Demonstration by 180 L detector

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for the AXEL Collaboration

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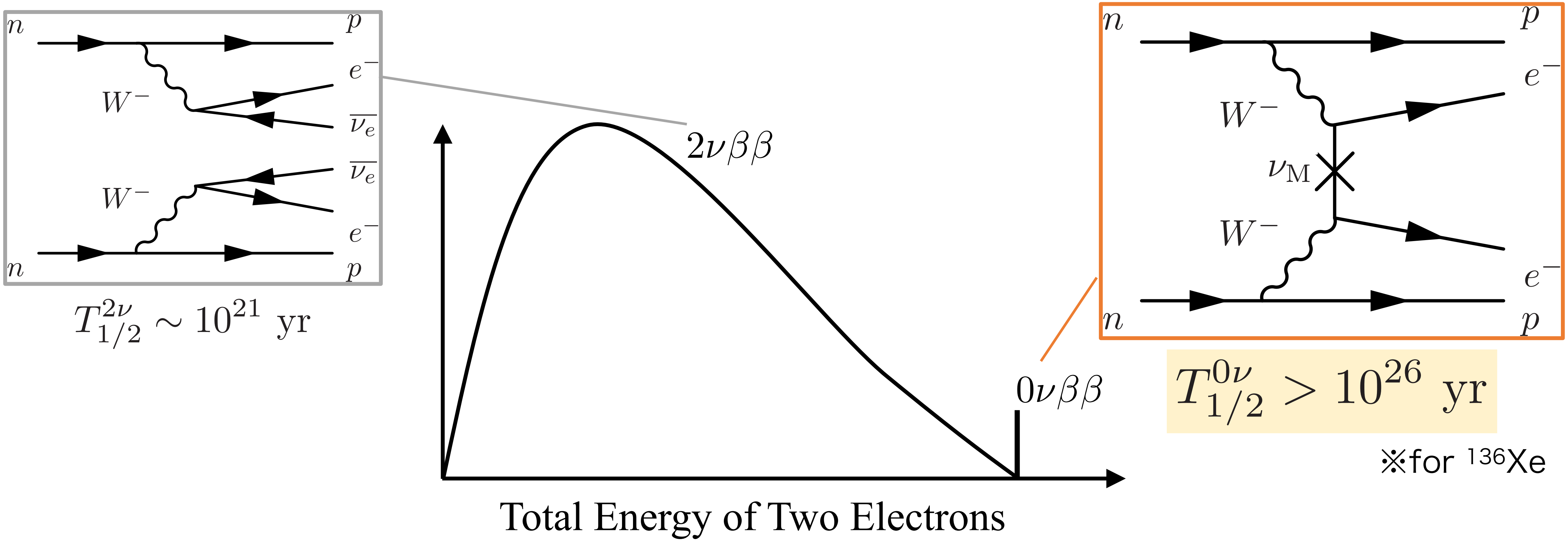
Exploration of Particle Physics and Cosmology with Neutrinos Workshop 2022

Neutrinoless Double Beta Decay



※for ^{136}Xe

✓ Take place only if neutrinos are Majorana fermions.

✓ Key to
- Origin of the light neutrino mass: See-Saw mechanism
- Matter-antimatter asymmetry in the universe: Leptogenesis

How to search for 0νββ

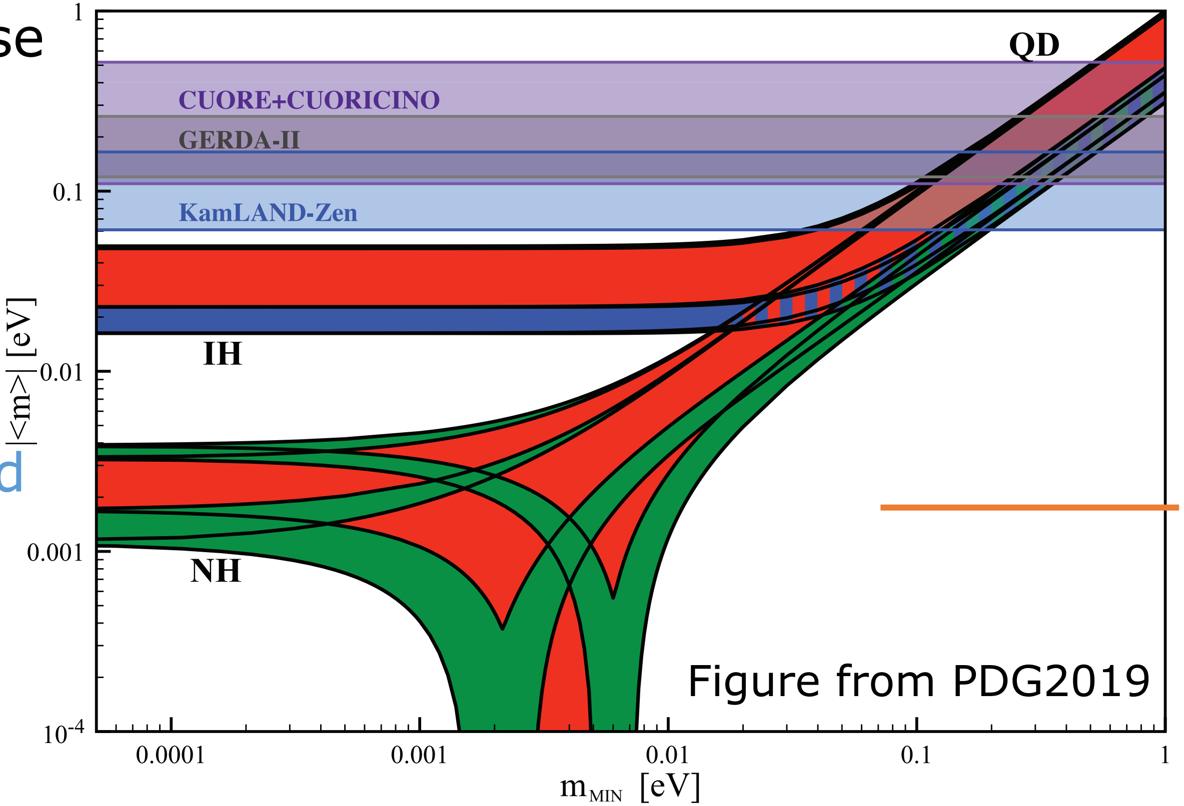
$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

BG-limited case

$$\propto \left(\frac{b\Delta E}{MT}\right)^{1/4}$$

a few ton
x a few years

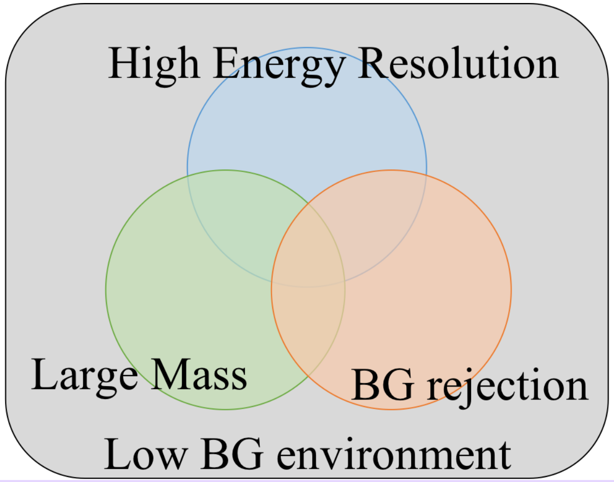
a few hundred ton
x a few years



BG-free case

$$\propto \frac{1}{\sqrt{MT}}$$

a few ton
x a few years



- **BG-free & ton-scale** for Normal hierarchy

← Important requirements
- Strategy? ⇨ High pressure Xe gas TPC!!

AXEL

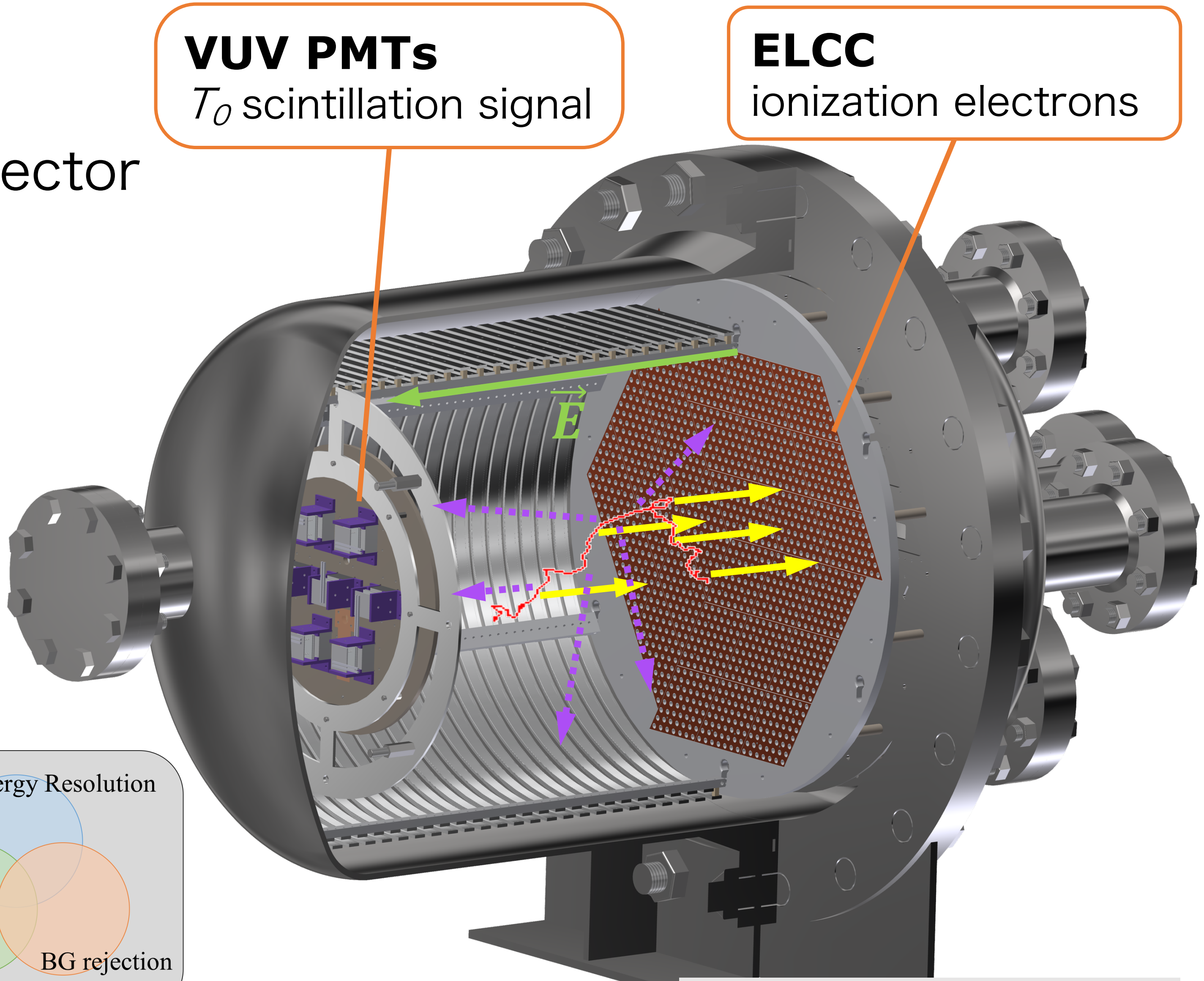
A Xenon ElectroLuminescence detector

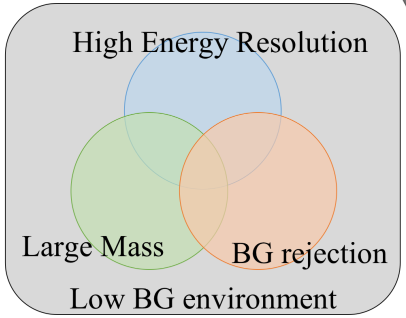
- High pressure xenon gas TPC
- 0νββ nuclei: ^{136}Xe

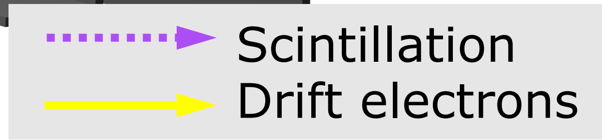
✓ High Energy Resolution
  - Initial ionization: 0.25% FWHM @Q-value 2458 keV
  - **Electroluminescence readout** → less fluctuation

✓ Large Mass
  - Extendable detection plane (ELCC)
  - High pressure gas (8 bar)

✓ BG rejection
  - 3D track reconstruction

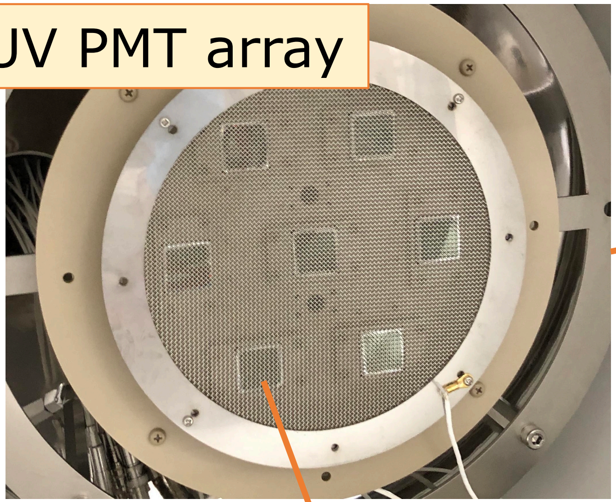


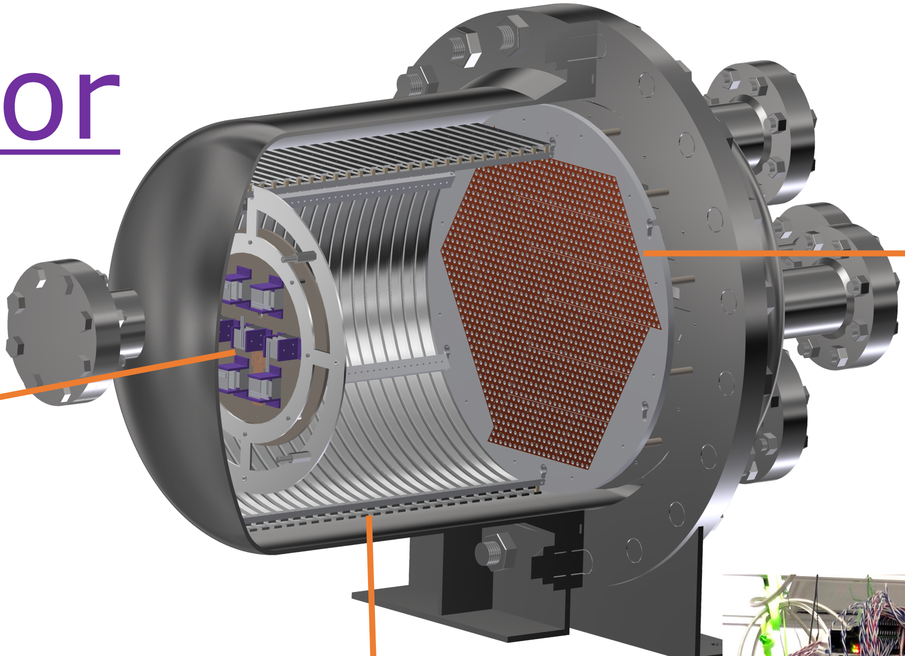


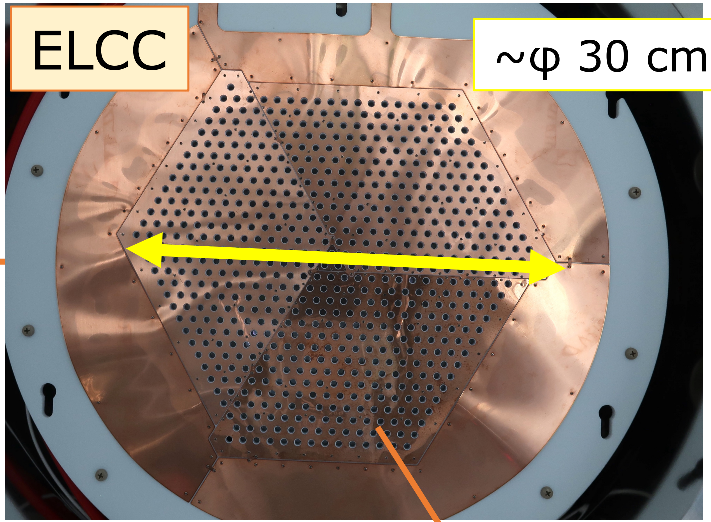


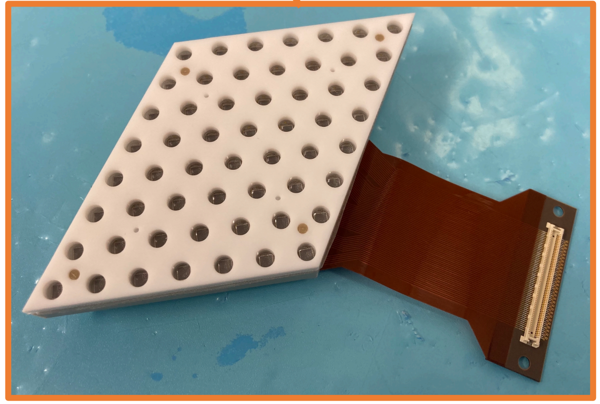
- **180 L detector : R&D** with natural xenon **(this talk)**
- 1000 L detector: physics search with ^{136}Xe enriched gas (next talk)

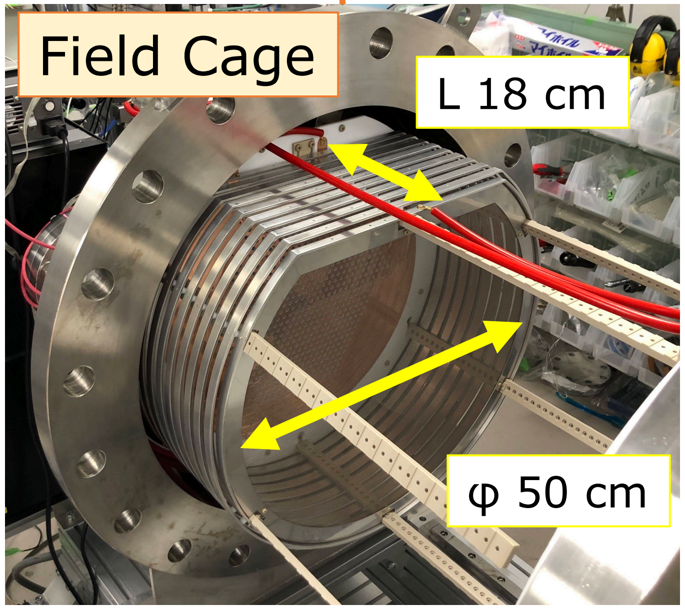
180 L detector

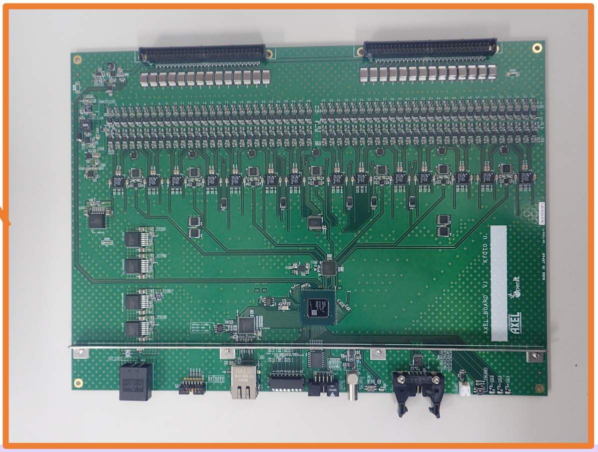












- Development from 2019
- In 2021
  ELCC: 3 units → **12 units**
  pressure: 5 bar → **8 bar**

⇨ Evaluation with 1.8 MeV γ

ELCC

Electroluminescence Light Collection Cell

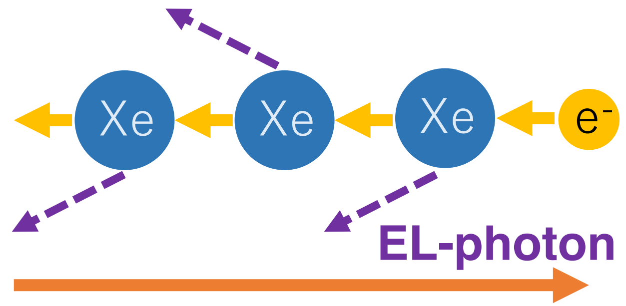
- Drawing ionization electrons into cells.
- EL process in the cells → photon count by MPPC
  → less position dependence
  less fluctuation of amplification

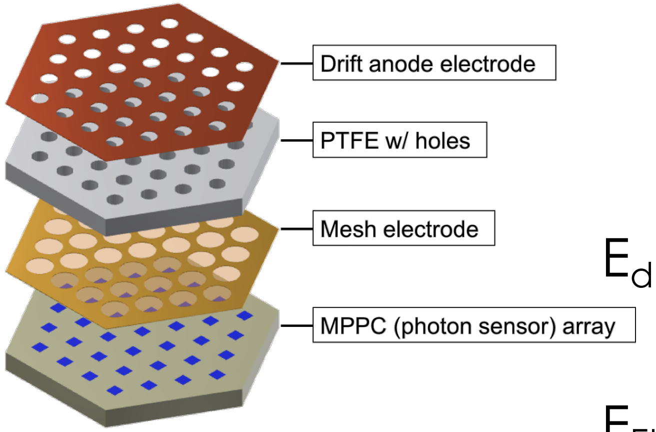
⇨ High Energy Resolution

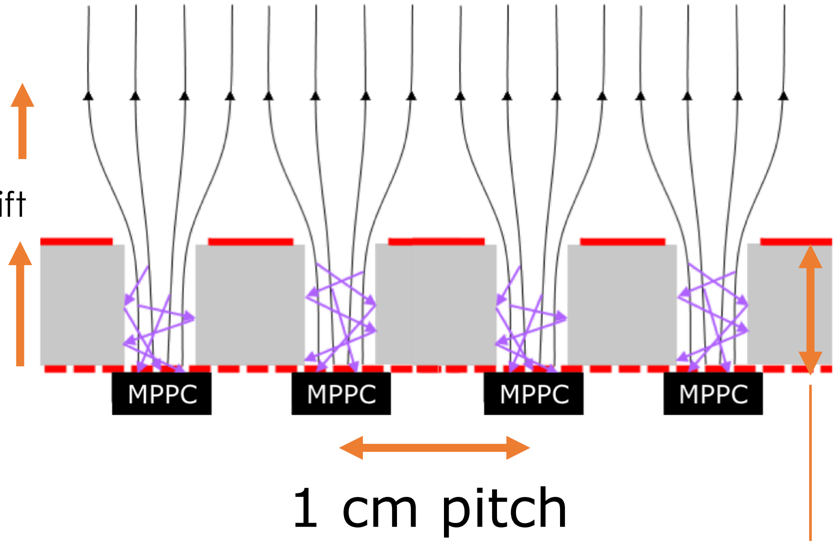
- Pixelized hit pattern + hit timing

⇨ 3D Track Reconstruction

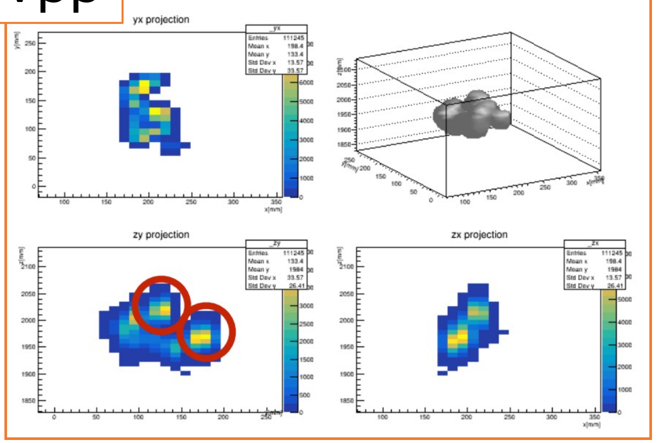
EL process



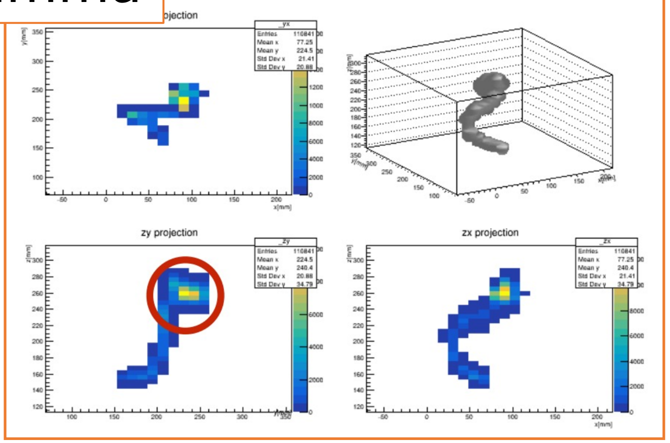




0νββ



gamma

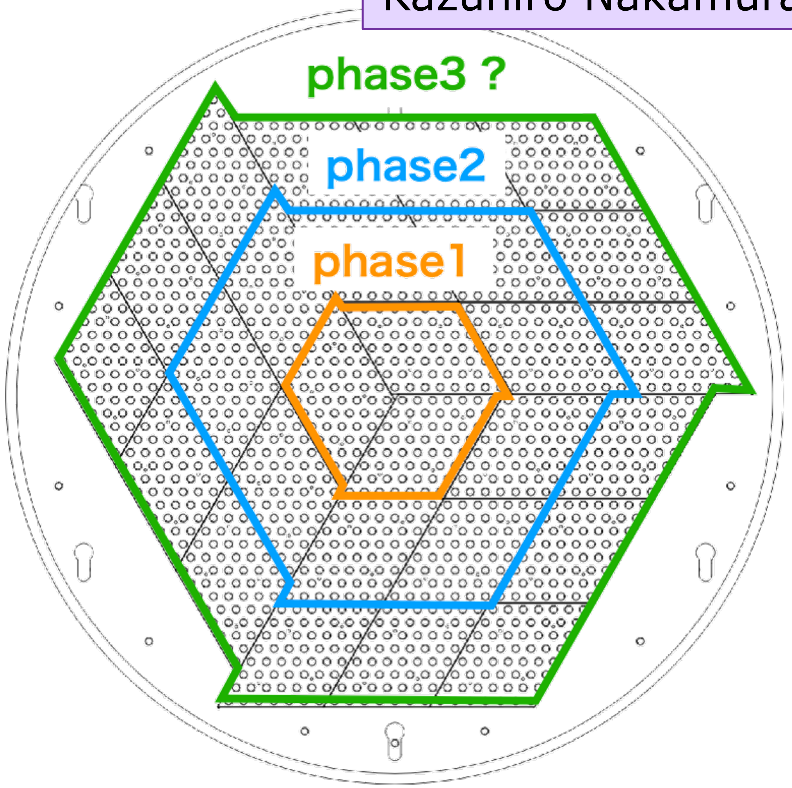


* both are simulation

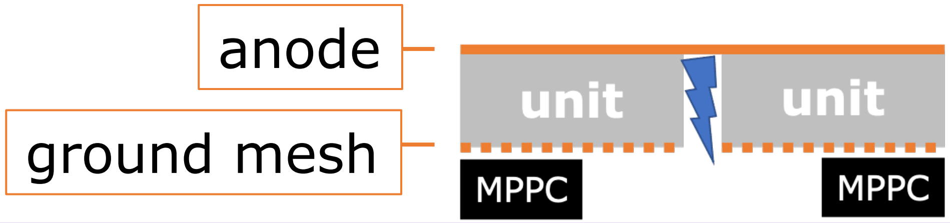
Kazuhiro Nakamura

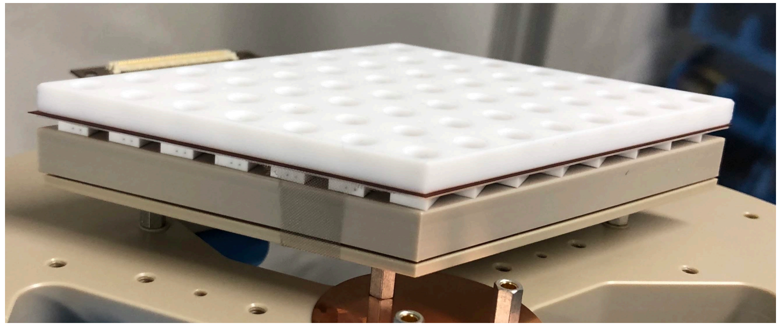
Development of ELCC

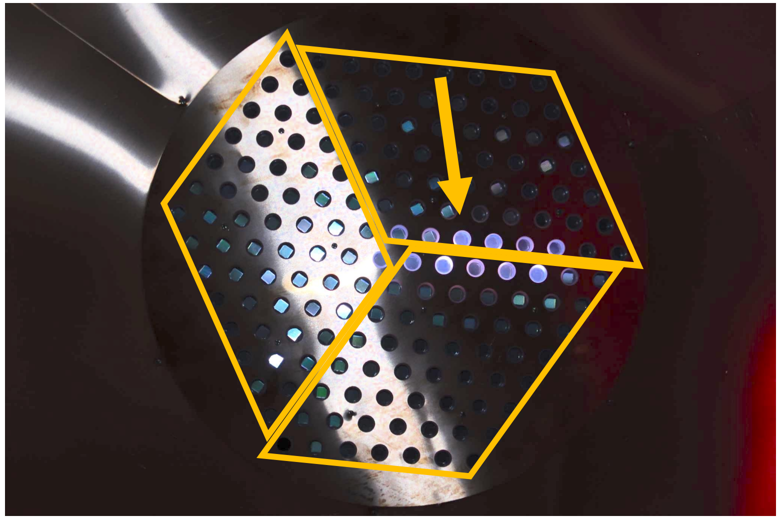
- ELCC is divided into units with 56 channels each.
- Easy extension to a larger area
- Step by step approach
  - phase1: 3 units (168 ch)
  - phase2: 12 units (672 ch)
  - (phase3: 27 units)



- At phase1, discharges between the anode electrode and ground mesh electrode was a problem.
  - ✓ E_{EL} = 3 kV/cm/bar → Higher pressure → Higher voltage ⇨ More discharge
  - ✓ Discharges at high rate under 5 bar (target: 8 bar)
  - ✓ **Gaps between units were the weak points.**
- Optimized the ELCC structure before the transition to phase2.







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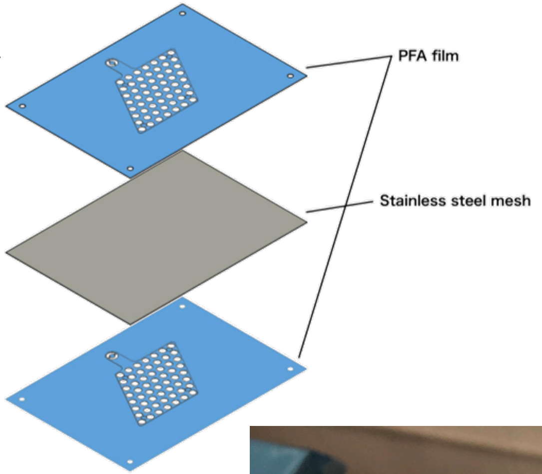
Countermeasure against discharge

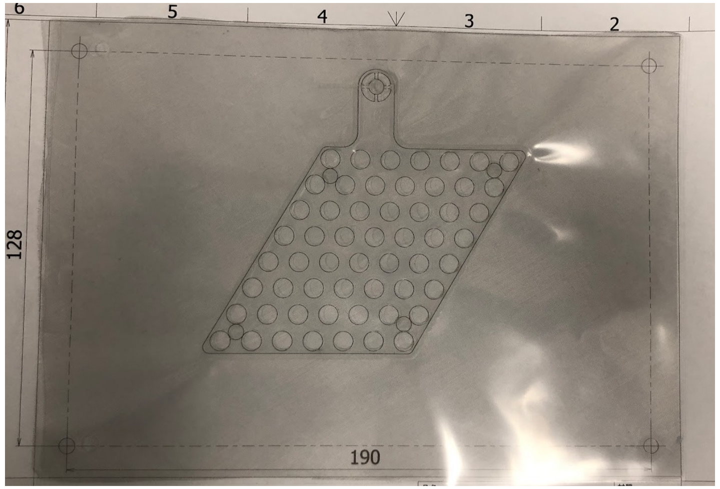
- The following measures were found to be effective (after a long struggle……).
  - ✓ Laminating ground mesh with PFA films
  - ✓ Hiding all gaps between ELCC units

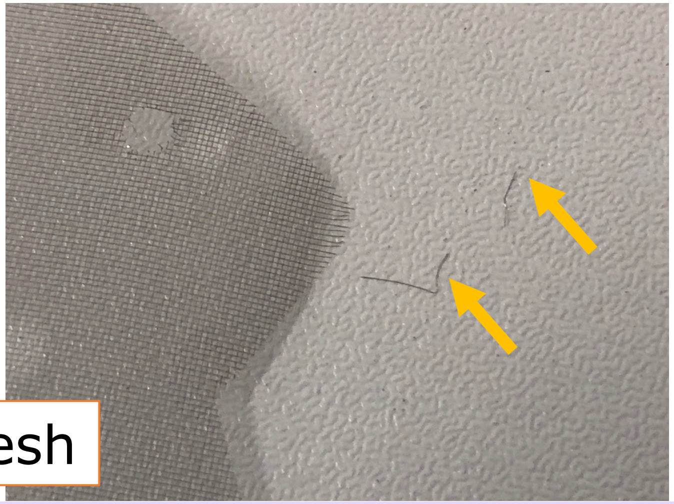
Laminating ground mesh with PFA films

- Stainless steel fragment from the edge of meshes induce discharges.

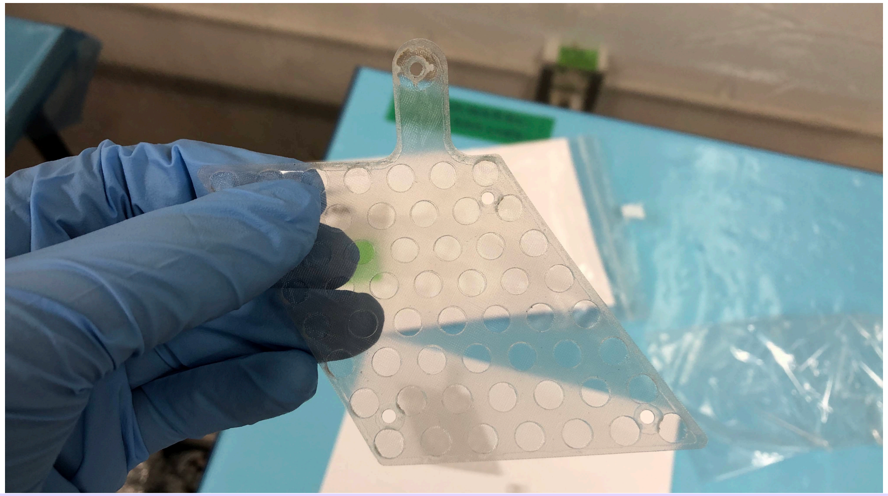
- ✓ Put the mesh between PFA films
- ✓ **Laser welding** of the edges







naked mesh



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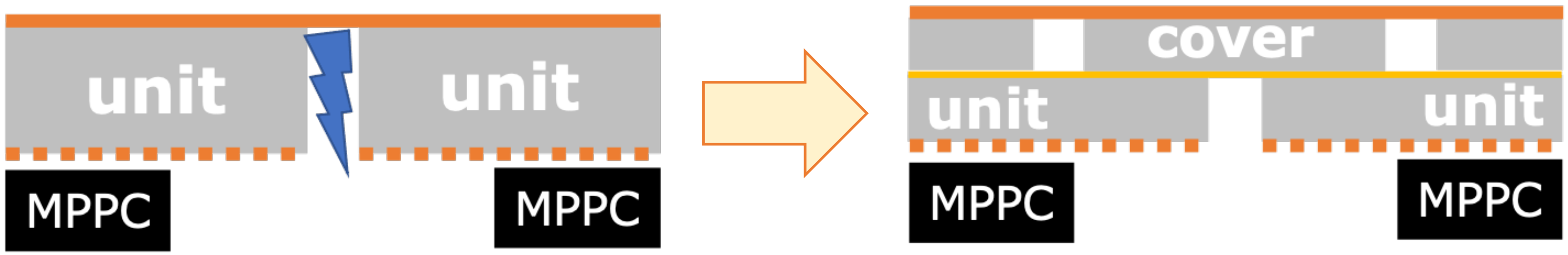
Countermeasure against discharge

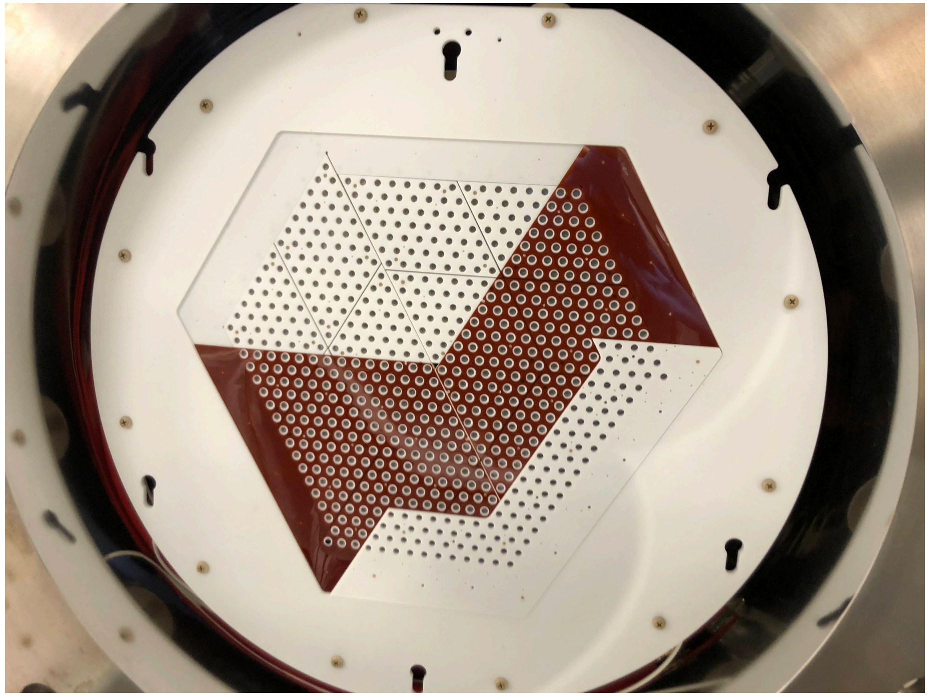
- The following measures were found to be effective (after the long struggles……).
  - ✓ Laminating ground mesh with PFA films
  - ✓ Hiding all gaps between ELCC units

Hiding all gaps between ELCC units

- Discharge path:
  Anode → Ground mesh through the gap of ELCCs

- ✓ Divide PTFE body into two layers
  → Shift the location of the gaps
- ✓ Insert polyimide sheet
  → Blocking all direct paths





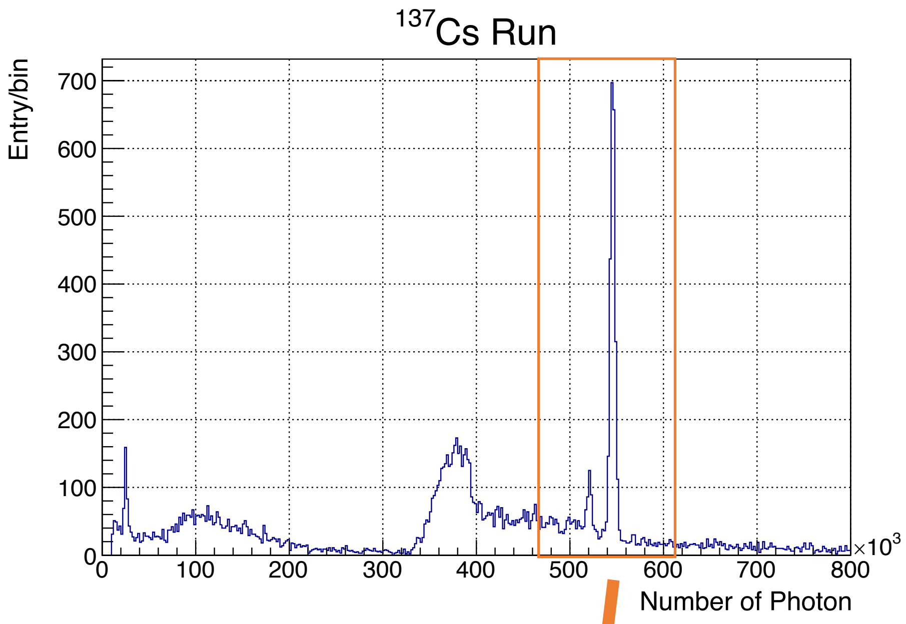
Stable Operation at **3 kV/cm/bar, 8 bar** is achieved!!

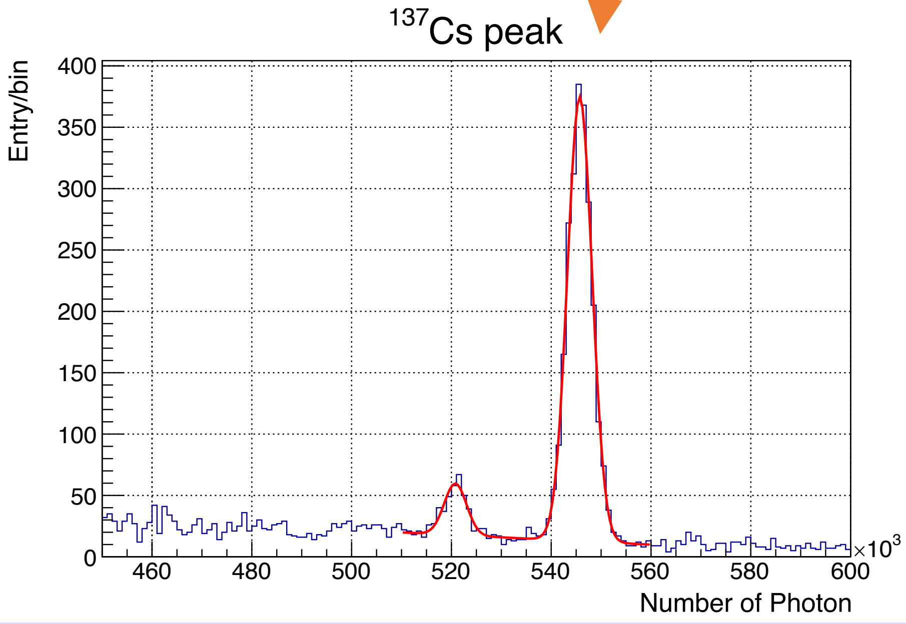
Masashi Yoshida

Evaluation with ^{137}Cs

- After taking countermeasures against discharges.
- Measurement with 3 units(phase1) detector.

- 8 bar xenon
- E_{drift} = 68.8 V/cm/bar
- E_{EL} = 2.75 kV/cm/bar





Energy Resolution

1.06 ± 0.02% FWHM @661.7 keV

extrapolate with √E

⇨ 0.55 ± 0.01% FWHM @Q-value(2458 keV)

✓ Almost achieved the target resolution (0.5% FWHM)!!

Proceeded to phase2

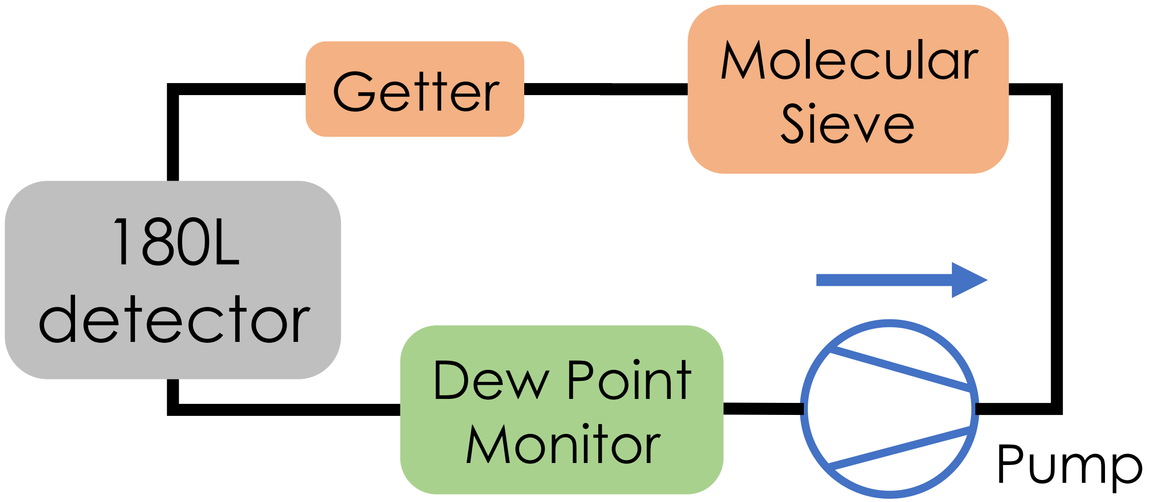
Kazuhiro Nakamura

^{88}Y measurement

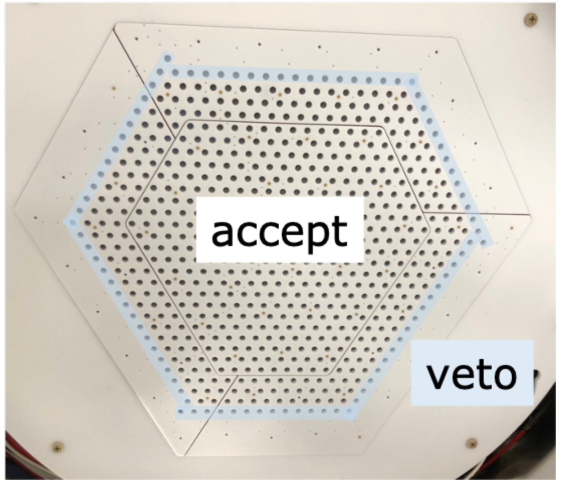
Source
- gamma rays from ^{88}Y : 898 keV, **1836 keV**
  → first performance evaluation over 1 MeV

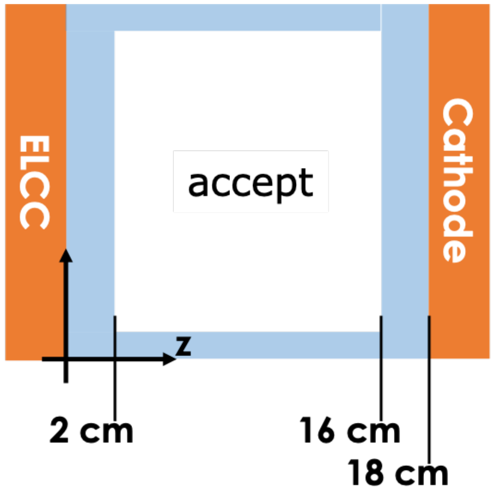
Gas
- pressure: 8 bar
- purification
  - Molecular sieve : H_2O, O_2, CO_2, etc……
  - Getter : N_2
- monitoring purity and temperature

Electric Field
- E_{drift} = 75 V/cm/bar
- E_{EL} = 2.25 kV/cm/bar
  - stable without discharge during the measurement



Cut
- Only accept fully contained events
- Online veto + Offline cut





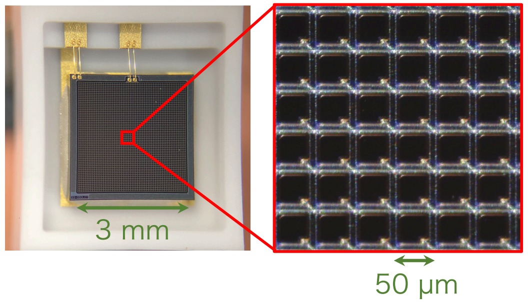
Analysis

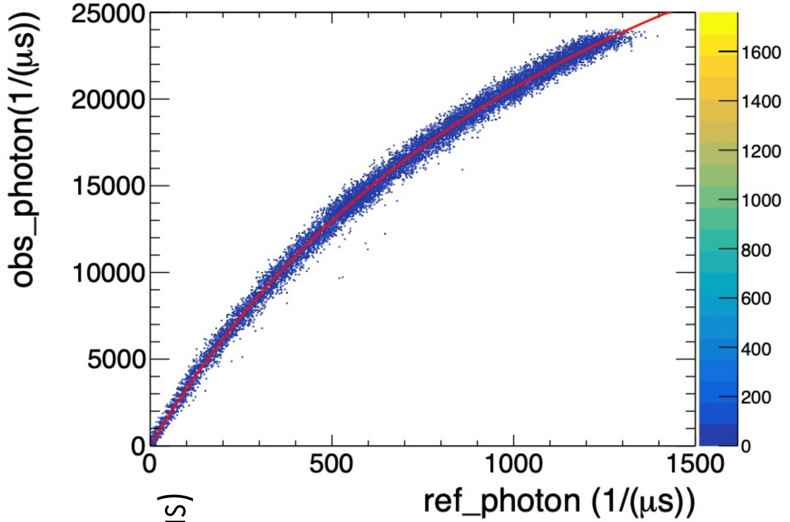
Kazuhiro Nakamura

MPPC Non-linearity Correction → EL gain Correction → Time Correction → z Correction

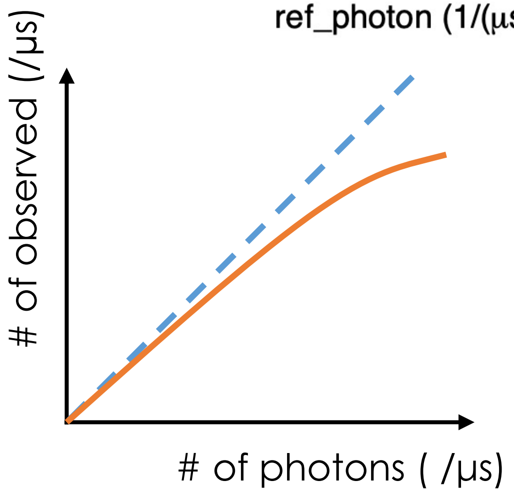
MPPC Non-linearity Correction

- Output of MPPC has saturation under high photon intensity $N_{photon} \sim N_{pix}$
- Characterized by recovery time τ
- τ's of each MPPC are measured with LED light in advance.





$$N_{\mathrm{obs}} = \frac{N_{\mathrm{true}}}{1 + \tau \dfrac{N_{\mathrm{true}}}{\Delta t \cdot N_{\mathrm{pix}}}}$$



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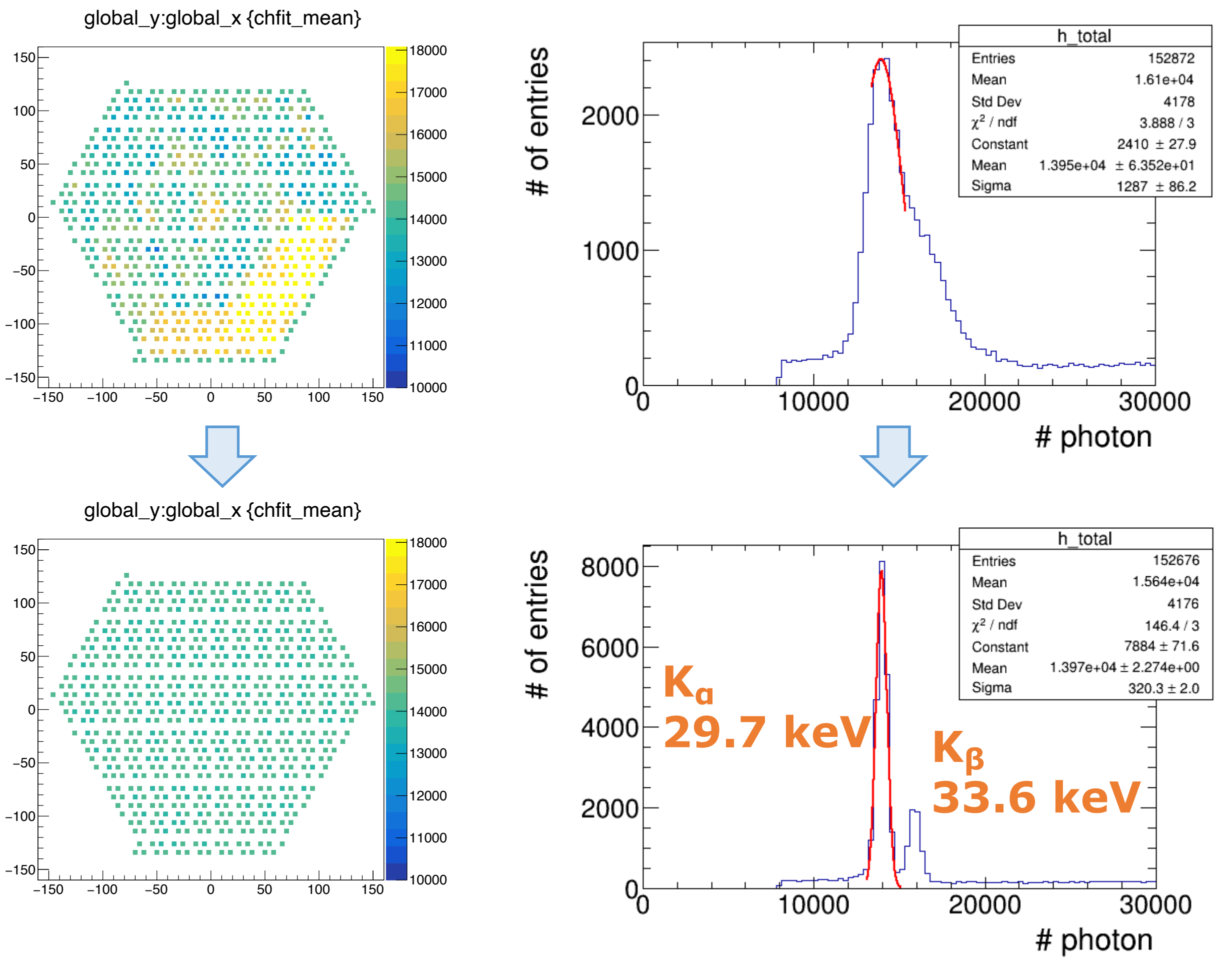
Analysis

MPPC Non-linearity Correction → **EL gain Correction** → Time Correction → z Correction

EL gain Correction

- Conversion factors of EL process are different for each ELCC cell.
- Apply correction making them uniform using xenon K_α X-ray (29.7 keV)



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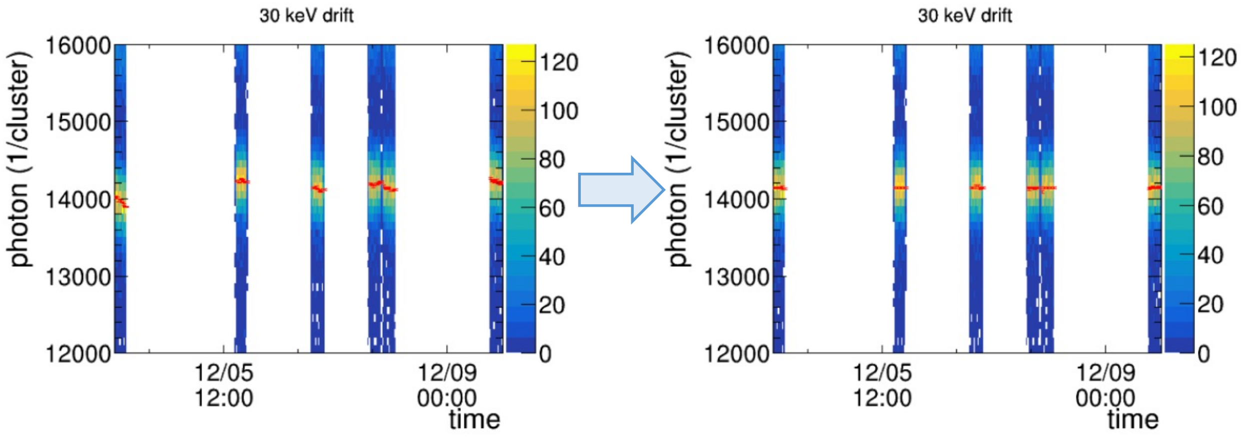
Analysis

MPPC Non-linearity Correction → EL gain Correction → **Time Correction** → **z Correction**

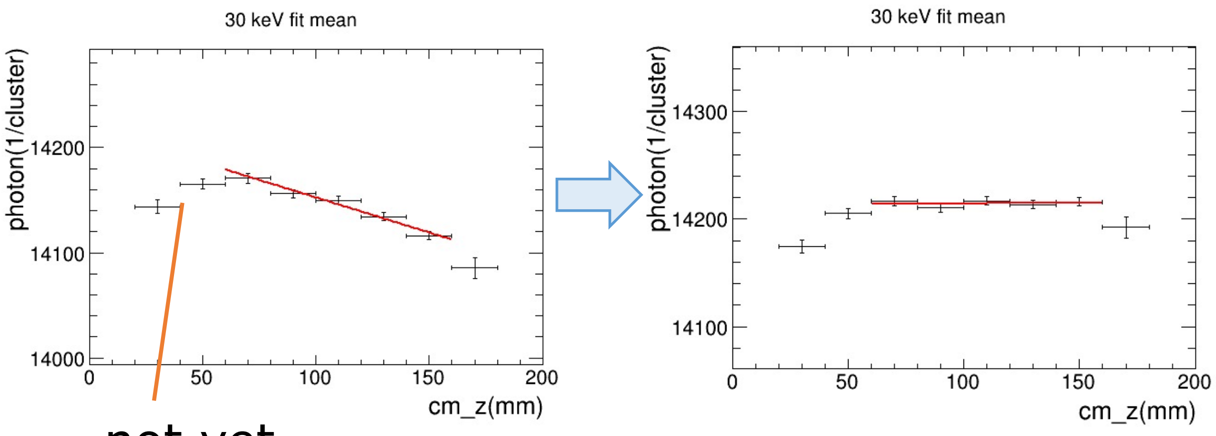
Time Correction

- Correct the time dependence
- Mainly caused by the change in the gain of the MPPCs by the temperature.



z Correction

- Correct the z dependence
- Caused by attachment of ionization electrons by impurity.



not yet understood

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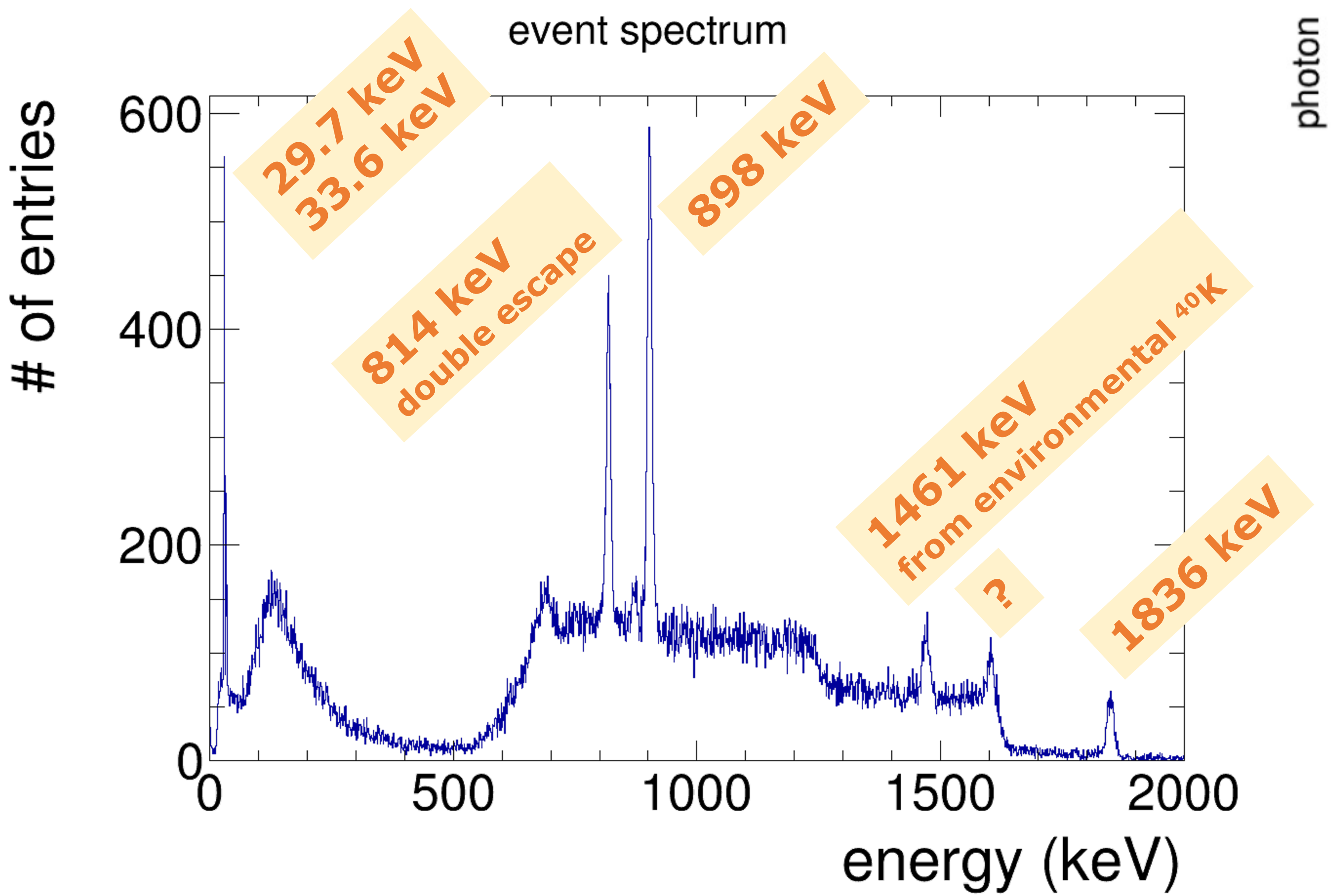
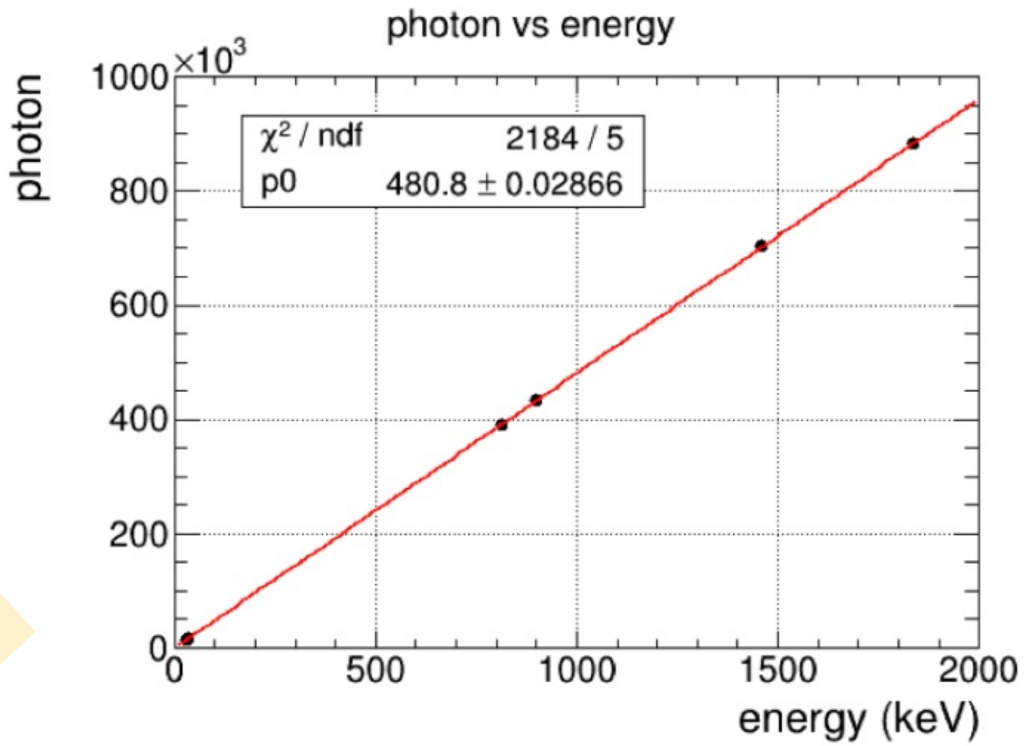
Analysis

Acquired Energy Spectrum





- Linearity is confirmed.

Analysis

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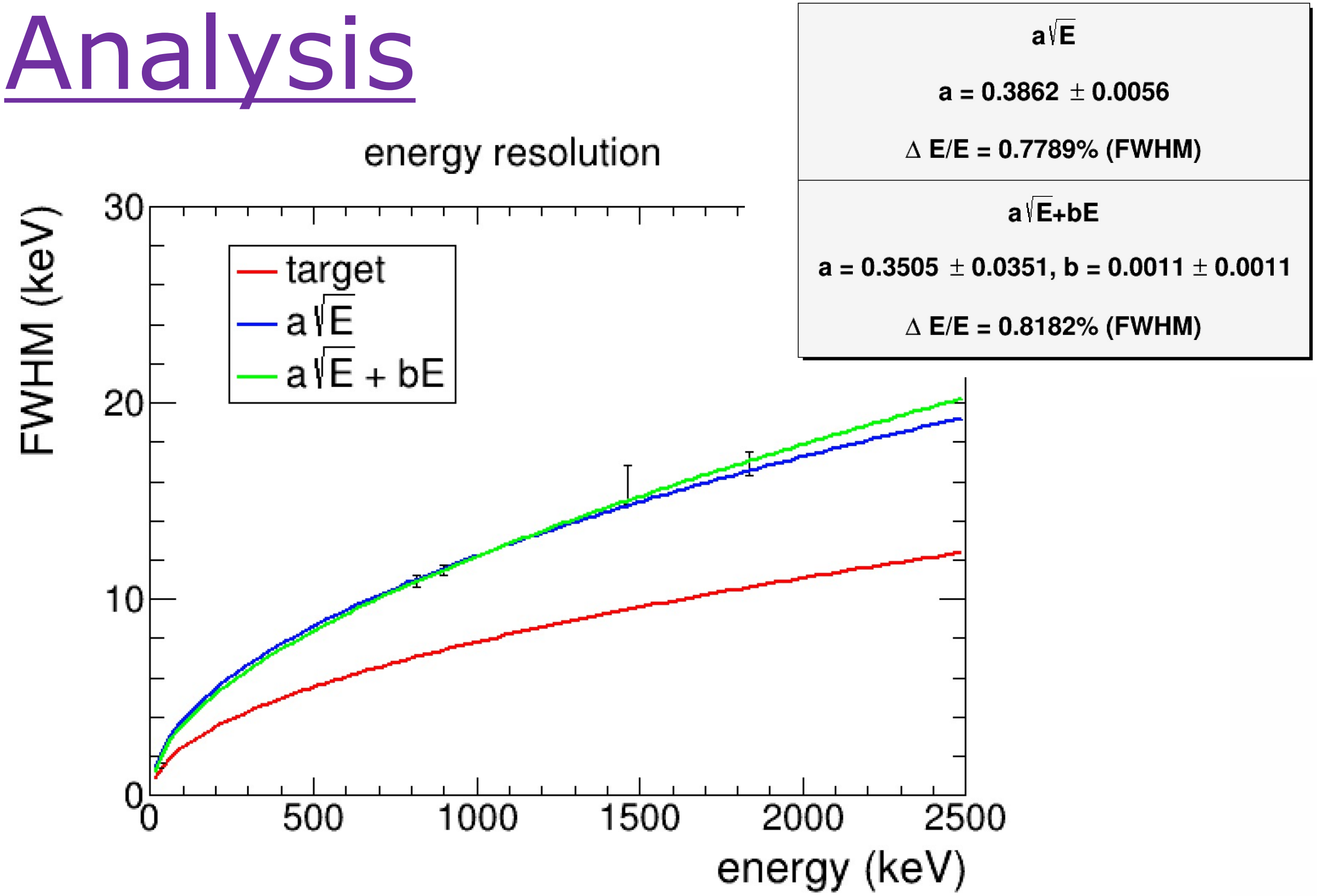
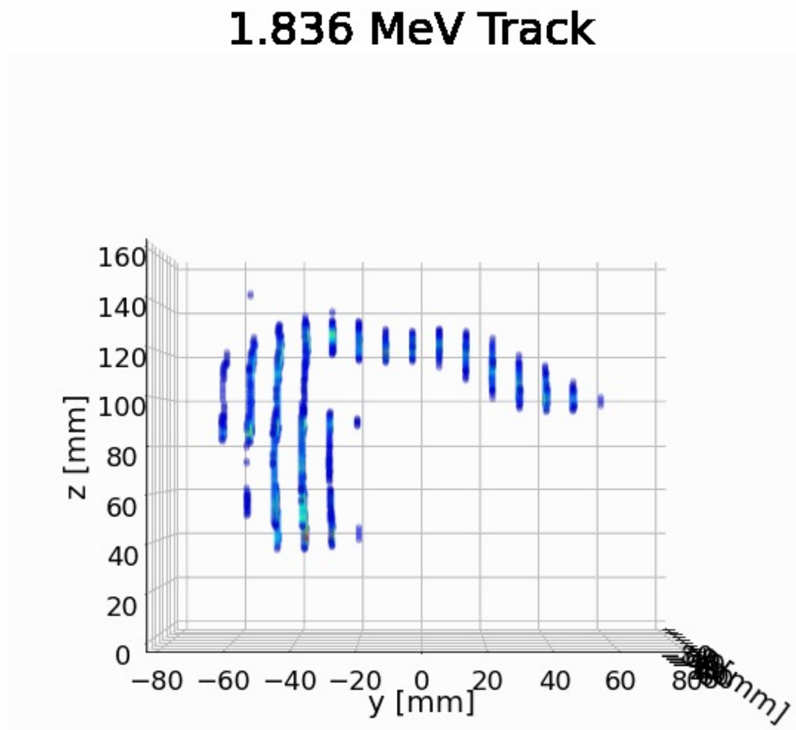


0.78 – 0.82% FWHM @ Q-value(2458 keV)!!

Scalability of ELCC method is establised!!

Reconstructed track image of 1836 keV gamma ray event



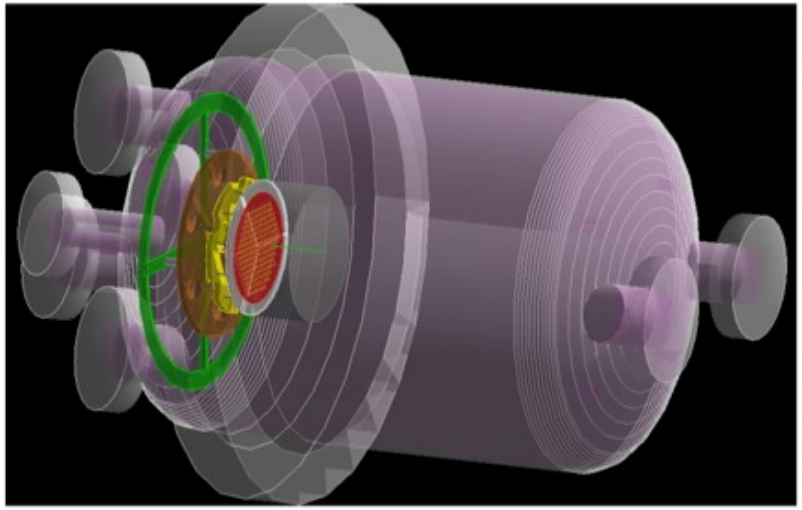
Sei Ban

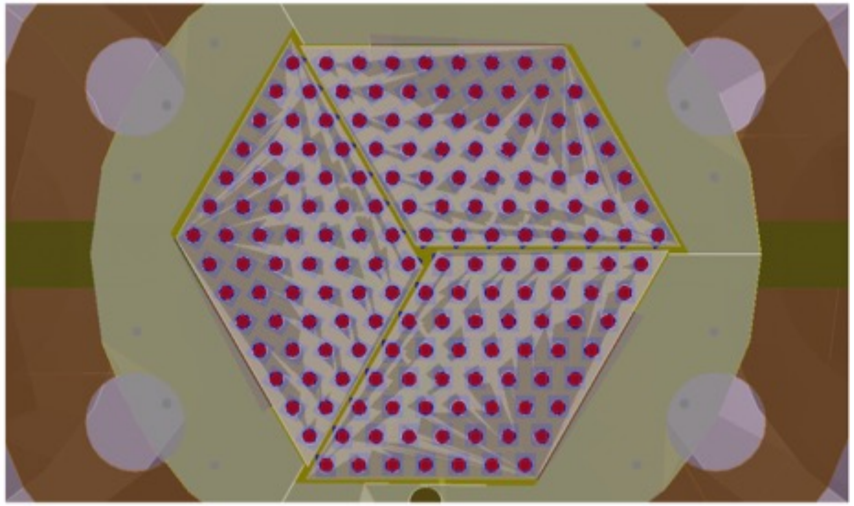
Detector full simulation

Event Generation with GEANT4 → Electron Drift → ELCC response → FEB signal digitization

- Developed detector full simulation framework
- To understand the breakdown of the energy resolution

Event Generation with GEANT4





Sensitive volume
- ϕ20 cm x L 10 cm

ELCC
- 3 units

Source
- ^{22}Na (511 keV)

For comparison with existing data set

Detector full simulation

Sei Ban

Event Generation with GEANT4 → **Electron Drift** → ELCC response → FEB signal digitization

Electron Drift

Energy deposit from GEANT4 → generation of ionization electrons → spatial distribution of electrons at ELCC

convert with known
- W value: 22 eV/ionization
- Fano factor: F = 0.13

Gaussian fluctuation with

$$\sigma_N = \sqrt{FN}$$

$\rightarrow$ intrinsic energy resolution

Drift property
- drift velocity
- transverse diffusion
- longitudinal diffusion

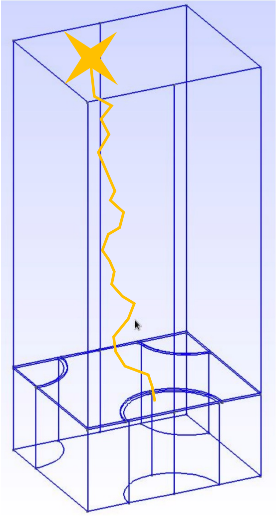
✓ Calculation with Magboltz

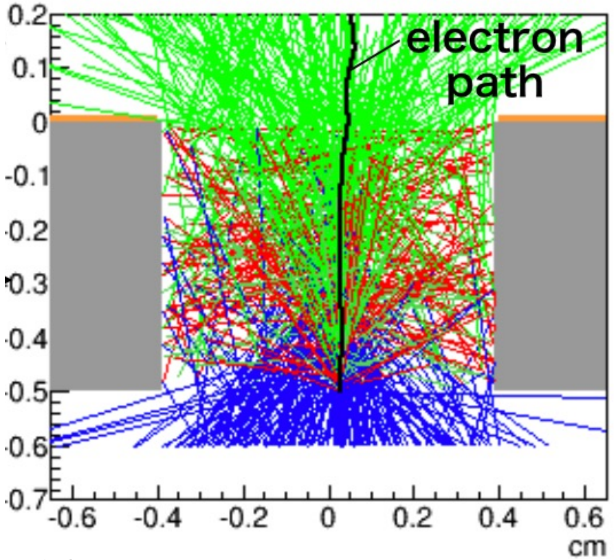
Detector full simulation

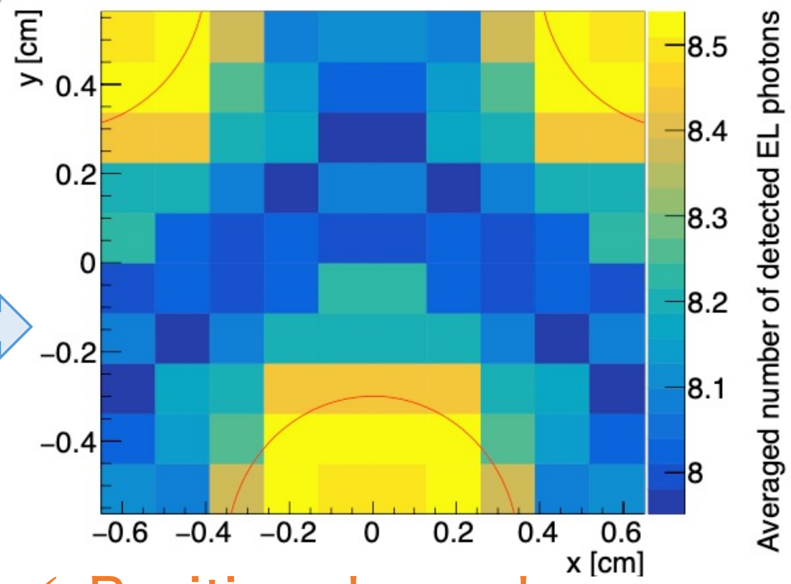
Sei Ban

Event Generation with GEANT4 → Electron Drift → **ELCC response** → FEB signal digitization

ELCC response







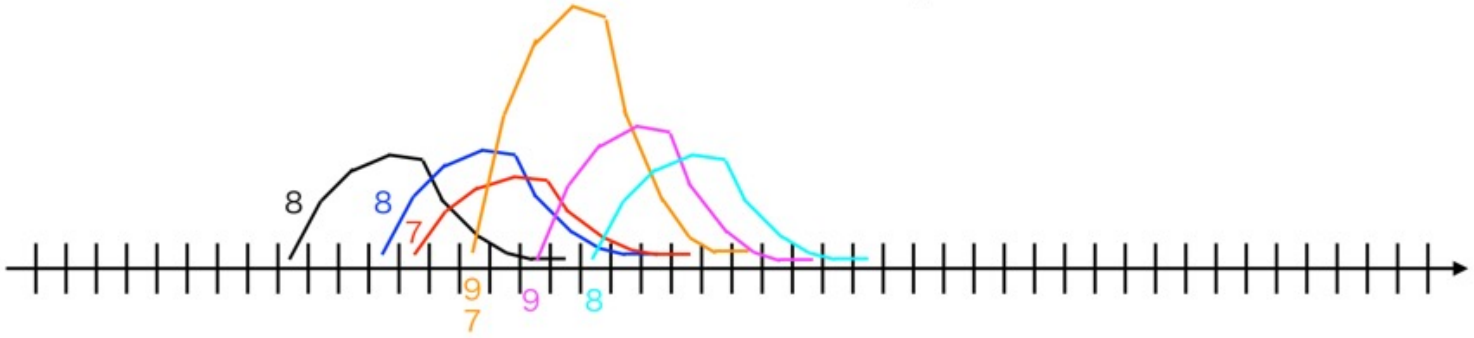
- ✓ Electric field of ELCC → Track of an electron
  gmsh, elmer, garfield++
- ✓ EL photon generation & transportation
- ✓ Position dependence of EL gain

➢ Poisson fluctuation of EL conversion and Difference of EL gain between channels are also included.

Detector full simulation

Event Generation with GEANT4 → Electron Drift → ELCC response → **FEB signal digitization**

FEB signal digitization



- Count the number of EL photons in each clock
- Generate pulse shape considering FEB filter → Sum up
- Digitize: 2 Vpp, 12 bit

- Fluctuation of the baseline is also included.

⇒

- Same format as real data
- Energy resolution is evaluated with the same analysis procedure.

Sei Ban

Detector full simulation

- Data sets with the sources of fluctuation switched ON/OFF.
  Position dependence of EL gain, fluctuation of EL conversion, EL gain difference b/w ch
  FEB pulse shape filter, Digitization

Breakdown	ΔE/E @511 keV
Intrinsic fluctuation	0.58%
Position dependence of EL gain	???
Fluctuation of EL conversion	0.58%
EL gain difference	0.40%
FEB pulse shape filter	0%
FEB digitization	0%
Total	0.85%

Not yet evaluated:
- Analysis threshold
- MPPC non-linearity
- Time dependence
- z dependence
- ……

* Data: 1.49%

Fluctuation of EL conversion found to have large budget

Better efficiency of photon detection & Larger EL gain will improve the energy resolution!!

Summary

- Are neutrinos Majorana fermions or not?
- Search for $0\nu\beta\beta$ with ton-scale and BG-free detector!

- AXEL: High pressure xenon gas TPC for $0\nu\beta\beta$ search
  - ✓ High Energy Resolution + Large Mass + BG Rejection

- 180 L detector for R&D
  - ✓ Succeeded in stable operation of ELCC under target gas pressure & electric field
  - ✓ Scalability maintaining energy resolution
  - ✓ Achieved energy resolution: 0.8% FWHM
  - ✓ Clear track pattern

    → Study of BG rejection based on event topology got ready to start.

- Detector full simulation
  - ✓ Development of framework has been completed.
  - ✓ Photon detection efficiency & EL gain are important for energy resolution.