Development of calibration method and performance evaluation for KamLAND2 prototype detector

NuDM-2024

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Neutrino-less double beta decay ($0\nu\beta\beta$)

Majorana nature of neutrinos

Majorana particle

$$\nu = \bar{\nu}$$

Key component of
small neutrino mass
matter dominant universe

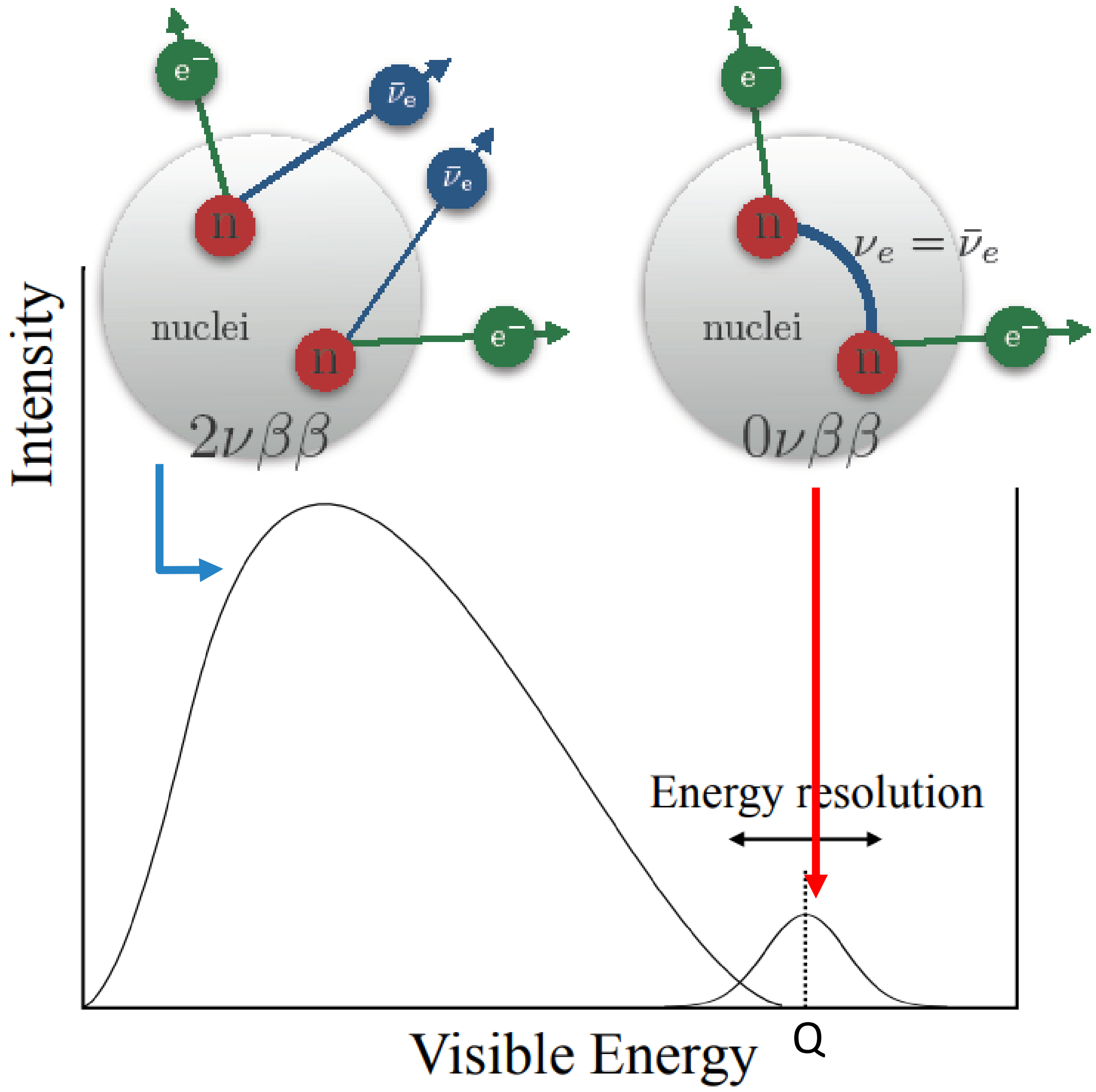
Neutrino-less double beta decay ($0\nu\beta\beta$)

- $0\nu\beta\beta$ happens only if ν is Majorana particle.

  = verifying the Majorana neutrino

- Requirements for detector: peak search around the Q-value
  High light emission & light yield
  background reduction

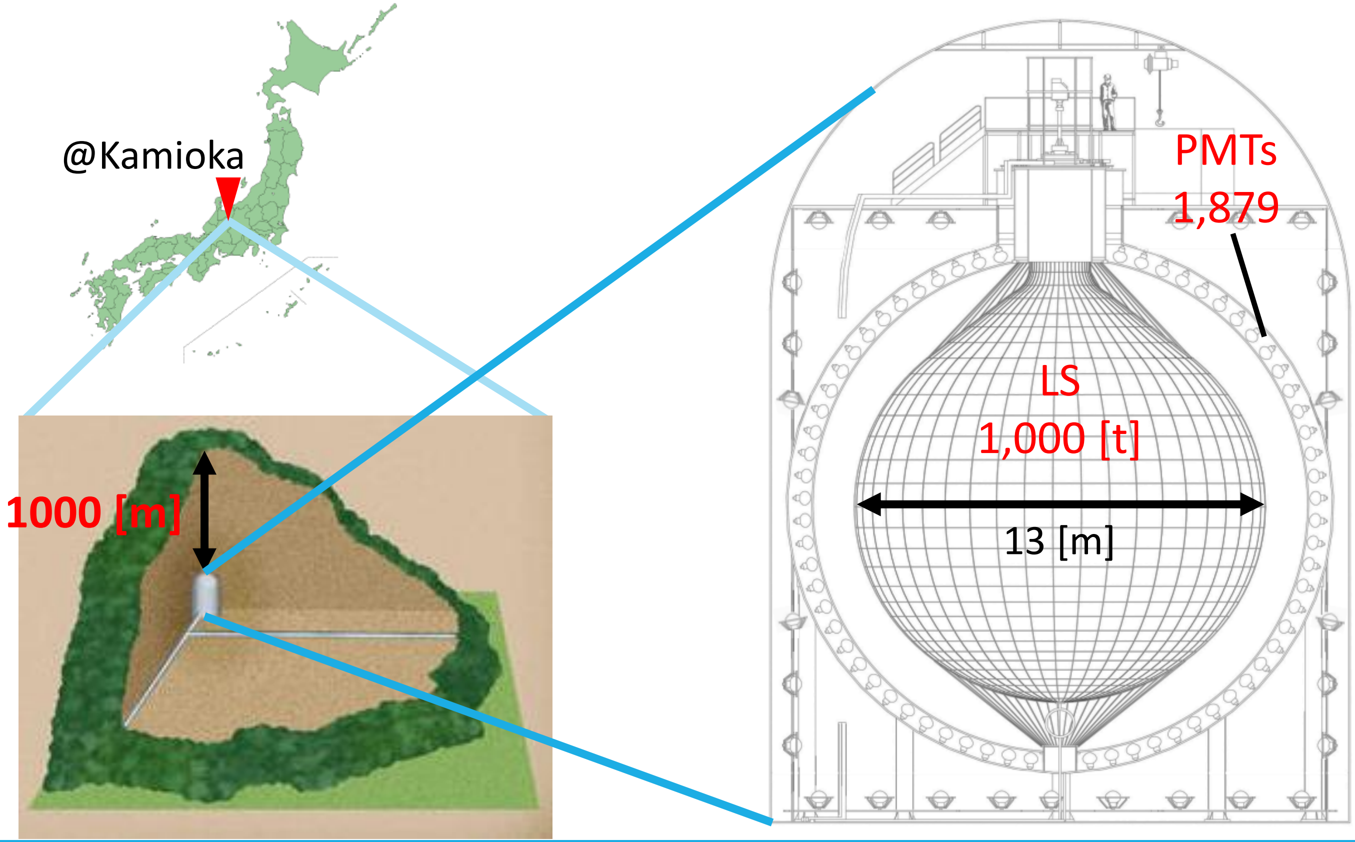
  → KamLAND is a suitable detector



KamLAND

KamLAND: The Kamioka Liquid-scintillator Anti-Neutrino Detector

Advantage: Extremely low-radioactivity + Large & high-sensitivity
→ **Ideal detector for rare decay search!**



Results:

- Neutrino oscillations of reactor neutrinos observed (world first)
  → Precision measurement of neutrino oscillations
- Antielectron neutrinos originating from Earth observed (world first)
  → Leading neutrino geophysics

Other scientific objectives:

- Solar neutrinos
- Atmospheric neutrinos
- Astrophysical neutrinos
- Proton decay
- $0\nu\beta\beta$ ← **KamLAND-Zen** experiment

KamLAND-Zen Experiment

KamLAND-Zen = ^{136}Xe + KamLAND
Zero-neutrino double-beta decay search

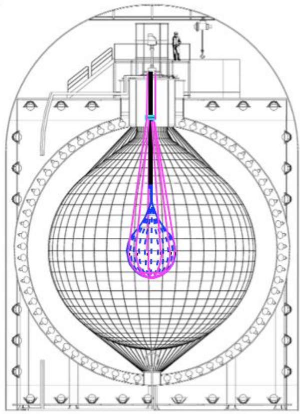
^{136}Xe: Double-beta decay source

- $0\nu\beta\beta$ Q-Value: 2.46MeV (below ^{208}Tl γ BG)
- Long $2\nu\beta\beta$ half life
- (Relatively) easy to enrich/purify by distillation
- Dissolved into liquid scintillator (LS) at 3%

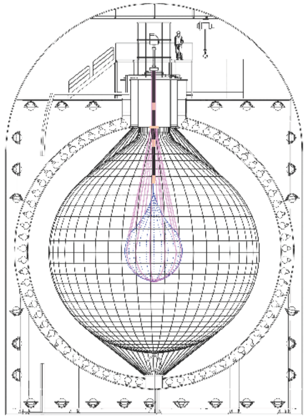
- Calculate the lower limit of the half-life of $0\nu\beta\beta$ from the observation time and the amount of Xe
- Calculate the upper limit of the effective Majorana mass from the half-life

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

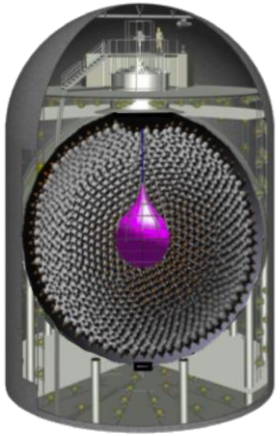
$G^{0\nu}$: Phase space factor
$|M^{0\nu}|^2$: Nuclear matric element (NME)



Increase in Xe



Now Upgrading!



KamLAND-Zen 400 (Xe: 320~380 [kg])
$T_{1/2}^{0\nu} > 0.9 \times 10^{26}$ [yesrs]
$\langle m_{\beta\beta}\rangle < 61 - 165$ meV
Phys. Rev. Lett. 117, 082503 (2016)

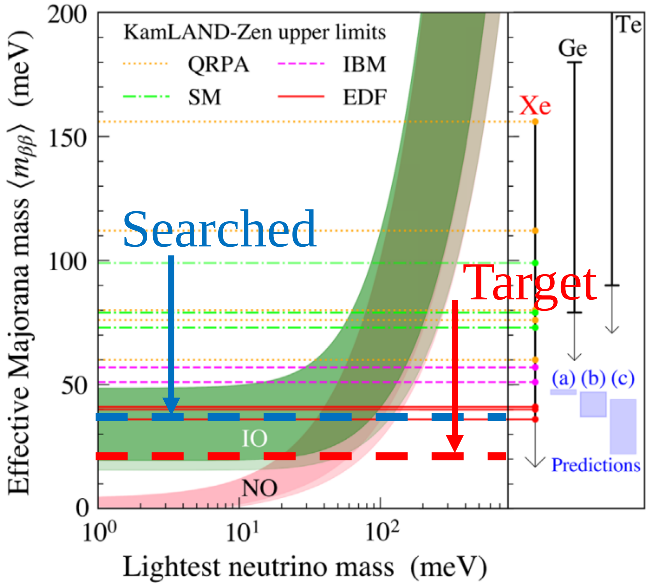
KamLAND-zen 800 (Xe: 745 ± 3 [kg])
$T_{1/2}^{0\nu} > 3.8 \times 10^{26}$ [yesrs]
$\langle m_{\beta\beta}\rangle < 28 - 122$ meV
Phys. Rev. Lett. 130, 051801 (2023)

KamLAND2-Zen (Xe: ~1,000 [kg])
Toward $T_{1/2}^{0\nu} = 2.0 \times 10^{27}$ [yesrs]
Toward $\langle m_{\beta\beta}\rangle = 20$ meV

KamLAND-Zen Experiment

KamLAND-Zen 400 + 800

- Current results: First in the world to reach IO band $\left(\begin{array}{l} T_{1/2}^{0\nu} > 2.3\times10^{26} \text{ year (90\%C.L.)} \\ \langle m_{\beta\beta}\rangle < 36\text{–}156 \text{ meV} \end{array} \right)$



KamLAND2-Zen (Future plan)

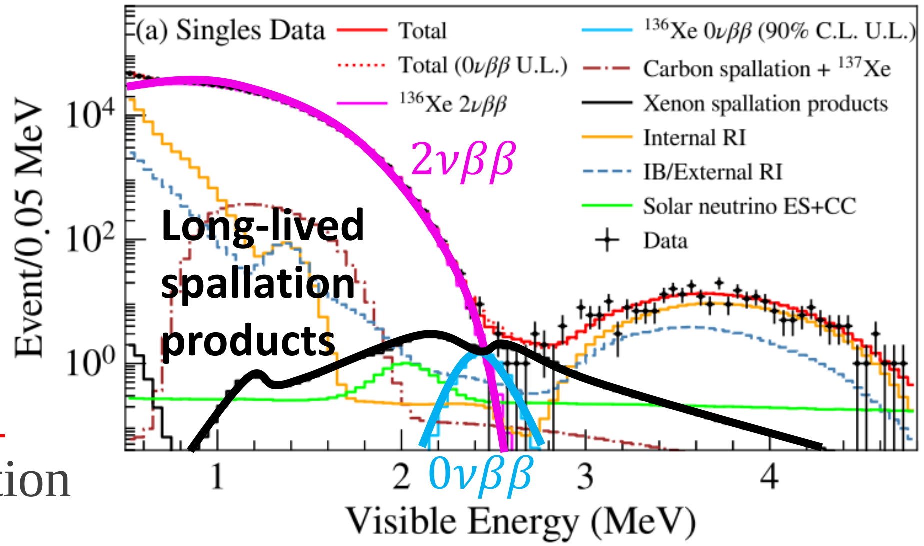
- Target sensitivity: Covering most of IO $\left(T_{1/2}^{0\nu} > 2.0\times10^{27} \text{ year} \quad (\langle m_{\beta\beta}\rangle \sim 20 \text{ meV})\right)$
- Main backgrounds of $0\nu\beta\beta$

$2\nu\beta\beta$

- Can only be separated by **improving energy resolution**
- Reduction target: 1/100

Long-lived spallation products

- Can be reduced by improving energy & vertex resolution



⇒ Aiming to **increase the number of observed photons!**

to improve energy resolution

Upgrade KamLAND2-Zen

Upgrade contents

- **Increase in light yield**

High quantum efficiency PMT (HQE-PMT) (x**1.9**)

Light-collecting Winston cone mirror (x**1.8**)

High light-yield liquid scintillator (New-LS) (x**1.4**)

Target of KamLAND2-Zen

- **5x increased effective light yield**

→ energy resolution σ: $4\% \rightarrow < 2.5\%$ $(E = 2.5\ \mathrm{MeV})$

$2\nu\beta\beta$ BG reduction by the order of 2

➔ **Test with prototype detector**

- State-of-the-art read-out electronics: **MoGURA2**

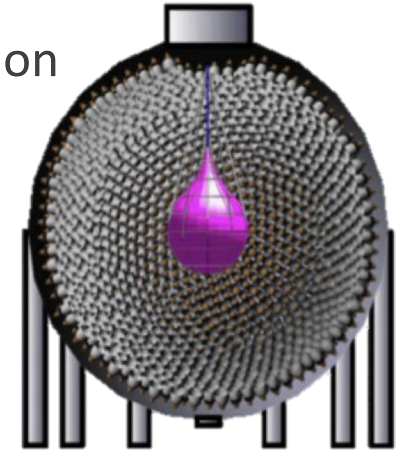
RFSoC powered data acquisition

Huge buffer for SN-burst detection

- $\sim$100% spallation neutron detection
- More efficient L.L. tagging

- **Increase in** ^{136}**Xe**: 745kg → $\sim$1,000kg

- More exposure



Upgrade contents

Optical properties registered in the simulation

(: Emission wavelength of New-LS)

- New-LS (candidate)

Light yield: x1.365 (Compared to conventional)

Composition:

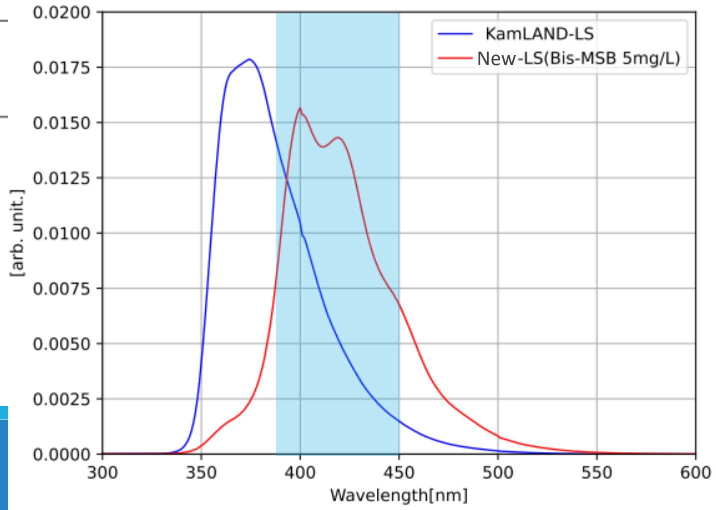
Components	Formula	Density [g/cm³]	Volume ratio
LAB	C_nH_{2n-6}	0.86	80%
PC	C_9H_{12}	0.875	20%
PPO	$C_{15}H_{11}NO$	–	2.00 g/L
Bis-MSB	$C_{24}H_{22}$	–	5 mg/L
LAB-LS	–	0.865	–

Emission time constant

:

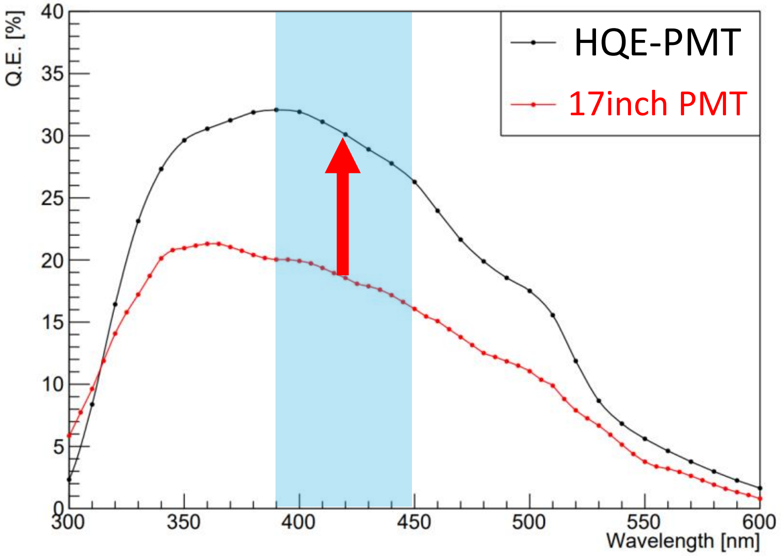
i	A_i [%]	τ_i[ns]
1	91.5	7.37
2	8.5	44.7

Emission spectrum:

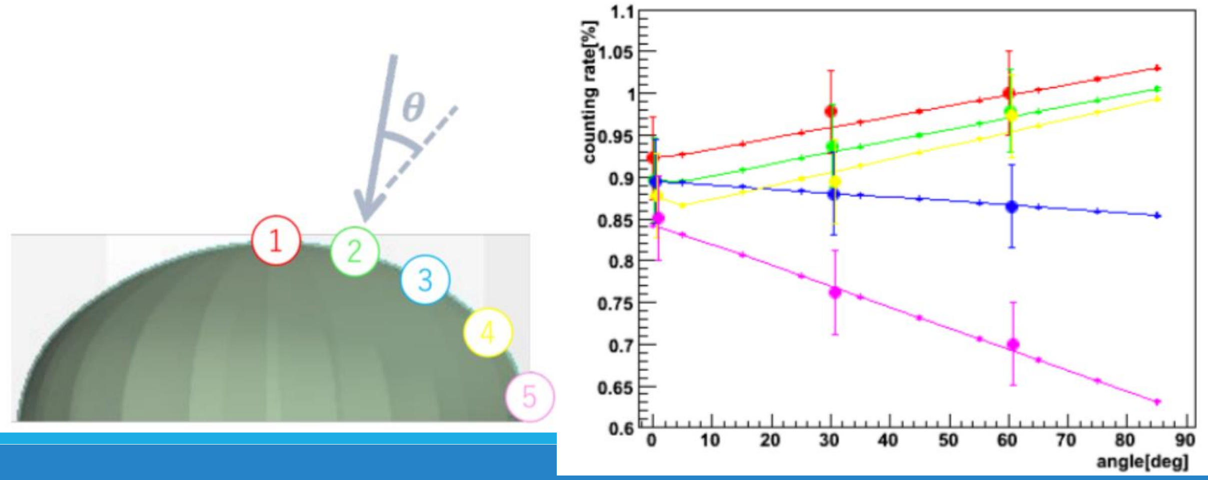


- HQE-PMT

Quantum efficiency:



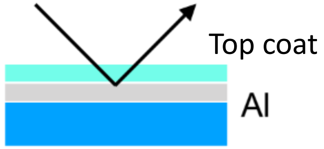
Incident position and angle dependency:



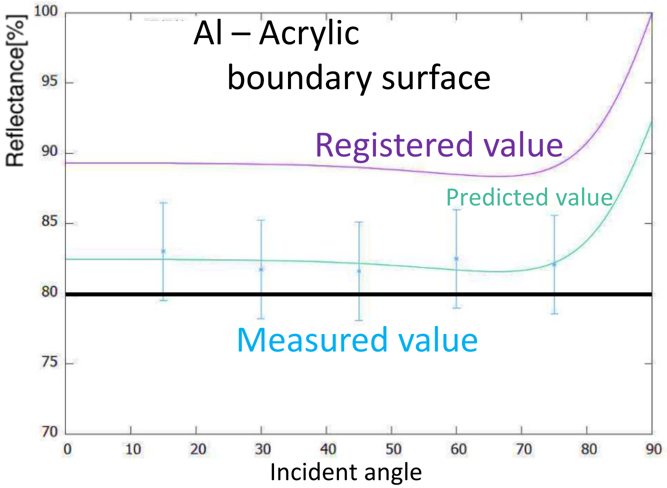
Upgrade contents

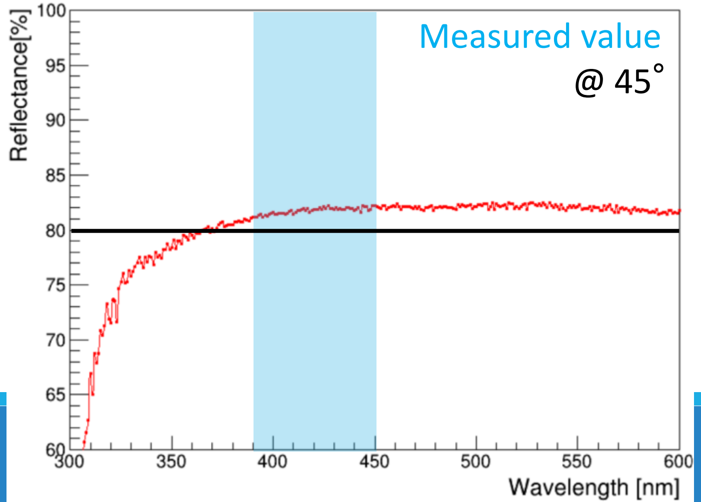
Optical properties registered in the simulation (: Emission wavelength of New-LS)

- Light-collecting mirror



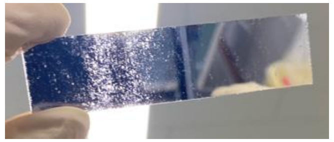
Reflectace:





Long-term stability:

20 days at 41℃
(≒ 6 months at 10℃ (usage environment))
In pure water : Reduction in reflectance
In LS : Stable



3 months at 20℃
(≒ 6 months at 10℃, by contractor)
In pure water : Stable

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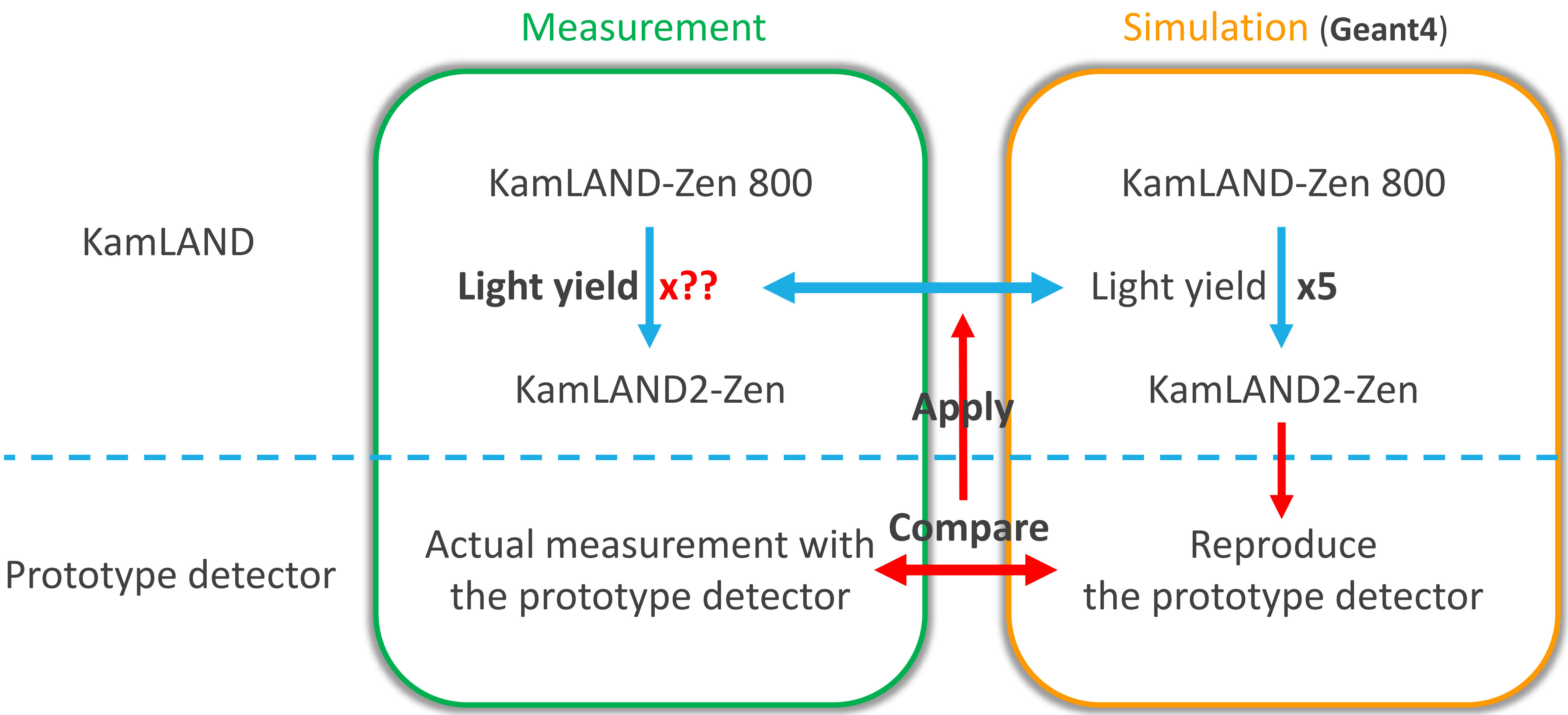
Flow of performance evaluation



Flow of performance evaluation

Compare

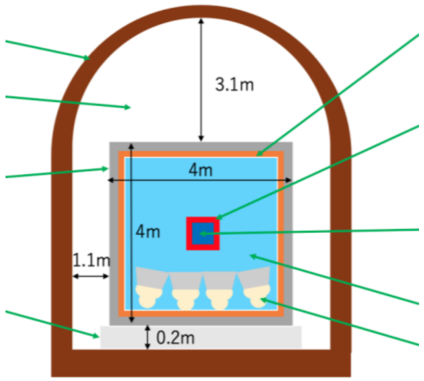
Measurement

Actual measurement with the prototype detector

Scintillation ball measurement	1. Light yield w/ or w/o mirrors → **Evaluate the collecting performance**
Radiation source measurement	3. Measure Compton edge by $^{137}\mathrm{Cs}$ & $^{60}\mathrm{Co}$ → **Evaluate the observed photons**

Simulation

Reproduce the prototype detector with Geant4

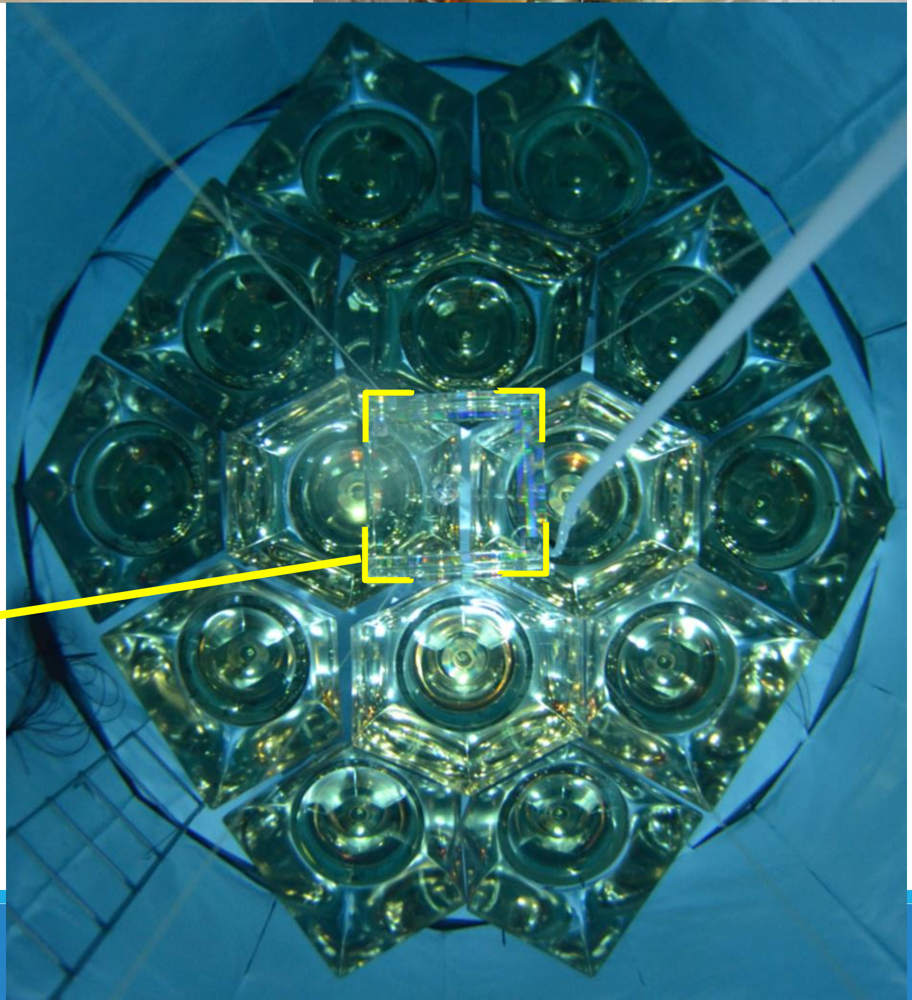


Register the values measured in individual studies for the composition and optical properties of the materials

Simulation to reproduce the actual measurement

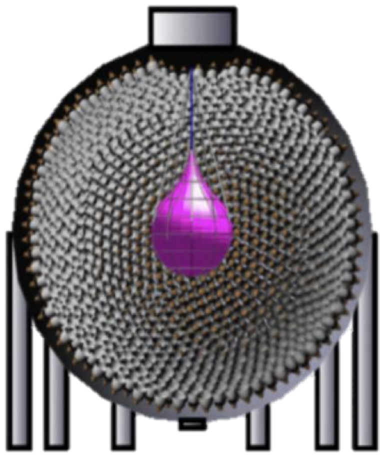
Construction: timeline

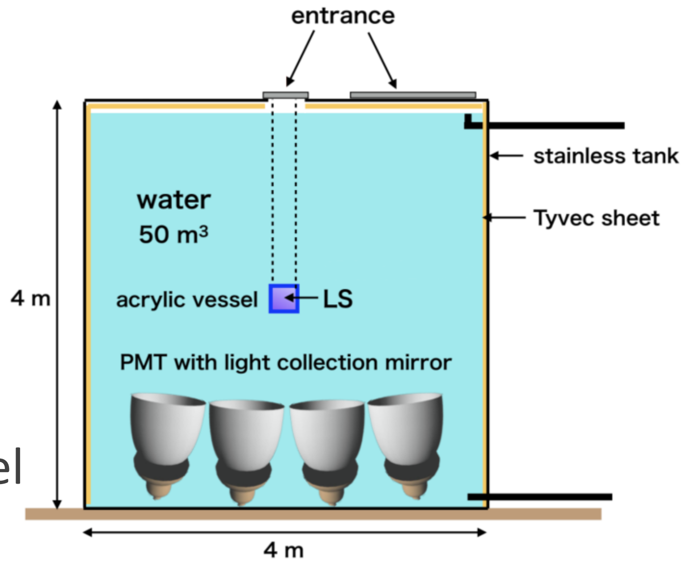
2021/11	Construct stainless steel tank
2021/12	Clean inside of the detector Install: Tyvek sheet, 7 HQE-PMTs Construct measurement hut
2022/2	manufacture light-collecting mirrors
2022/7	Install: 7 mirrors
2022/8	Replace defective PMT Install: 5 HQE-PMTs, 5 mirrors
2022/10	Install: 2 HQE-PMTs, 2 mirrors
2022/11	Inject pure water
2022/12	Prepare New-LS Install: New-LS
2024/1	Dismantle



KamLAND2-Zen vs Prototype detector

KamLAND2-Zen		Prototype detector
Spherical	Shape	Cylindrical
18 [m] in diameter	Size	4 [m] in diameter & 4 [m] in height
Black sheet	**Inside**	Tyvek sheet
1879	PMTs, Mirrors	14
7～11 [m]	**Emission point ↔ PMT**	1～2 [m]
Buffer oil (BO)	Buffer	Pure water
Nylon balloon	LS container	Acrylic vessel
1×10^{6} [kg]	LS volume	23 [kg]





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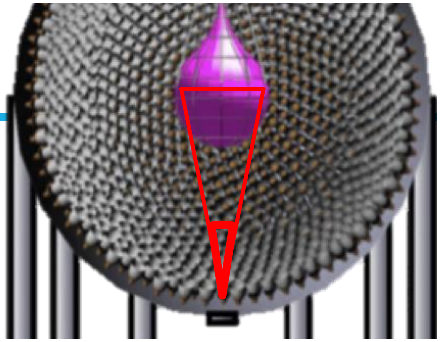
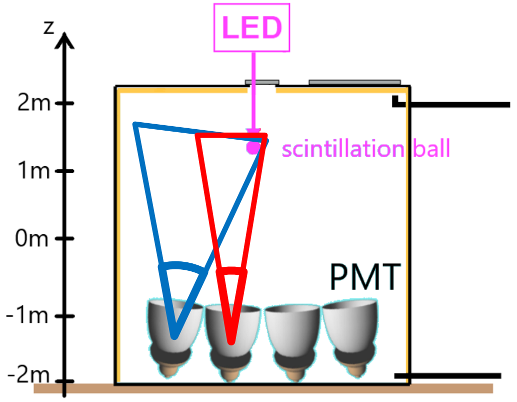
Light collection performance

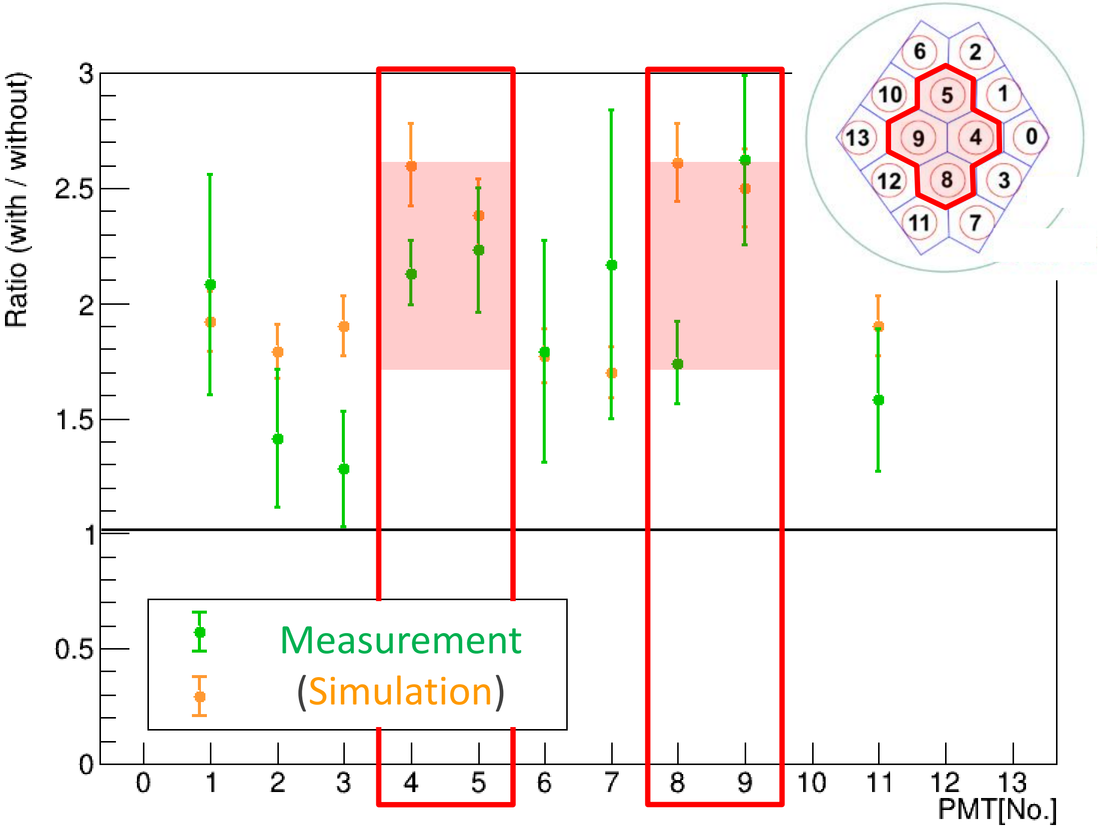




Light collection performance: $\frac{\text{Effective light yield w/ mirror: } \lambda_{w/}}{\text{Effective light yield w/o mirror: } \lambda_{w/o}}$

*Evaluate only the central 4 PMTs (No.4,5,8,9)

Reproduce the angle of incidence of 2-Zen



Performance results: x1.7～2.6

➔ **Introducing collecting mirrors to the KamLAND2-Zen increases the effective light yield!!**

*Evaluate the ratio with simulation

$$\begin{pmatrix} \text{Average of measurement} = \text{x}2.06 \pm 0.10 \\ \text{Average of simulation} = \text{x}2.52 \pm 0.09 \\ \rightarrow \text{Ratio} = \mathbf{0.82} \pm 0.07 \end{pmatrix}$$

➔ The performance did not reach the expected level

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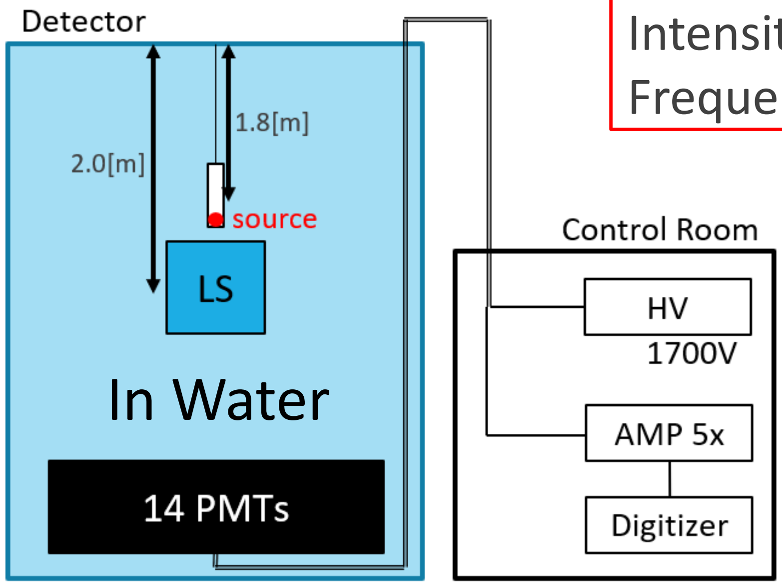
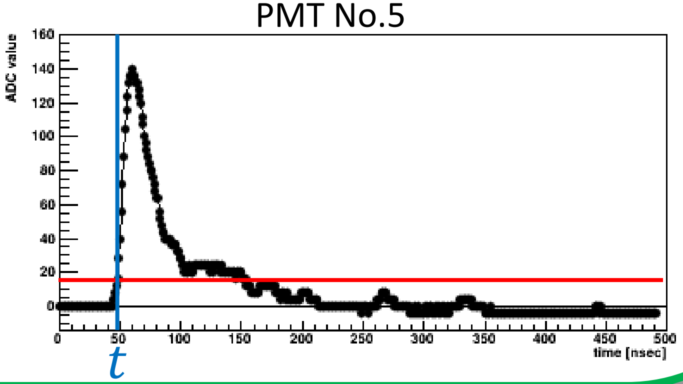
Total observed photons of the prototype detector

Radiation source measurement



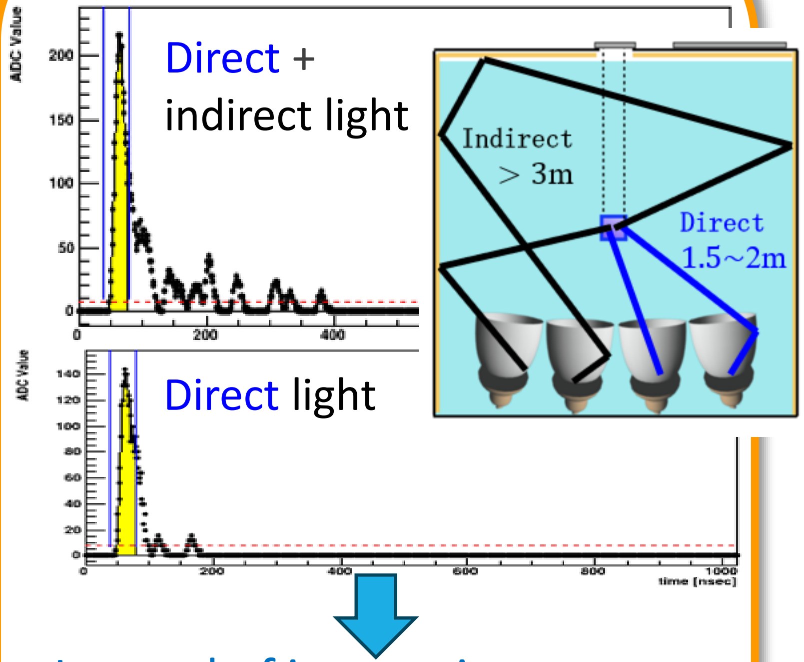
Light emitter: New LS (By Radiation source)
Position: On the central axis, $z = 20$ [cm]
Intensity: ~ 1000 [p.e.]
Frequency: 100 [Hz]

PMT signal (self trigger) x14
t: Elapsed time
amp: x5
threshold : 16ch ($\simeq$ 4 [p.e.])



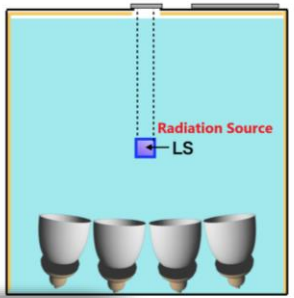
Selection of direct light signal

Reproduce the waveform



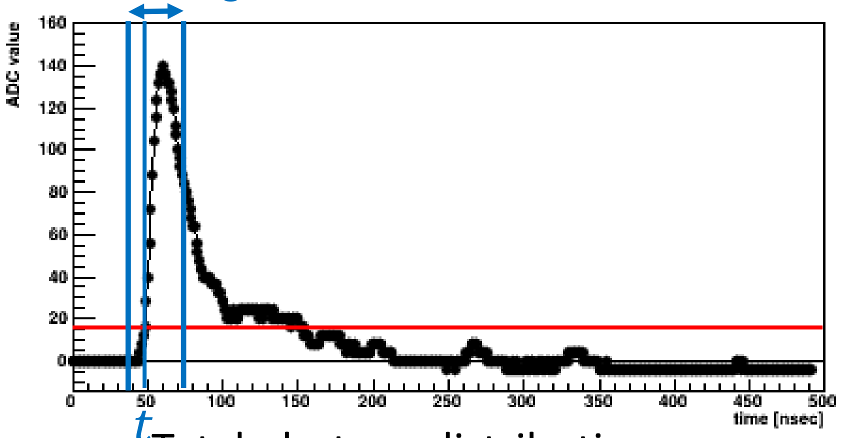
Interval of integration:
$t - 10[\text{ns}] \sim t + 25[\text{ns}]$
(Contamination of indirect signal: 8.2%)

Total observed photons of the prototype detector

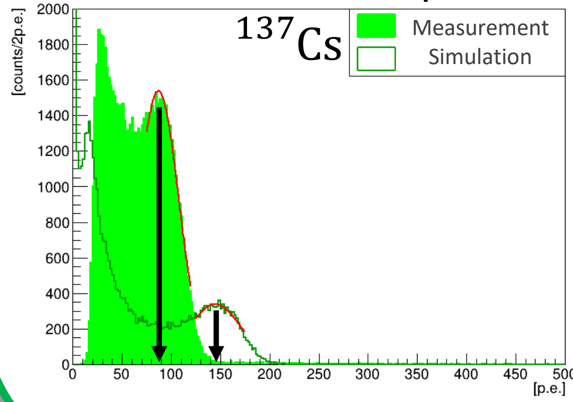


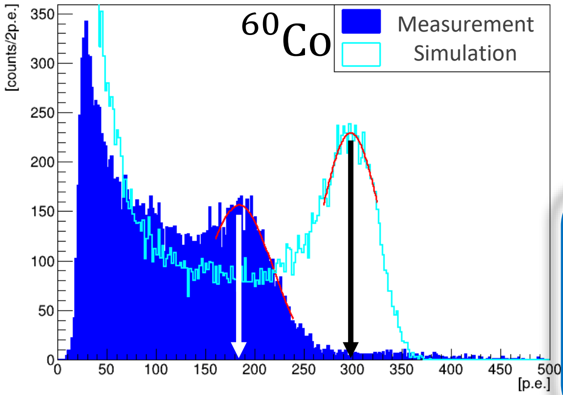
Radiation source measurement

Interval of integration



Total photons distribution





Each event of each PMT signal

$$(I\ [\mathrm{ch}]) = \sum_{t_{\mathrm{PMT}}-10\ [\mathrm{ns}]}^{t_{\mathrm{PMT}}+25\ [\mathrm{ns}]} (\mathrm{ADC}\ [\mathrm{ch}])$$

Number of photons of each PMT:

$$q\ [\mathrm{p.e.}] = (I\ [\mathrm{ch}])/(1\mathrm{p.e.\ gain\ value}\ [\mathrm{ch}])$$

Total photons of all PMT:

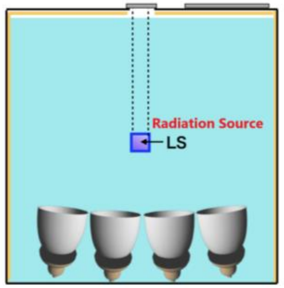
$$Q\ [\mathrm{p.e.}] = \sum_{0}^{13} q\ [\mathrm{p.e.}]$$

Total observed photons:

Mean value of the peak of the total photon distribution

Compare measurement and simulation
+
Evaluate stability for one year (six measurements)

Total observed photons of the prototype detector

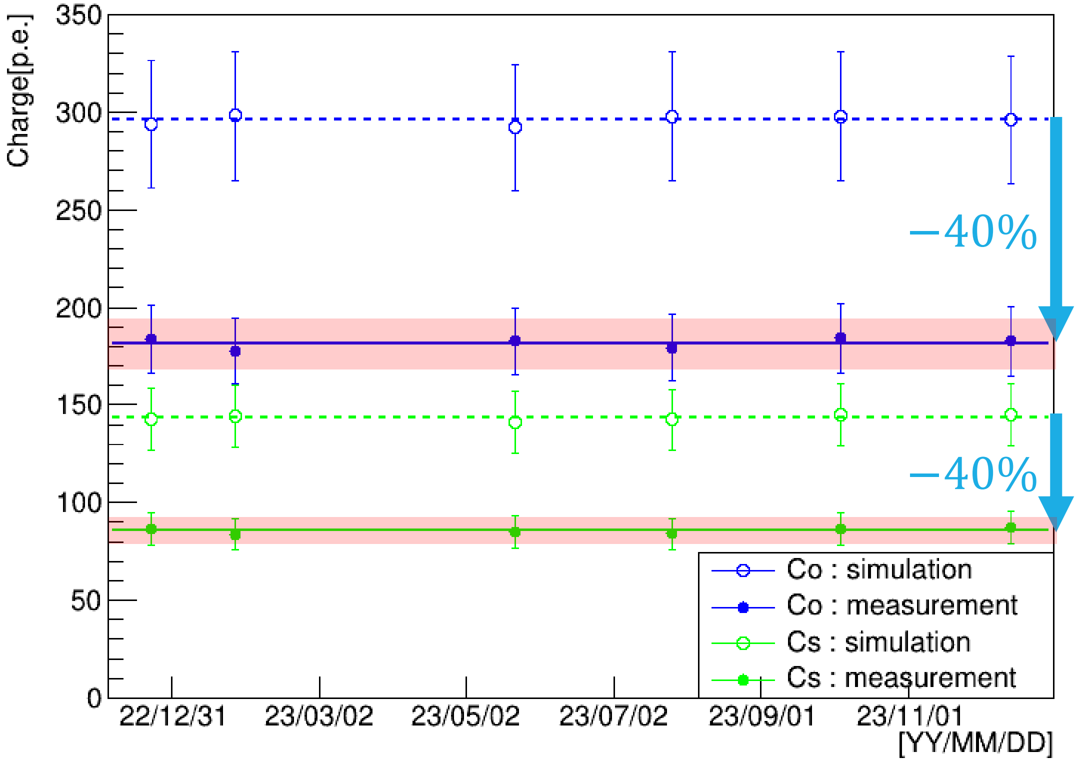


Compare the measured and simulated total observed photons

Result: Measured results were about **40% lower** (both ^{137}Cs & ^{60}Co)

Cause of the lower result:

- The actual performance of the mirrors is lower than the simulation ($\sim -20\%$)
- Indirect light signal is contaminate into the selected direct light signal ($\sim 8\%$)
- Uncertain Q.E. of HQE-PMT ($\sim 10\%$)
- Detector problems during construction & operation (→ Next page)



Evaluate **the long-term stability**

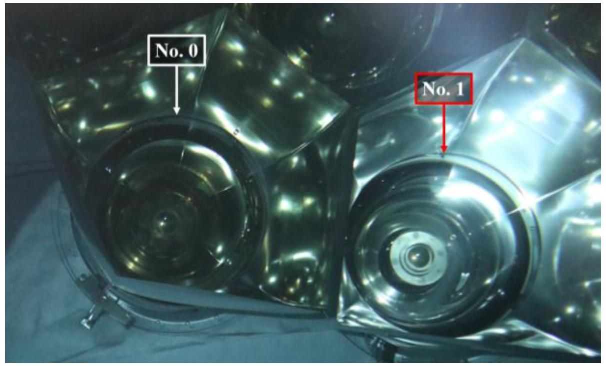
Result: **Very stable** for one year within error

⇒ The observed photons will be maintained with KamLAND2-Zen!!

Detector problems during construction & operation

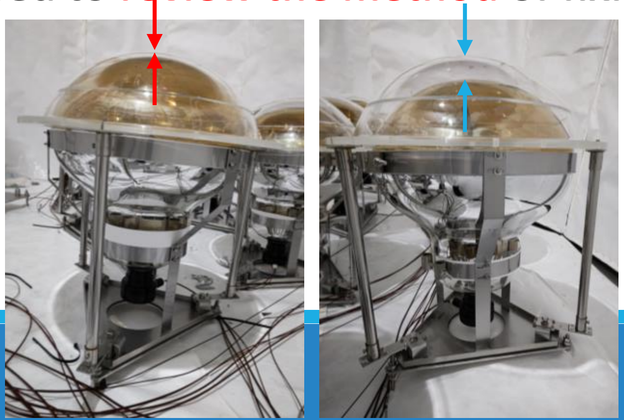
Initial defects or failures of 3 HQE-PMTs

Causes: Peeling of the photocathode,
Resistance value decrease
→ **The root cause is under investigation**
by the manufacturer



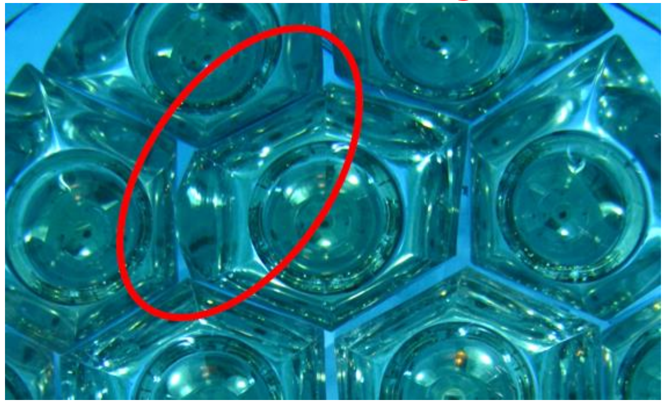
PMTs floating due to buoyancy (After water injection)

Effect: Contact with acrylic base
→ May damage the surrounding PMTs
and become a fatal problem
Need to review the method of fixing the PMT



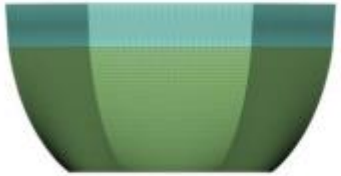
Contact and deformation of the mirrors (After water injection)

Causes: Distortion of tank bottom plate
→ **Need to change the material of the opening**



→

↓ Sheet mirror



Peeling of Al from the mirrors (After water injection)

Causes: Erosion by pure water
(↔ **LS resistance test passed**)
→ May deteriorate further with long-term use
Need for careful LS resistance test

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Summary

- KamLAND2-Zen : Aiming for **5x the observed photons**
  by HQE-PMT(x1.9)、Light collecting mirror(**x1.8**)、New-LS(x1.4)

Test with prototype detector

Construction &
1 year operation maintenance

The performance of the collecting mirror: **x1.7～2.6**

The performance of the prototype detector (HQE-PMT + mirror + LAB-LS): **Very stable for one year**

⇒ The observed photons will increase & be maintained with KamLAND2-Zen

- Now…
  We are **investigating and studying problems** with the prototype detector
  and **making improvements** for KamLAND2-Zen