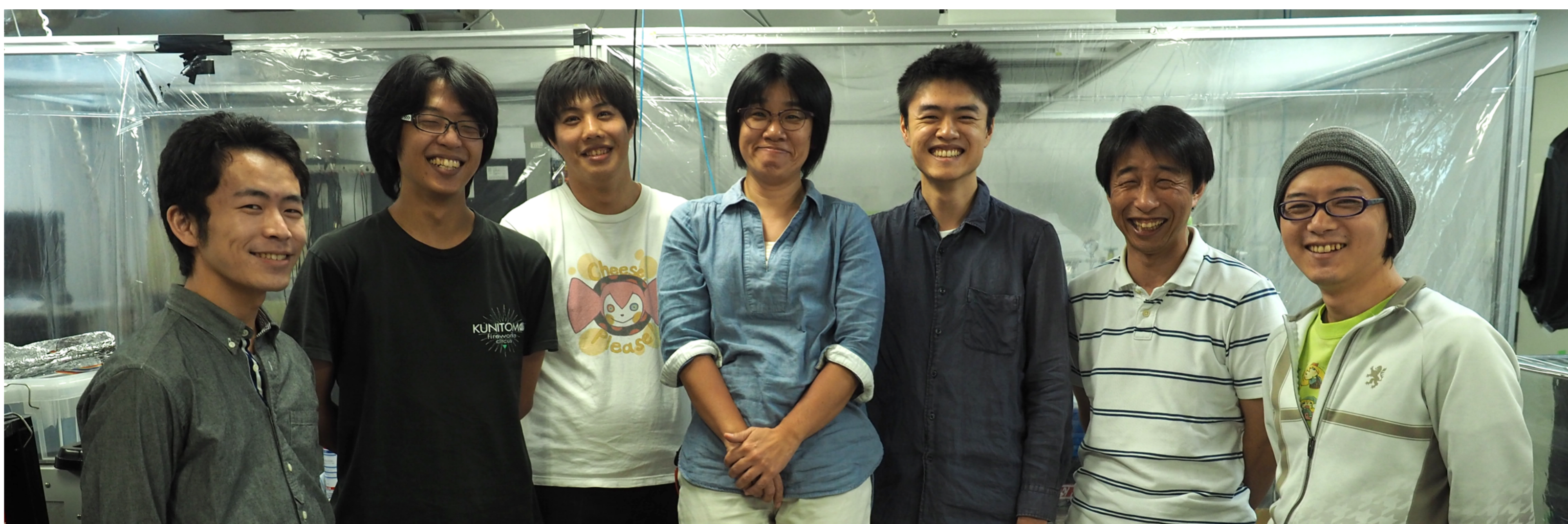
A high-pressure xenon gas TPC detector AXEL to search for neutrino-less double beta decay

Kazuhiro Nakamura, Kyoto University
on behalf of the AXEL collaboration



Physics motivation

- Is neutrino Majorana particle or not?

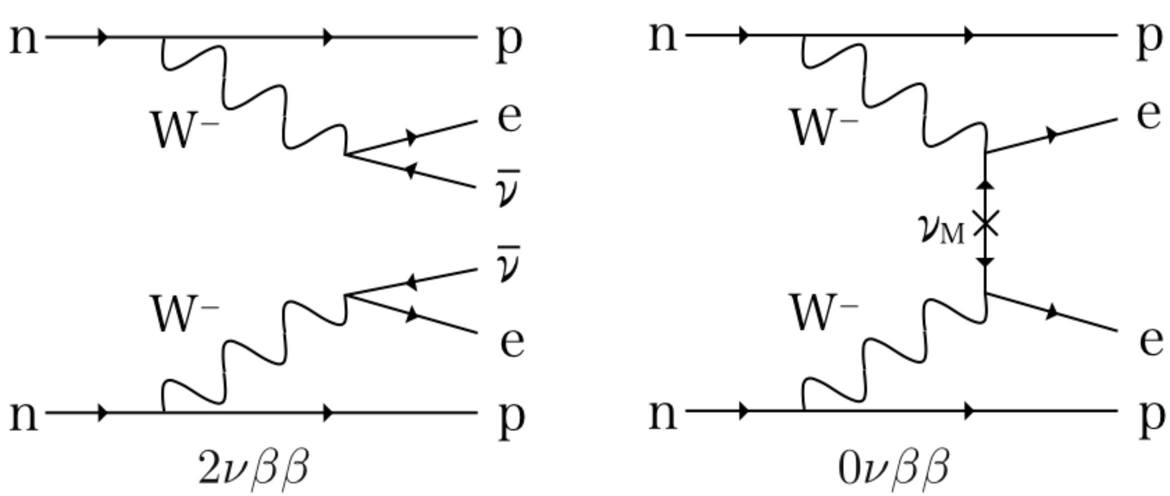
  Important to validate:

  - Seesaw model
  - Leptogenesis model

- Neutrino-less double beta decay (0νββ)

  - Happens if neutrino is Majorana particle
  - **BUT** it is very rare event, even if it occurs... (half-life>10^{26} years with ^{136}Xe[1])

    → **Large mass** and very **low-background** is needed



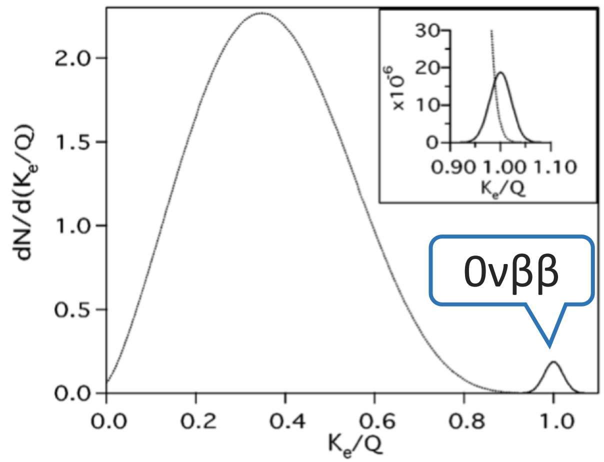
[1] PRL 117, 082503 (2016)

0νββ search

- Signal of 0νββ
  - Sum of two electron energy is equal to Q-value
  - High energy tail of the standard double beta decay (2νββ) could become background
    → **High energy resolution** is required
- Requirements for inverted hierarchy search
  - Large mass (~1 ton)
  - Low background (<1 event/year)
  - High energy resolution (<1~2% FWHM)

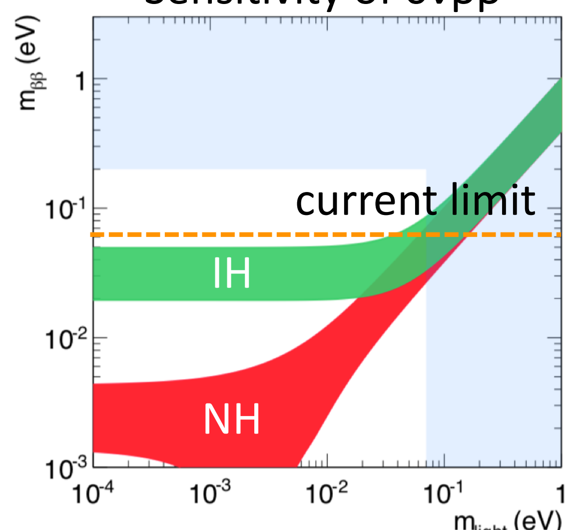
→We are aiming to achieve these requirements with high pressure xenon gas TPC

Energy spectrum



Annu. Rev. Nucl. Part. Sci. 2002. 52:115–51

Sensitivity of 0νββ



arXiv:1502.00581

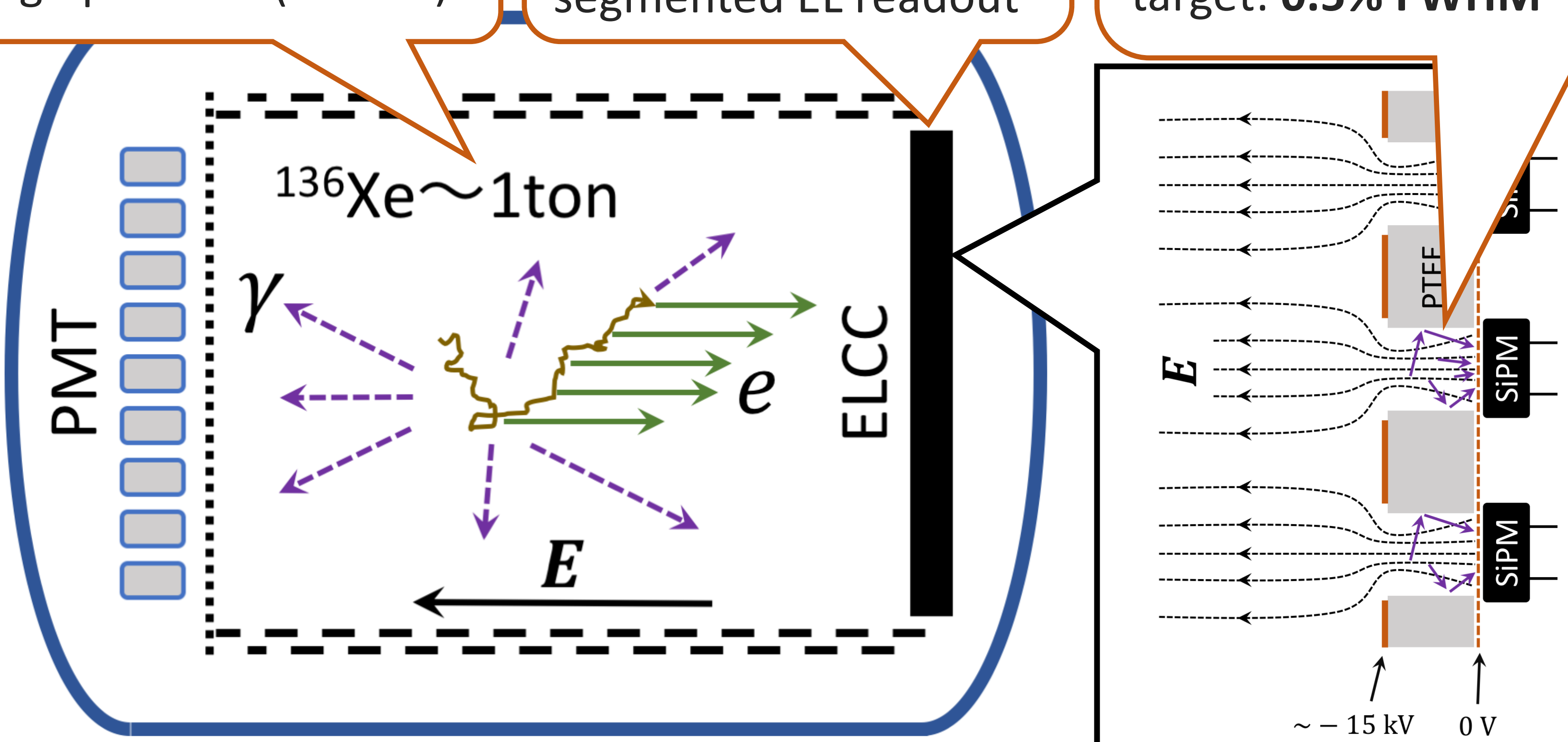
AXEL experiment

- High pressure xenon gas TPC for 0νββ search

Mass scalability:
high pressure (10 atm)

Background rejection:
tracking with
segmented EL readout

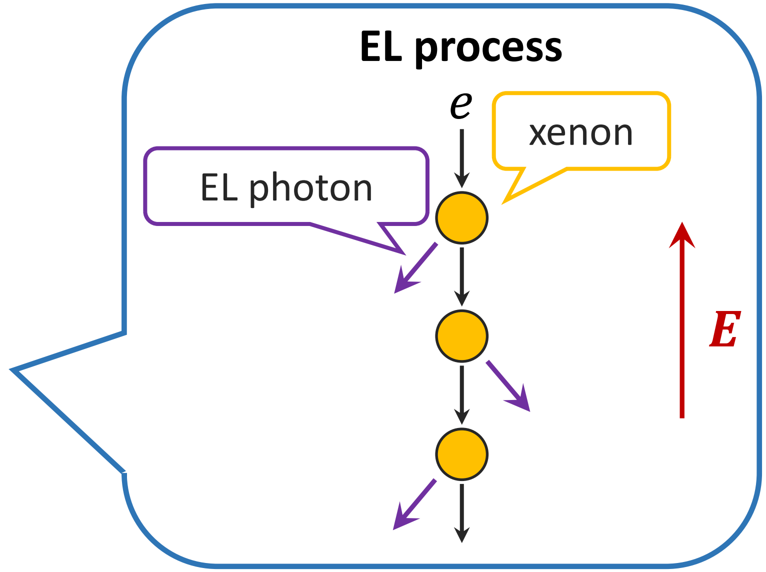
High energy resolution:
electroluminescence
(EL) process readout
target: **0.5% FWHM**

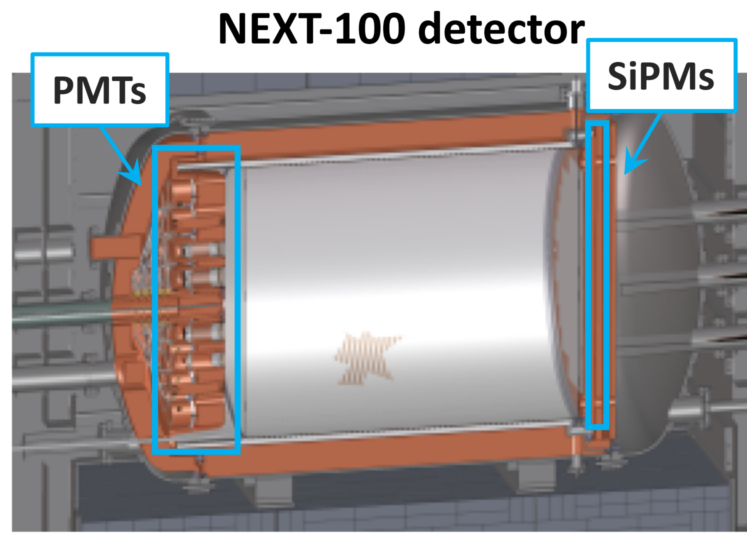


High pressure xenon gas TPC

- Good point
  - **Scalable to large mass**
  - **High energy resolution**
    - Small ionization W-value
    - Linear amplification process (EL process)
    - → Fluctuation can be small
- Similar concept experiment NEXT
  - Pioneer experiment
  - Separated EL readout
    - Energy measurement: PMTs
    - Tracking: SiPMs

We introduced a new idea “ELCC” for signal readout

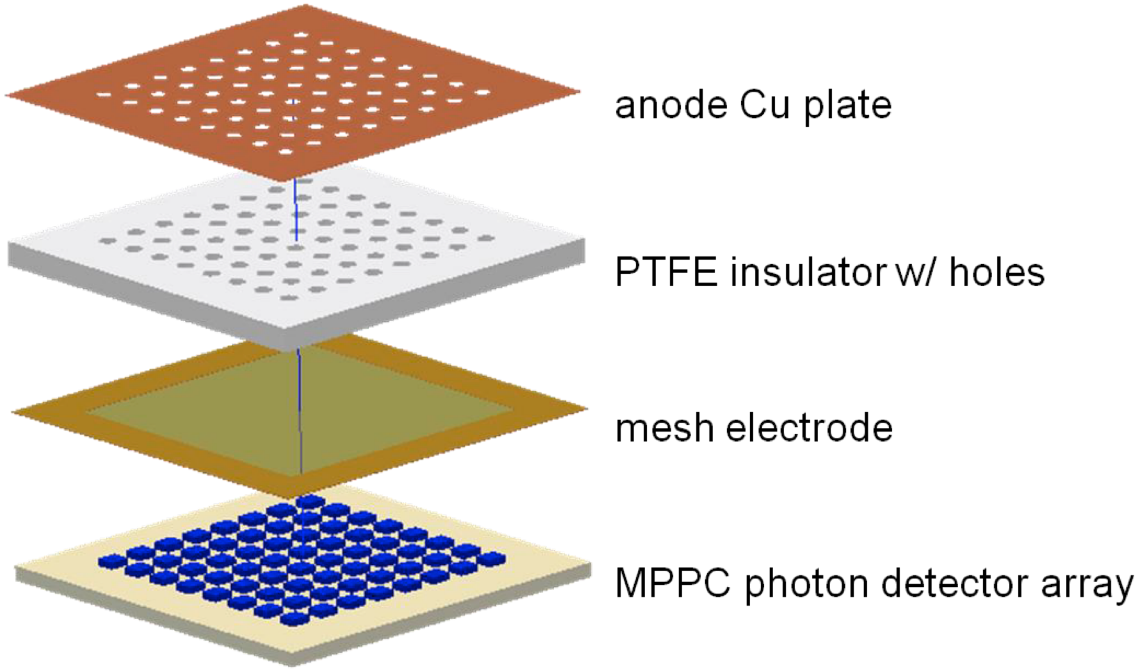


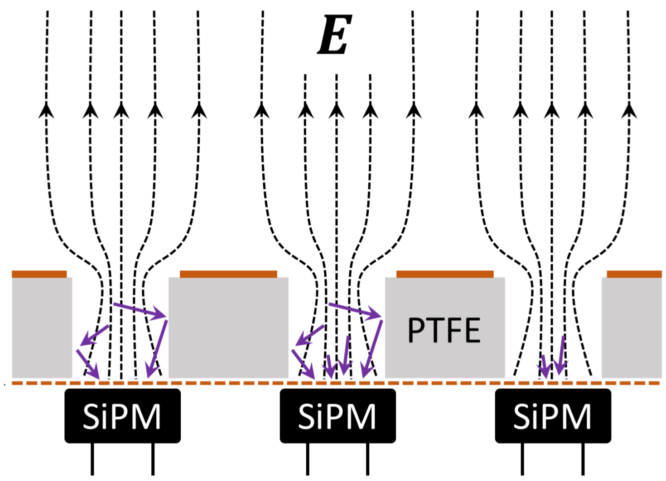


arXiv: 1511.09246

Segmented EL readout: ELCC

- Tracking and Energy measurement with SiPMs in individual cells
  - Uniform response in wide area
  - Rigid structure
  - → Scalability is good

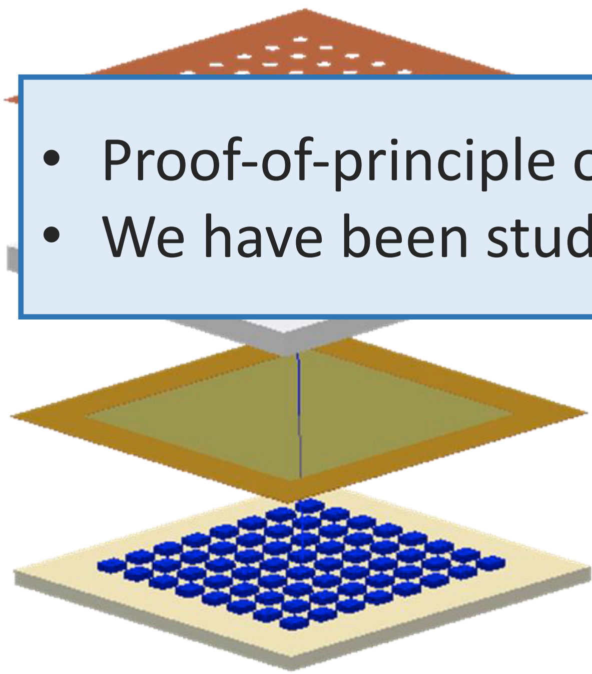




Segmented EL readout: ELCC

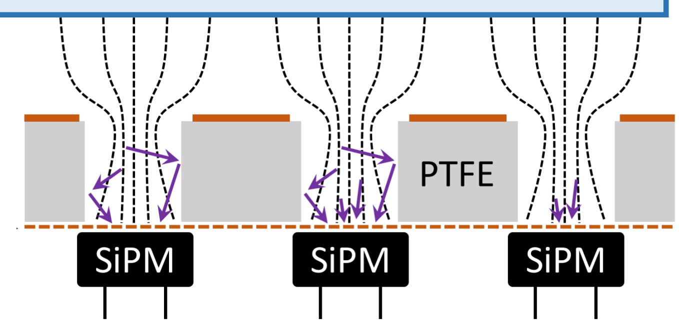
- Tracking and Energy measurement with SiPMs in individual cells
  - Uniform response in wide area
  - Rigid structure
  - → Scalability is good

- Proof-of-principle of ELCC is needed
- We have been studied it with simulation and prototype detector



mesh electrode

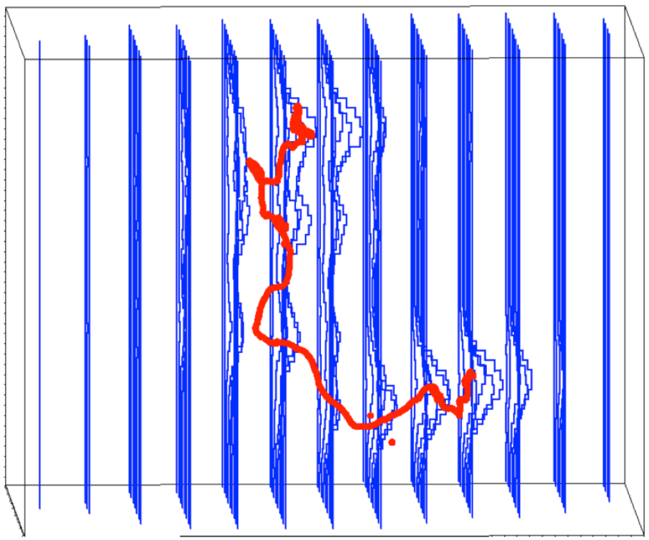
MPPC photon detector array

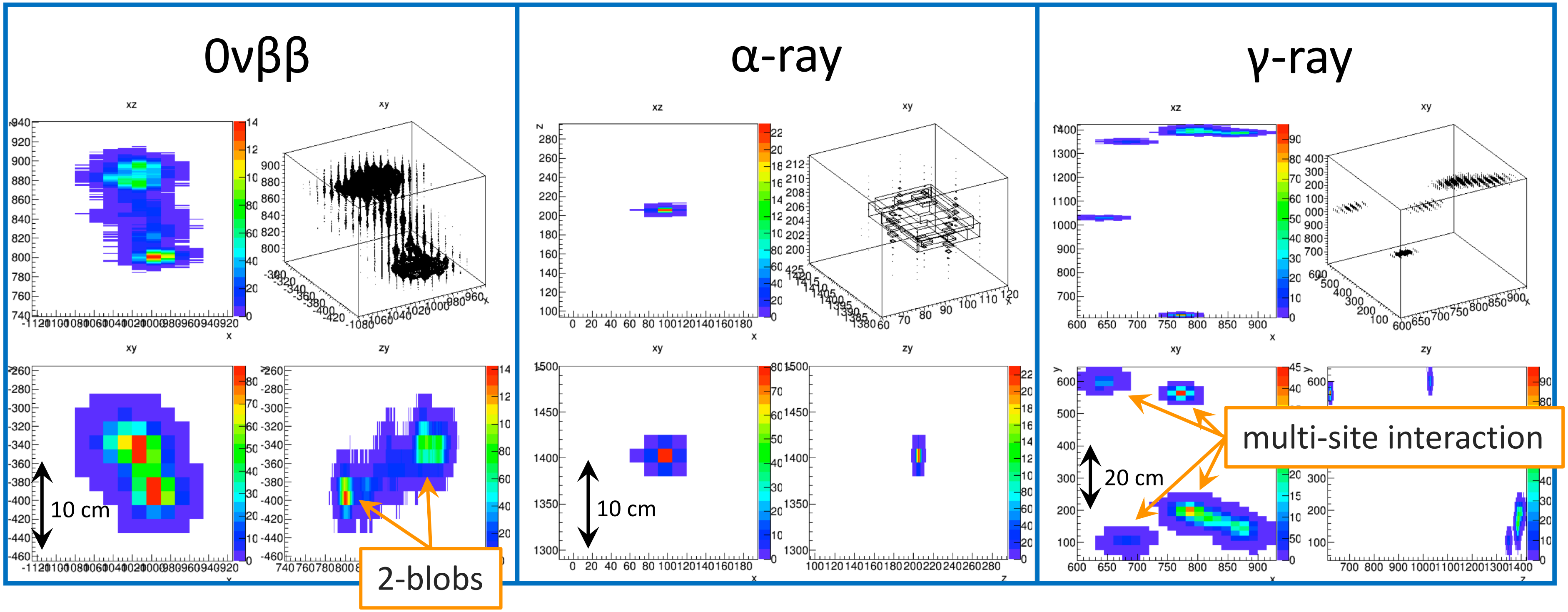


Expected event topologies

- Track topology (Geant4 simulation)
  - 0νββ: 2-blobs at the end
  - α-ray: small
  - γ-ray: multi-site interaction (98%)

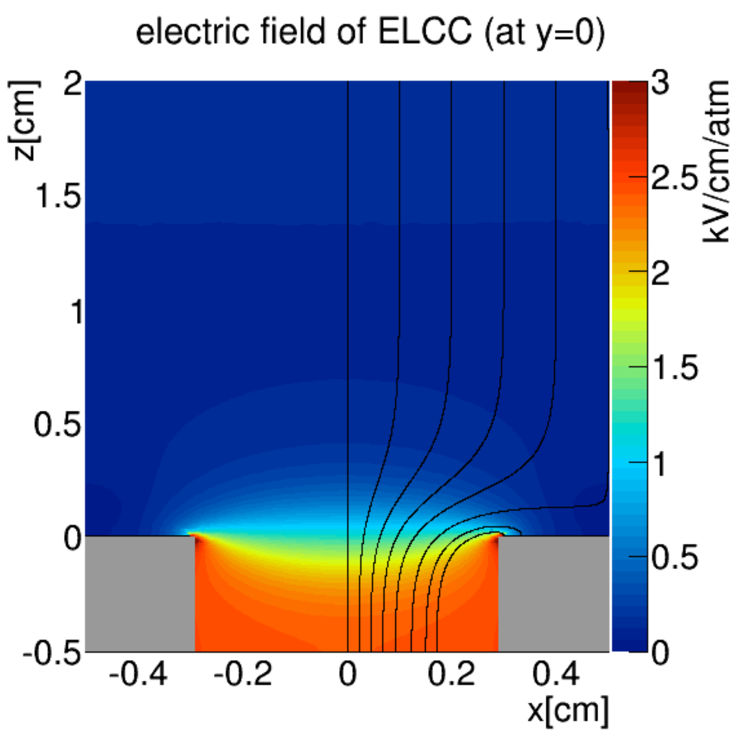
  → Background rejection from event topologies



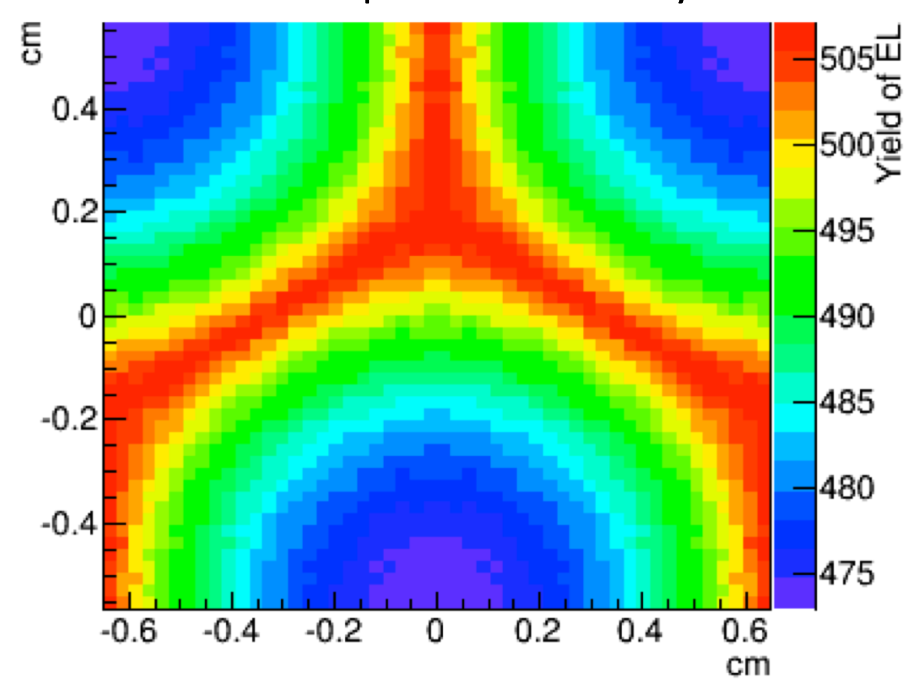


Simulation of ELCC

- Electric field calculation by elmer
  - All electric field lines are collected into cells when E_{EL}/E_{drift} is sufficiently large (E_{drift}=100 V/cm/atm, E_{EL}>2.5kV/cm/atm)
  - Position dependence of EL yield is 1.7% (rms)
    →Effect for the energy resolution is **<0.005%** (since the number of initial electrons is sufficiently large ~10^5)

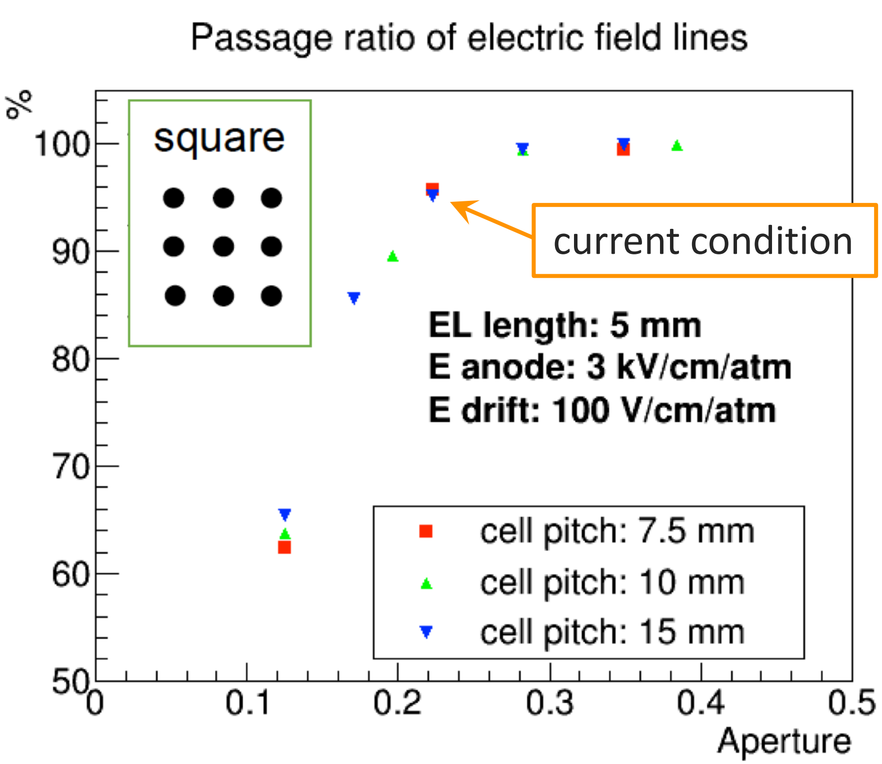


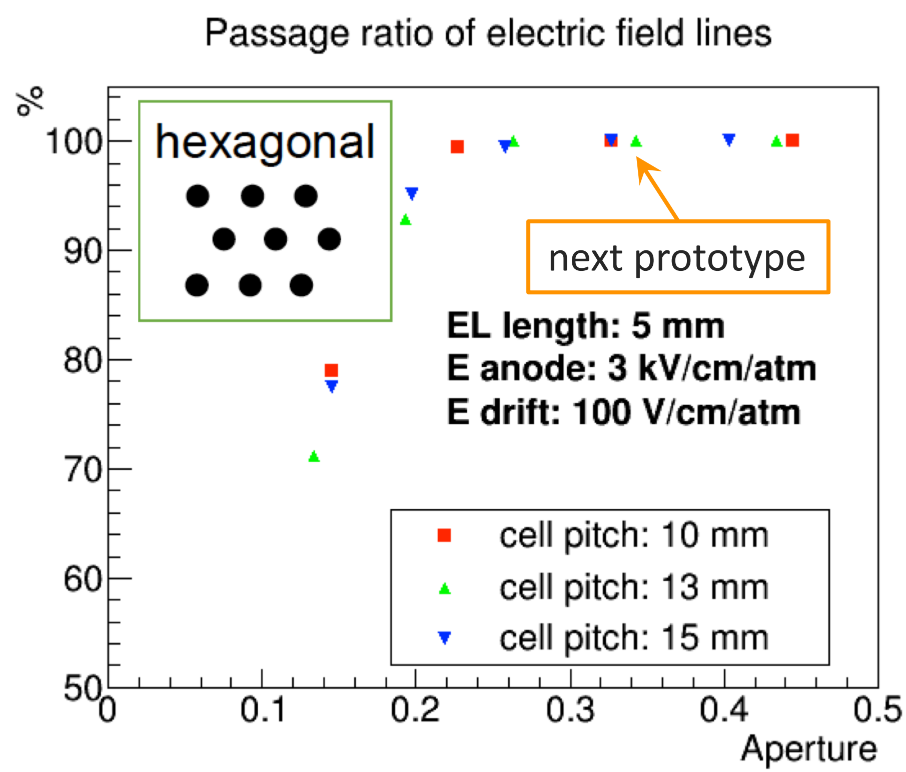
Position dependence of EL yield



Optimization of cell configuration

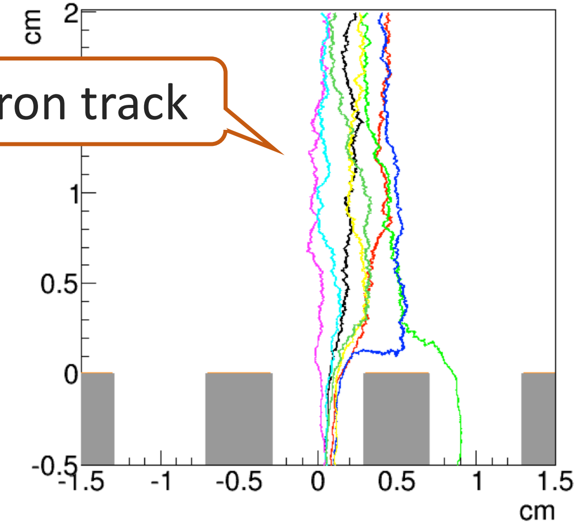
- Hexagonal cell configuration is better for the collection of electric field (under same electric field and EL length)



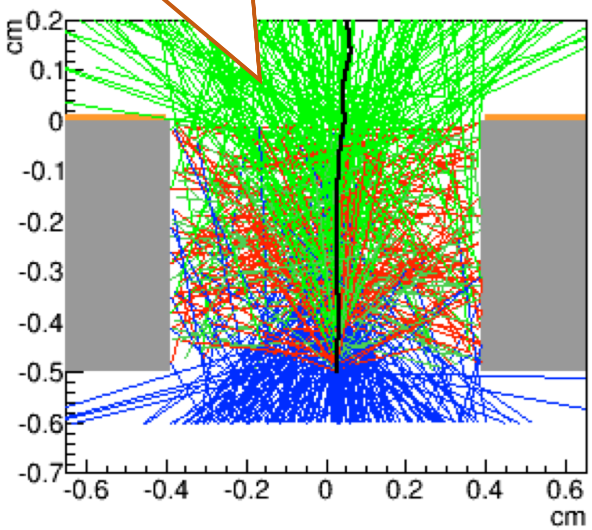


Electron and photon propagation simulation

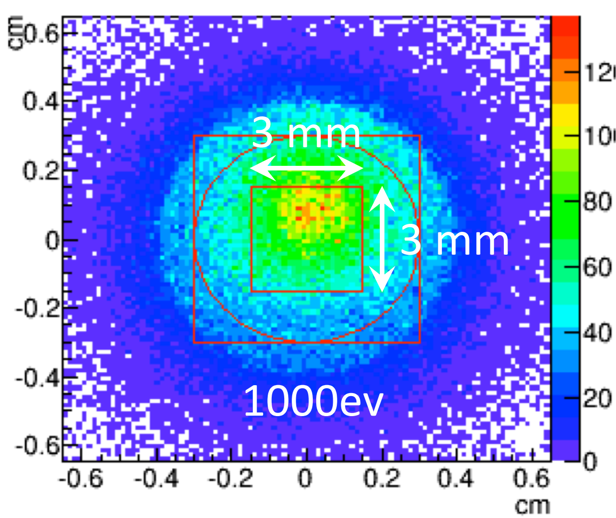
- Electron track by Garfield++
- EL photons by a hand-made program
- 6 photons/electron on SiPM (3 mm square)



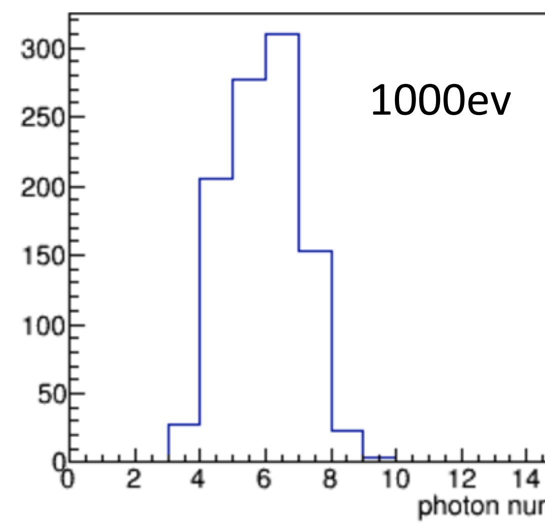
Generated photons



Hit position on SiPM

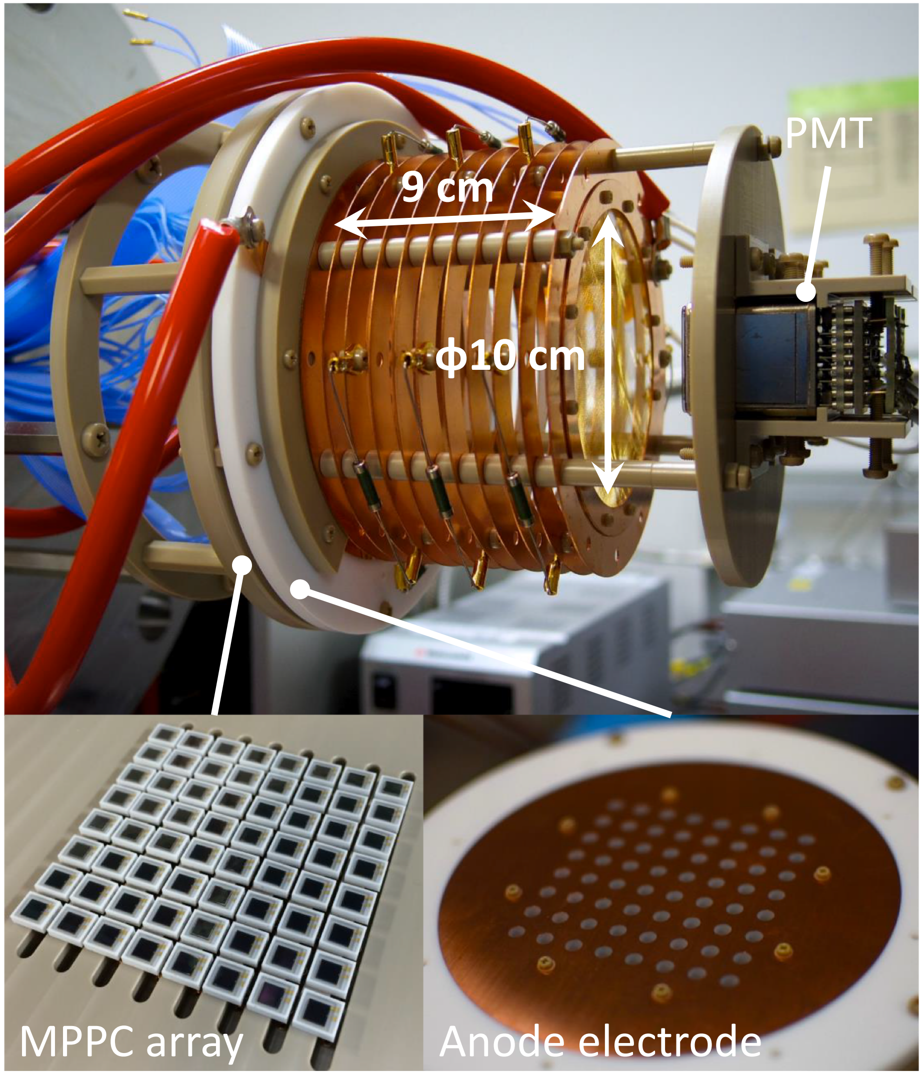


Number of detected photons for each electron



10L prototype detector

- Motivation
  - Proof-of-principle of ELCC
  - Performance evaluation at 511keV
- Conditions
  - Sensitive region: ϕ10 cm× 9 cm
  - Number of SiPMs: 64ch
  - Gas pressure: 4 bar
  - E_{drift}: 100 V/cm/atm
  - E_{EL}: 2.7 kV/cm/atm
- SiPM
  - Hamamatsu MPPC VUV3 sensitive to 170 nm
  - Size: 3 mm square
  - PDE: 23%

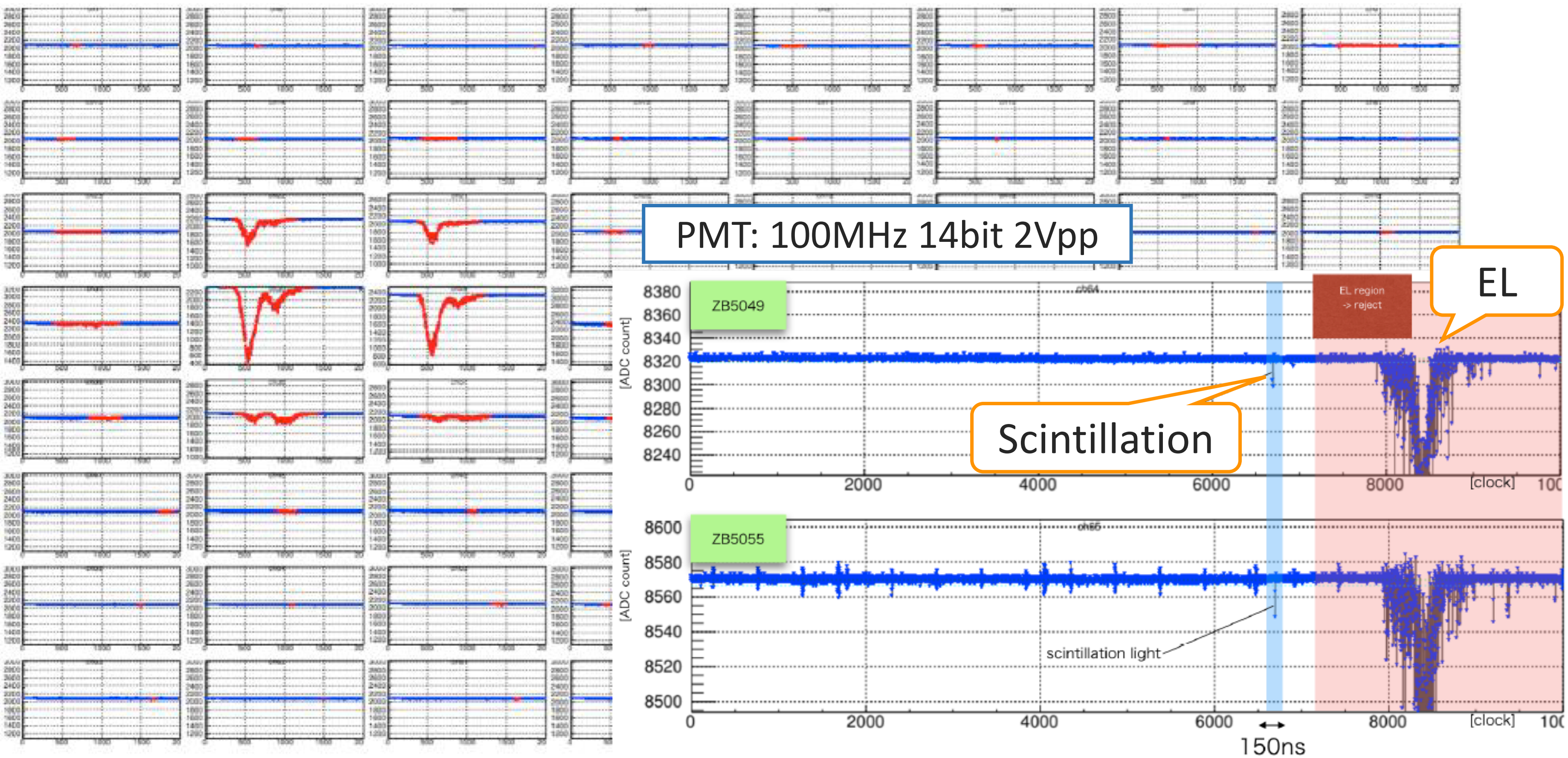


Event example

- Waveforms of MPPC's and PMT's
- EL light and scintillation light are observed

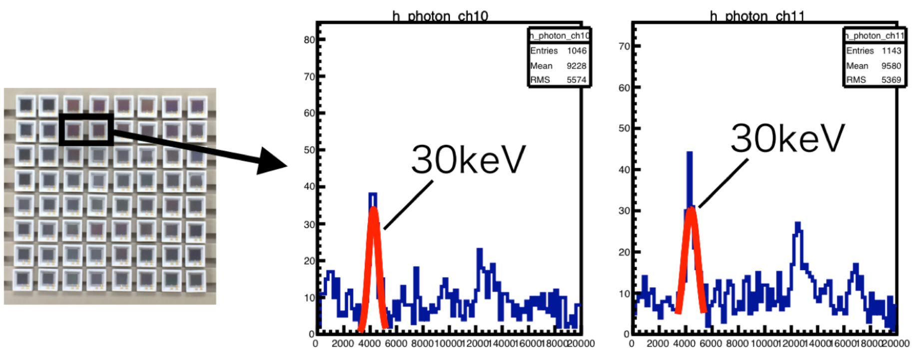
MPPC: 65MHz 12bit 2Vpp

PMT: 100MHz 14bit 2Vpp

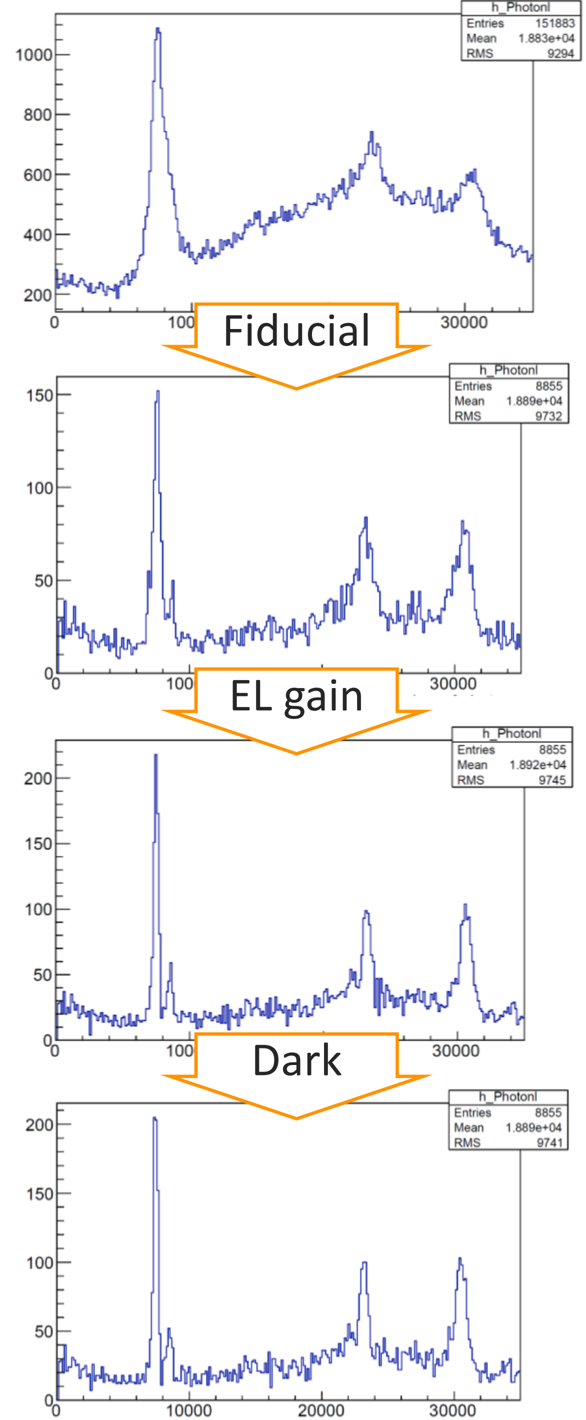


Analysis flow

- Fiducial cut
  - XY with hit channel, Z with PMT timing
- EL gain correction
  - Calibrate each cell gains with 30 keV peak

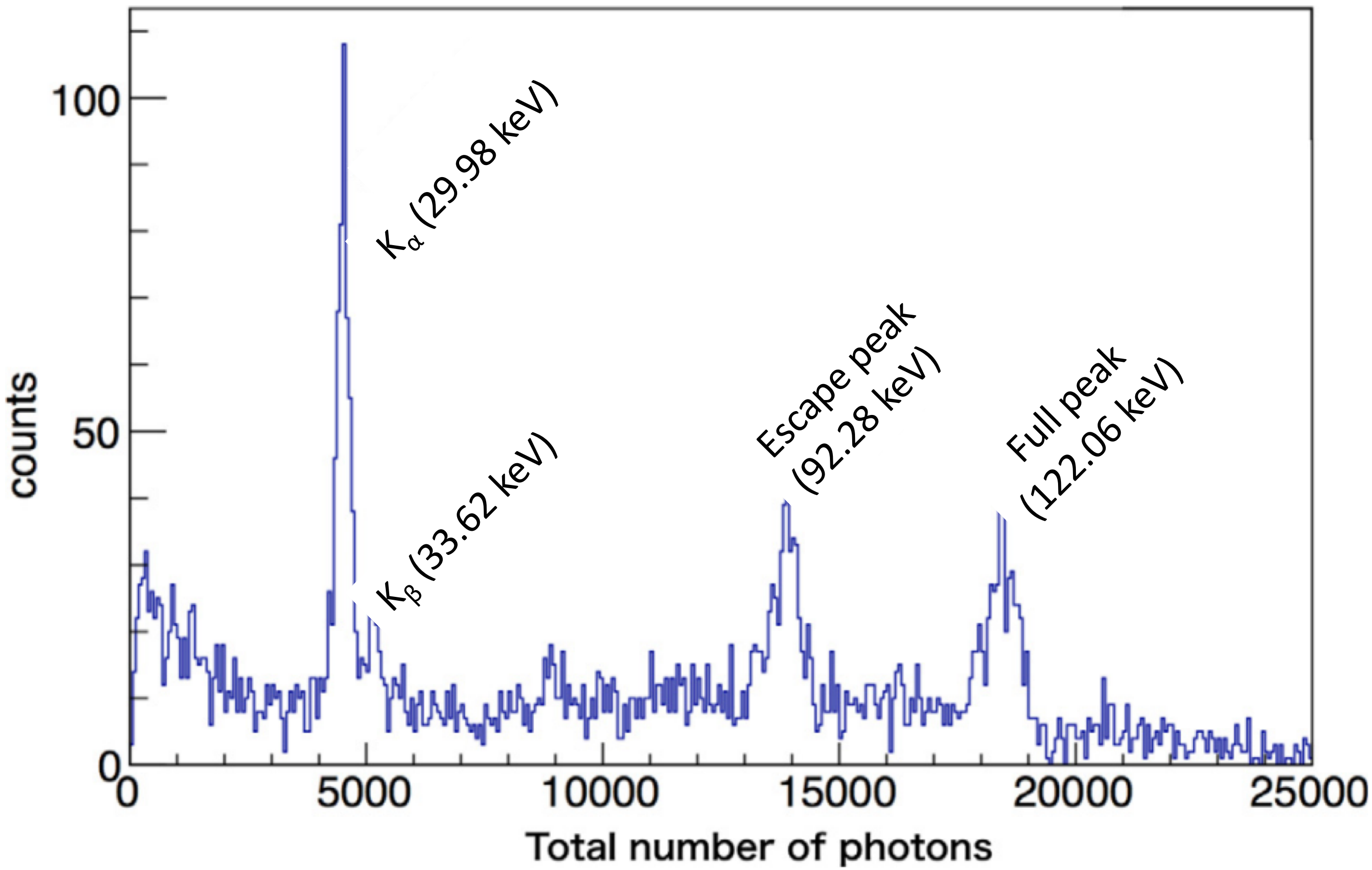


- Dark current subtraction
  - Subtract dark count from EL waveform



Measured energy spectrum

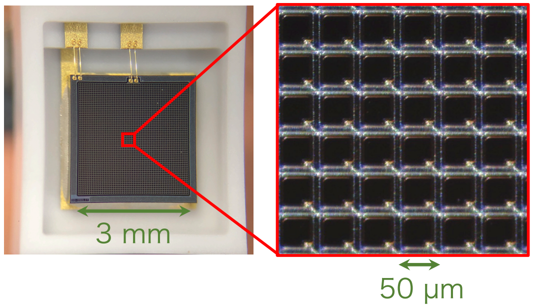
- Four peaks are observed with ^{57}Co source



NIM, A 875 (2017) 185–192

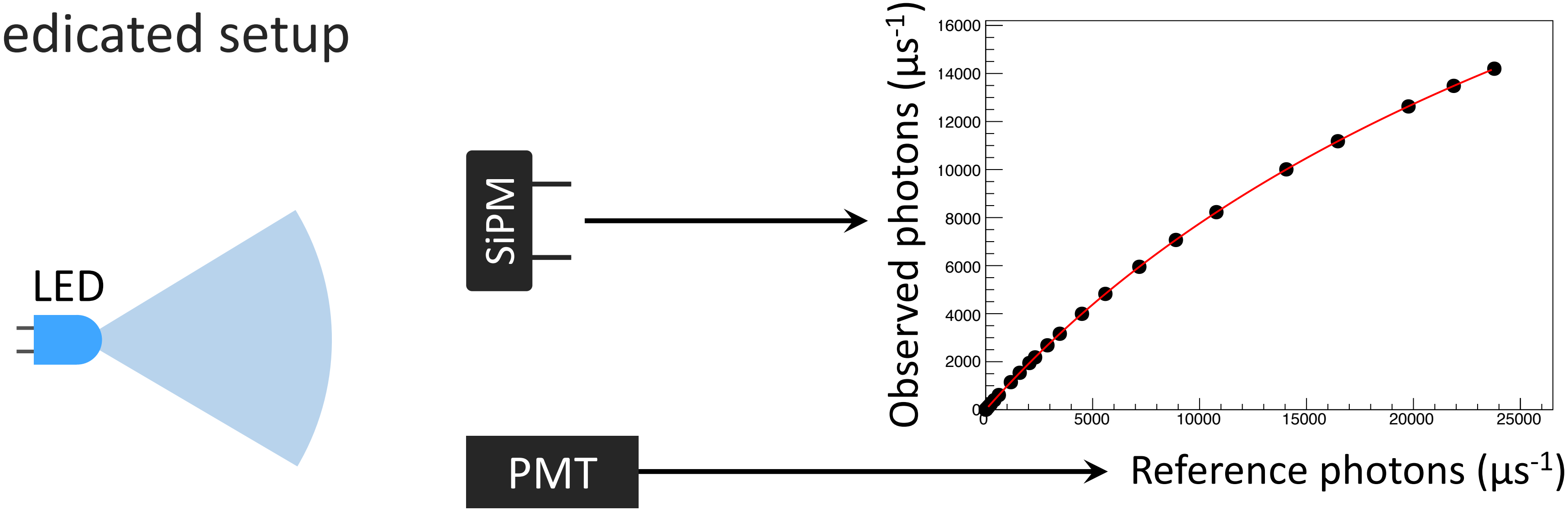
Measurement of higher energy electron

- More photons are detected in one cell as gas pressure and electron energy are increased
  →Energy resolution could be worse because of the non-linear response of SiPMs



- Non-linearity is modeled with the pixel recovery time constant
- The recovery time was measured by a dedicated setup

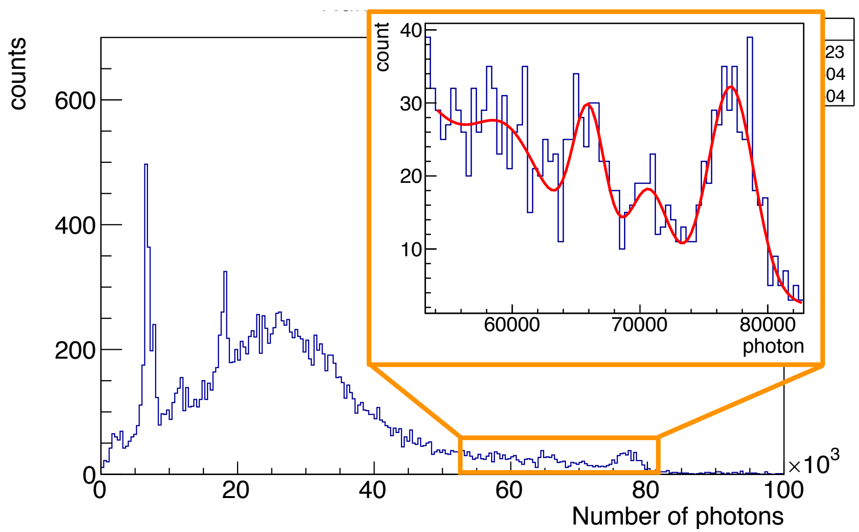
$$N_{\mathrm{obs}} = \frac{\alpha N_{\mathrm{ref}}}{1 + (\tau_1/\Delta t \cdot N_{\mathrm{pix}})N_{\mathrm{ref}}} + \frac{\beta N_{\mathrm{ref}}}{1 + (\tau_2/\Delta t \cdot N_{\mathrm{pix}})N_{\mathrm{ref}}}$$



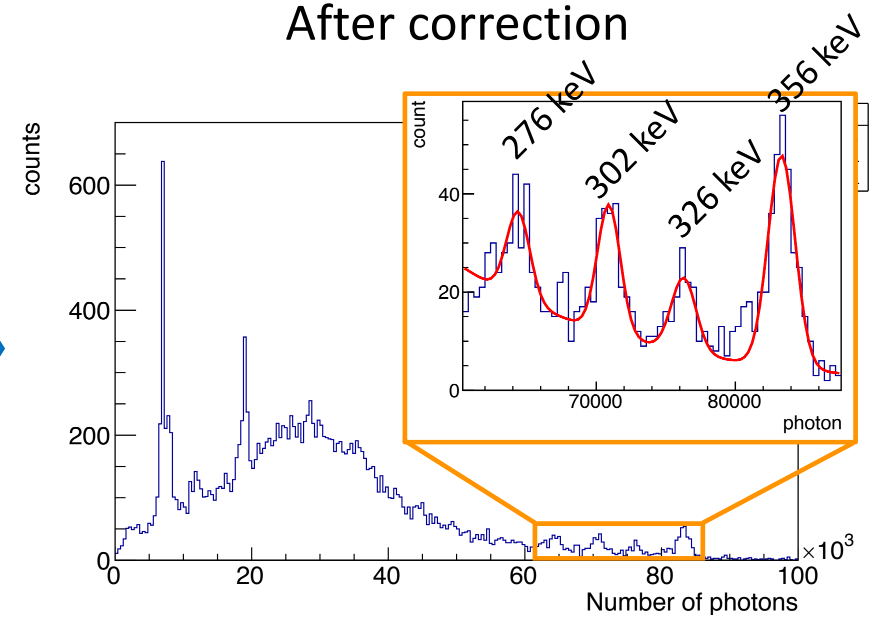
Improvement of energy resolution

- Energy resolution is improved by correcting MPPC non-linearity
  - ^{133}Ba 356 keV peak
  - Energy resolution: **5.4%→2.5%**@356 keV

Before correction



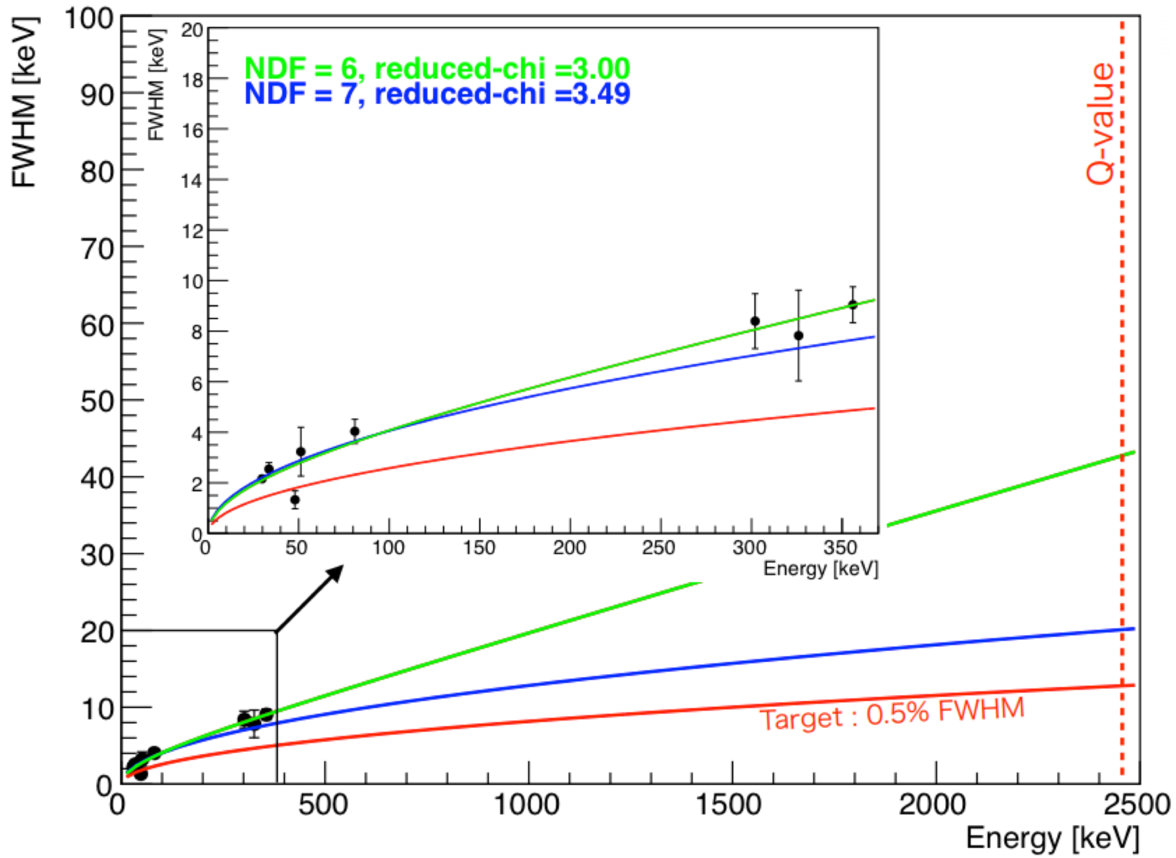
After correction



Energy resolution at Q-value

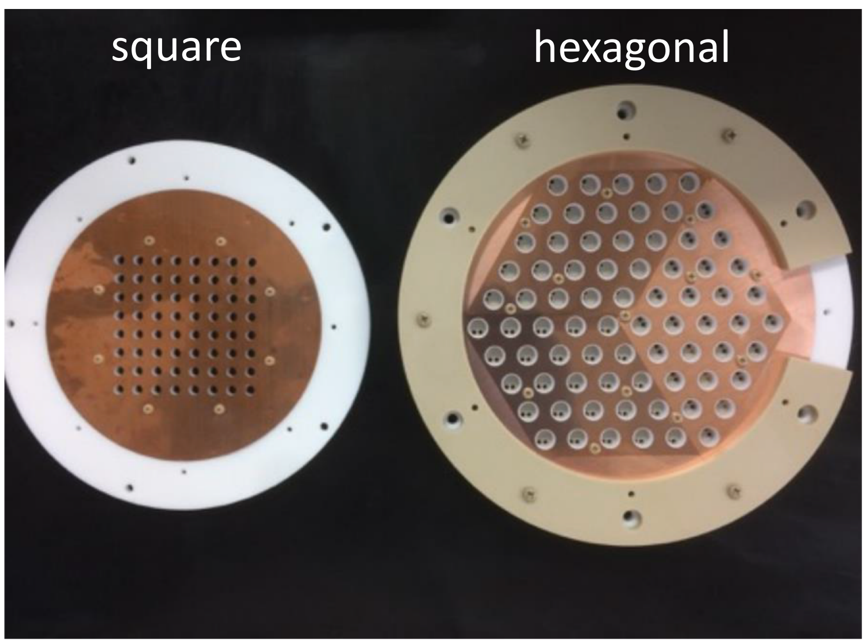
- Extrapolation to the Q-value (2.5 MeV)
  - $A\sqrt{E + BE^2}$: 1.74% FWHM
  - $A\sqrt{E}$: 0.82% FWHM

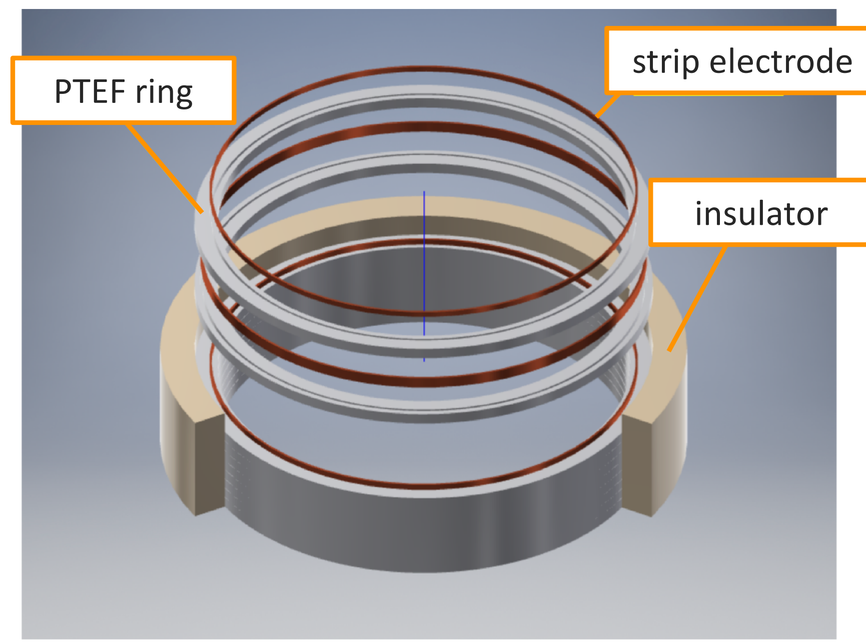
c.f. Our target is 0.5% (FWHM). The next setup is a measurement at higher energy.



Upgrade of the 10L prototype detector

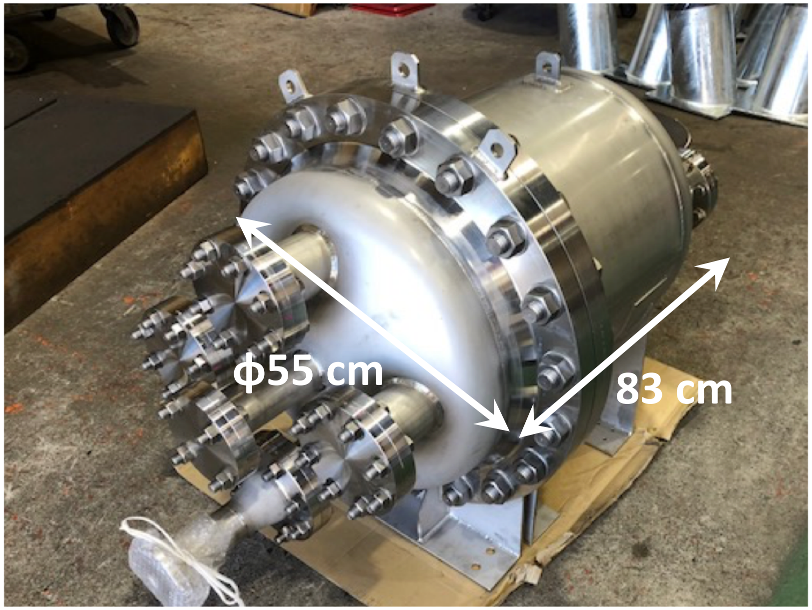
- New ELCC and field cage for the higher energy measurement
  - Hexagonal cell configuration (Electric field line correction efficiency is better)
  - Double strip electrode (Good uniformity of the electric field, higher resistance to break down)
  - PTFE ring structure (Reflection of the scintillation light)





Next prototype: 180L detector

- Purpose
  - Evaluation at Q-value (2.5 MeV)
  - Tracking test
  - Establishment of large-sized technology
- Spec
  - Fiducial volume: ~100 L
  - Number of SiPMs: ~1000 ch
  - Drift top voltage: 65 kV



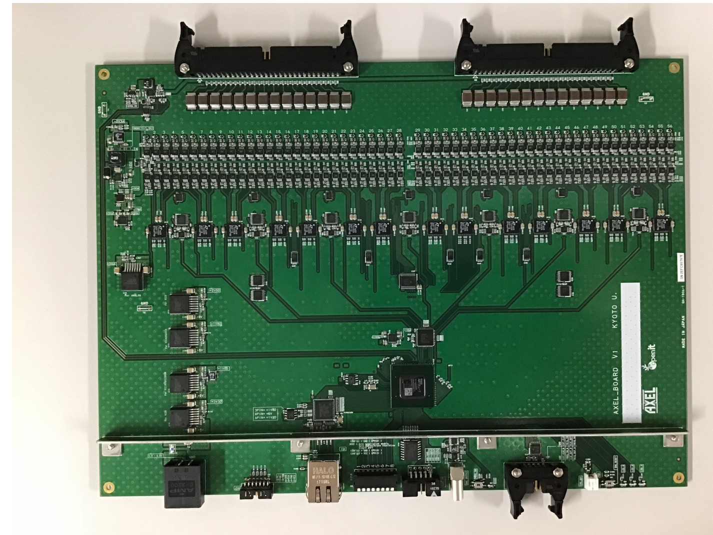
Development of components is on going!!!

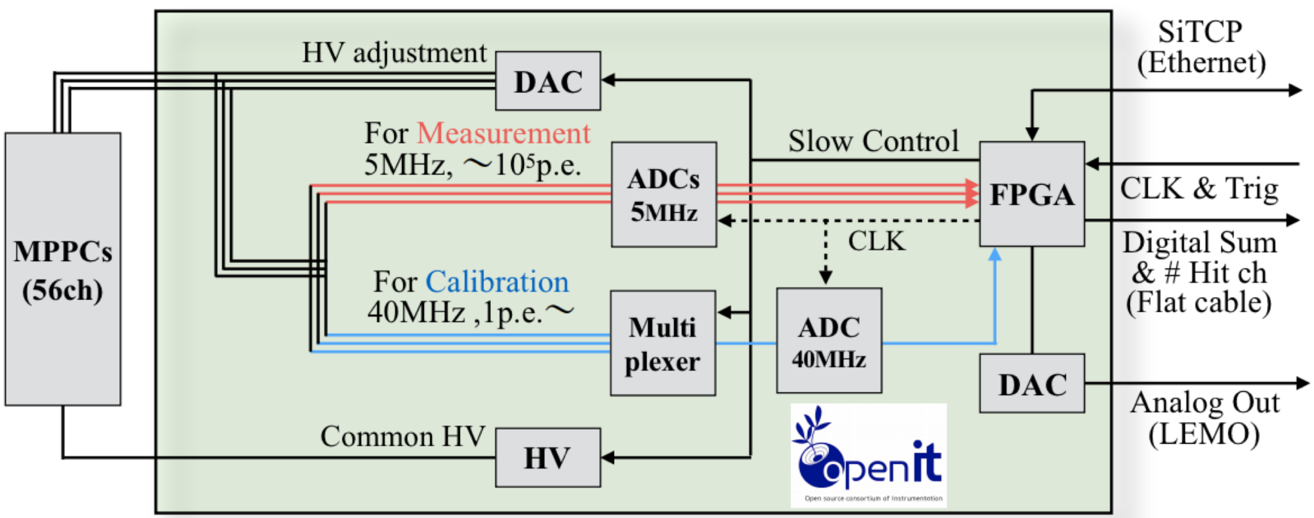
- Electronics
- HV supplement
- Cabling
- etc...

Electronics

- Multi channel with low cost
- Waveform acquisition at 5 MHz sampling for 500 μs
- Wide dynamic range (full energy and 1p.e. measurement)
- Bias voltage can be set for each SiPM

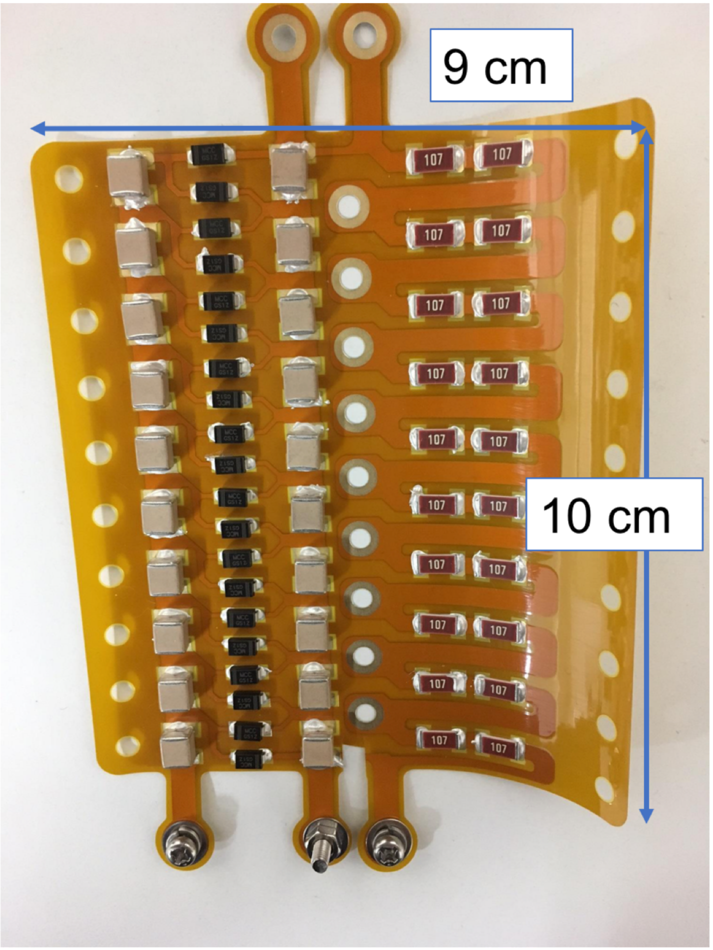
New board testing is on going





HV supply for field cage

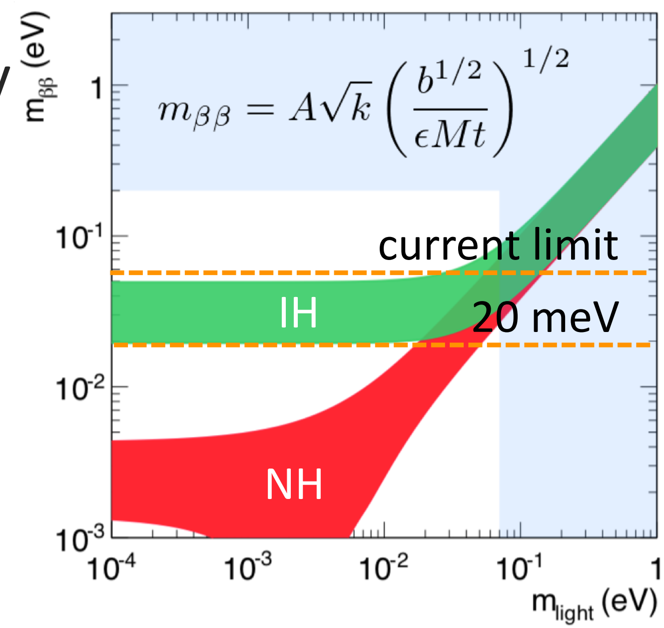
- Maximum voltage: 65 kV
  - Electric discharge will be a severe problem, especially at the feedthrough
  - → Generate HV inside the chamber
- Cockcroft-Walton voltage generator
  - Flexible Print Circuit (FPC) to avoid outgas
  - Succeed to generate 10 kV with a prototype



Sensitivity estimation for 1 ton detector

- To cover all inverted-hierarchy region
  - Need to reach $m_{\beta\beta}$ = 20 meV
  - Background free (<1 event/year) is required
- Gamma absorption at 2.5 MeV gamma-ray will be a severe background
  - 2.9 ppt ^{214}Bi in chamber (Upper limit of EXO's coper)
  - BG: 75 event/year → $m_{\beta\beta}$ = 72 meV

Sensitivity of 0νββ



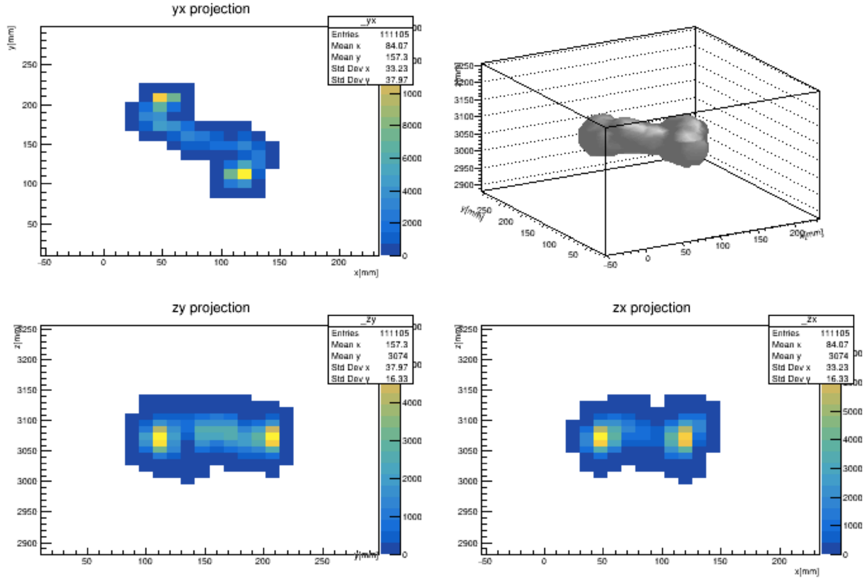
arXiv:1502.00581

Sensitivity estimation for 1 ton detector

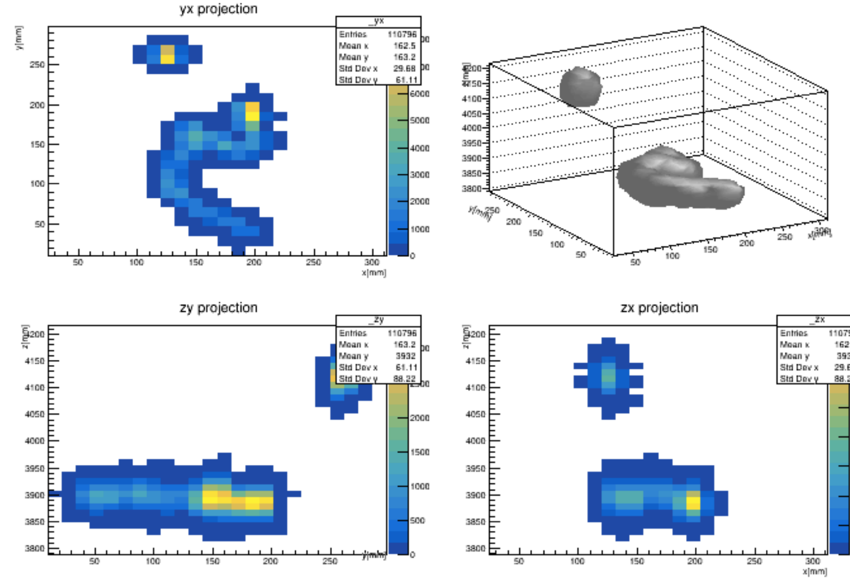
- Deep learning application
  - Learning with simulation 0νββ and gamma-ray data
  - Remaining background is 0.0044% when signal efficiency is 51.82%
  - BG: 7.9 event/year → $m_{\beta\beta}$ = 36.6 meV

Additional reduction is still needed

0νββ



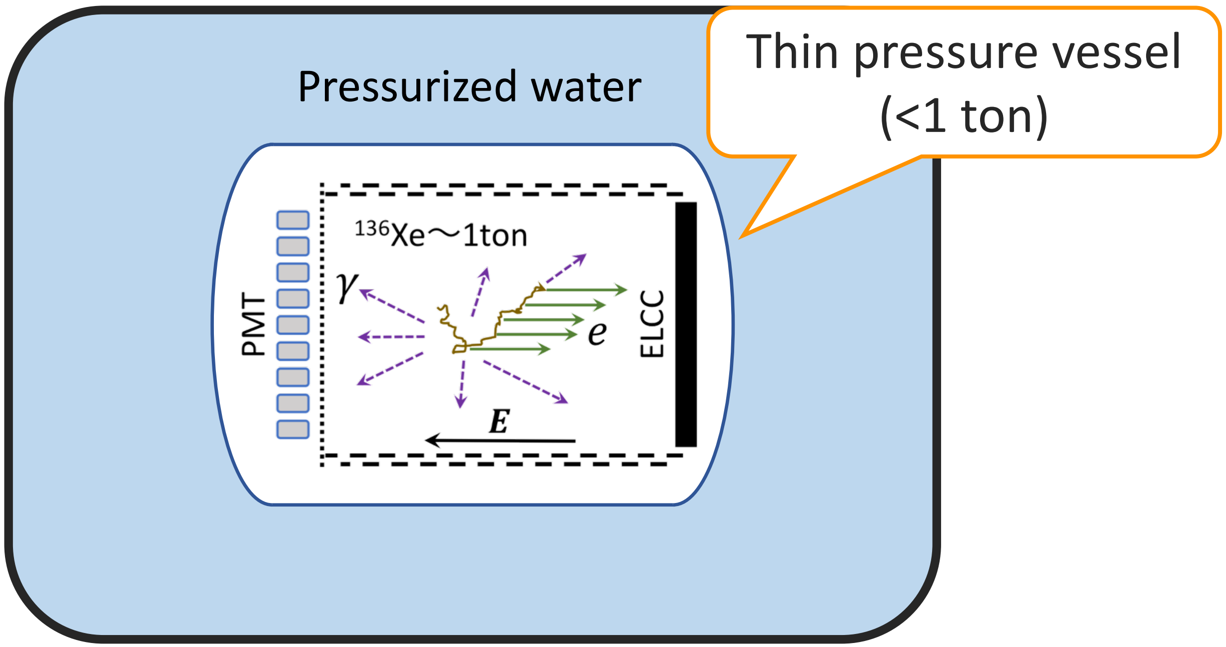
gamma-ray (^{214}Bi)



Sensitivity estimation for 1 ton detector

- Dominant background source
  - Mass of pressure vessel is 10 ton

→ We will develop a low mass pressure vessel with high pressure water shield
→ Active vessel with the PEN scintillator is also under consideration

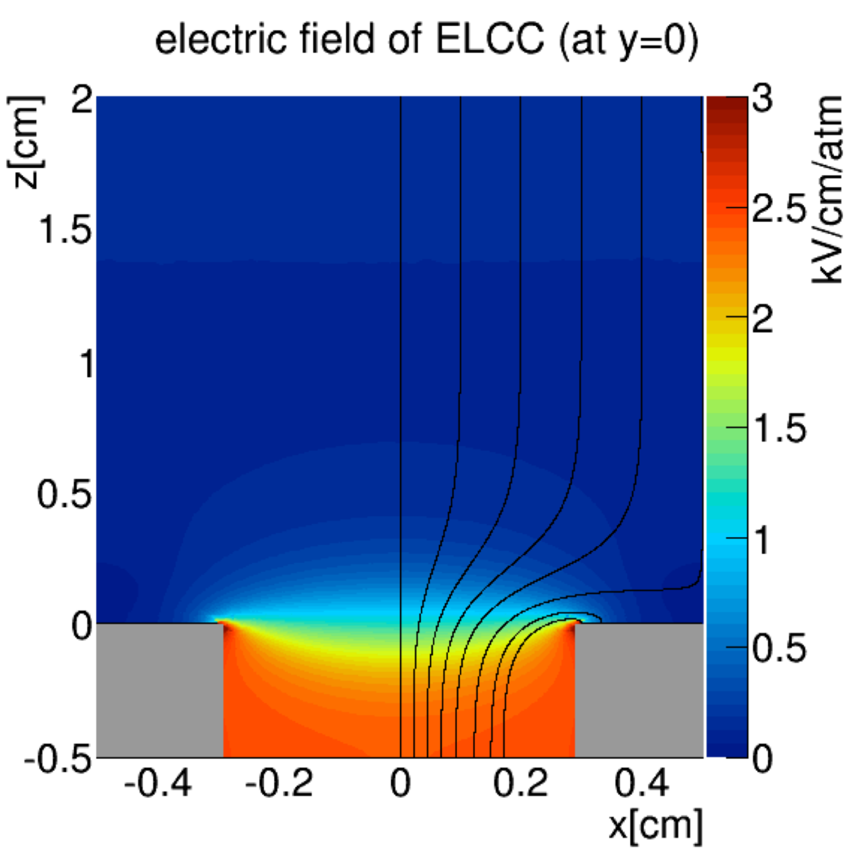


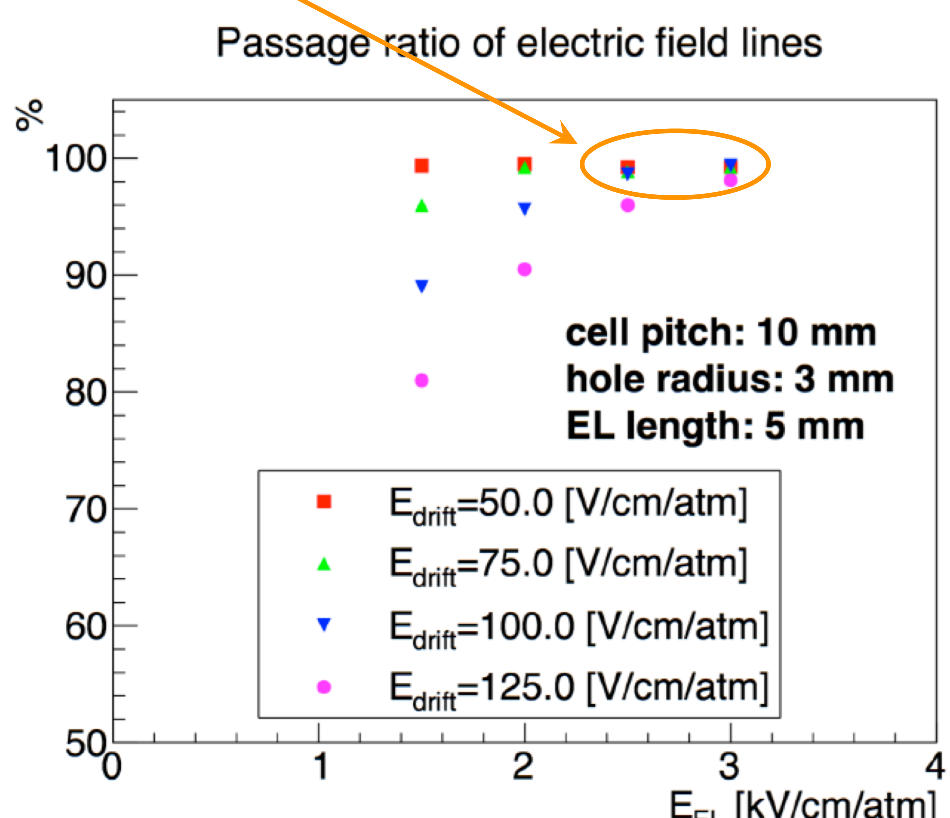
Summary

- AXEL project is developing a high pressure xenon gas TPC for $0\nu\beta\beta$ search.
- Segmented EL readout (ELCC) is a key component.
  → We have been demonstrated it from a simulation and 10L prototype detector.
- Energy resolution extrapolated to 2.5 MeV is 0.82–1.74% FWHM.
- Construction of the next 180L prototype detector is on going.
- AXEL is aiming to reach to 20 meV sensitivity with some ideas.

Simulation of ELCC

- Electric field calculation by elmer
  - All electric field lines are collected into cells when E_{EL}/E_{drift} is sufficiently large (E_{drift}=100 V/cm/atm, E_{EL}>2.5kV/cm/atm)

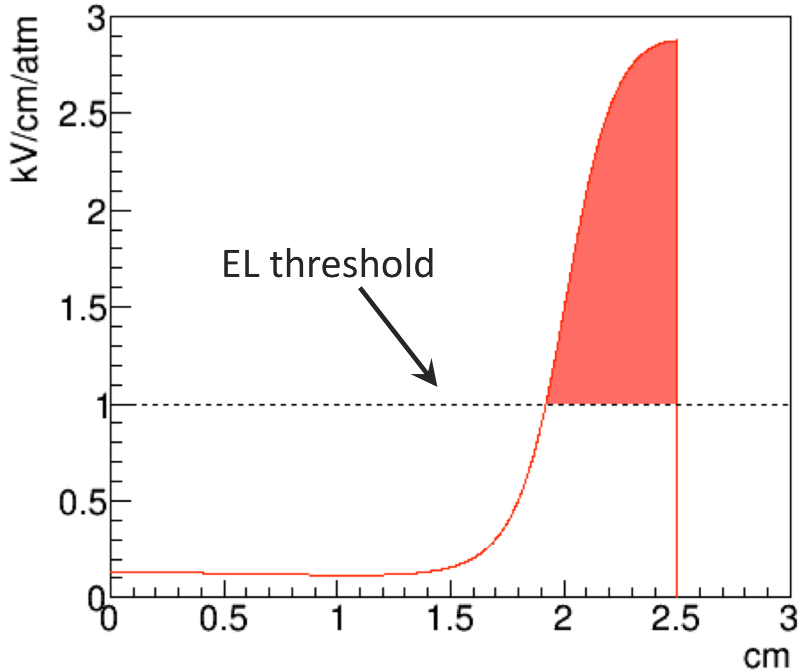




Simulation of ELCC

- Electric field calculation by elmer
  - Position dependence of EL yield is 1.7% (rms)
    →Effect for the energy resolution is **<0.005%** (since the number of initial electrons is sufficiently large ~10^5)

Electric field strength along the line



Integral value distribution