AXEL : High pressure xenon gas TPC for neutrinoless double beta decay search

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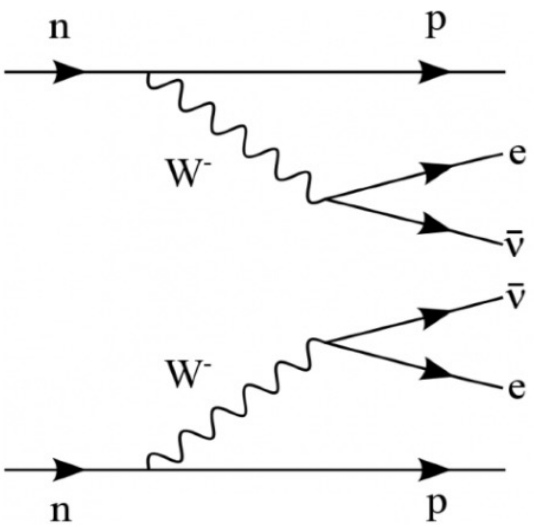
Neutrinoless double beta decay ($0\nu\beta\beta$)

$0\nu\beta\beta$ can occur if neutrino is Majorana particle

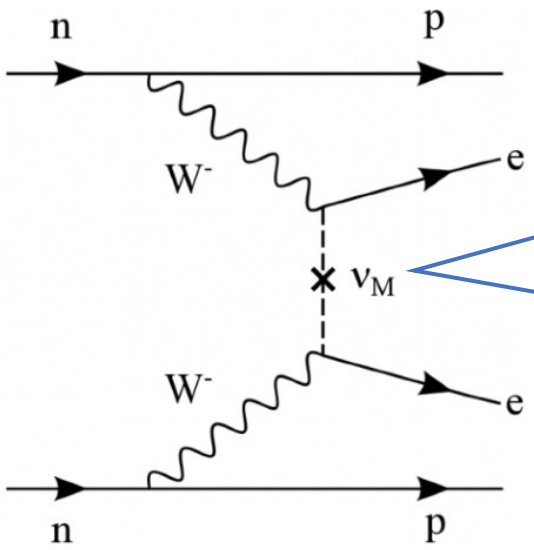
※Majorana particle: fermion which is the same as its anti-particle

If the neutrino is Majorana particle,

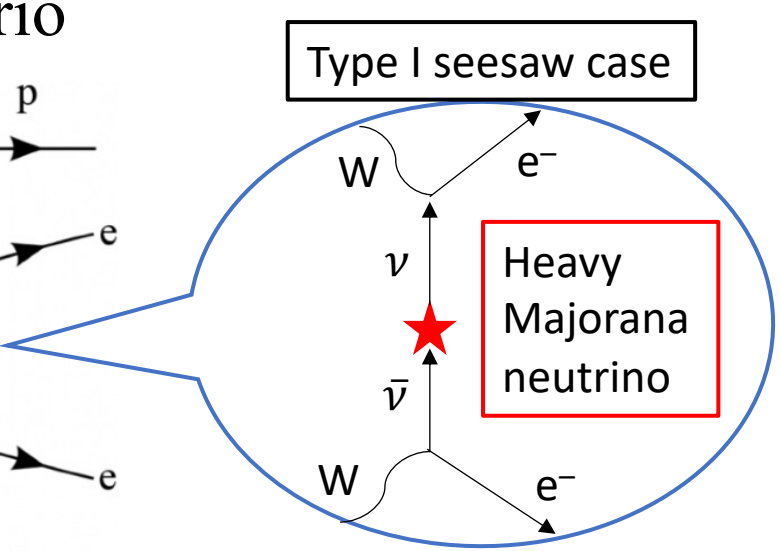
- The smallness of the neutrino mass may be explained by seesaw mechanism
- Matter-antimatter symmetry of the Universe may be explained by Leptogenesis scenario



$2\nu\beta\beta$



$0\nu\beta\beta$



Lepton number violation

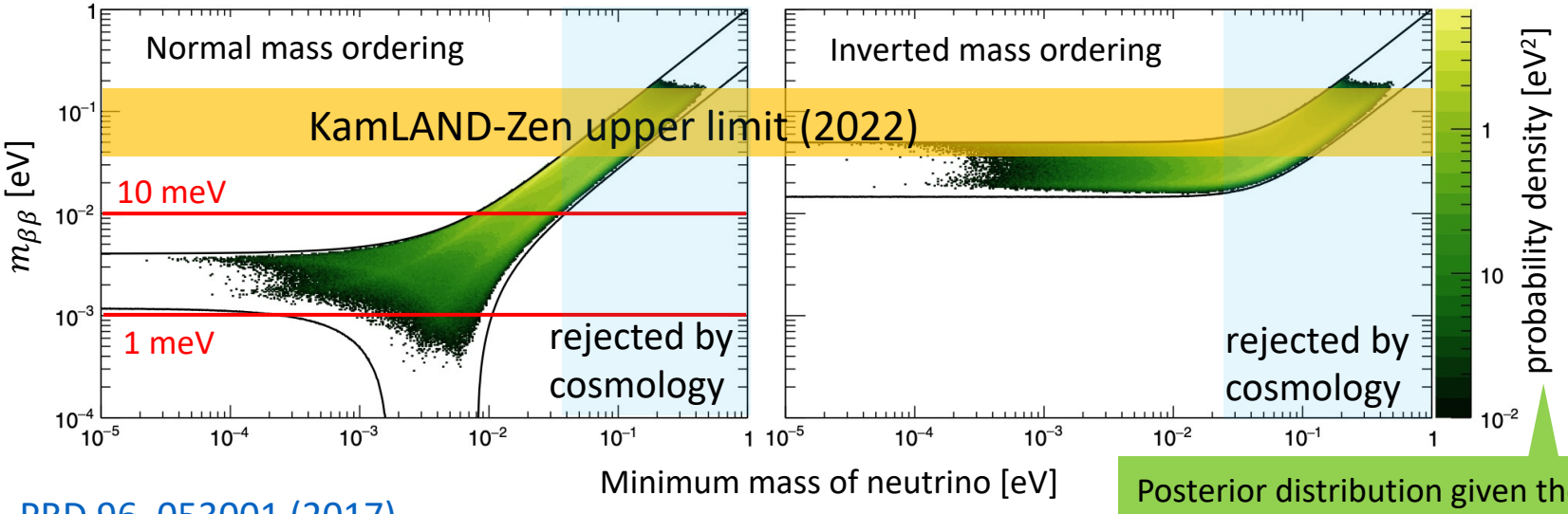
$\Delta L = 2$

Current status of $0\nu\beta\beta$ search

- Lower limit of half-lifetime in ^{136}Xe:
  2.3×10^{26} year (90% C.L.) by KamLAND-Zen
  PRL 130, 051801 (2023)

→ Neutrino effective mass ($m_{\beta\beta}$) upper limit: 36-156 meV

- Normal mass ordering is favored by neutrino oscillation and cosmology observations
- Half-lifetime is proportional to $m_{\beta\beta}^{-2}$



PRD 96, 053001 (2017)

Posterior distribution given the knowledge on neutrino mixing parameters

Contents

How to search for $0\nu\beta\beta$

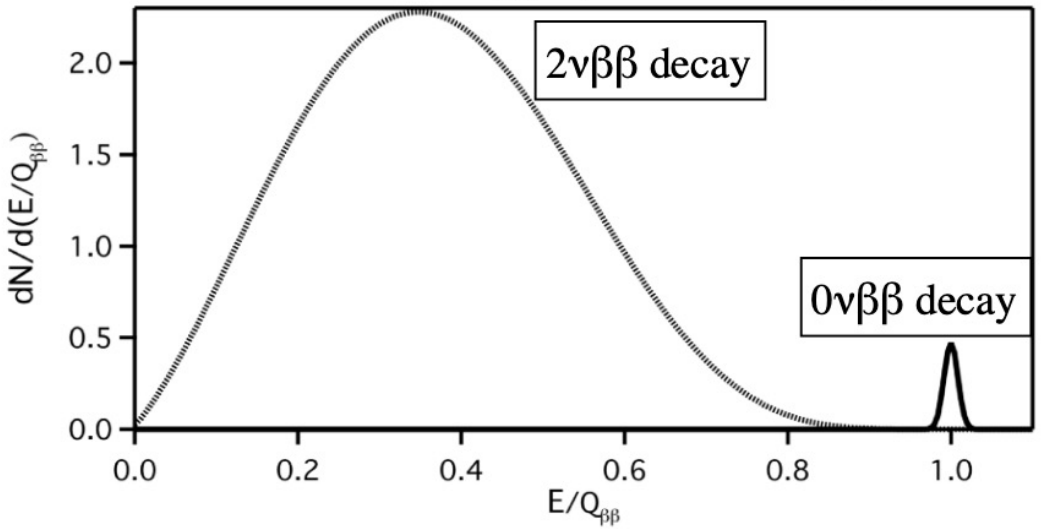
$0\nu\beta\beta$ is very rare decay → **Large mass** and **Low BG**

$0\nu\beta\beta$ can be identified by

- Sum energy of two electrons → **Good energy resolution**
- Event topology → **Tracking capability (BG rejection)**

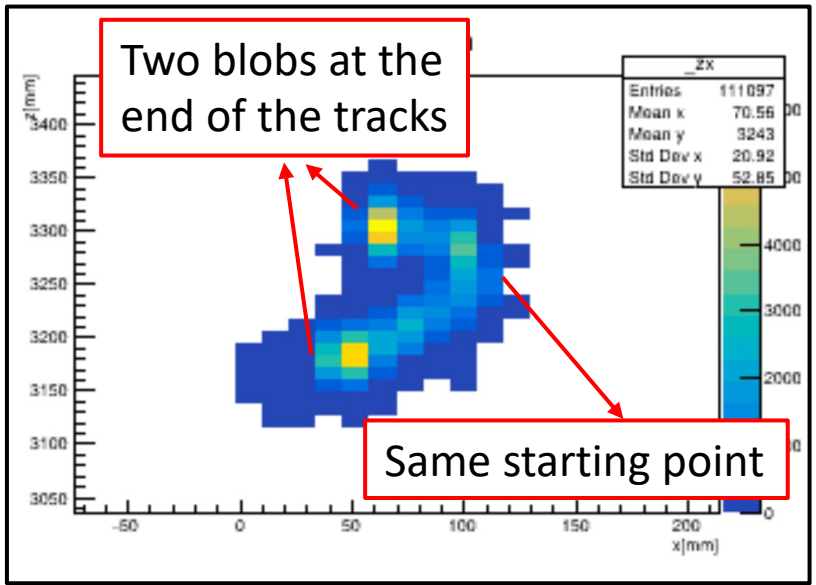
Using ^{136}Xe → **High Q-value (Less BG contamination)**

Schematic energy spectrum of ββ



Redrawn from *Rev. Mod. Phys., 80:481–516, Apr 2008.*

$0\nu\beta\beta$ event topology in simulation

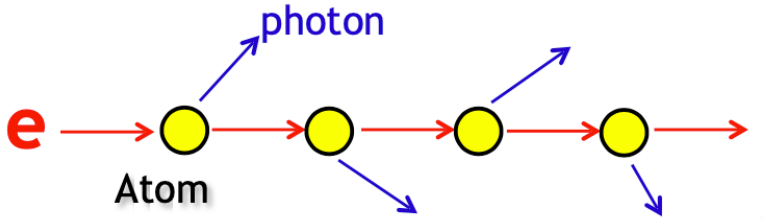


A Xenon ElectroLuminescence: AXEL

High pressure Xe gas TPC for $0\nu\beta\beta$ search

Detection of ionization electrons

Electroluminescence (EL) process

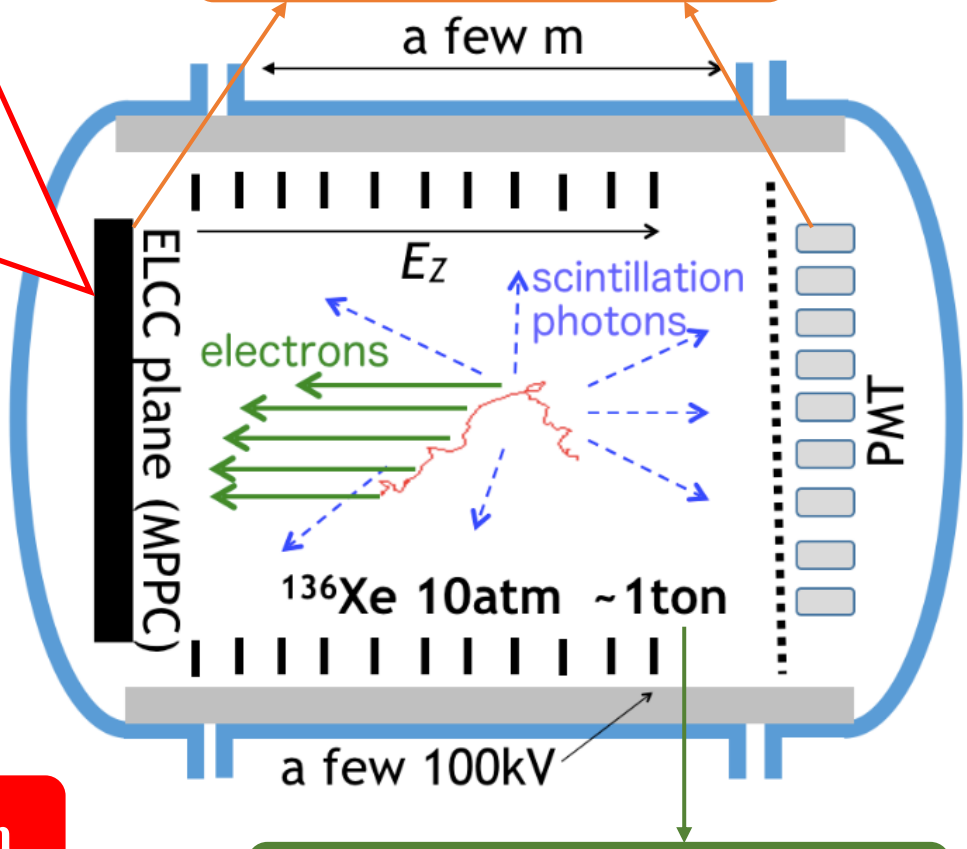


Linear amplification process
→ Less fluctuation of amplification than avalanche process

Detail is in the next page

Good energy resolution

Tracking: BG rejection

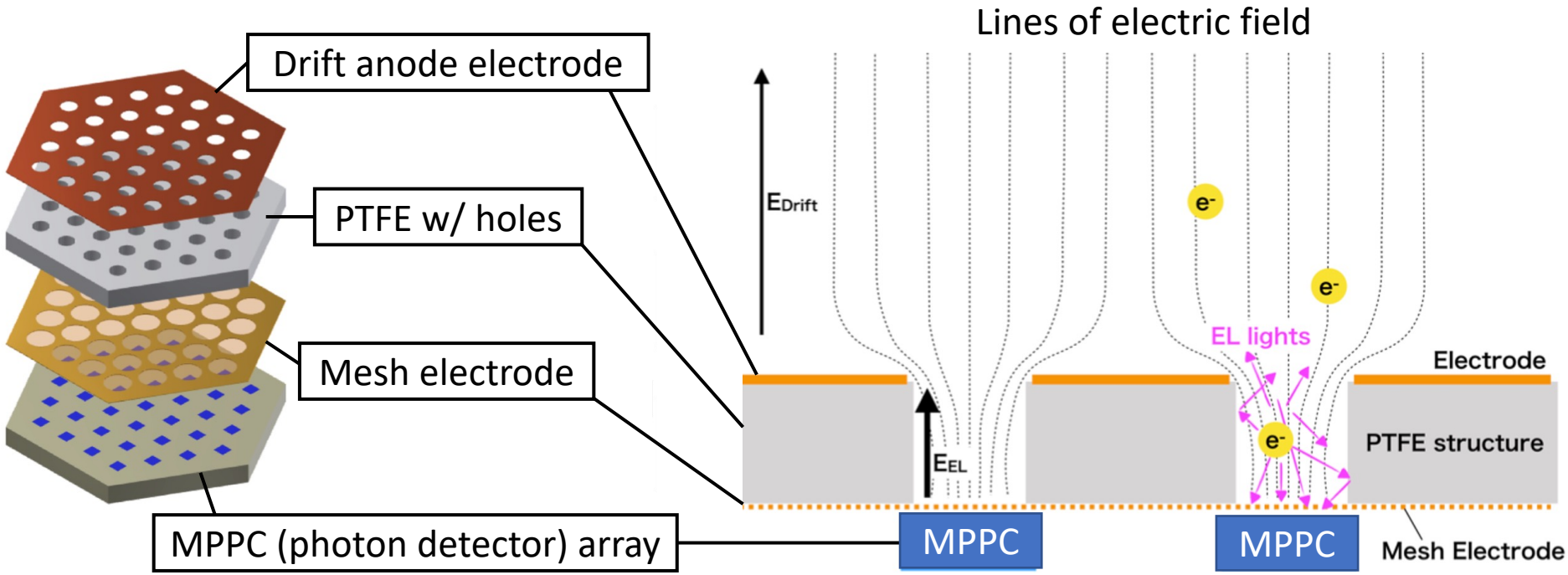


Large mass: ton scale ^{136}Xe

Readout system for ionization electron

Electroluminescence Light Collection Cell: ELCC

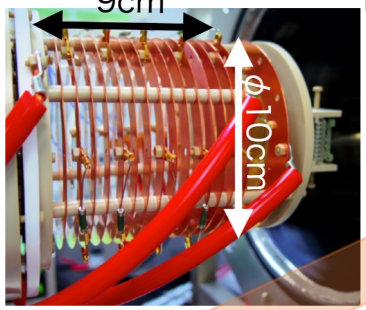
- Detect EL lights with VUV-sensitive MPPC
- Using EL process: good energy resolution
- Cellular structure: uniform detection → tracking
- Rigid unit structure: easy to extend



Road map of AXEL experiment

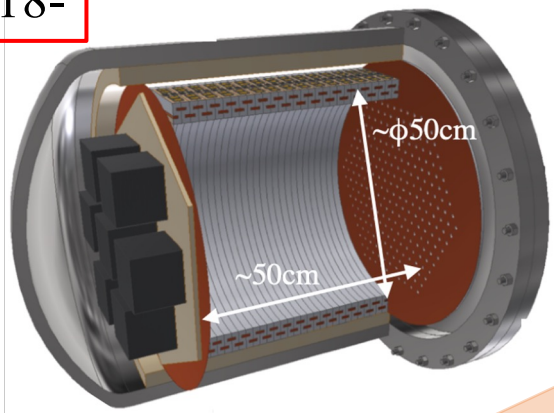
- Evaluation with 180 L prototype is ongoing
- Construction of 1000 L detector for physics run has begun in 2022

2014-2018



- ~80 g Xe
- Demonstrate the ELCC concept

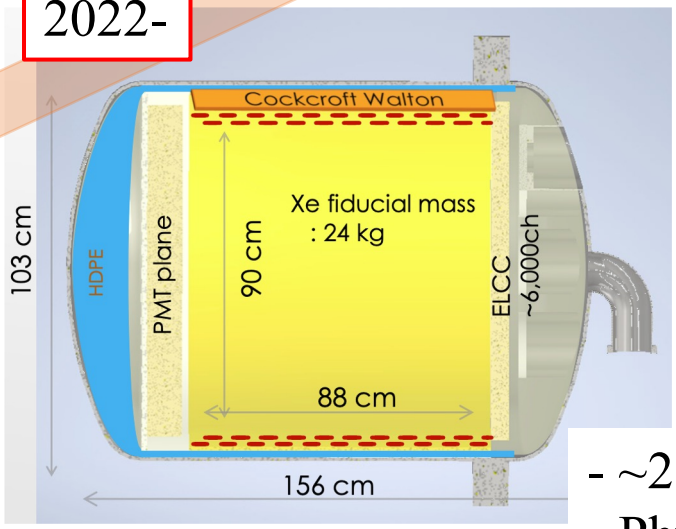
2018-



- ~5.6 kg Xe
- Prove enlargement ability
- Establish analysis method

200 kg detector

2022-



- ~20 kg Xe
- Physics run

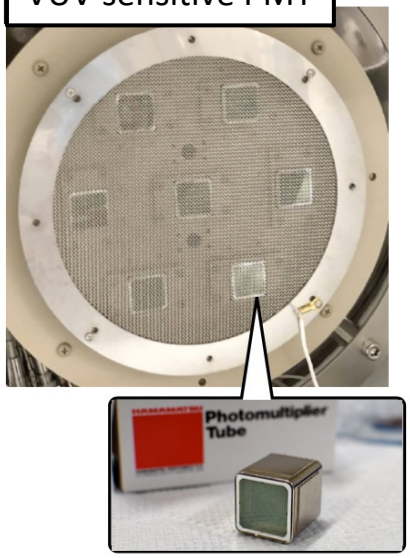
1 t detector

- NO region search

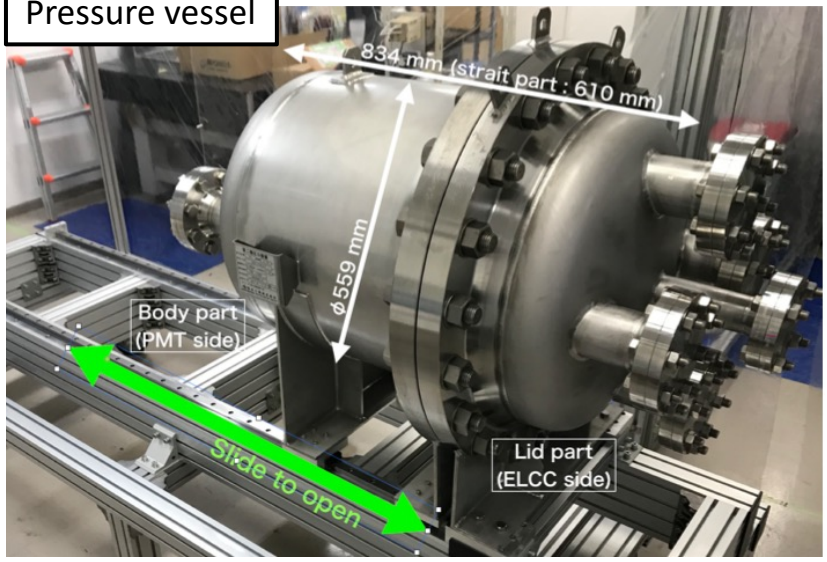
Contents

180 L prototype

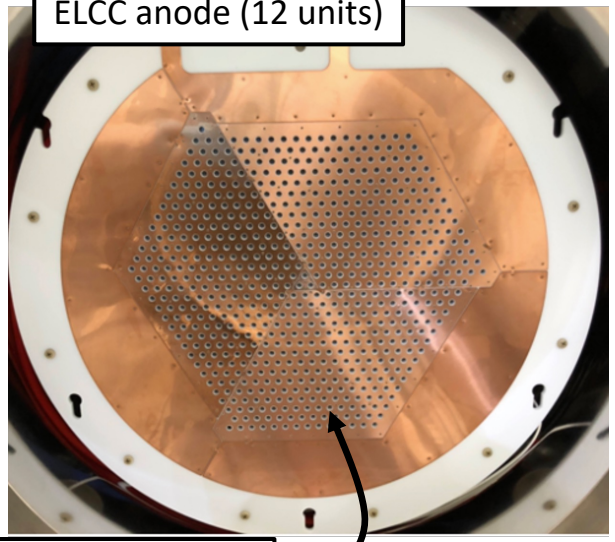
VUV-sensitive PMT



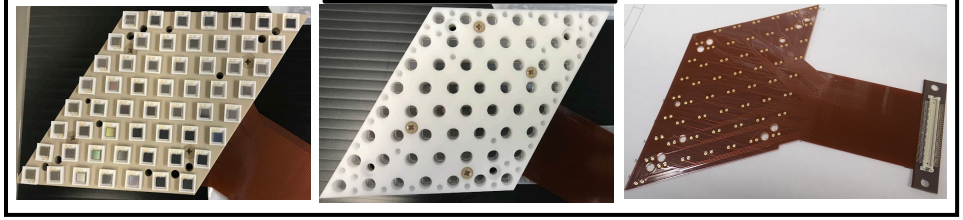
Pressure vessel



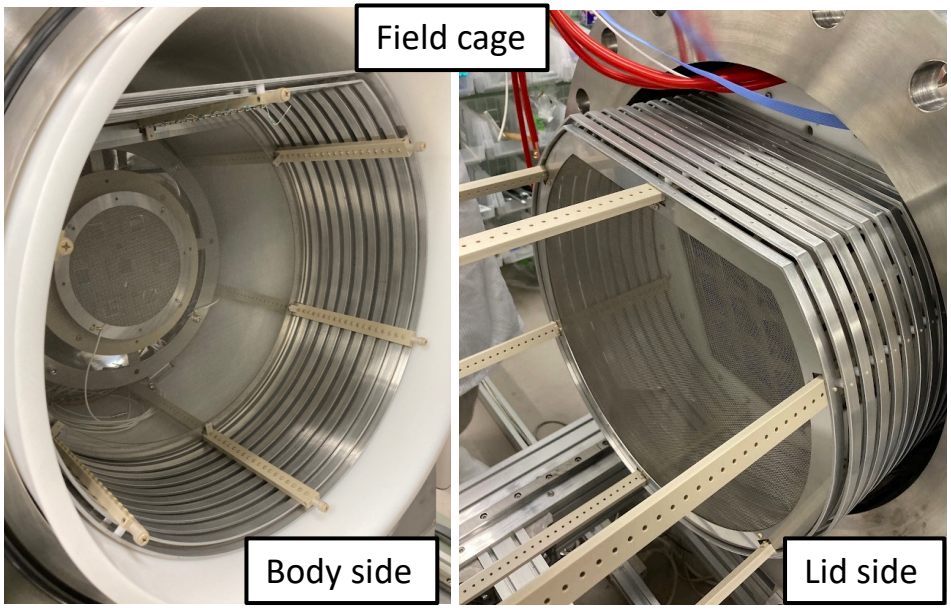
ELCC anode (12 units)



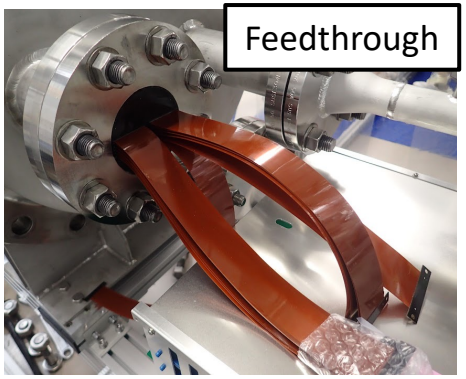
Single ELCC unit



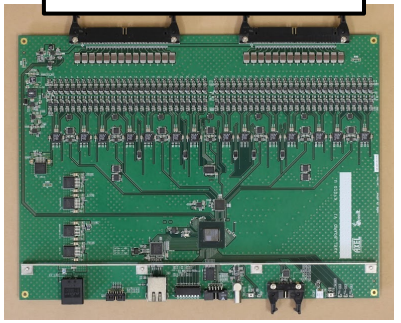
Field cage



Feedthrough



Electronics board

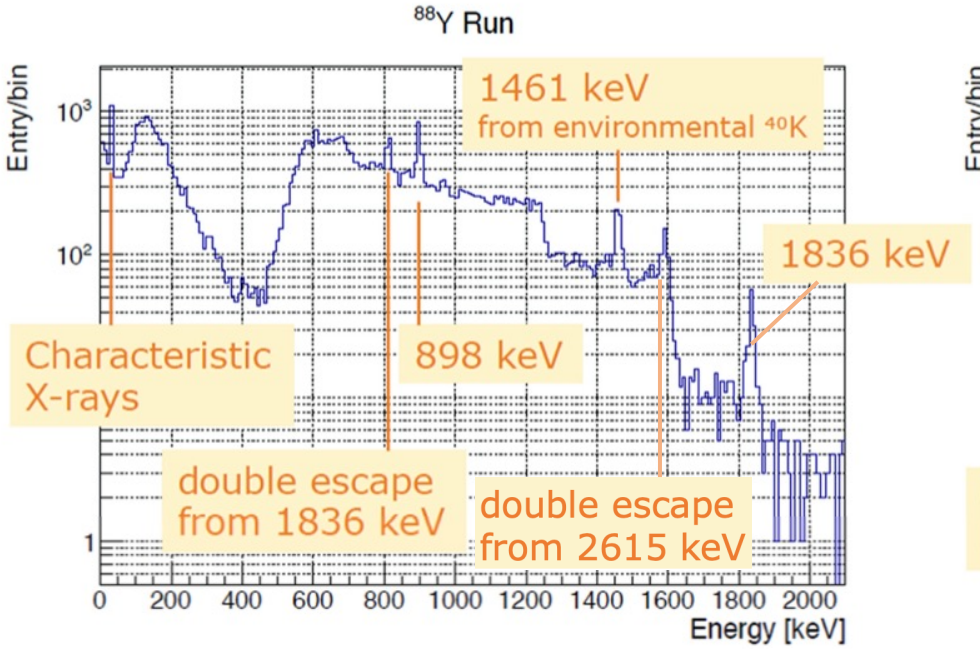


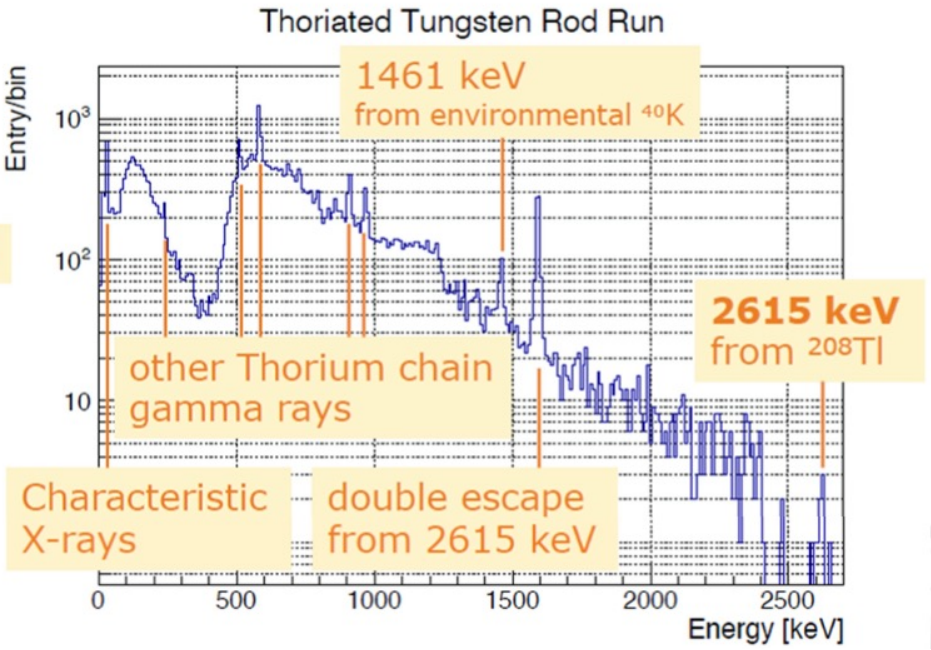
Energy measurement

Two kinds of the measurement were done

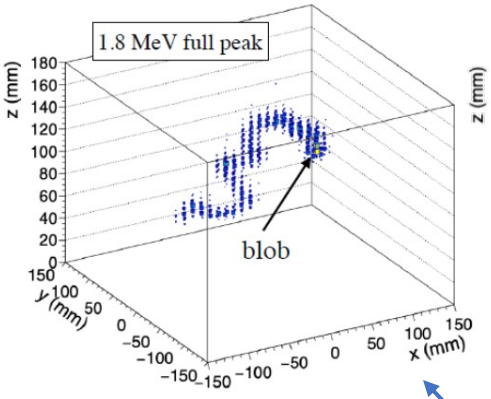
- ^{88}Y source: 1.8 MeV
- Thoriated tungsten rod: 2.6 MeV

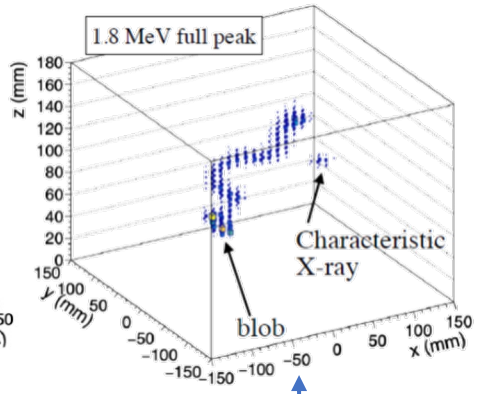
c.f. ^{136}Xe $\beta\beta$ Q-value: 2.5 MeV

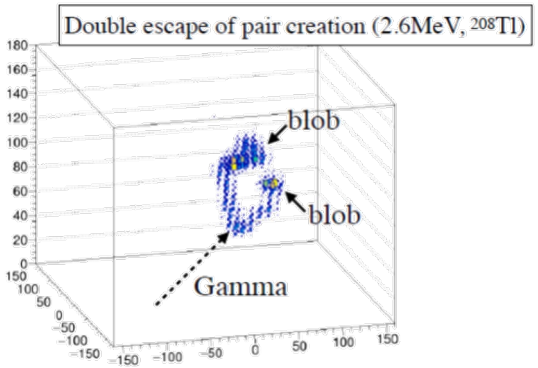


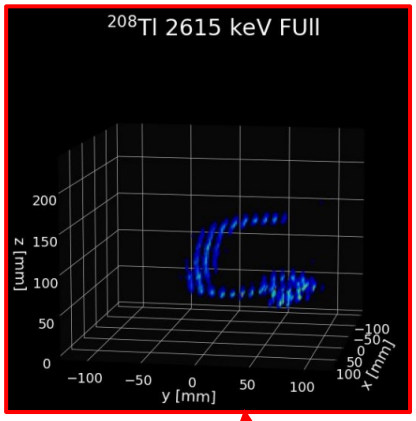


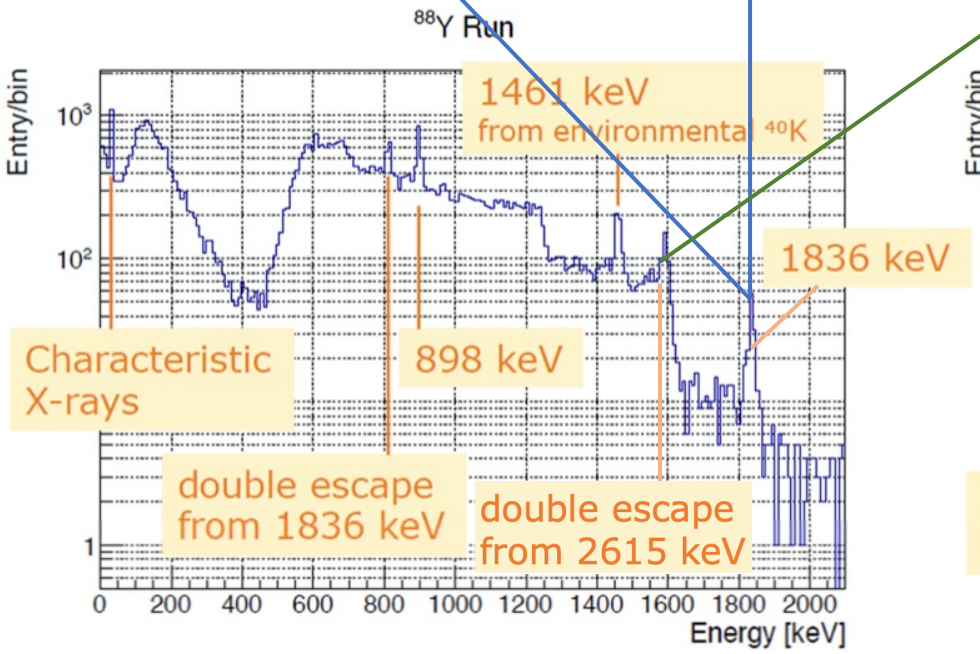
Event topology

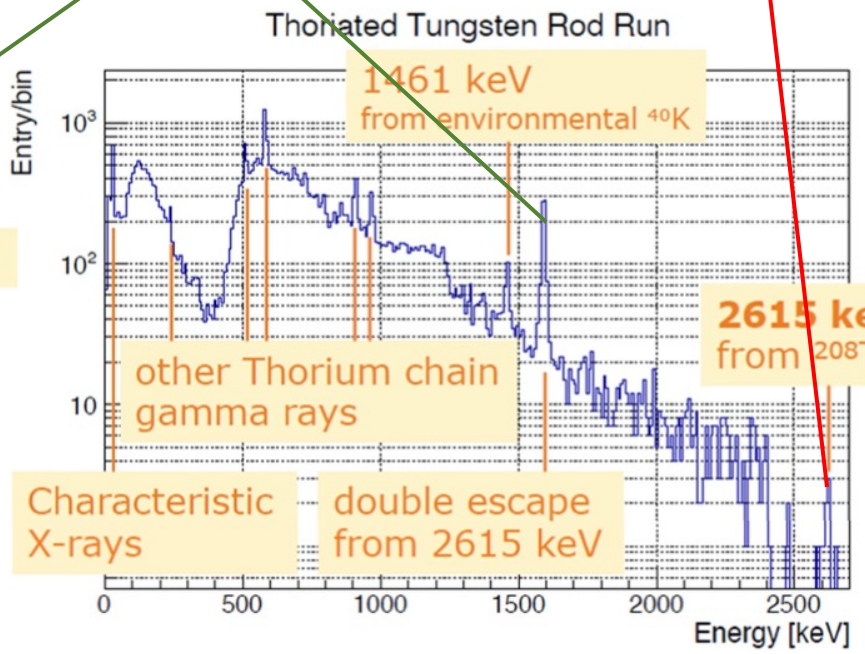










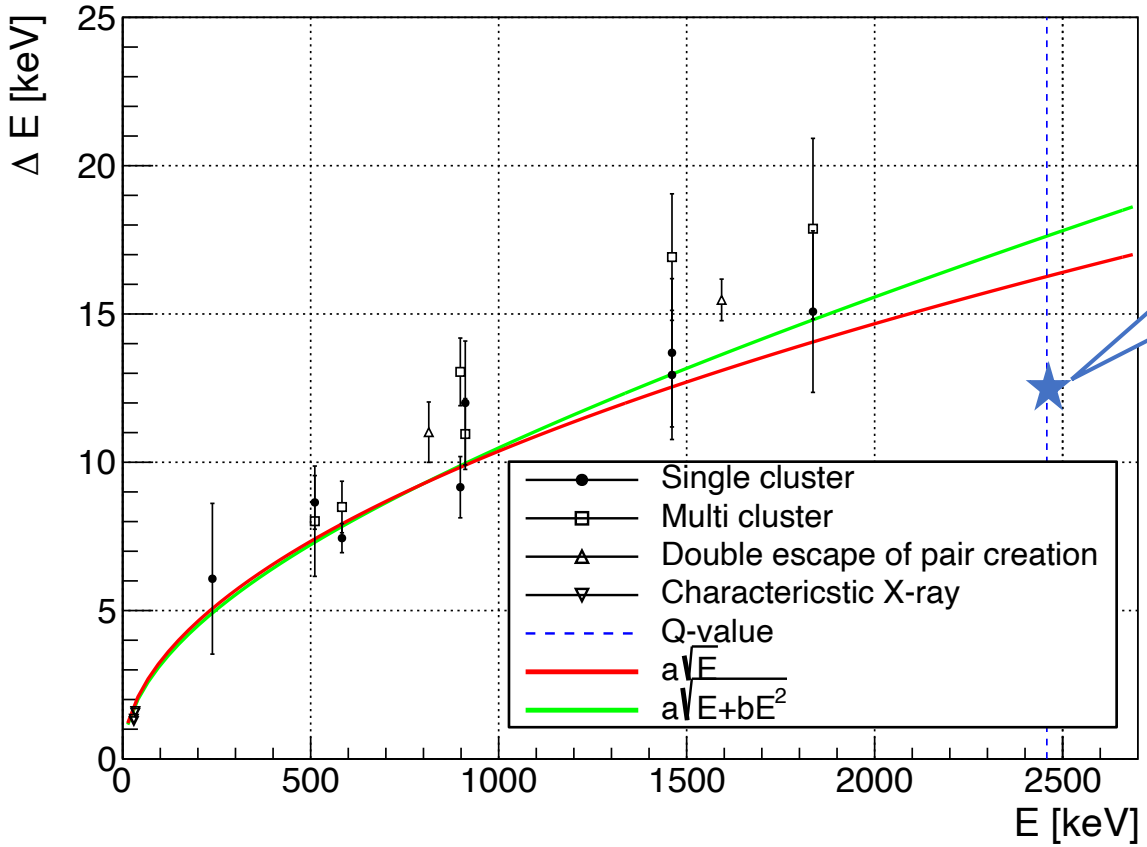


Evaluation of energy resolution

Extrapolation of $\Delta E/E$ (FWHM) to Q-value

- $a\sqrt{E}$: 0.662 ± 0.029 %
- $a\sqrt{E + bE^2}$: 0.717 ± 0.209 %

0.7 % (FWHM) @Q-value



Target: 0.5 % (FWHM)

Only single cluster is used for the evaluation

Breakdown of energy resolution

Breakdown of the energy resolution (FWHM) at 1.8 MeV

Fluctuation of the number of the initial ionization electrons	0.29 %	(inevitable)
Fluctuation of the EL conversion	0.24 %	
Position dependence of the EL gain	negligible	
Waveform processing in AxFEB	negligible	
Error in EL gain calibration	0.22 %	
Accuracy of MPPC recovery time measurement	negligible	
Error in time dependence correction	0.39 %	
Error in z dependence correction	negligible	
Dependence on the drift electric field	0.22 %	
Offset of the baseline less than 1 ADC count	< 0.05 %	
Fluctuation of the MPPC non-linearity	0.23 %	
Total (estimated)	0.67 %	
Total (data)	0.82±0.15 %	(1σ error)

Better detection efficiency of EL photon is desired

Need further study

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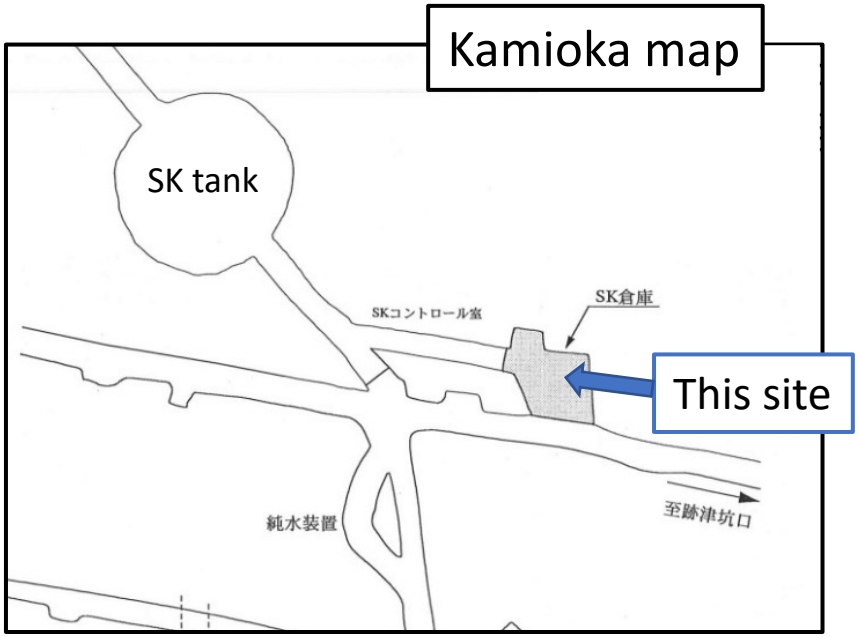
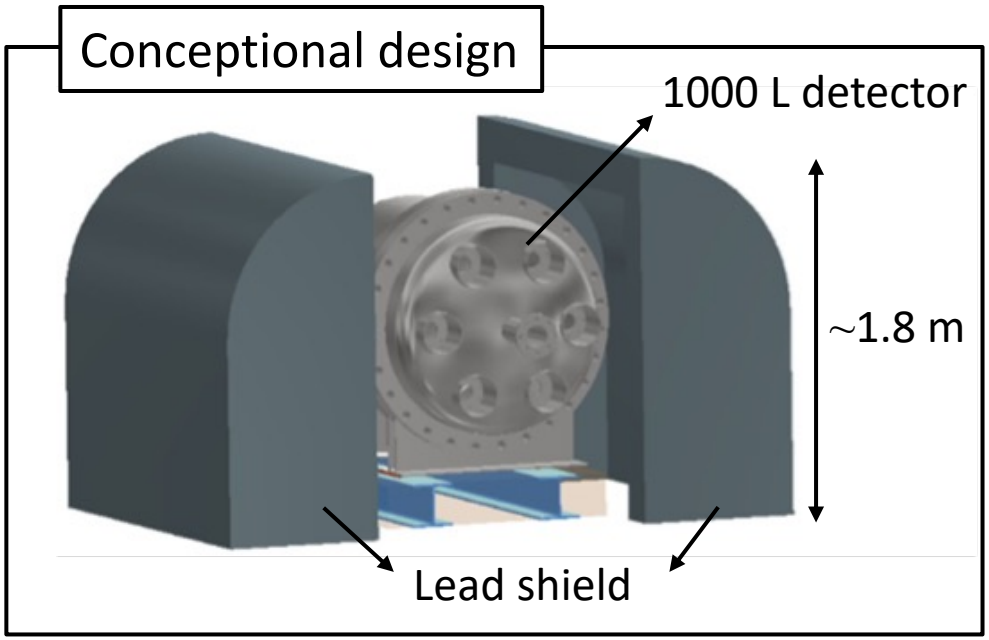
1000 L detector experiment

Site: Kamioka observatory of ICRR (near Super Kamiokande)
→ About 1,000 m underground

Estimated performance (simulation)

- $0\nu\beta\beta$ event rate: 0.25 events/year (@ $T_{1/2} = 2.3\times10^{26}$ year)
- Background rate: < 0.1 events/year (^{214}Bi dominant)





Pressure vessel

Specification

- Size: 1.0 mϕ × 1.5 m
- Weight: 1.4 ton
- Pressure resistance: vac-10 atm
- Inner-fixed feedthrough
  - Save space for electronics
  - Shorten cable length

↑inside the lid

Arrive at Kamioka (30.Mar.2023)

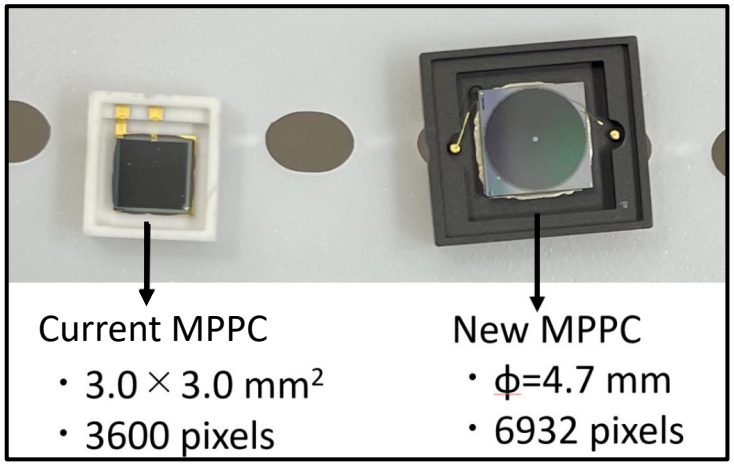
Complete installation (17.May.2023)

New MPPC

Large-area MPPC

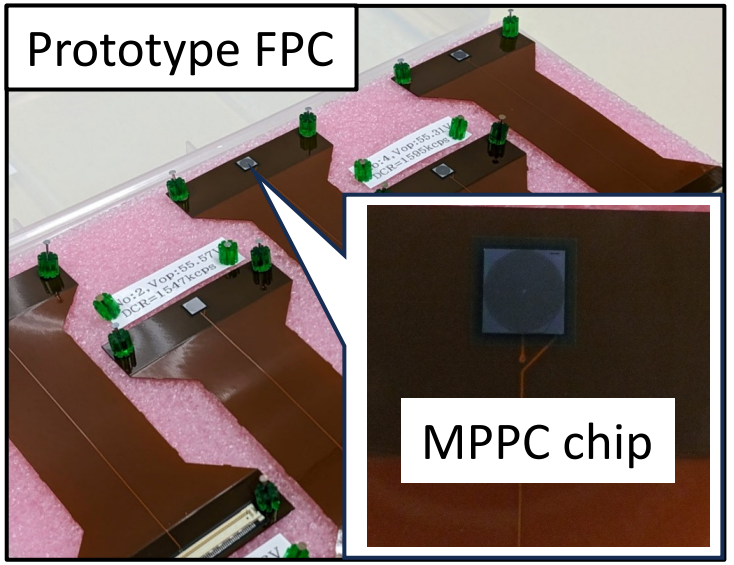
- ~ twice larger area than before
- Reduce statistical fluctuation of EL photon

→ Improve fluctuation of EL conversion



MPPC without package

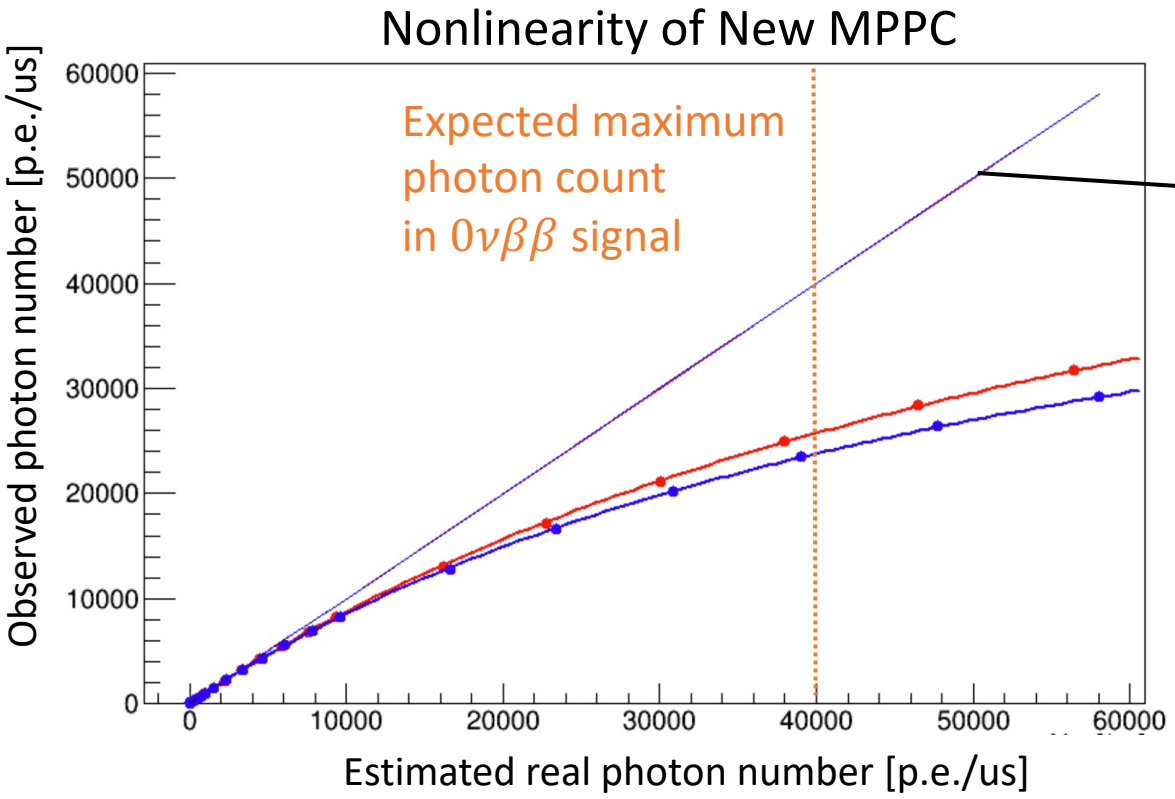
- Remove ceramic package because of its RI contamination
- Place the MPPC chip directly on flexible printed circuit (FPC)
- Finish the evaluation of prototype FPC with 1 channel



Readout electronics board

Modifications

- Higher density (to increase ELCC unit channels: 56ch→64ch)
- Optimization of the gain (for new MPPC)
- Change readout resistance: 50Ω→10Ω (to suppress nonlinearity)



In the case of linear behavior

Red: 25 Ω readout

Blue: 50 Ω readout

Nonlinearity is corrected in analysis

High voltage supply

Cockcroft-Walton (CW) circuit

- Make high voltage in the chamber

→ Avoid big feedthrough

Achieved

- 49 kV in atmosphere (50 steps)
- 30 kV in Xe gas (30 steps)

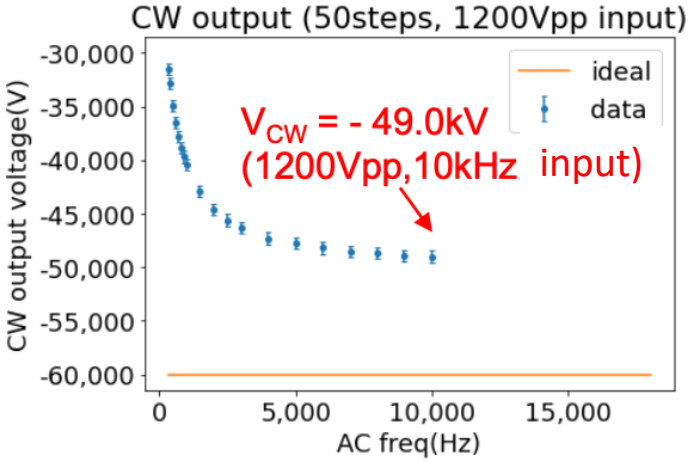
＊Problem: discharge at the edge of FPC

→ Apply varnish on the surface

For higher voltage

- ➢ Higher input frequency
- ➢ Larger input amplitude
- ➢ More steps

→ Target voltage: 76 kV (100 V/cm/bar)

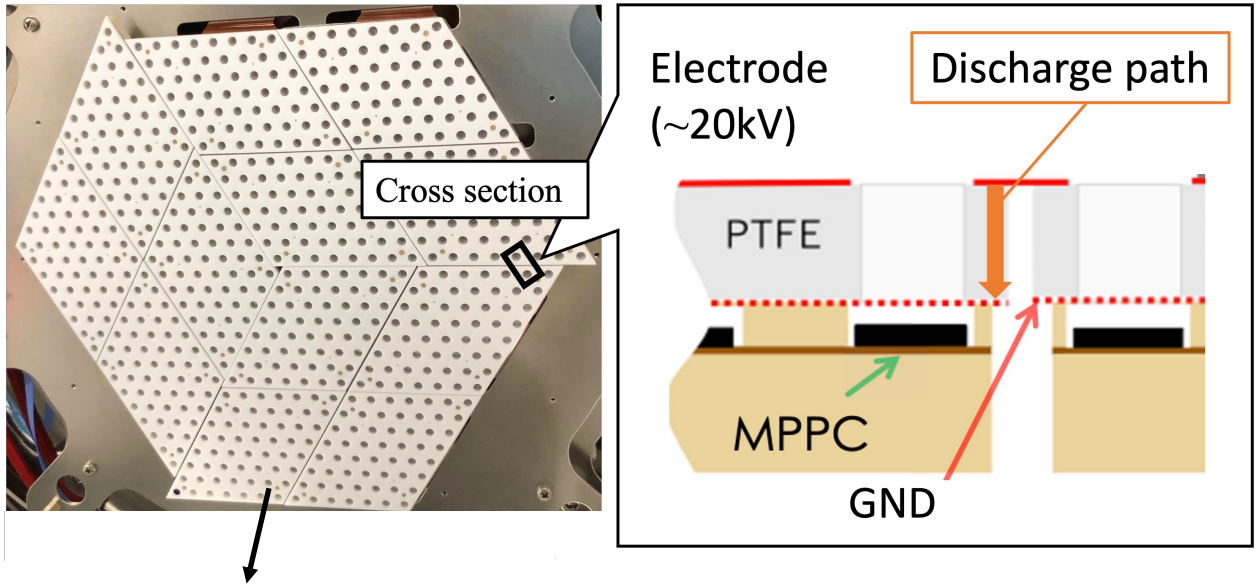


High resistive electrode

- To reduce discharge at ELCC, replace part of electrode with high resistive material

→ Diamond-like carbon (DLC)

- Its evaluation with prototype will be coming soon



12-unit ELCC without electrodes

DLC coating electrode
(150 MΩ/mm^2)

Scintillation light detection

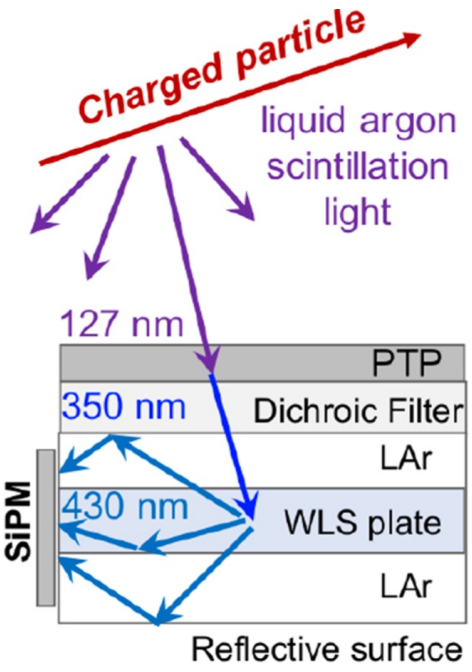
Issues with 180 L prototype

- Using 7 VUV-sensitive PMTs

→ Small detection area (2.1 mm×2.1 mm)

- Many accidental coincidence pulses with 1 p.e. threshold

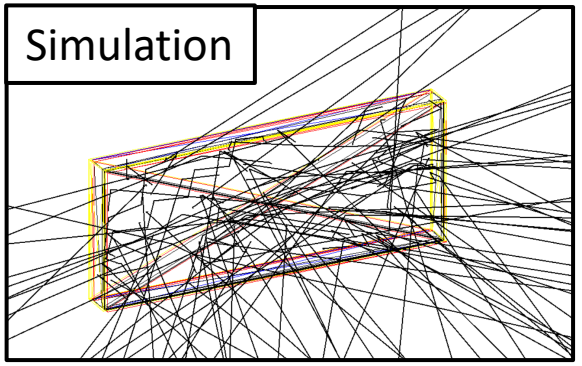
→ Mistake the z-position reconstruction



C. Brizzolari et al 2021 JINST 16 P09027

X-Arapuca-like configuration

- X-Arapuca: proposed in DUNE
- Large detection area with MPPCs
- Select scintillation pulse by total light yield
- Study with simulation is in progress



→ ~13 % light transported to edge (preliminary)

Contents

Summary

AXEL is a high pressure xenon gas TPC for neutrinoless double beta decay search

- High energy resolution with EL process
- BG rejection with topological information

→ Achievable using ELCC.

Detector performance demonstrated with 180 L prototype

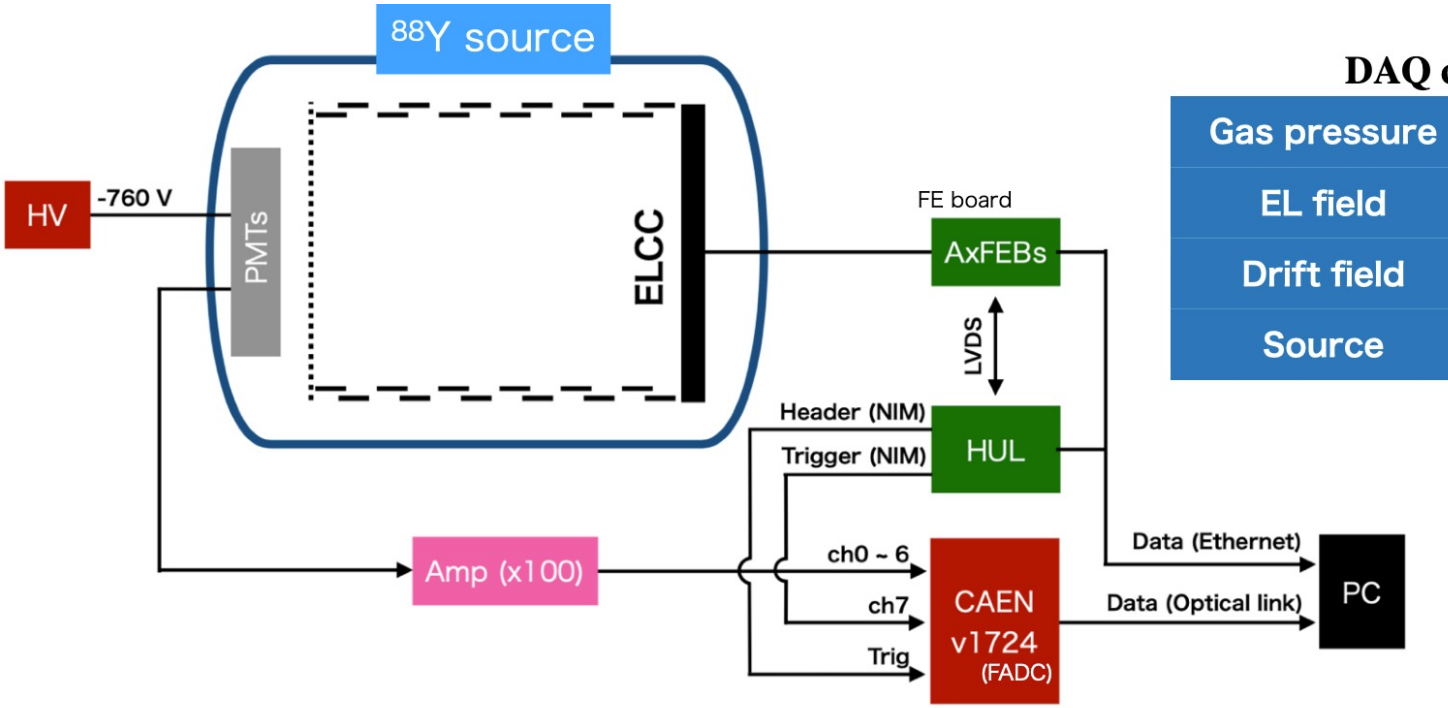
- Energy are measured up to 2.6 MeV
- Track patterns are observed
- Energy resolution extrapolated to the Q-value: 0.7 % (FWHM)

R&D and construction for 1000 L detector is ongoing

For further information, please find documents on our web page:
https://www-he.scphys.kyoto-u.ac.jp/research/Neutrino/AXEL/publication.html

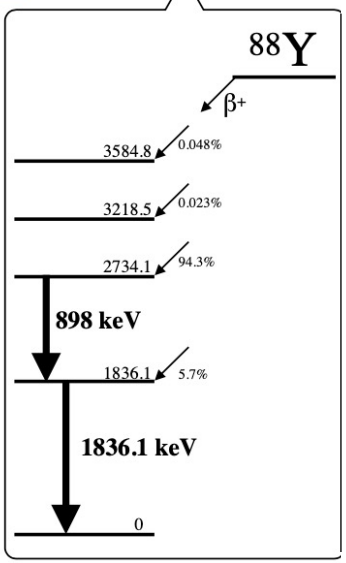
Back up

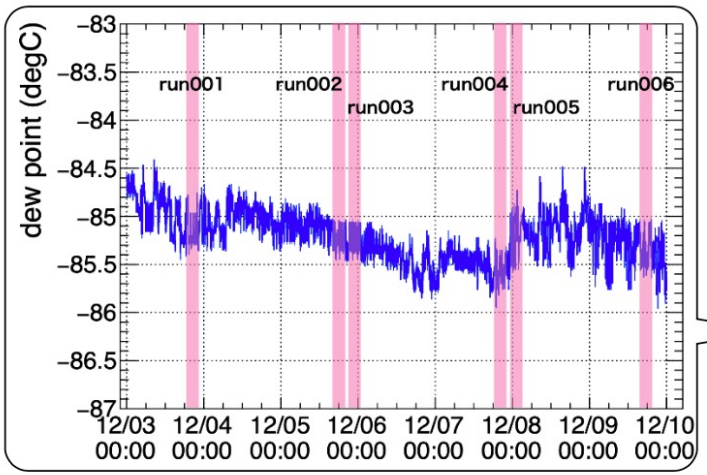
Data taking in 180 L prototype



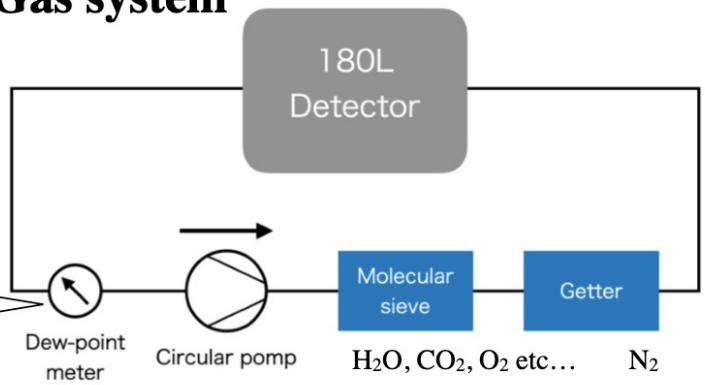
DAQ conditions

Gas pressure	8 bar
EL field	2.25 kV/cm/bar
Drift field	75 V/cm/bar
Source	88Y





Gas system

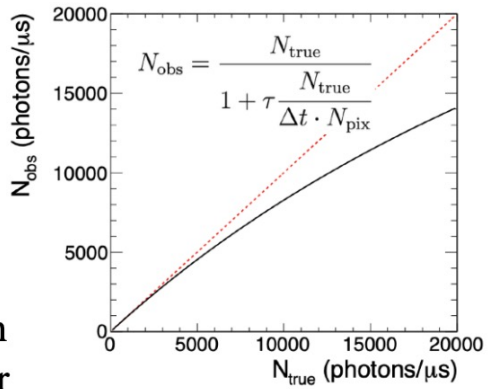


Analysis flow in 180 L prototype

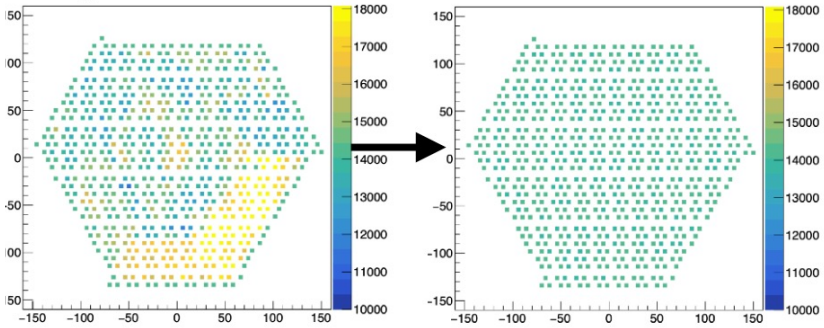
Pulse Search → Clustering → Hit reconstruction → Event selection → Global correction

Calibration & correction for each cell (sensor)

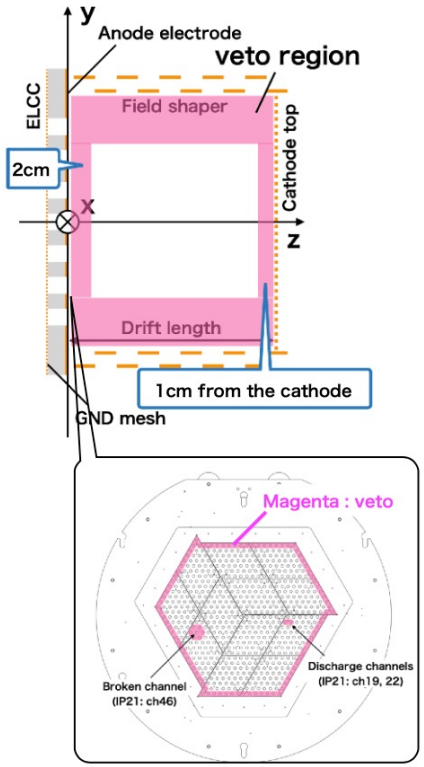
Correction of MPPC non-linearity
- recovery times of each MPPC were measured in advance



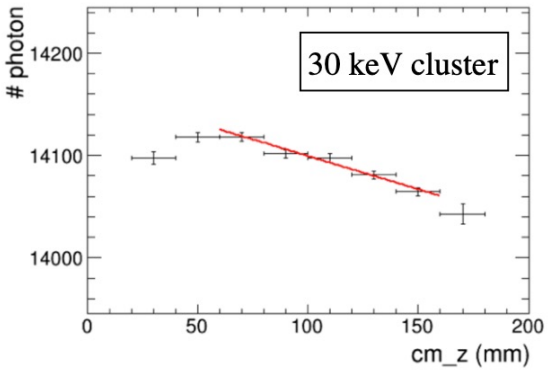
Cell gain calibration using 30 keV cluster



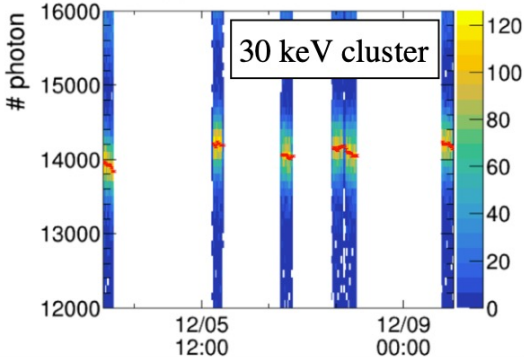
Fiducial cut



z position dependence



time dependence



Signal and BG in 1000 L detector

Geant 4 simulation using the geometry of 1000 L detector

→ Condition: Fully-contained & ROI (Q-value$\pm 1\sigma$)

<u>$0\nu\beta\beta$ signal</u>

- Generate the signals and scale with the current limit

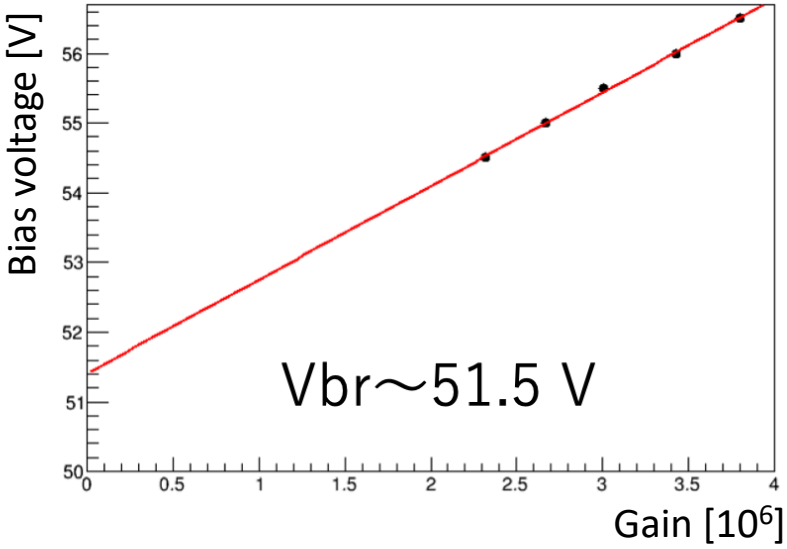
→ 0.25 events/year @ $T_{1/2} = 2.3\times10^{26}$ year

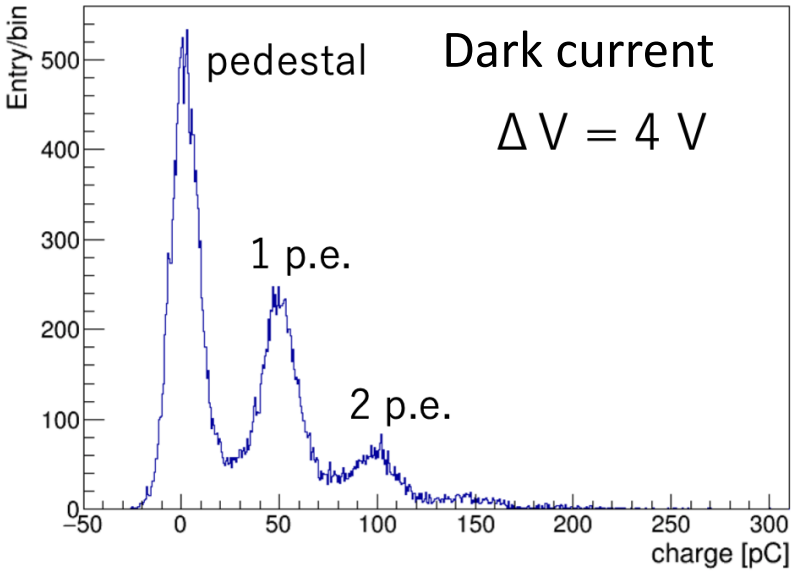
<u>Background (mainly gamma ray from ^{214}Bi: 2448 keV)</u>

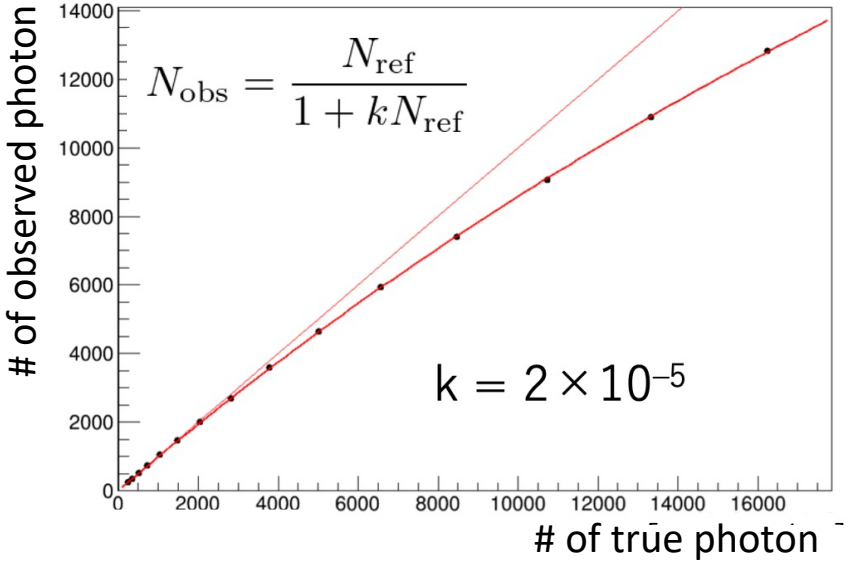
- Detector components: < 162 events/year
- Environment: < 580 events/year (with 20 cm Pb shield)
- BG rejection efficiency with deep learning: 0.013 %

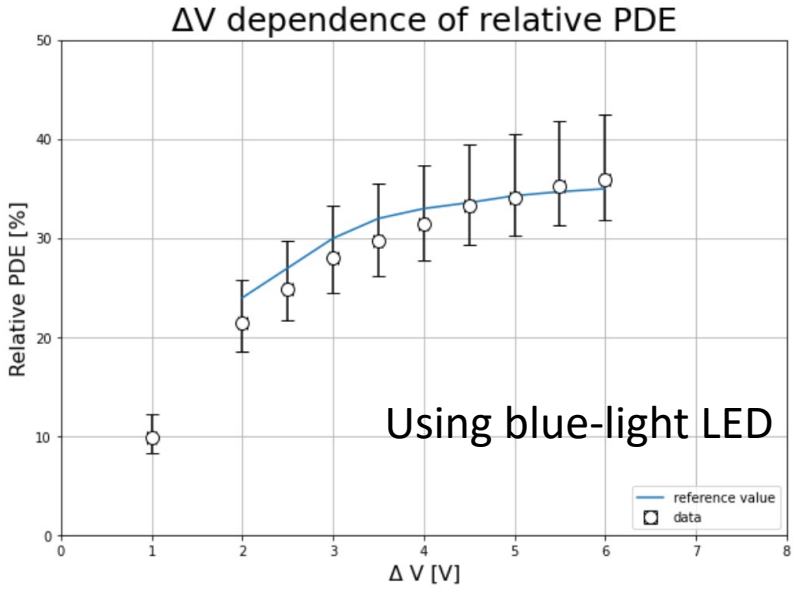
→ < 0.1 events/year

New MPPC evaluation









Nonlinearity of MPPC

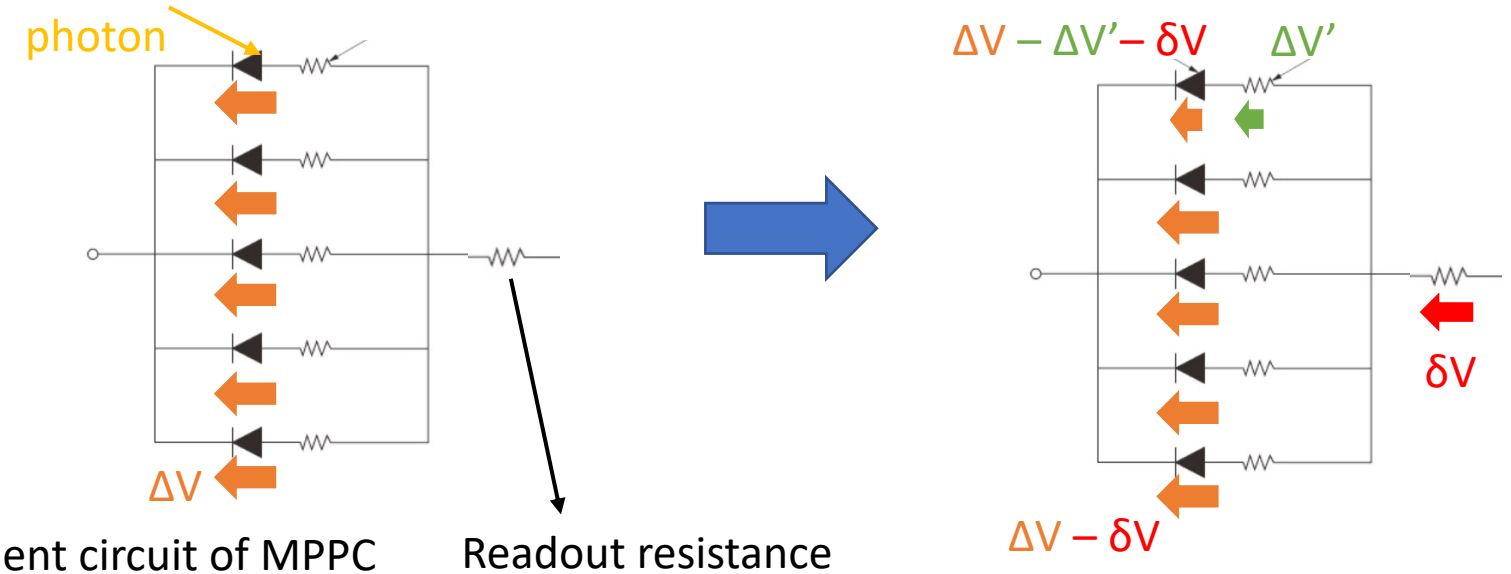
Operational principle of MPPC

- The gain is proportional to applied voltage
- When photon comes into a pixel, output constant charge

Cause of nonlinearity

- Voltage drop in an output pixel
- Voltage drop from readout resistance

Reduce MPPC gain
→ take time to recover

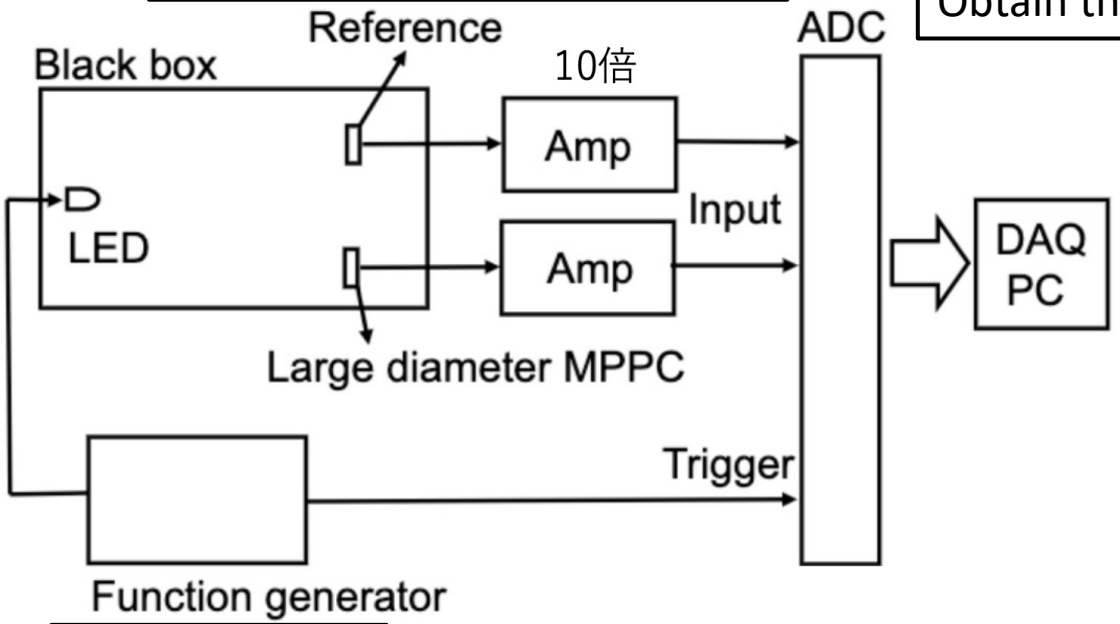


Equivalent circuit of MPPC

Readout resistance

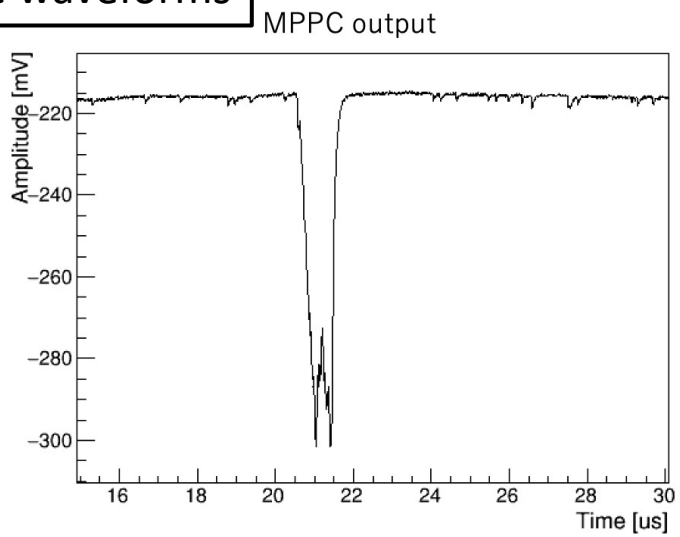
Measurement of MPPC nonlinearity

Reference detector: PMT
→ suppress its nonlinearity



Width: 1 us
Period: 100 Hz

Obtain the waveforms



Calibrate PMT output with MPPC output in small photon count
→ Estimate real photon count from PMT output

Estimation of radioactivity

Most serious BG-source isotope: ^{214}Bi

- From ^{238}U decay chain
- Emits a 2448 keV gamma

→ 0.4 % difference from the Q-value

Measurement using Ge detector was done

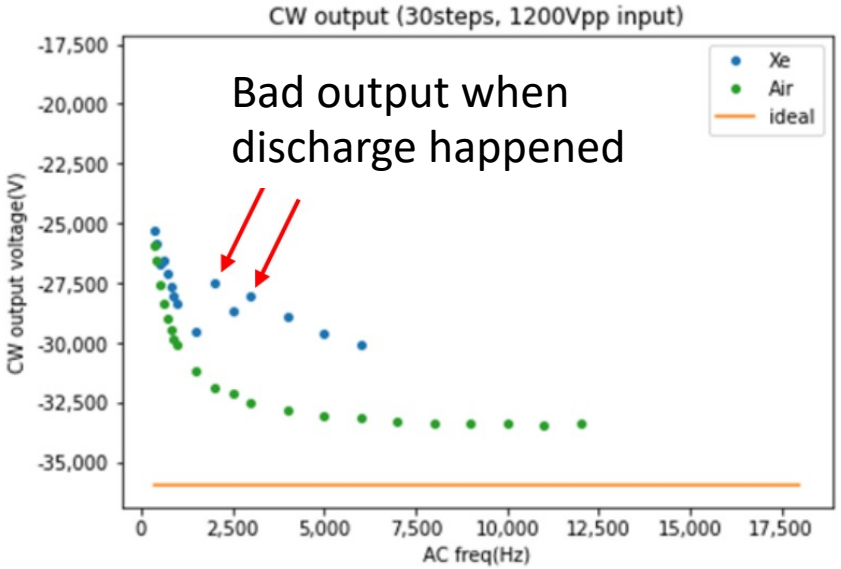
→ MPPC packages is too contaminated

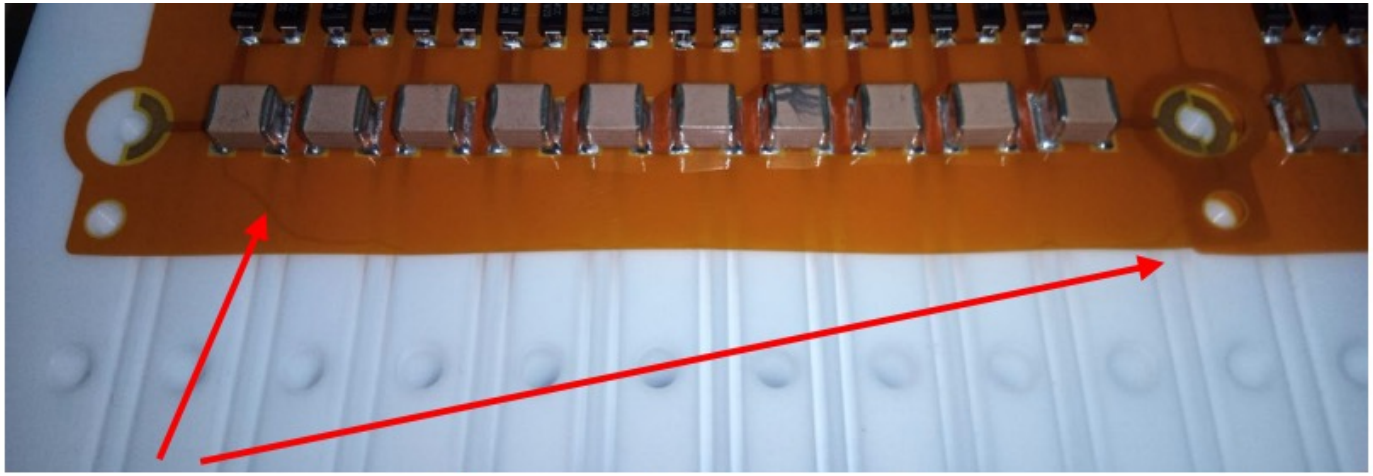
	Mass (kg)	Total activity of ^{214}Bi (^{238}U)
Pressure Vessel (stainless steal)	948	< 436 mBq *
ELCCs w/o MPPC packages	22	< 64.1 mBq
ELCC sustainers	34.7	< 40.1 mBq *
PMTs + PMT sustainers	13.4	< 103 mBq
MPPC Packages	1.9	> 60000 mBq

* The upper limit of ^{238}U activity in stainless steal refers to data measured by NEXT exp.

J. Martin-Albo et al, Journal of High Energy Physics, 159 (2016)

Detail of CW discharge problem

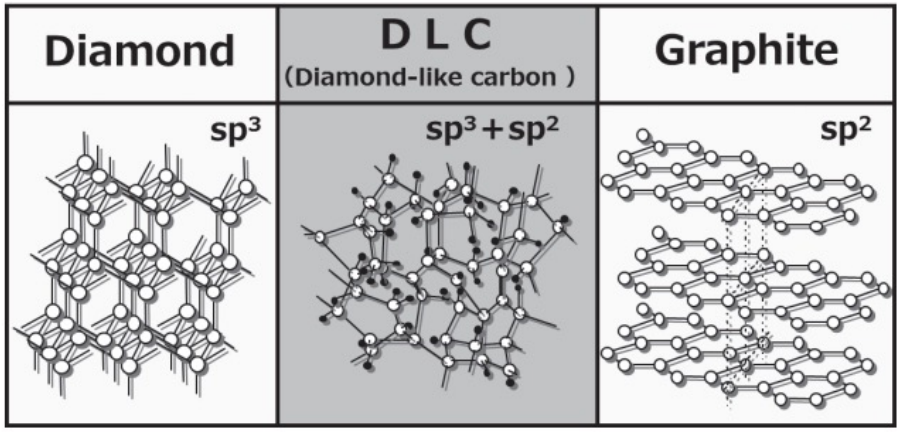




Discharge path:
Condenser → FPC edge → FPC connection point

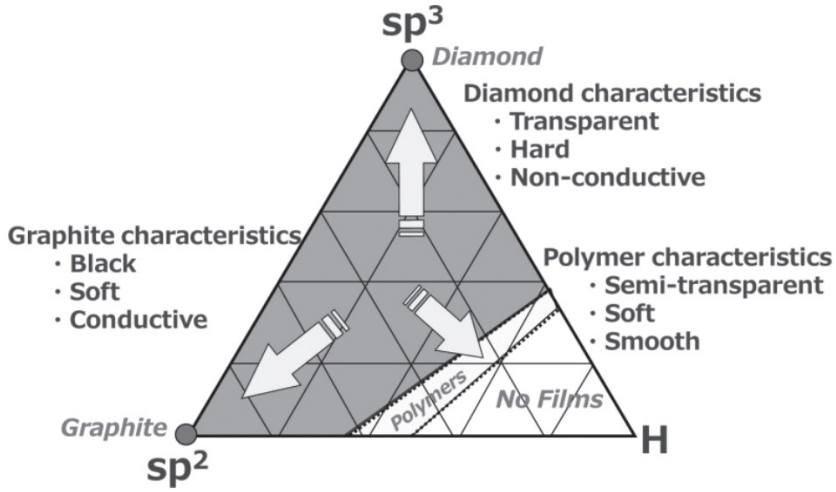
Diamond-like carbon

- Unique material which has both graphite and diamond structure



Structure of DLC

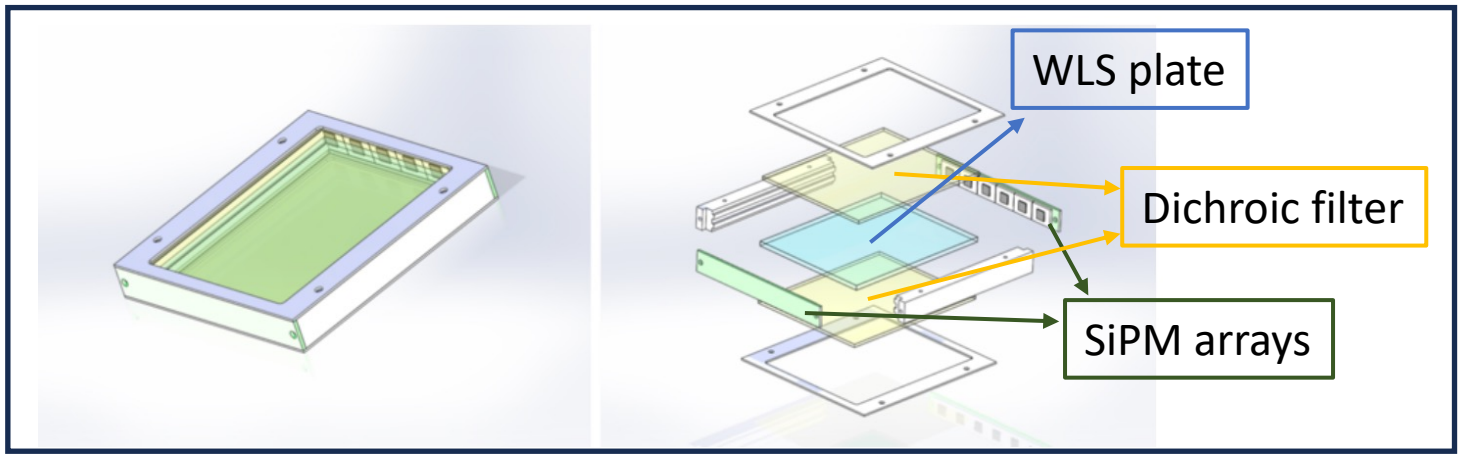
- Change its properties depending on the ratio of including structures.

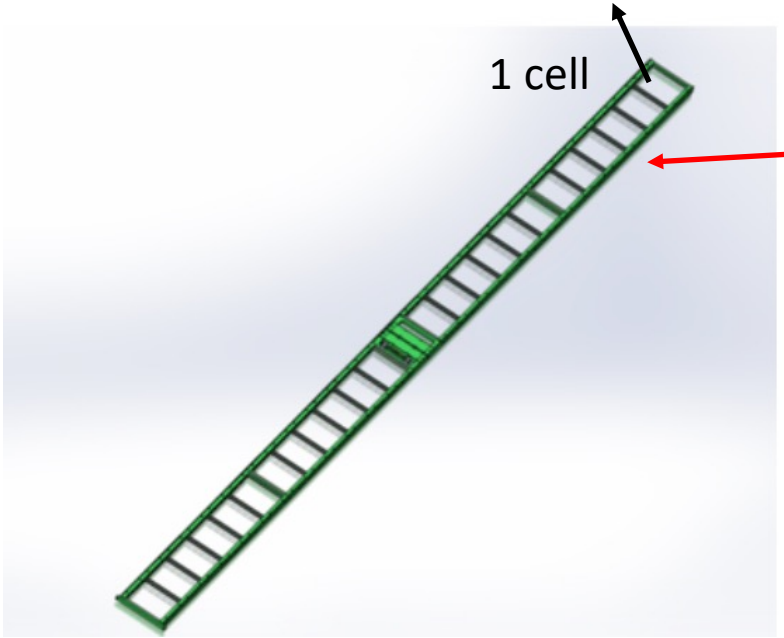


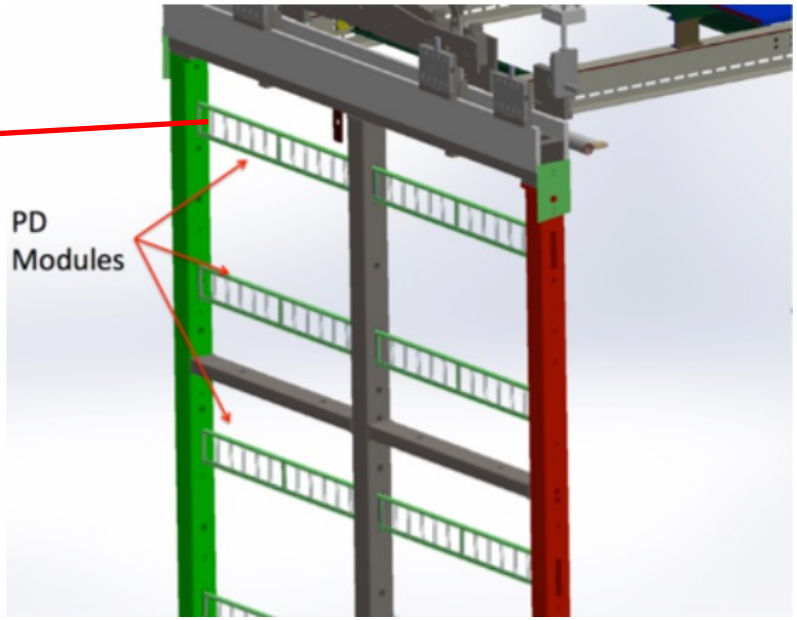
Properties of DLC (gray area)

https://sumitomoelectric.com/sites/default/files/2020-12/download_documents/E88-30.pdf

X-Arapuca in protoDUNE







Anode plane

B.Abi et al., *Volume I. Introduction to DUNE* (2020)

BG rejection using topology

Deep Learning

- Learning with simulated 0νββ and gamma-ray
- Signal acceptance: 27 %, BG rejection: 99.9996 % @ threshold 0.9 (assuming 2448 keV gamma-ray from ^{214}Bi as background)
- The DL performance can be evaluated by prototype real data