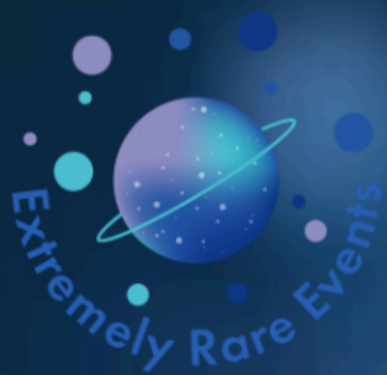




極稀事象で探る宇宙物質の起源と進化

新たな宇宙物質観創生のフロンティア

Direction-sensitive dark matter search using low pressure gaseous detectors

Satoshi Higashino

on behave of NEWAGE collaboration

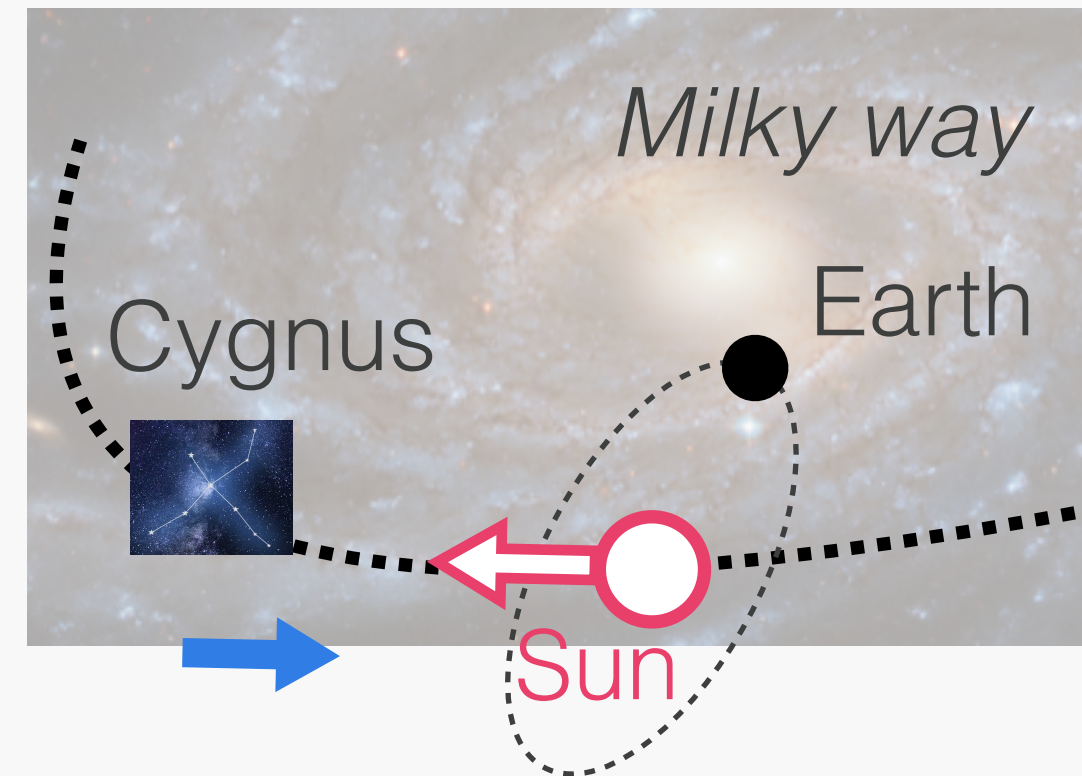
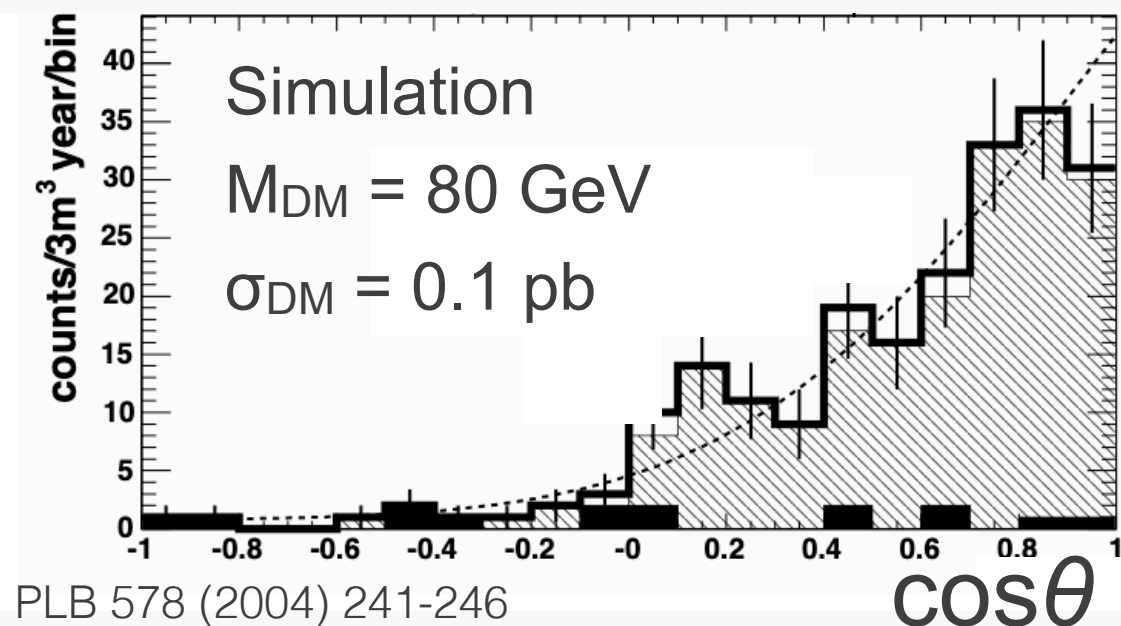
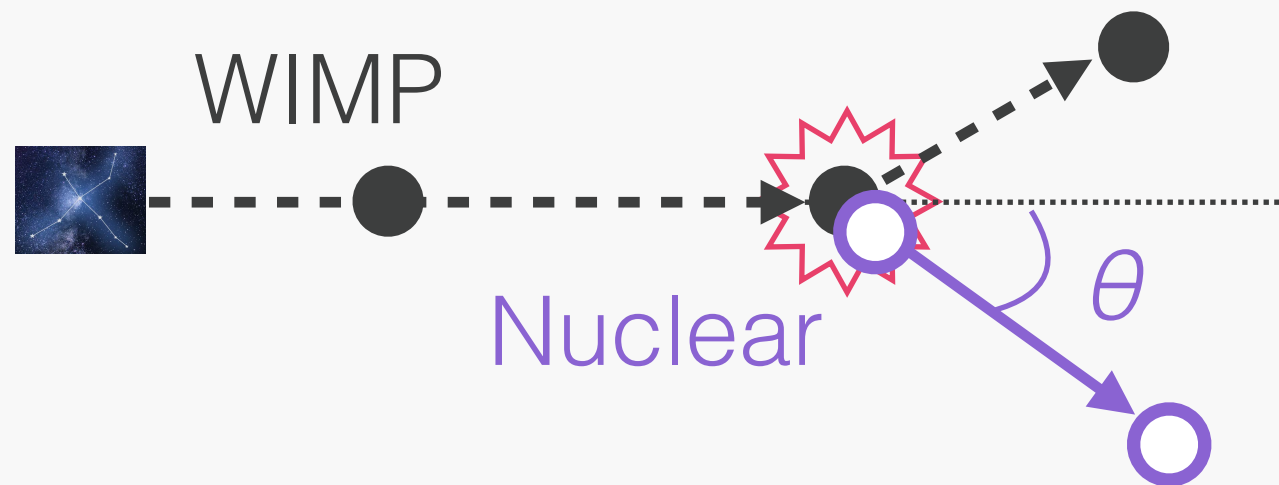
29 / 9 / 2026



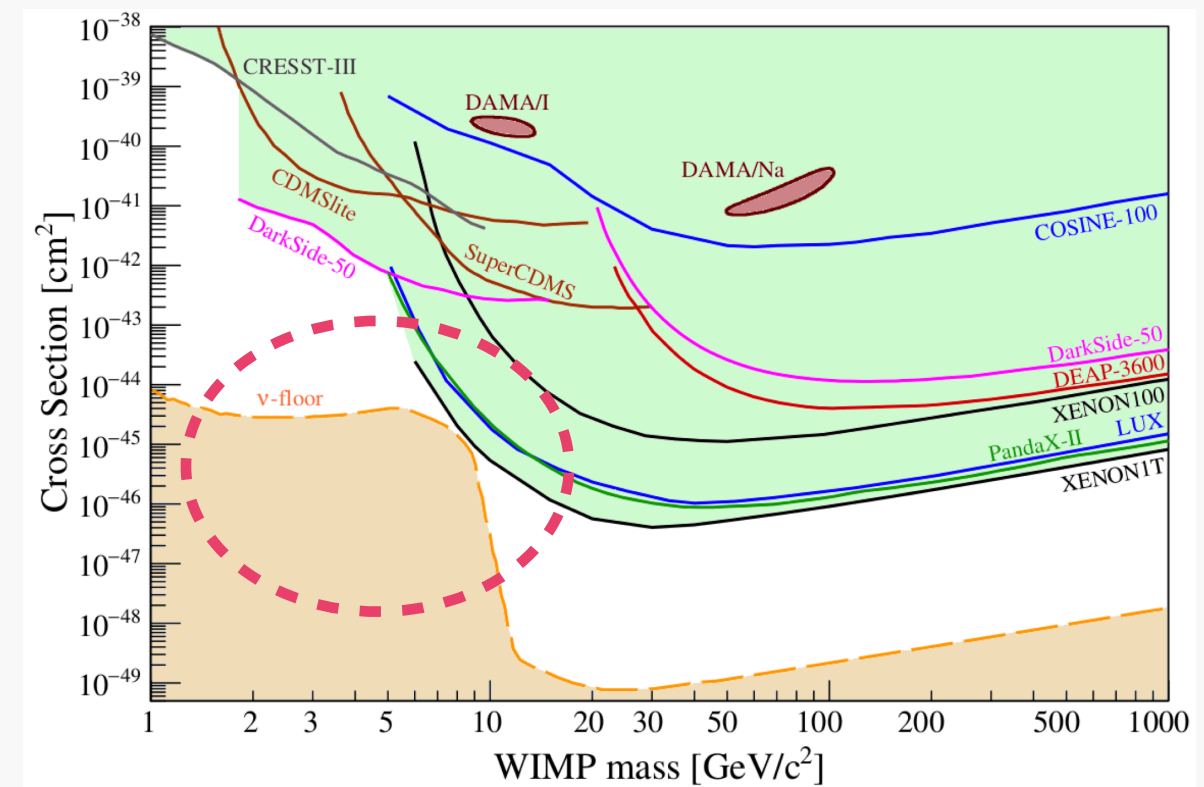
Introduction

Direction-sensitive DM searches

- Detection of scattering angle of nuclear recoils (NR) from the “Cygnus direction”
 - leads a strong signature of WIMP
 - allows to explore beyond the neutrino fog
- Also sensitive for other directional DM candidates such as “CRDM”

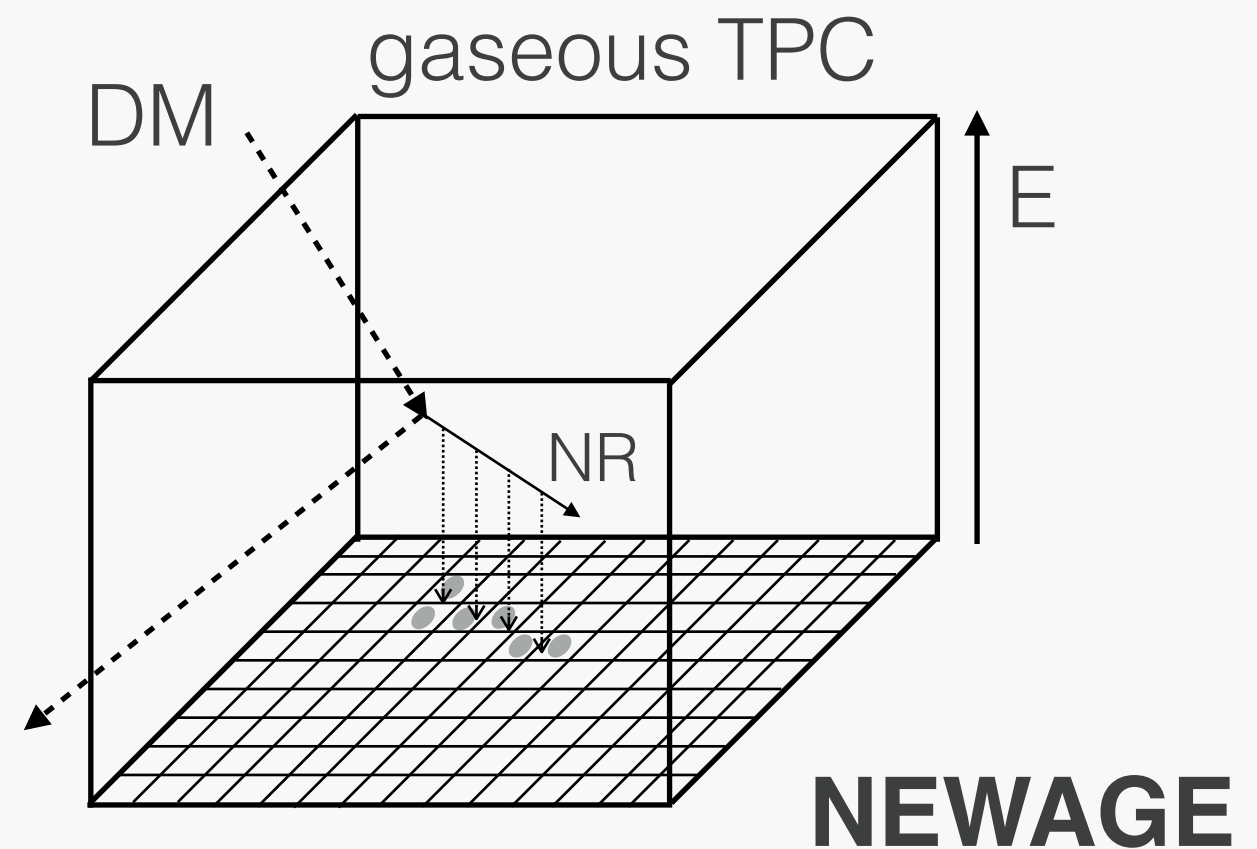
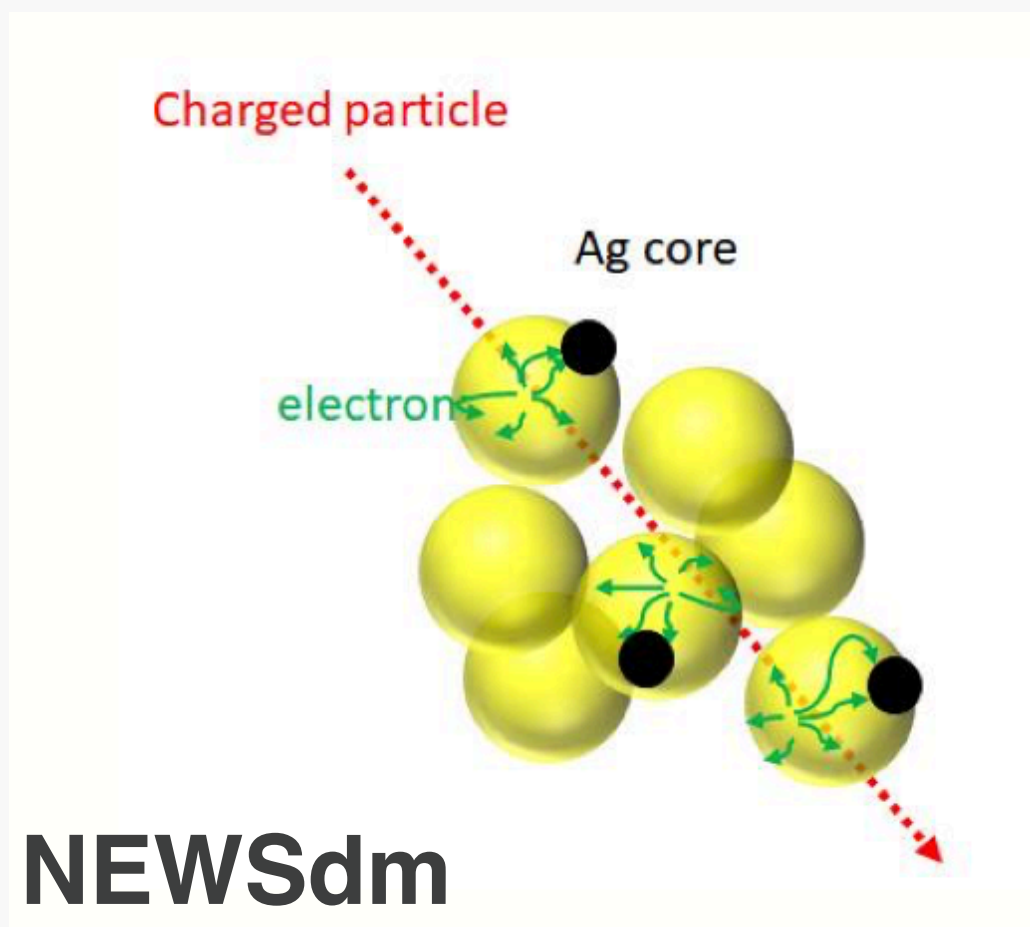


WIMP wind from Cygnus!



Directional search methods

- **Particle tracking** is necessary to measure scattering angle from the Cygnus direction
 - Need to measure < 10 keV nuclear recoil (**VERY short track!**)
- To achieve < 10 keV nuclear recoil track reconstruction, ...
 - ultra-fine granularity detector (NEWSdm: *next talk by N.Chin*)
 - use **low pressure gas** to extend trajectory (e.g. **NEWAGE / CYGNUS**)





CYGNUS2026

Kobe University, Japan
23-25th, Feb. 2026

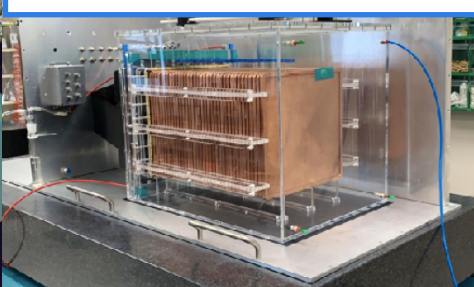
- CYGNUS: World-wide consortium with low pressure gas + low BG toward DM, neutrino physics
- International workshop “CYGNUS2026” was held at Kobe on February

He+SF₆
GEM+wire readout



CYGNUS-UK
Boulby, UK

He+CF₄ (SF₆)
sCMOS+PMT readout



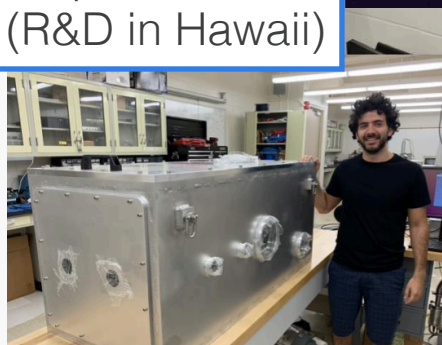
CYGNUS-KM
Kamioka, Japan

CF₄ (SF₆)
Strip readout



~1 m³

He+CF₄+X
Strip readout
(R&D in Hawaii)



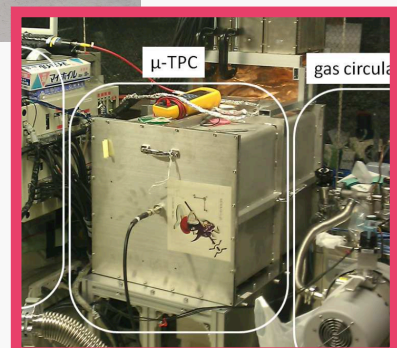
CYGNUS-US
Lead, South Dakota

CYGNO
Gran Sasso, Italy

CYGNUS-OZ
Stawell, Aus.

CYGNUS-Andes
Chile/Argentina

arxiv:2008.12587



~30 cm³

CYGNUS2026 photo



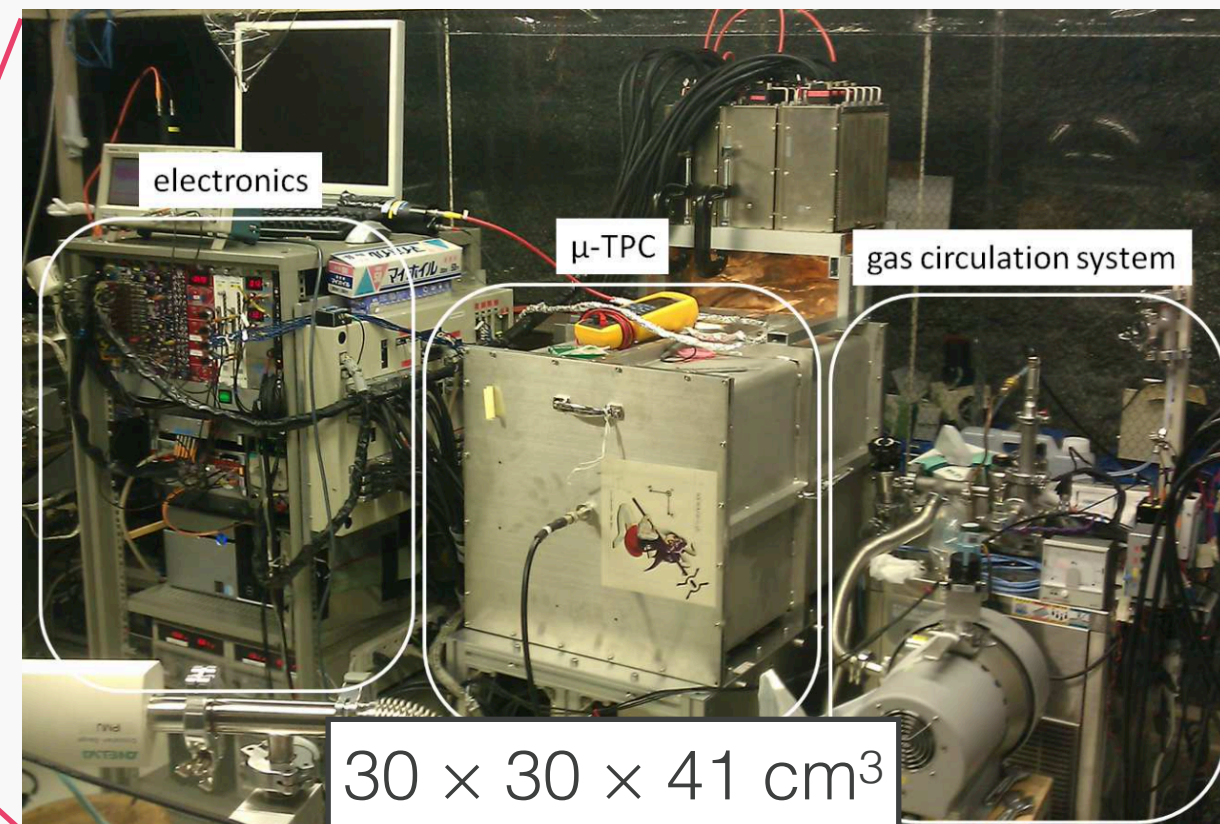
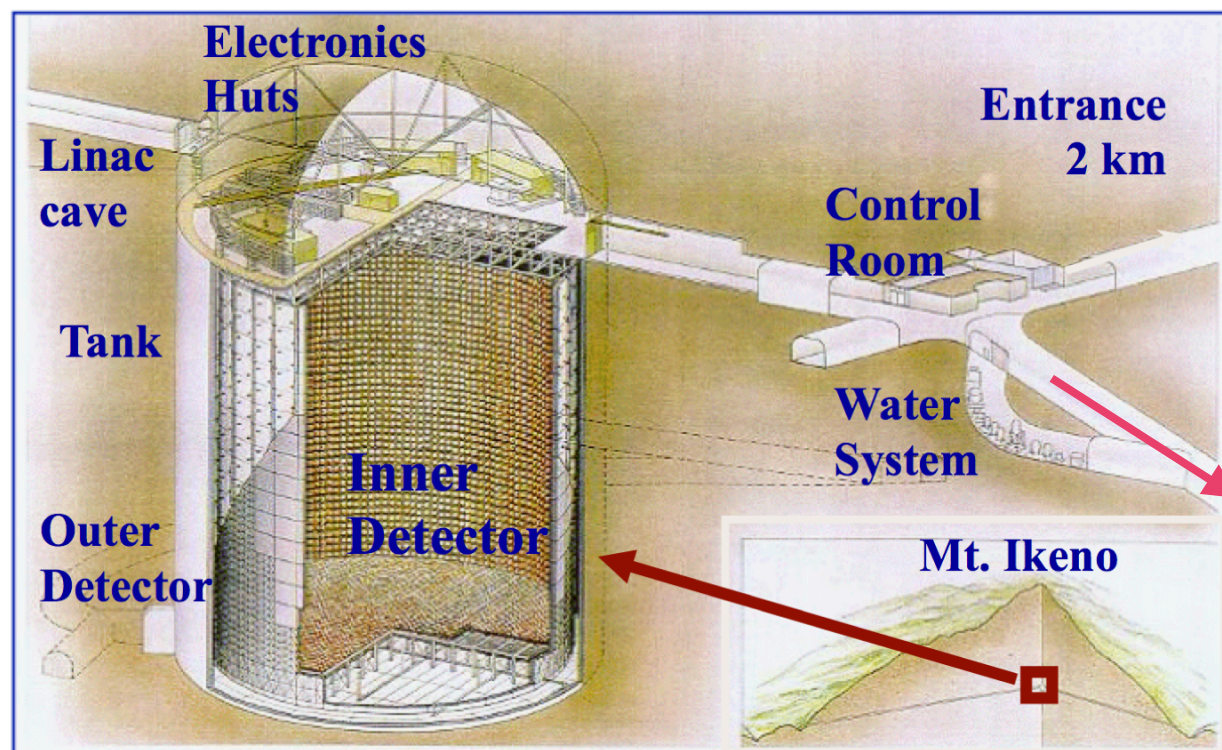
Many fruitful discussions there!

Migdal community
It was the first time we've gotten together in person!

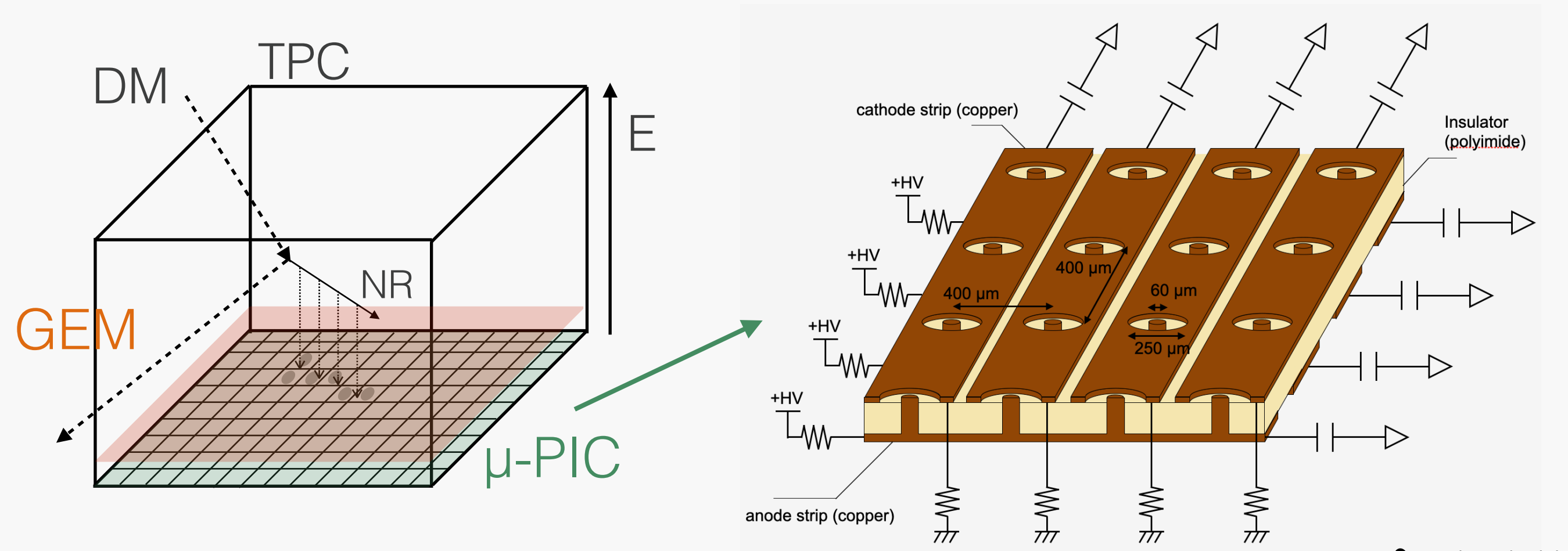


NEWAGE

- 1,000 m underground experiment in the Kamioka mine
- Low pressure gaseous TPC
 - ➔ $30 \times 30 \times 41 \text{ cm}^3$ fiducial volume
 - ➔ filled with CF_4 gas (0.1 atm): spin-dependent search



NEWAGE: 3D track reconstruction

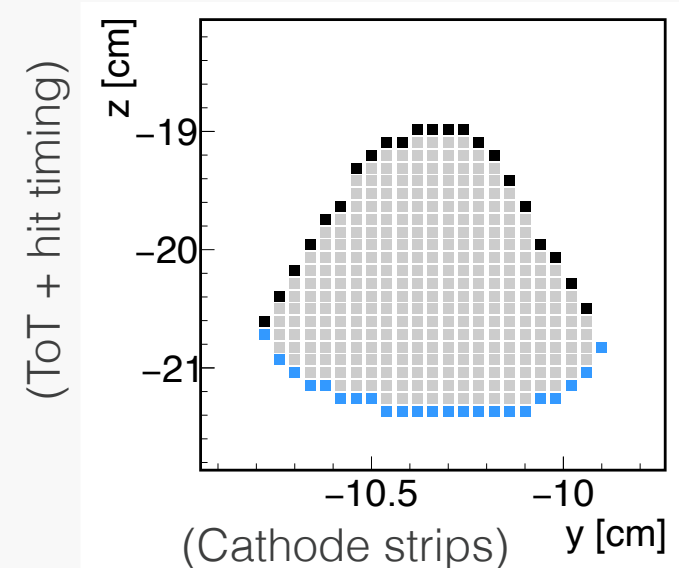
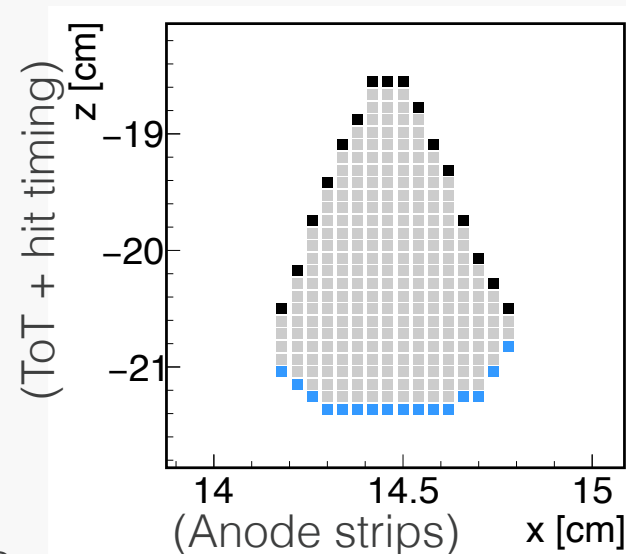


- GEM: Gas amplification
- μ-PIC:
 - ➔ 400 μm pitch 2D strip readout
 - ➔ Gas amplification

2D position + drift time

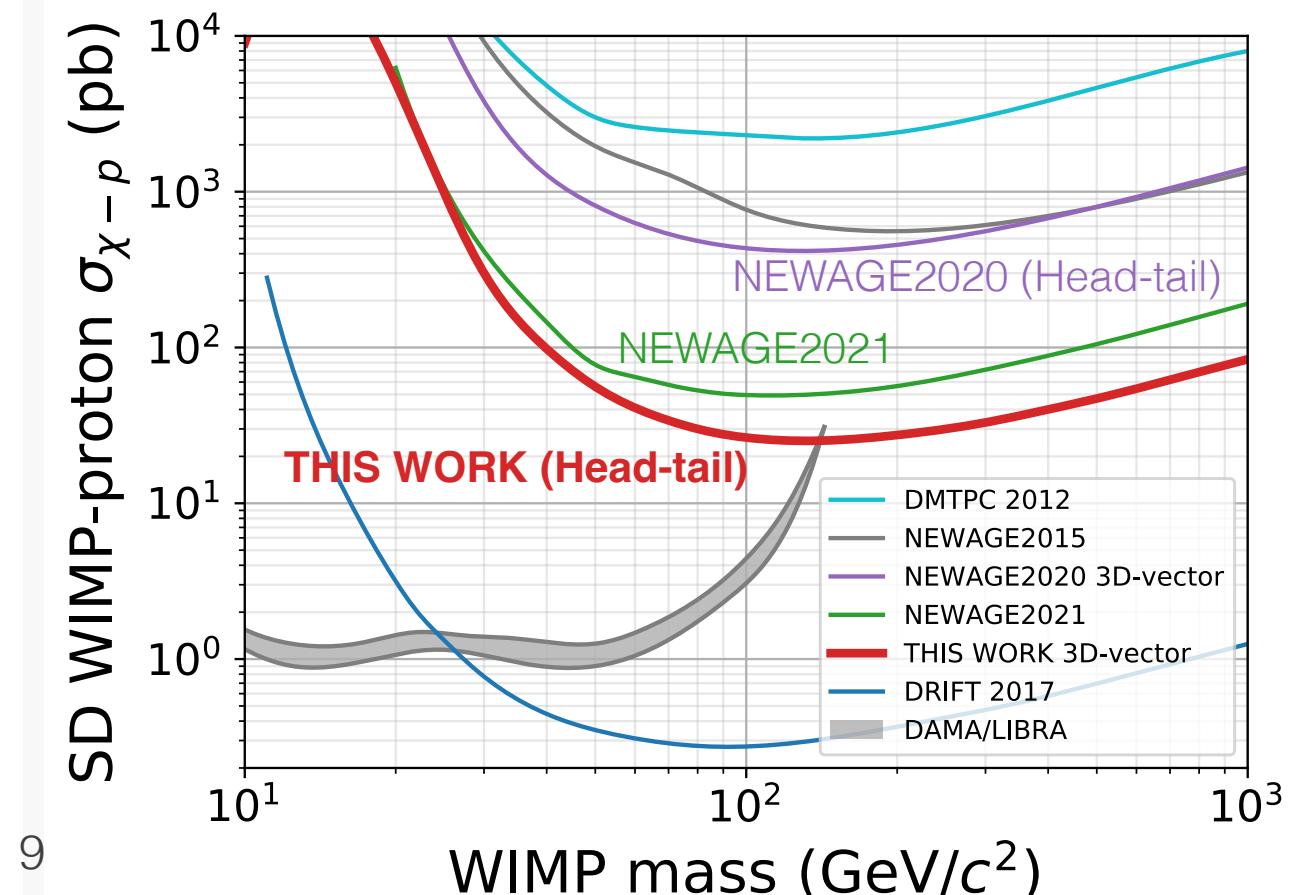
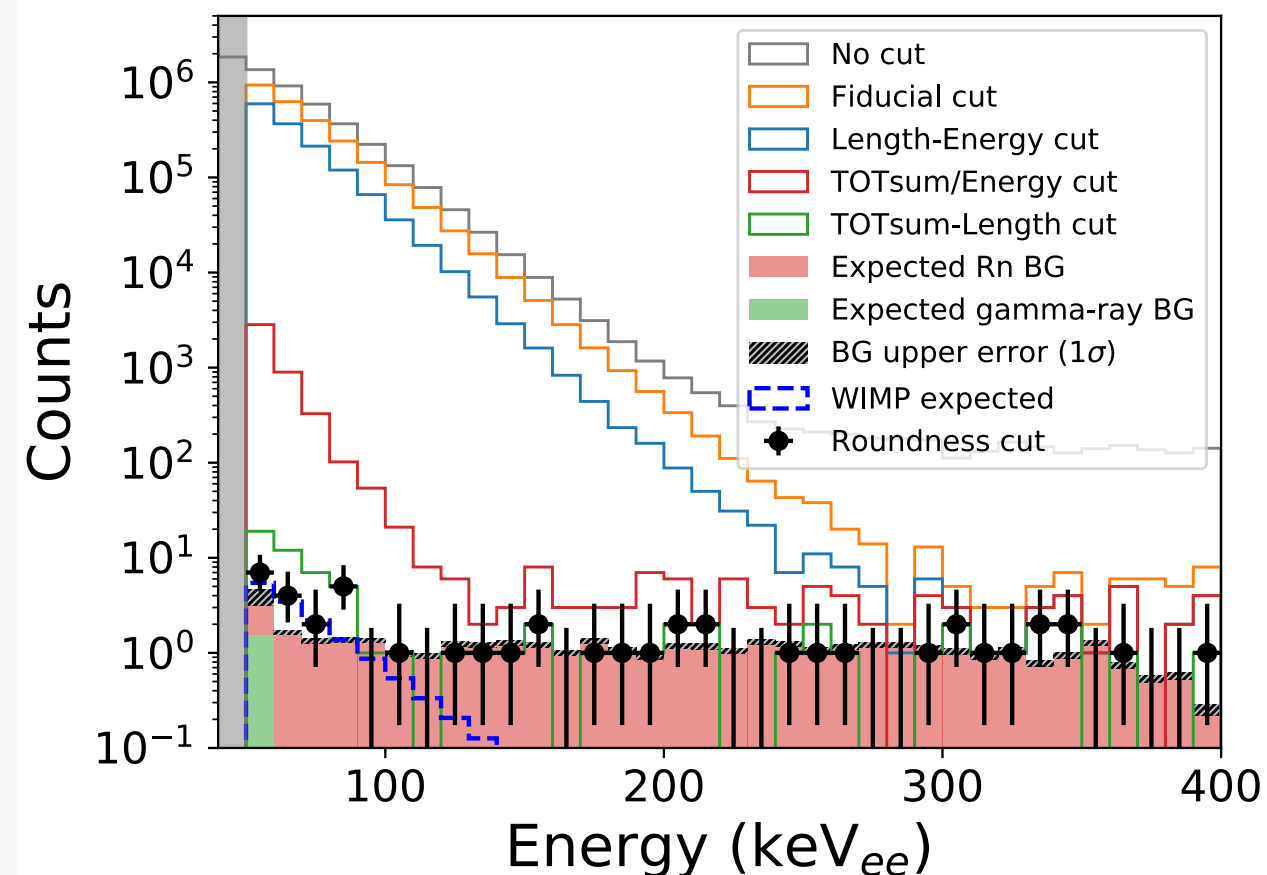
→ WIMP search with 3D track

NR event display



Latest result

- Null-consistent result in energy and directional distributions
 - ➔ Electron recoil rejection analysis updated and exposure increased
 - ➔ Limit is approaching DAMA/LIBRA allowed region
 - ➔ Head-tail recognition successfully implemented
- Future work: **BG rejection** and **large target volume**



Strategy of BG rejection

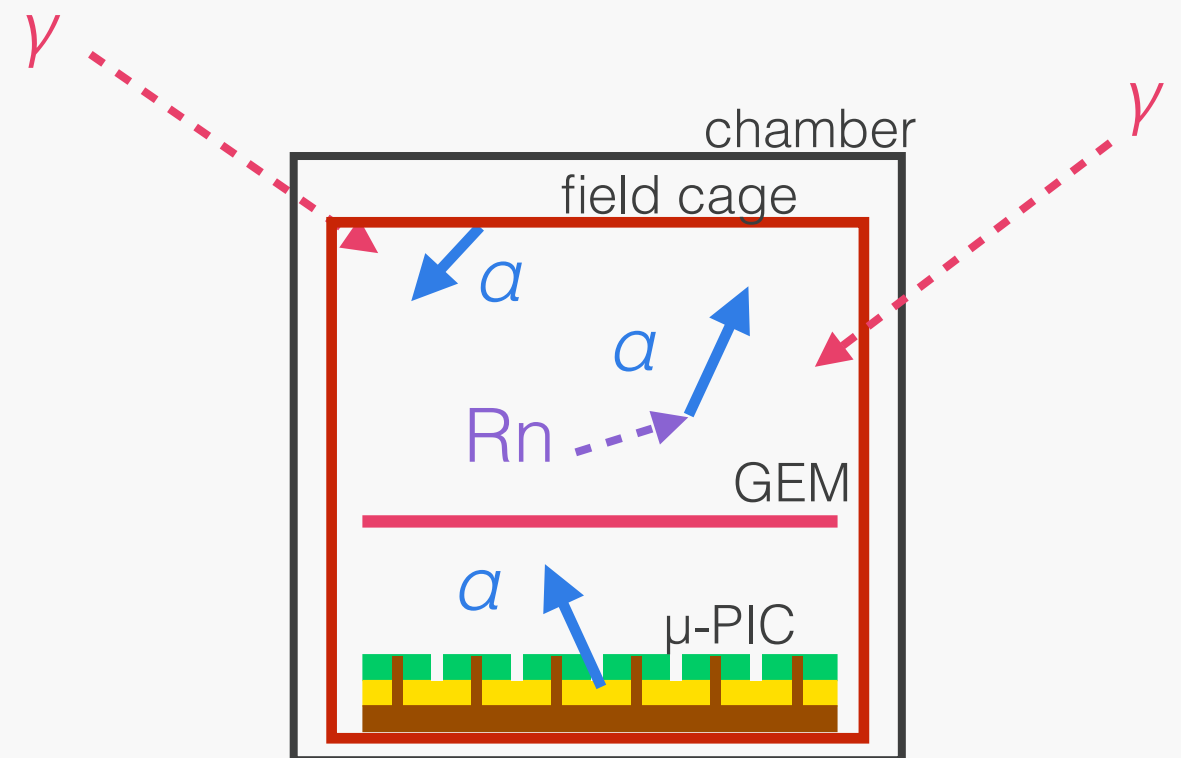
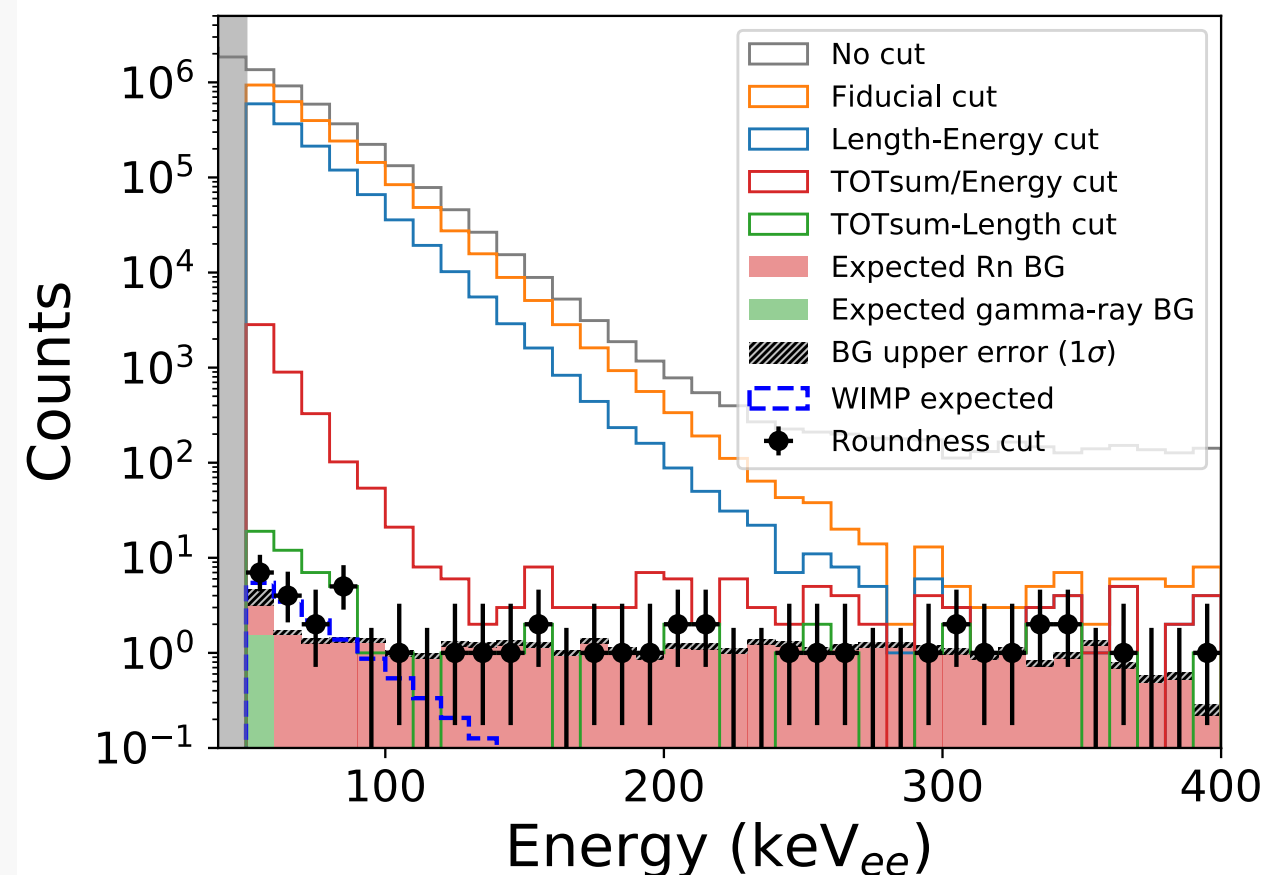
- External BG

- ➔ Ambient gamma (and neutron): shielding

- Internal BG

- ➔ Radon emanation:

- ▶ “clean” detector development and gas purification



Strategy of BG rejection

- External BG

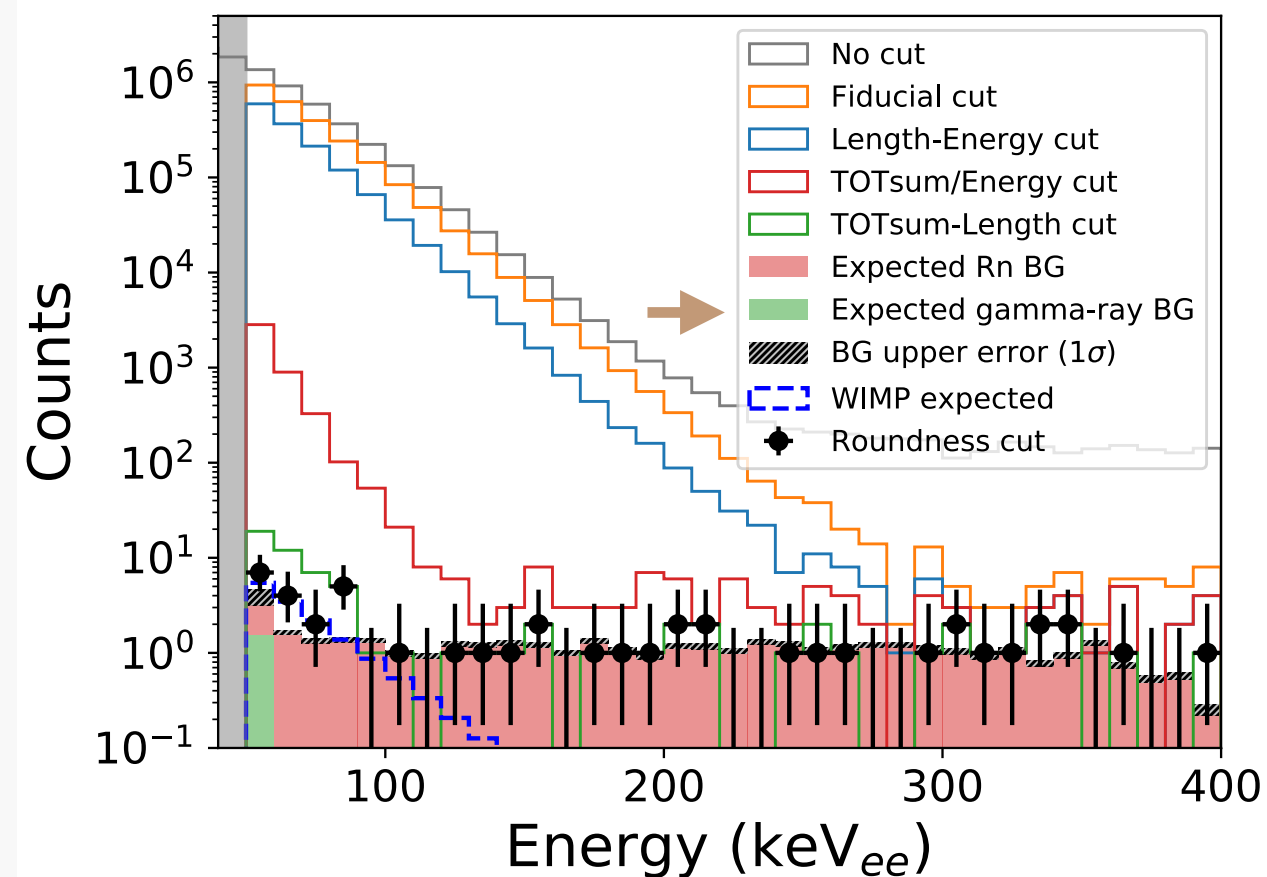
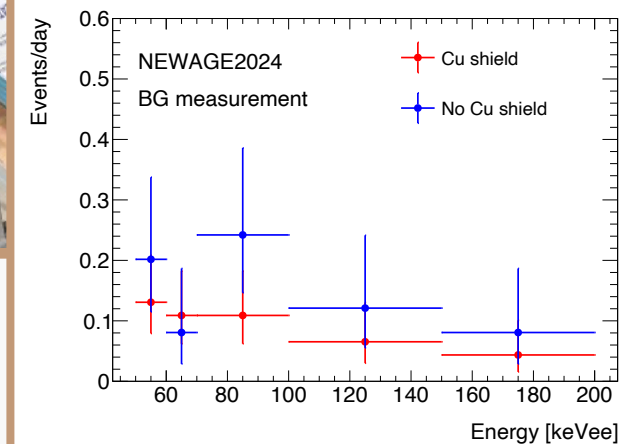
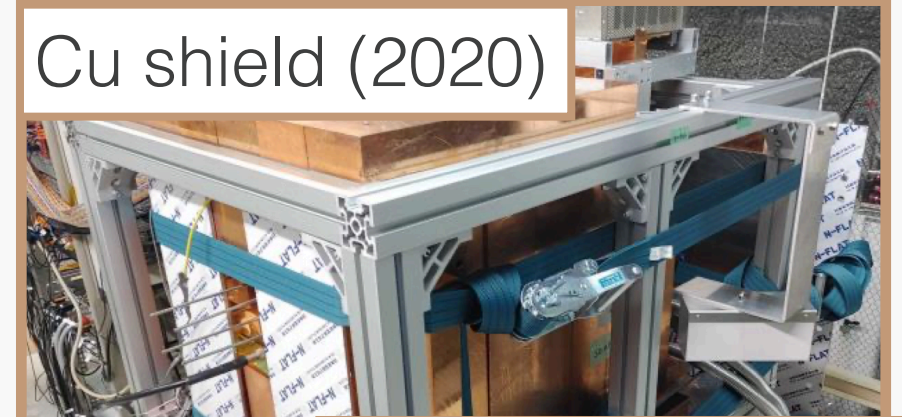
- ➔ Ambient gamma (and neutron): shielding

- Internal BG

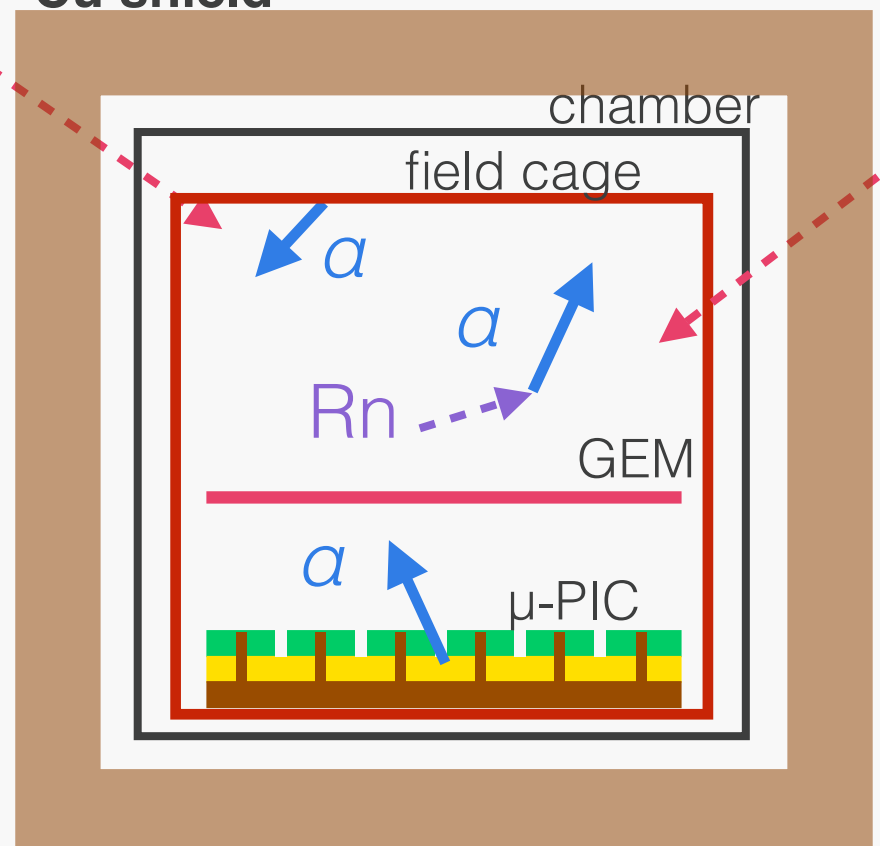
- ➔ Radon emanation:

- ▶ “clean” detector development and gas purification

Cu shield (2020)

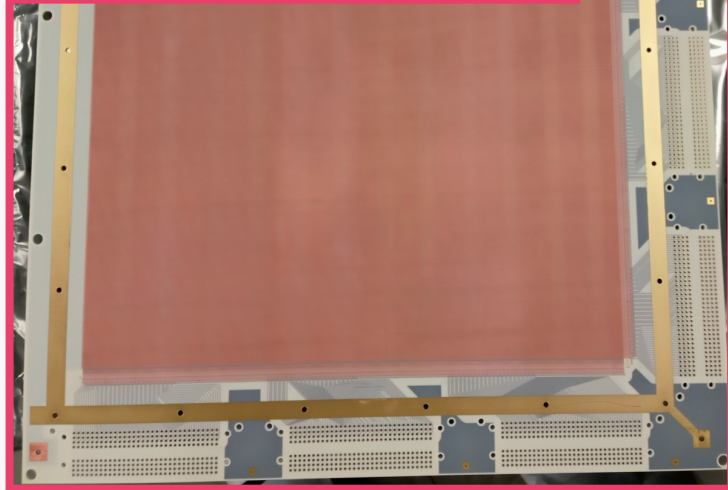


Cu shield



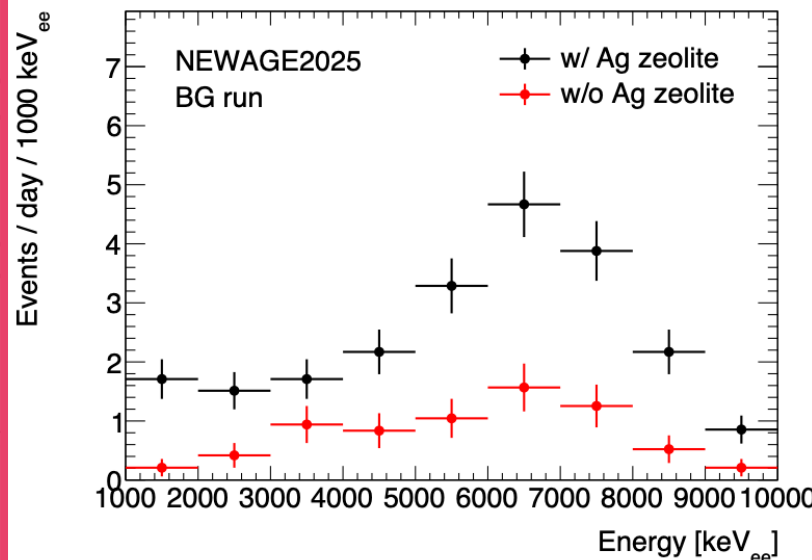
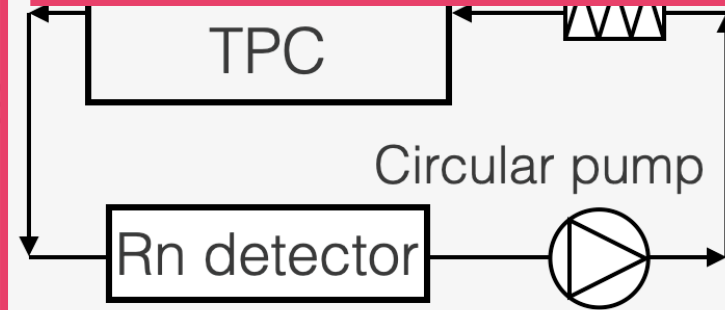
Strategy of BG rejection

Low-BG detector
(2023)

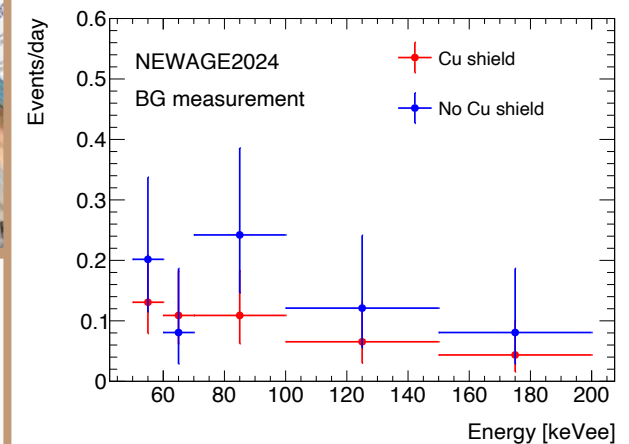
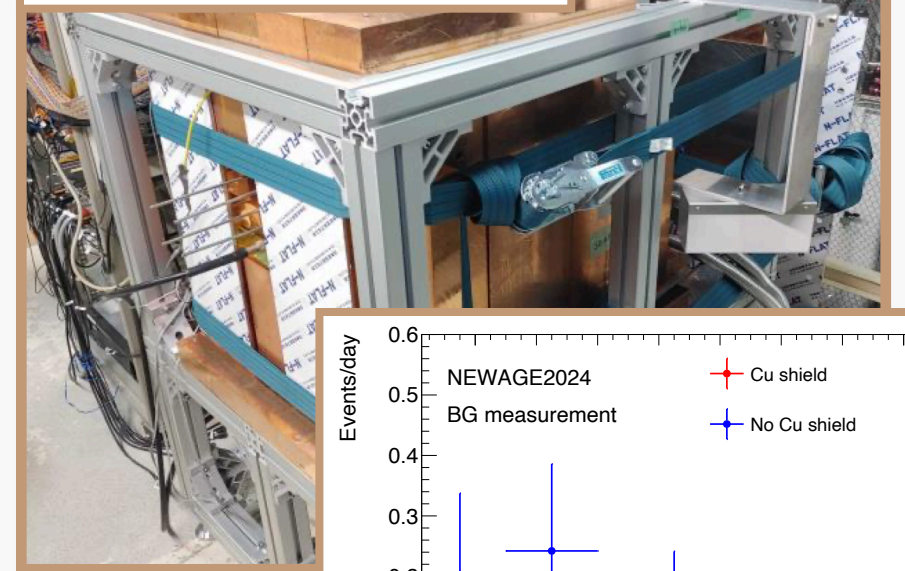


► “clean” detector

Ag-zeolite filter (2025)
(8Ag-FER-B)

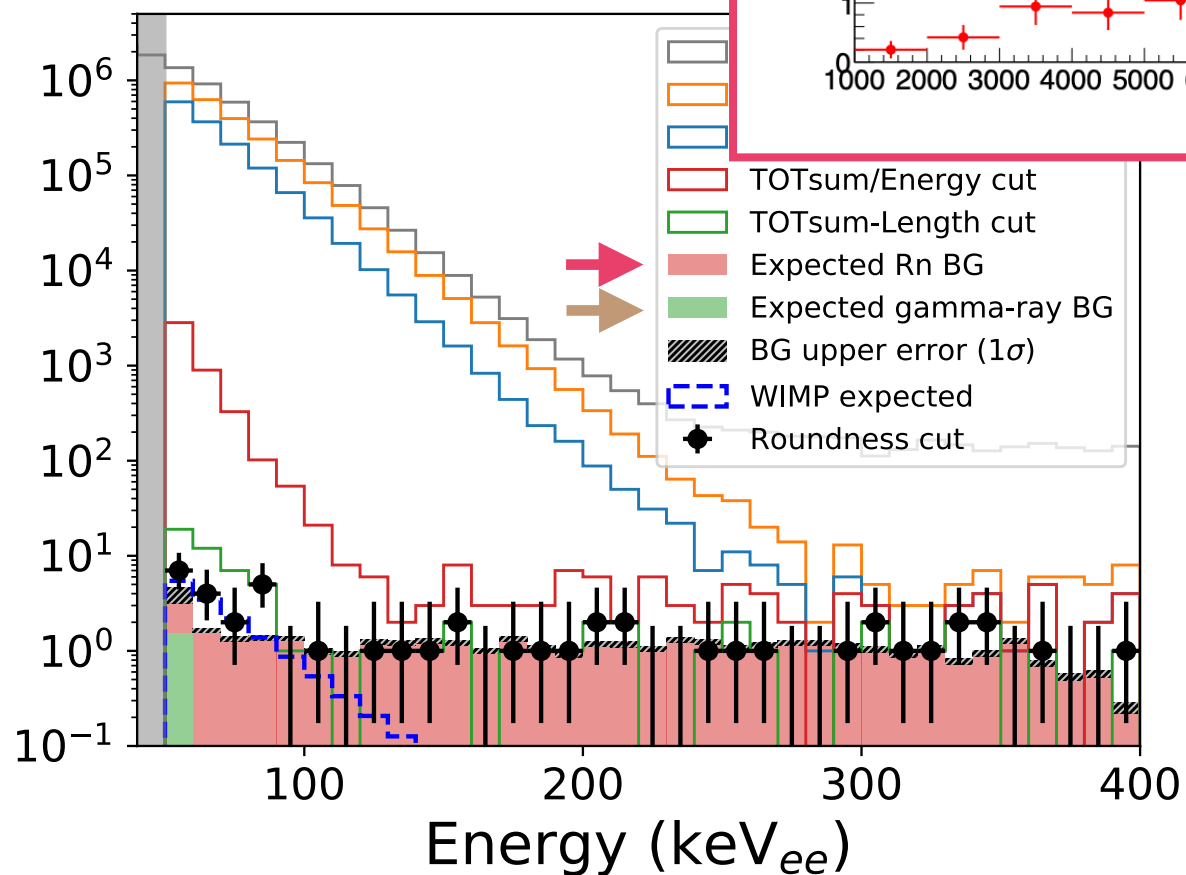
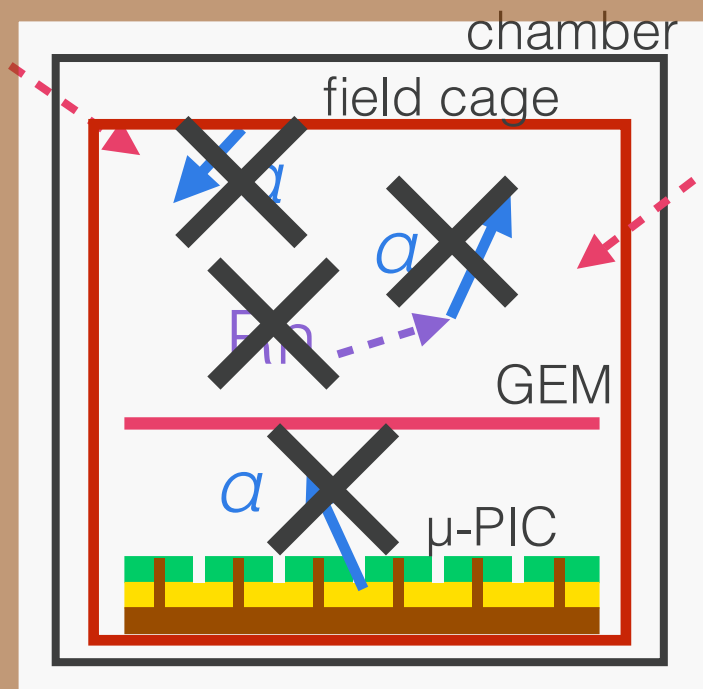


Cu shield (2020)



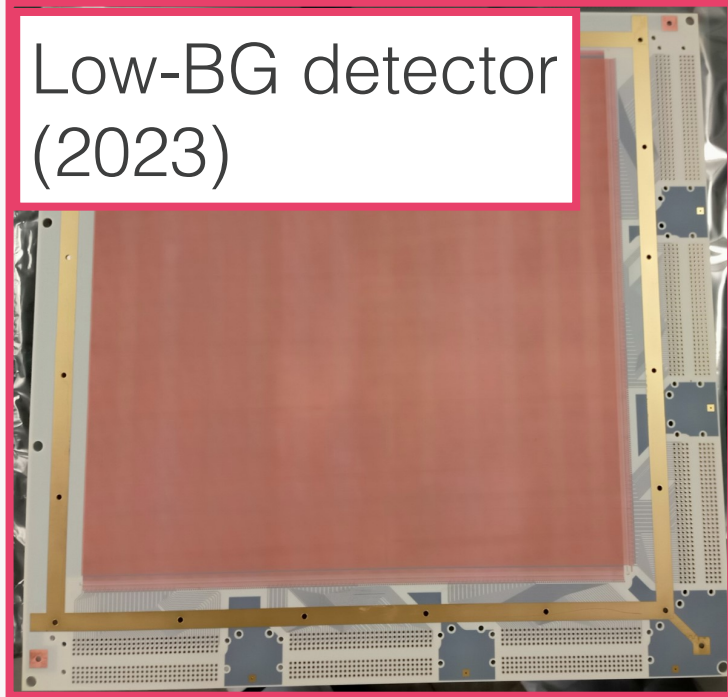
purification

Cu shield



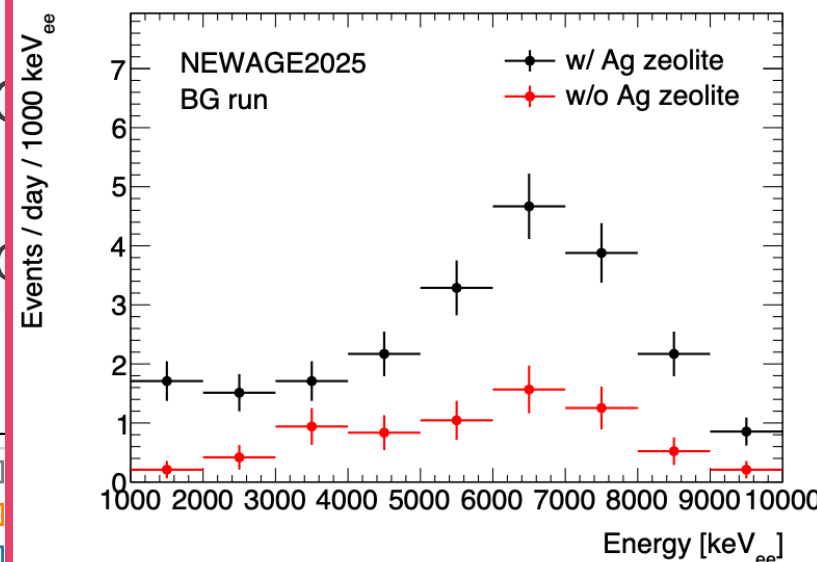
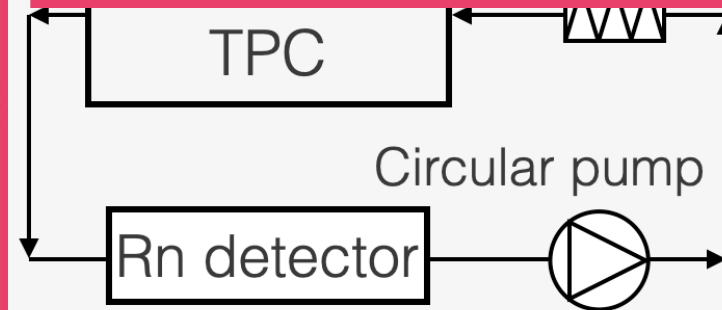
Strategy of BG rejection

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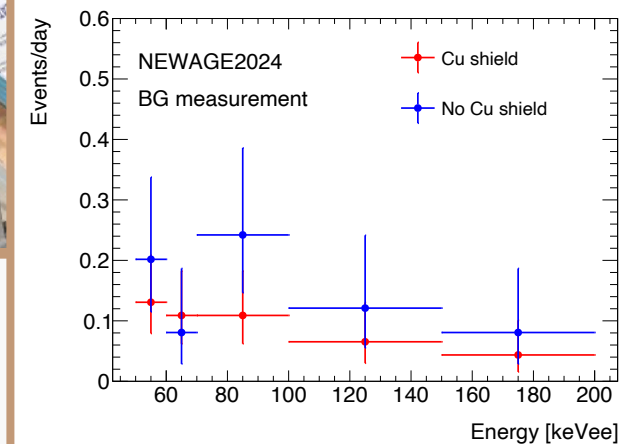
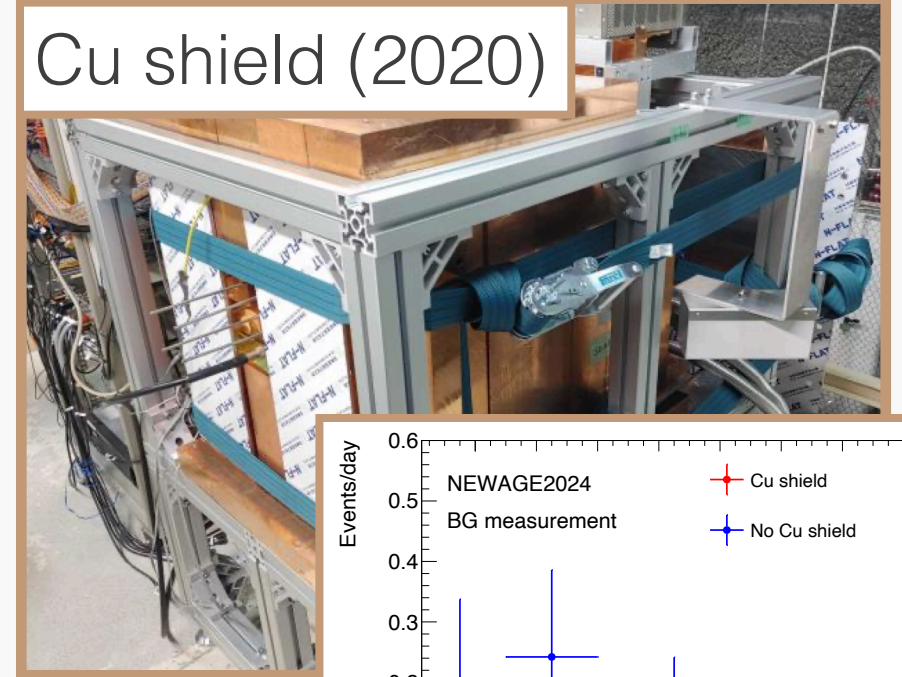


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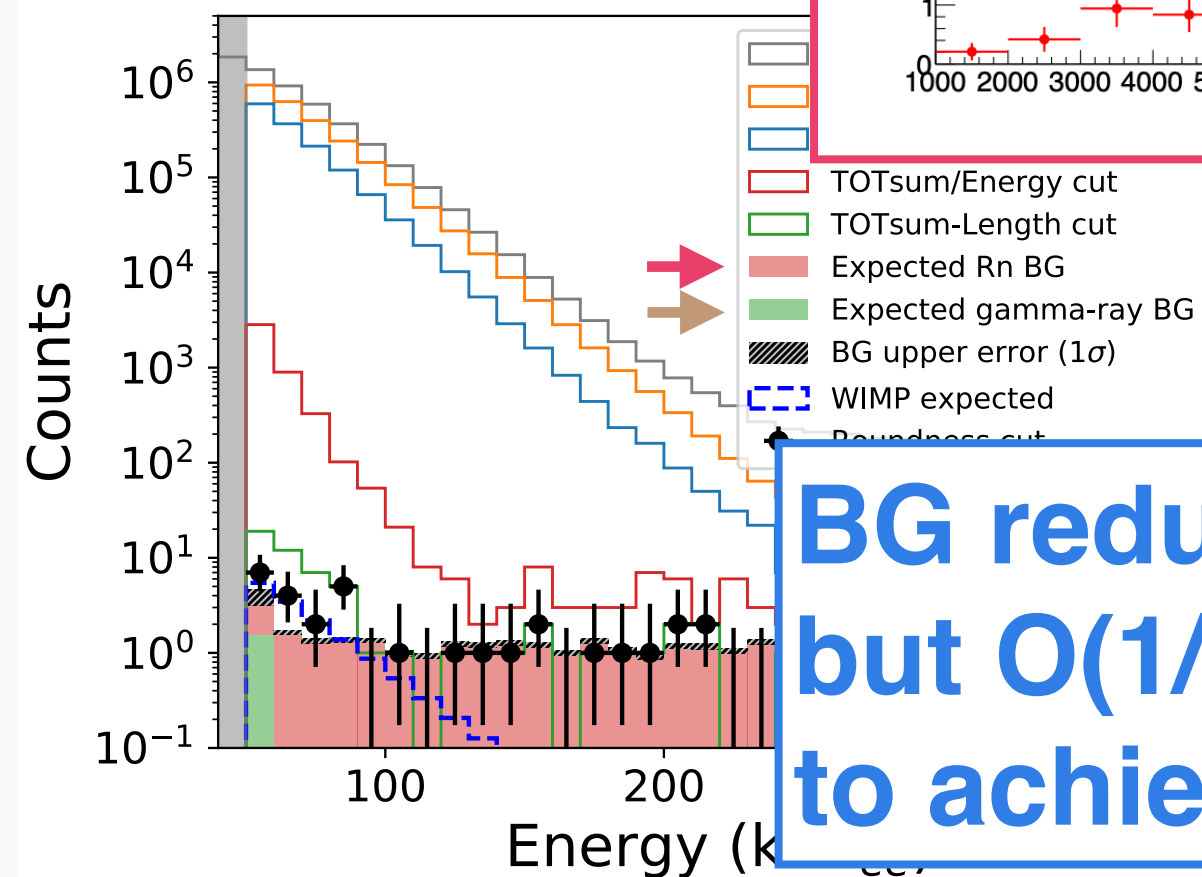
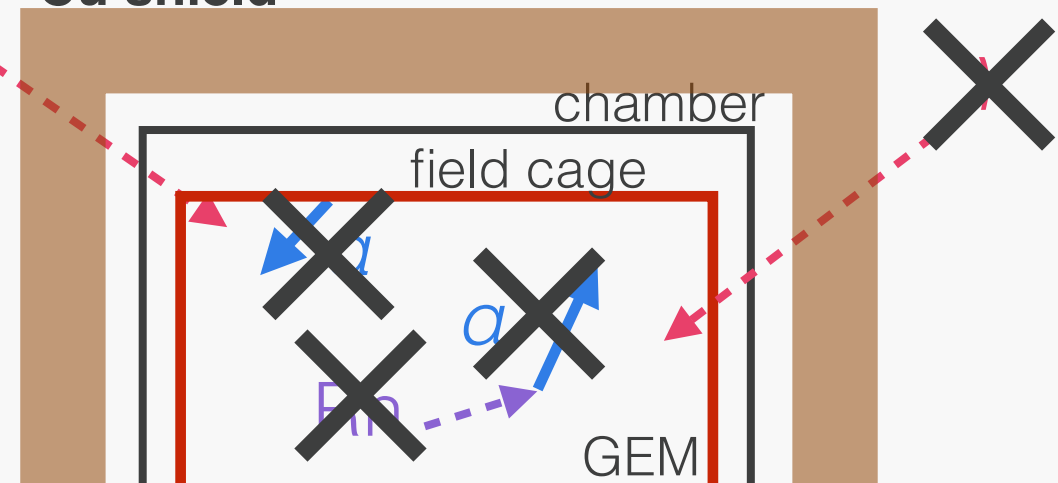


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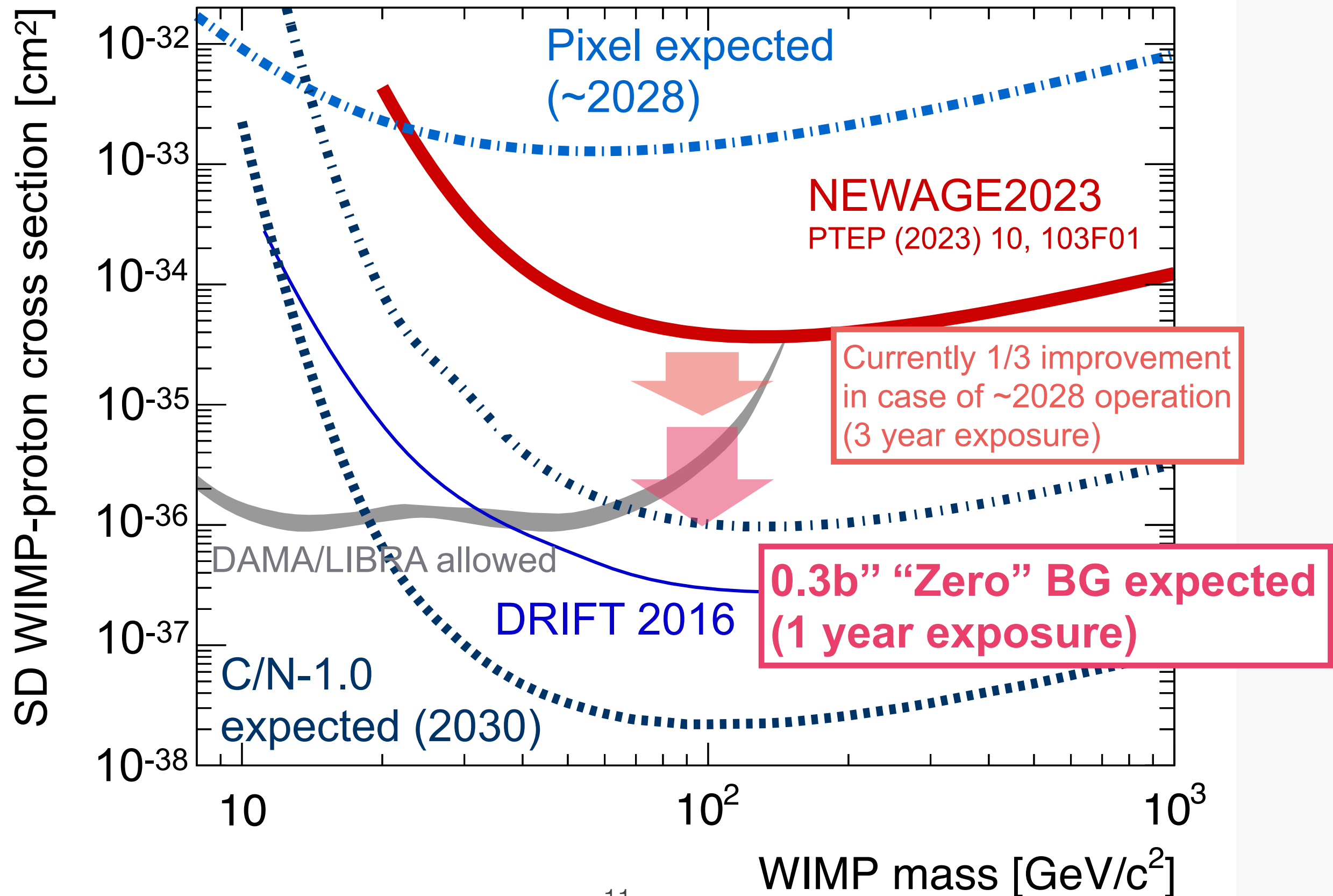
purification

Cu shield



BG reduced by 1/3!
but O(1/10) reduction required
to achieve “zero” BG measurement

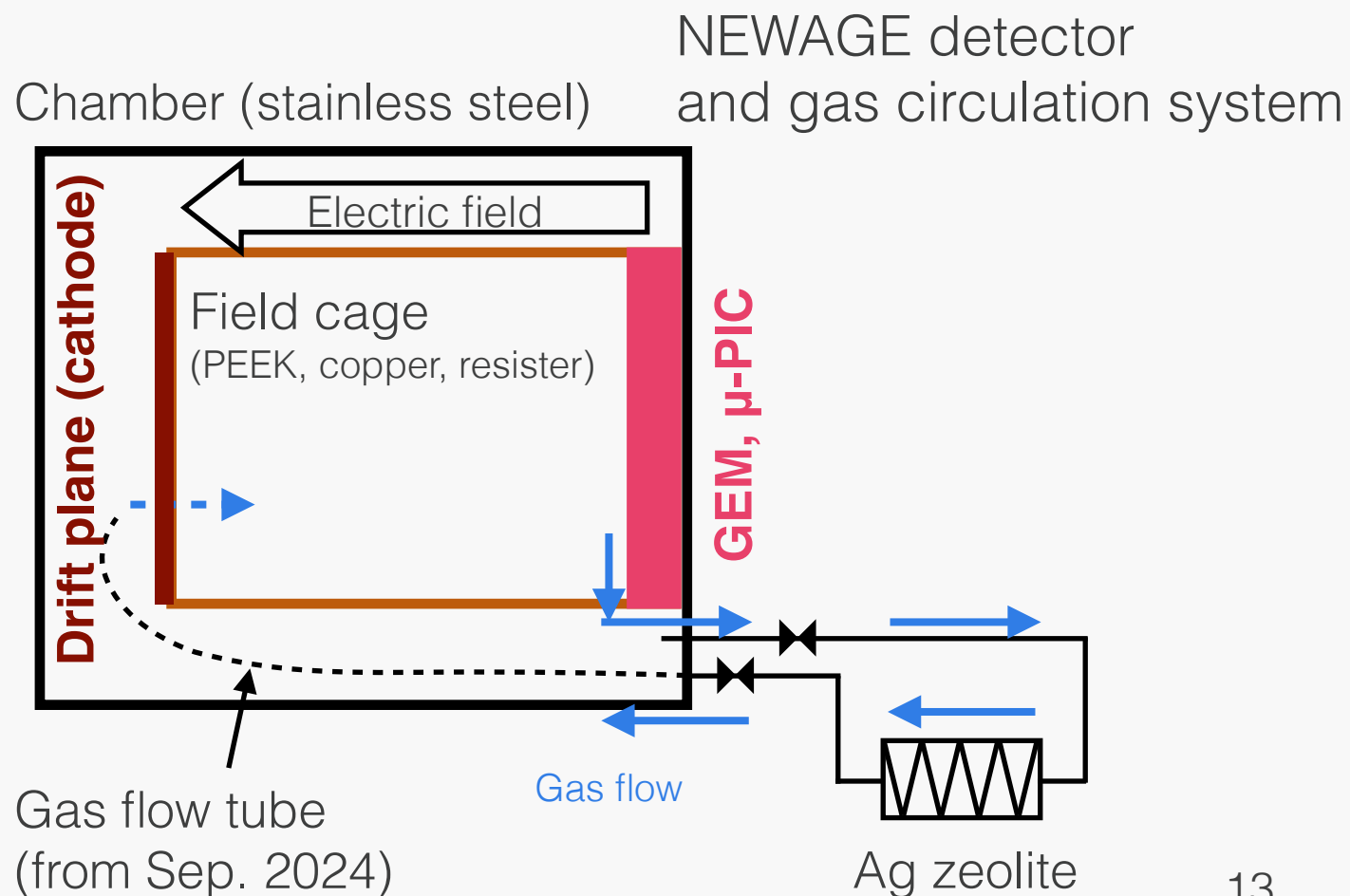
Expected limits



Recent activities

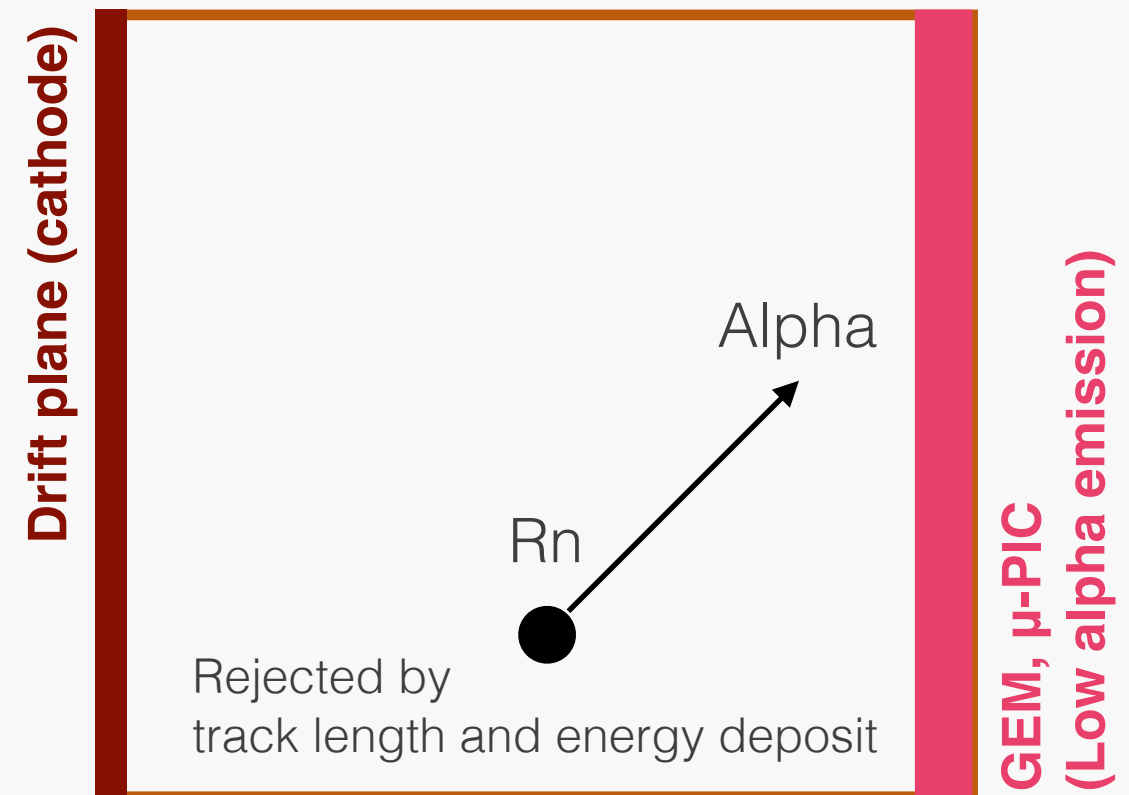
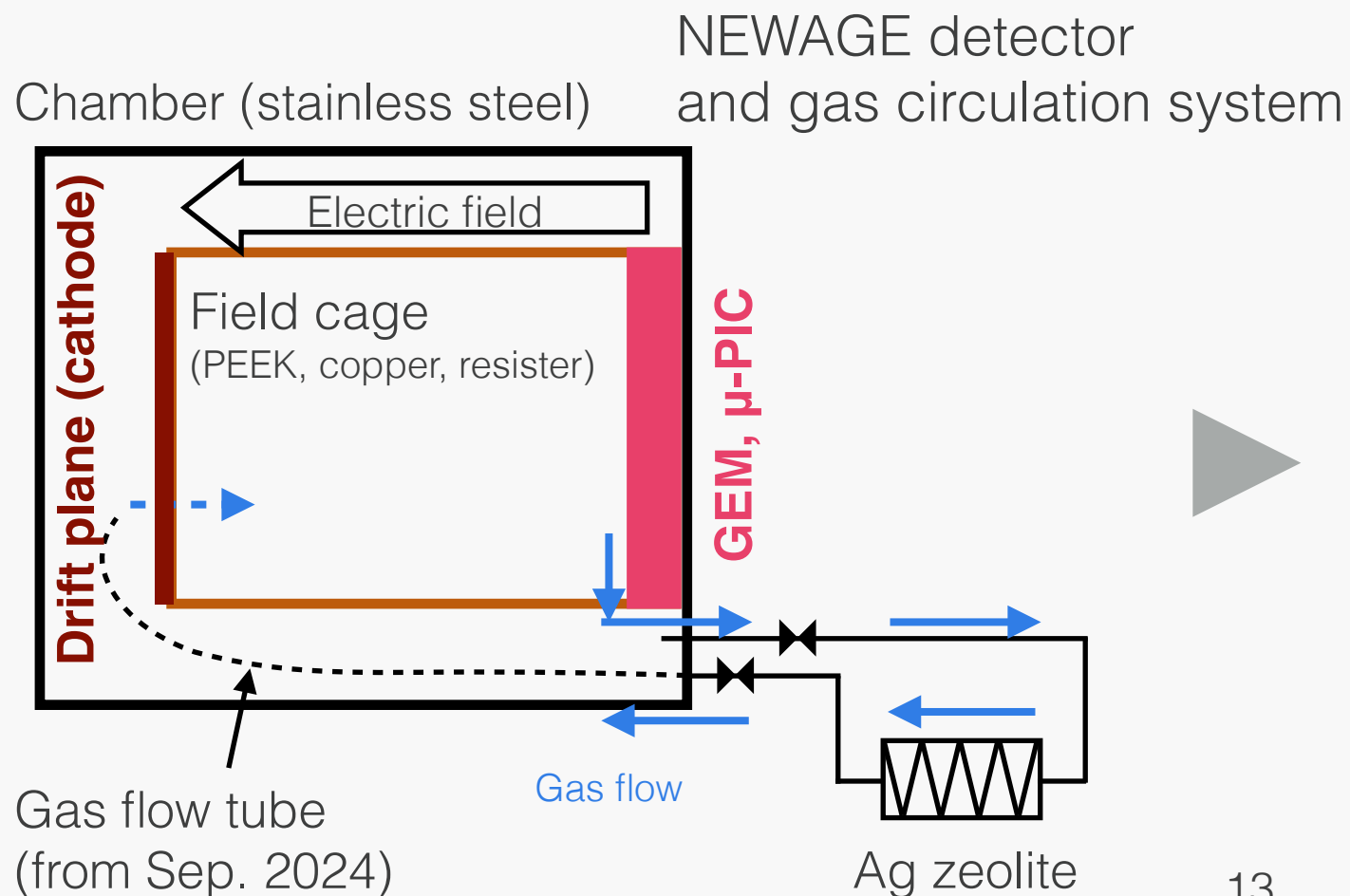
Radon (and its progenies) -oriented alpha rays

- The gas circulation pass is currently constructed inside the chamber
 - ➔ Only radon emanation from the field cage and detector seems to be effective
 - ➔ Radon-alpha emitted nearby the drift top (cathode) and detector surface will be misidentified as nuclear recoil
- Contribution of surface alpha-rays is also background candidates but estimated to be small
 - ➔ However, we need to identify its source because the material might also emit radons



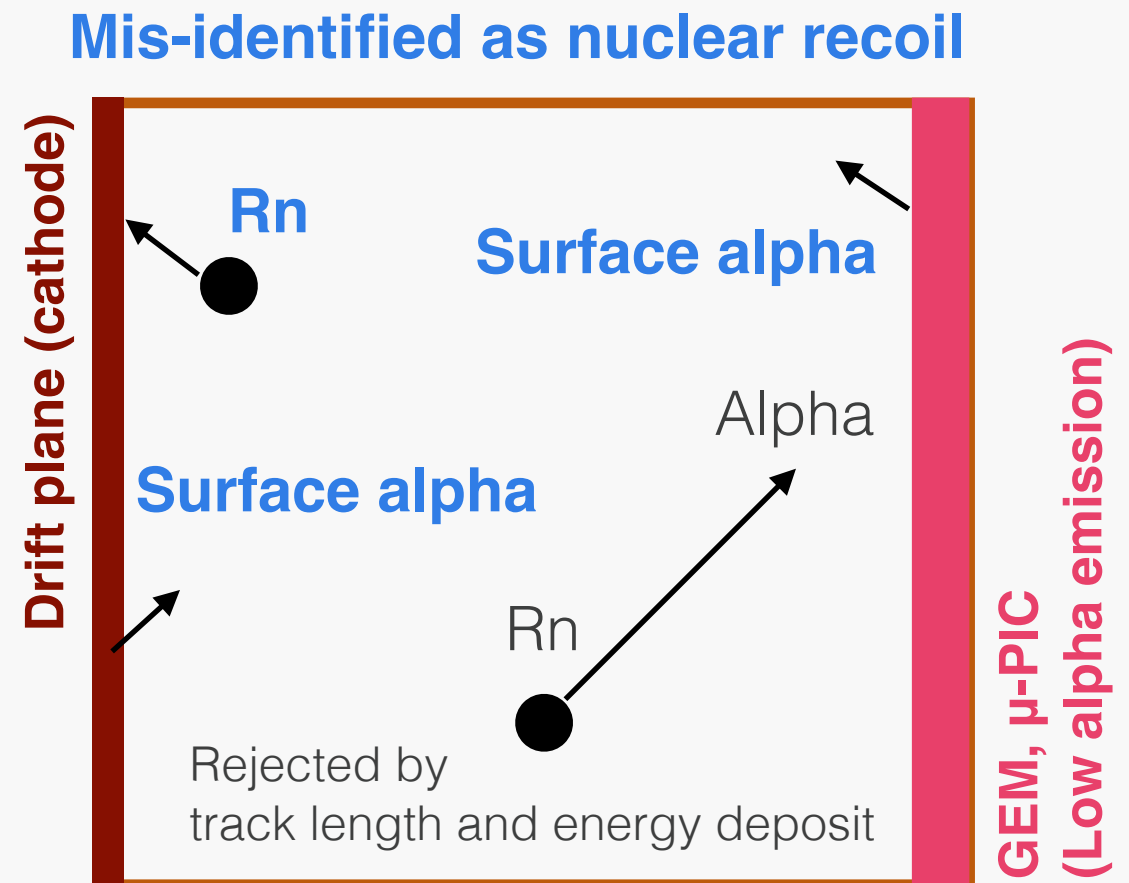
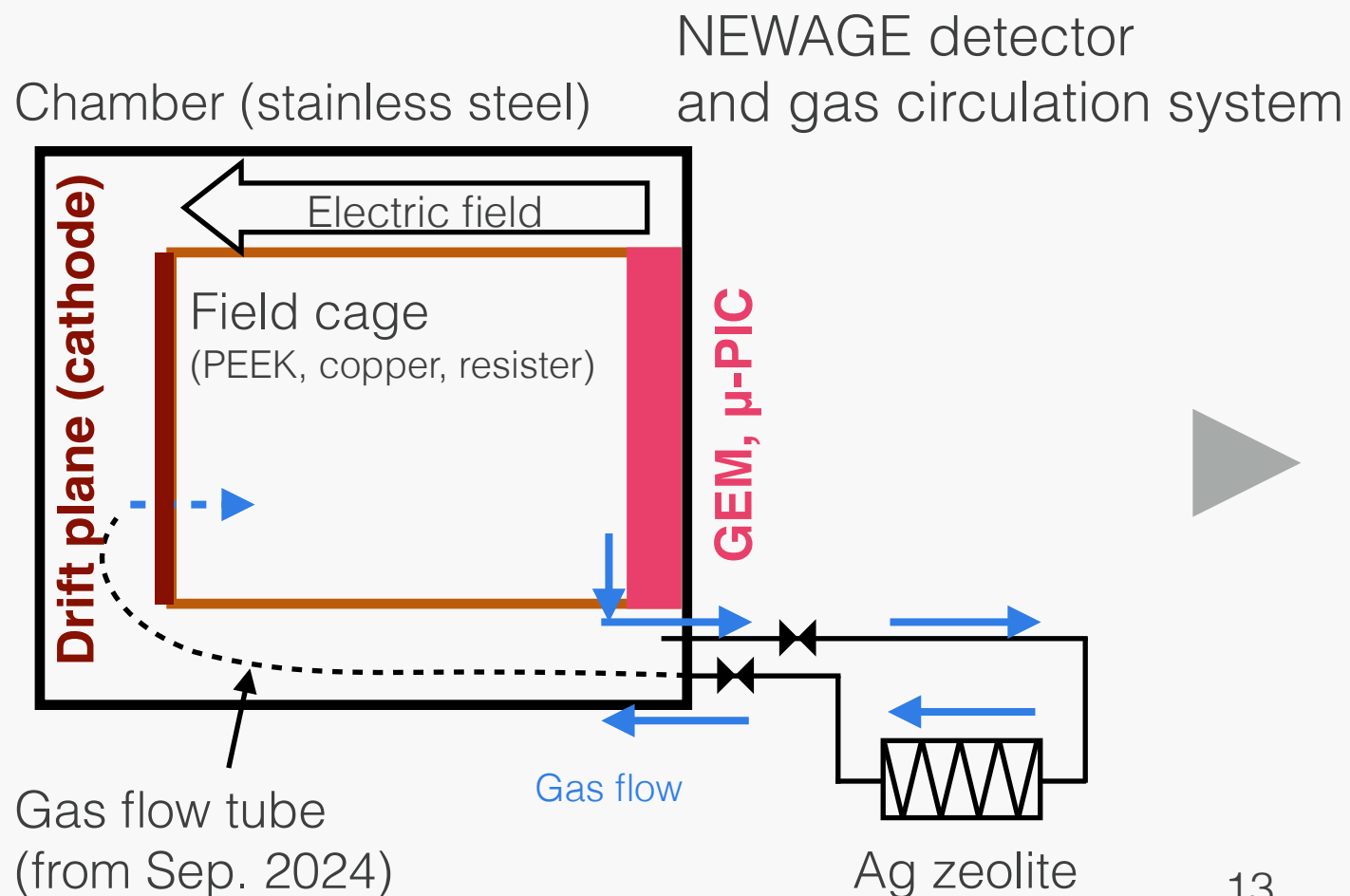
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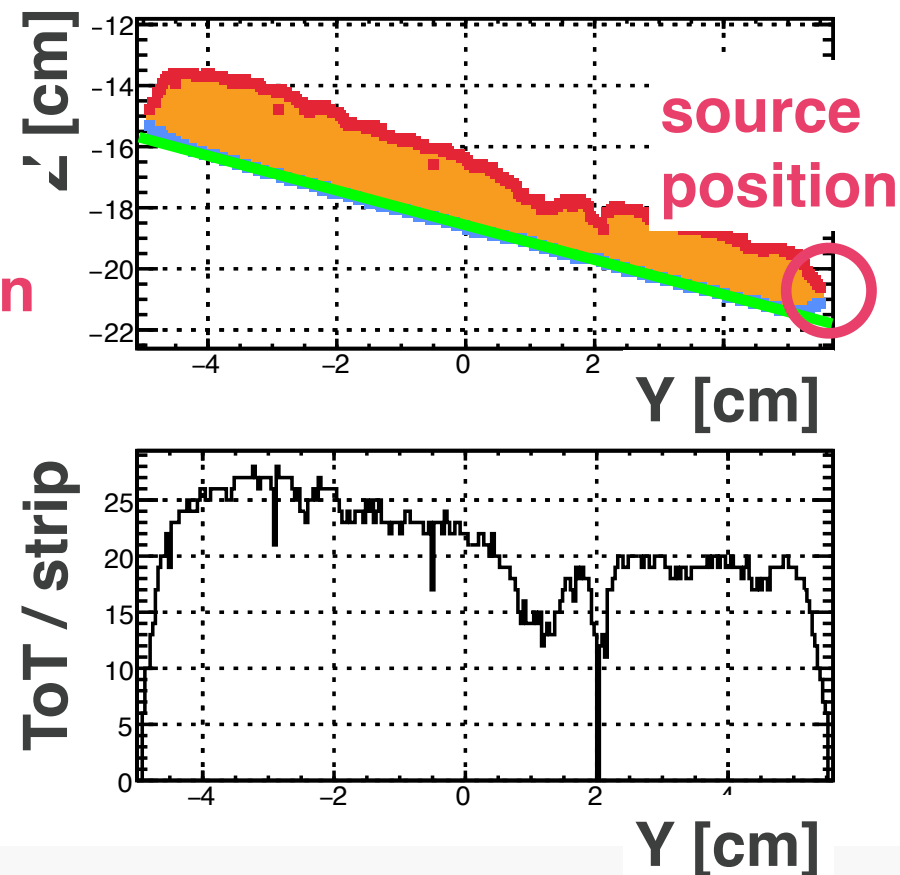
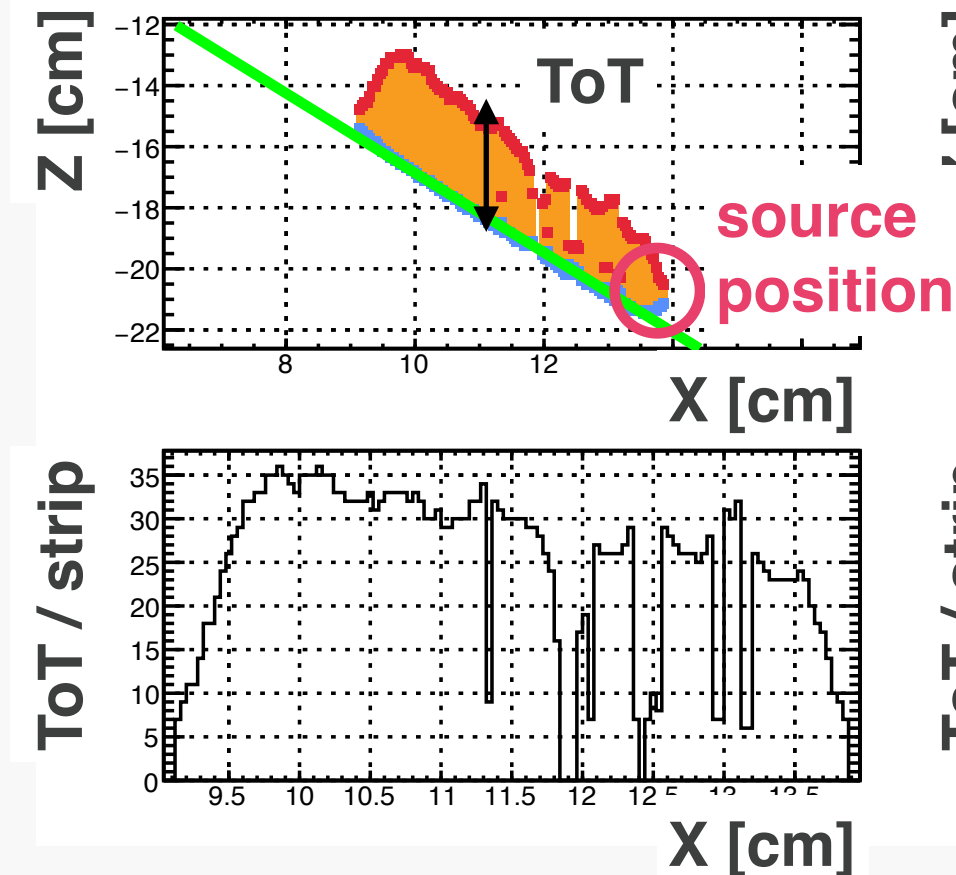
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Study of alpha-ray source position

- 3D track reconstruction analysis will make identify source position of alpha-rays
 - ➔ Alpha tracks will make a bragg peak just before stopping
 - ➔ Measurement of Time over Threshold for each strip allows to identify a bragg peak
 - We can determine a particles' direction of flight and consequently identify its source position



NEWAGE Event Display

Dataset : 20260701, period : 33

File ID : 91, Trigger ID : 467

Energy: low = 4621.0, high = 6209.1 [keV]

Track Length = 12.8 [cm]

TOT-sum=8265

Roundness = 0.068

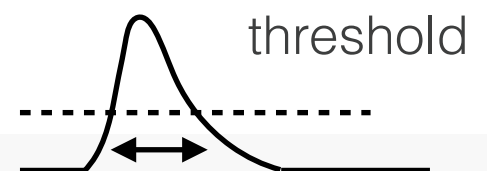
Elevation Angle = -27.51 [deg]

Absolute Azimuth Angle = 66.45 [deg]

Skewness X : -0.031078

Skewness Y : -0.038586

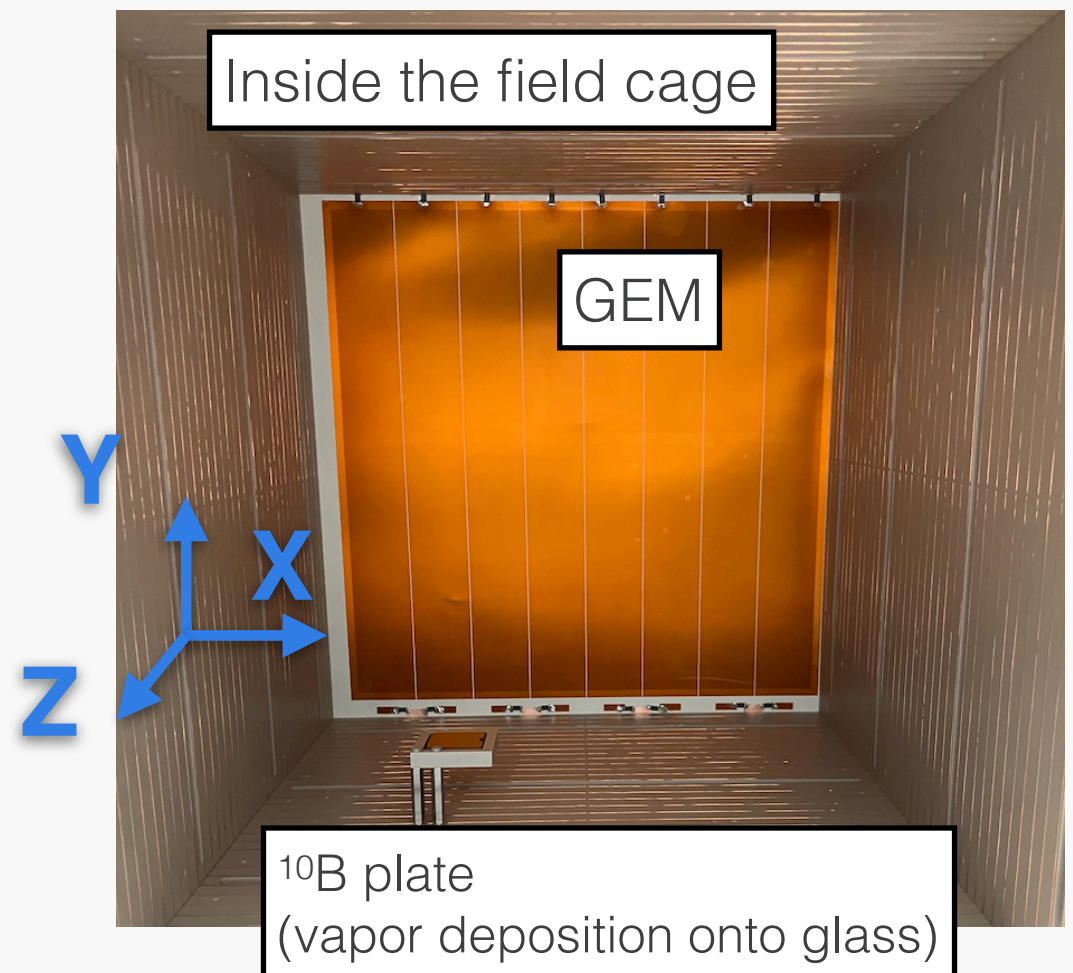
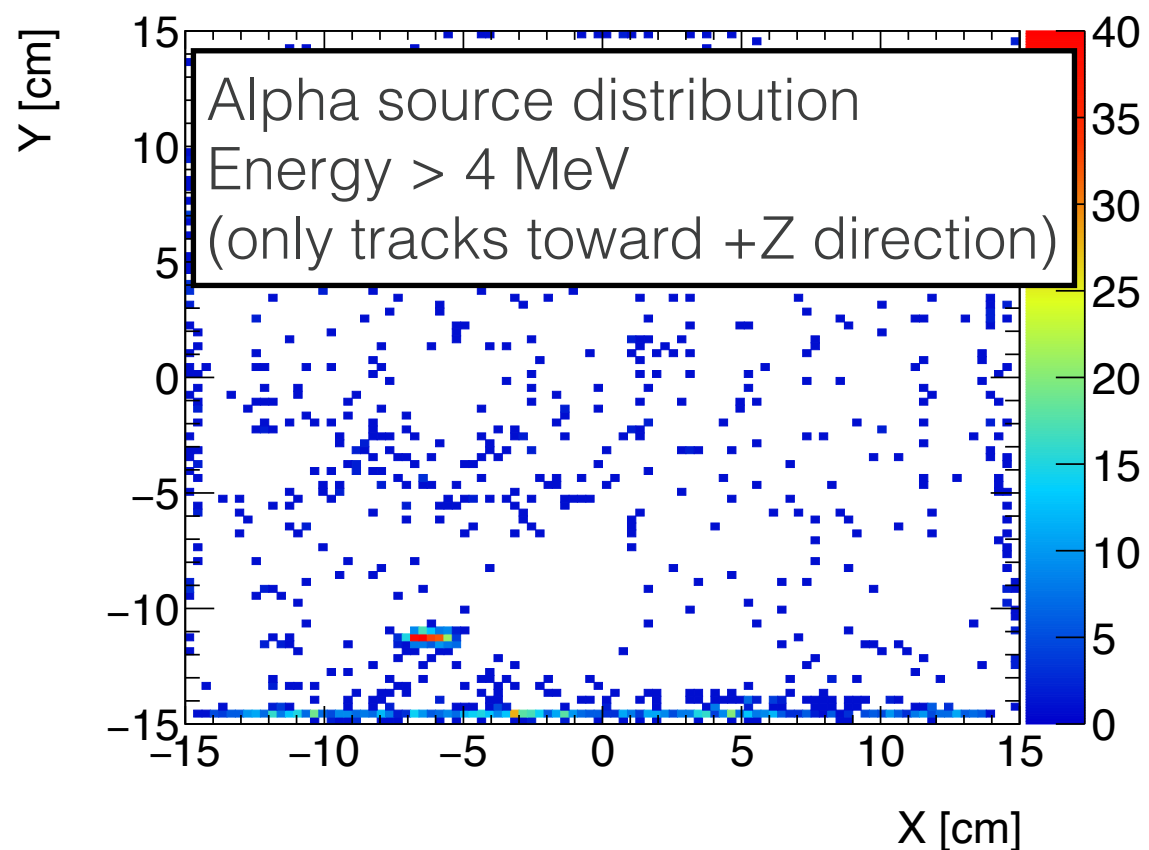
Skewness 2D : -0.021399



Time over Threshold (ToT)

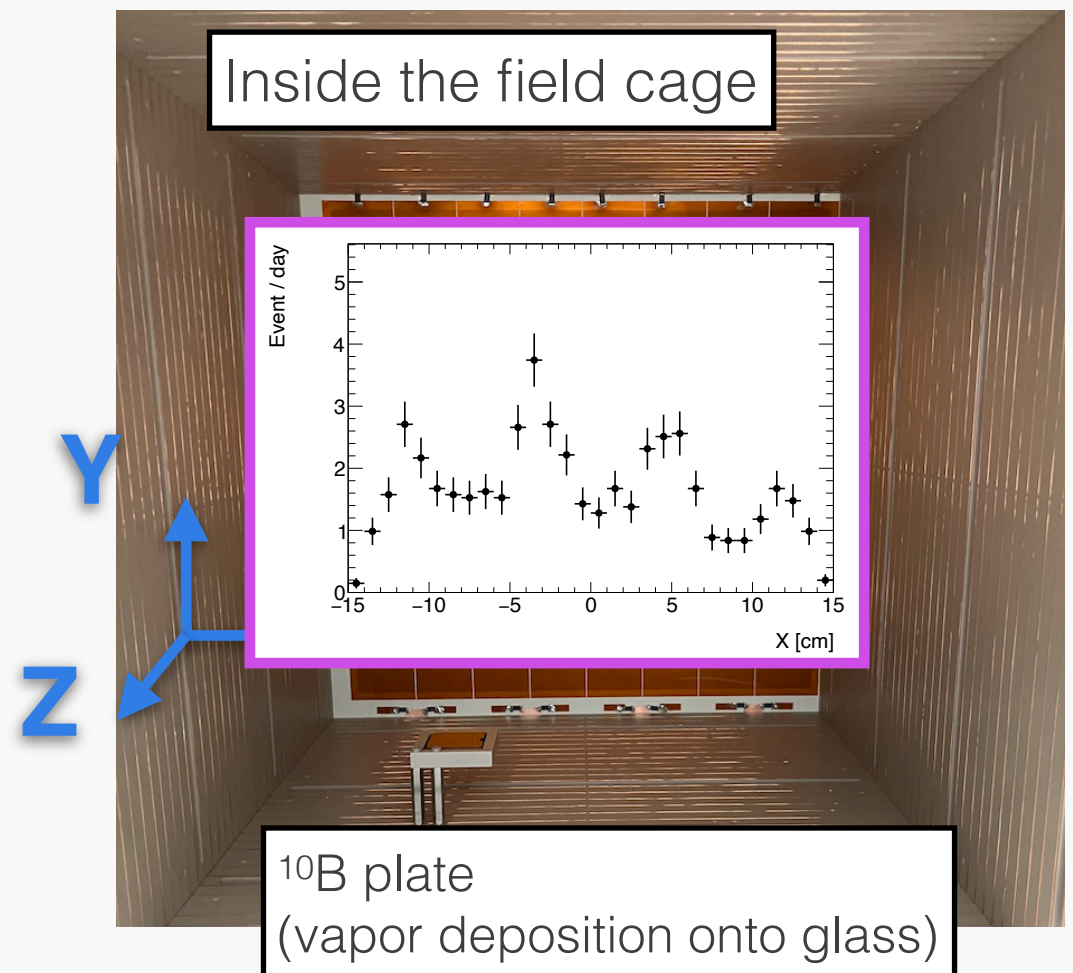
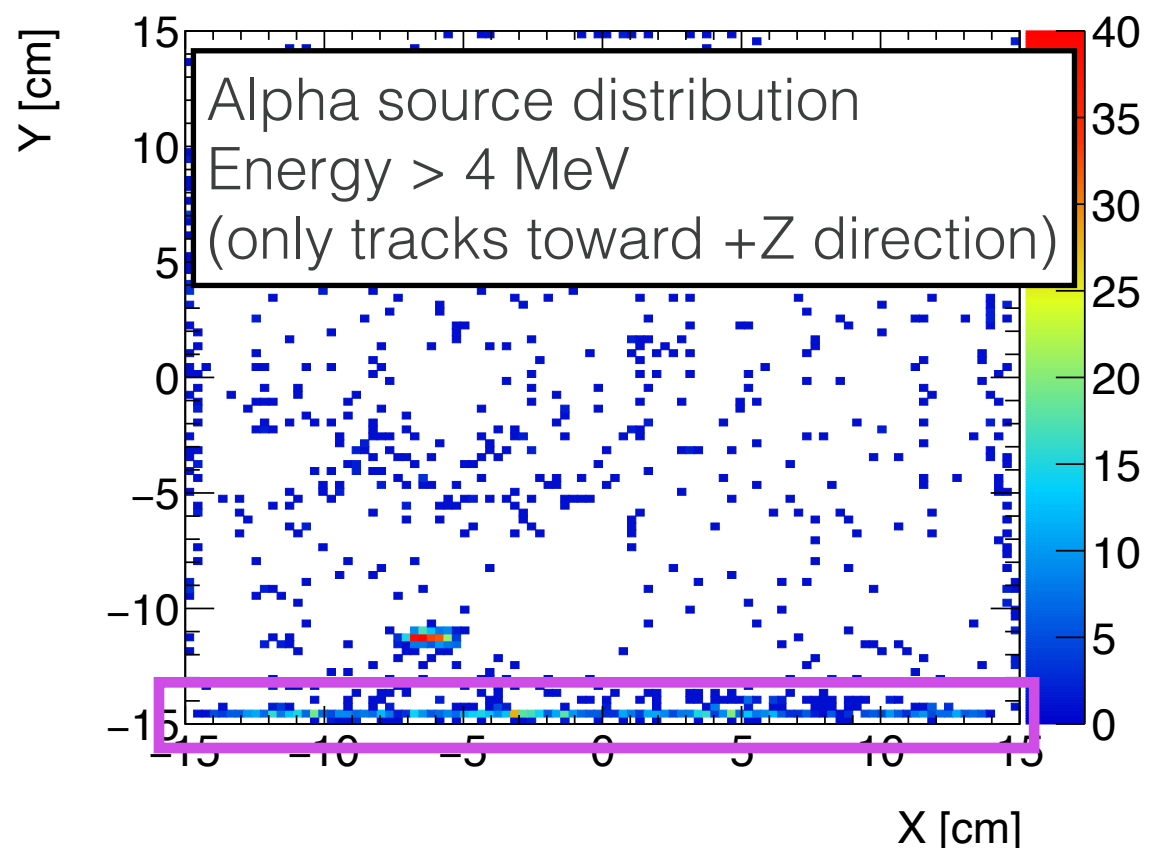
Alpha source distribution

- Track analysis performed to identify the source position of alpha-rays
 - ➔ ^{10}B plate (for energy calibration) , and unknown distribution in -Y region??
 - Radon emanation from ^{10}B plate was already investigated ... not a dominant source
 - Bias resisters, Pb-free solder and Copper tapes (for GEM bias supply) placed in -Y region
 - Their radon emanation was also measured and was not consistent with NEWAGE BG



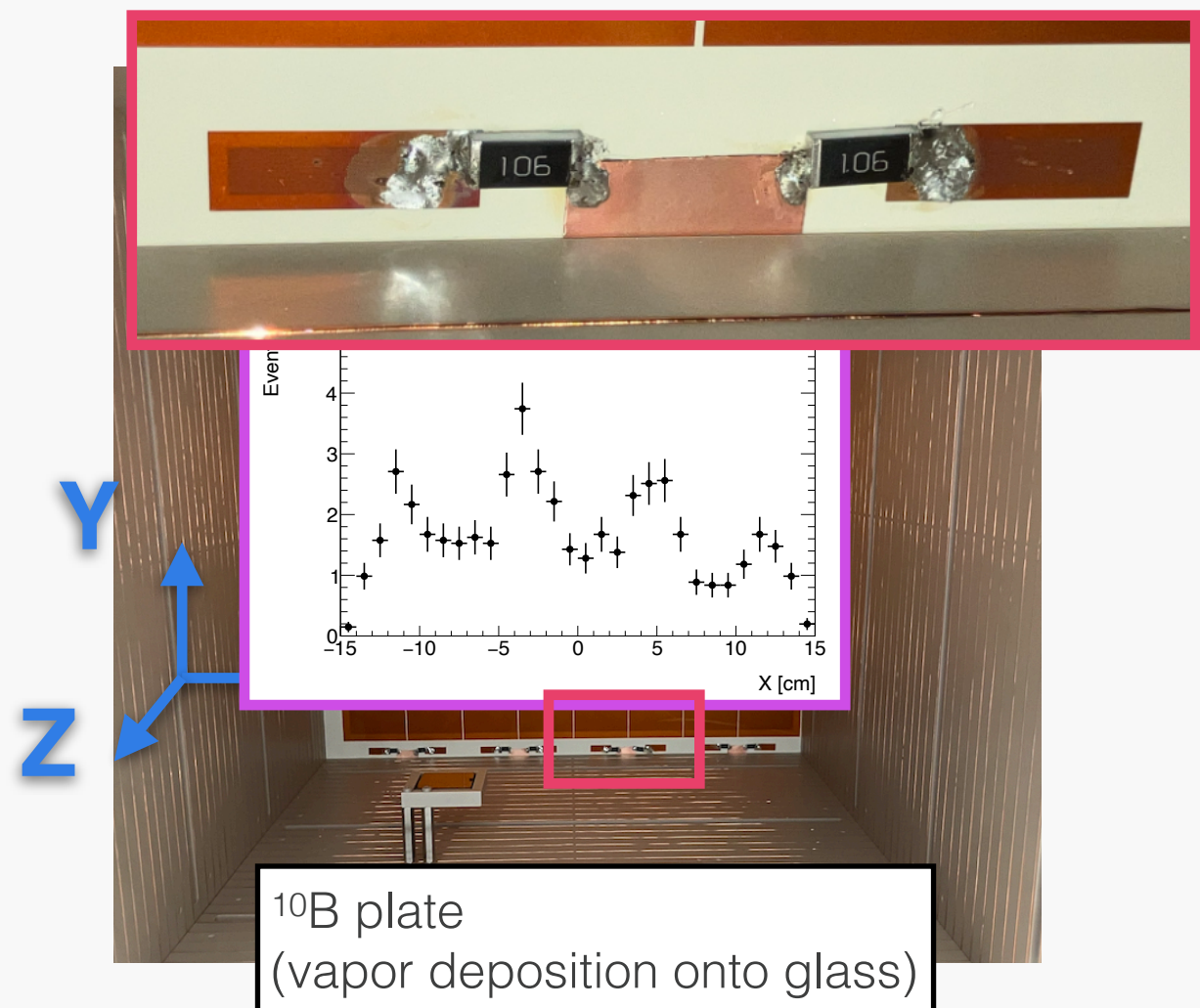
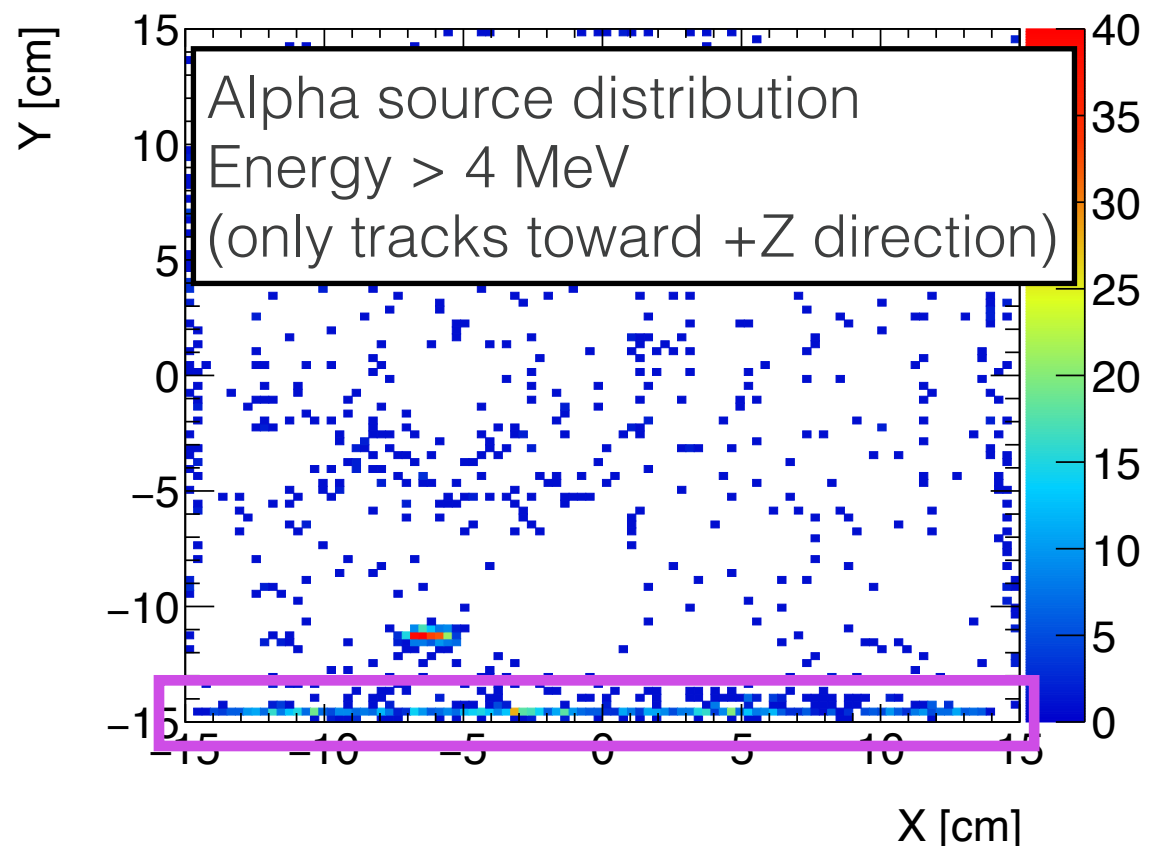
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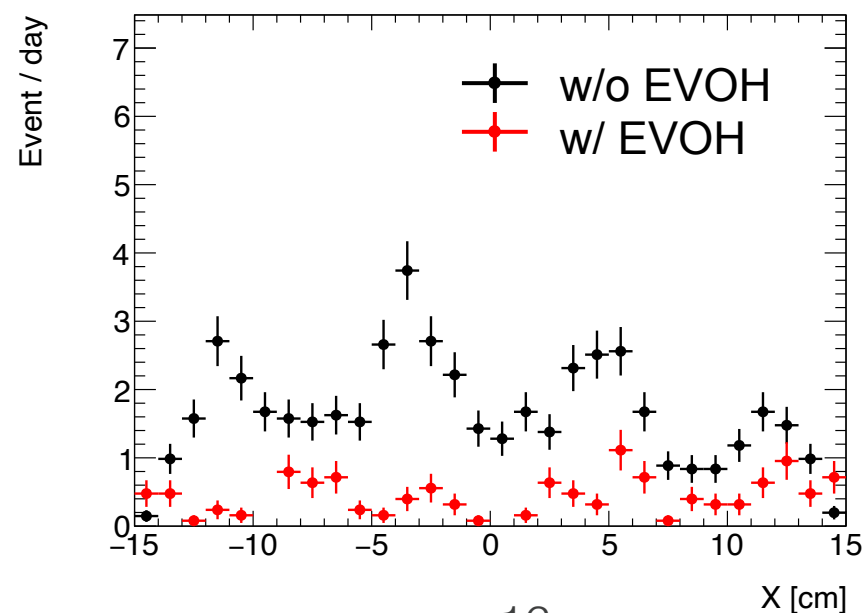
Gas barrier with EVOH film

- Bias resistors was covered with **EVOH** (Ethylene-vinyl alcohol copolymer) film
 - ➔ to suppress surface alpha and radon contamination to the gas region
- **Surface alpha successfully rejected**, but internal radon decays still appear
 - ➔ Slightly decreasing but statistics not sufficient yet to conclude it
 - ➔ Also need to investigate the ROI region in lower energy
- **Demonstration of BG reduction campaign using track analysis achieved!!**

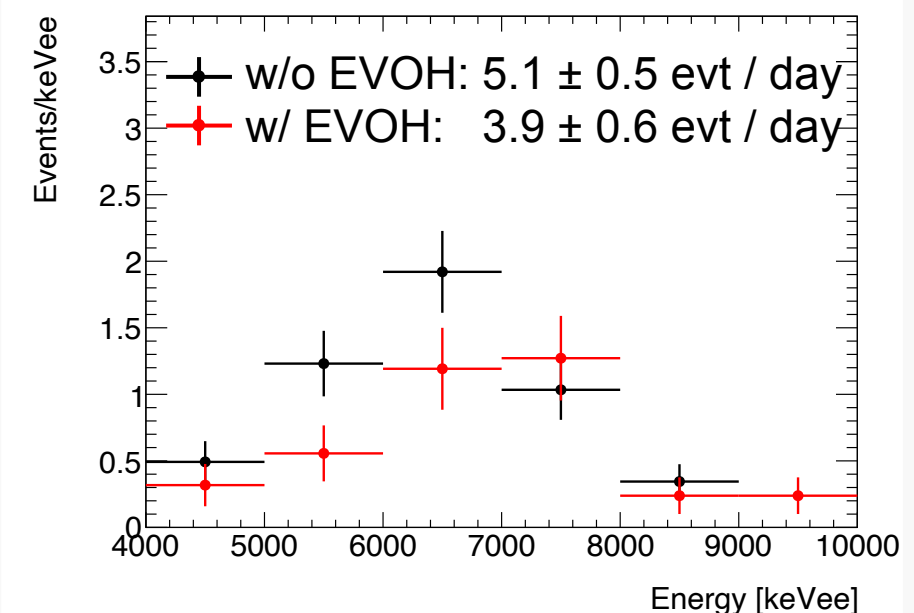
Cover with EVOH film



Track source distribution around -Y region



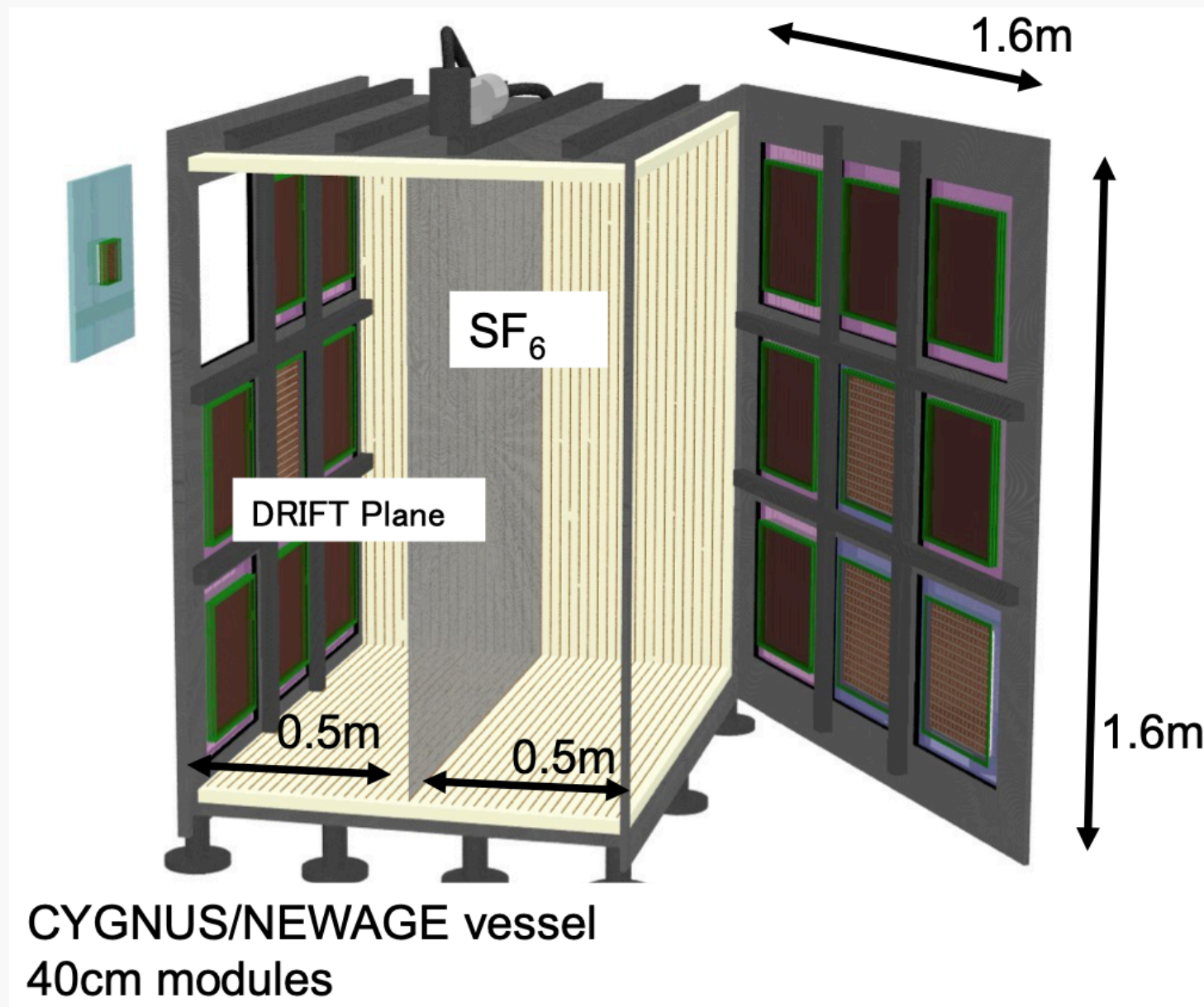
Energy distribution (radon-alpha events will make a peak around 6 MeV)



CYGNUS-KM / NEWAGE (C/N-1.0)

- Modulated chamber ($\sim 1 \text{ m}^3$) : 18 module windows are available
 - ➔ Enables to install the conventional NEWAGE detector ($30 \times 30 \text{ cm}^2$ fiducial area)
 - ➔ We can accept detectors from any other groups: your “clean” detectors are candidates!

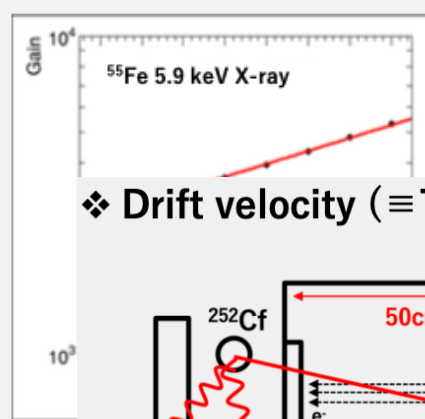
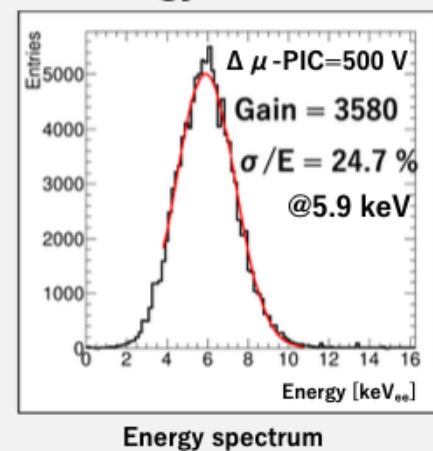
Ryota will present the status of C/N-1.0 commissioning!



C/N-1.0 commissioning w/ a modular detector

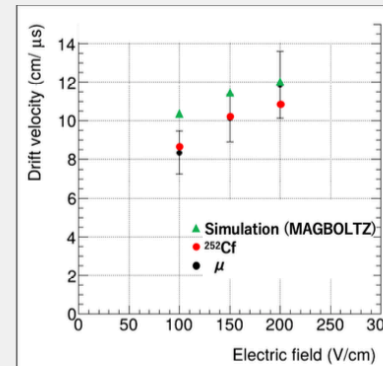
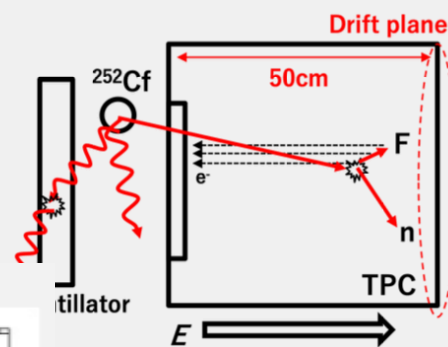
- Test with small area ($10 \times 10 \text{ cm}^2$) GEM + μ -PIC system
 - ➔ 2 strip bundled readout ($\approx 800 \mu\text{m}$ pitch) due to limited electronics

❖ Energy

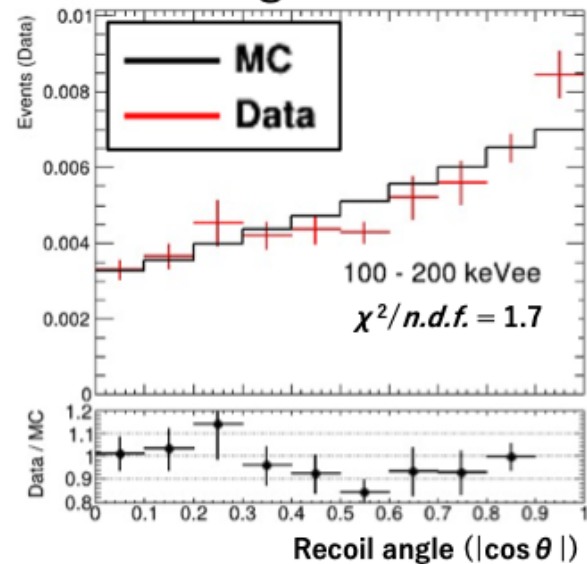


Lots of demonstrations !

❖ Drift velocity ($\equiv$ Track length)

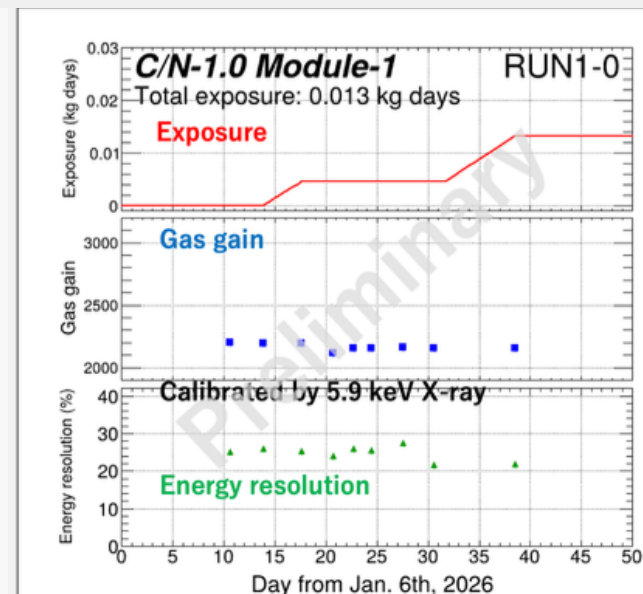


Recoil angle distribution

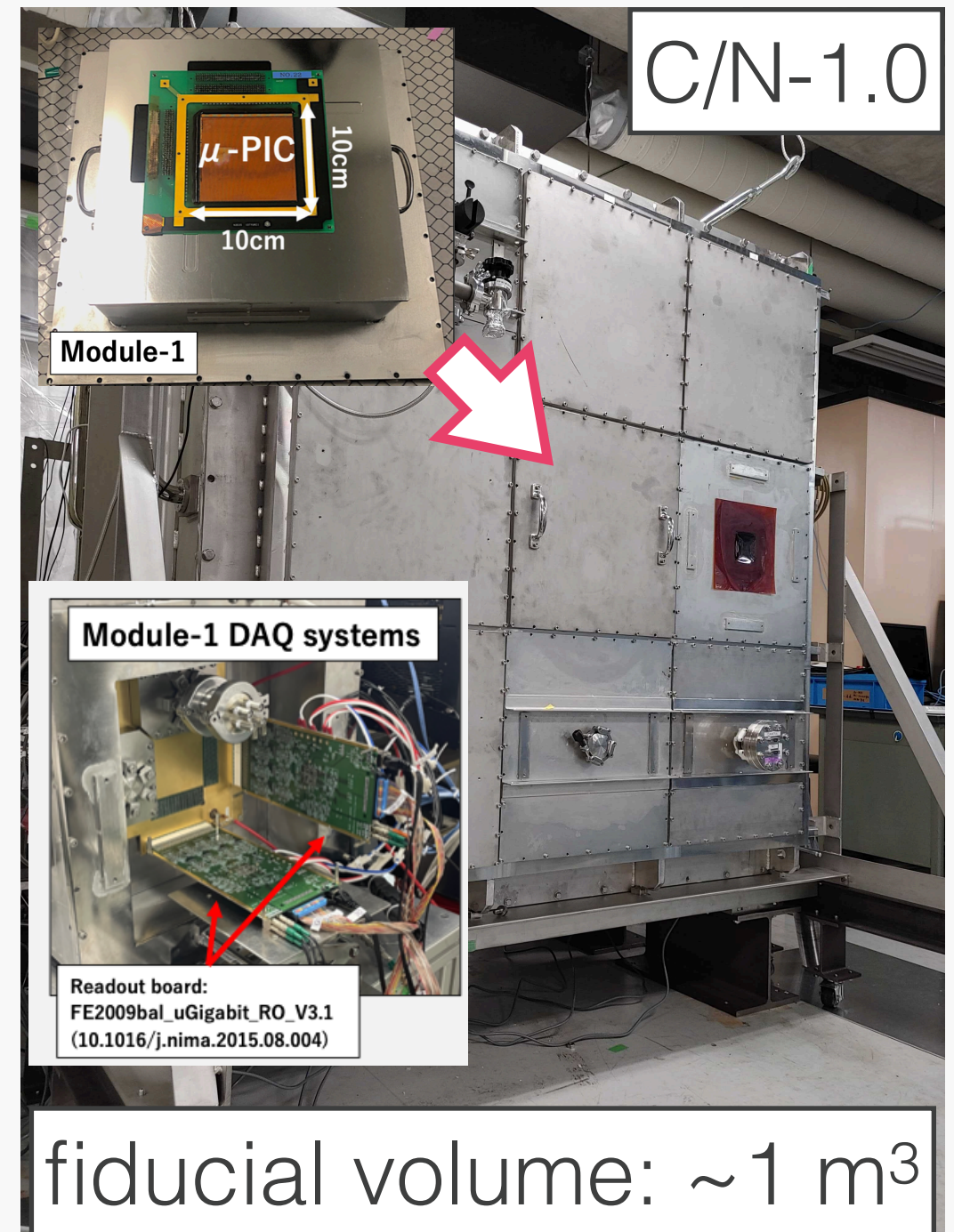


Schematic of measurement

Electric field vs. Drift velocity



Detector status transition



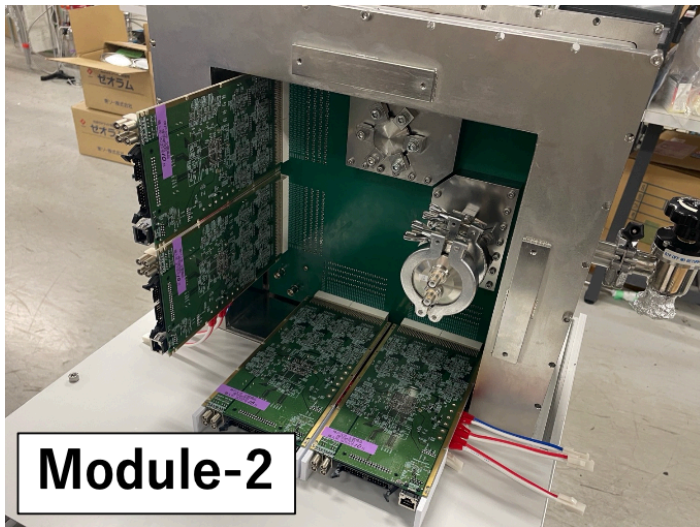
Poster:
(P25 R.Namai)

LAST SURFACE COMMISSIONING!!!

- Test with small area ($10 \times 10 \text{ cm}^2$) GEM + μ -PIC system

400 μm

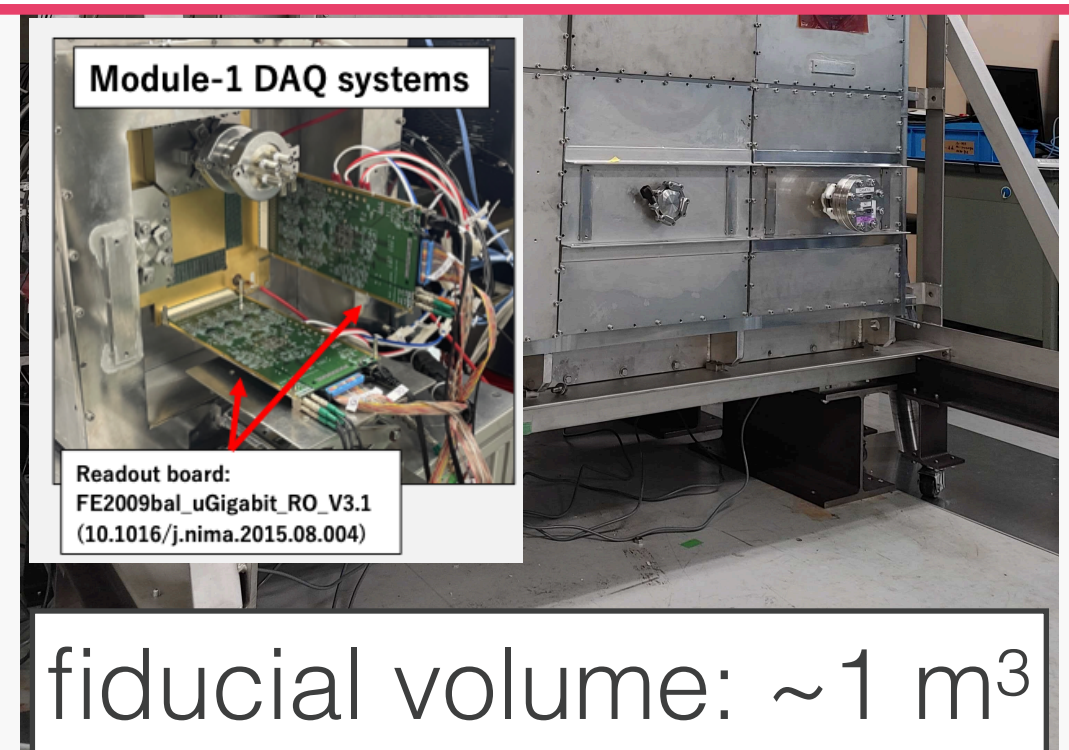
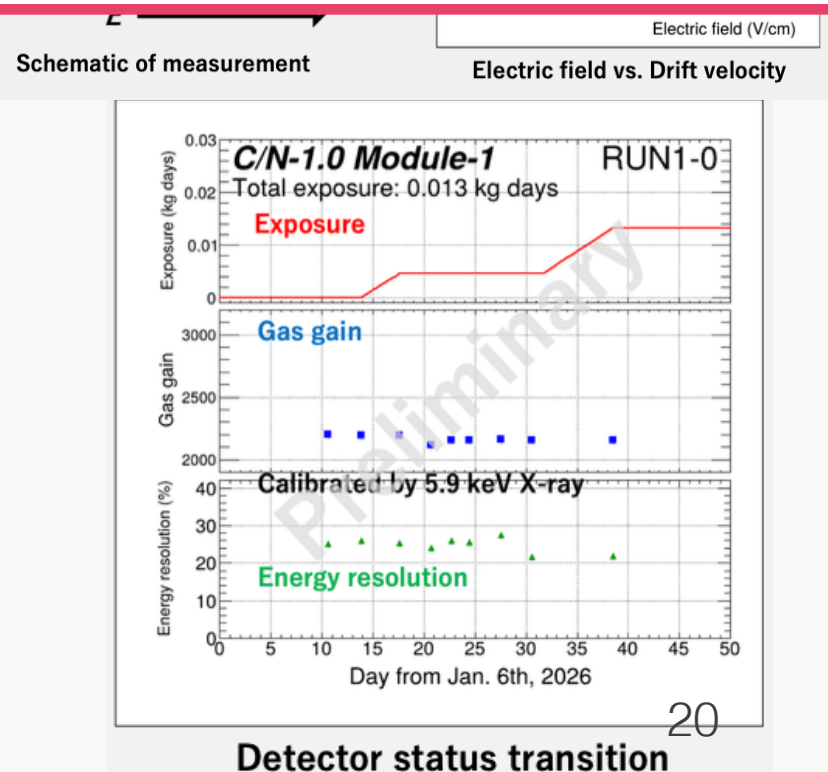
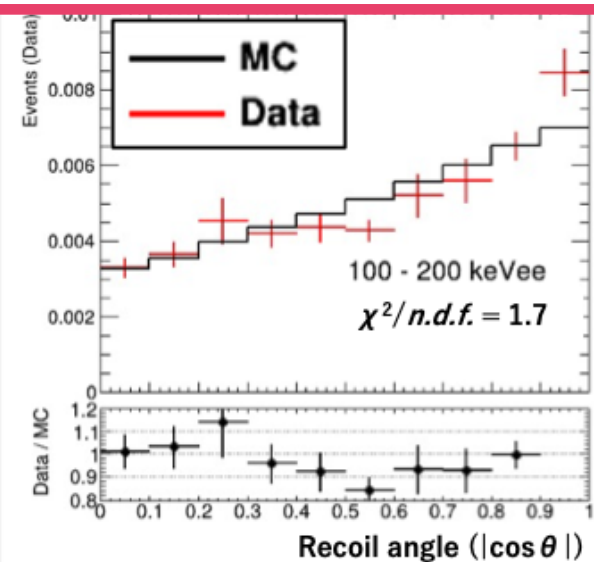
→ ~~2 strip bundled readout ($\pm 800 \mu\text{m}$ pitch)~~ due to limited electronics



$10 \times 10 \text{ cm}^2$ modular detector w/ full electronics already prepared (equivalent to the detector in Kamioka).

Small but more stable detector will achieve high gain operation, allowing to explore **lower mass region**.

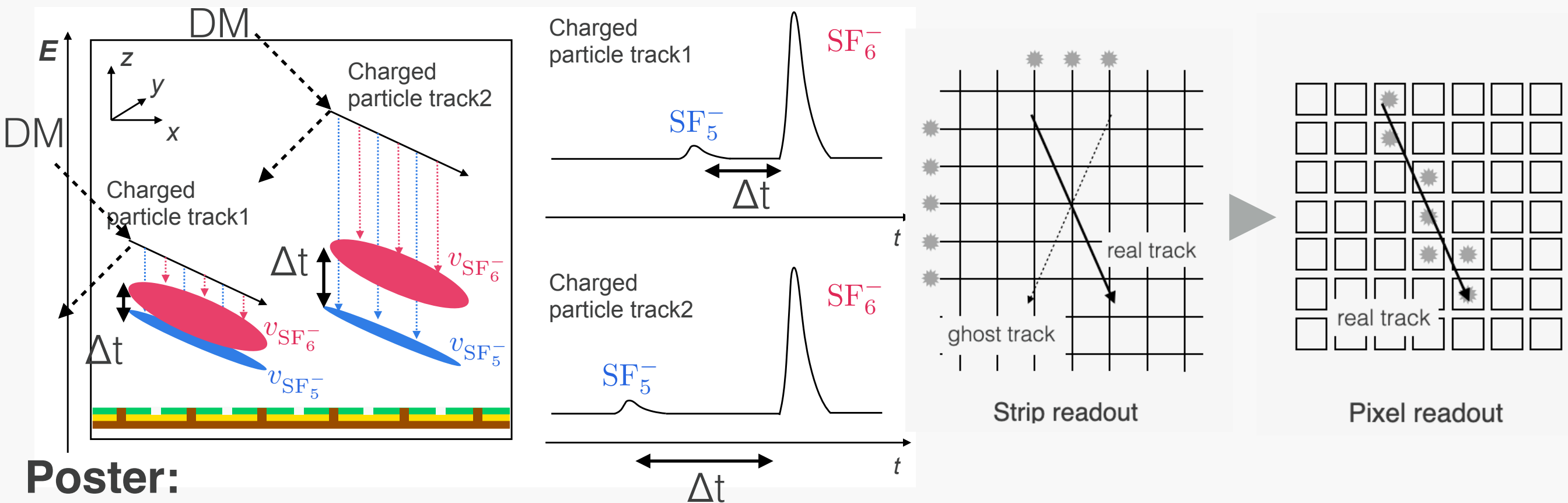
The detector will be installed right after UGRP2026!



Poster:
(P25 R.Namai)

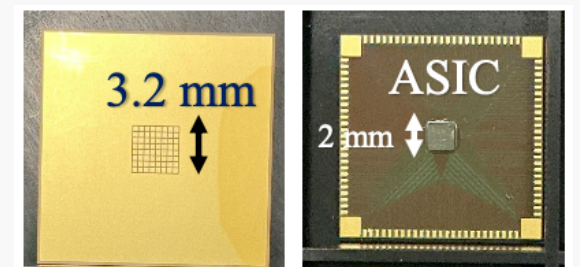
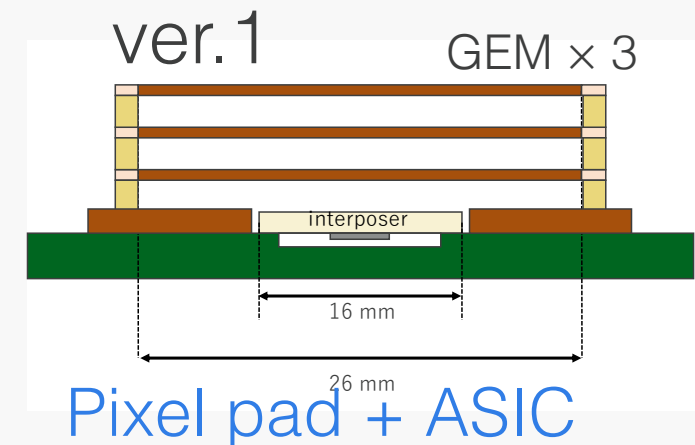
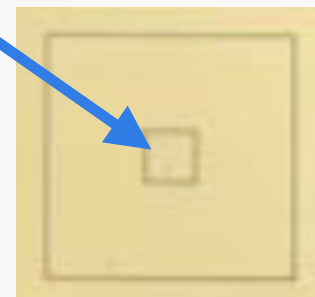
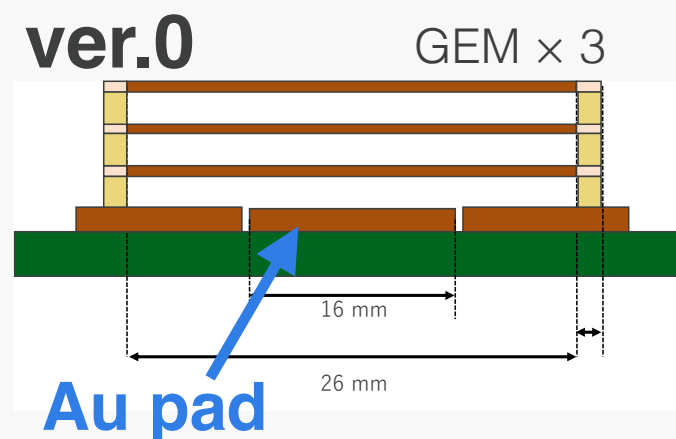
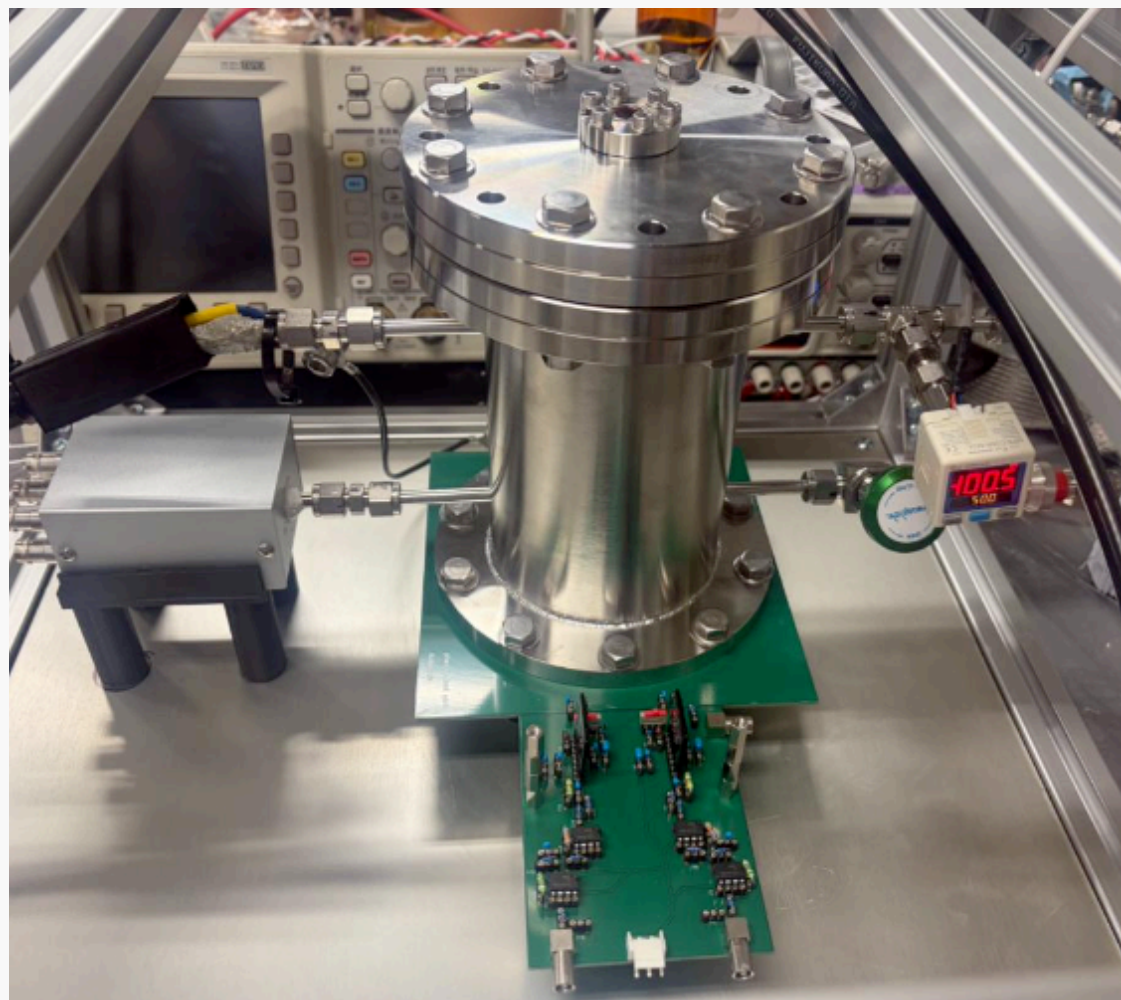
Future detector: Negative-ion $\times$ Pixel

- “Negative-ion gas” such as SF_6 allows to reconstruct absolute 3D position
 - Ionized electrons are attached to SF_6 and form mainly two types of negative ion
 - Time difference between these pulse corresponds to charged track position along the drift coordinate
 - **Background events nearby detector surface and drift plane can be rejected analytically**
 - Diffusion of negative-ion drift is relatively smaller than that of electron drift
- Combination of high granularity pixelated electrode leads more precise track reconstruction
 - Pixel readout resolves track ambiguity



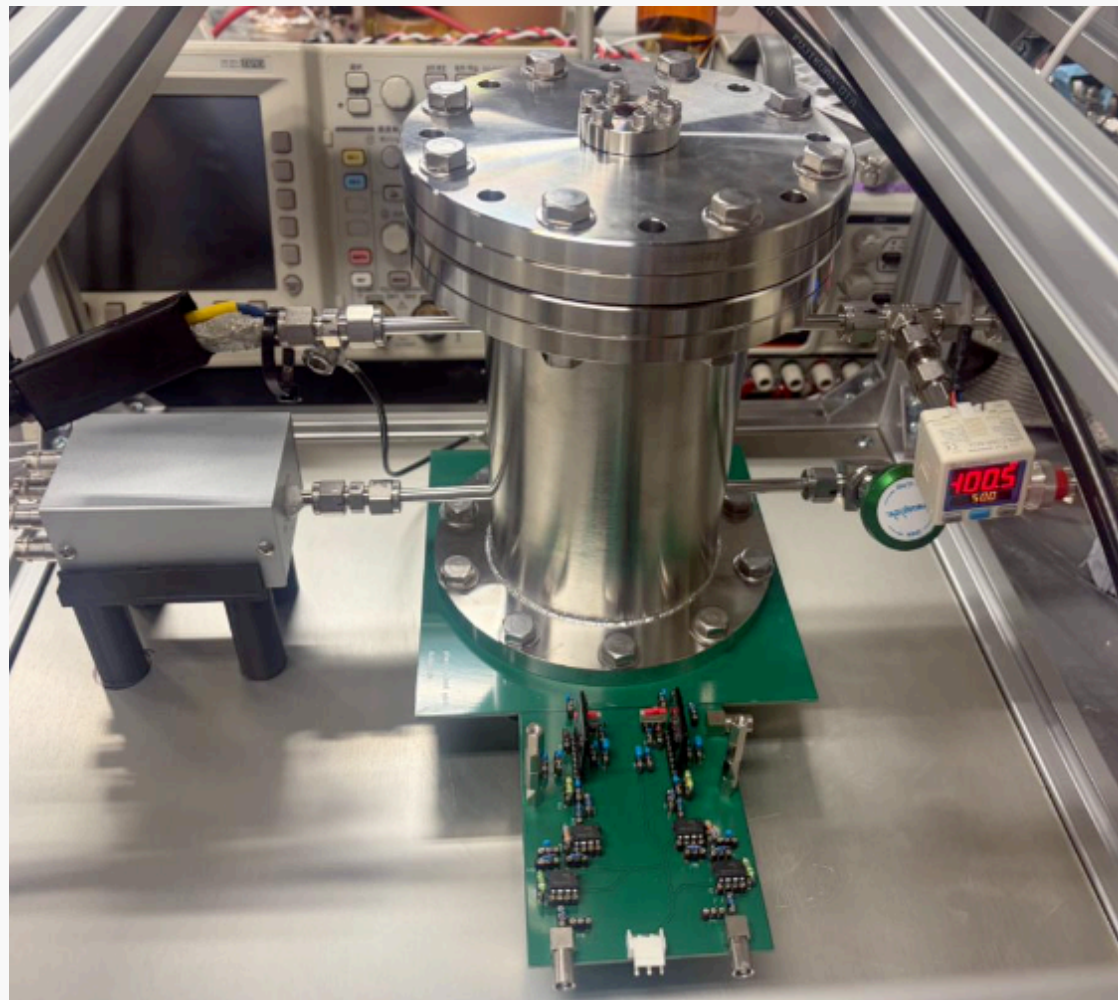
Detector development

- Prototype detector being preparation
 - ➔ **Ver.0**: Simple 1 channel pad electrode for gas studies
 - ➔ Ver.1: 64 ch, 400 μm pitch pixelated electrodes (electronics under development)

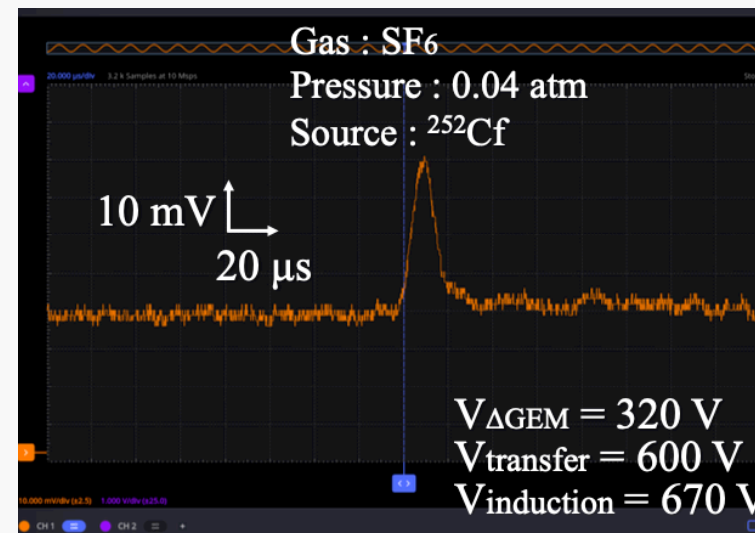
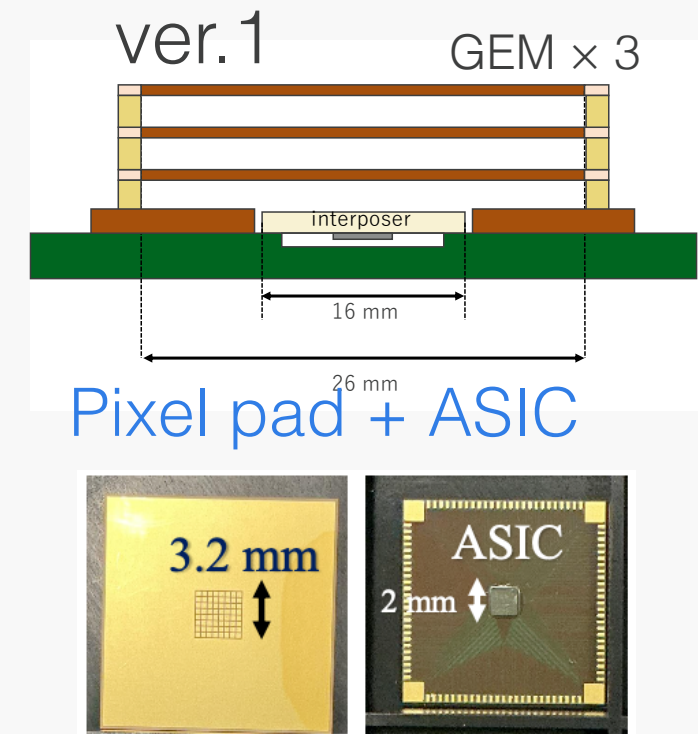
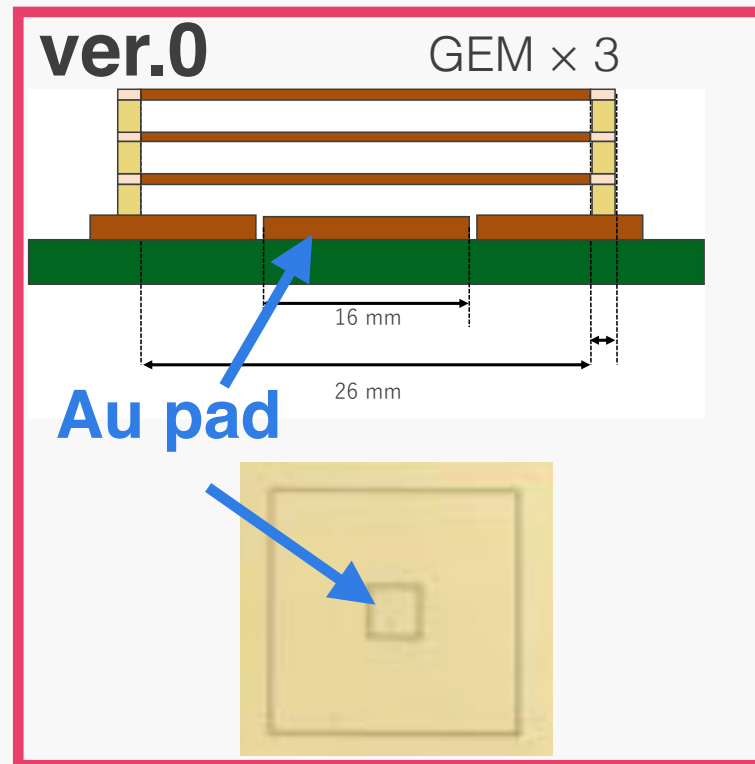


Detector development

- Prototype detector being preparation
 - ➔ **Ver.0**: Simple 1 channel pad electrode for gas studies
 - ➔ Ver.1: 64 ch, 400 μm pitch pixelated electrodes (electronics under development)



Poster:
(P18 W.Toyama)

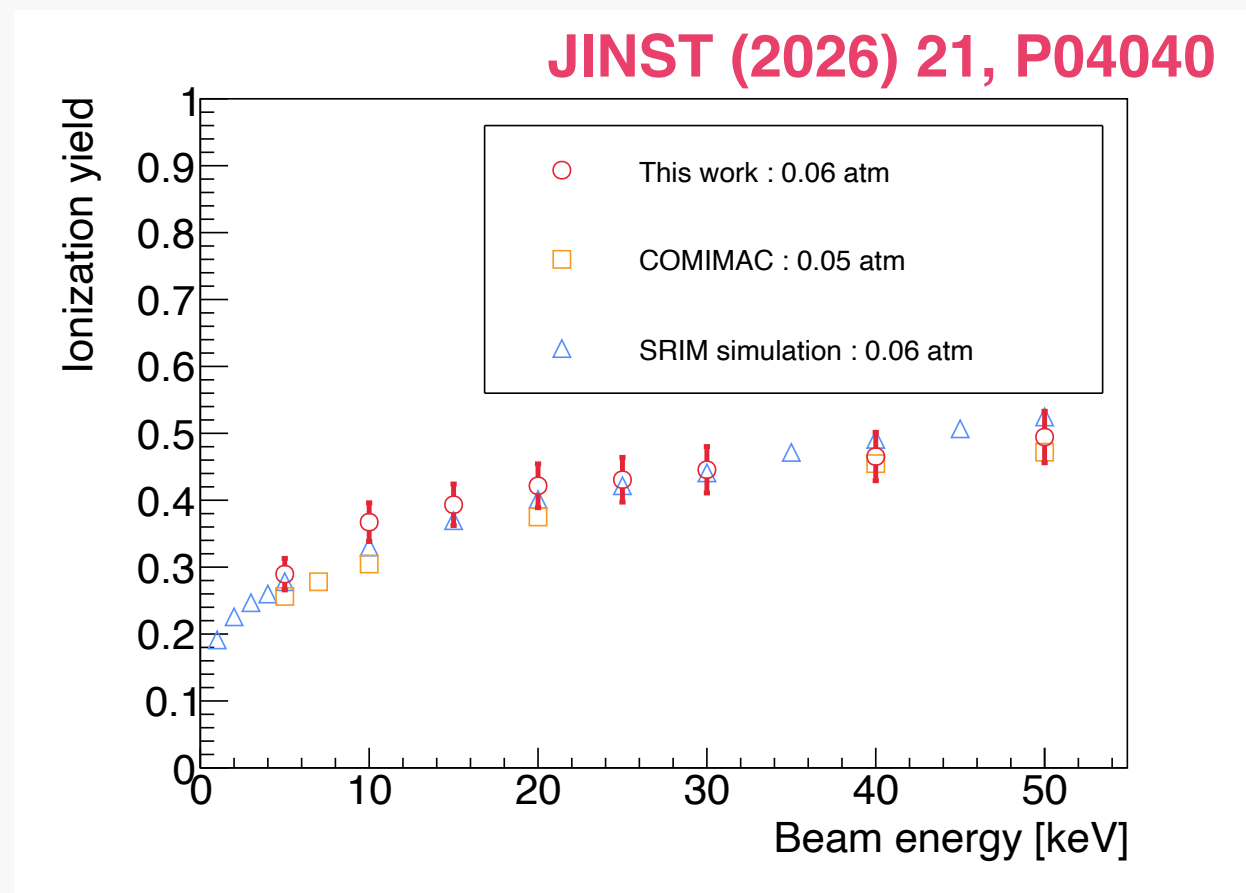
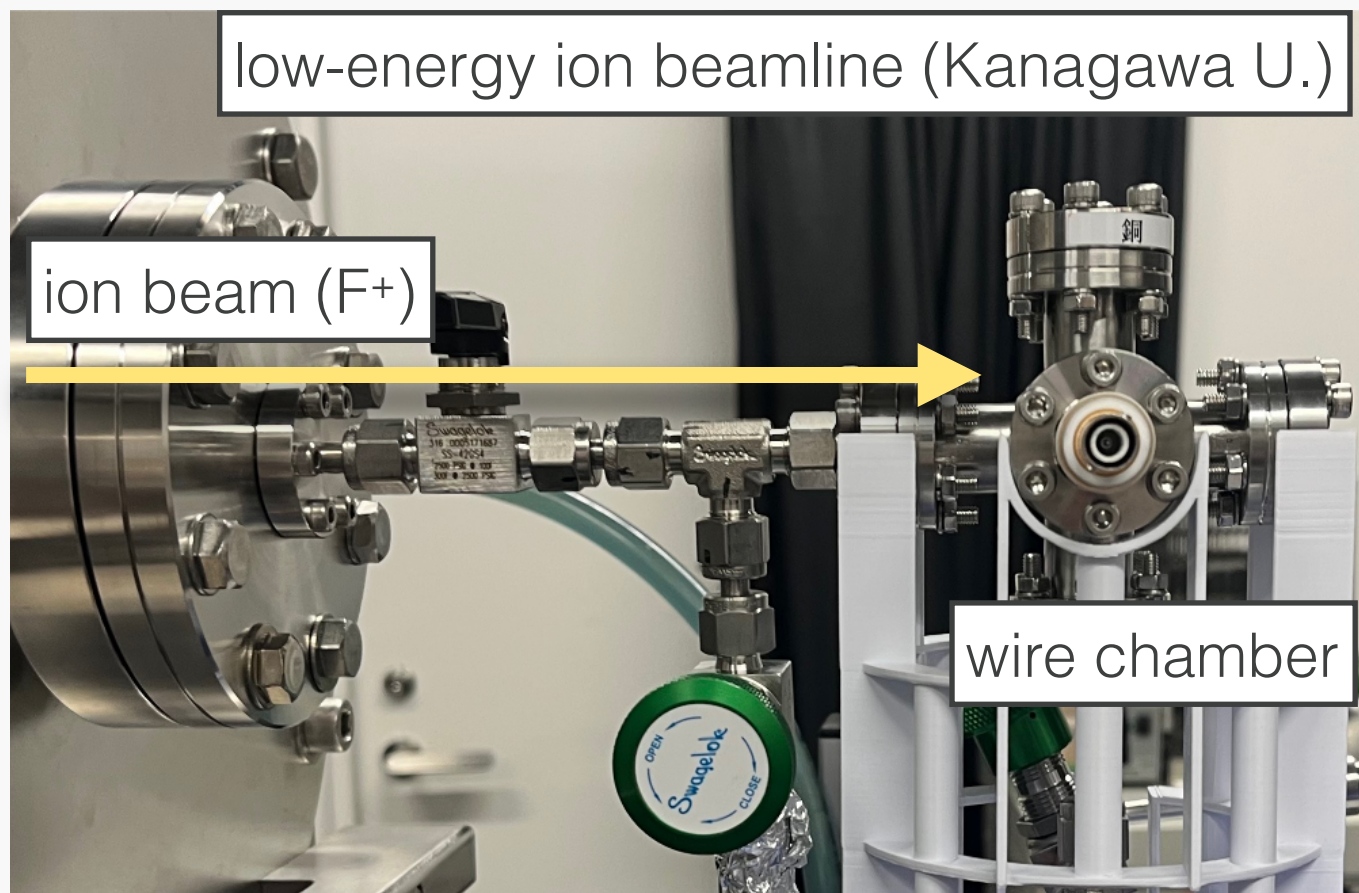


First light for the
prototype detector!

Ver.1 pixelated detector
stay tuned!!

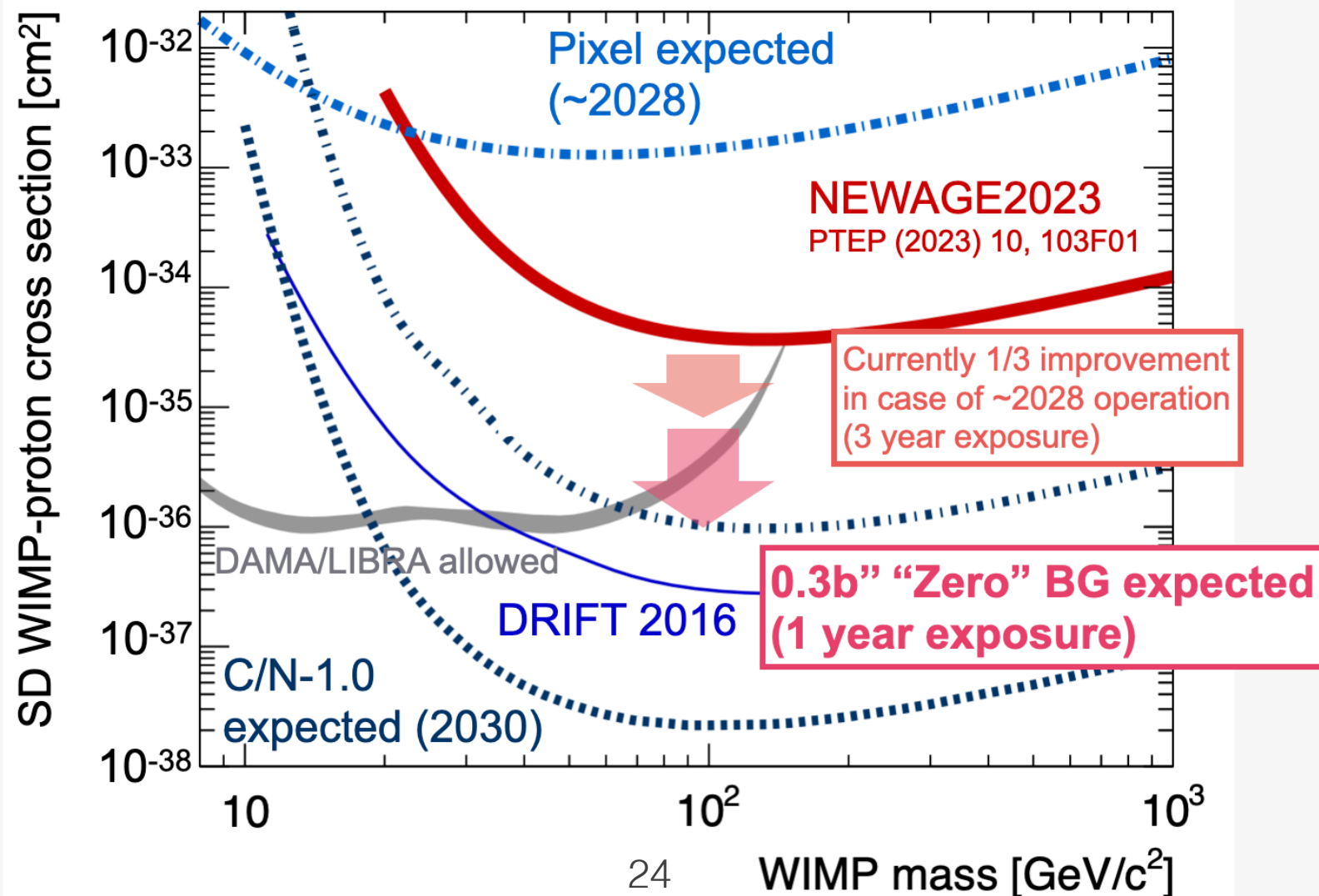
Ionization yield measurement

- Precise energy measurement is important as well as the directionality
 - ➔ Low-energy ion beam test was performed at 5-200 kV acceleration facility at Kanagawa U.
- 5 - 50 keV fluorine ions were injected to single-wire proportional chamber
 - ➔ filled with 0.06 atm CF_4 gas (assuming low-pressure NEWAGE operation)
- Result is consistent with COMIMAC and SRIM
 - ➔ Good demonstration of low-energy ion injection into gas detector in Japan!



Conclusion

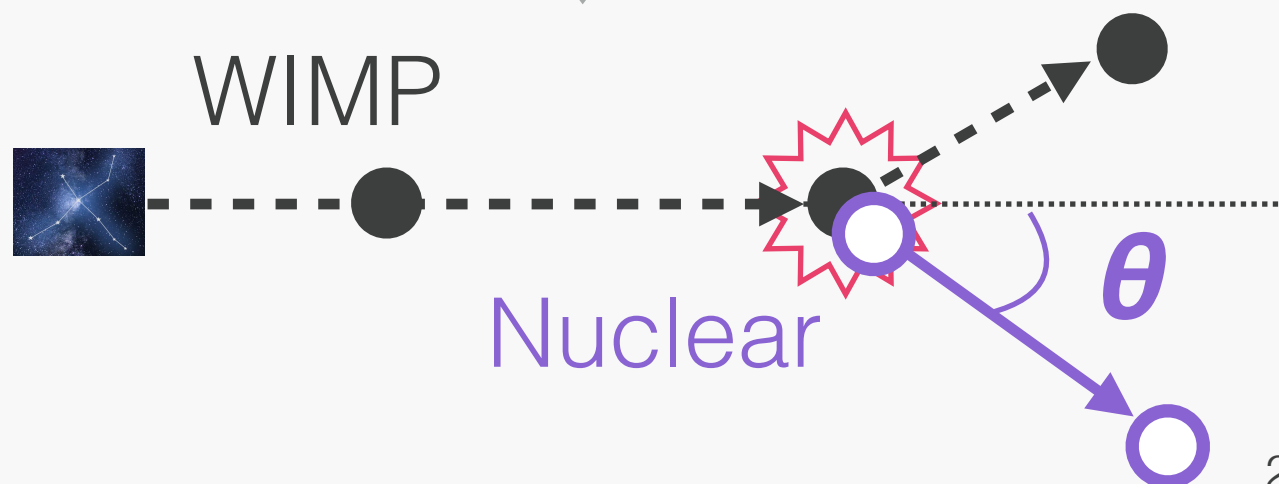
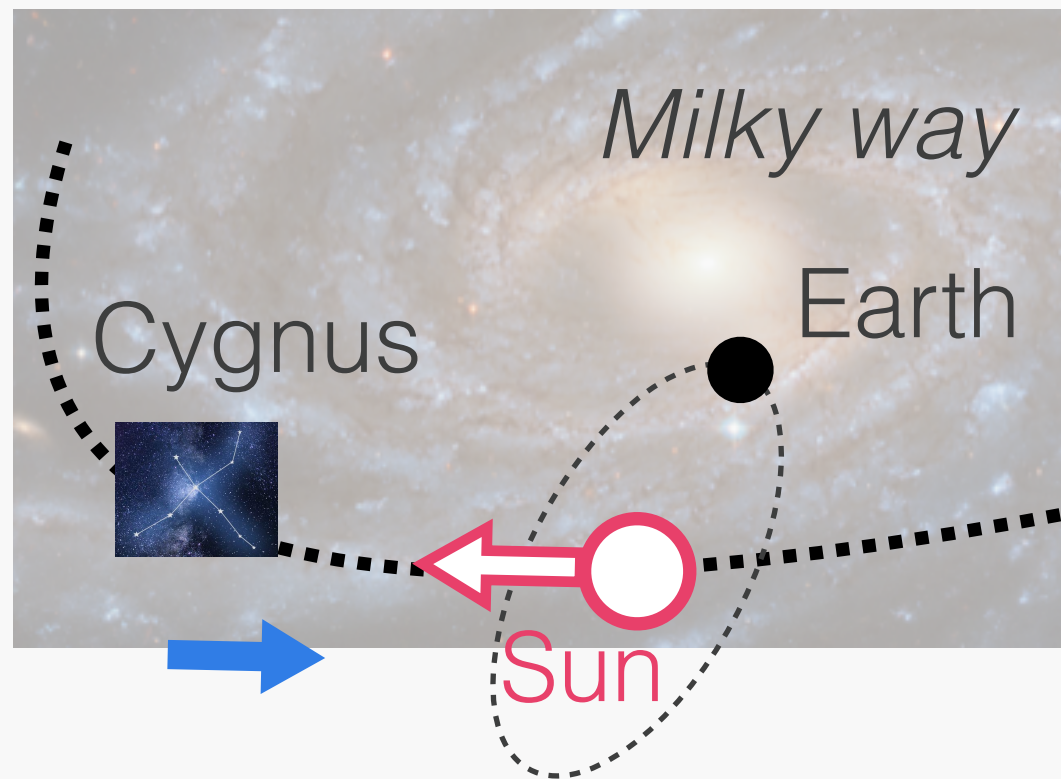
- NEWAGE conducts direction-sensitive dark matter search using gaseous TPC
 - ➔ Background reduction and scalability studies mainly ongoing to obtain more sensitivity
- Track analysis can make identify radon emanation sources
- Large scale ($\sim 1 \text{ m}^3$) chamber will be in a final commissioning phase right after this conference
- Next generation detector: negative-ion gaseous TPC assuming pixelated detection system under development



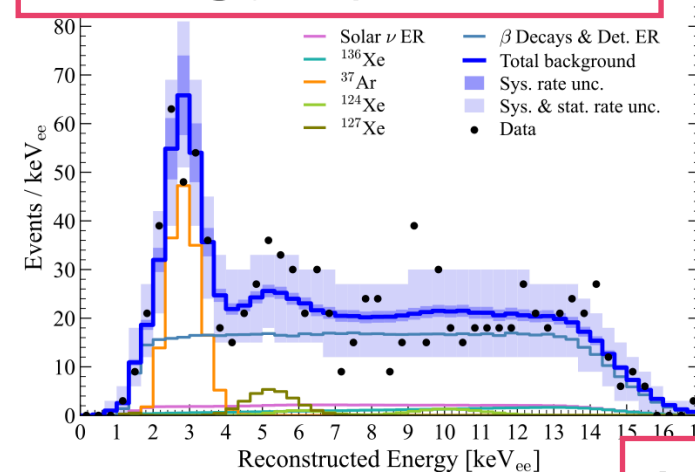
Backup

Direct dark matter (WIMP) searches

- Direct search = SM particle recoil detection
 - ➔ Its kinematics depends on the motion of the Earth, the sun, and the Milky Way Galaxy

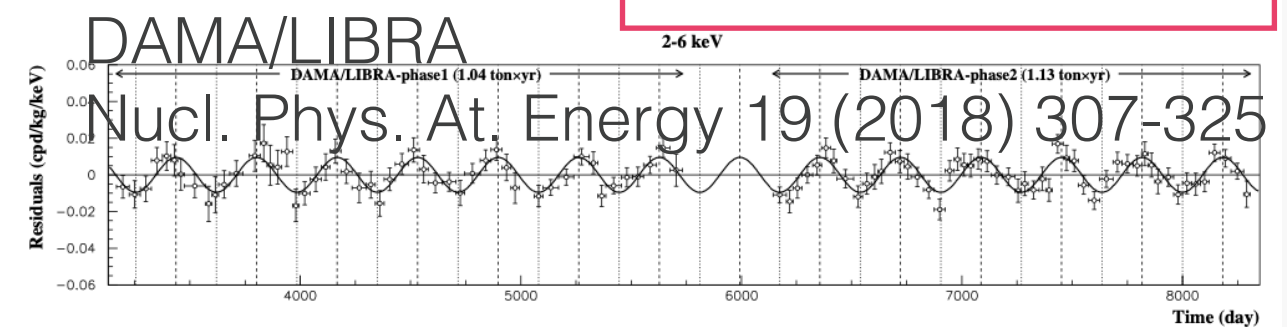


Energy spectrum



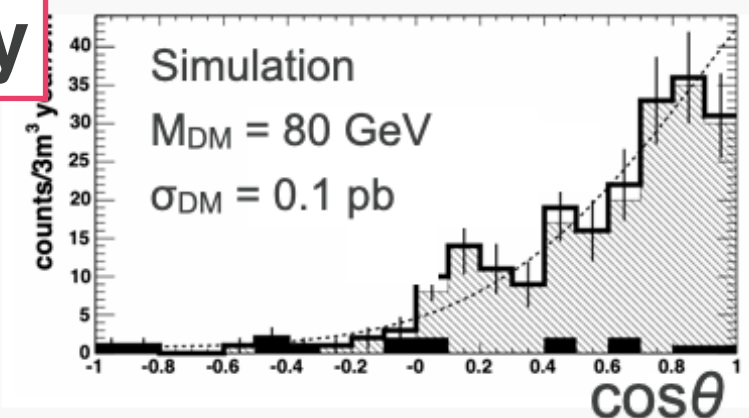
LZ: arXiv:2207.03764

Annual modulation



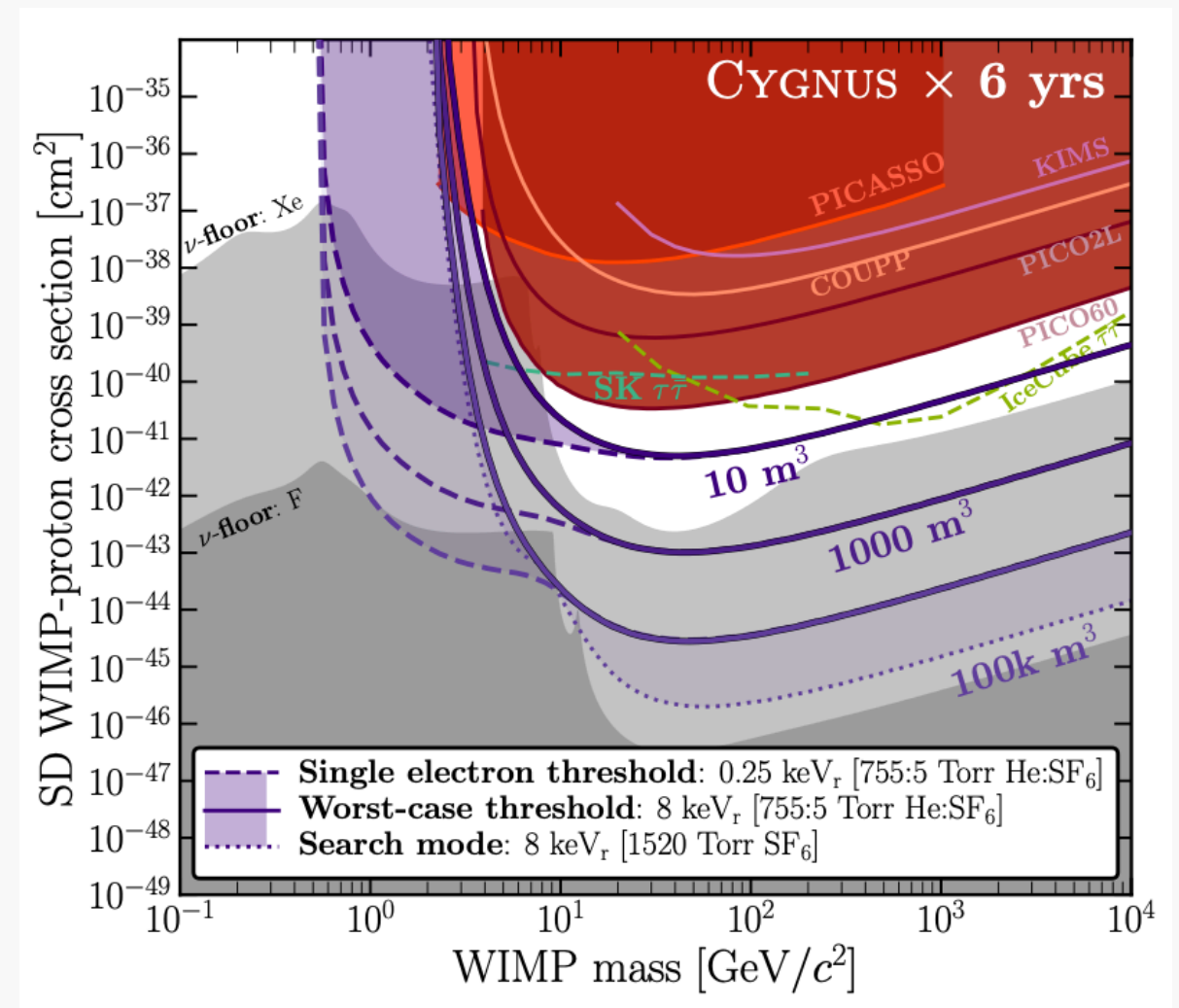
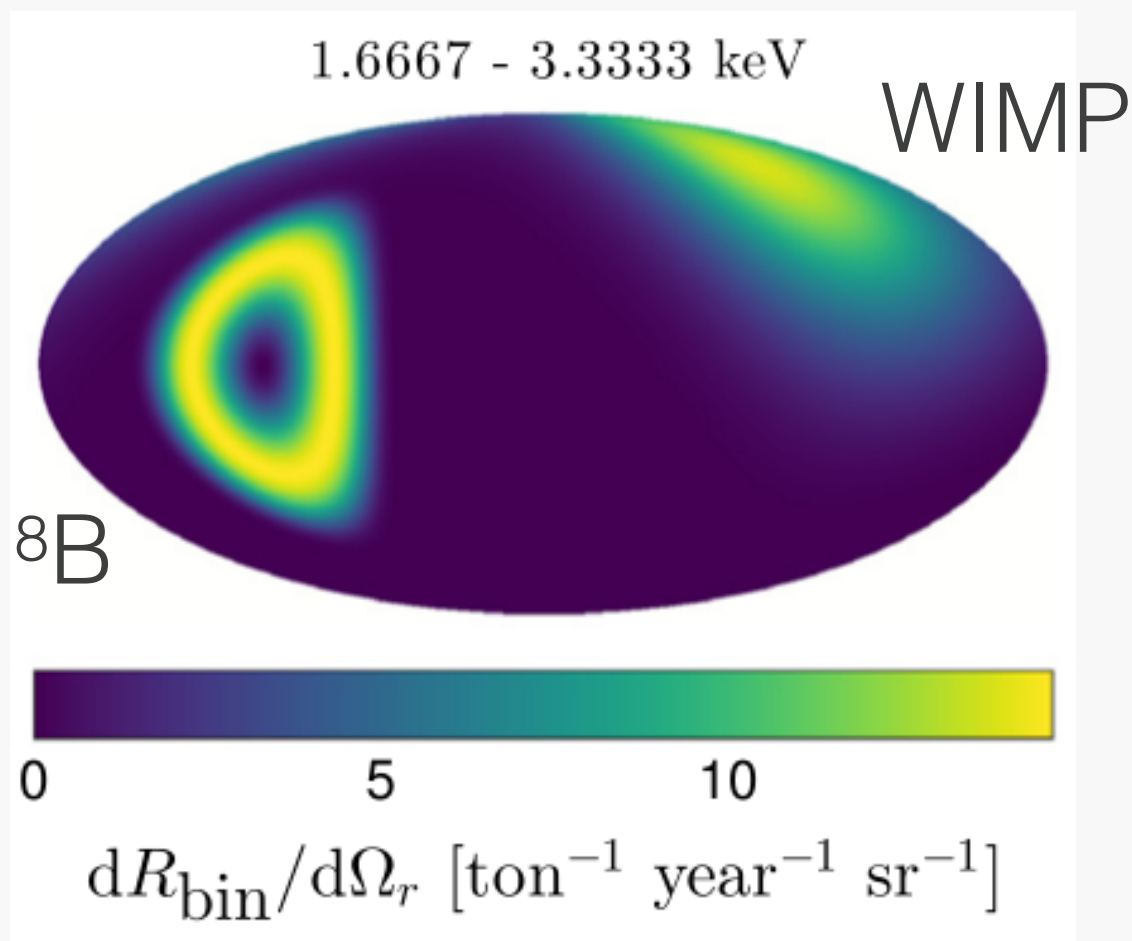
Directionality

PLB 578 (2004)
241-246



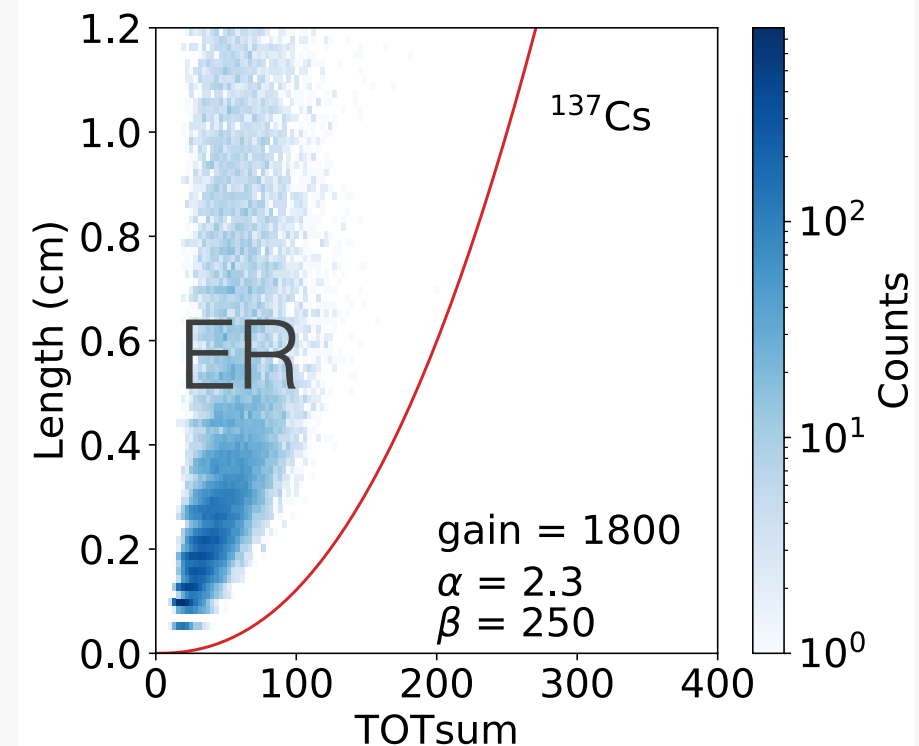
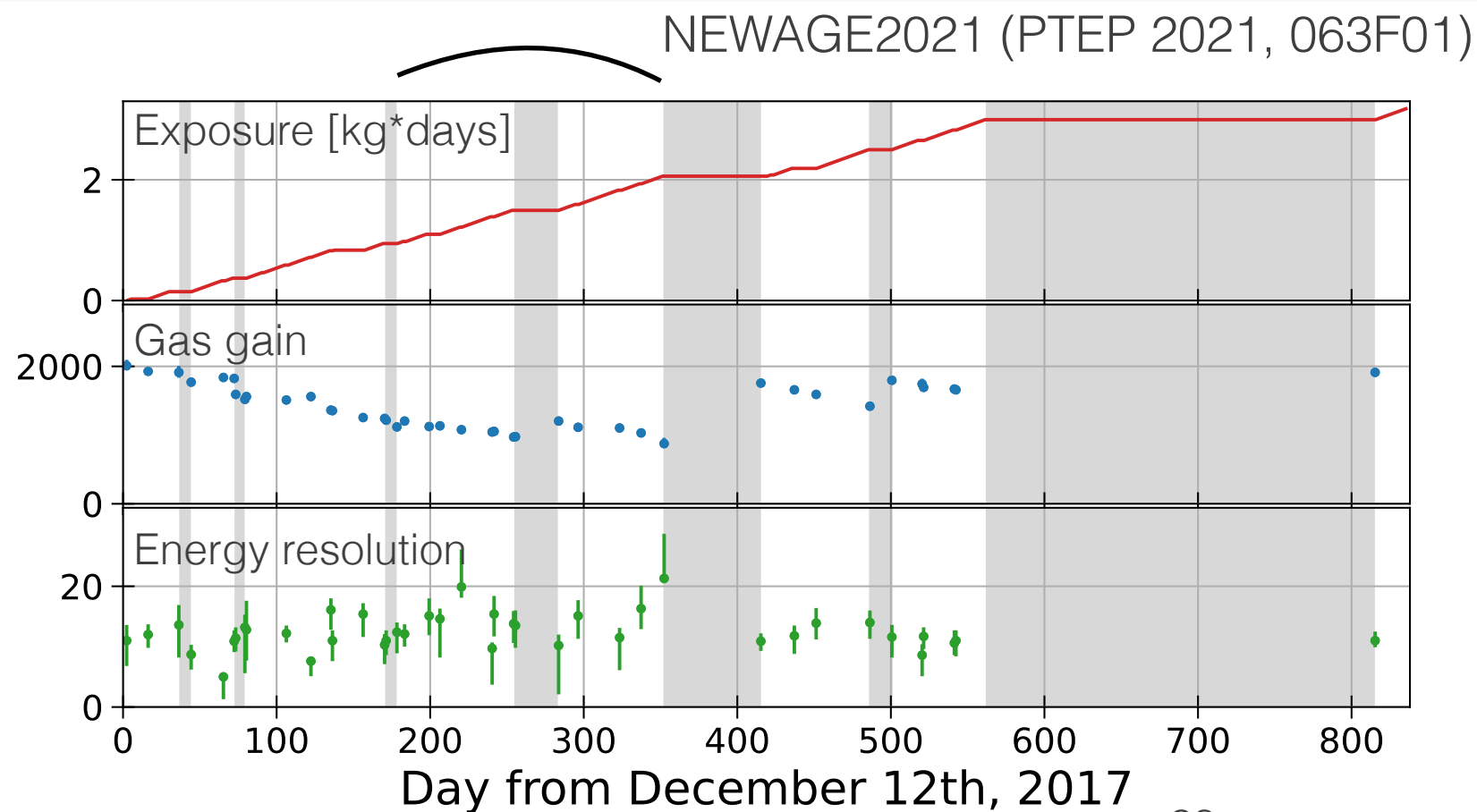
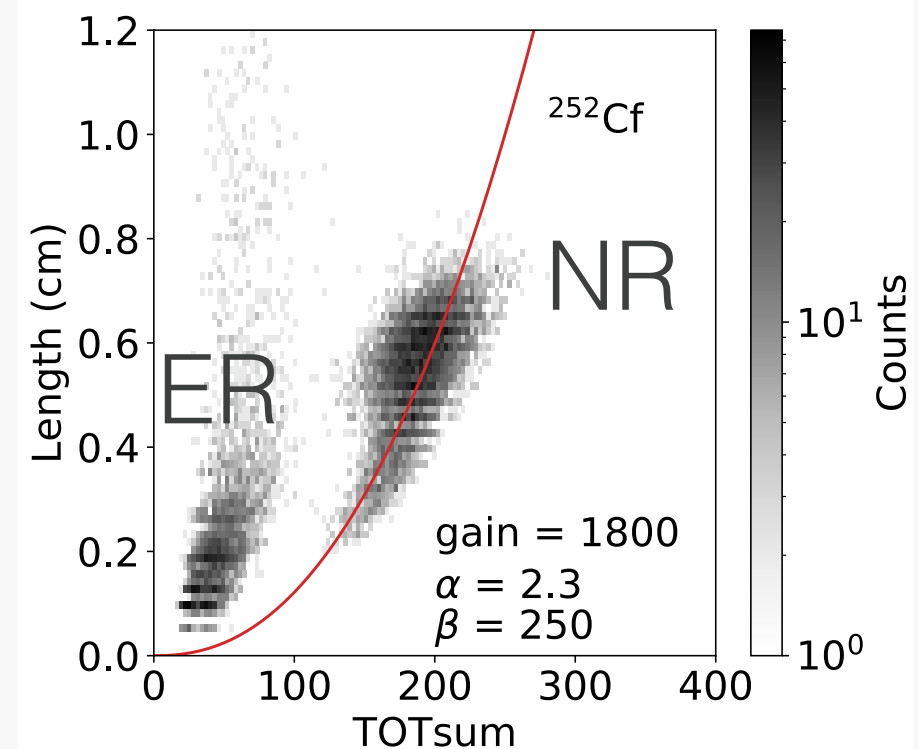
Benefits

- Strong signature of WIMP (CDM)
- Kinematics of DM (isotropic or non-isotropic?)
- ^8B ν rejection allows to explore “neutrino floor”
 - Neutrino-nucleus coherent scattering will be irreducible BG without directionality



Underground measurement

- Increase statistics: 108 days $\rightarrow$ 318 days ($\times 3$)
PTEP 2021, 063F01 (NEWAGE2021)
 - $\rightarrow$ Use higher gain operation run
 - $\rightarrow$ Electron recoil (ER) by gamma rays should be removed
- Additional selection applied with multi-variate analysis
 - $\rightarrow$ correlation between track length, ToT and energy

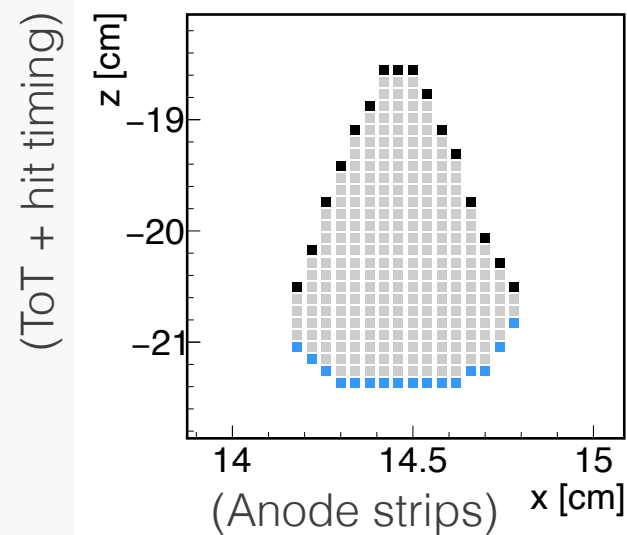
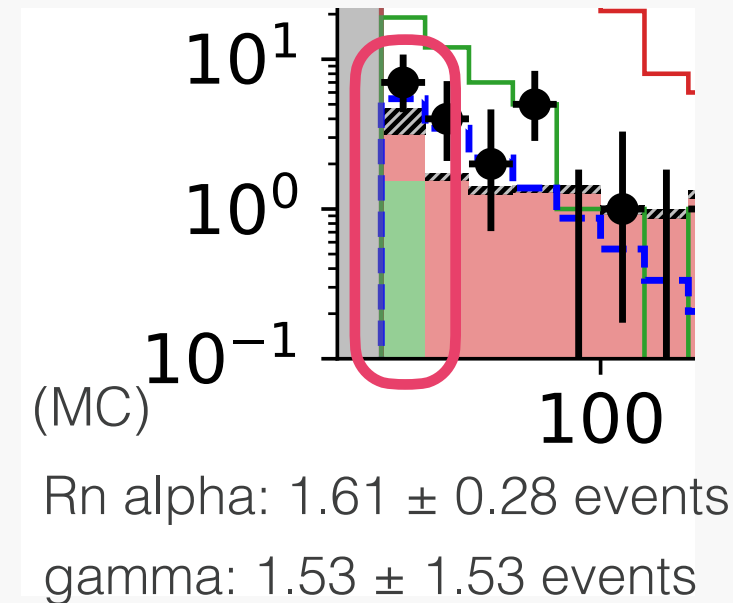


Gamma rejection

(Copper shield)

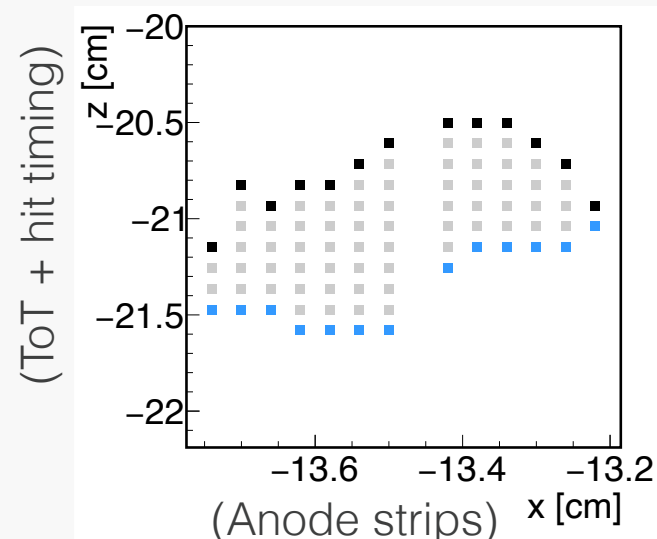
Review of ambient gamma-induced electron recoil

- The lowest energy bin is the most sensitive
 - ➔ Ambient gamma flux had been measured by Csl
 - ➔ Expected events were simulated but 100% unc. assigned
 - Detector response was not completely understood



Nuclear recoil-like event
in ^{252}Cf source run

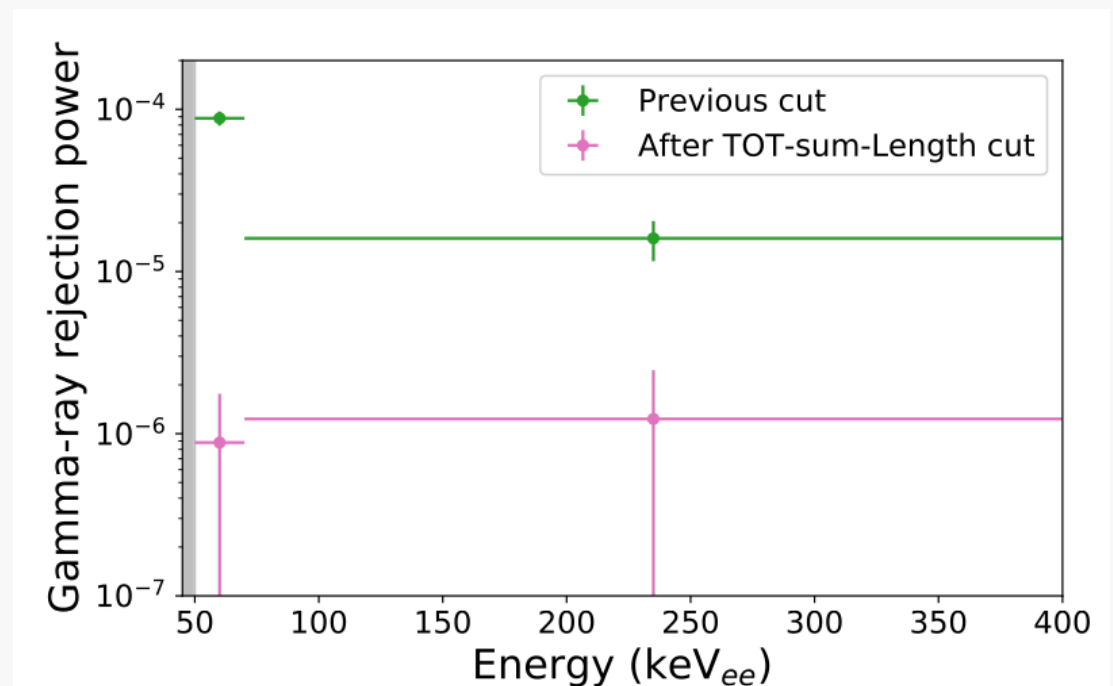
$$E = 160 \text{ keV}_{ee}$$



Electron recoil-like event
in ^{137}Cs run

$$E = 72 \text{ keV}_{ee}$$

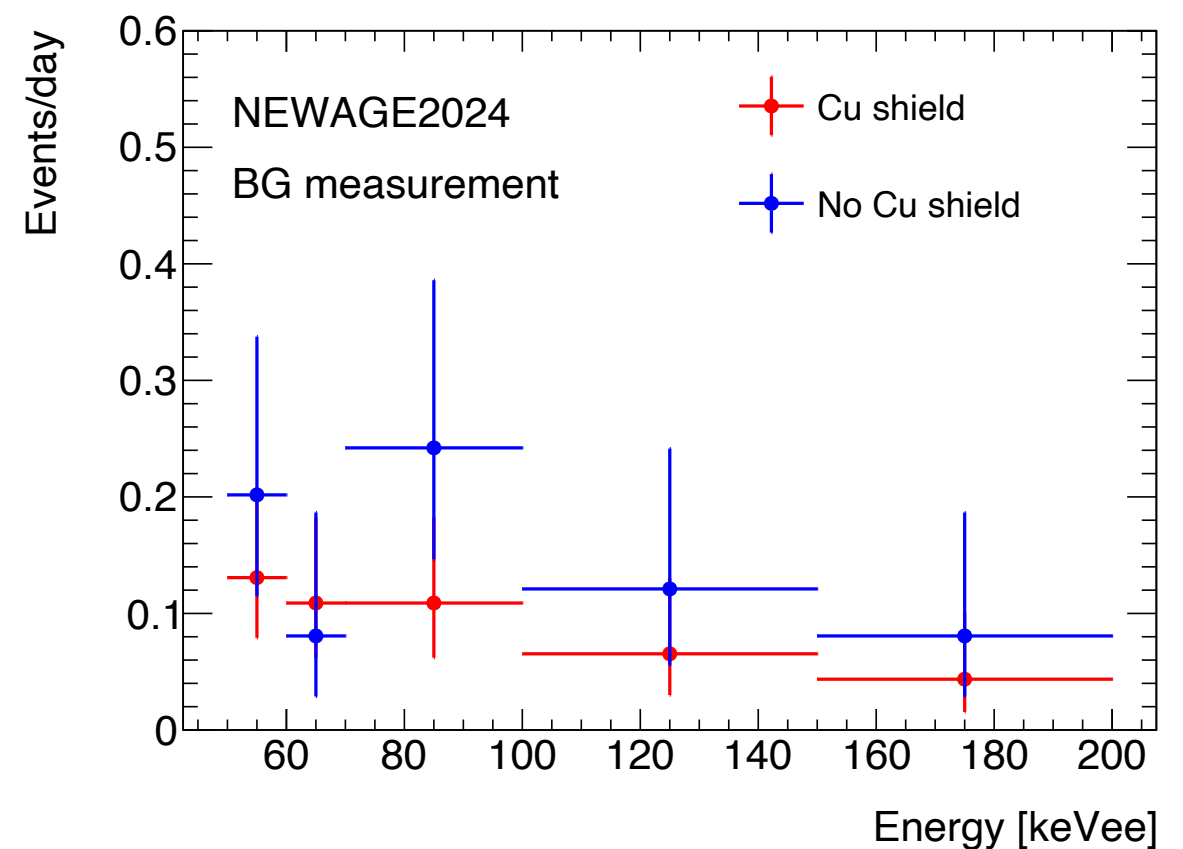
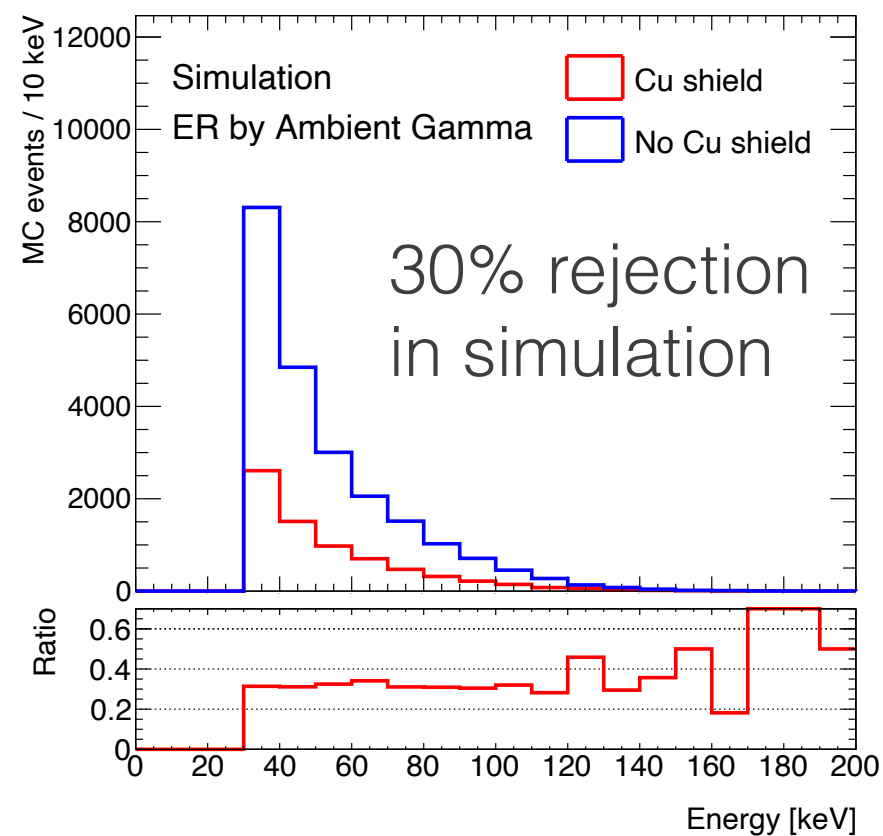
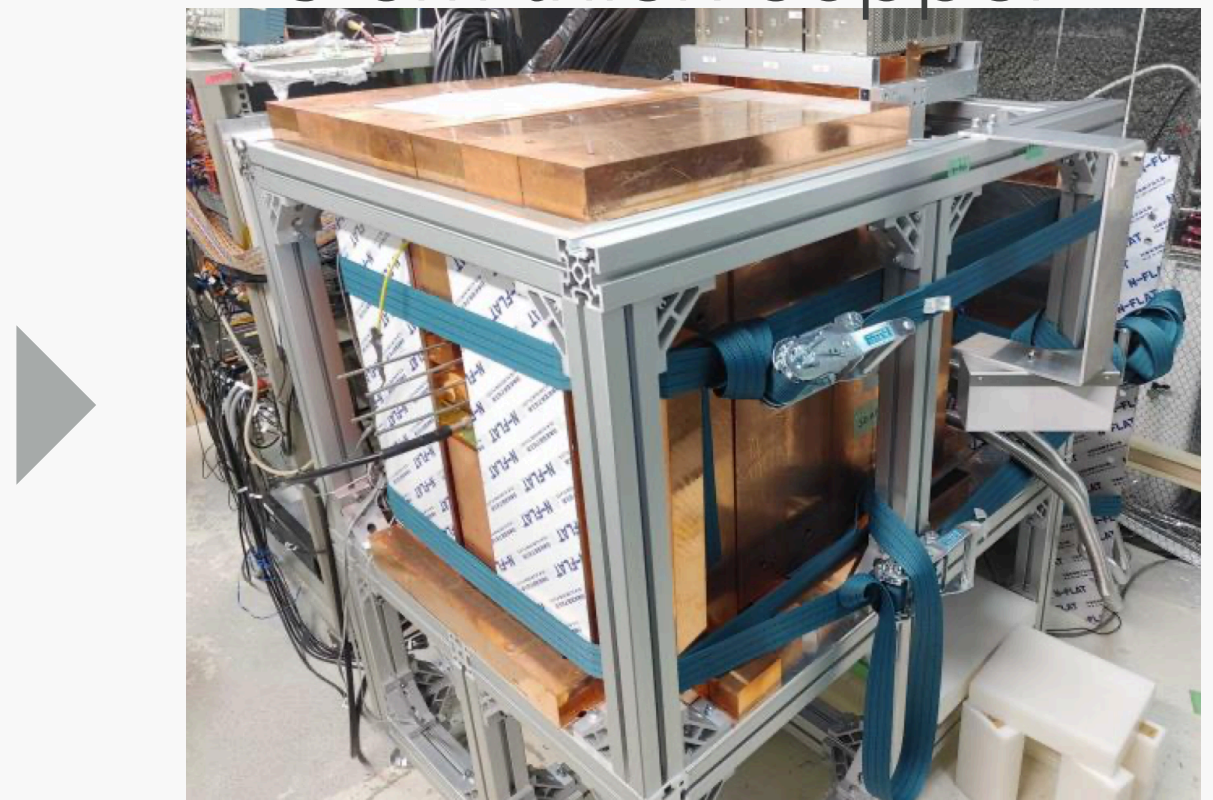
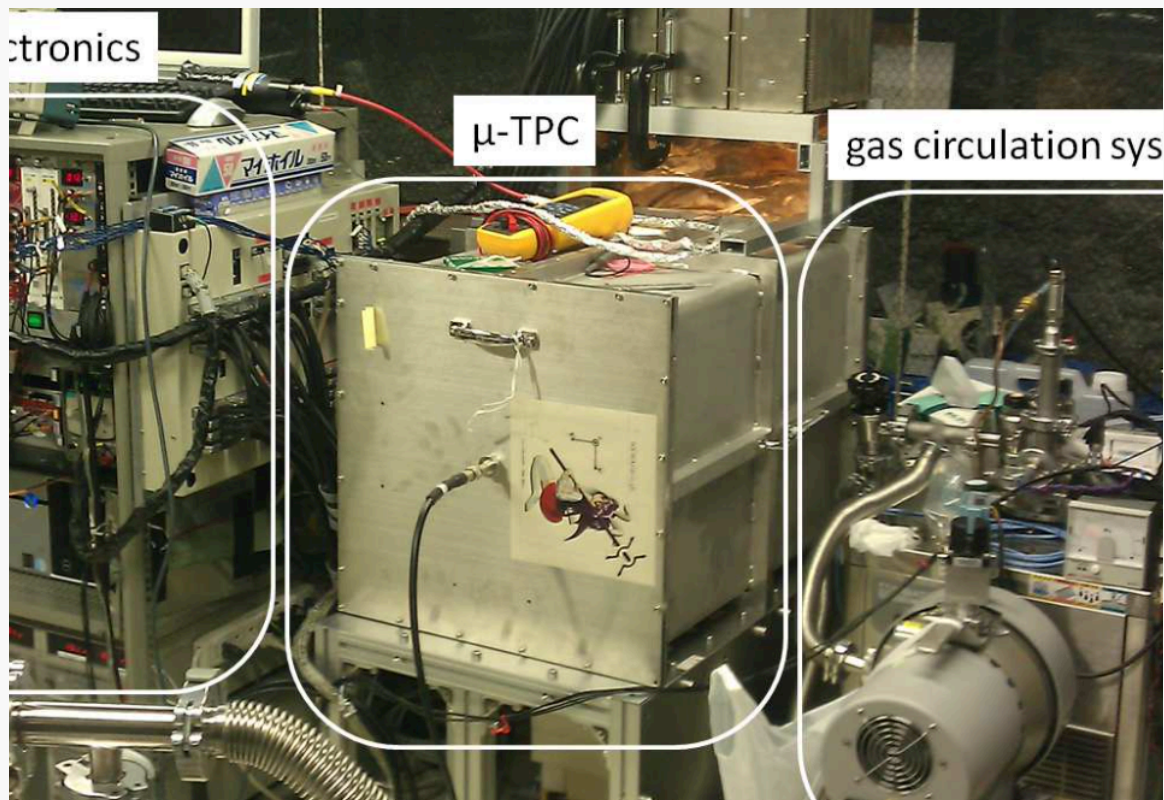
(this event was dropped
by our event selection)



Rejection power: $\sim 10^{-6}$
but need to reduce the ambient
gamma flux into our chamber itself

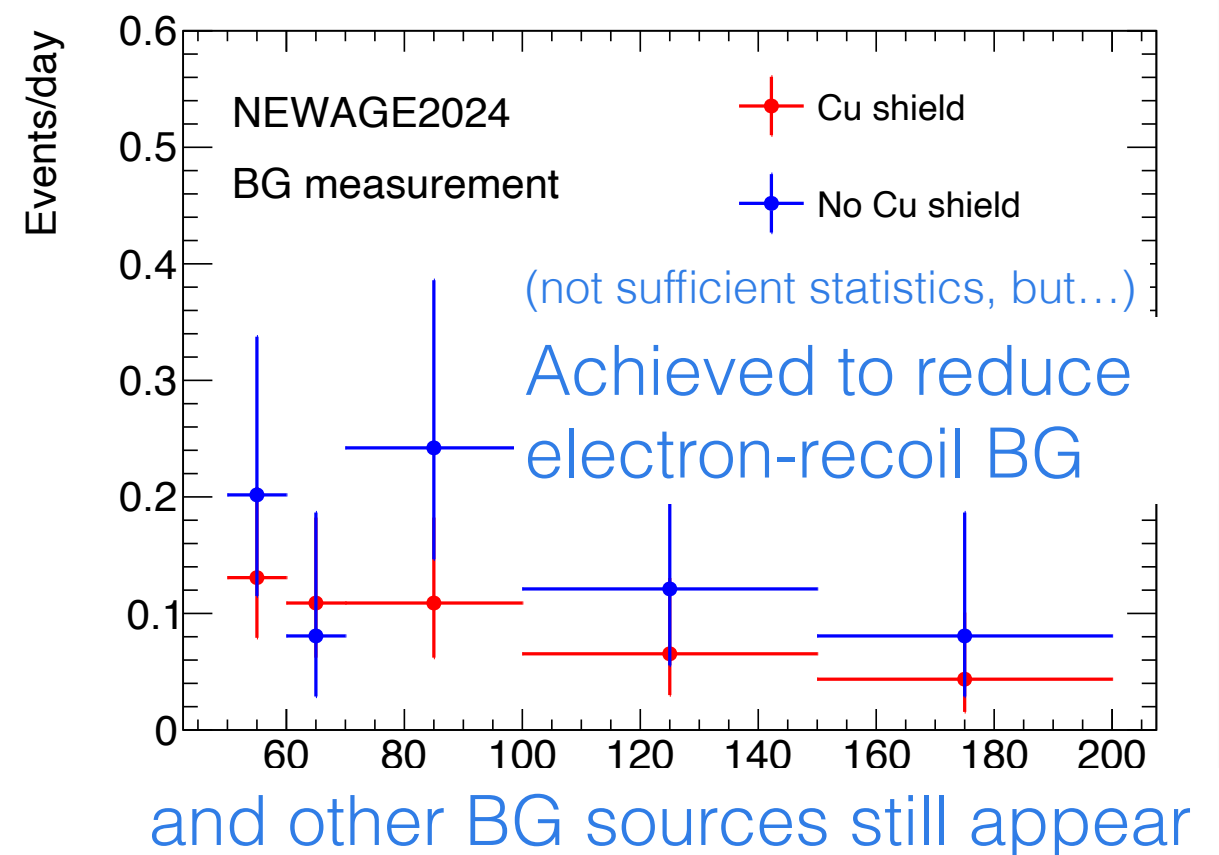
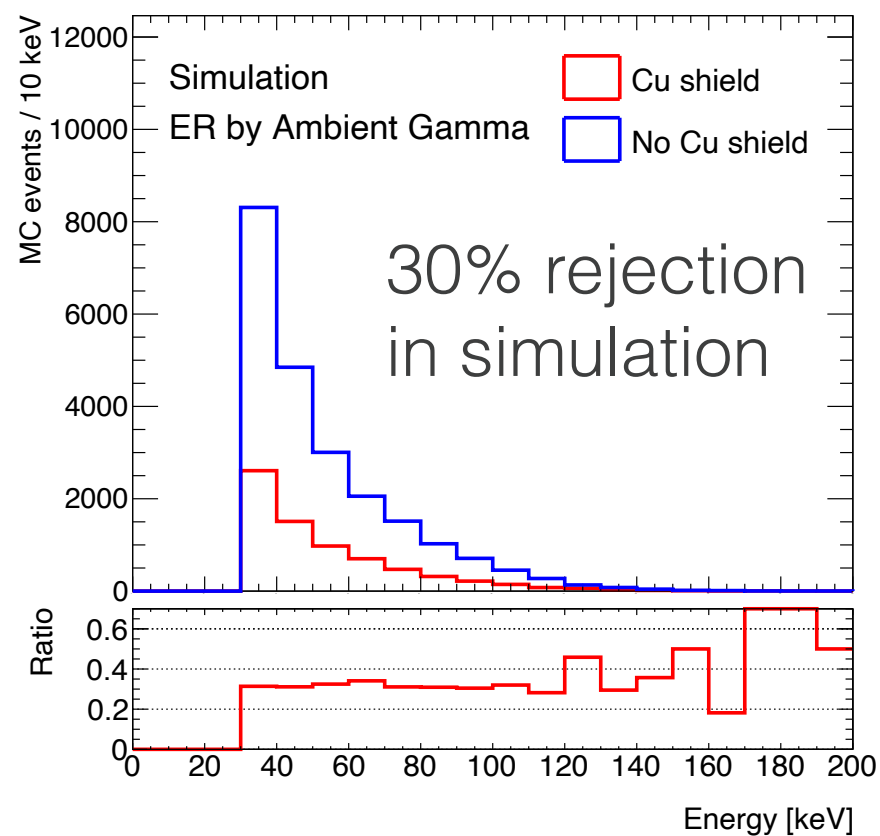
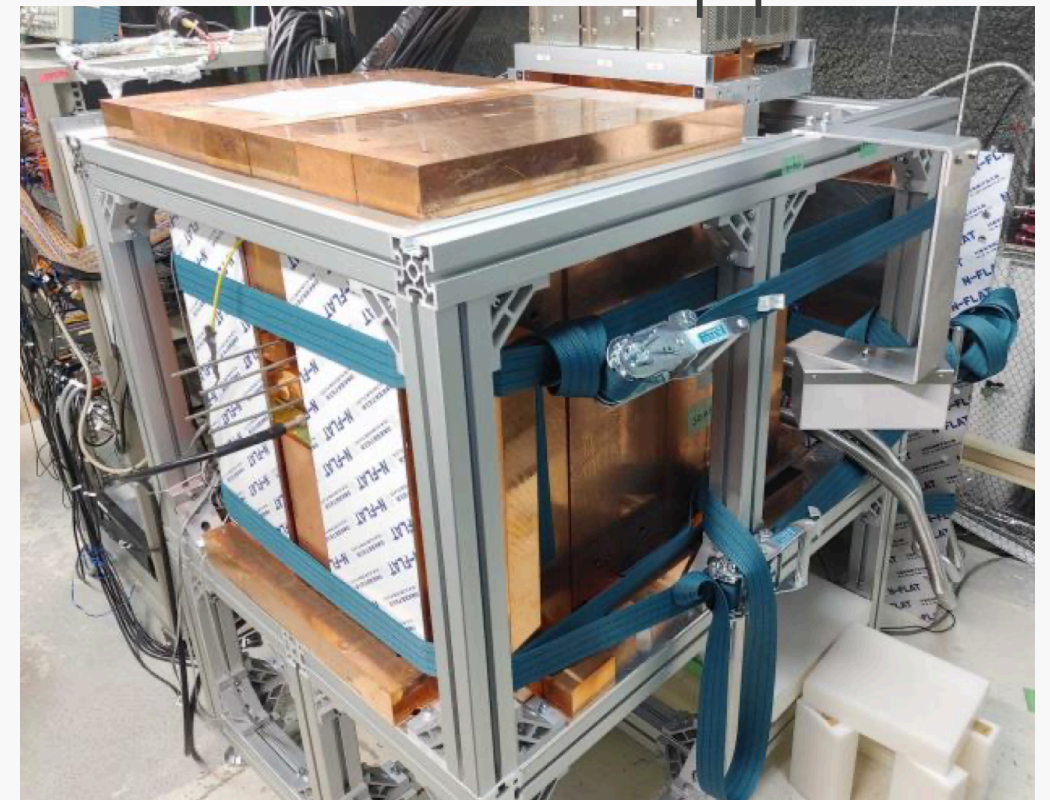
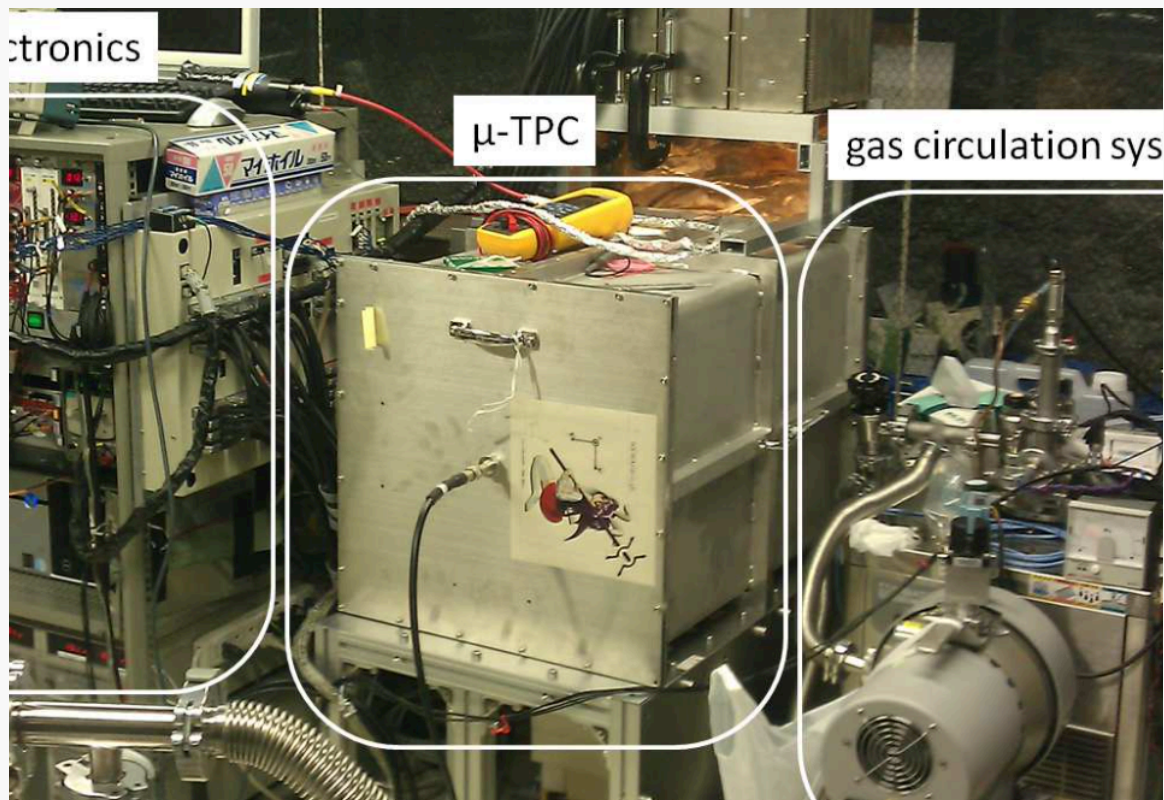
Copper shield

5 cm thick copper

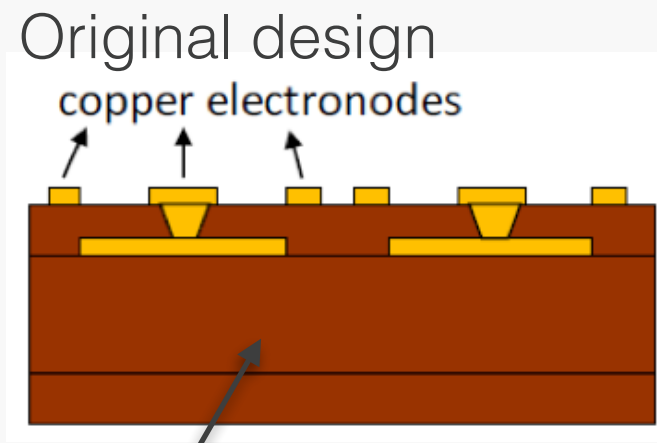


Copper shield

5 cm thick copper

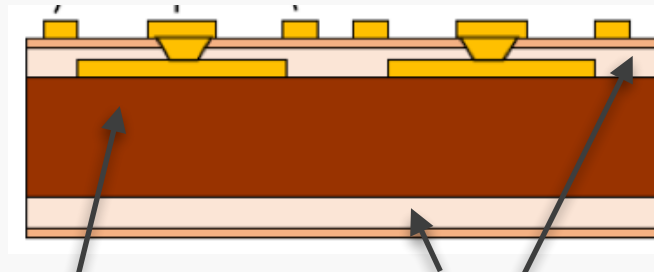


Development of “clean” detector



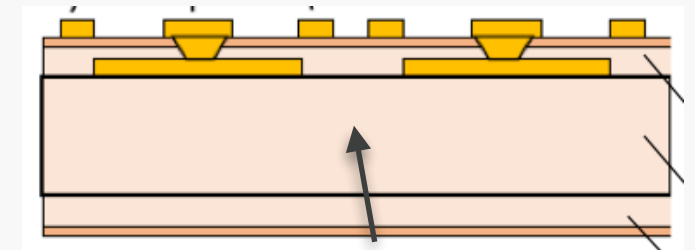
Polyimide
w/ glass cloth
(Rn contaminated)

Low **surface** alpha version
(LApμ-PIC: 2017-)



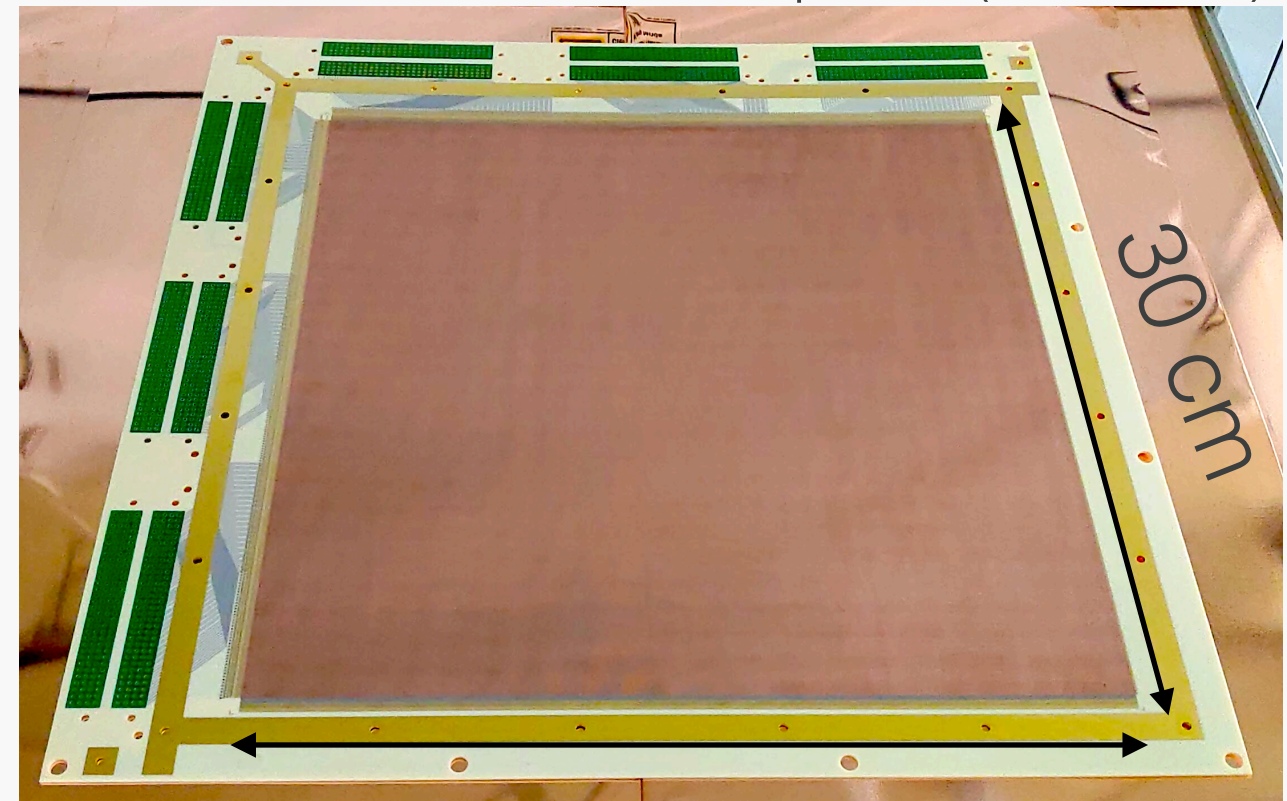
Polyimide
w/ glass cloth

Low-BG μ-PIC
(2020-)



Quartz + Resin

LBGμ-PIC (DNP Inc.)



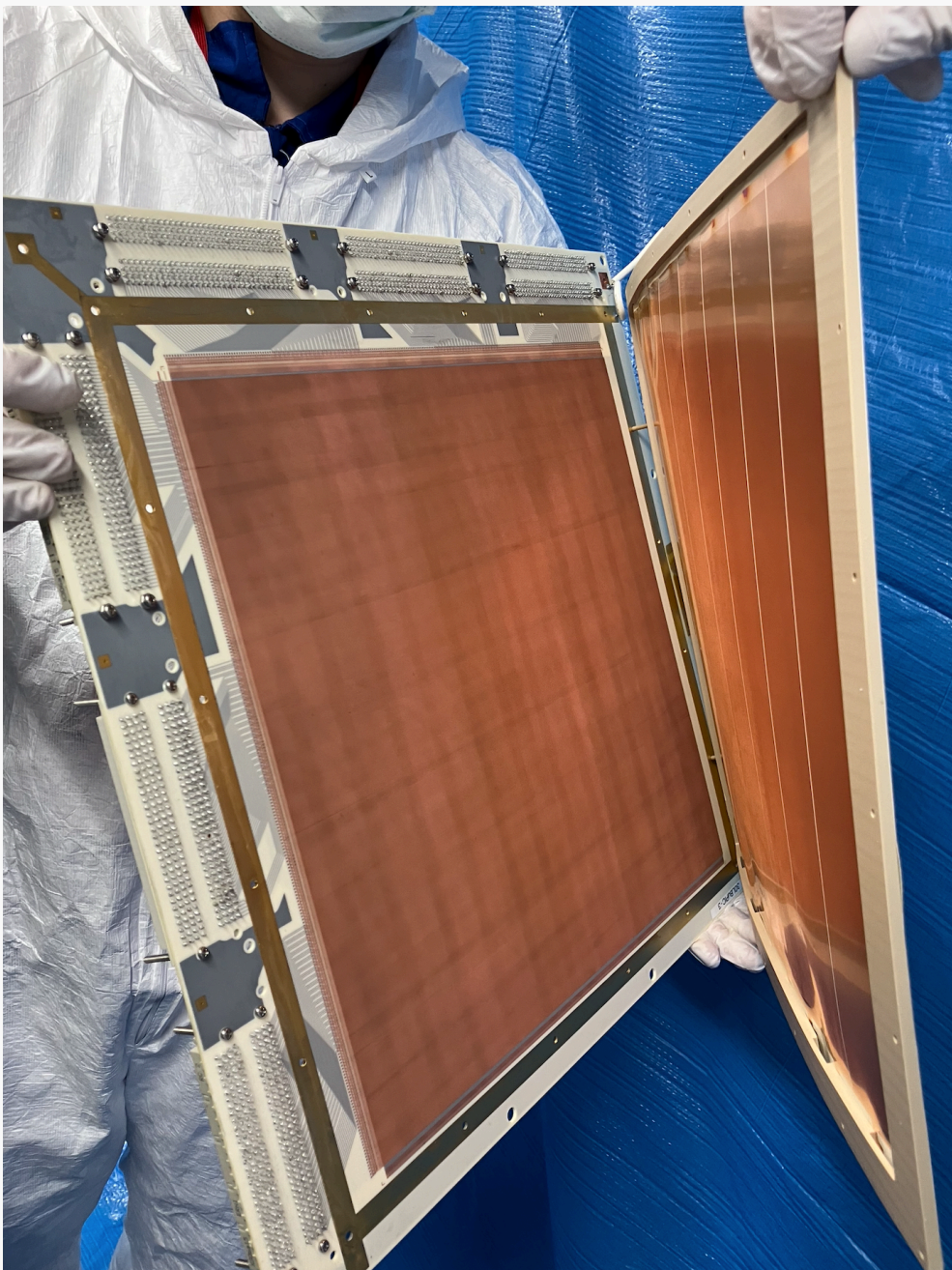
Radon emanation measurement:
LApμ-PIC: **2.3 ± 0.5** [mBq / μ-PIC]



LBGμ-PIC: **<0.17** [mBq / μ-PIC]
(90% C.L.)

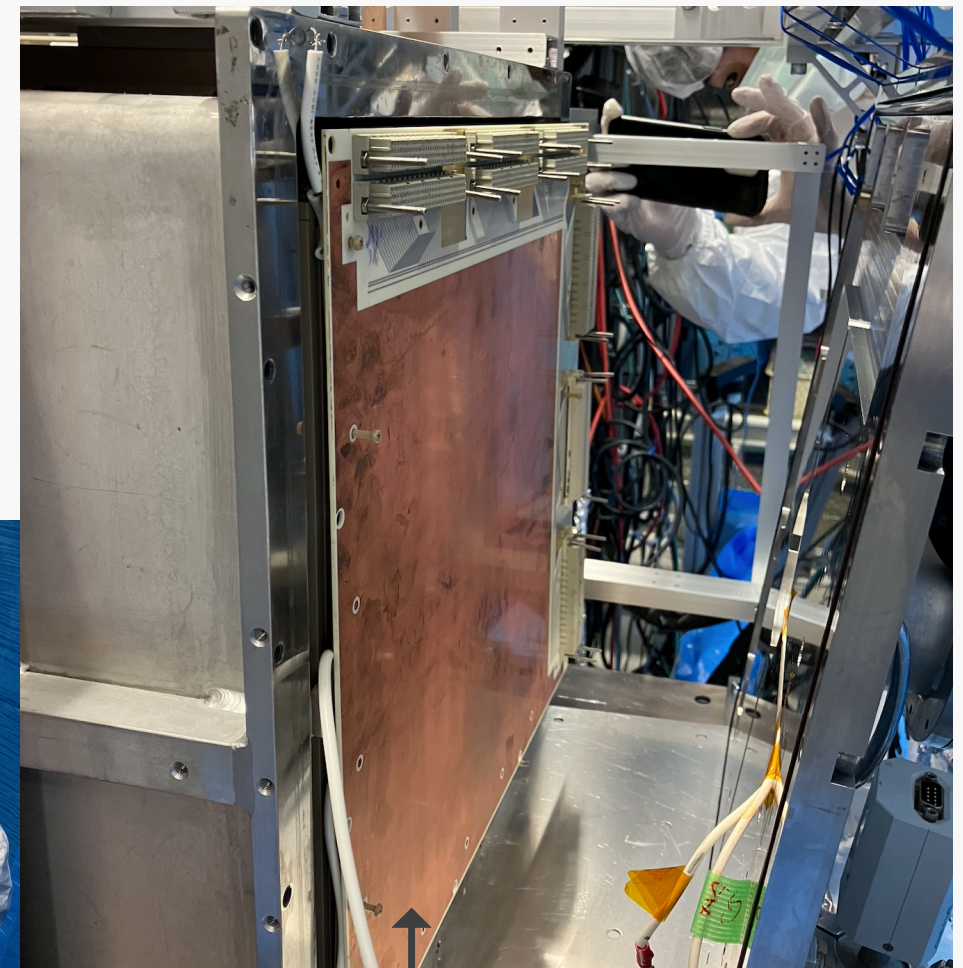
NIM A 1072 (2025) 17014

Detector installation (Dec. 2023)



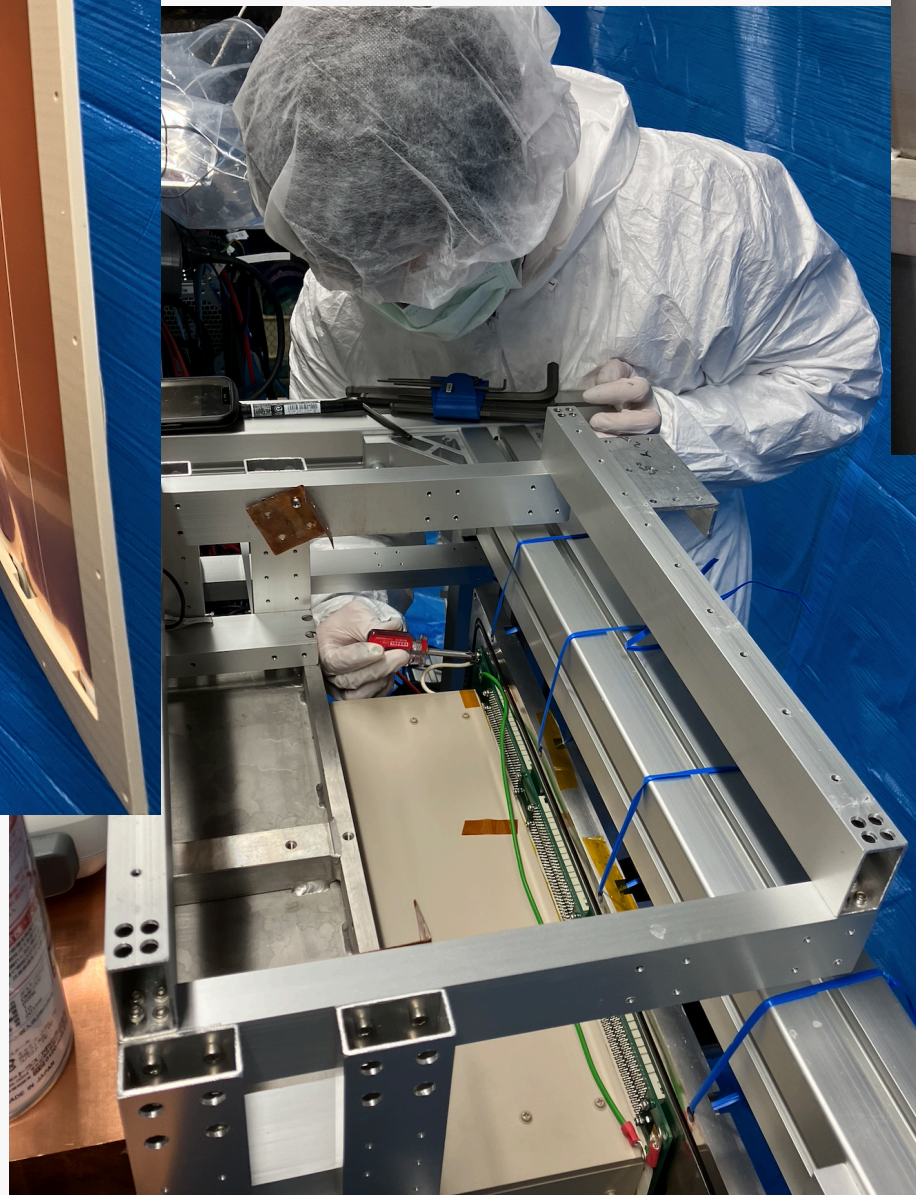
← GEM

↓ Ryota



μ -PIC backplane

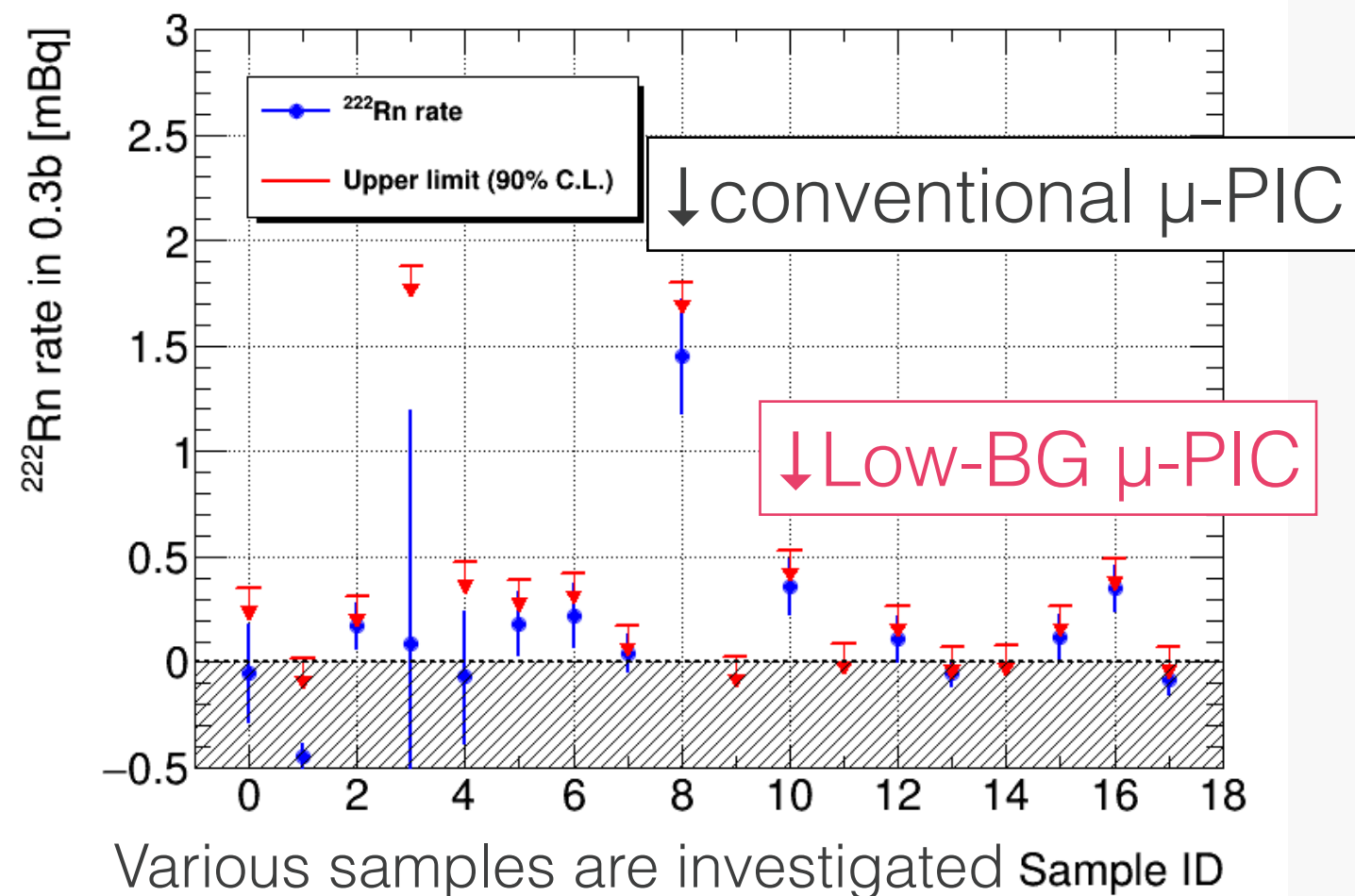
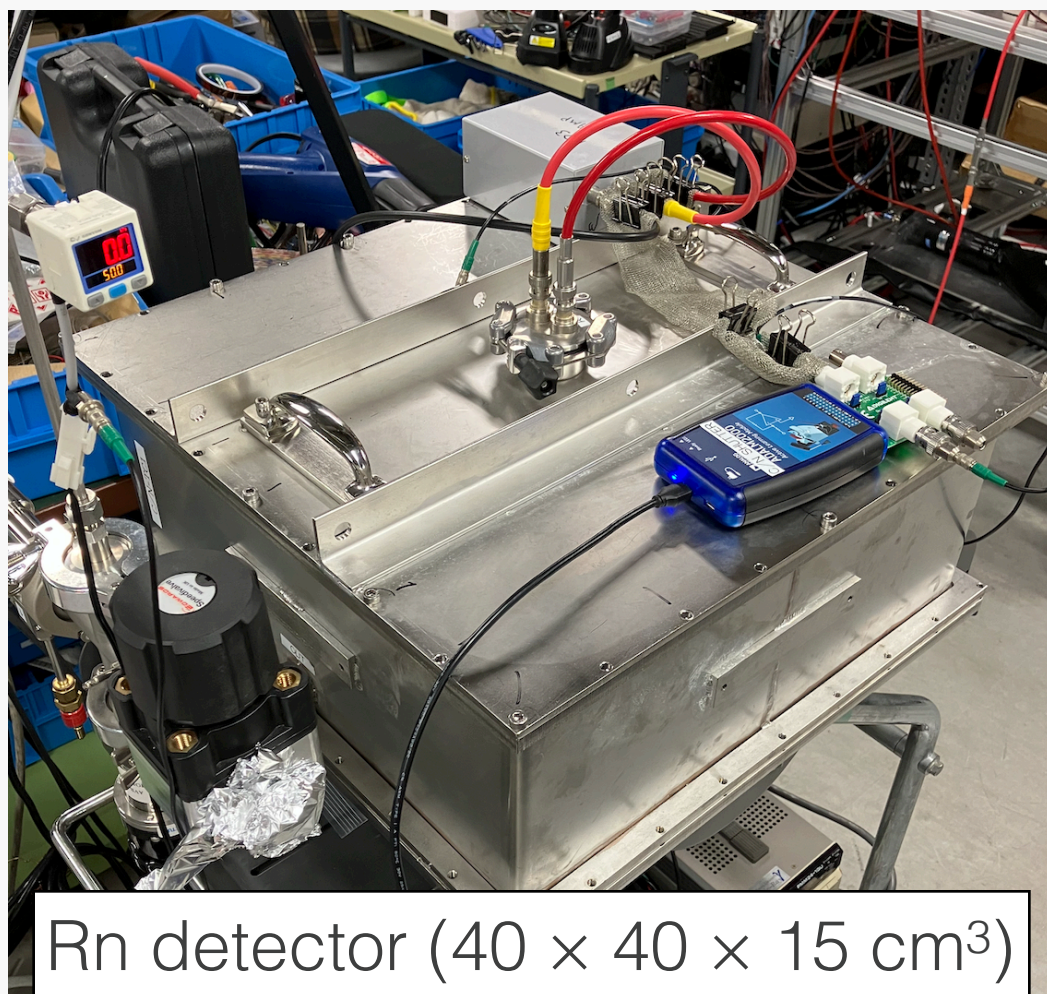
μ -PIC↑



CYGNUS2023 (Dec.)

What is the source of Rn BG?

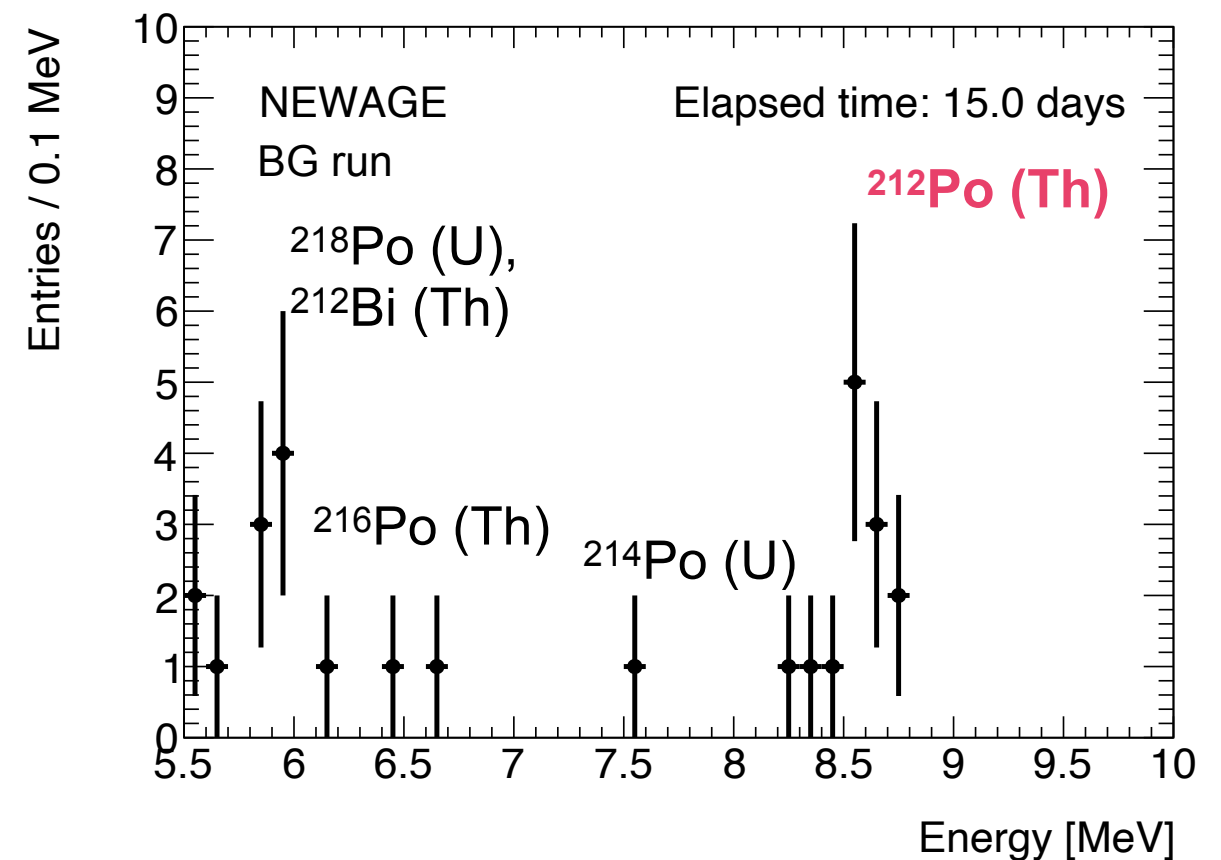
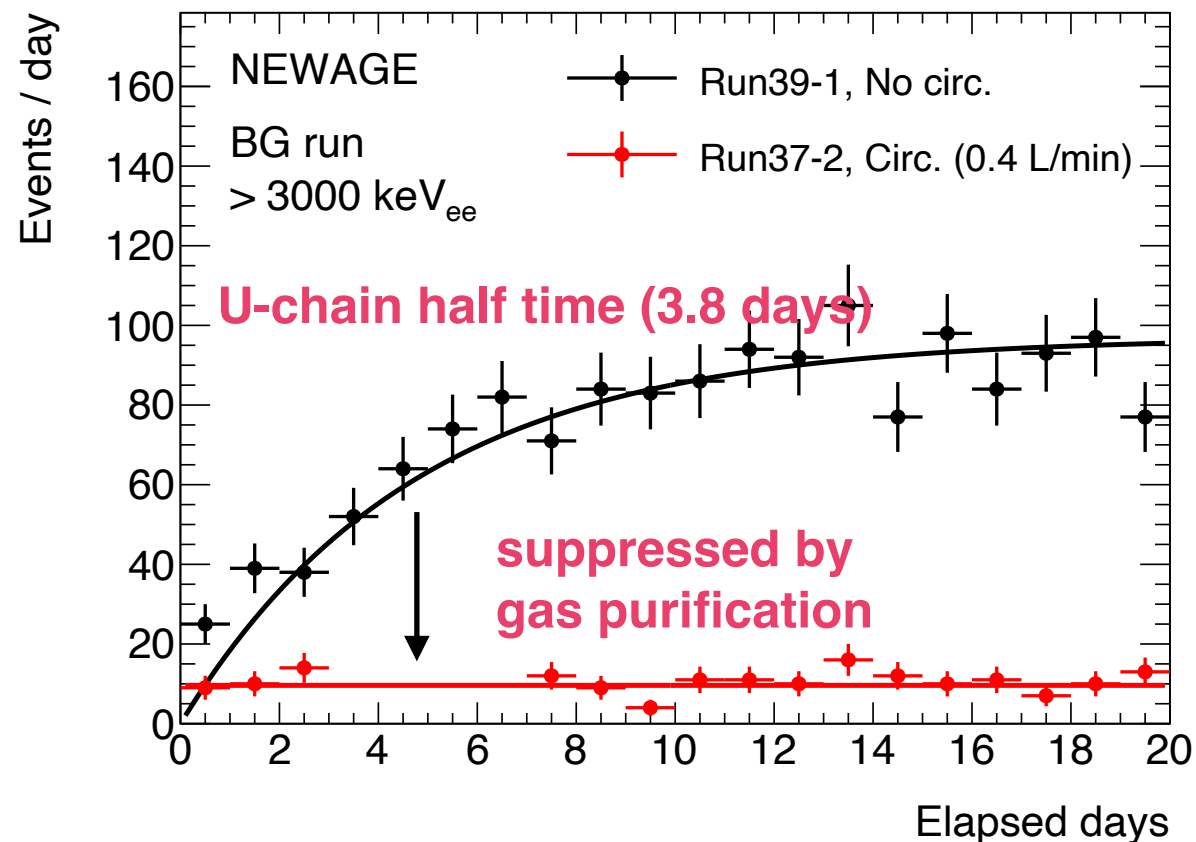
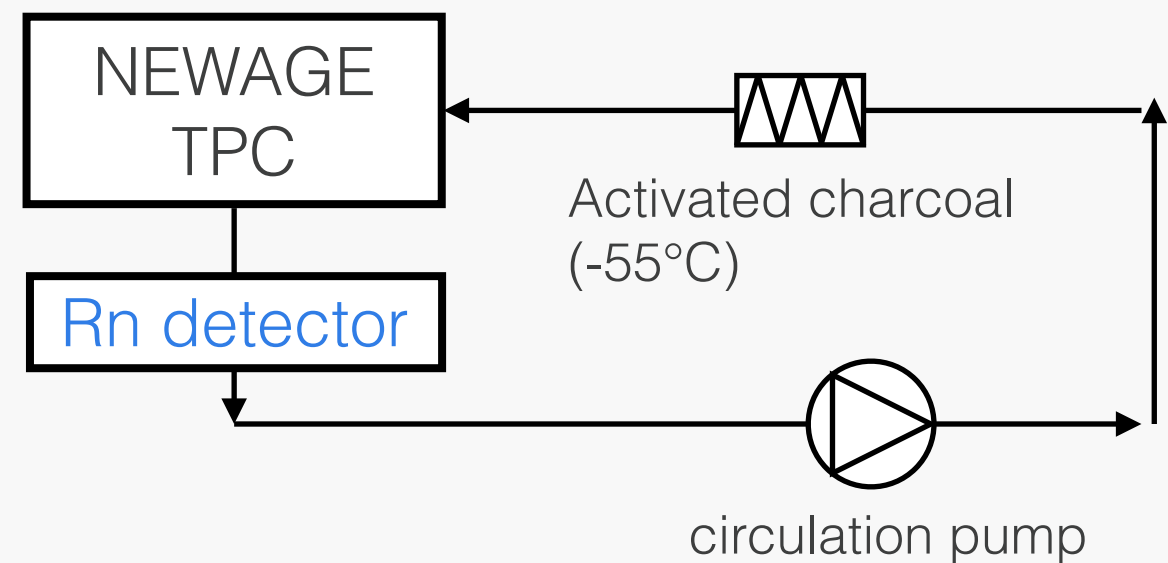
- Rn emanation rate for various TPC components was measured with electrostatic collection Rn detector
 - ➔ e.g. μ -PIC, intermediation PCB, field cage (PEEK), O-ring, HV feedthrough, ...
- No component can explain the amount of Rn BG in the NEWAGE detector



U / Th decay chain?

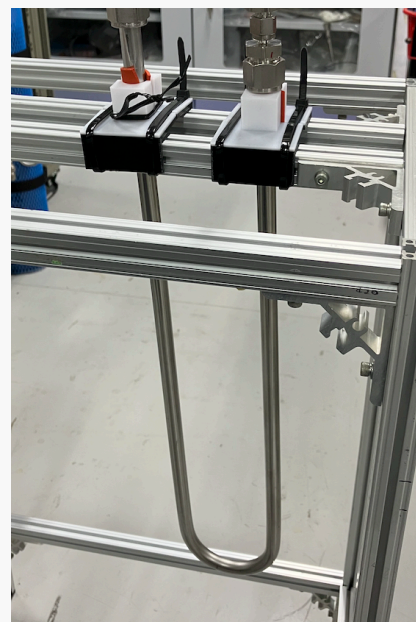
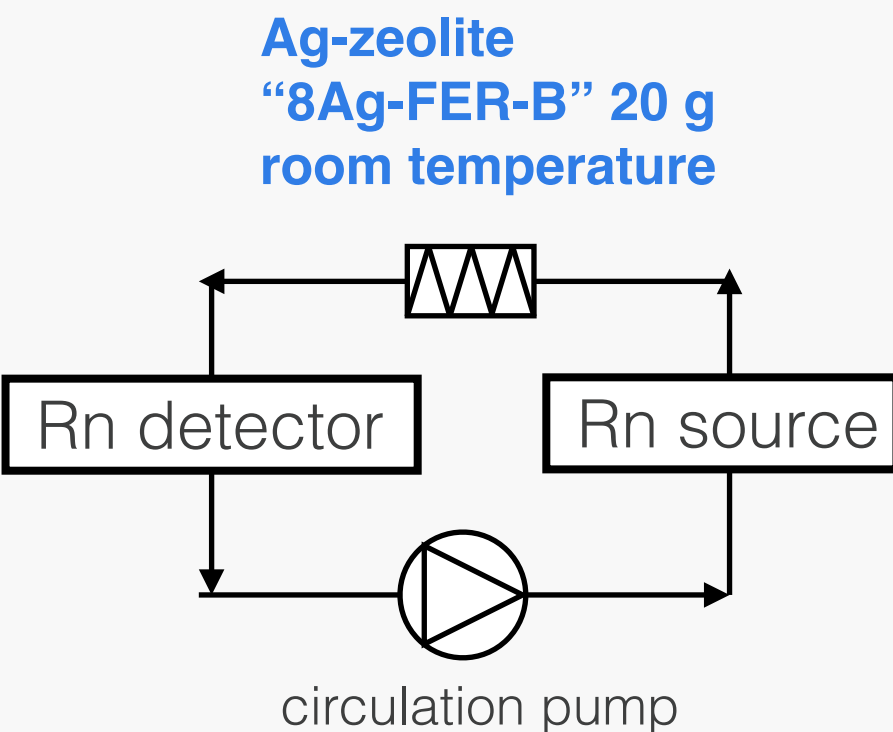
- Two independent tests were taken place
 - ➔ Circulation ON / OFF
 - ➔ Rn detector installation in the circulation system
- **Th-chain (^{220}Rn : 55.6 sec, ^{212}Pb : 10.6 h) is the dominant Rn source**
 - ➔ and these two results are consistent

NEWAGE circulation system (simplified)

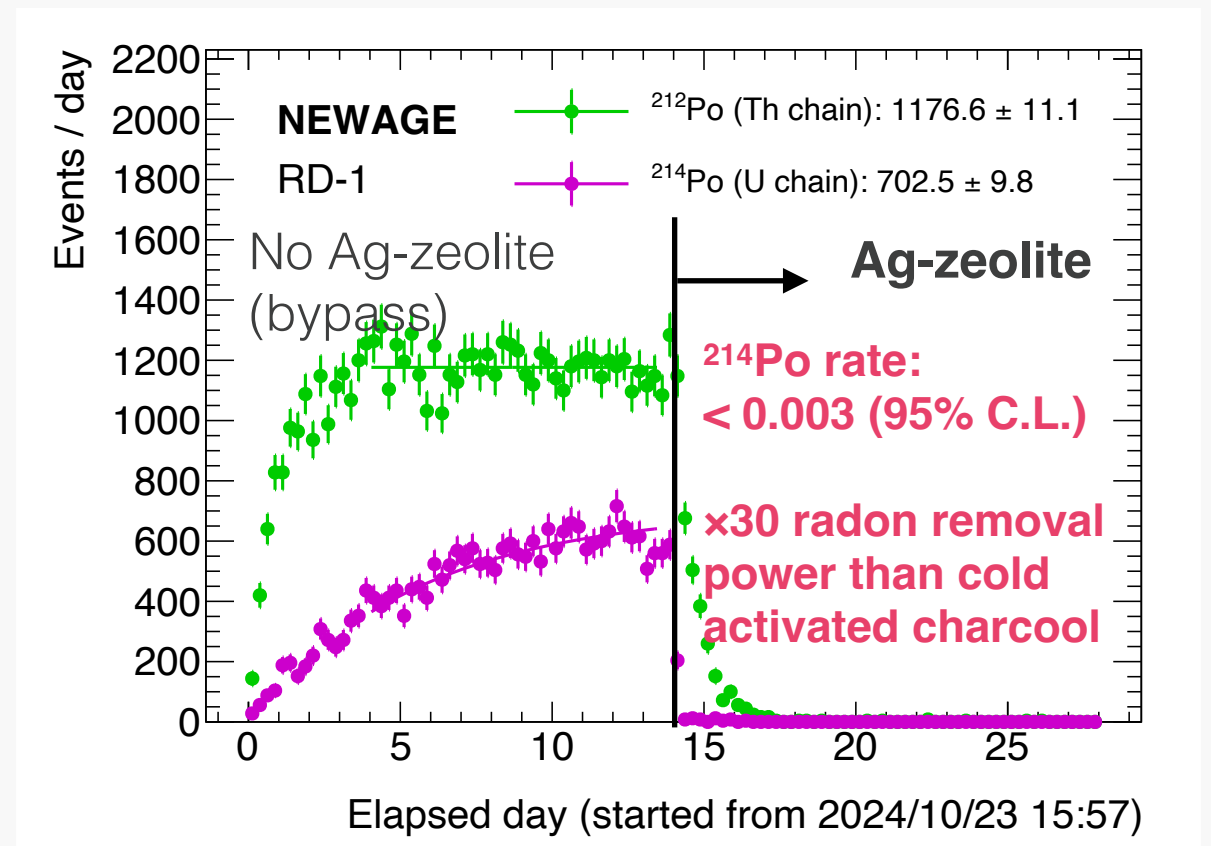


Ag-zeolite for Rn filtering

- We discuss about “clean” gas purification filter for a long time
 - ➔ especially for Rn reduction (JINST (2021) 16 P06024, JINST (2024) 19 P02004)
- SK/HK group reported a radon removal performance of silver-ion exchanged zeolite (“Ag-zeolite”)
 - ➔ PTEP 2025 (2025) 1, 013H01
 - Powerful radon removal performance even at room temperature
 - **Prof. Yasuo Takeuchi will give us a beneficial summary of the radon removal study tomorrow morning!**
- NEWAGE group also tested to introduce an Ag-zeolite filter with low-pressure pure CF_4 gas



Ag-zeolite is filled in
1/2" stainless pipe

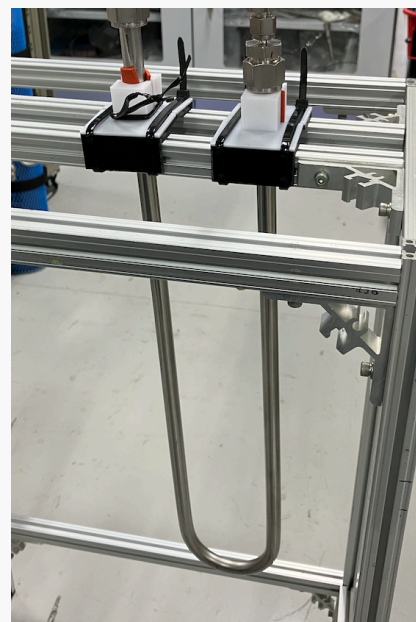
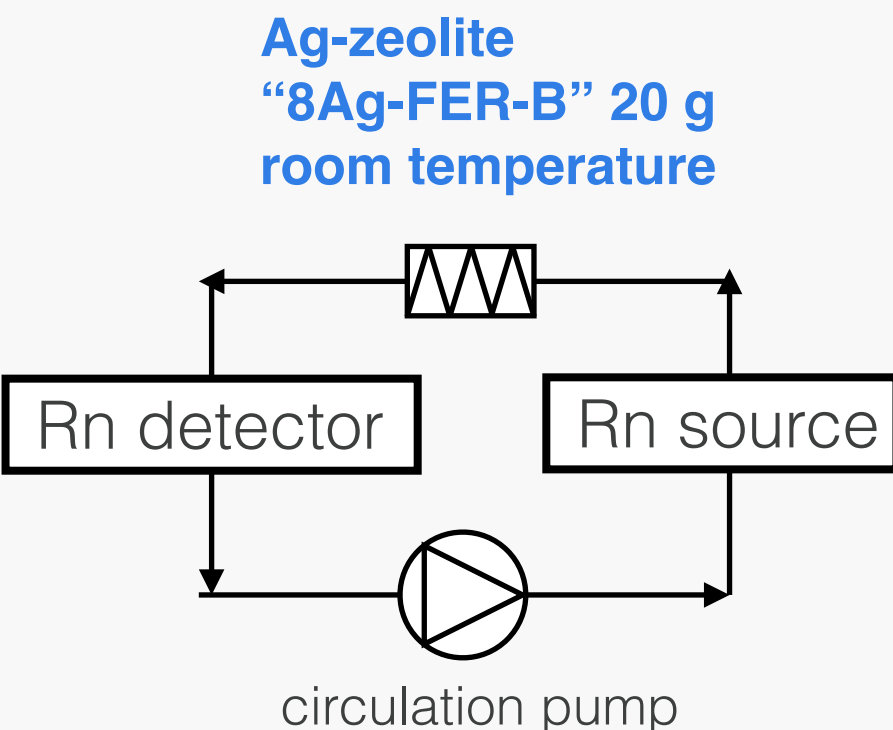


Ag-zeolite for Rn filtering

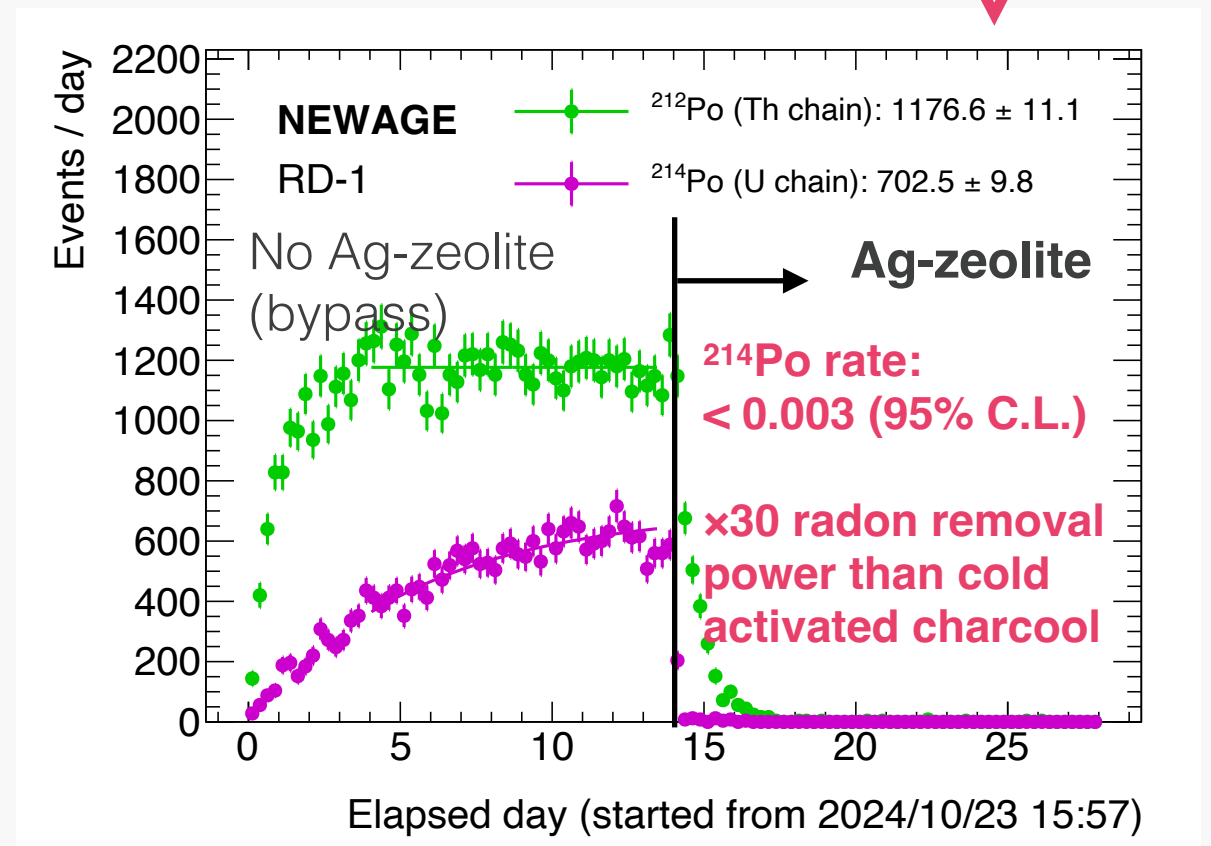
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 - especially for Rn reduction (JINST (2021) 16 P06024, JINST (2024) 19 P02004)
- SK/HK group reported a radon removal performance of silver-ion exchanged zeolite (“Ag-zeolite”)
 - PTEP 2025 (2025) 1, 013H01

And very effectively remove Th-chain radon!
Installed Ag-zeolite filter in NEWAGE system on July 2025

- NEWAGE group also tested to introduce an Ag-zeolite filter with low-pressure pure CF₄ gas

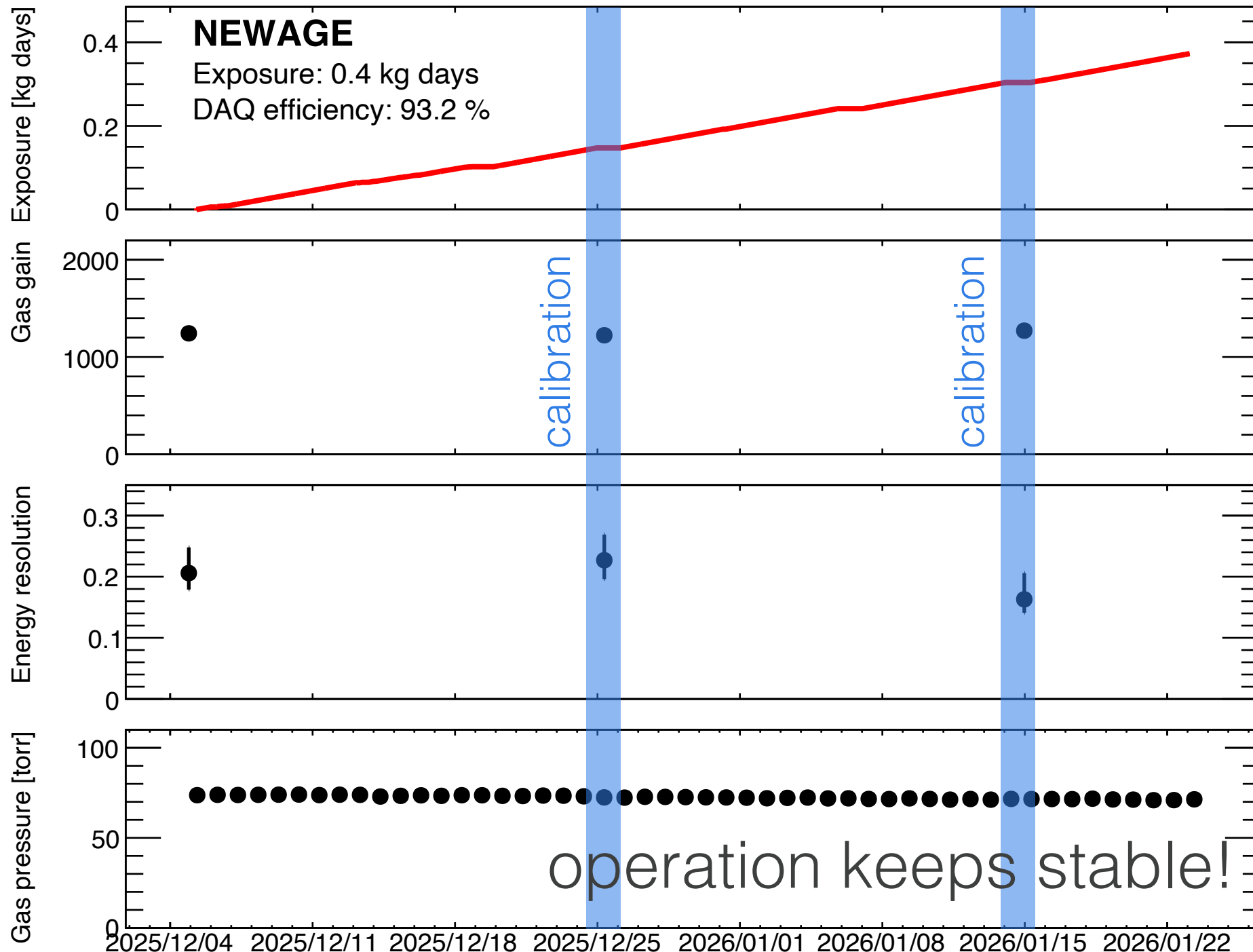


Ag-zeolite is filled in
1/2" stainless pipe



NEWAGE2025

- Measurement has started from Dec. 4 2025 after commissioning
 - ➔ only 1/8 exposure obtained comparing with the NEWAGE2023 analysis



Search Kobe PP

newage_status_monitor

Messages Files +

NEWAGE SM na2 APP 3:51 PM
NEWAGE 0.3b status 😊
<http://10.240.101.210:3000/d/3tq-AbFnk/newage-0-3b-status?orgId=1&from=now-7d&to=now>
<http://10.240.101.210:3000/d/3tq-AbFnk/newage-0-3b-status?orgId=1&from=now-2d&to=now>
<http://10.240.101.210:3000/d/3tq-AbFnk/newage-0-3b-status?orgId=1&from=now-6h&to=now>
3 files | Download all



NEWAGE SM na2 APP 7:51 PM
NEWAGE 0.3b status 😊
<http://10.240.101.210:3000/d/3tq-AbFnk/newage-0-3b-status?orgId=1&from=now-7d&to=now>
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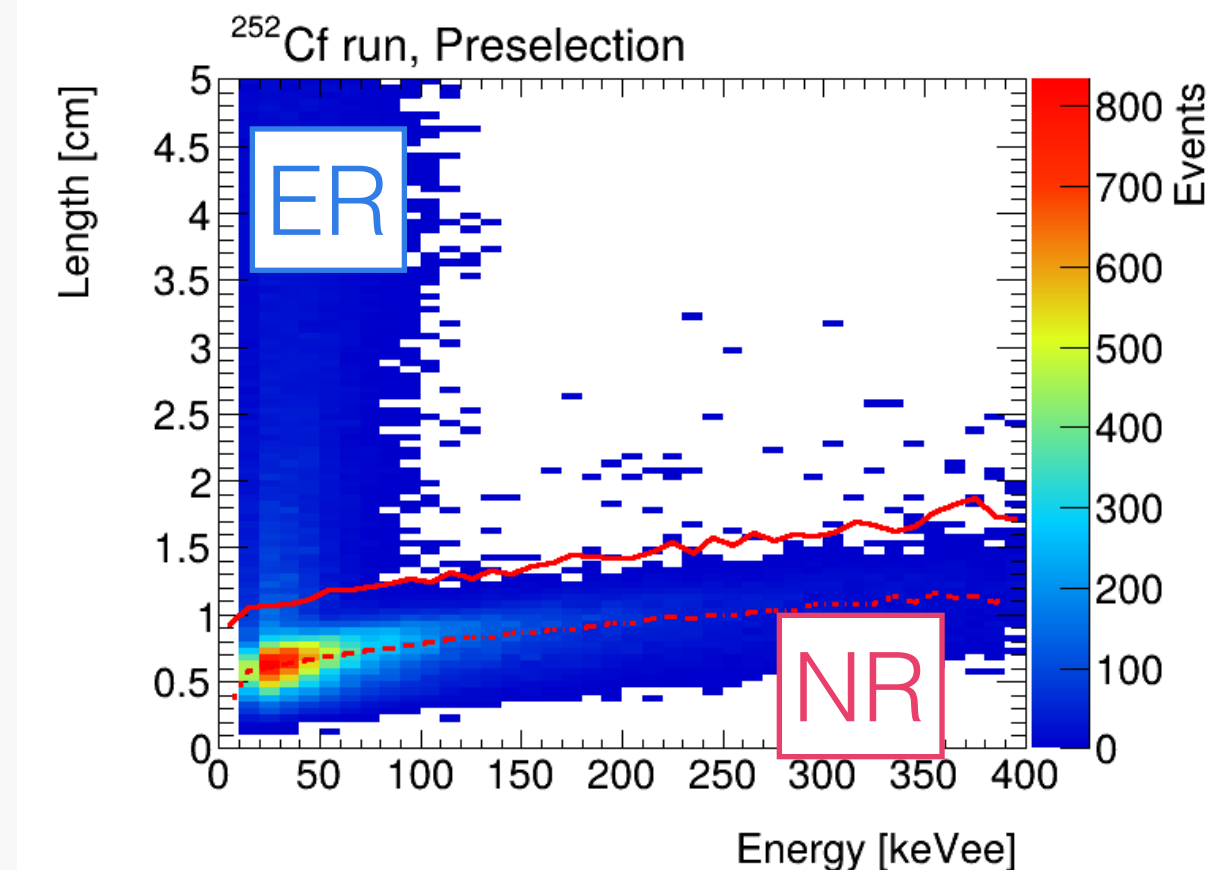
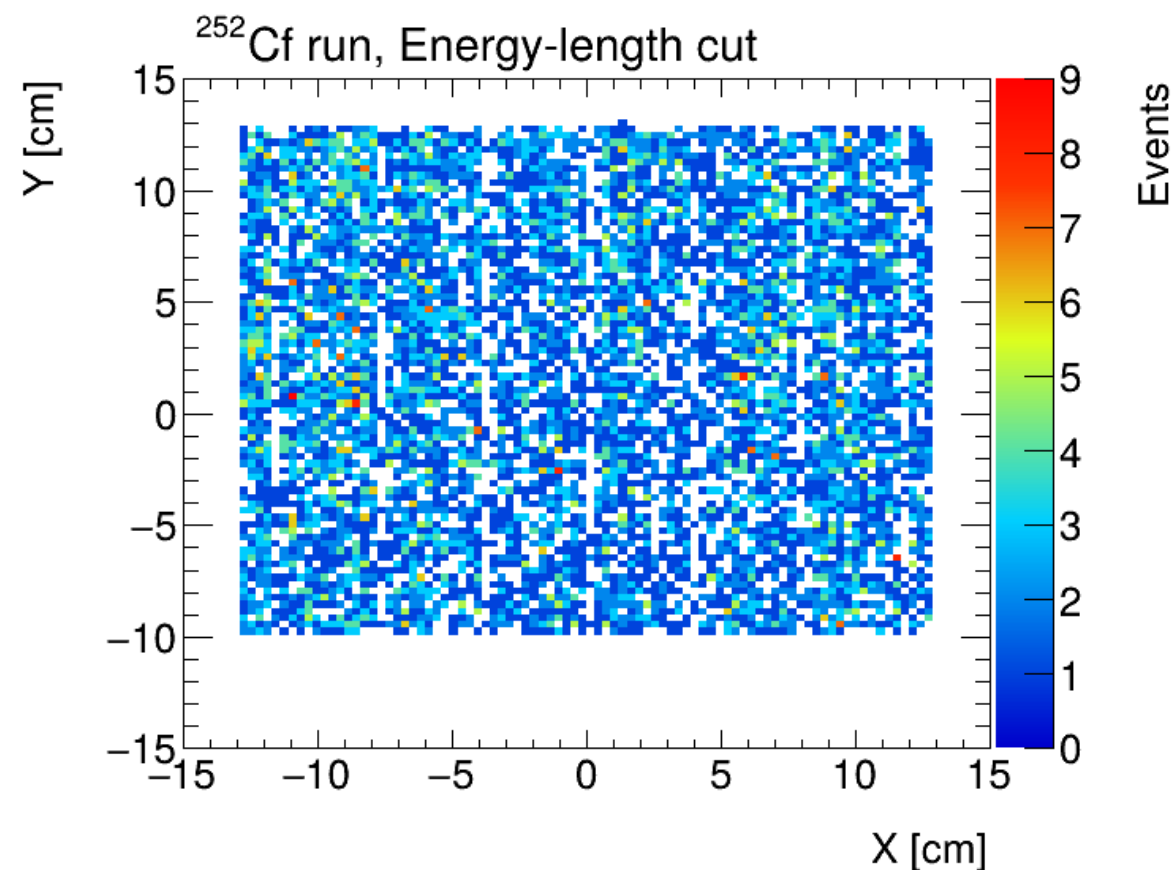


Detector status is monitored from Kobe University with Grafana + slack automatic posting

Measurement is ongoing now!

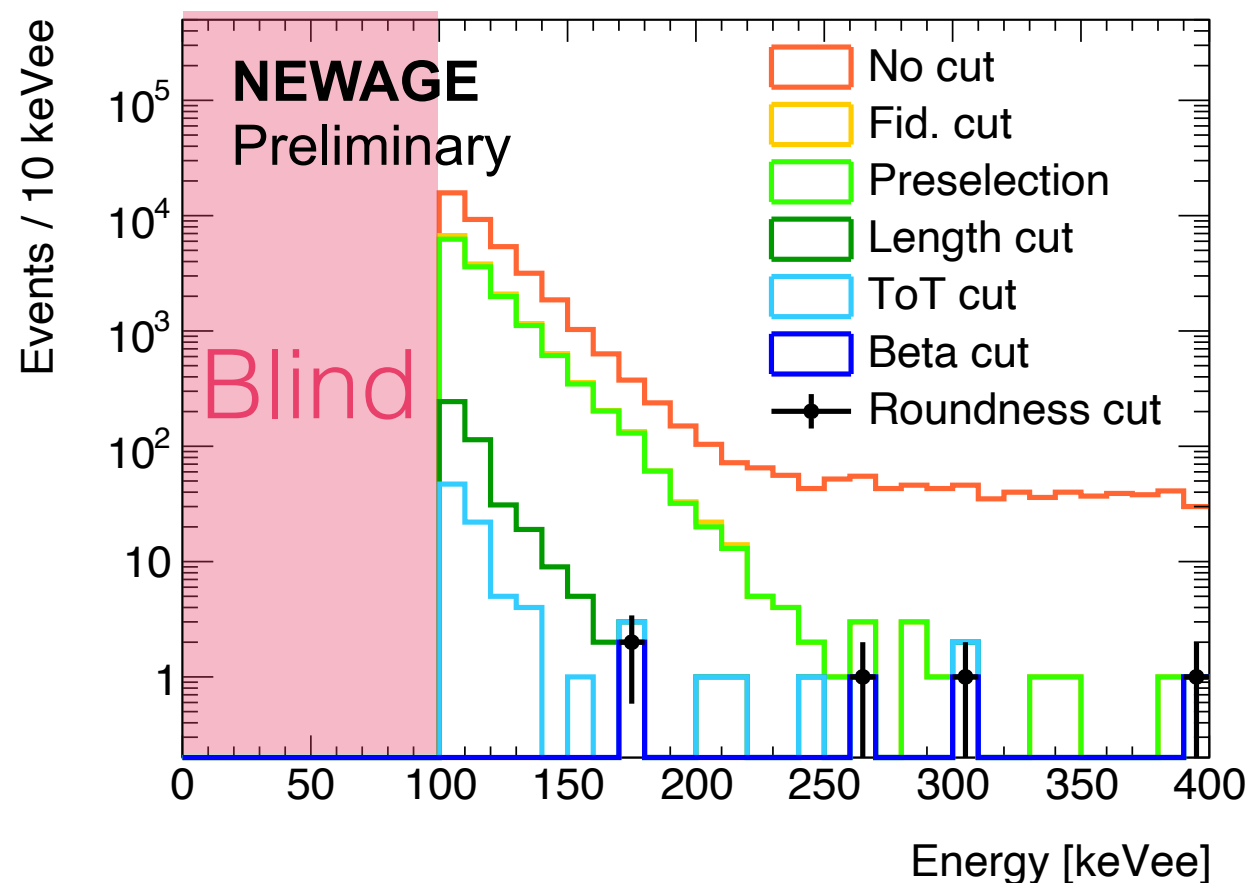
Neutron irradiation test (^{252}Cf source)

- Performance demonstration using ^{252}Cf source
 - ➔ Neutron irradiation from the top of the drift plane direction
 - ➔ Uniform distribution for detector plane was obtained
 - ➔ NR-ER separation successfully working by track information

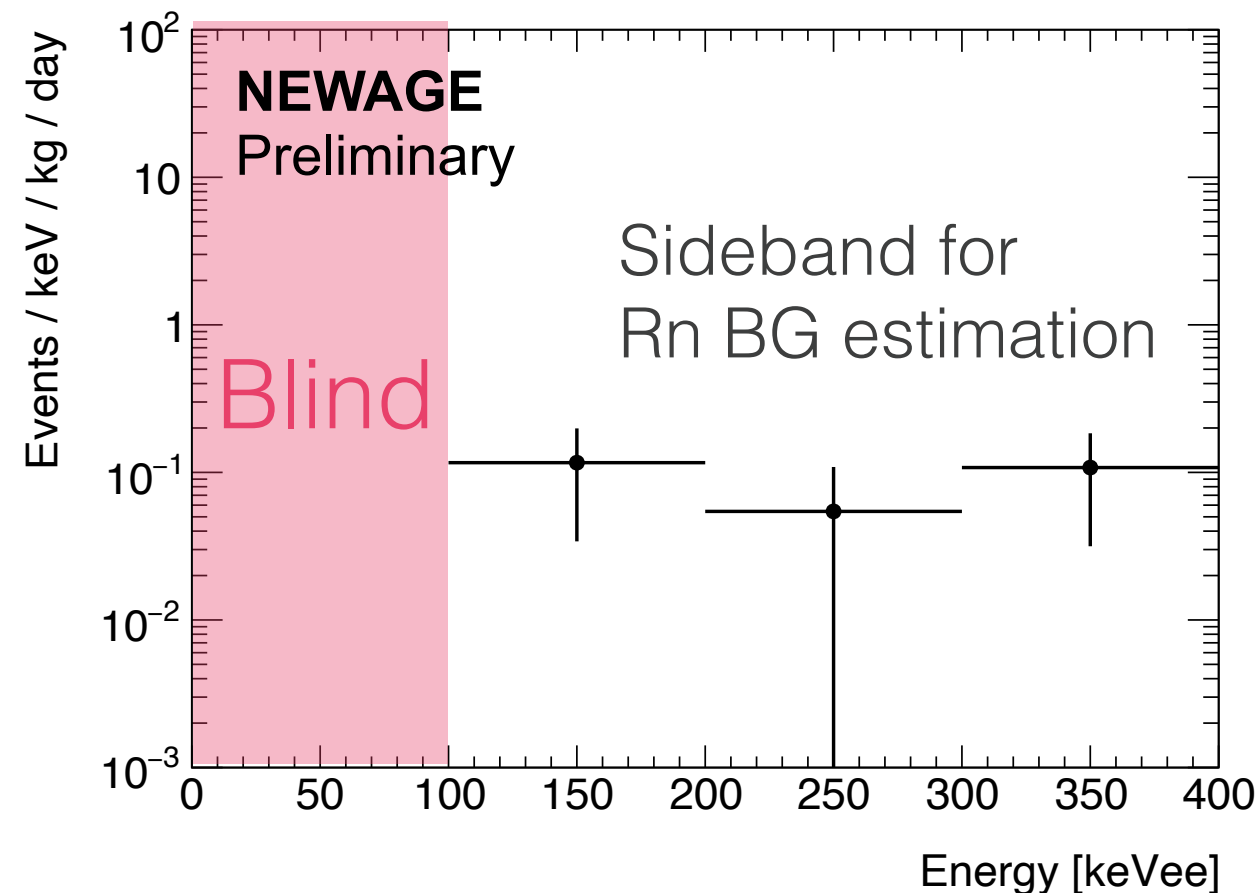


Energy spectrum

- NEWAGE standard event selection applied (detail skipped)
 - ➔ BG rejection performed by each selection
 - ➔ < 100 keVee region and its directionality still blinded (analysis ongoing)
- Event rate considering detection and selection efficiencies keeps low
 - ➔ **Also 1/3 reduction after Ag-zeolite installation in the sideband (Rn BG-rich)**
 - **Consistent with ~ 6 MeV peak event reduction!**
- But remaining BG still limits the sensitivity → need to investigate the BG source more and more

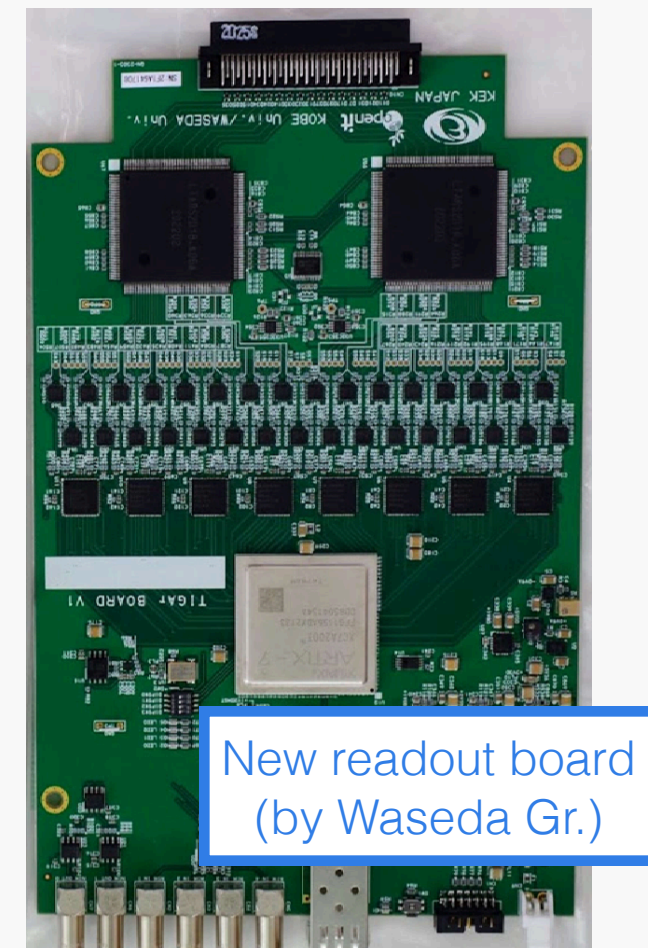
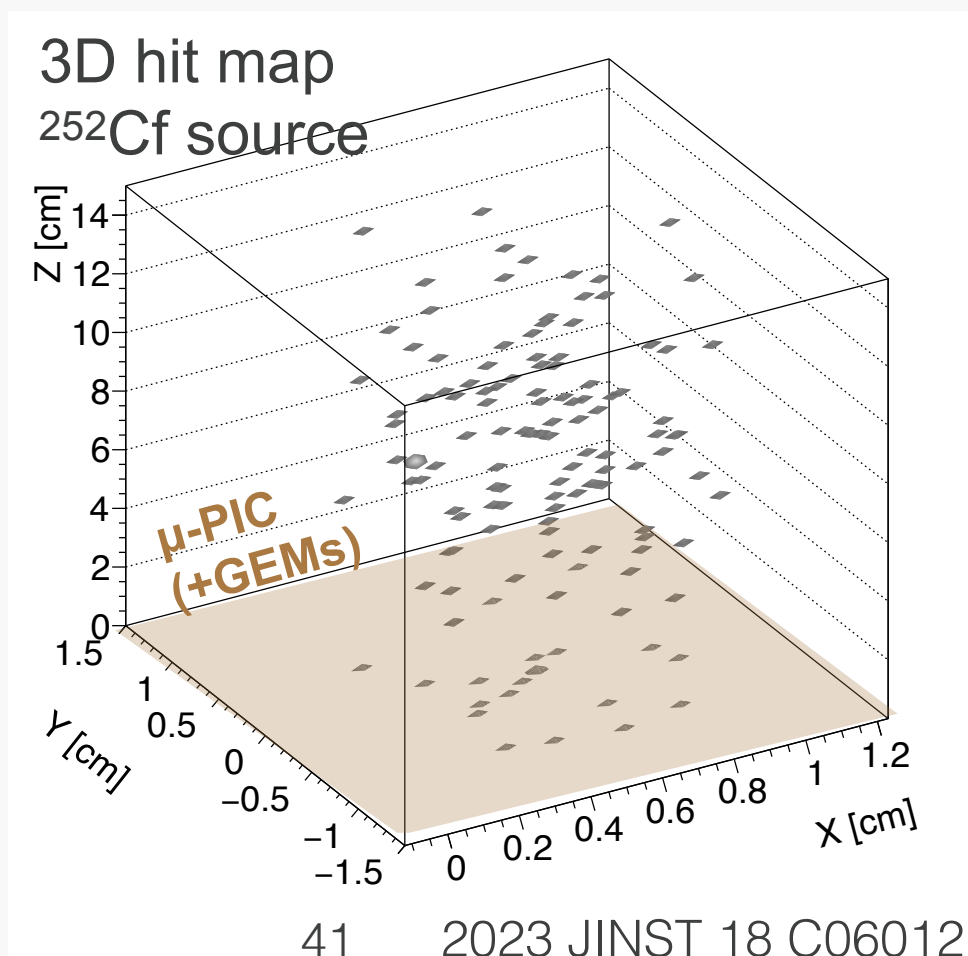
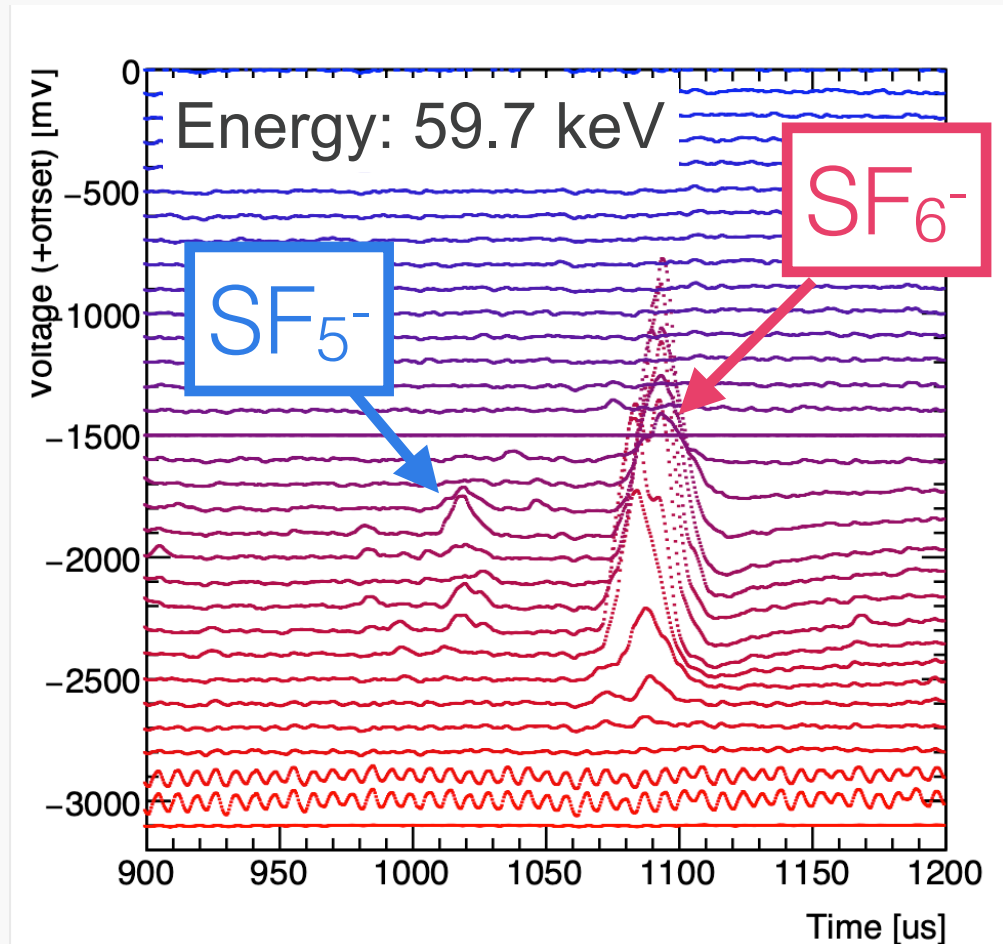
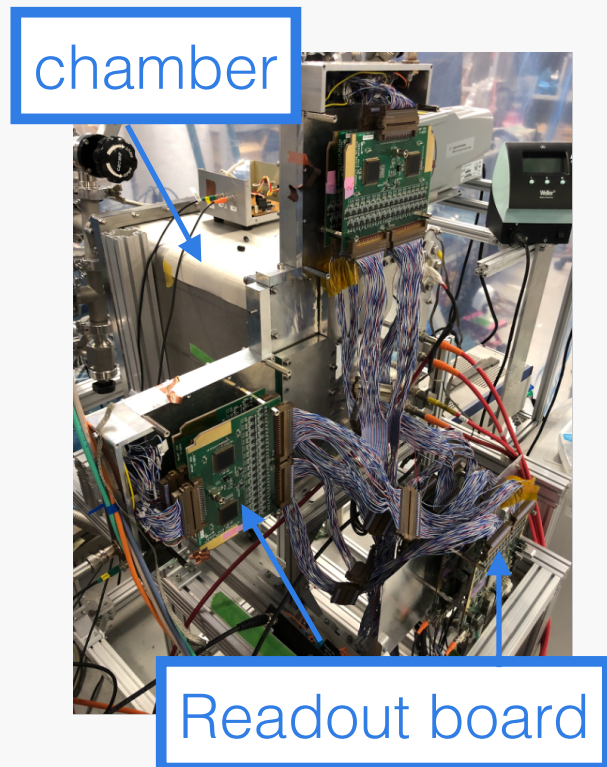


40



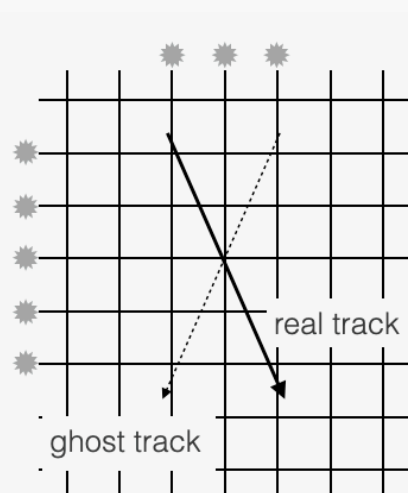
SF₆

- Tested using small detector with prototype electronics
- 2-peak signals are detected with a ²⁵²Cf source
 - ➔ SF₅⁻ peak detection efficiency is 70%
 - ➔ succeeded in reconstructing 3D position
- New readout board is developed by Waseda Gr.
 - ➔ Mass production is preparing to allow O(1000) ch readout

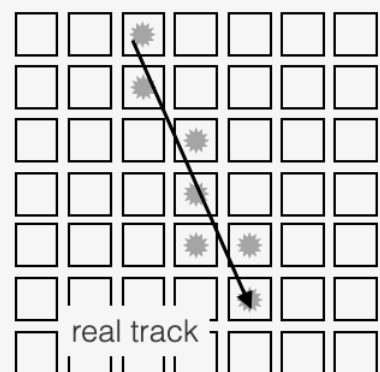


Pixelization

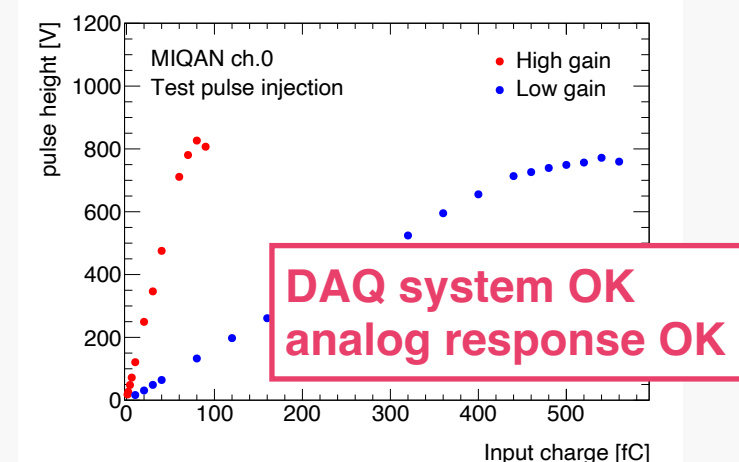
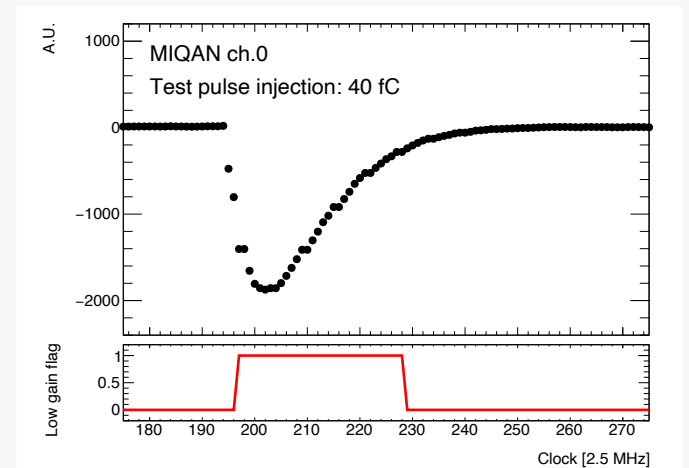
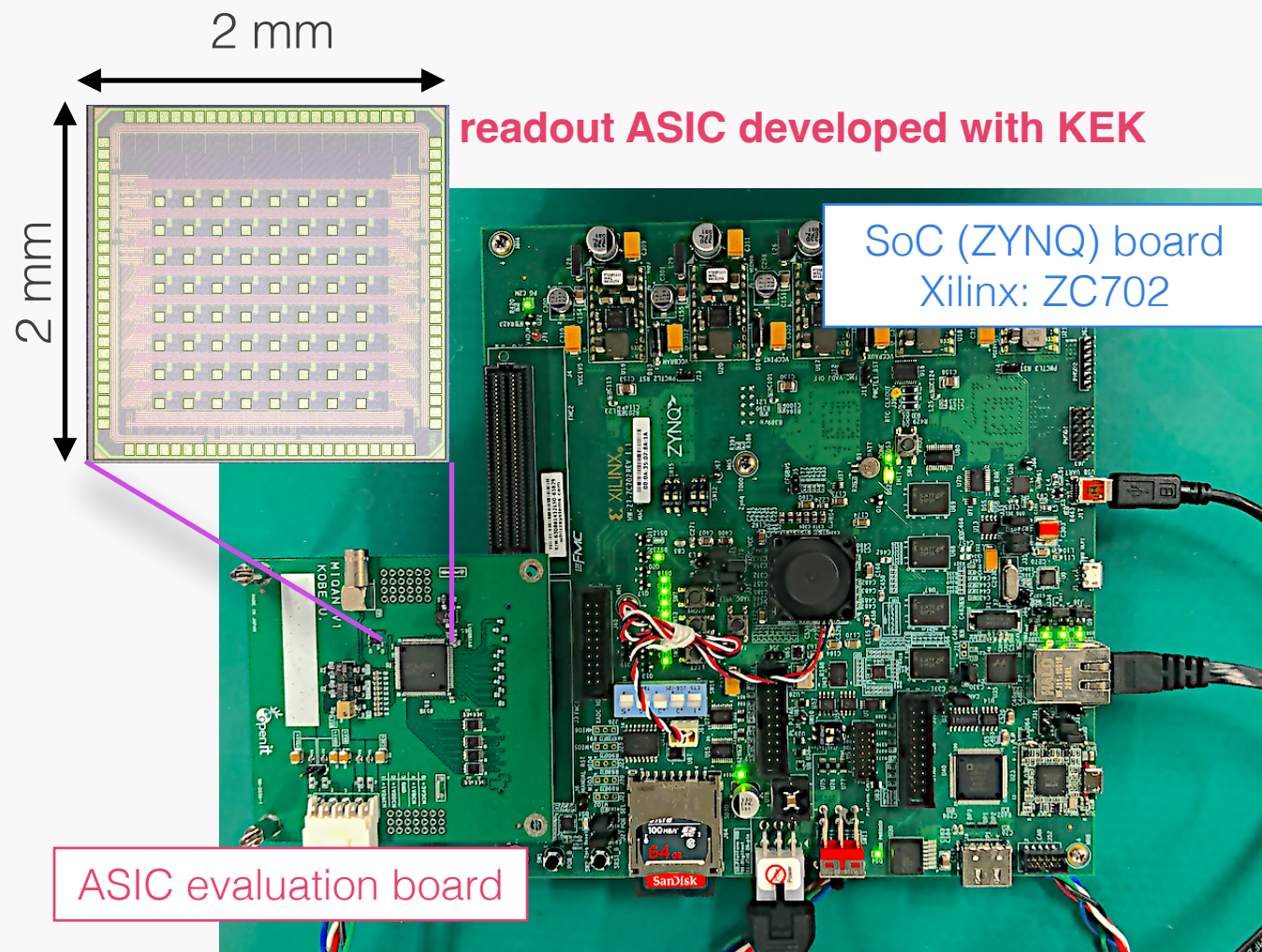
- Equal to low energy nuclear recoil detection
- Energy threshold is limited due to electrode's strip pitch (400 μm)
 - ➔ Started to develop fine granularity “pixel” readout detector
 - to reduce “ghost track” reconstruction
 - ➔ Dedicated readout electronics (prototype) was prepared



Strip readout

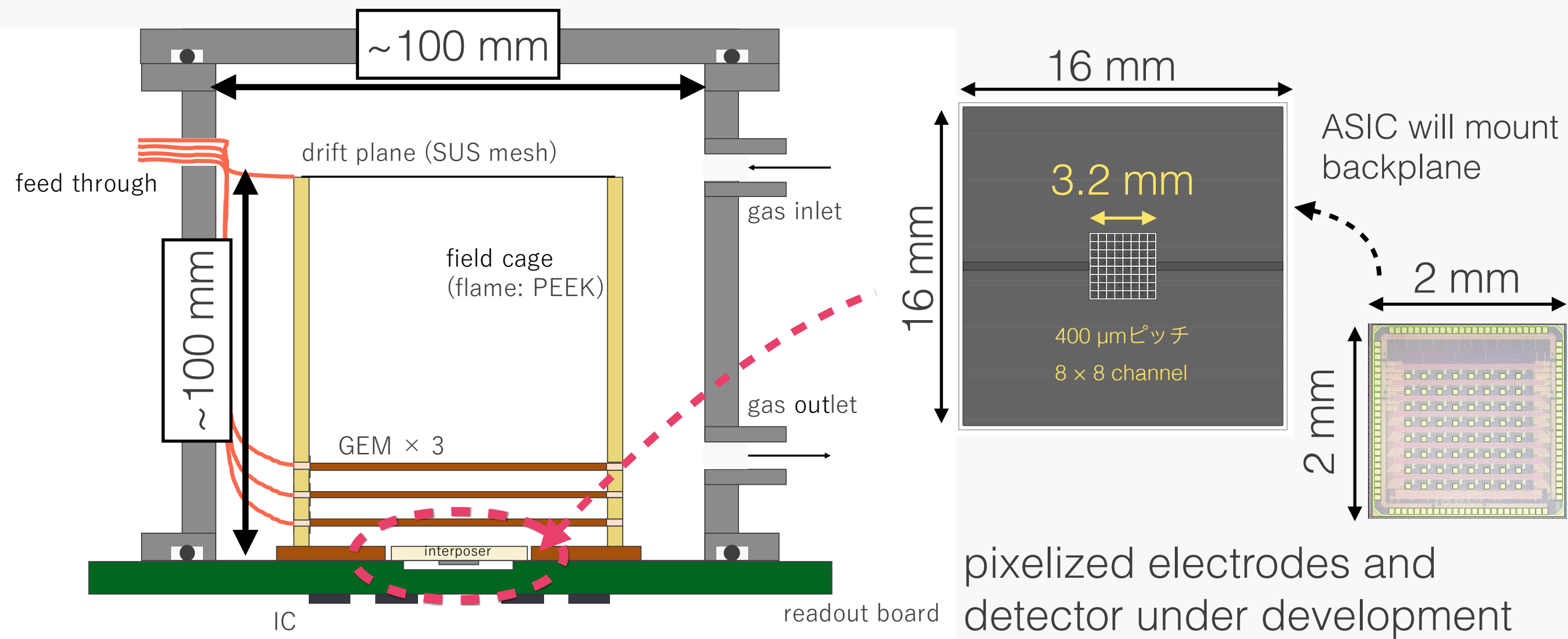


Pixel readout



Prototype pixel detector

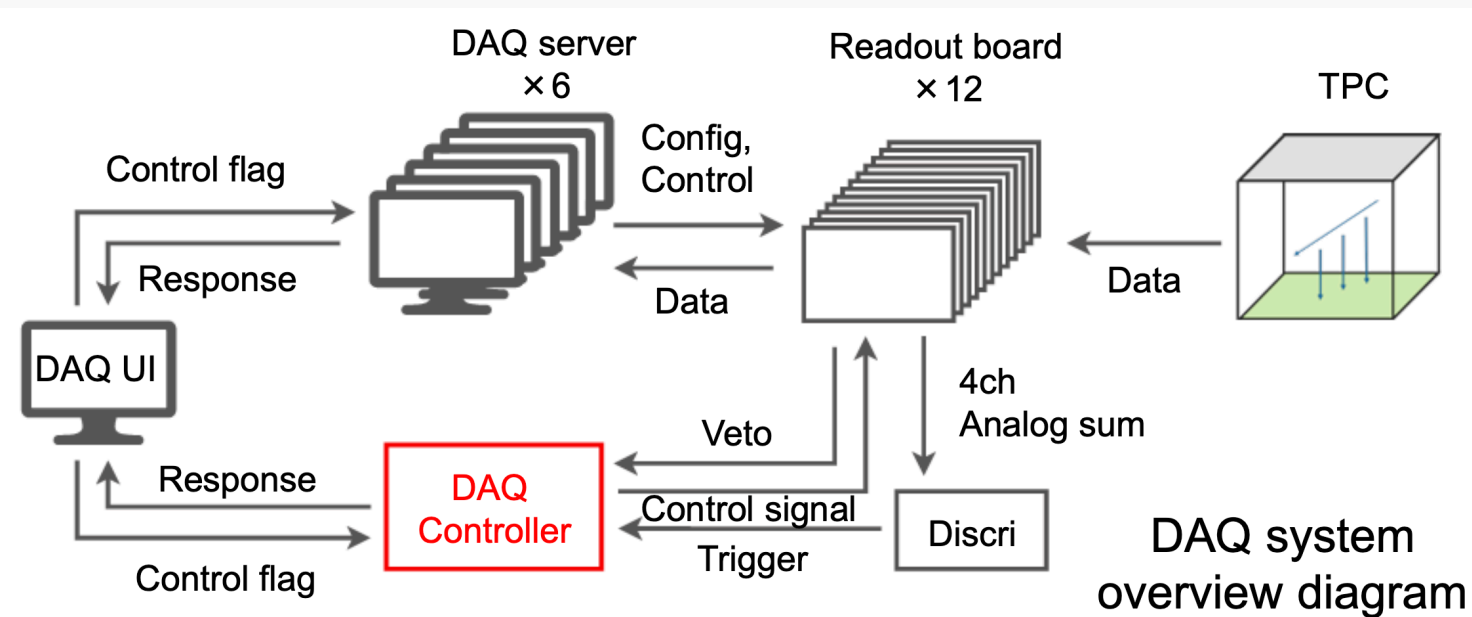
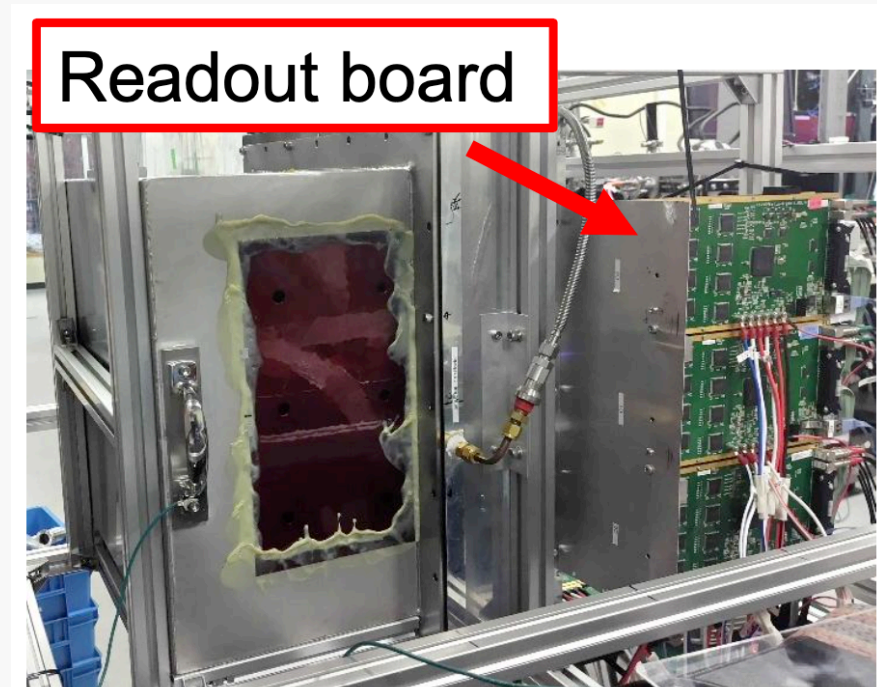
- Started to develop a small size detector
 - ➔ for demonstration of pixel readout at the first stage
 - ➔ Pixel pitch keeps 400 μm (due to difficulties of fine pitch electrode production)
- Assuming to use low pressure pure SF_6 gas to enable additional SF_6 studies



Integrated DAQ system

- NEWAGE is using old DAQ system
 - ➔ need to replace electronics
- New system was developed for a Migdal search experiment
 - ➔ Enable to use it in NEWAGE as well
- Multi-DAQ servers are integrated in this system
 - ➔ DAQ for any detector can be integrated with this technology
 - ➔ **capable of reconstructing long tracks or back-to-back processes**

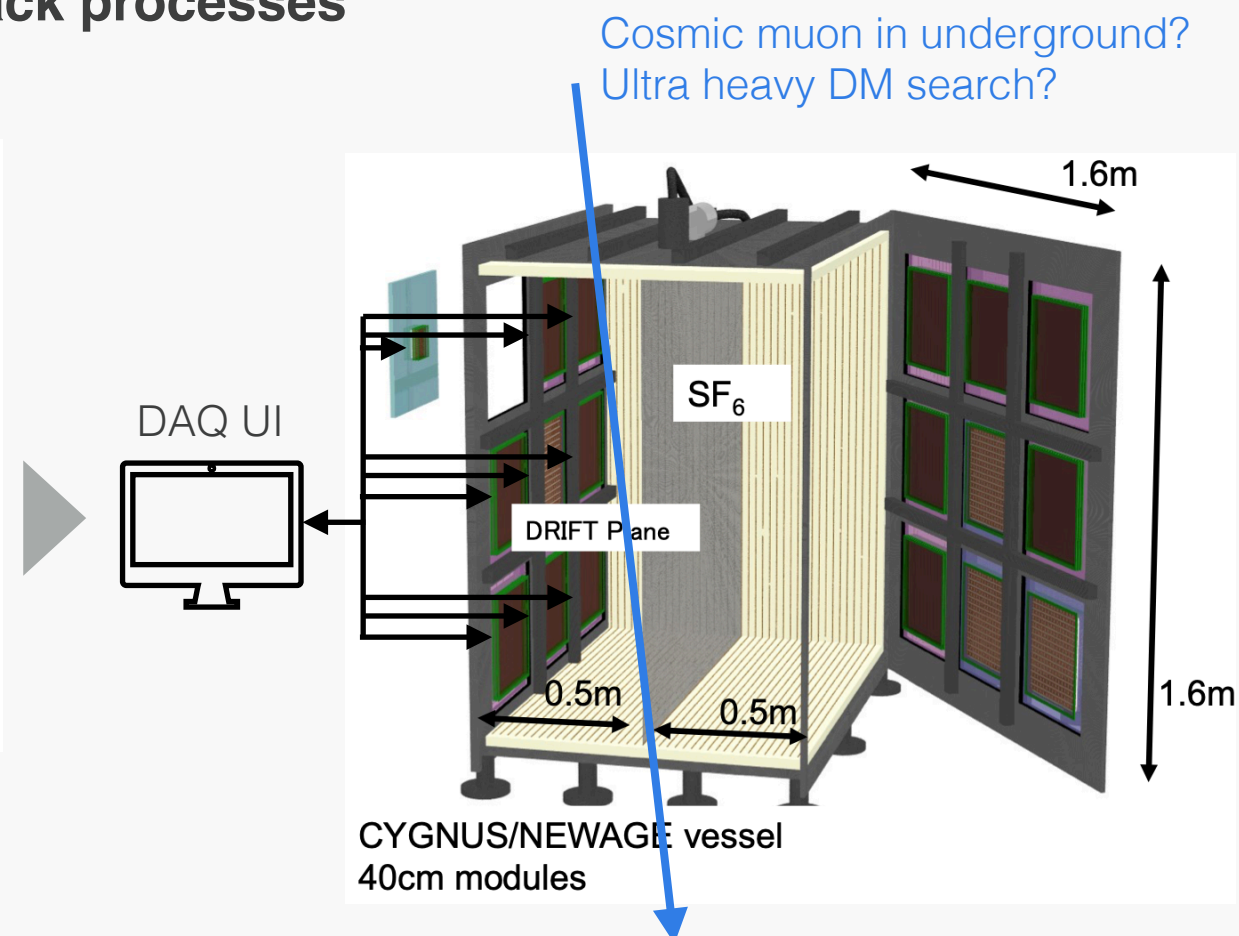
(Keishi's talk)



DAQ system overview diagram

Shiori's poster

(focusing on the DAQ development for the Migdal search)



MIMAC latest result

arXiv: 2607.23527

- Directional search with low pressure gaseous TPC (50% i-C₄H₁₀ + 50% CHF₃ @0.03 atm)
- 424 μm pitch pixelated detector coupled to a Micromegas structure
 - ➔ Low energy track reconstruction performed, resulting low energy threshold (0.45 keVee) achieved
- They set an upper limit on the SD DM-p cross section of $< 6.65 \times 10^{-36} \text{ cm}^2 \text{ (C.L.)}$

