New Detector Development and Performance Evaluation for KamLAND2-Zen experiment

VCI 2025

Research Center for Neutrino Science, Tohoku University

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

Majorana nature of neutrinos

Majorana particle

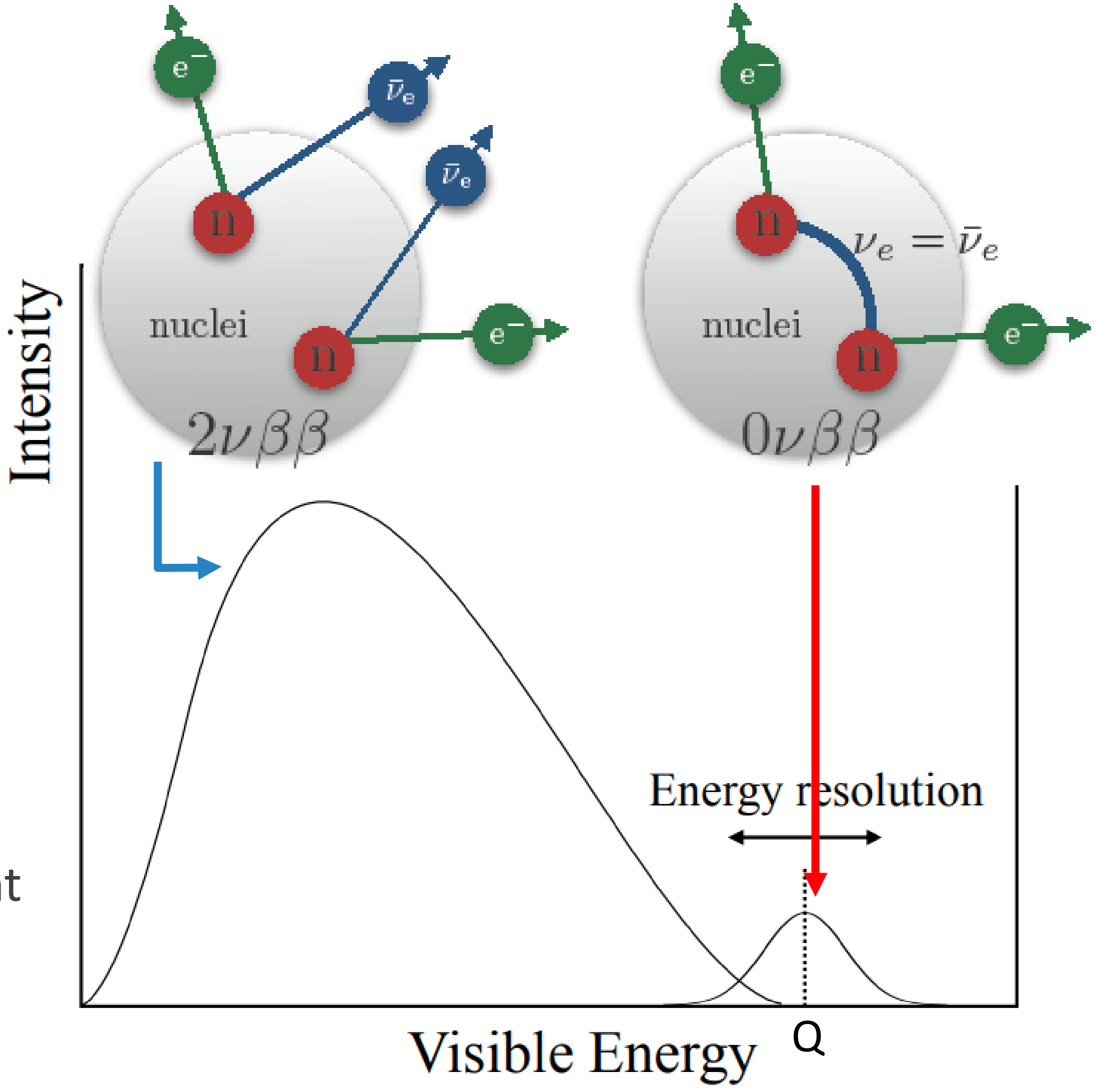
$$\nu = \bar{\nu}$$

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: High energy resolution
  → Can separate 0ν and 2ν
  Ultra low background environment
  → $\mathrm{U, Th} < 10^{-17}$ [g/g]

→ KamLAND is a suitable detector



KamLAND

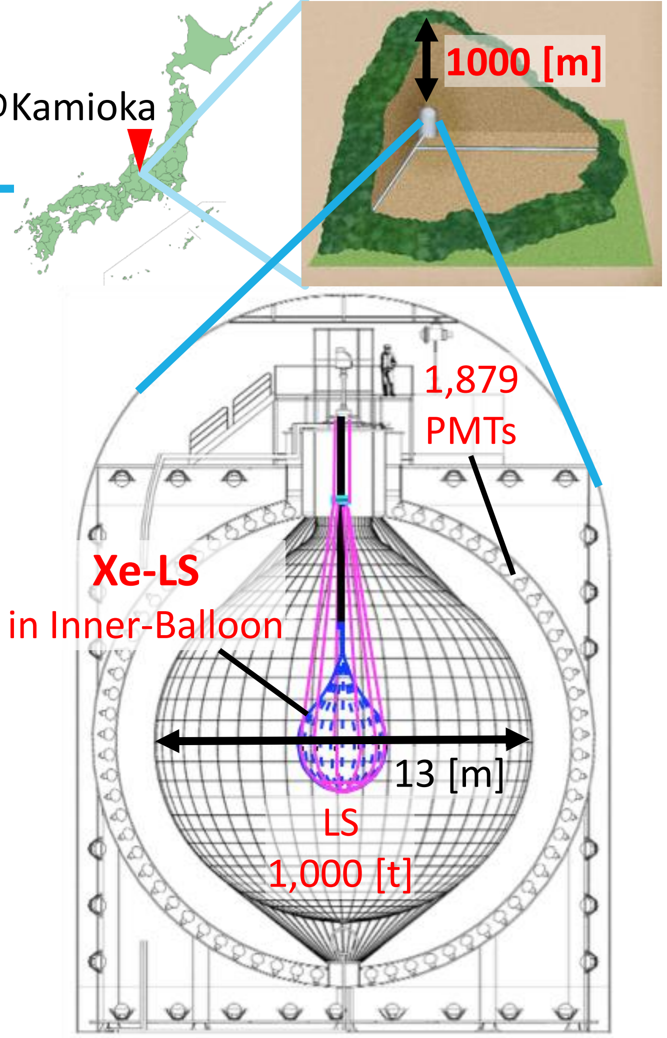
Advantage: **Huge** detector & **High-sensitivity** & Extremely **low-radioactivity**

→ **Ideal detector for rare decay search!**

Results: ▪ Neutrino oscillations of reactor neutrinos observed (world first)

▪ Antielectron neutrinos originating from Earth observed (world first)

Other scientific objectives: $\boldsymbol{0\nu\beta\beta}$, Solar neutrinos, Atmospheric neutrinos, Astrophysical neutrinos, Proton decay,



KamLAND-Zen experiment for $0\nu\beta\beta$ search

= ^{136}Xe + KamLAND

▪ Set the lower limit of the half-life of $0\nu\beta\beta$ from the observation period and the amount of Xe

▪ Set the upper limit of the effective Majorana mass from the half-life

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2 \quad \left(\begin{array}{l} G^{0\nu}\text{: Phase space factor} \\ |M^{0\nu}|^2\text{: Nuclear matrix element (NME)}\end{array}\right)$$

^{136}Xe: Double-beta decay source

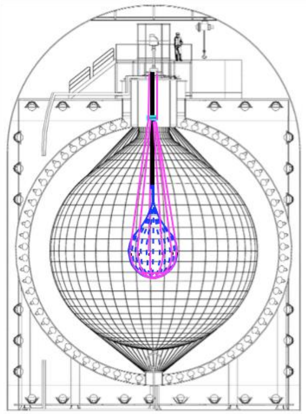
▪ $0\nu\beta\beta$ Q-Value: 2.46MeV (below ^{208}Tl γ BG)

▪ Long $2\nu\beta\beta$ half life

▪ (Relatively) easy to enrich/purify by distillation

▪ Dissolved into liquid scintillator (LS) at 3%

KamLAND-Zen Experiment



2011～2015

KamLAND-Zen 400

(Xe: 320~380 [kg])

Increase in ^{136}Xe

2019～2024

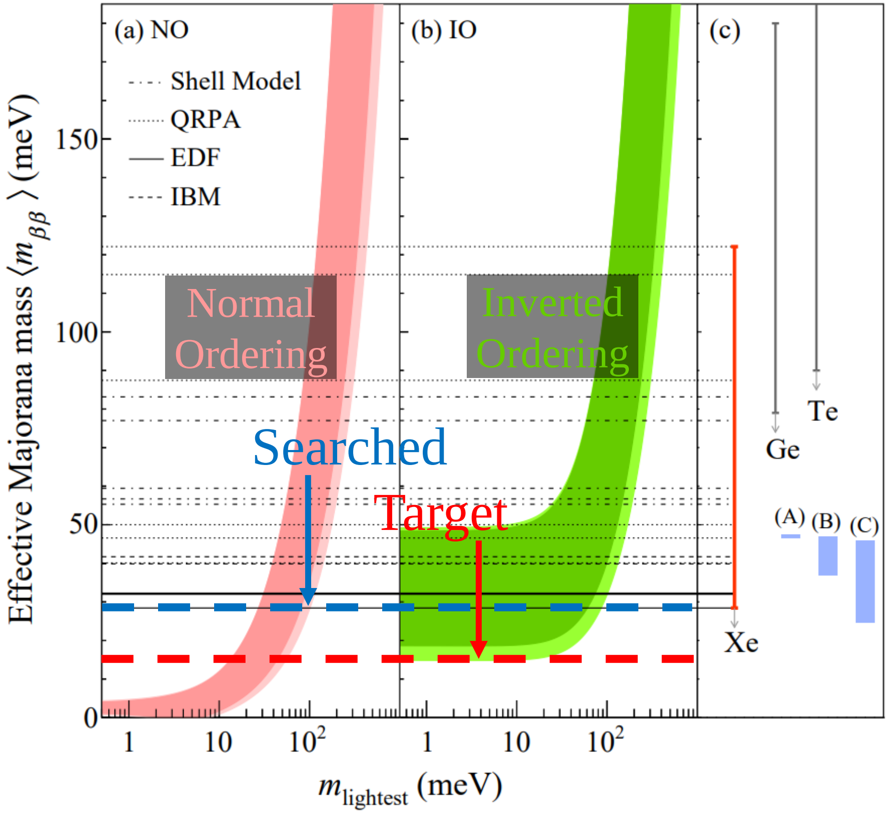
KamLAND-Zen 800

(Xe: 745 ± 3 [kg])

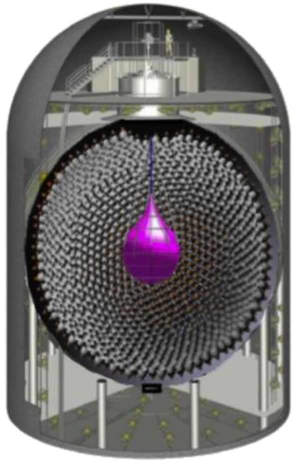
400 + 800 result: First in the world to reach IO band

$$T^{0\nu}_{1/2} > 3.8 \times 10^{26} \text{ [years]}, \langle m_{\beta\beta} \rangle < 28 - 122 \text{ meV}$$

arXiv 2406.11438 (2024)



Now Updating!!



KamLAND2-Zen

(Xe: ~1,000 [kg])

Target sensitivity: Covering most of IO

Toward $T^{0\nu}_{1/2} = 2.0 \times 10^{27}$ [yesrs],

$$\boldsymbol{\langle m_{\beta\beta} \rangle = 15 \text{ meV}}$$

Upgrade KamLAND2-Zen

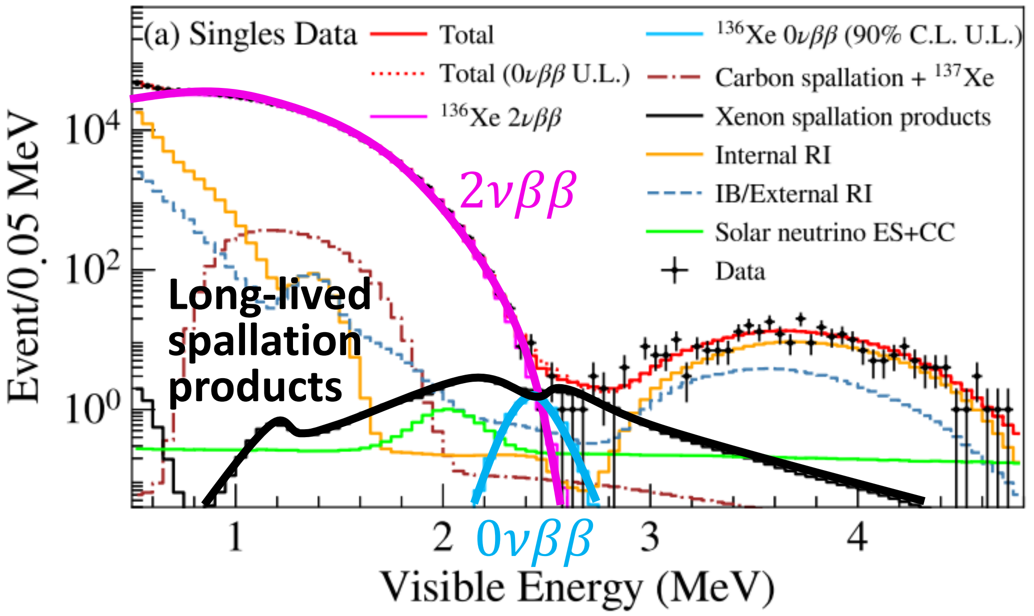
Main backgrounds of $0\nu\beta\beta$

$2\nu\beta\beta$

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

Long-lived spallation products

- Can be reduced by improving energy & vertex resolution



Upgrade contents

- **Increase in light yield**
  - High quantum efficiency PMT (HQE-PMT) (x**1.9**)
  - Light-collection Winston cone mirror (x**1.8**)
  - High light-yield liquid scintillator (New-LS) (x**1.4**)
- State-of-the-art read-out electronics: MoGURA2
  - RFSoC powered data acquisition
  - Huge buffer for SN-burst detection
- Increase in total Xe: 745kg → ~1,000kg

Target of KamLAND2-Zen

- **5x increased effective light yield**
  - → Energy resolution σ: 4% → < 2.5% (E = 2.5 MeV)
    - → $2\nu\beta\beta$ BG reduction to 1/100

➔ **Test with prototype detector**

- ~100% spallation neutron detection
- More efficient L.L. tagging
- More exposure

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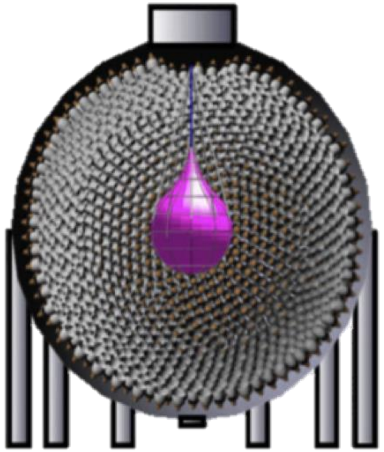
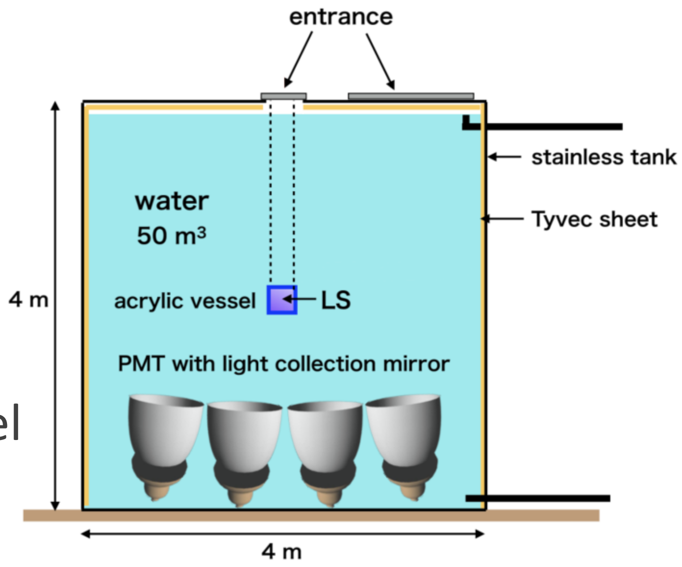
KamLAND2-Zen vs Prototype detector

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
1x10^6 [kg]	LS volume	23 [kg]



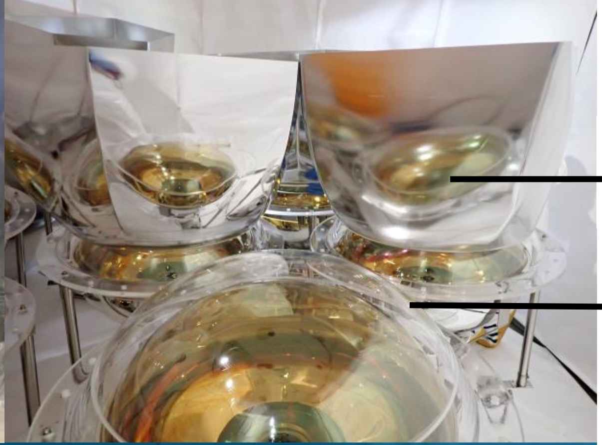


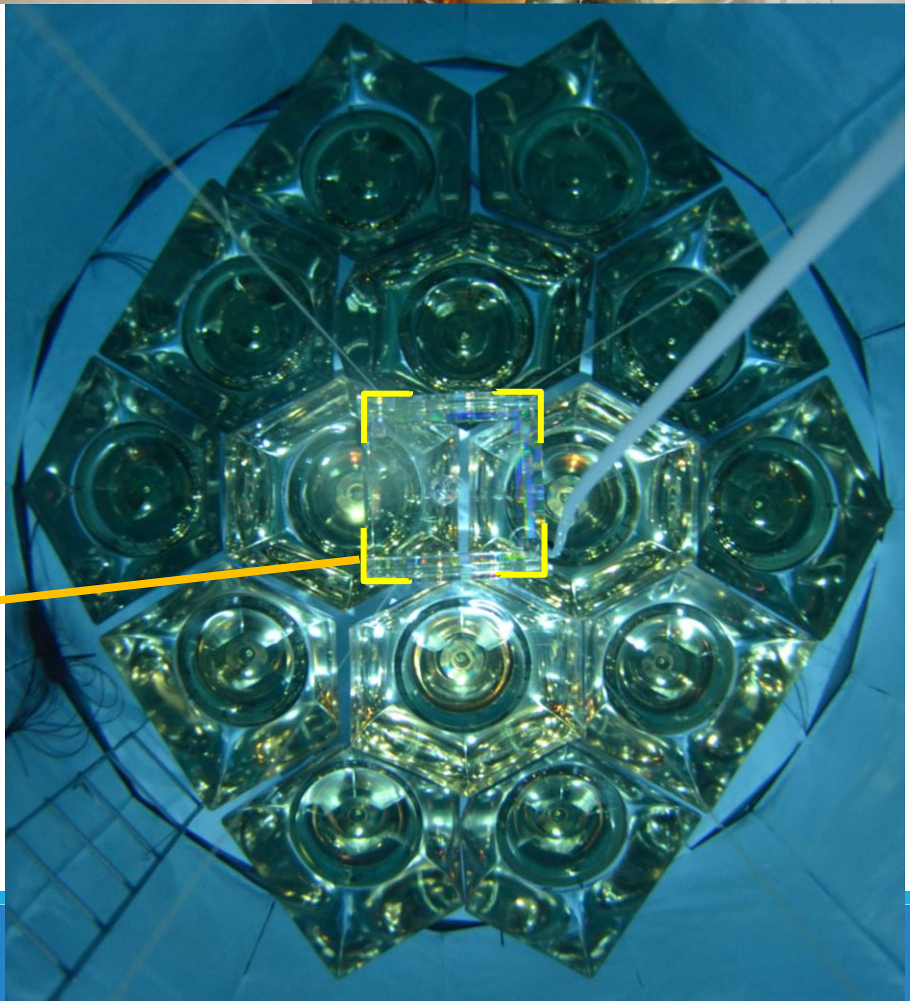
Target: 5x increased light yield!

Constructed for performance verification

Construction: timeline

2021/11	Construct stainless steel tank
2021/12	Clean inside of the detector Install: 7 HQE-PMTs Construct measurement hut
2022/2	manufacture light-collection 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	Install: New-LS
2024/1	Dismantle





New Devices (: Emission wavelength of New-LS)

New-LS (candidate)

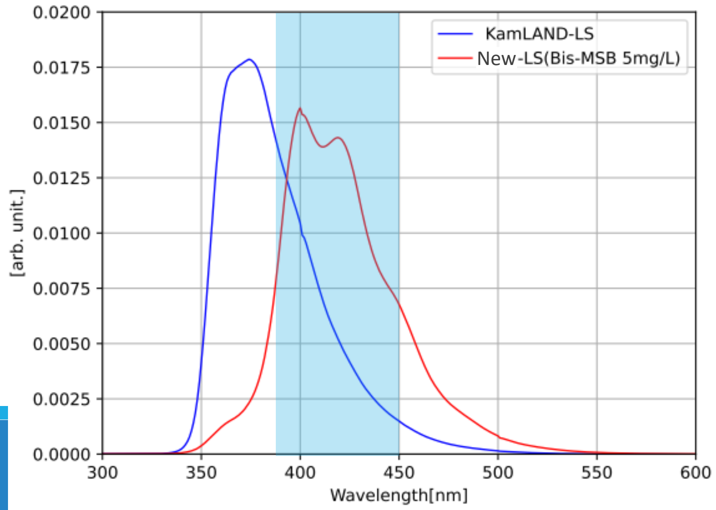
- Light yield: x1.365 (Compared to conventional)
- Composition

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
New-LS	–	0.865	–

- Emission time constant

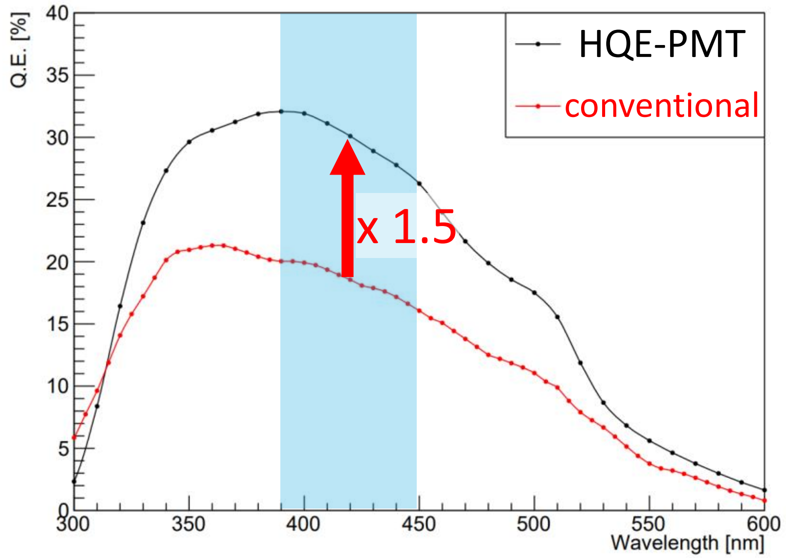
i	A_i [%]	τ_i[ns]
1	91.5	7.37
2	8.5	44.7

- Emission spectrum

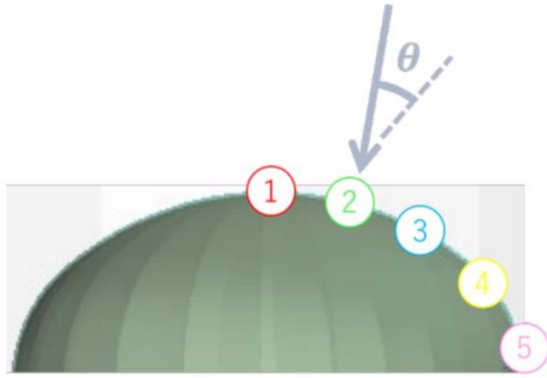


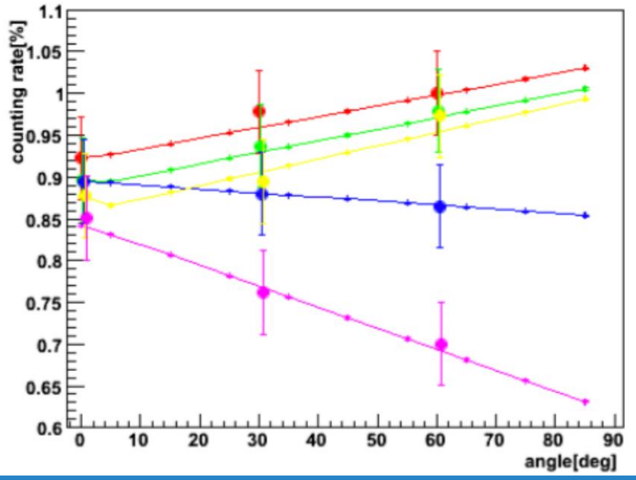
HQE-PMT

- Quantum efficiency

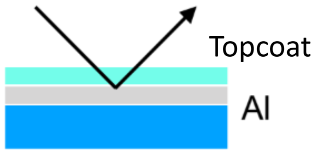


- Incident position and angle dependency

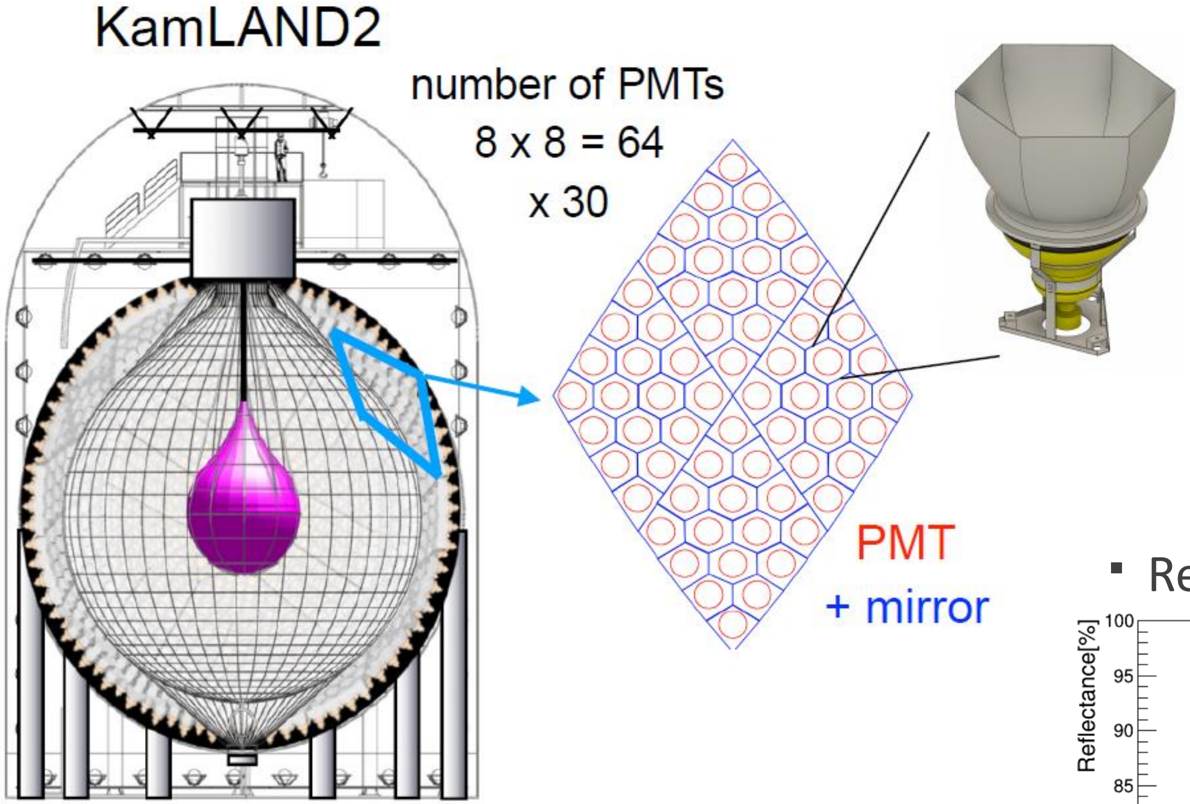




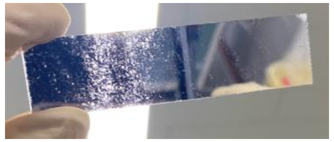
New Devices (: Emission wavelength of New-LS)



Light-collection mirror

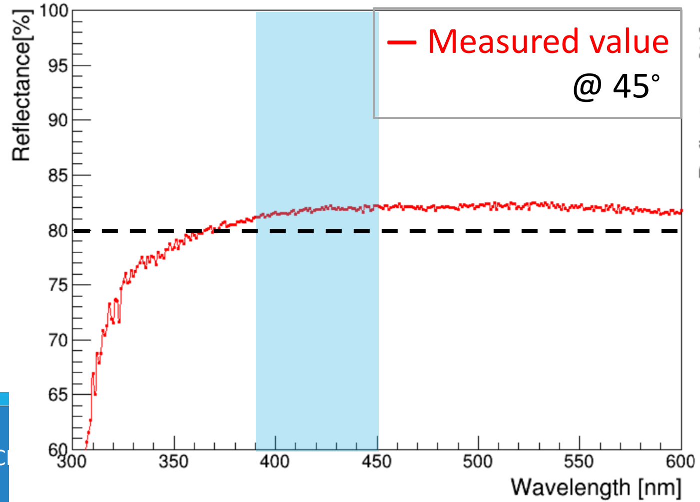


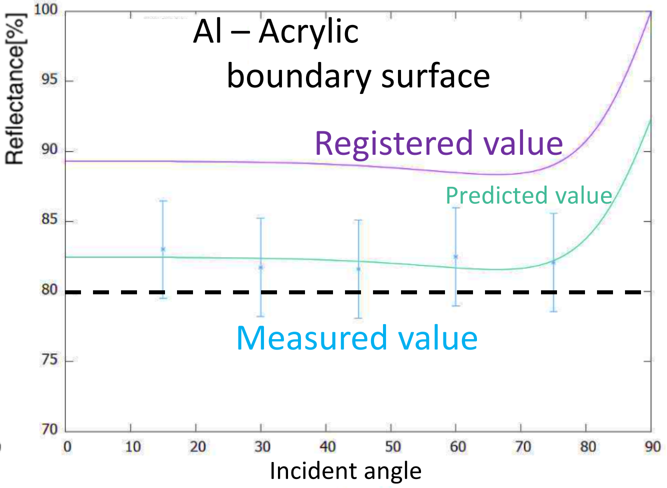
- Long-term stability
  - 20 days at 41°C
    (≒ 6 months at 10°C (usage environment))
    In pure water: **Reduction** in reflectance
    In LS : Stable



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

- Reflectance against wavelength & incident angle (>80%)





Evaluation of Prototype Detector

Under Construction

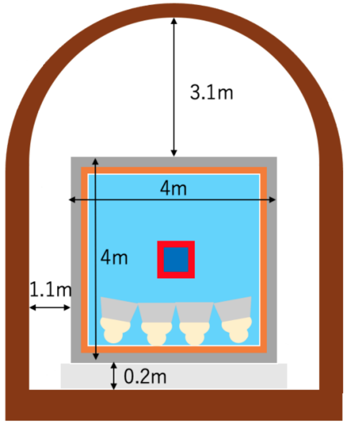
Photon counting measurement

Compare

without ⟷ **with**

light-collection mirrors

Evaluate performance of **light-collection mirrors**



After Construction

Radiation source (^{137}Cs & ^{60}Co) measurement

Compare

MC Simulation (**Geant4**)

Reproduce the prototype detector

Evaluate **light yield of prototype detector**

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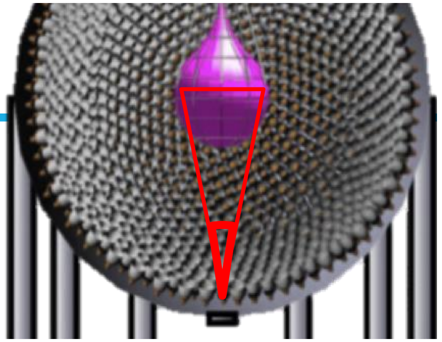
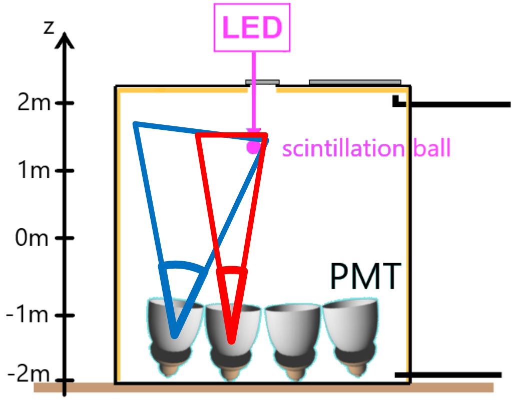
Light-Collection Mirror Performance

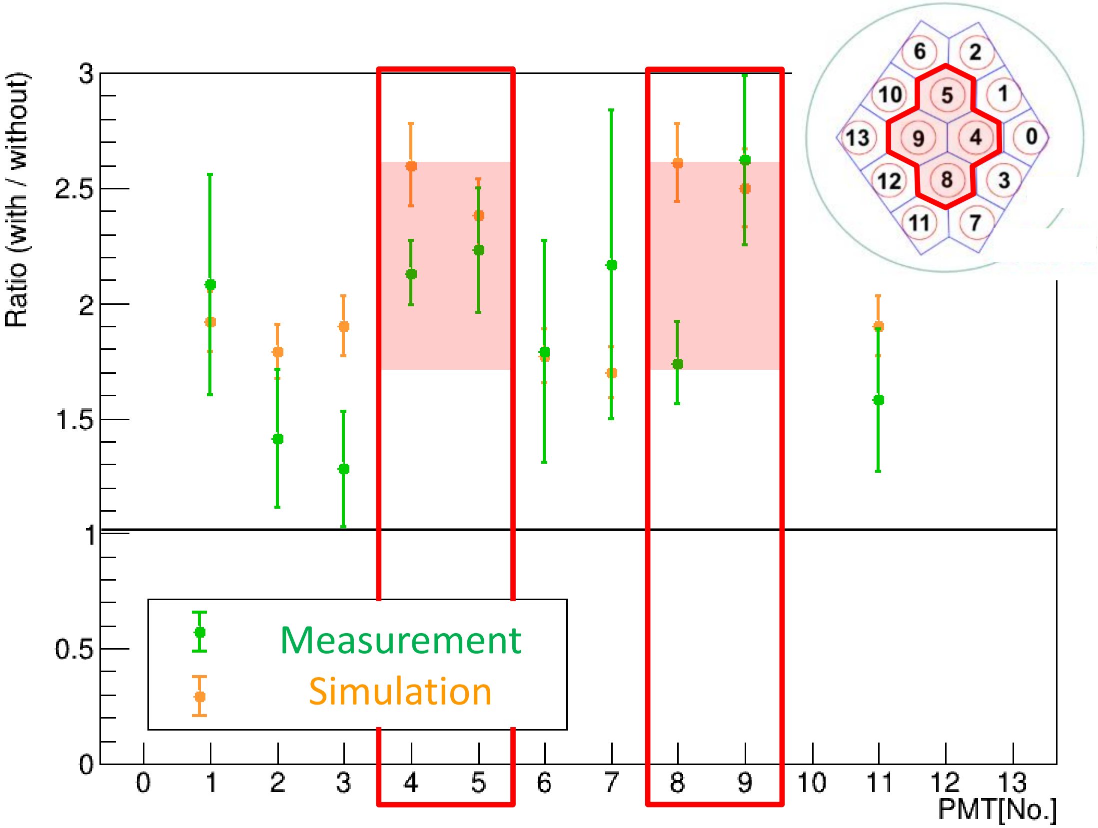




Light collection performance: $\frac{\text{Effective light yield w/ mirror: } \lambda_{w/}}{\text{Effective light yield w/o mirror: } \lambda_{w/o}}$

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

Reproduce the angle of incidence of KL2-Zen



Performance results: x1.7～2.6

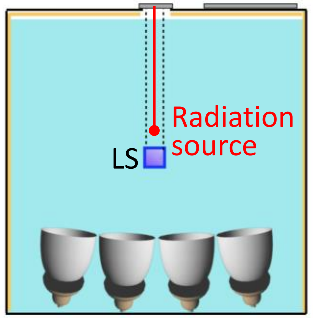
➔ **Introducing collection mirrors to the KamLAND2-Zen increases the effective light yield!!**

*Evaluate the ratio with simulation

$$\left(\begin{array}{ll} \text{Average of measurement} & = \text{x}2.06 \pm 0.10 \\ \text{Average of simulation} & = \text{x}2.52 \pm 0.09 \\ \rightarrow \quad \text{Ratio} & = \mathbf{0.82} \pm 0.07 \end{array}\right)$$

➔ The performance did not reach the expected level

Light Yield of Prototype Detector

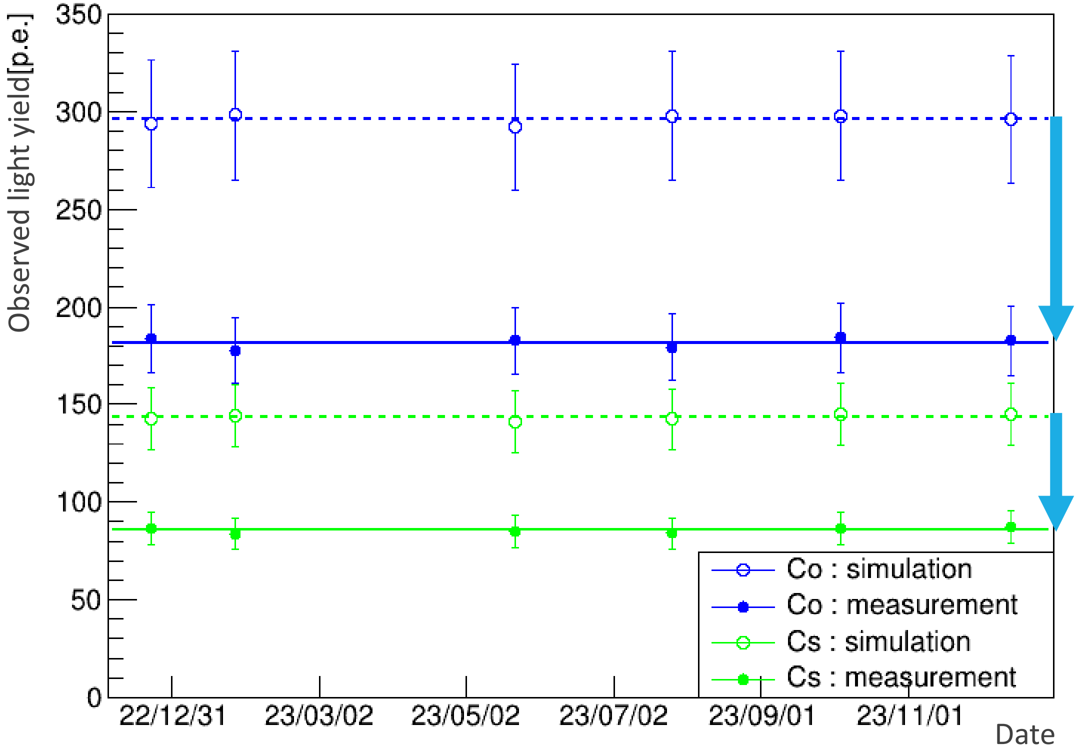


Compare the measured and simulated **Light Yield**

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**

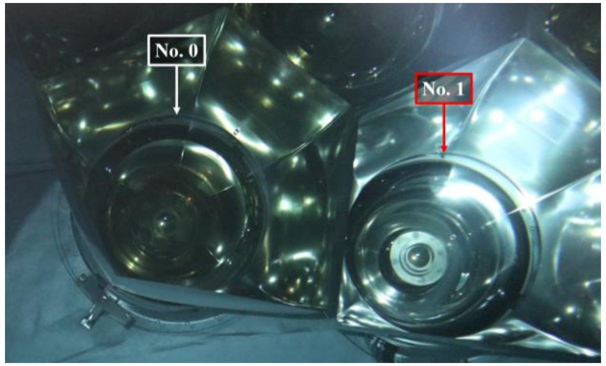
Result: **Very stable** for one year within error

⇒ The light yield 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 was investigated**
by the manufacturer

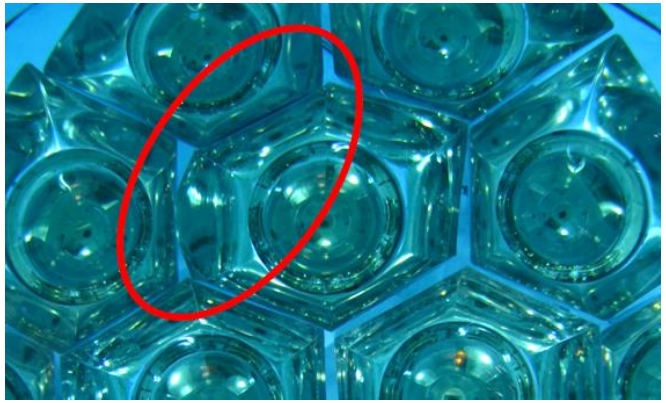


PMTs floating due to buoyancy (After water injection)

Effect: Contact with acrylic base
→ May damage the surrounding PMTs
and become a fatal problem
Improved 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**



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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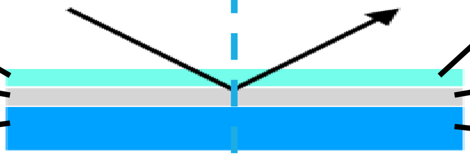
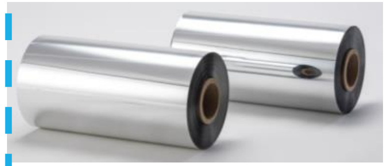
Light-Collection Mirror Plans (Reduce Effects of Contact)

Prototype Detector Plan | Latest Plan

Structure



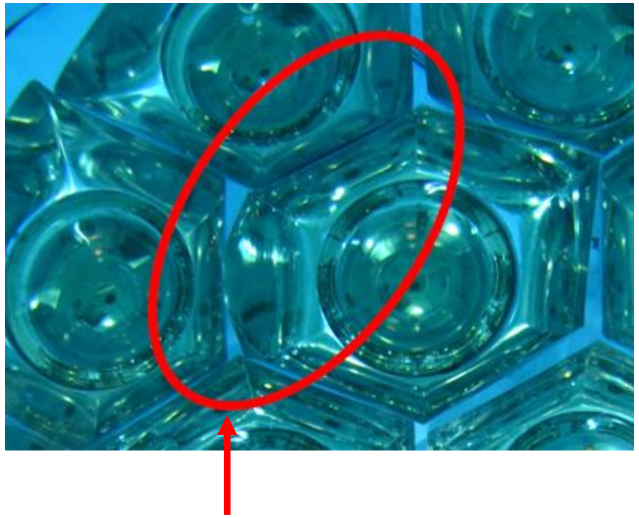
\+



TORAY
メタルミー®

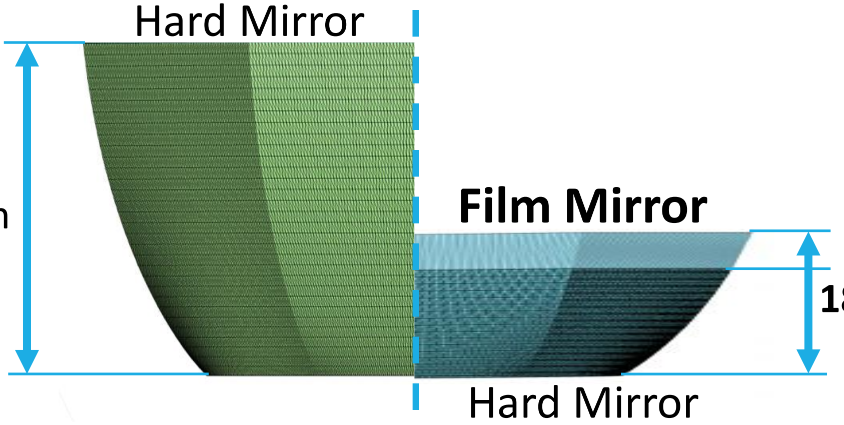
⇐

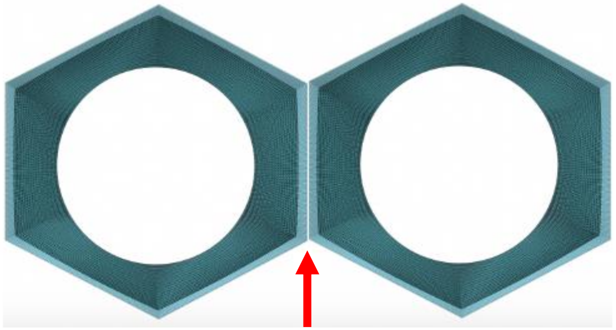
Aluminum Deposition
PET Film (Base)



✗ If contacted, the entire mirror will be severely distorted.

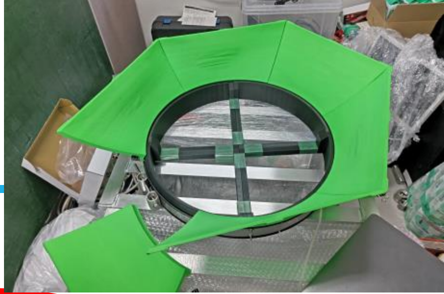
Shape





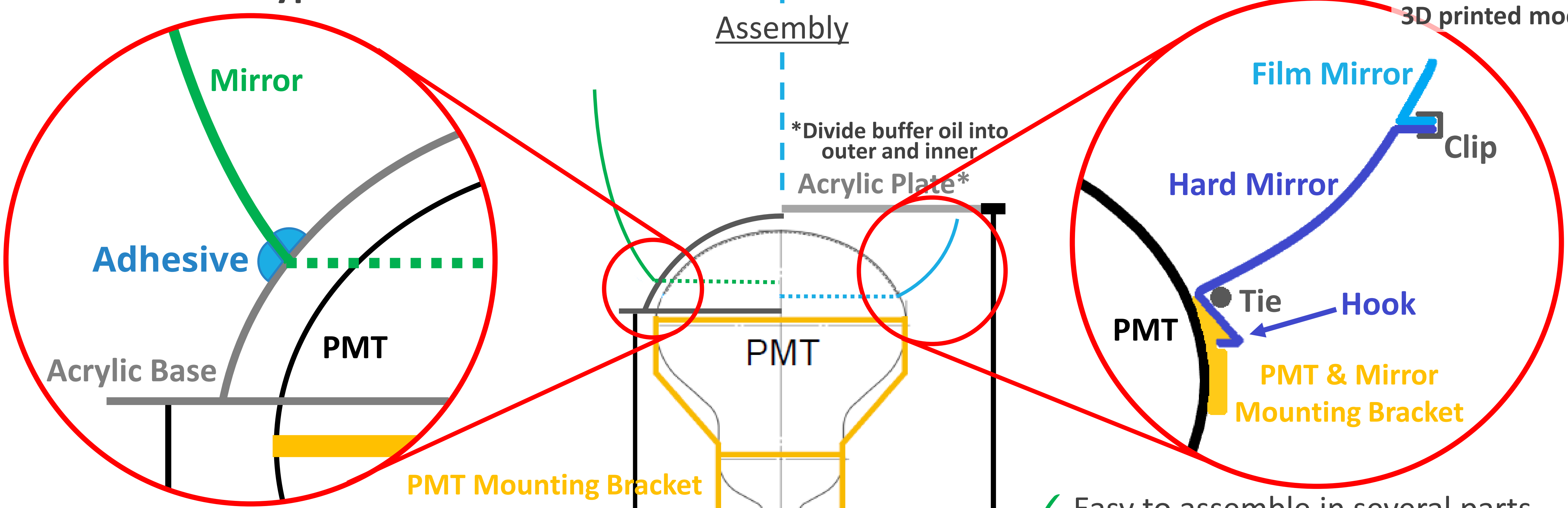
✓ Even if contacted, the film mirror is only slightly deformed.

Light-Collection Mirror Plans (Easy Assembly)


3D printed model

Prototype Detector Plan

Latest Plan



- ✗ Inefficient installation of acrylic base
- ✗ Difficult to glue mirror to downward facing PMT

- ✓ Easy to assemble in several parts
- ✓ No acrylic base required
- ? Need to test performance and stability with actual products

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Summary

- KamLAND2-Zen : Aiming for **5x the light yield** by HQE-PMT、light-collection mirror、new-LS

Test with prototype detector

The performance of the **light-collection mirror**: **x1.7～2.6**

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

⇒ **The light yield will increase & be maintained with KamLAND2-Zen.**

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

&

We are dismantling KamLAND.

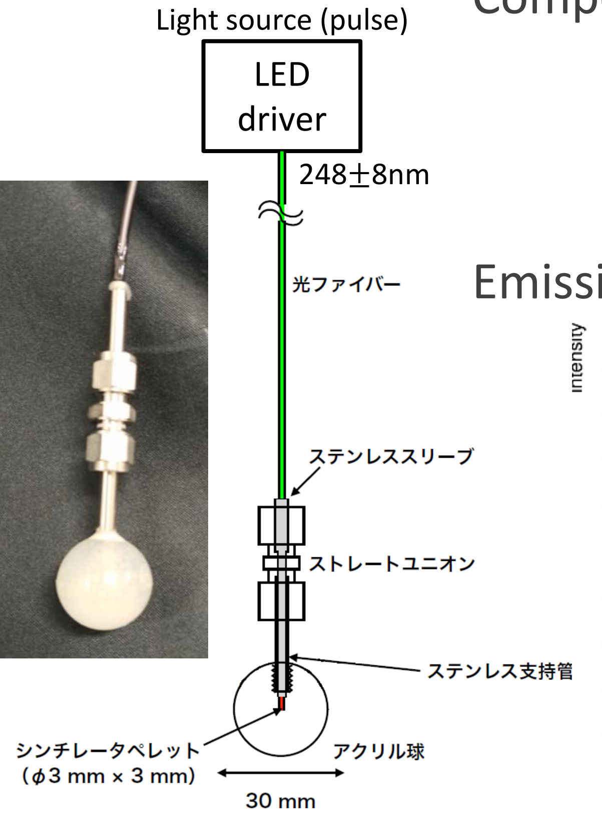
We aim to start KamLAND2 in 2027!!

Back Up

Main equipment in the detector

Scintillation ball used for measurement

Purpose of production: **Constant and weak light emission** regardless of time and direction
Emission wavelength **close to LAB-LS**



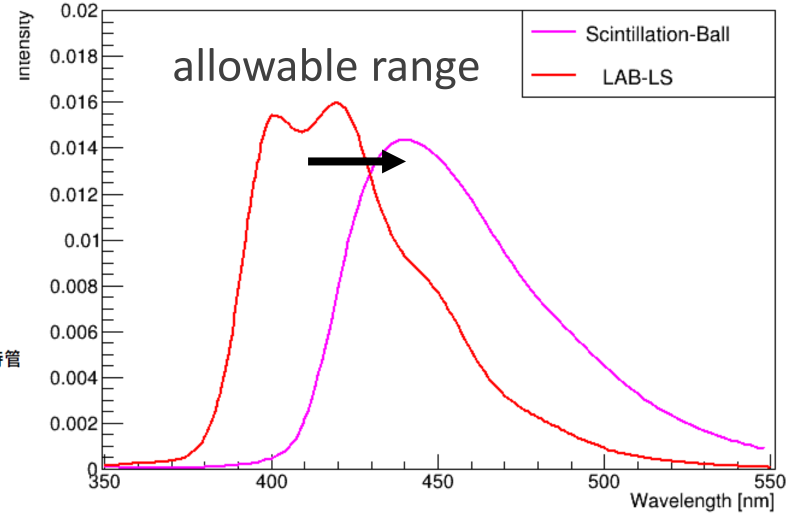
Composition:

成分	組成式	比率/含有量
紫外線透過アクリル	–	100%
TPB	$C_{28}H_{22}$	1.5 wt.%
POPOP	$C_{24}H_{16}N_2O_2$	0.02 wt.%
酸化マグネシウム (MgO)	–	0.3 wt.%

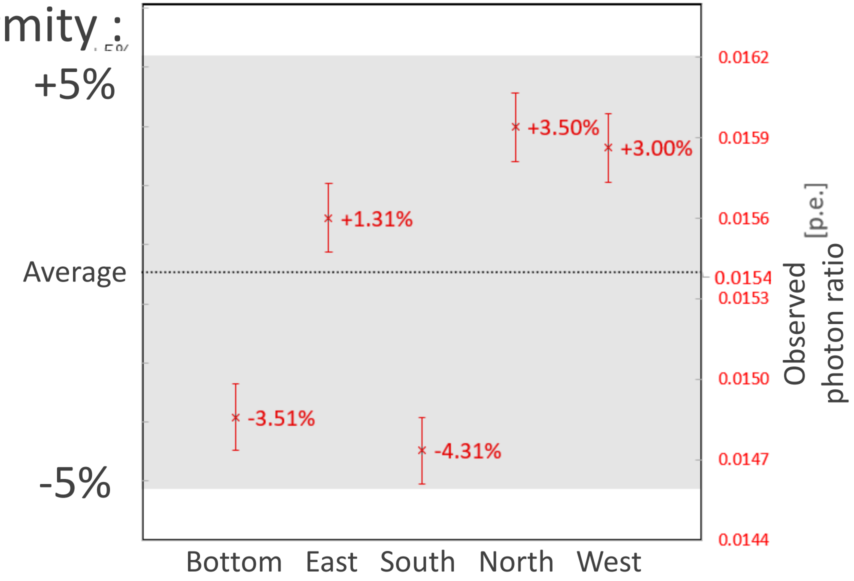
others:

発光時間幅 (FWHM)[ns]	~ 4
発光第一時定数 [ns](割合)	2.3(37%)
発光第二時定数 [ns](割合)	14(30%)
発光第三時定数 [ns](割合)	2.0×10^2(33%)

Emission spectrum:



Emission uniformity :

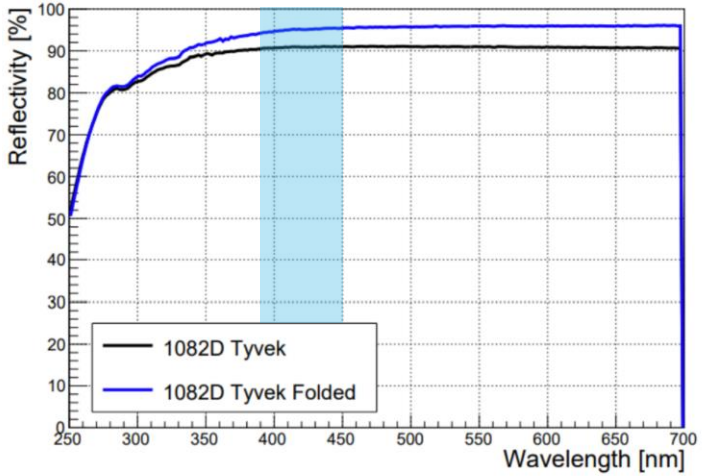


Main equipment in the detector

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

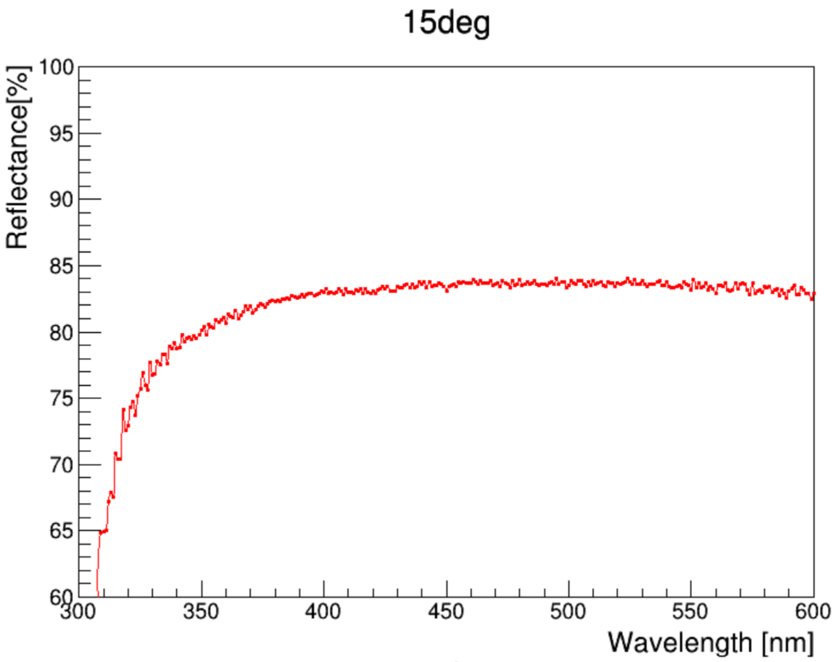
- Tyvek sheet

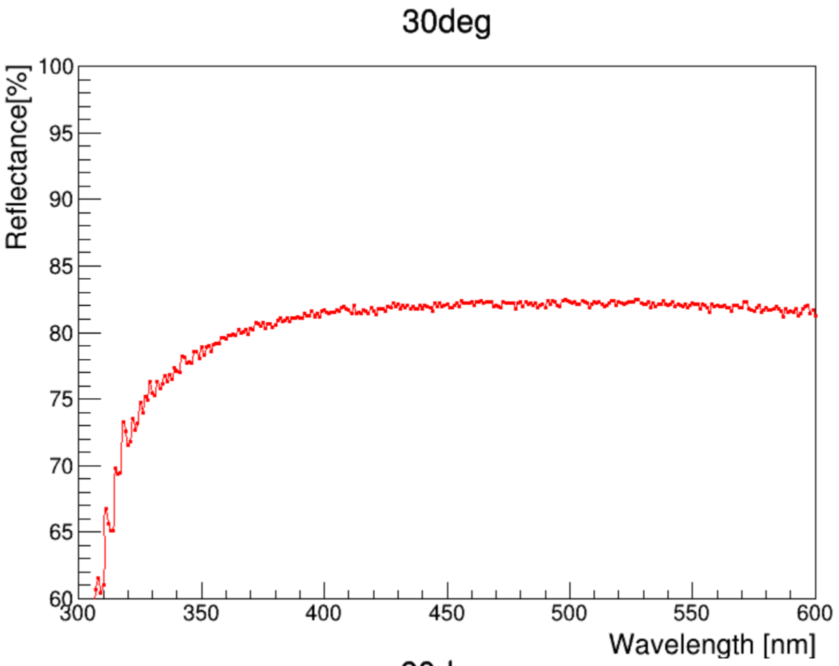
Reflectance (in air)



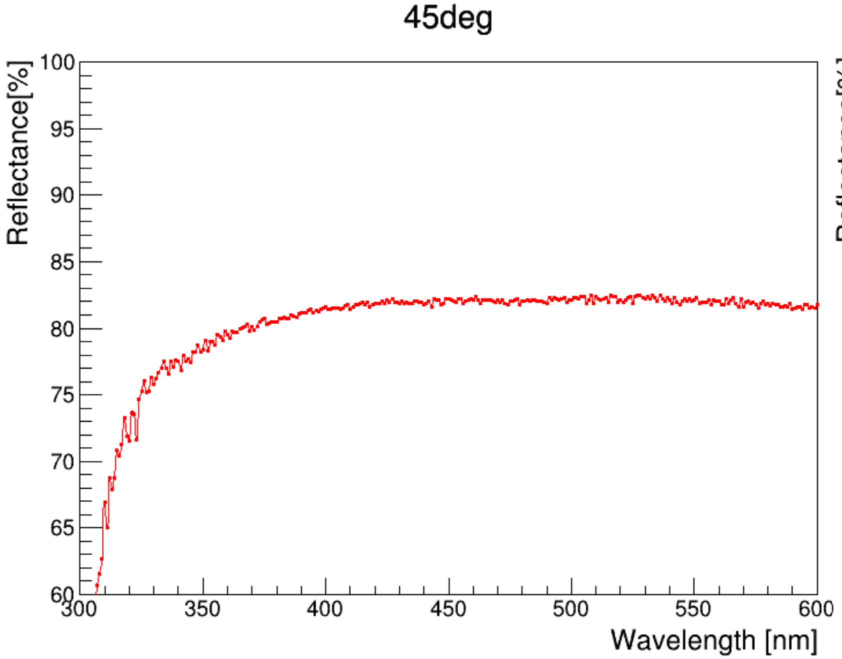
* Reflectance in water not measured

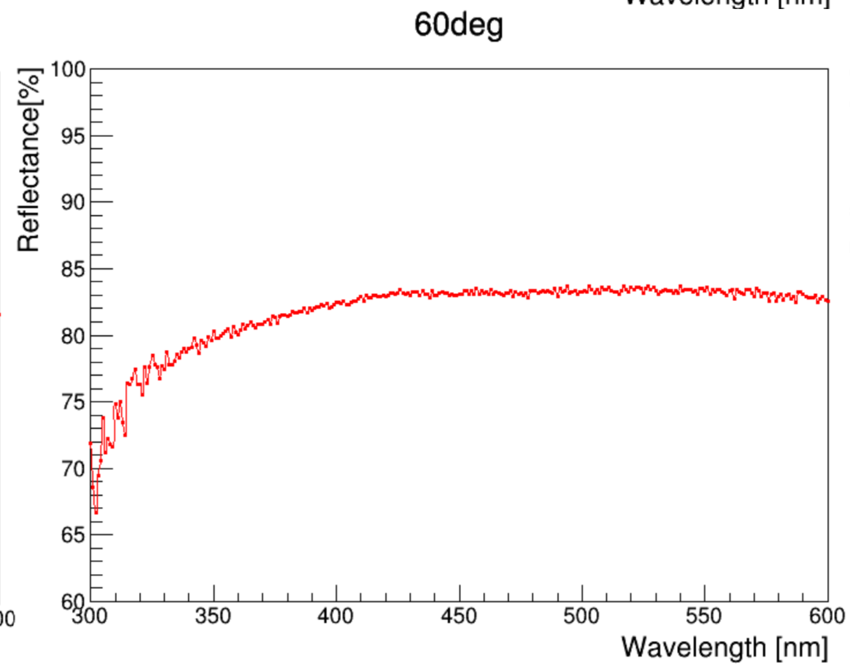
→ Calibration results: ~90% (at 400 [nm])

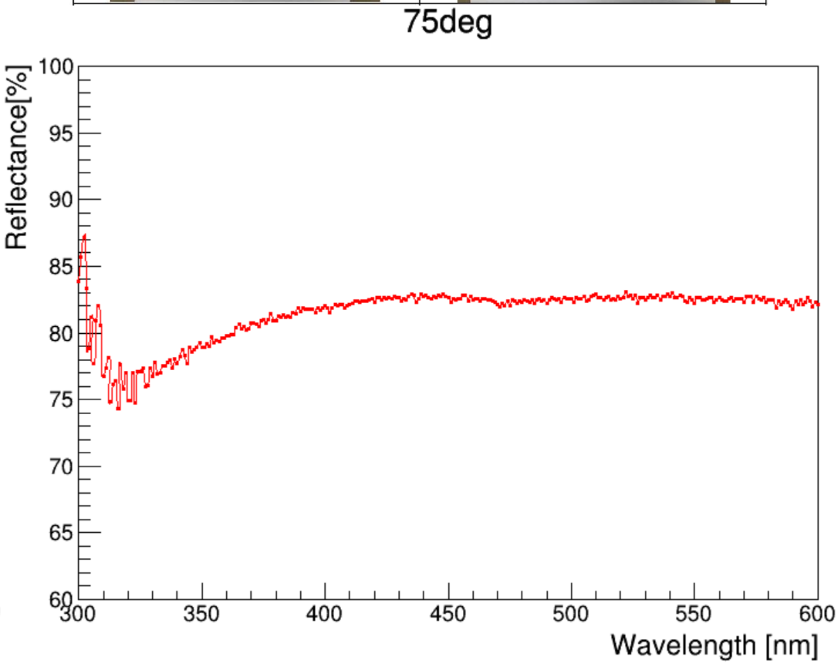

15deg
Reflectance[%]
Wavelength [nm]


30deg
Reflectance[%]
Wavelength [nm]

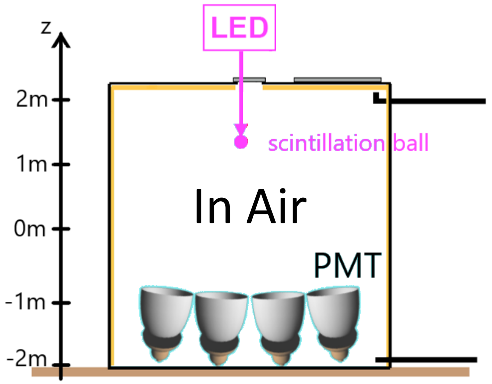

アルミ蒸着試験片 純水常温浸漬テスト
使用純水レベル
2021年12月17日 浸漬テスト開始時
オルガノ
ピュアライト
PRO-0500
サイスイ
スイシツ: 0.1μS/cm
選択
登録
2021年12月29日現在
12/17 ~ 12/29
2022年1月14日現在
2022.1.14
2022年1月27日現在
2022.1.27


45deg
Reflectance[%]
Wavelength [nm]

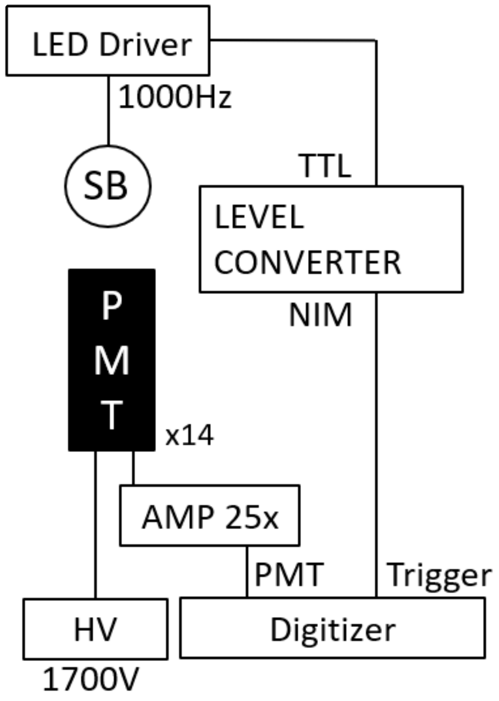

60deg
Reflectance[%]
Wavelength [nm]


75deg
Reflectance[%]
Wavelength [nm]

Light collection performance of the mirror



Scintillation ball measurement

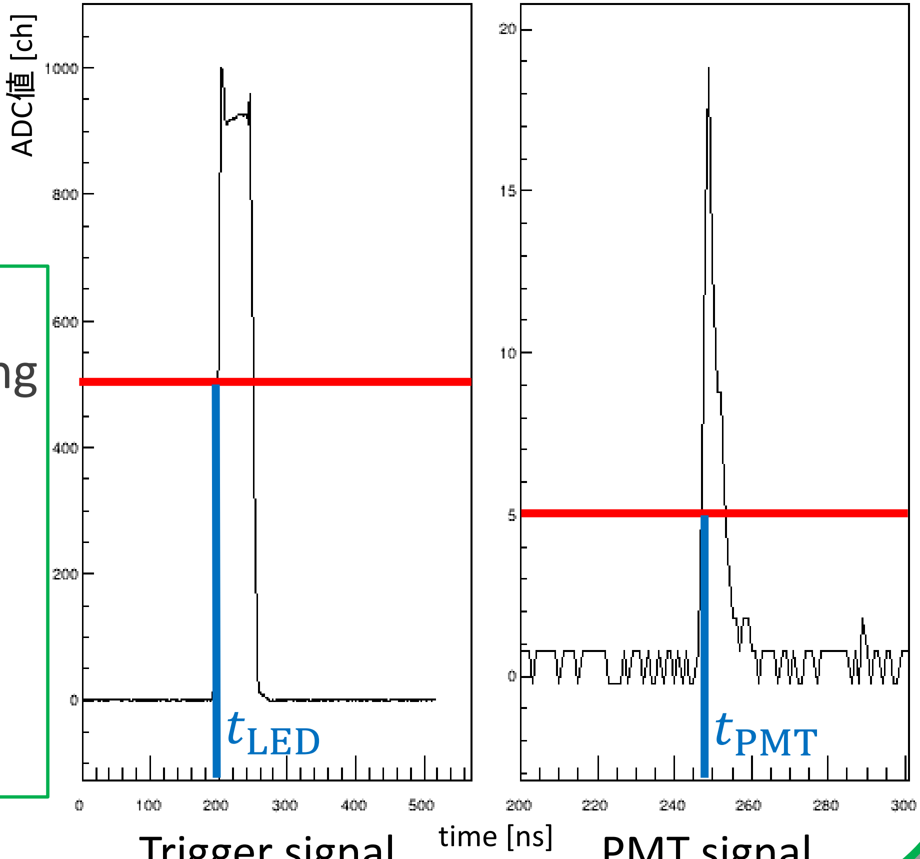


Light emitter: Scintillation Ball
Position: On the central axis, $z = 1.0$ [m]
Intensity: ~ 0.01 [p.e.]
Frequency: 1000 [Hz]

Trigger signal (self trigger) : t_{LED}
synchronized with LED emission timing

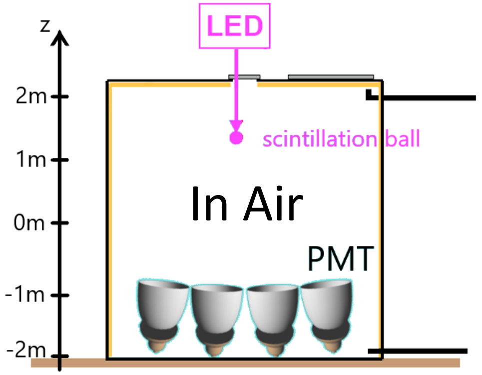
PMT signal (coincidence trigger) x14 : t_{PMT}
trigger : each PMT signal
amp : x25

Time delay: $\Delta t = t_{\mathrm{PMT}} - t_{\mathrm{LED}}$



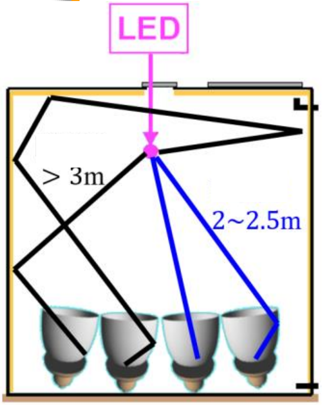
Trigger signal   PMT signal

Light collection performance of the mirror



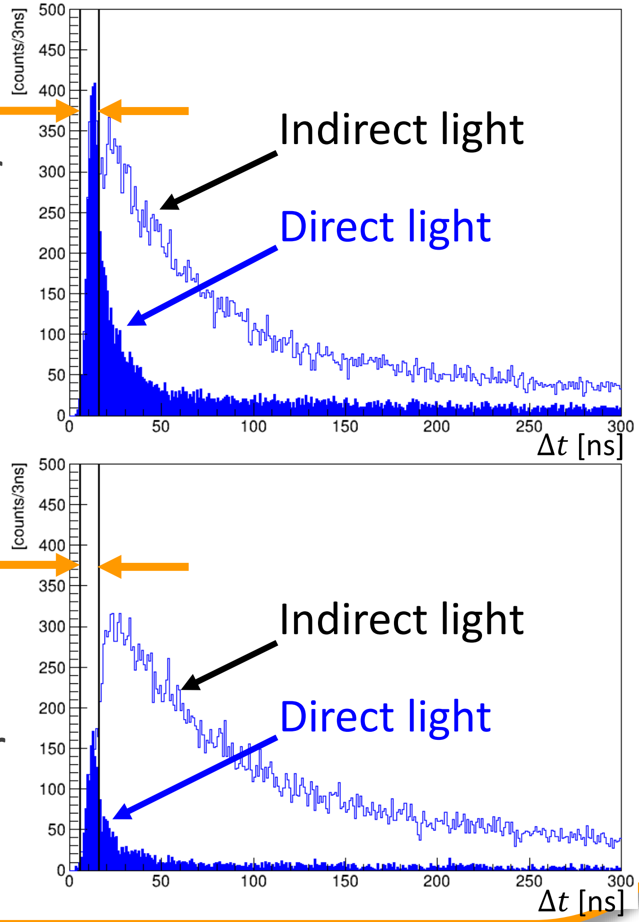
Selection of direct light events

Time delay distribution (PMT No.4)



w/ mirror

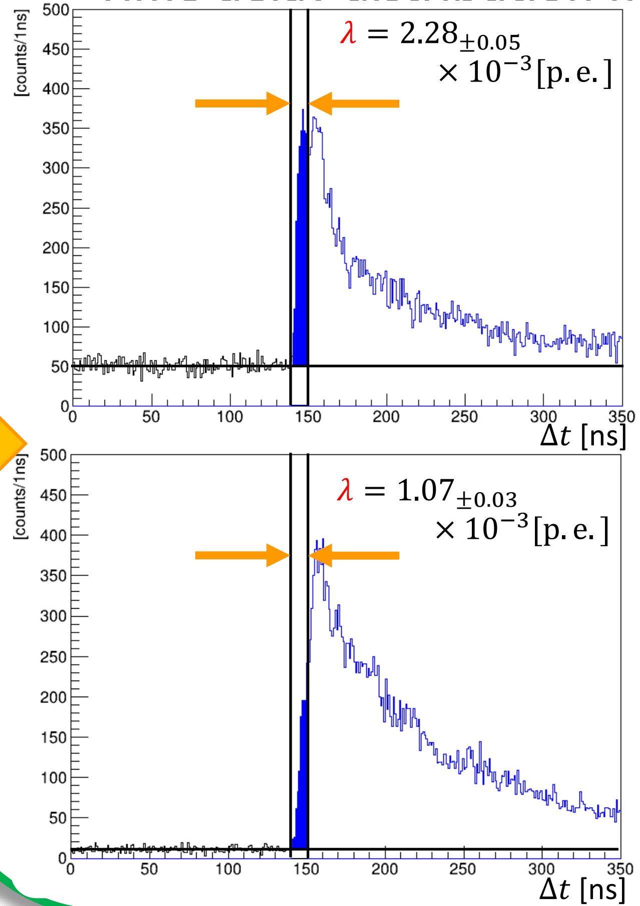
w/o mirror



10ns

Effective light yield

Time delay distribution (PMT No.4)



Assumption:
The probability that the PMT detects 1 [p.e.] follows a Poisson distribution.

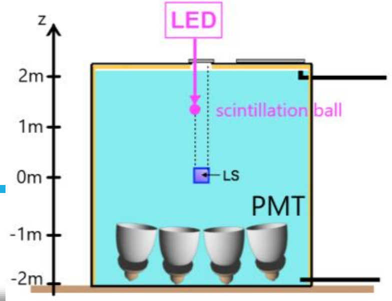
The probability that any PMT detects >1 [p.e.] with one scintillation ball emission is

$$P(n \geq 1) = 1 - e^{-\lambda}.$$

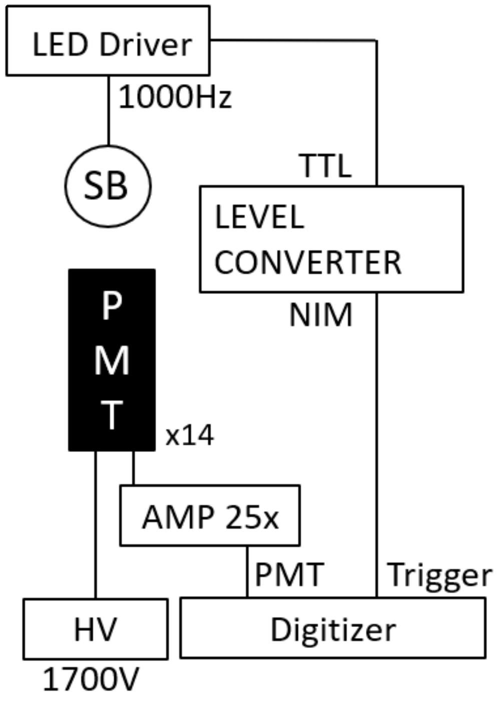
$$P(n \geq 1) = \frac{\text{Number of events}}{\text{Number of emissions}}$$

λ : Effective light yield

Calibration of 1p.e. Gain



Scintillation ball measurement

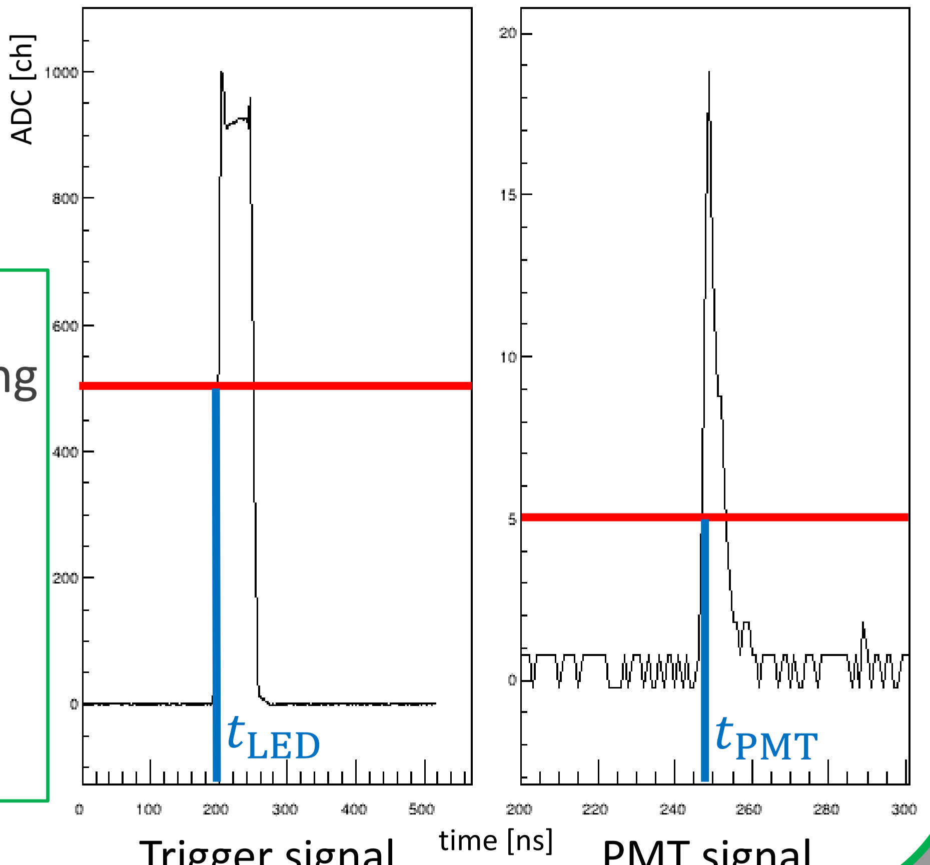


Light emitter: Scintillation Ball
Position: On the central axis, $z = 1.0$ [m]
Intensity: ~ 0.01 [p. e.]
Frequency: 1000 [Hz]

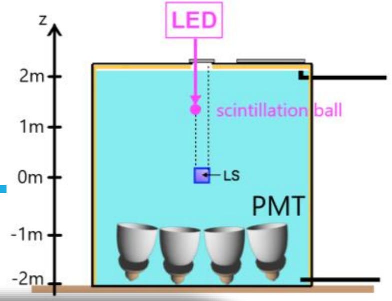
Trigger signal (self trigger) : t_{LED}
synchronized with LED emission timing

PMT signal (coincidence trigger) x14 : t_{PMT}
trigger : each PMT signal
amp : x25

Time delay: $\Delta t = t_{\mathrm{PMT}} - t_{\mathrm{LED}}$

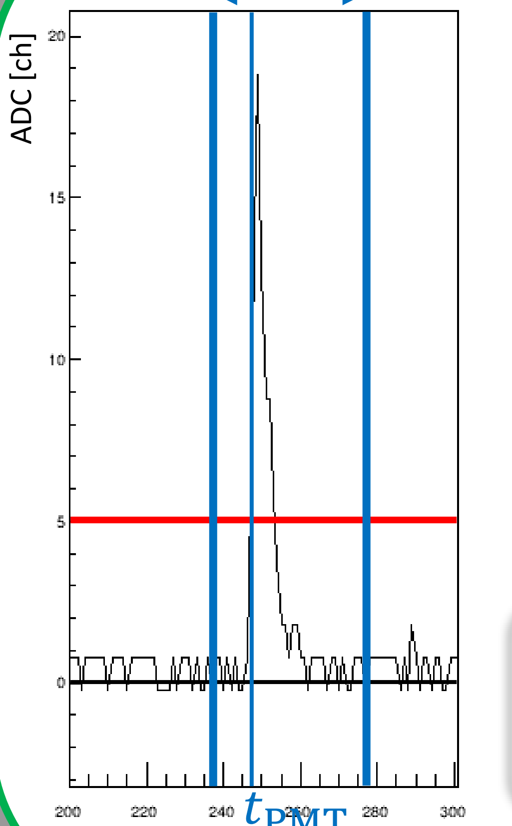


Calibration of 1p.e. Gain



Scintillation ball measurement

Interval of integration



PMT signal

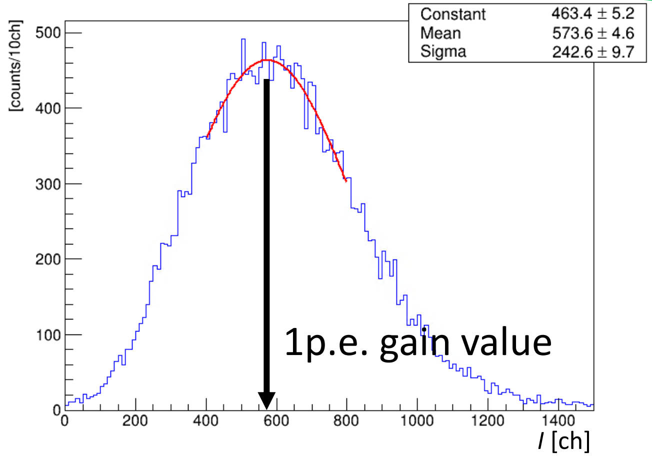
Each event of each PMT signal

$$(I\ [\mathrm{ch}]) = \sum_{t_{\mathrm{PMT}}-10\ [\mathrm{ns}]}^{t_{\mathrm{PMT}}+30\ [\mathrm{ns}]} (\mathrm{ADC}\ [\mathrm{ch}])$$

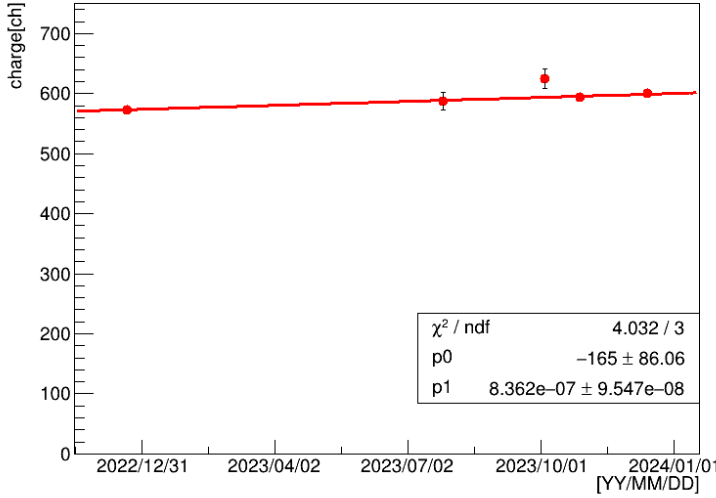
1p.e. gain value: Mean value of the peak of I distribution

Fit the time change in five measurements with a linear function

Calibrate the 1 p.e. gain of each PMT
→ **Improved the accuracy** of the observed photons in the analysis

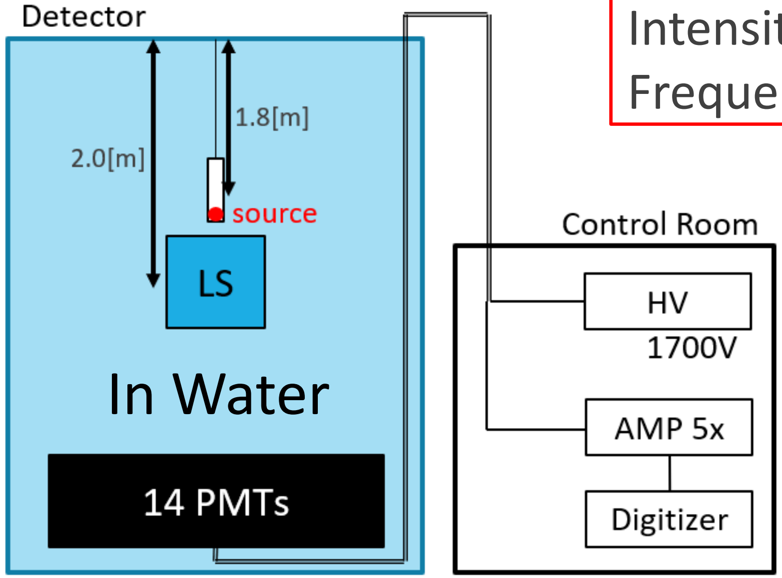


PMT No.7



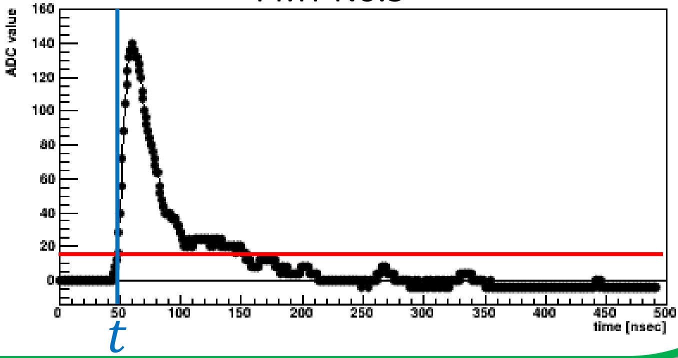
Total observed photons of the prototype detector

Radiation source measurement



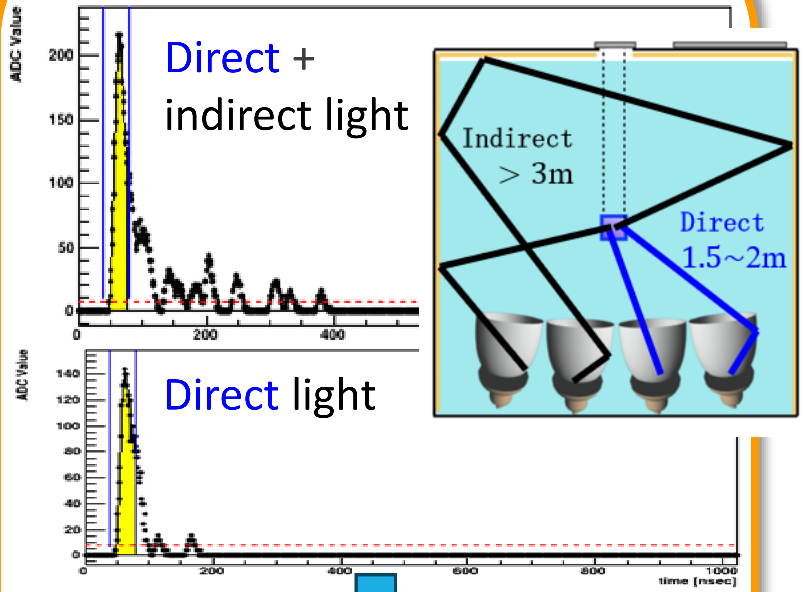
Light emitter: New LS (By Radiation source)
Position: On the central axis, $z = 20$ [cm]
Intensity: ~ 1000 [p.e.]
Frequency: 100 [Hz]

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



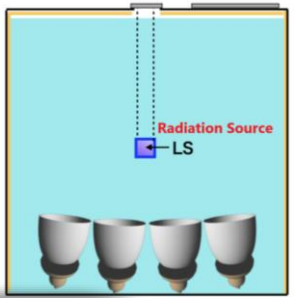
Selection of direct light signal

Reproduce the waveform



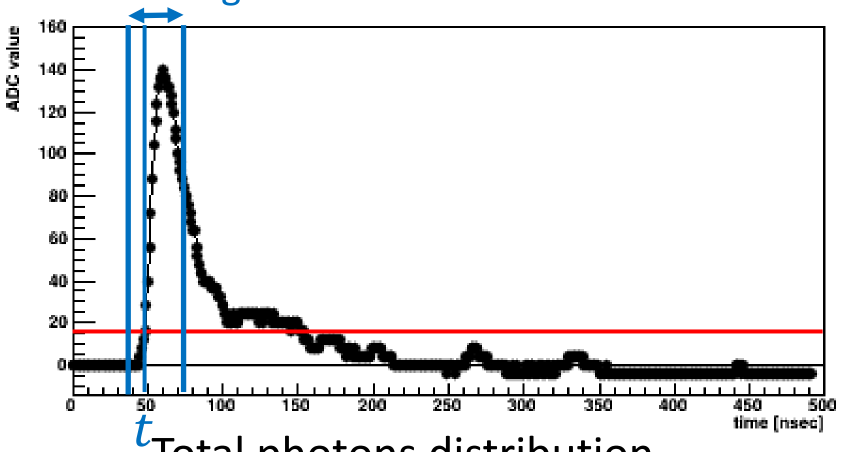
Interval of integration:
$t - 10[\text{ns}] \sim t + 25[\text{ns}]$
(Contamination of indirect signal: 8.2%)

Total observed photons of the prototype detector

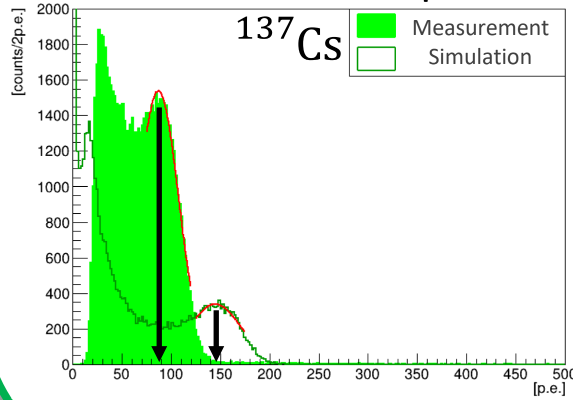


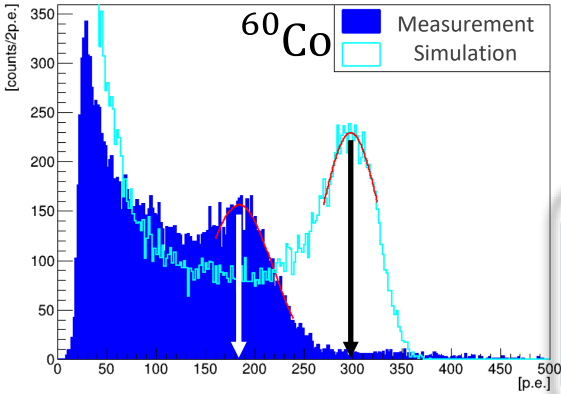
Radiation source measurement

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)

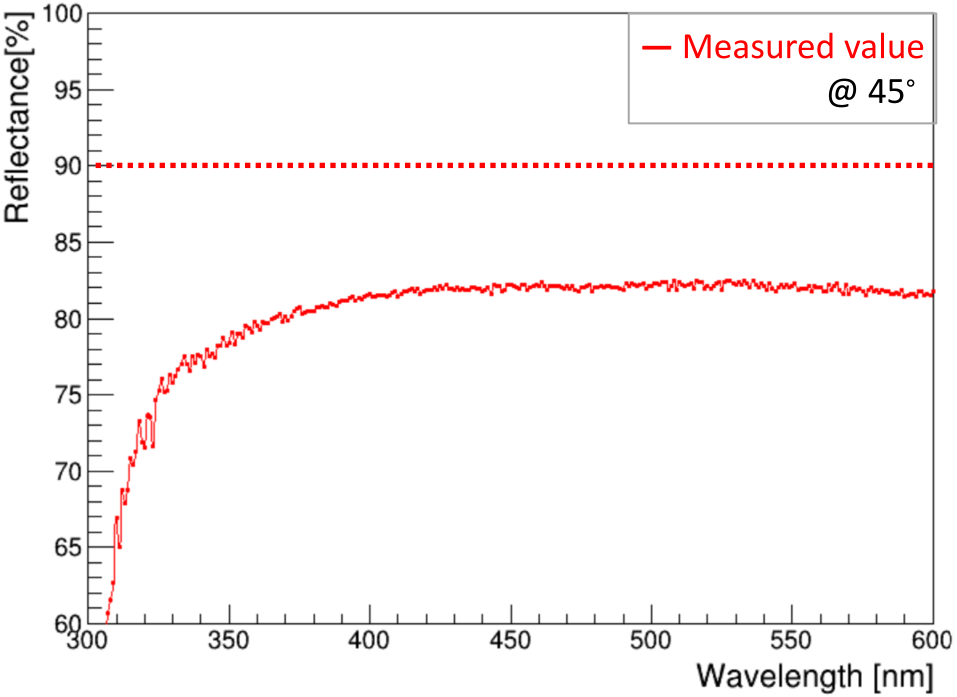
Light-Collection Mirror Plans (Reflectance in Air)

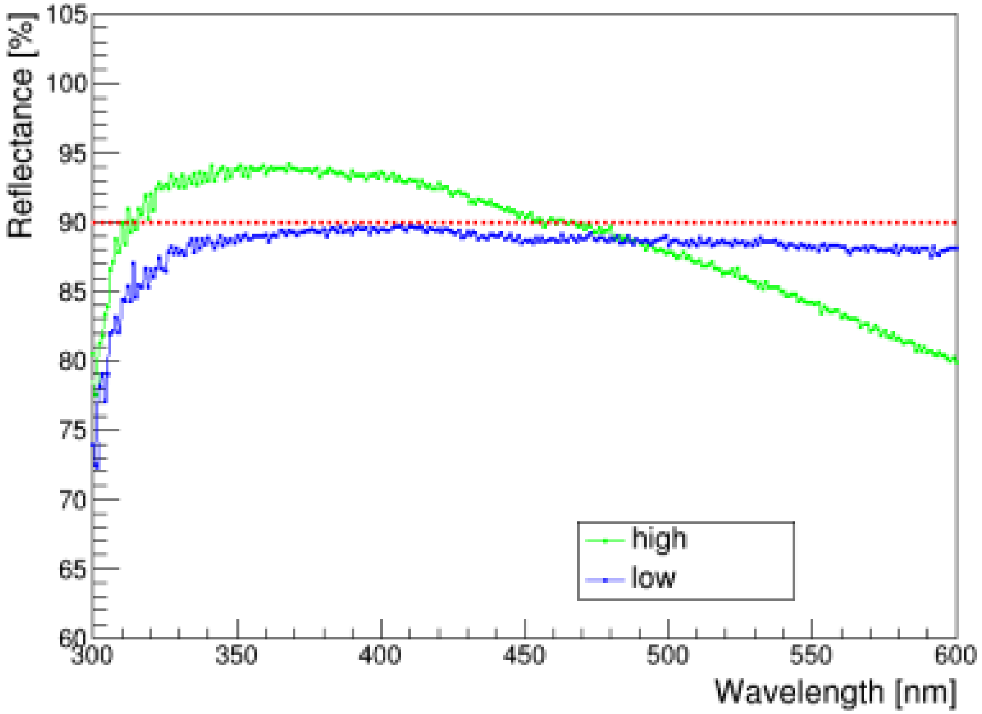
Latest Plan

- aluminum-deposited sample (These sample has a coating that increases reflectance)
  - sample① : 228 million yen、 high reflectance, composition is Al + SiO_2 + ZrO_2 + SiO_2
  - sample② : 146 million yen、low reflectance

※This price is the total cost of the Light Collecting Mirror

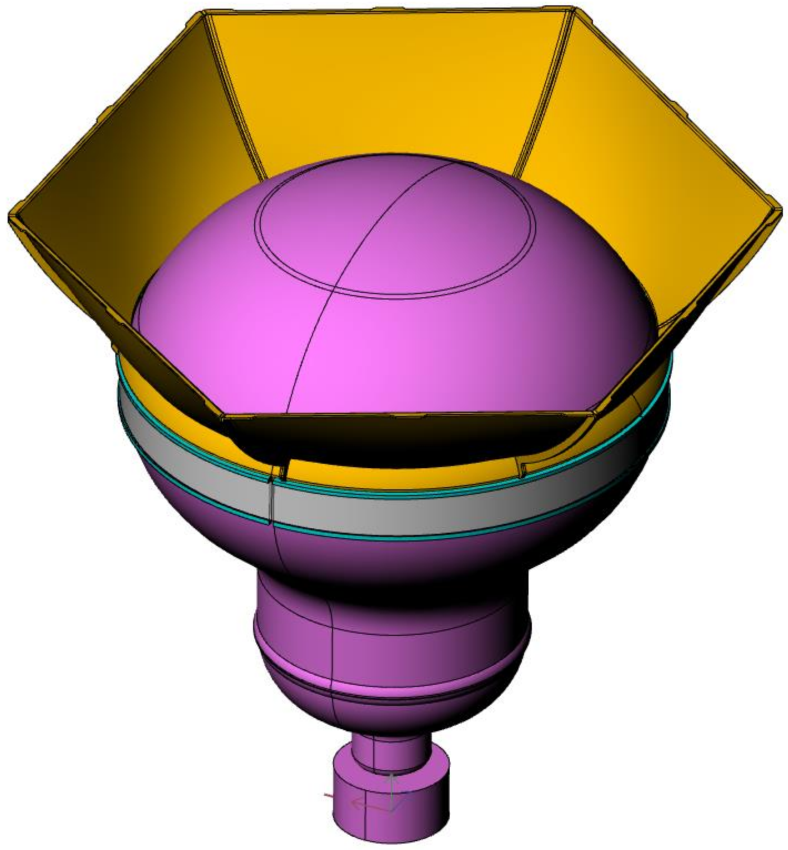
Prototype Detector Plan



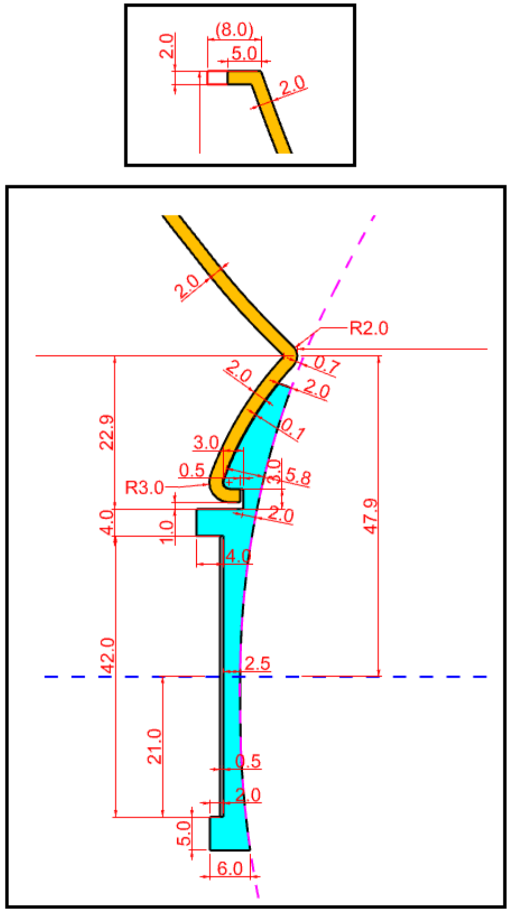


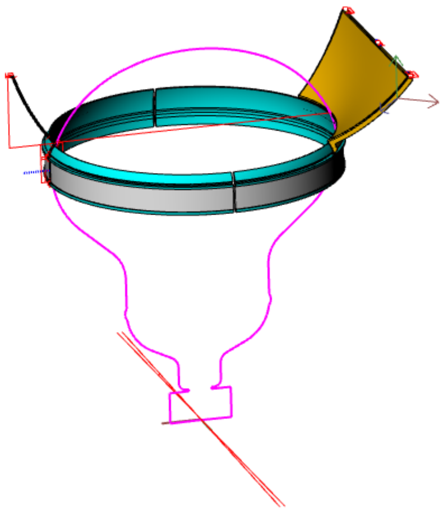
Light-Collection Mirror Plans (Assembly)

Latest Plan



DEOC241213_集光ミラー.3dm





DEOC241213_集光ミラー途中データ.3dm