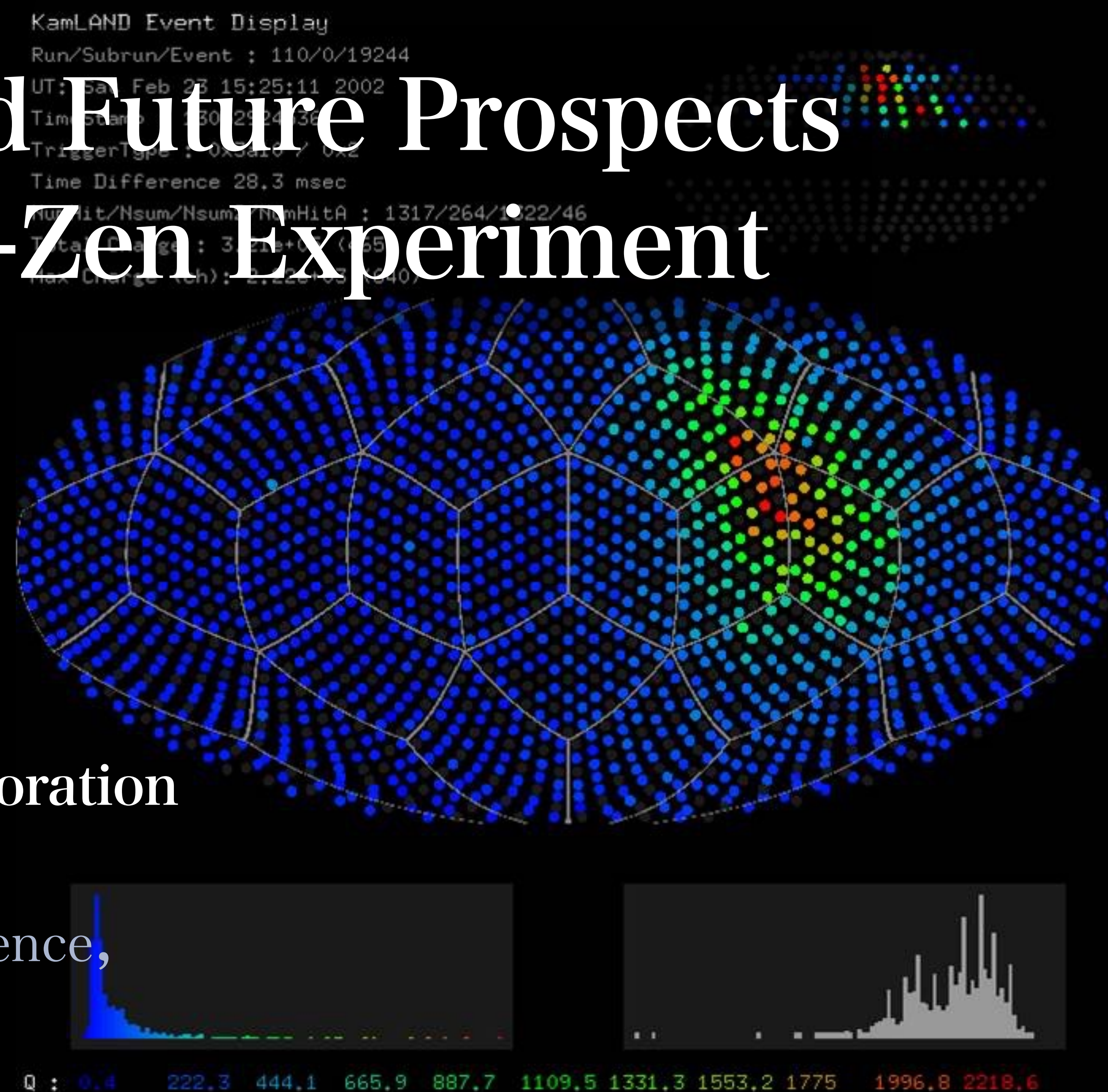
Latest Results and Future Prospects of the KamLAND-Zen Experiment



Haruhiko MIYAKE

for the KamLAND-Zen collaboration

Research Center for Neutrino Science,

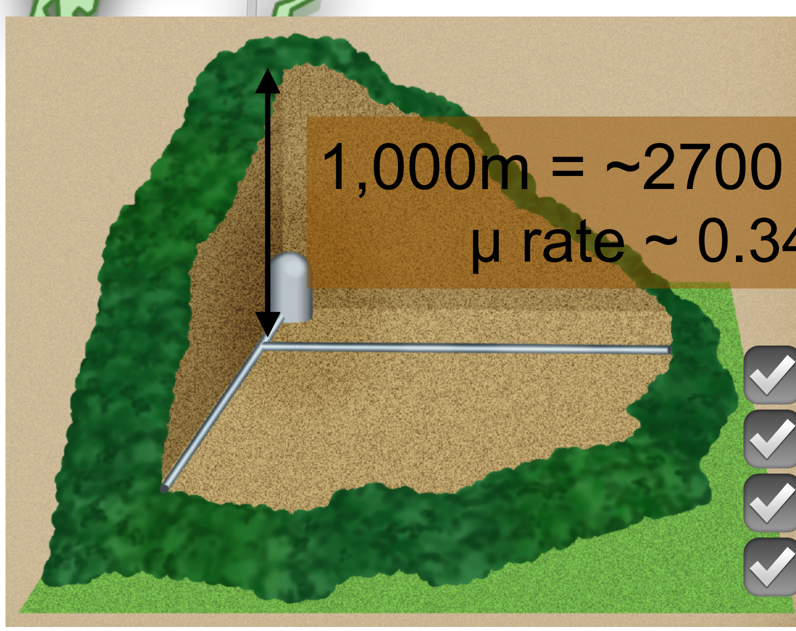
Tohoku University

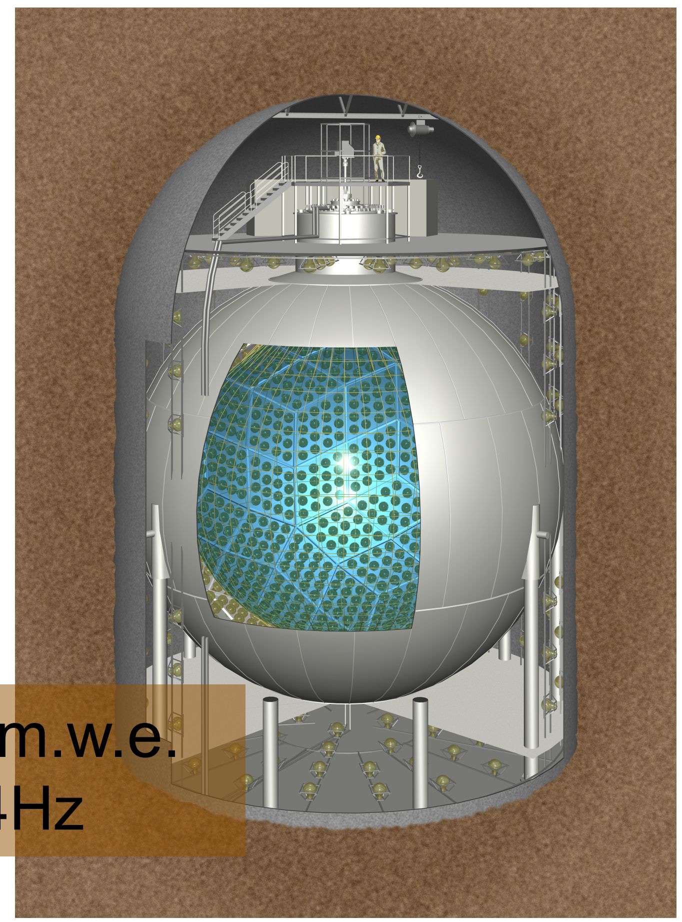
43rd International Symposium on Physics in Collision

NCSR "Demokritos", October 23, 2024

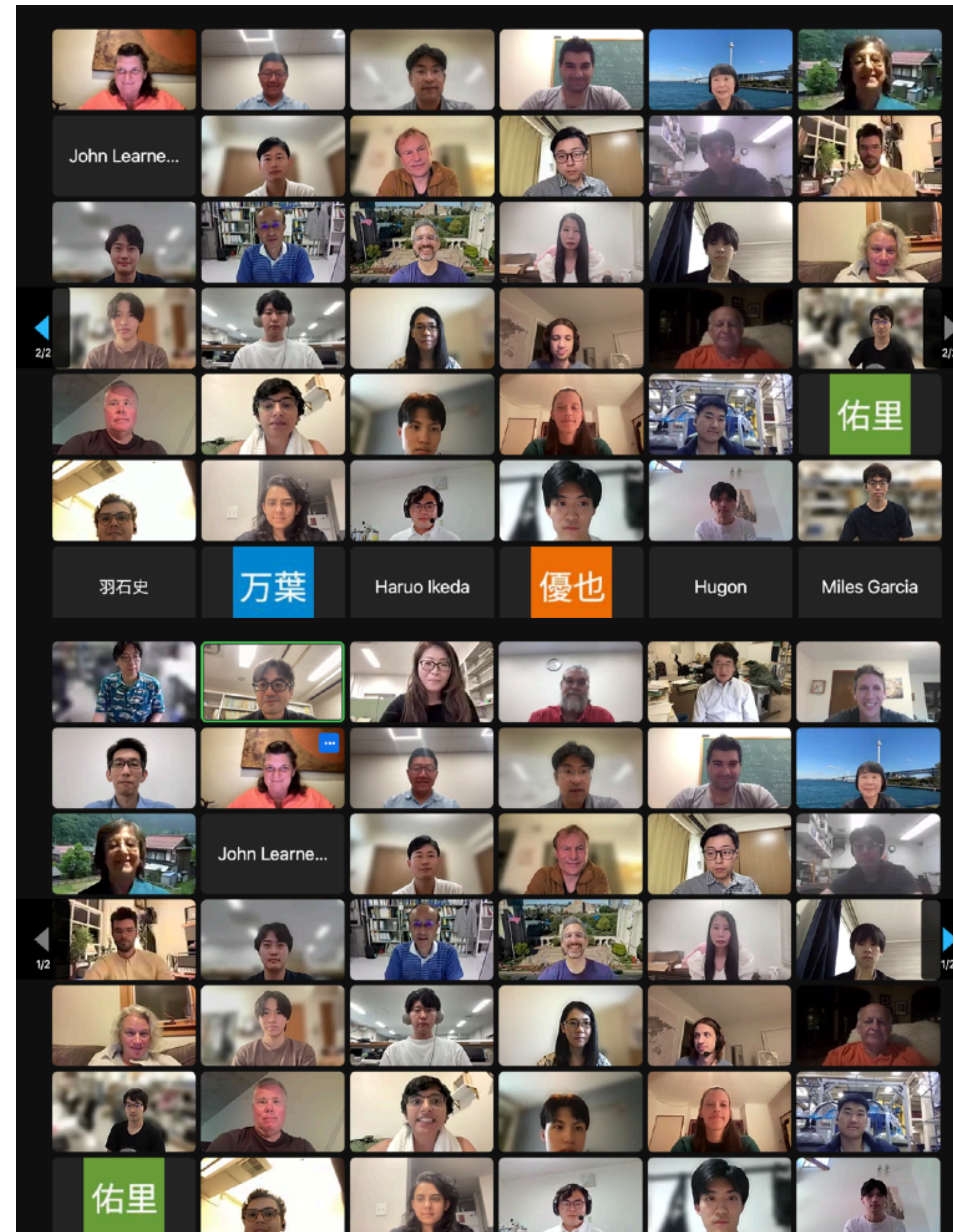
KamLAND/KamLAND-Zen Collaboration

~50 physicists work on this project





- 1 kton liquid scintillator
- 2000 PMTs
- ϕ13m balloon vessel
- Water Cherenkov outer detector



Online collaboration meeting in Sep. 2024

TOHOKU UNIVERSITY · 東京大学 THE UNIVERSITY OF TOKYO · 大阪大学 OSAKA UNIVERSITY · TOKUSHIMA UNIVERSITY · BERKELEY LAB · THE UNIVERSITY OF TENNESSEE KNOXVILLE · TUNL · MIT · VIRGINIA TECH · UNIVERSITY of HAWAI'I · BOSTON UNIVERSITY · Nikhef · Obihiro University of Agriculture and Veterinary Medicine

Neutrinoless Double beta decays

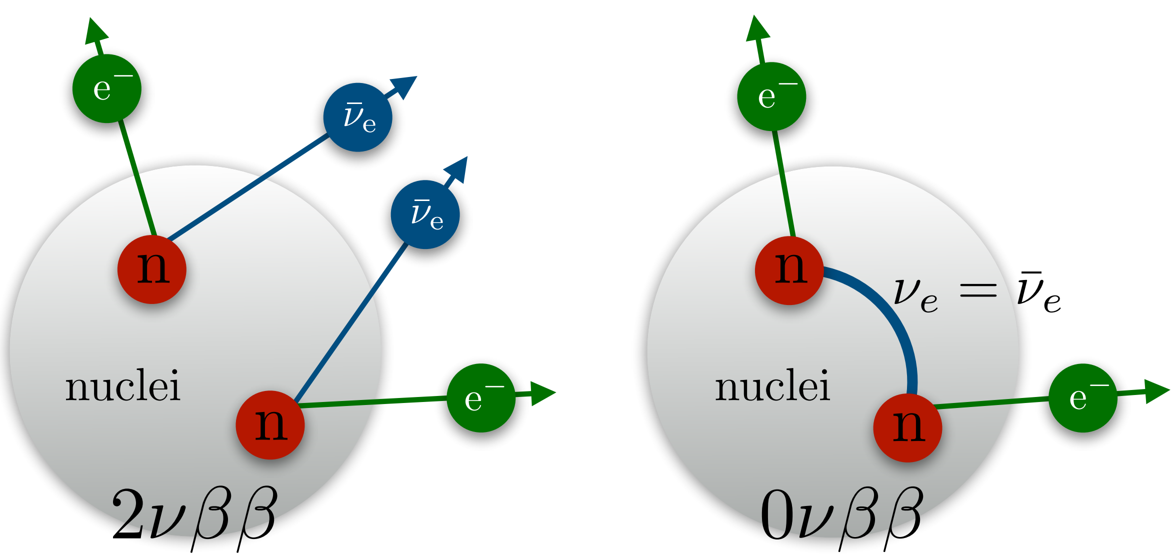
0νββ decay search is the direct test of

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**



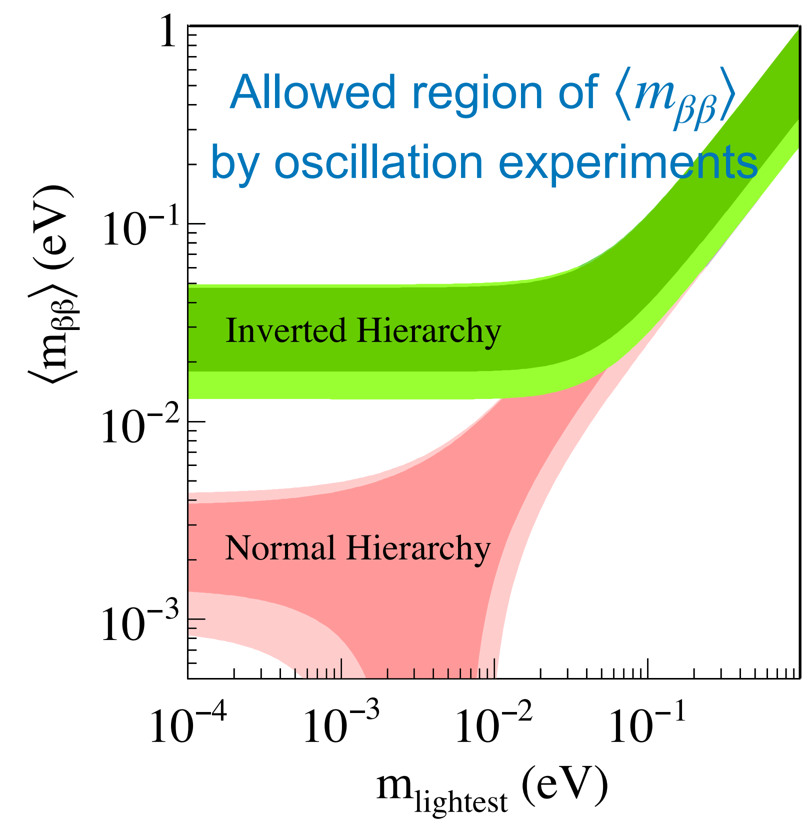
Allowed in S.M.	Forbidden in S.M.
Observed	**NOT observed**

- **Access neutrino mass**

Half life / Effective Majorana mass

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

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

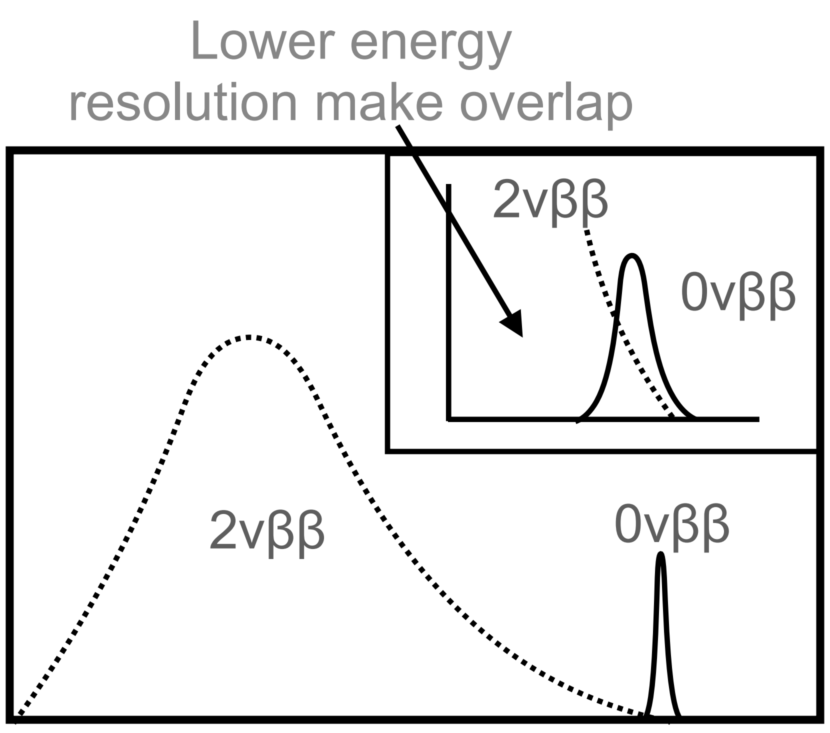
Merit of KamLAND-Zen ↑

- 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

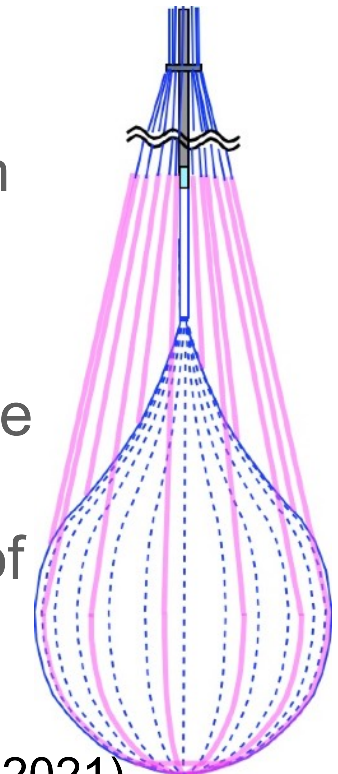
- Q-value 2.458 MeV
- Enrichment ~90%
- Dissolved into LS ~3% by weight
  - Xe loaded liquid scintillator (Xe-LS)

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

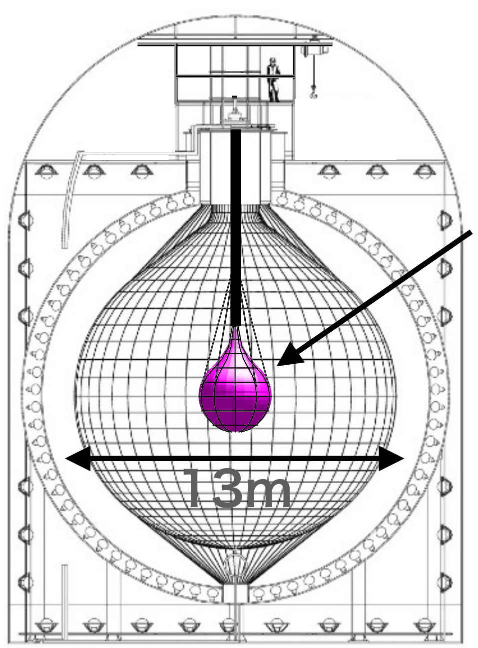
➡Ultra low BG is achieved



JINST 16 P08023 (2021)

Past
KamLAND-Zen 400

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

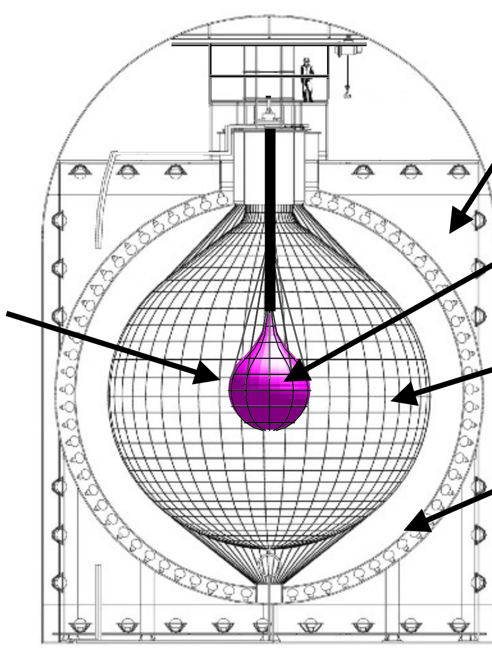


detector upgrade

Present
KamLAND-Zen 800

~750 kg of Xenon
DAQ started in 2019

φ4m



Water Cherenkov detector for active cosmic muon veto

Xe loaded liquid scintillator (Xe-LS)

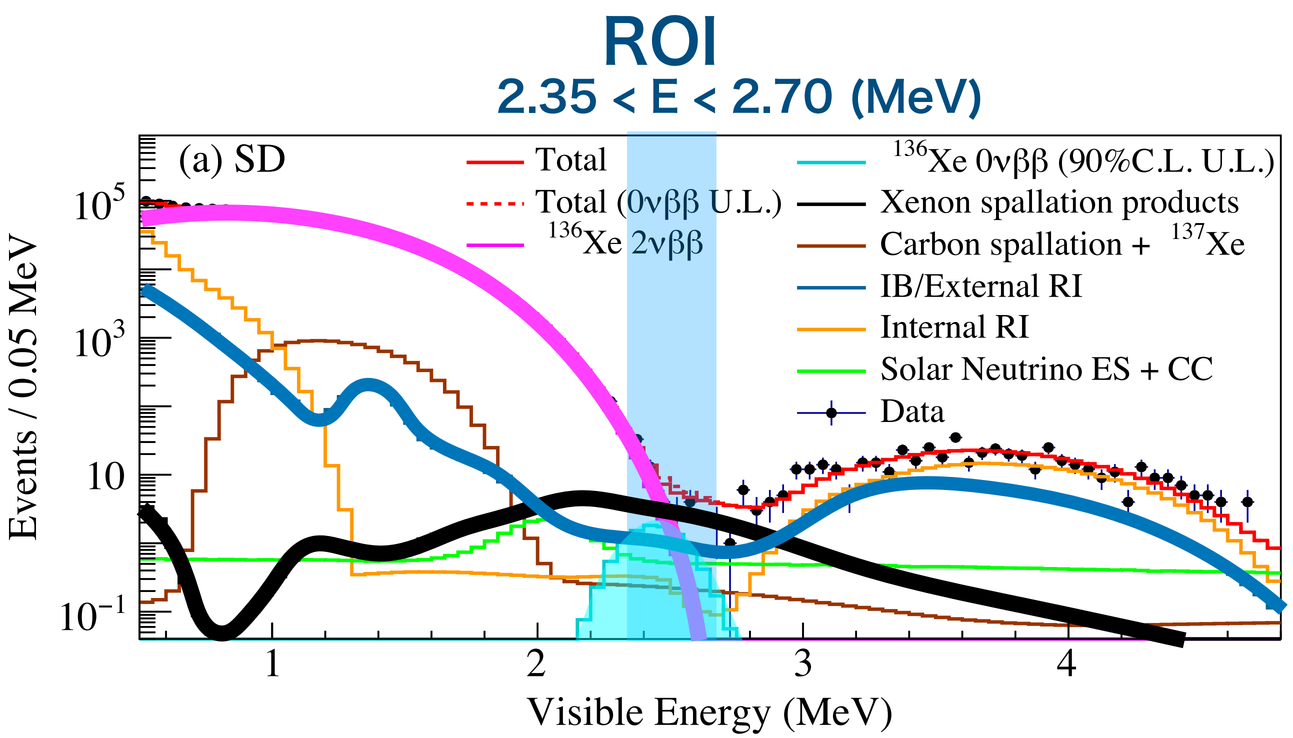
Liquid scintillator (no Xe)
Geo-neutrinos, solar-neutrinos etc..

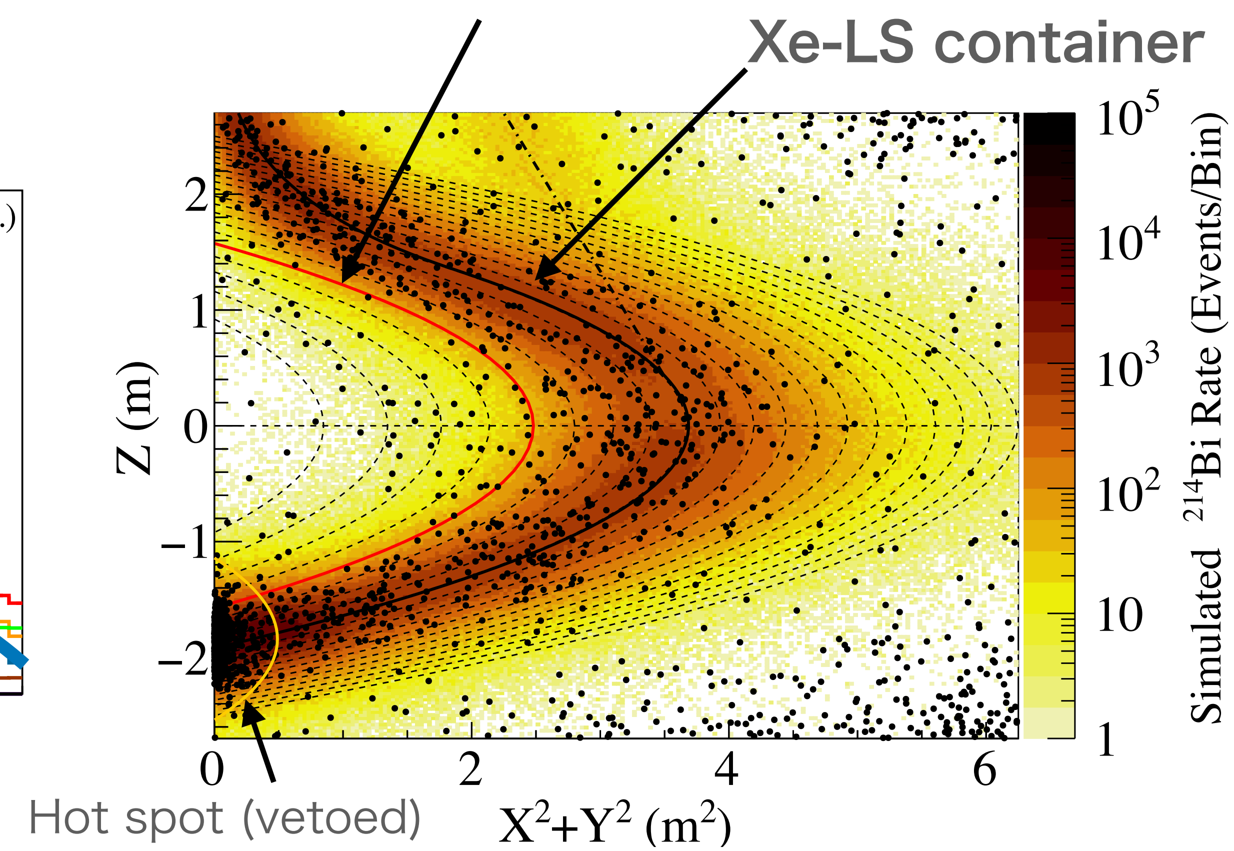
Event vertex and energy are reconstructed from time and charge of 1879 PMTs

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

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

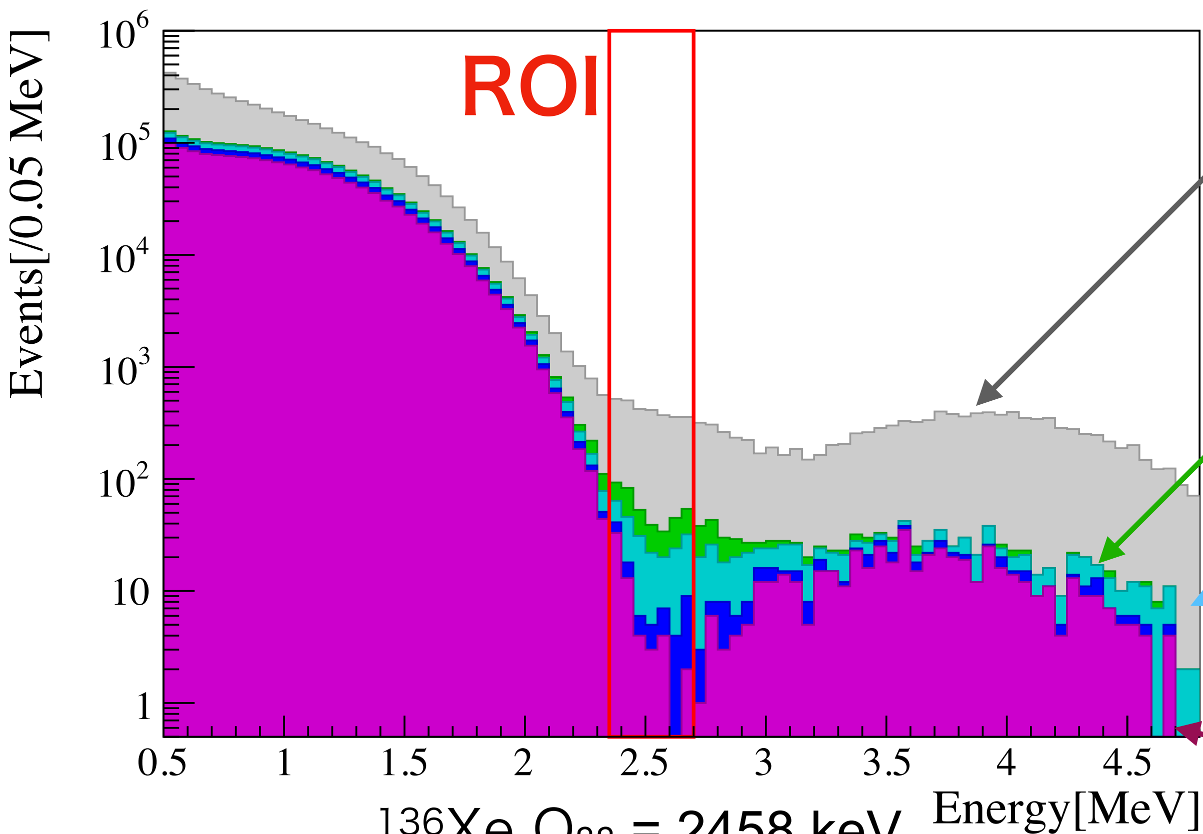
Dominant Backgrounds





- **^{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)

Event Selection, livetime



^{136}Xe $Q_{\beta\beta}$ = 2458 keV

- Within 2.5m radius
- muon itself & 2msec veto

- Within sensitive volume (r<1.57m)
- (Veto ^{214}Bi on the inner balloon)

^{214}Bi-Po, ^{212}Bi-Po veto (in Xe-LS)
(Delayed coincidence＋Pileup veto)

Short lived spallation（^{10}C, ^{6}He, ^{12}B)

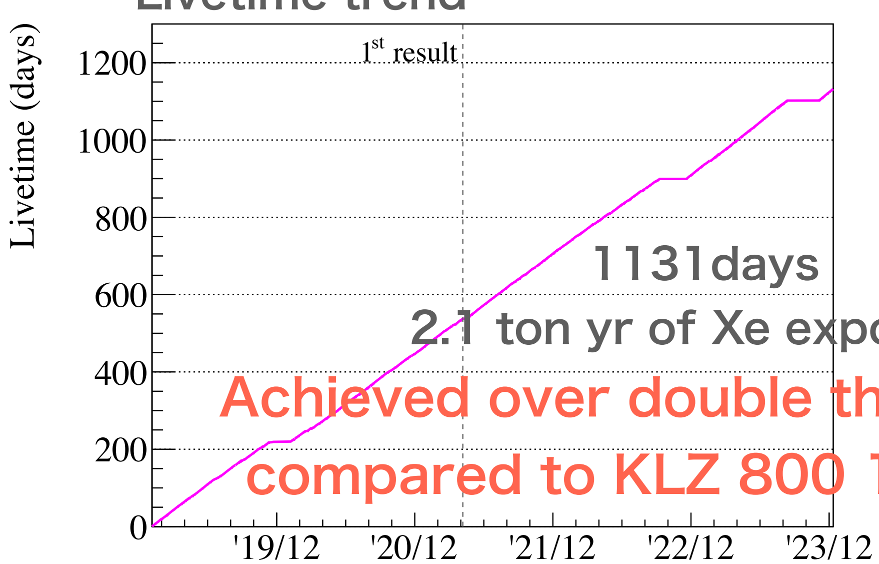
Long lived spallation

Likelihood selection

Untagged data	Tagged data
Singles data (SD) (sensitive to 0νββ rate)	Long-lived data (LD) (constrain the LL rate)

simultaneous fit

Livetime trend



1131days

2.1 ton yr of Xe exposure

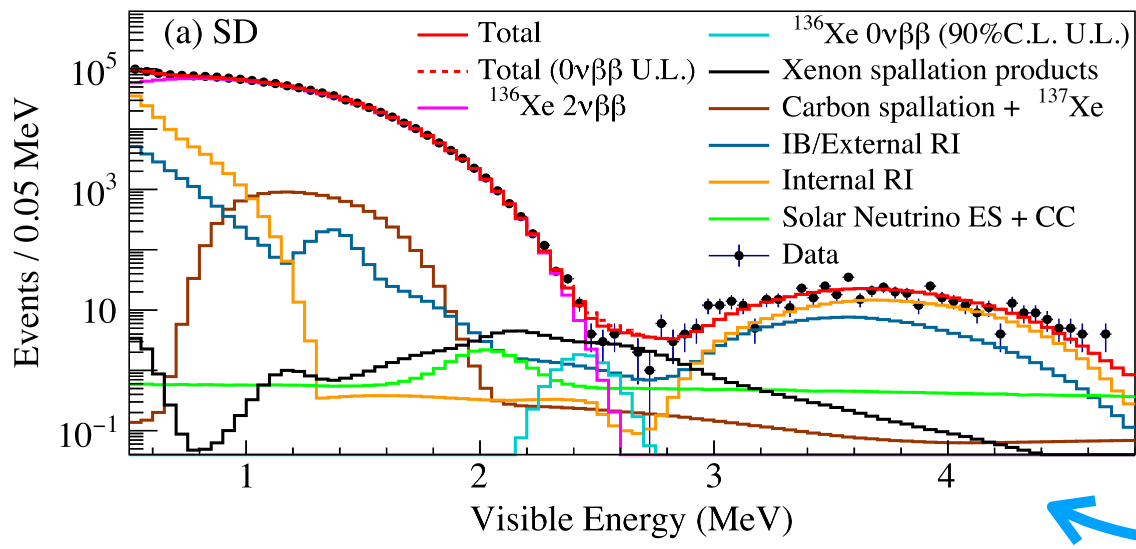
Achieved over double the exposure compared to KLZ 800 1st paper!!

^{136}Xe 0νββ decay Half-life limit

arXiv:2406.11438[hep-ex]

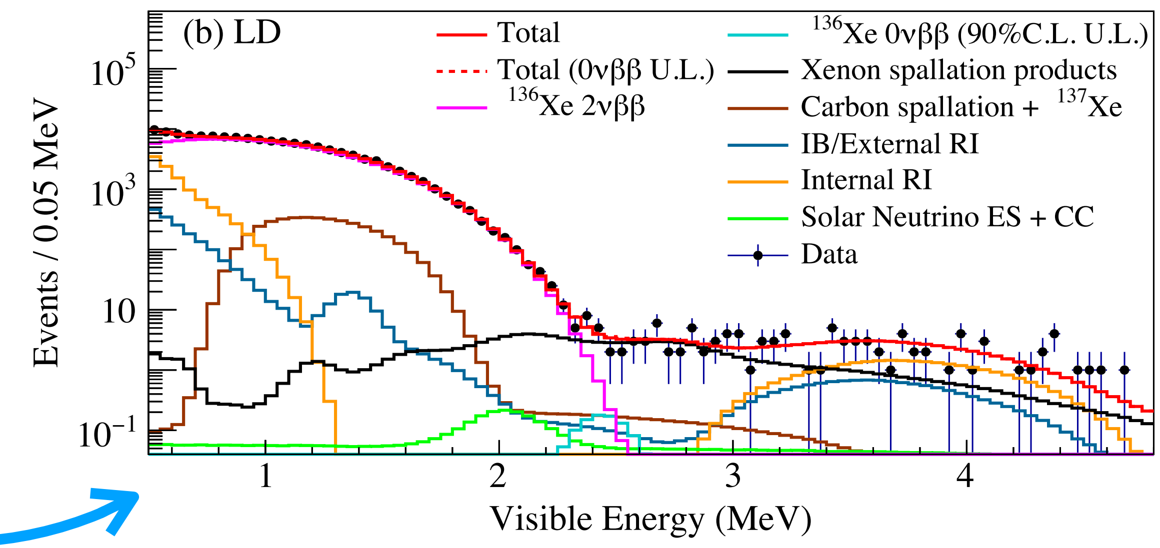
Singles data (SD)
(sensitive to 0νββ rate)

Livetime = 1131 days



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

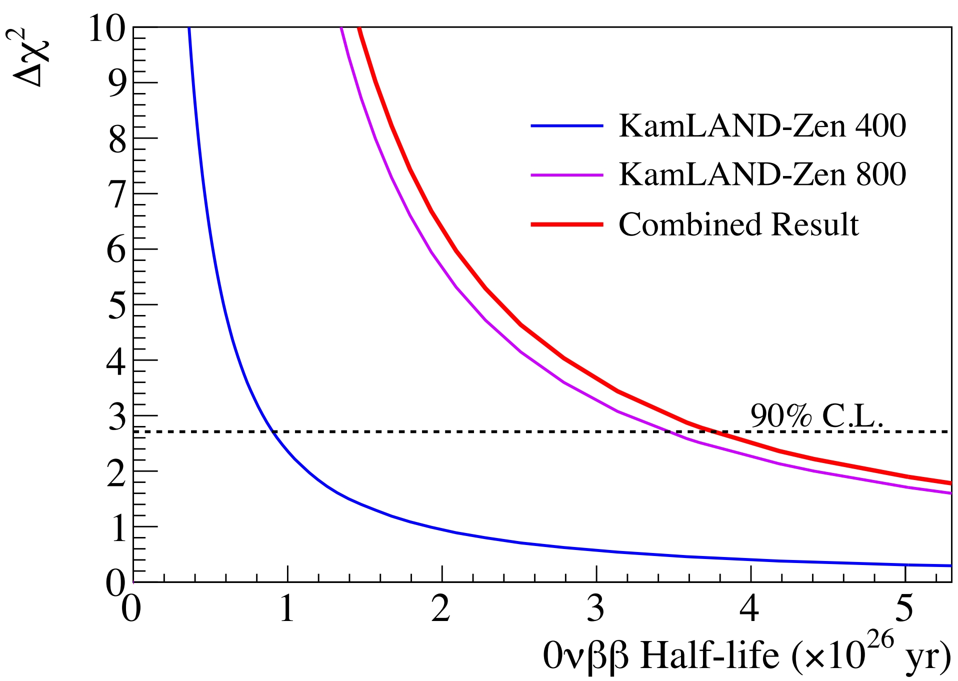
Livetime = 111.0 days



simultaneous fit

KamLAND-Zen 800 only result : $T^{0\nu}_{1/2} > 3.4 \times 10^{26}$ **yr (90% C.L.)**

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



KLZ 400 only : 0.9×10^{26} yr

Combined result (90% C.L.):

$$T^{0\nu}_{1/2} > 3.8 \times 10^{26}\ \text{yr}$$

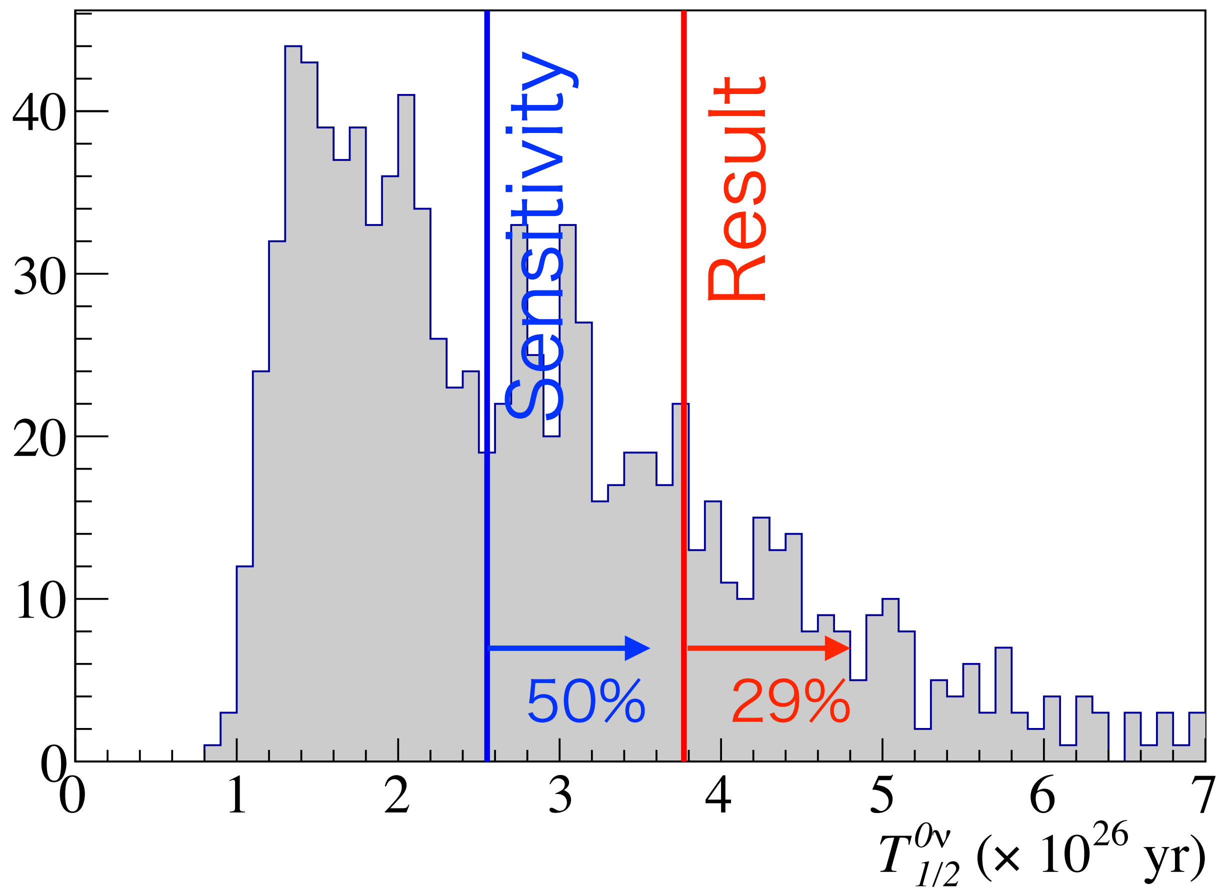
Sensitivity (90% C.L.)

$$T^{0\nu}_{1/2} = 2.6 \times 10^{26}\ \text{yr}$$

Upper limits from Toy MC

To evaluate the validity of the fit results, the experimental sensitivity was assessed.

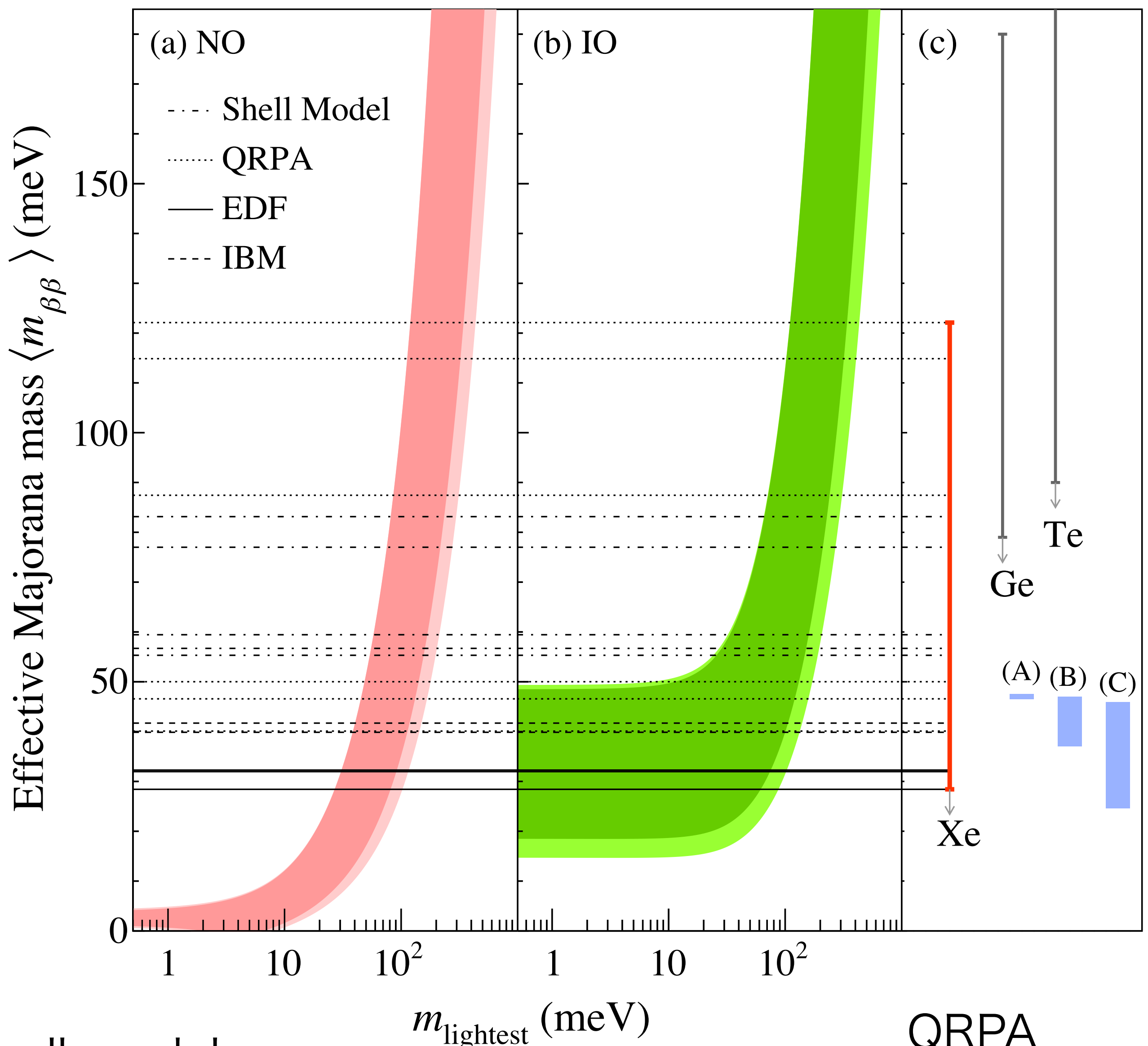
- Generated 1,500 ToyMC datasets assuming a Poisson distribution based on the best-fit model.
- Calculated the 90% confidence level limit for each of the 1,500 MC datasets.
- Defined the median of the 1,500 trials as the experimental sensitivity (Median Sensitivity).



Sensitivity: $T^{0\nu}_{1/2} > 2.6 \times 10^{26}$ yr (90% C.L.)

Result: $T^{0\nu}_{1/2} > 3.8 \times 10^{26}$ yr (90% C.L.)

Limit on the effective Majorana mass



Lower limit of half life

$$T^{0\nu}_{1/2} > 3.8 \times 10^{26}\ \text{yr}$$

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

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

Upper limit of Majorana mass

⟨$m_{\beta\beta}$⟩ < 28-122 meV

Most stringent test of the neutrino mass in the IO

Shell model

[1] J. Menéndez, J. of Phys. G **45**, 014003 (2018).
[2] M. Horoi and A. Neacsu, Phys. Rev. C **93**, 024308 (2016).
[3] L. Coraggio, A. Gargano, N. Itaco, R. Mancino, and F. Nowacki, Phys. Rev. C **101**, 044315 (2020).
[4] L. Coraggio *et al.*, Phys. Rev. C **105**, 034312 (2022).

EDF

[10] T. R. Rodríguez and G. Martínez-Pinedo, Phys. Rev. Lett. **105**, 252503 (2010).
[11] N. L. Vaquero, T. R. Rodríguez, and J. L. Egido, Phys. Rev. Lett. **111**, 142501 (2013).
[12] L. S. Song, J. M. Yao, P. Ring, and J. Meng, Phys. Rev. C **95**, 024305 (2017).

QRPA

[5] M. T. Mustonen and J. Engel, Phys. Rev. C **87**, 064302 (2013).
[6] J. Hyvärinen and J. Suhonen, Phys. Rev. C **91**, 024613 (2015).
[7] F. Šimkovic, A. Smetana, and P. Vogel, Phys. Rev. C **98**, 064325 (2018).
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[9] J. Terasaki, Phys. Rev. C **102**, 044303 (2020).

IBM

[13] J. Barea, J. Kotila, and F. Iachello, Phys. Rev. C **91**, 034304 (2015).
[14] F. F. Deppisch, L. Graf, F. Iachello, and J. Kotila, Phys. Rev. D **102**, 095016 (2020).

Theoretical model

(A) K. Harigaya, M. Ibe, and T. T. Yanagida, Phys. Rev. D 86, 013002 (2012)
(B) T. Asaka, Y. Heo, and T. Yoshida, Phys. Lett. B 811, 135956 (2020).
(C) K. Asai, Eur. Phys. J. C 80, 76 (2020)

Limit on the effective Majorana mass

	Ref.	$M^{0\nu}$	$\langle m_{\beta\beta}\rangle$ (meV)
Shell model	[1]	2.28, 2.45	59.4, 55.3
	[2]	1.63, 1.76	83.1, 77.0
	[3, 4]	2.39	56.7
QRPA	[5]	1.55	87.4
	[6]	2.91	46.6
	[7]	2.71	50.0
	[8]	1.11, 1.18	122, 115
	[9]	3.38	40.1
EDF theory	[10]	4.20	32.3
	[11]	4.77	28.4
	[12]	4.24	32.0
IBM	[13]	3.25	41.7
	[14]	3.40	39.9

: NMEs in IO (< 50 meV)

Lower limit of half life

$$T_{1/2}^{0\nu} > 3.8 \times 10^{26}\ \text{yr}$$

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

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

Upper limit of Majorana mass

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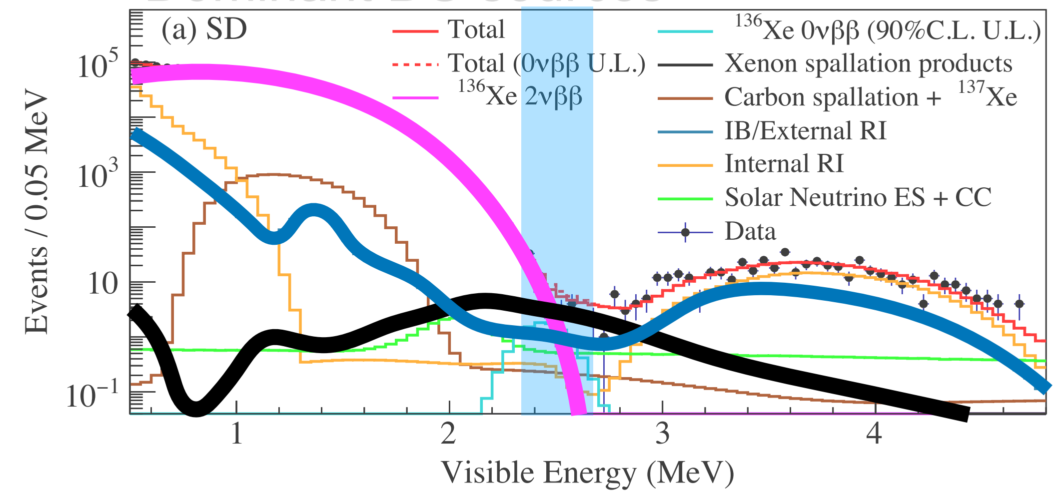
(C) K. Asai, Eur. Phys. J. C 80, 76 (2020)

KamLAND2-Zen

Next generation detector R&D is now in progress

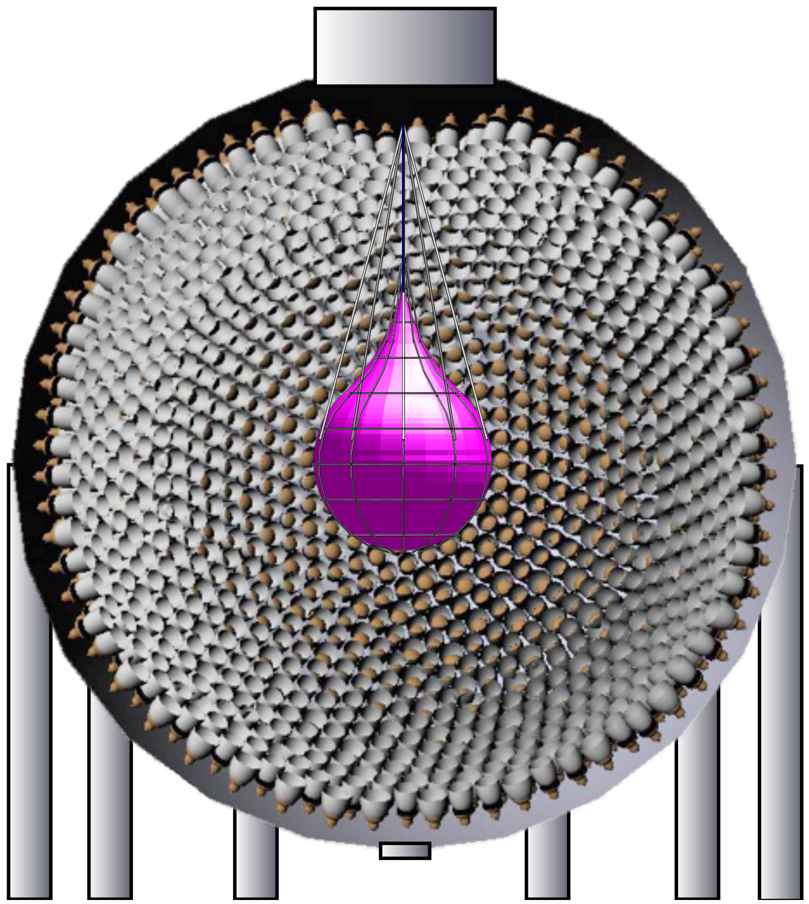
- Dominant BG sources



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

1000 kg of Xe

Increase isotope mass

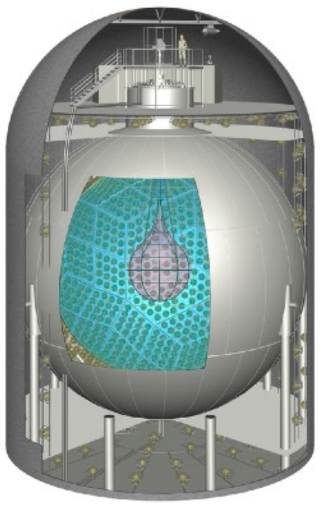
Cosmic muon induced Xe spalllation products

New Dead-time free electronics

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

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

Plan of Detector Upgrades



KamLAND &
KamLAND-Zen

2024 2025 2026 2027

KamLAND2 &
KamLAND2-Zen

Xe & Inner Balloon extraction — Done!!

LS extraction — here!!

Super clean facility

Outer balloon & PMT dismantling

KamLAND Dismantling

High QE PMT & Mirror installation

Cleaner Outer balloon

High light yield LS

New electronics

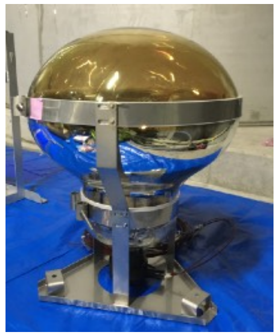
Calibration system

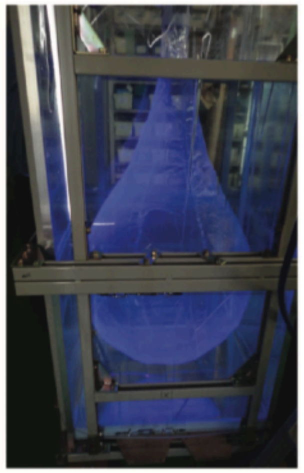
KamLAND2 construction

Scintillation balloon

Xe LS

KamLAND2-Zen



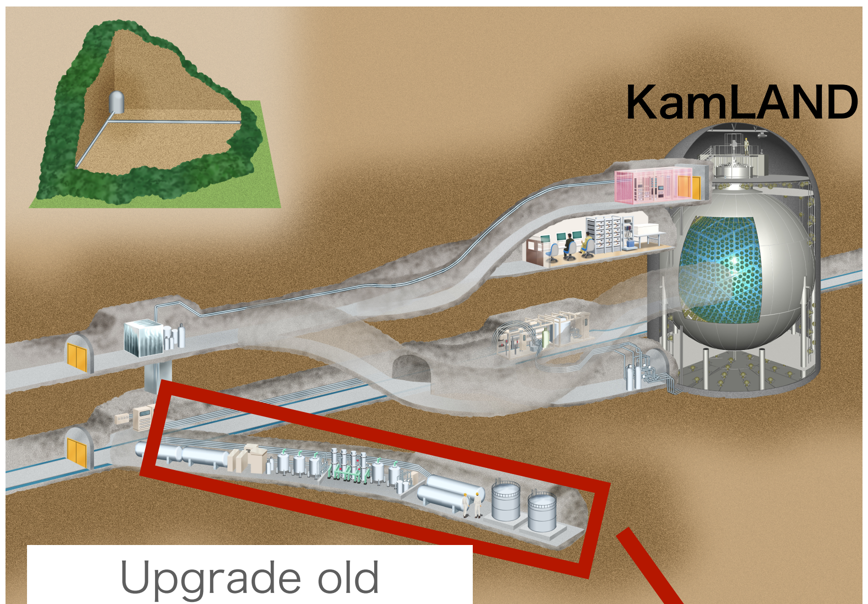


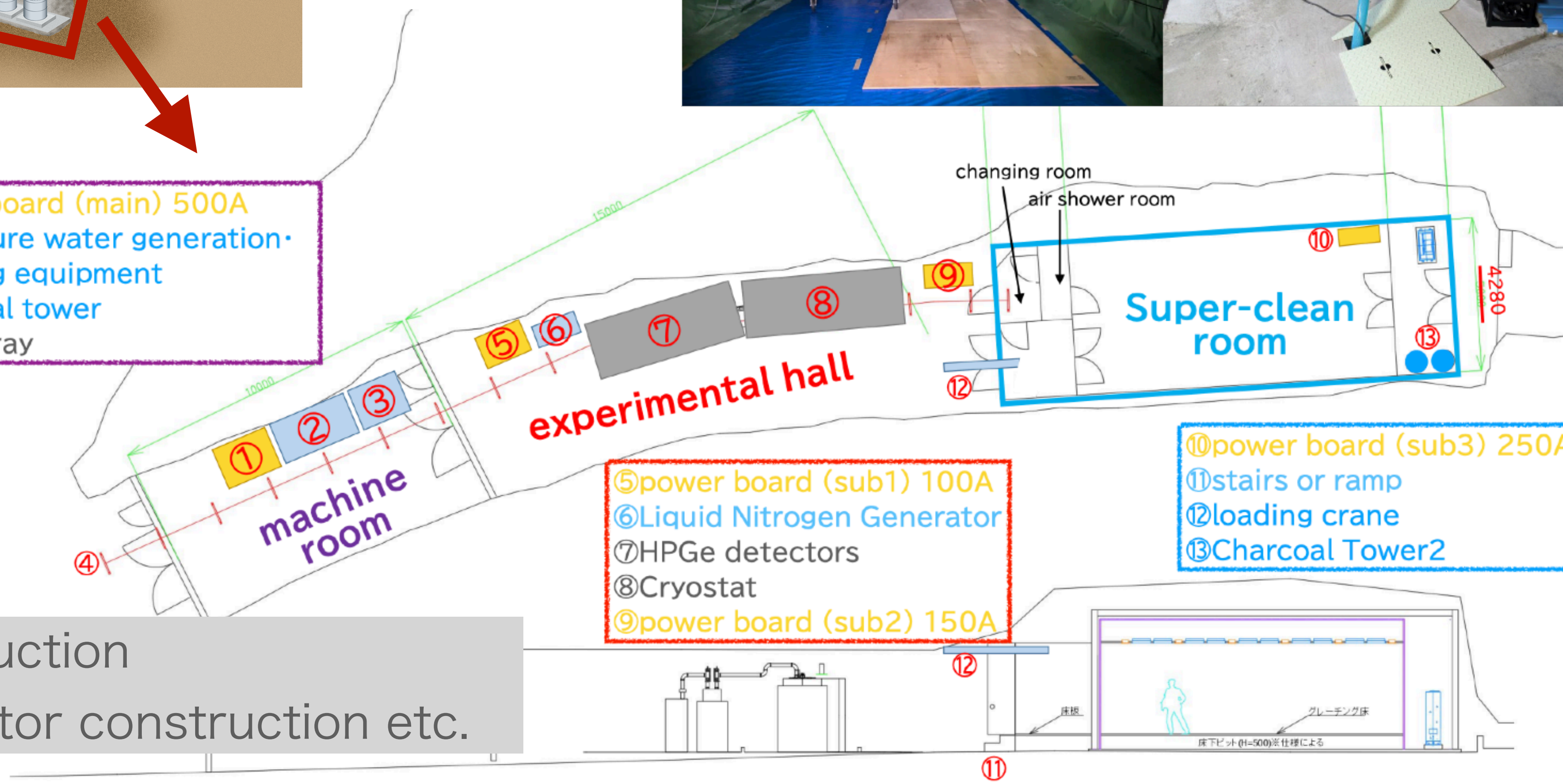
We started detector upgrades in this year and plan to launch KamLAND2 in 2027!!

KERNEL 神岡極稀現象研究拠点

Kamioka Extremely Rare phenomena and NEutrino research Lab

We are now constructing super clean facility in Kamioka mine





- Inner balloon construction
- crystallization, detector construction etc.

Summary

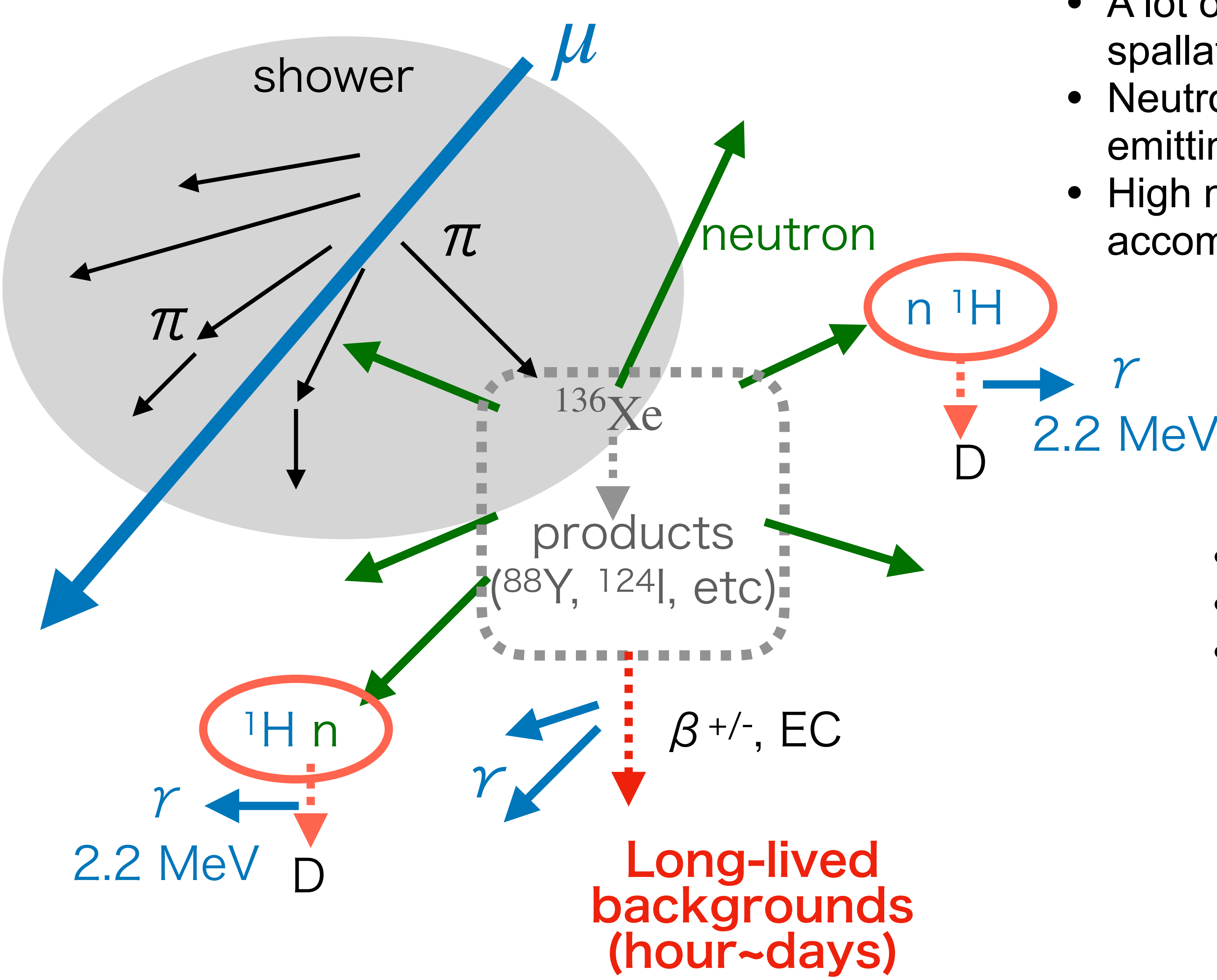
- ☑ KamLAND-Zen searches for neutrinoless double beta decay with ^{136}Xe loaded liquid scintillator.
  - Combined result for KamLAND-Zen 400 + 800

$$T_{1/2}^{0\nu} > 3.8 \times 10^{26}\ \text{yr}, \quad \langle m_{\beta\beta} \rangle < 28 - 122\ \text{meV}$$

- ☑ We started detector upgrade toward KamLAND2/KamLAND2-Zen.
  - Expand sensitive volume (scintillation balloon)
  - Enhanced energy resolution (HQEPMT, Light guide)
  - Enhanced tagging efficiency of Xe spllation products (New electronics)
- ☑ The target of KL2-Zen is $\langle m_{\beta\beta} \rangle$ =20 meV

Backup

Cosmic muon induced backgrounds



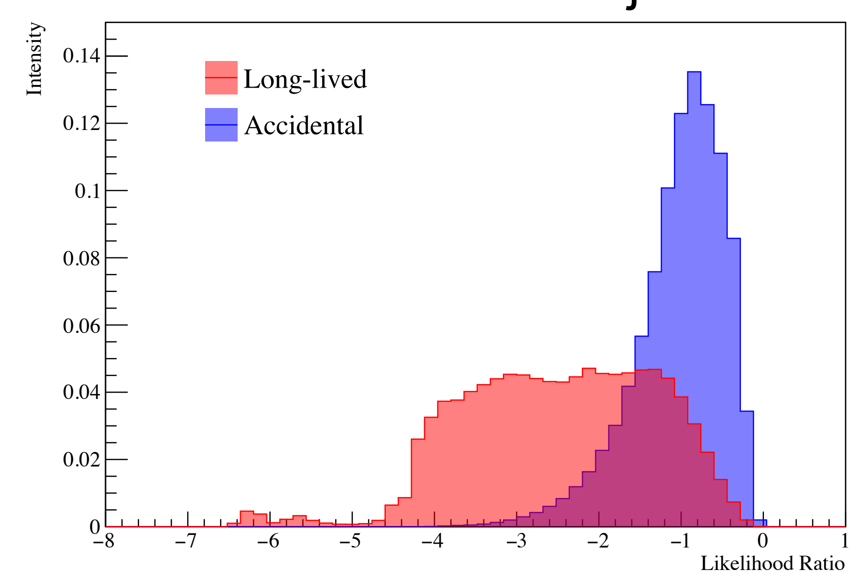
Decay of this long-lived spallation products make serious background in KamLAND-Zen

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,

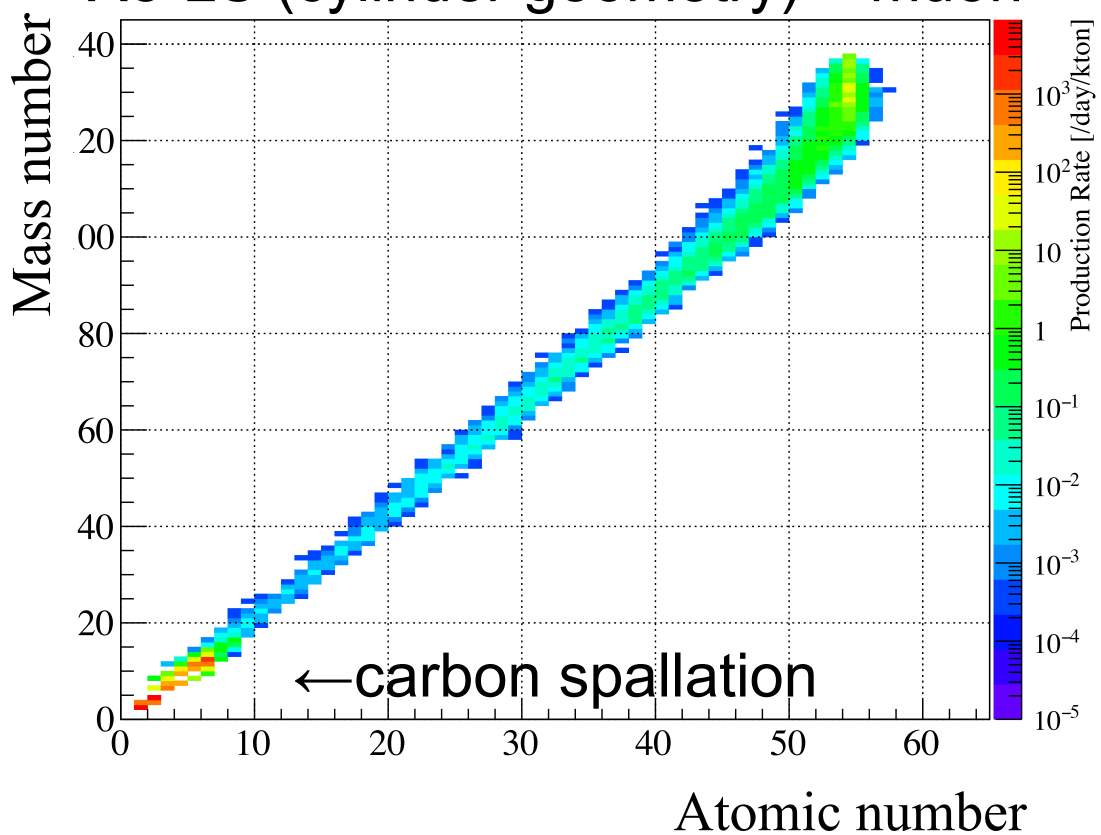
- Neutron multiplicity
- Distance from neutron capture
- Delta-time from muon injection



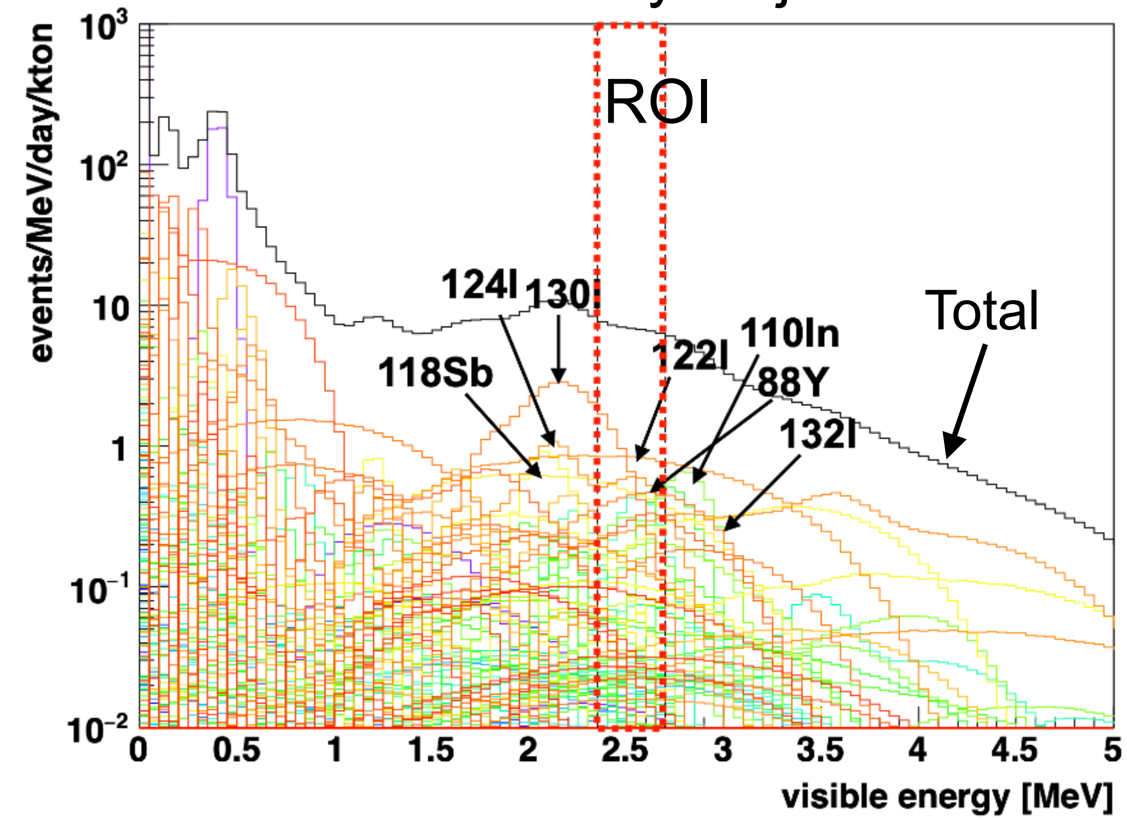
Xenon spallation products (Long-lived products)

- ☑ 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

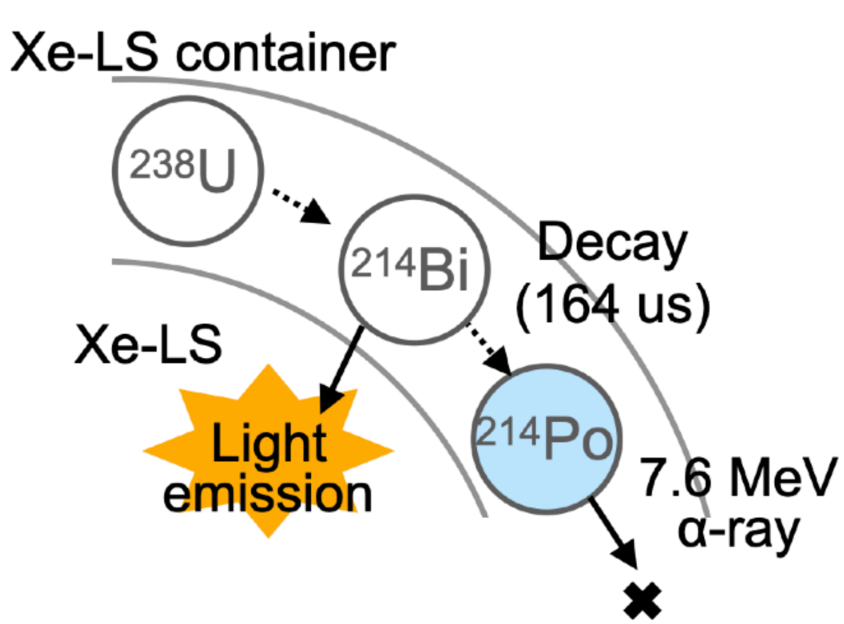
^{238}U ~3×10^{-12} g/g$_{film}$

ref. initial film (after washed)

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

Difficult for further improvement

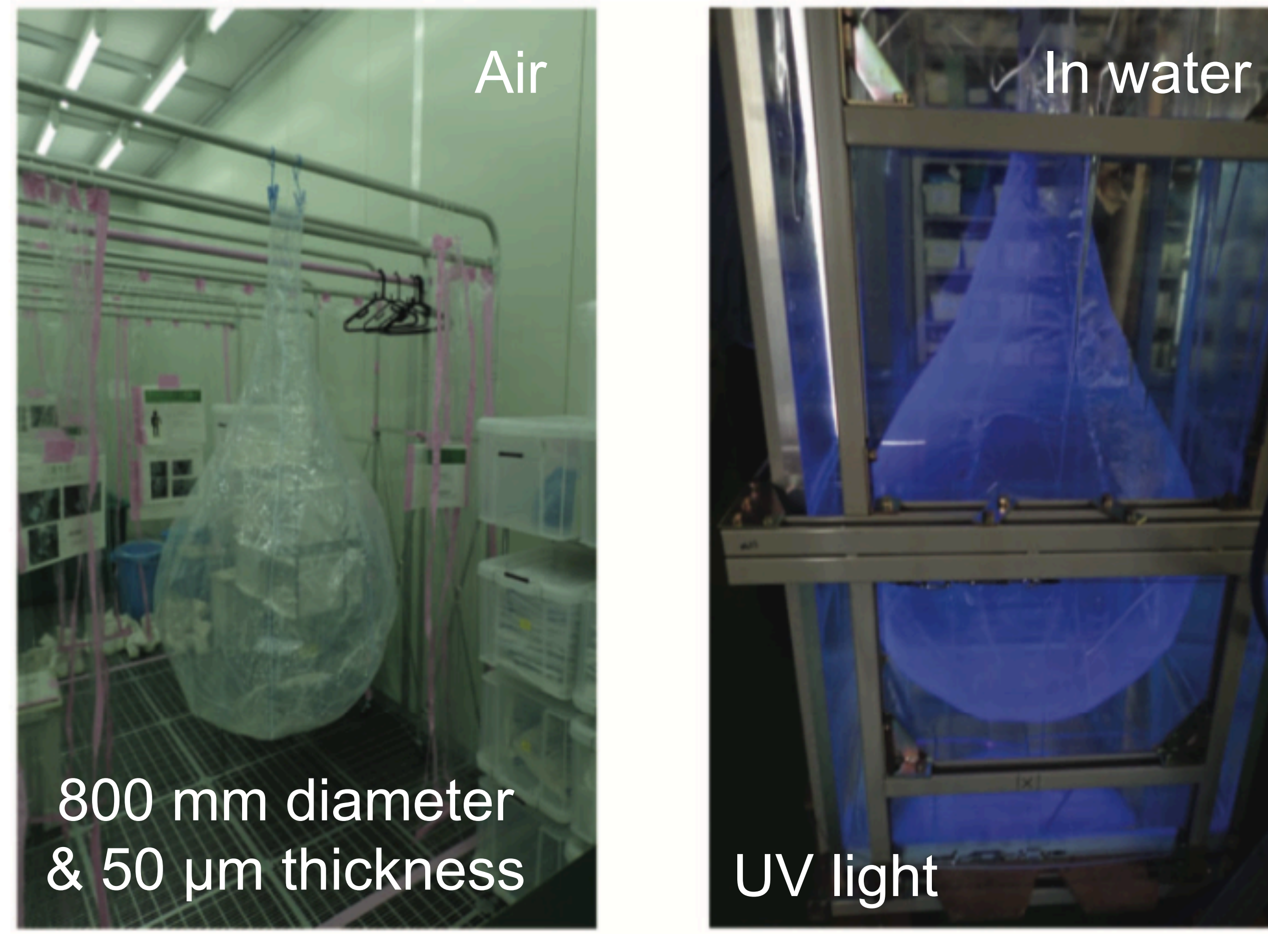
- Current tagging efficiency
  ~50% due to ^{214}Po alpha decay

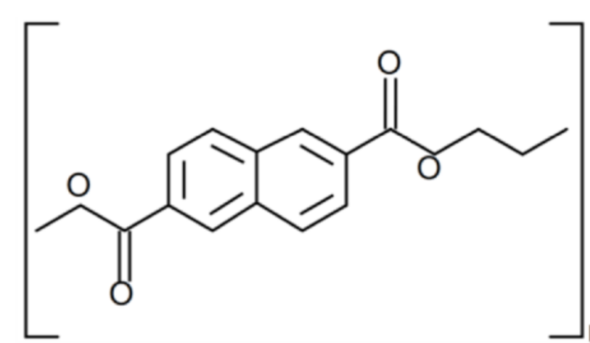


cf) Xe-LS tagging eff. 99.97%

Tag this decay with scintillation inner balloon

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

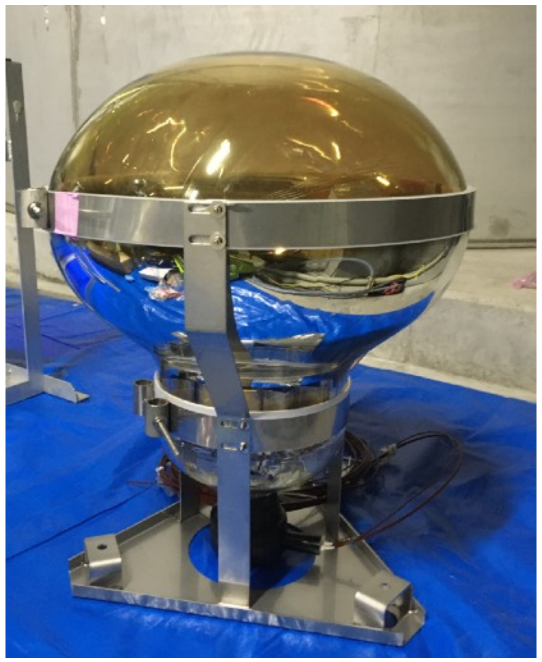




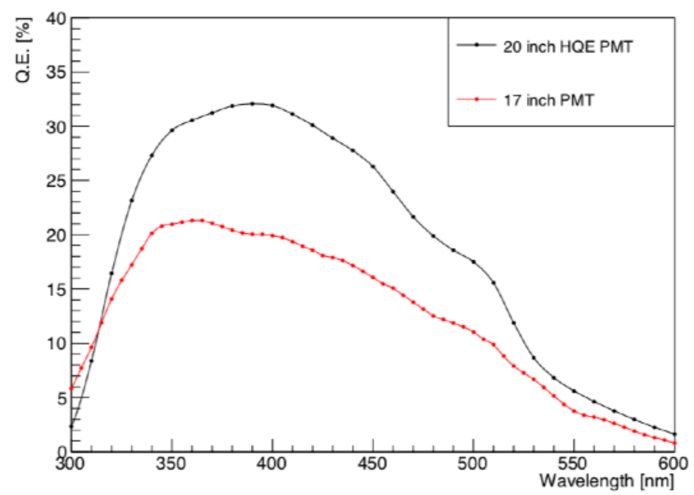
PolyEthylene Naphthalate (PEN)

High QE PMT & light guide

20 inch PMT (R12860-03LXA)



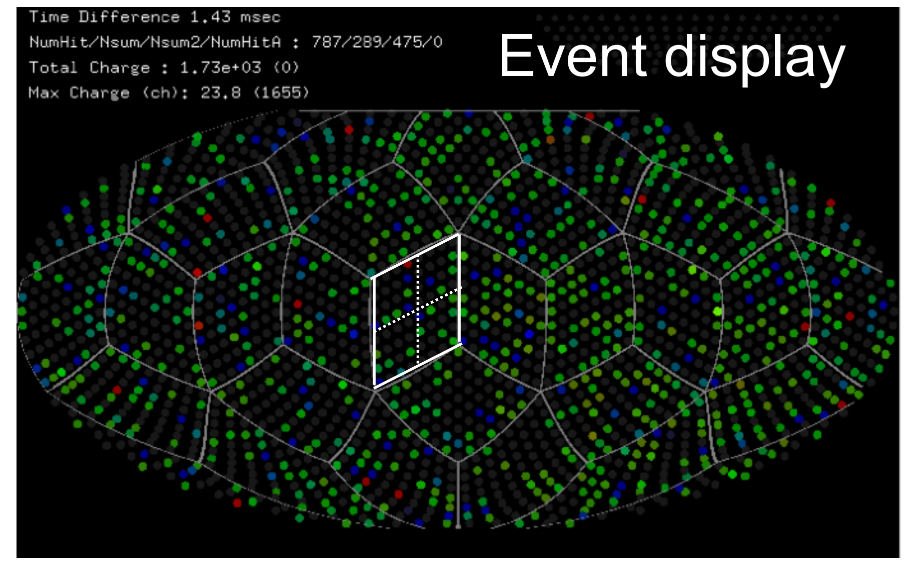
High quantum efficiency



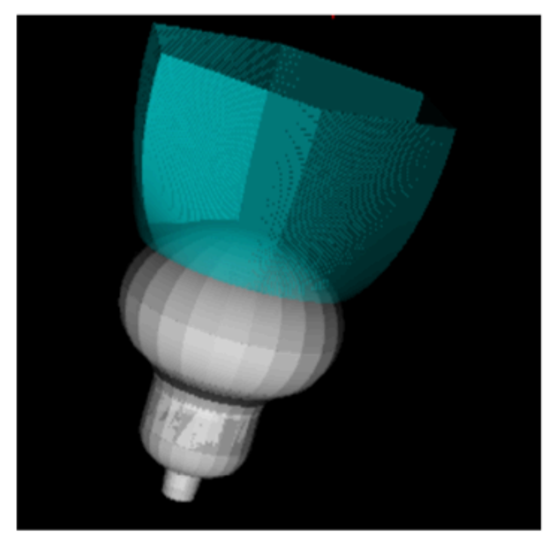
PMT spec:	New 20”	17”
Dynode	Box & line	Line-focus
Q. E. @400nm	31.9%	23%@390 nm
P/V ratio	3	3.4
Raise time [ns]	6	
Time Transit Spread [ns]	2.4	3.5
Dark pulse rate (ave.) [kHz]	8	22.1

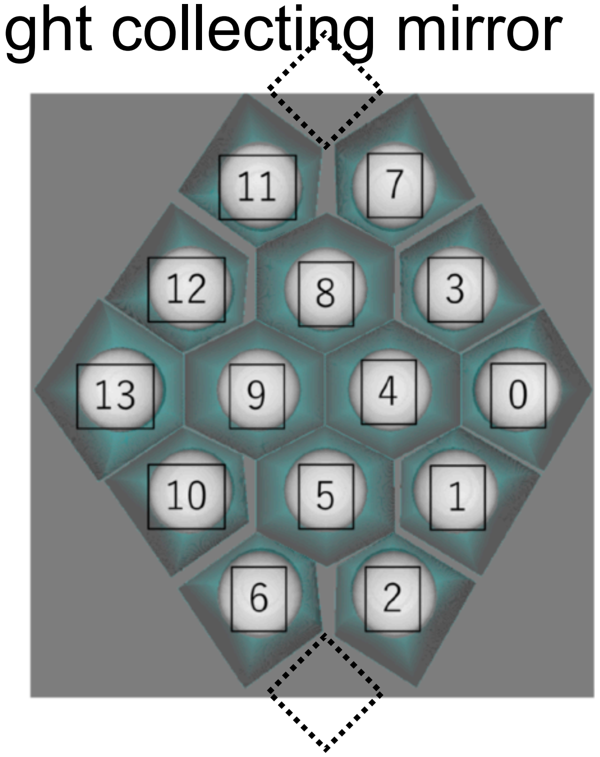
PMT placed at rhombic triacontahedron

(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%**

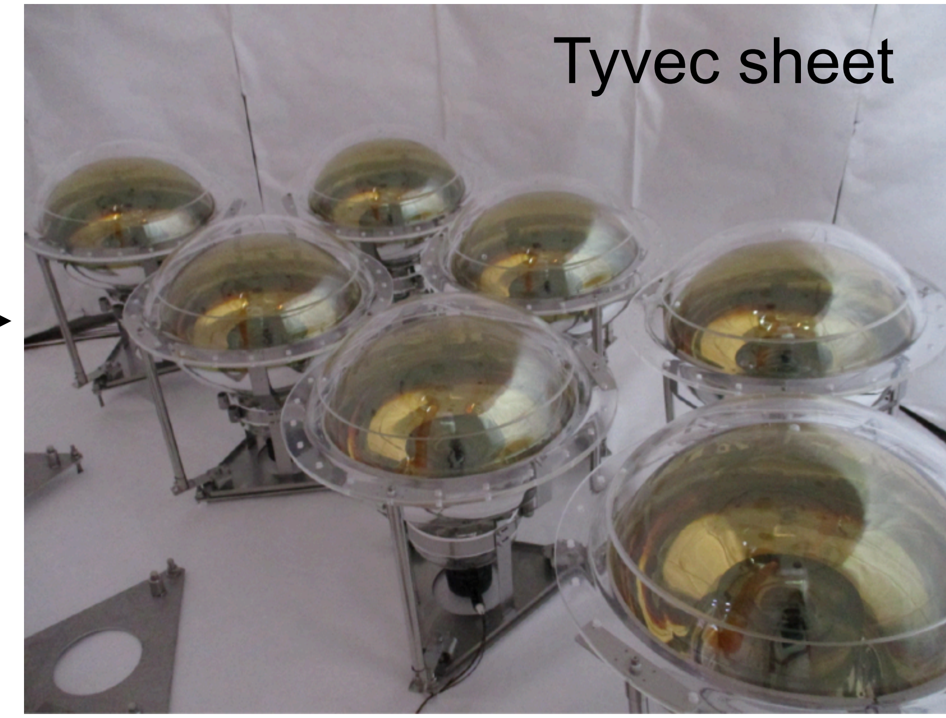
Prototype detector for KL2

Cleaning is important work!

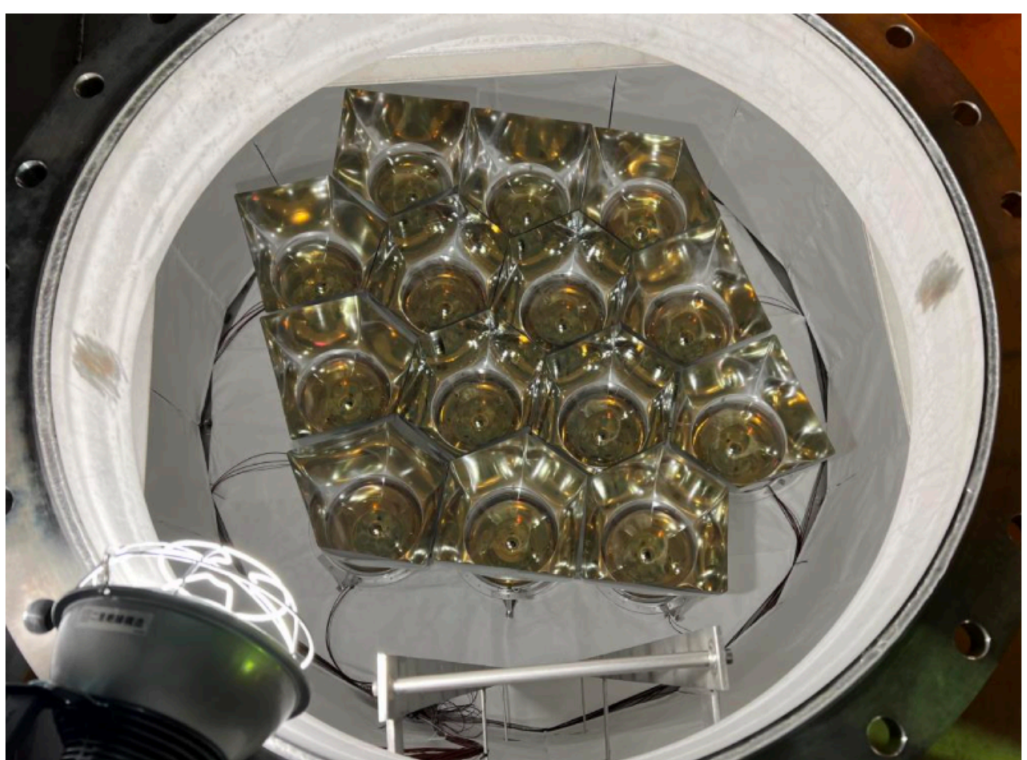
→

→

Inside of the detector
PMTs w/o light collection mirror

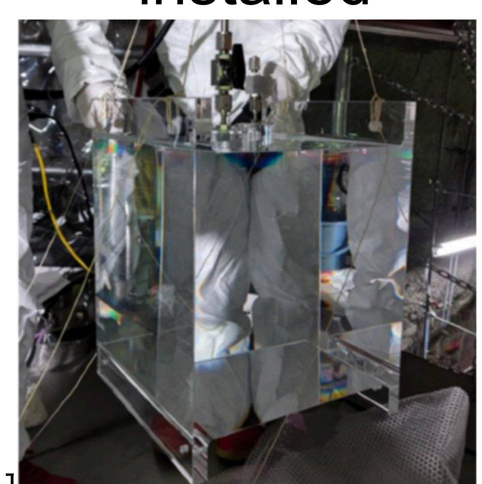


All PMTs & mirrors installed



Pure
water
injection
→

30L LS box
installed



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