana mass ($m_{\beta\beta}$)

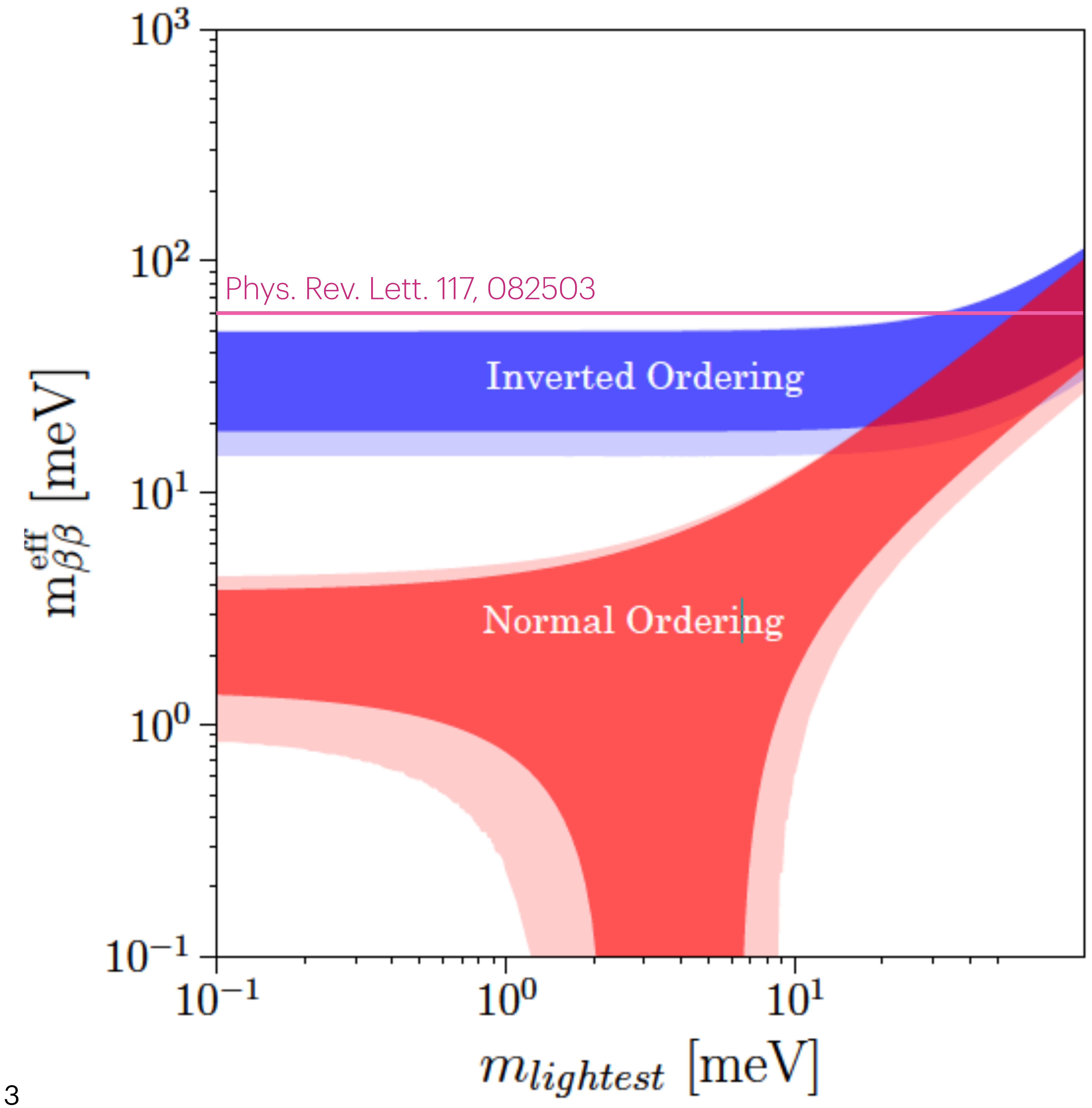
- $m_{\beta\beta}$ can be expressed as a function of lightest neutrino mass
- subject to uncertainties in oscillation angle and neutrino mass ordering

$m_{\beta\beta}$ can also be obtained experimentally by measuring $0\nu\beta\beta$ half-life:

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}|M^{0\nu}|^2 m^2_{\beta\beta}$$

- $G^{0\nu}$: Phase space factor
- $|M^{0\nu}|^2$: nuclear matrix element
- $|m_{\beta\beta}| = |\sum_i U^2_{ei} m_i|$: effective Majorana mass

Prior to this result, the best $m_{\beta\beta}$ limit is given by the KamLAND-Zen and GERDA experiments



KamLAND-Zen

Liquid Scintillator Detector

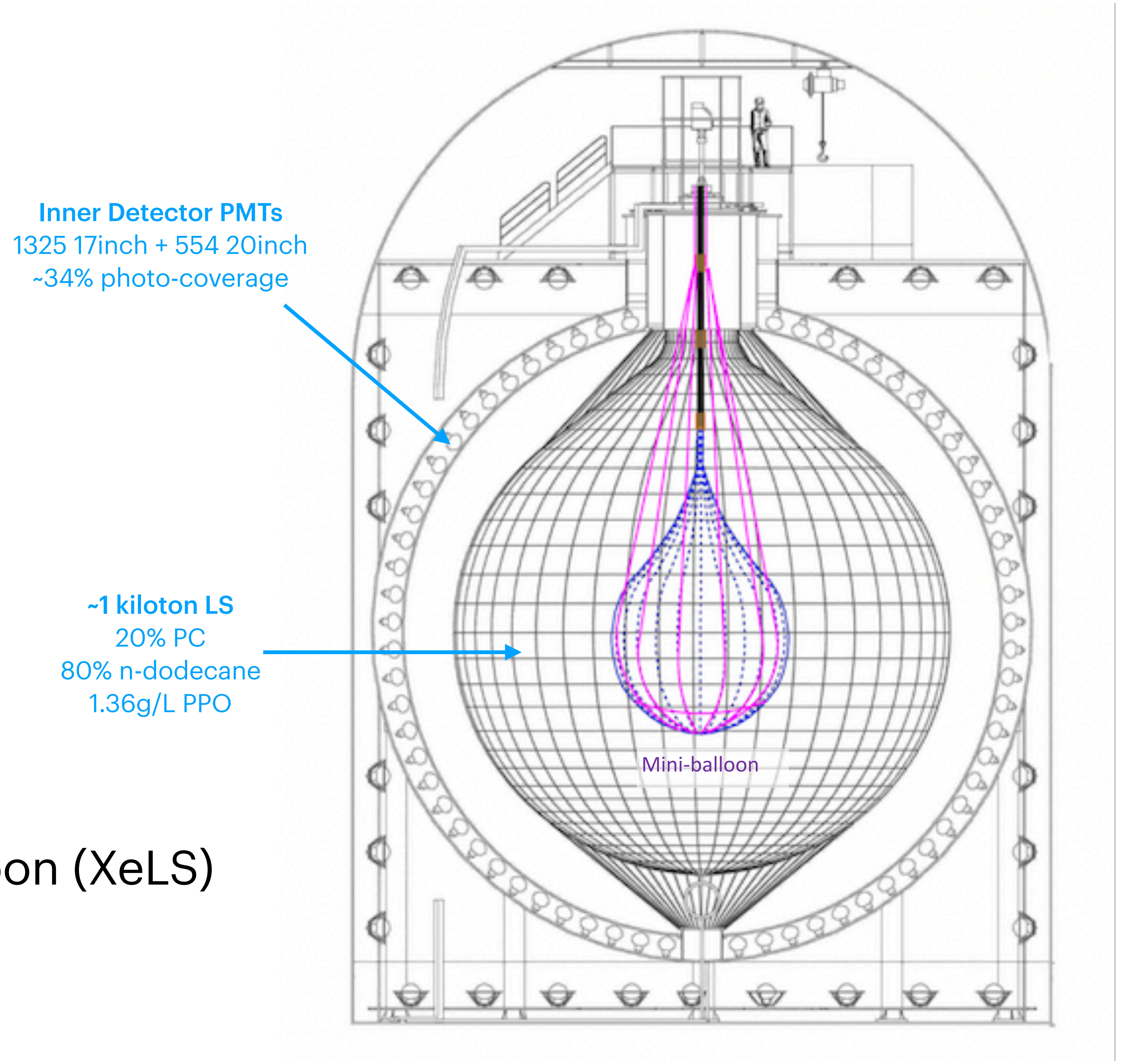
Located in Kamioka mine with 2700m w.e.

Mini-balloon:

- 25-μm-thick nylon film (durable)
- Fabricated in class-1 clean room
- Highly transparent (~99% at 400 nm)

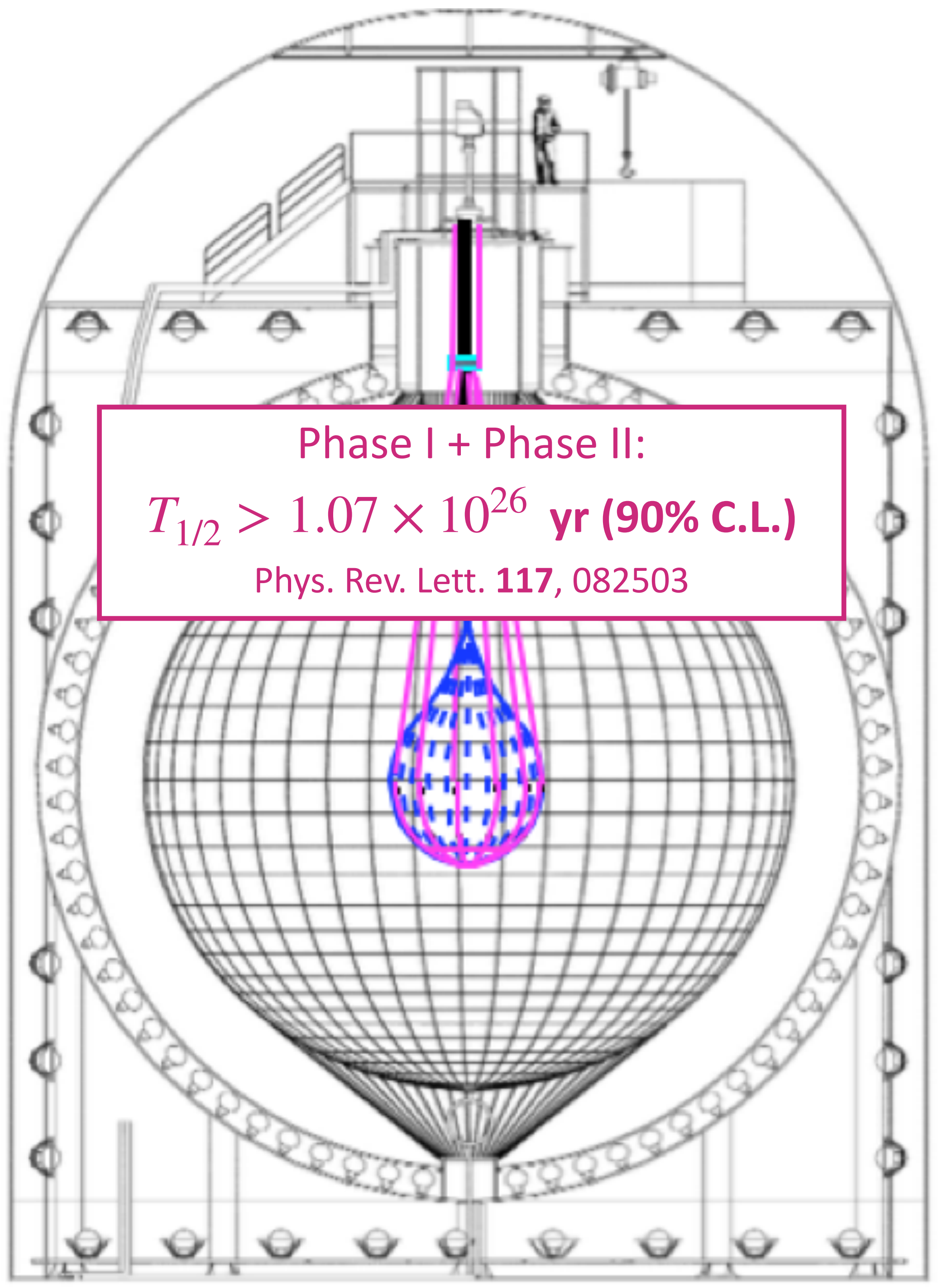
Xenon Loading:

- 91% enriched ^{136}Xe loaded in LS inside mini-balloon (XeLS)
- Purification is well-established
- Chemically stable (noble gas)



Progress of KamLAND-Zen

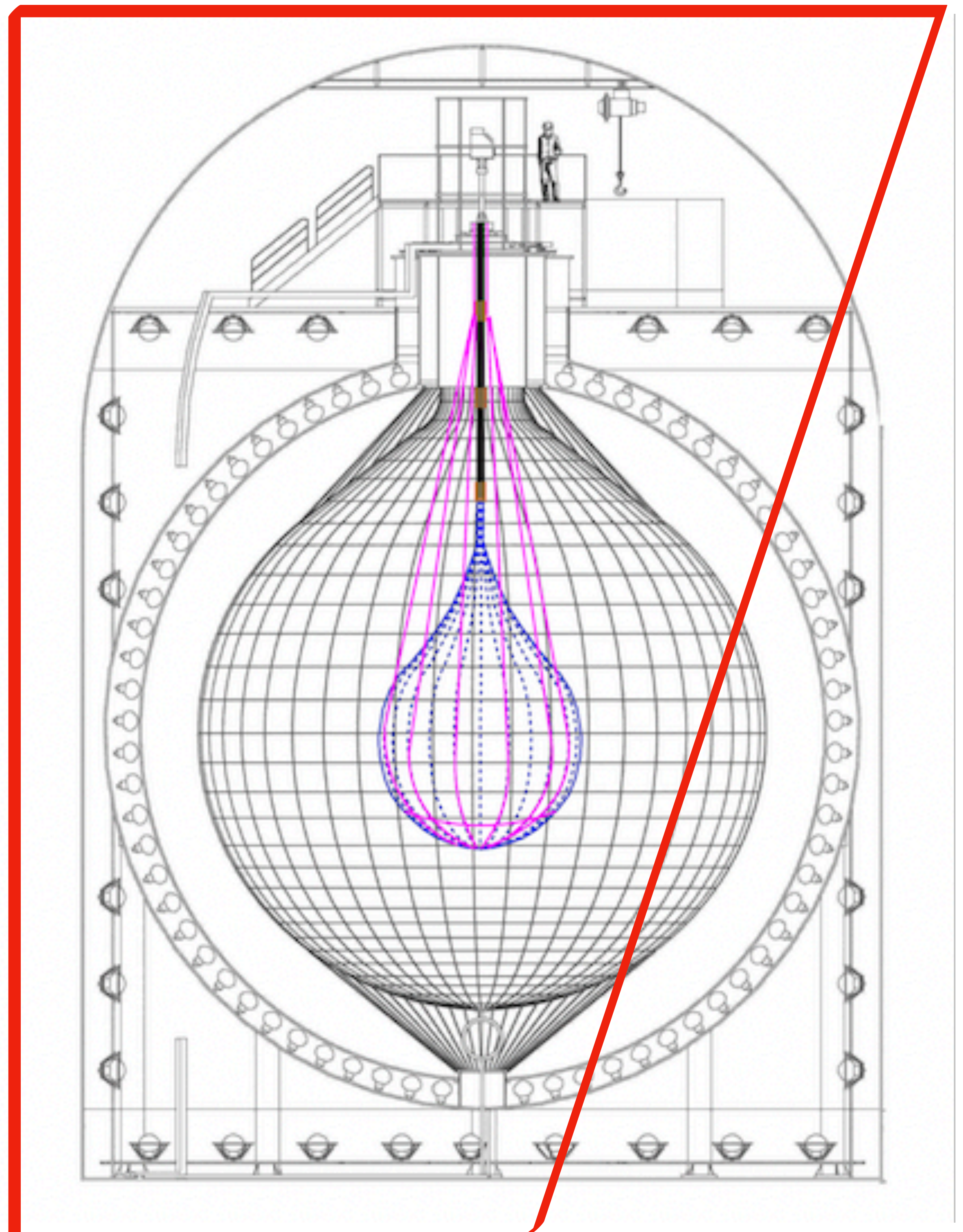
Past



KamLAND-Zen 400:

- Mini-balloon Radius = 1.54 m
- Xenon mass = 320 ~ 380 kg
- Duration: 2011 ~ 2015

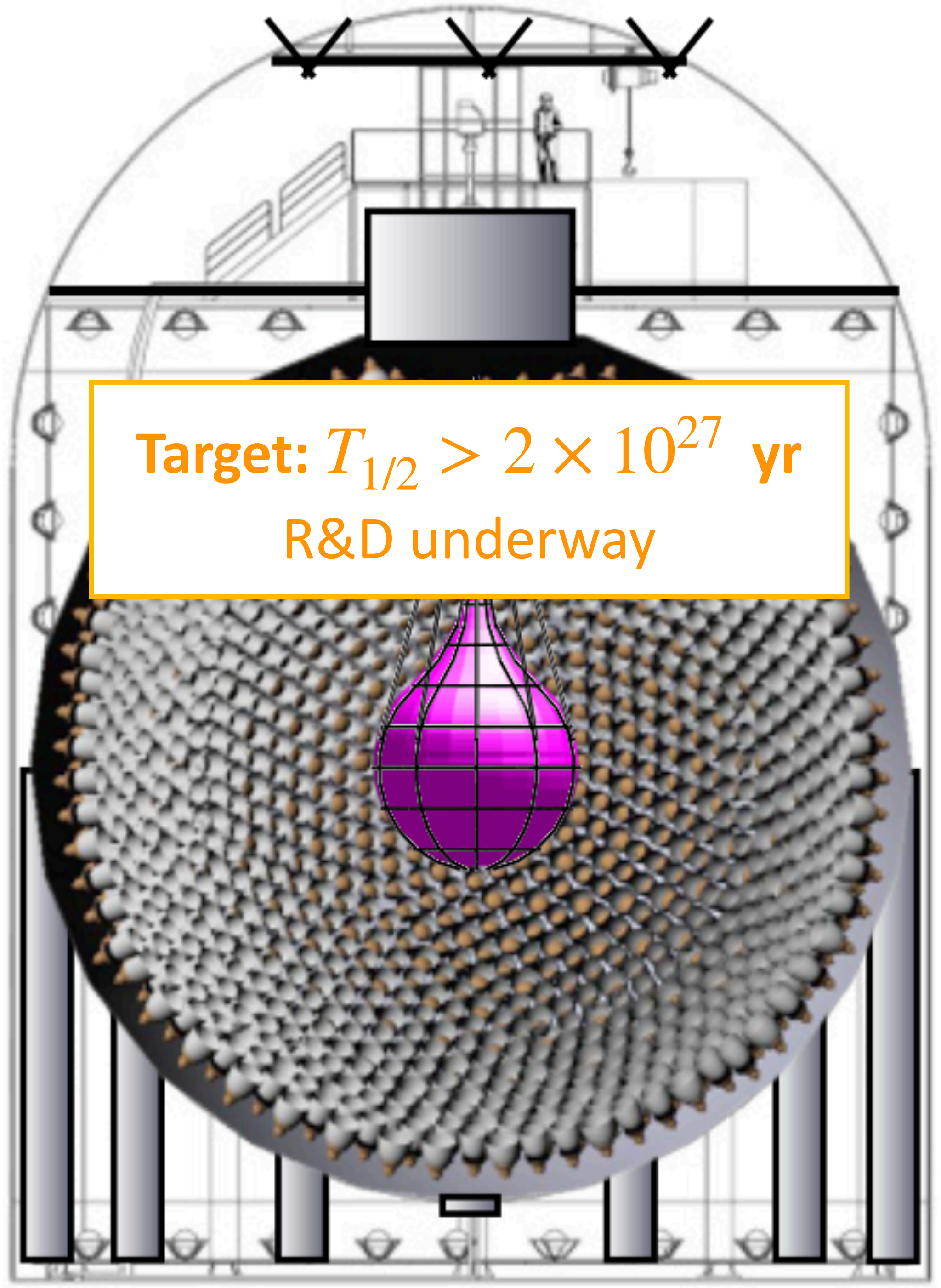
Present



KamLAND-Zen 800:

- Mini-balloon Radius = 1.90 m
- Xenon mass = 745 kg
- Data taking starts Jan. 2019

Future



KamLAND2-Zen:

- Xenon mass ~ 1ton
- Aiming at 100% Photocoverage
- PEN scintillation balloon film

Mini-balloon

2017 — May 2018 — Jan. 2019

Balloon Manufacturing at Sendai, Class 1 Clean Room | LS Purification and Xe Loading | Data Taking

① Film Washing

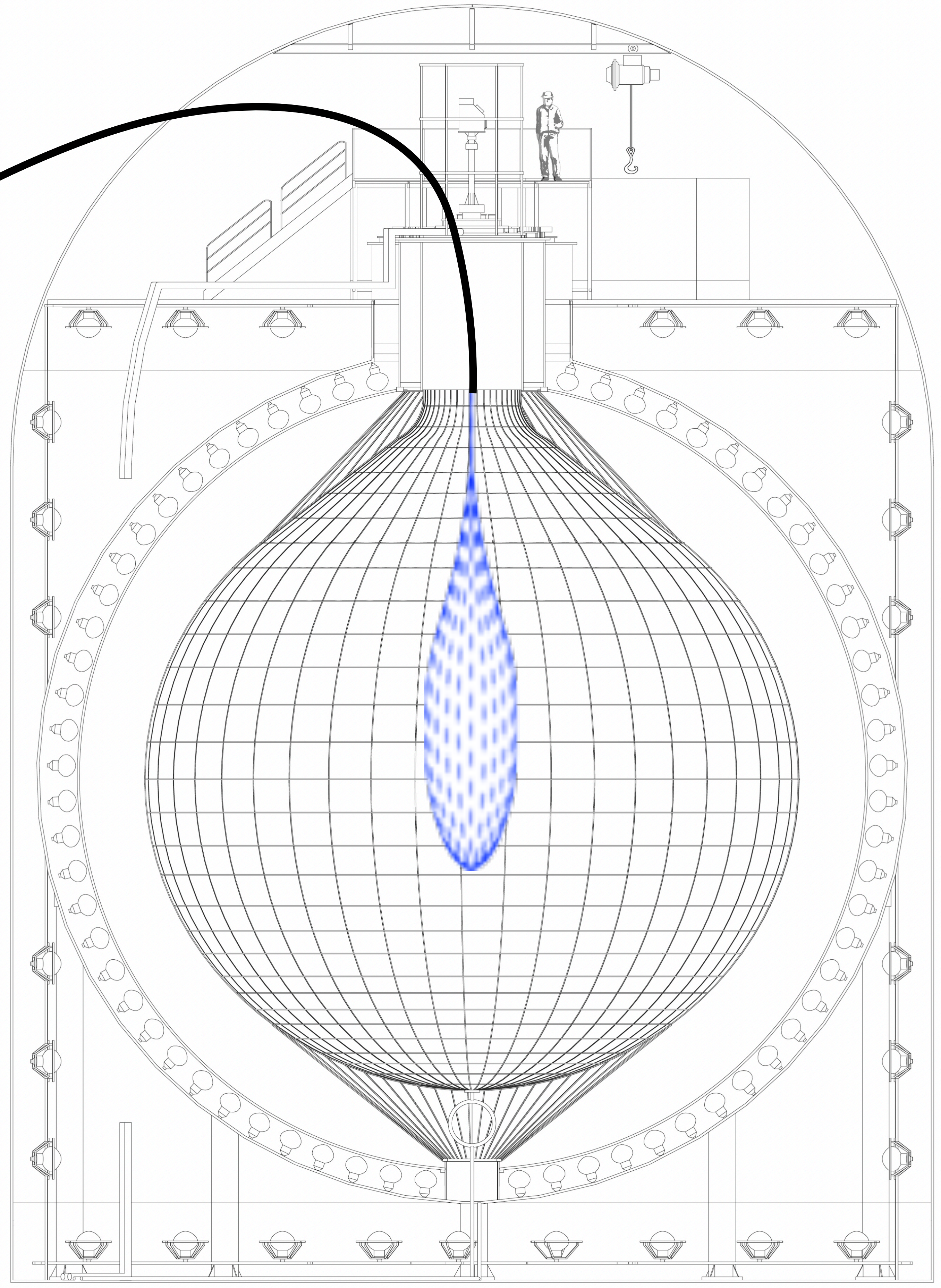
② Seam Welding

③ He leak test + repairs

④ Folding

⑤ Packaging

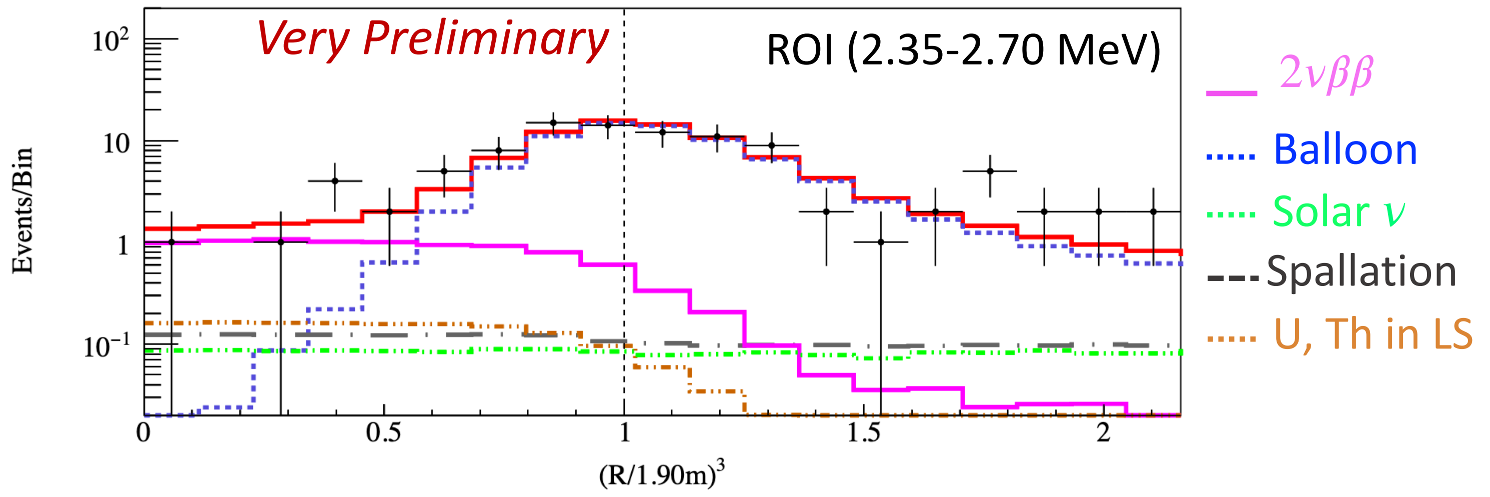
⑥ Deployment

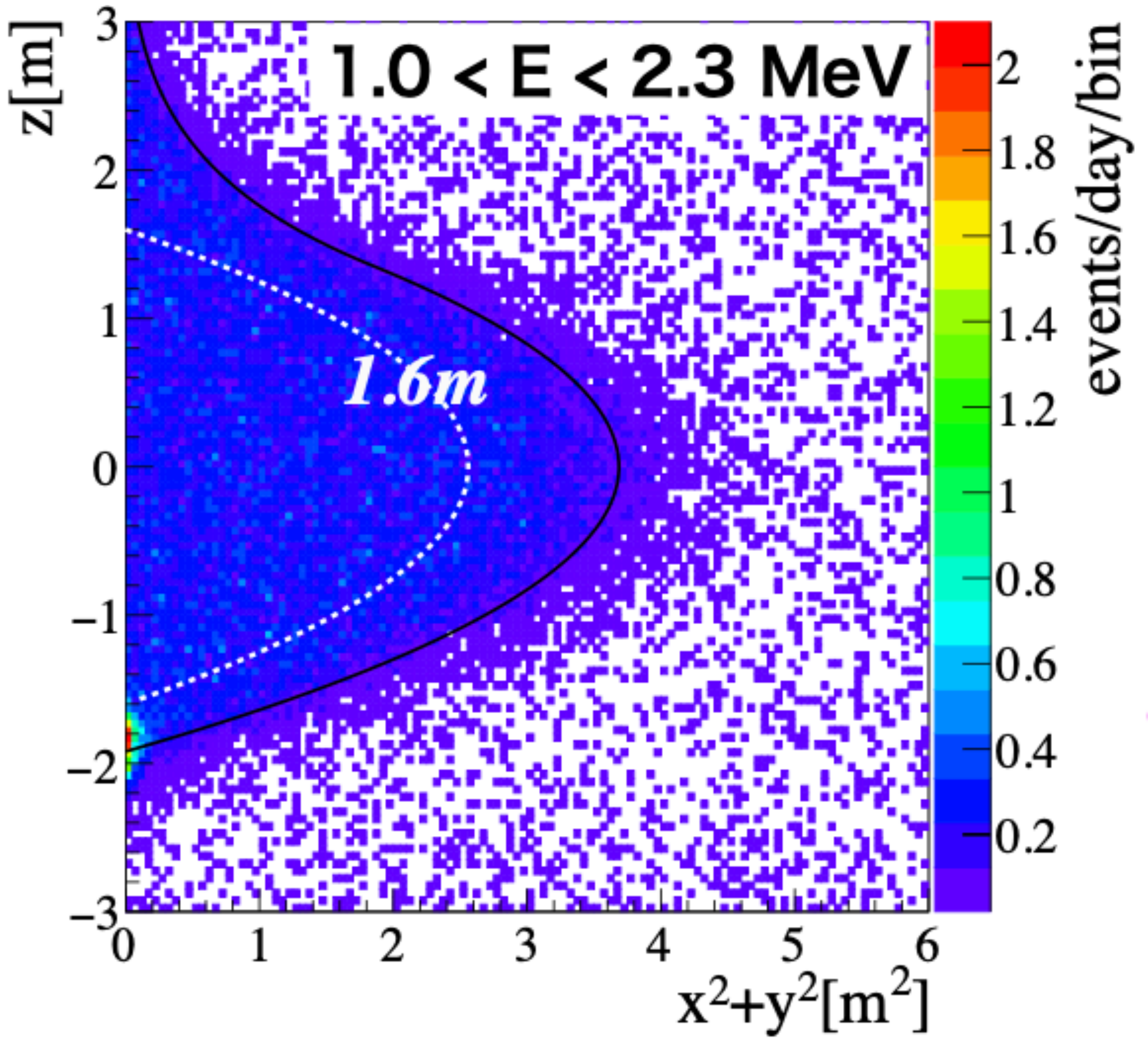


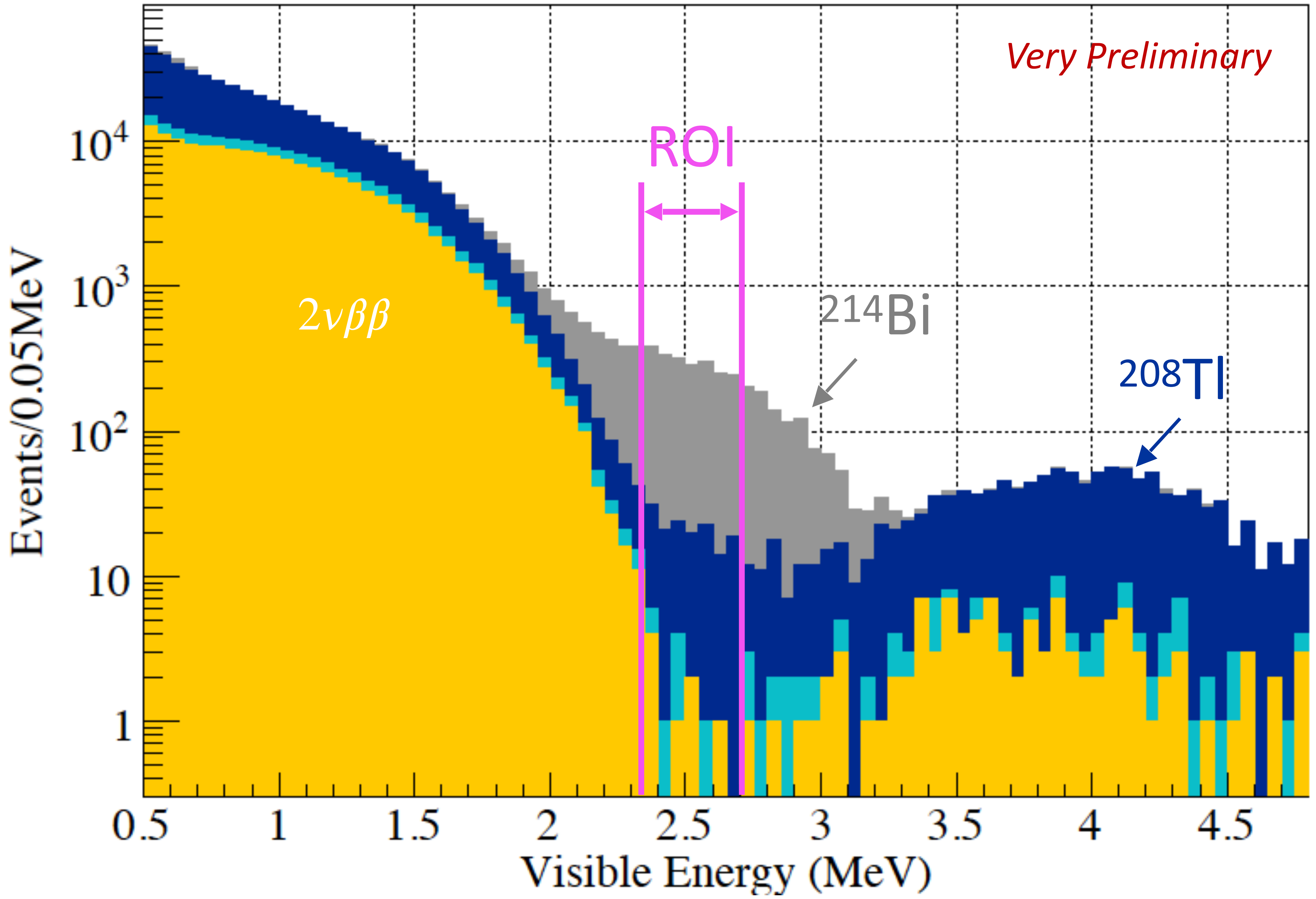
Background Reduction

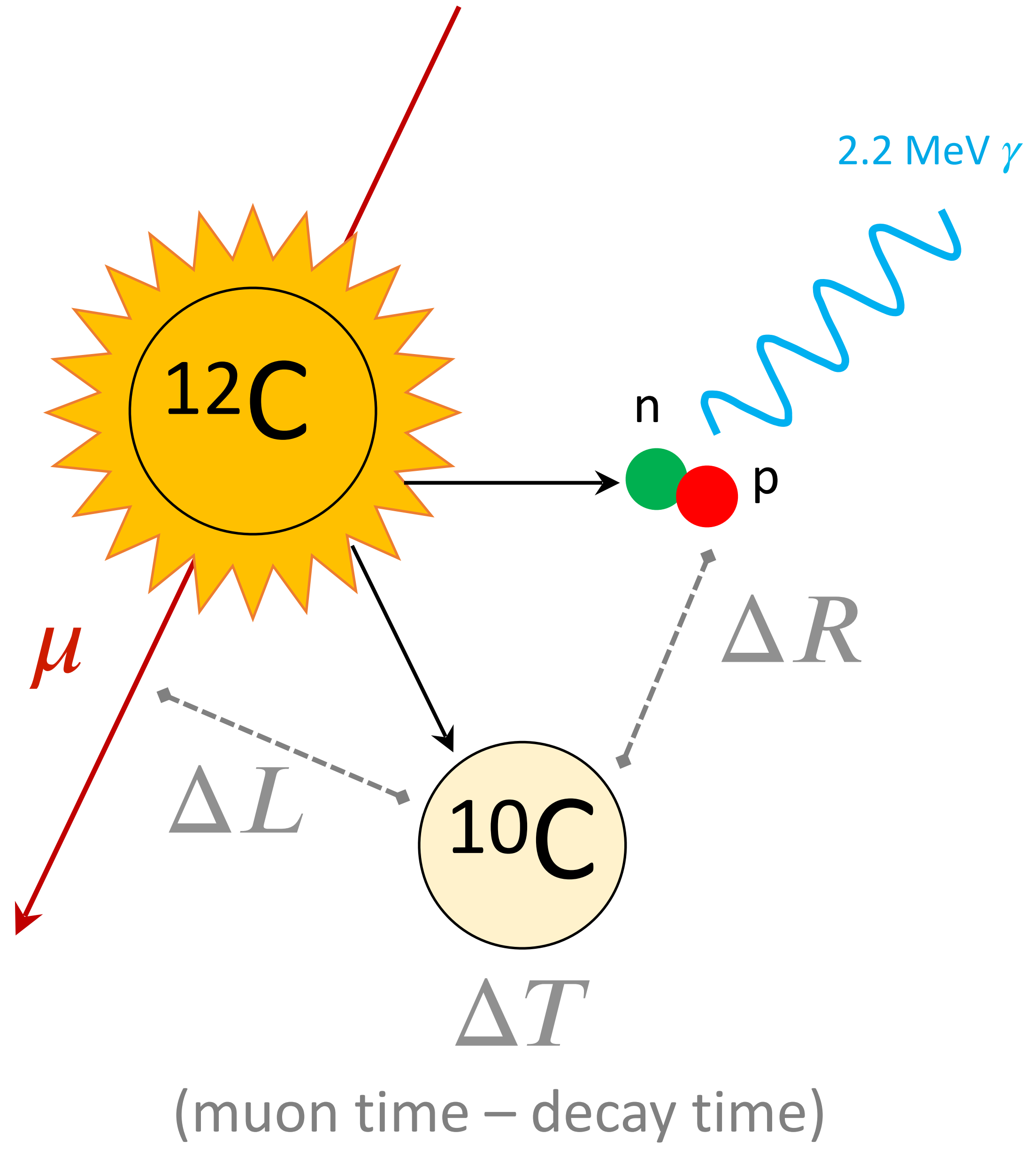
Balloon Film Backgrounds:

- $^{238}U \sim 3 \times 10^{-12} g/g$
- $^{232}Th \sim 4 \times 10^{-11} g/g$
- $\times$ 10 reduction compared to KLZ400 mini-balloon





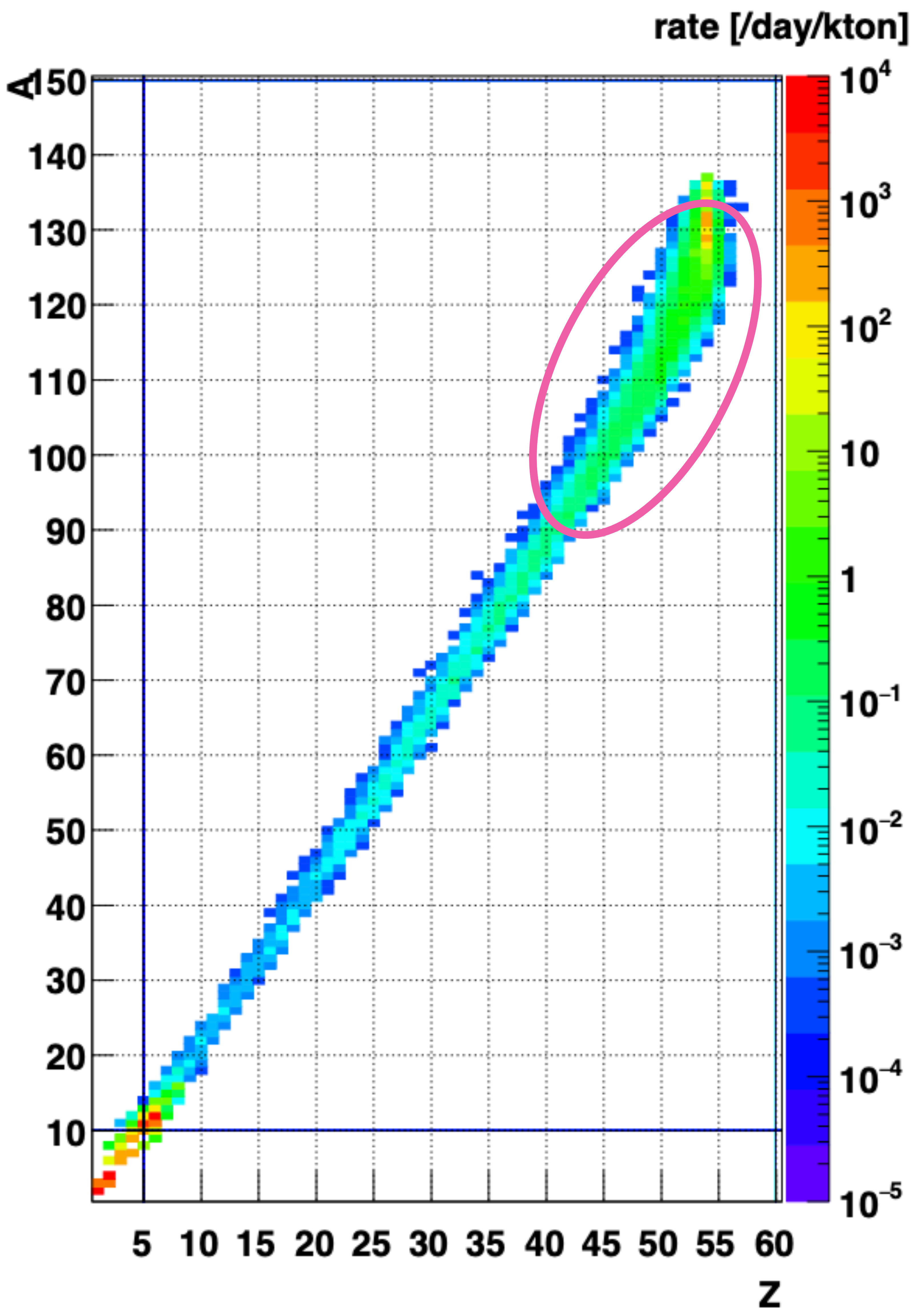


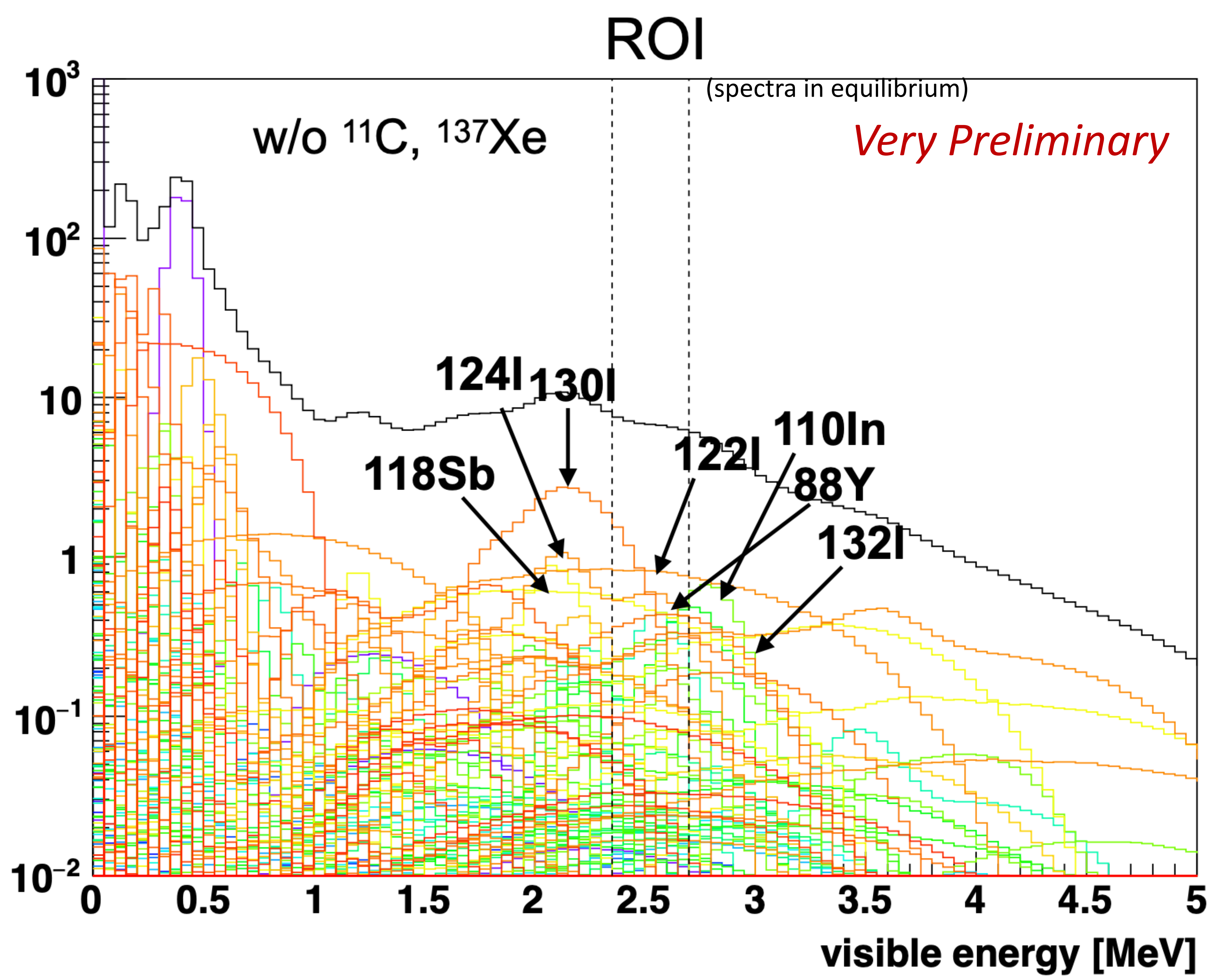


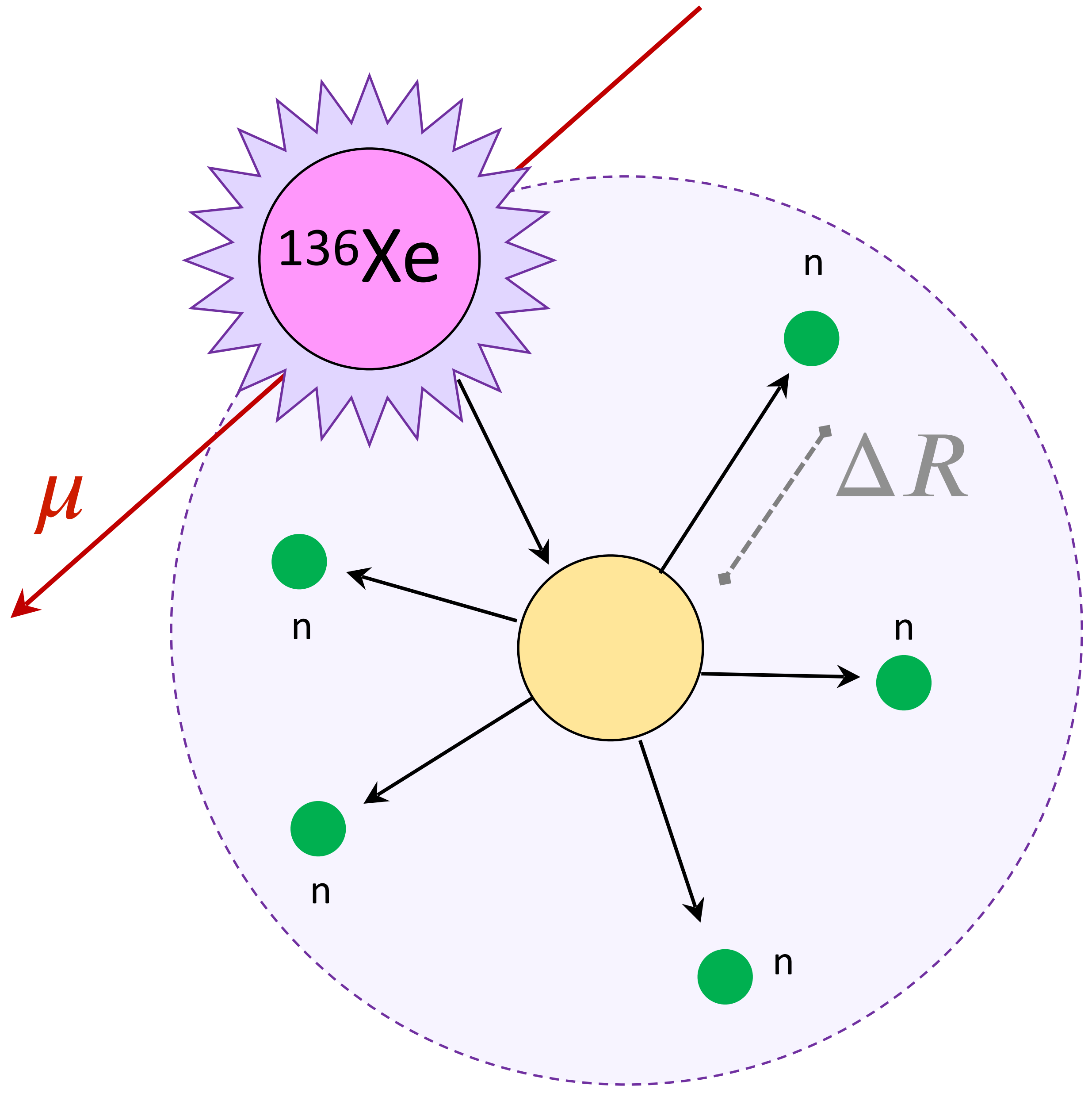
XeLS Backgrounds:

- **Rn cut:** Delayed coincidence cut for ^{214}Bi – ^{214}Po and ^{212}Bi – ^{212}Po
  - ~100% tagging efficiency in XeLS region and 50% tagging efficiency near the IB
- **Spallation Cut:** Remove events correlated with muons
  - **Triple coincidence tag:** Muon - ^{10}C - neutron capture
  - > ~95% tagging efficiency

Muon Spallation on ^{136}Xe



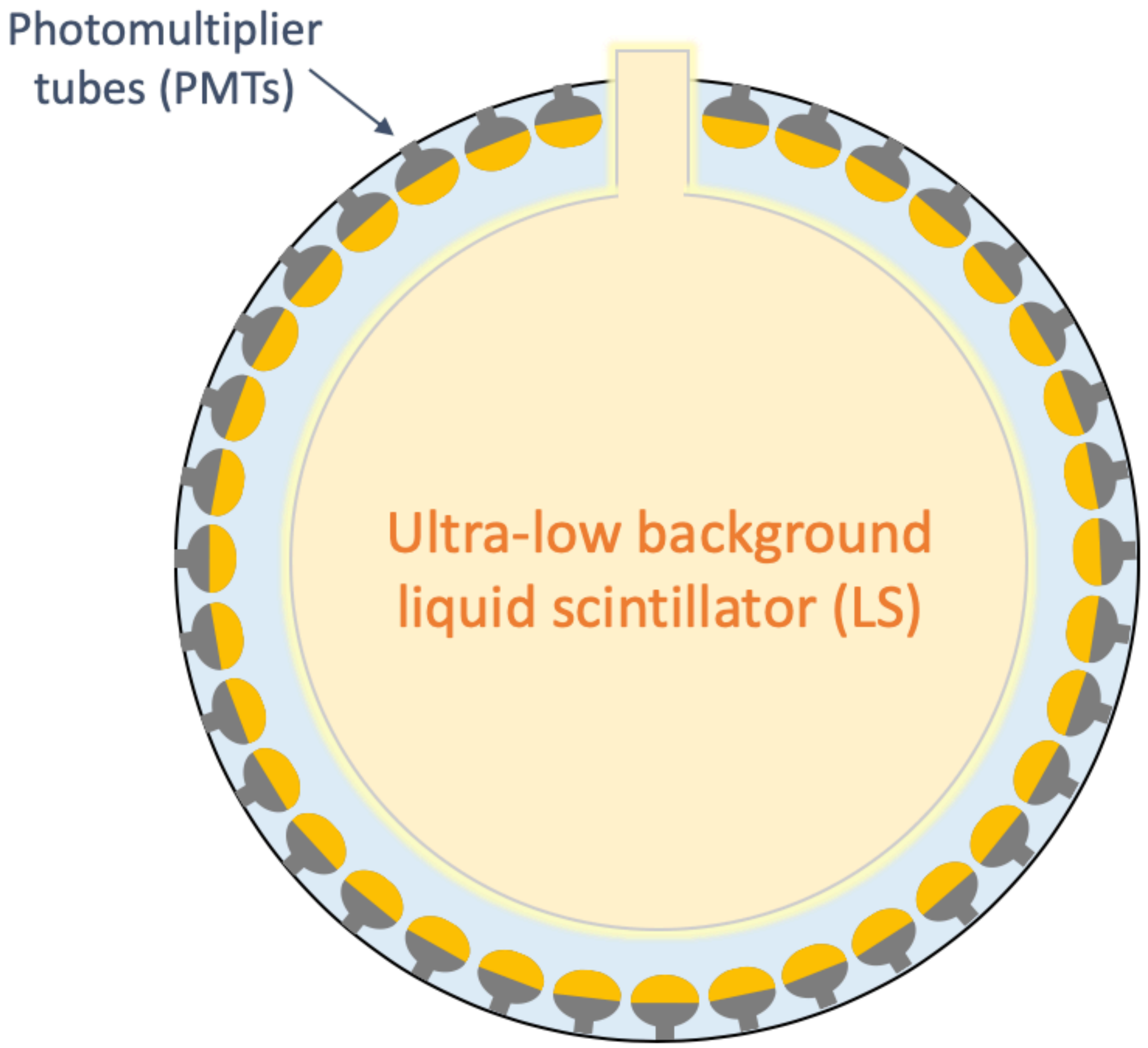




Long-lived Spallation Products:

- Spallations of ^{136}Xe nuclei produce radioactive isotopes with high mass number
- $\beta^{+/-}$ decay, dominating backgrounds in ROI
- Long-lived: half-lives range from ~hours to ~days, making coincidence tagging tricky
- A day-long LL spallation tagging is developed to tag 42.0±8.0% of these events
  - 8% signal sacrifice
- **Non-coincidence PID** could be the remedy

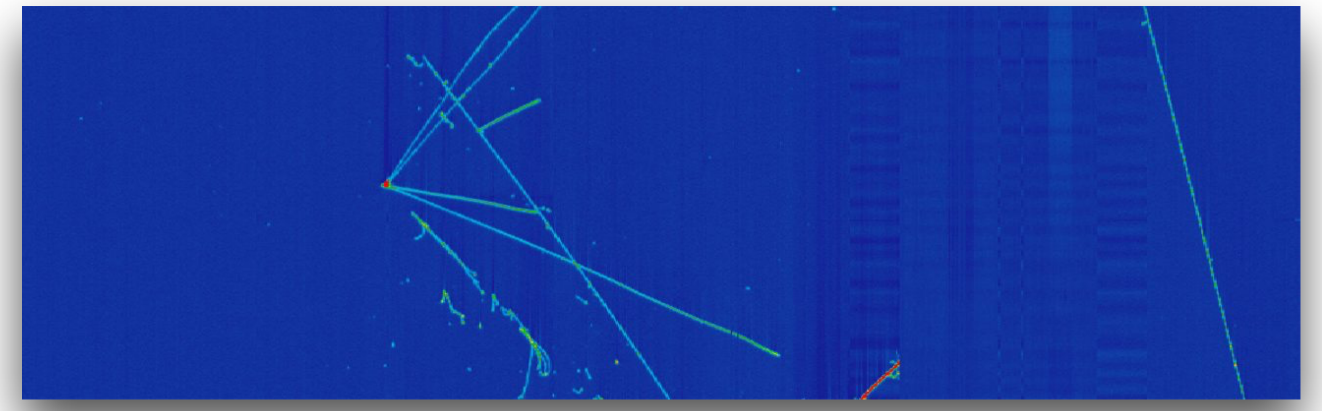
Calorimeter vs. Tracker



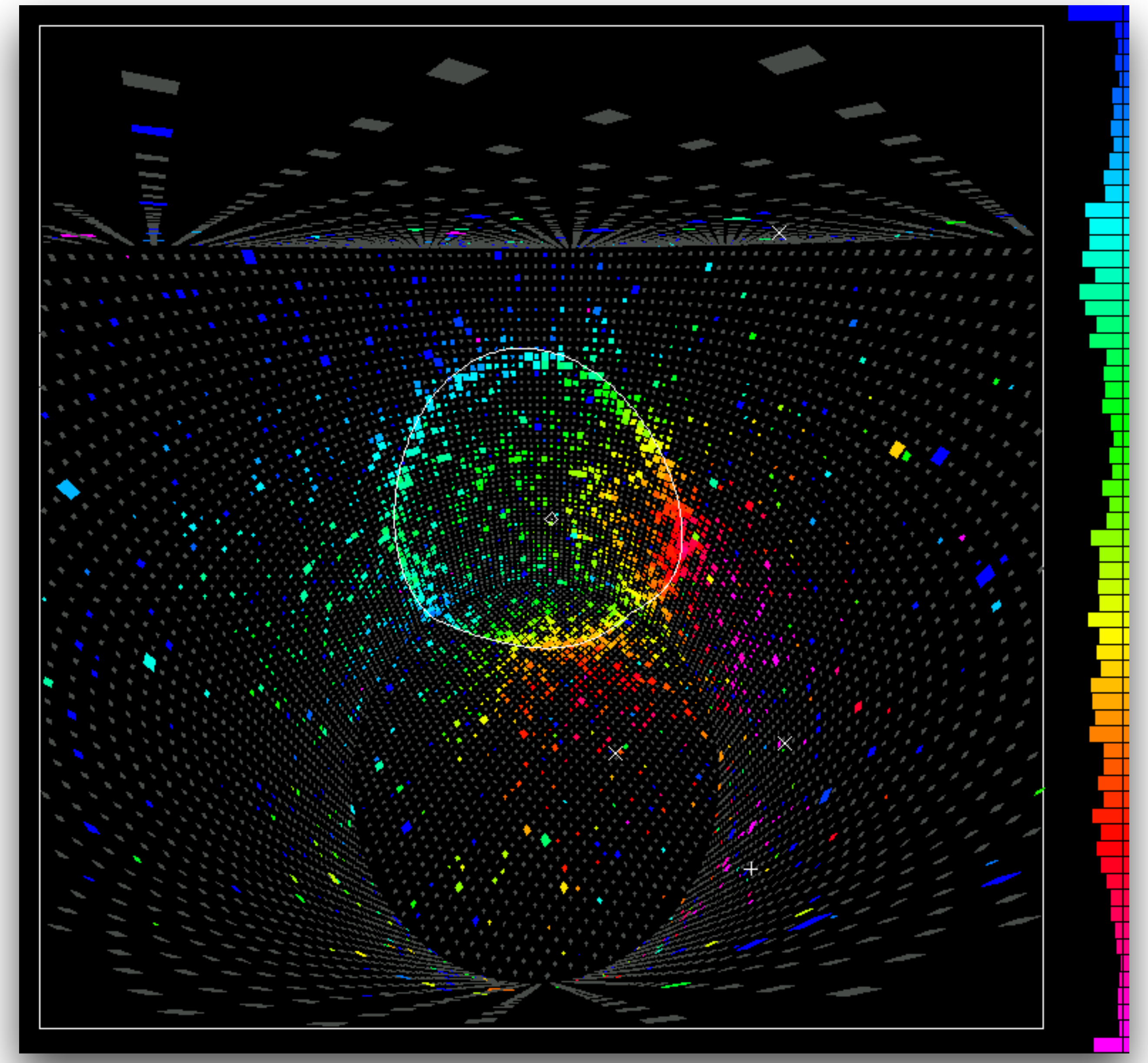
Liquid Scintillator Detector

- Has been at the heart of many great discoveries in neutrino physics
- Function primarily as a calorimeter at ~MeV range

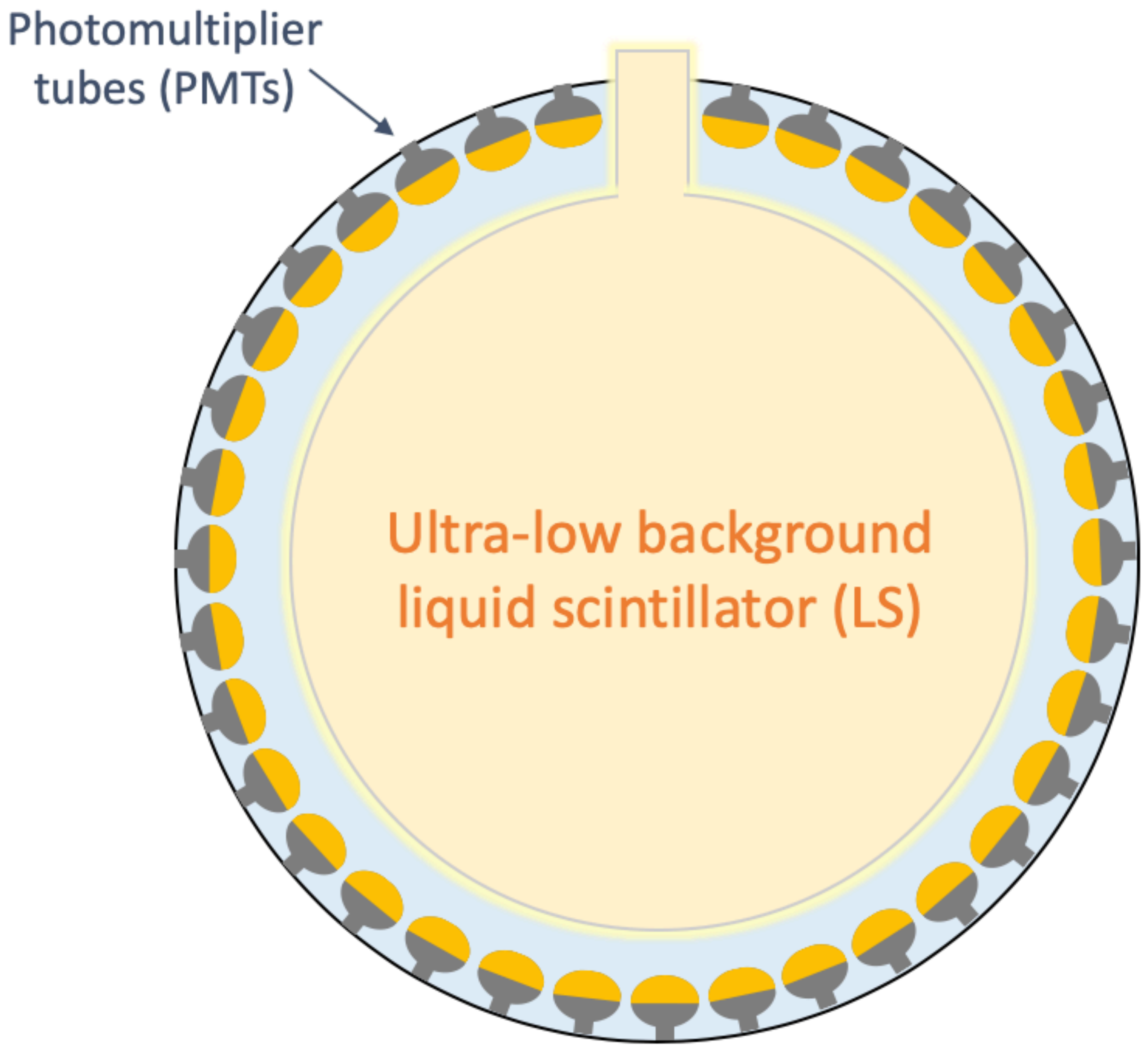
Time Projection Chamber



Water Cherenkov Detector



Calorimeter vs. Tracker



Liquid Scintillator Detector

- Has been at the heart of many great discoveries in neutrino physics
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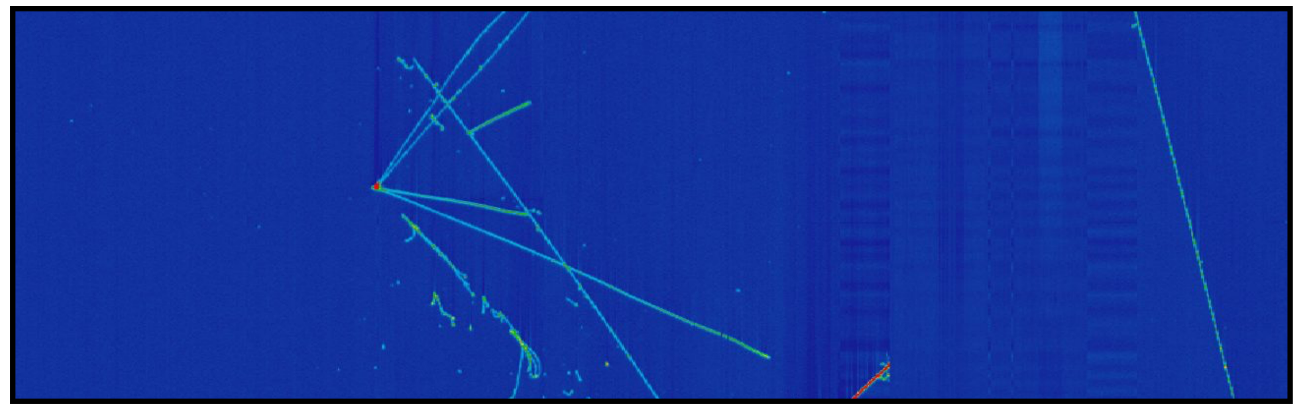
Enhancing **monolithic LS detectors** with the capability to discriminate between different event types based on **tracking** and **topology** would be a revolutionary advancement

Time Projection Chamber



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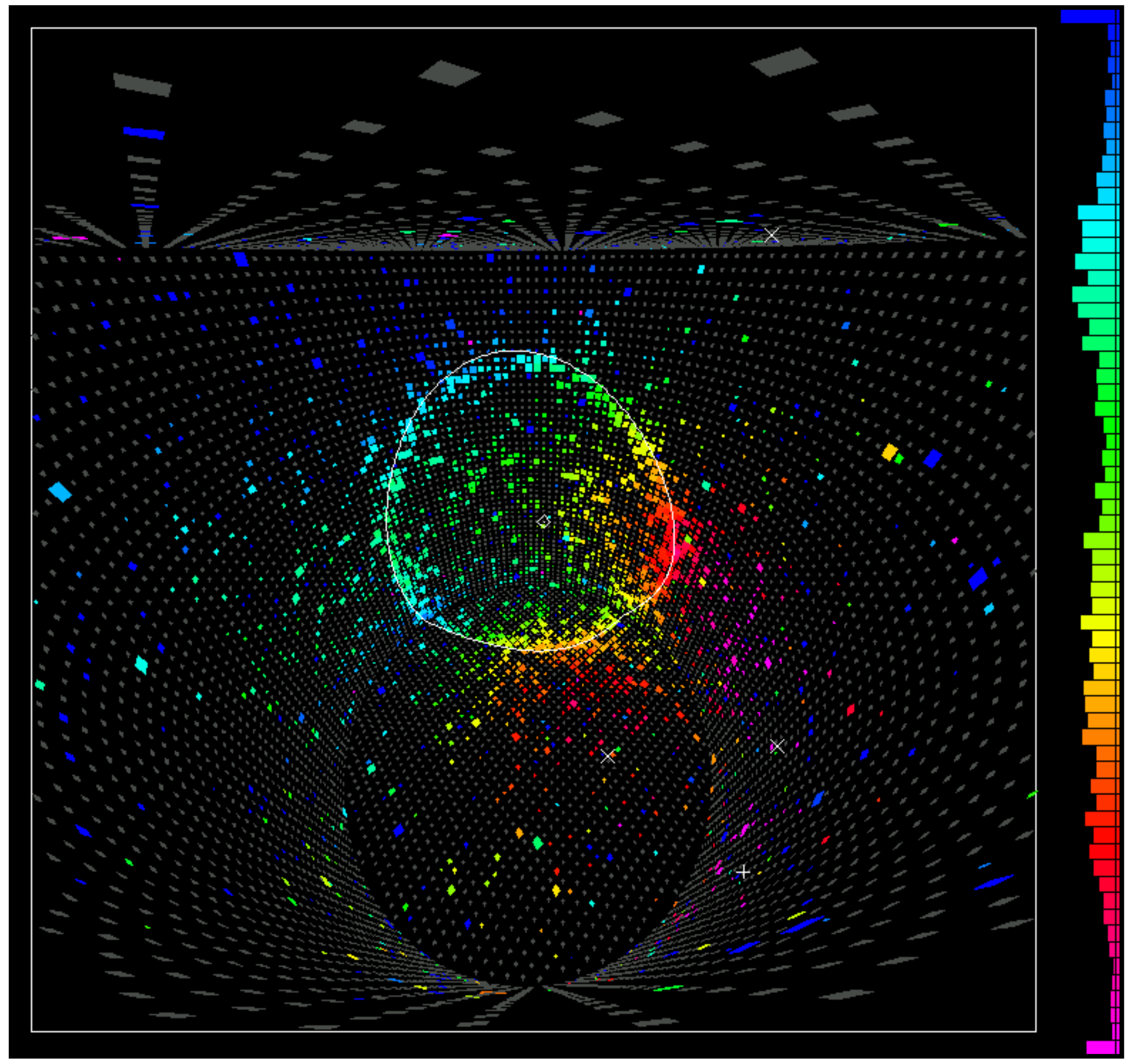

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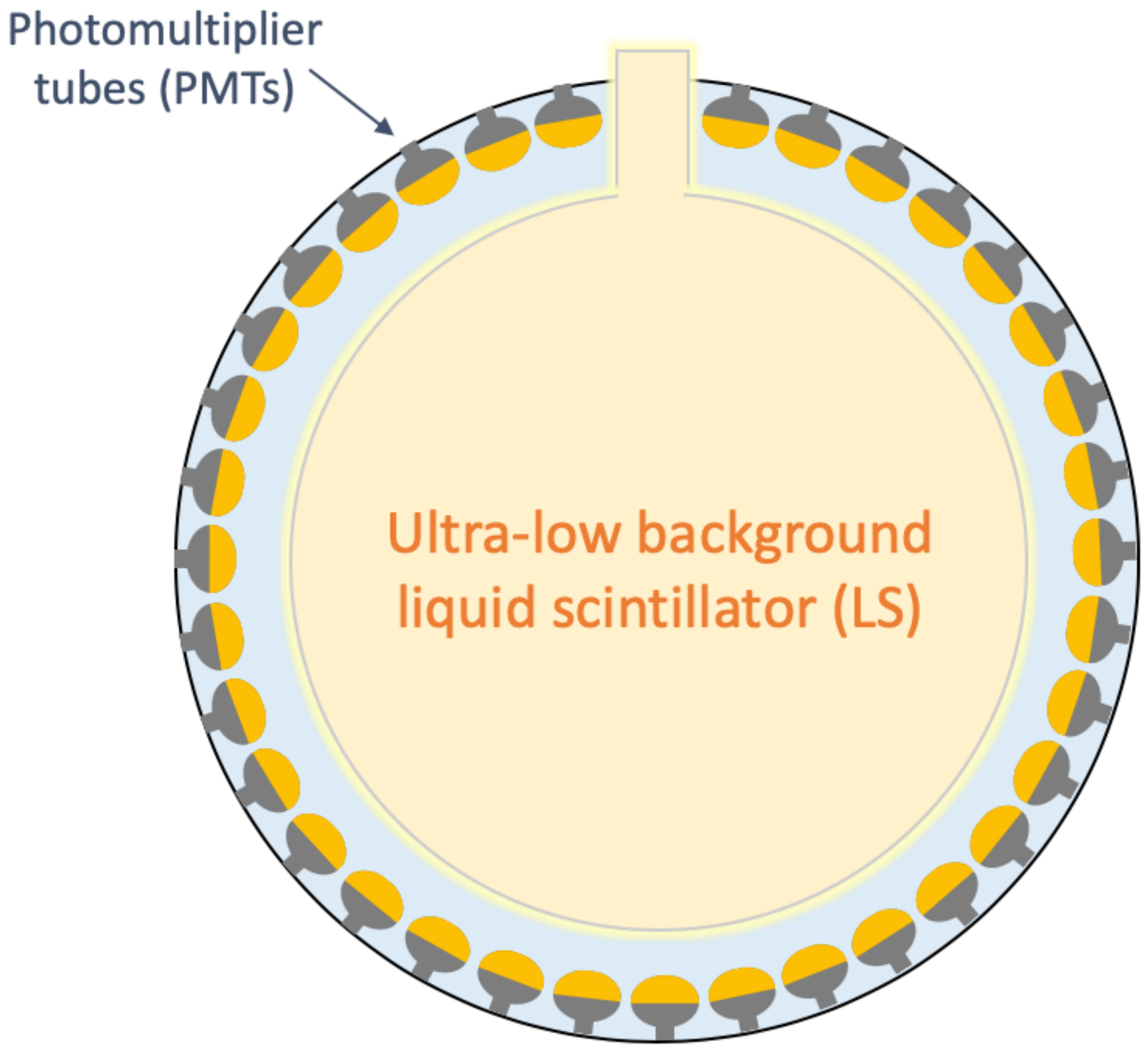

Liquid Scintillator Detector

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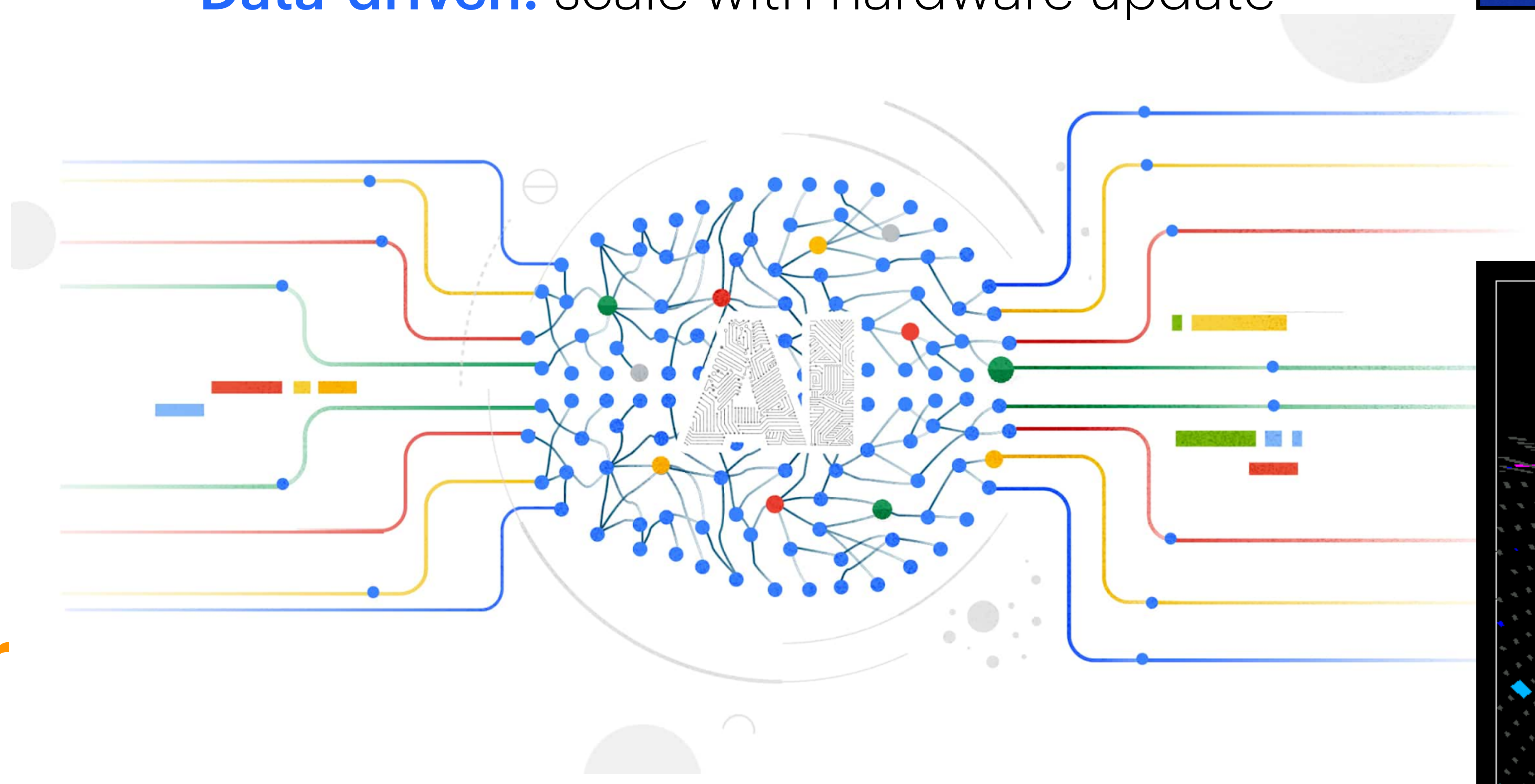
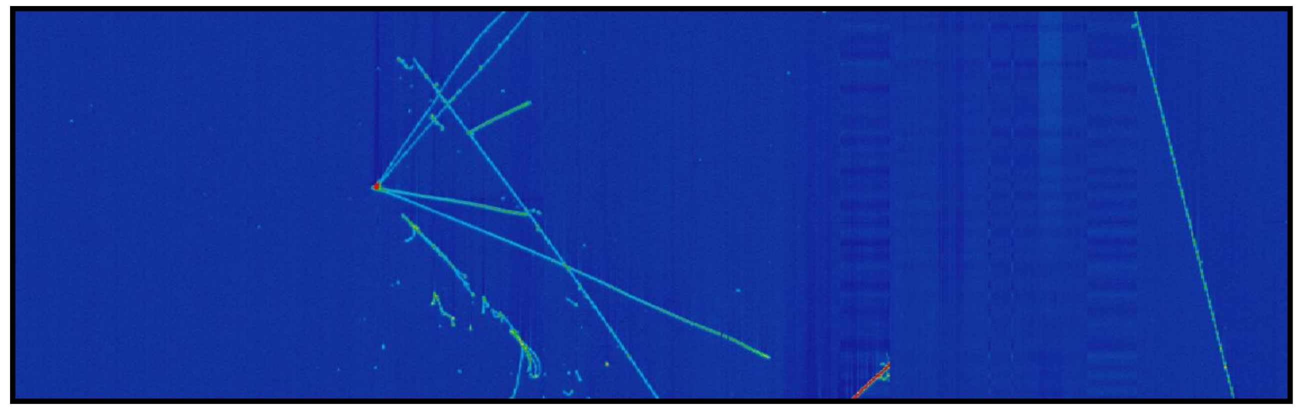
Machine Learning Approach

- **Analysis-based:** compatible with current generation detector
- **Data-driven:** scale with hardware update



Time Projection Chamber



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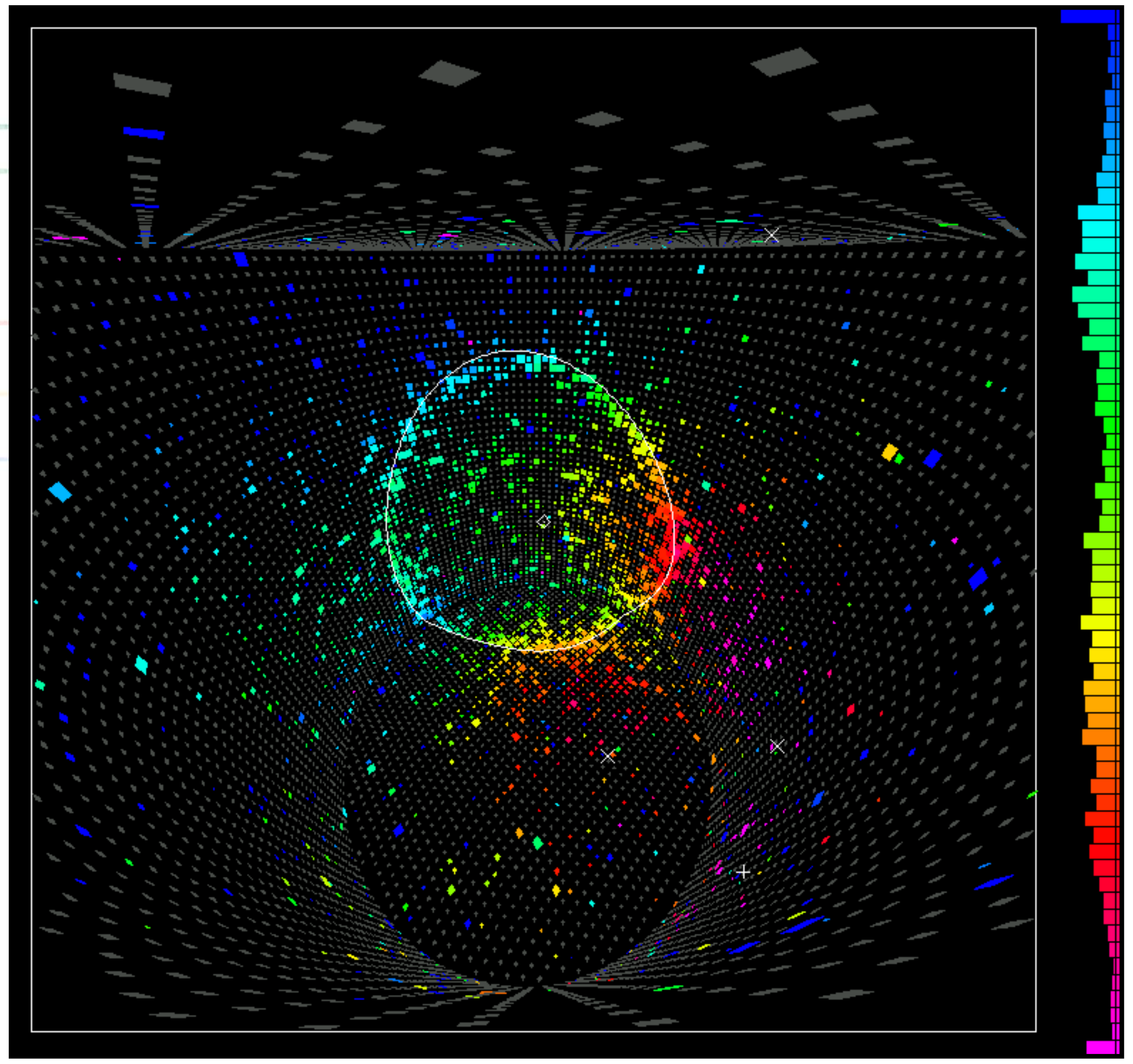
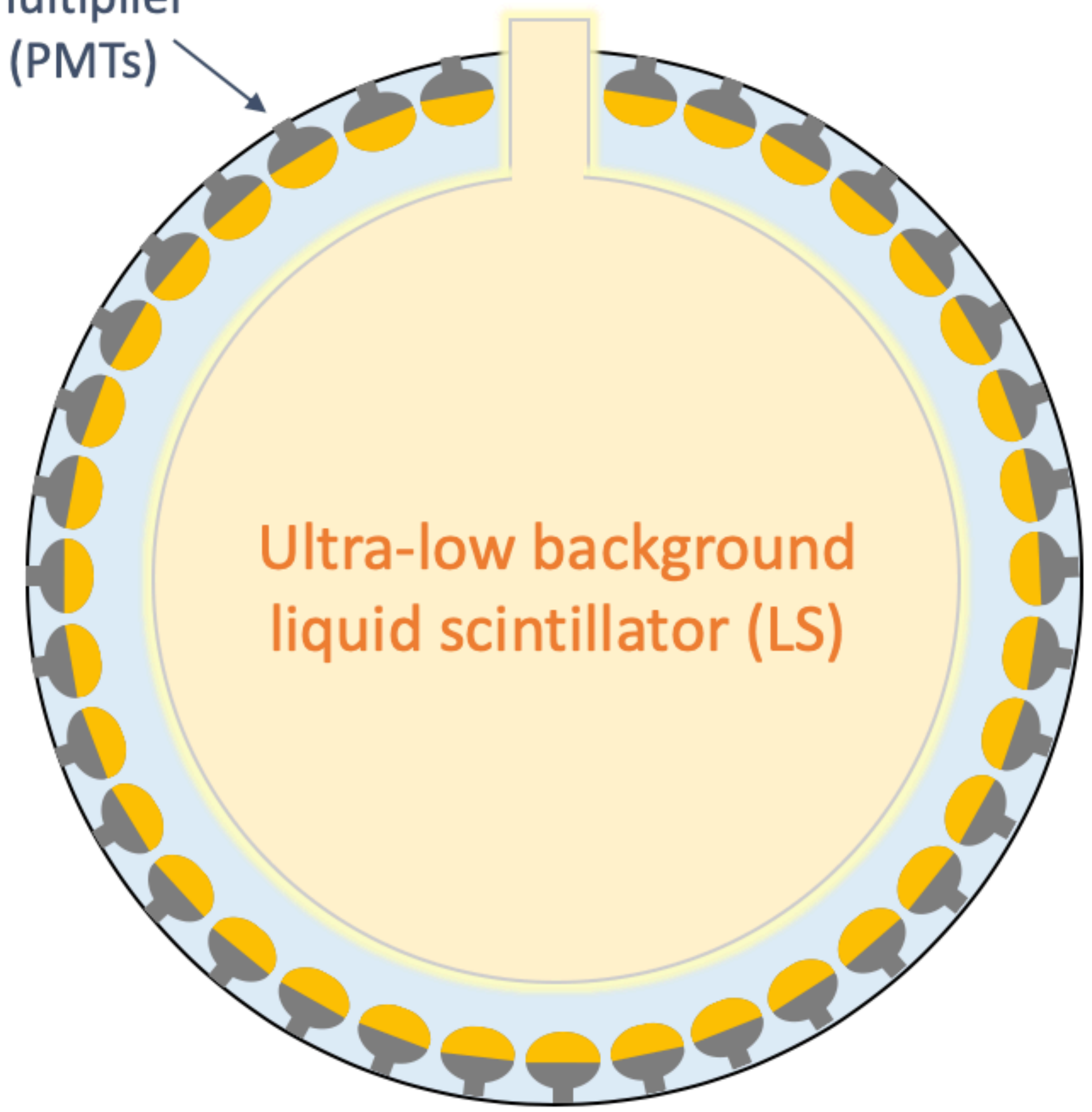


Calorimeter vs. Tracker



Liquid Scintillator Detector

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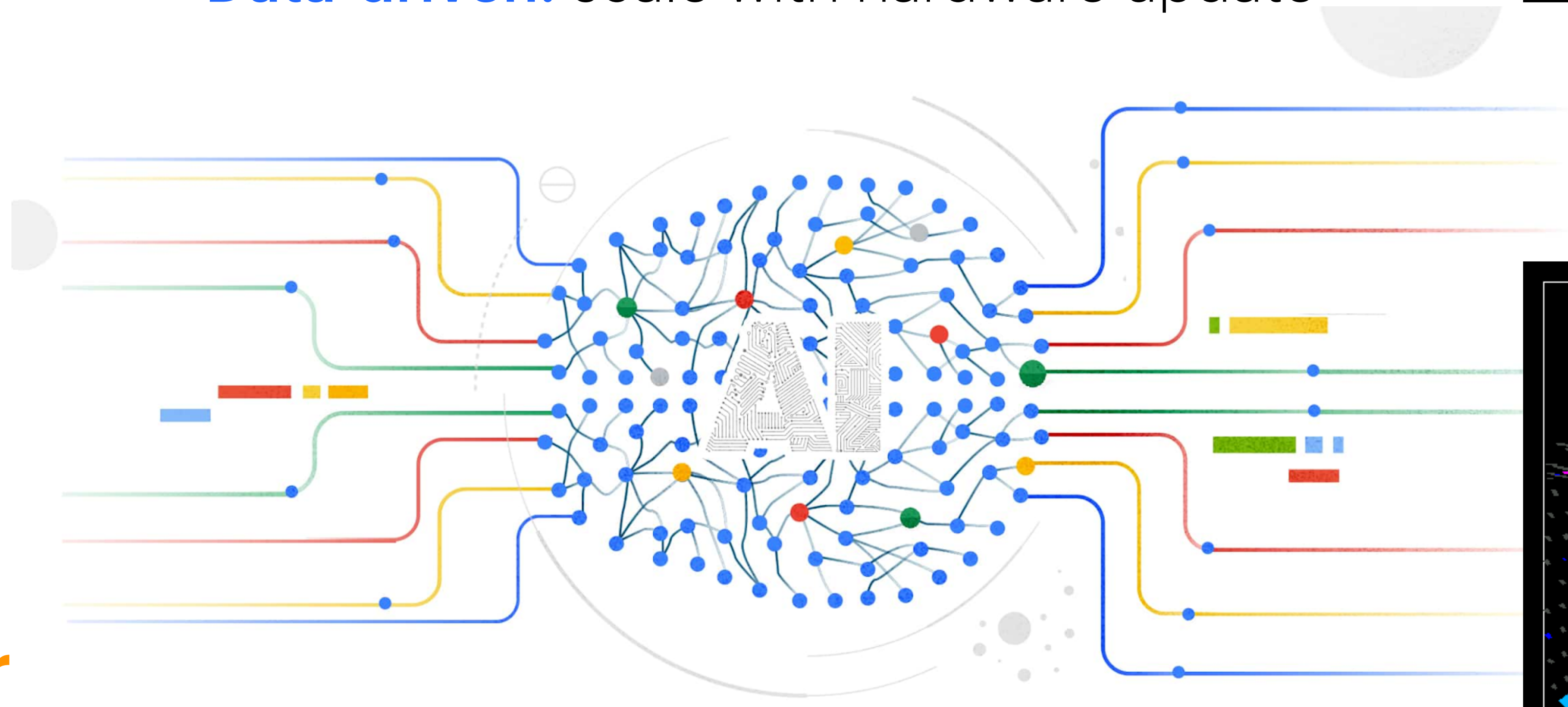
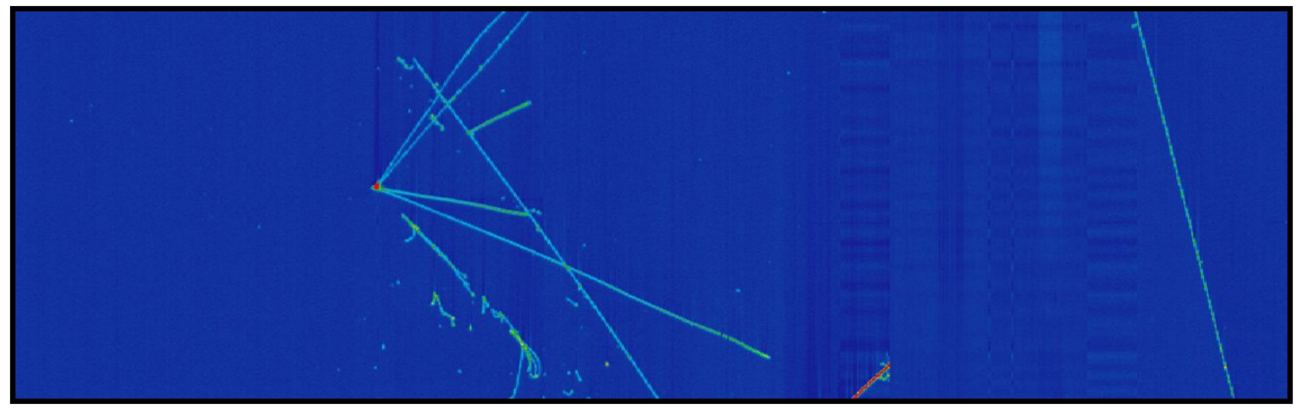


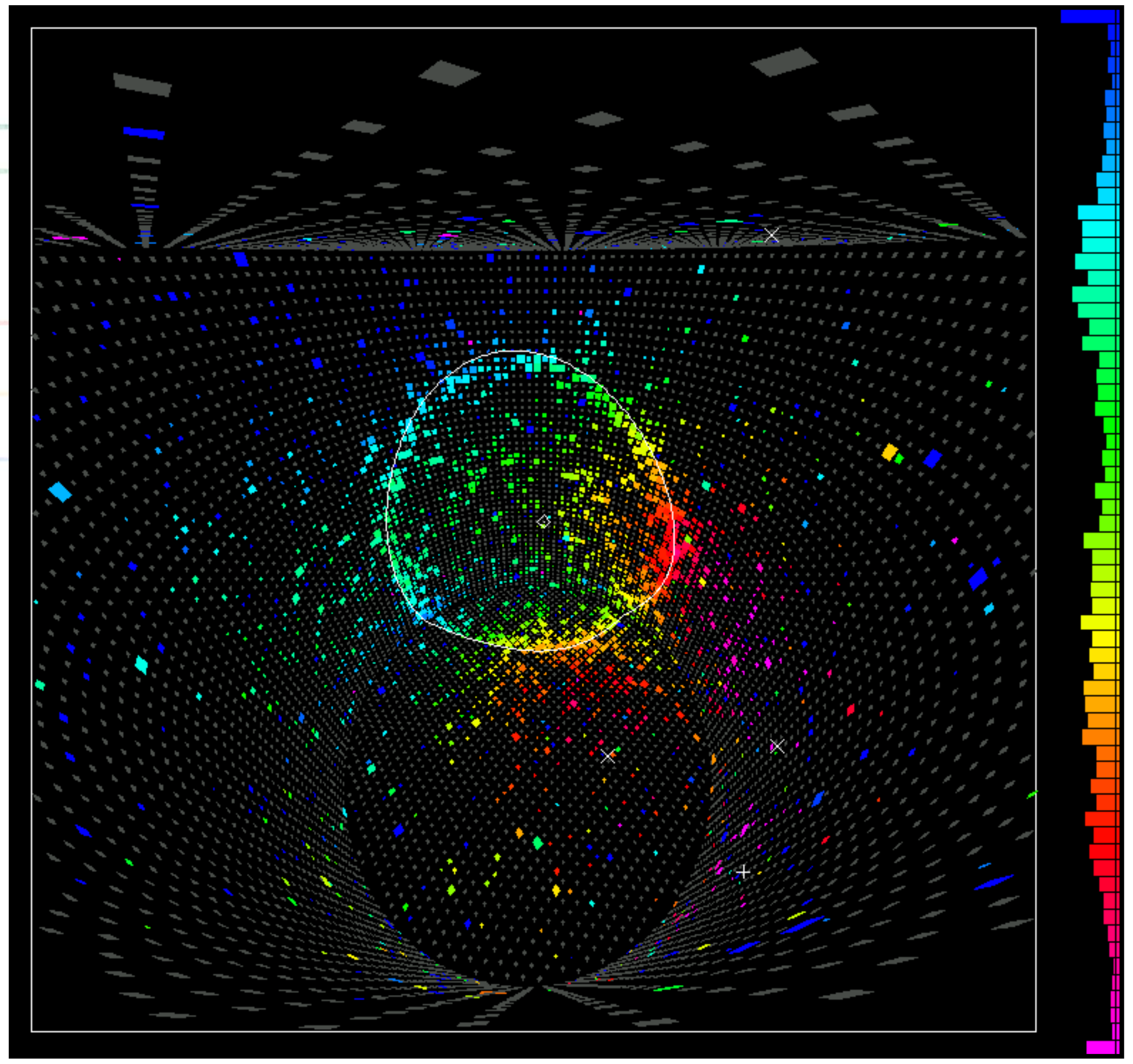
Next generation technology applicable to current generation detector

Is this even possible?

Time Projection Chamber



Water Cherenkov Detector

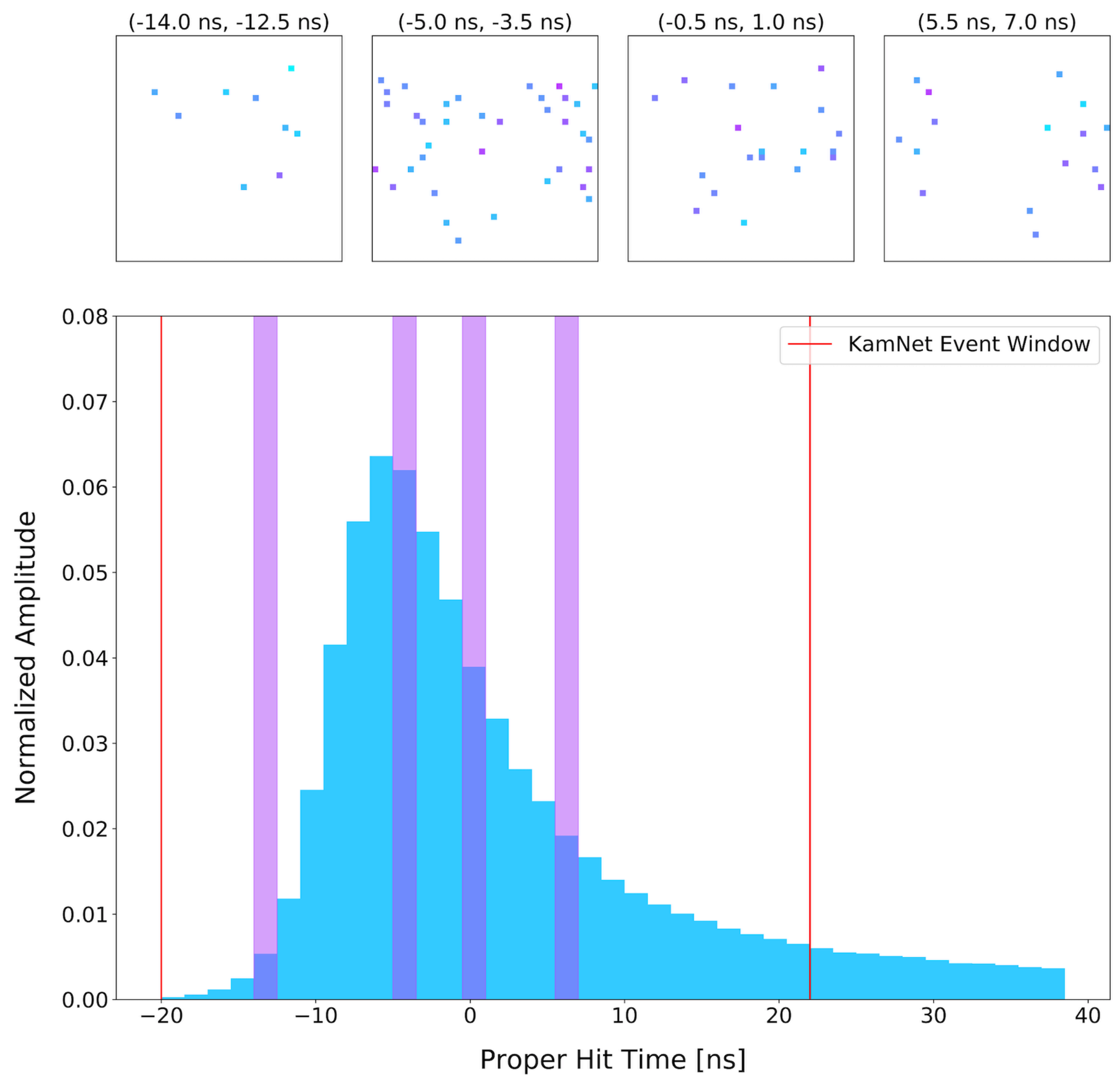


KamNet: An Integrated Spatiotemporal Neural Network

KamNet

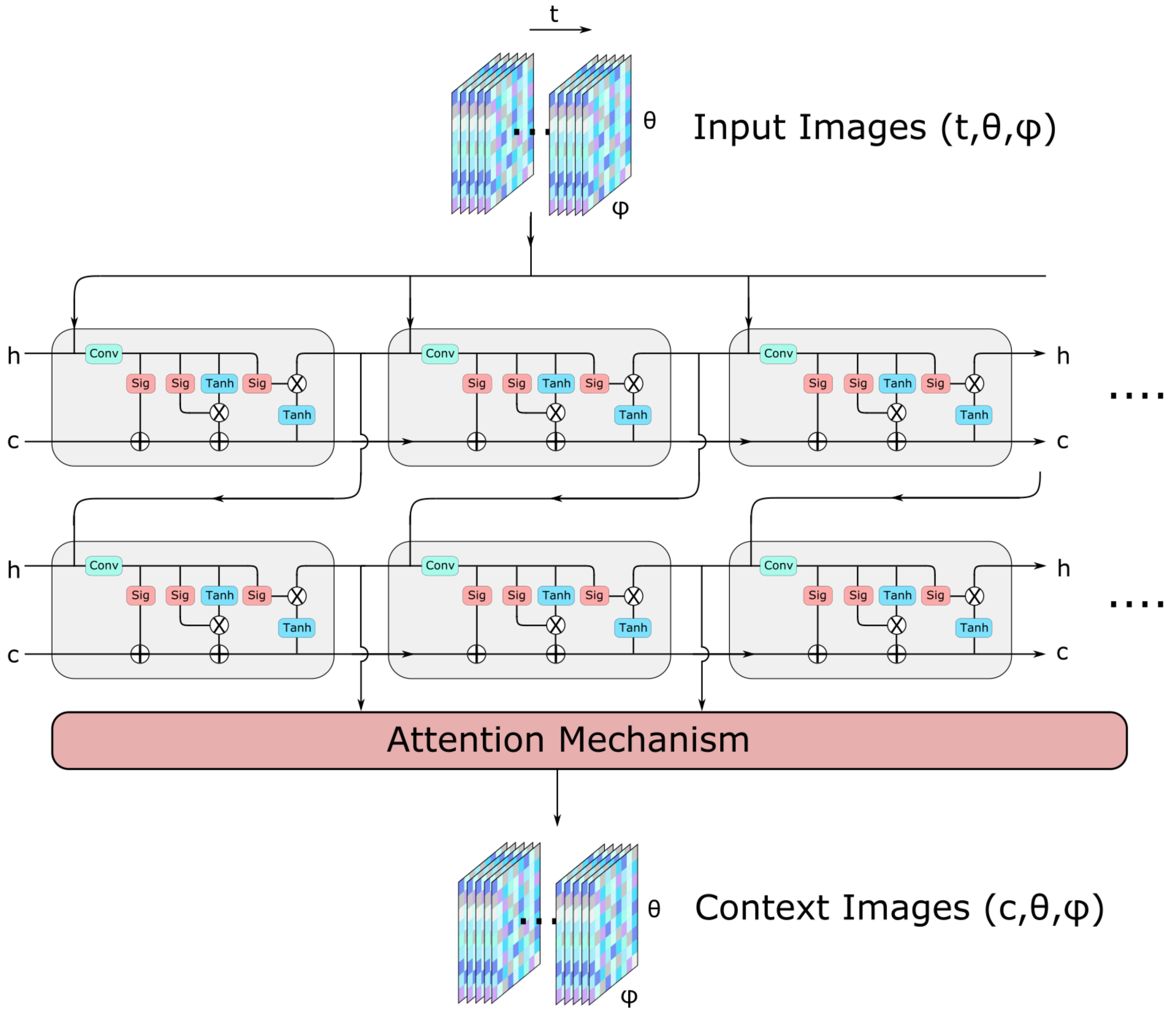
Maximal information extraction
for spherical LS detector

Spatiotemporal Data



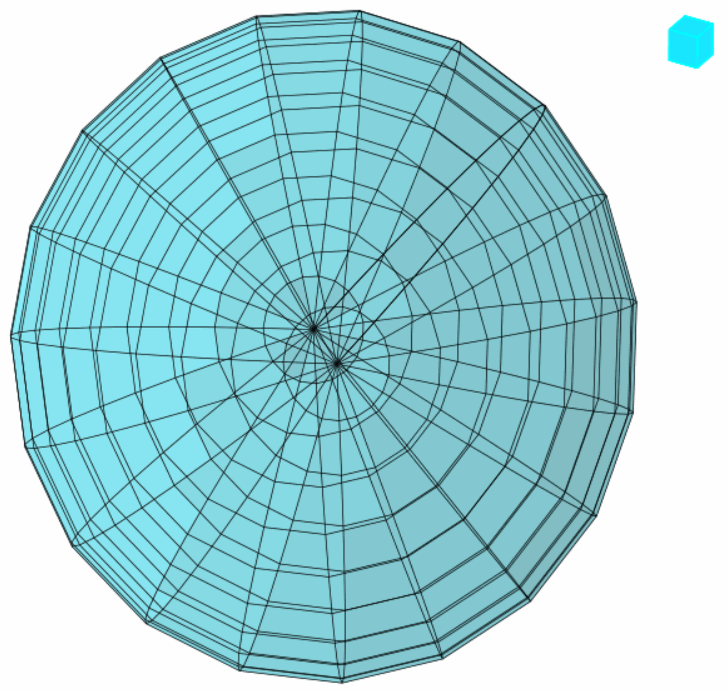
AttentionConvLSTM

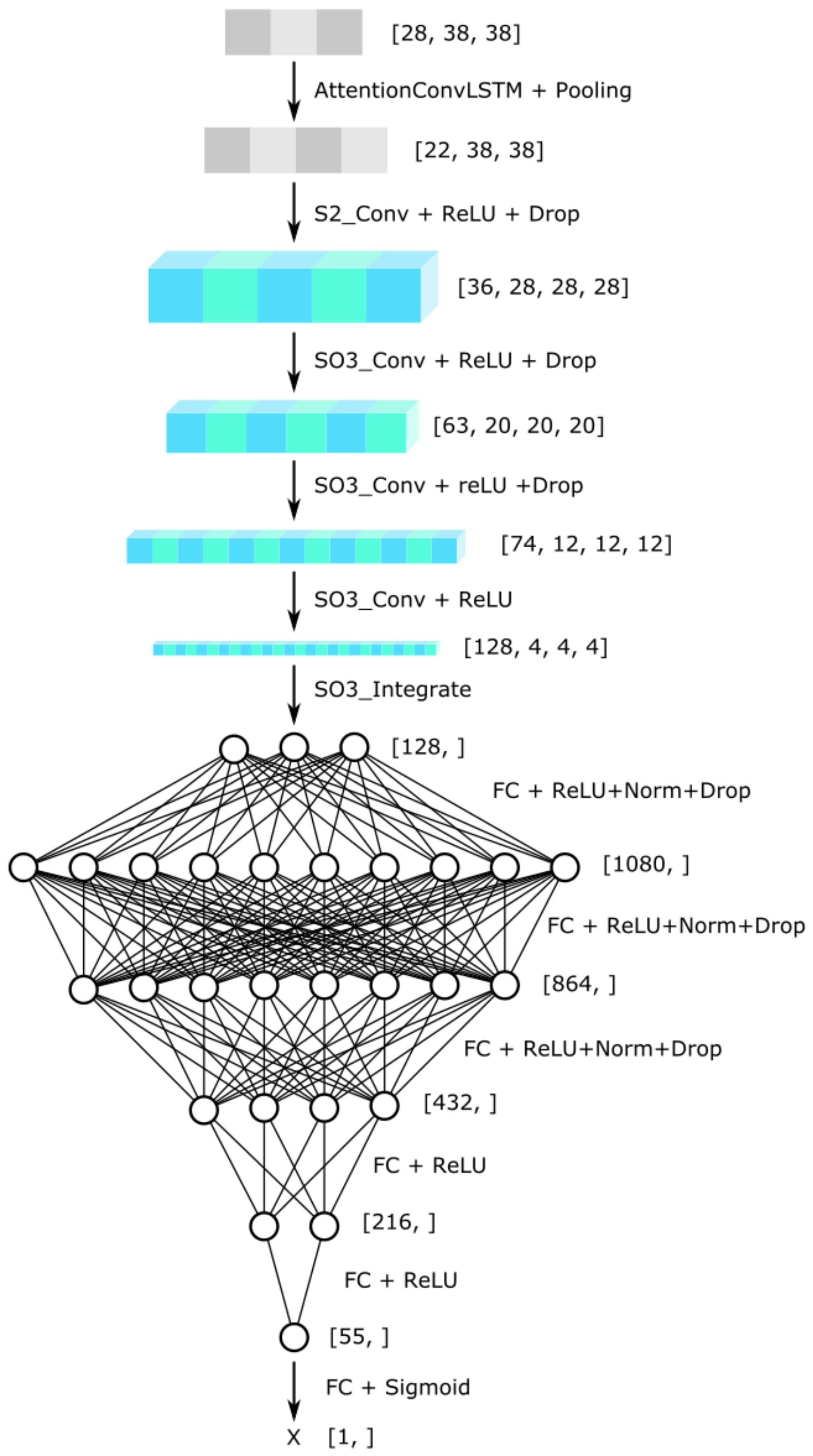
for Spatiotemporal symmetry



Spherical CNN

for SO(3) symmetry in
spherical detector

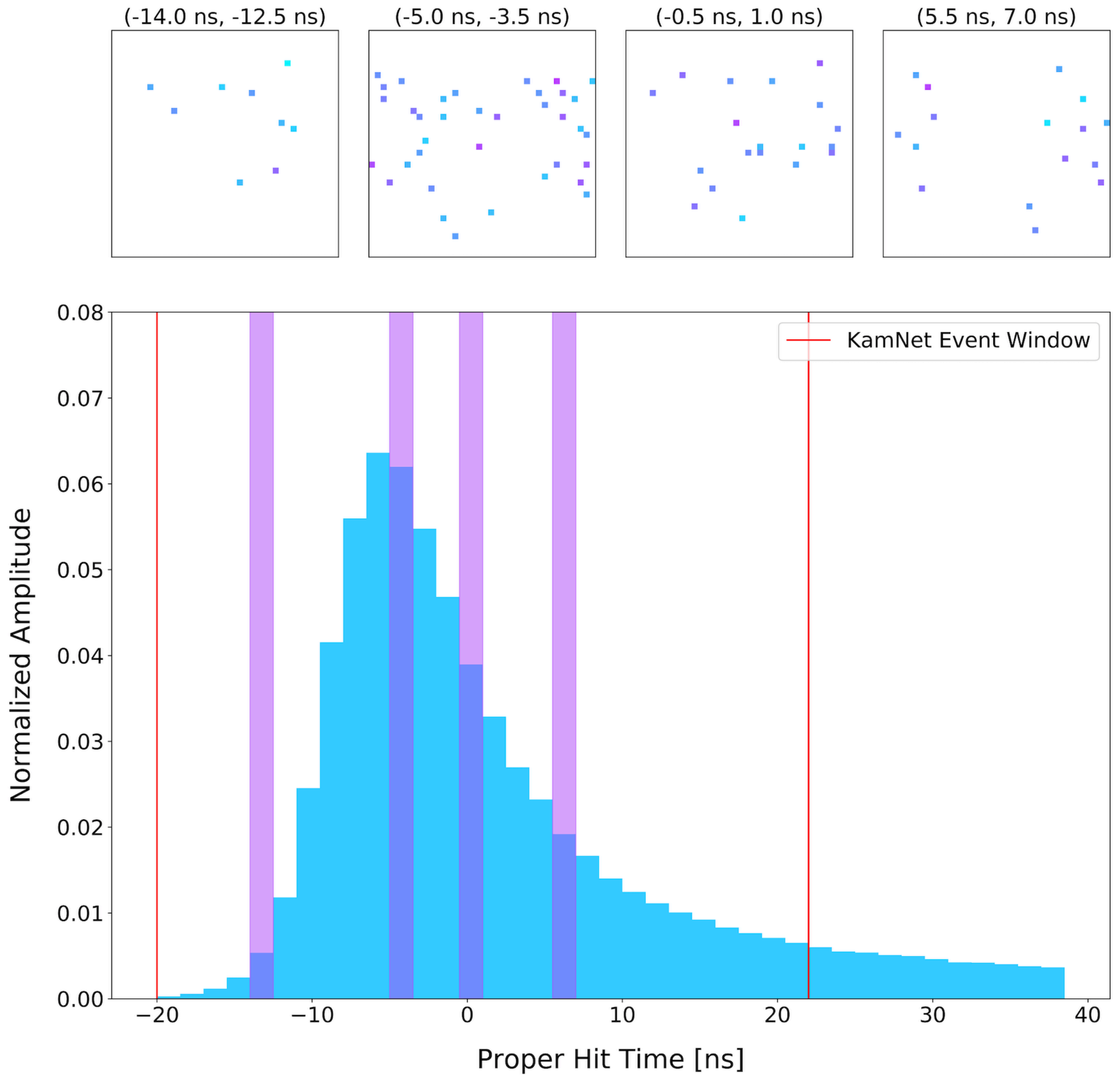




KamNet Score

KamNet: An Integrated Spatiotemporal Neural Network

Spatiotemporal Data



AttentionConvLSTM

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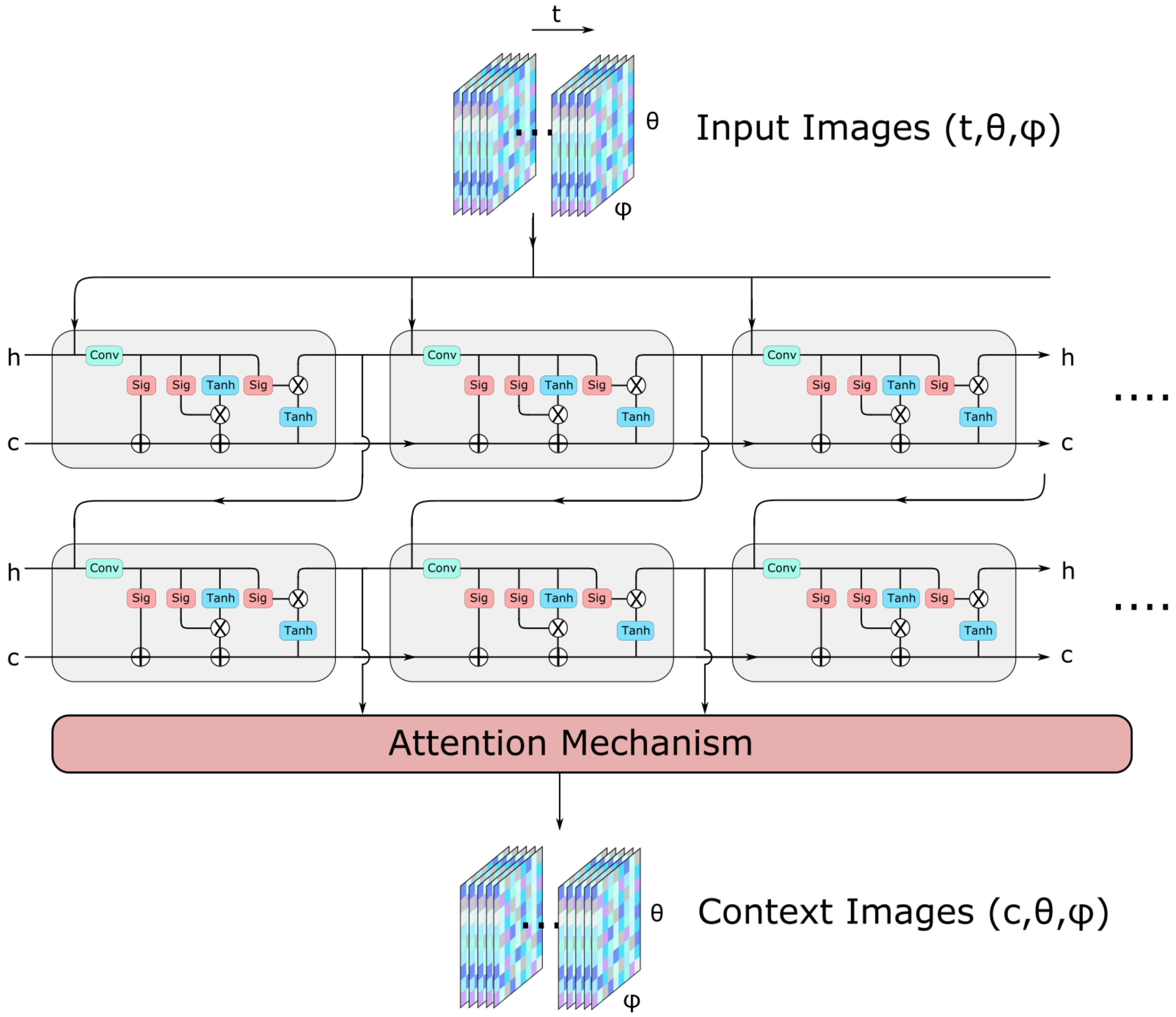
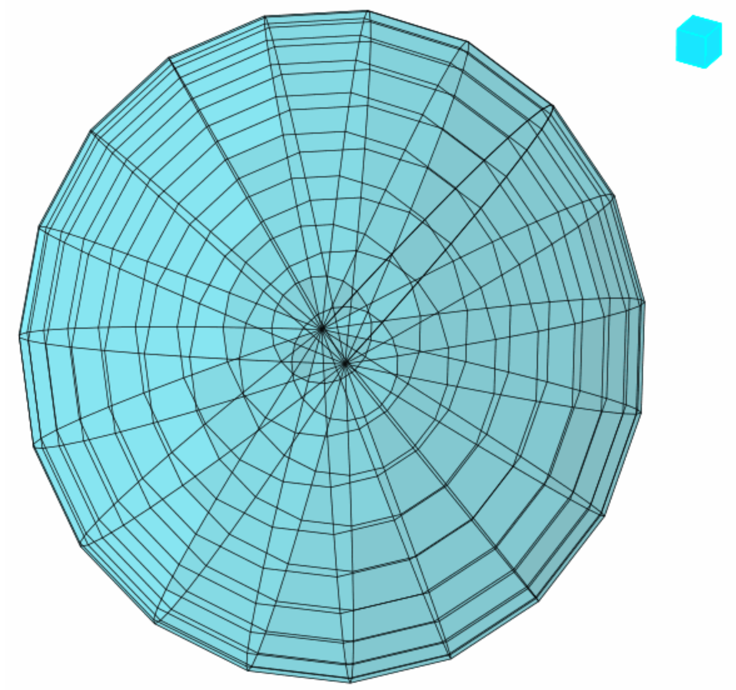


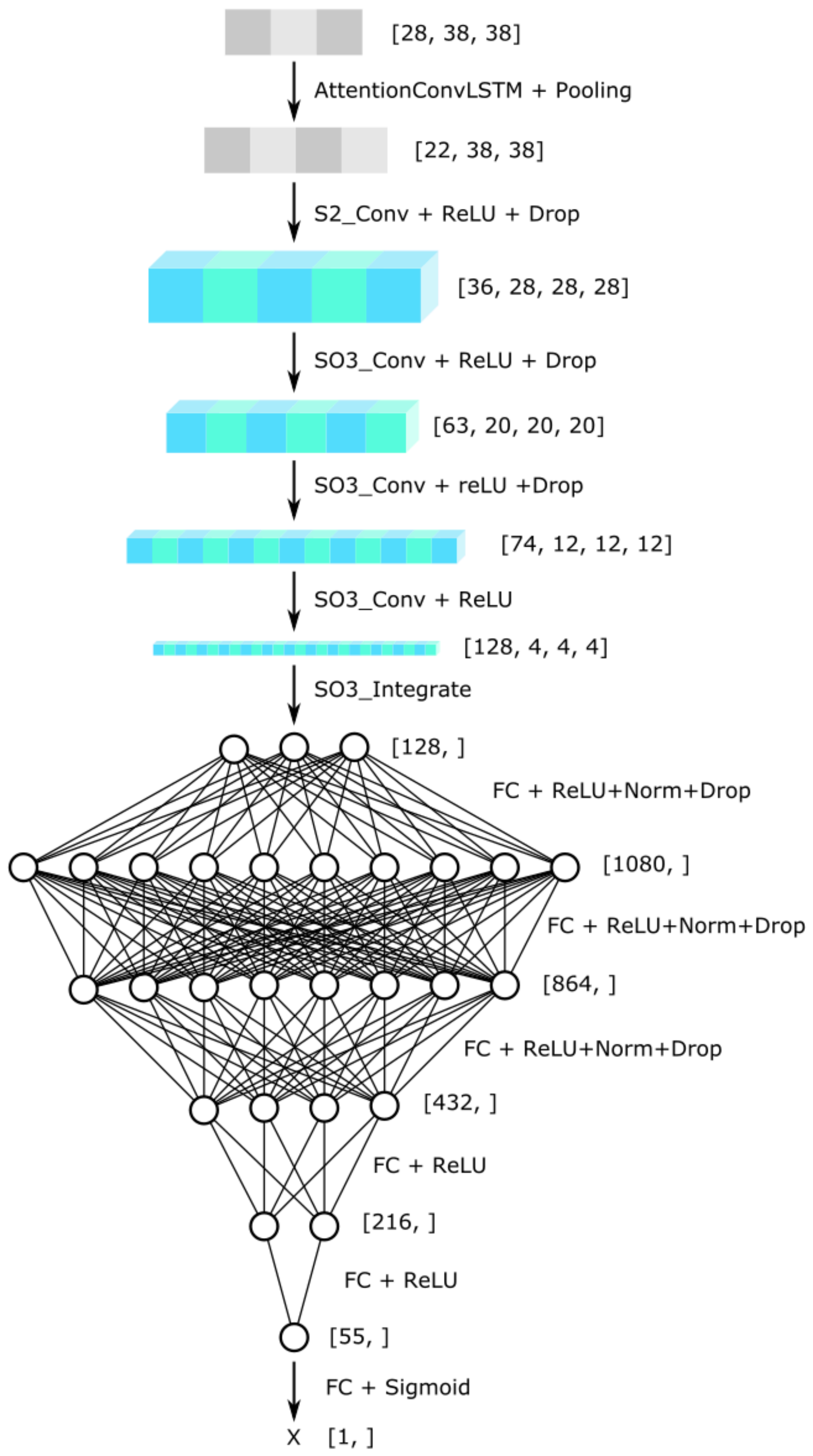
Spherical CNN

for SO(3) symmetry in spherical detector



KamNet

Maximal information extraction for spherical LS detector

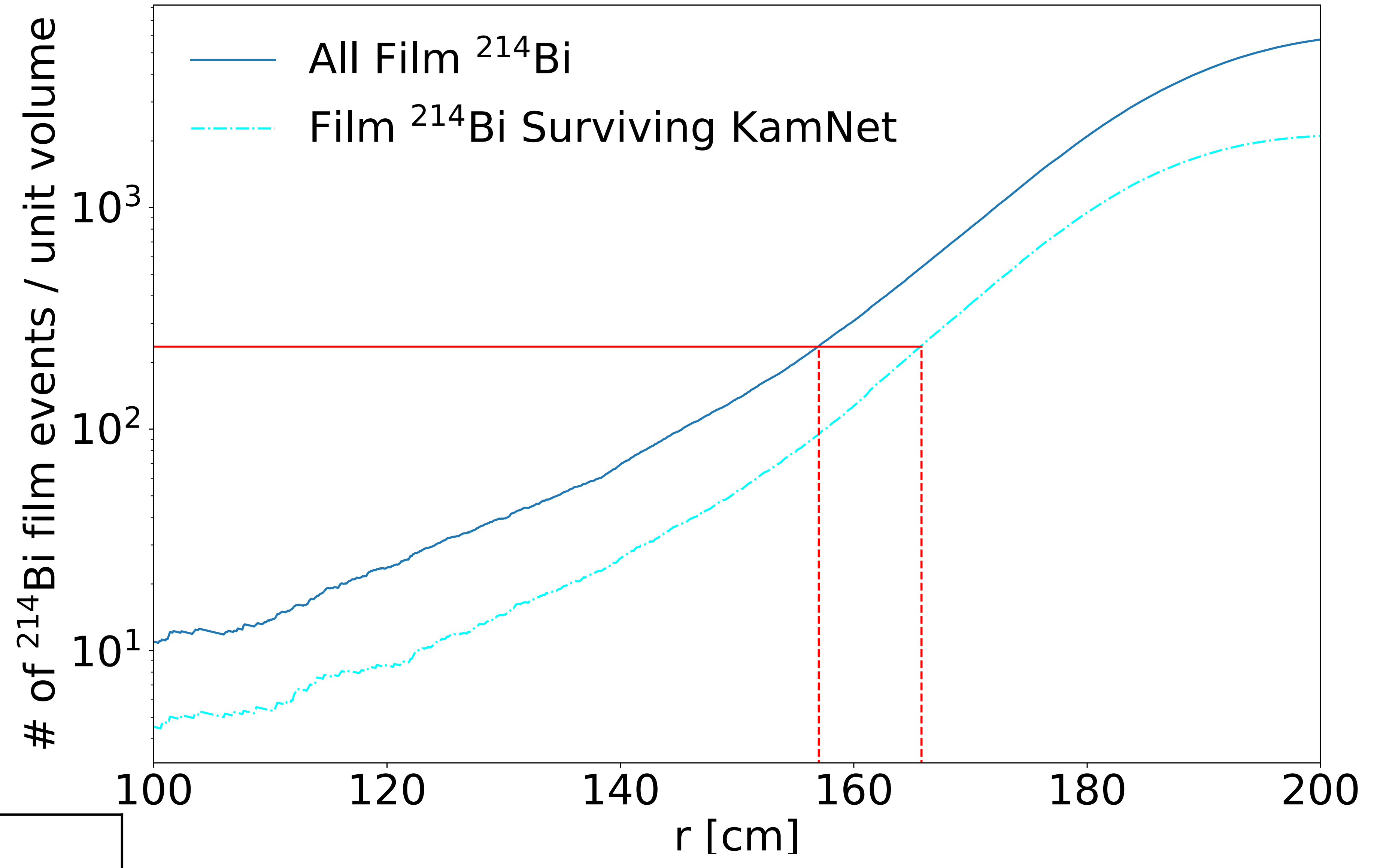


KamNet Score

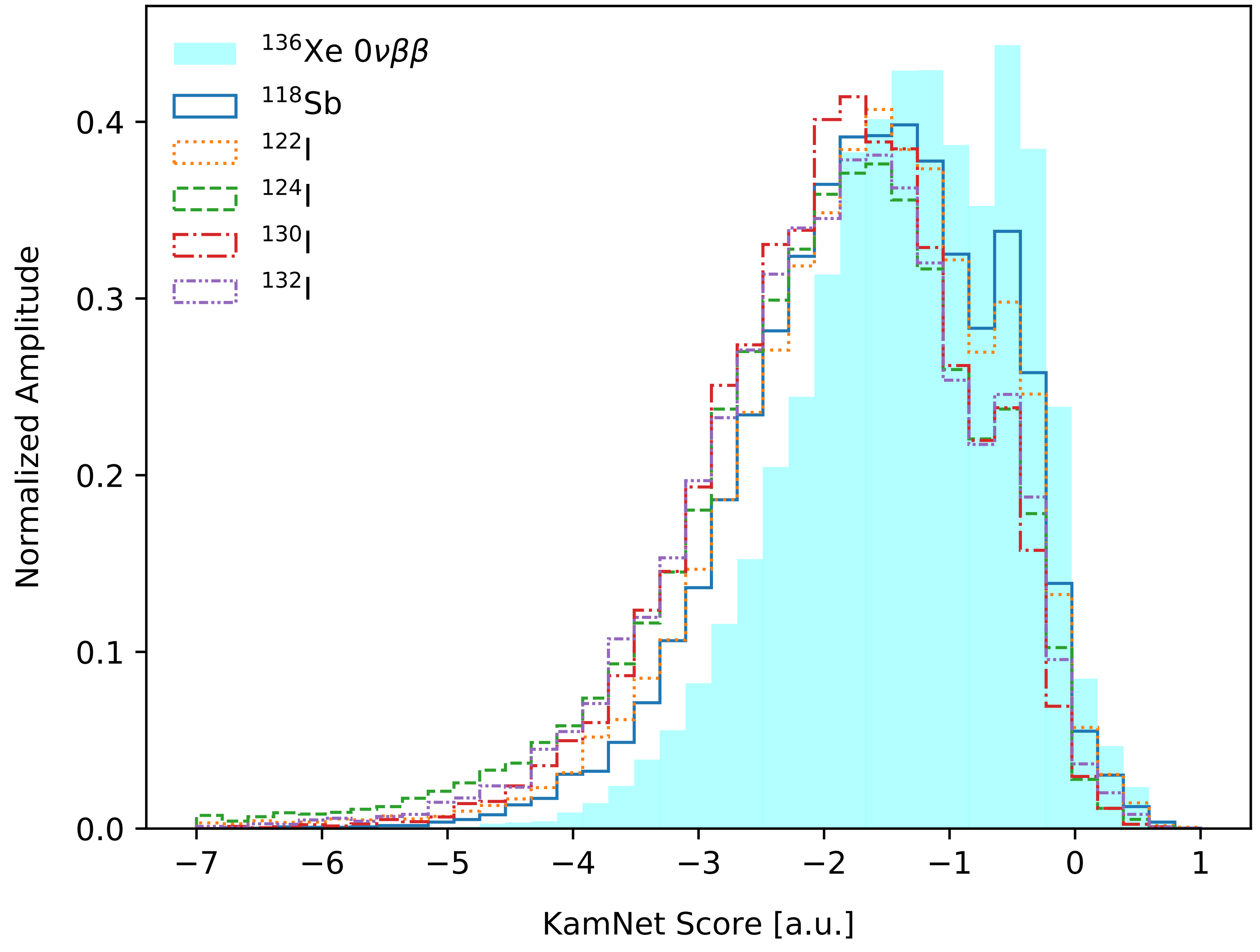
KamNet Results

KamNet is trained on precisely tuned MC simulations and evaluated on various backgrounds in KamLAND-Zen 800

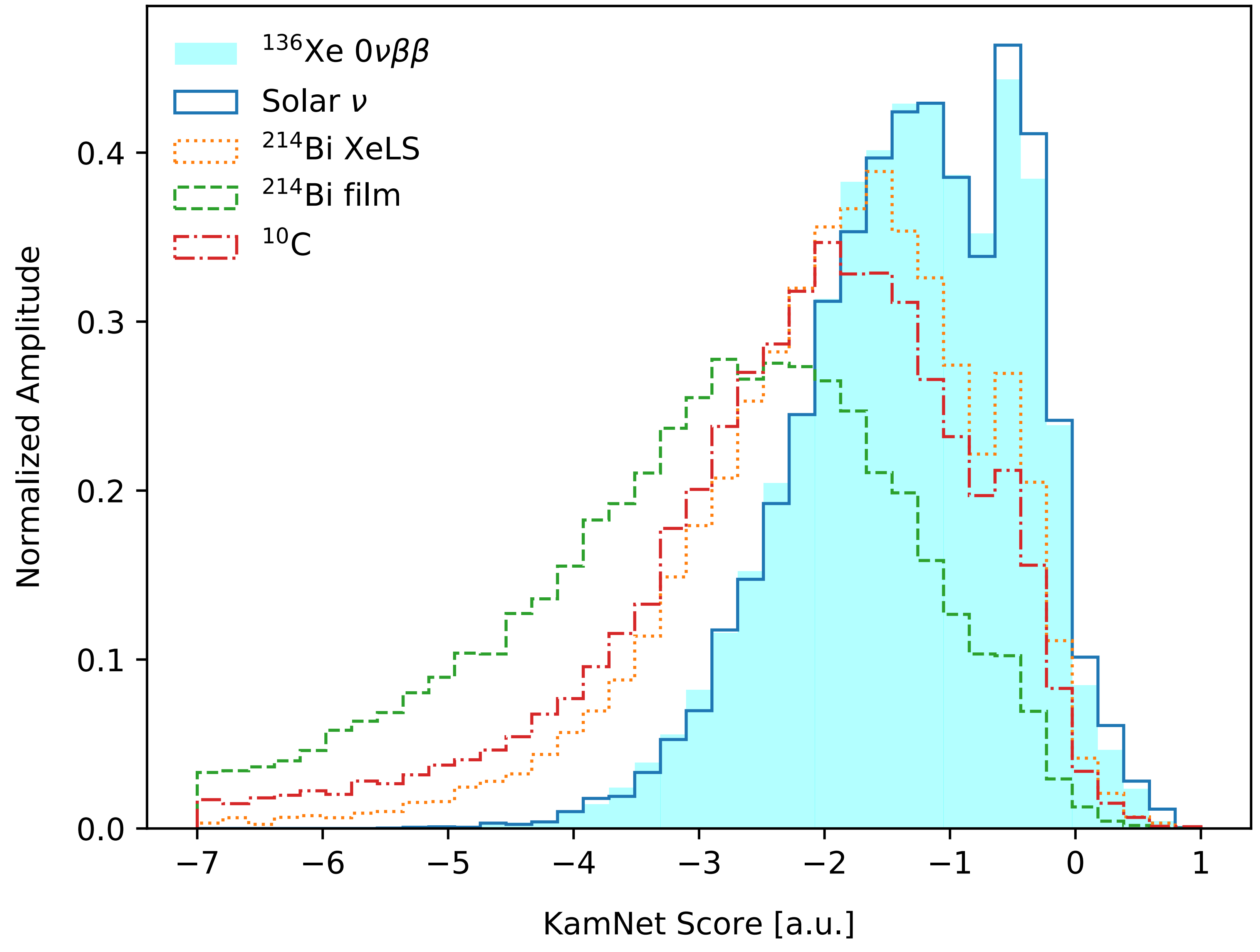
While accepting **90%** of $0\nu\beta\beta$ events, KamNet rejects **~27%** of XeLS backgrounds (including LL spallation) and **~59%** of film backgrounds



Long-Lived Spallation



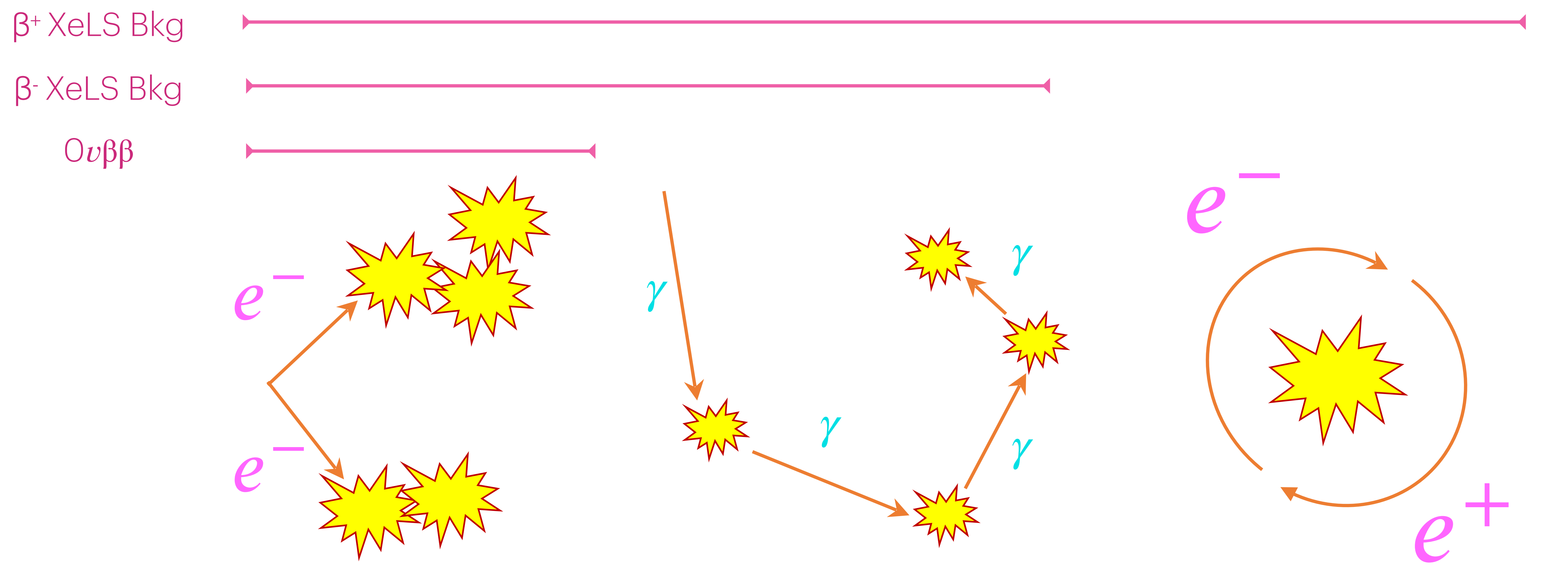
Other Backgrounds

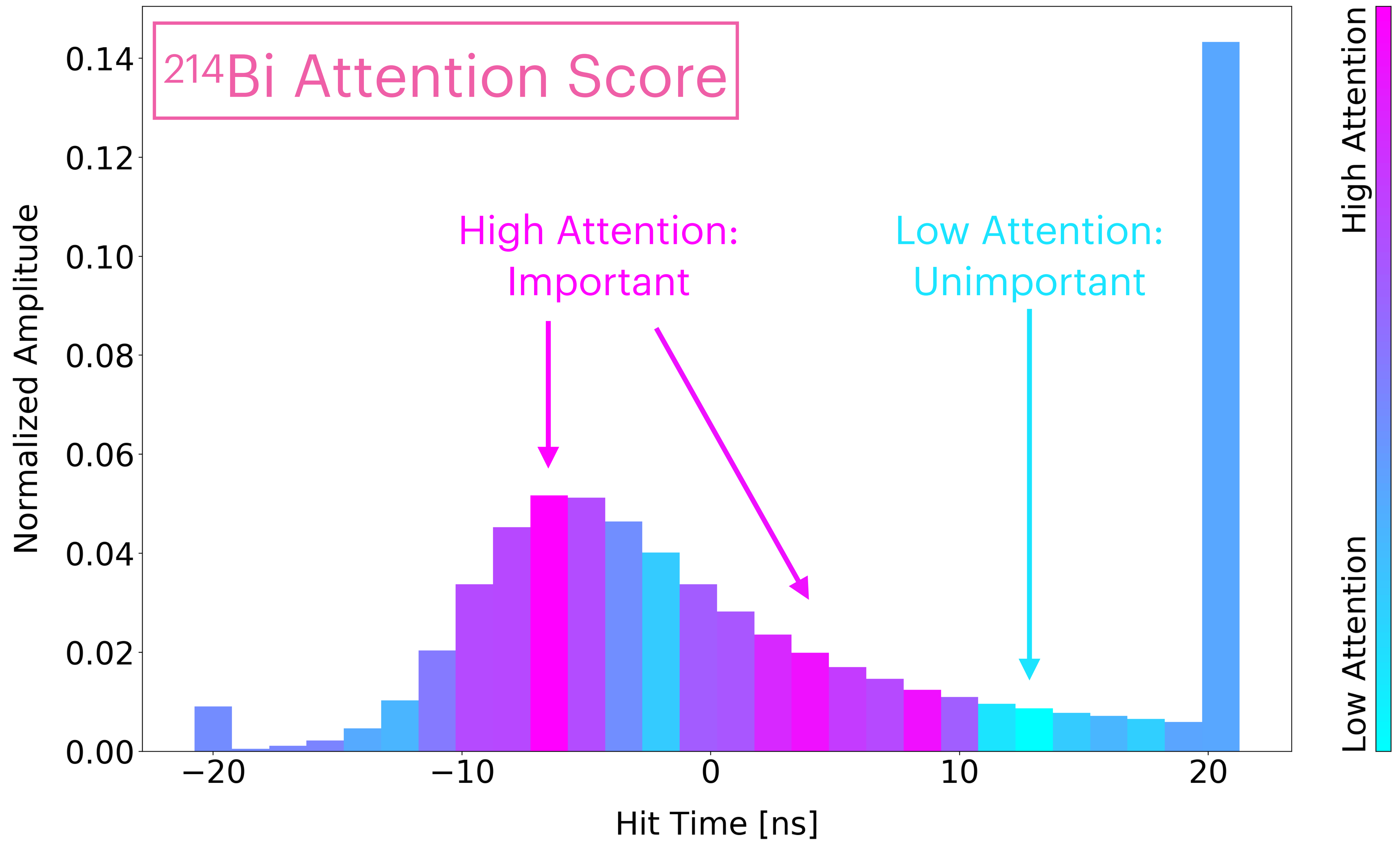


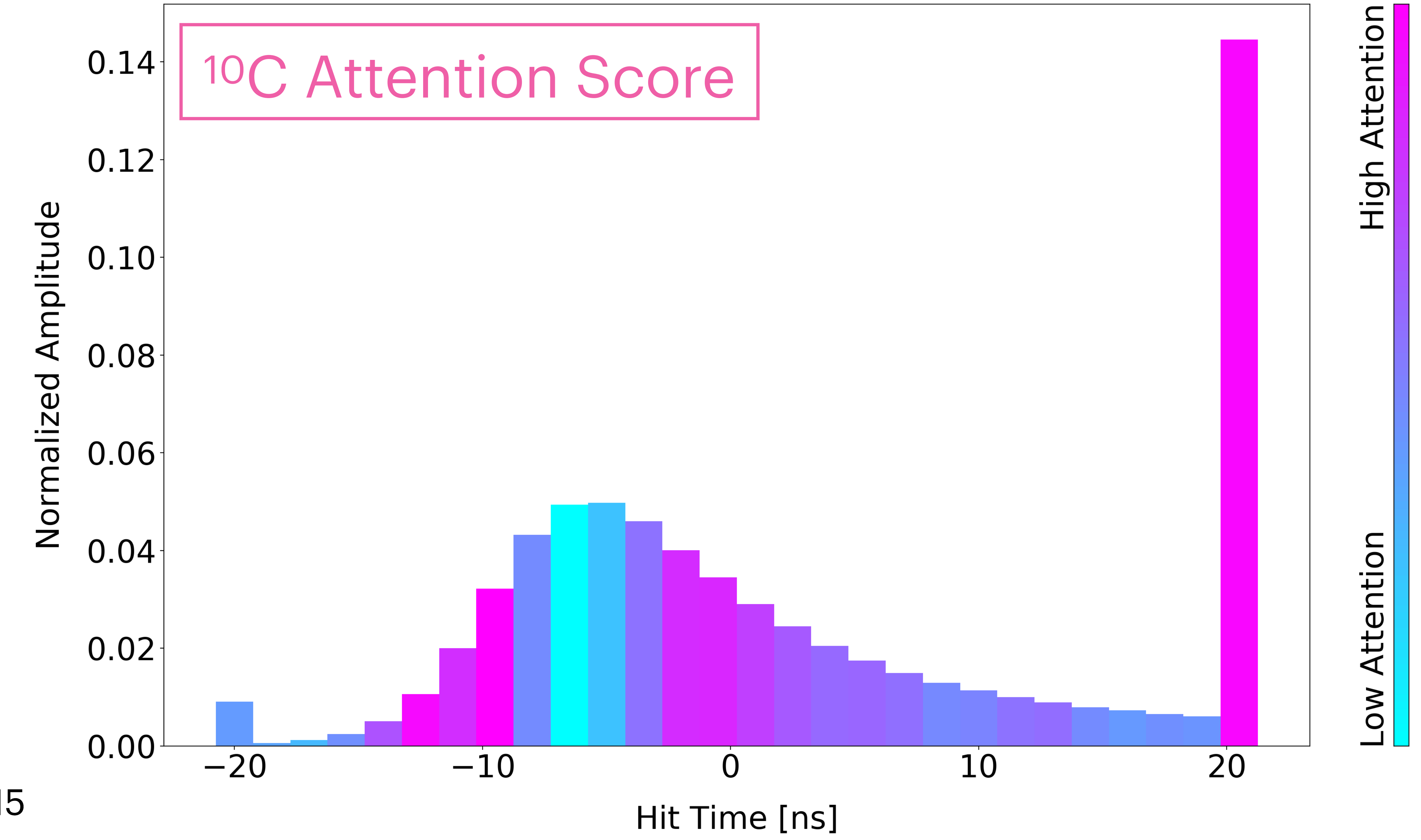
The increased rejection of backgrounds on mini-balloon film allows for the expansion of the fiducial volume from 157cm to 165.8cm, resulting in **17.7% gain** on exposure without hardware upgrades

KamNet Interpretability

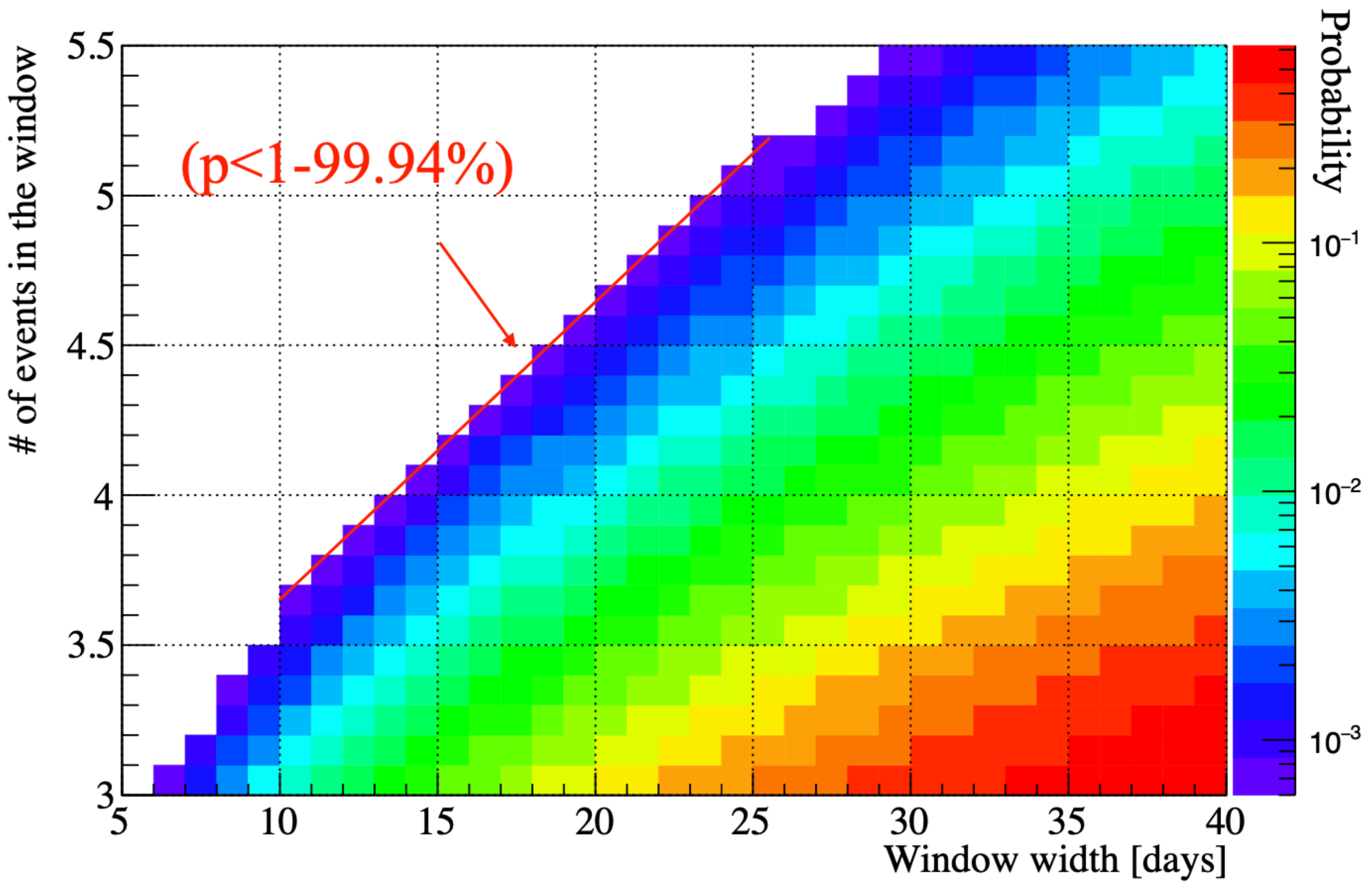
- β-like signal events are strictly **single-vertex events**, all energy is deposited in a very localized region
- γ-like backgrounds are **closely-spaced multi-vertex events**, part of event energy is deposited by one (or more) γs that slightly alter the PMT hit-time distribution
- If background events undergo β+ decay, the **ortho-positronium decay time** will delay the energy deposition, making the last bin more important







KamNet for KamLAND-Zen 800



KamNet paper submitted to Phys. Rev. C
Preprints available at [arXiv:2203.01870]

γ cluster search

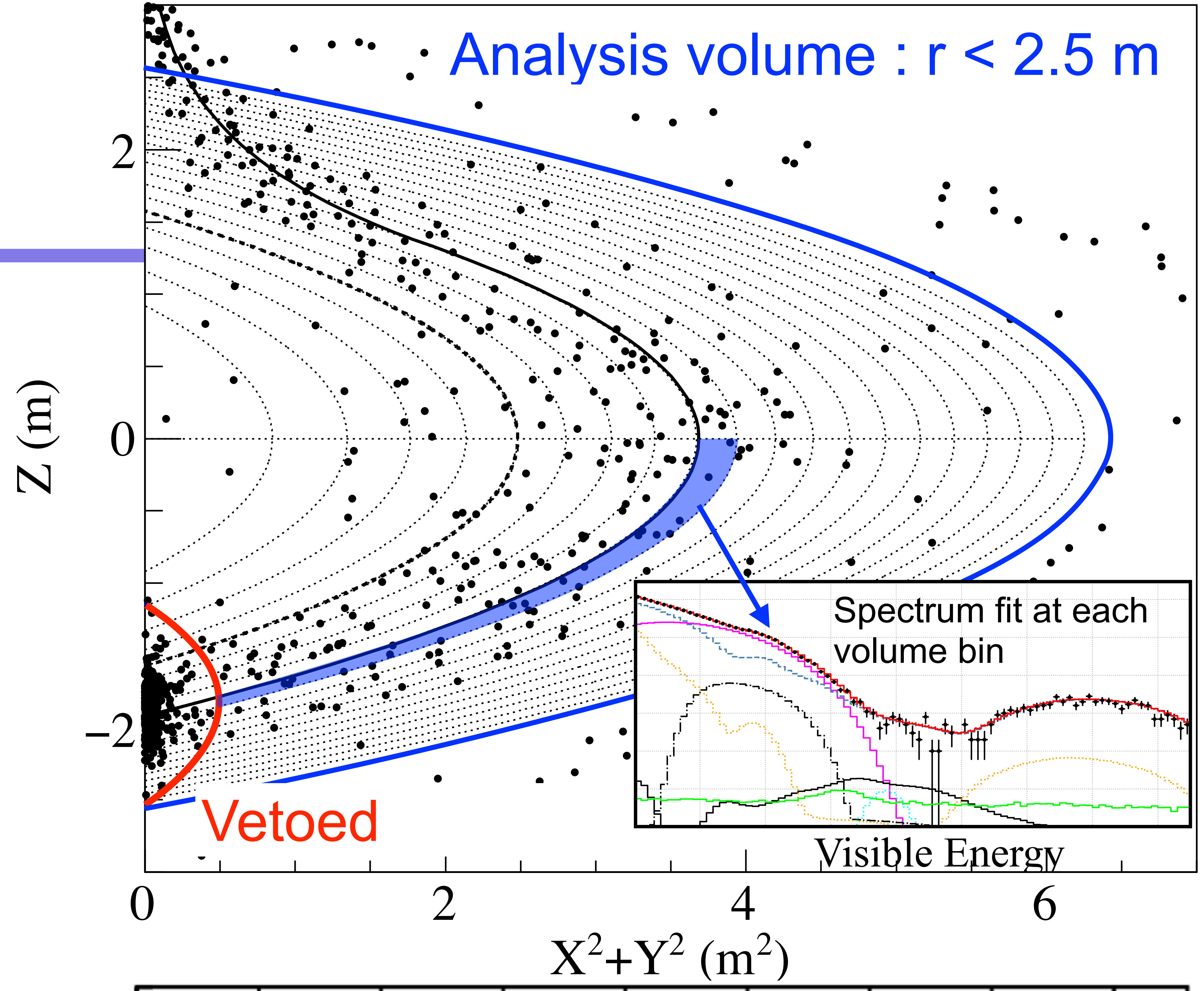
- Based on the likelihood profile of KamNet score
- Independently identify periods with high background noise
- Cut at p-value of only 0.06%
- Lead to the official half-life limit of KamLAND-Zen 800

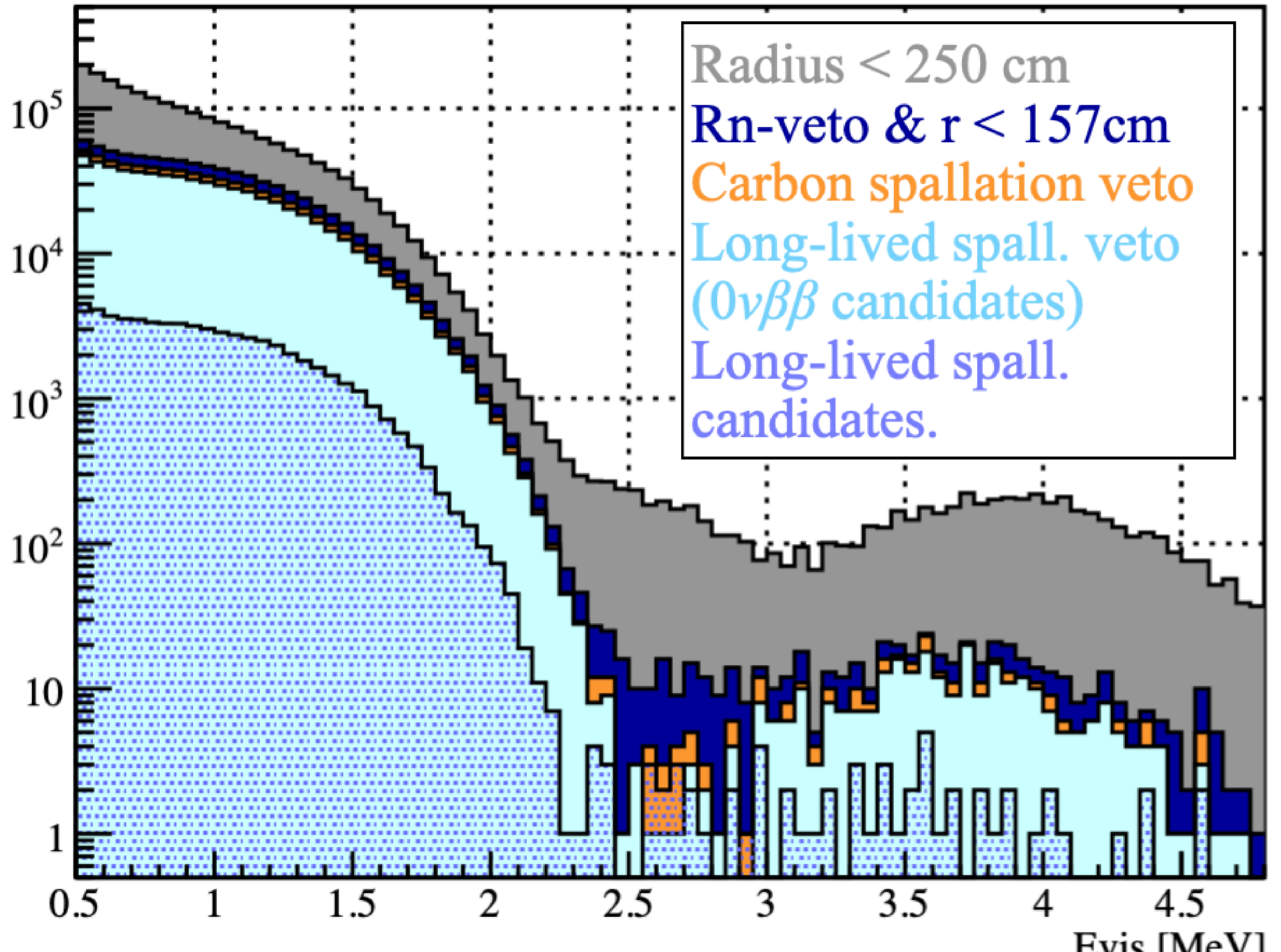
Apply KamNet to the Entire Dataset

- Use KamNet to identify β-like signal and γ-like background
- Simultaneous fitting both types of events in all period
- Lead to 35% boost upon official half-life limit

Generic Analysis Conditions

- 40 volume bins:
  - radius 20 × {upper sphere, lower sphere}
- 3 distinct time bins:
  - Independently tuned MC spectrum
  - Fitted simultaneously using the same normalization (rate)
- Event selection cuts:
  - Radius <2.5m and >0.7m away from bottom
  - Radioactive decays vetoed by coincidence cut
  - $\bar{\nu}$ identified by coincidence cut
  - Poorly reconstructed events are rejected
  - Veto noisy period with KamNet γ-cluster search

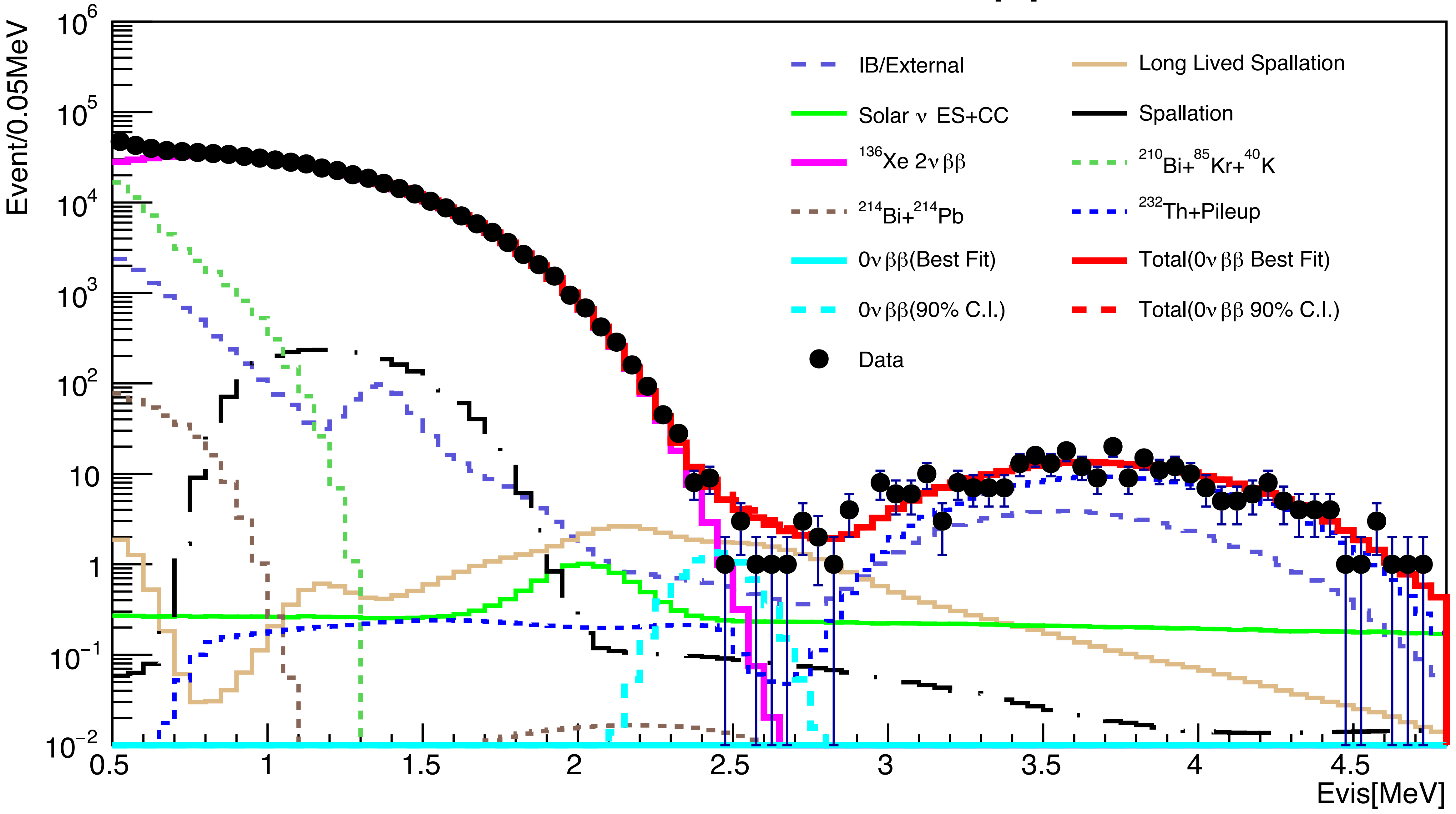




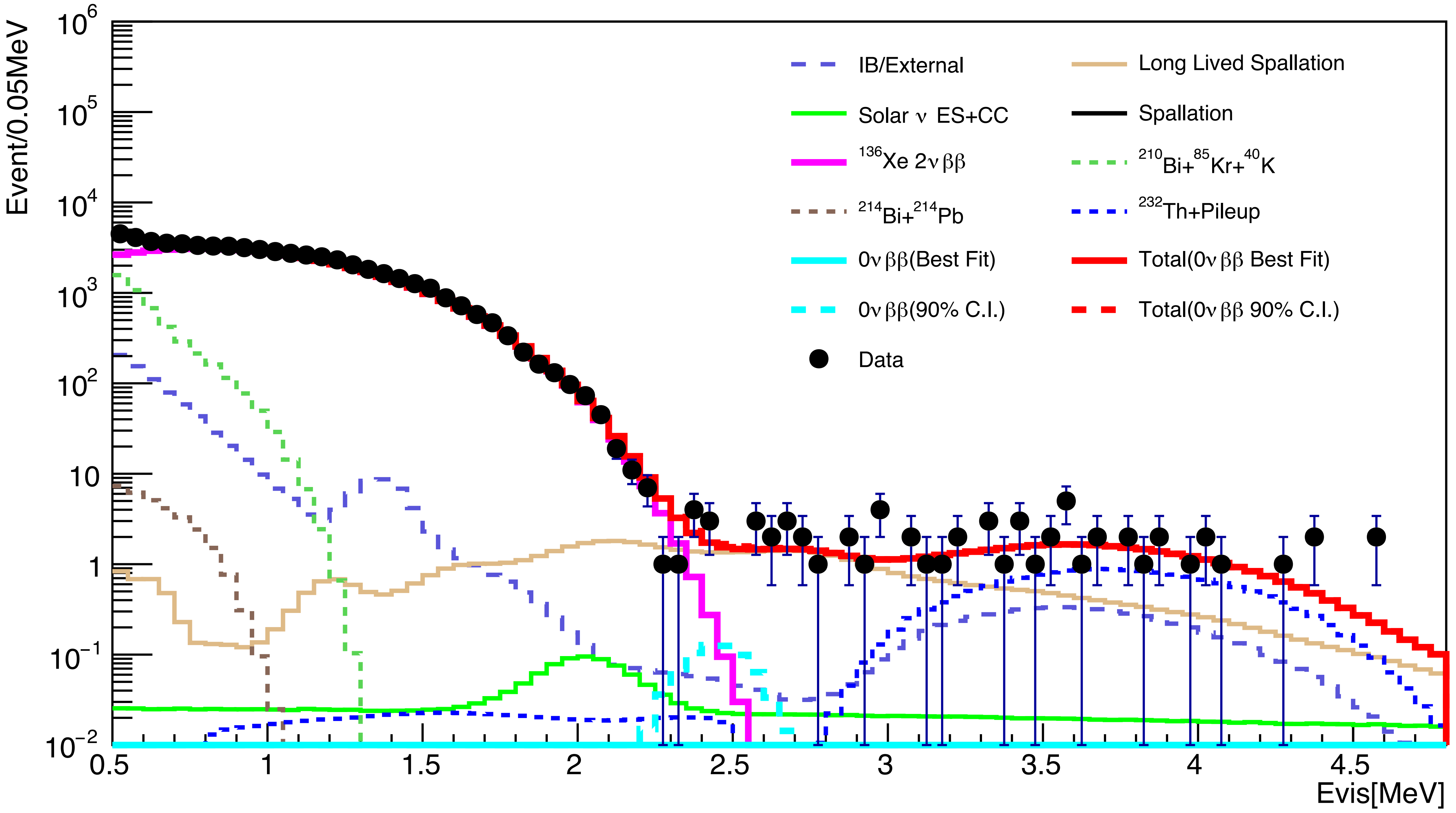
Long-lived & Single

- Simultaneous fit the 0νββ spectrum and a long lived spectrum to constrain backgrounds.
- Report the limit on the 0νββ decay rate in both a **Bayesian** and a **Frequentist framework**

0νββ candidate data set (single dataset)
(dataset sensitive to 0νββ rate)



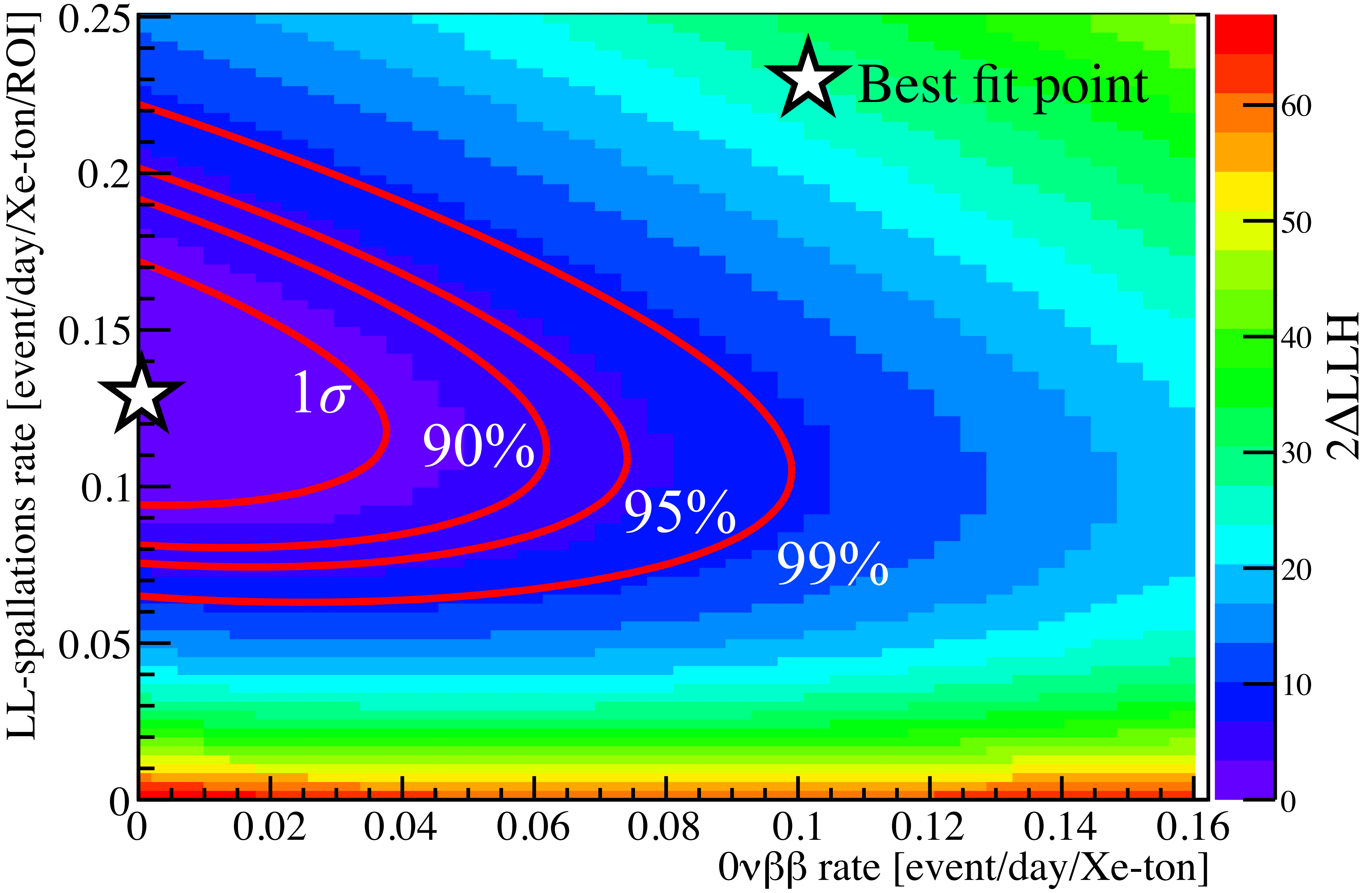
Long-lived product data set (LL dataset)
(used to constrain the LL rate)



Combined spectra include the data from the inner of 10 volume bins in fiducial-volume (radius < 1.57 m)

The KamLAND-Zen 800 Frequentist result

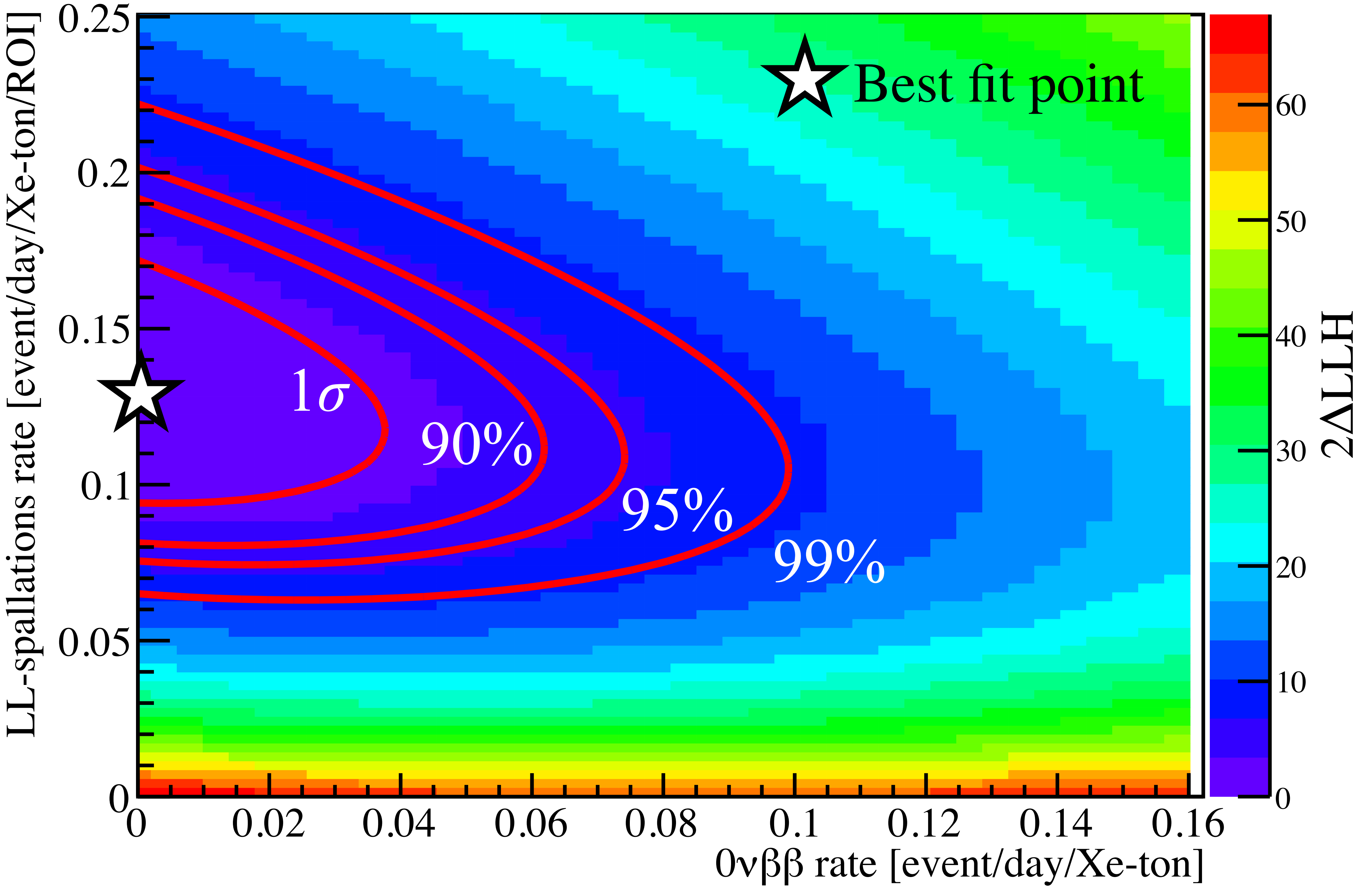
Maximum likelihood calculation with raster scan of **LL spallation rate** and **0νββ rate**.



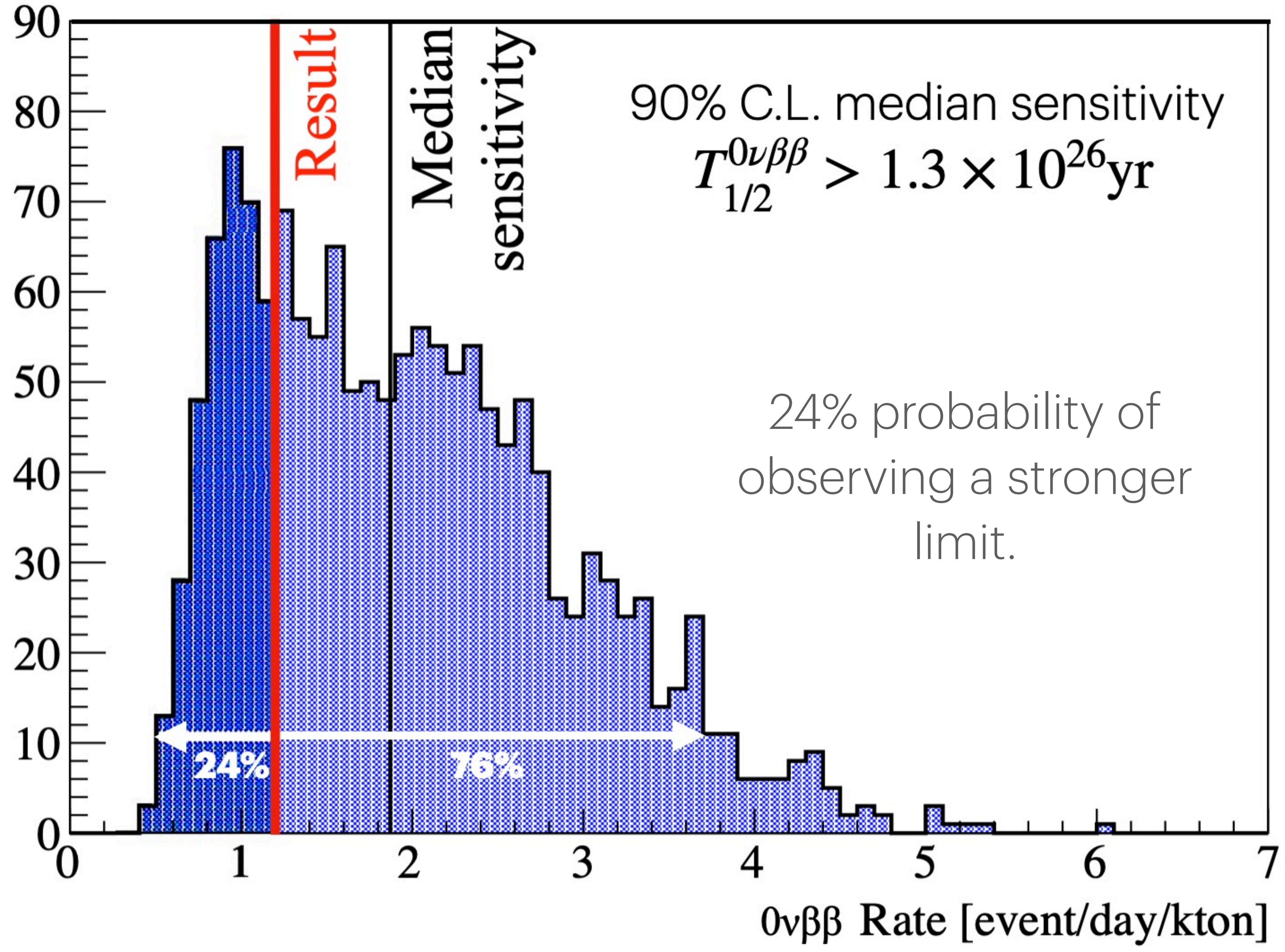
$$T_{1/2}^{0\nu\beta\beta} > 1.98 \times 10^{26}\text{yr} \ (90\,\%\,\text{C.L.})$$

The KamLAND-Zen 800 Frequentist result

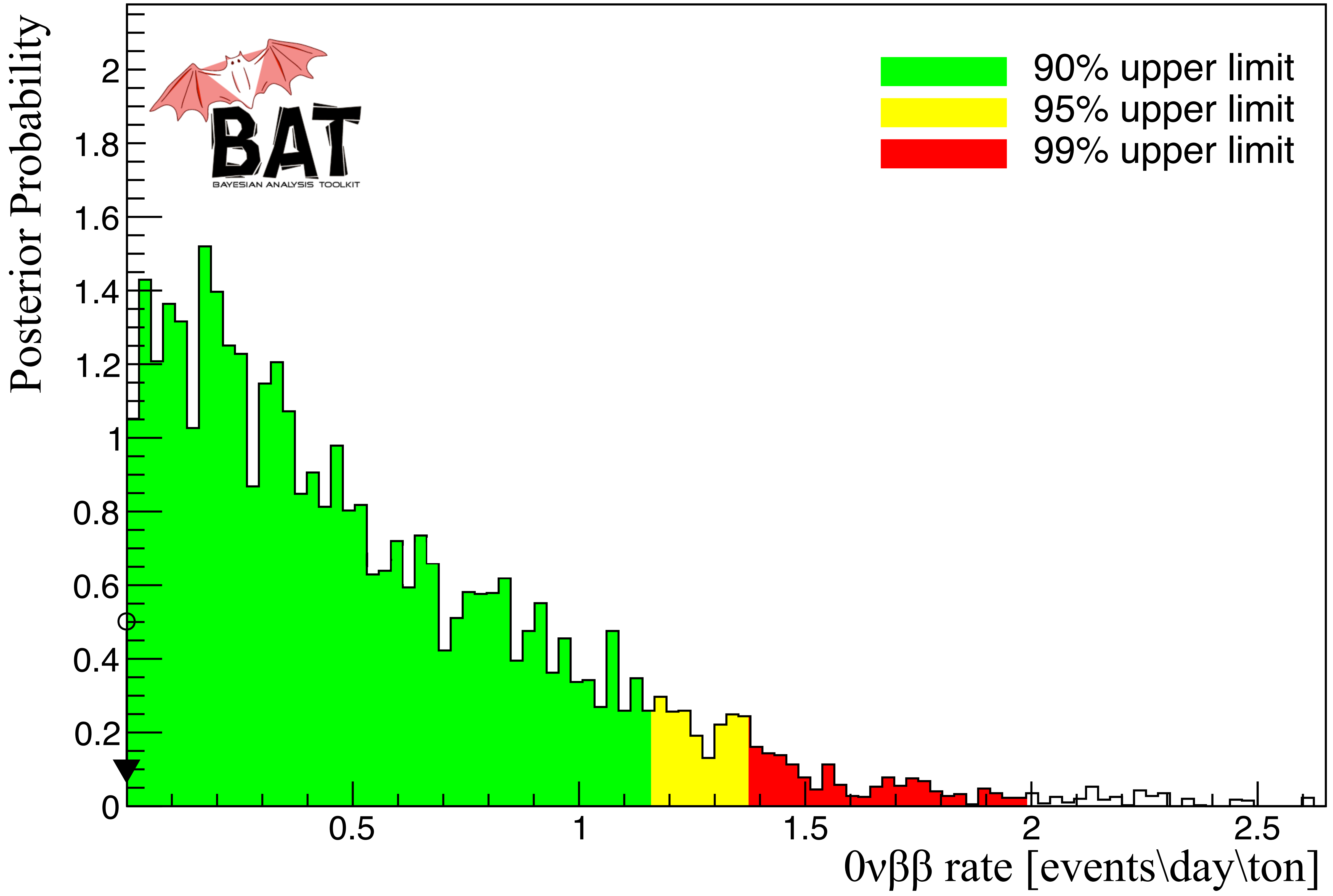
Maximum likelihood calculation with raster scan of **LL spallation rate** and **0νββ rate**.

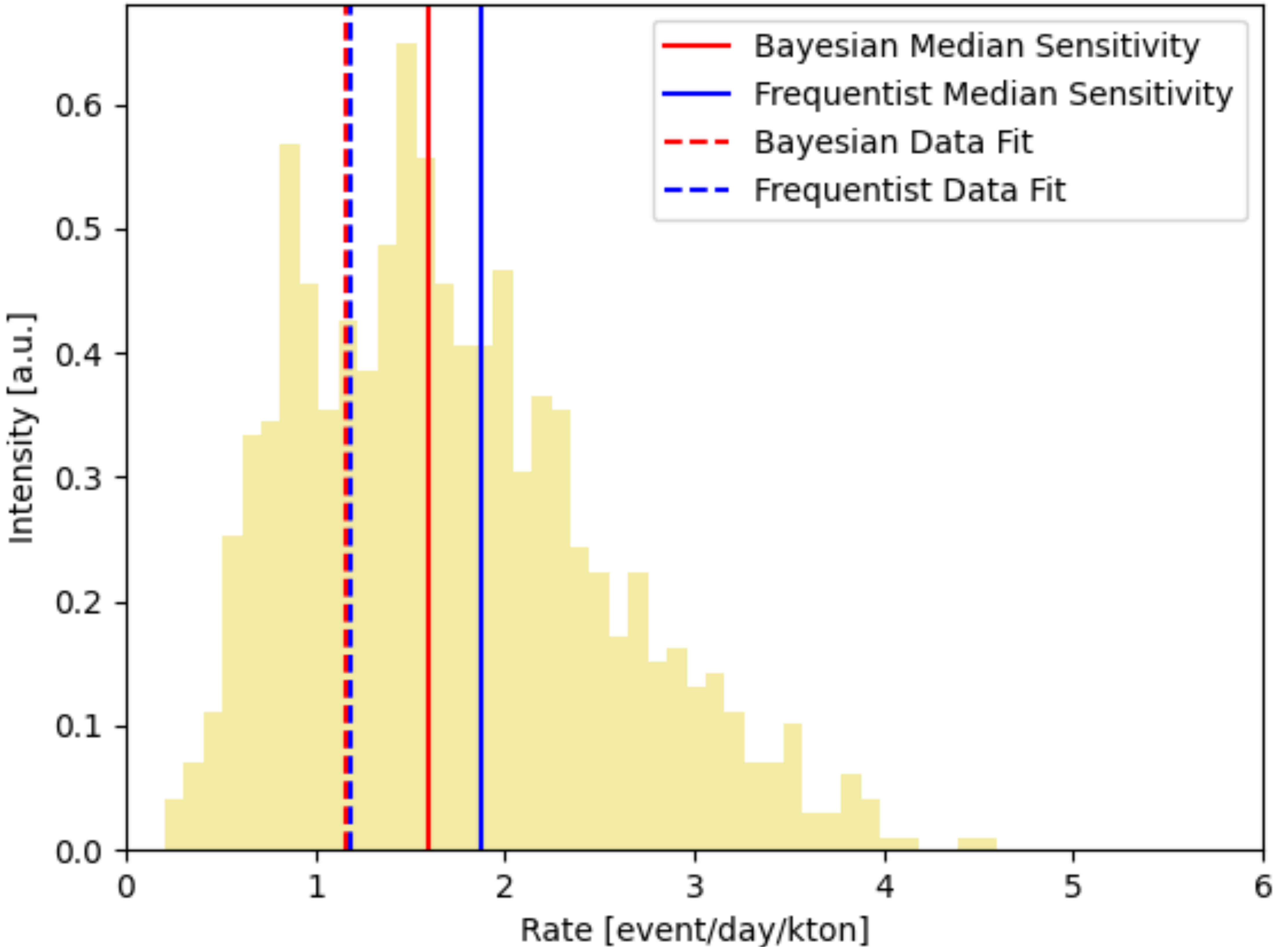


$$T^{0\nu\beta\beta}_{1/2} > 1.98 \times 10^{26}\text{yr (90 \% C.L.)}$$



The KamLAND-Zen 800 Bayesian Result





Flat prior in event rate was used

90 C.I. Bayesian Limit:

$$T_{1/2}^{0\nu\beta\beta} > 2.06 \times 10^{26}\text{yr (90 \% C.I.)}$$

90 C.L. Median Sensitivity:

$$T_{1/2}^{0\nu\beta\beta} > 1.49 \times 10^{26}\text{yr (90 \% C.I.)}$$

Summary of KamLAND-Zen 800 result

Background	Best-fit	
	Frequentist	Bayesian
^{136}Xe $2\nu\beta\beta$	11.98	11.95
Residual radioactivity in Xe-LS		
^{238}U series	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	1.65
Spallation products		
Long-lived	12.52	11.80
^{10}C	0.00	0.00
^{6}He	0.22	0.21
^{137}Xe	0.34	0.34

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Bayesian result:

$$T_{1/2}^{0\nu\beta\beta} > 2.06 \times 10^{26}\text{yr (90 \% C.I.)}$$

Frequentist confidence limit:

$$T_{1/2}^{0\nu\beta\beta} > 1.98 \times 10^{26}\text{yr (90 \% C.L.)}$$

Apply KamNet to entire dataset result:

$$T_{1/2}^{0\nu\beta\beta} > 2.7 \times 10^{26}\text{yr (90 \% C.L.)}$$

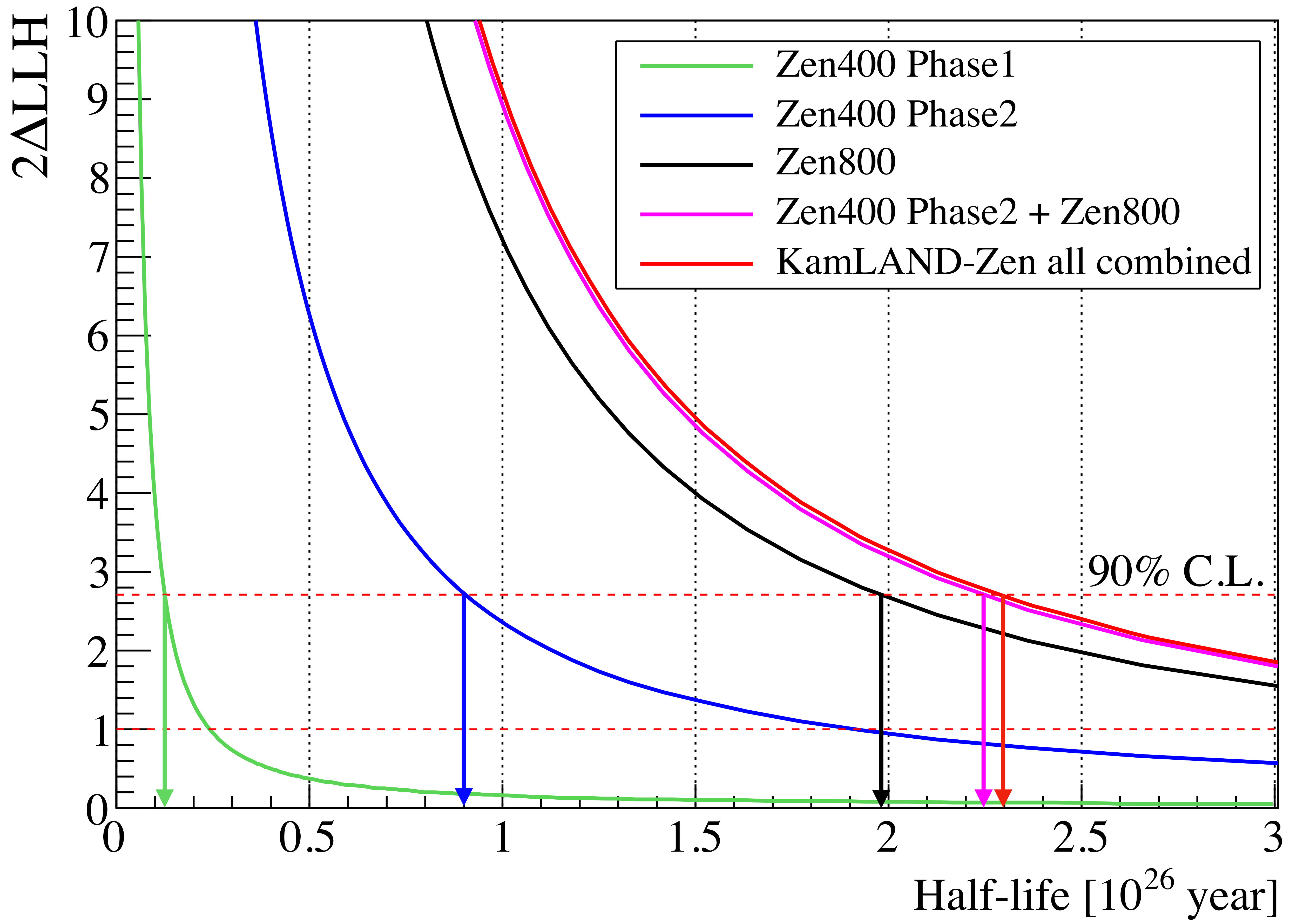
Frequentist Feldman-Cousins calculation result:

$$T_{1/2}^{0\nu\beta\beta} > 2.3 \times 10^{26}\text{yr (90 \% C.L.)}$$

KamLAND-Zen 400 & 800 combined result

The combined fit is performed in a frequentist framework.

Re-analyze the KamLAND-Zen 400 data with **updated background rejection techniques** and **long-lived spallation** consideration.



Limit :

$$T_{1/2}^{0\nu\beta\beta} > 2.3 \times 10^{26} \text{yr}$$

Sensitivity :

$$T_{1/2}^{0\nu\beta\beta} > 1.5 \times 10^{26} \text{yr}$$

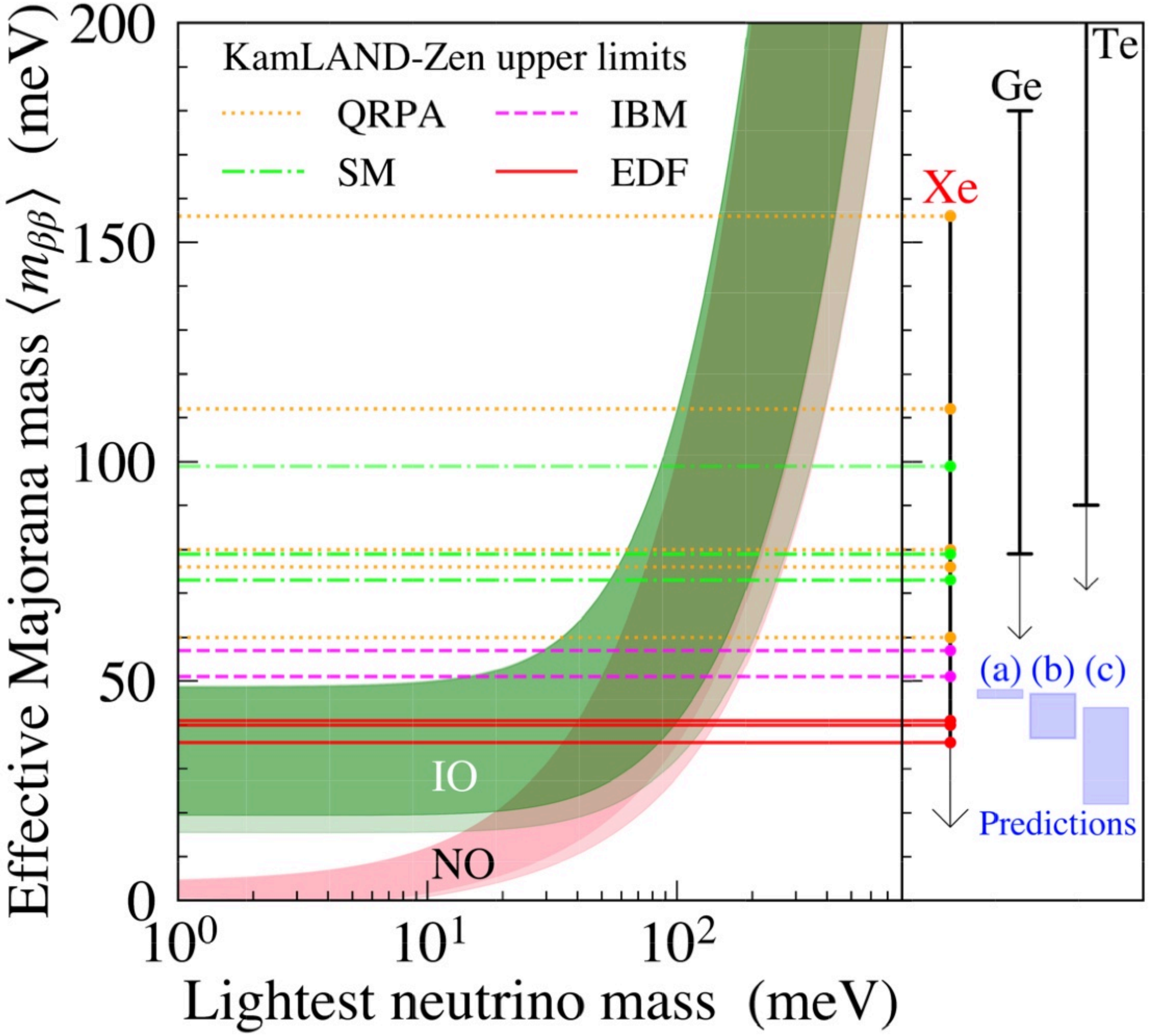
Observe consistency between the long-lived fitted values and FLUKA/Geant4 MC predictions.

The limits on the Effective Majorana mass

$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} |M^{0\nu}|^2 m^2_{\beta\beta}$

$T^{0\nu\beta\beta}_{1/2} > 2.3 \times 10^{26}$yr

$\langle m_{\beta\beta} \rangle < 36\text{–}156$ meV



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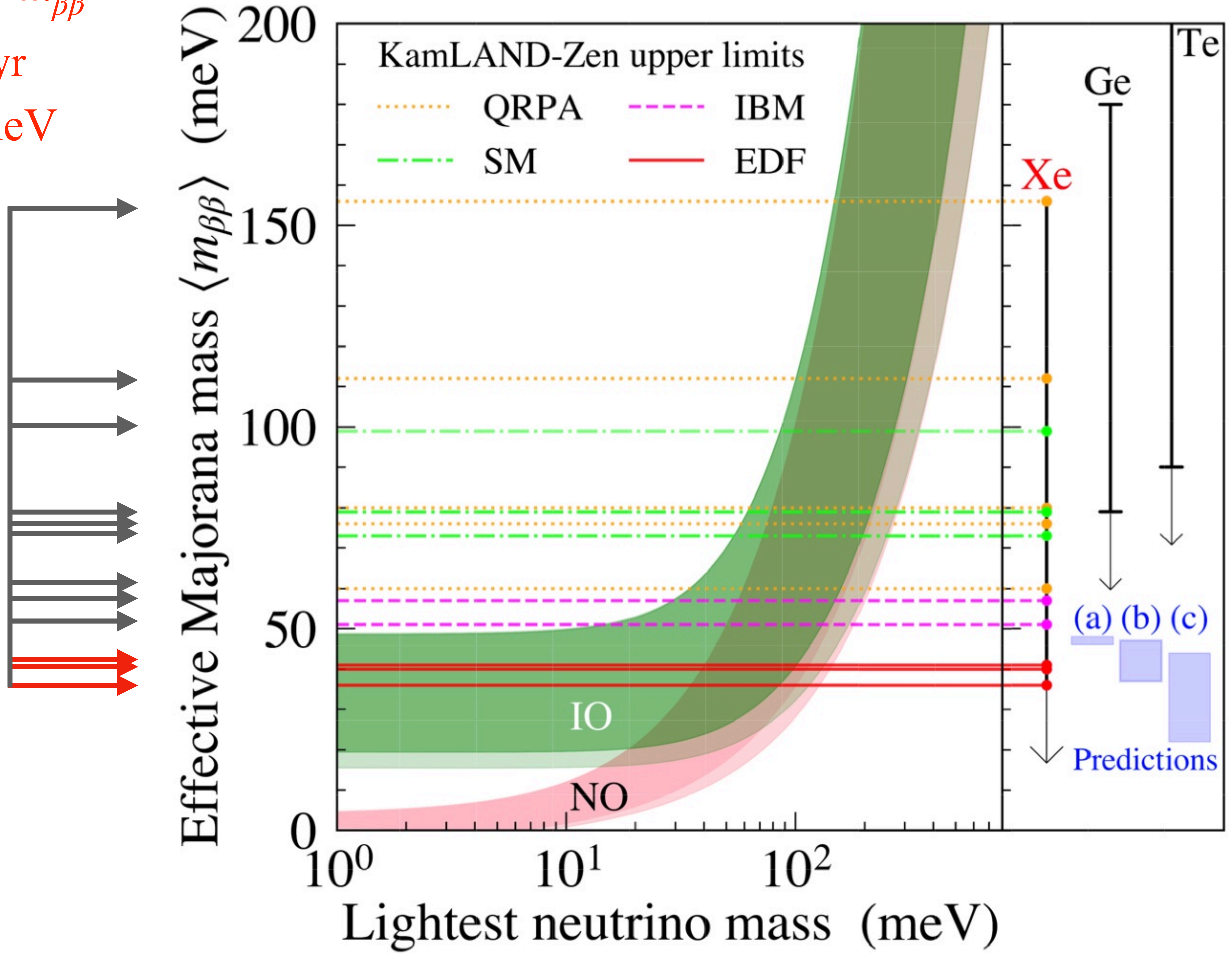
Result dependent on individual NMEs



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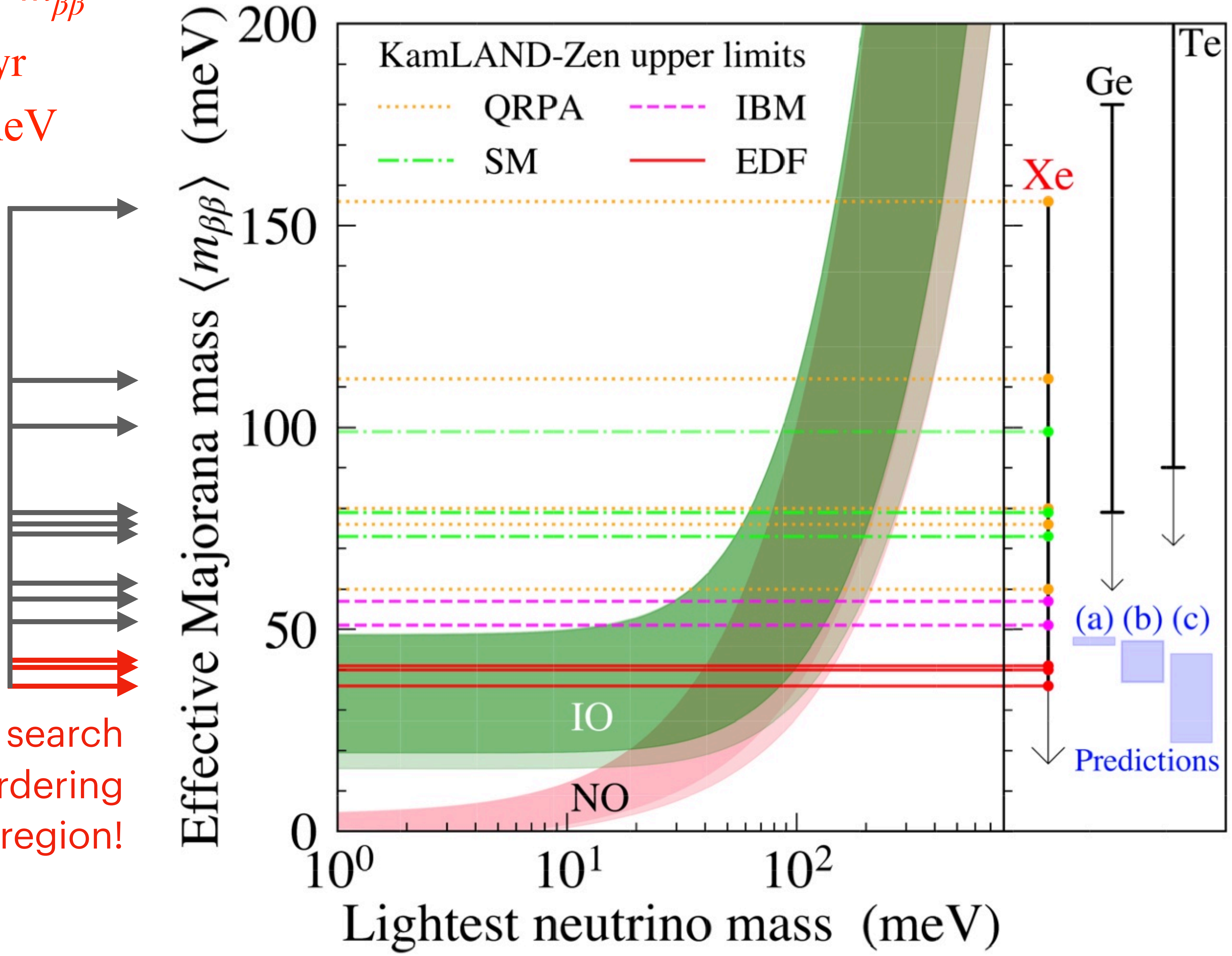
This is the first 0νββ search in the inverted ordering region!



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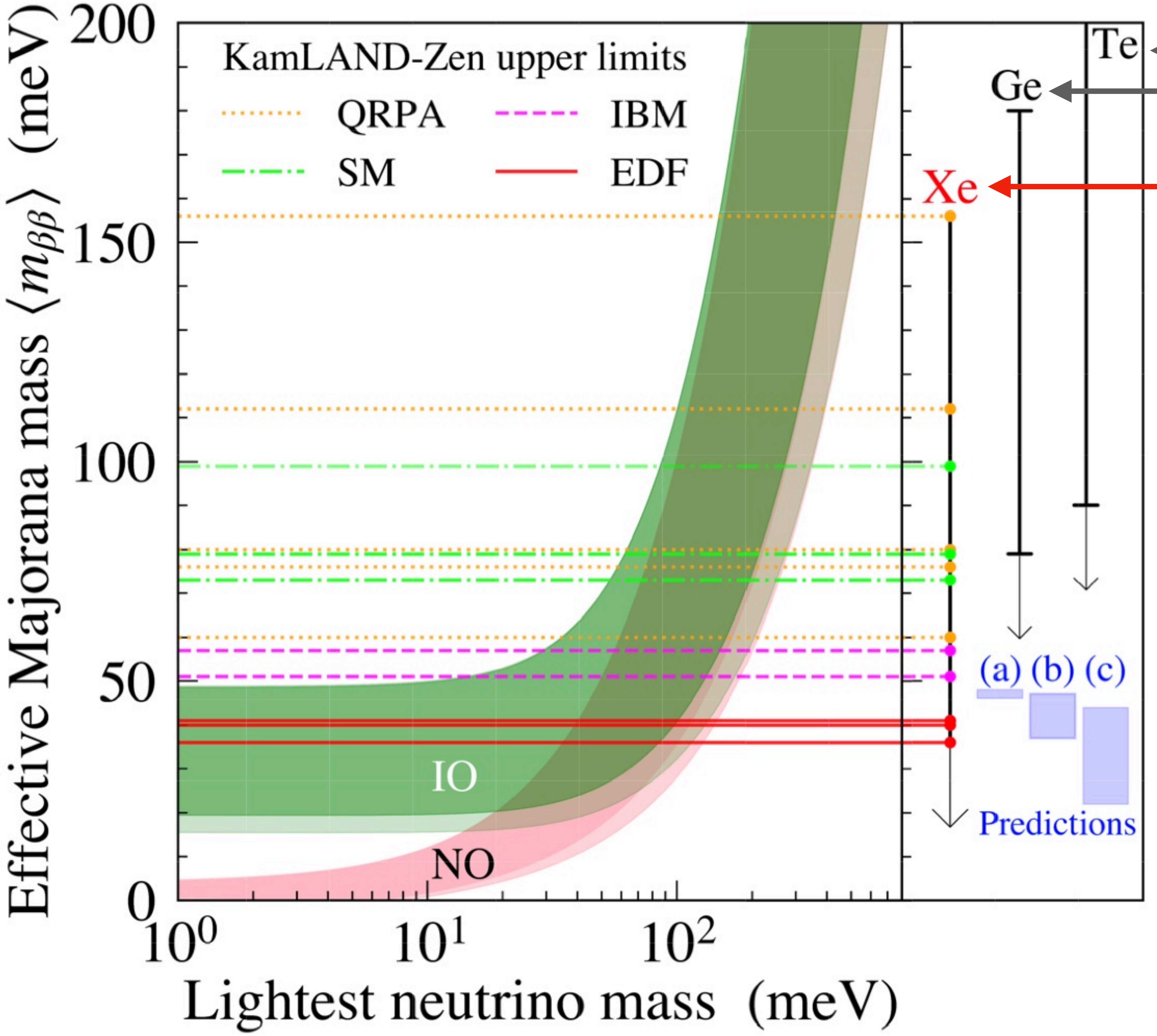

This Xe $0\nu\beta\beta$ search represents the **worlds most stringent limit** on the effective Majorana mass

(Ge) GERDA: Phys.Lett. **125** 252502
(Te) CUORE: arXiv: 2104.06906v1

The limits on the Effective Majorana mass

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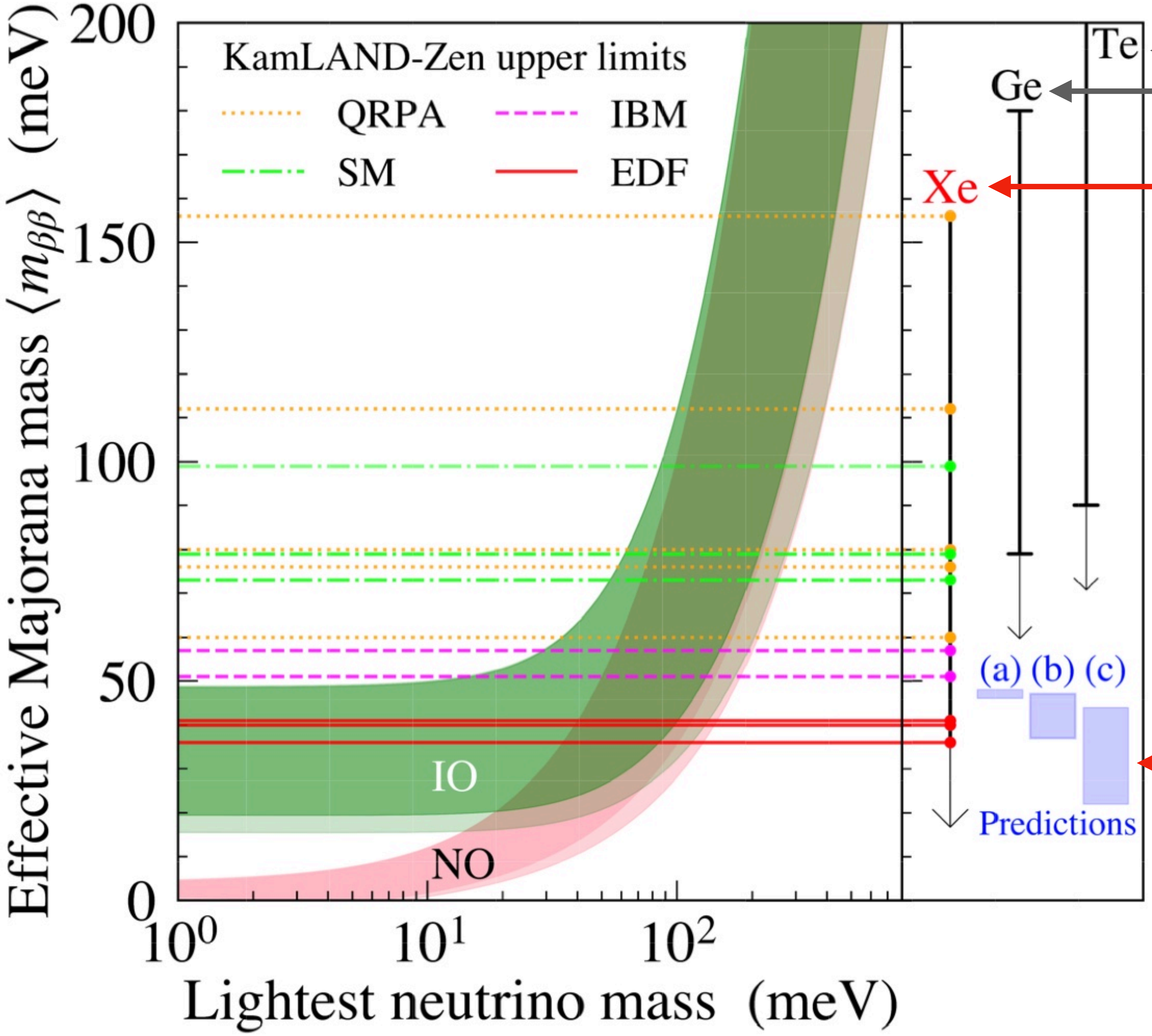

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First tests of theoretical predictions.

(a) K. Harigaya et al, Phys. Rev. D 86, 013002
(b) T. Asaka et al, Phys. Lett.B 811 , 135956
(c) K. Asai et al, Euro.Phys.J.C 80, 76

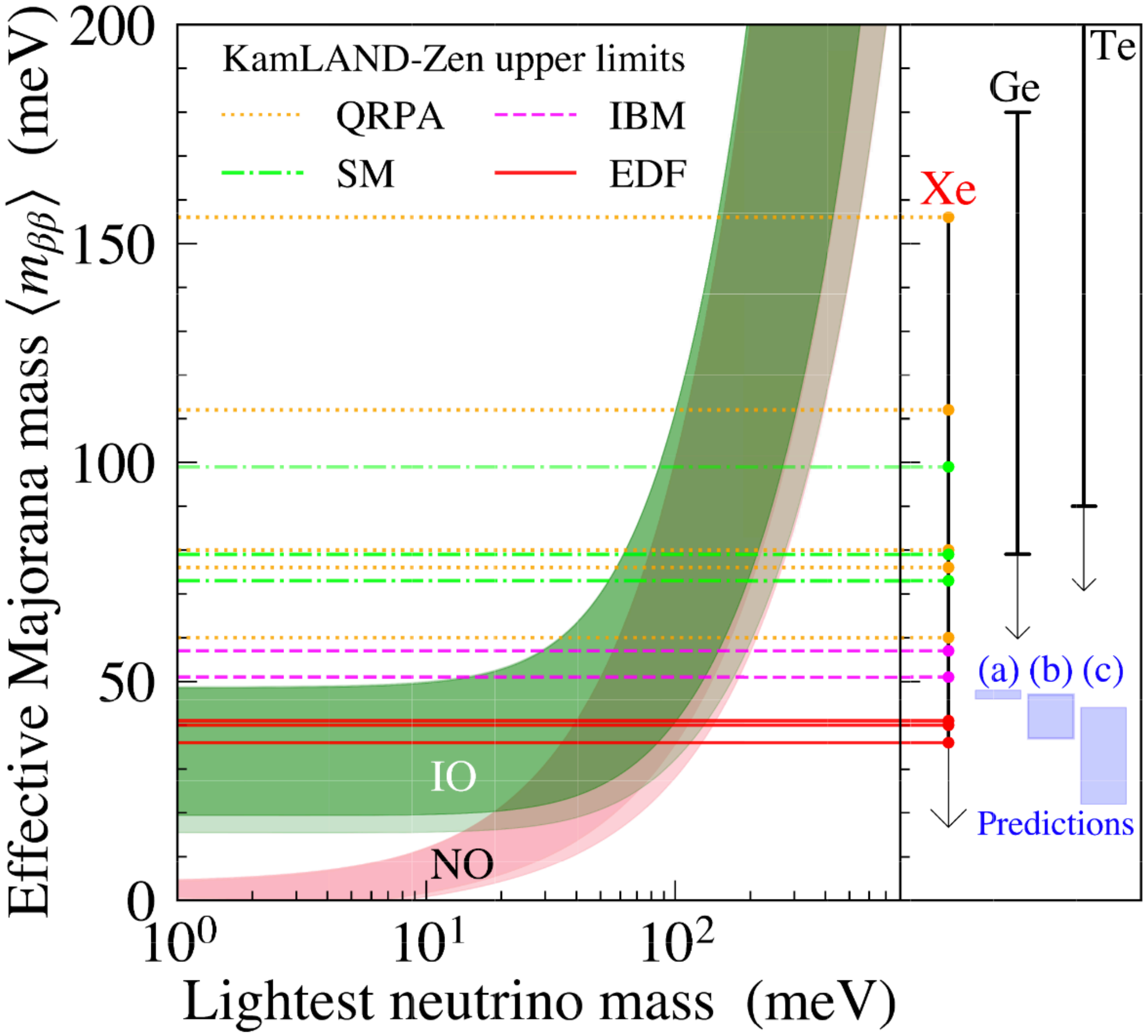
Summary & Outlook

Major technical milestone for liquid scintillator technology that has leveraged:

- scalability at low cost (increased Xe loading from KLZ-400 to KLZ-800)
- deep learning algorithms (KamNet background rejection)

Future plan:

- State-of-the-art electronics upgrade (MoGURA2 for improved background rejection)
- Improved light yield, improved light collection, and increased Xe loading in scintillating balloon (KamLAND2 upgrade)



Summary

With nearly a 1-ton-year exposure, KamLAND-Zen is searching for Majorana neutrinos in the IO region for the very first time!

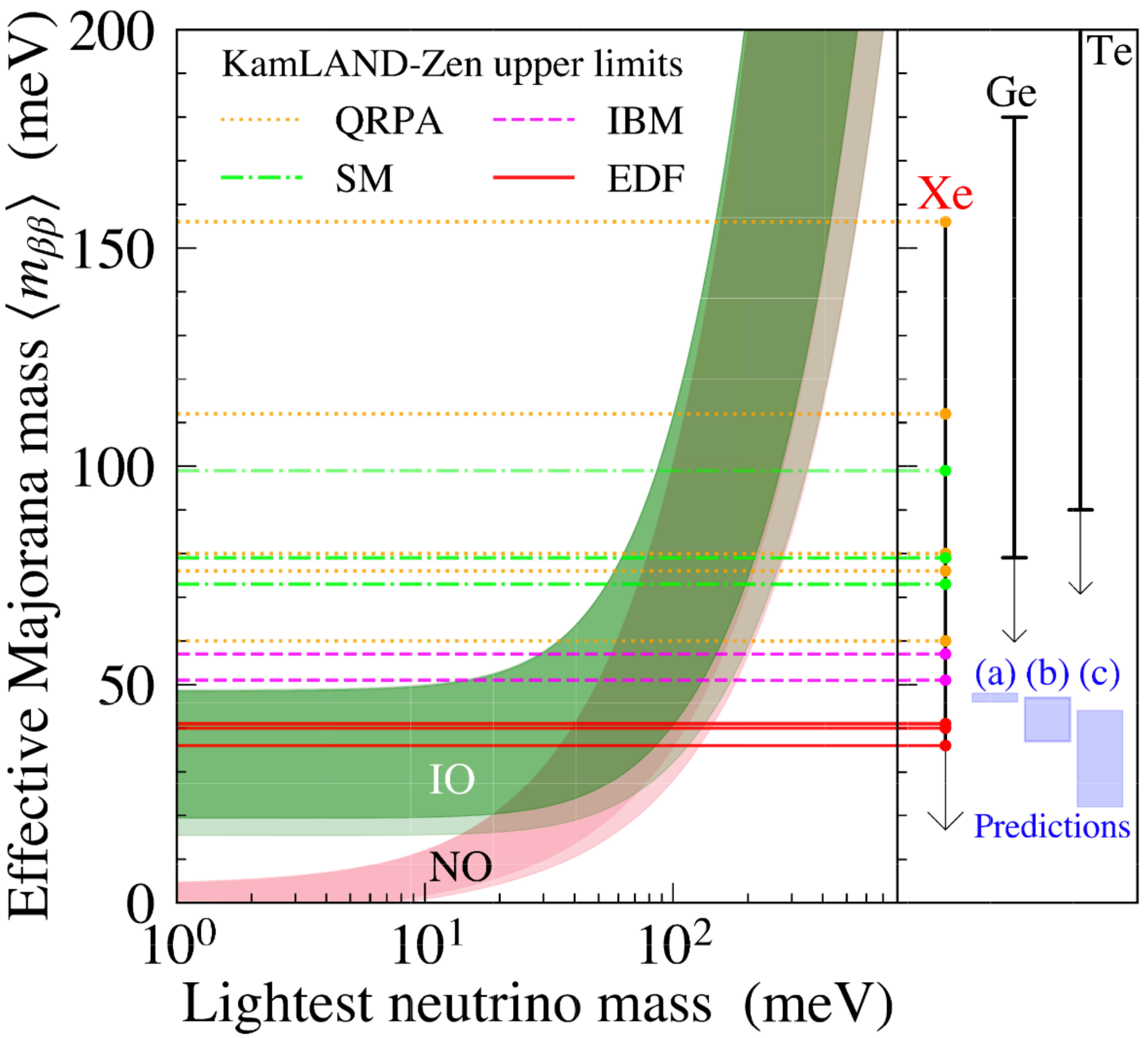
KLZ-800:

$$T_{1/2}^{0\nu\beta\beta} > 2.0 \times 10^{26} \text{yr (90 \% C.L.)}$$

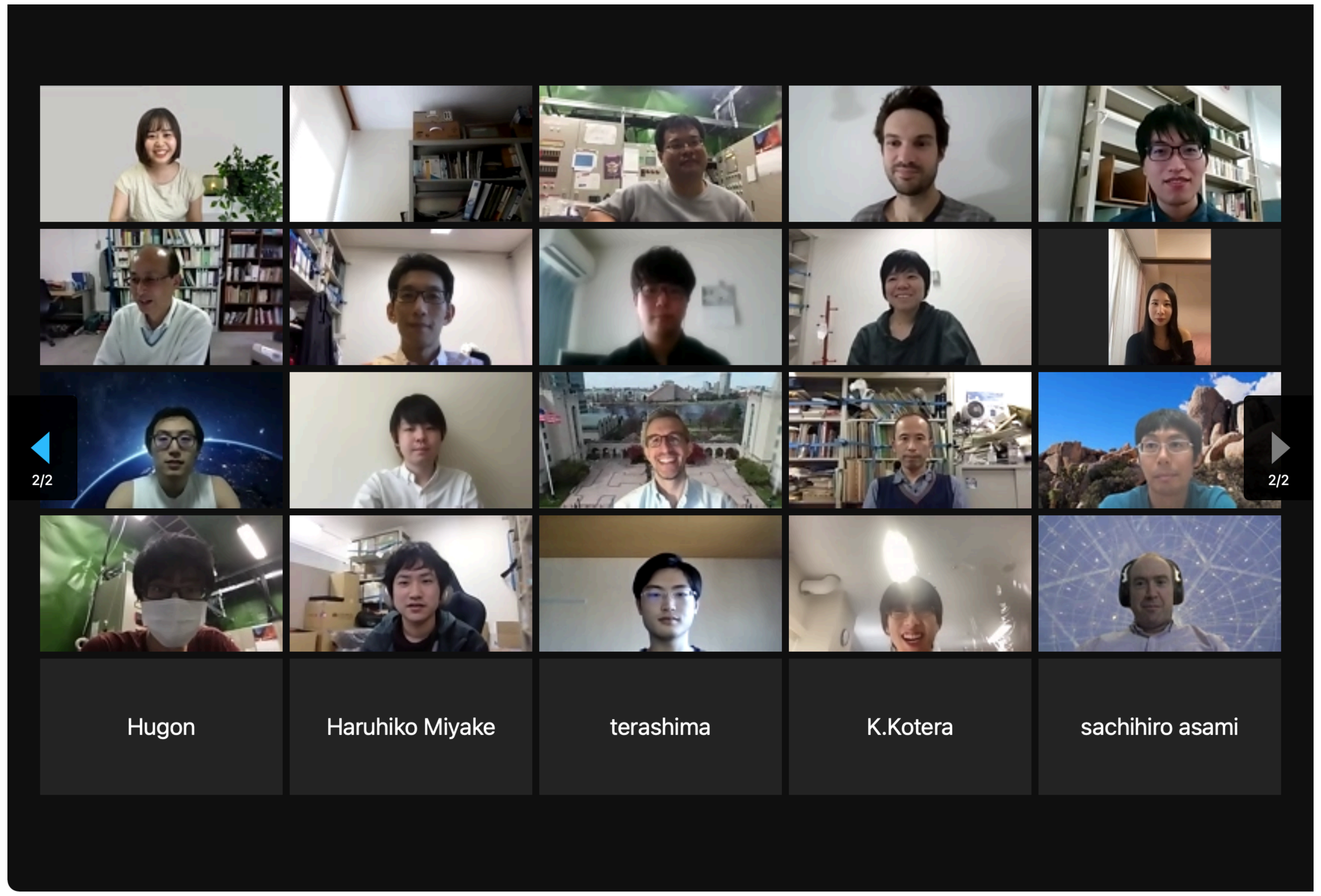
KLZ-400 + KLZ-800 combined:

Limit: $T_{1/2}^{0\nu\beta\beta} > 2.3 \times 10^{26}$ yr, $\langle m_{\beta\beta} \rangle < 36 - 156$ meV

Sensitivity: $T_{1/2}^{0\nu\beta\beta} > 1.5 \times 10^{26}$ yr, $\langle m_{\beta\beta} \rangle < 45 - 193$ meV



Thank You for Your Attention!



First Search for the Majorana Nature of Neutrinos in the Inverted Mass Ordering Region with KamLAND-Zen

A PRL preprint can be found at arXiv:2203.02139

KamNet: An Integrated Spatiotemporal Deep Neural Network for Rare Event Search in KamLAND-Zen

A PRC preprint can be found at arXiv:2203.01870

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