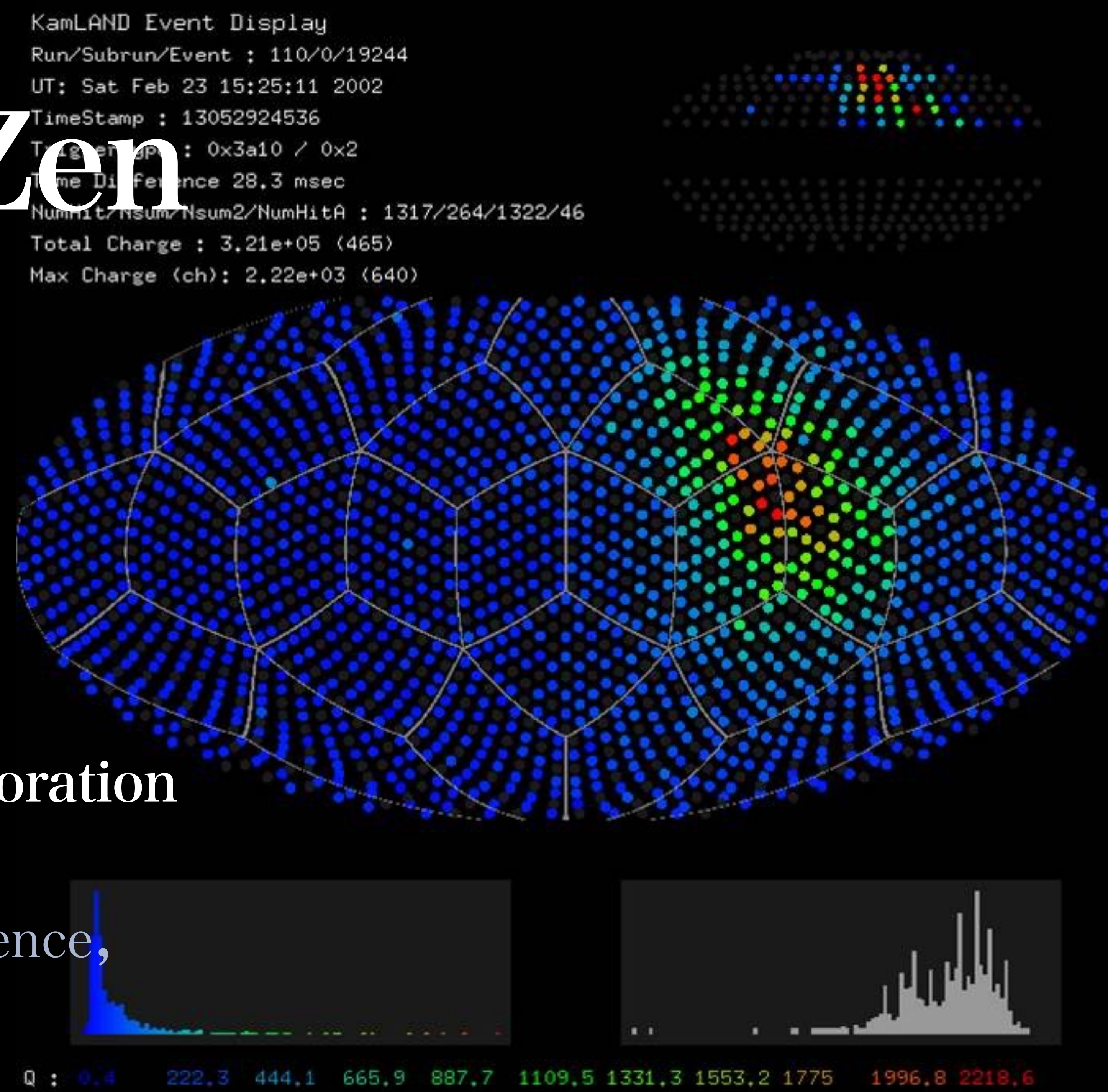
KamLAND-Zen

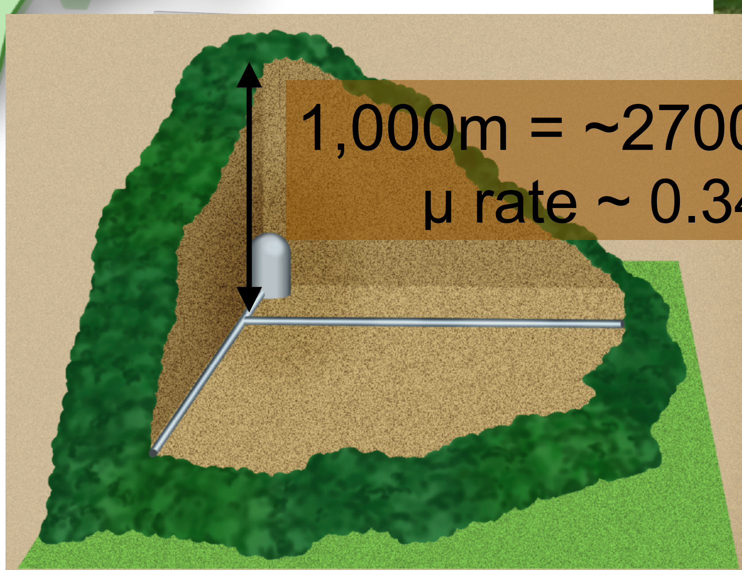


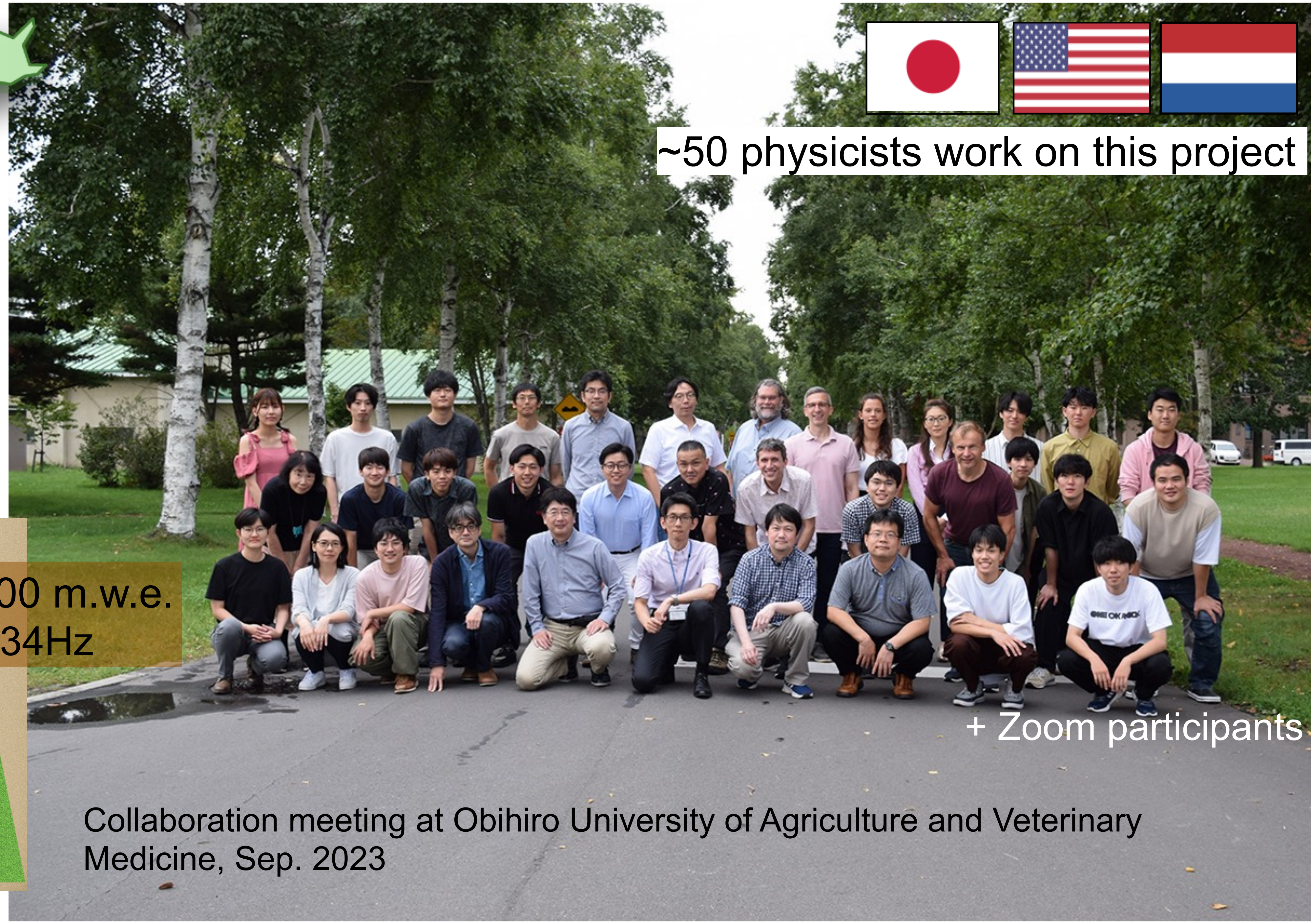
Haruhiko MIYAKE
for the KamLAND-Zen collaboration

Research Center for Neutrino Science,
Tohoku University

Lake Louise Winter Institute
February 21, 2024

KamLAND/KamLAND-Zen Collaboration





Collaboration meeting at Obihiro University of Agriculture and Veterinary Medicine, Sep. 2023

Neutrinoless Double beta decays

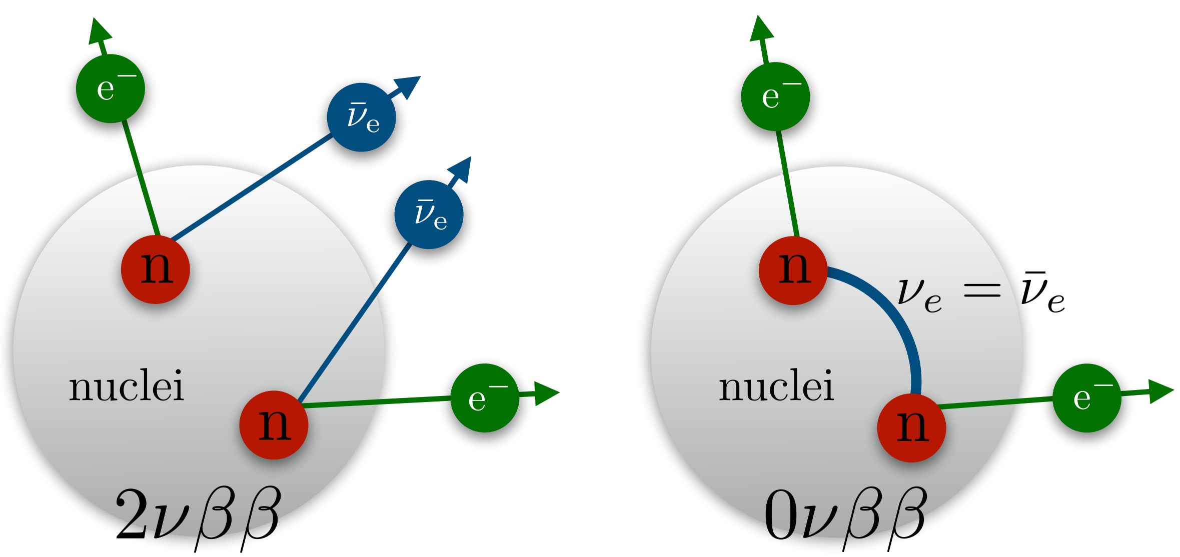
0νββ decay search is the direct test of

Majorana nature $(\nu = \bar{\nu})$

Needed by promising scenarios to explain the **matter dominant universe**

- see-saw mechanism
- Leptogenesis

- **Two dominant double beta decay mode**



Allowed in S.M.
Observed

Forbidden in S.M.
NOT observed

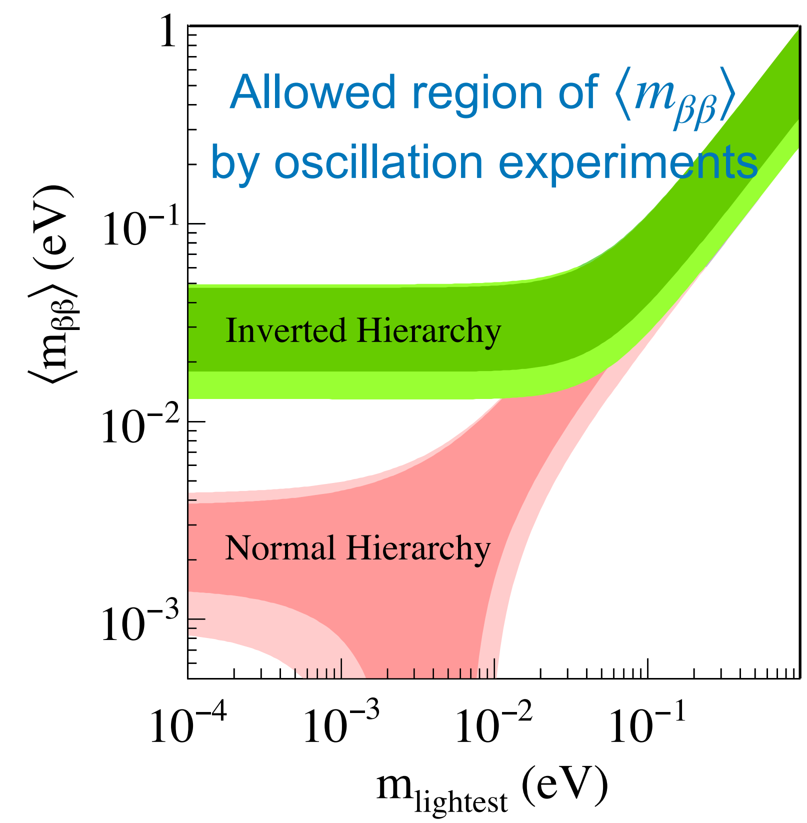
- **Access neutrino mass**

Half life

Effective Majorana mass

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

Effective Majorana mass is one of the channels to access neutrino mass



Very long 0νββ decay half-life (> 10^{18} yr) = Ultra rare events

→ **Large amount of isotopes & low BG environment** is needed.

Requirements for Experiments

- 0νββ decays are extremely rare events requiring special experimental design

1. Large amount of targets Merit of KamLAND-Zen ↑

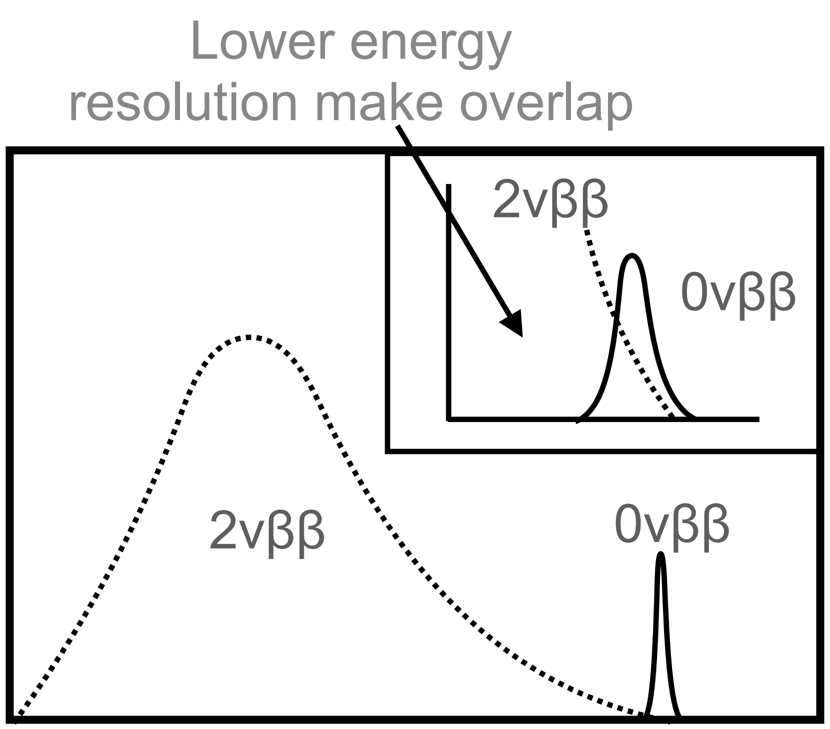
- Larger detector
- Isotopic enrichment

2. Super clean detector Merit of KamLAND-Zen ↑

- Environmental radioactivity (^{238}U, ^{232}Th) in detector material should be reduced.
- Underground experiment to reduce cosmic muon rate

3. Energy resolution Demerit of KamLAND-Zen ↓

- Observe total kinetic energy of 2 electrons.
- The larger overlap of 2nbb and 0nbb makes 2nbb a serious background.
- Ge detector has excellent energy resolution



KamLAND-Zen

Double beta decay isotope: ^{136}Xe

- Q-value 2.458 MeV
- Enrichment ~90%
- Dissolved into LS ~3% by weight
    - Xe loaded liquid scintillator (Xe-LS)

Xe-LS container

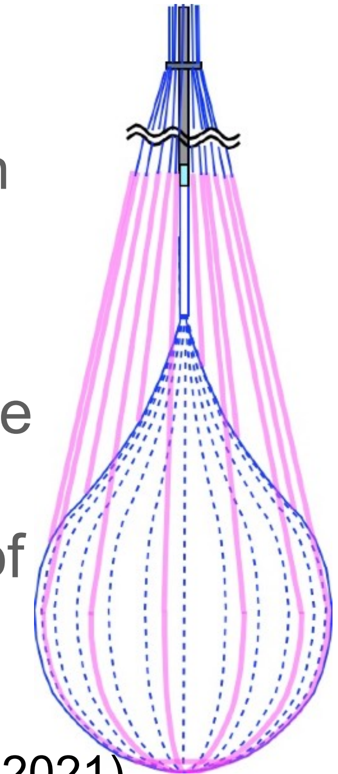
✓ thin(25μm) nylon film balloon

- φ3m for KLZ400
- φ4m for KLZ800

‣ Xe is installed only within the container

- Utilize cleanest volume of the large detector

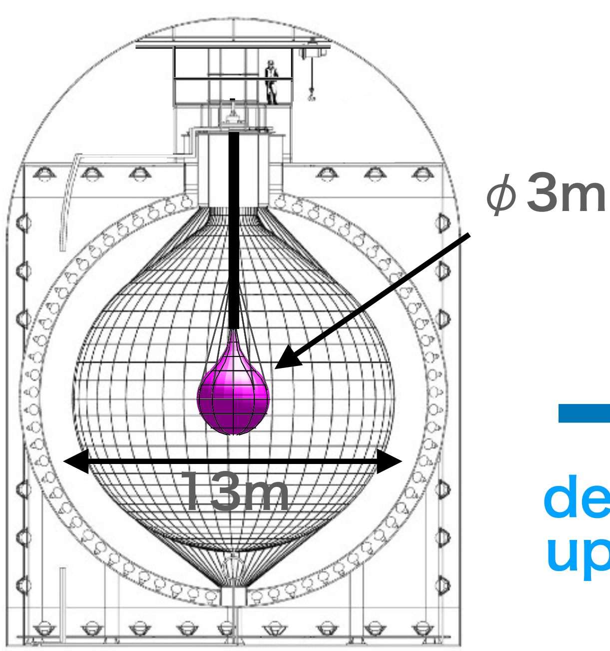
➡Ultra low BG is achieved



JINST 16 P08023 (2021)

Past
KamLAND-Zen 400

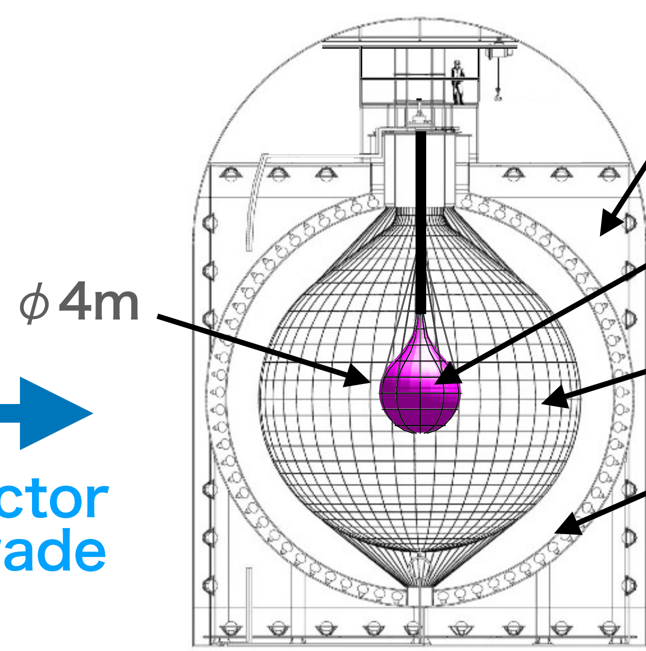
320-380 kg of Xenon
Data taking in 2011 - 2015



detector upgrade

Present
KamLAND-Zen 800

~750 kg of Xenon
DAQ started in 2019



Water Cherenkov detector for active cosmic muon veto

Xe loaded liquid scintillator (Xe-LS)

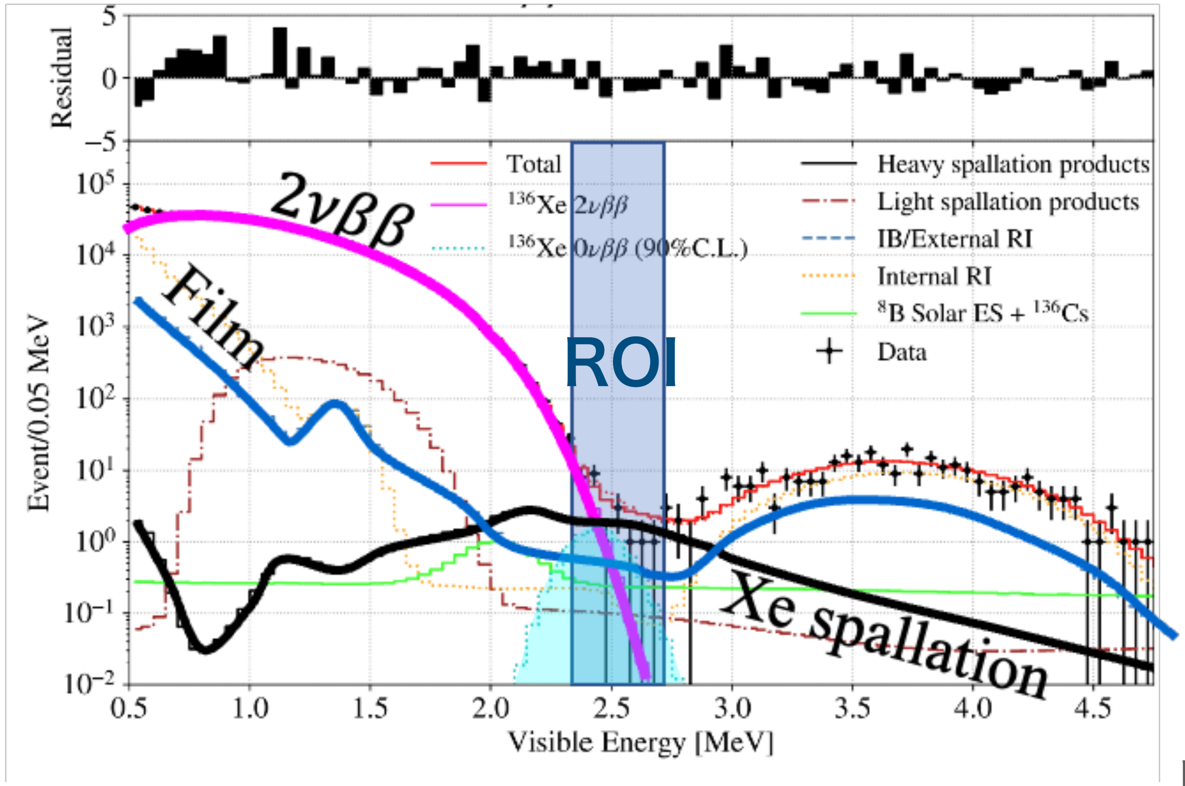
Liquid scintillator (no Xe)
Geo-neutrinos, solar-neutrinos etc..

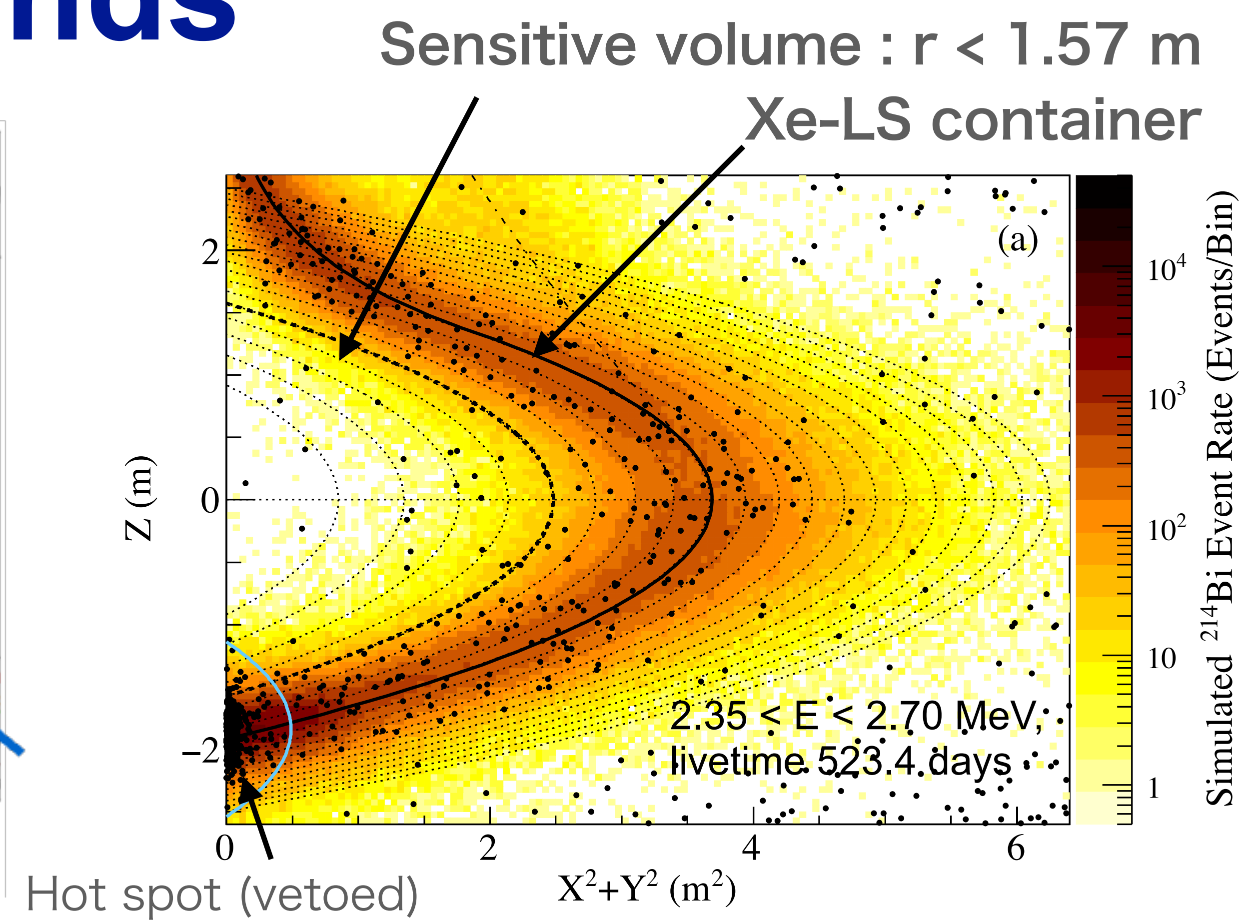
Event vertex and energy are reconstructed from time and charge of 1879 PMTs

$6.7\,\%/\sqrt{E(\mathrm{MeV})}, 13.7\mathrm{cm}/\sqrt{E(\mathrm{MeV})}$

KamLAND-Zen 800 completed DAQ on Jan. 11, 2024

Dominant Backgrounds





- **^{238}U, ^{232}Th on the balloon (XeLS container) film**
  - The delayed coincidence, ^{214}Bi(β)→^{214}Po(α), does not effectively work on the film due to a quenching of α decays (delayed signal).
- **2νββ decays**
  - Inevitable background source
  - Enhancing detector energy resolution will reduce 2νββ in ROI.
- **Cosmic muon induced Xe spallation products (Long-lived products)**
  - A few hours or a few days life-time isotopes are difficult to tag by the delayed coincidence or simple volume cut. Phys. Rev. C **107**, 054612 (2023)

^{136}Xe 0νββ decay Half-life limit

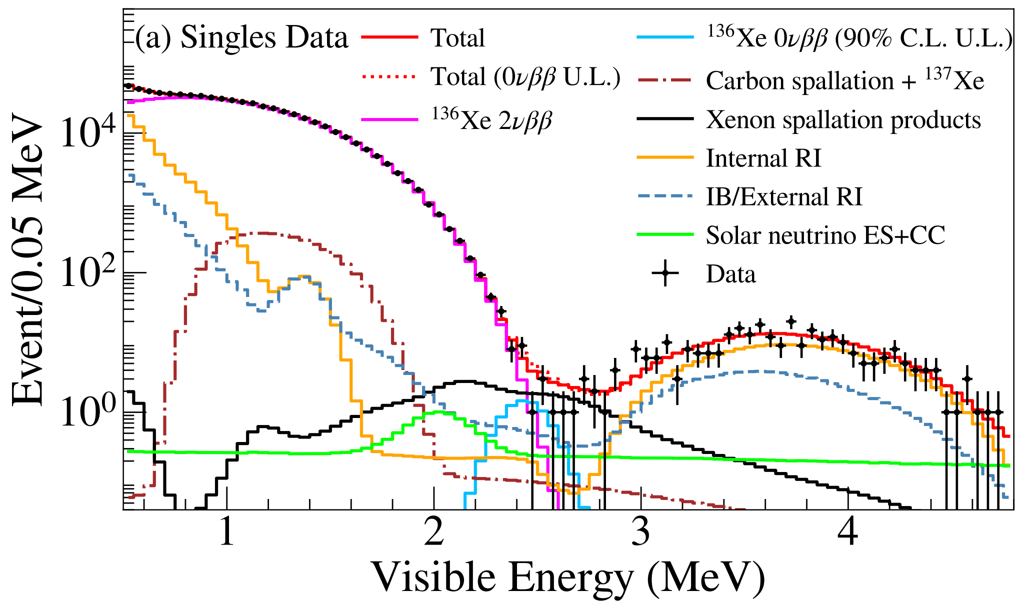
Phys. Rev. Lett. 130, 051801 (2023)

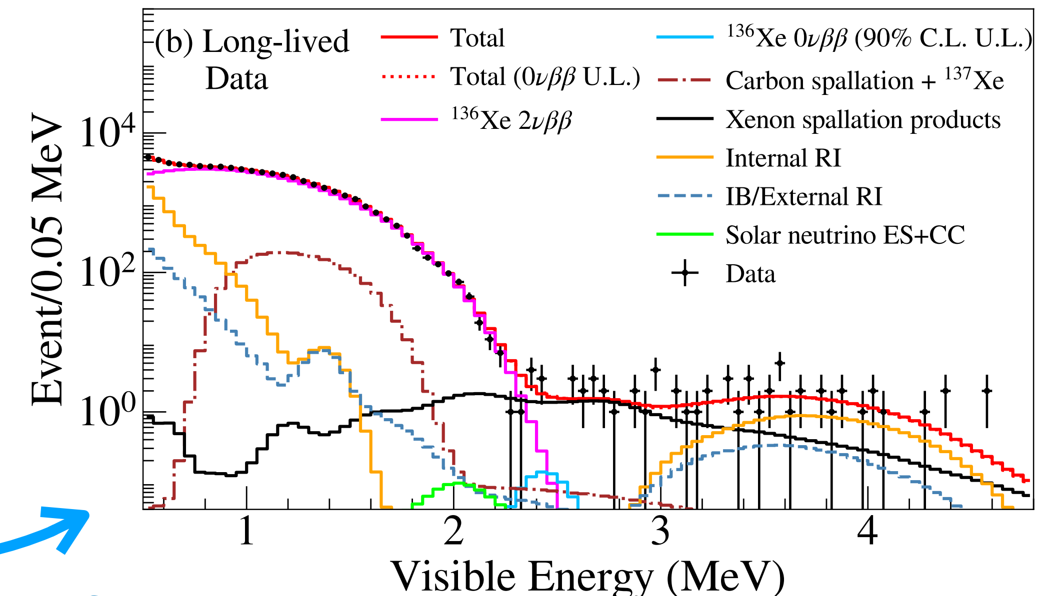
Singles data (SD)
(sensitive to 0νββ rate)

Livetime = 523.4 days

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

Livetime = 49.3 days

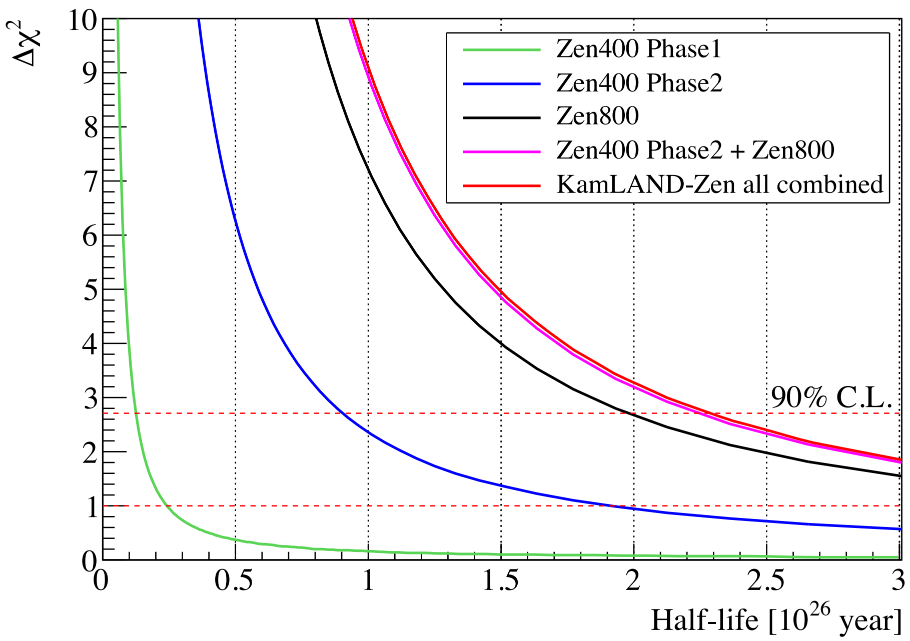




simultaneous fit

KamLAND-Zen 800 only result : $T^{0\nu}_{1/2} > 2.0 \times 10^{26}$ **yr (90% C.L.)**

- **Combined analysis** (KamLAND-Zen 400 + 800)



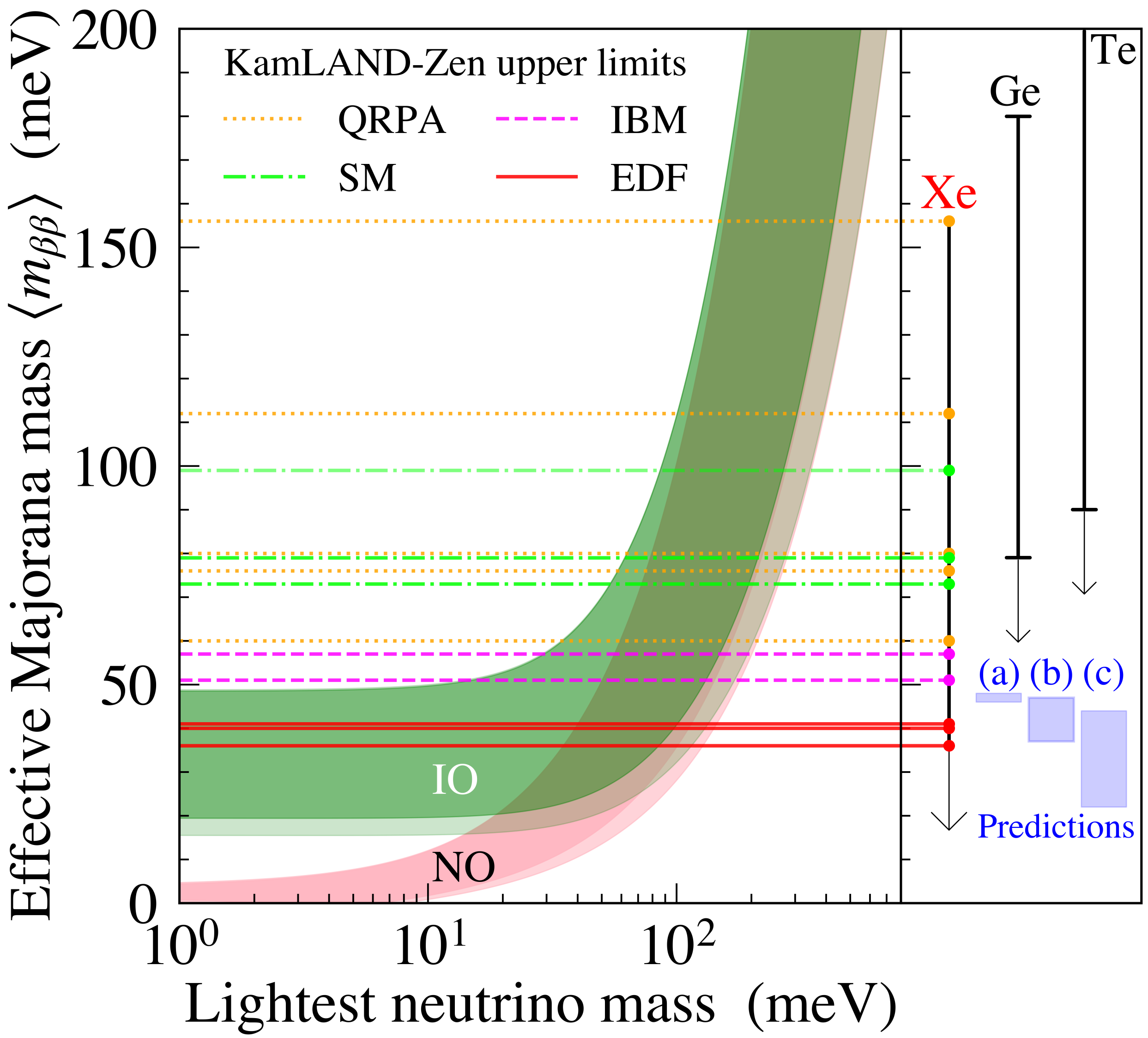
Combined result (90% C.L.)

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

Sensitivity (90% C.L.)

$$T^{0\nu}_{1/2} = 1.5 \times 10^{26} \text{ yr}$$

Limit on the effective Majorana mass



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

Theoretical predictions:
(a) Phys. Rev. D 86, 013002
(b) Phys. Lett. B 811, 135956
(c) Euro. Phys. J. C 80, 76

Lower limit of half life

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

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

NME ($M^{0\nu}$) : 1.11–4.77
assuming g_A ~ 1.27

Upper limit of Majorana mass

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

The first search for inverted mass ordering

NME references
Quasi-particle Random Phase Approximations:
Phys.Rev.C 102, 44303 (2020), Phys.Rev.C 91, 024613 (2015), Phys.Rev.C 87, 045501 (2013), Phys.Rev.C 87, 064302 (2013), Phys.Rev.C 97, 045503 (2018).

Shell models:
Phys. Rev. C 101, 044315 (2020), Phys. Rev. C 91, 024309 (2015), Phys. Rev. A 818, 139 (2009).

Interacting boson models:
Phys. Rev. D 102, 095016 (2013), Phys. Rev. C 91, 034304 (2015).

Energy density functional theory:
Phys. Rev. Lett. 111, 142501 (2013), Phys. Rev. C 91, 024316 (2015), Phys. Rev. Lett. 105, 252503 (2010).

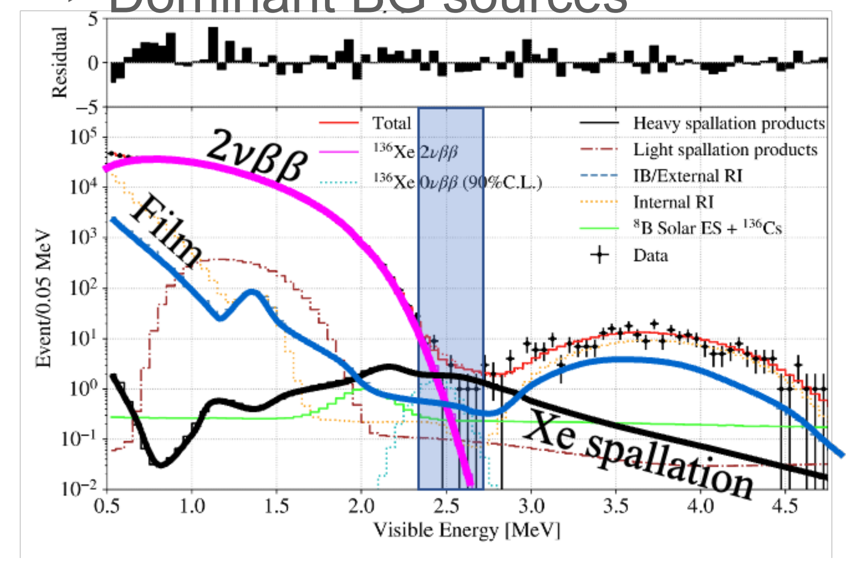
KamLAND-Zen 800 completed its observation

We have double the data from 1st result.
Analysis with full dataset is in progress.

KamLAND2-Zen

Next generation detector R&D is now in progress

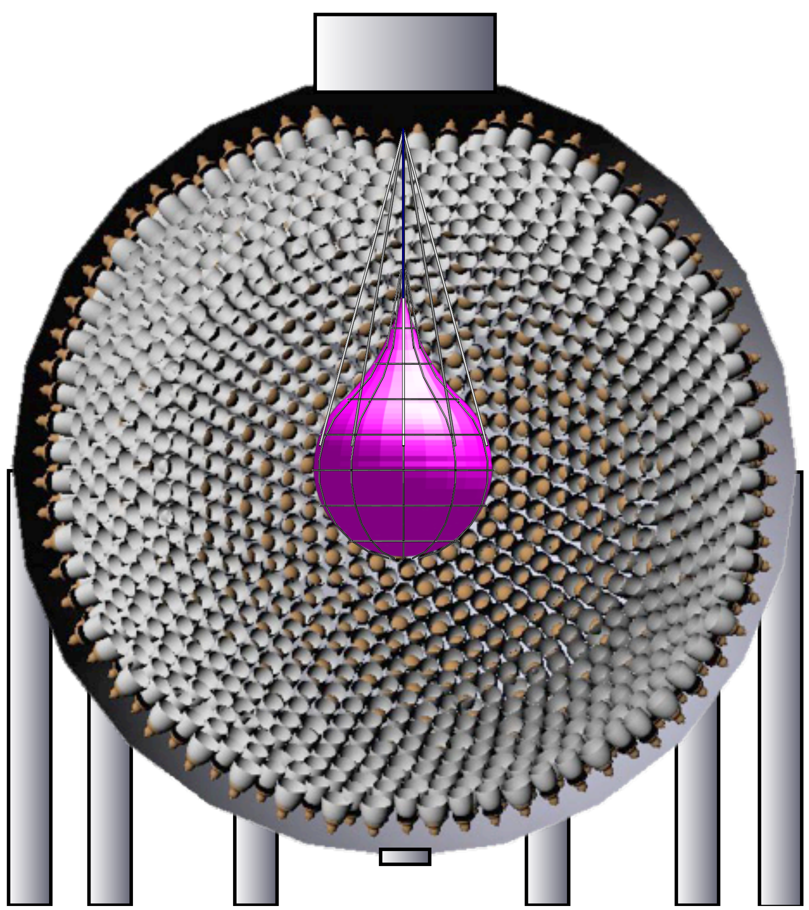
- Dominant BG sources



Film BG reduction

Scintillation balloon film

Enlarge sensitive volume by tagging ^{214}Bi(β)→^{214}Po(α) sequential decay on the film.



2νββ decay

Enhance detector energy resolution (σ(2.6MeV)4%→~2%)

High QE PMT & Light guide mirror

Improve light collection efficiency and photo coverage

Brighter LS

Higher light yield and transmittance

Cosmic muon induced Xe spalllation products

New Dead-time free electronics

Collect all the neutron information (multiplicity, vertices) from the noisy period

1000 kg of Xe

Increase isotope mass

Target ⟨$m_{\beta\beta}$⟩ ~20 meV (5 yrs)

Summary

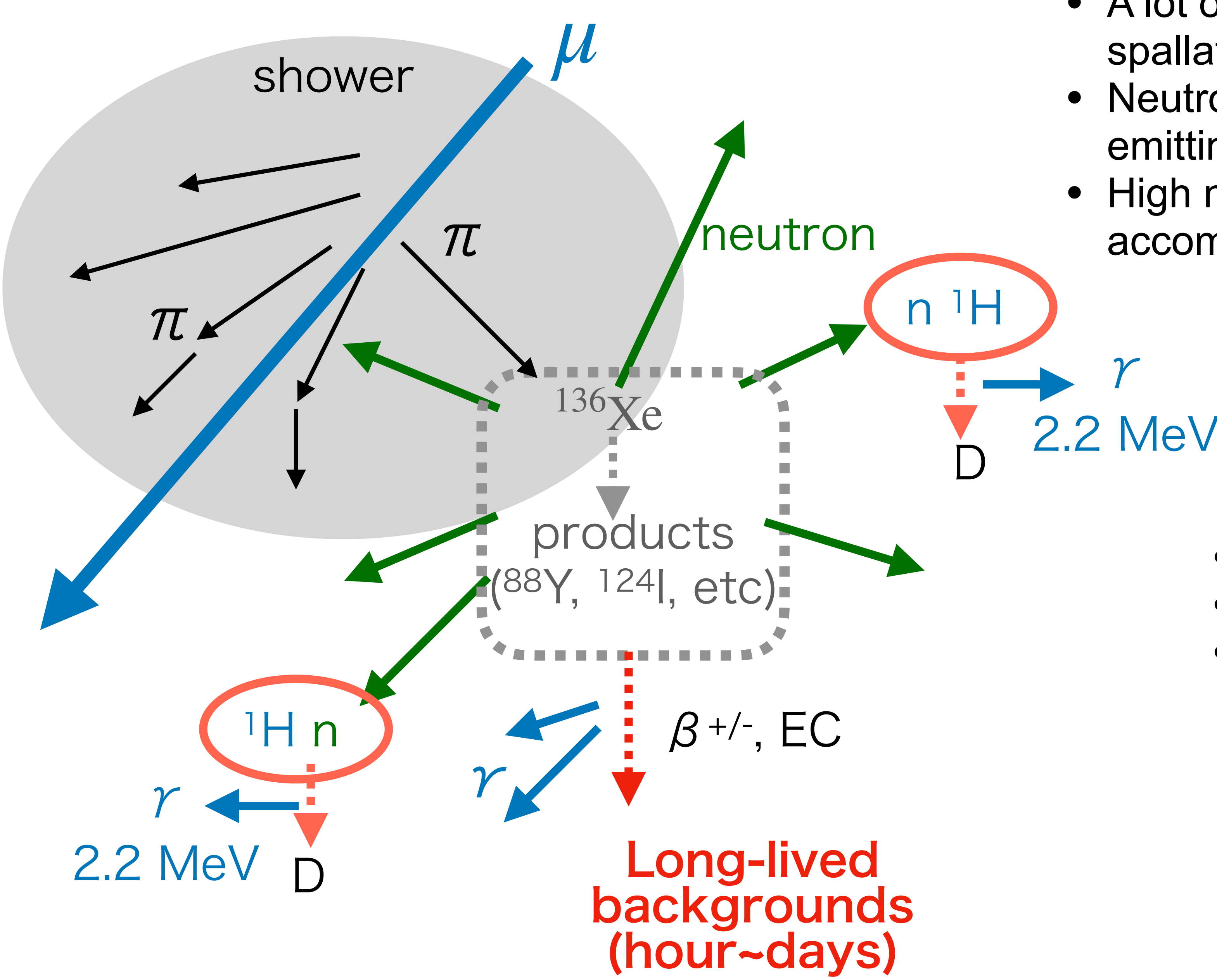
- KamLAND-Zen searches for neutrinoless double beta decay with ^{136}Xe loaded liquid scintillator.
  - Combined result for KamLAND-Zen 400 + 800

$$T^{0\nu}_{1/2} > 2.3 \times 10^{26}\ \textbf{yr,}\ \langle m_{\beta\beta} \rangle < 36 - 156\ \textbf{mV}$$

- We completed KamLAND-Zen 800 DAQ on Jan. 11, 2024.
  - Data analysis with full dataset is in progress.
- R&D for KamLAND2-Zen is in progress.
  - Increase amount of target isotope
  - Expand sensitive volume (scintillation balloon)
  - Enhance energy resolution (HQEPMT, Light guide)
  - Enhance tagging efficiency of Xe spllation products (New electronics)
- The target of KL2-Zen is $<m_{\beta\beta}>$=20 meV

Backup

Cosmic muon induced backgrounds



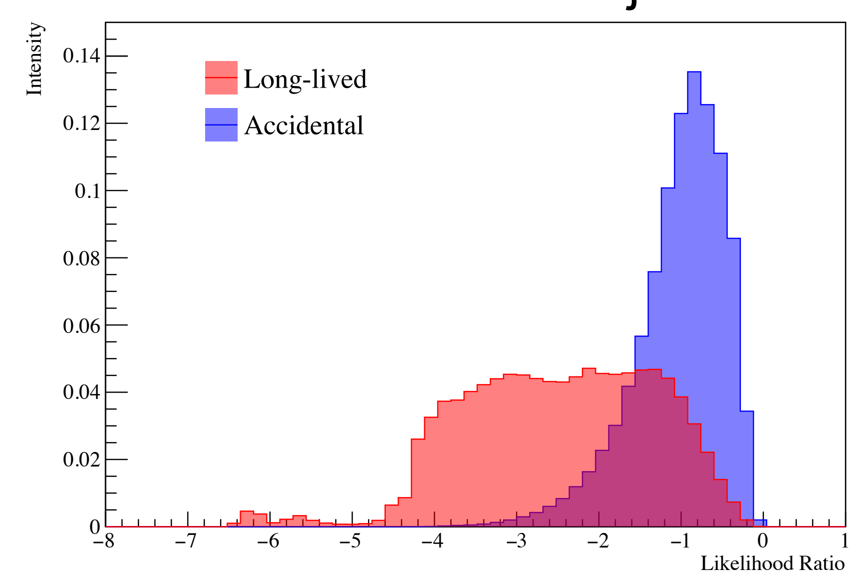
Decay of this long-lived spallation products make serious background in KamLAND-Zen

Neutrons give us information

- A lot of neutrons are produced at the same time of spallation products.
- Neutrons are immediately (207μs) captured by ^{1}H emitting 2.2 MeV gamma in LS.
- High neutron multiplicity events are likely to be accompanied by spallation products.

Likelihood selection based on,

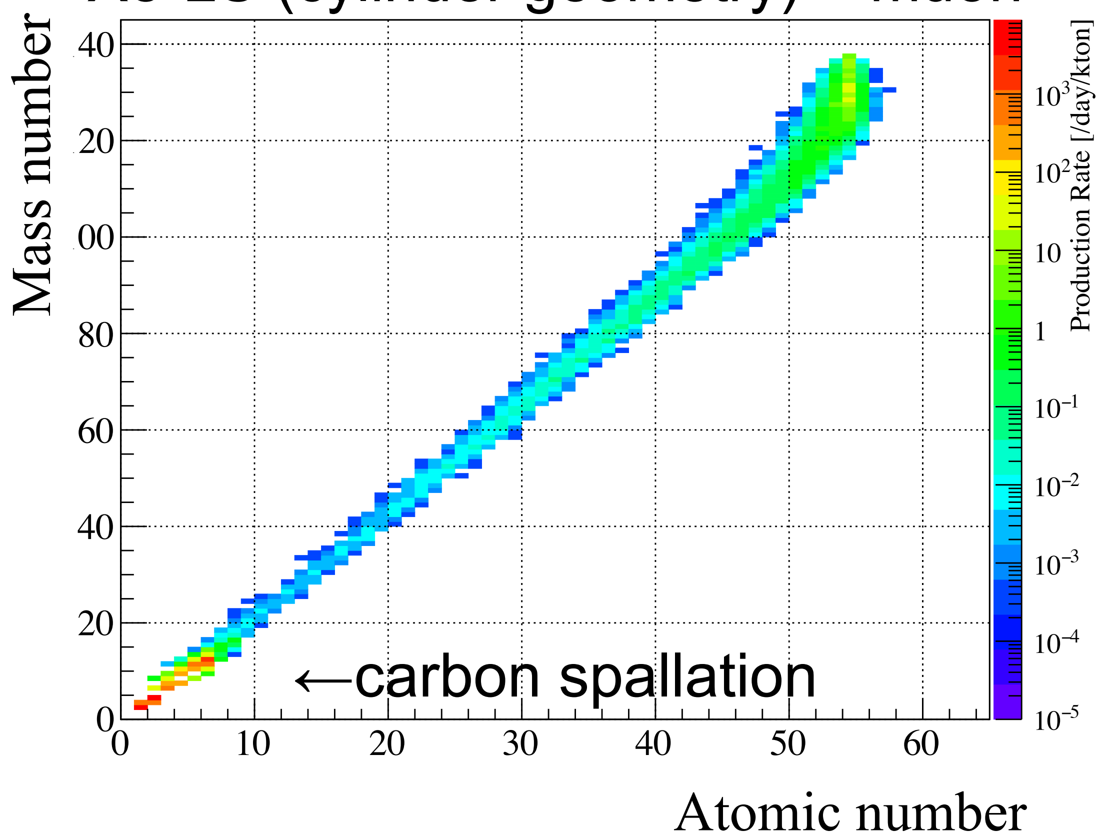
- Neutron multiplicity
- Distance from neutron capture
- Delta-time from muon injection



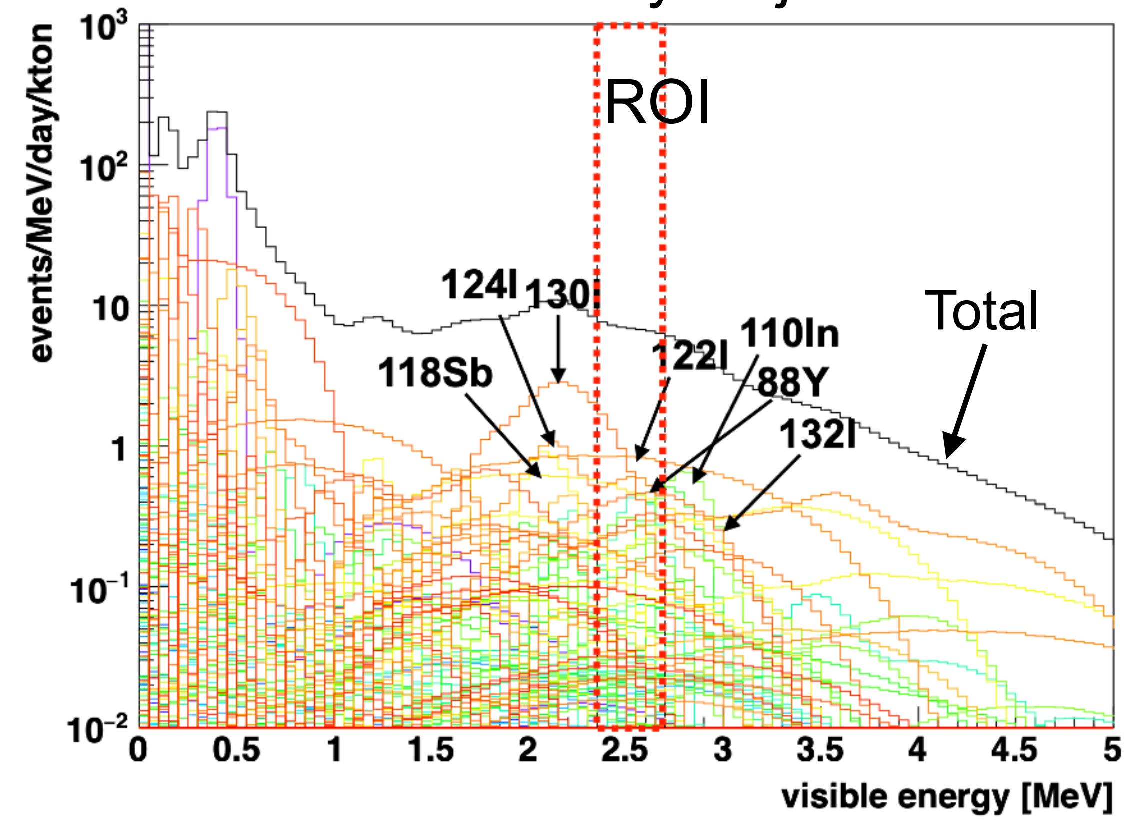
Xenon spallation products (Long-lived products)

- ☑ Individual yields are small but many candidates are produced
- ☑ Total yield become one of the main background → new major background

FLUKA
Xe-LS (cylinder geometry) + muon



Energy spectra of products
~90% by major 32 nuclei



- Longer half-lives (~hours to ~days)
- Neutron multiplicity is higher than carbon's

A likelihood method is developed

Parameters: Time difference from muon, distance between Xe-spallation and neutron capture gamma, effective number of neutron

Rejection efficiency 42.0±8.8%

This rejected data-set is also used for simultaneous fitting (next page)

Scintillation inner balloon

- BG(^{214}Bi) reduction from Xe-LS container

- Current background level

  ^{238}U ~3×10^{-12} g/g$_{film}$

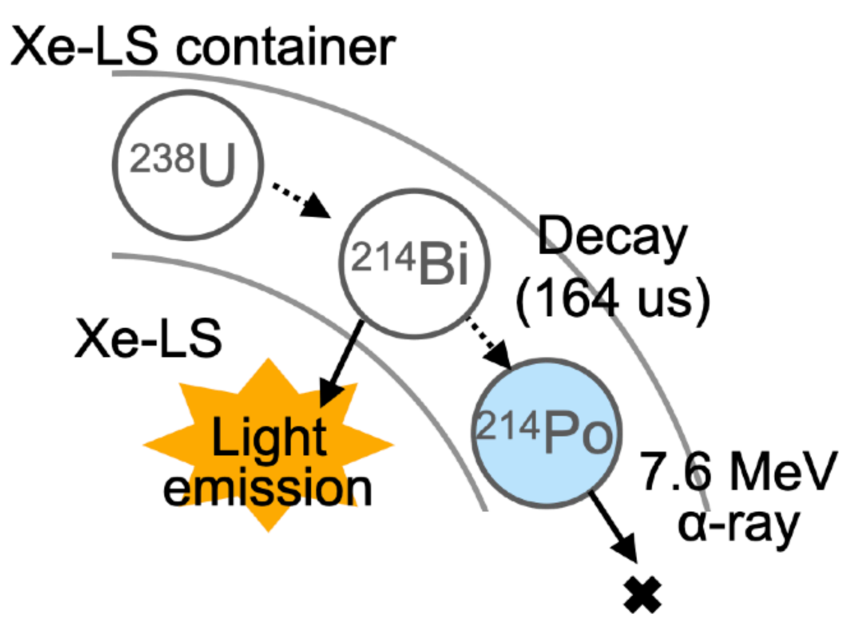
  ref. initial film (after washed)

  ^{238}U~2×10^{-12} g/g$_{film}$ ← Almost same level

Difficult for further improvement

- Current tagging efficiency

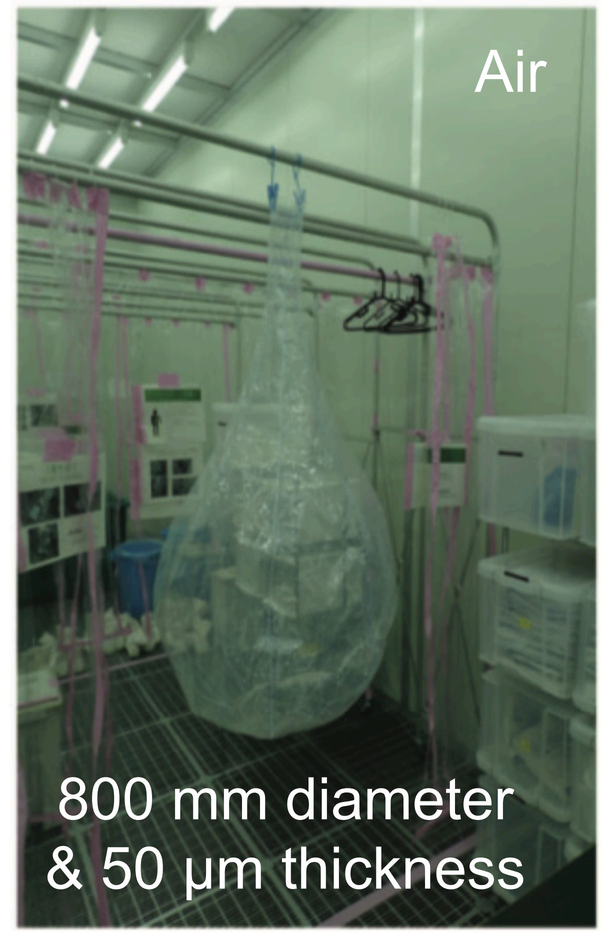
  ~50% due to ^{214}Po alpha decay

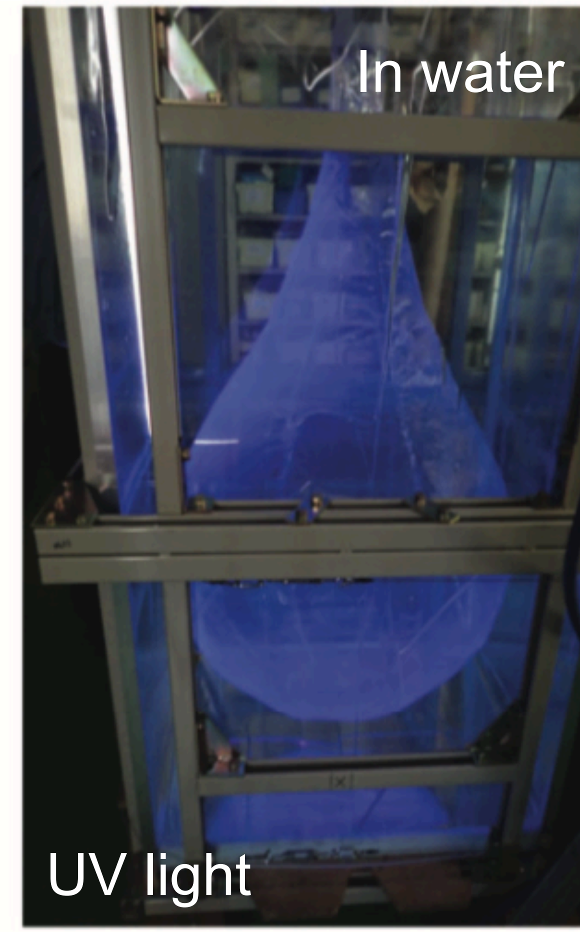


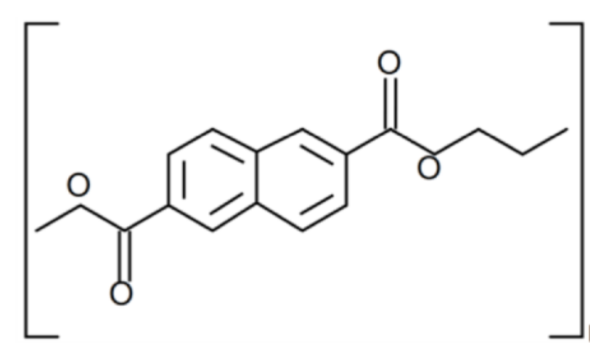
cf) Xe-LS tagging eff. 99.97%

Tag this decay with scintillation inner balloon

PTEP. Volume 2019, Issue 7, 073H01, S. Obara et al.



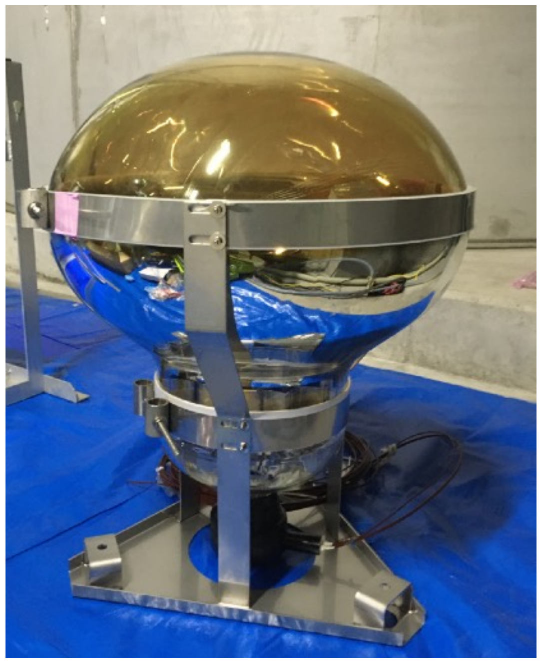




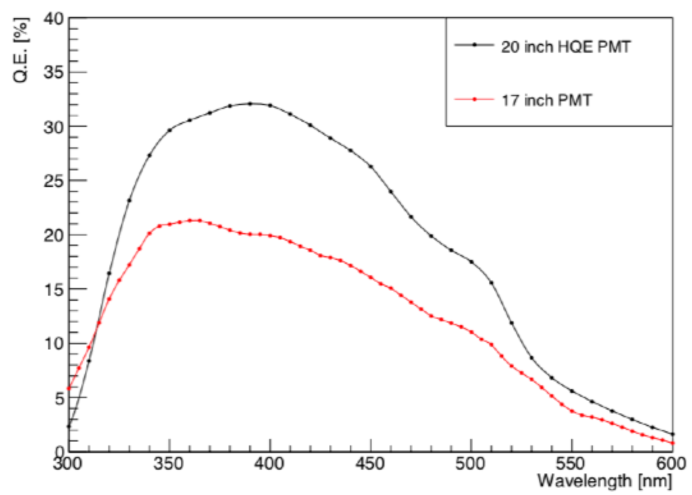
PolyEthylene Naphthalate (PEN)

High QE PMT & light guide

20 inch PMT (R12860-03LXA)



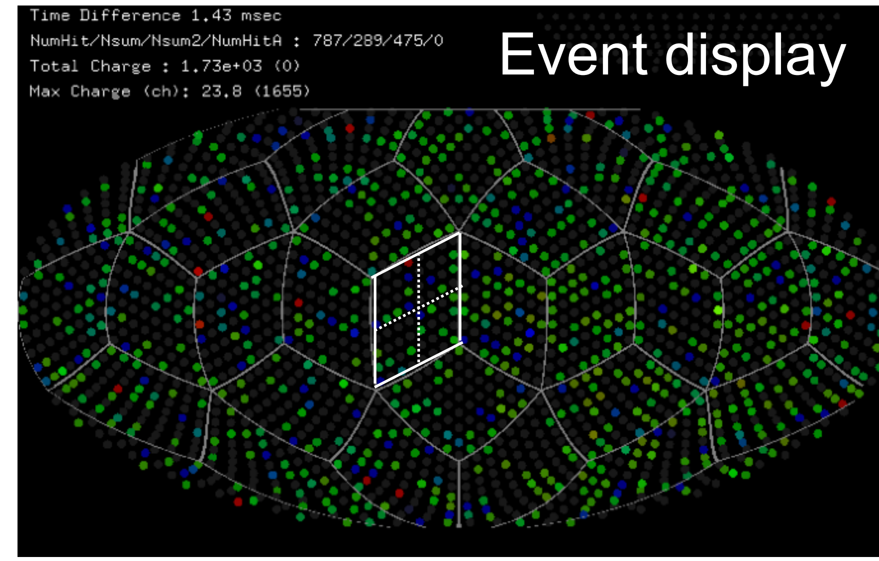
High quantum efficiency



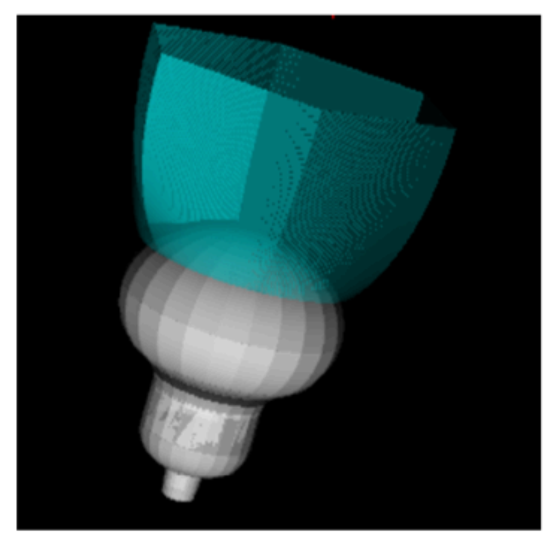
PMT spec:	New 20”	17”
Dynode	Box & line	Line-focus
Q. E. @400nm	31.9%	23%@390 nm
P/V ratio	3	3.4
Raise time [ns]	6	
Time Transit Spread [ns]	2.4	3.5
Dark pulse rate (ave.) [kHz]	8	22.1

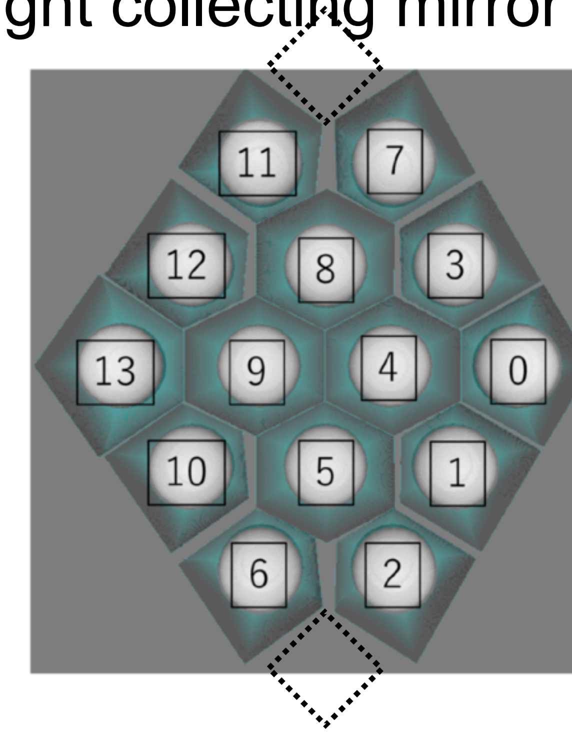
PMT placed at rhombic triacontahedron

(Current KL: 1325 17 inch & 554 20 inch PMTs)



Fill in the gaps with light collecting mirror





4 hexagons + 10 pentagons + 2 squares

Photo coverage ~34% → **~100%**

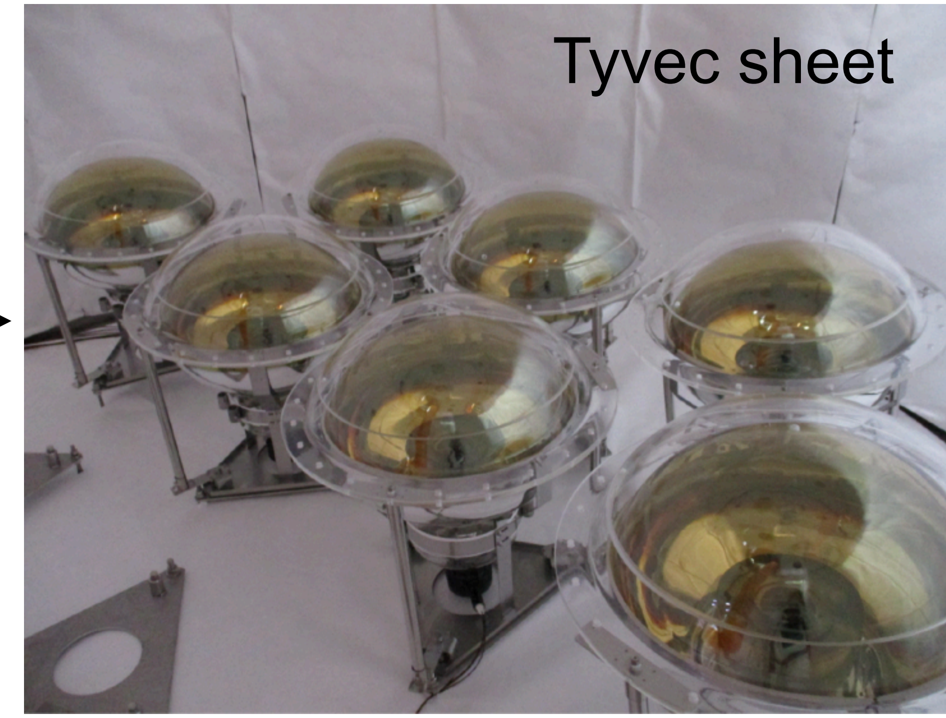
Prototype detector for KL2

Cleaning is important work!

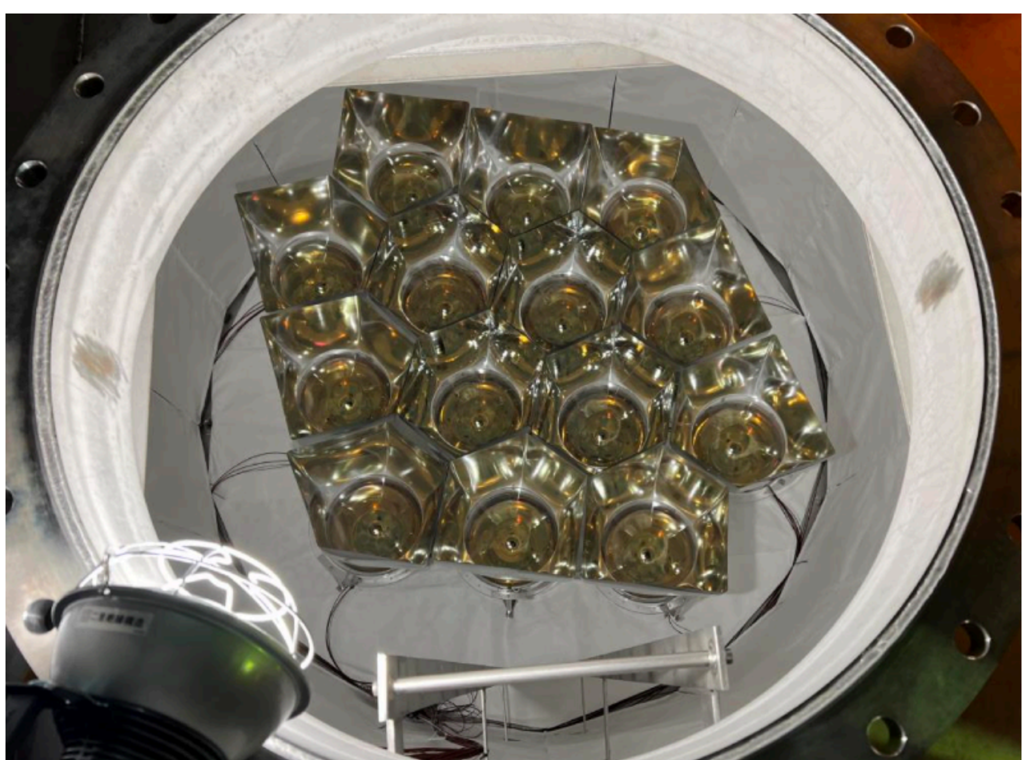
→

→

Inside of the detector
PMTs w/o light collection mirror

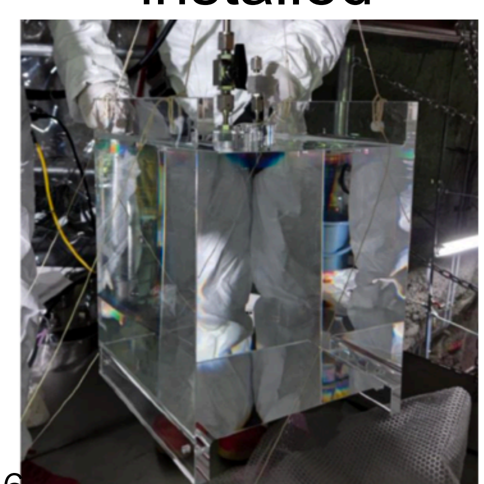


All PMTs & mirrors installed



Pure water injection →

30L LS box installed



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