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

Junya HIKIDA, Kyoto University (Japan)

for the AXEL collaboration

20th February. 2025, VCI 2025

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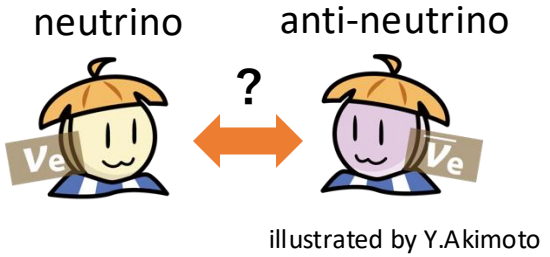
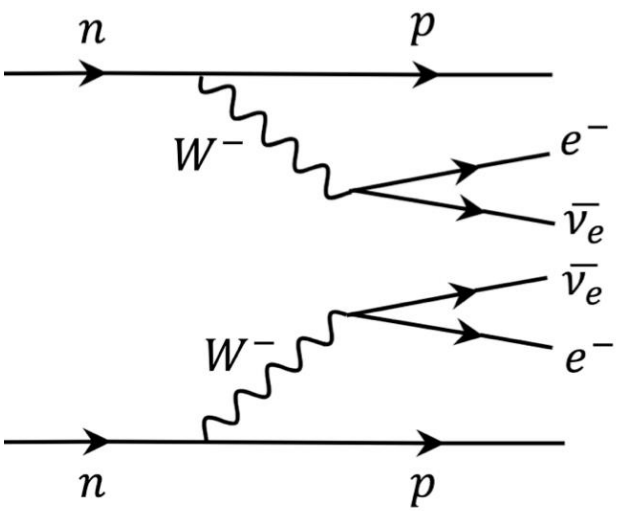
- Neutrinoless double beta decay
- AXEL experiment
- Results of 180L-size prototype
- R&D for 1000L-size detector construction
- Summary

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

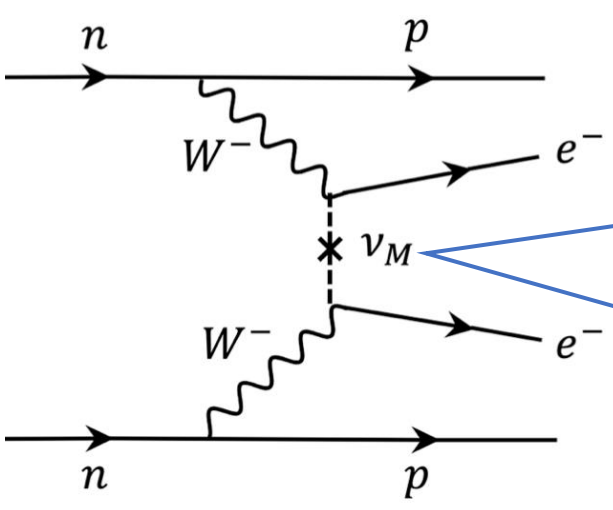
$0\nu\beta\beta$ can occur if <u>neutrino is the same as anti-neutrino</u>
called **Majorana** particle

Majorana nature of neutrino may be the origin of
- Too small mass of neutrino
- Matter-antimatter asymmetry of the universe



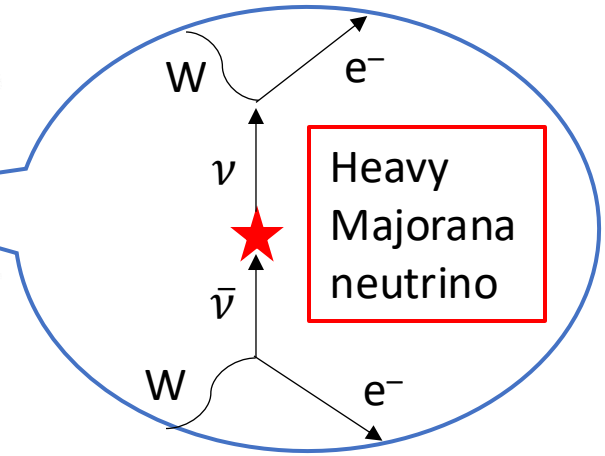


$2\nu\beta\beta$



$0\nu\beta\beta$

Type I seesaw mechanism



Lepton number violation
$\Delta L = +2$

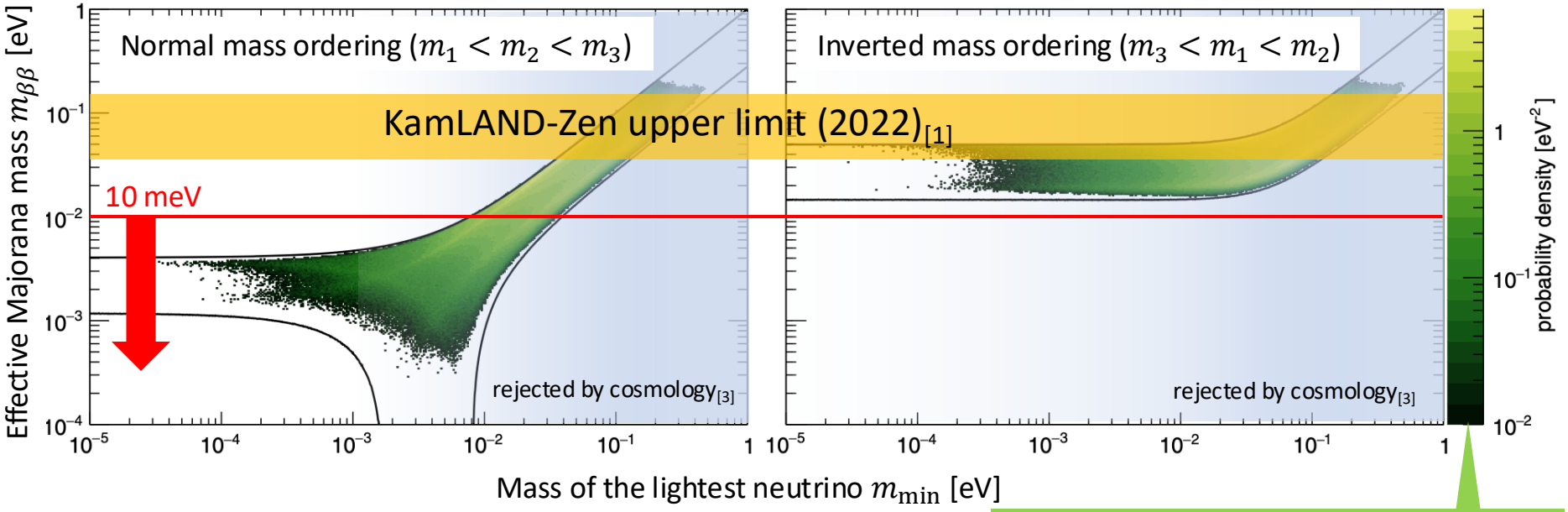
Status of $0\nu\beta\beta$ search

Relation of half-life time and effective Majorana mass: $T_{1/2}^{0\nu\beta\beta} \propto m_{\beta\beta}^{-2}$

→ Current upper limit of $m_{\beta\beta}$: 36-156 meV (model dependent)[1]

Toward $0\nu\beta\beta$ search in normal mass ordering region ($m_{\beta\beta}$<10 meV), more sensitive detector is necessary

Posterior distributions for $m_{\beta\beta}$ and m_{min}[2]



Posterior distribution given the knowledge on neutrino mixing parameters

[1]KamLAND-Zen Collaboration, PRL 130, 051801 (2023)
[2]M.Agostini, et. al., PRD 96, 053001 (2017)
[3]Particle Data Group: *Neutrinos in Cosmology, Neutrino masses*

Requirements for $0\nu\beta\beta$ search

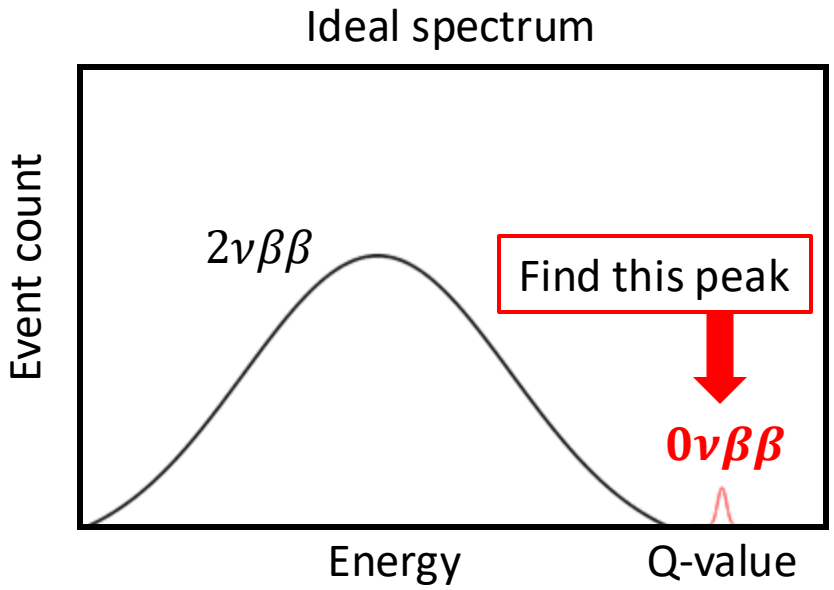
$0\nu\beta\beta$ is very rare: $T_{1/2}^{0\nu\beta\beta} > 2.3 \times 10^{26}\ years$ (90 % C.L.) for ^{136}Xe

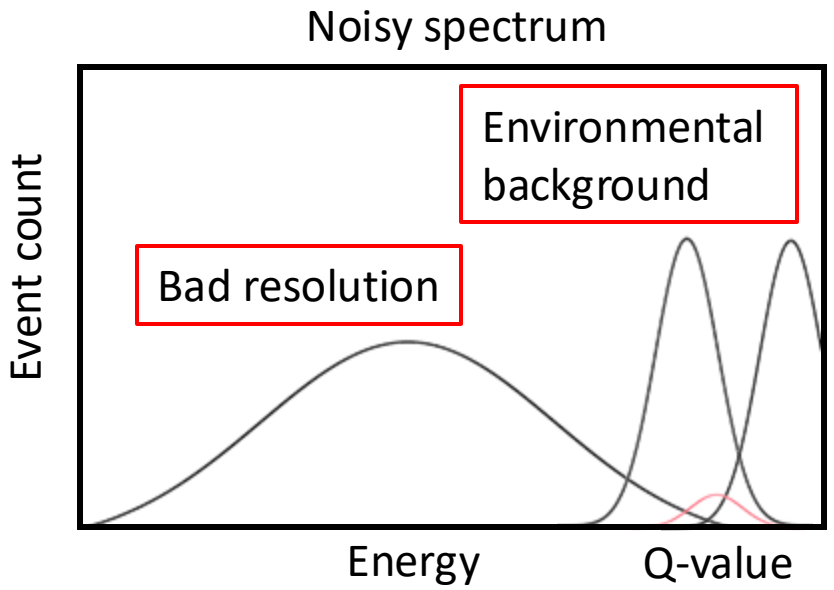
→ Collecting **large mass** and **reducing background** are required

To realize large mass, **scalable detector** is desirable

To realize background-free $0\nu\beta\beta$ search,

- **High energy resolution**
- **Distinction of environmental background**





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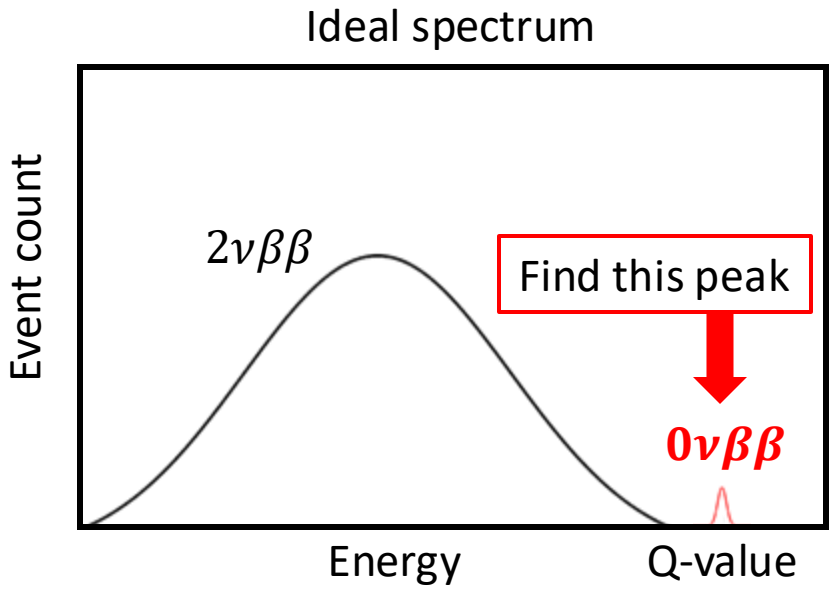
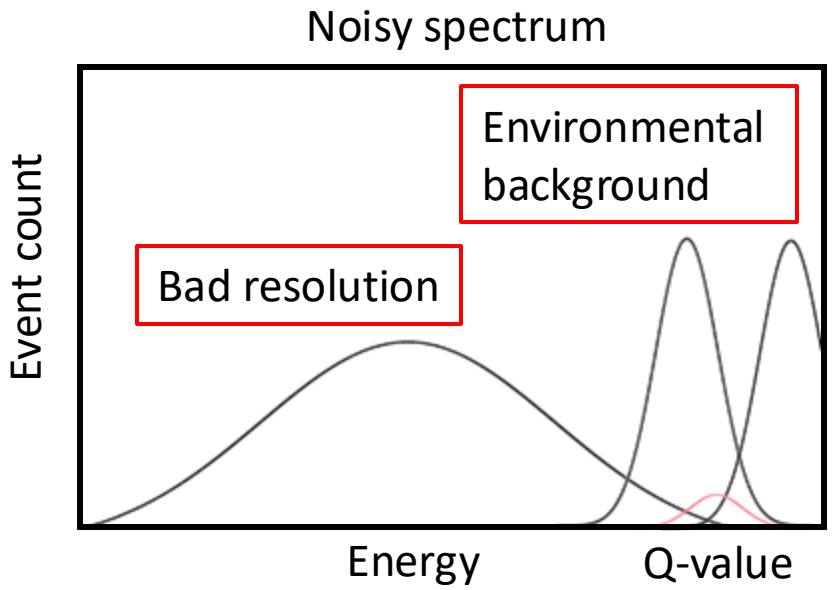
Xe gas TPC can meet all these requirements!





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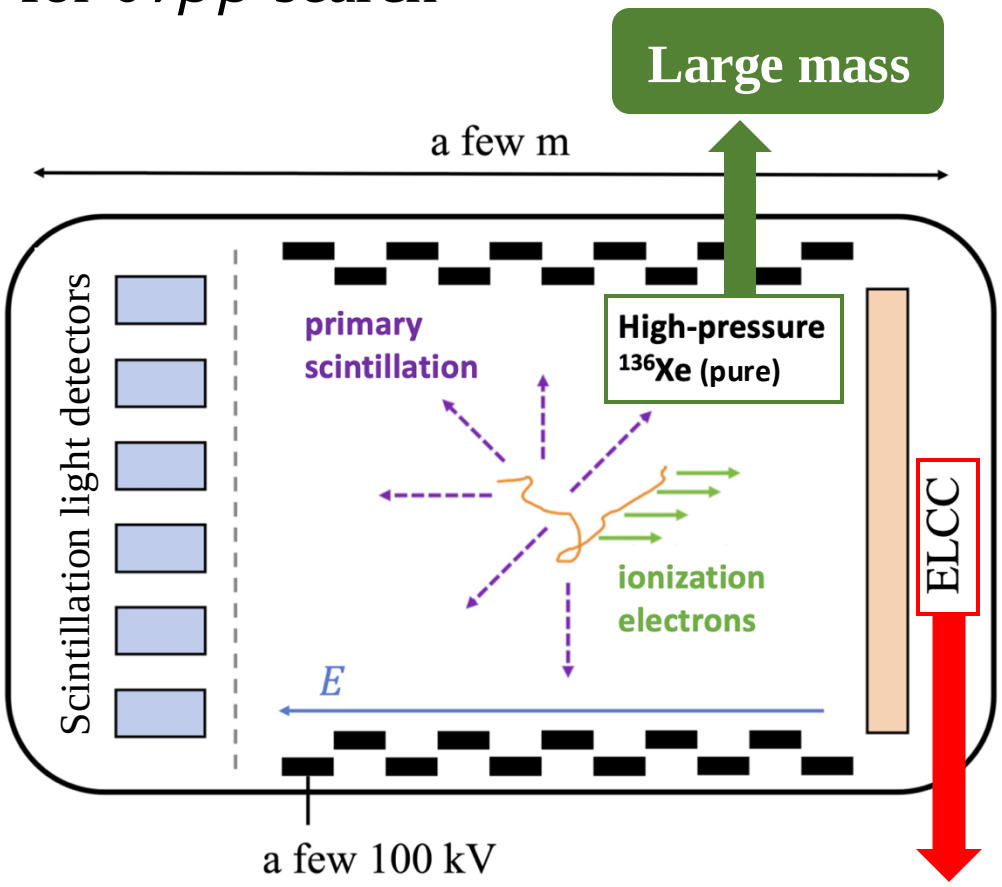
AXEL ~A Xenon ElectroLuminescence

High-pressure Xe gas Time Projection Chamber
for $0\nu\beta\beta$ search



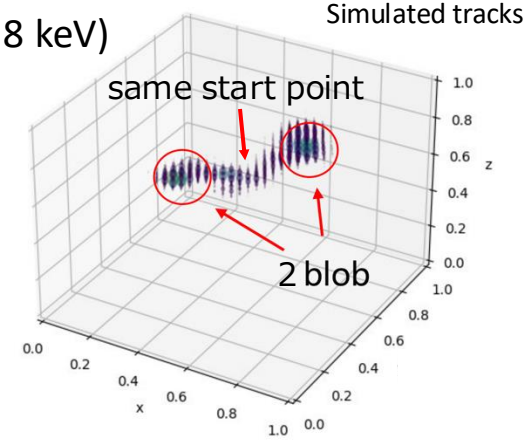
High energy resolution

Next page in details

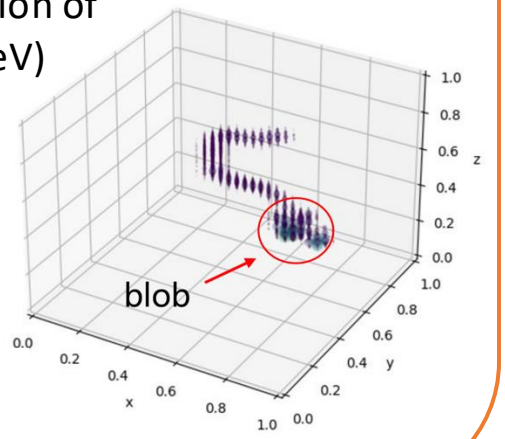
3D tracking for background rejection

$0\nu\beta\beta$ (2458 keV)

Simulated tracks



Photoabsorption of γ-ray (2615 keV)



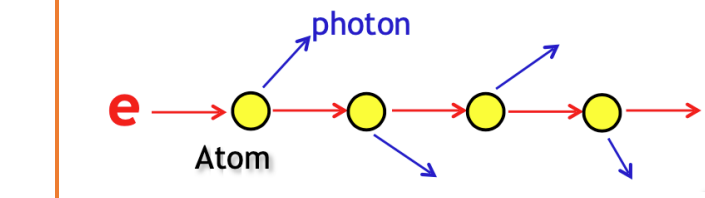
※blob: stopping point of charged particle

ELCC ~Electroluminescence Light Correction Cell

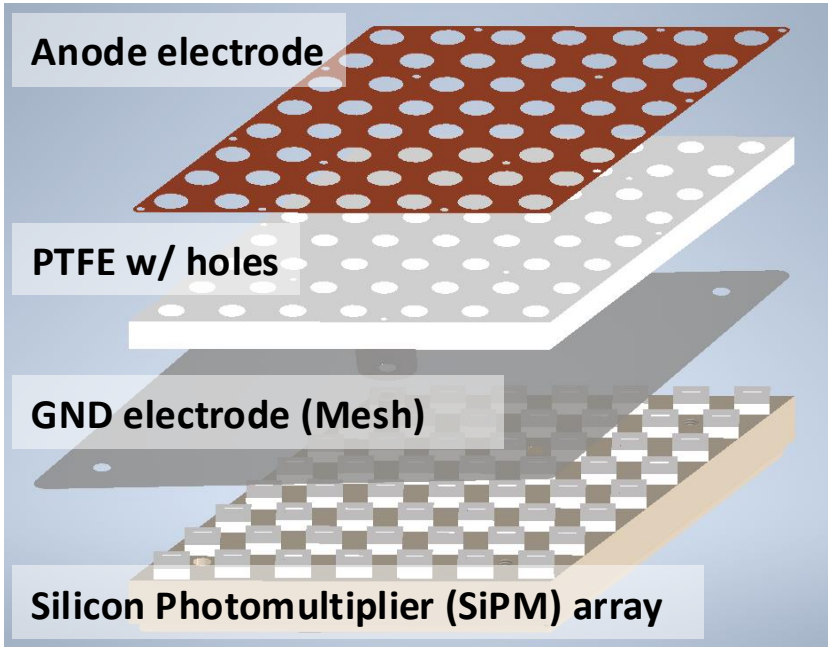
- Using electroluminescence (EL) process to suppress gain fluctuation

→ **High energy resolution**

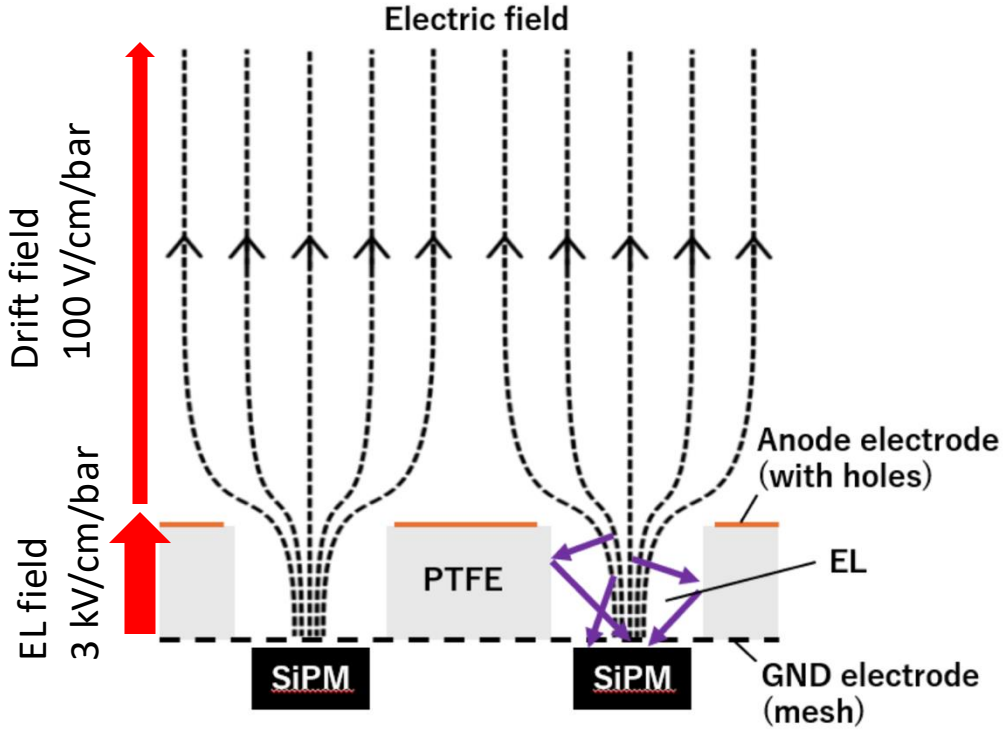
- Pixelated structure→ **Tracking**
- Rigid structure→ **Easy extension**



EL process:
# of photons ∝ # of electrons



Basic structure of ELCC



Detection principle of ELCC

Road map of AXEL experiment

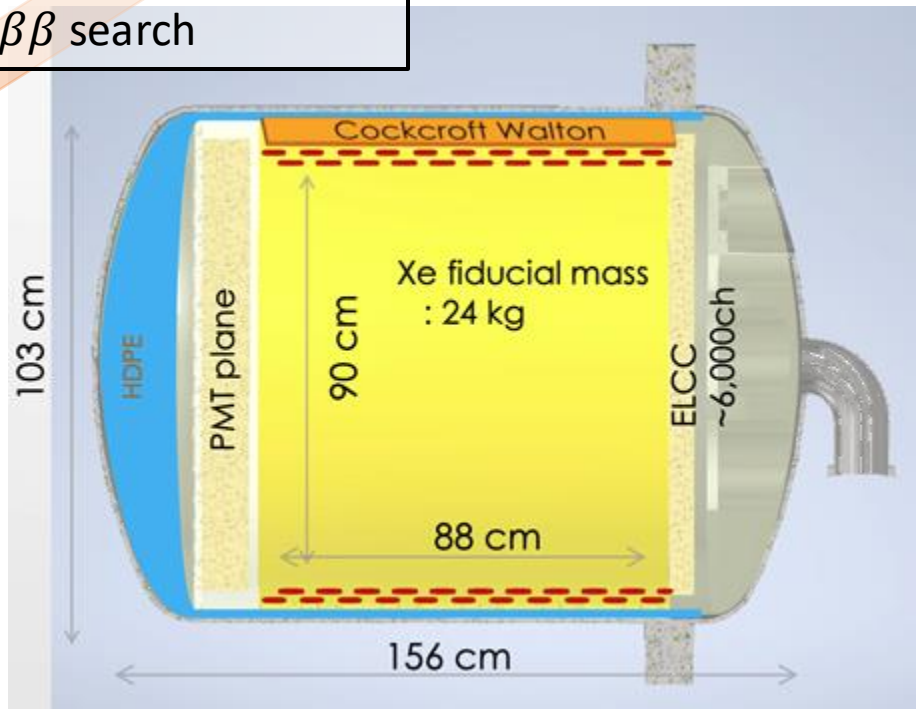
10-ton detector

1-ton detector

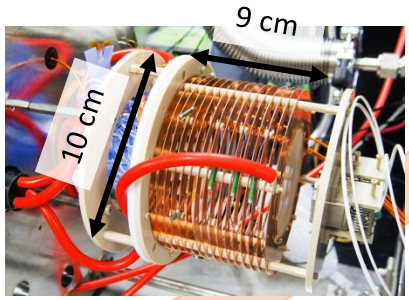
200-kg detector

1000L detector (2022-)
- ~20 kg Xe
- $0\nu\beta\beta$ search

@Kamioka underground

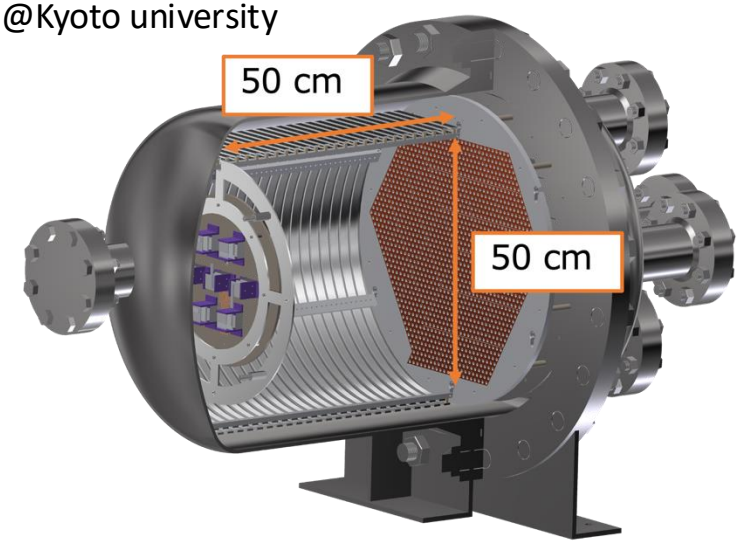


180L prototype (2018-)
- ~4.5 kg Xe
- Scalable structure
- R&D of components



10L prototype (2014-2018)
- ~50 g Xe
- ELCC proof of principle

@Kyoto university



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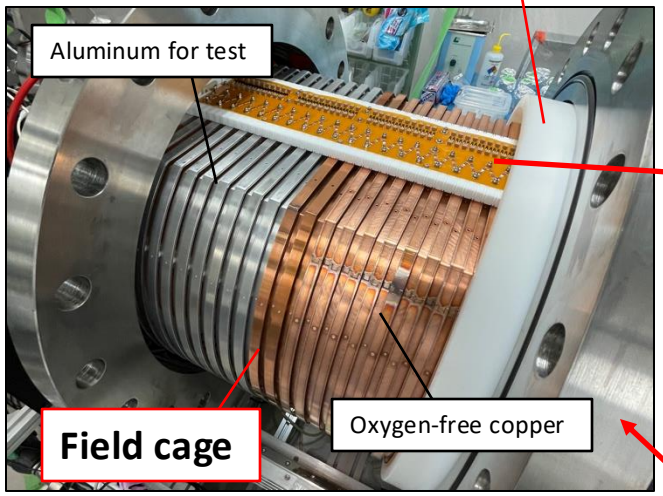
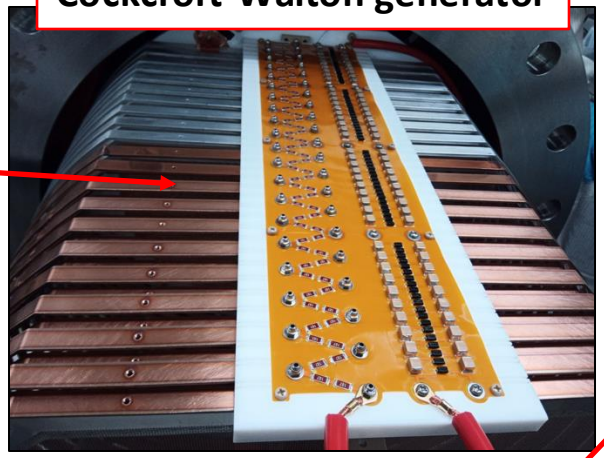
Summary of the latest results is here:
https://arxiv.org/abs/2501.08554

Overview of 180L prototype components

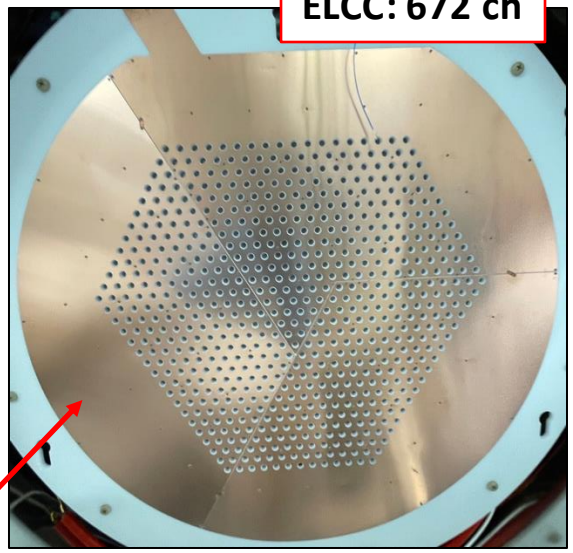
High-density polyethylene cylinder



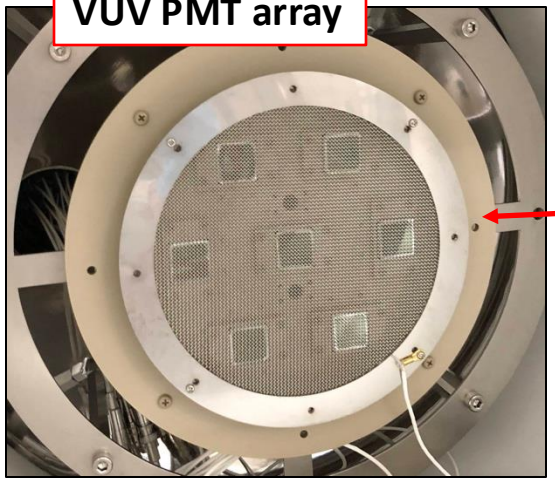
Cockcroft-Walton generator

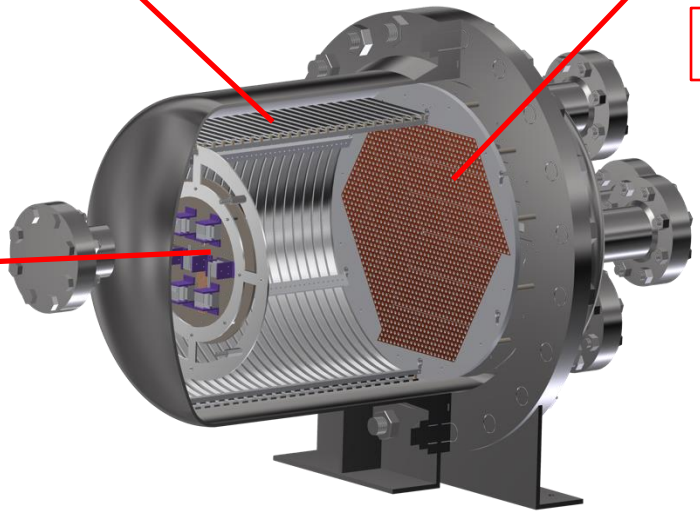


ELCC: 672 ch

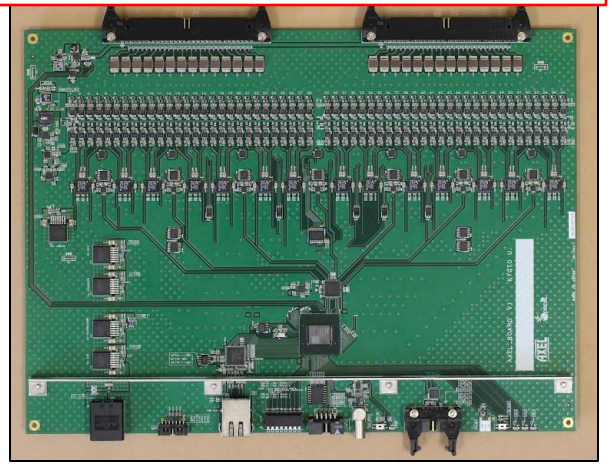


VUV PMT array



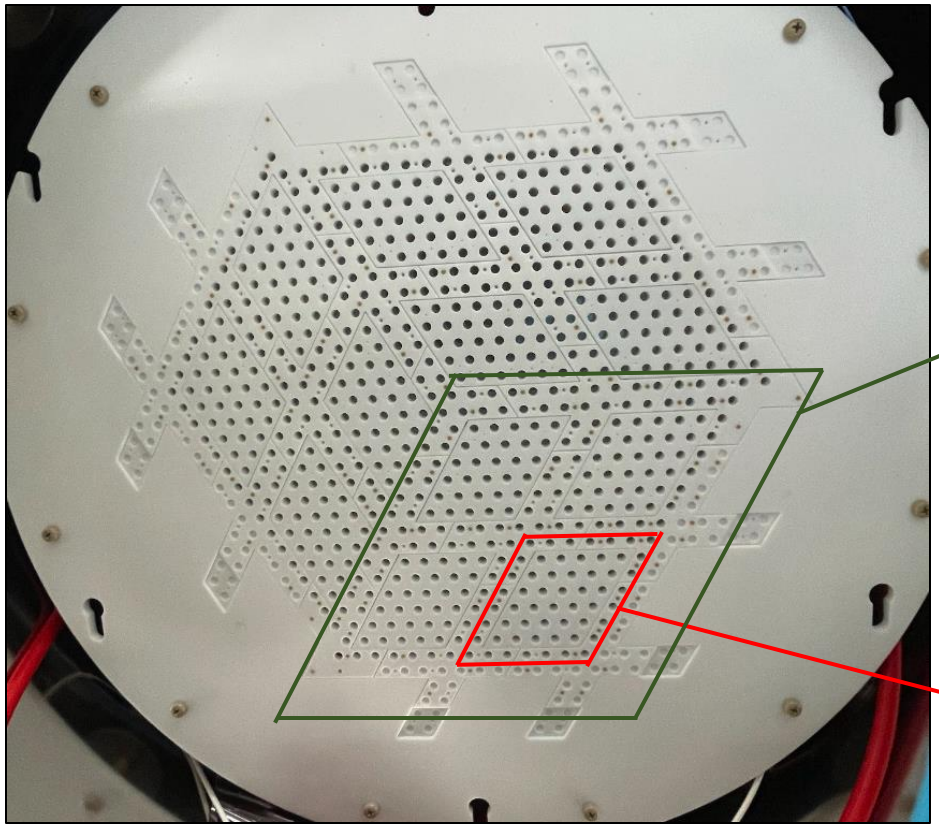


Readout electronics: 56ch/board

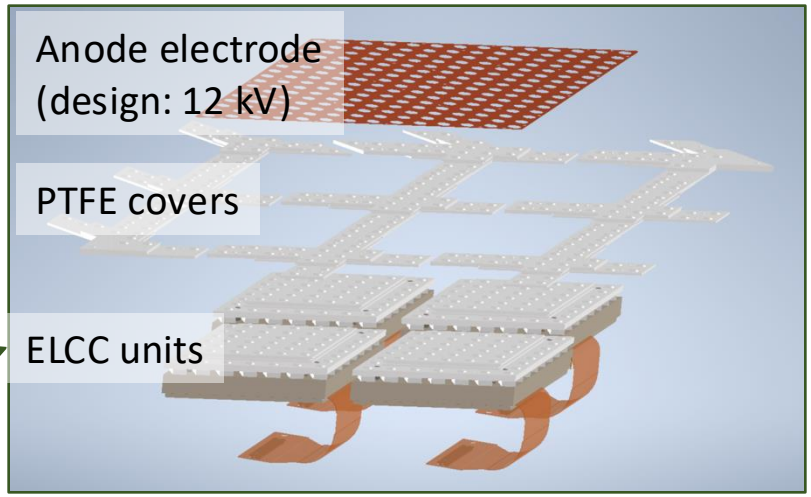


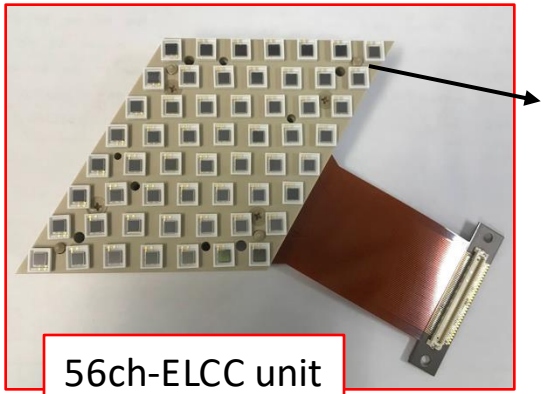
ELCC structure of 180L prototype

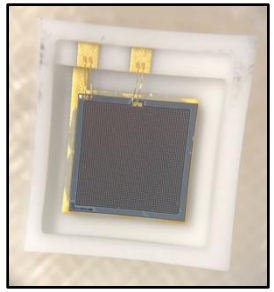
- SiPM: VUV-sensitive Multi-Pixel Photon Counter (VUV-MPPC)
- Unit structure for scalability
- No direct gap b/w units to suppress creeping discharge



12-unit ELCC before attaching anode electrodes







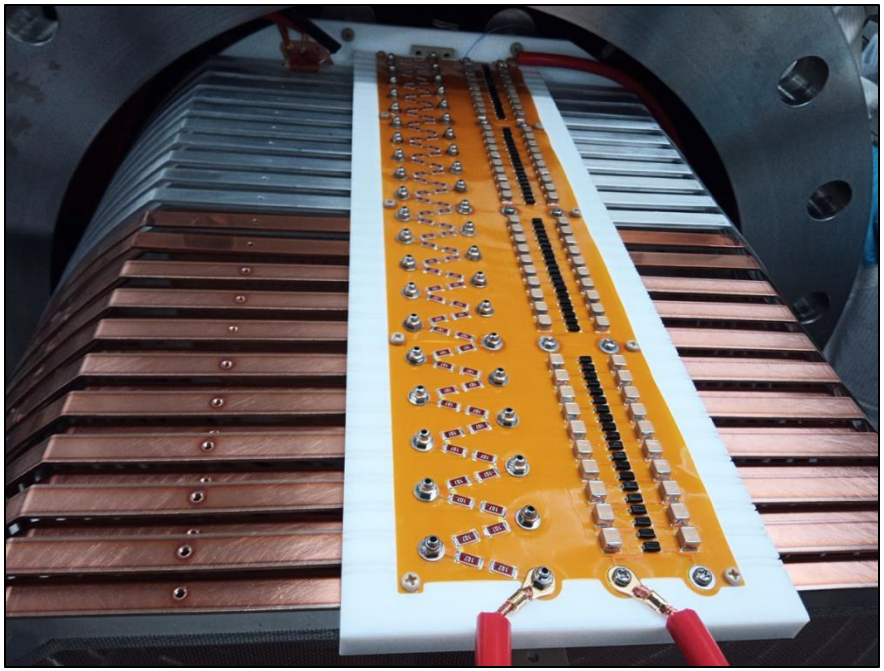
VUV-MPPC
(S13370-3050CN)

Cockcroft-Walton generator

Generate high DC voltage (>30 kV) from low AC input (~1 kV_{pp})
→ No necessity of feedthrough for high pressure and ultra-high voltage

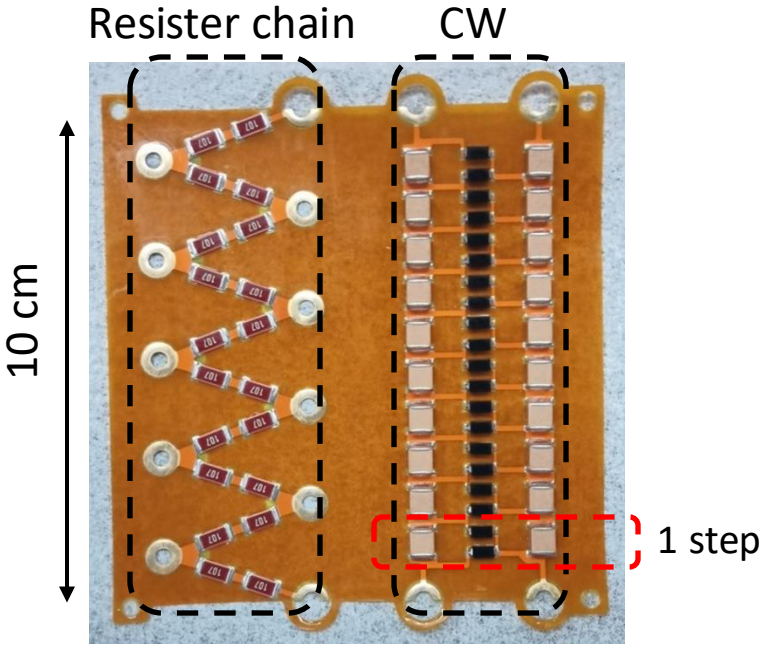
Achievements

- 34.3 kV in Xe gas at 6.8 bar (input: 1.2 kV_{pp}, 6 kHz)
- Negligible noise effect to MPPC waveform



40-step CW generator in 180L prototype

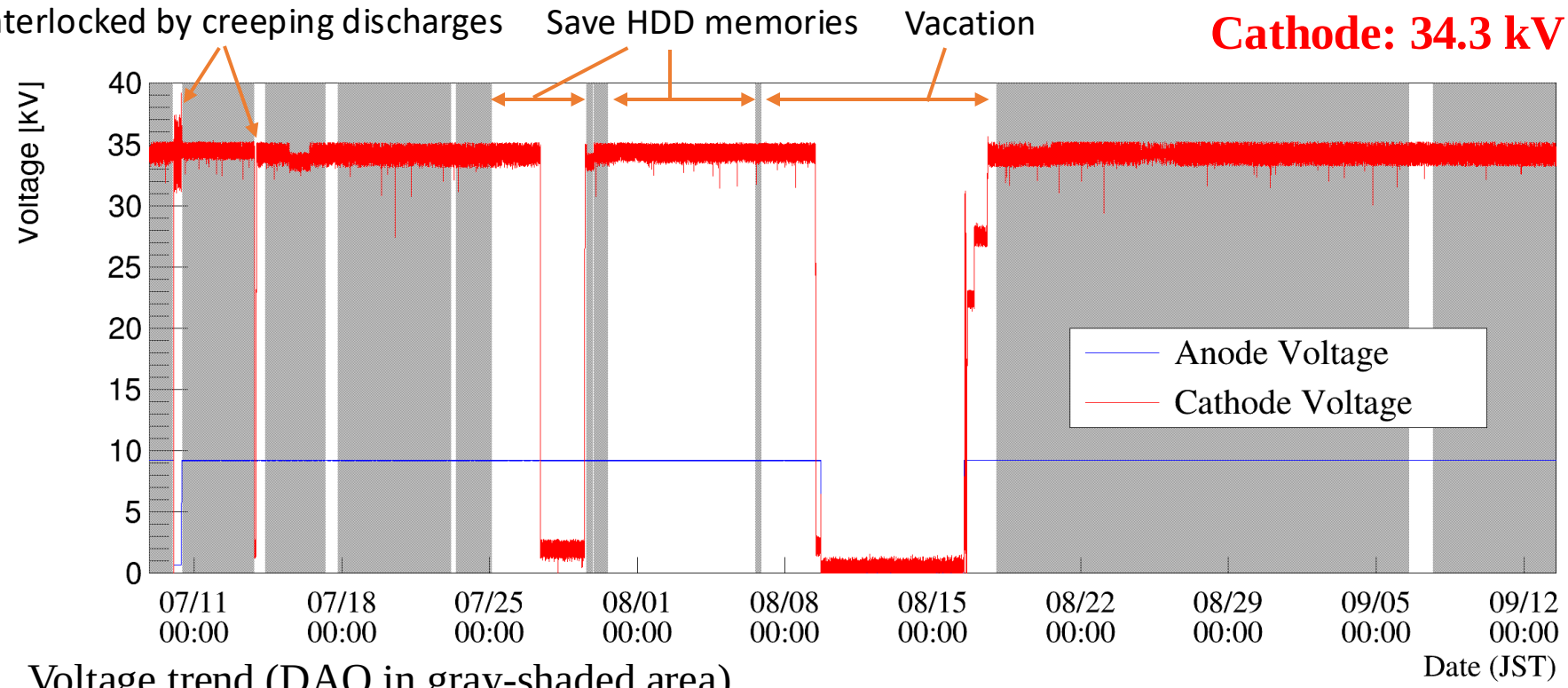
First demonstration for TPC in the World!



Measurement

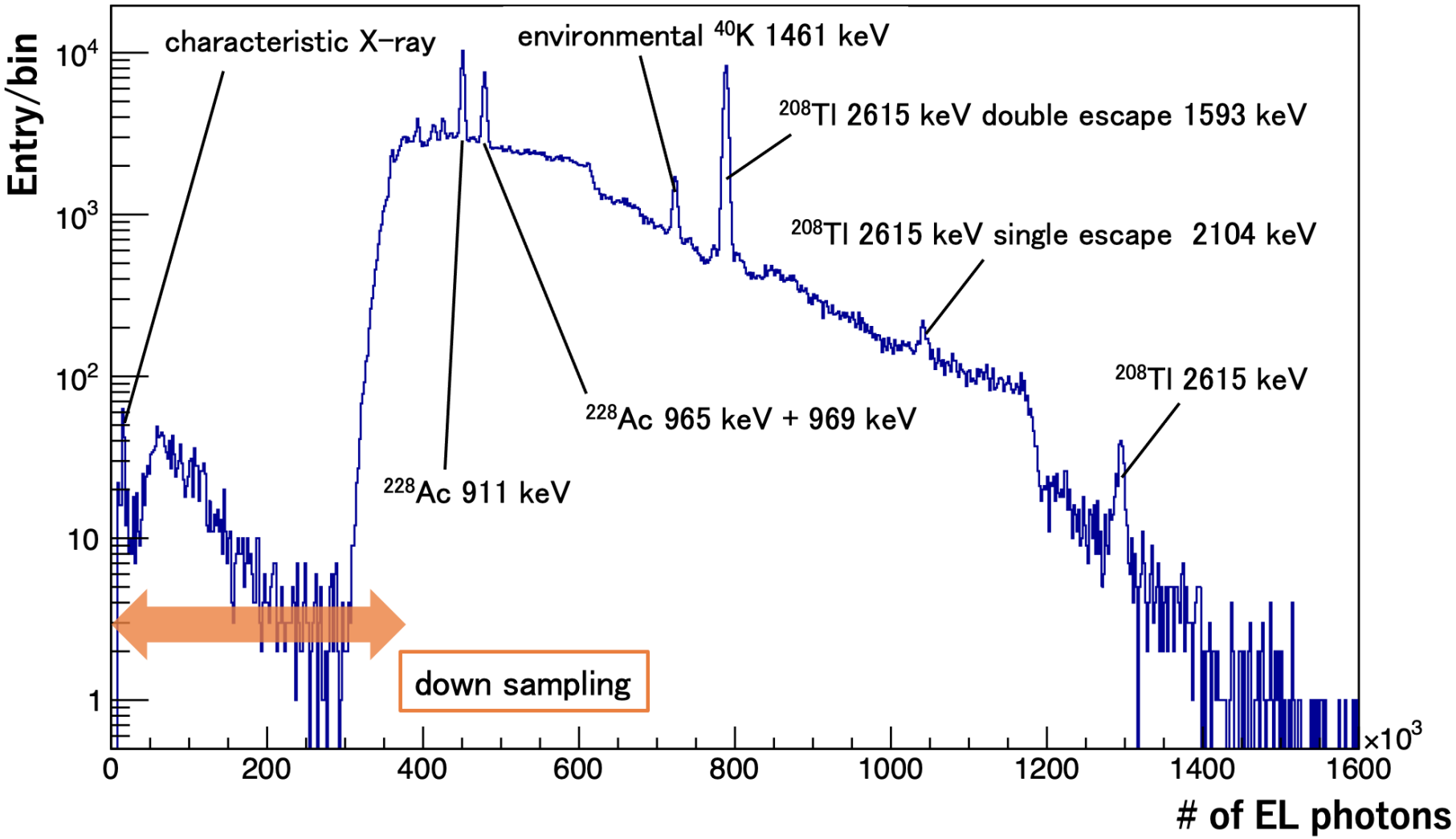
- RI source: Thorium-doped tungsten rods (γ-ray of Th series)
- Xe gas pressure: ~6.8 bar
- Voltage: 90 % of our design (EL: 2.7 kV/cm/bar, Drift: 90 V/cm/bar)
- Measurement period: ~2 months

Anode: 9.18 kV
Cathode: 34.3 kV



Voltage trend (DAQ in gray-shaded area)

Energy spectrum

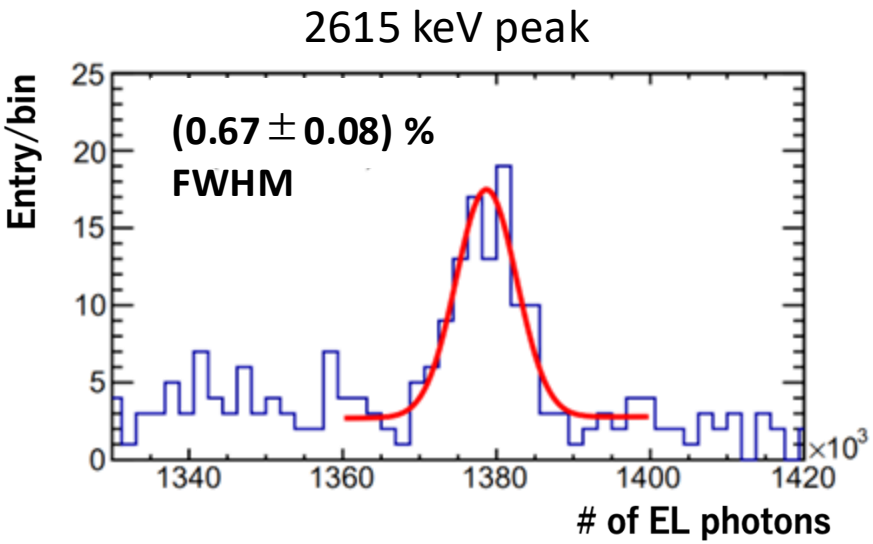


Energy resolution

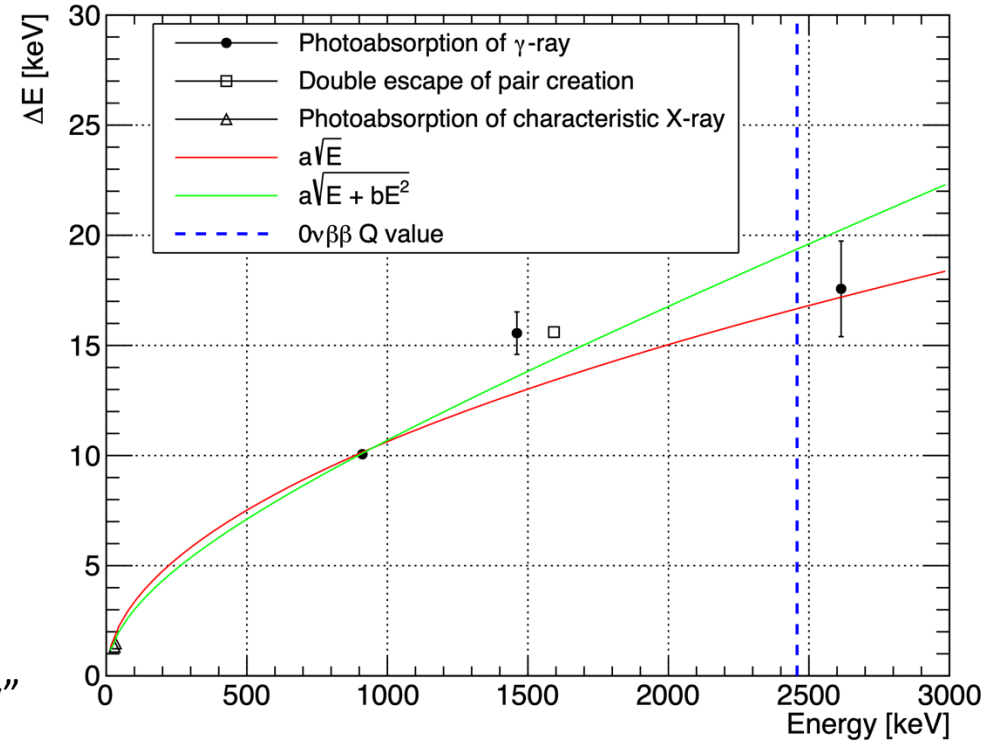
- FWHM resolution @2615 keV: (**0.67 ± 0.08) %** (1σ error)
- Extrapolated FWHM resolution @Q-value (2458 keV)

  $a\sqrt{E}$: **(0.68±0.01) %**, $a\sqrt{E + bE^2}$: **(0.79±0.08) %**

→ **Better than 1 % FWHM resolution around Q-value**



※ Only points of "Photoabsorption of γ-ray" are used for extrapolation fit



Extrapolation of resolution

Breakdown of resolution @2615 keV

z mis-reconstruction	0.28 %
Initial ionization (inevitable)	0.25 %
Fluctuation of the EL generation and detection	0.20 %
Error in EL gain correction	0.18 %
Error in time variation correction	0.18 %
Recombination	0.17 %
Variation in time bin of time variation correction	0.12 %
Offset of the baseline	≦0.11 %
Error in z dependence correction	≦0.06 %
Accuracy of the MPPC recovery time	≦0.03 %
Fluctuation of the attachment	≦0.02 %
Estimation total	(0.54-0.55) %
Data total	(0.67 ± 0.08) %

Research on additional contributions is ongoing!

"Fluctuation of the MPPC nonlinearity" (0.18% @1.8 $MeV_{[4]}$) is being evaluated

[4]M.Yoshida et al., PTEP, 2024(1), 013H01 (2024)

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Due to low Scinti. det. efficiency
→ Developing new detector (p26)

Limited by stat. of EL photon
→ Can be improved with larger area MPPC (p23)

Developing new correction methods
→ Expect less than 0.1 %

Can be improved with higher drift field (100 V/cm/bar) by more discharge resistive structure

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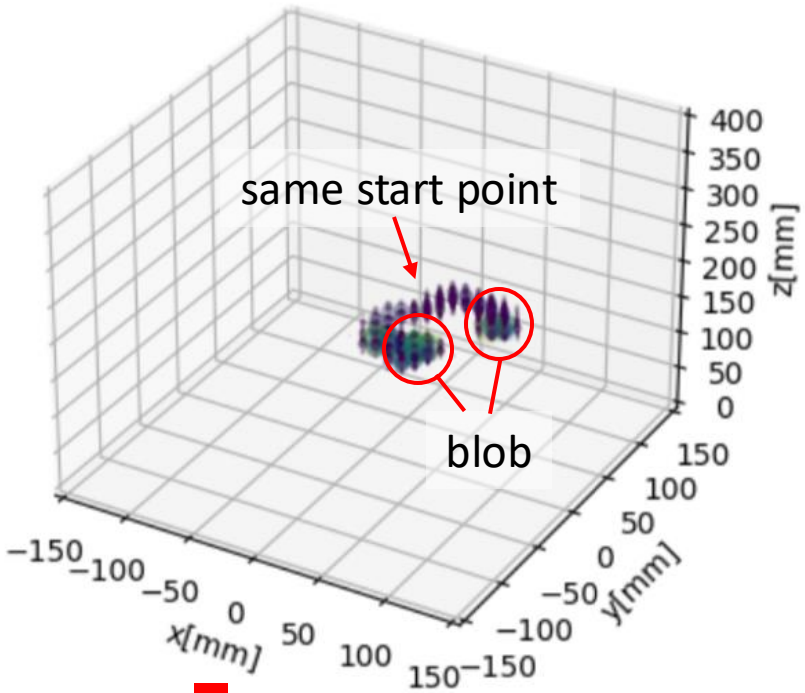
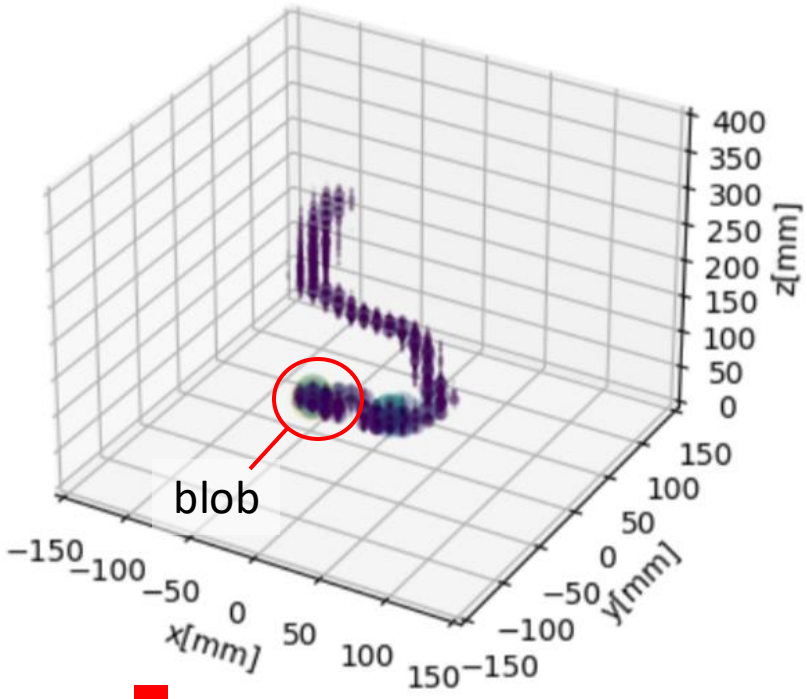
3D track reconstruction (Real data)

Measured track around 1593 keV
(Double escape, i.e. e^+e^- creation)



Same features as
double beta decay signal

Measured track around 2615 keV
(Photoabsorption of γ-ray from ^{208}Tl)



Main background tracks
in $0\nu\beta\beta$ search window

Machine learning (ML)

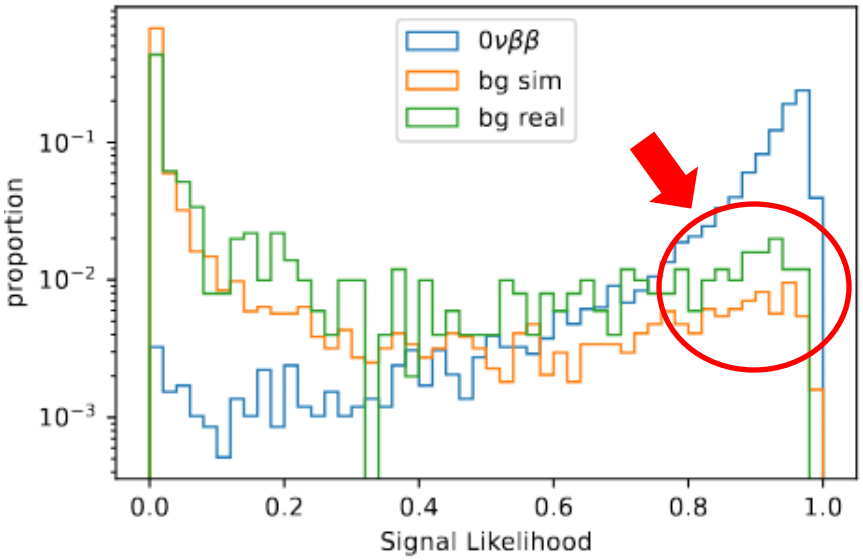
- Distinguish background tracks by track pattern with ML
- Check the performance using measured (real) tracks

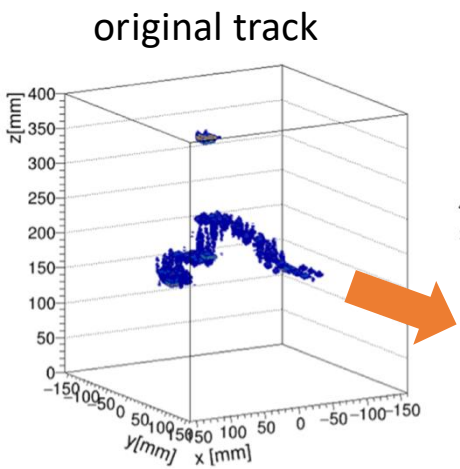
→ Higher signal likelihood than simulation…

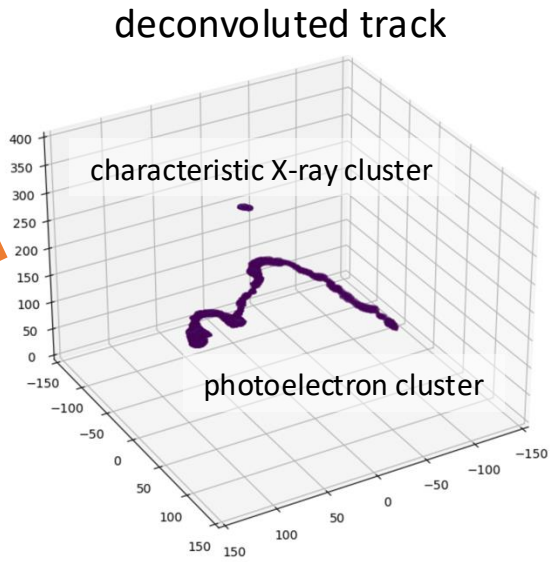
Further study is continuing!

- Developing method based on Richardson-Lucy deconvolution[5] to obtain precise tracks before diffusion

→ Expect to improve ML selection using deconvoluted tracks







[5]L. B. Lucy, Astronomical Journal, Vol. 79, p. 745 (1974)

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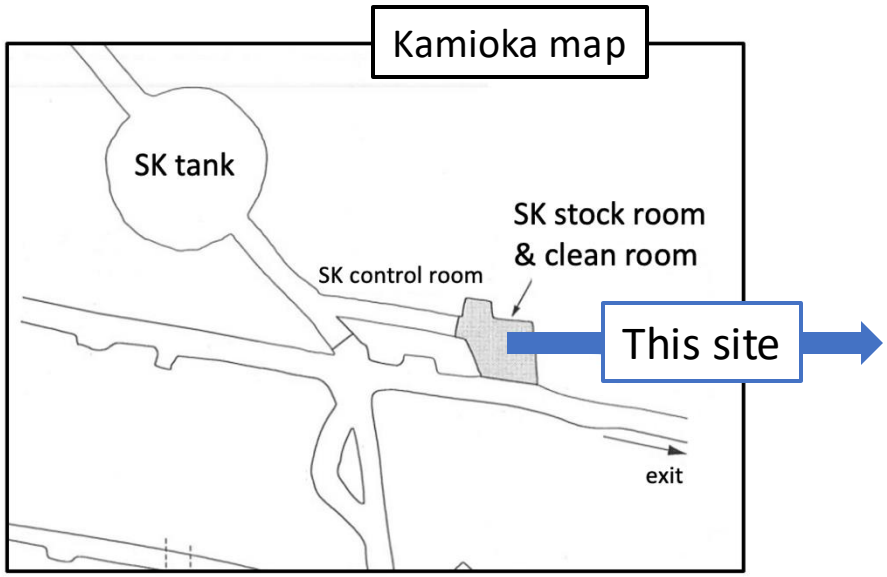
1000L detector project

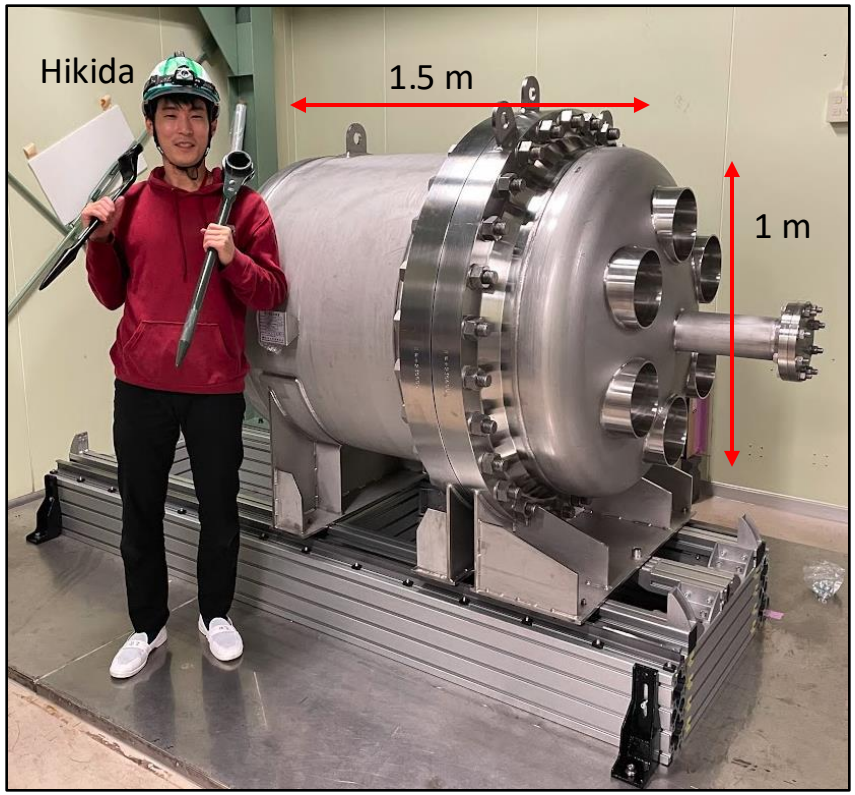
Physics target

- First $0\nu\beta\beta$ search with AXEL detector
- Demonstration of great background rejection ability

Site: Kamioka observatory of ICRR

- ~1000 m underground to reduce cosmic ray track accumulation
- Vessel of 1000L detector was installed in 2023





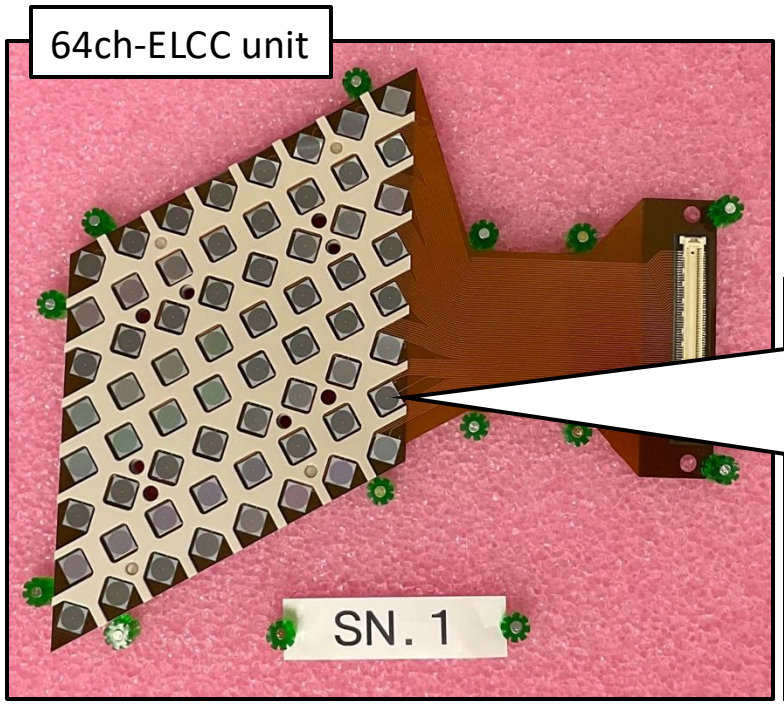
New ELCC unit

- 64 channels in a unit
- Round-shape (ϕ4.7 mm) MPPC with larger detection area

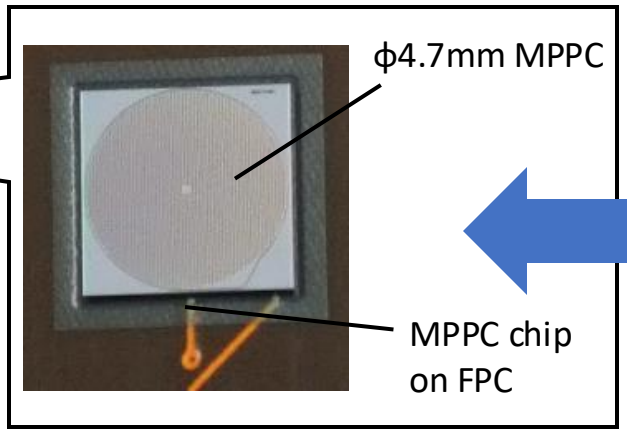
→ Increase statistics of EL photon ※Diameter of ELCC holes: ϕ4.5 mm

- Mount the MPPC chip directly on flexible printed circuit (FPC)

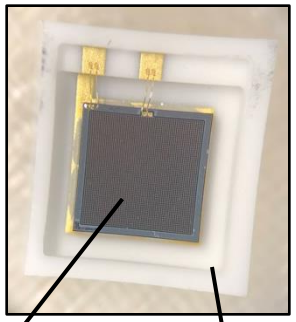
→ Remove ceramic package containing a lot of RI sources



Performance evaluation is planned for next summer with 180L prototype

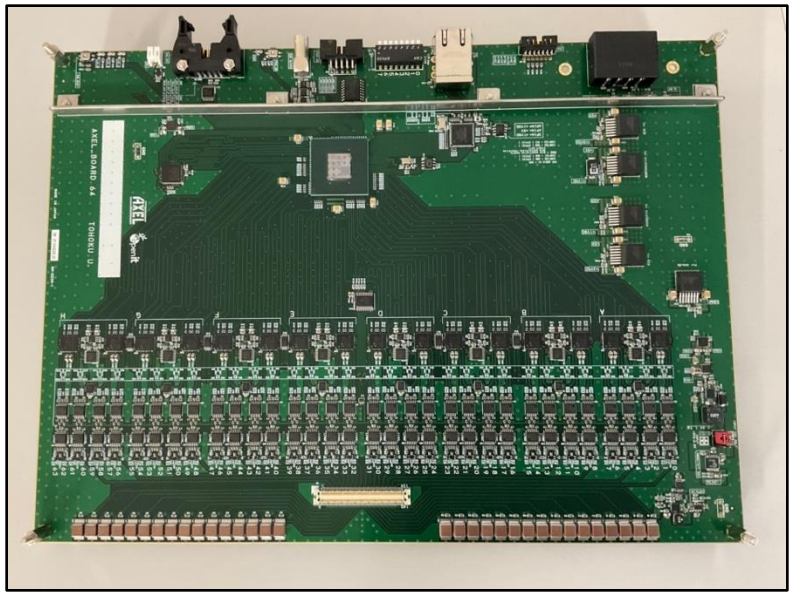


MPPC on 56ch-ELCC unit

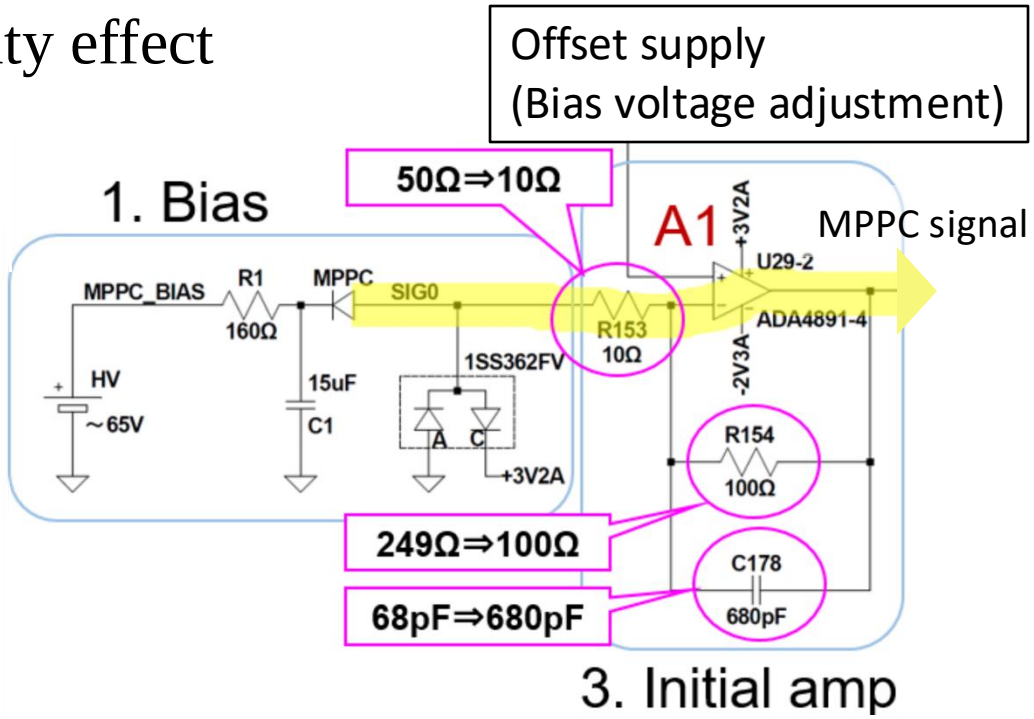


Readout electronics

- 64 ch/board, 5 MS/s for EL signal readout, multiplexed 40 MS/s high gain for 1 p.e. calibration
- Adjust bias voltage of each MPPC to align gain
- DC coupling to avoid waveform (max: 150 μs) distortion
- Input impedance is changed from 50 Ω to 10 Ω to suppress MPPC nonlinearity effect



Readout electronics for 64ch-ELCC unit



Readout circuit

Cockcroft-Walton generation

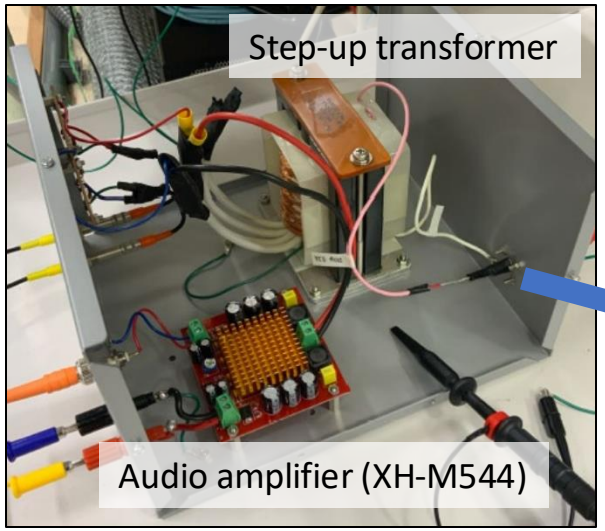
- Design value: 76.4 kV
- Develop high-power AC power supply to increase efficiency of CW output

→ **76 kV achieved in atmosphere** (input: 1.8 kV_{pp}, 13 kHz)

- Need to suppress voltage drop by ripple

→ Symmetrical CW generator[6]

Self-built
AC power supply →



Function generator

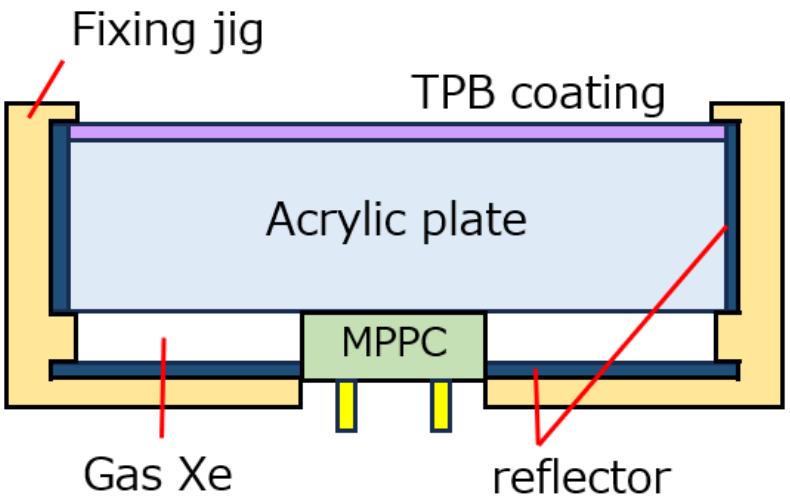
[6]M.Ruzbehani, Journal of Electrical and Computer Engineering, 2017, 4805268 (2017)

Scintillation detection

Low detection efficiency of high-pressure-tolerant VUV-PMT due to small detection area (~0.7 photon/PMT @Q-value) causes mis-reconstruction of *z* position

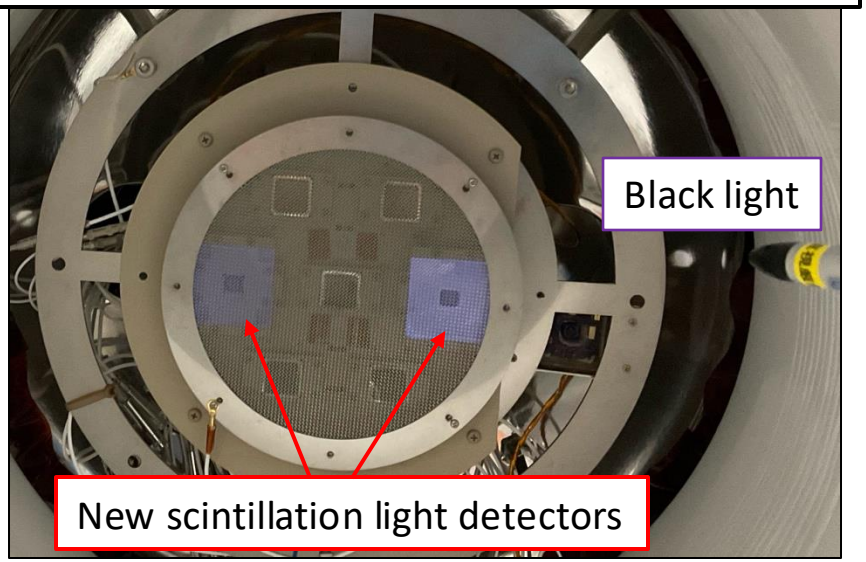
→ Developing new scintillation light detector

- Wavelength-shifter (TPB)+ Acrylic plate + MPPC (S13360-6075PE)
- Larger detection area: 20.5×20.5 mm^2 → 50×50 mm^2
- Expect 11 photon/plate @Q-value



Drawing of new scintillation light detector

Evaluate the performance with 180L prototype



- Neutrinoless double beta decay
- AXEL experiment
- Results of 180L-size prototype
- R&D for 1000L-size detector construction
- Summary

Summary

- AXEL aims to search for $0\nu\beta\beta$ using high-pressure Xe gas TPC.

- 180L prototype has demonstrated great ability of AXEL detector.
  - ✓Scalable structure
  - ✓High voltage generation with Cockcroft-Walton generator inside vessel
  - ✓Resolution: (0.67 $\pm$ 0.08) % FWHM @2615 keV
  - ✓Reconstruction of 3D electron tracks
  - ✓Background rejection by track pattern with machine learning

- R&D for 1000L detector construction is in progress.
  - ➢ 64ch-ELCC unit with new MPPC and electronics
  - ➢ High voltage generation with Symmetrical Cockcroft-Walton generator
  - ➢ New scintillation light detector

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

Reference list

[1]KamLAND-Zen Collaboration, PRL 130, 051801 (2023)

[2]M.Agostini, et. al., PRD 96, 053001 (2017)

[3]Particle Data Group: *Neutrinos in Cosmology* , *Neutrino masses*

[4]M.Yoshida et al., PTEP, 2024(1), 013H01 (2024)

[5]L. B. Lucy, Astronomical Journal, Vol. 79, p. 745 (1974)

[6]M.Ruzbehani, Journal of Electrical and Computer Engineering, 2017, 4805268 (2017)

Summary of 180L-size prototype results:
https://arxiv.org/abs/2501.08554

Back up

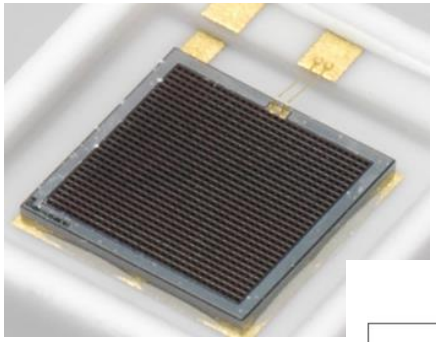
MPPC ~Multi-Pixel Photon Counter

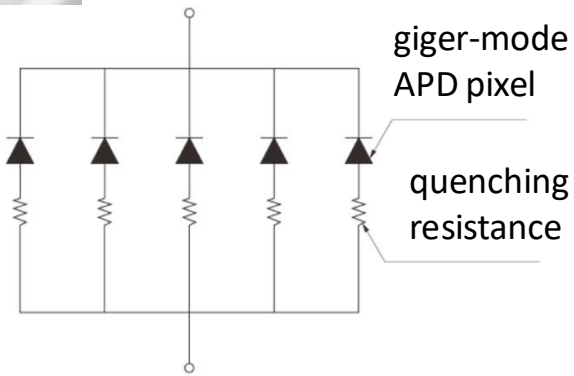
- Produced by Hamamatsu Photonics
- Arrange a lot of pixels in parallel
- Operated by applying higher voltage than breakdown voltage

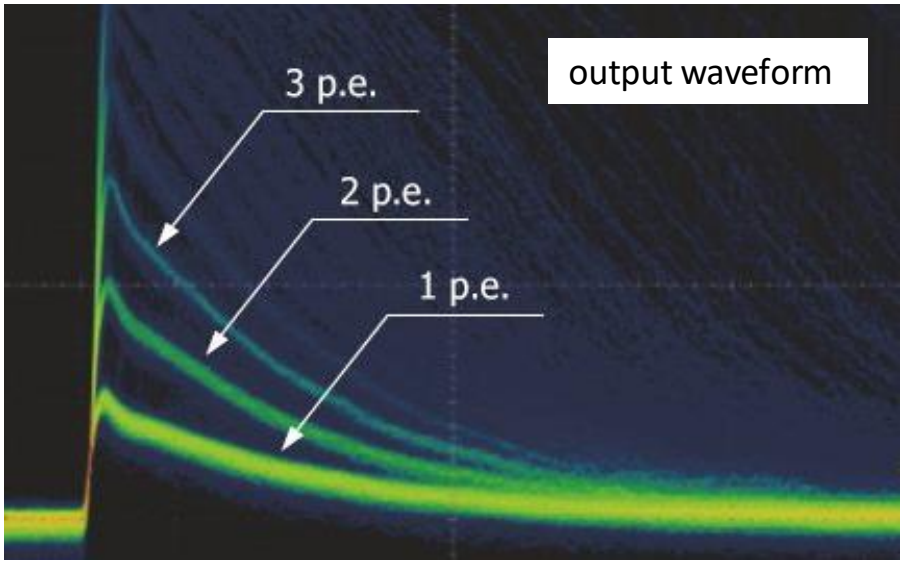
→ Output charge is proportional to over voltage

- Constant charge output in 1 pixel detection

→ Count # of detected photon as # of output pixel







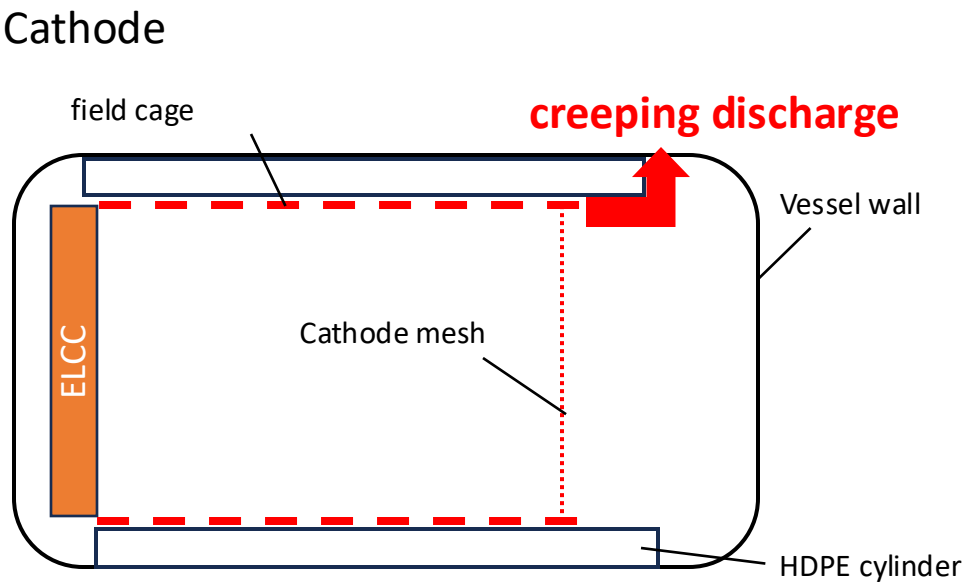
Creeping discharge in 180L prototype

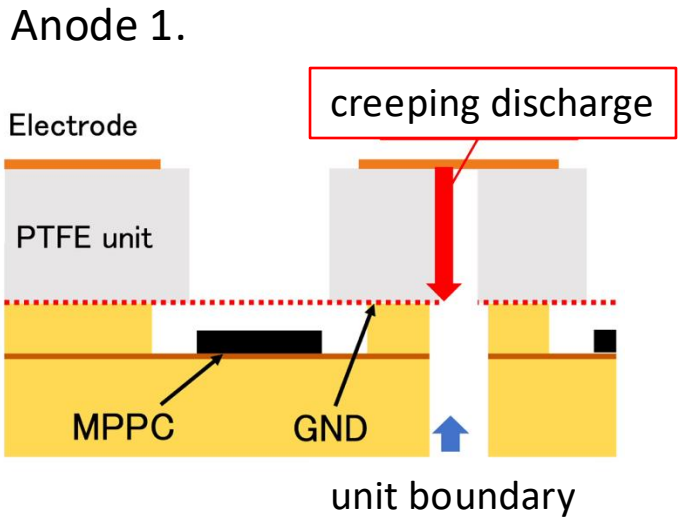
Anode side

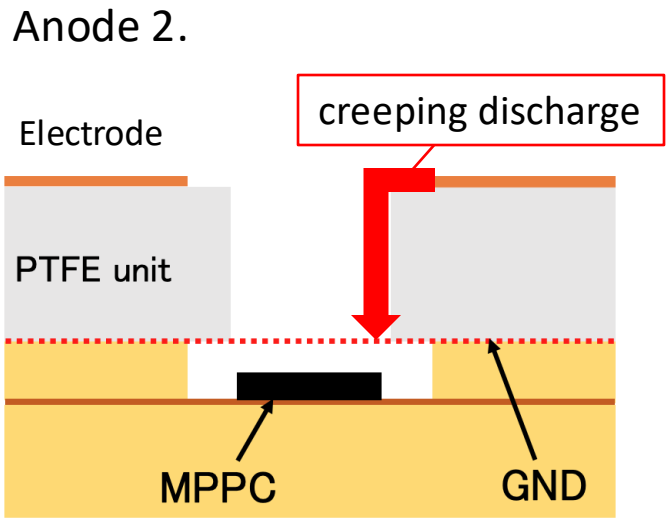
1. Gap b/w units
2. ELCC holes directly

Cathode side

- Cathode to vessel along HDPE surface







Countermeasures for creeping discharge

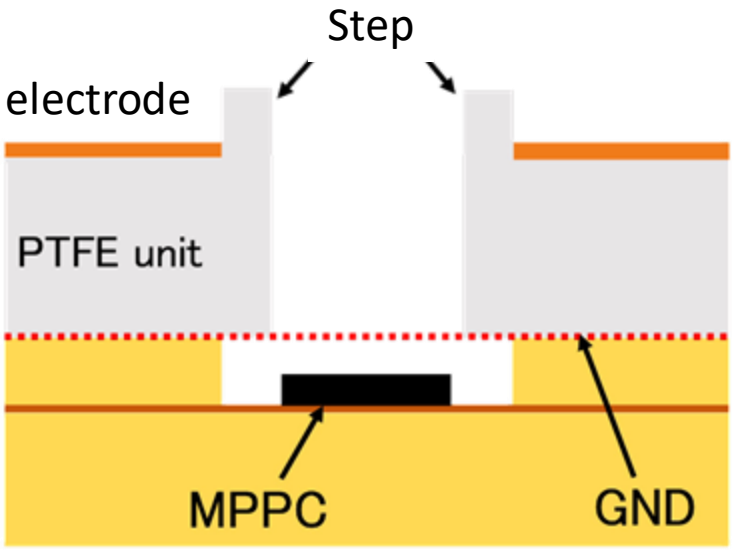
Anode side

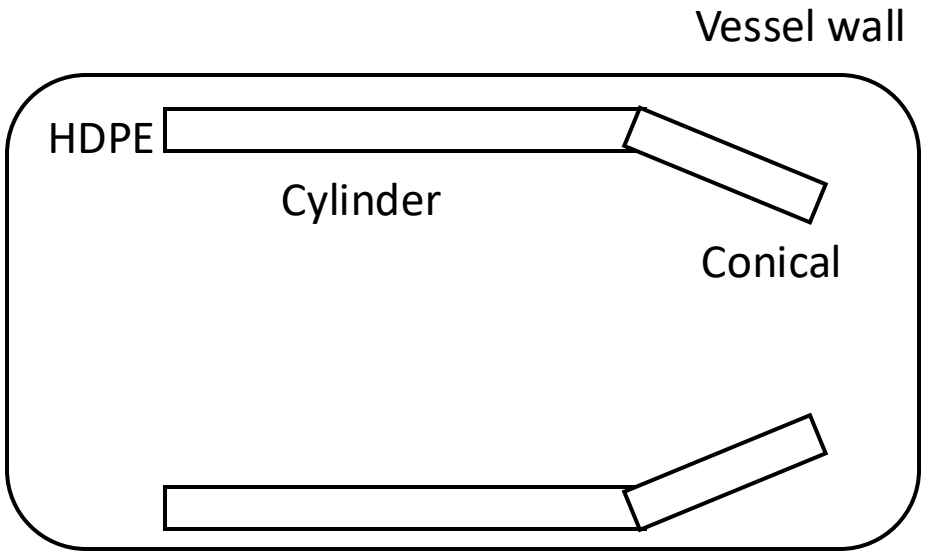
1. Gap b/w units → No gap structure (p13)
2. ELCC holes directly → Plan to structure with steps around holes

Cathode side

- Cathode to vessel along HDPE surface

→ HDPE with "cylinder + conical at the end" structure with many grooves to extend discharge path





Principle of CW generator

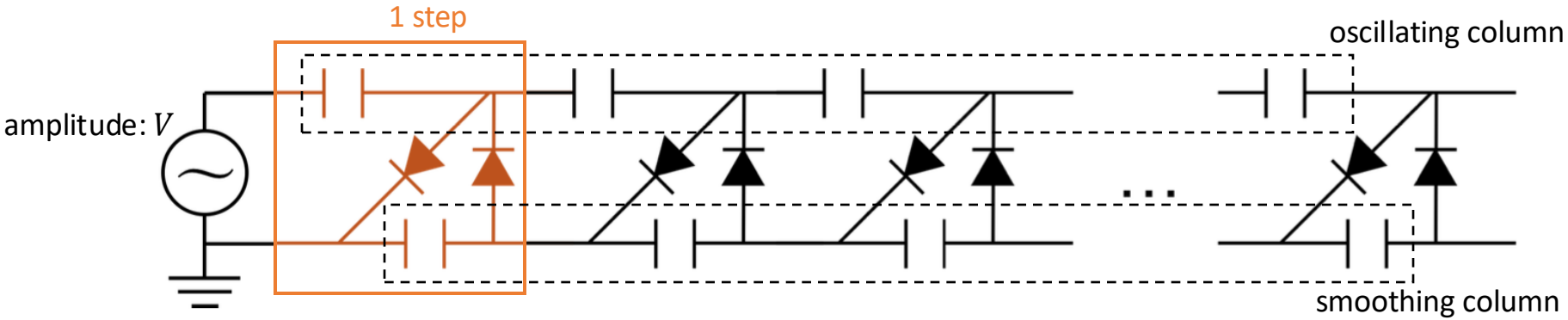
- 1 step composed of 2 capacitors and 2 diodes
- Voltage oscillation of capacitors in oscillating column supply charges to capacitors in smoothing column

→ Ideal output voltage: $2NV$ N: number of steps

- Voltage drop occurs by discharge of capacitors in smoothing column due to ripple effect:

$$\Delta V = \frac{I}{fC}\left(\frac{2}{3}N^3 + \frac{1}{2}N^3 + \frac{1}{3}N\right)$$

I: current in resister chain
f: frequency of input AC
C: capacitance



Drawing of Cockcroft-Walton circuit

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

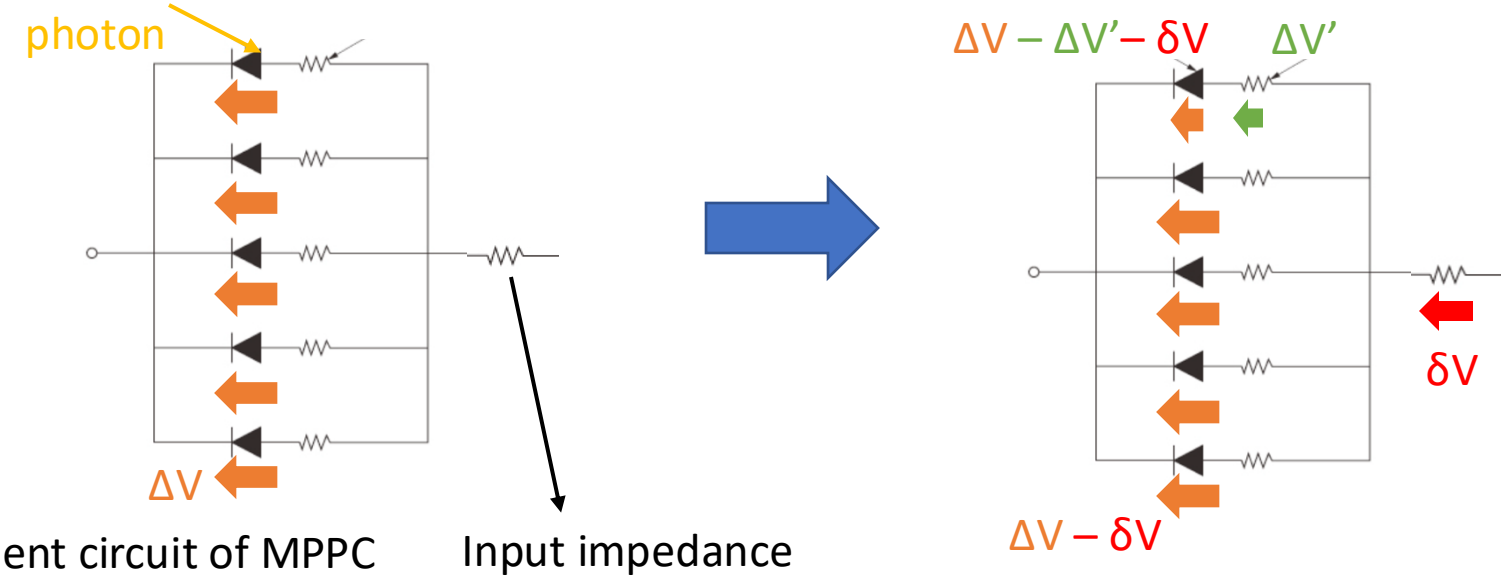
* The upper limit of ^{238}U activity in stainless steal refers to data measured by NEXT exp.

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

Cause of MPPC nonlinearity

1. When some pixels detect photons successively before they finish recovering (typical recovering time: ~100 ns), the effective gain is decreased

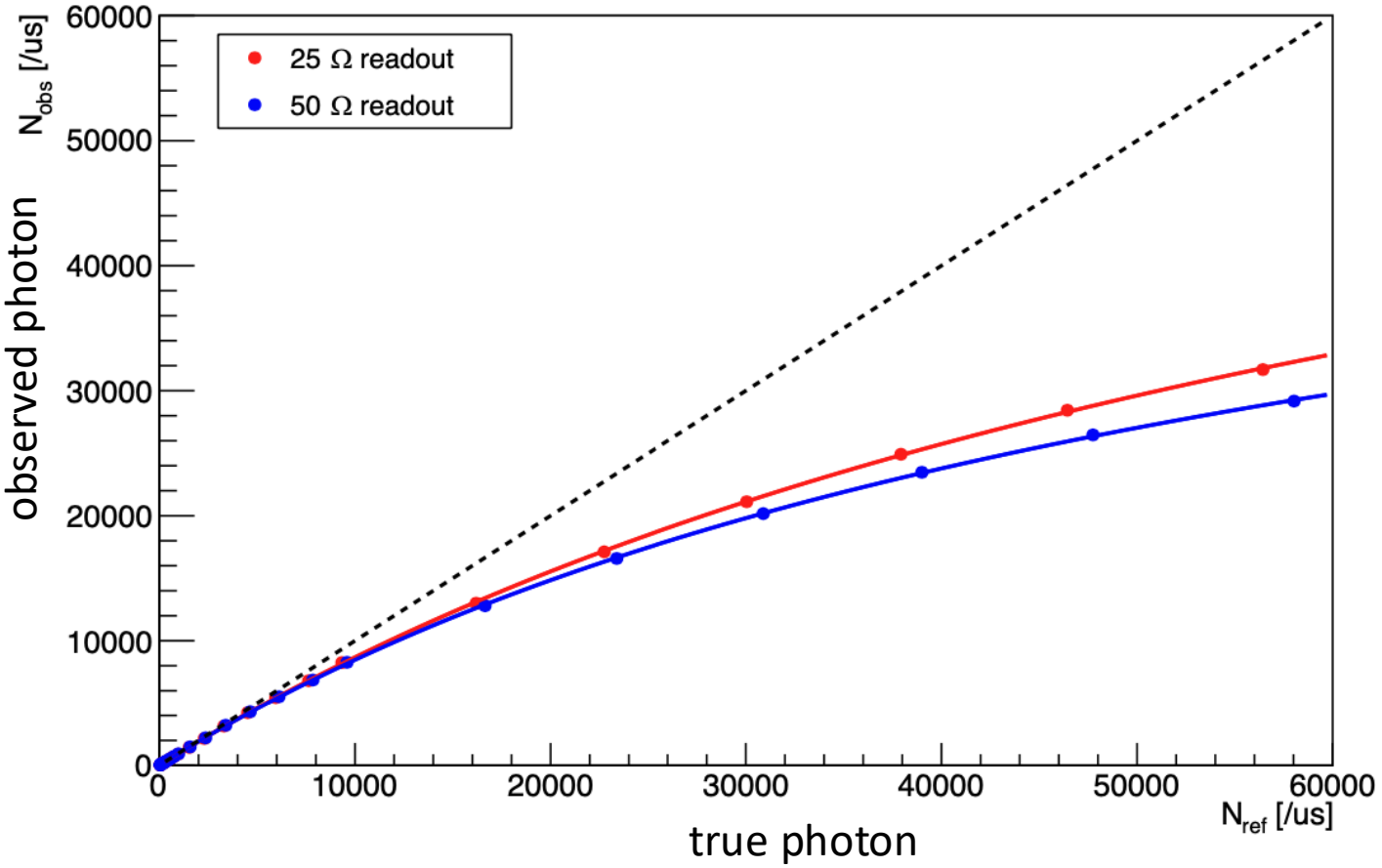
2. When readout voltage is not negligible compared to over voltage applied to MPPC, the effective gain is decreased. (shown in figure below)



Readout resistance & MPPC nonlinearity

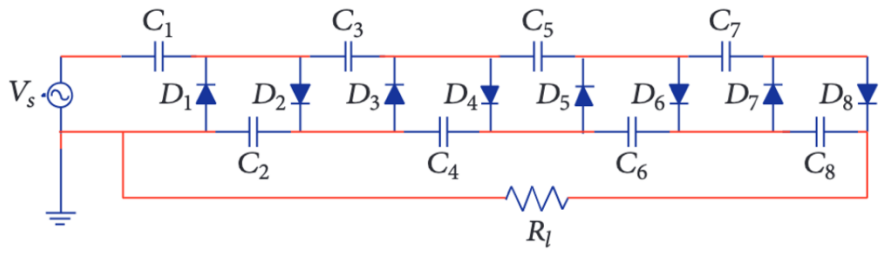
- MPPC nonlinearity effect is suppressed with small readout resistance
- Less than 10 Ω readout, overshoot is observed in signal wave

➡ 10 Ω readout is adopted for new electronics



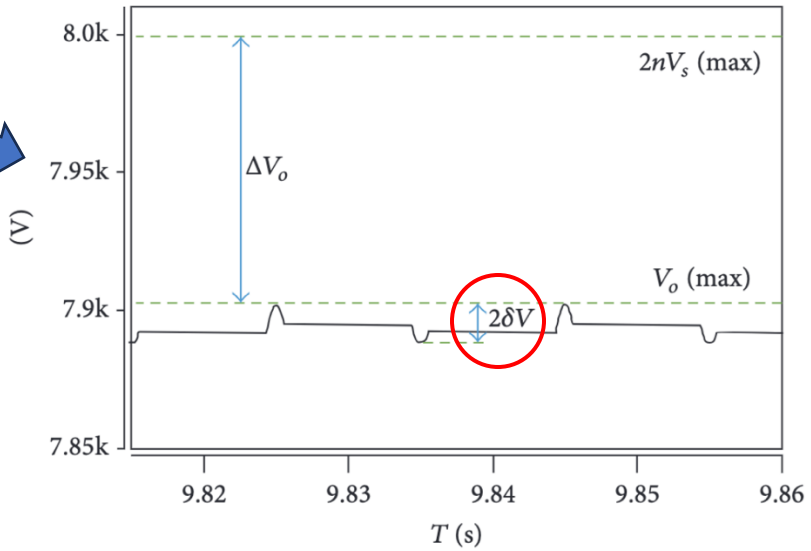
Symmetrical Cockcroft-Walton[6]

Normal CW generator

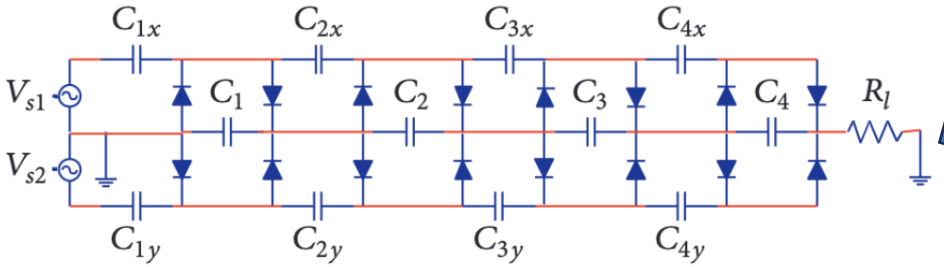


Ripples in all smoothing capacitors affect the output voltage stability

Simulation

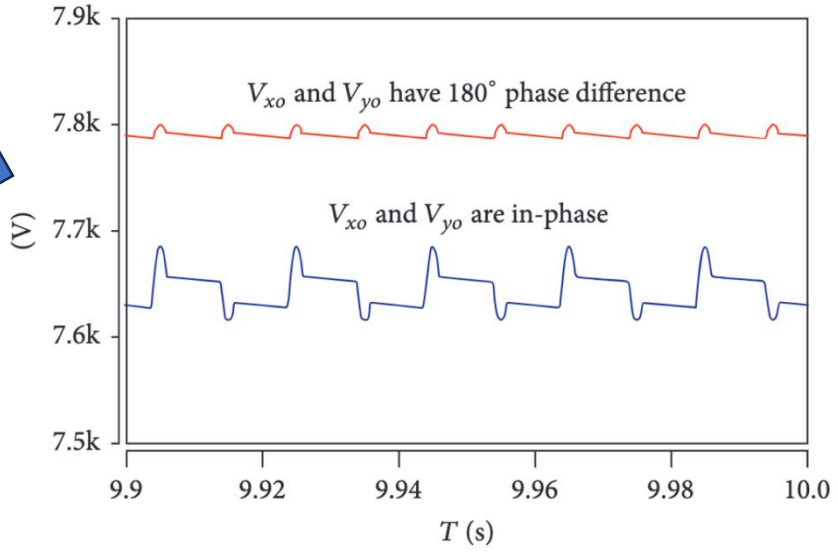


Symmetrical CW generator



Reduce the ripple voltage on 180-deg phase difference operation

→ Cancel the ripples on each capacitor



Correction & analysis flow

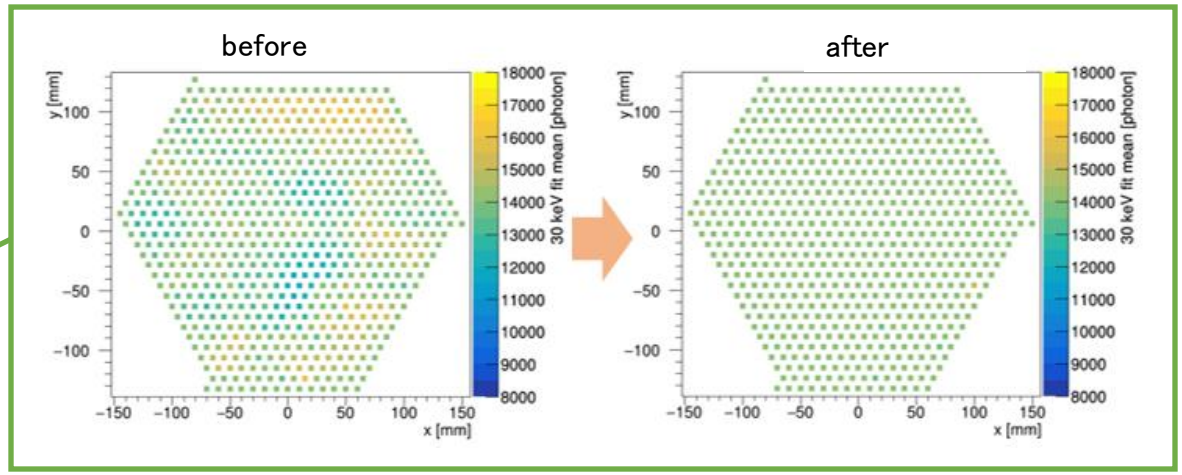
MPPC nonlinearity

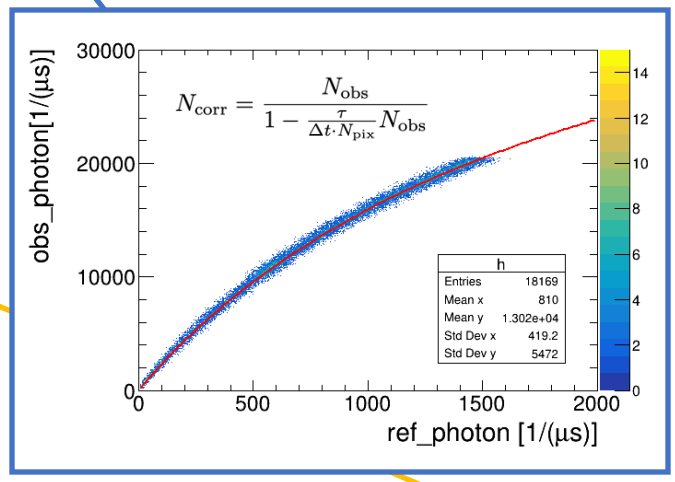
EL gain

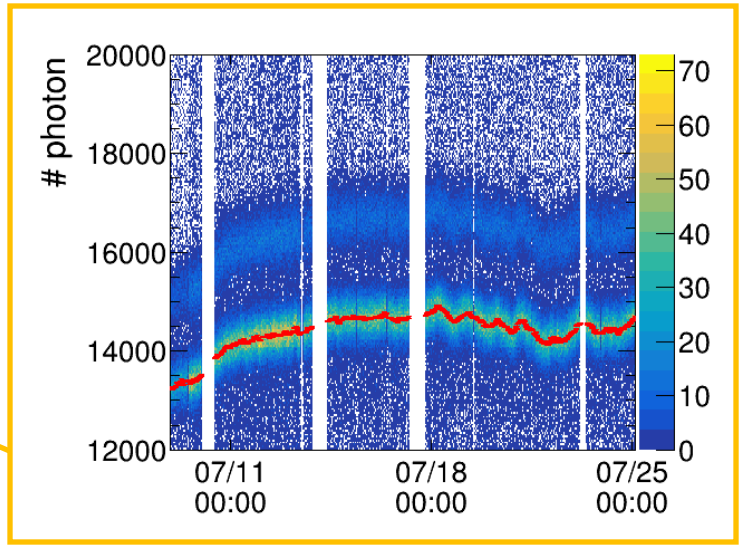
Time variation

z position

Adjustment of parameter of MPPC nonlinearity







Correction & analysis flow

※ Using characteristic X-ray events (～30 keV) for each correction

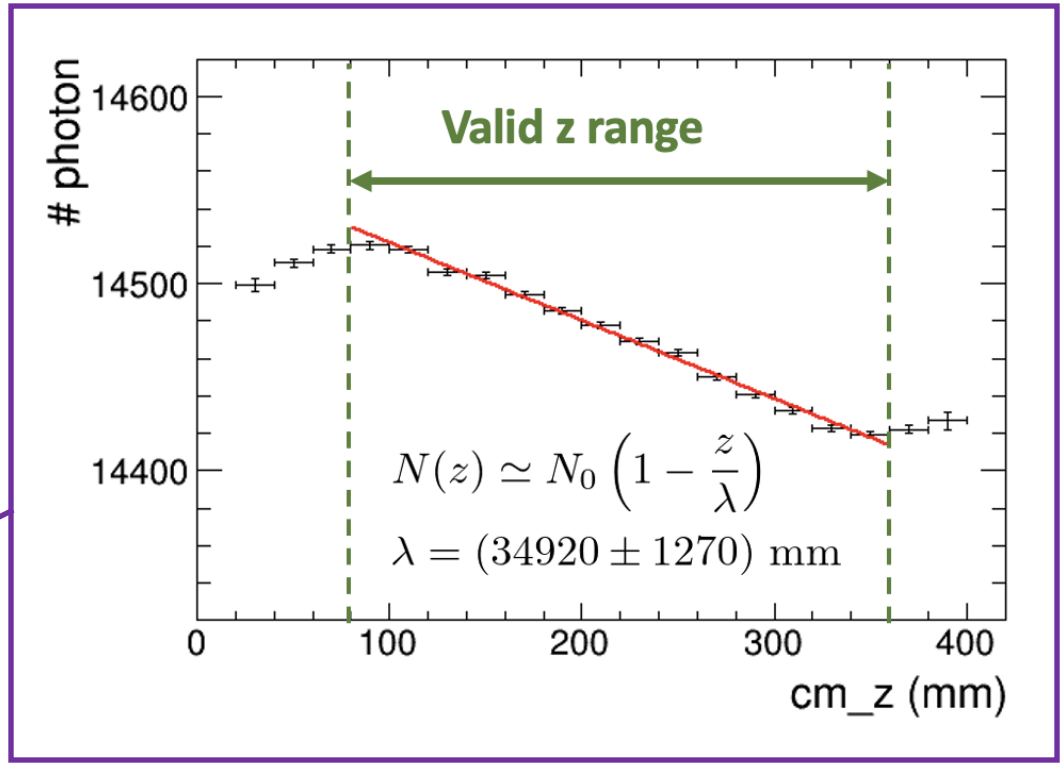
MPPC nonlinearity

EL gain

Time variation

z position

Adjustment of parameter of MPPC nonlinearity



Confirming density of detected EL photon by defining new parameter called CSS (see ref[4])