

KamLAND-Zen

RCNS, Tohoku univ.^a

Takahiko HACHIYA^a for KamLAND Collaboration



UGRP2026



Majorana neutrino and neutrinoless double-beta decay ($0\nu\beta\beta$)

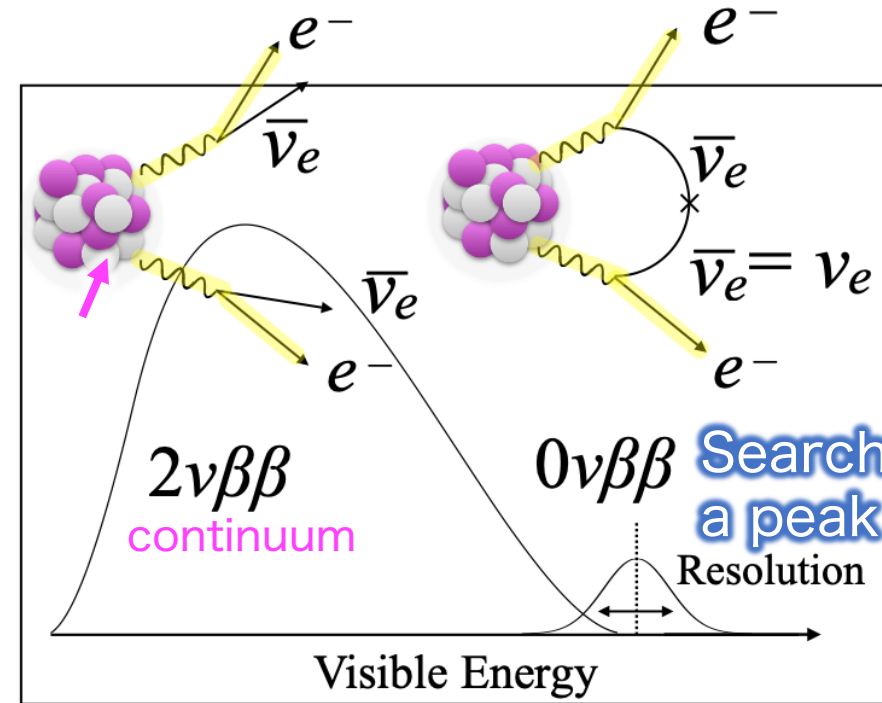
$$\nu = \bar{\nu} \text{ ?}$$

Majorana neutrino is a key to

- ✓ Tiny neutrino mass
 - See-saw mechanism*
- ✓ Matter/anti-matter asym.
 - Leptogenesis**

$0\nu\beta\beta$ decay

- Can occur only happen if ν 's are Majorana particles
- Lepton-number violation



~Summed e^- kinetic energy

Experimental requirements

- $O(100-1000)$ kg isotope
- BG reduction at $Q_{\beta\beta}$
- Better energy resolution

*M. Gell-Mann, P. Ramond, R. Slansky ('79), T. Yanagida ('79),
R. N. Mohapatra, G. Senjanovic ('80), **M. Fukugita, T. Yanagida ('86)

Effective Majorana mass

Convert half life
to effective Majorana mass

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

G : Phase space factor

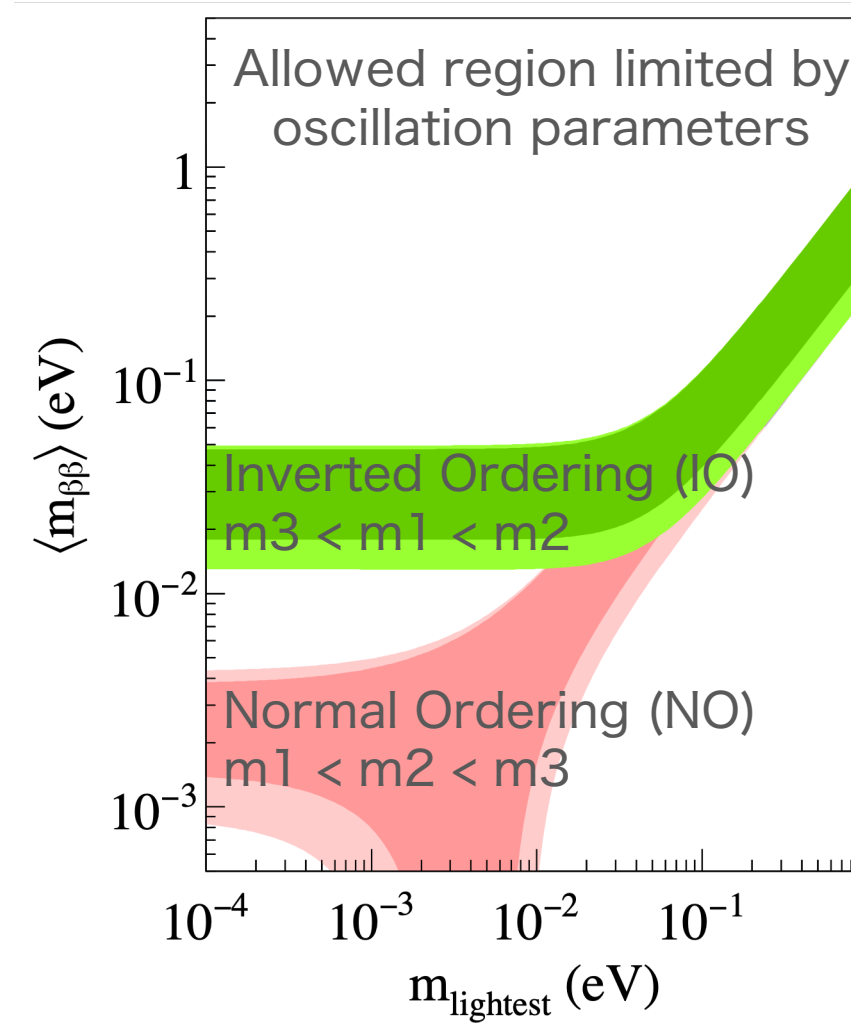
M : Nuclear matrix element

$$\langle m_{\beta\beta} \rangle \equiv \left| \sum_i U_{ei}^2 m_i \right|$$

U : PMNS matrix

m_i : neutrino mass eigenvalue

Hint for absolute mass scale



KamLAND(-Zen)

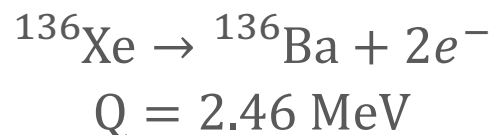
Kamioka Liquid scintillator Anti-Neutrino Detector
(Zero-neutrino double-beta decay search)

KamLAND

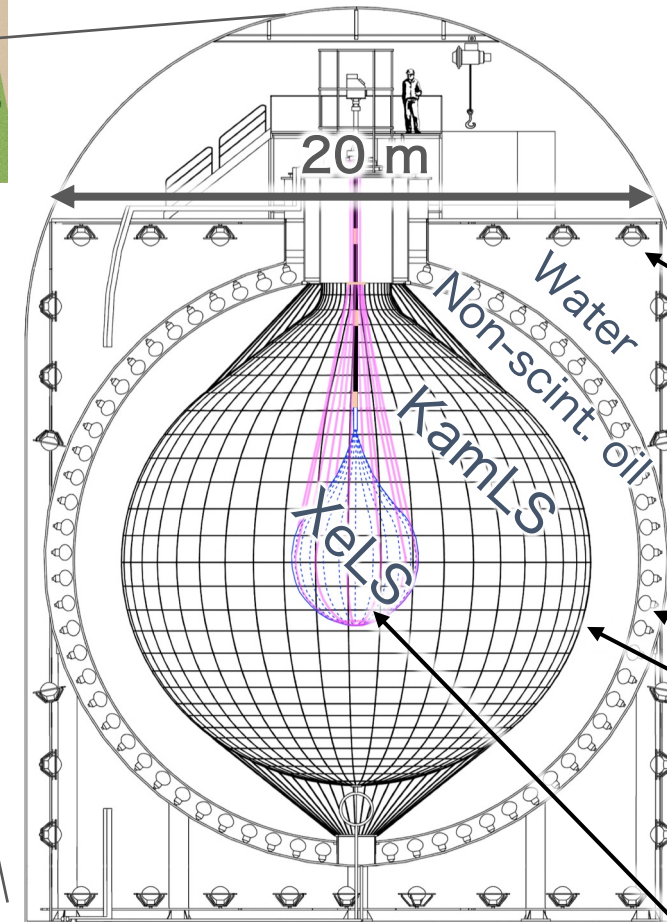
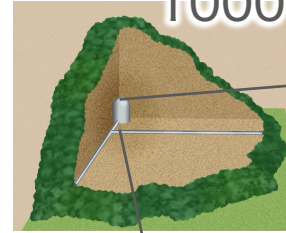
- Versatile 1-kt liquid scintillator (LS) detector
 - Reactor, geo, solar, and astrophysical ν observations
 - Rare event searches (DM etc.)

KamLAND-Zen

- A search for $0\nu\beta\beta$ decay using Xe-loaded LS (XeLS) introduced into KamLAND.
- Ultra low-BG KamLS (U, Th $\lesssim 10^{-17}$ g/g) serves as an active veto.
- Isotope: ^{136}Xe (91% enriched)
 - Dissolved in LS (3 w%).



@Kamioka, Gifu, Japan
1000 m underground



Outer Detector (OD)

- Water Cherenkov detector with 140 Photomultiplier tubes (PMTs)

Inner Detector (ID)

- $\Phi 18$ m SUS tank
- ~2000 PMTs
- $\Phi 13$ m balloon
 - Nylon+EVOH
- Non-scint. oil
- KamLS (1 kt)

Zen

- Nylon Inner Balloon (IB) contains XeLS ⁴

KamLAND-Zen collaboration

~70 researchers from 10+ institutes

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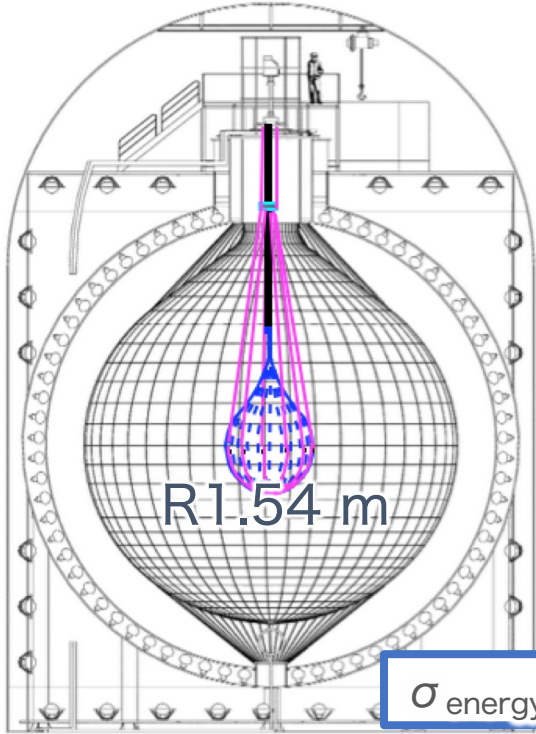
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(Dated: March 24, 2026)



Detector upgrades

2011—2015

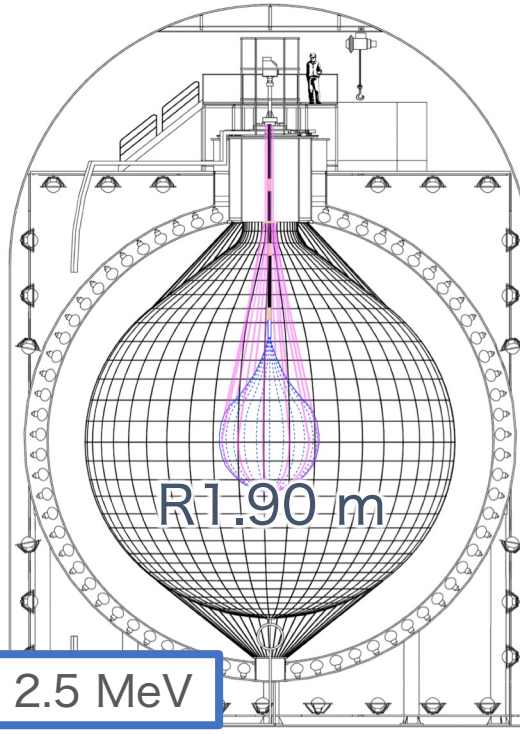


KamLAND-Zen 400

- 380 kg_{Xe}
- Rapidly achieved world-leading sensitivity
- $\langle m_{\beta\beta} \rangle < 61\text{—}165$ meV

Phys. Rev. Lett. **117**, 082503 (2016)

2019—2024

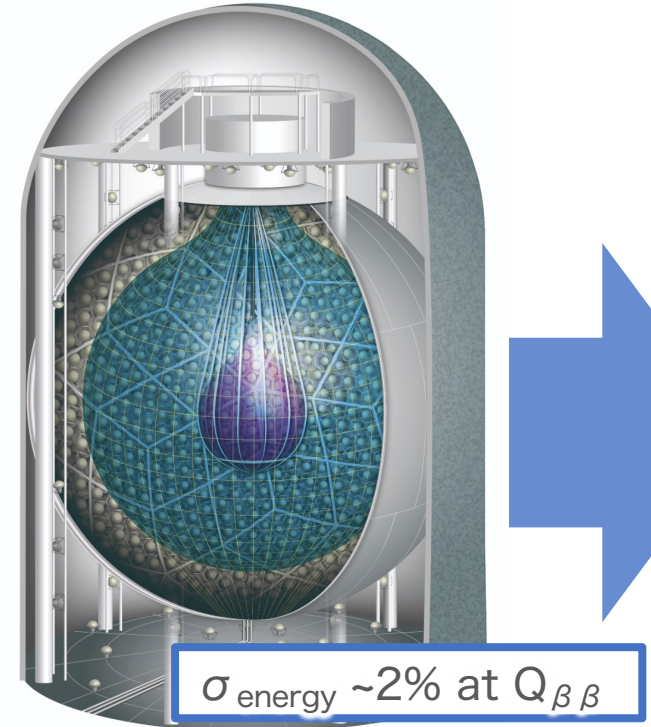


KamLAND-Zen 800

- 750 kg_{Xe}
- Larger and cleaner IB
- $\langle m_{\beta\beta} \rangle < 28\text{—}122$ meV

Phys. Rev. Lett. **135**, 262501 (2025)

Future



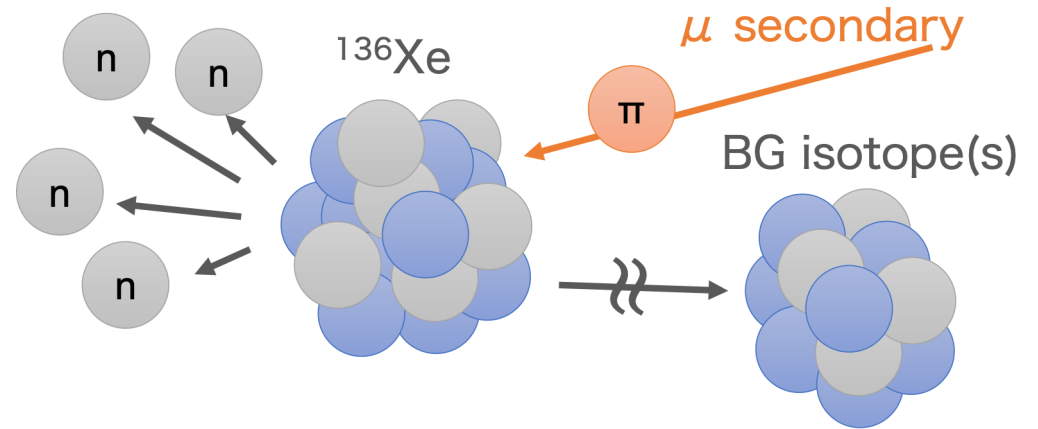
KamLAND2-Zen

- 750 (or more?) kg_{Xe}
- Higher light yield
- Many upgrades
- Target $\langle m_{\beta\beta} \rangle \sim 20$ meV

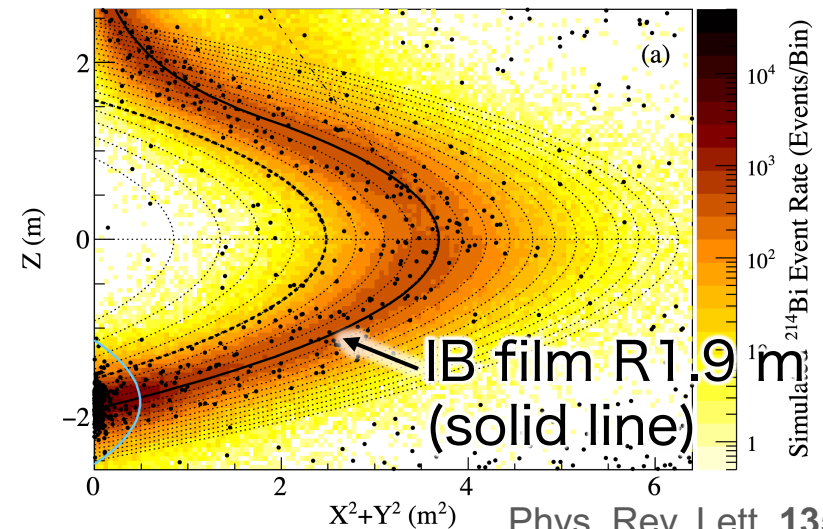
Background events for $0\nu\beta\beta$ search

- $^{136}\text{Xe } 2\nu\beta\beta$
 - Need higher energy resolution to reduce
- **Xe spallation isotopes**
 - Produced by cosmic-ray muons
 - Muon rate at KamLAND ~ 0.3 Hz
 - Many isotopes with long lifetimes
 - $\tau \sim \text{O(hours)}$
 - Accompanied by many neutrons at the spallation
 - Tagging efficiency of a likelihood cut using neutrons: $(44.0 \pm 8.7)\%$
- **^{214}Bi from IB film**
 - ^{238}U series (^{238}U in film 3×10^{-12} g/g)
 - Limits the sensitive volume

Production of Xe spallation isotopes



[MC] ^{214}Bi from IB film (color map)

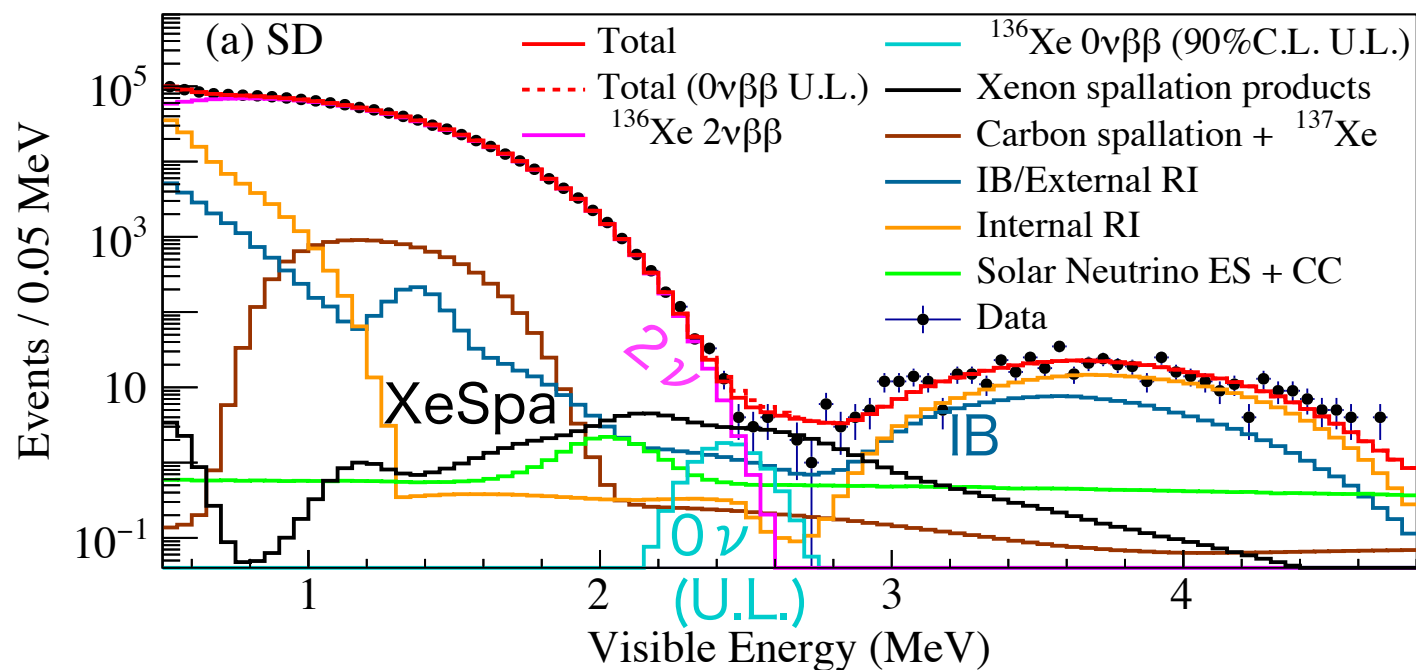


Latest results

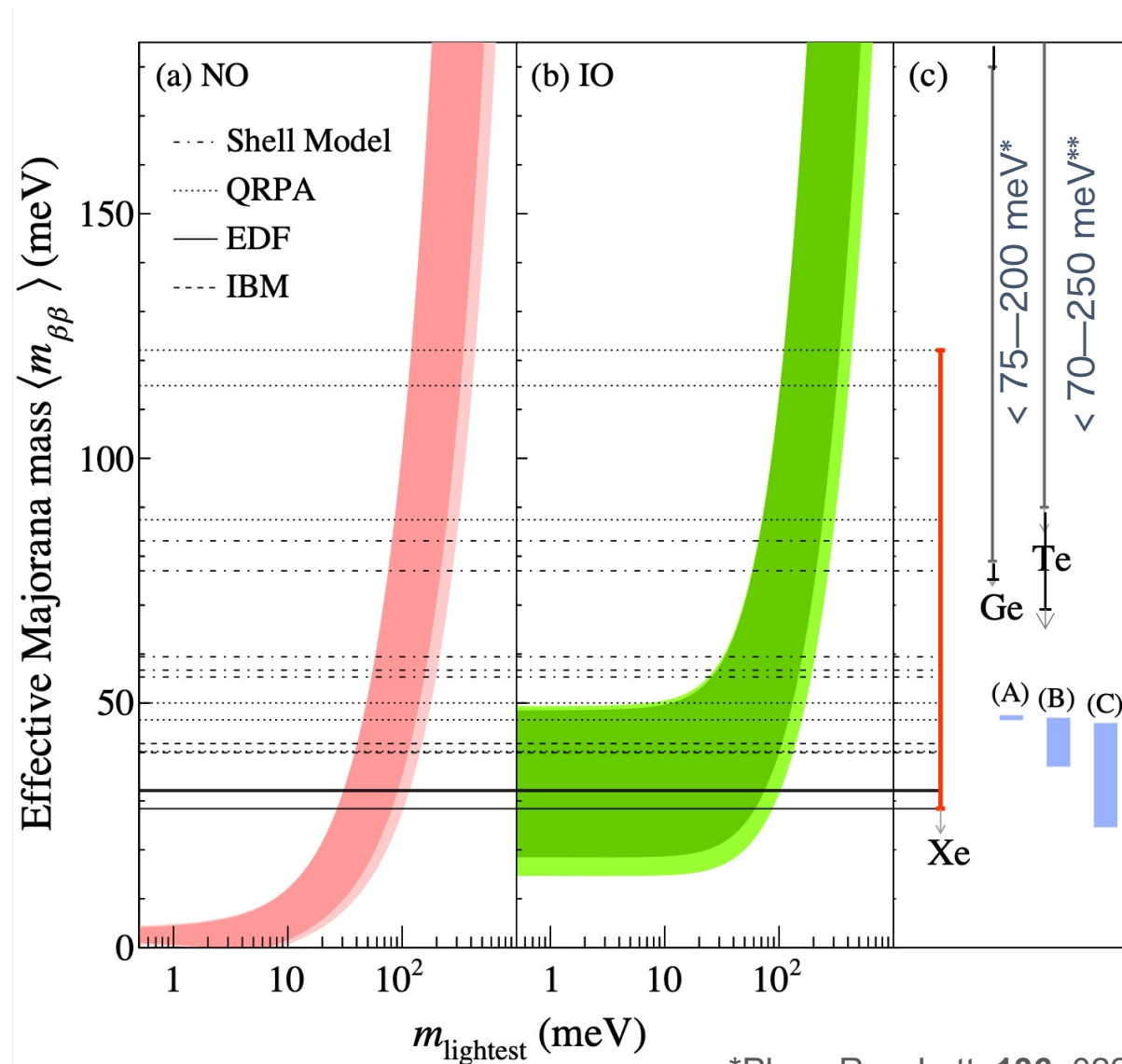
Phys. Rev. Lett. **135**, 262501 (2025)

- KamLAND-Zen 800 data taking completed on Jan. 2024.
- Total exposure: 2.1 ton-yr of ^{136}Xe
 - High-sensitivity region ($R < 1.57$ m): 1.13 ton-yr
- Simultaneous likelihood fit to the binned energy spectra of 40 volume bins ($R < 2.5$ m)
 - $0\nu\beta\beta$ best fit: 0 events
 - U.L.: < 9.7 events (90% C.L.)
 - $T_{1/2}^{0\nu} > 3.5 \times 10^{26}$ (90% C.L.)
- Zen400 and 800 combined
 - $T_{1/2}^{0\nu} > 3.8 \times 10^{26}$ (90% C.L.)
 - $\langle m_{\beta\beta} \rangle < 28\text{--}122$ meV (90% C.L.)

Energy spectrum of KamLAND-Zen 800 ($R < 1.57$ m)



Limit on effective Majorana mass



$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu} |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

G : Phase space factor

M : Nuclear matrix element (NME)

World-leading limit:

$\langle m_{\beta\beta} \rangle < 28\text{--}122$ meV (90% C.L.)

($g_A \sim 1.27$ assumed)

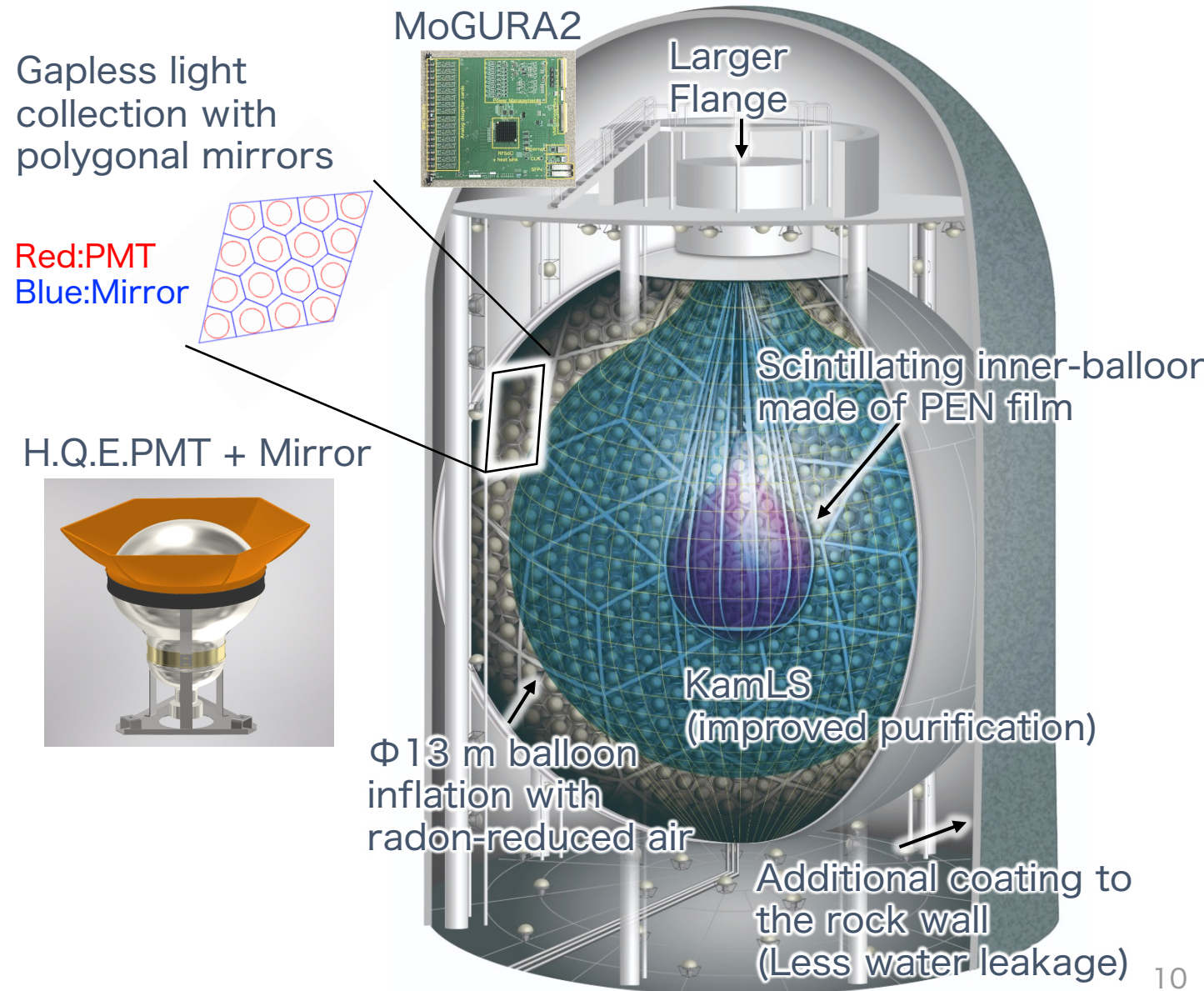
Entering IO region with some NMEs

*Phys. Rev. Lett. **136**, 022701 (2026)

**Science vol. 390, issue 6777, pp. 1029 (2025)

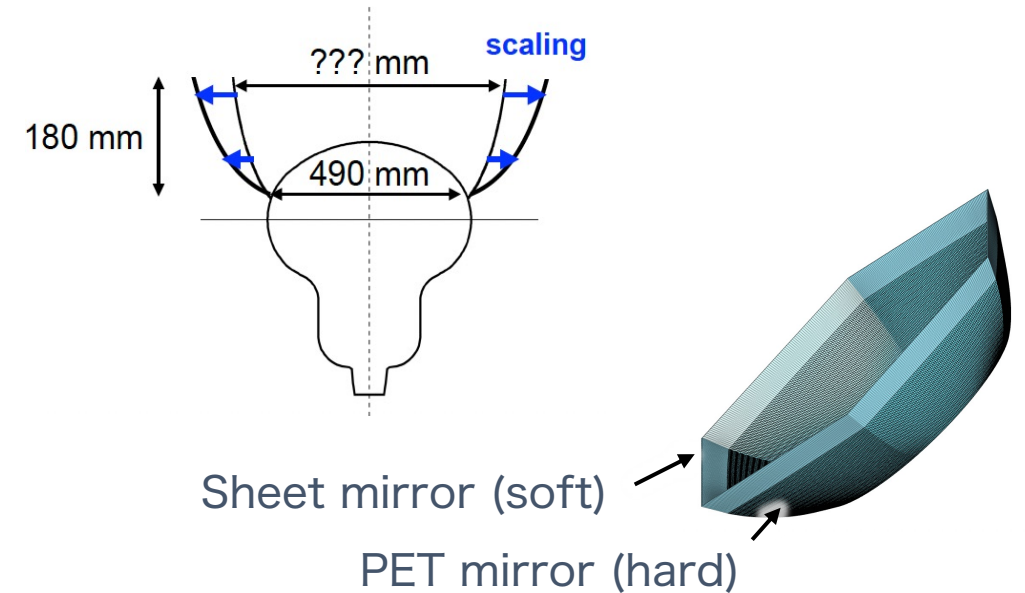
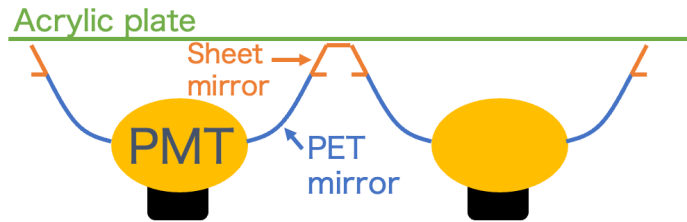
KamLAND2(-Zen)

- **1/100 $2\nu\beta\beta$ BG reduction with higher light yield**
 - 5x L.Y. to be achieved by:
 - **Light collecting mirror: 1.8x**
 - **High Q.E. PMT: 1.9x**
 - **Improved LS: 1.4x**
 - σ_{energy} at $Q_{\beta\beta} = 2\%$
 - Also improves particle ID (β/γ discrimination)
- **New electronics (MoGURA2)**
 - $\rightarrow$ Xe-spallation BG reduction
- **Scintillating inner balloon**
 - $\rightarrow$ ^{214}Bi (film) BG reduction
- **+ Several other upgrades!!**
- Target sensitivity (5 yr obs.)
 - **$T_{1/2}^{0\nu} > 2 \times 10^{27} \text{ yr } (\langle m_{\beta\beta} \rangle \sim 20 \text{ meV})$**
 - Covers most of IO region

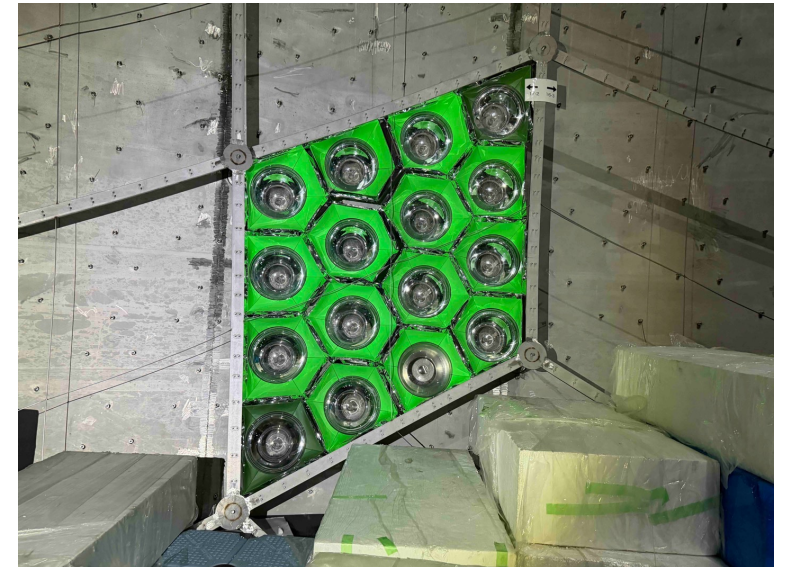


Light collecting mirror

- PET coated with aluminum
- Mirror shape was designed based on string method and modified to polygonal shape to fill gaps between PMTs.
- Sheet mirror to avoid interference with acrylic plates

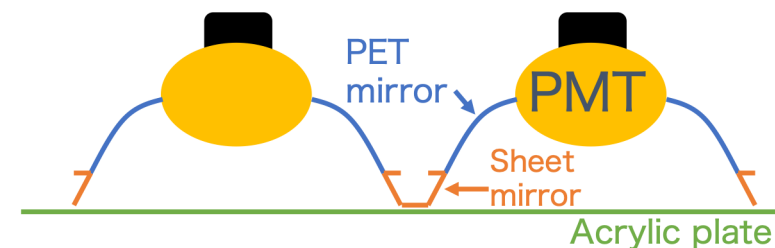


A set of 16 PMTs with mockup mirrors



Light collecting mirror production and installation test

- PET mirror production by a company completed
- Sheet mirror
 - Design finalized
 - In-house production
 - Started in Mar. 2026
 - 60% done
 - To be completed in Oct. 2026
- Final installation test of PMT + PET mirror + Sheet mirror + Acrylic plate went well (Aug. 2026).



Liquid scintillator

- We will use the same KamLS in KamLAND2
 - Composition
 - Pseudocumene (PC): 20%
 - Dodecane (N12): 80%
 - 2,5-diphenyloxazole (PPO): will be increased (~5--10% brighter)
 - KamLS: 1.36 g/L → ~1.5 g/L
 - XeLS: 2.5 g/L → ~4 g/L
 - KamLS used in KamLAND1 is now being stored in rental tanks in Wakayama
- In KamLAND1, light yield of the KamLS decreased by ~24% after on-site distillation.
- Recent laboratory-scale study showed that the optical performance can be recovered by well-controlled distillation.
- We are considering optimizing the on-site distillation process to recover the optical performance.

Scintillating inner balloon

- Material: Polyethylene naphthalate (PEN)
- By detecting the alpha decay of ^{214}Po in the film, we can tag ^{214}Bi events.
- Challenges for implementation
 - **Welding**
 - Direct heat welding often causes holes in the film.
 - We tested heat welding with hot-melt film (polyester). It satisfied mechanical requirements.
 - Next challenge is RI requirements.
 - **Purification of wavelength shifter (Bis-MSB)**
 - Bis-MSB needs to be added to the XeLS to allow the scintillation light to pass through the PEN film.
 - Recently, we found that purification by recrystallization can reduce RI levels below the required limits.

No helium leak was found in a PEN bag welded with hot-melt film



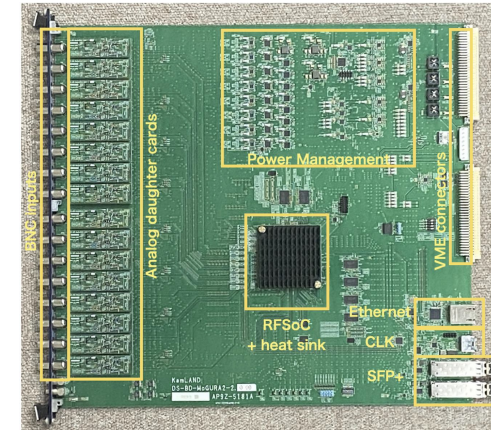
Bis-MSB RI analysis using ICP-MS of Univ. of Tsukuba (Sample of Aug. 2026)

	^{238}U (ppt)	^{232}Th (ppt)
Required	< 30	< 1
Bf. Purif.	~10000	~1000
Aft. Purif.	0.5 ± 0.1	0.4 ± 0.2

New electronics (MoGURA2)

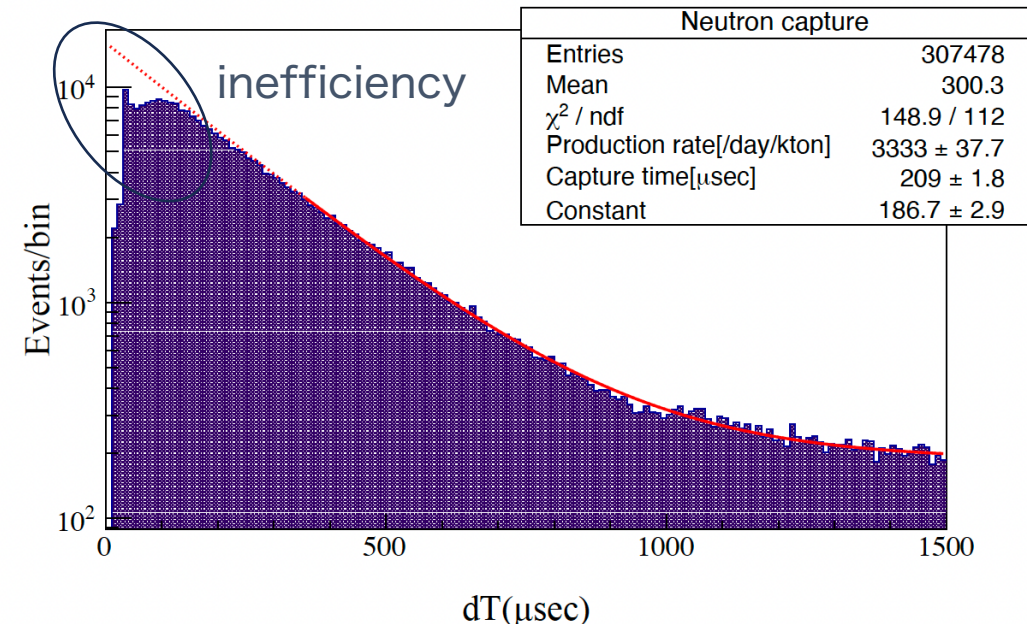
JINST 19 (2024) 03, P03013

MoGURA2 board



- Large on-board memory
- Fast data transfer
- Neutron detection efficiency after muons:
 - ~80% (now) $\rightarrow$ 99% (expected)
 - Xe-spallation tagging efficiency:
44%(now) $\rightarrow$ 65% (expected)
- Other physics
 - Nearby supernovae
 - ν_e absorption on ^{136}Xe (longer event window)
- Poster P26 by Hanwook BAE

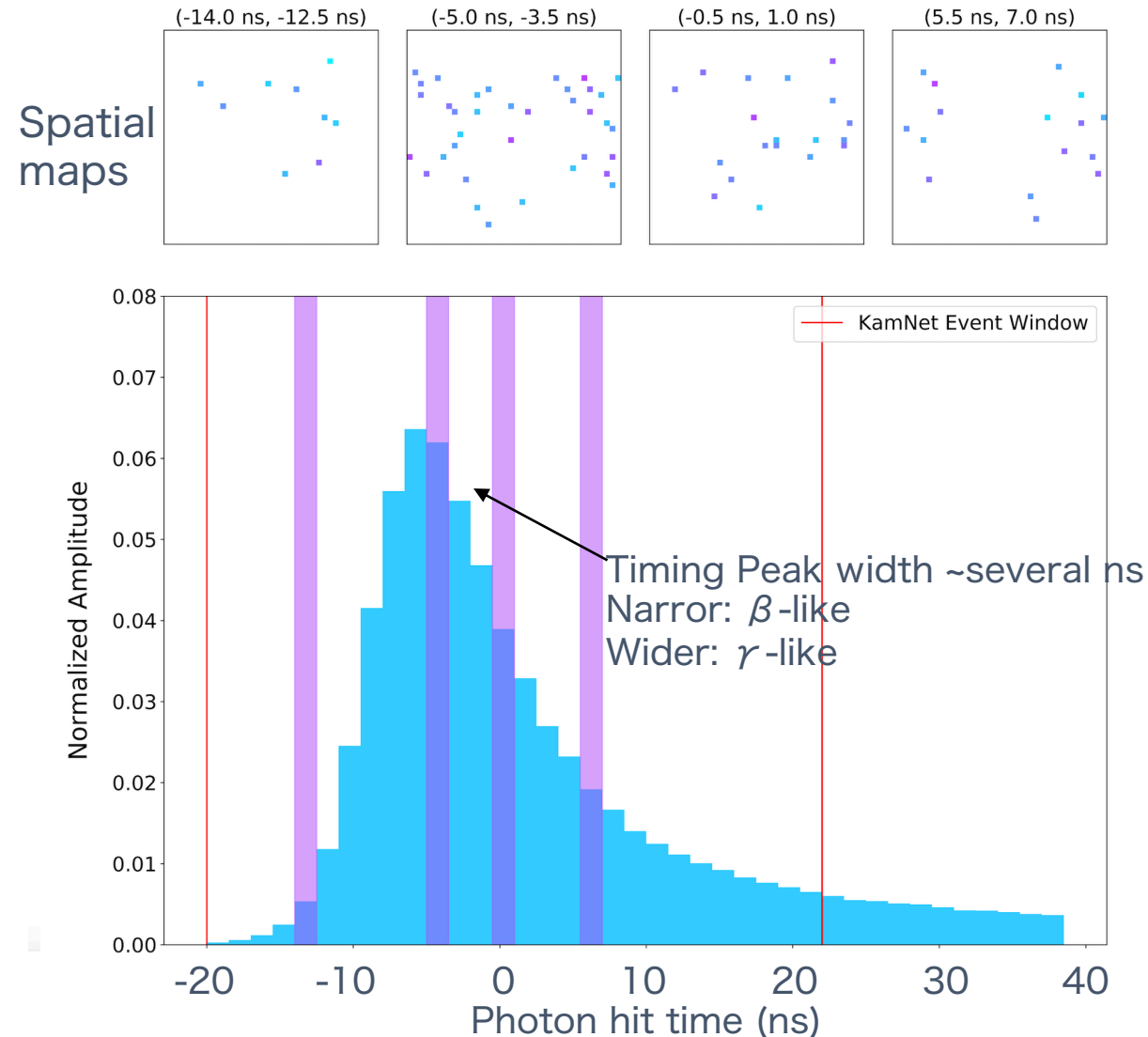
μ —n time difference (KamLAND1 data)



Particle ID

- $0\nu\beta\beta$ events are point-like, while γ backgrounds are more extended
 - Most Xe-spallation backgrounds are accompanied by γ -rays
- ML-based particle identification methods are being studied using the spatial and temporal distribution of photon hits
 - E.g., KamNET* *Phys. Rev. C 107, 014323 (2023)
 - For Zen800, ~20—30% of γ -BG rejection at 90% sig. eff.
- KamLAND2-Zen has more photons
 - At 2.5 MeV: 600 hits $\rightarrow$ 3000 hits
 - γ -BG rejection efficiency is expected to reach ~60–80%

Example of spatial and temporal distributions of photon hits in an event



KamLAND2(-Zen) timeline

'24				'25				'26				'27				'28			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4

- End of Zen800

Xe collection

- IB removal

Xe distillation

- End of KamLAND1

OD dismantling

Oil removal

Drying period

- $\Phi 13$ m balloon removal

ID dismantling

LS fluor (PPO) distillation

OD wall coating

OD PMT installation

ID tank & installation material cleaning

(Now)

ID PMT & mirror installation

- New ID flange installation

$\Phi 13$ m balloon production

- $\Phi 13$ m balloon installation

Oil filling

New electronics installation

- Start of KamLAND2

IB production & installation

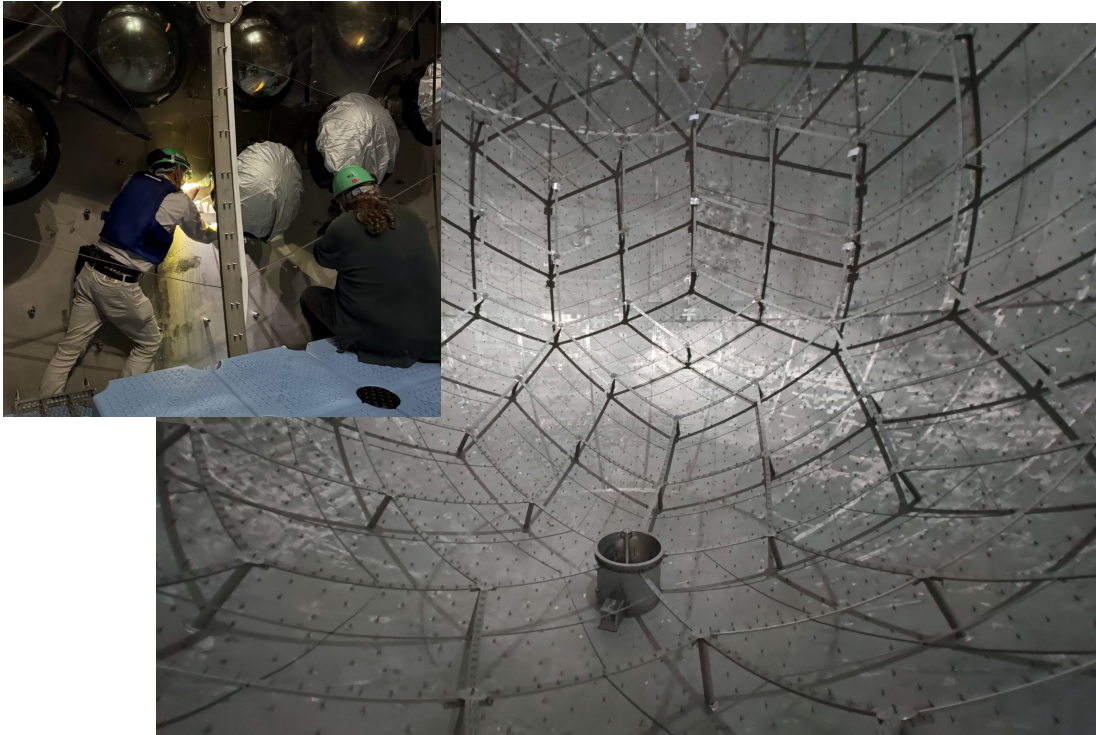
XeLS filling

- Start of KL2-Zen

Recent on-site work

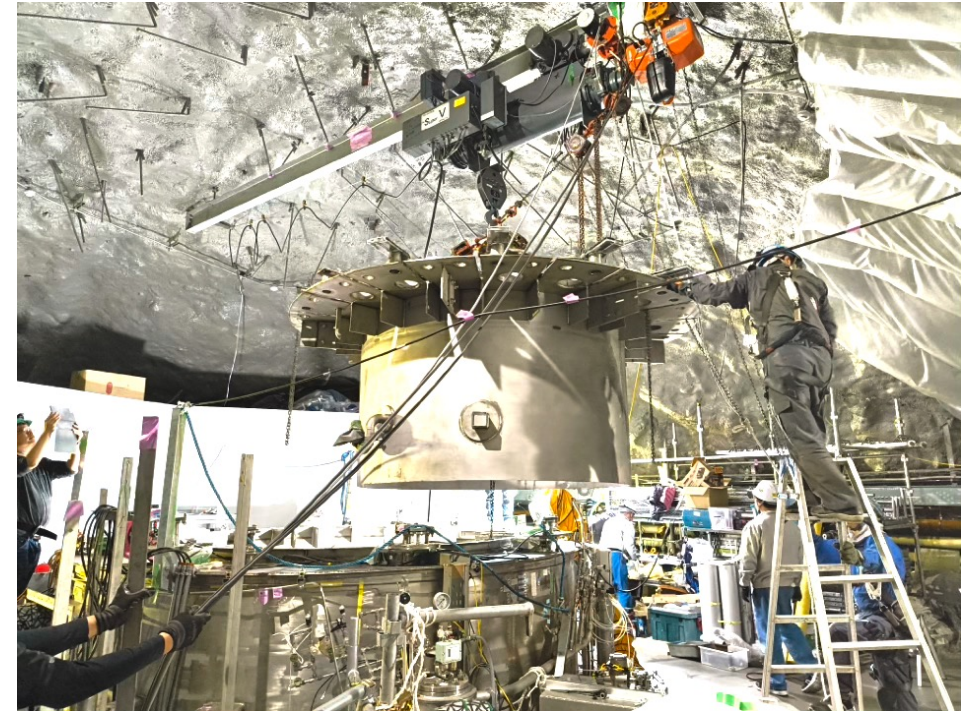
Inner Detector (ID) Dismantling

Old PMT removal (Jul—Oct. 2025)



- Removed using a floating platform after filling the tank with water.

$\Phi 2$ m chimney removal (Oct. 2025)



- It had to be removed to install the acrylic plates.
- It will be replaced with one with a larger opening.

Preparation for PMT Installation (Started in June 2026. Now ongoing)

Broken bolt removal from
boss



Tank cleaning



Cleaning of items for
installation



<https://pro.kao.com/jp/products/kps05/4901301505996/>



https://www.kikulon.com/products/kikulon_a.html



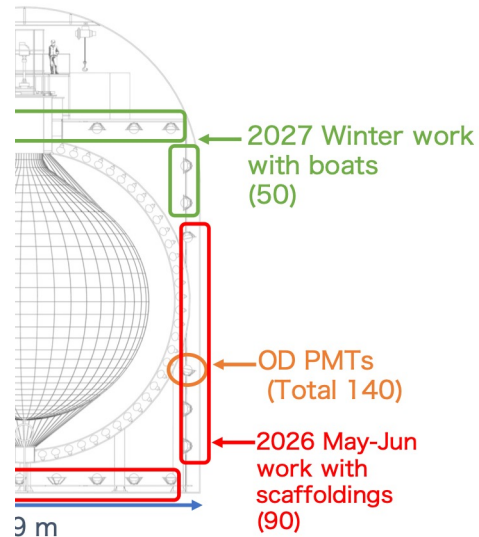
Outer Detector Reassembly

Waterproof spraying
(Jan—Mar 2026)



PMT installation (May—Jun 2026)

- 90 PMTs and Tyvek sheets on accessible parts were installed using scaffolding.
- Remaining PMTs and Tyvek sheets to be installed using boats after the ID is filled with oil.



Distillation of LS fluor (PPO) (Oct--Dec. 2025)

- During the 2024 oil recovery from the ID, PPO distillation was incomplete due to a vacuum pump failure
- We swapped the pump with a good one and distilled ~1.5 t of PPO.

Before distillation
(90% PPO
+ 10% Dodecane
+ Others)



After distillation



High-purity N₂ generator dismantling

- The generator is no longer available due to the end of manufacturer support.
- We will use commercial N₂ in KamLAND2
 - Purity concern: ⁸⁵Kr
 - Removal by cryo-adsorption is being studied
- We dismantled and removed the generator (Jul--Aug. 2026)
- The freed up space will be used for ID PMT preassembly



Summary and Prospects

- KamLAND2: A major KamLAND upgrade featuring 5× higher light yield and various other improvements
 - KamLAND2-Zen:
Target sensitivity (5 yr obs.): $T_{1/2}^{0\nu} > 2 \times 10^{27} \text{ yr } (\langle m_{\beta\beta} \rangle \sim 20 \text{ meV})$
- The construction phase has shifted: Dismantling → Reassembly
 - More than half of OD PMTs have already been installed
 - ID PMT installation starts soon (from Nov. 2026)
 - Φ13 m balloon production starts soon
- We aim to start
 - KamLAND2 data taking in FY2027
 - KamLAND2-Zen data taking in FY2028