



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

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For the AXEL collaboration

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Neutrinoless double beta decay

AXEL experiment

Prototype detector

R&D for more sensitivity

Summary



Neutrinoless double beta decay

AXEL experiment

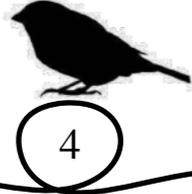
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Neutrinoless double beta decay



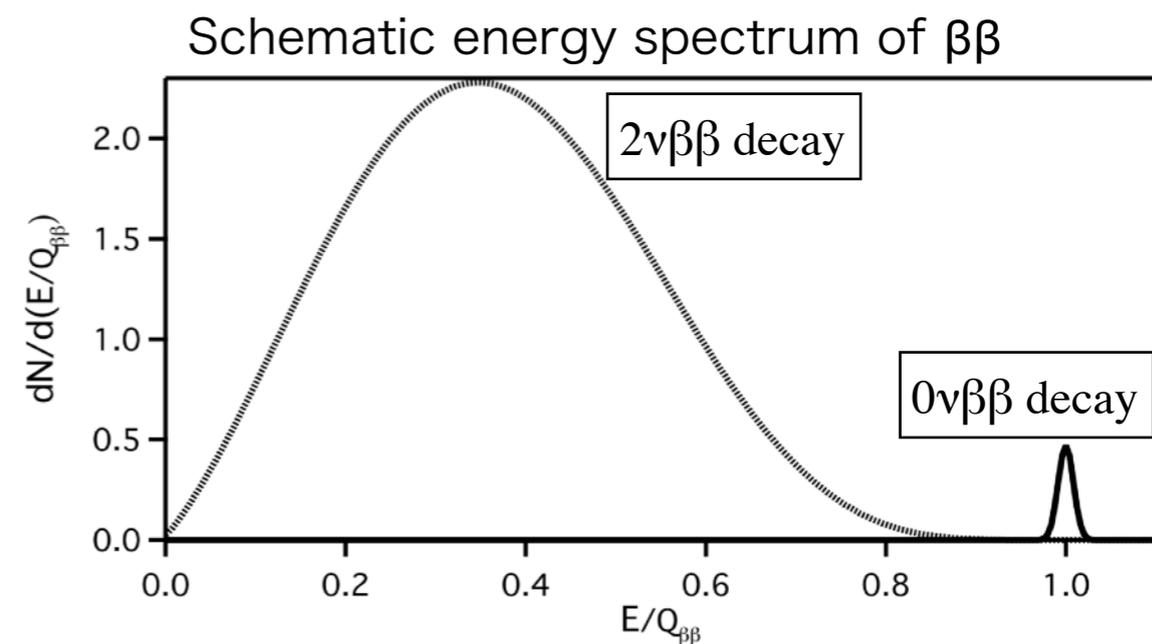
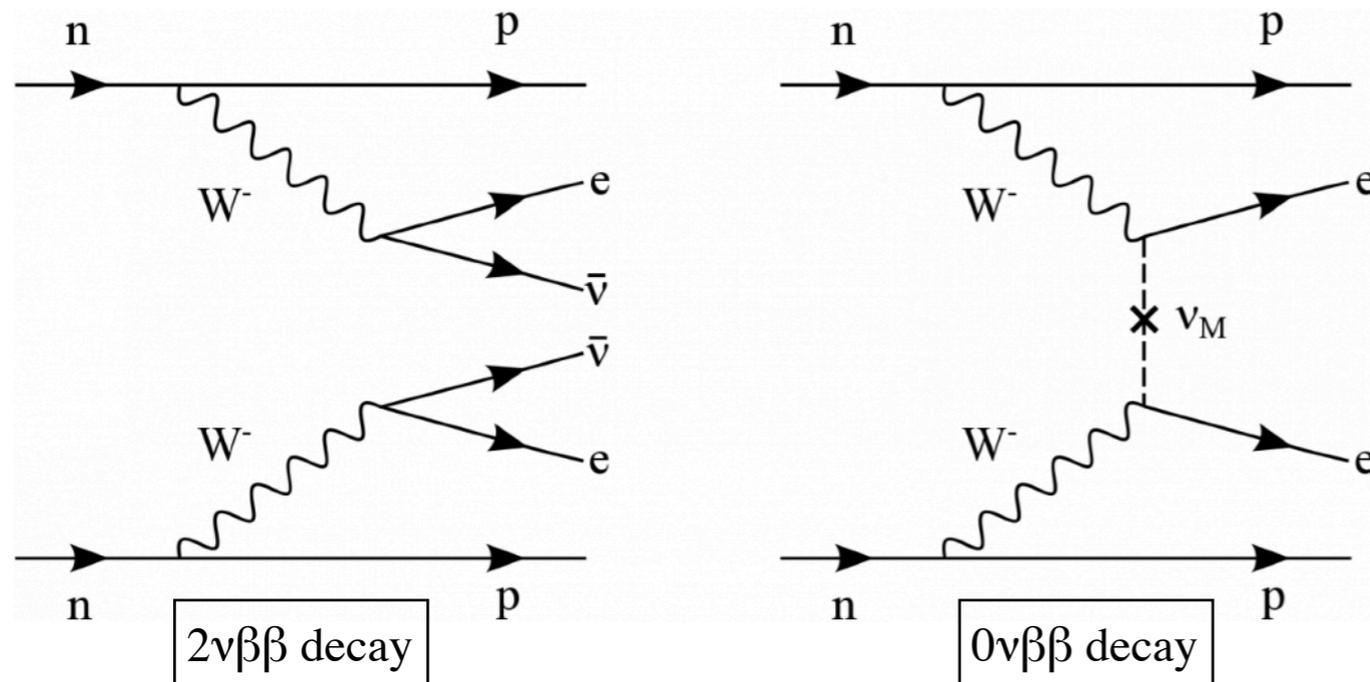
It occurs only if the neutrino has Majorana mass term

If the neutrino is Majorana

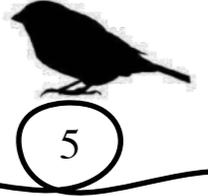
- naturally explains the smallness of the neutrino mass
- One of the conditions of Leptogenesis scenario

It can be identified by

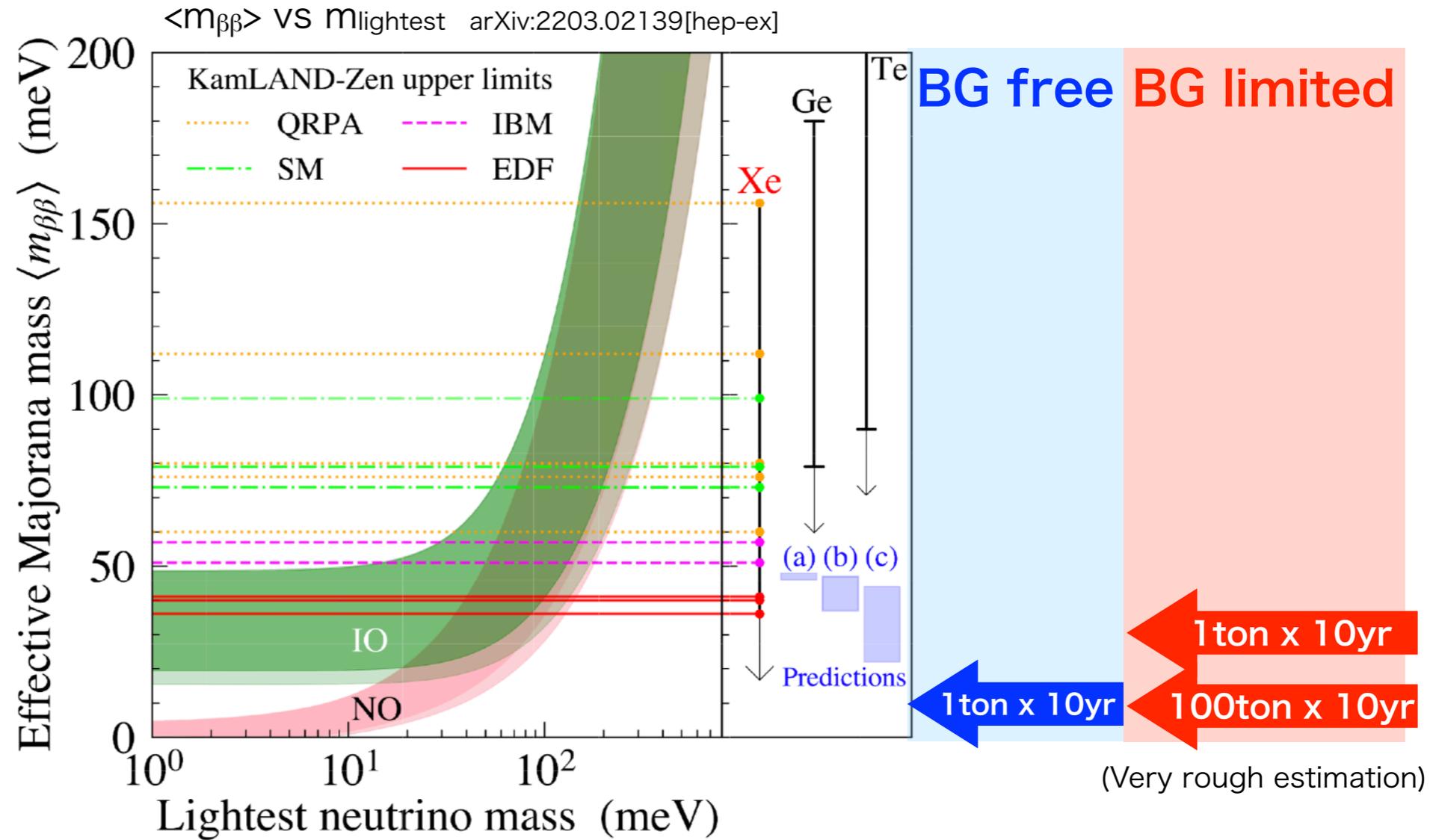
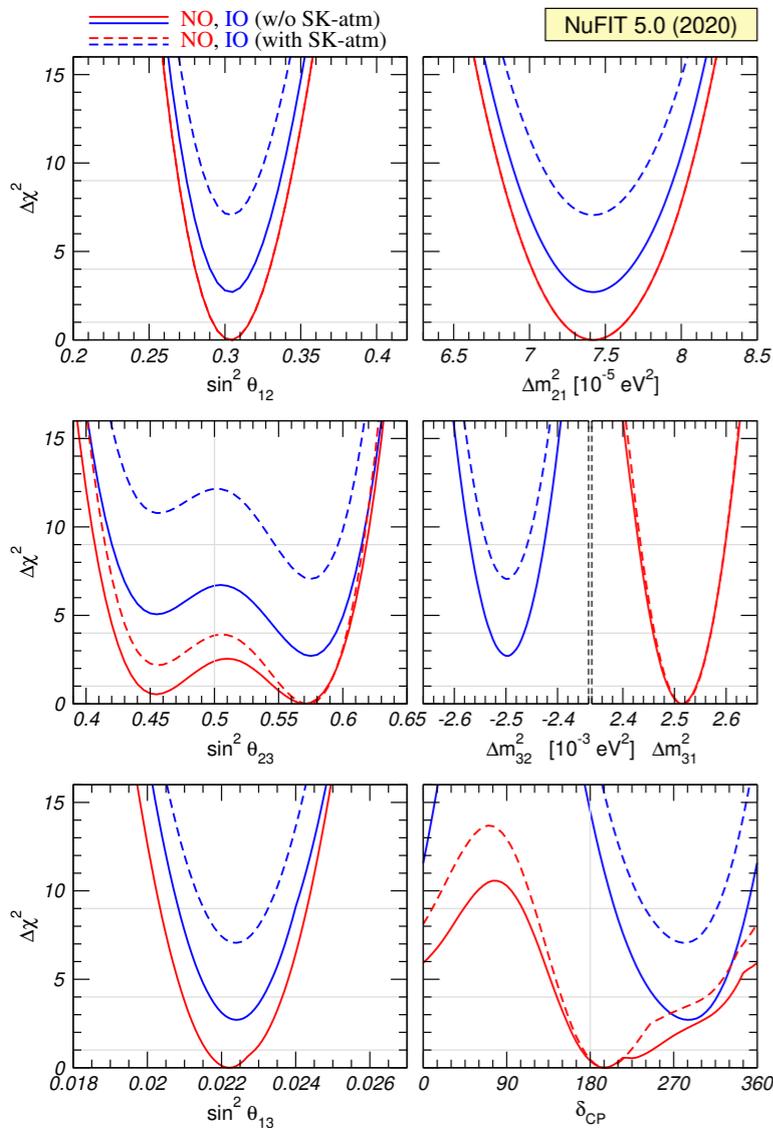
- Energy of two electron sum : mono-peak
- Event topology : only two electrons from the same starting point
→ **good energy resolution and tracking capability** are required



Neutrinoless double beta decay

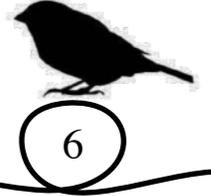


Mass ordering of neutrino : currently, normal ordering is favored



Ton scale & background free are required

→ high pressure xenon gas TPC is a good solution



Pioneering works by the NEXT group demonstrate superiority of high pressure gas xenon for $0\nu\beta\beta$ search

- Source = Detection media
 - ^{136}Xe : natural abundance $\sim 9\%$
 - can concentrate more ($\sim 90\%$) easily by centrifugation
 - Good energy resolution with small W-value : ~ 20 eV
 - take this advantage using “Electroluminescence multiplication”
 - Event topology can be obtained due to gas
- High Q-value
 - higher than the environmental gamma-rays \rightarrow reduce BGs
 - high $0\nu\beta\beta/2\nu\beta\beta$ fraction

Neutrinoless double beta decay

AXEL experiment

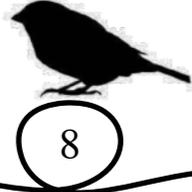
Prototype detector

R&D for more sensitivity

Summary



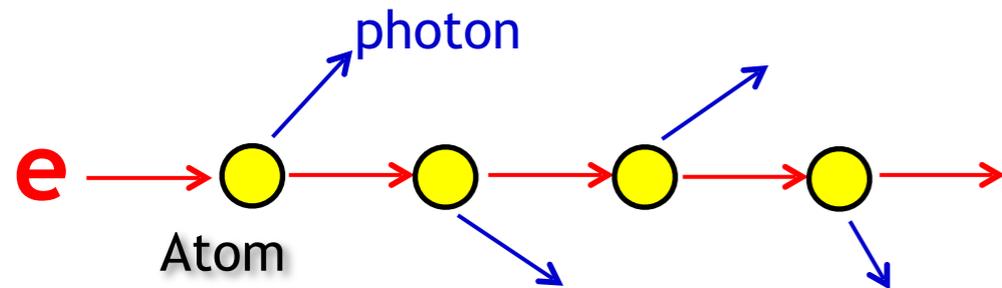
A Xe ElectroLuminescence : AXEL



High pressure Xe gas TPC with unique cell readout structure for $0\nu\beta\beta$ decay search

Detection of Ionization signals

- Electroluminescence (EL) process



Linear response to applied electric field

Without avalanche process
→ less fluctuation of multiplication

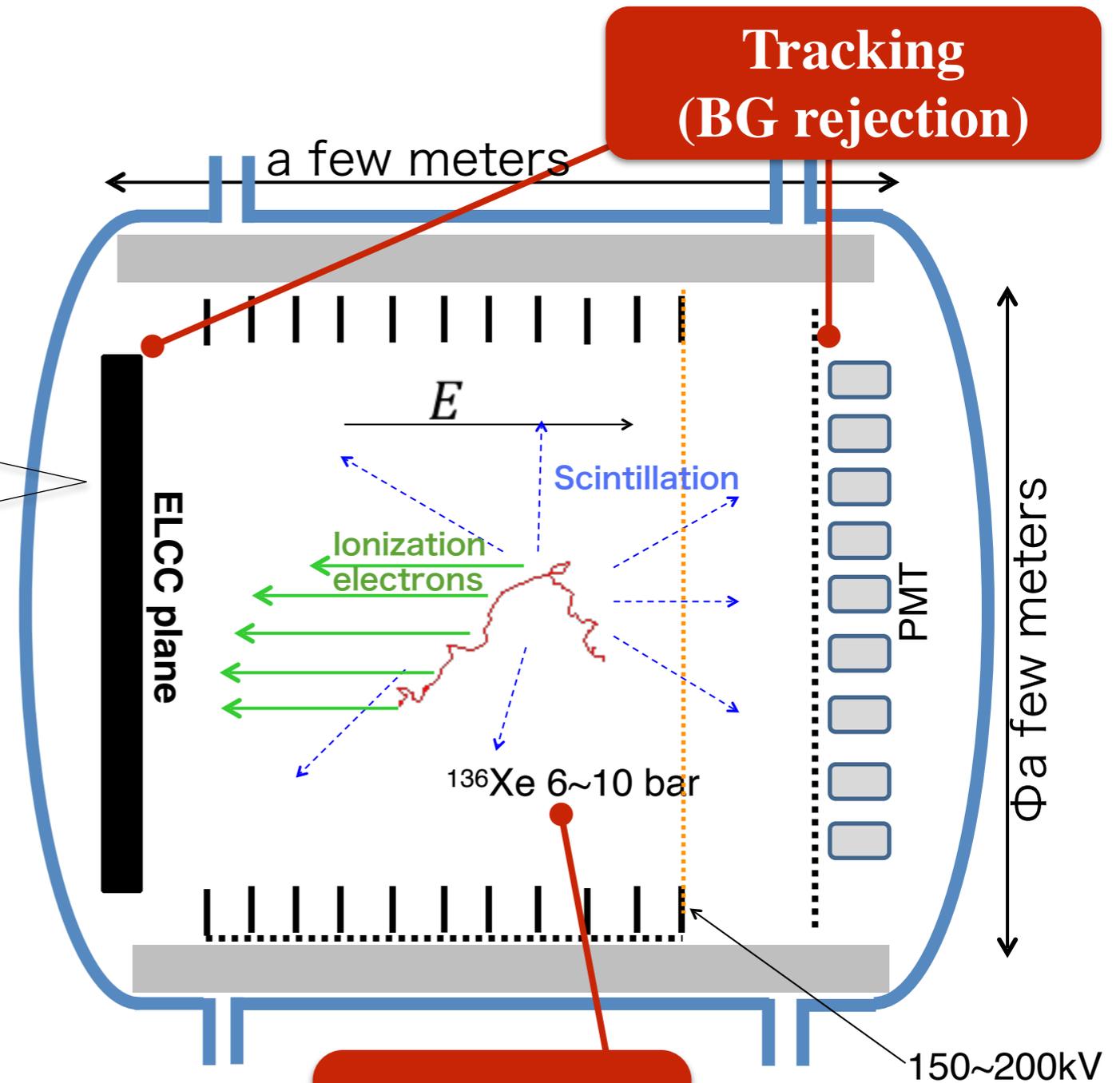
Detail is in the next page

Good energy resolution

→ goal : **0.5%FWHM @ Q-value**

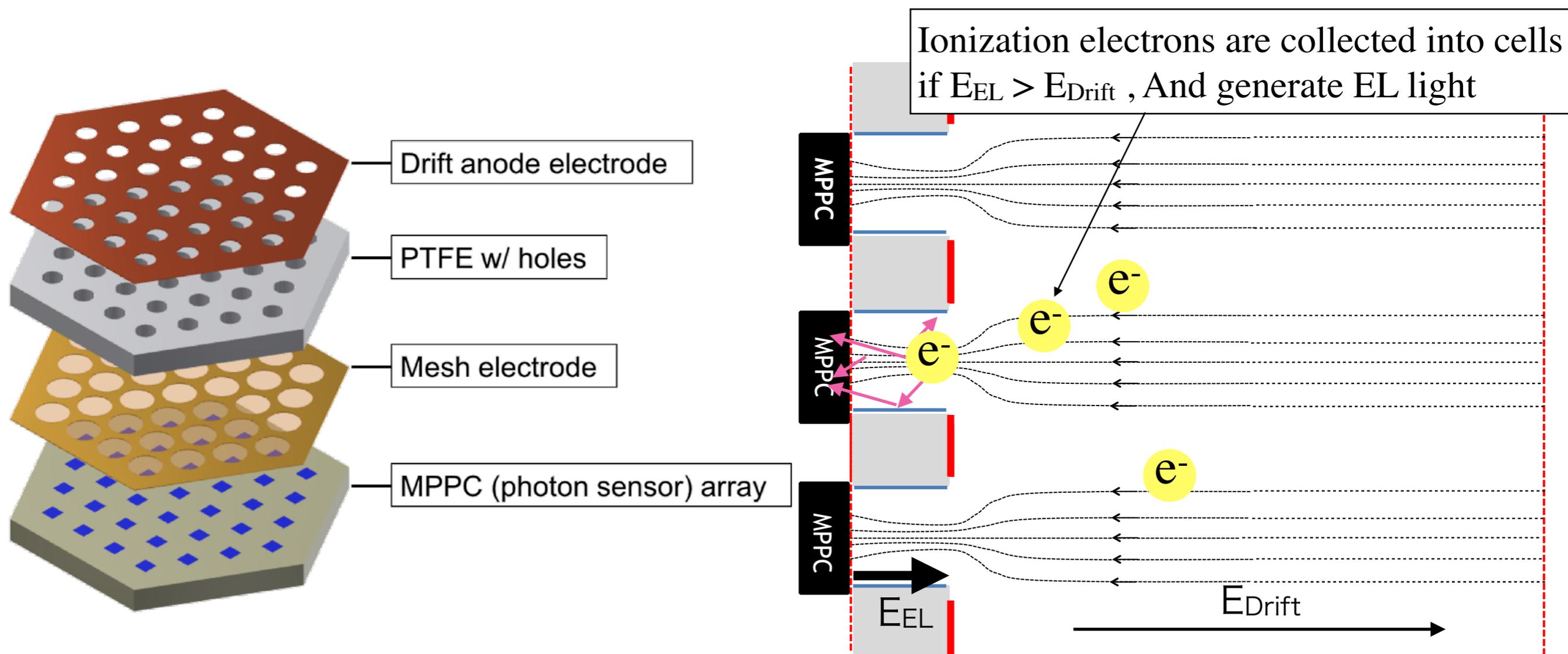
Large mass

→ ton scale ^{136}Xe ($\beta\beta$ -decay nucleus)



Electroluminescence Light Collection Cell : ELCC

- Energy measurement and Tracking
- Uniform response regardless of event position
- Energy reconstruction of each cluster is easy
- Extendable to large size thanks to its rigid structures



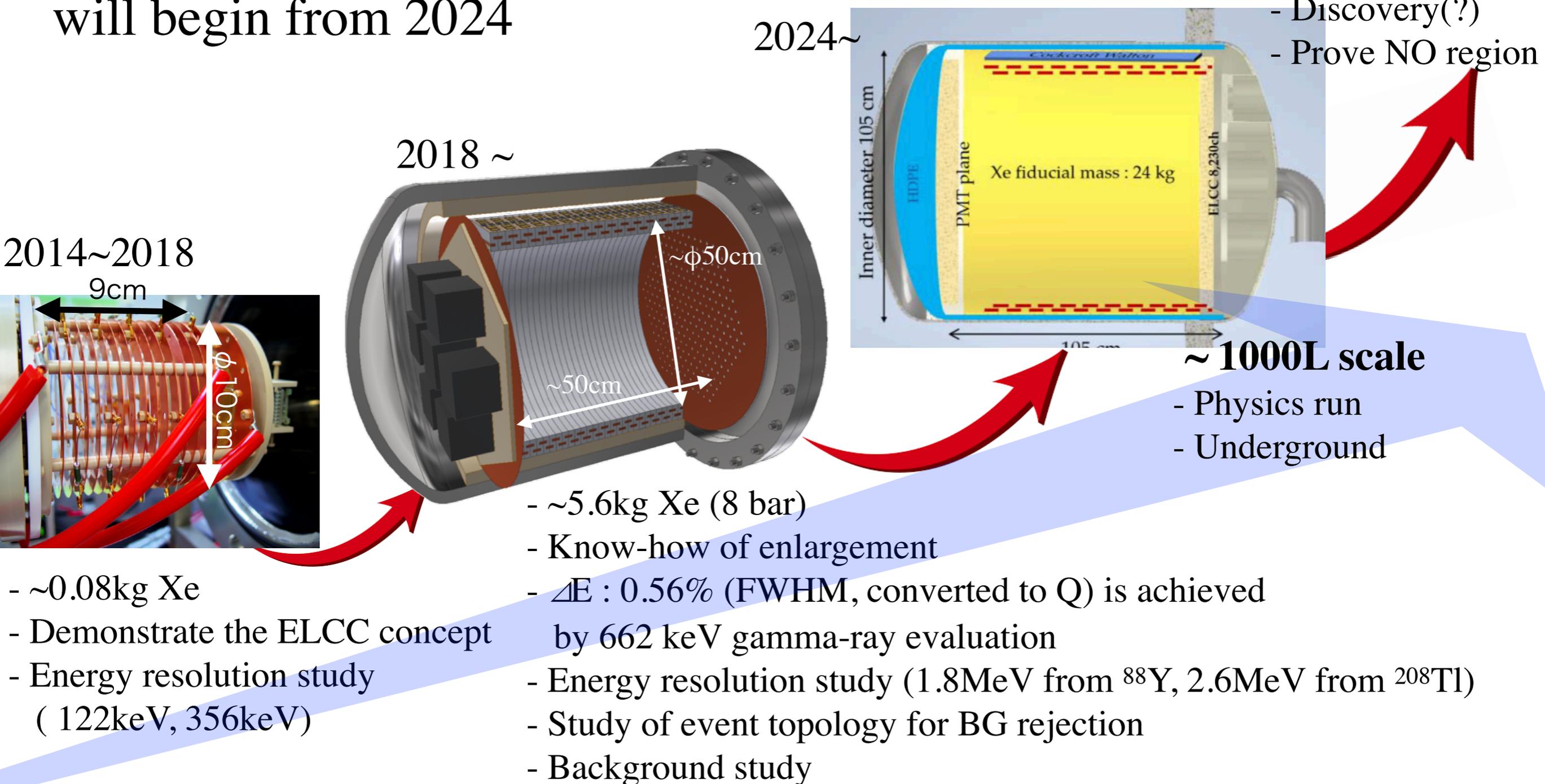
A Xe ElectroLuminescence : AXEL

Road map of the AXEL experiment

- Evaluation with the prototype detectors is ongoing
- Construction of a detector (1000L) for physics run will begin from 2024

ton scale

- Discovery(?)
- Prove NO region



Neutrinoless double beta decay

AXEL experiment

Prototype detector

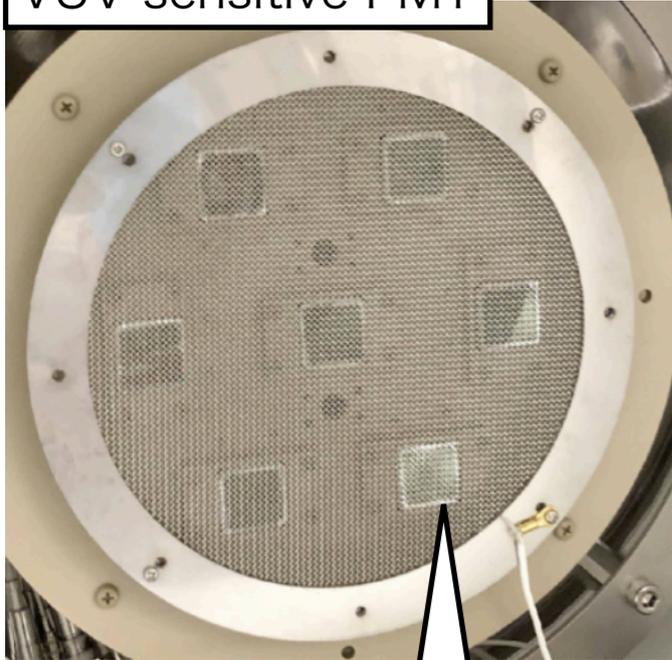
R&D for more sensitivity

Summary

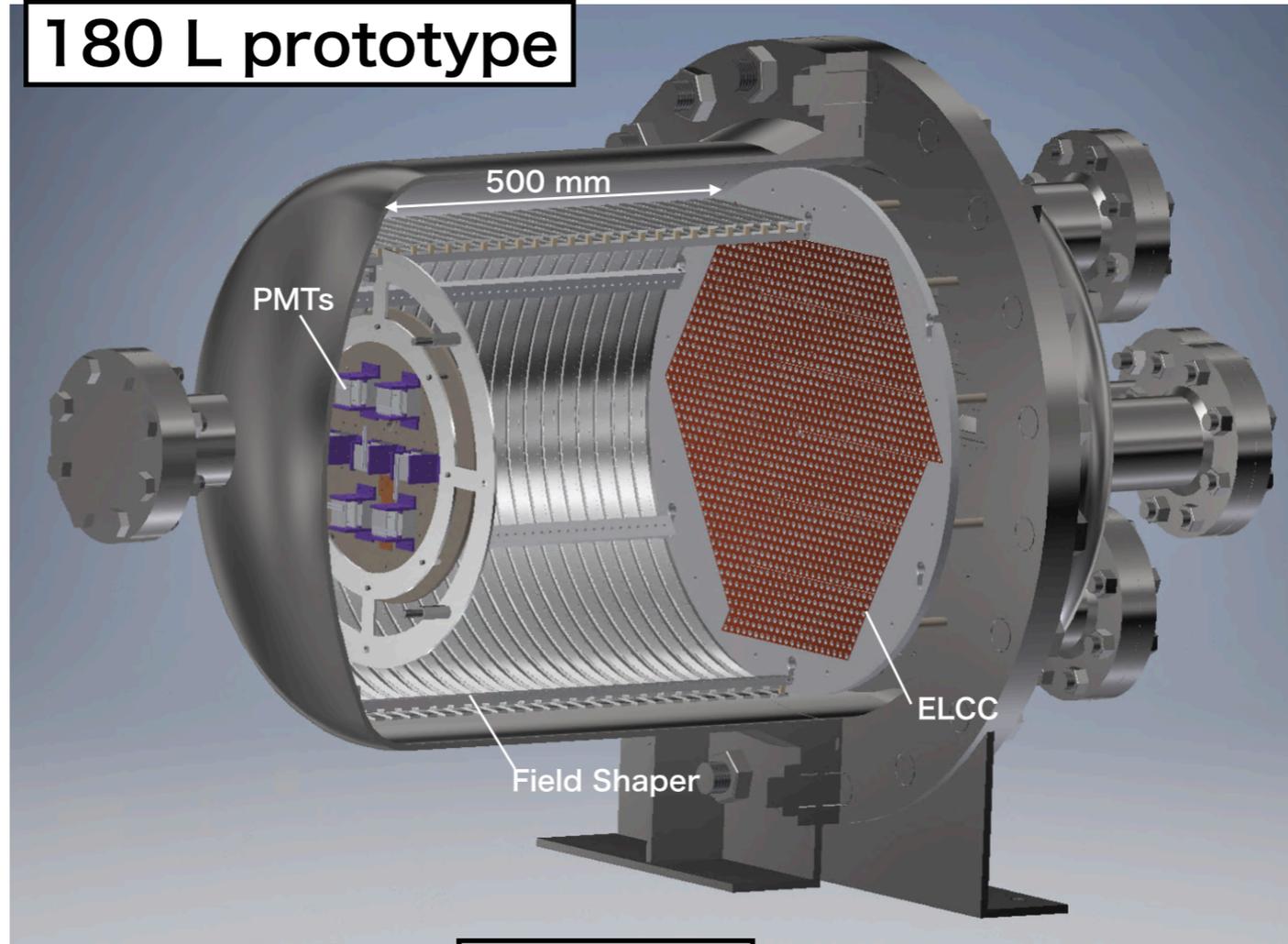


Prototype detector

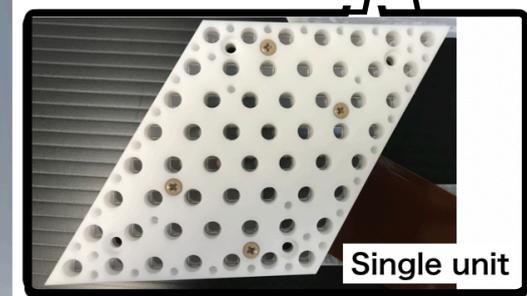
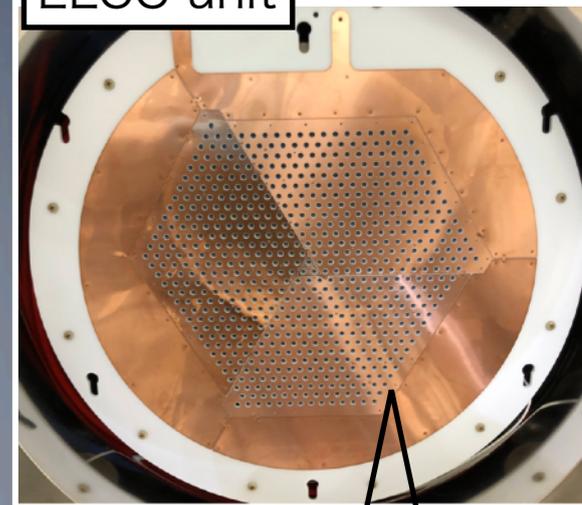
VUV-sensitive PMT



180 L prototype

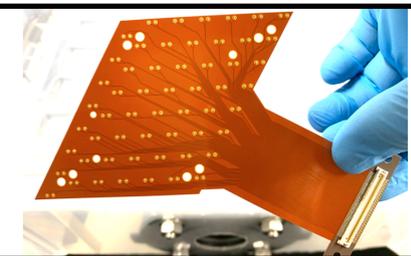


ELCC unit

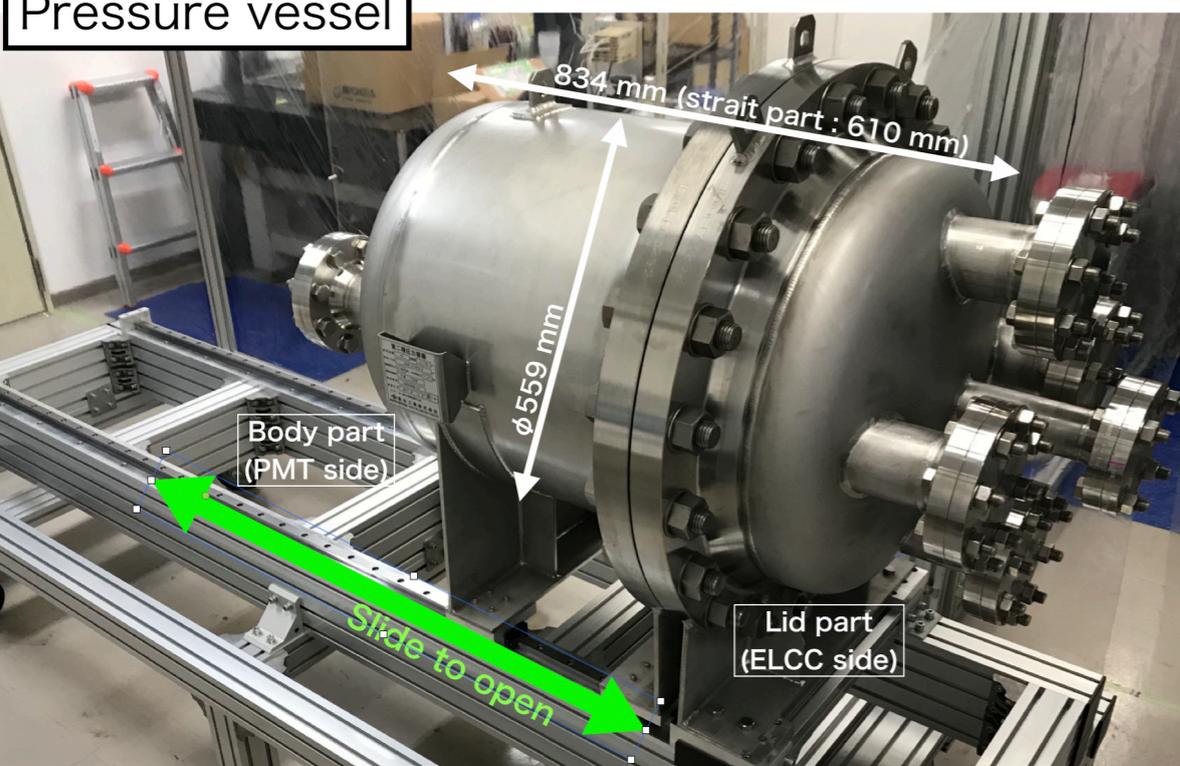


Single unit

Flexible Printed Circuit



Pressure vessel



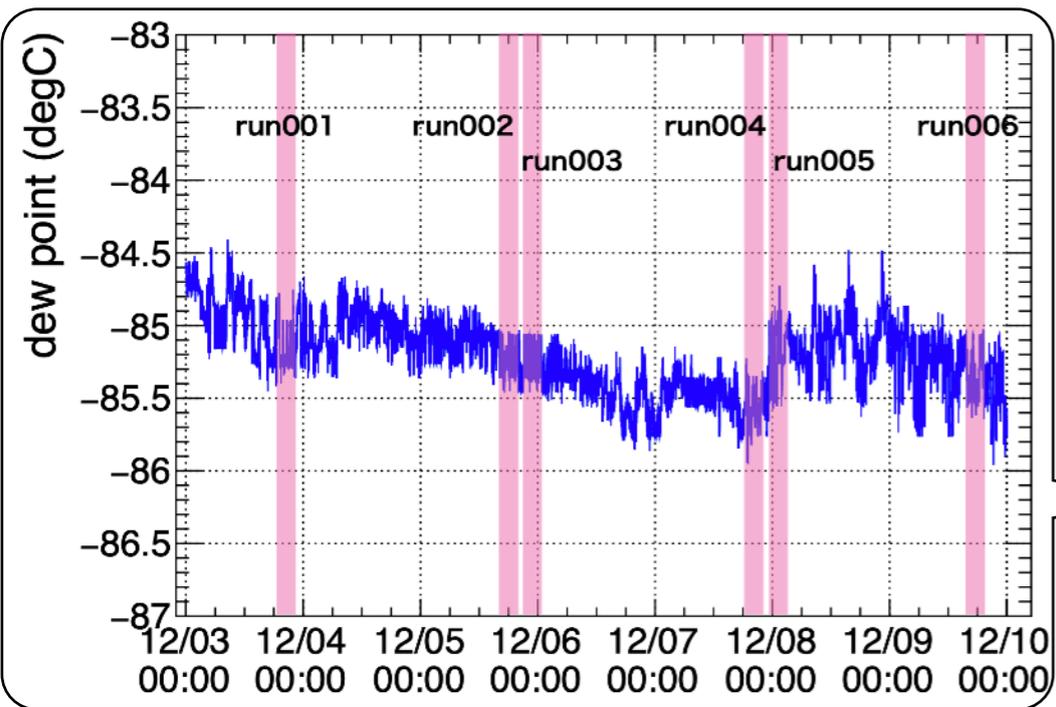
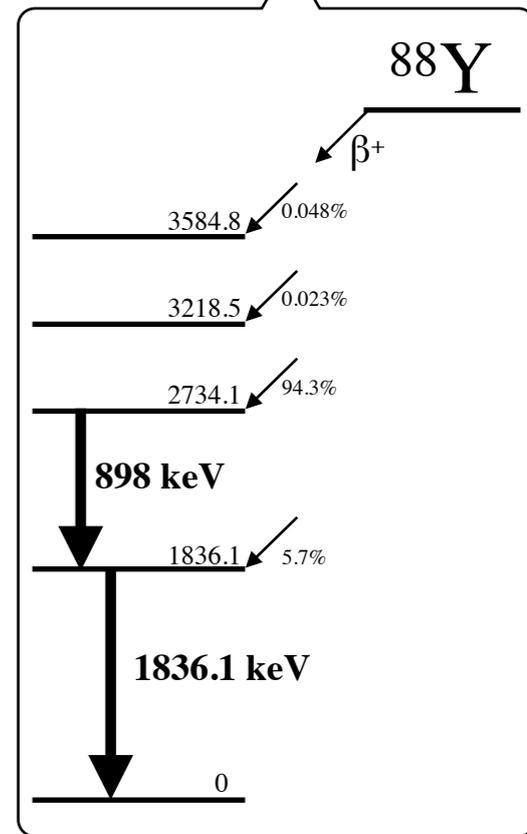
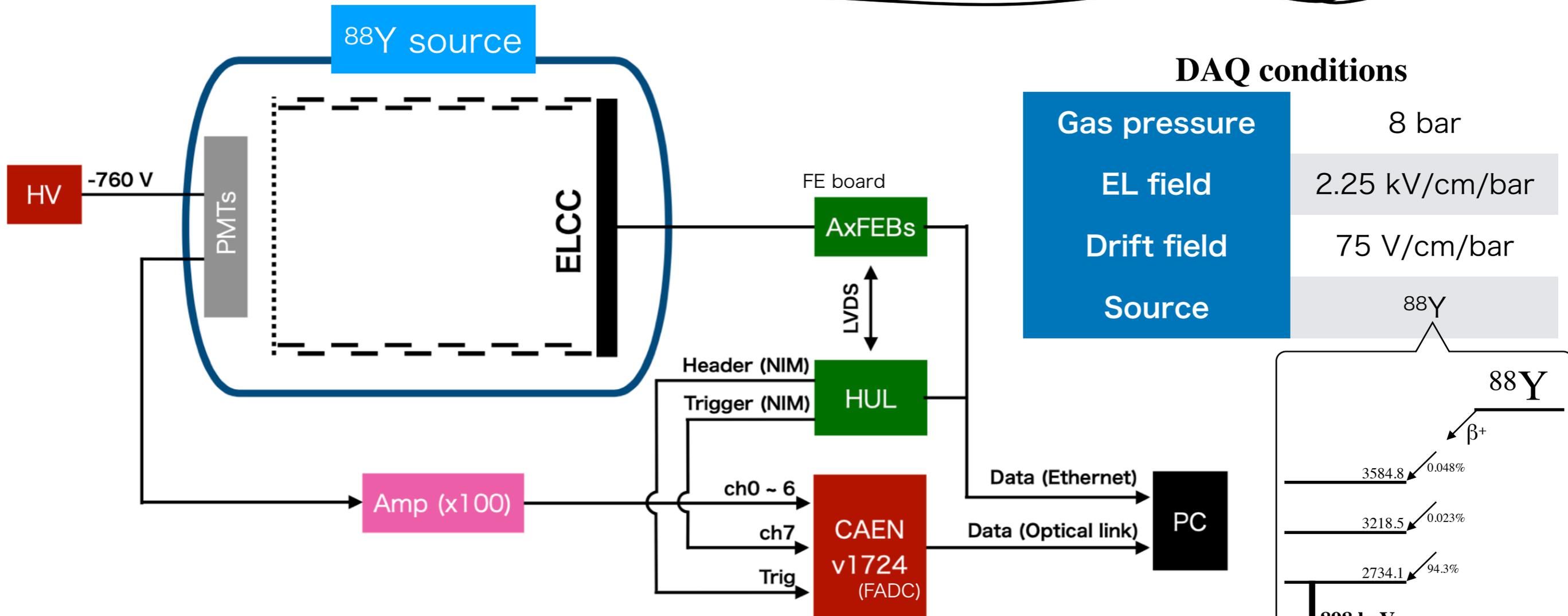
Field shaper



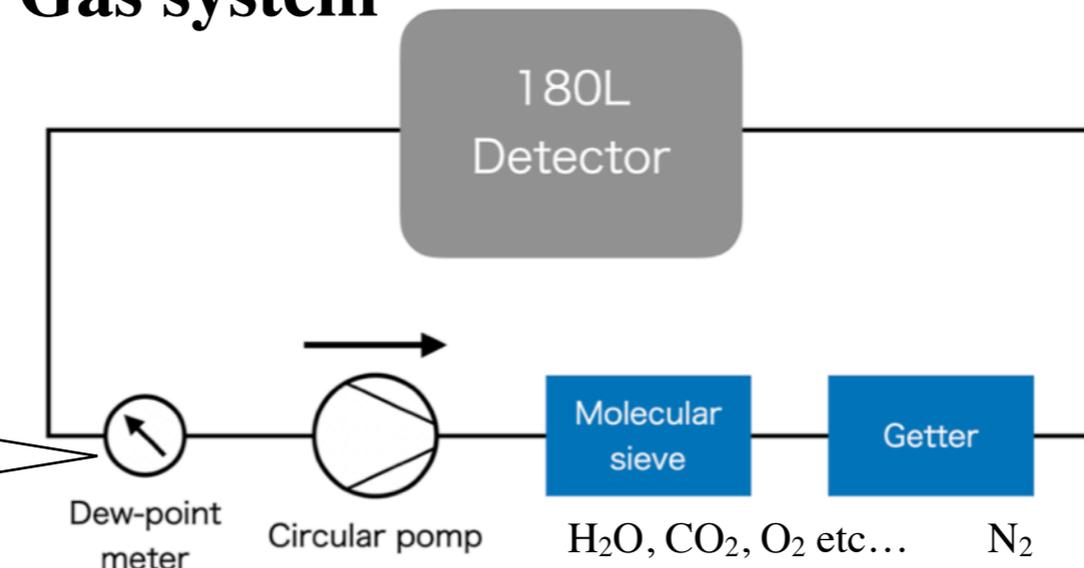
Front-end Electronics Board
ref: arXiv:2001.02104



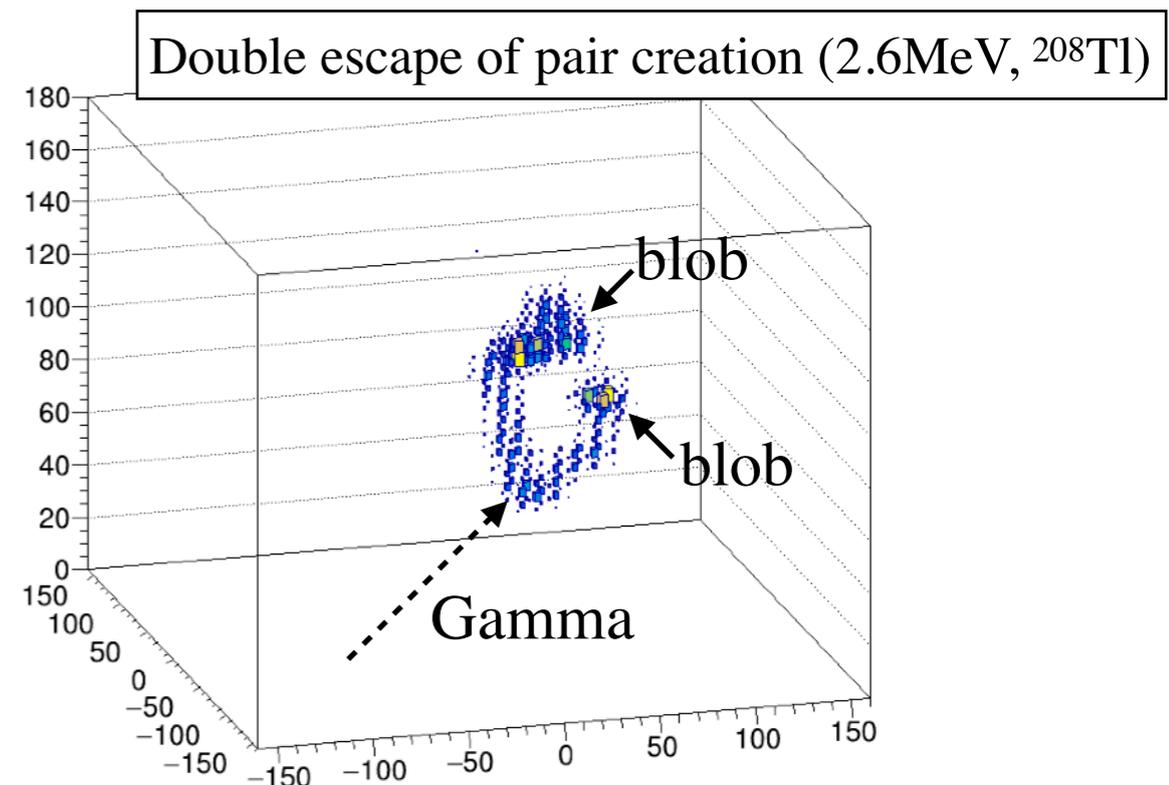
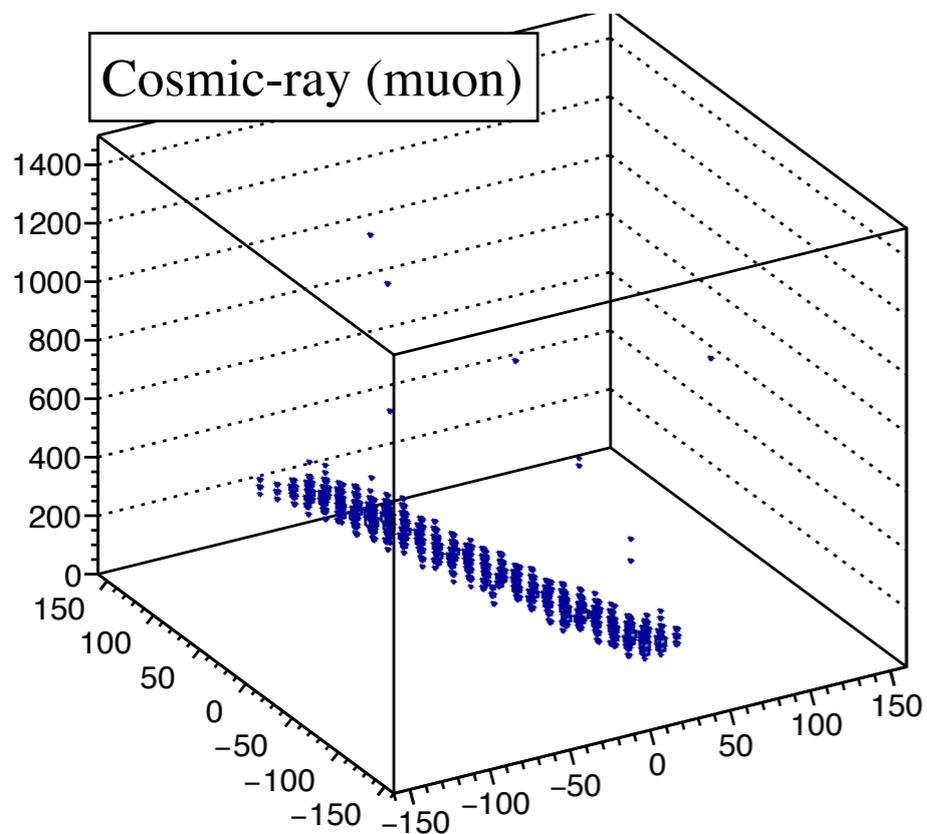
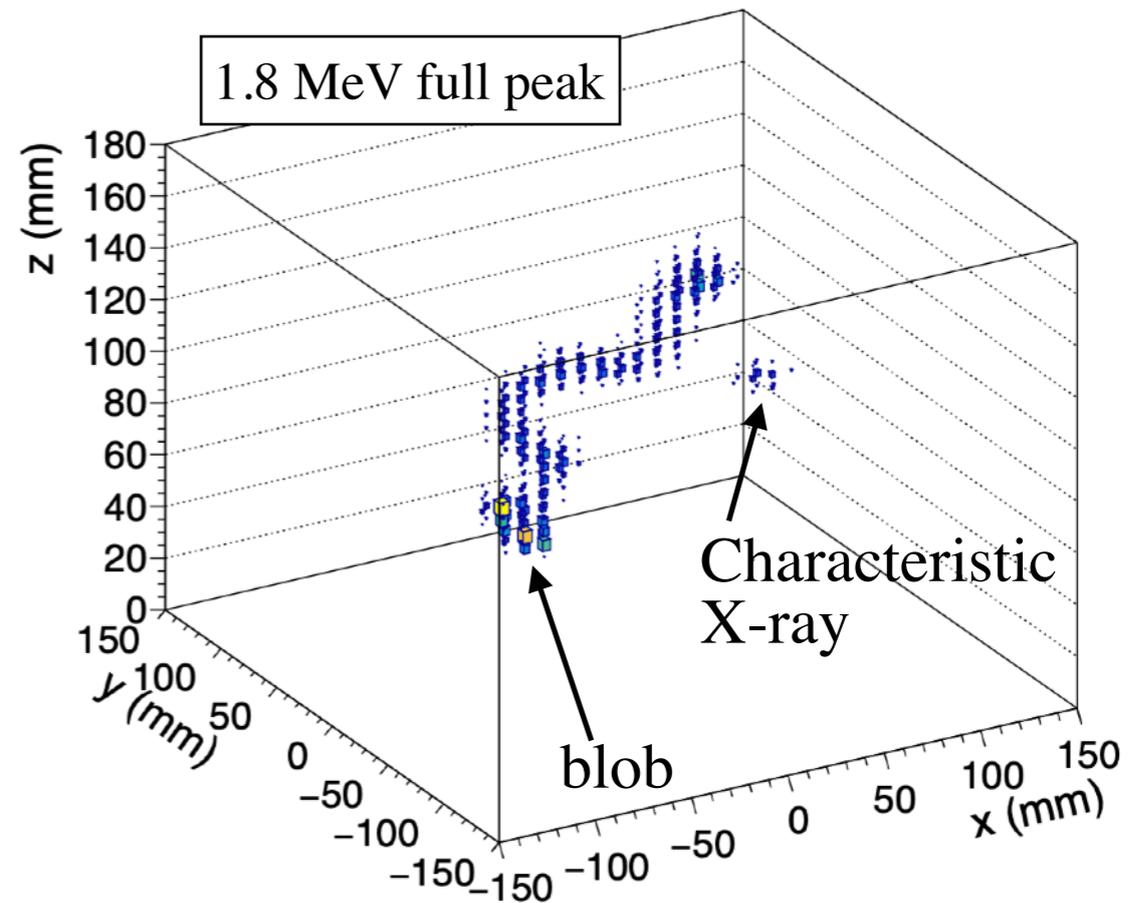
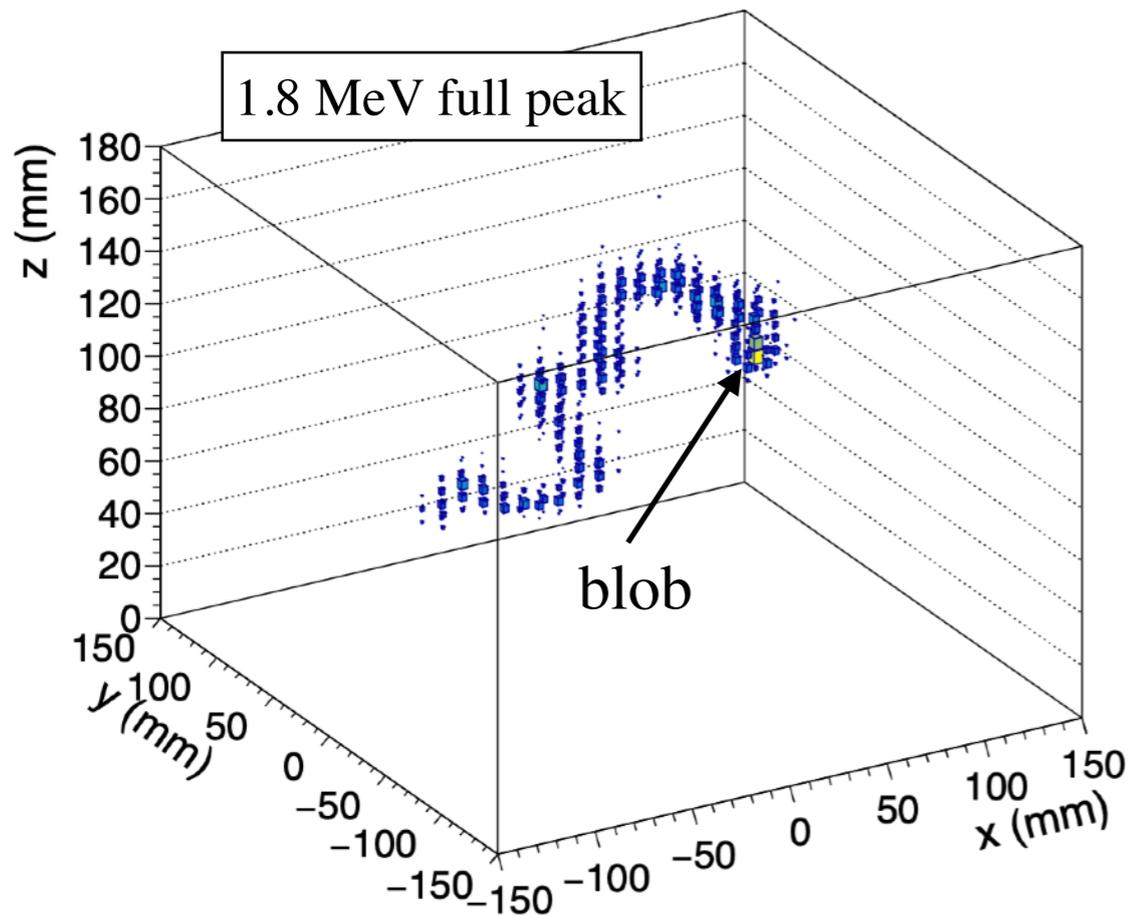
Data taking



Gas system



Event display



Analysis flow

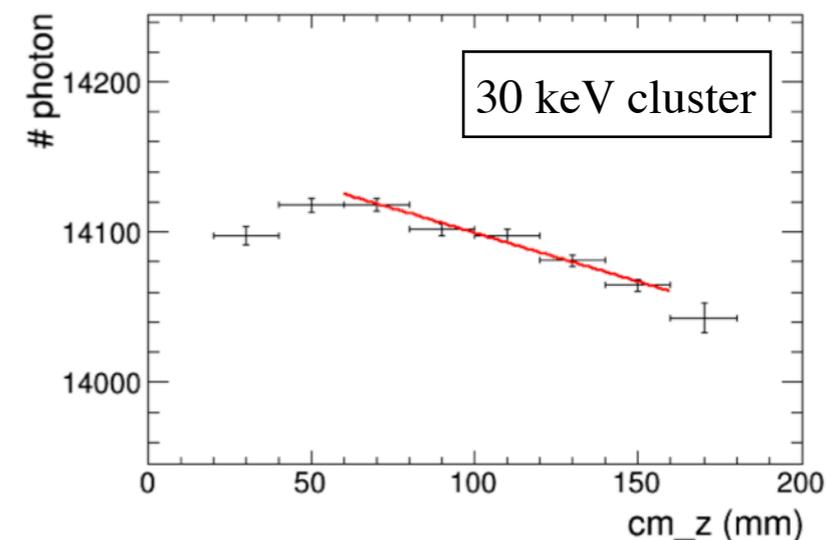
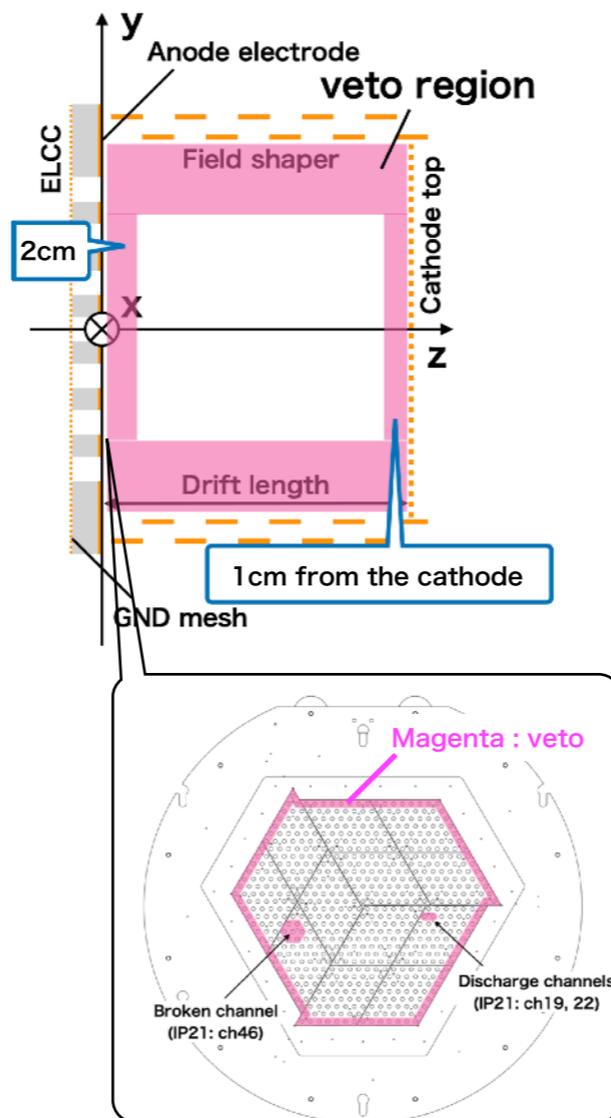
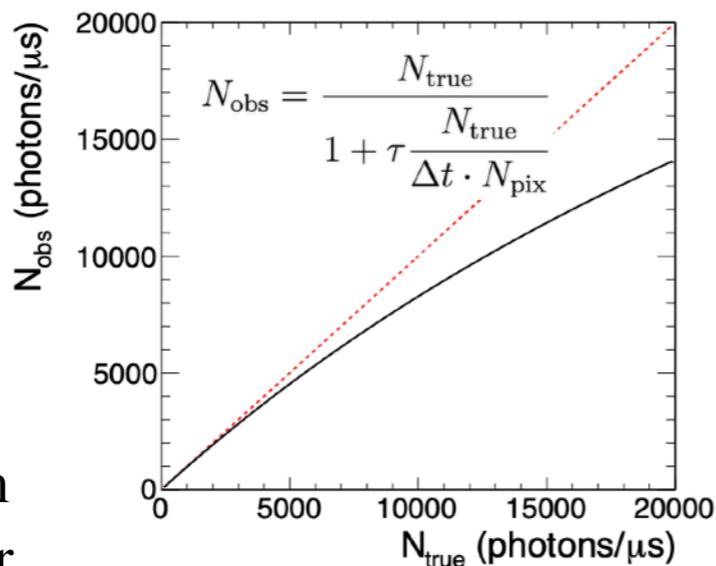


Calibration & correction for each cell (sensor)

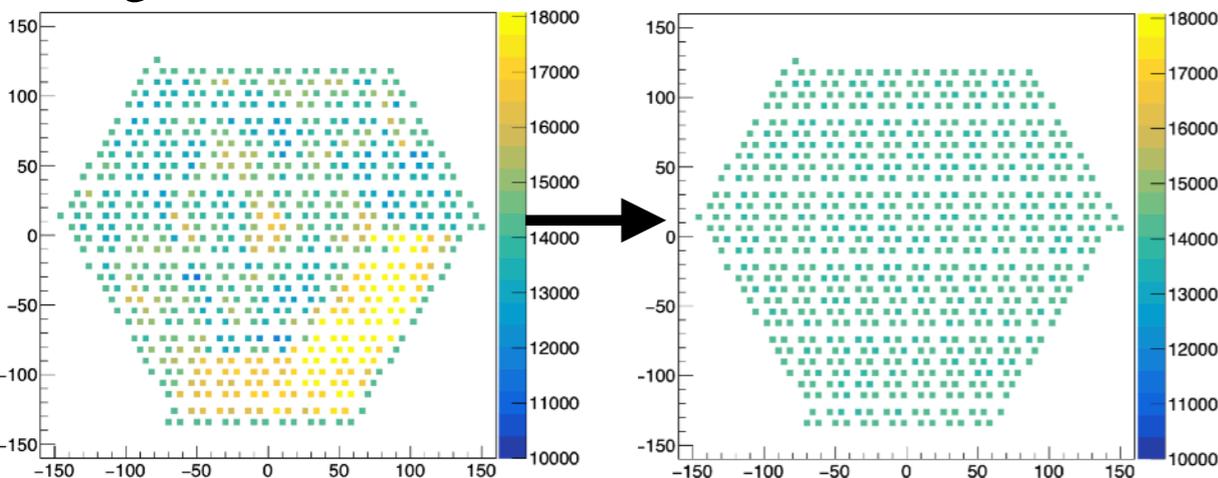
Fiducial cut

z position dependence

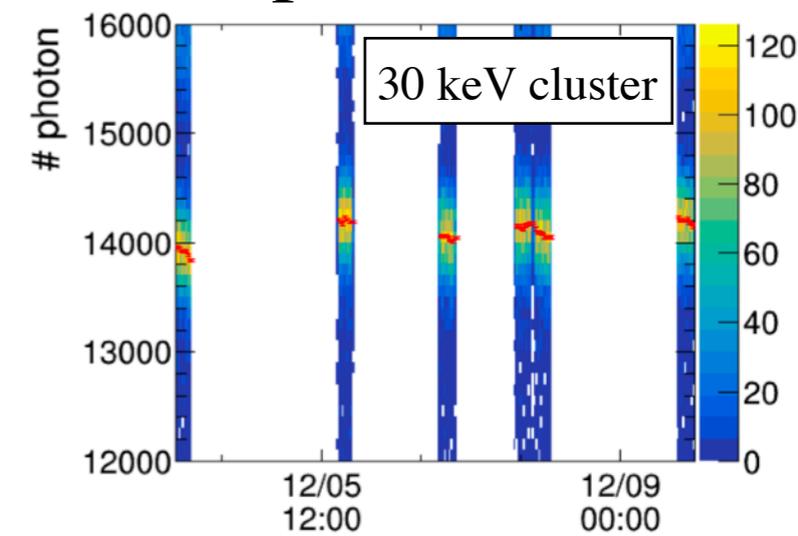
Correction of MPPC non-linearity
- recovery times of each MPPC were measured in advance



Cell gain calibration using 30 keV cluster



time dependence

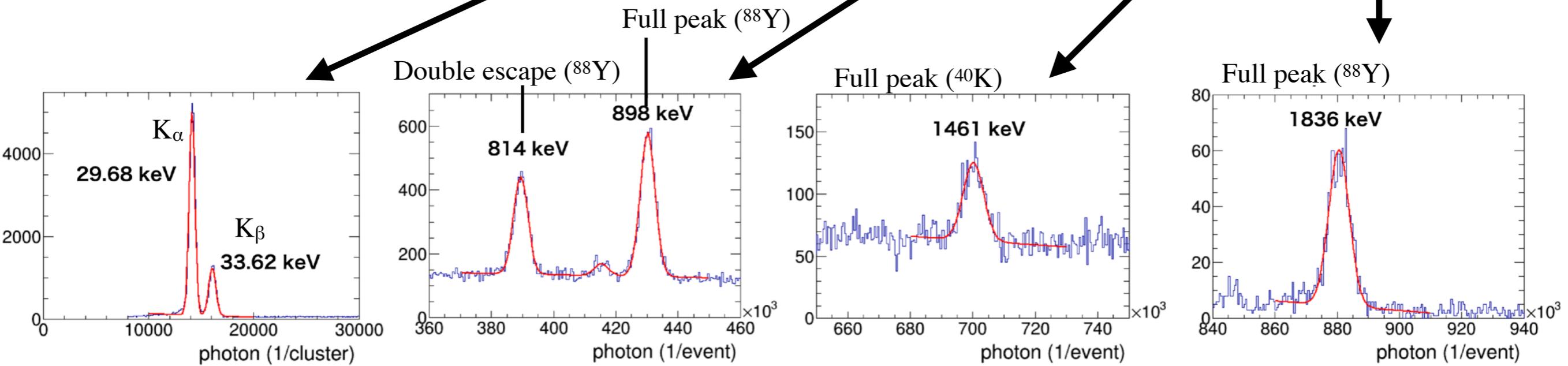
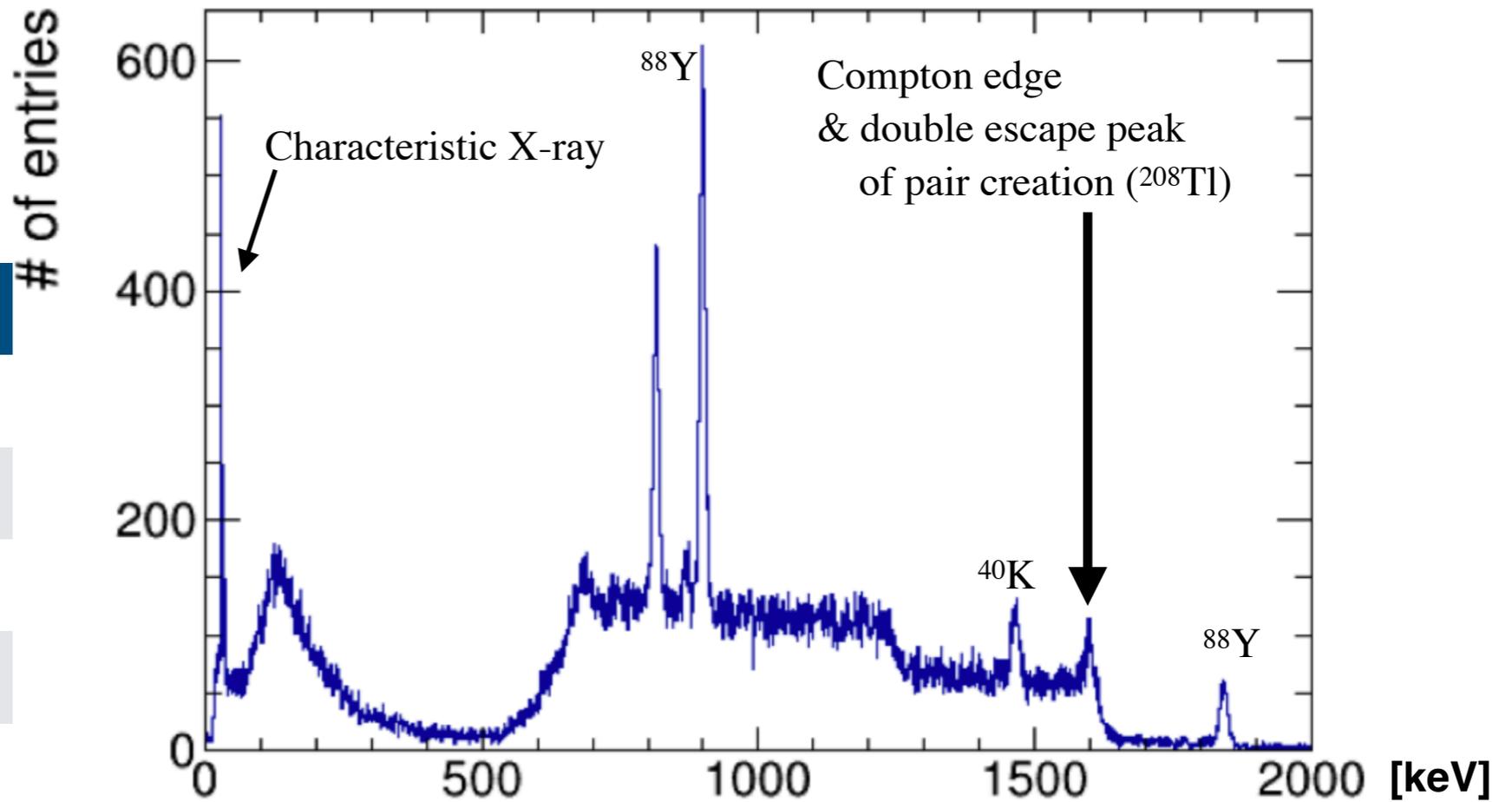


Energy spectrum and performance

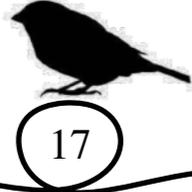
Energy spectrum

- Each peak is fitted by Gaussian

	$\Delta E/E$ (FWHM)
K_α 29.78 keV	4.67 ± 0.02 %
K_β 33.62 keV	4.98 ± 0.05 %
Double escape : 814 keV	1.28 ± 0.03 %
^{88}Y : 898 keV	1.21 ± 0.03 %
^{40}K : 1461 keV	1.10 ± 0.05 %
^{88}Y : 1836 keV	0.89 ± 0.03 %



Evaluation of energy resolution

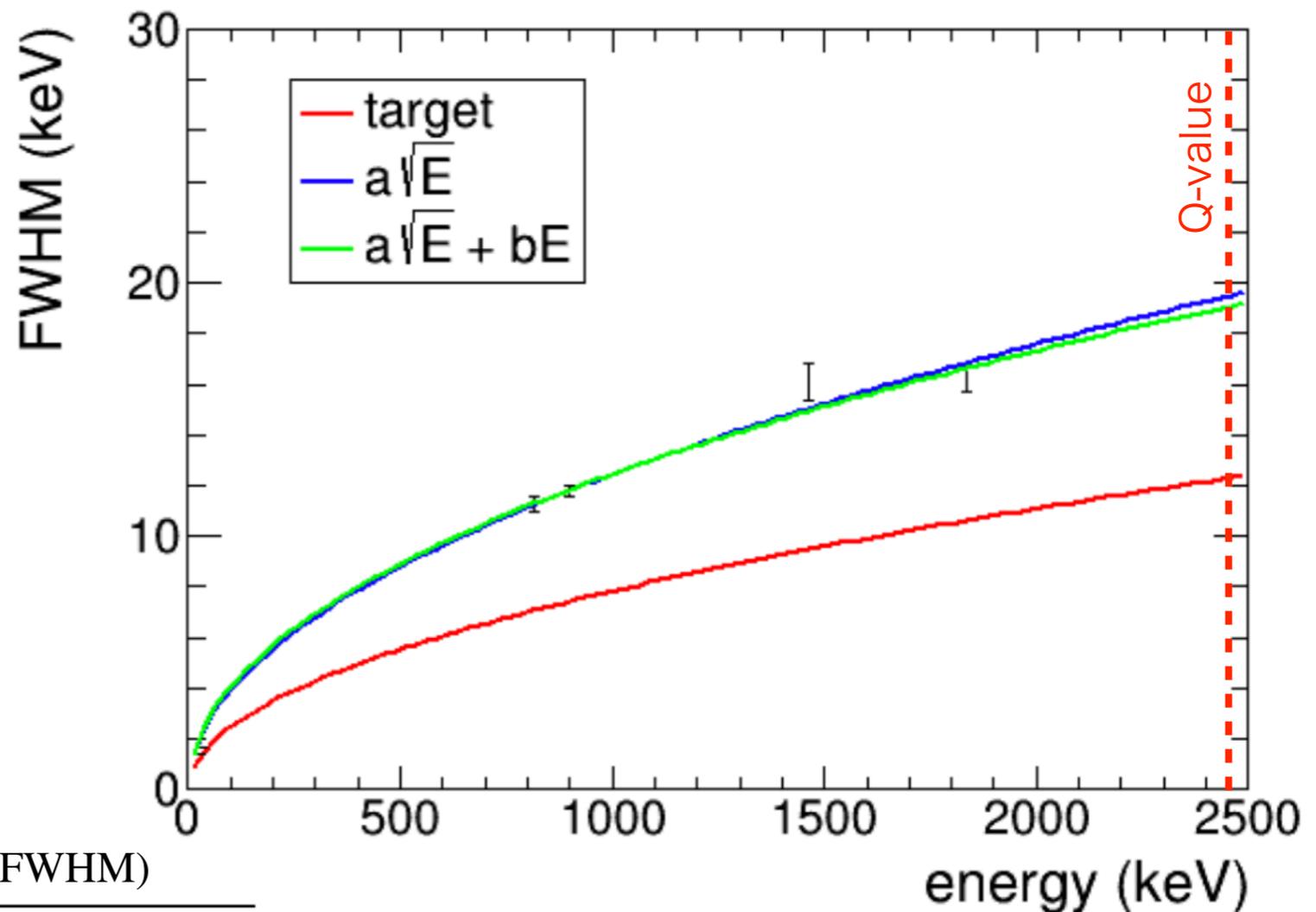


Obtained energy resolutions are extrapolated to Q-value

$$\Delta E/E = 0.79\% \text{ (FWHM)}$$

- can be converted by \sqrt{E}
- No linear components

Breakdown of $\Delta E/E$ is also estimated as below :



Estimated breakdown for 1.8 MeV peak (0.89% FWHM)

Fluctuation of the number of ionization electrons produced	0.25%
Fluctuation of EL amplification	0.30%
Position dependence of EL amplification factor	negligible
Waveform processing in AxFEB	negligible
Error in EL gain calibration	0.12%
Accuracy of MPPC recovery time measurement	negligible
Error in time correction	0.20%
Error in z correction	0.31%
Dependence of the drift electric field	0.27%
Unknown	0.62%
Total	0.89%
Target which corresponds to 0.5% FWHM at Q-value	0.58%

We still have large unknown components

→ further investigation should be done.

Neutrinoless double beta decay

AXEL experiment

Prototype detector

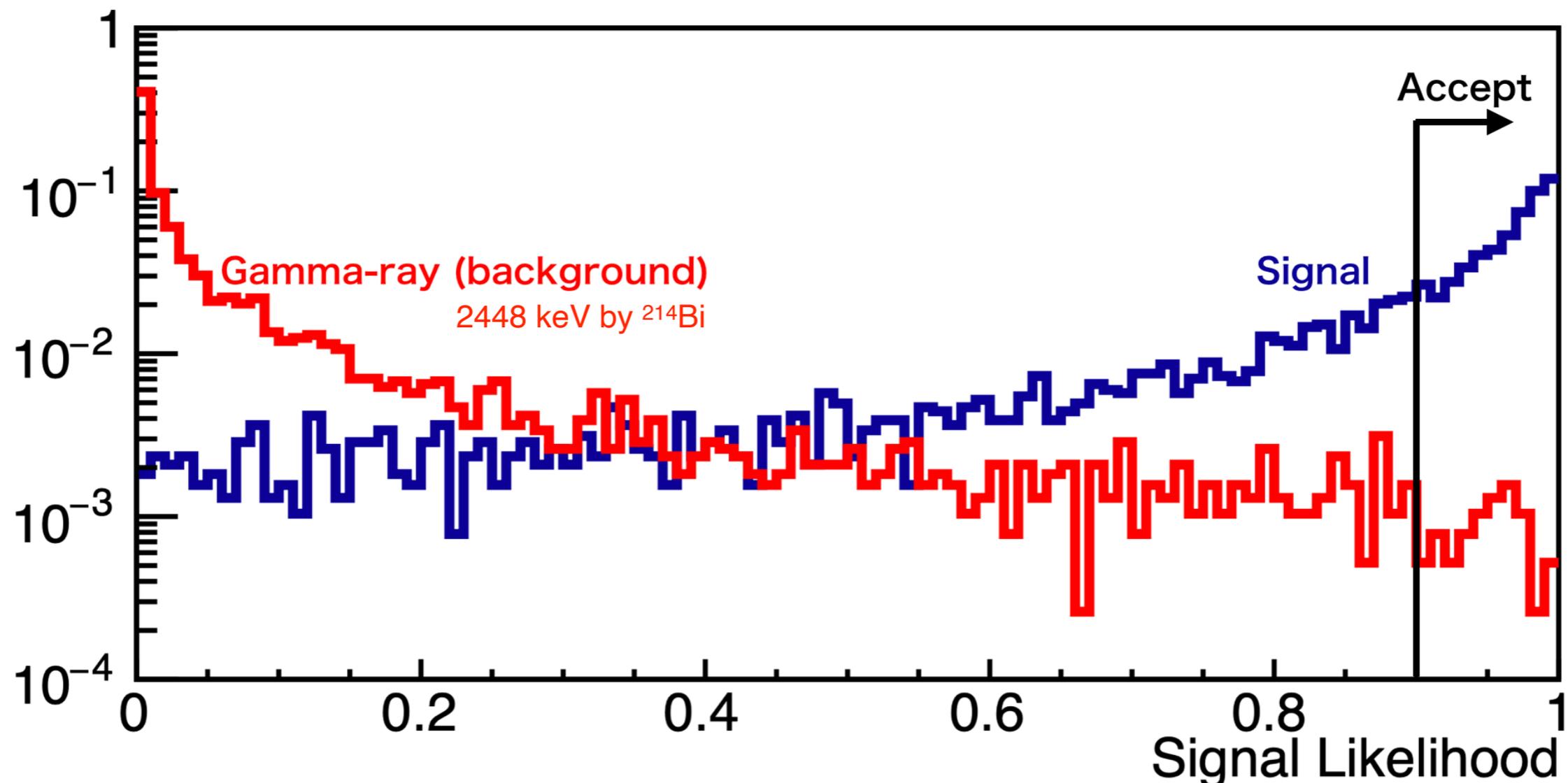
R&D for more sensitivity

Summary



Deep Learning

- Learning with simulated $0\nu\beta\beta$ and gamma-ray
- Signal efficiency : 50%, BG rejection : 99.95% by Deep learning (assuming 2448 keV gamma-ray from ^{214}Bi as background)
- The DL performance can be evaluated by prototype real data



Diffusion in xenon gas

- electron : large (a few **cm** with 1 m drift in 10 bar)
- ion : small (a few **mm** with 1 m drift in 10 bar)

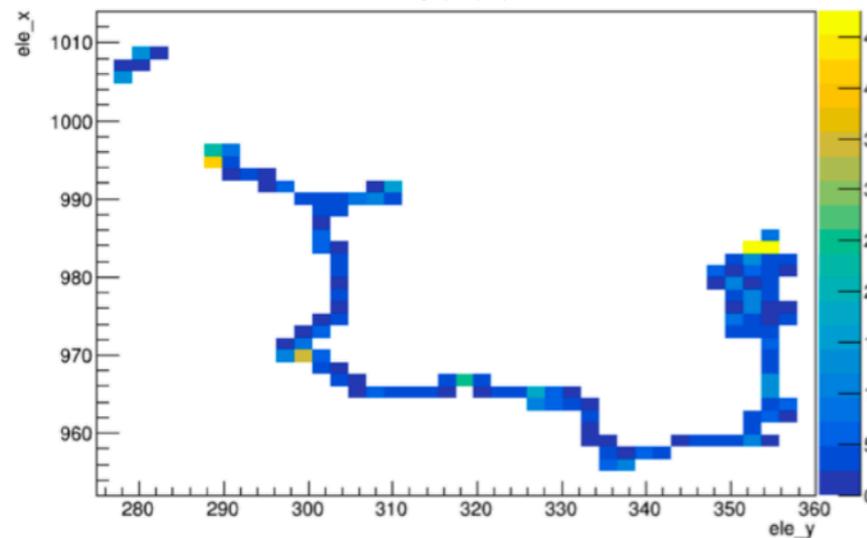
Ionization ions can be used for more precise track reconstruction

→ **Ion detection**

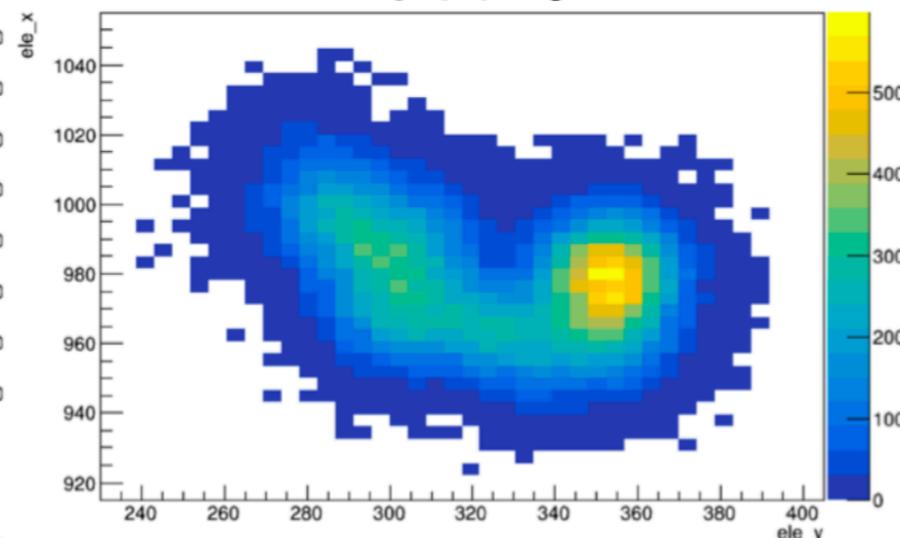
It may improve the performance of track distinction by DL

Track pattern (simulation)

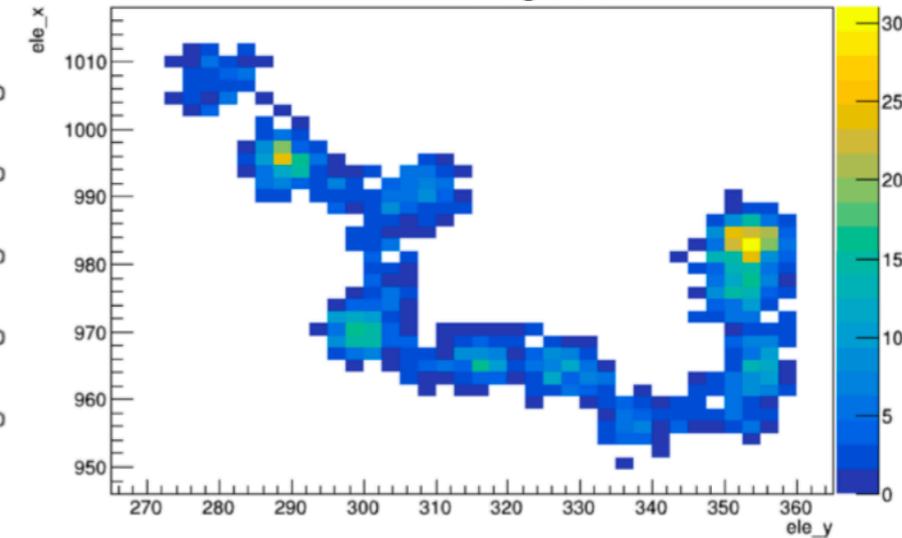
Raw



Electron



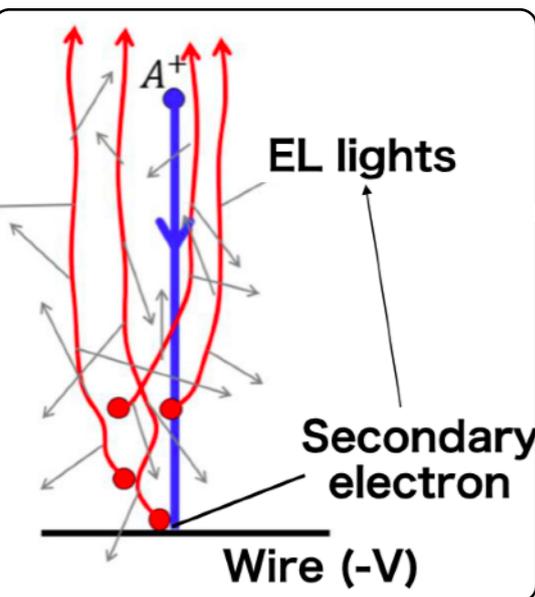
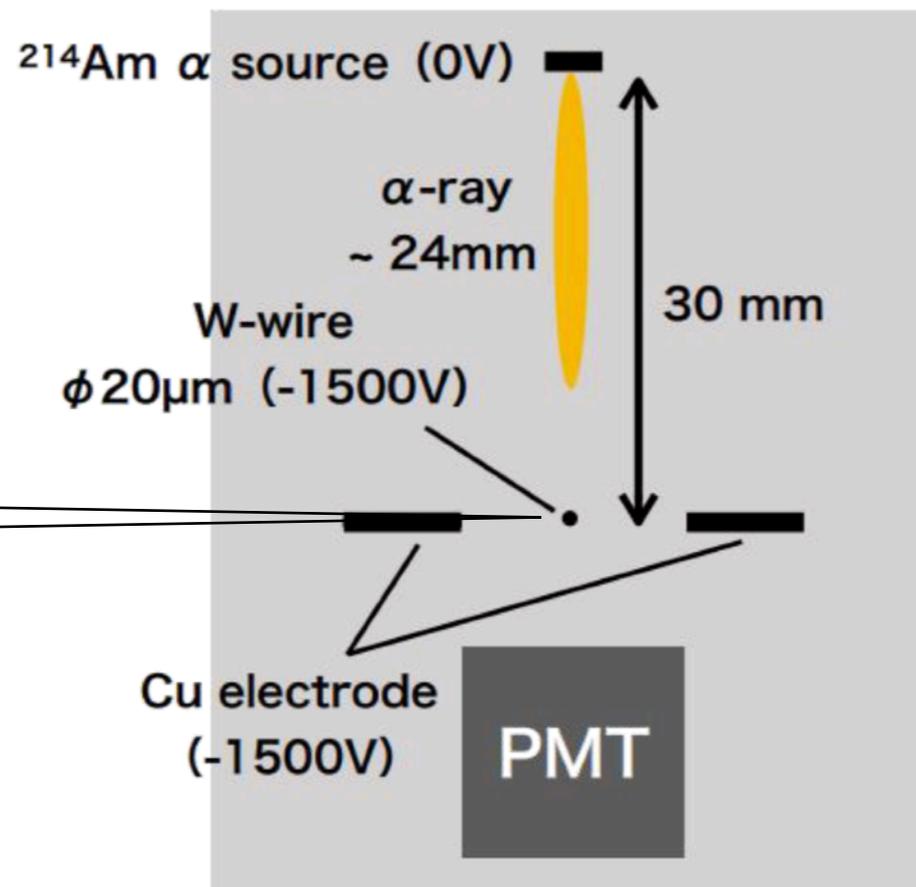
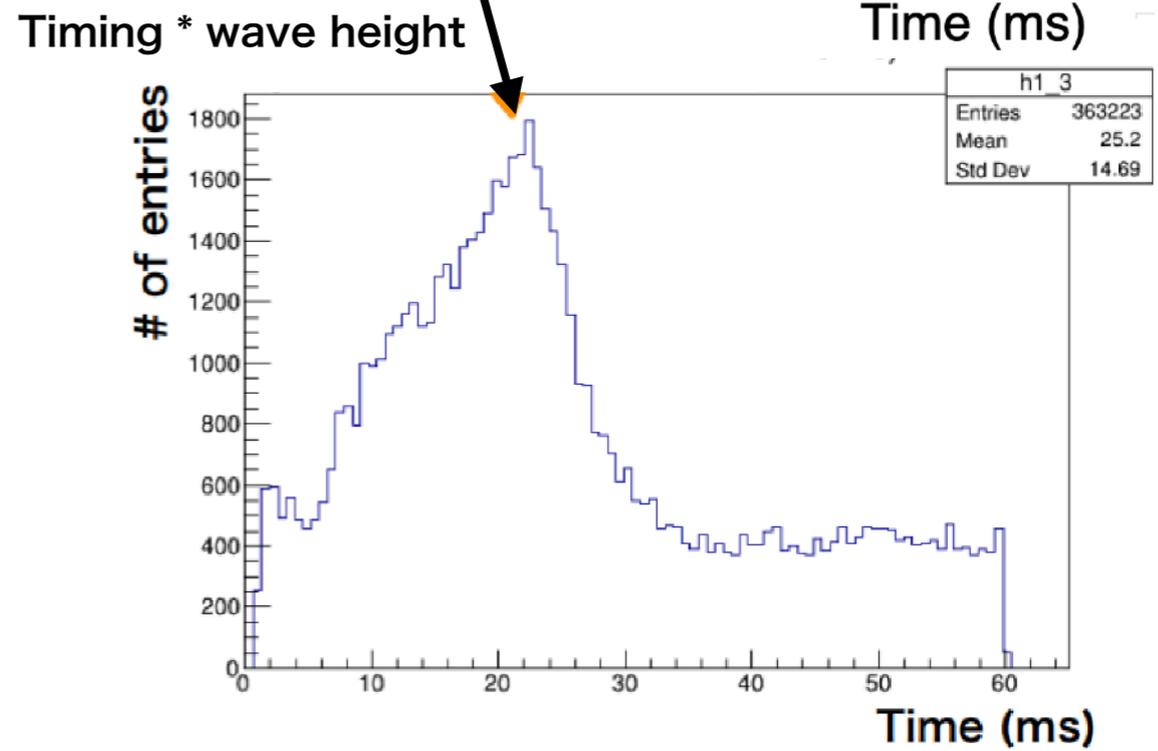
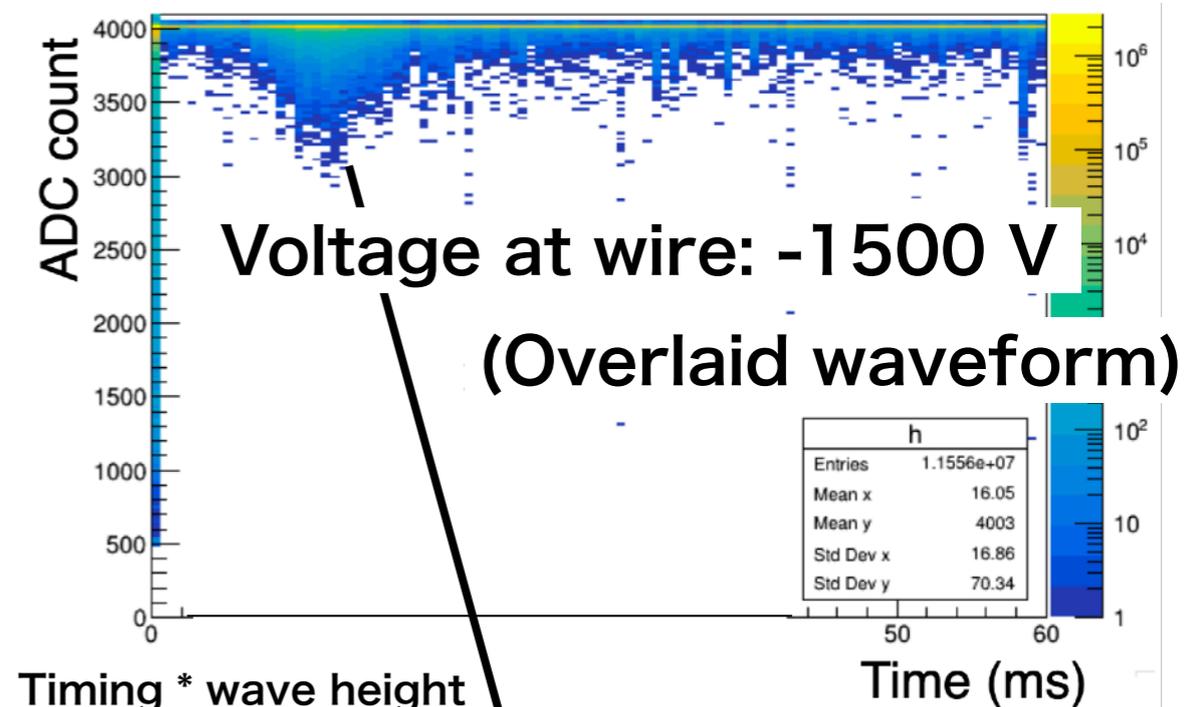
Ion



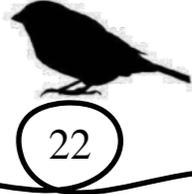
Topology of ions

Detect the EL lights from secondary electrons generated by ions hit at anode wires

- Tried to detect ions in test chamber with single wire
- Succeeded to detect ion signal (?)
~20 msec after the scintillation

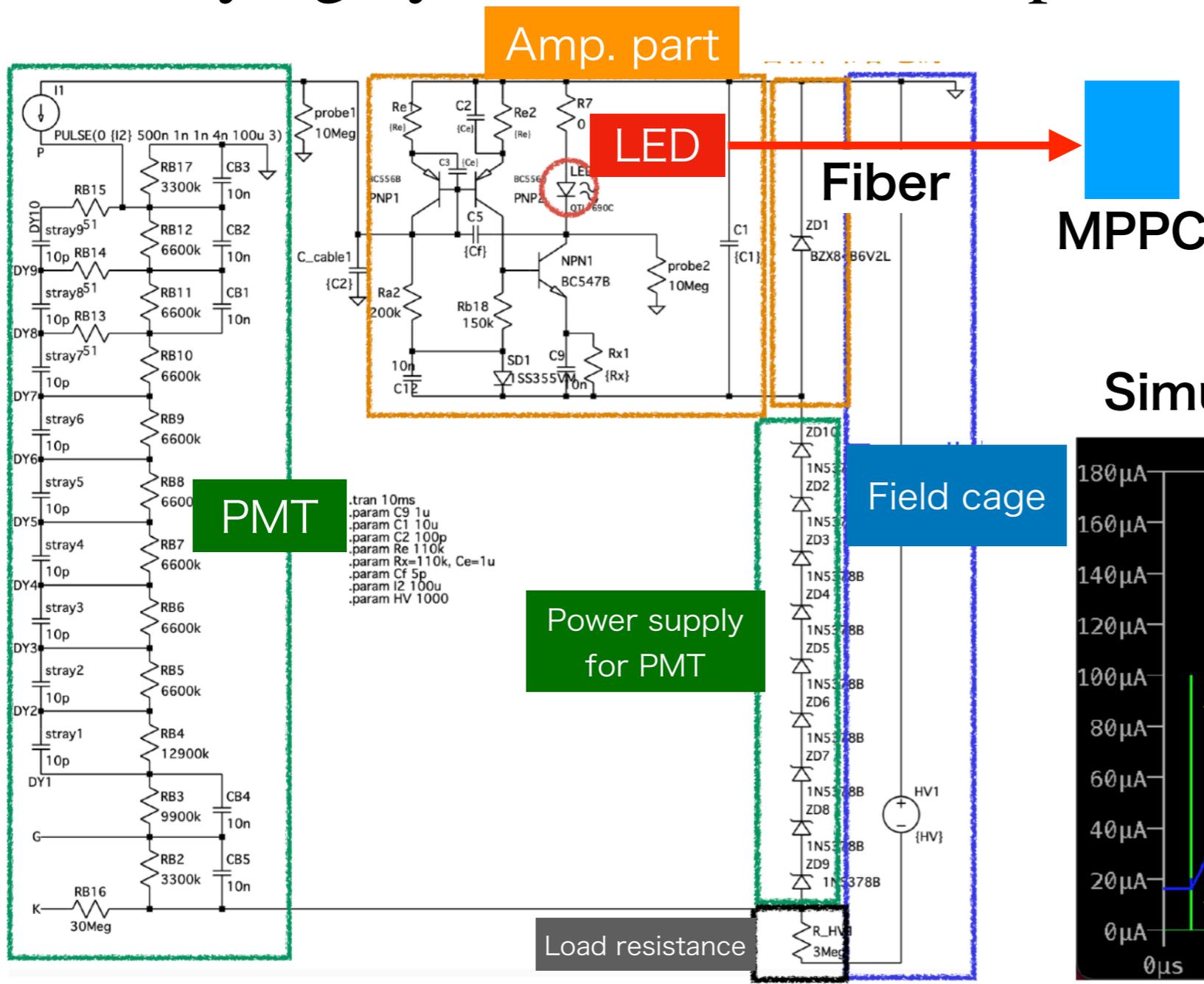
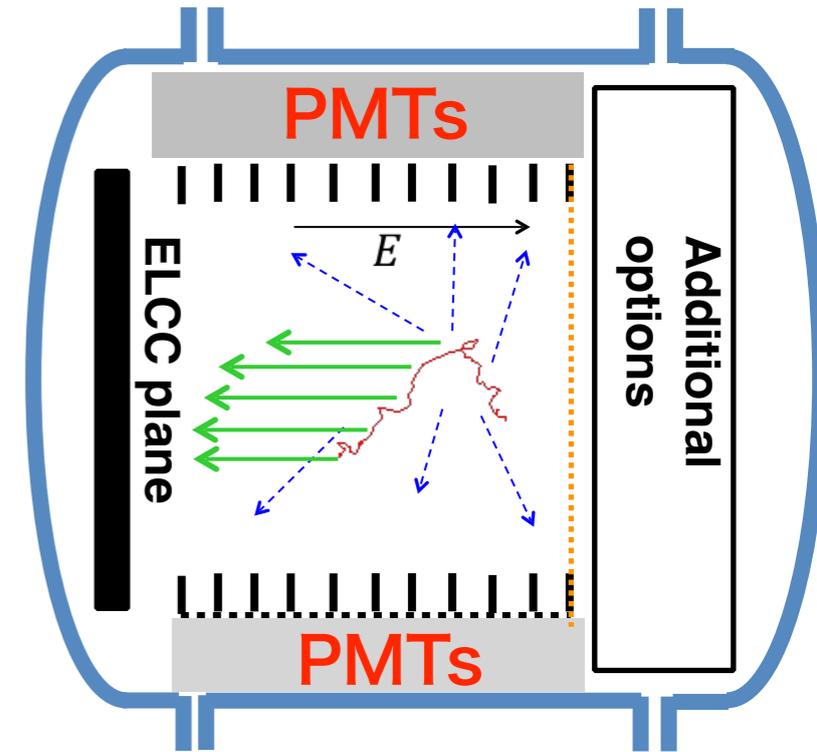


PMT at the side wall

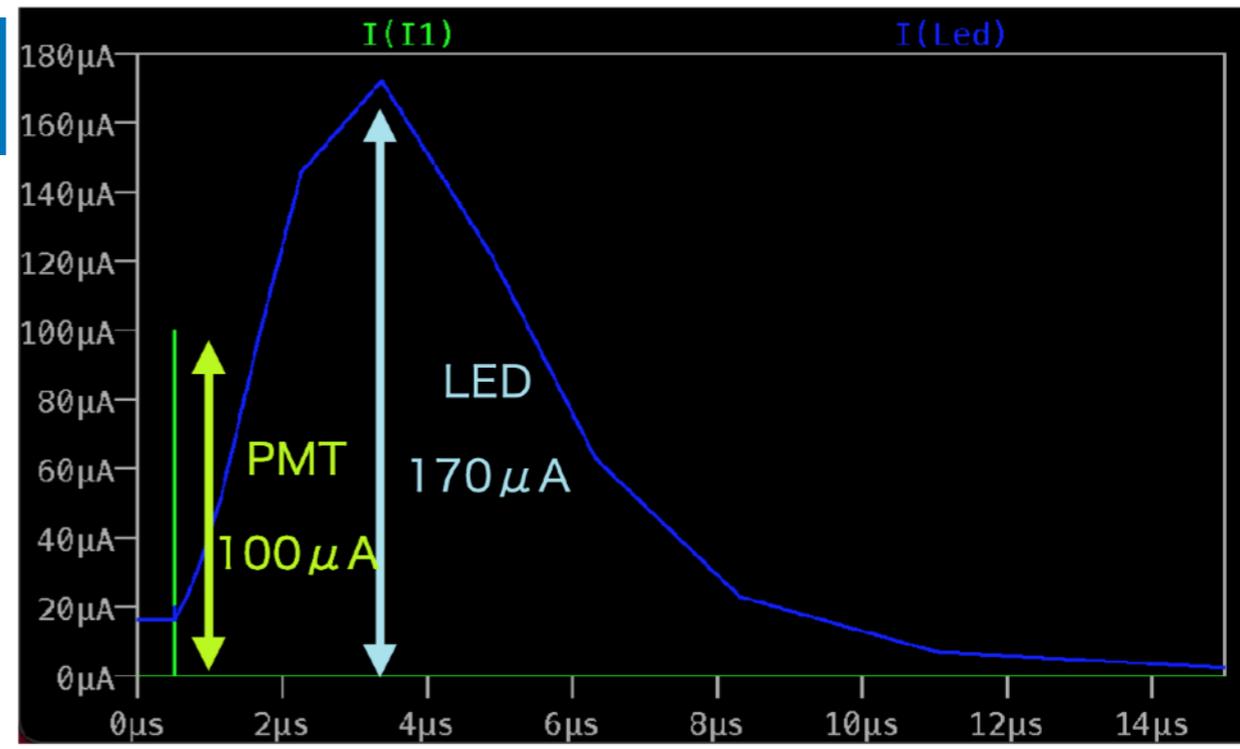


PMTs on the side wall **with electric potentially floating**

- Some additional options can be installed
- Ion detection, Ba⁺⁺ ion trap, etc...
- Studying by circuit simulation, prototype



Simulation result



Neutrinoless double beta decay

AXEL experiment

Prototype detector

R&D for more sensitivity

Summary



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

- High energy resolution with EL and cellular detection scheme
- Topological information

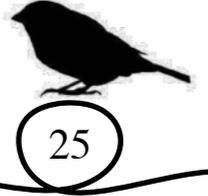
Detector demonstration is performed

- using 1.8 MeV gamma-ray (^{88}Y) to achieve $\Delta E/E : 0.89\%$ FWHM
→ extrapolate to the Q-value (2458 keV) : 0.78 % FWHM

Studies for more sensitivity are also ongoing

- Background rejection using deep learning based topology selection
- Ion detection for more clear track
- PMT with electrically floating to put on the side wall (field cage)
- Further improvement foreseen with ELCC upgrade

Thank you !



For further information, please find documents on our web page!

: <https://www-he.scphys.kyoto-u.ac.jp/research/Neutrino/AXEL/publication.html>



Core members



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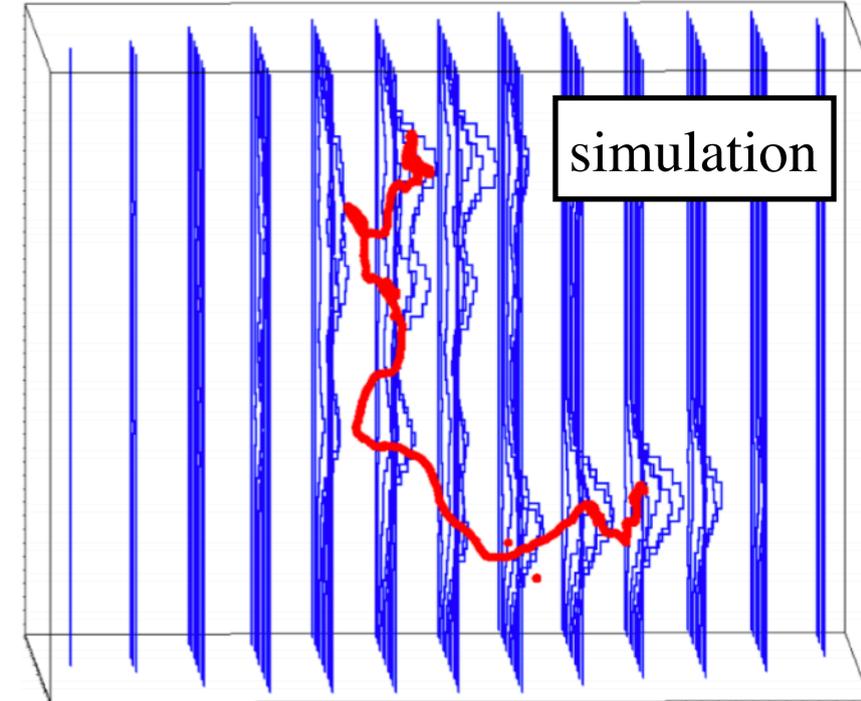
Backup

A Xe ElectroLuminescence : AXEL



Event topology from hit pattern and waveform

- α -ray and γ -ray multi-site events are firmly removed
- γ -ray photo-absorption events are distinguished with Deep Learning (Later)



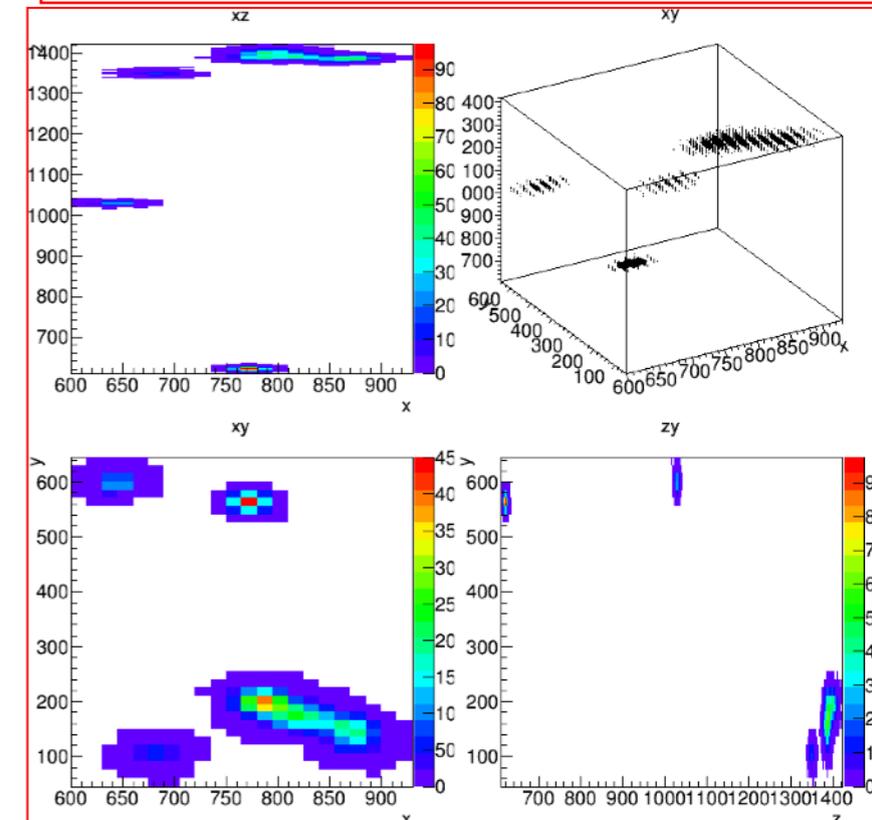
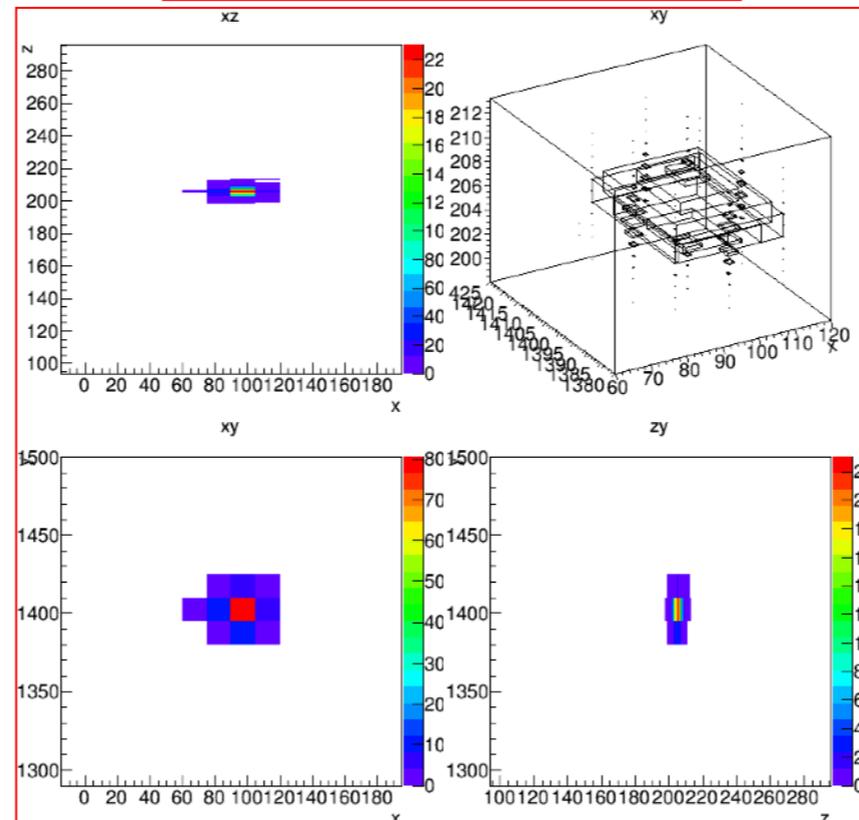
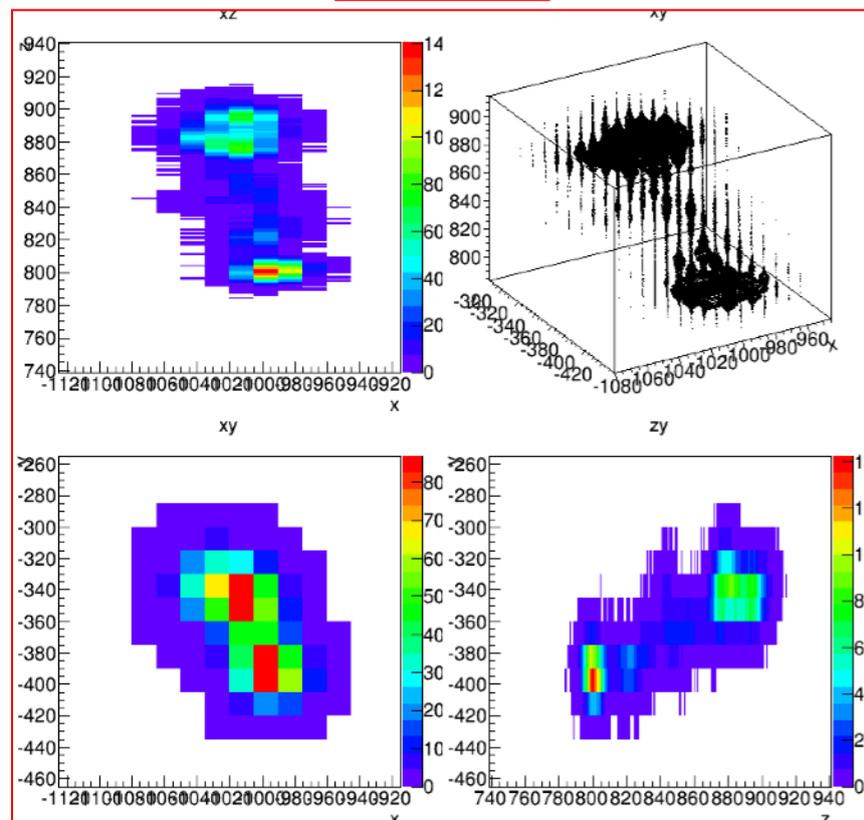
Expected event displays

(simulation : 10 bar Xe, 15mm-pitch, 1MHz sampling)

$0\nu\beta\beta$

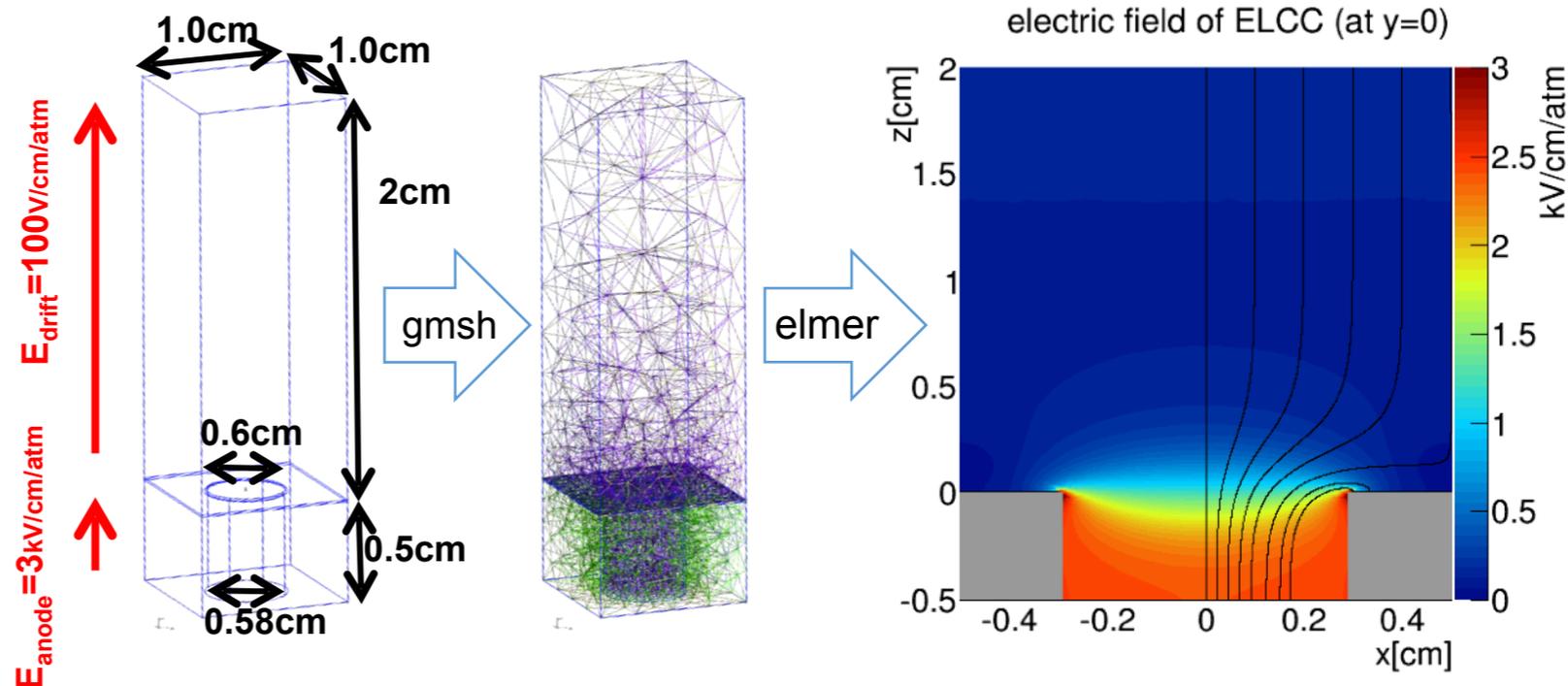
α -ray (2.5MeV)

Compton γ -ray (2.5MeV)

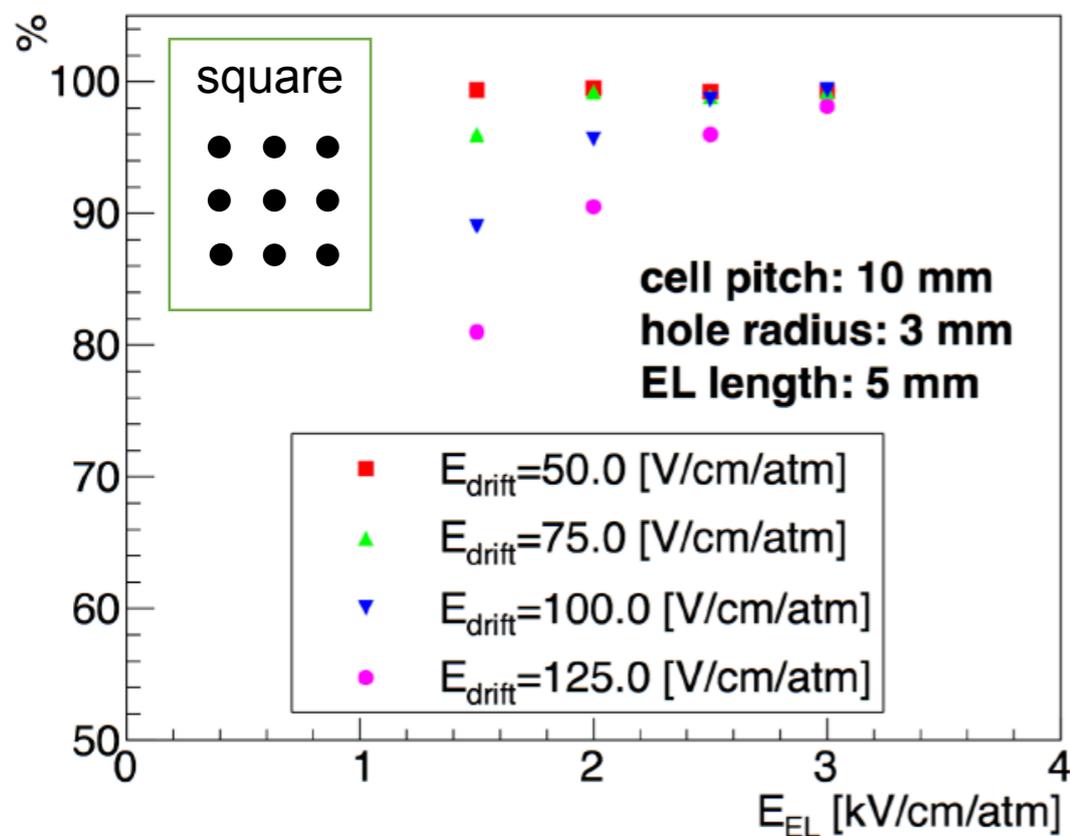


Simulation study

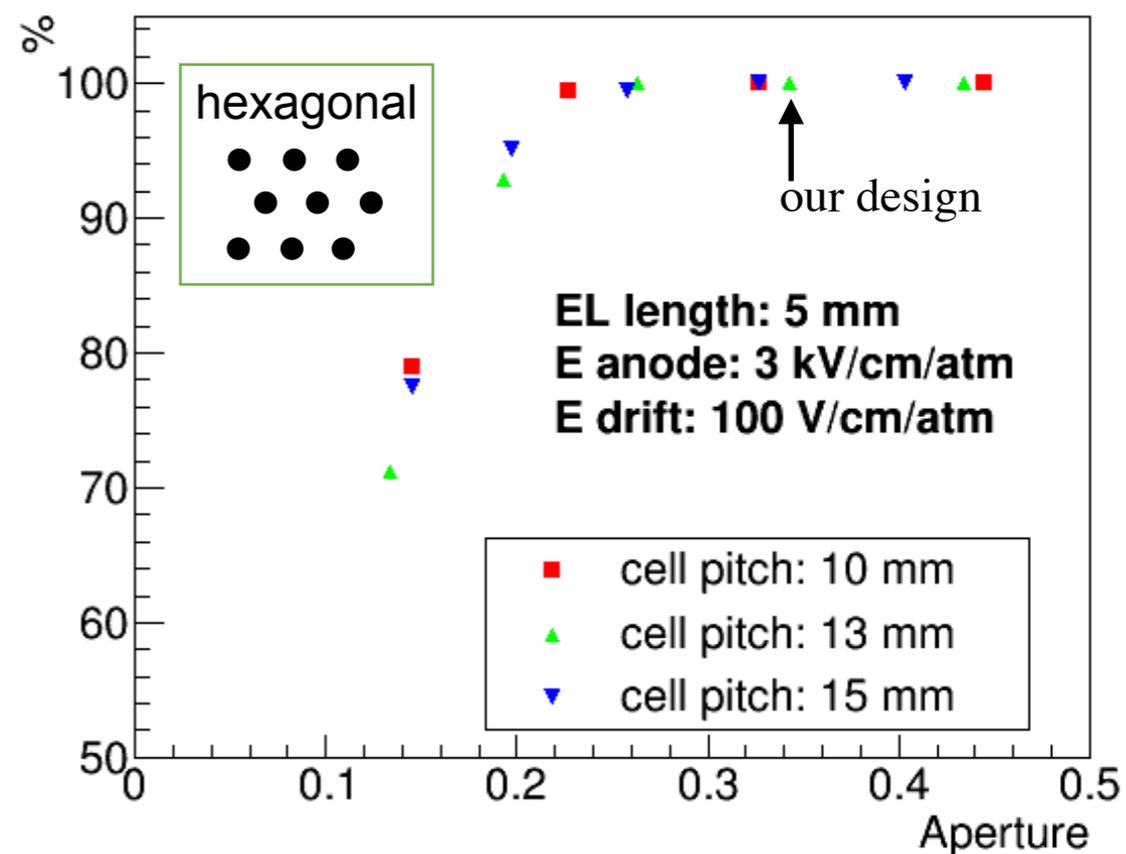
Collection efficiency of electric field line is checked by simulation (gmsh + Elmer)



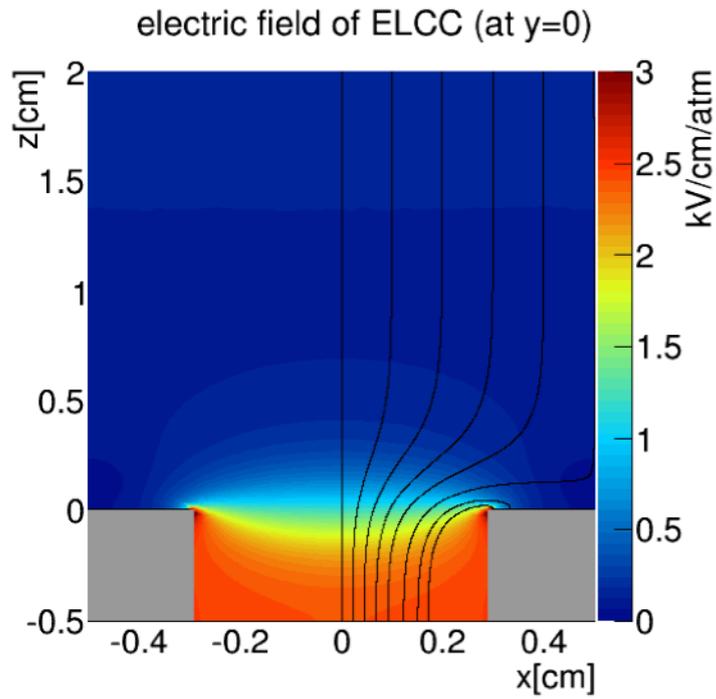
Passage ratio of electric field lines



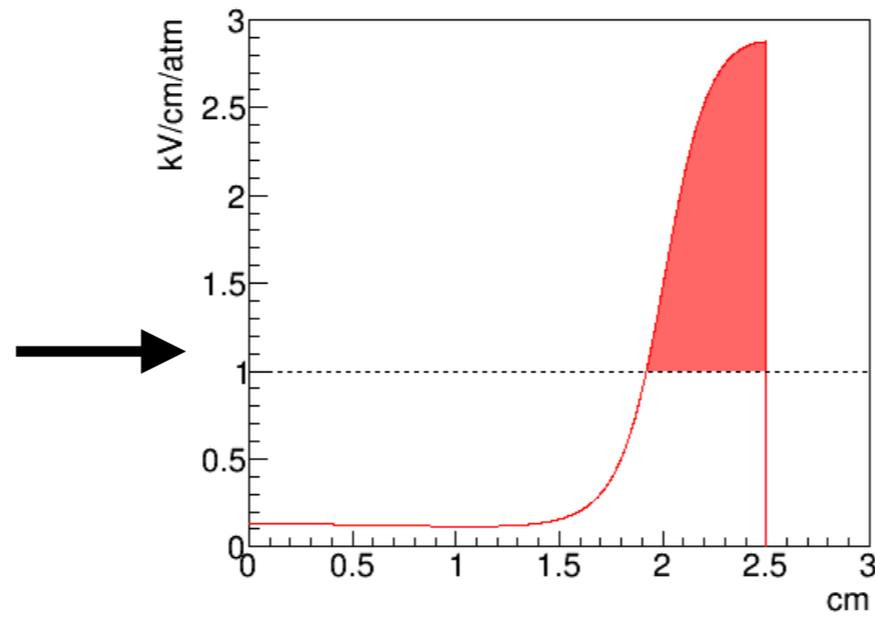
Passage ratio of electric field lines



Simulation study

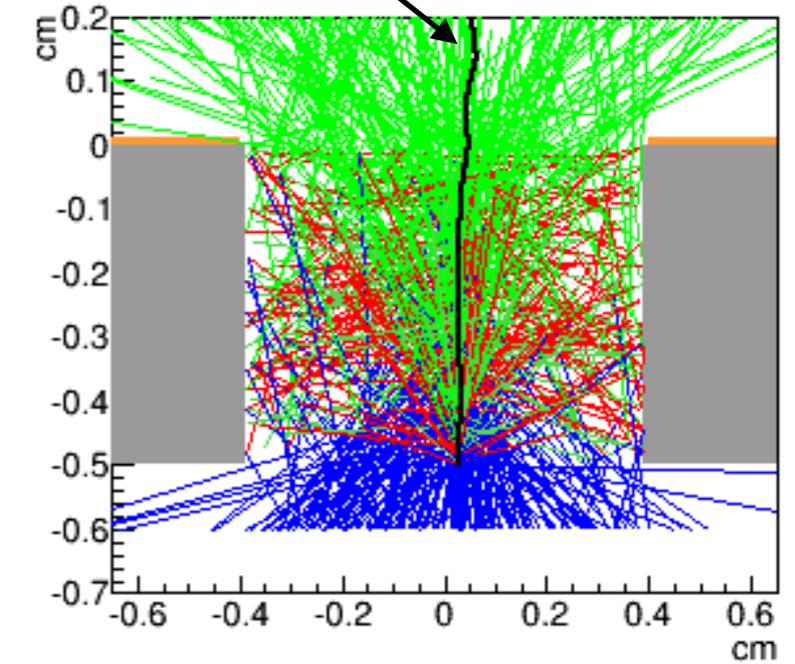


Line of electric field



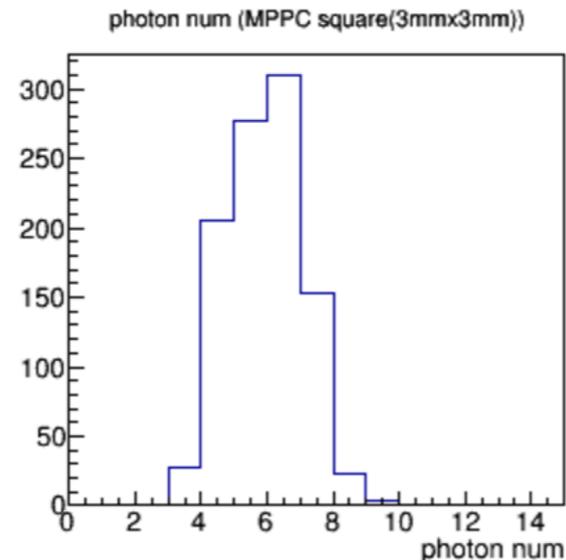
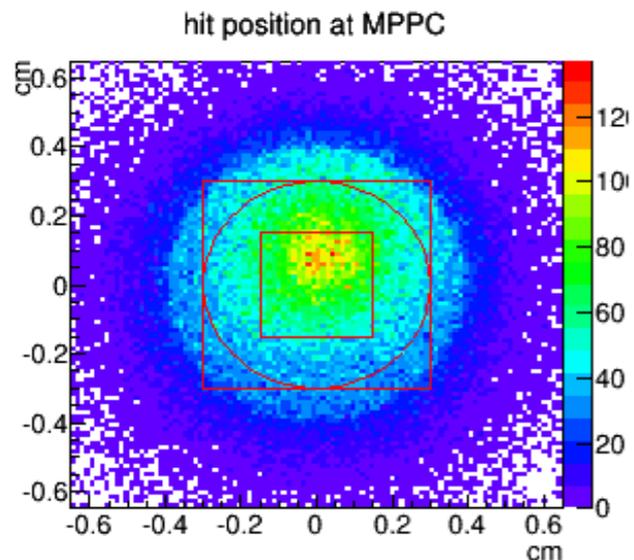
Electric field strength along the line
(red : EL region)

Electron track by Garfield++

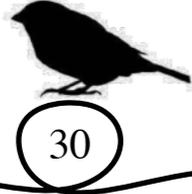


Generate EL lights by MC method
(reflect coefficient of PTFE : 60%)

Photon counts

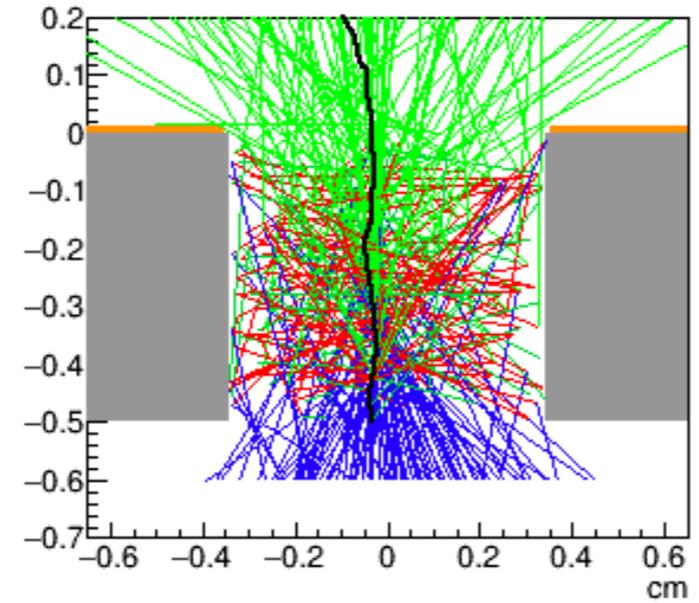
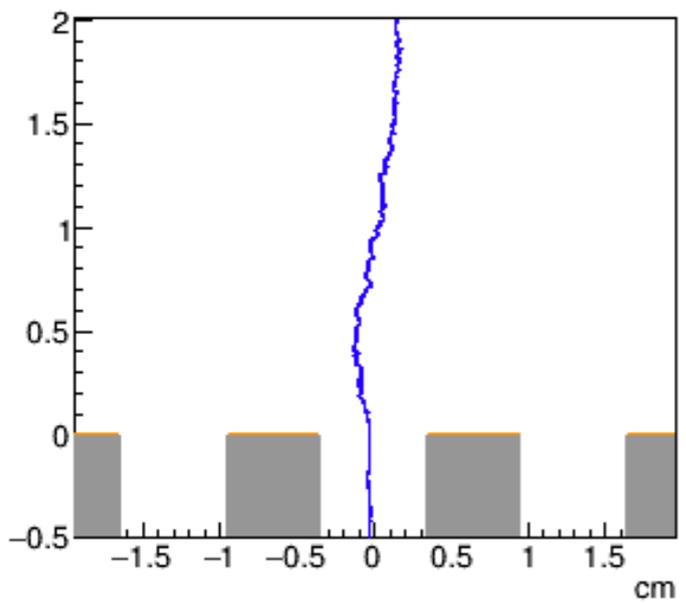


Prototype detector (1) : 10L prototype

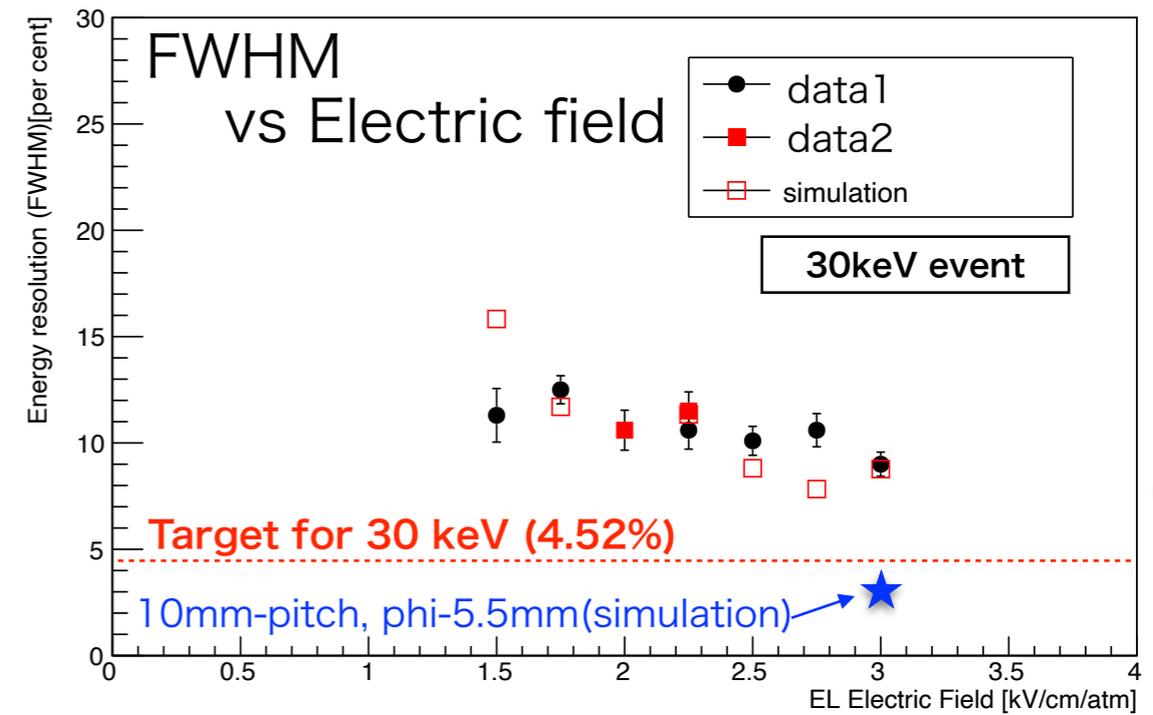
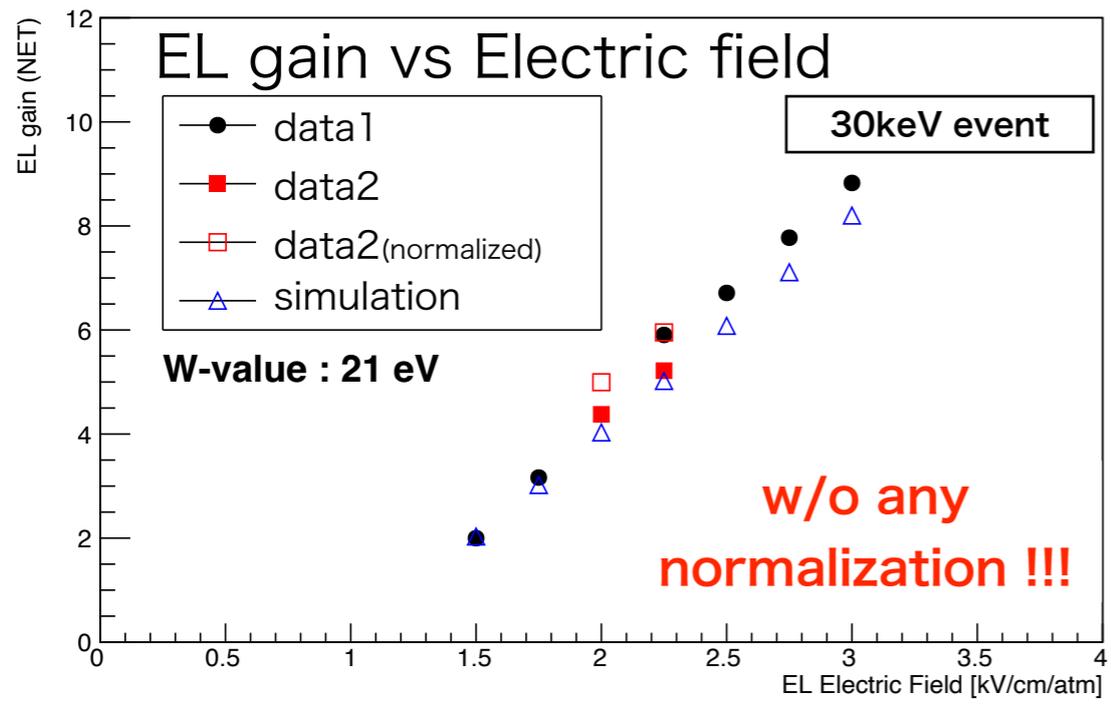
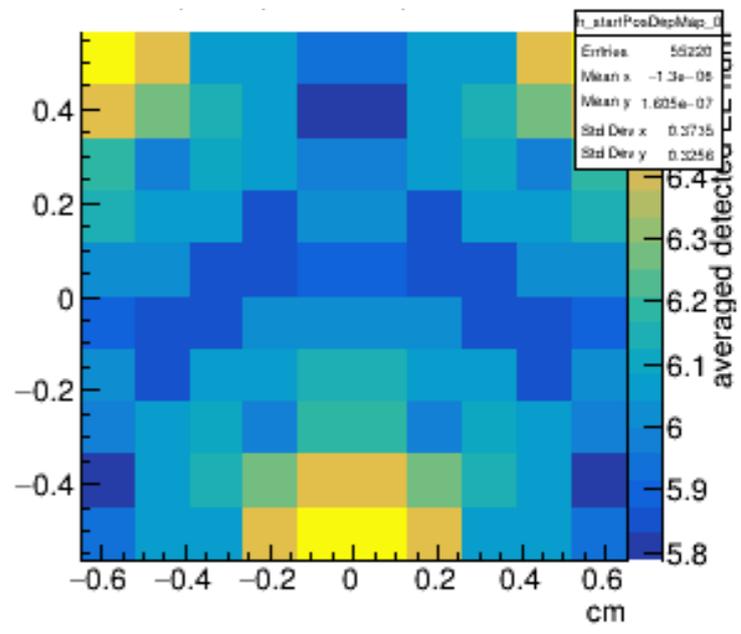


Simulation of the ELCC

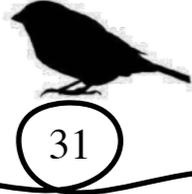
- Electron track simulation → Position dependence of EL gain
- Generate 30 keV events by Geant4 → Reproduce EL signal with position dependence
- With these results, configuration of cell is optimized : **10mm-pitch, $\phi 5.5\text{mm}$**
- Compare with data of prototype detector to conform the validity of the simulation



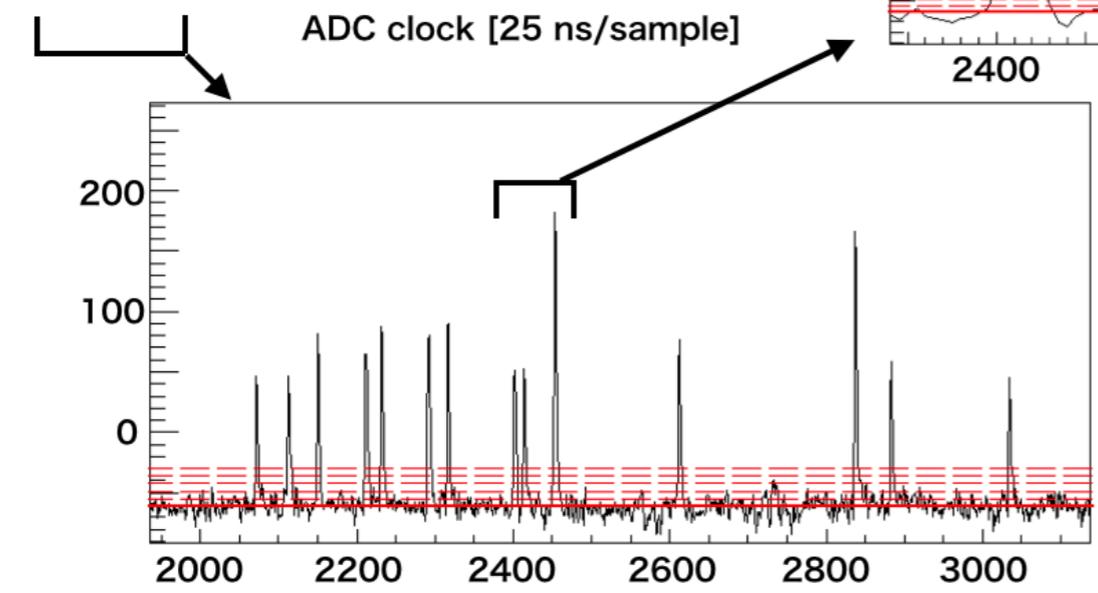
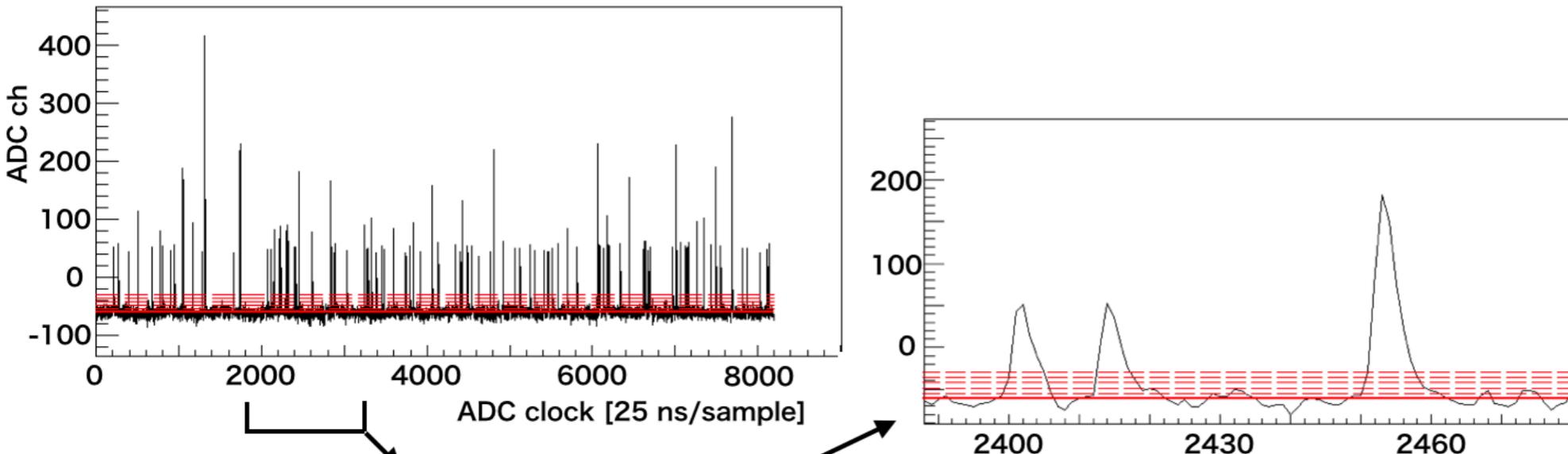
Position dependence
→
FWHM : 7.5%
(13mm-pitch, phi-7mm)



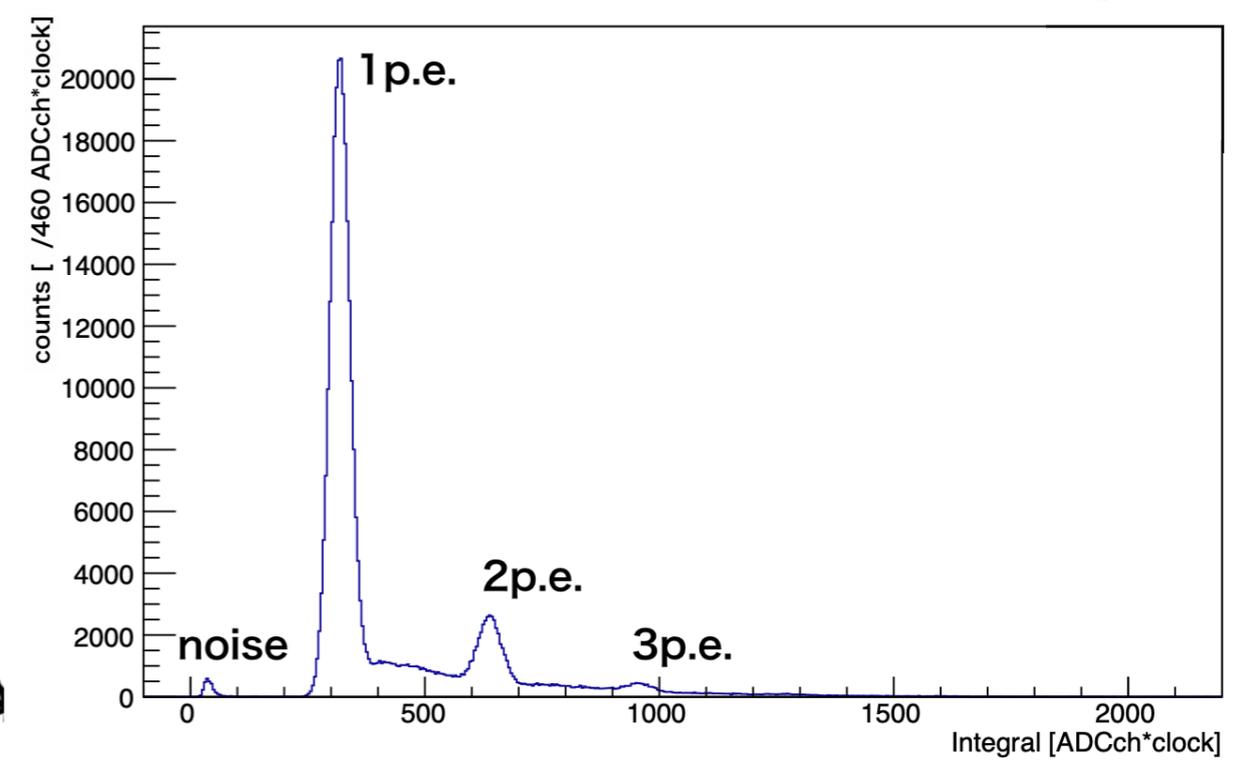
Prototype detector (2) : 180L prototype



Commissioning with a single unit



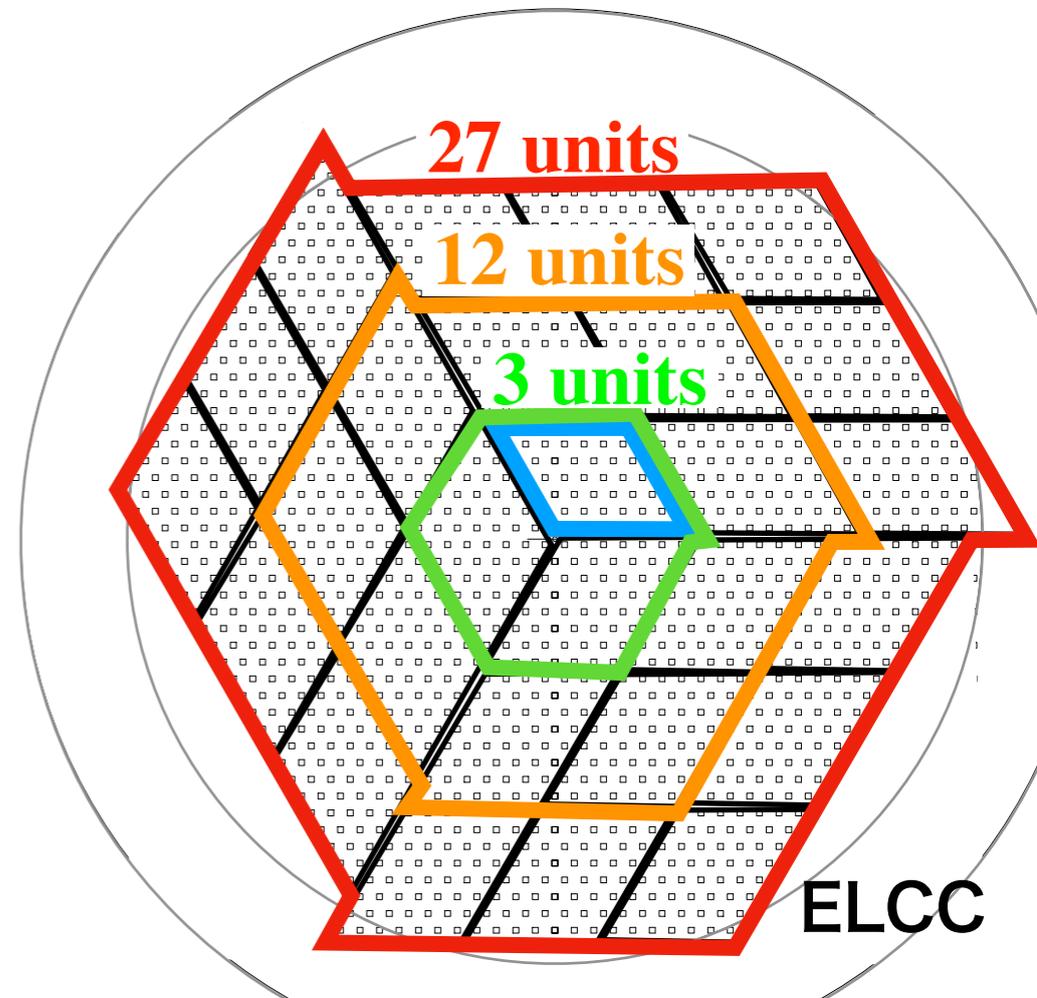
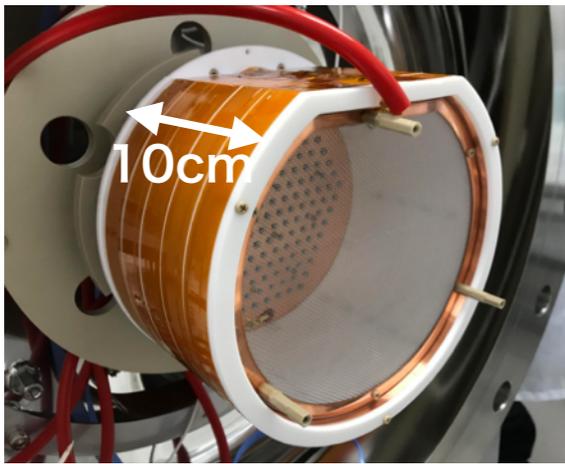
Distribution of dark current charge



Prototype detector

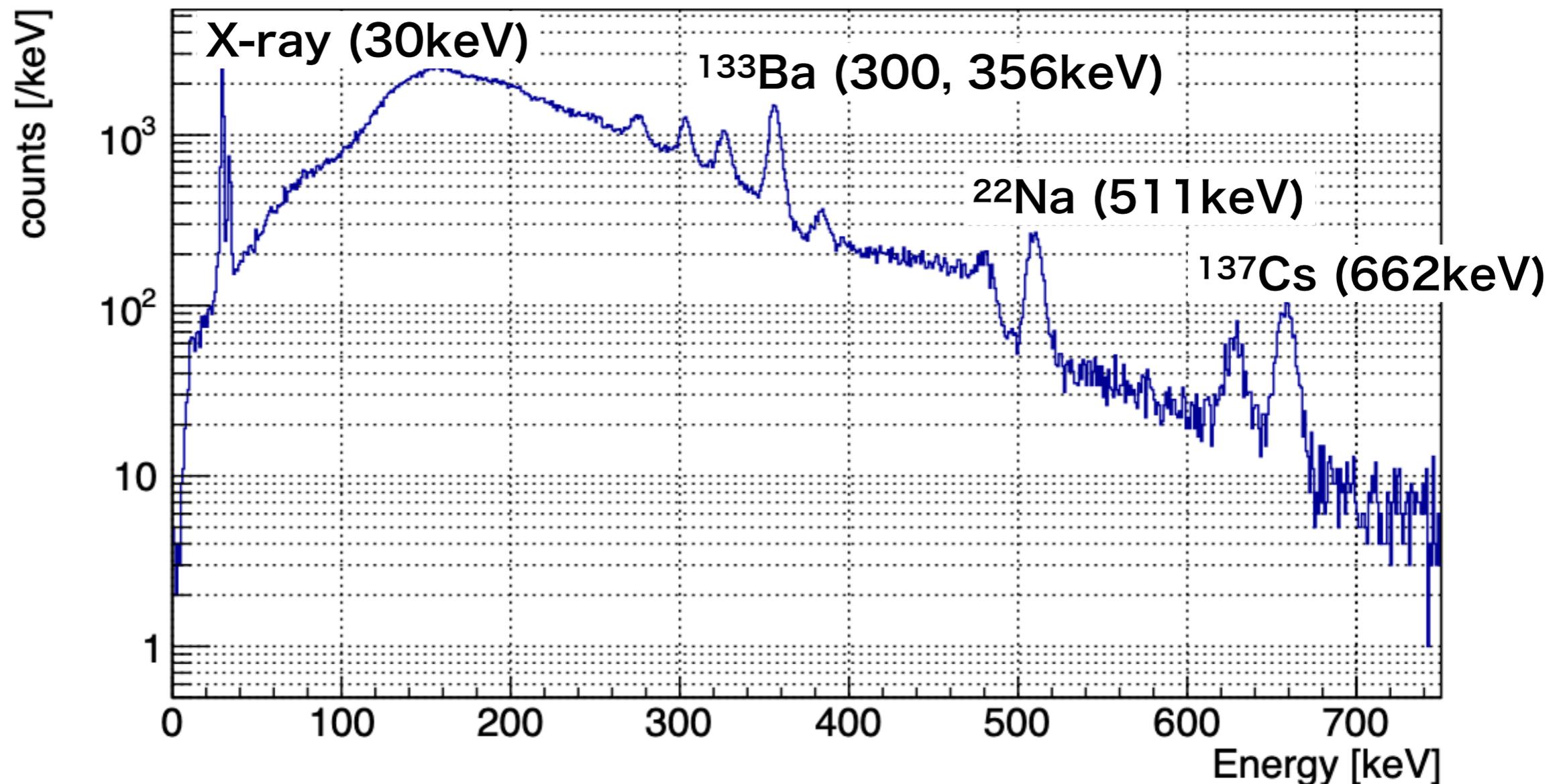
1-Unit (56ch) Commissioning

Start to construct 1000L



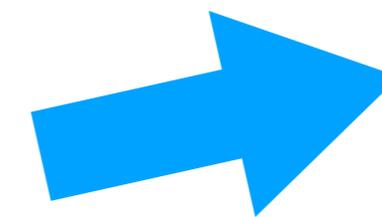
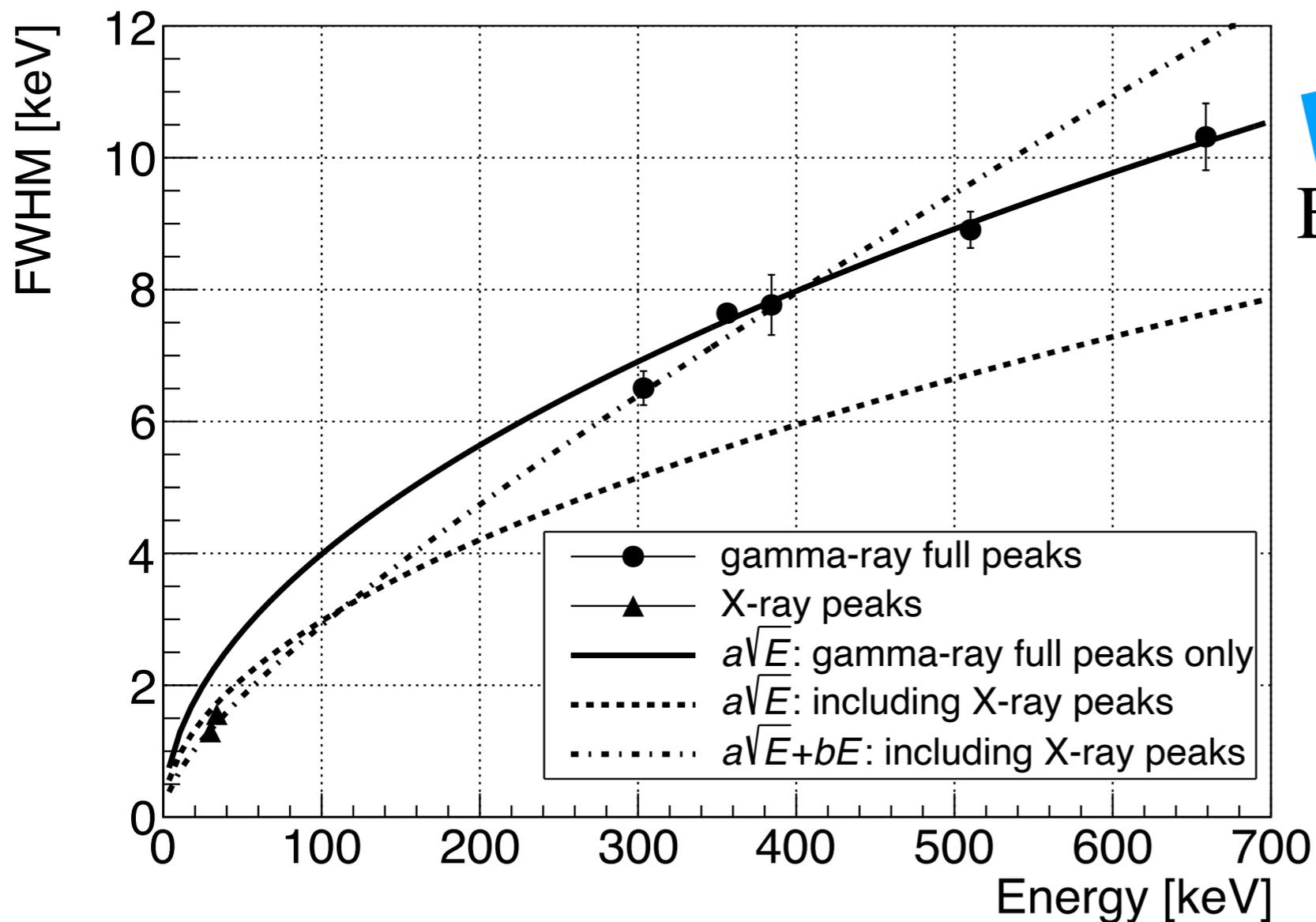
Performance evaluation

- Energy spectrum after cuts and corrections.
- Clear peaks from ^{133}Ba , ^{22}Na , ^{137}Cs sources are seen.
- Energy resolution is evaluated by Gaussian fitting
 - **1.57 %** at 662 keV \rightarrow **0.81 %** at Q-value by \sqrt{E} (FWHM)



Performance evaluation

- Estimation with two assumption : $\Delta E \propto A\sqrt{E}$ or $A\sqrt{E + BE^2}$
- Estimated energy resolution at Q-value : **0.81~0.84 % (FWHM)**

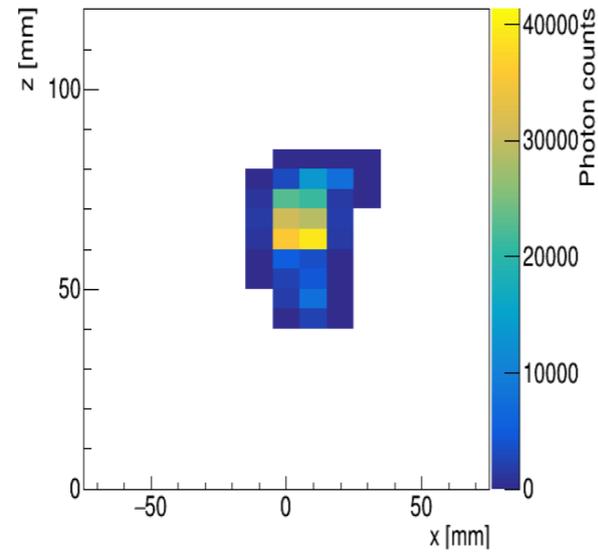
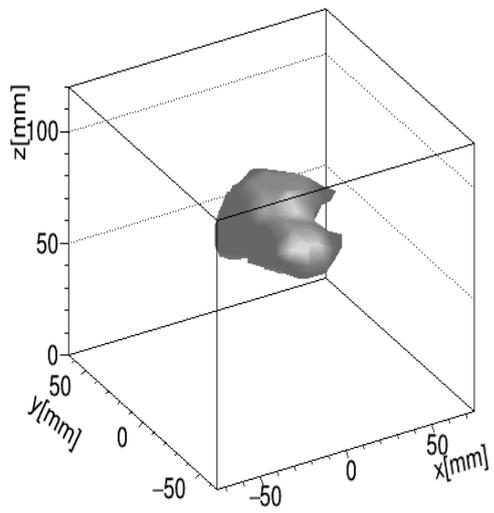


Extrapolate to the Q-value
(2458 keV)

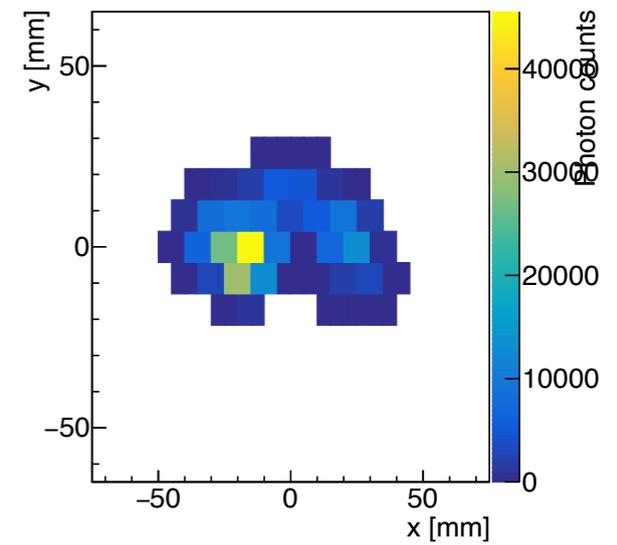
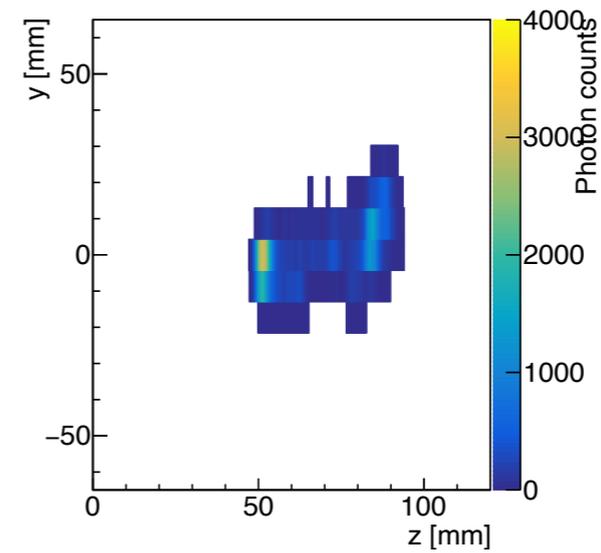
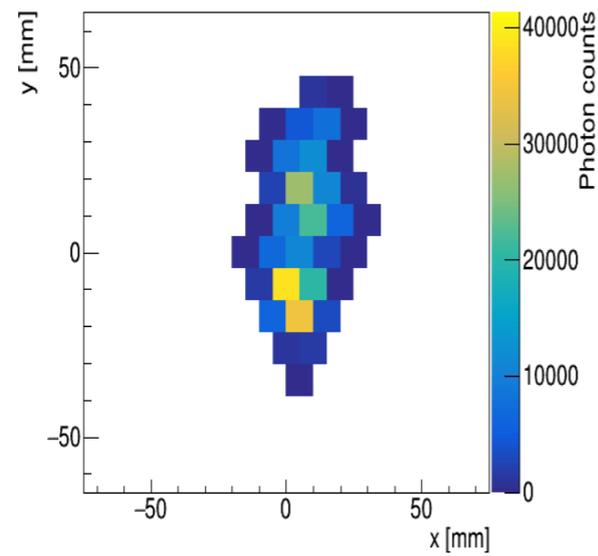
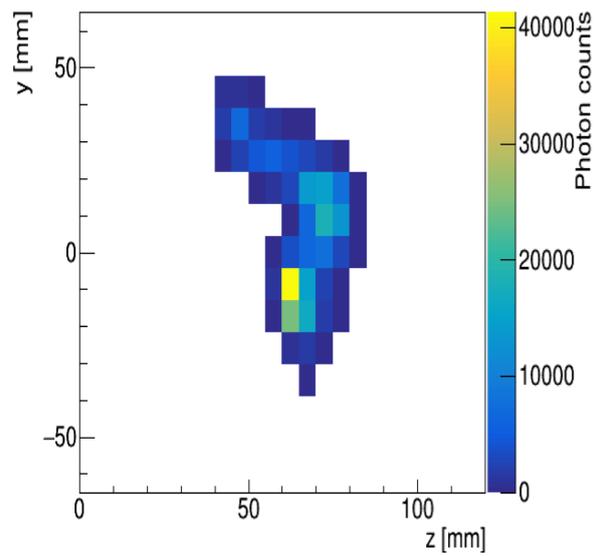
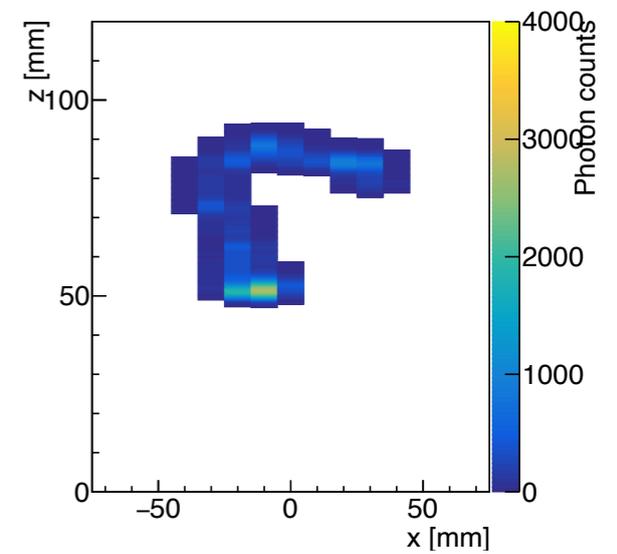
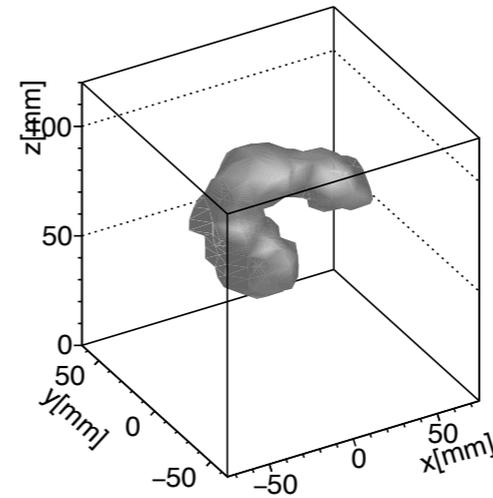
Prototype detector

Track pattern

511 keV



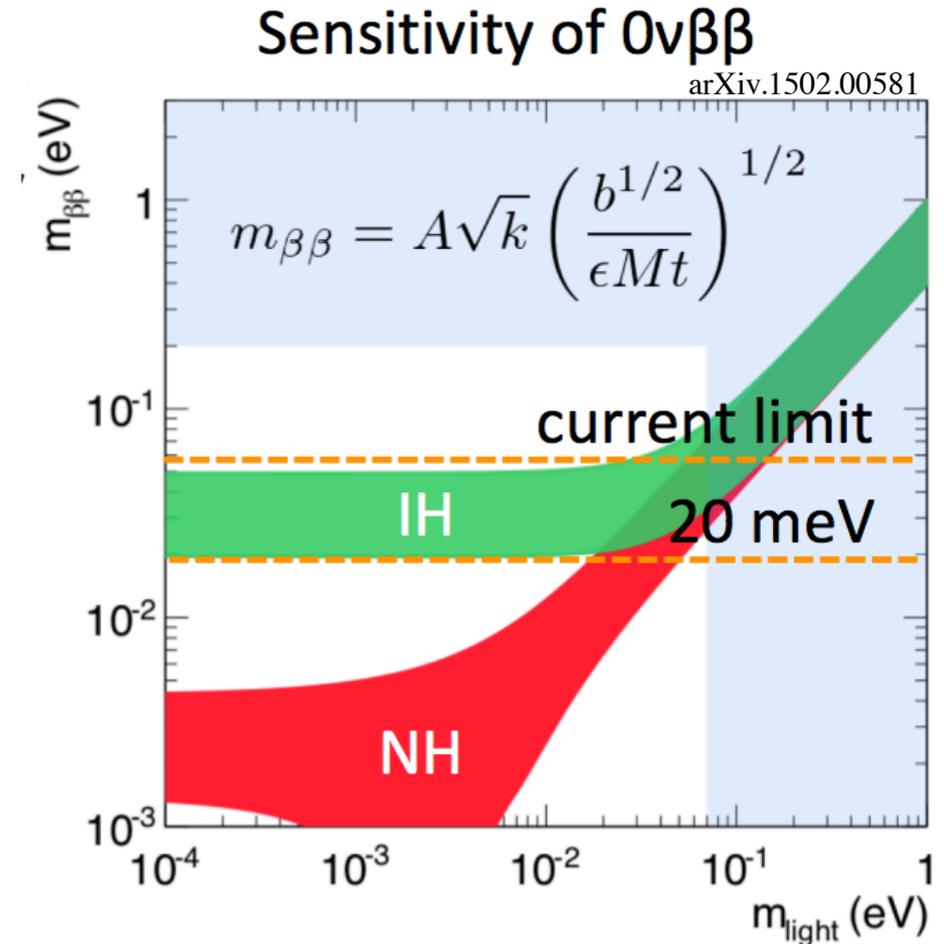
662 keV



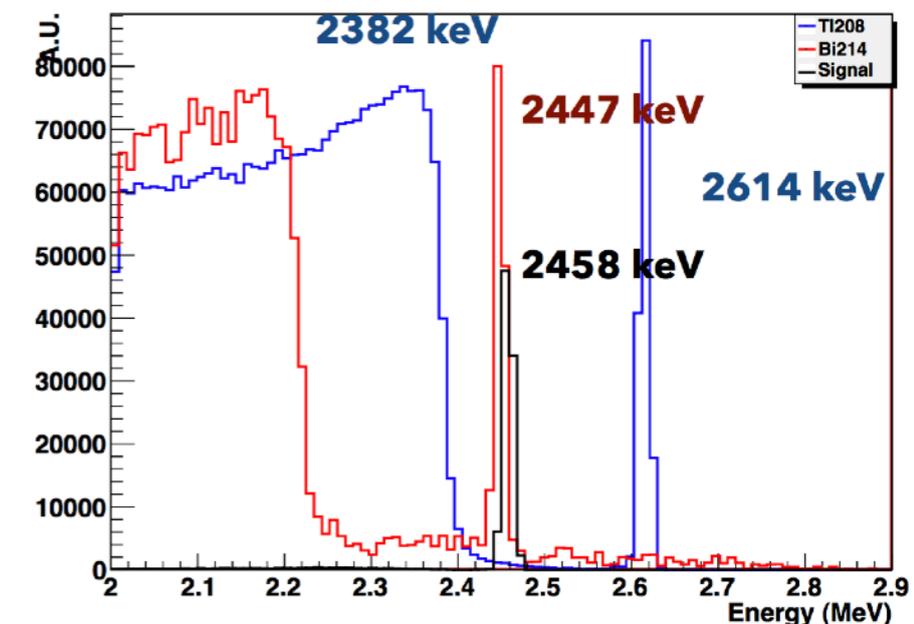
Future prospect

Sensitivity estimation for 1 ton detector

- Need to reach $m_{\beta\beta} = 20$ meV
- Background free is required
- ^{214}Bi (2447 keV) is serious BG source
- Main source : Pressure vessel (~ 10 ton)
- Even if we use oxygen-free copper
2.9 ppt ^{214}Bi (cf. EXO-200)
 $\rightarrow 75$ event/year for 1 ton detector



arXiv:1106.3630v1 [physics.ins-det] from NEXT paper



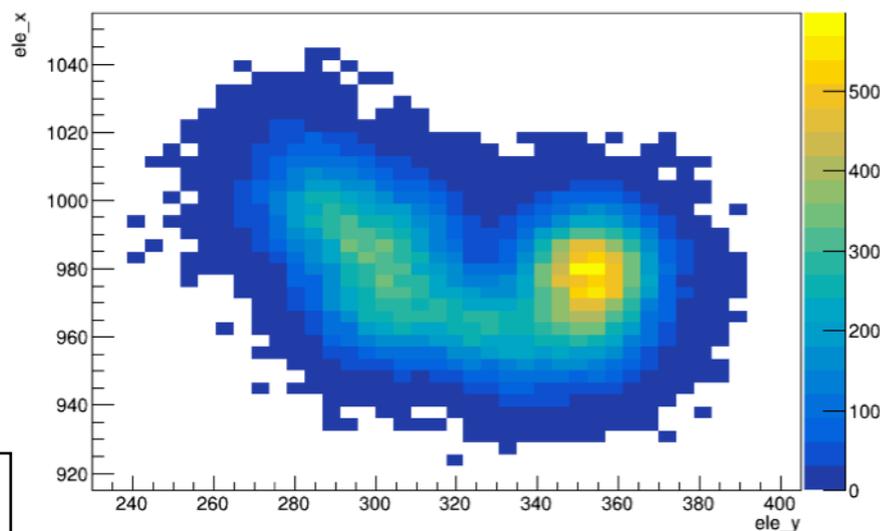
Future prospect

More ideas...

- Positive-Ion Tracking

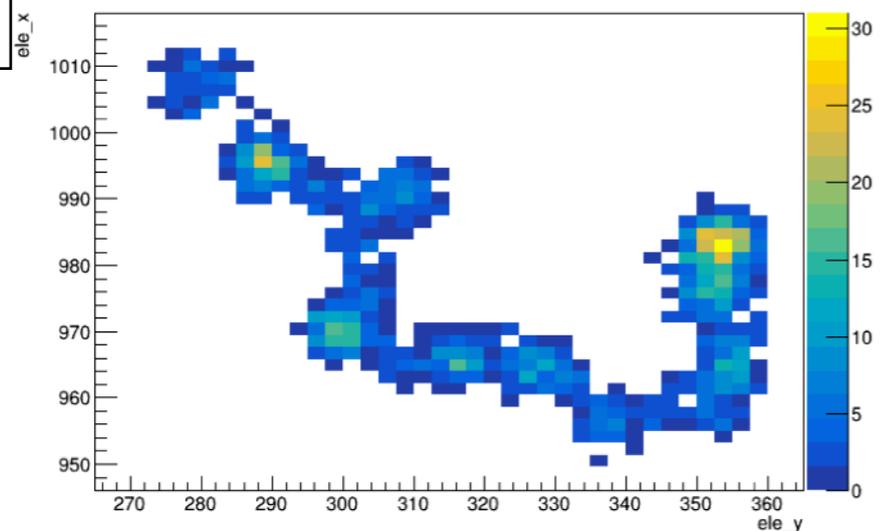
- electron has a large diffusion constant in xenon gas
 - Diffusion constant of xenon ion in xenon gas is much smaller
- Clear track image

electron



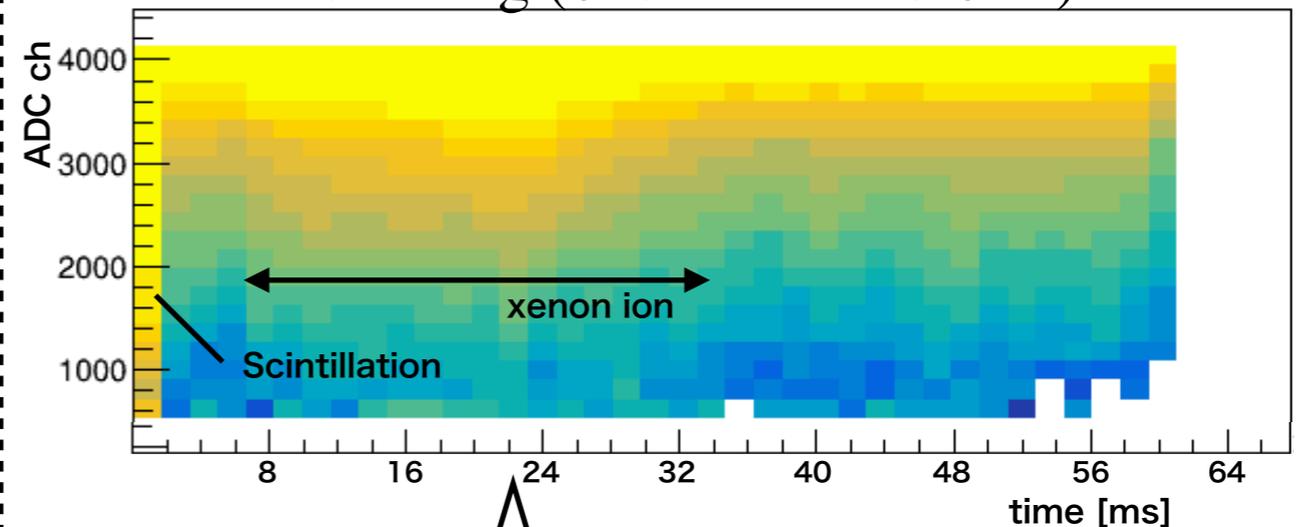
same event
(simulation)

ion



- Detection of Xe+ by secondary electron emission at electrode surface

Pulse timing (overlaid waveform)



²⁴¹Am α -ray source



Wire : -1500V

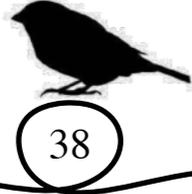
PMT

xenon : 1 bar

Wire : $\phi 20 \mu\text{m}$

HV : -1500 V

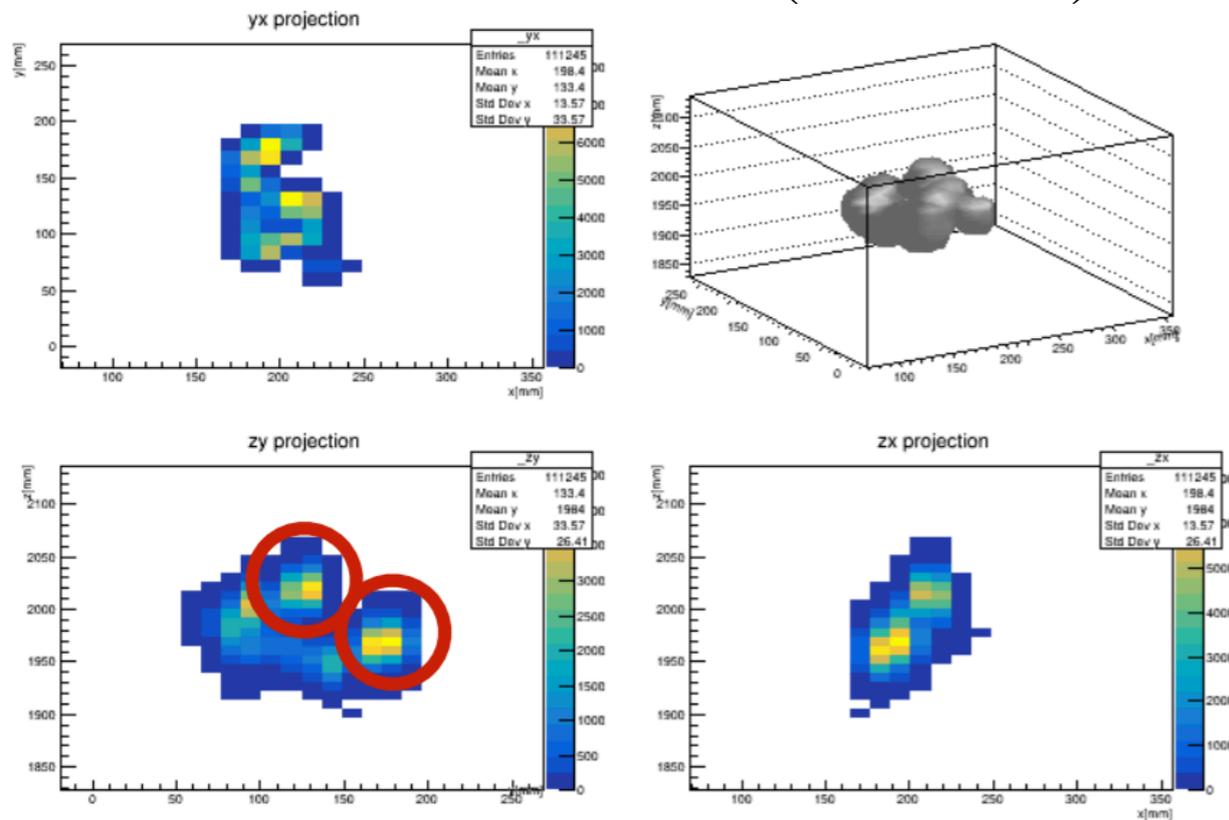
BG rejection using topology



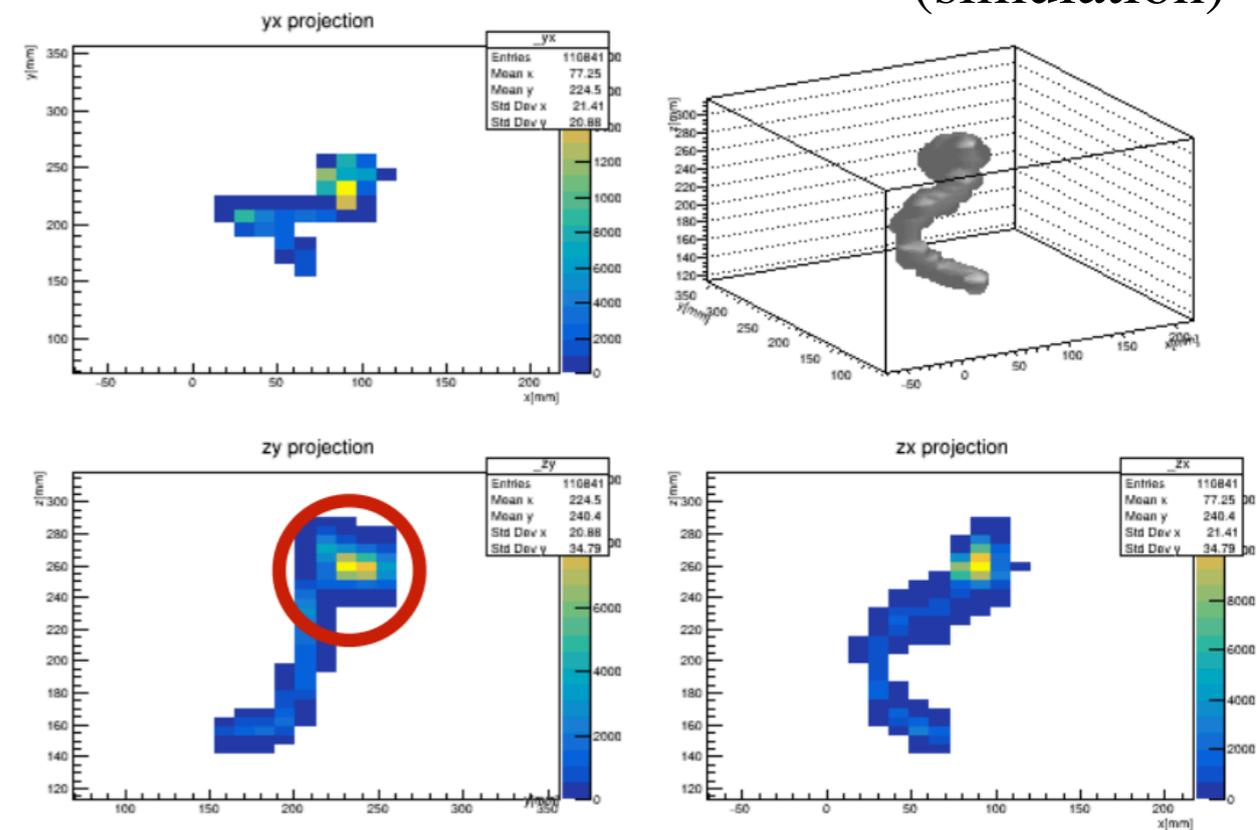
38

- Gamma-ray photo-absorption event will be a serious BG (mainly from ^{214}Bi)
- Topological information
 - $0\nu\beta\beta$ decay has two blobs
 - Photoelectric absorption of gamma event has only one blob

$0\nu\beta\beta$ (simulation)



Gamma-ray (simulation)



Future prospect

Topological information

- Deep Learning is one of the options
- Learning with simulation of $0\nu\beta\beta$ and gamma-ray
- Pitch of readout cell is variable to optimization (performance vs costs...)
- Signal efficiency : 41% : BG : 121 evt/yr \rightarrow 3.2 evt/yr (1 ton Xe)
(assuming 10 tons of pressure vessel made of Oxygen-free Cu, 10mm-pitch readout)
- Estimated sensitivity : $m_{\beta\beta} = 32$ meV (1 ton yr Xe, 10 mm-pitch)

