



Migdal effect search using Argon-based gaseous μ -TPC

Keishi Suzuki (Kobe U.)

Introduction

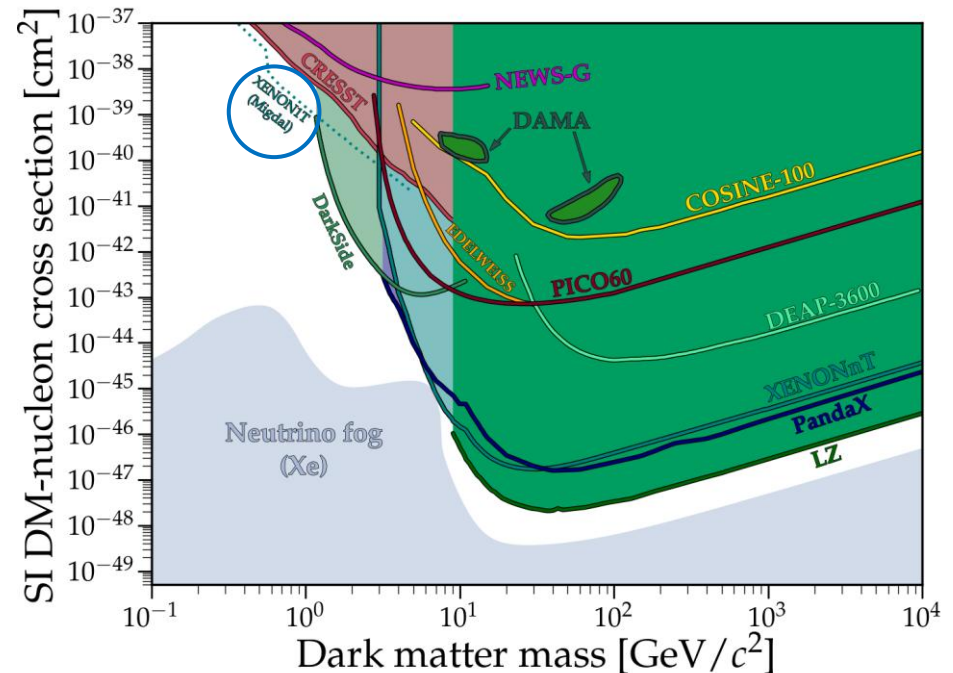
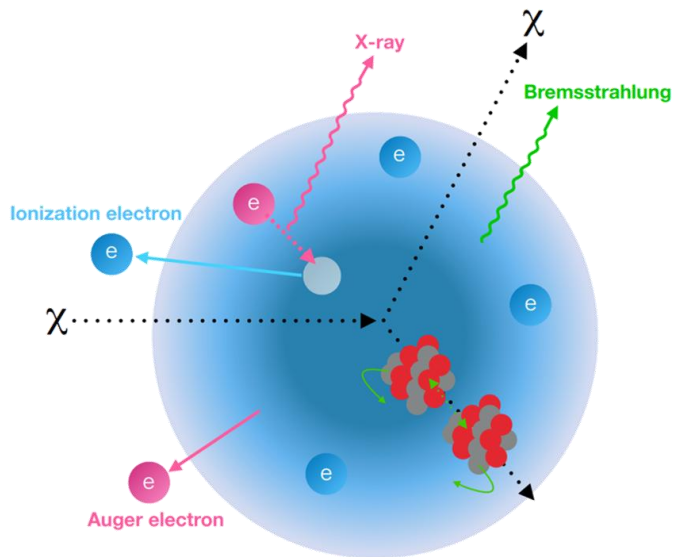
Migdal effect and WIMP search

Migdal effect (rare event)

- Atomic ionization or excitation occurs when a nucleus suddenly moves.

Migdal effect induced by nuclear recoil (NR)

- Since the additional electronic signal can be detected, the sensitivity to low-mass WIMP is enhanced.
- First direct observation was reported in Jan, 2026 (next talk).



Migdal effect and WIMP search

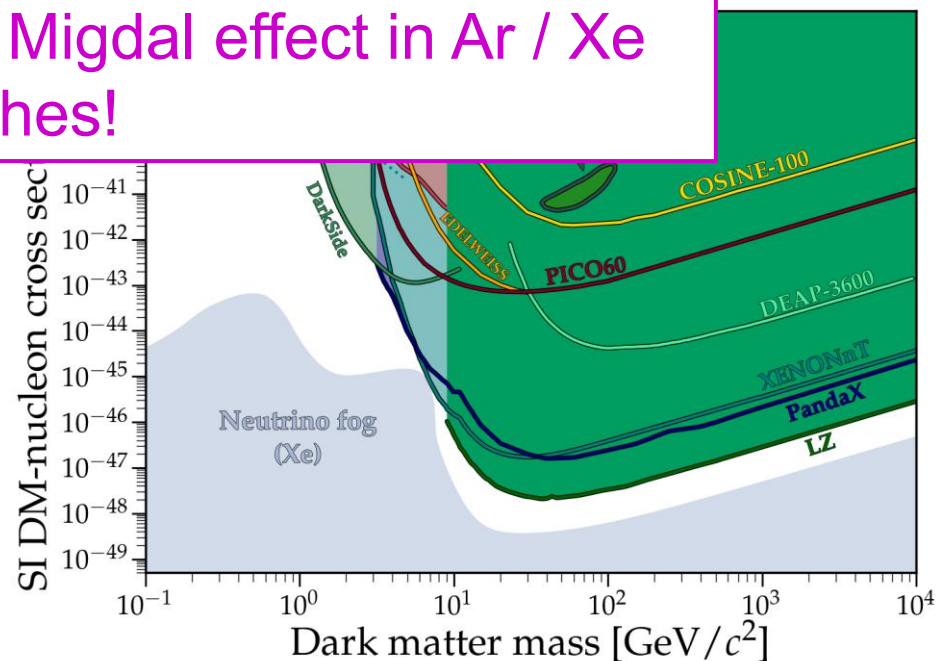
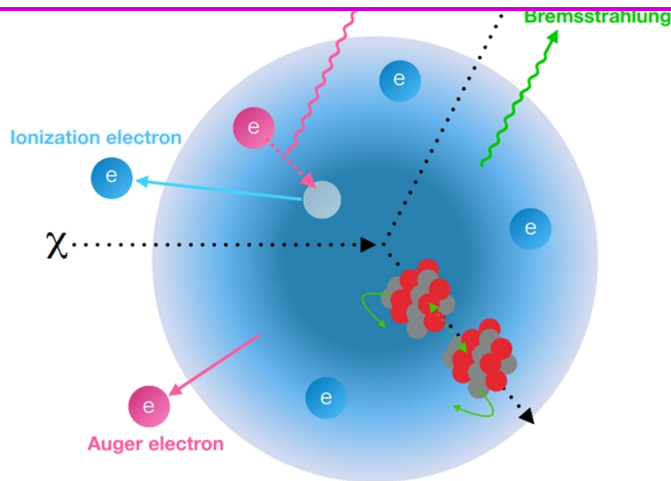
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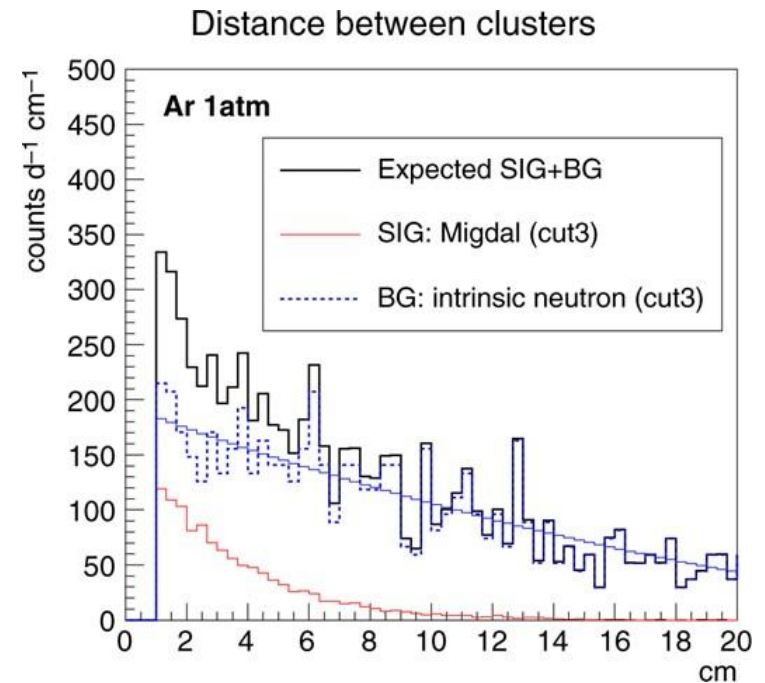
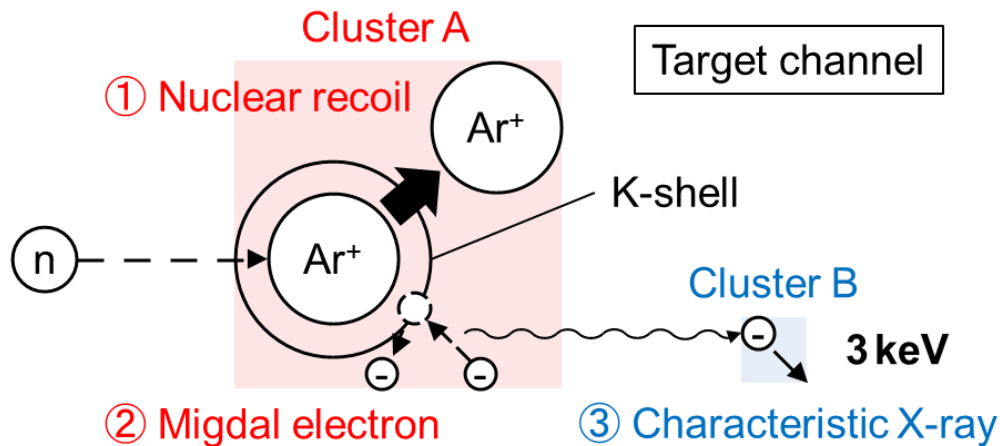
◎ It is important to observe Migdal effect in Ar / Xe to apply it to WIMP searches!



MIRACLUE experiment

Migdal effect search in **neutron beam experiment**

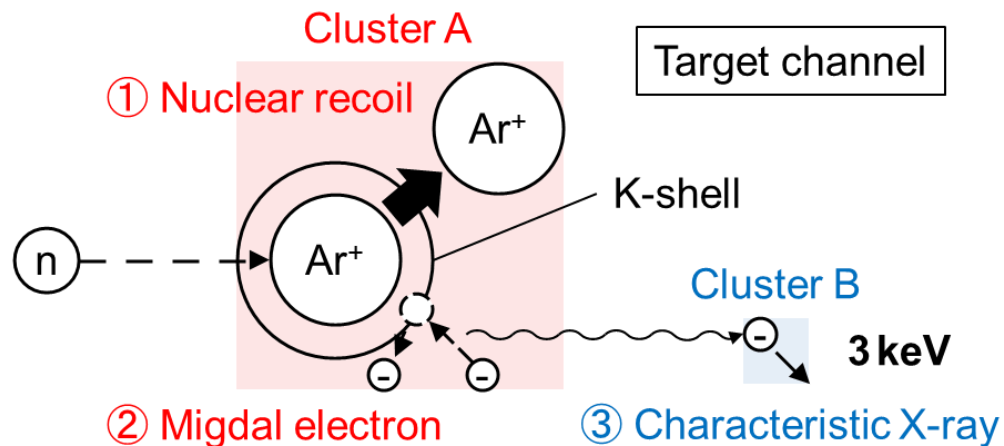
- Target gas: Ar / Xe ← direct interests in DM searches!
- **2-cluster method** using gaseous TPC (PTEP 2021, 013C01)
 - NR + characteristic X-ray of Ar
 - Measure energy of each cluster and distance between clusters.



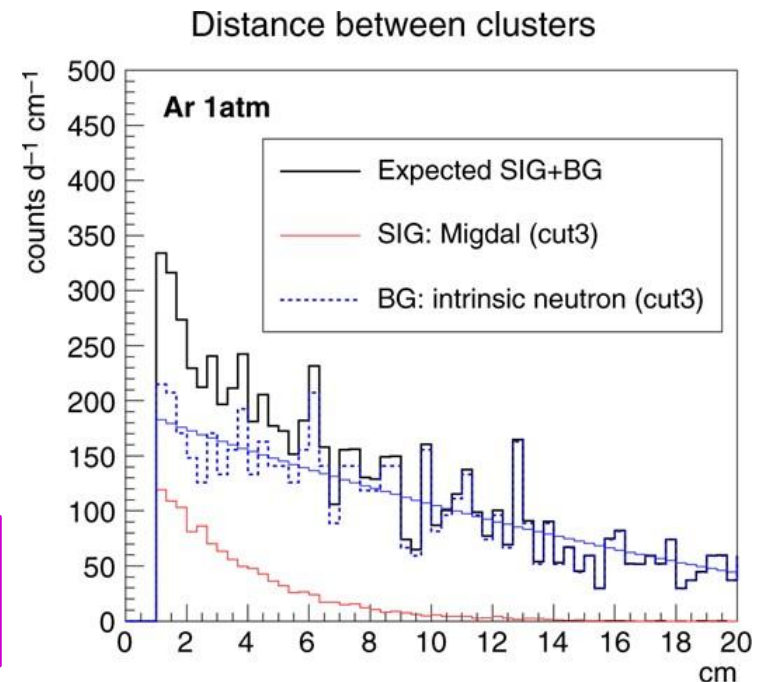
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⊙ Distance distribution between clusters can distinguish signal from BGs!

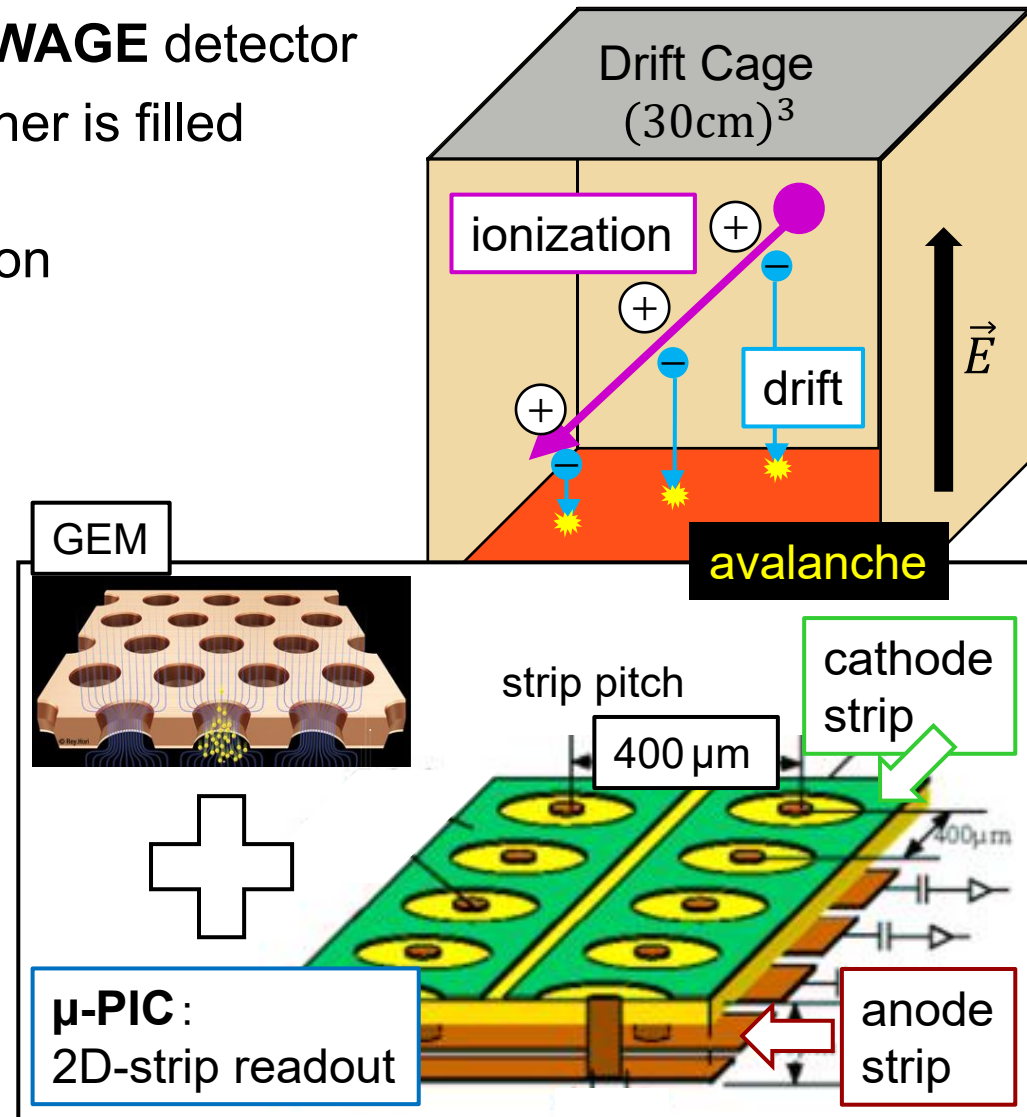
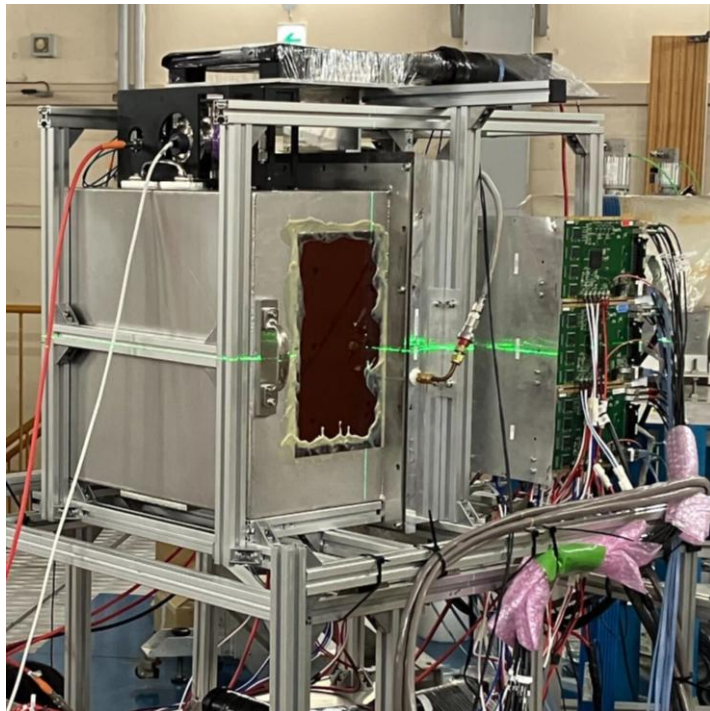


Argon-based gaseous μ -TPC

Detector overview

A gaseous μ -TPC based on **NEWAGE** detector

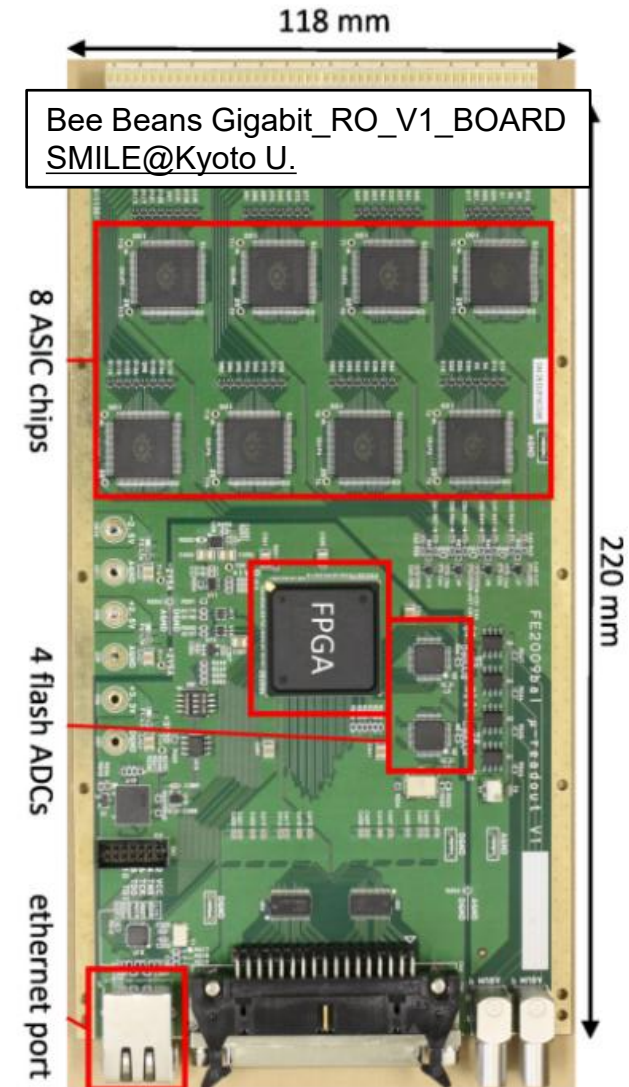
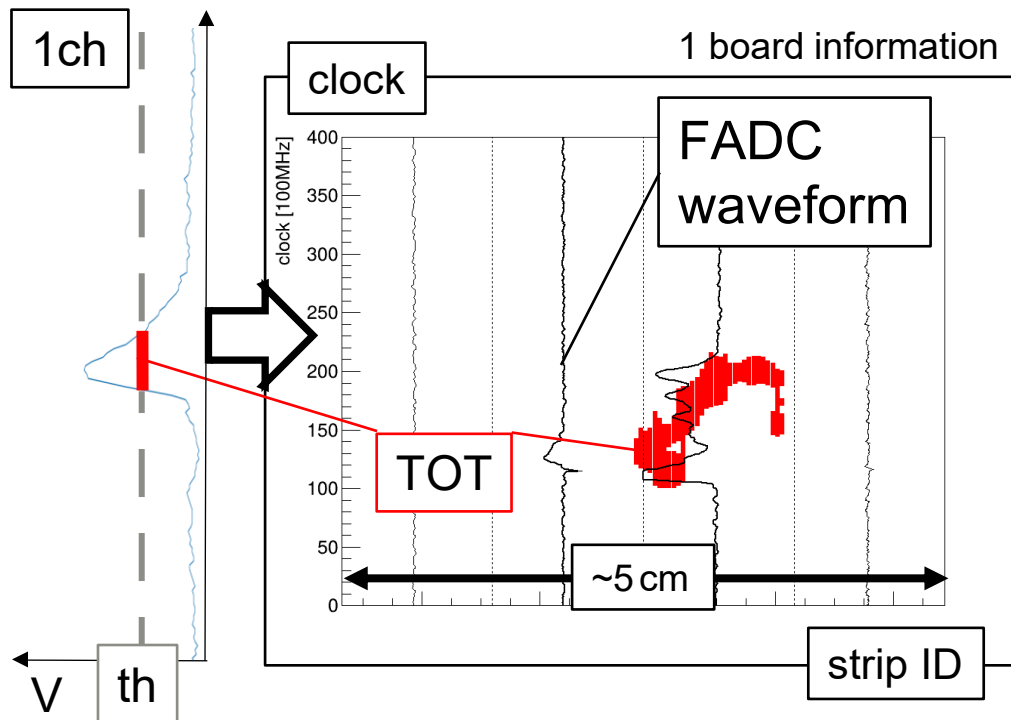
- A gas mixture of Ar and quencher is filled at a total pressure of 1 atm.
- Measure energy and 3D position of charged particles.



Readout board

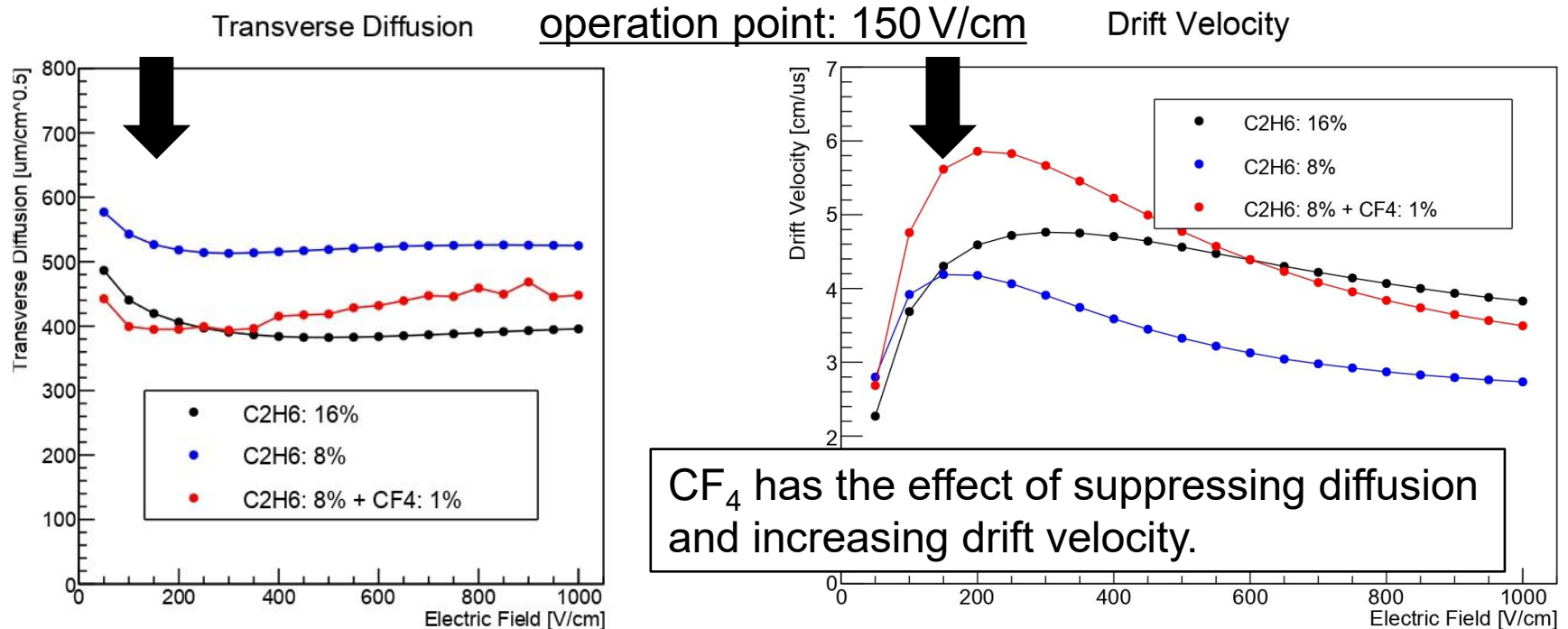
GBKB (Giga Bit Kobe Board)

- Capable of 128 ch readout per board
- 3D position is reconstructed by hit information.
 - Strip address (2D) + Arrival timing (1D)
- Energy is calculated using FADC information.



Gas mixture: **Ar (91%) + C₂H₆ (8%) + CF₄ (1%)**

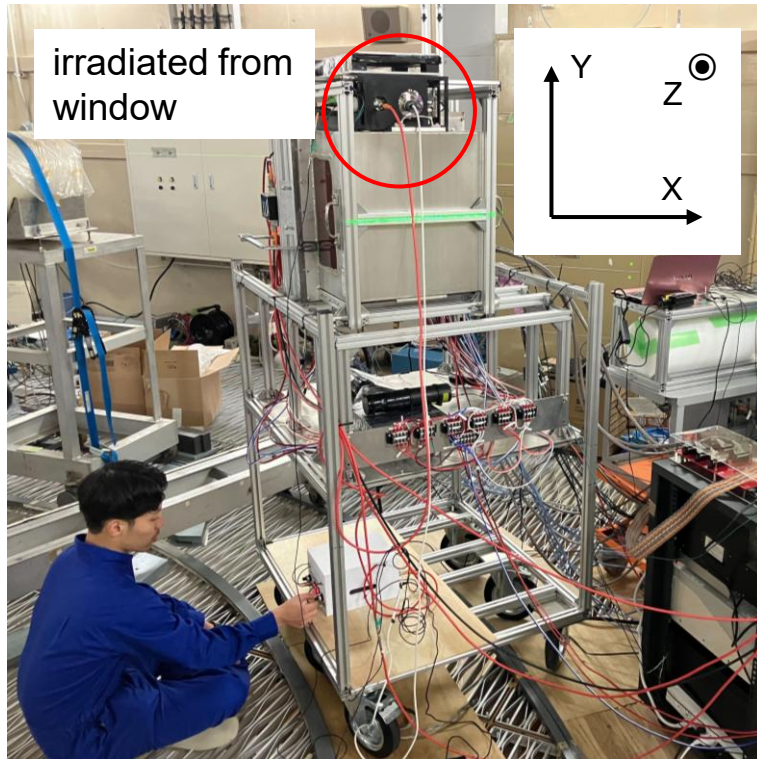
- Reduce the number of non-Ar nuclei and keep discharge tolerance
 - Non-Ar nuclei also cause 2-cluster BGs.
(ex: Multiple scattering, Accidental coincidence)
- Keep detector performance (position resolution, detection efficiency)



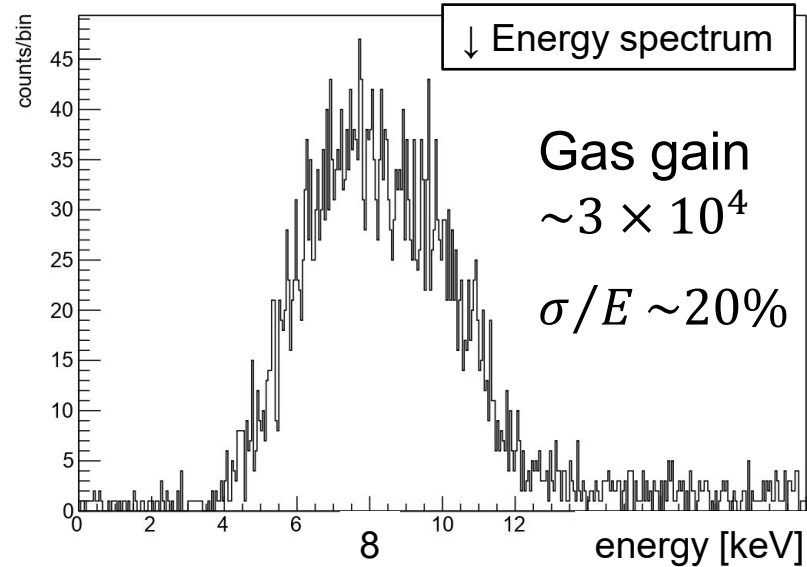
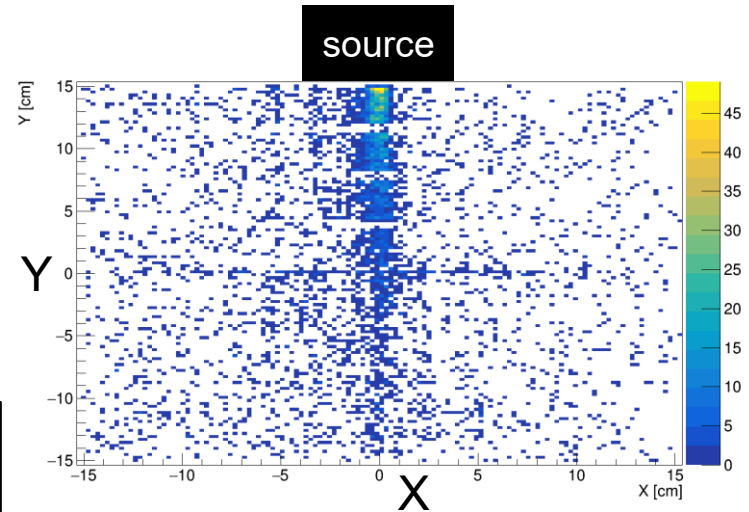
Evaluation (energy calibration)

Portable X-ray source (Cu K_{α} , 8 keV)

⊙ Measured gas gain and energy resolution meet requirement.



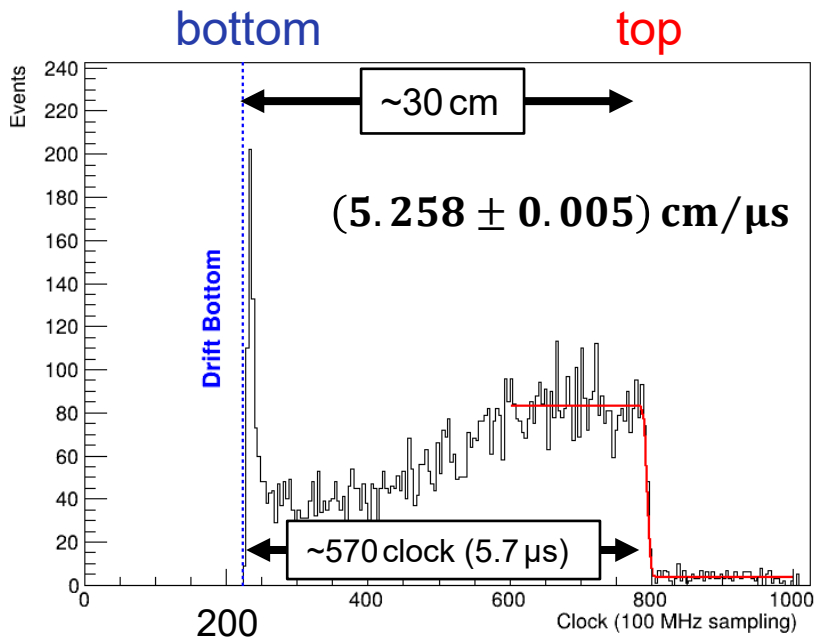
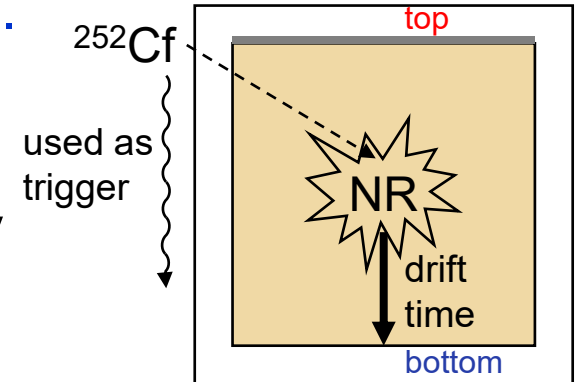
Event map →



Evaluation (drift velocity)

Neutrons and γ -rays emitted from ^{252}Cf were used.

- Measure the time difference between the trigger and the TPC signal.
- ⊙ It was confirmed that the measured drift velocity meets the requirement.



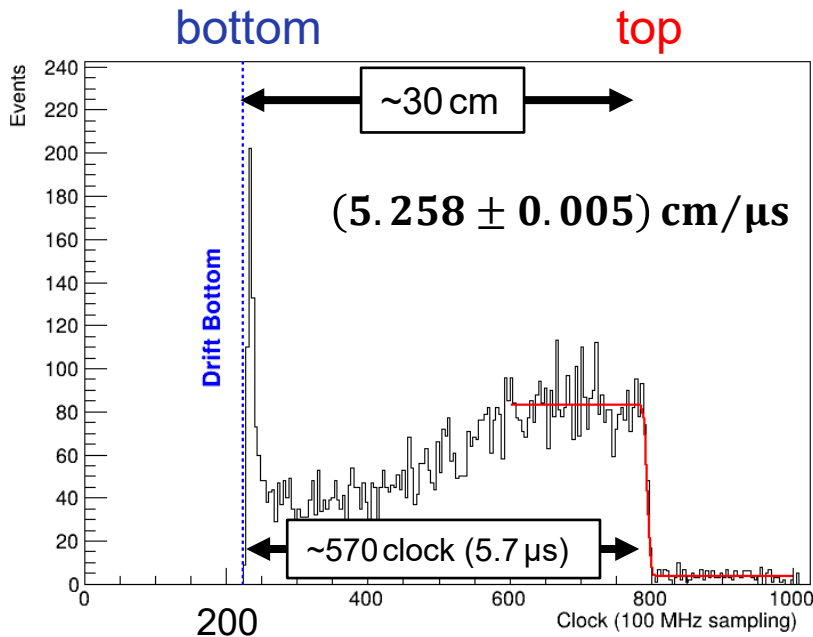
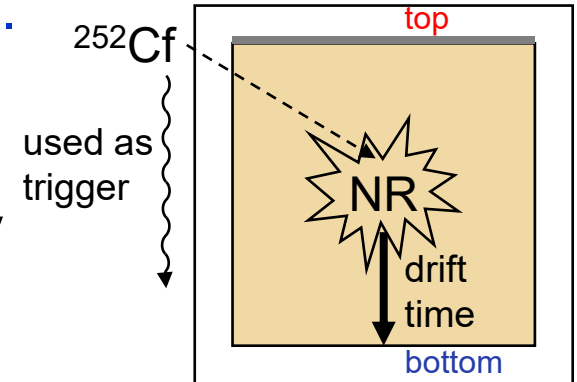
Detector Performance

Parameter	Measured	Required
Gas gain	2.8×10^4	$> 10^4$
Energy resolution	33% @3 keV	60% @3 keV
Drift velocity	5.3 cm/ μ s	> 4.0 cm/ μ s

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⊙ Gaseous TPC is ready!

Neutron beam experiment

Experiment overview

November, 2025@AIST, Japan

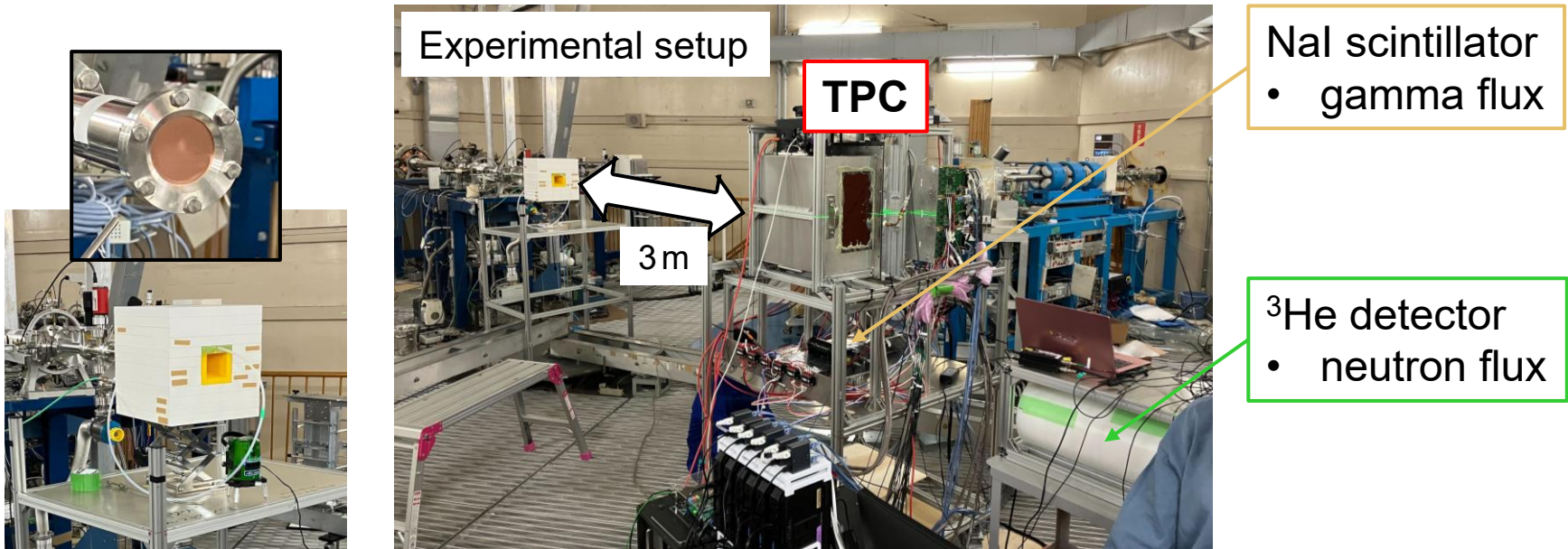
- Neutron beam: ${}^7\text{Li}(p,n){}^7\text{Be}$ reaction (565 keV)
- LiF loaded (50%) polyethylene shielding
 - avoid laboratory (n, γ) BGs
- Detectors are calibrated before / after physics run.

Experimental Parameters

Live time: 1105 sec

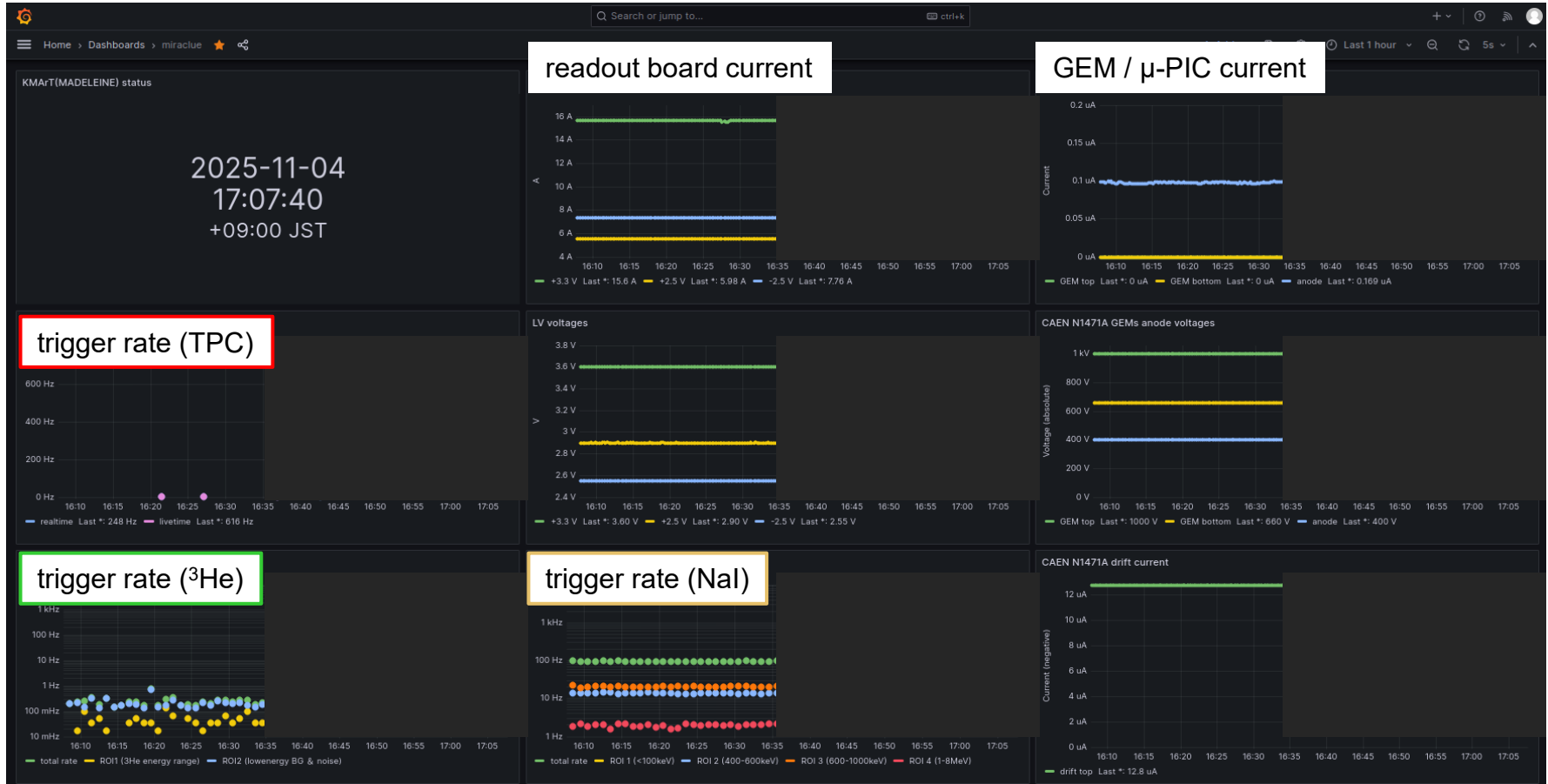
Incident: $\sim 10^9$ neutrons

Triggered: $\sim 10^6$ events



Data-taking (Monitoring)

The DAQ status was monitored using **Grafana**.



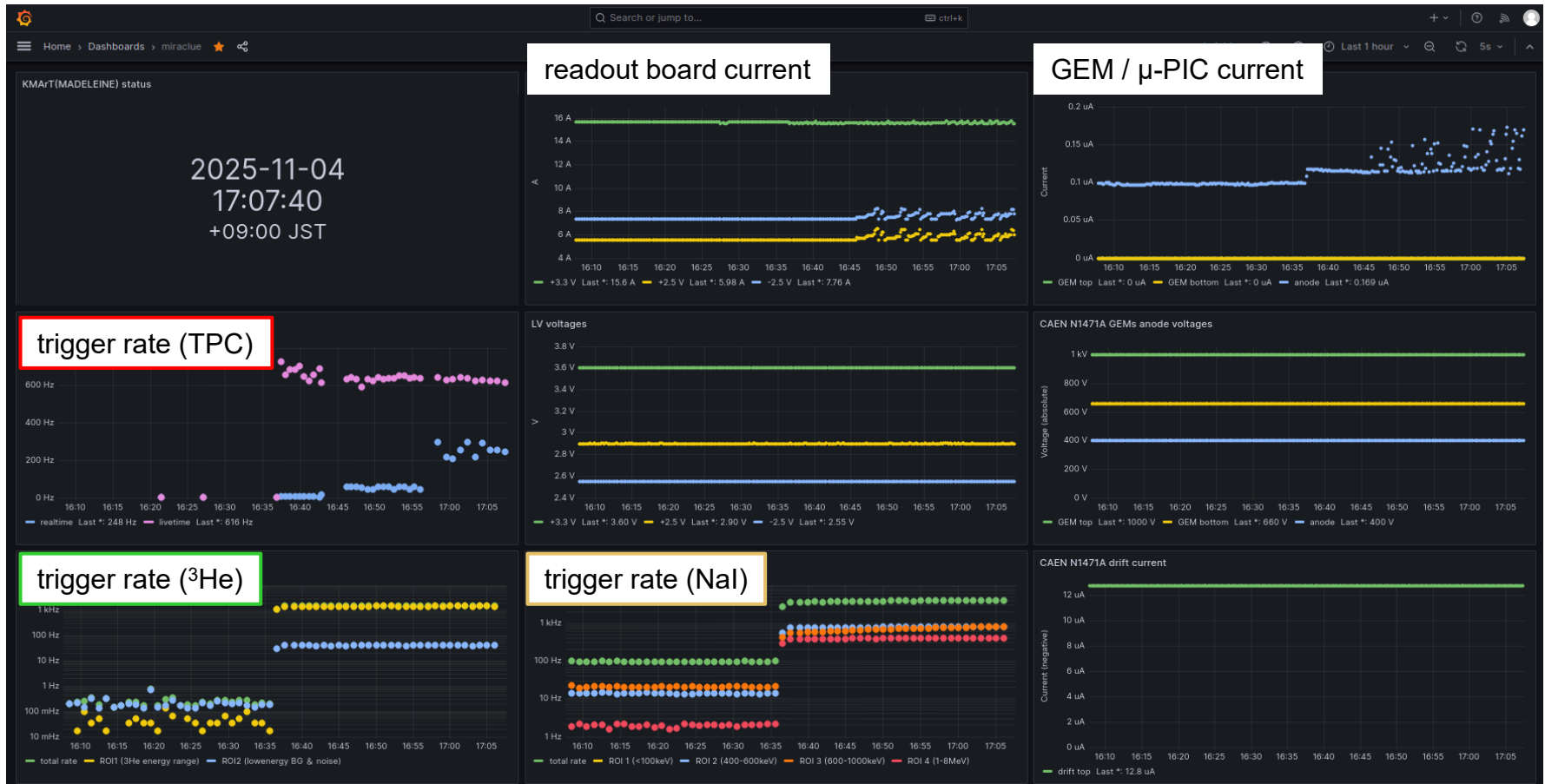
beam OFF

beam OFF

beam OFF

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beam OFF

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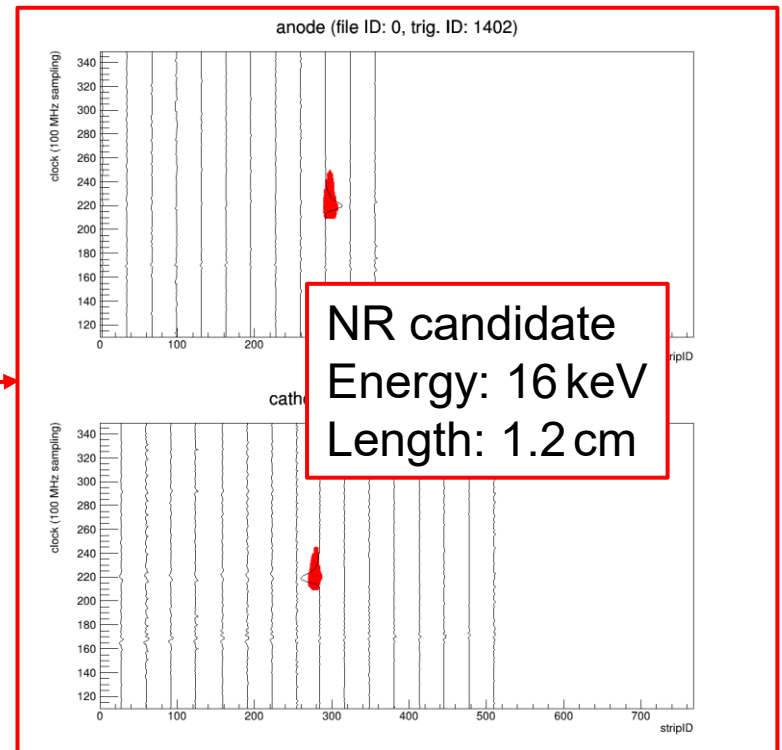
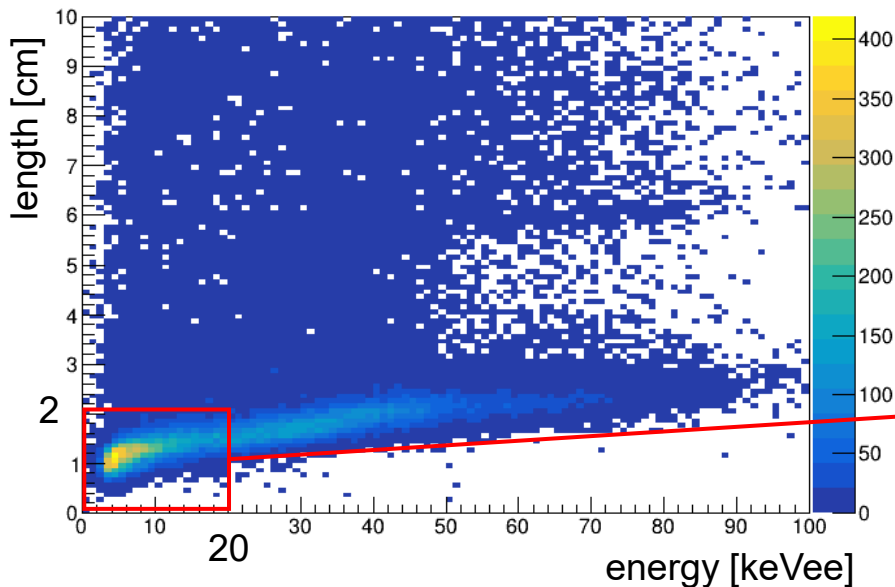
beam OFF

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Data-taking (Quality check)

Quick analysis using partial data

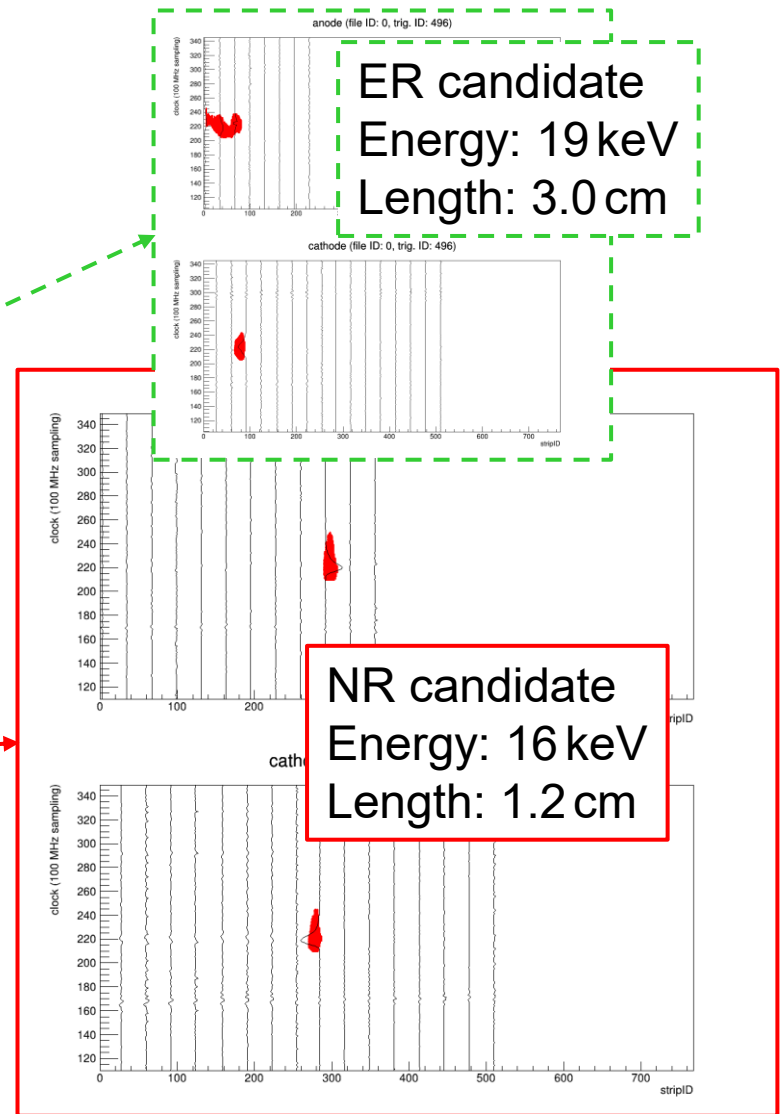
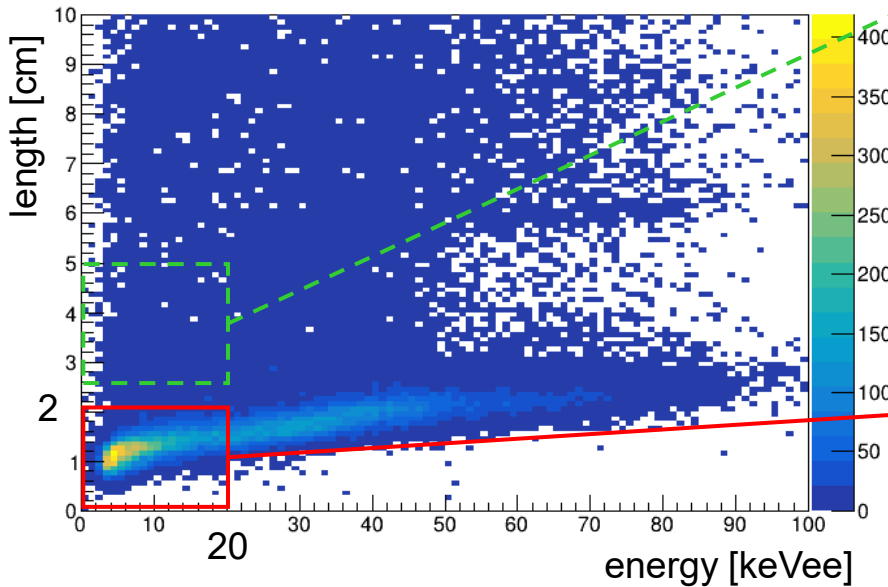
- NR candidates are observed.
- Track length can separate NR / ER.



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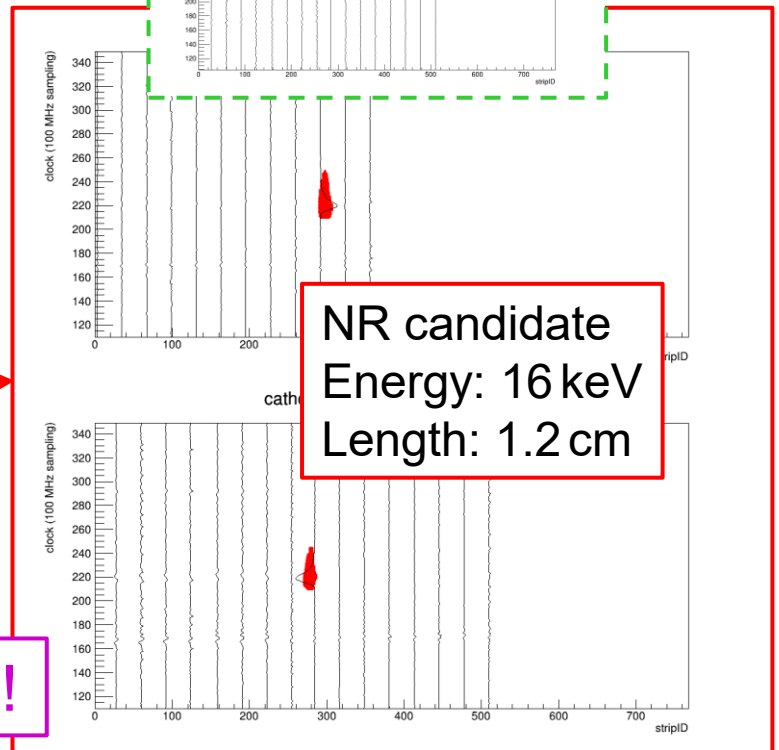
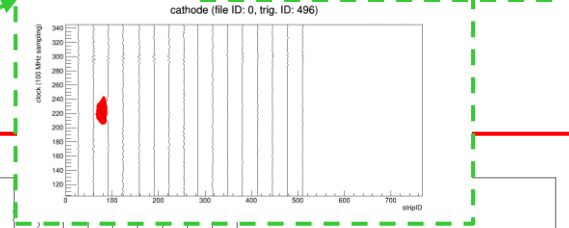
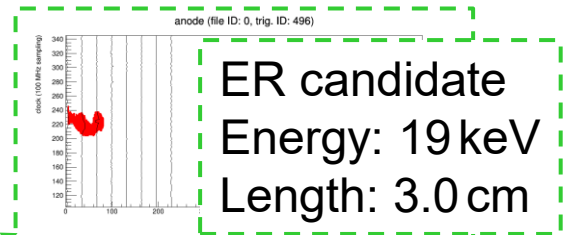
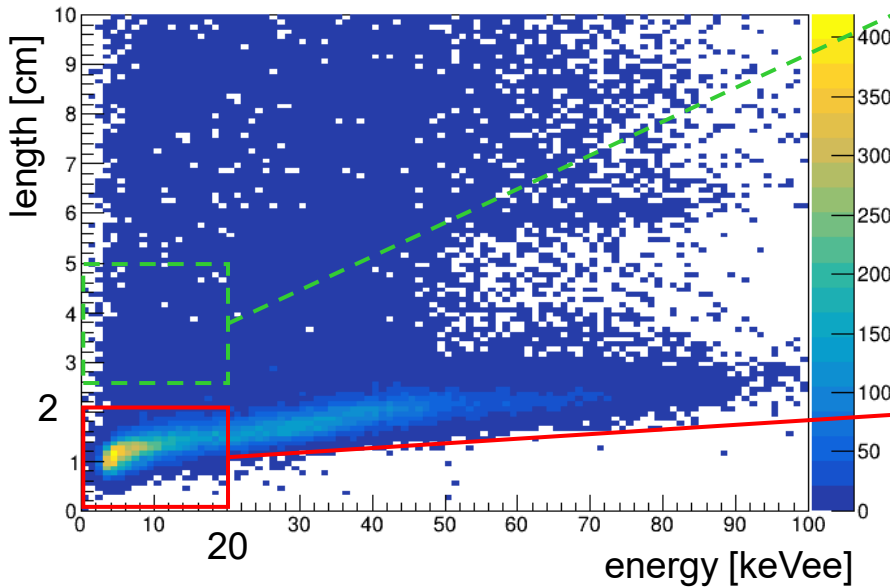
- NR candidates are observed.
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Data-taking (Quality check)

Quick analysis using partial data

- NR candidates are observed.
- Track length can separate NR / ER.



⊙ proper data-taking is confirmed!

Analysis

The way to derive branching ratio

In this analysis, branching ratio is calculated as follows.

$$BR = \frac{\text{Migdal event candidates}}{\text{Ar nuclei recoil events}}$$

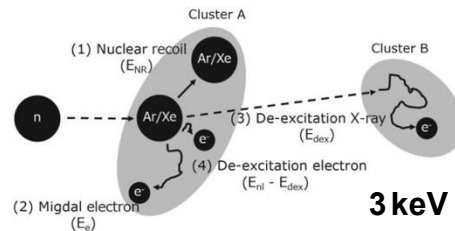
(K-shell)

① Ar nuclear recoil events (N_{Ar})

- The following BG events need to be subtracted.
 - Non-Ar nuclear recoil events (N_{HCF})
 - The number of events induced by gamma ray (N_{γ})

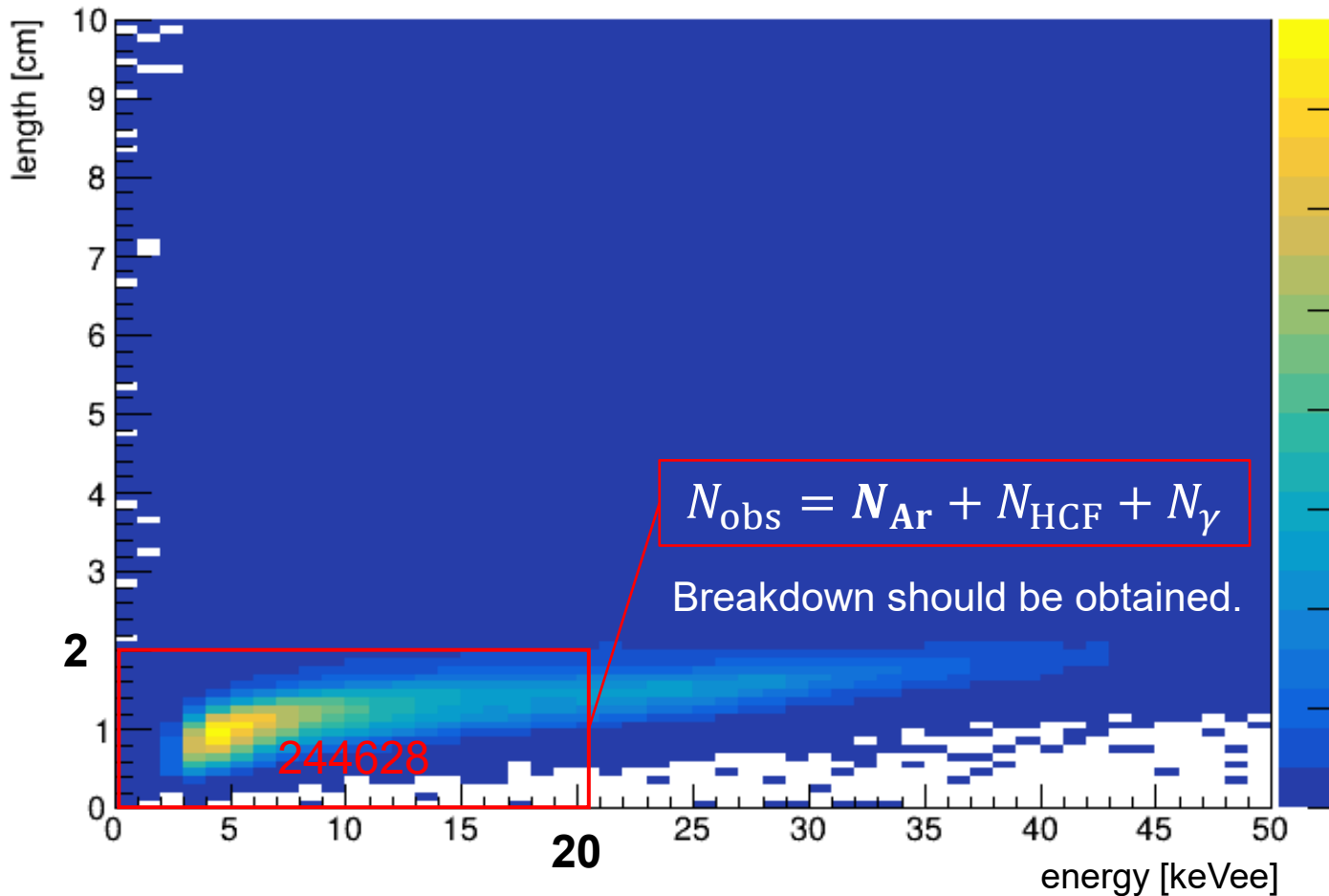
② Migdal event candidates (N_{sig})

- 2-cluster events with the energy of the characteristic X-ray



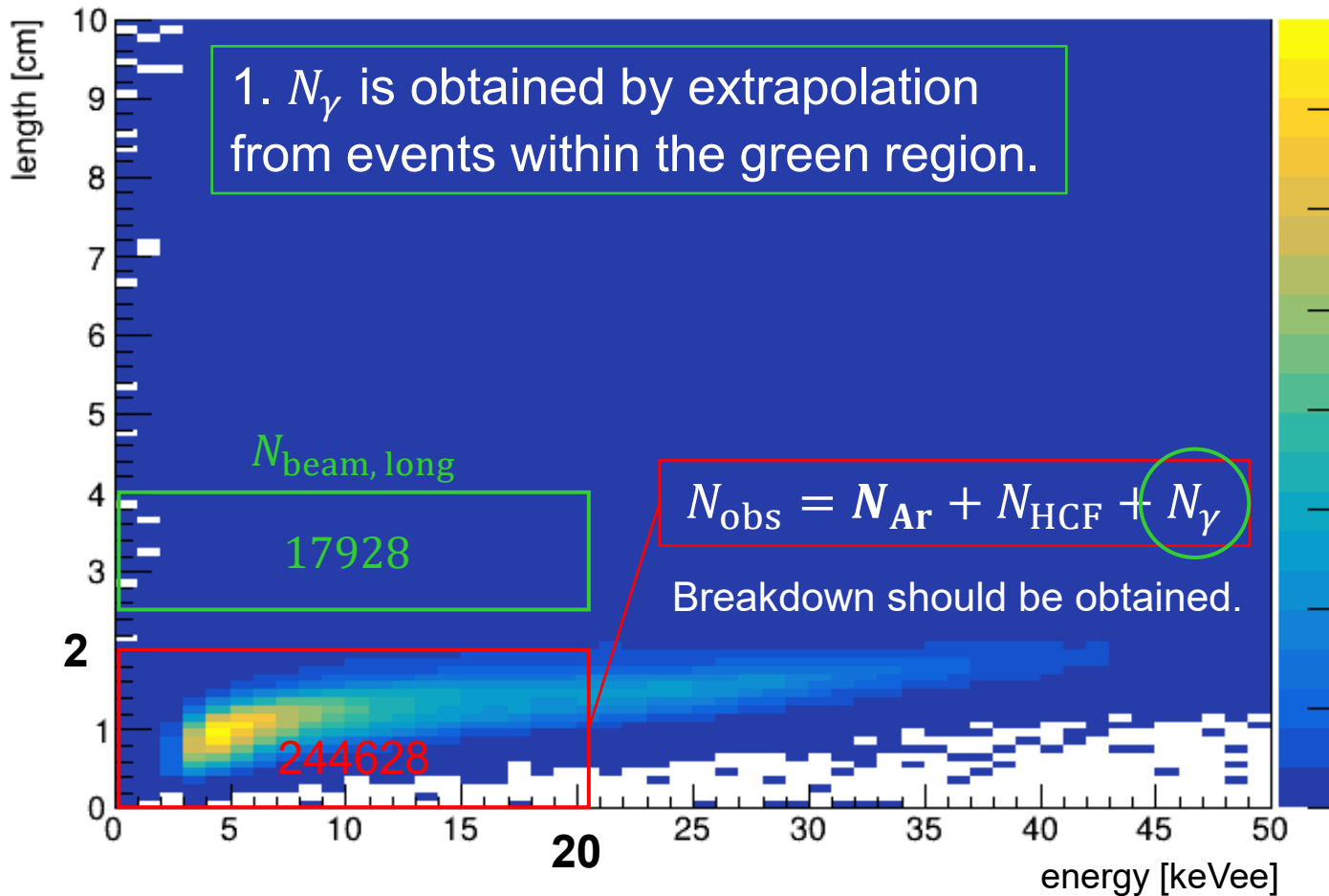
N_{Ar} estimation

- ROI (Region of Interest):** energy < 20.5 keV and length < 2 cm
- 20.5 keV is the maximum energy detected in Ar nuclear recoil.



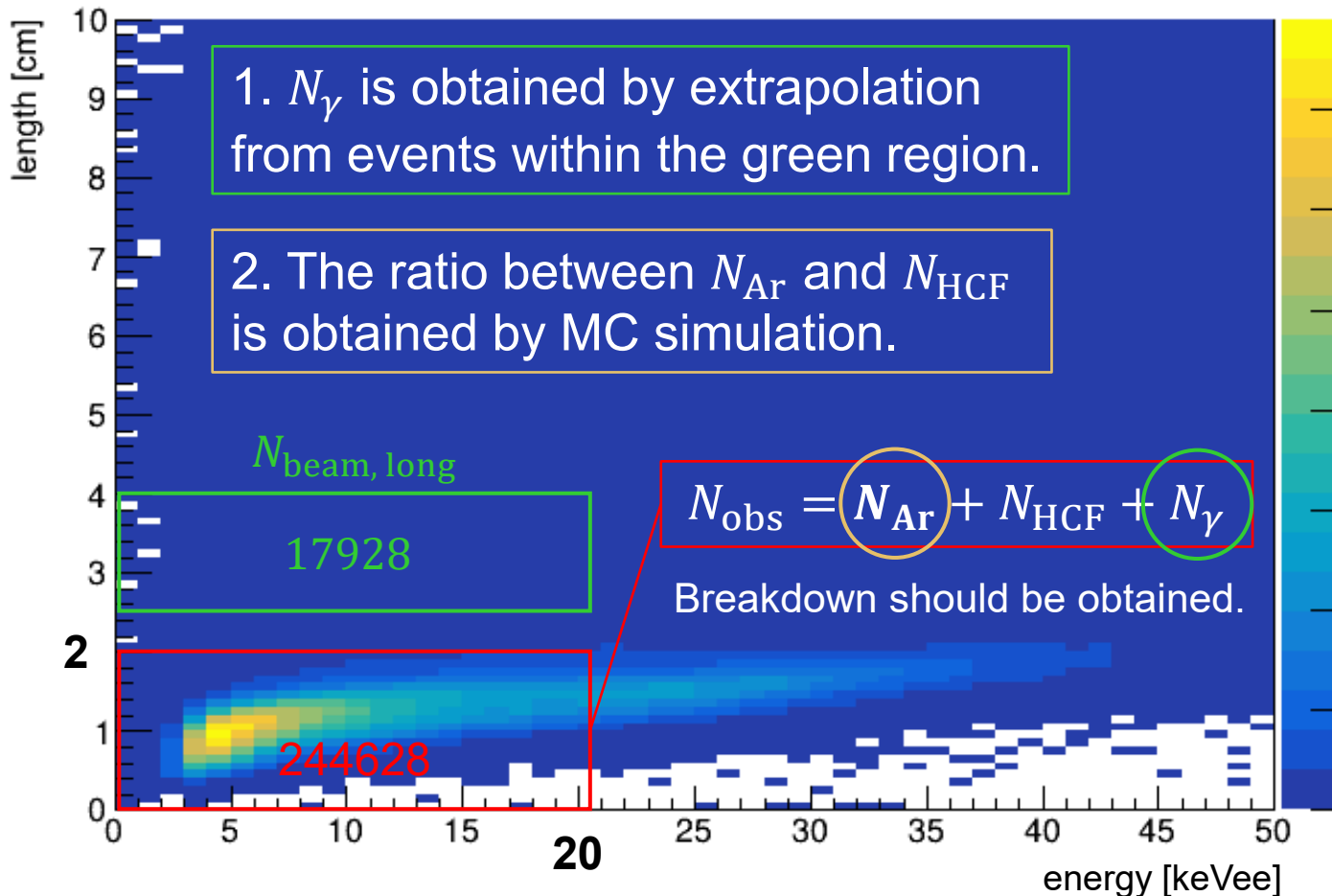
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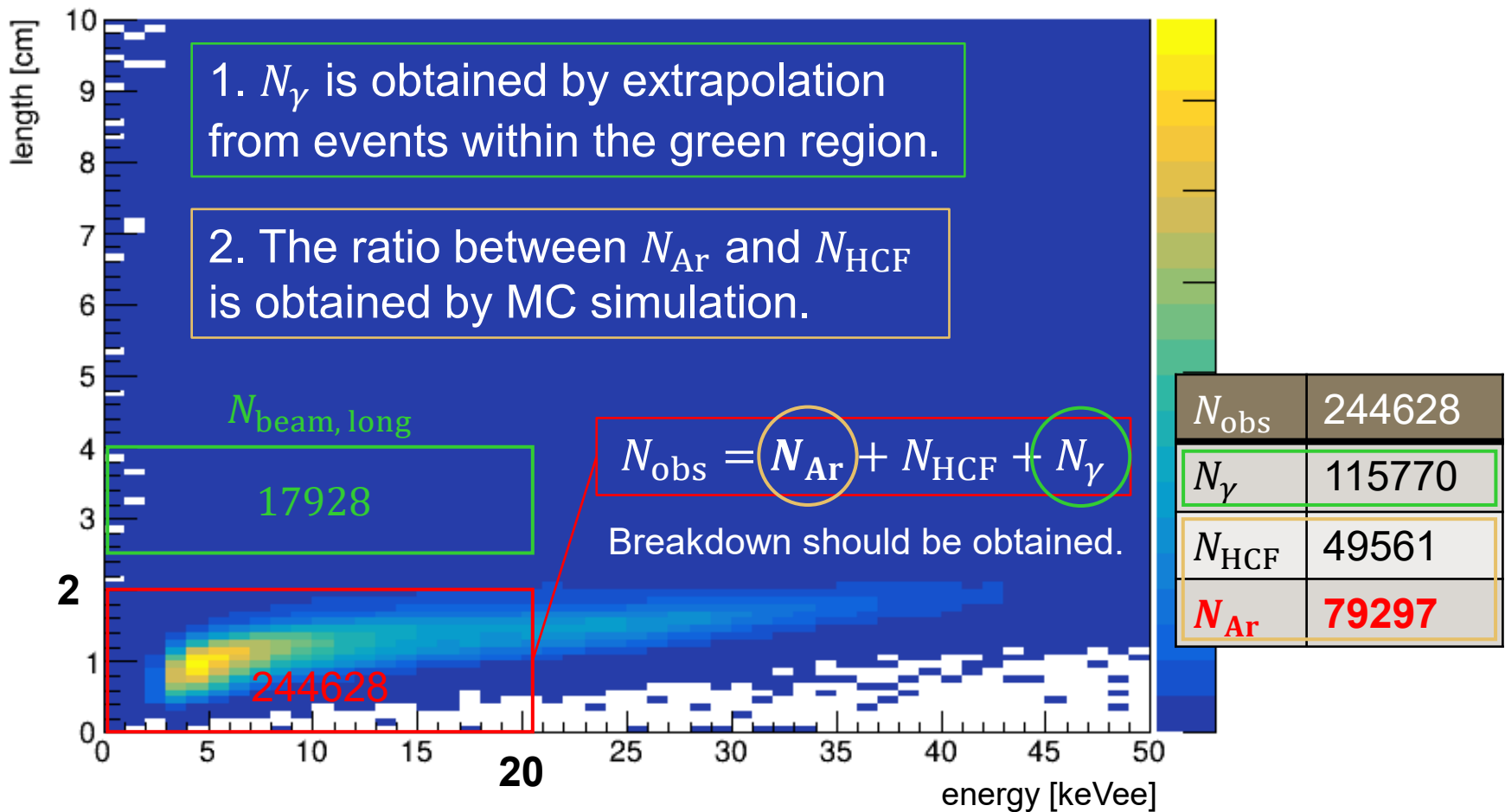
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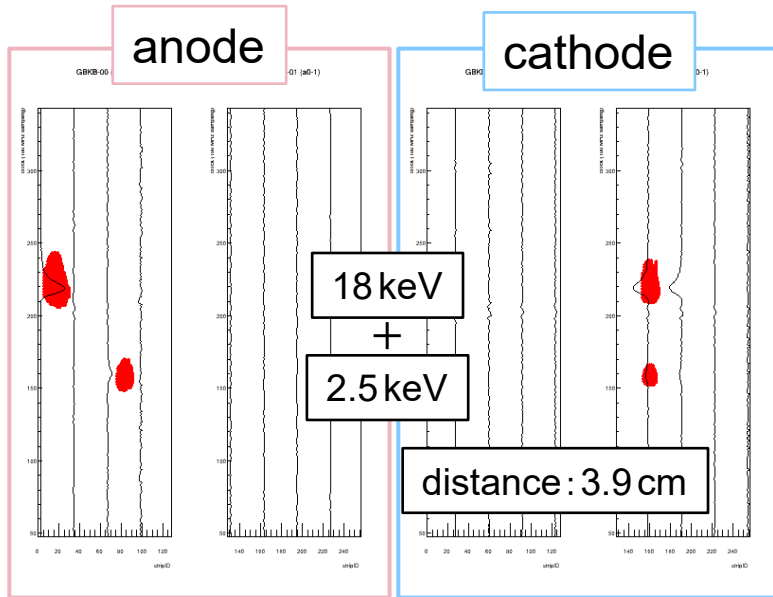
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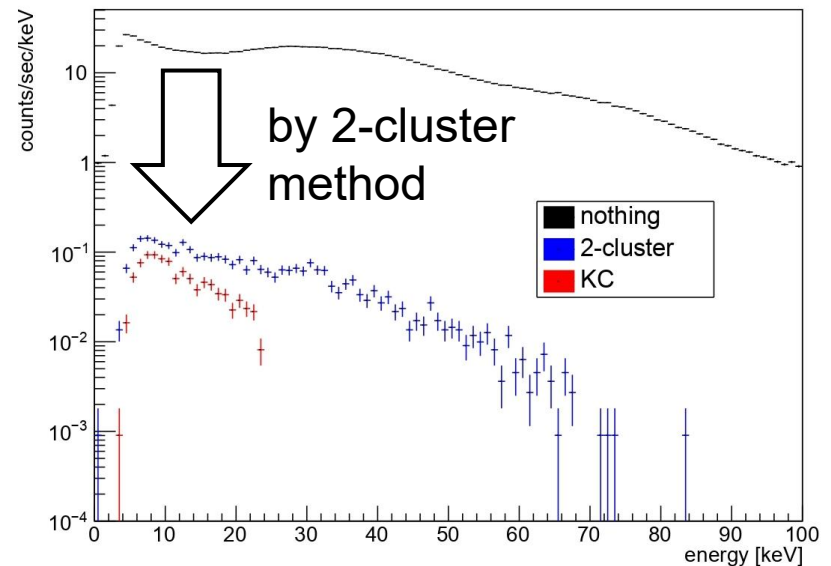
N_{sig} estimation

K-shell Criteria (KC) : requires at least one (3.0 ± 1.5) keV cluster

✘In addition, we require the energies of both clusters be less than 20.5keV.



↑Particular 2-cluster event satisfying KC

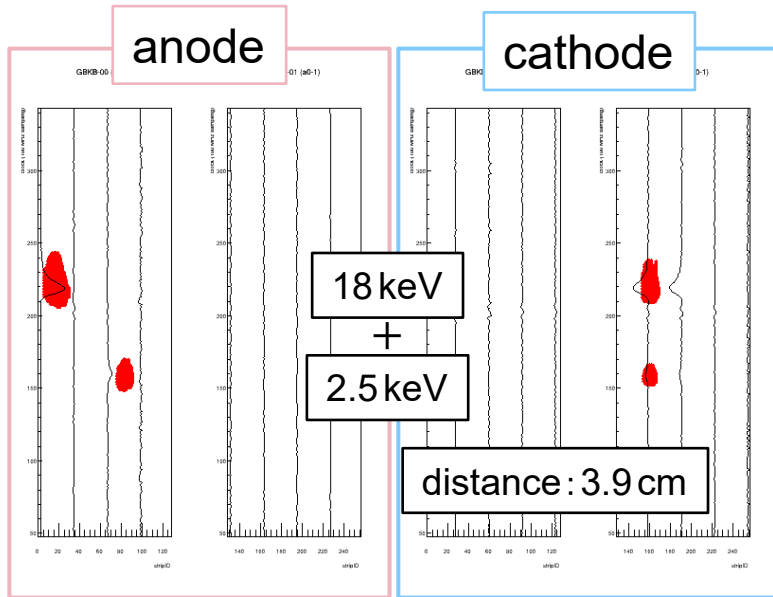


Applied cut	Passed events
Nothing	1.2×10^6
2-cluster	
KC	

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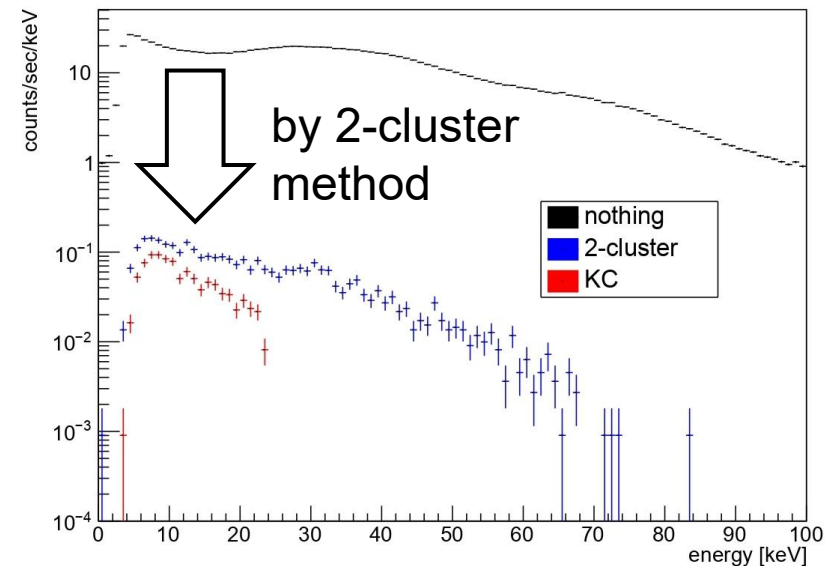
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↑Particular 2-cluster event satisfying KC

◎2-cluster method can reduce BGs by 3 order of magnitudes!



Applied cut	Passed events
Nothing	1.2×10^6
2-cluster	3499
KC	1058

Branching ratio of Migdal effect



Based on the analysis performed so far,

- Ar nuclear recoil events (N_{Ar}) : 7.93×10^4
- Migdal event candidates (N_{sig}) : 1058

preliminary

Theoretical branching ratio is $10^{-5} \rightarrow 1058$ events are thought to be BGs.

The conservative upper limit of branching ratio

$$\bullet BR < \frac{N_{sig} + 1.96\sqrt{N_{sig}}}{N_{Ar}} = \frac{1058 + 1.96 \times \sqrt{1058}}{7.93 \times 10^4} = 1.4 \times 10^{-2}$$

(95% confidence level)

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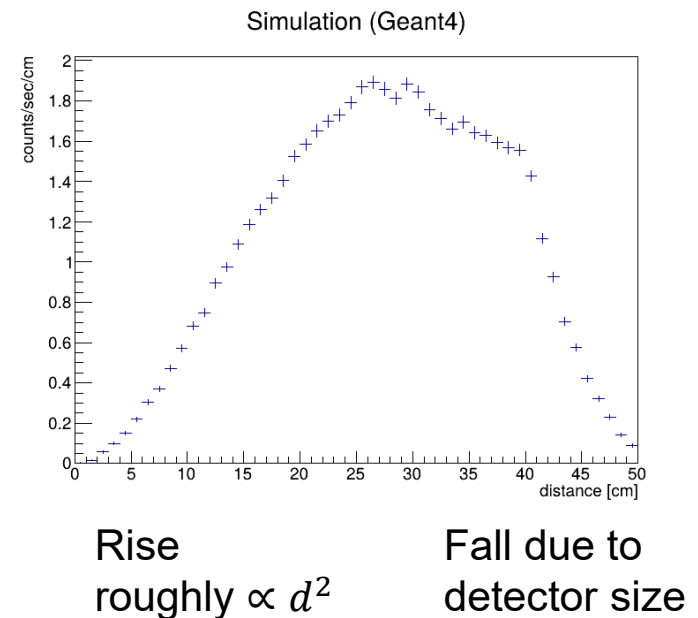
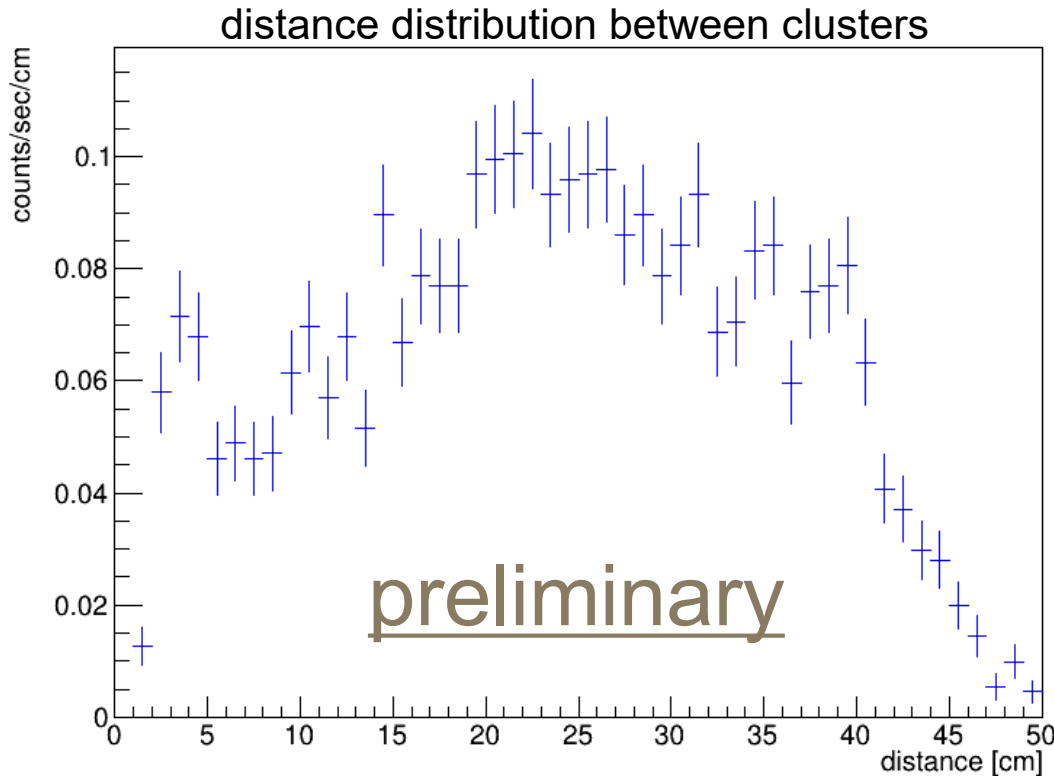
© first constraint with an argon target.

(Further BG study is needed to observe Migdal effect.)

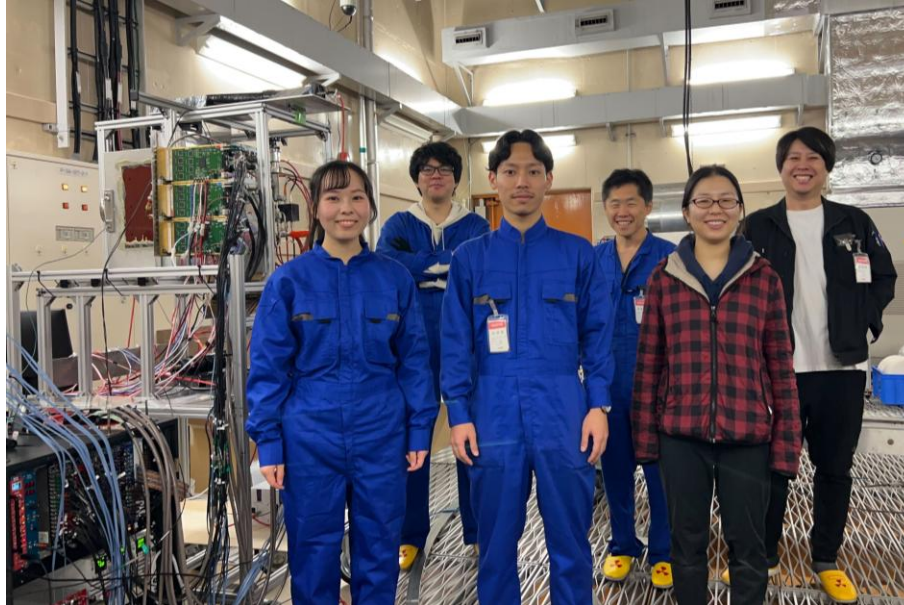
2-cluster Backgrounds

Discrimination of 2-cluster BGs is essential.

- Accidental coincidence events are thought to be dominant because of the shape of distance distribution.
- The contribution of gamma BGs should also be estimated.



- MIRACLUE: Migdal effect search for low-mass WIMP search
 - BGs are discriminated using 2-cluster method with a gaseous TPC.
- We conducted neutron beam experiment in Nov, 2025.
 - Data for the Migdal effect search were successfully obtained.
- An upper limit of 1.4×10^{-2} was set on the branching ratio.
 - This is the first constraint with an argon target.



Backup

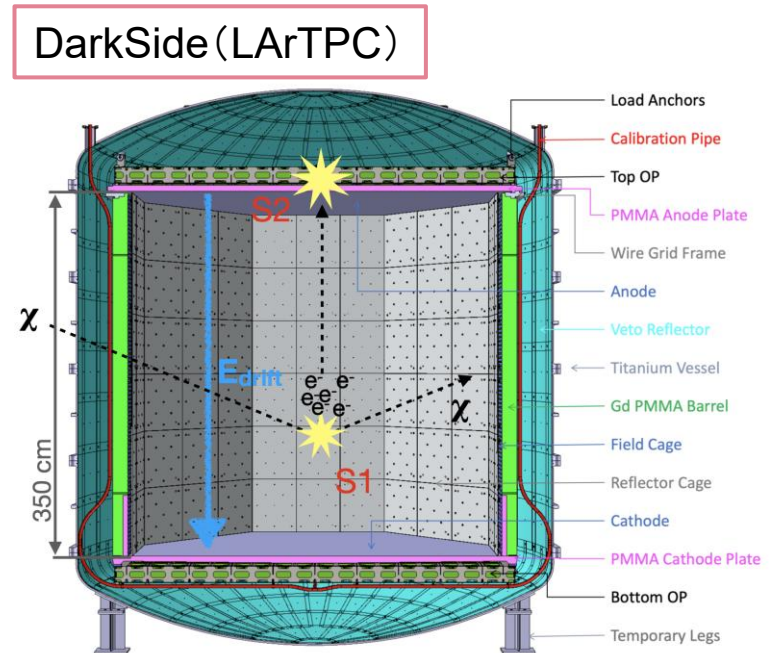
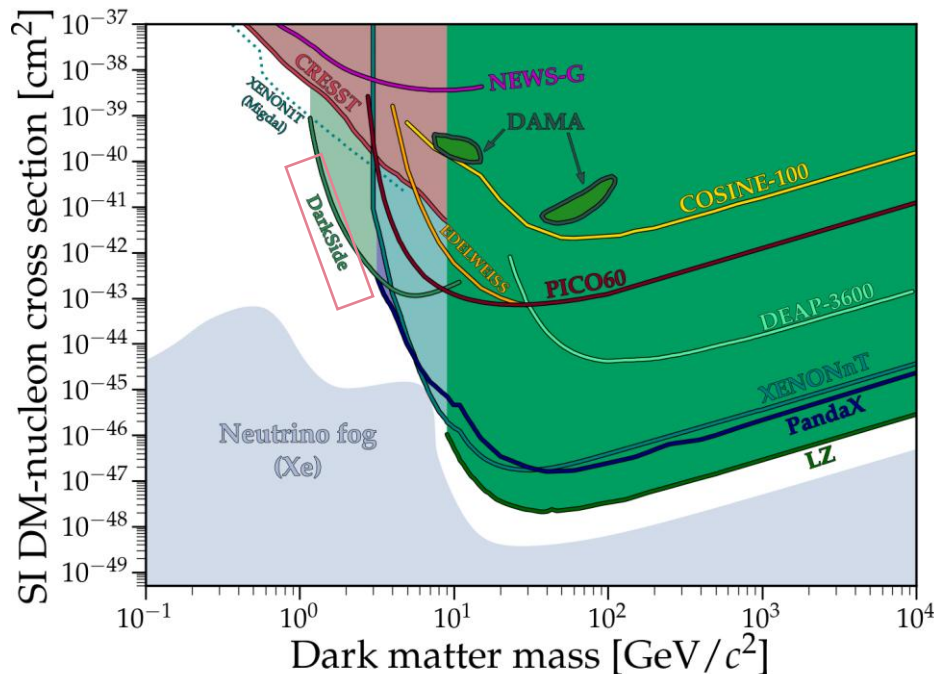
WIMP direct search

DM has been suggested by various observations.

- One of the leading candidates is WIMP

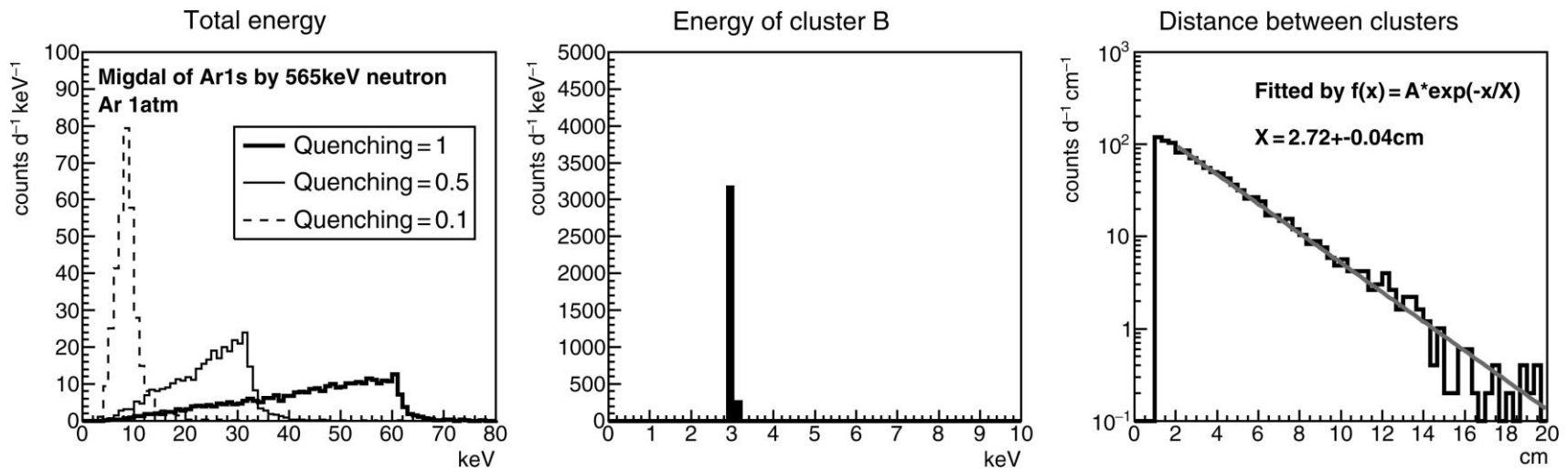
In direct search, we observe scattered nucleus by WIMP.

- In spite of high-sensitivity search using liquid noble gas, no significant excess is observed so far.



Signal simulation

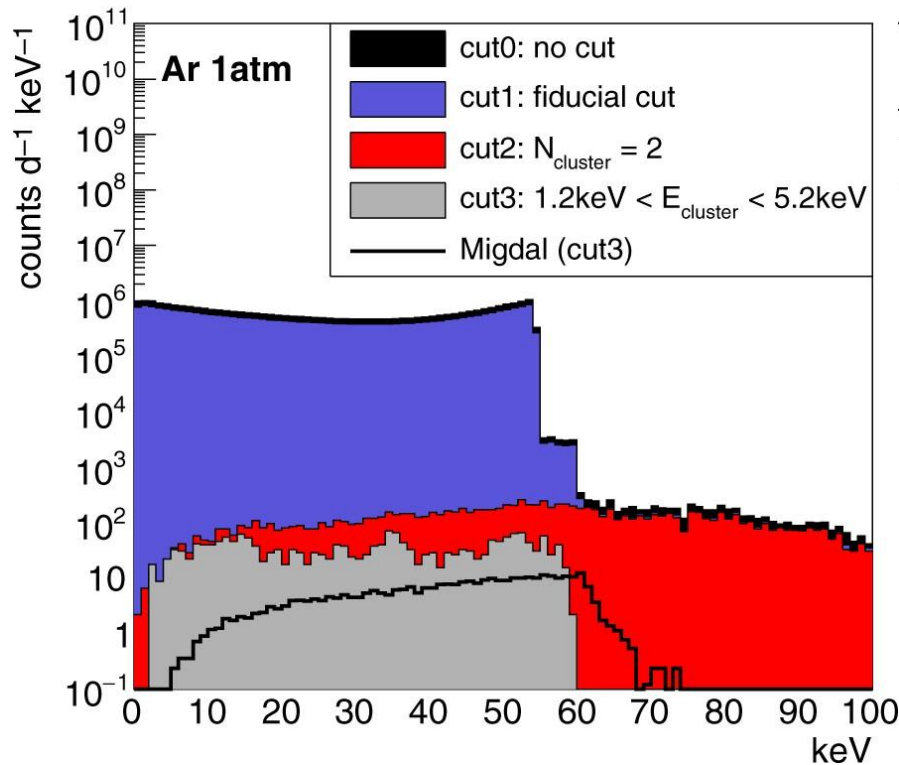
Prog. Theor. Exp. Phys. 2021, 013C01



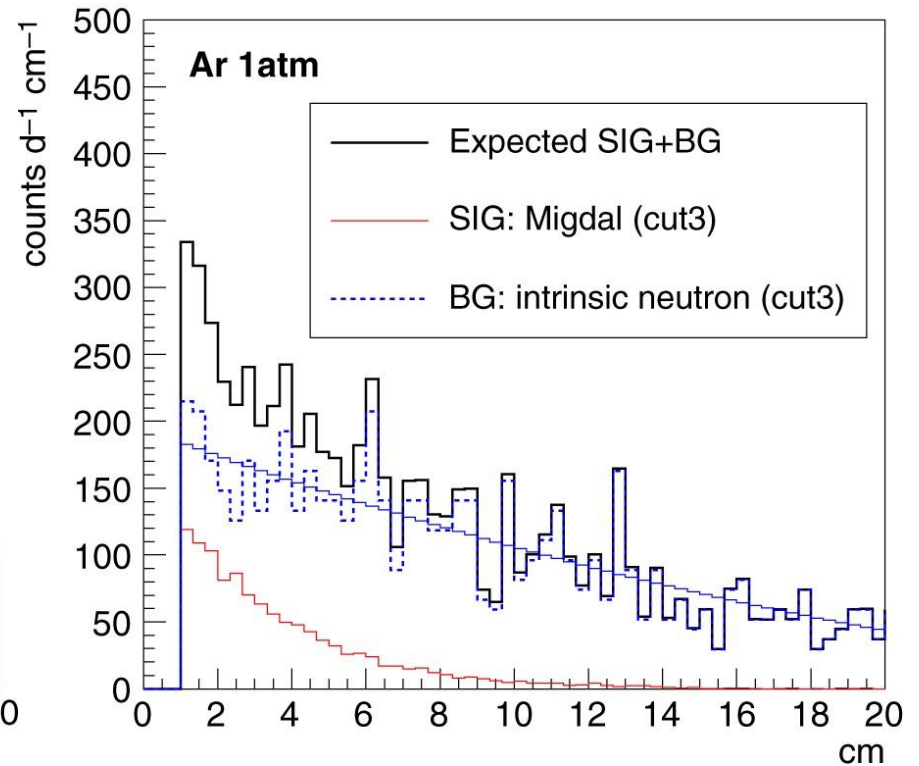
BG discrimination from signal

Prog. Theor. Exp. Phys. 2021, 013C01

Intrinsic neutron BG



Distance between clusters



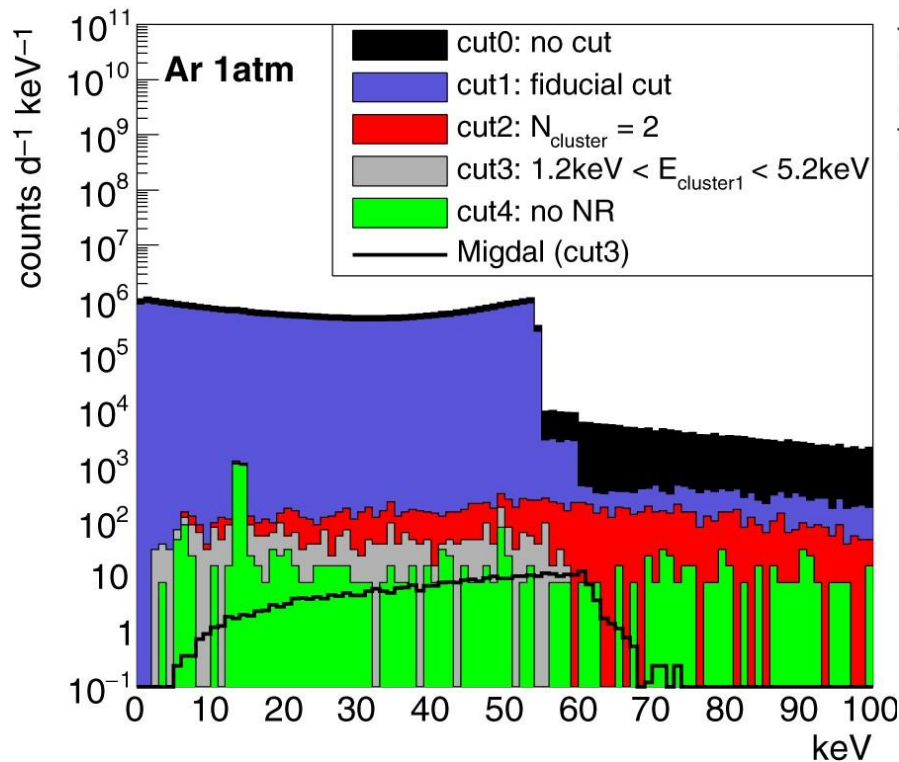
(n, γ) BG estimation

Prog. Theor. Exp. Phys. 2021, 013C01

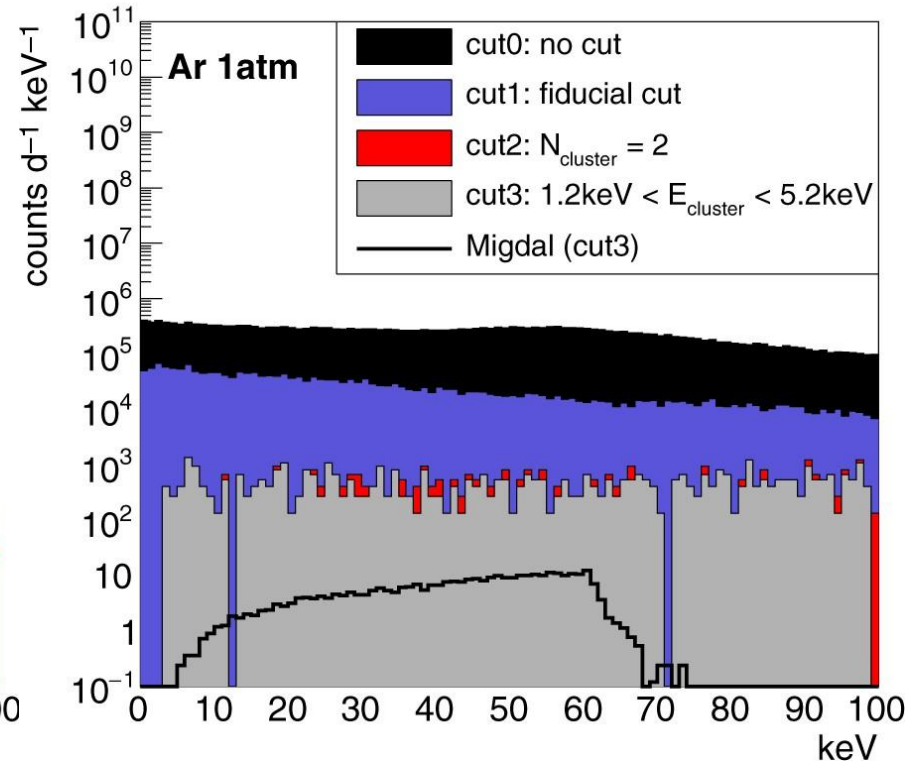
Can be reduced by using proper material for assembling a chamber

Can be reduced by shielding

Chamber (n, γ) BG + neutron BG

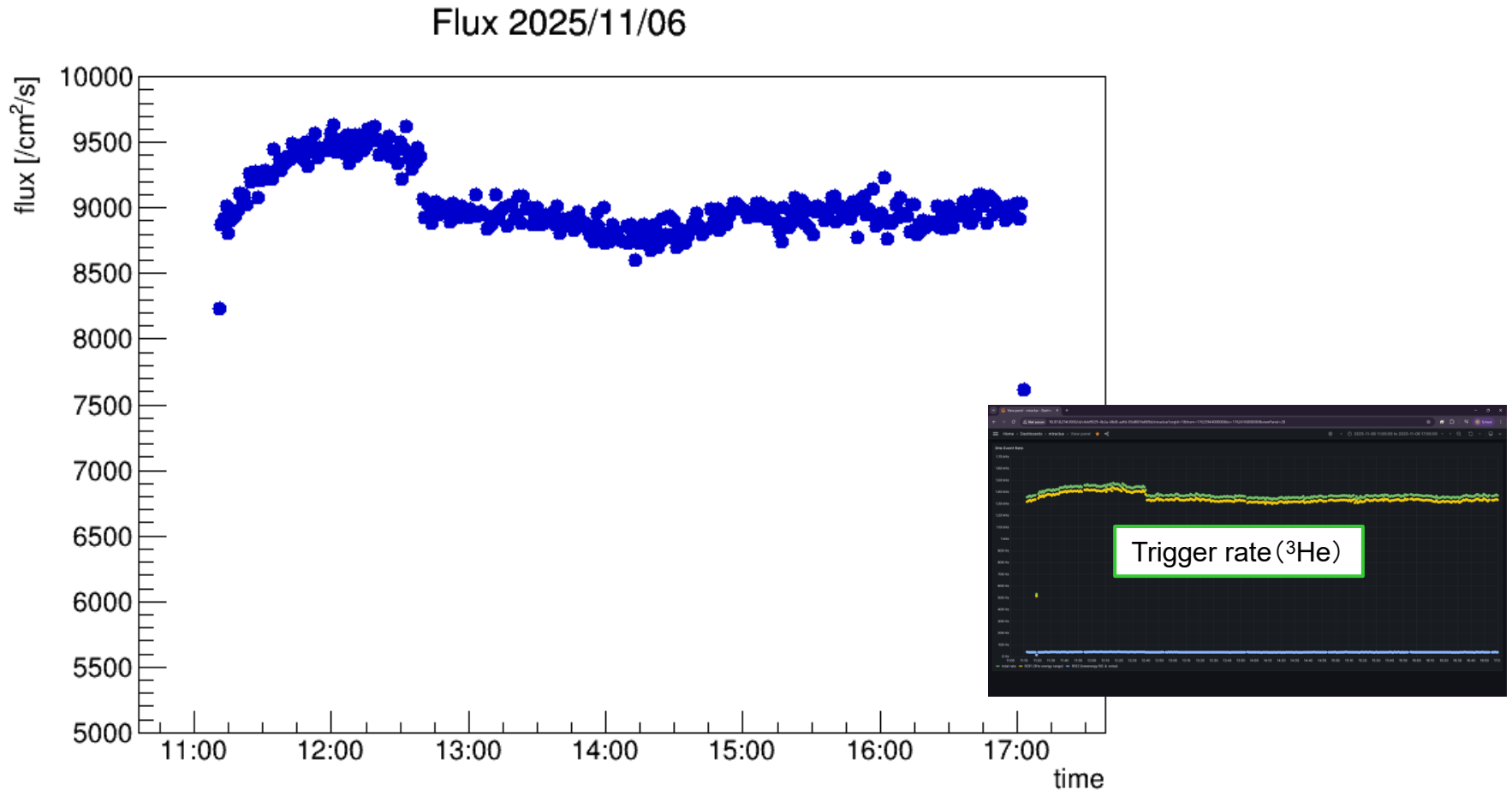


Laboratory (n, γ) BG



Neutron beam flux

Average: $(9034 \pm 227) \text{ cm}^{-2}\text{s}^{-1}$ @1m



2-cluster analysis

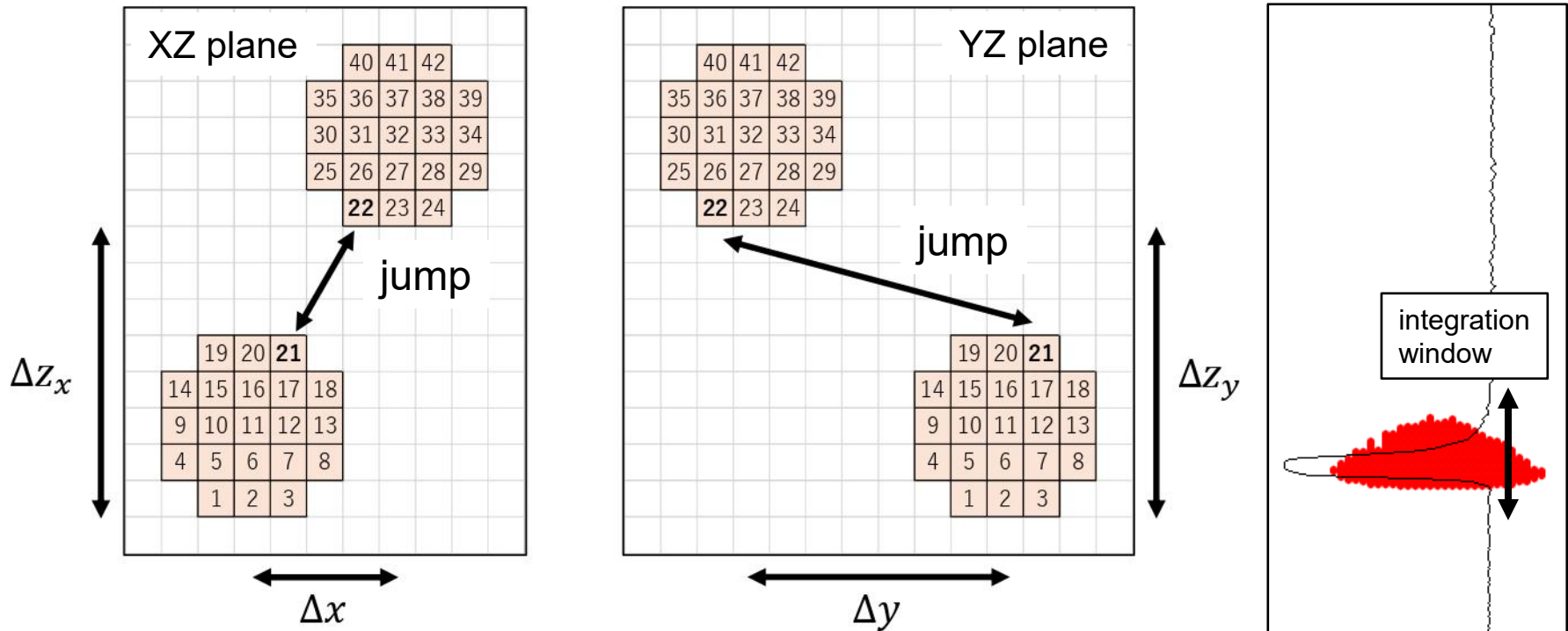
Search for events which have single “jump”

- Calculate distance using hit information.

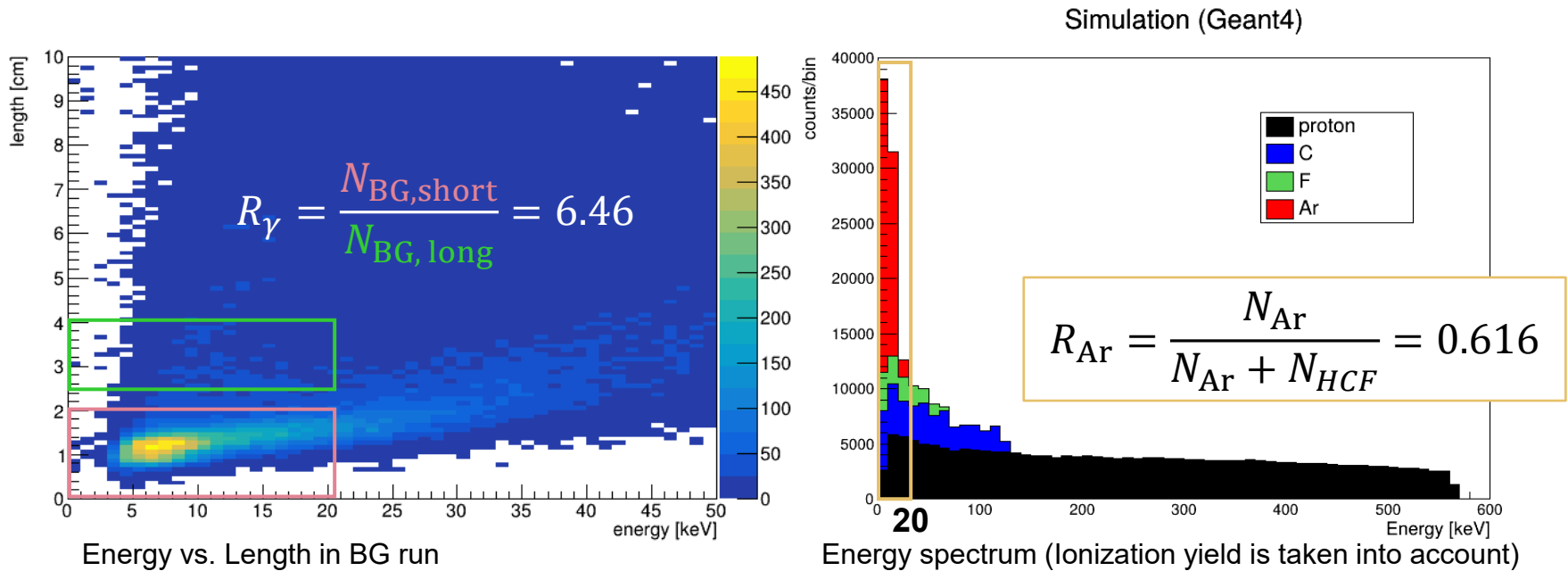
$$d = \sqrt{(\Delta x)^2 + (\Delta y)^2 + \left\{(\Delta z_x + \Delta z_y)/2\right\}^2}$$

- Calculate energy of each cluster by waveform integral.

jump threshold
longitudinal: 1 clock
X/Y: 1.28 cm



Evaluated gamma effect using BG run.



$$N_\gamma = N_{\text{beam,long}} \times R_\gamma = 17928 \times 6.46 = 115770$$

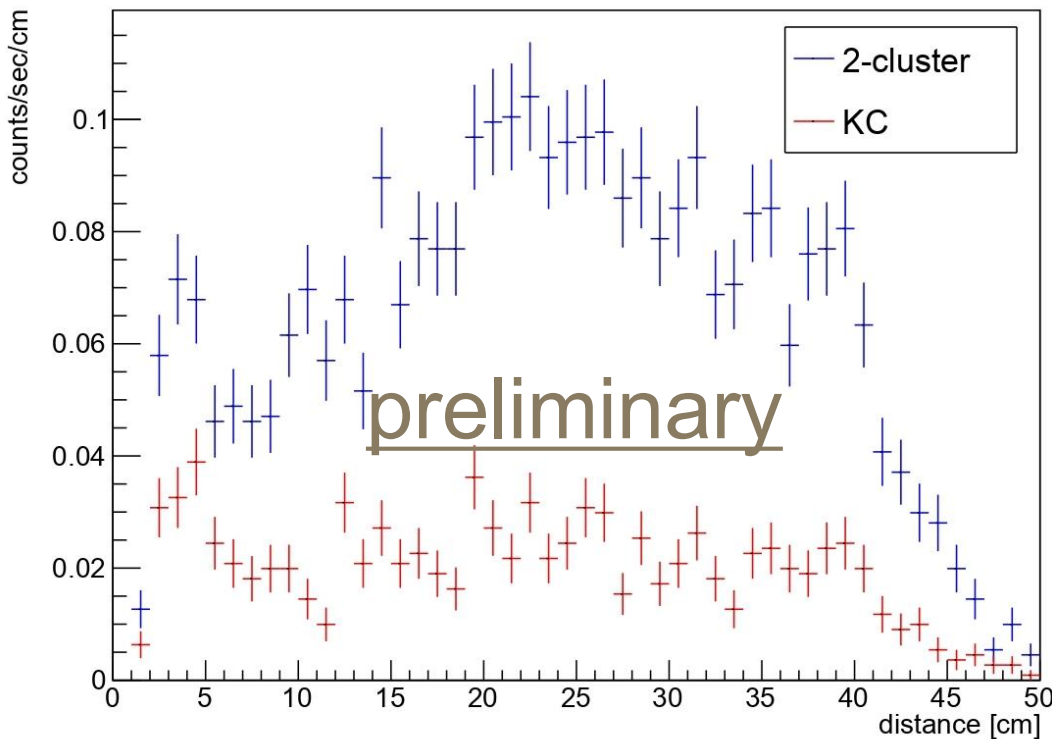
- Assumption: R_γ is equal in BG run and beam run.

$$N_{\text{Ar}} = (N_{\text{obs}} - N_\gamma) \times R_{\text{Ar}} = (244628 - 115770) \times 0.616 = 7.93 \times 10^4$$

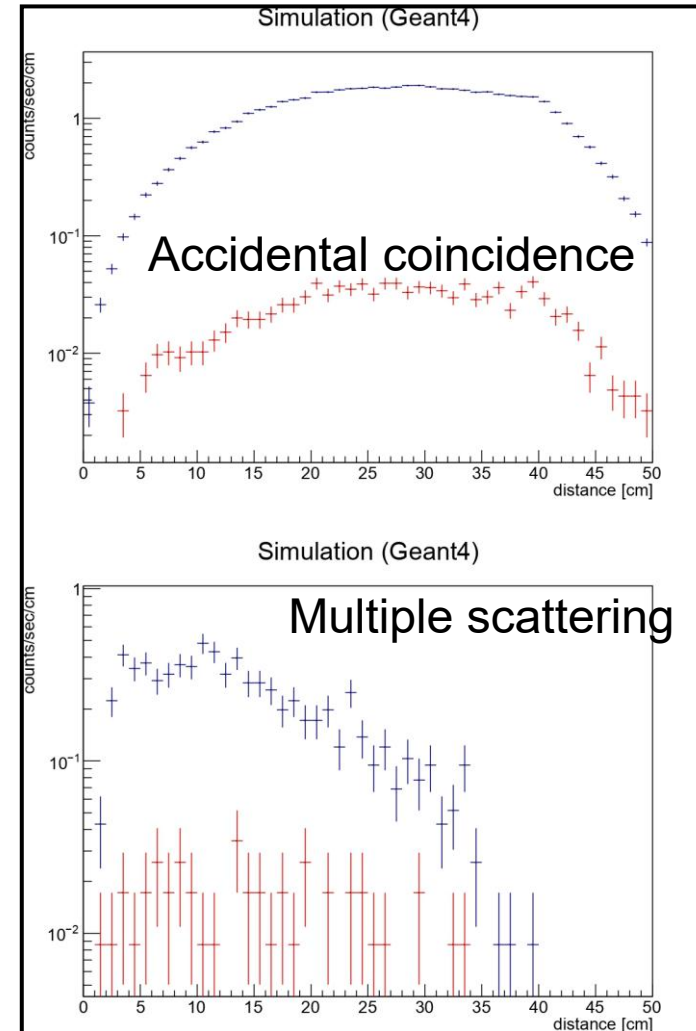
2-cluster Backgrounds

The distance distribution of the events satisfying KC is not totally understood.

- Accidental coincidence + ??
 - Multiple scattering, gamma BGs, ...



Simulation

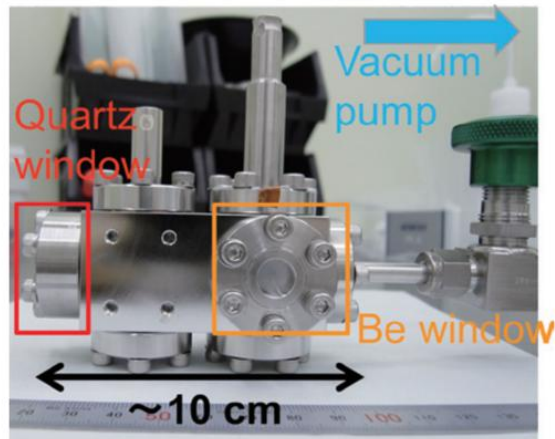


Portable X-ray source

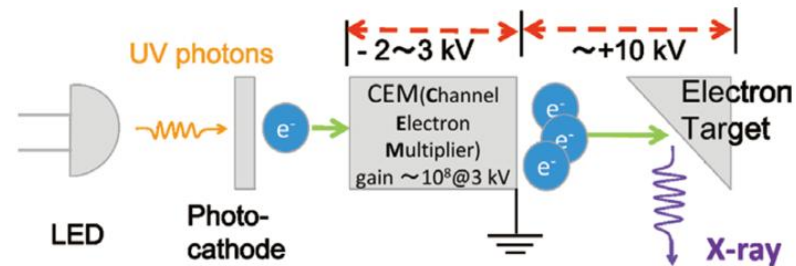
Kentaro's slide in MPGD 2025 workshop

- MXS

- 小型(ICF34のCUBE × 2unitサイズ)のX線源
- UV (外部LED) → 光電面 (MgO) → 電子加速 (CEM) → ターゲット (Ti)



W.B.Iwakiri, et.al,
RIKEN Accel. Prog. Rep. 48 (2015)



W.B.Iwakiri, et.al,
RIKEN Accel. Prog. Rep. 48 (2015)

- UV LEDの照射コントロールでパルス化可能
- (原理的に) ターゲット変更可能

Ionization Quenching Factor

In this analysis, we adopt values obtained by SRIM simulation.

Simulation (SRIM)

