

Direct observation of the Migdal effect induced by neutron bombardment [*Nature* 649, 580–583 \(2026\)](#)



易涤凡

yidifan18@mailsucas.ac.cn

(on behalf of **MARVEL** group)

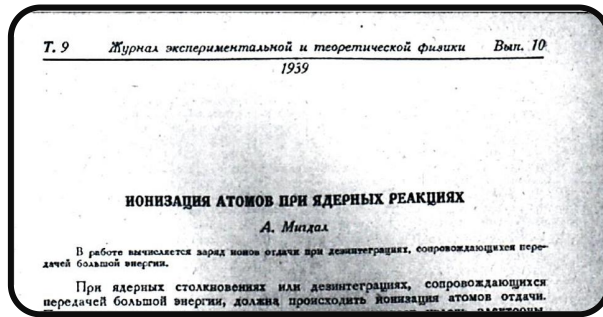
July, 16th, 2026 Guangzhou

MigdAI pRocess Validation by nEutral scattering

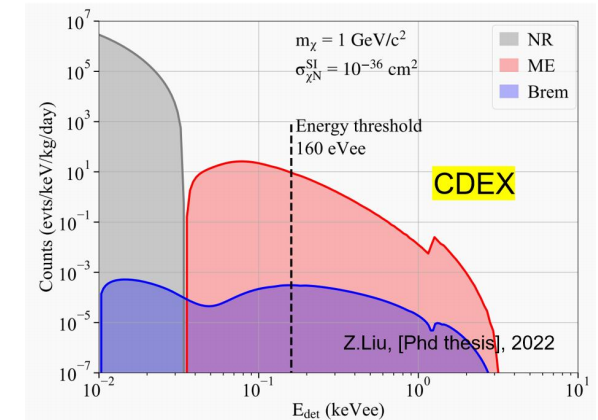
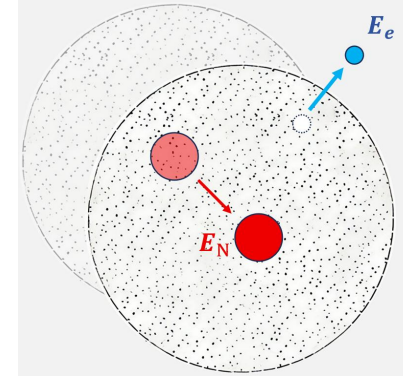
University of Chinese Academic of Sciences



Migdal effect



First predicted by Arkady Migdal
in 1939-1940



- The approximate treatment of the Original Migdal's method

Nuclear rest frame, the electronic cloud state:

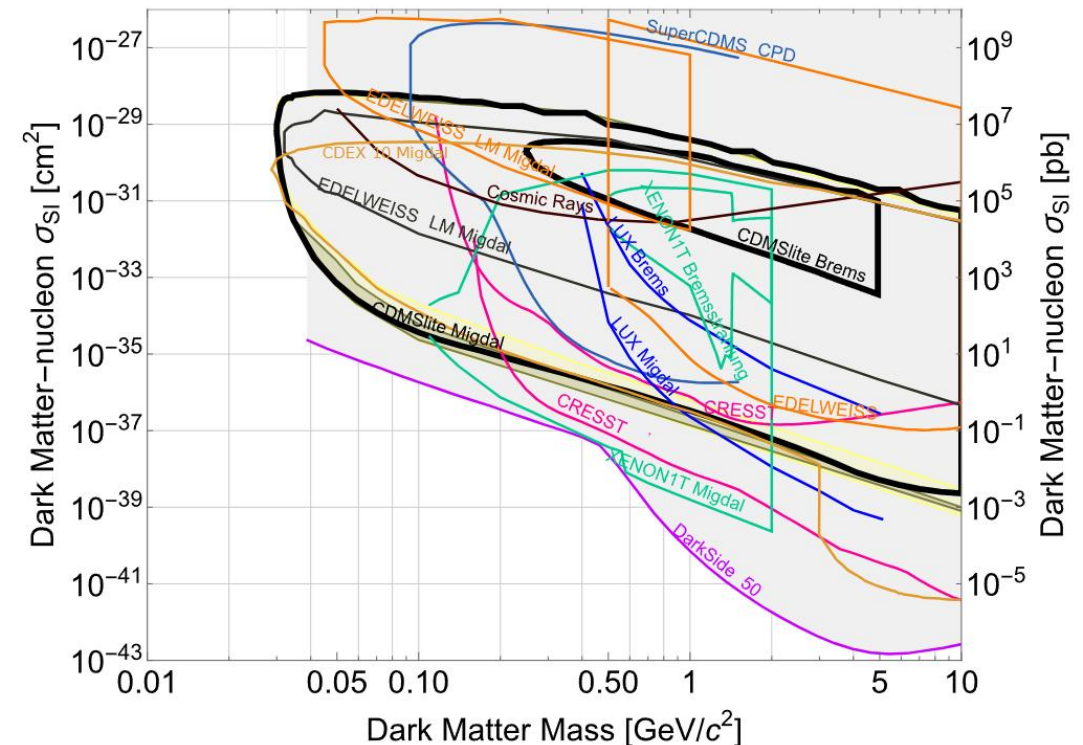
$$|\Phi'_{ec}\rangle = e^{-im_e \sum_i \mathbf{v} \cdot \hat{\mathbf{x}}_i} |\Phi_{ec}\rangle$$

Nucleus recoil

Ionization probability : $\mathcal{P} = |\langle \Phi_{ec}^* | \Phi'_{ec} \rangle|^2$

- Separate treatment of final-state ionization & nuclear recoil
- Obscure energy-momentum & probability conservation

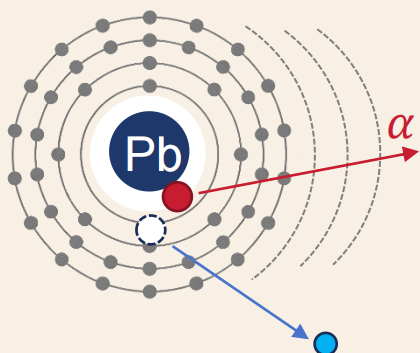
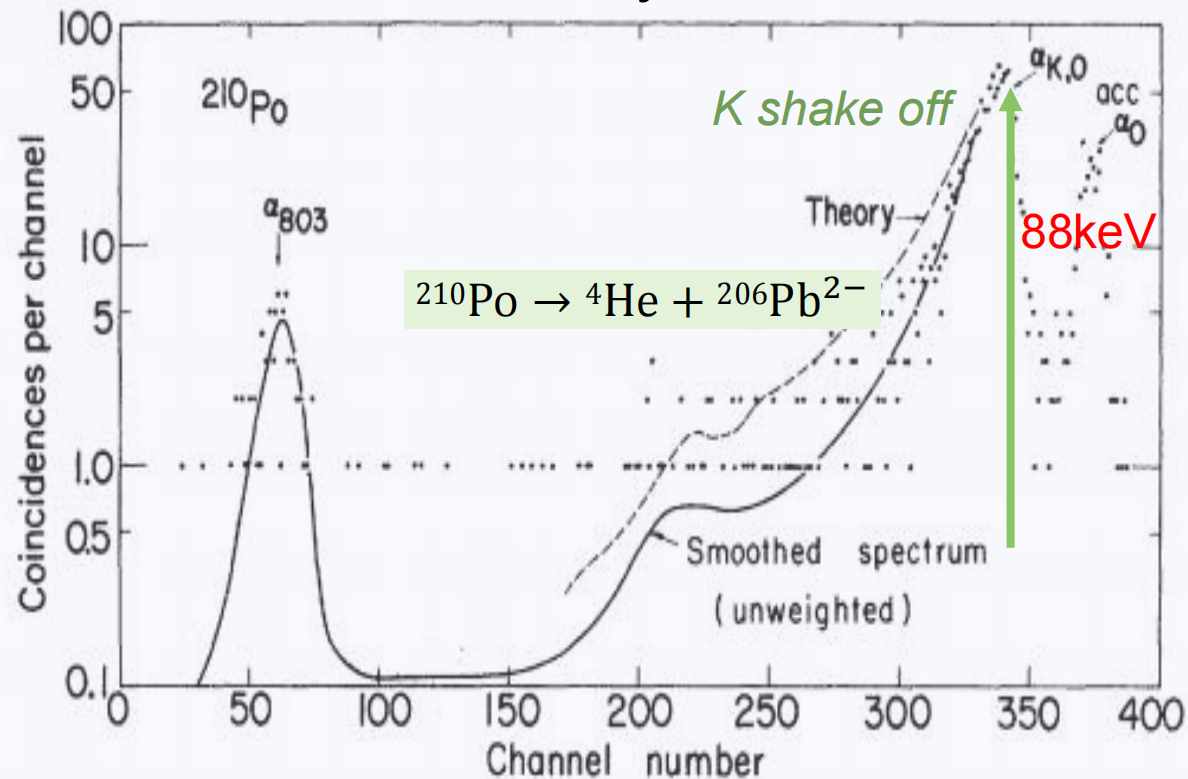
(Ibe, IBS, 2017)



Indirect measurement of the Migdal effect

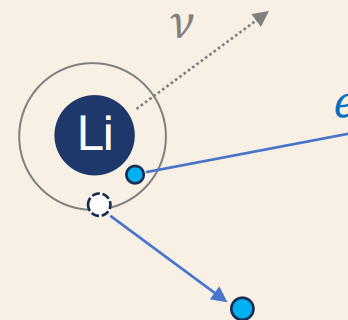
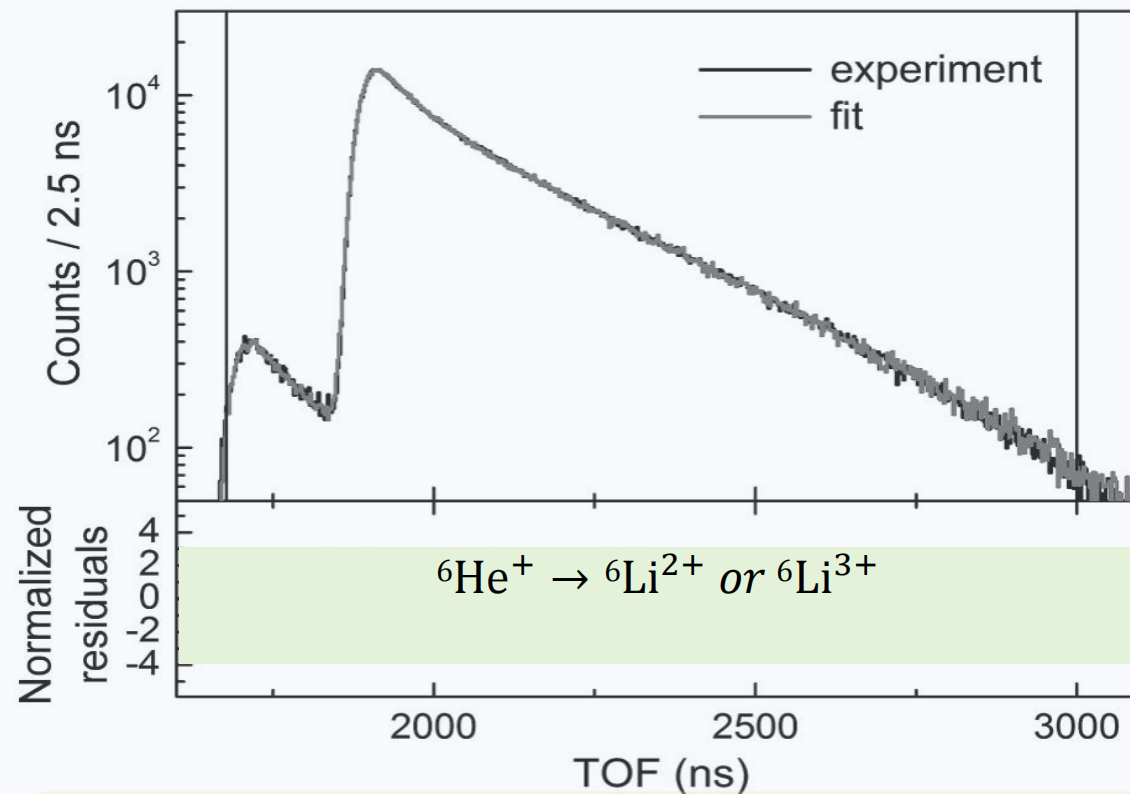
α decay

PhysRevC.11.1740 (1975)

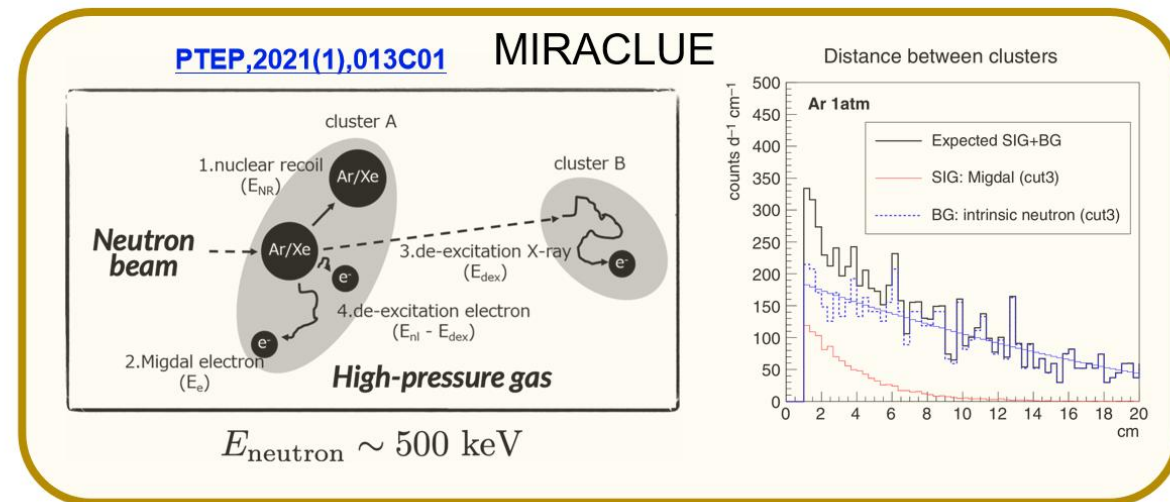
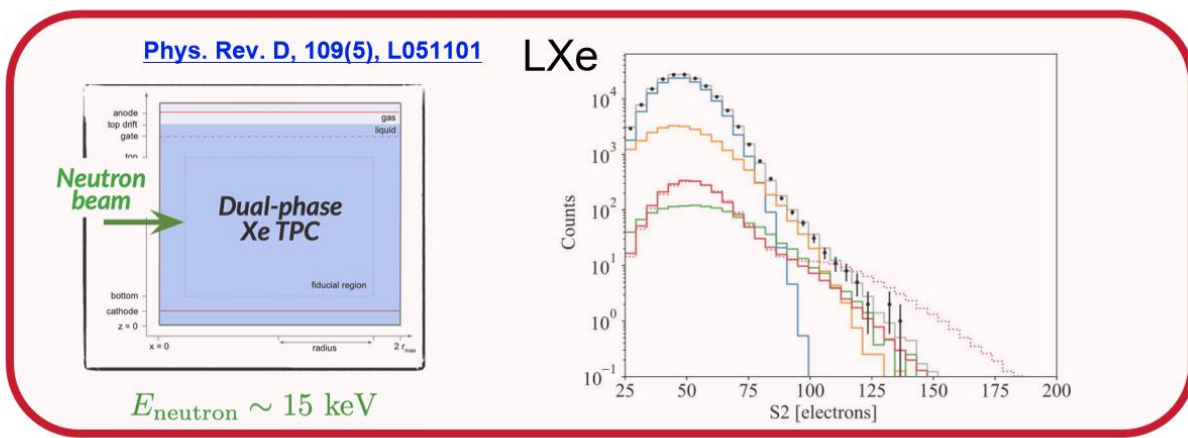
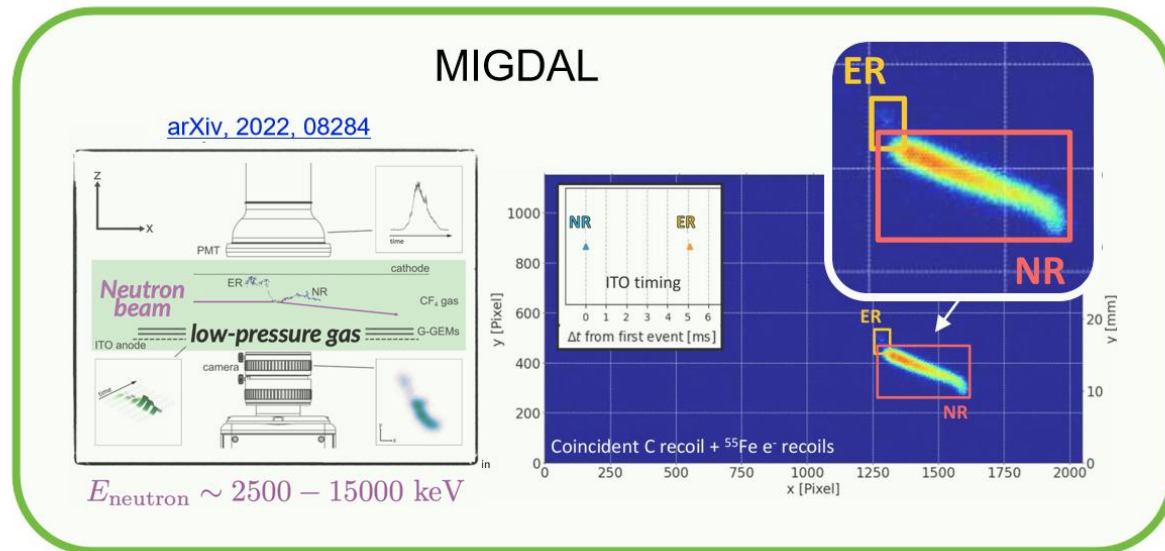


β decay

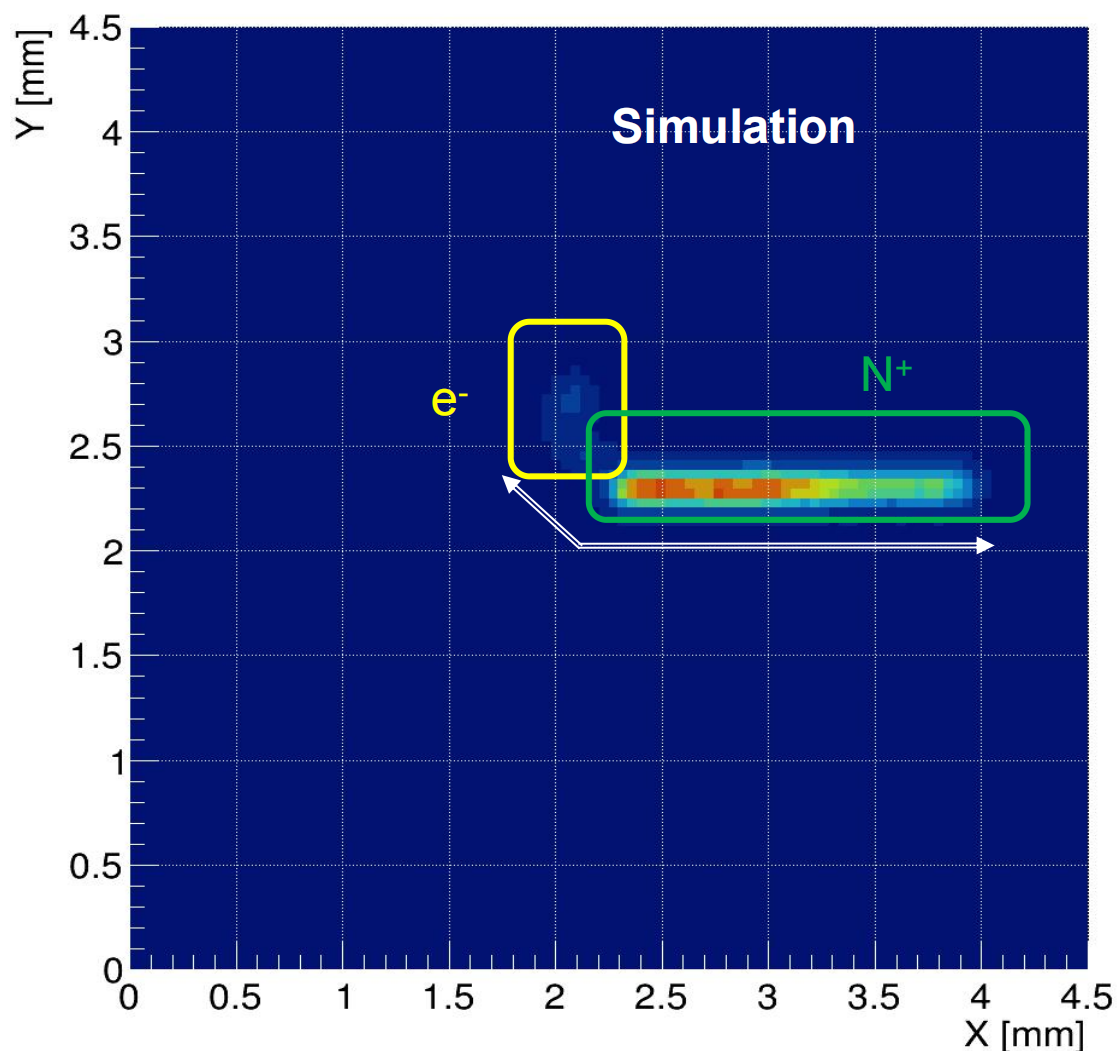
PhysRevLett.108.243201 (2012)



Migdal effect detection Experiments



ER: 5.9 keV , NR: 300 keV

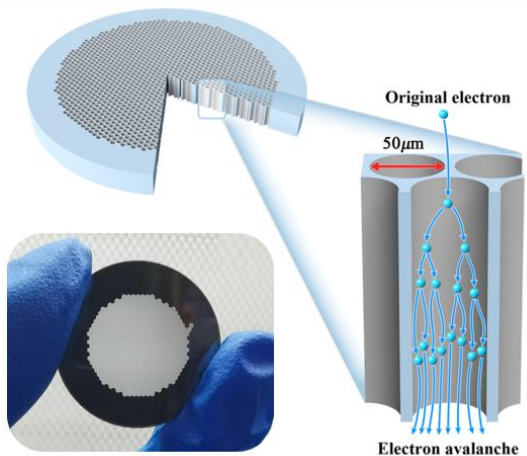


- **ER~keV, NR~hundreds keV**
 - Good energy resolution
 - Large dynamic range.
- **ER shares vertex with NR**
 - Good vertex resolution
- **Reduce possible background**
 - Good time resolution

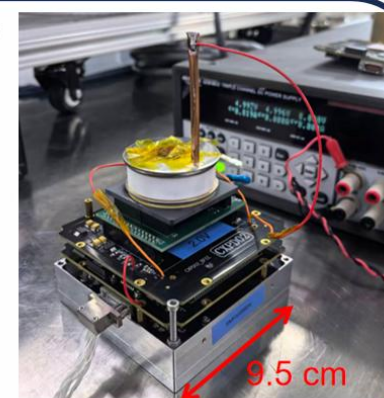
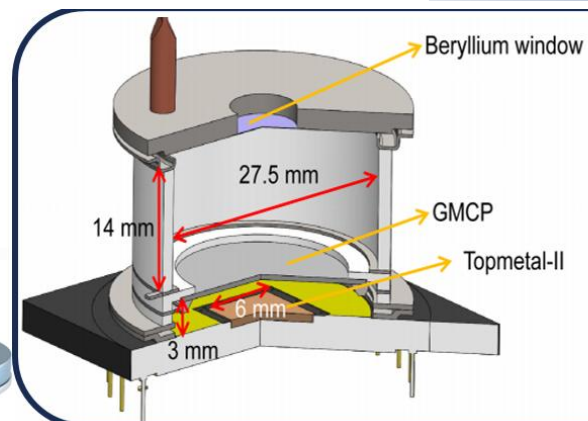
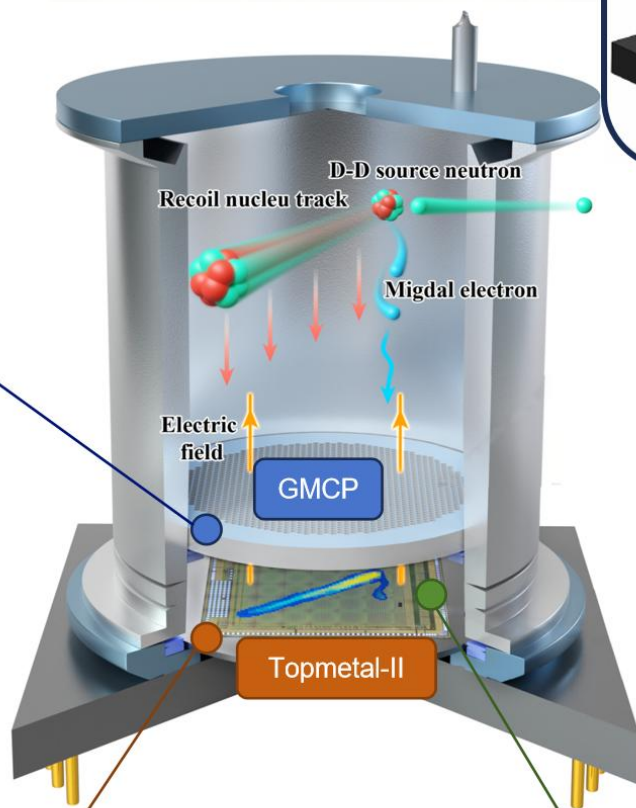
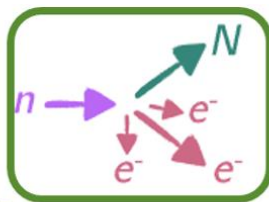
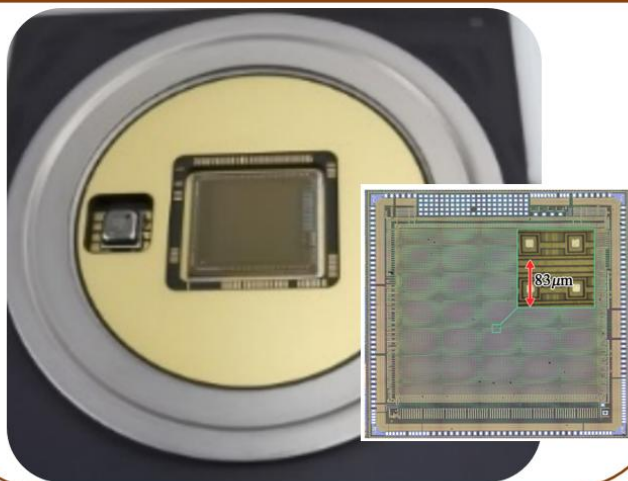
MARVEL Experiment-Detector



GMCP



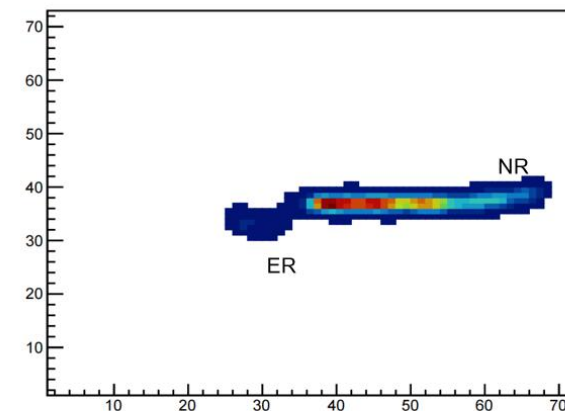
Topmetal-II



DD neutron source

Migdal topology

Electron E_k : 5.2500 keV, Ion E_k : 0.2300 MeV

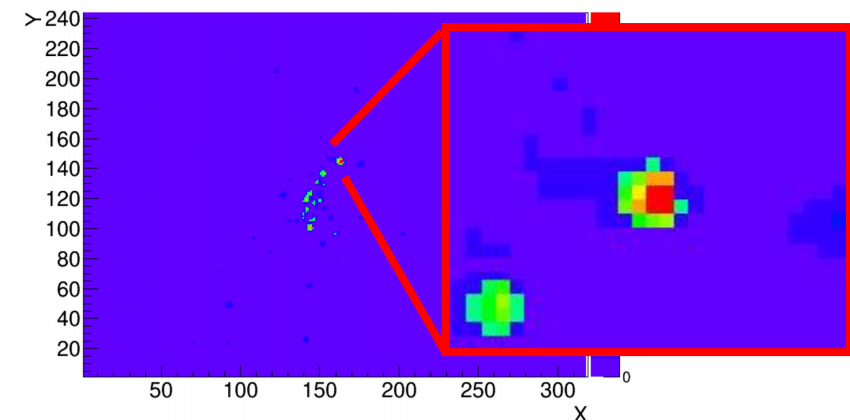
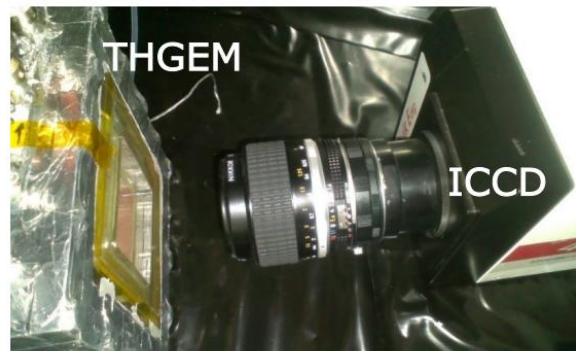
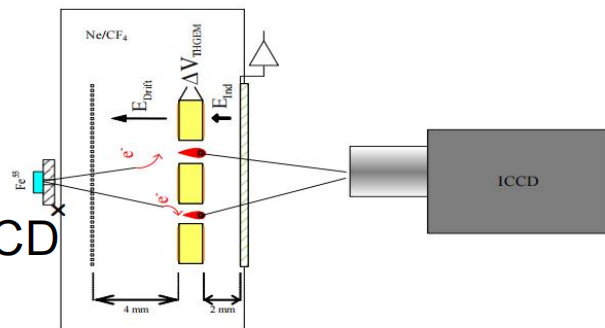


Development of the detector design

[10.1088/1748-0221/13/06/P06011](https://doi.org/10.1088/1748-0221/13/06/P06011)

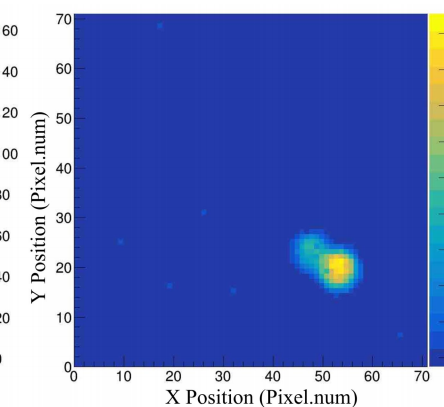
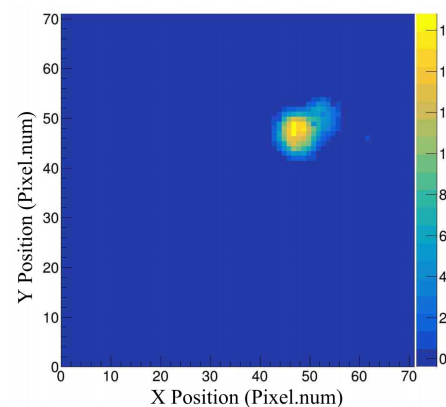
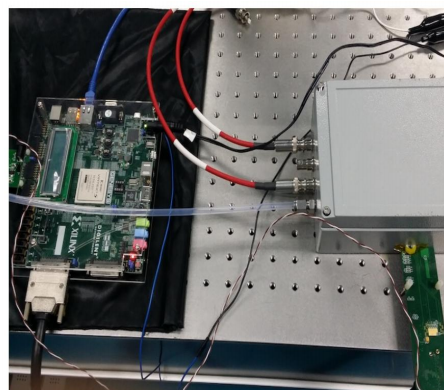
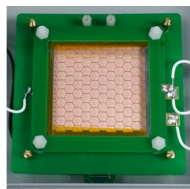
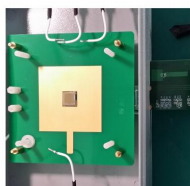
2015-2018

THGEM/Mesh+CCD

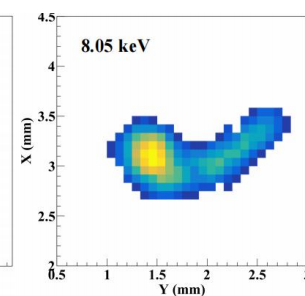
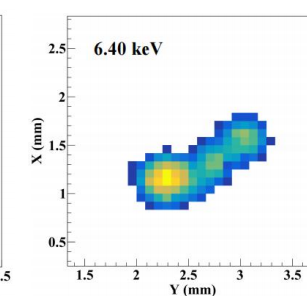
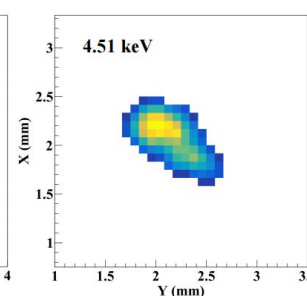
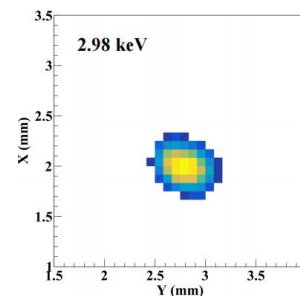
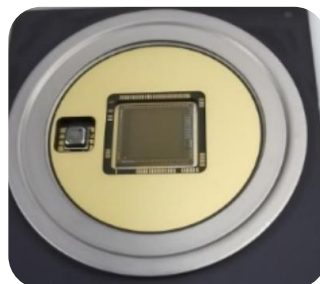
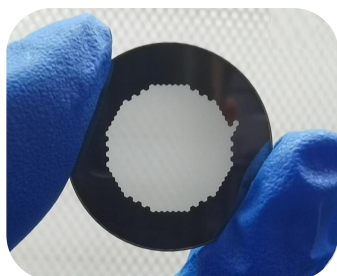


2019-2020

THGEM+Topmetal

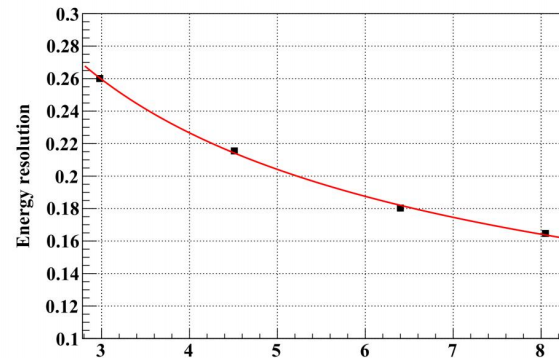
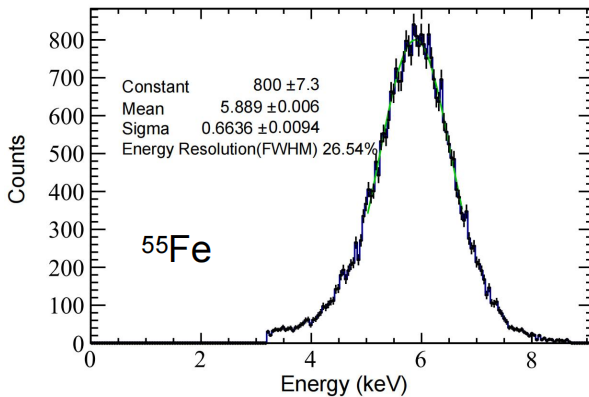


2021-now
GMCP+Topmetal



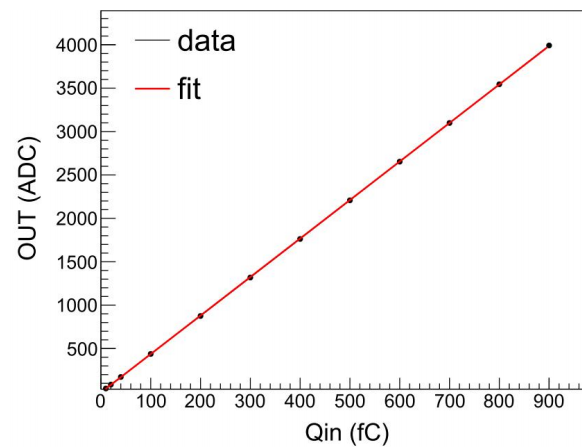
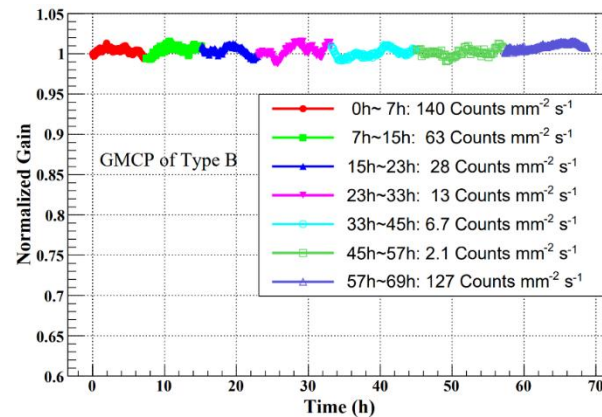
Detector performance

Energy resolution



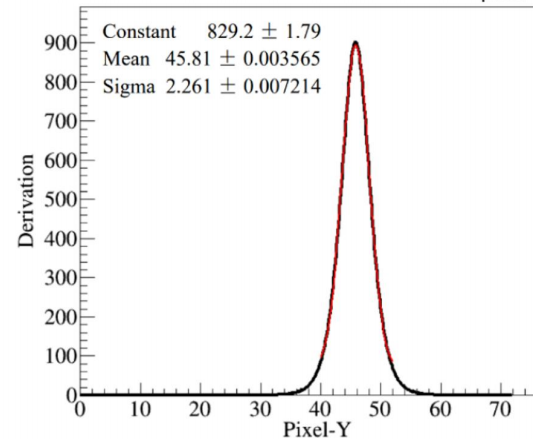
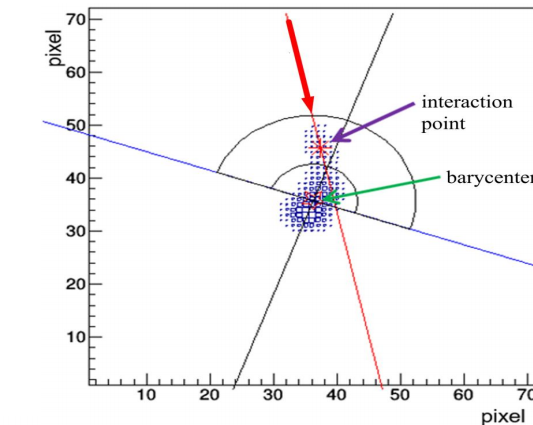
- Good linear energy response
- 20%-30% energy resolution(FWHM)
- Energy resolution follows the relationship $\sim 1/\sqrt{E}$

Dynamic range



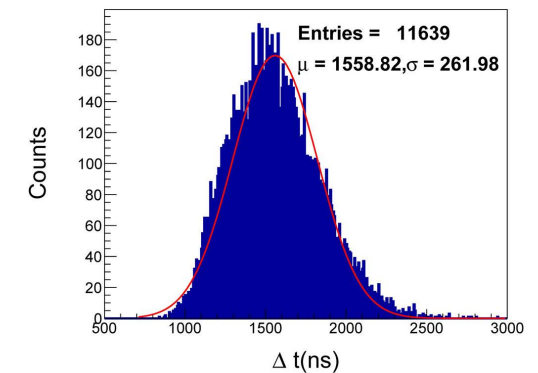
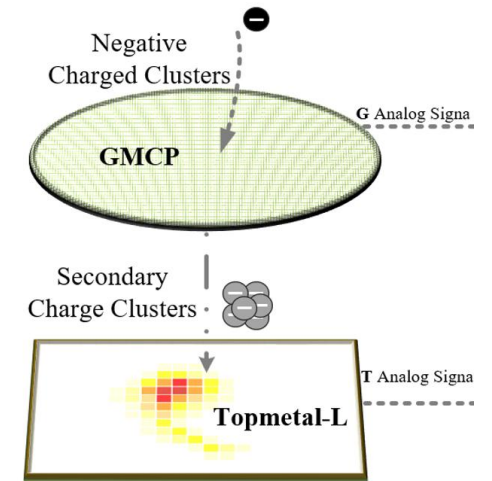
- Stable gain under different count rates(no pile up)
- Good linearity in charge response

Vertex resolution

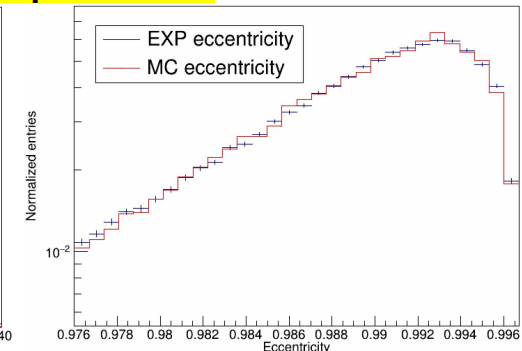
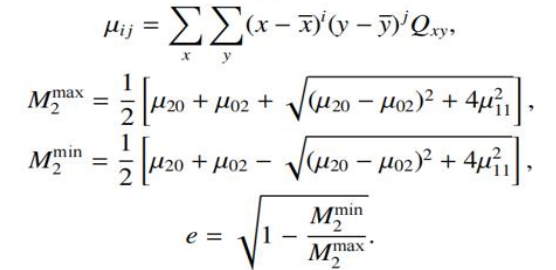
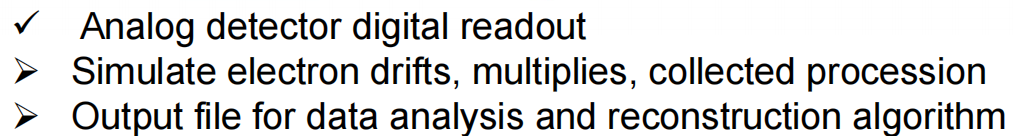


- $\sim 200 \mu\text{m}$ vertex resolution @ 6.4 keV

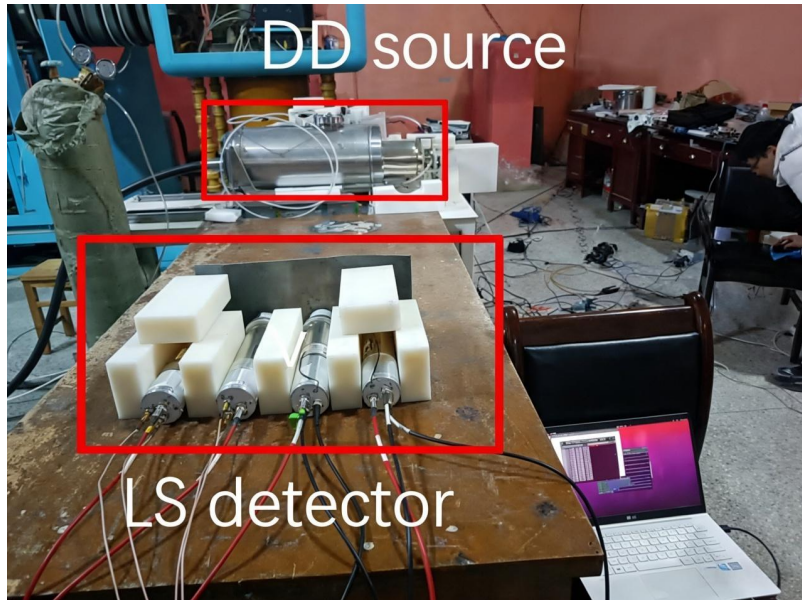
Time resolution



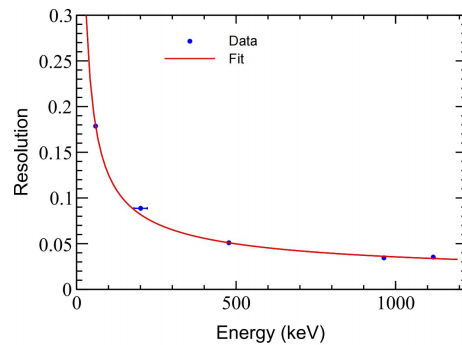
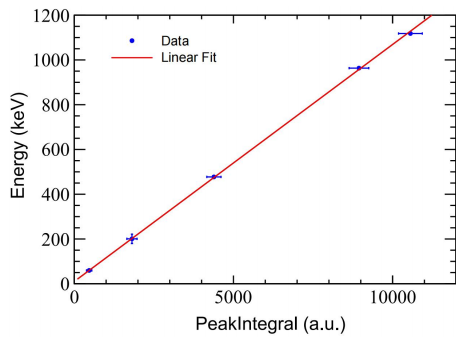
- $\sim 262 \text{ ns}$ time resolution



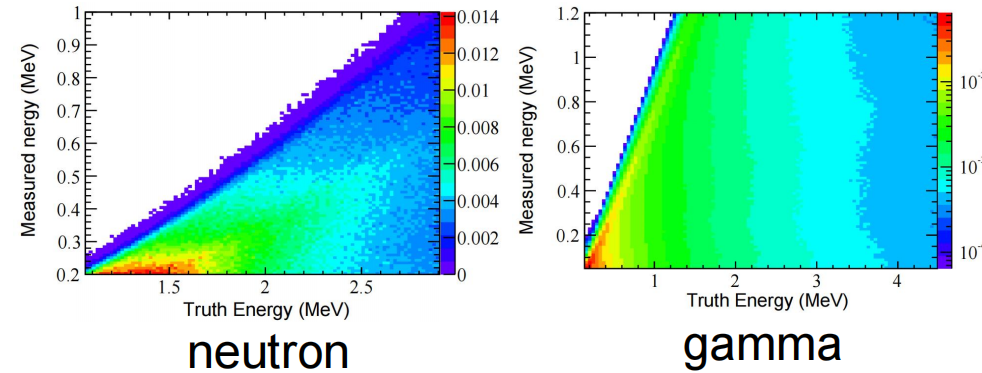
Neutron/gamma measurement



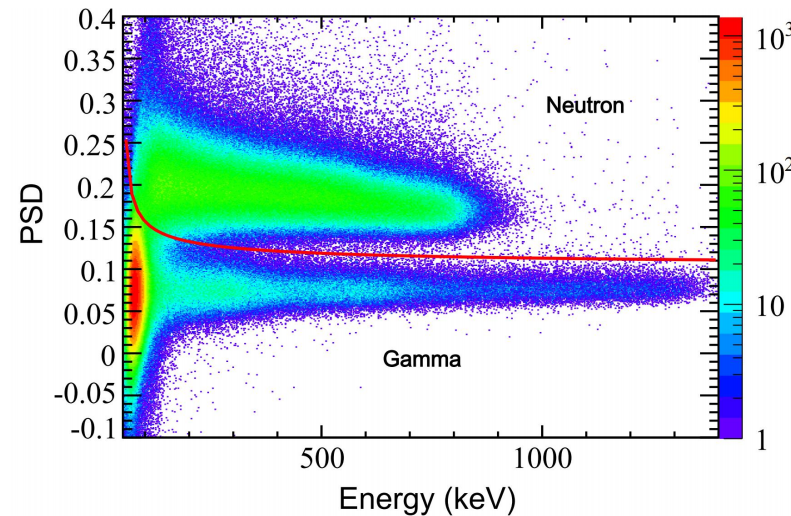
1. LS detector calibration:



2. Generate the Response matrix by GEANT4

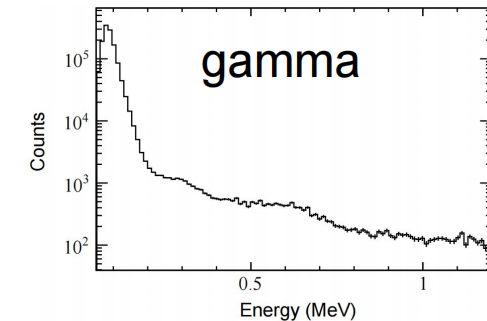
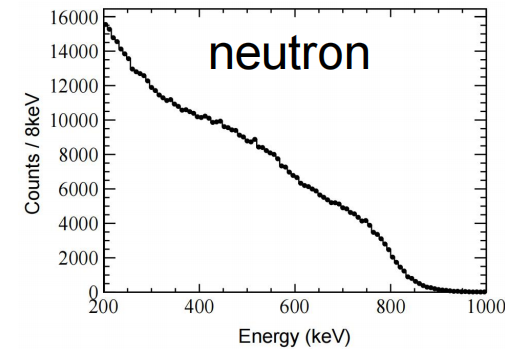


3. Neutron/gamma selection by PSD



https://gitee.com/schg_ucas/unfold-err
https://gitee.com/schg_ucas/unfold-multi

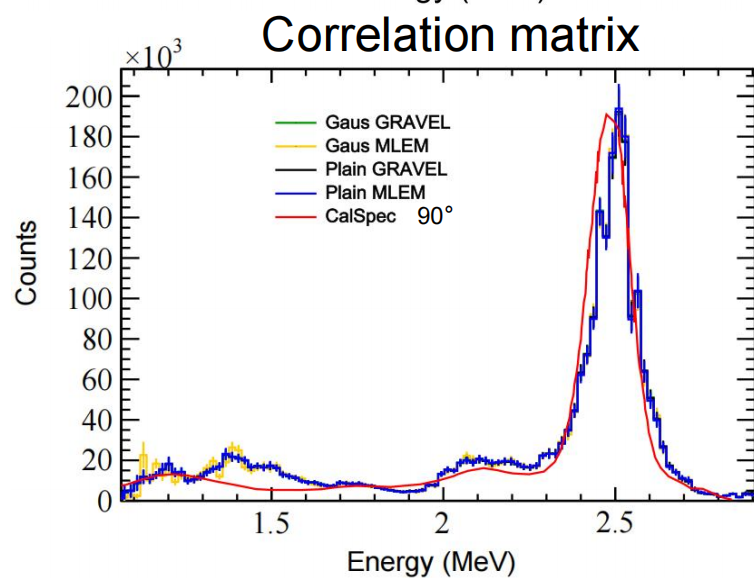
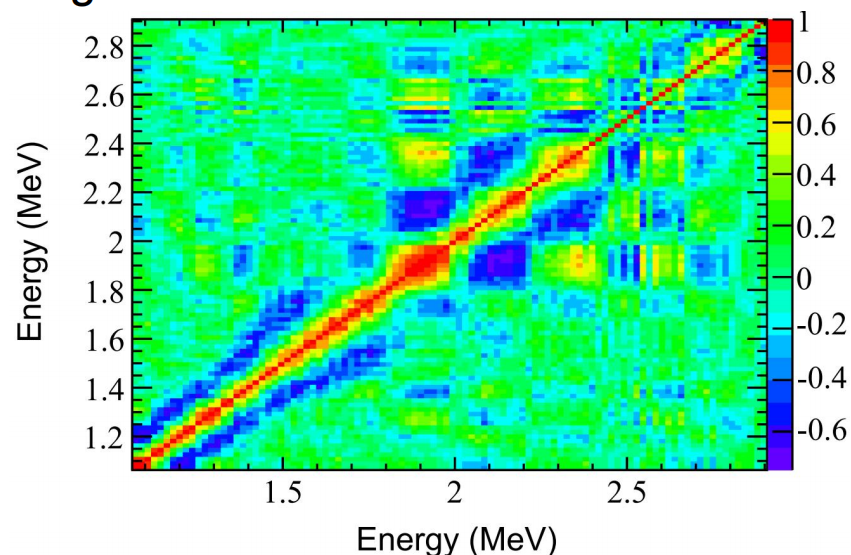
4. Do the unfolding



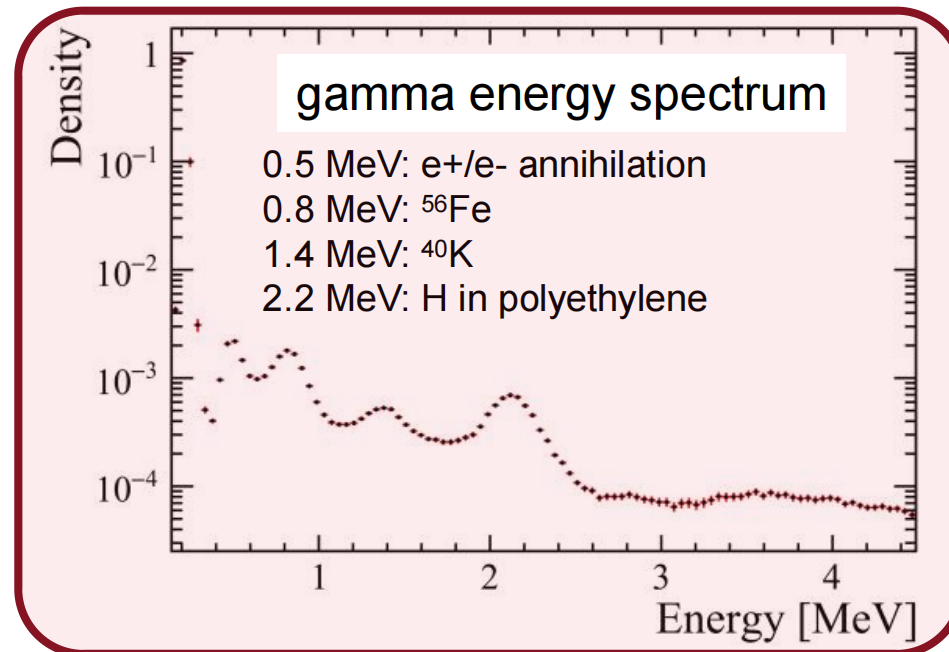
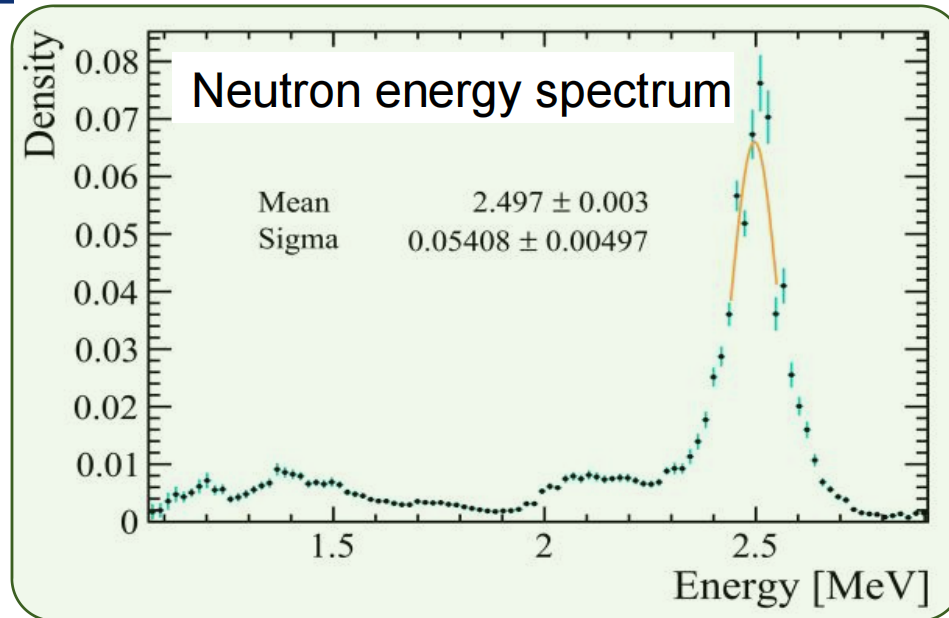
measured spectra

Neutron/gamma measurement

Unfolding result:

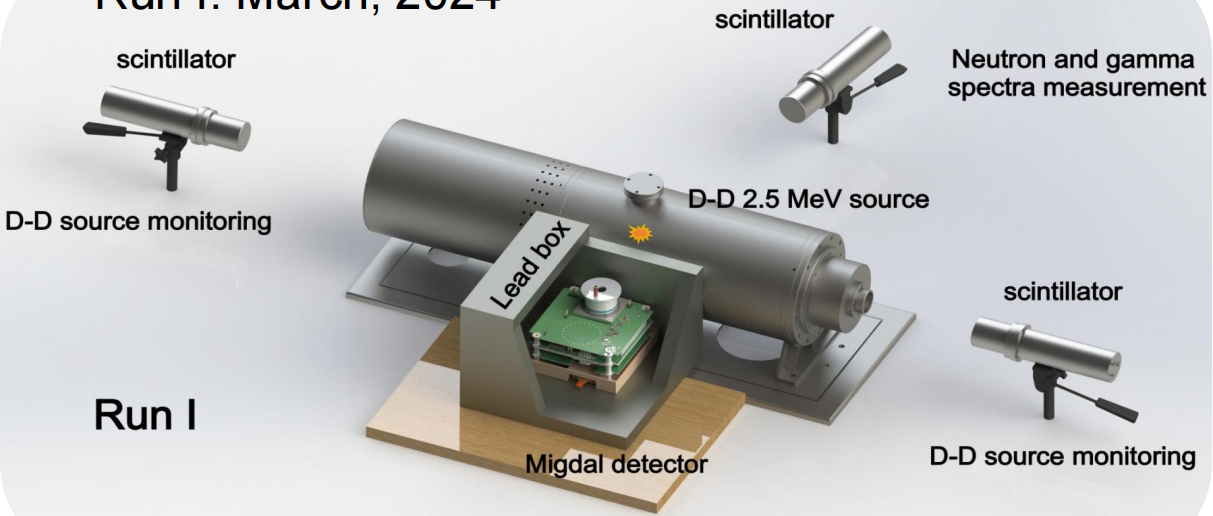


Measured at 87°, harder than 90°

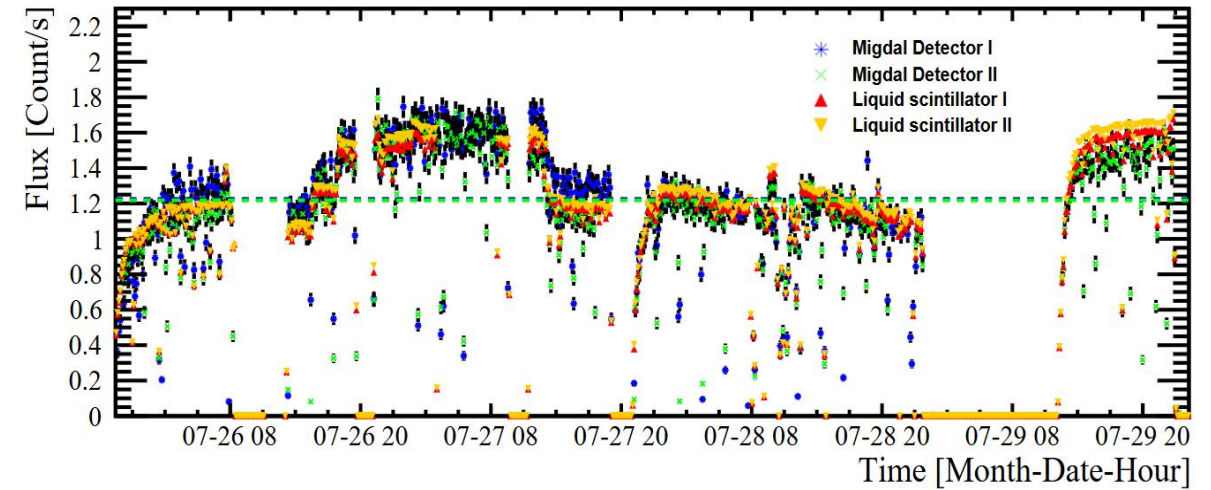
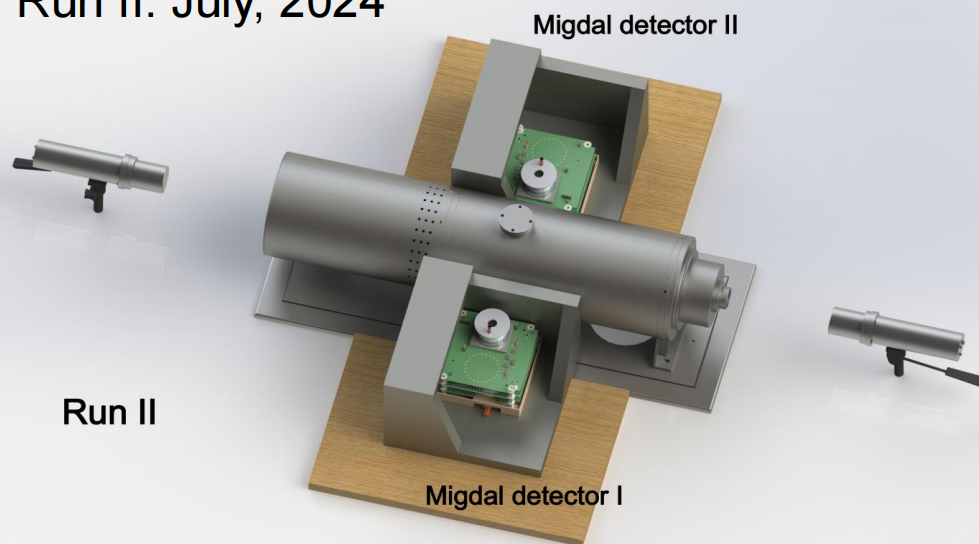


D-D source experiment

Run I: March, 2024



Run II: July, 2024



AI-assisted event selection

Data

YOLO*1
preselection

NR
reconstruction

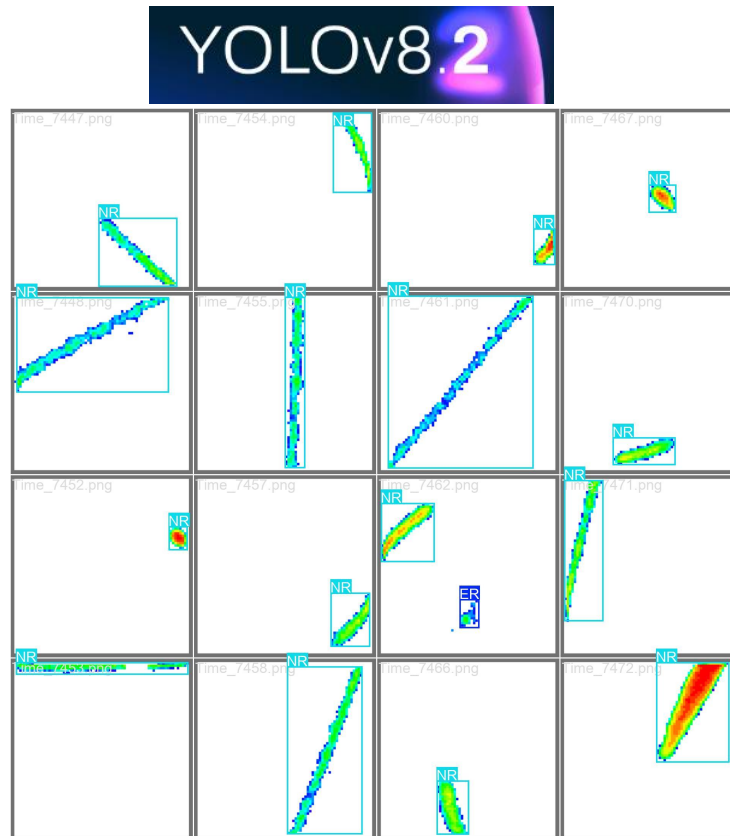
ER
reconstruction

Vertex cut

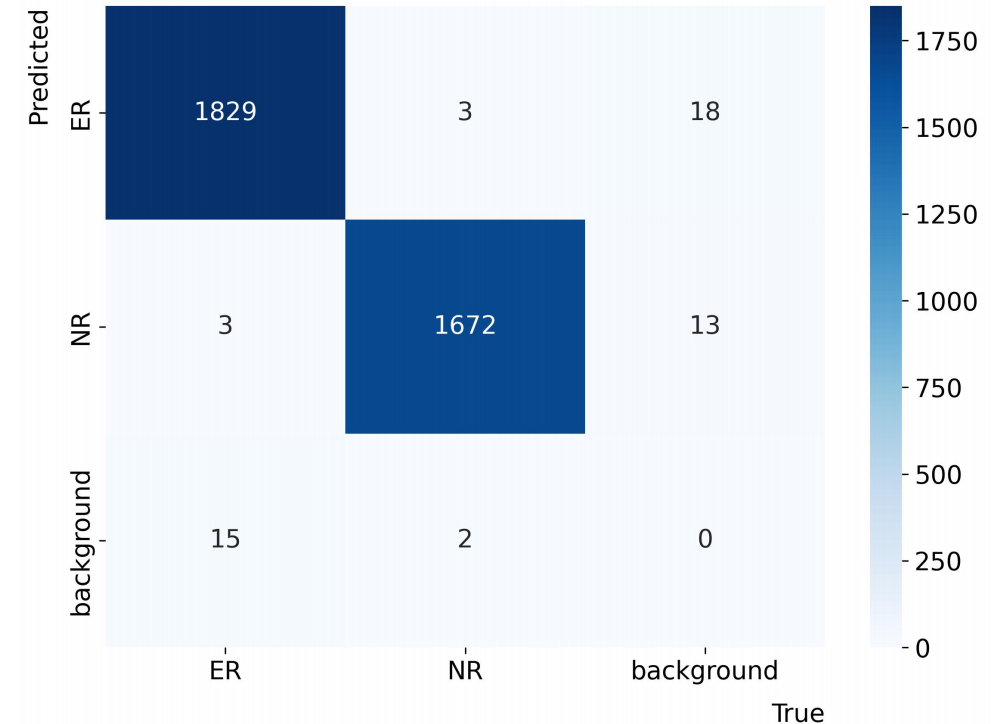
Inspired by MIGDAL collaboration's work: [10.1103/PhysRevD.111.072004](https://arxiv.org/abs/10.1103/PhysRevD.111.072004)

Labeling

Dataset		Train	Valid
Exp	⁵⁵ Fe	3000	1493
	D-D	2994	1354
Sim	ER	1200	301
	NR	1200	301
Total		8394	3449



Training



*1 <https://github.com/ultralytics/ultralytics>

Data

YOLO*1
preselection

NR
reconstruction

ER
reconstruction

Vertex cut

1. Search for the NR vertex through recursive iteration:

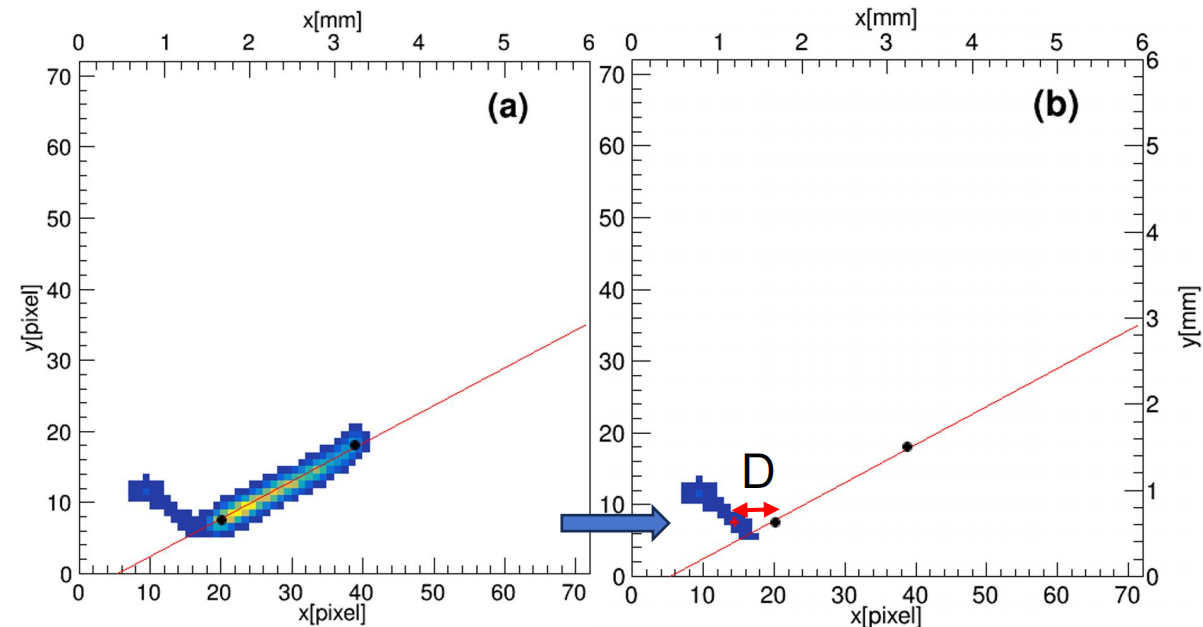
$$\text{ADC} \cdot \exp(d/d_0)$$
$$(x_0, y_0) \longrightarrow (x_n, y_n)$$

2. Fit the NR(direction, diffusion σ) and remove it from the image.

3. Search for the electron vertex using adaptive cutting algorithm.

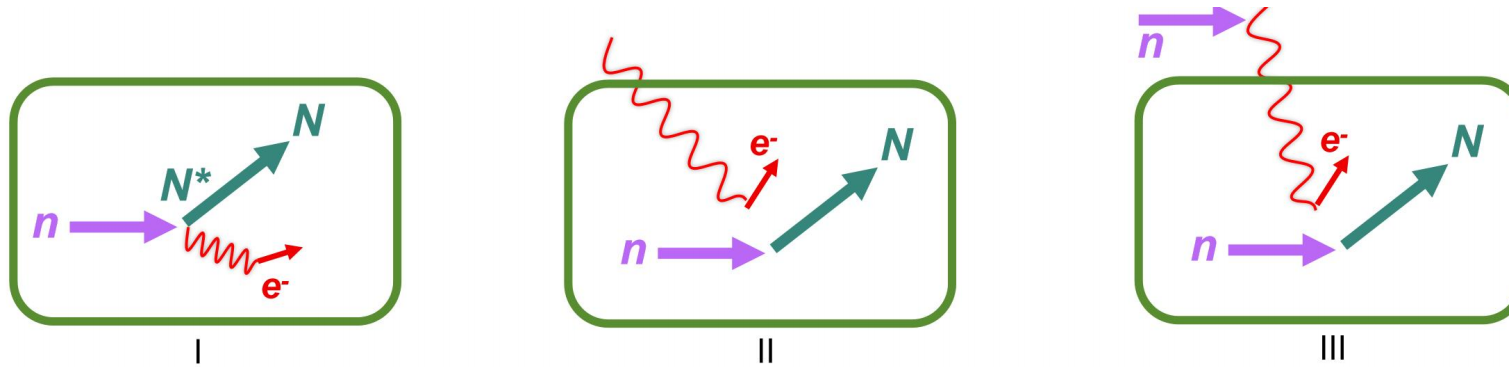
4. Determine whether the electron vertex is adjacent to the nucleon vertex.

$$R = \frac{D - 4\sigma}{L_{\text{ER}}} < 0.5$$



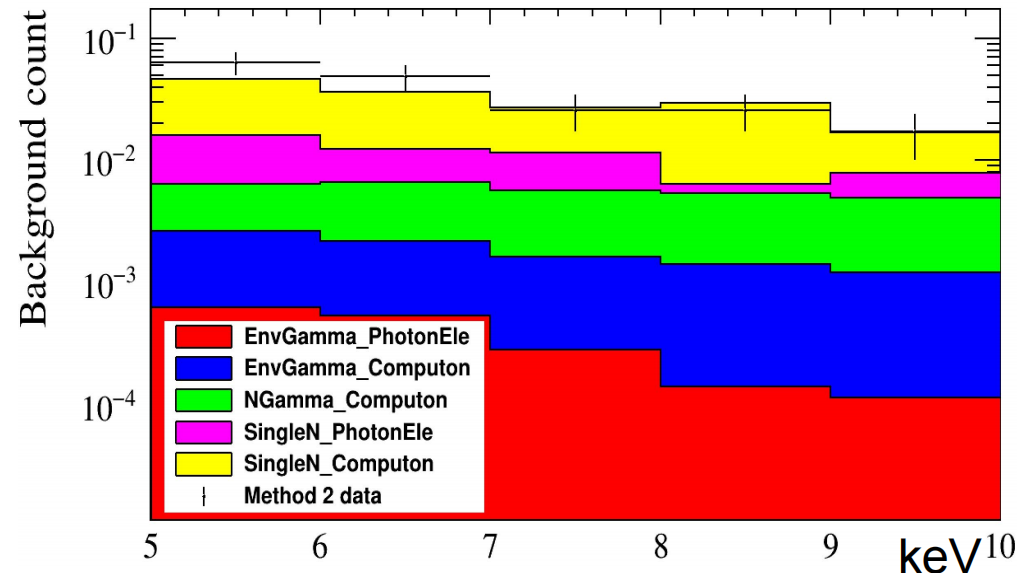
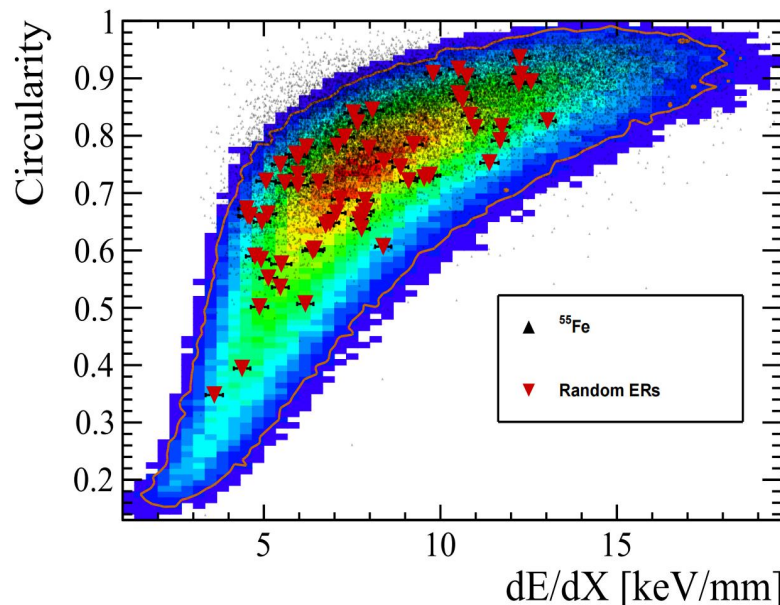
Background Component	Description	Expectation value (5 - 10 keV)
Recoil induced δ ray	δ electron near NR track origin	$0.035 \pm 0.023(\text{stat.}) \pm 0.0068(\text{sys.})$
Particle Induced X-ray Emission		
X-ray emission	Photoelectron near NR track origin	0
Auger electrons	Auger electron near NR track origin	0
Bremsstrahlung processes		
Quasi-Free Electron (QFEB)	Photoelectron near NR track origin	≈ 0
Secondary Electron (SEB)	Photoelectron near NR track origin	≈ 0
Atomic (AB)	Photoelectron near NR track origin	≈ 0
Nuclear (NB)	Photoelectron near NR track origin	≈ 0
Random track coincidences	Photo-/Compton electron near NR track	$0.180 \pm 0.022(\text{stat.}) \pm 0.042(\text{sys.})$
Muon induced δ ray	δ electron near NR track origin	0.013
Gas radioactivity		
Trace contaminants	Electron from decay near NR track origin	$0.001 \pm 0.00087(\text{sys.})$
Neutron activation	Electron from decay near NR track origin	≈ 0
Secondary nuclear recoil fork	NR track fork near track origin	≈ 0
Total background		$0.229 \pm 0.032(\text{stat.}) \pm 0.043(\text{sys.})$

Radom track conincidence



	NR	Compton e ⁻	photonEle
I	1	4.32×10^{-5}	1.06×10^{-5}
II	1	6.06×10^{-6}	$\sim 3.63 \times 10^{-8}$
III	1	3.11×10^{-6}	7.15×10^{-7}

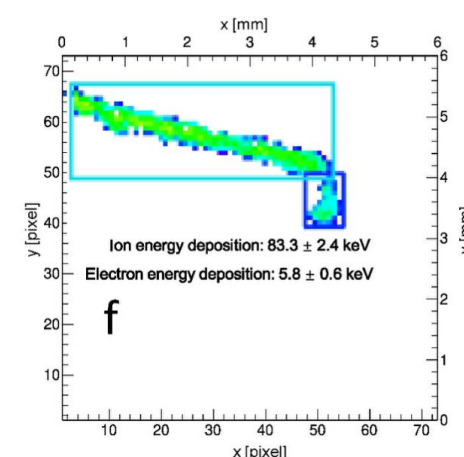
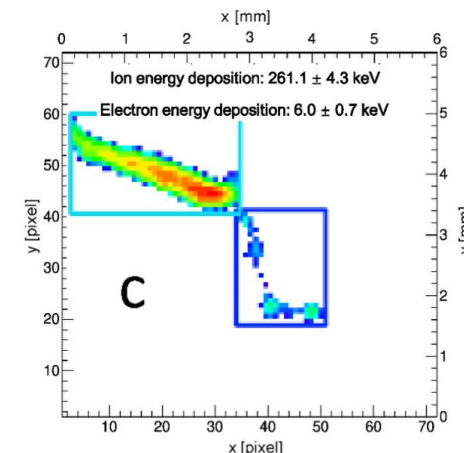
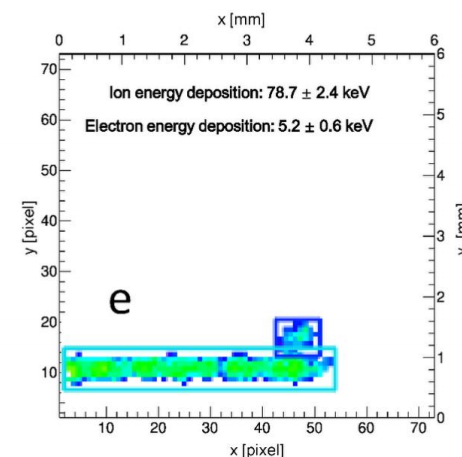
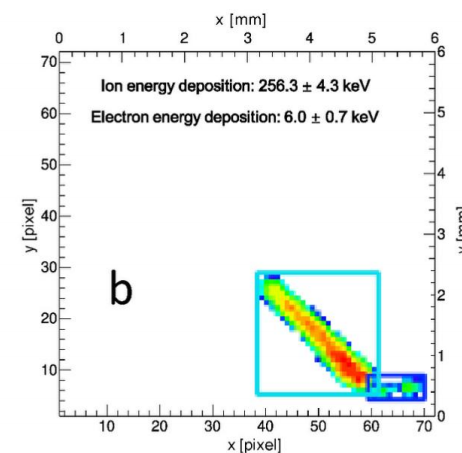
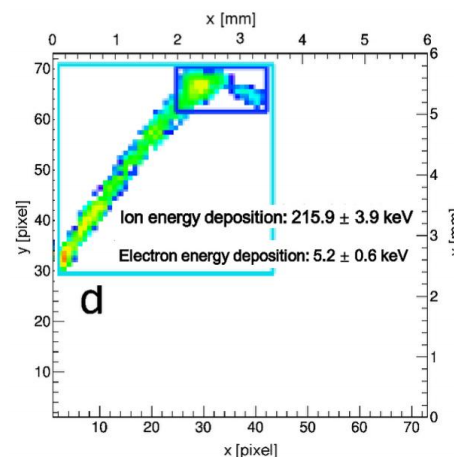
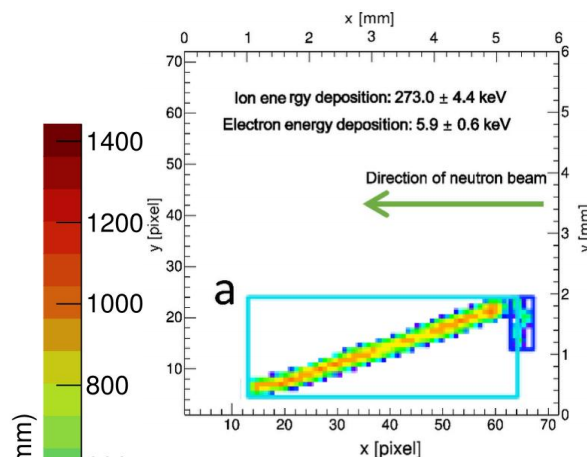
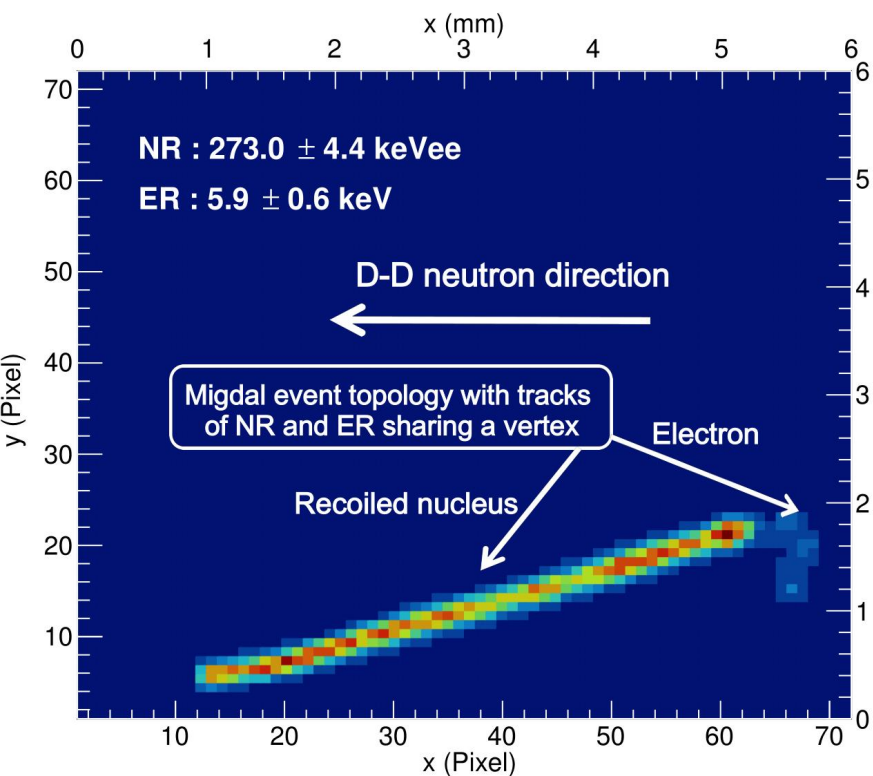
- Method 1 expected background contribution of the 3 components in total is: **$0.16 \pm 0.01(\text{stat.})$**



The results from the liquid scintillation + GEANT4 are consistent with the data obtained from the Migdal detector.

- Method 2 expected background value is **$0.180 \pm 0.022(\text{stat.}) \pm 0.042(\text{sys.})$**

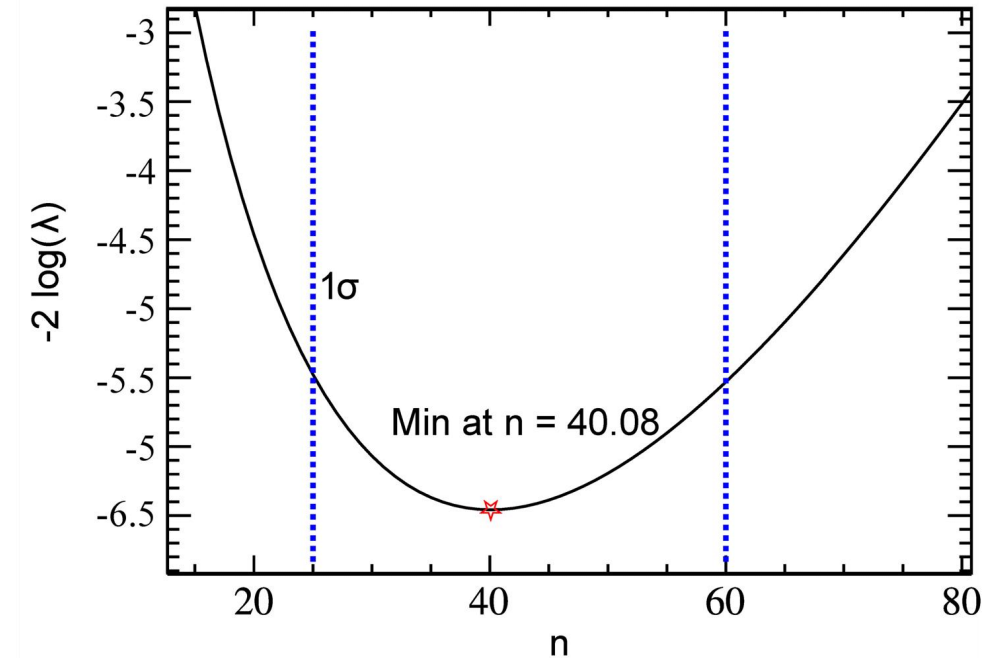
Migdal candidates



Cross section ratio calculation

- Probability: $P_{\text{Migdal}}(5\text{keV} < \text{ER} < 10\text{keV}, \text{NR} > 35\text{keV}) = \frac{\left(\frac{n_{\text{obs}}^{\text{ER}} - n_{\text{obs}}^{\text{bg}}}{\varepsilon_{\text{acc}} \varepsilon_{\text{NR}} \varepsilon_{\text{ER}}} \right)}{\left(\frac{n_{\text{tot}}^{\text{NR}}}{\varepsilon_{\text{acc}} \varepsilon_{\text{NR}}} \right)} = \frac{(n_{\text{obs}}^{\text{ER}} - n_{\text{obs}}^{\text{bg}})}{\varepsilon_{\text{ER}} n_{\text{tot}}^{\text{NR}}}$
- Parameters:

	Efficiency/Count	Statistical Error	Systematic Error
Efficiency ε_{ER}	14.4% 29%(YOLO)*49%(vertex rec)	$\pm 0.1\%$	$\pm 1.9\%$
$n_{\text{tot}}^{\text{NR}}$	8.17×10^5	± 903	± 35880
$n_{\text{obs}}^{\text{ER}}$	6		
$n_{\text{obs}}^{\text{bg}}$	0.229	± 0.032	± 0.043



- upper/lower bounds: $\Delta P_{\pm} = \sqrt{\left(\frac{n_{\text{min}} - n_{\text{ul/l}}}{n_{\text{min}}} \right)^2 + \left(\frac{n_{\text{tot}}^{\text{NR}} \text{error}}{n_{\text{tot}}^{\text{NR}}} \right)^2} \cdot \frac{n_{\text{min}}}{n_{\text{tot}}^{\text{NR}}}$

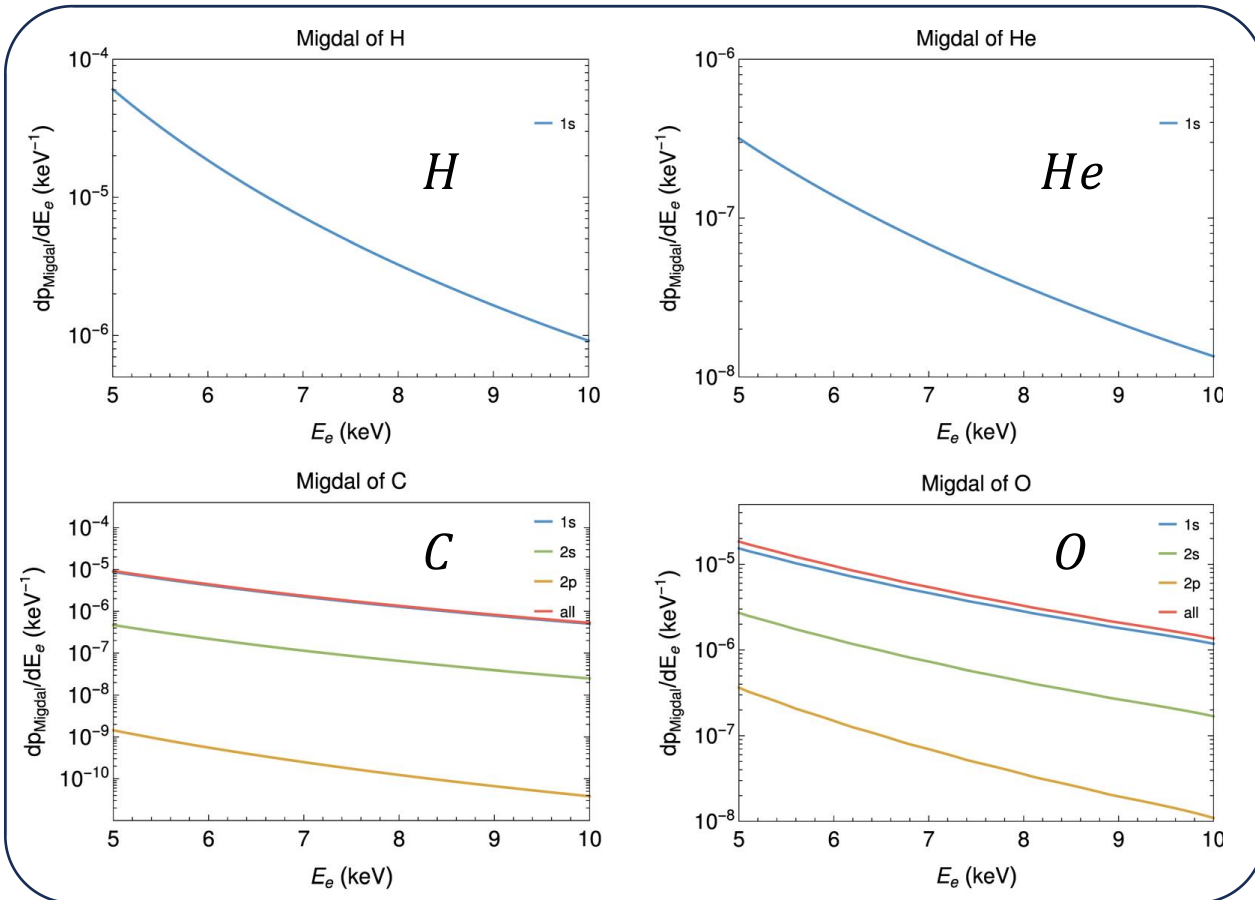
Result: $4.9_{-1.9}^{+2.6} \times 10^{-5}$

Theory: 3.9×10^{-5}

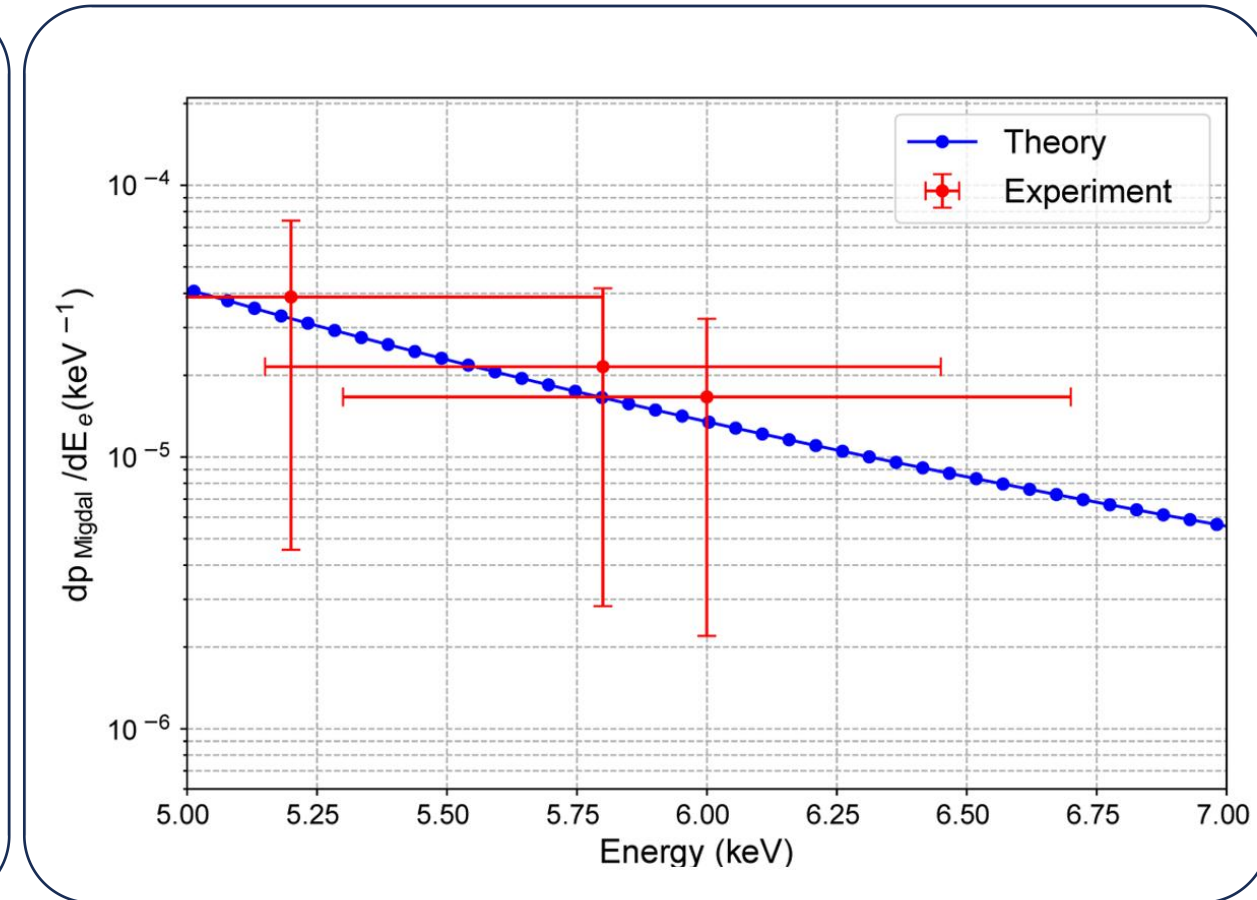
The total transition probability

$$\sum_{nl} \frac{dp^i(nl \rightarrow E_e)}{dE_e}$$

The transition probability for ionization of an electron from an initial state (n, l) to a final state with energy E_e .

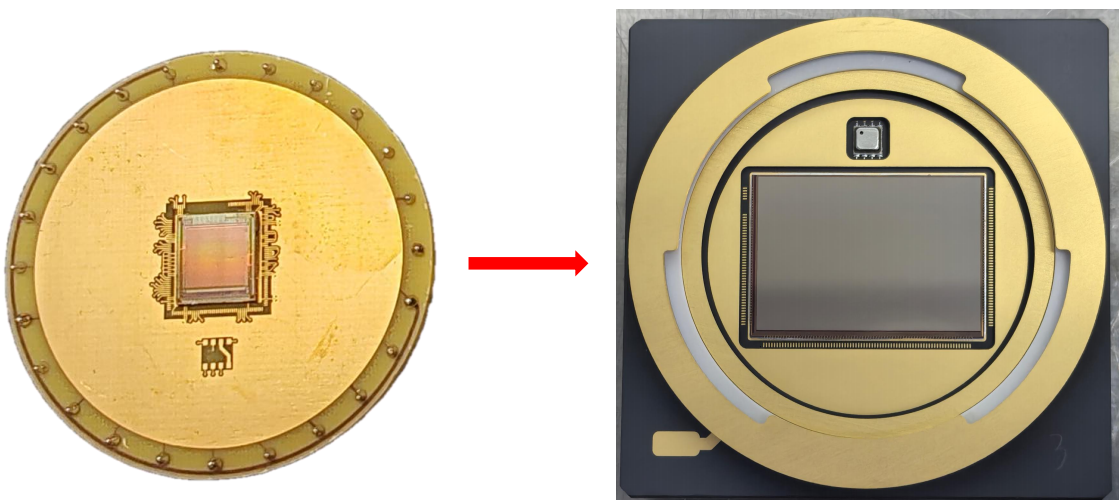


Transition probability of each element



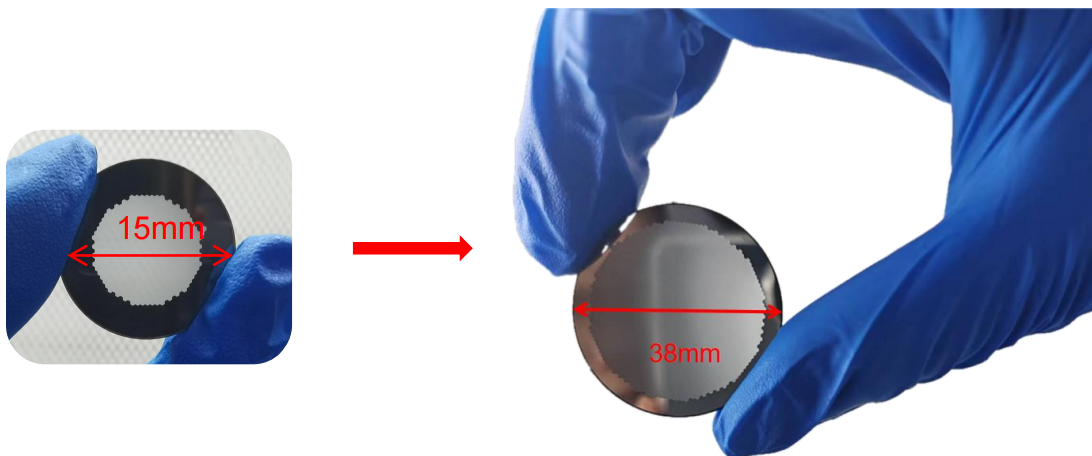
Total Transition probability

Upgrade in progress



Topmetal-II

Topmetal-L



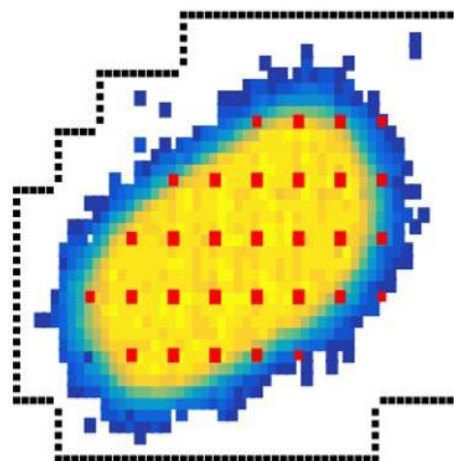
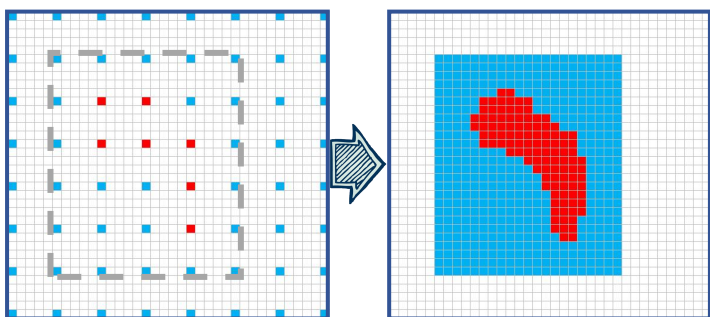
Larger GMCP

	Topmetal-II ⁻	Topmetal-L
Chip size [mm²]	8 × 9	17 × 24
Active area [mm²]	6 × 6	16.02 × 23.04
Pixel array	72 × 72	356 × 512
Pixel density [pixels/mm²]	145	494
Power density [W/cm²]	2.778	0.195
Pixel gain [μV/e⁻]	-	76.04
ENC [e⁻]	13.9	22.8
Readout mode	Rolling Shutter	Rolling Shutter / Sentinel
Time cost	2.6 ms/frame	0.73 ms/frame @ Sentinel

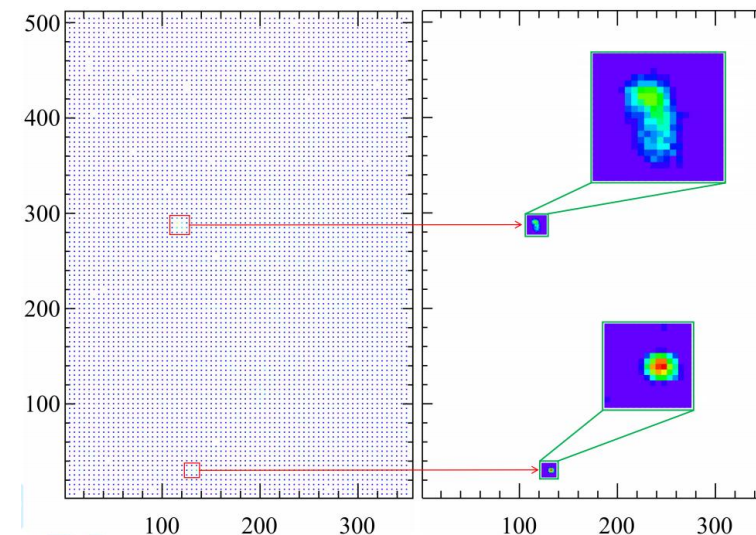
- 6x6 mm, 83 um in pitch -> 2.3x1.5 cm, 45 um in pitch
- Fresh time: 2.6 ms/Frame -> 0.7 ms/Frame
- Readout logic: Rolling Shutter -> Sensitive area

Upgrade in progress

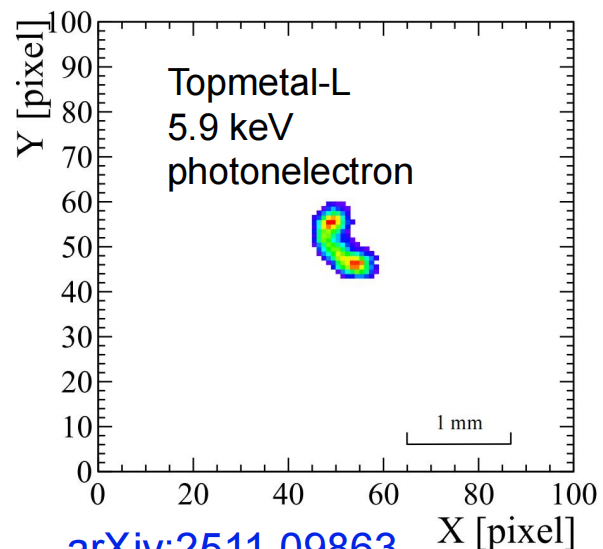
Sensitive area readout:



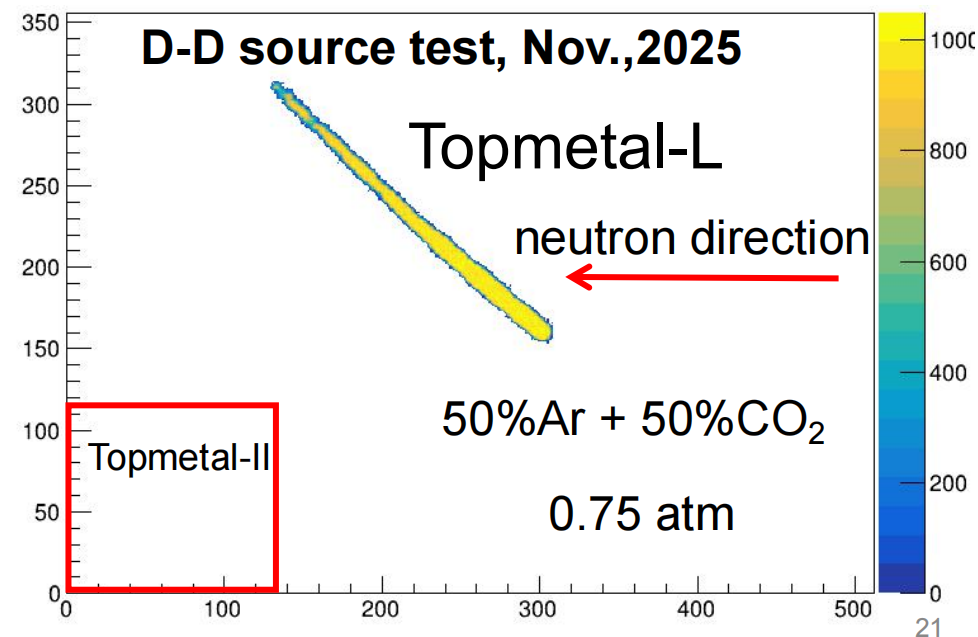
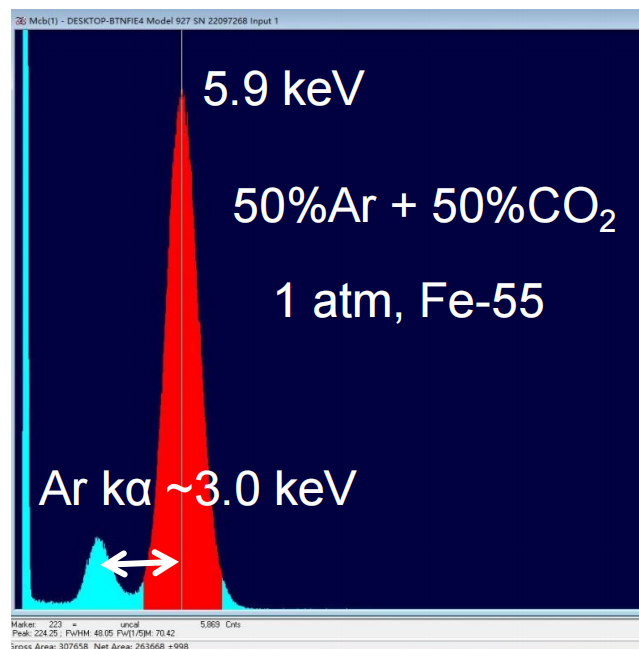
■ Sensitive pixels
■ Readout pixels range



[arXiv:2511.15130](https://arxiv.org/abs/2511.15130)



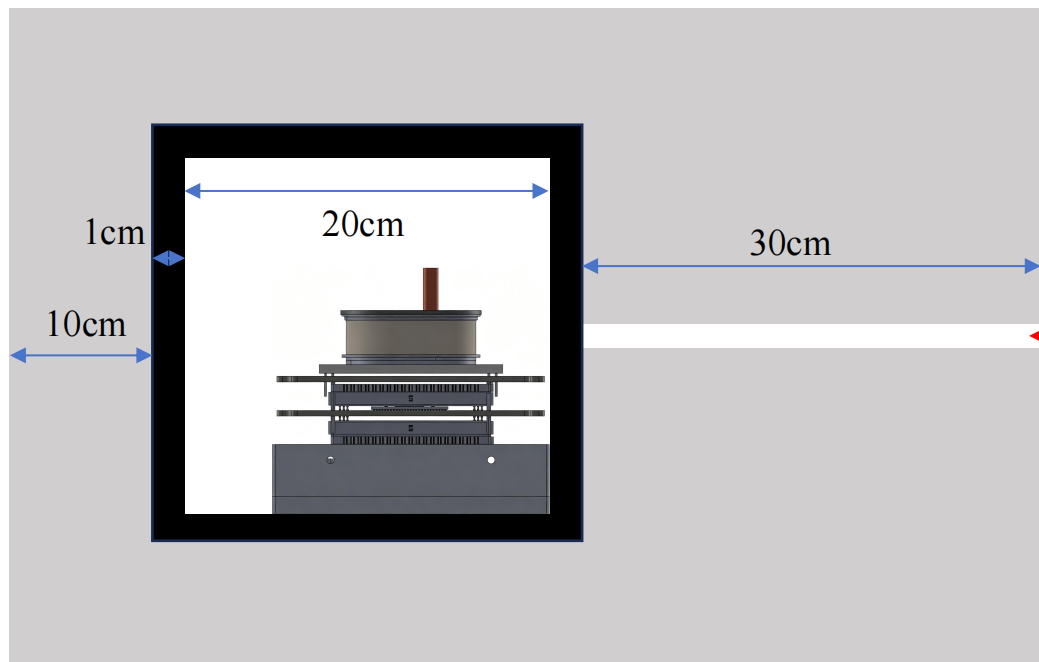
[arXiv:2511.09863](https://arxiv.org/abs/2511.09863)



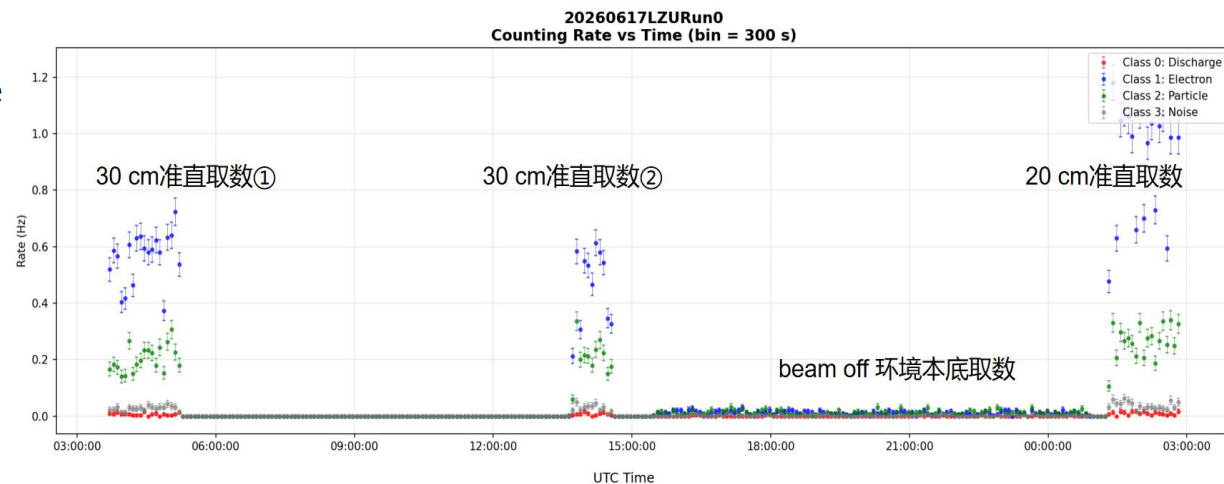
MARVEL-II pilot experiment



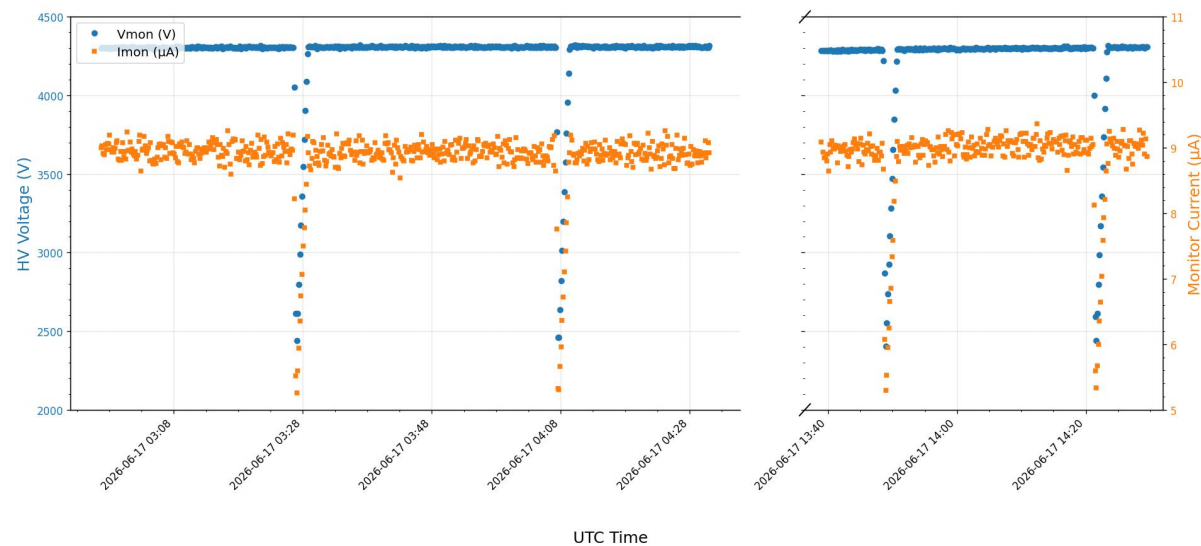
Add collimator



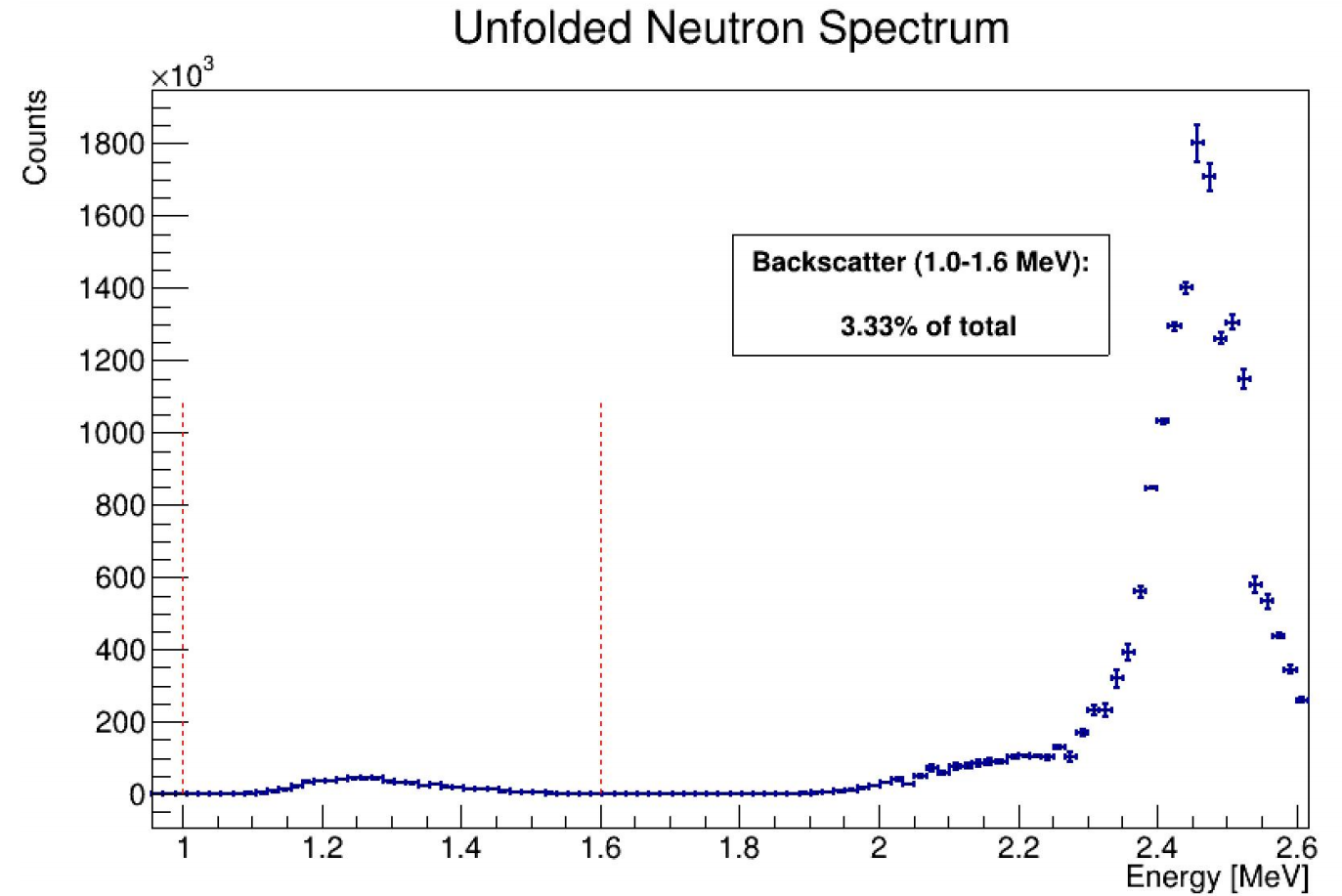
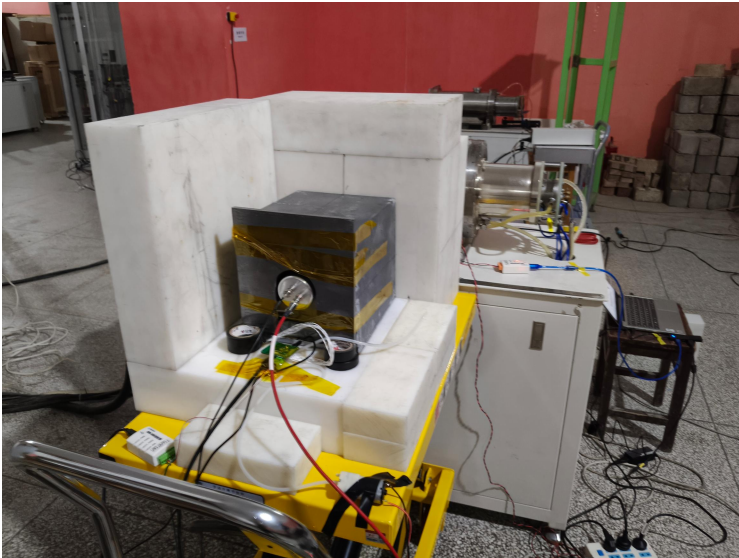
D-D source



Add discharge protection



MARVEL-II pilot experiment

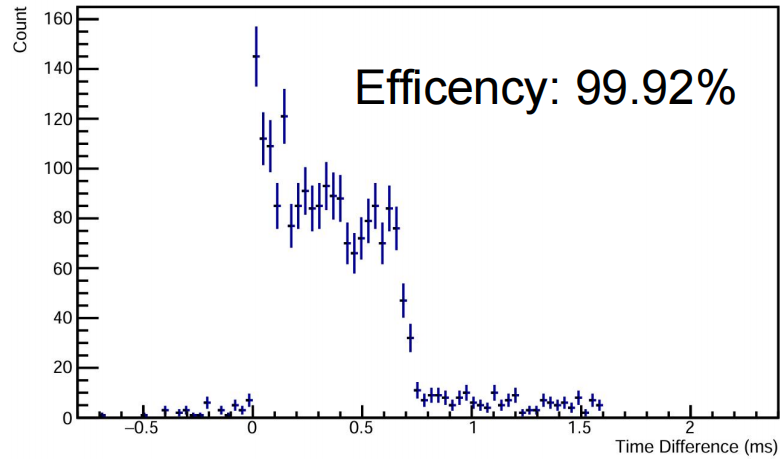


Back scattering neutron decrease from 20% to 3%.

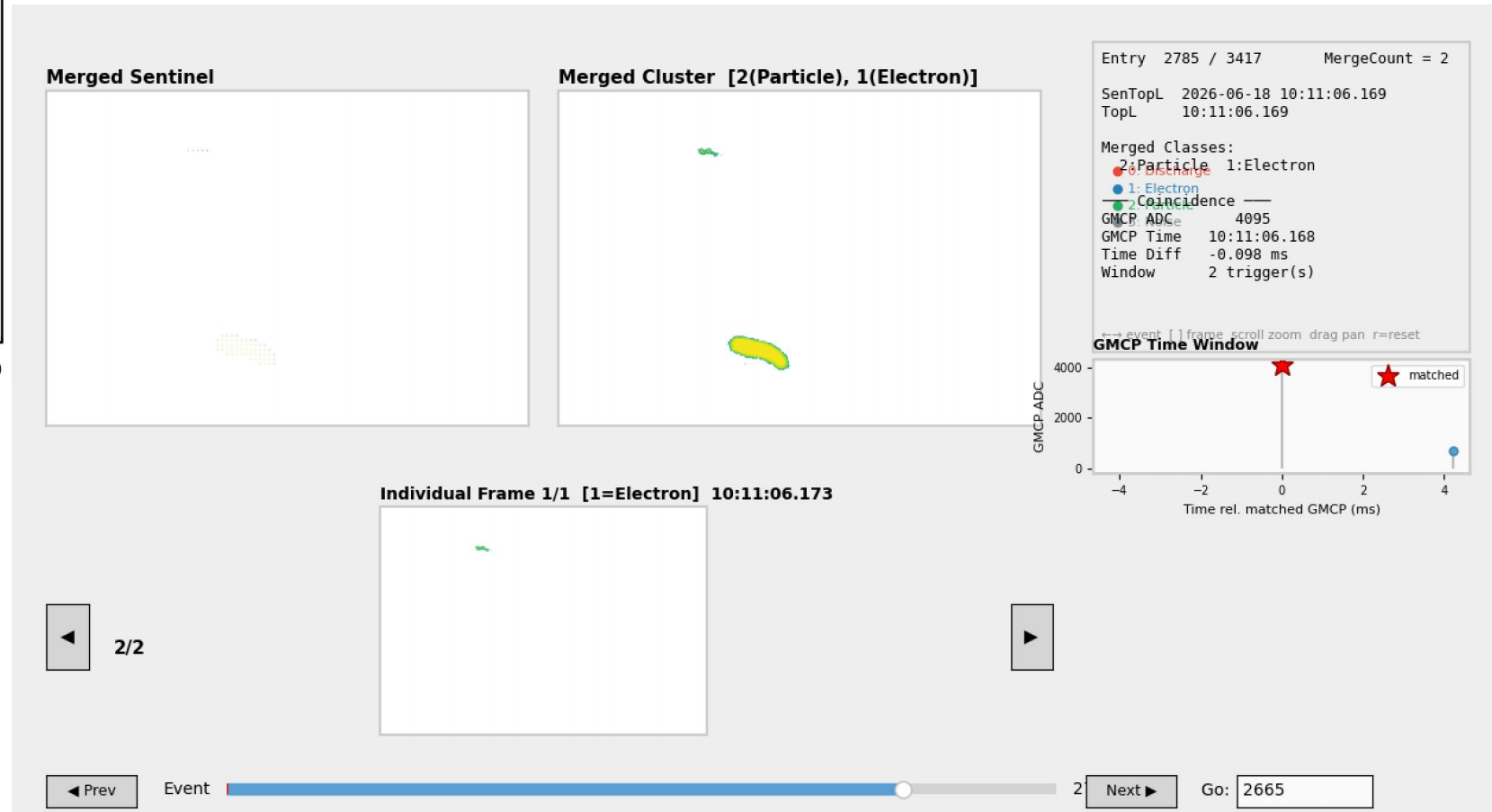
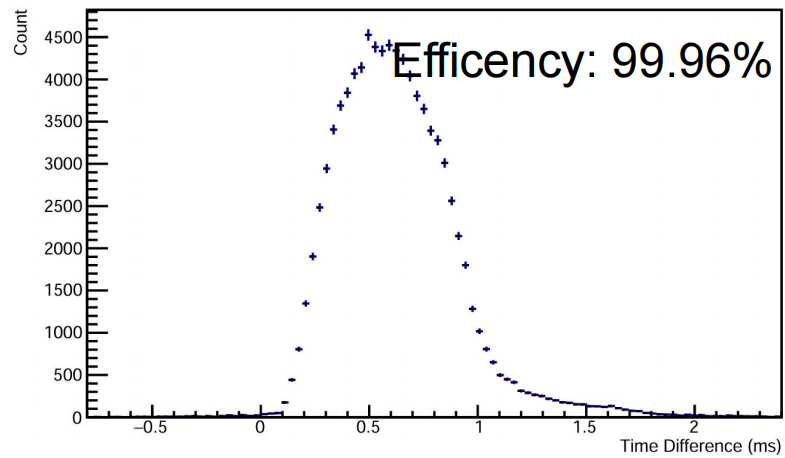
Use CsI + PMT to measure gamma to get better resolved spectrum.
Spectrum unfolding is underway.

Time coincidence

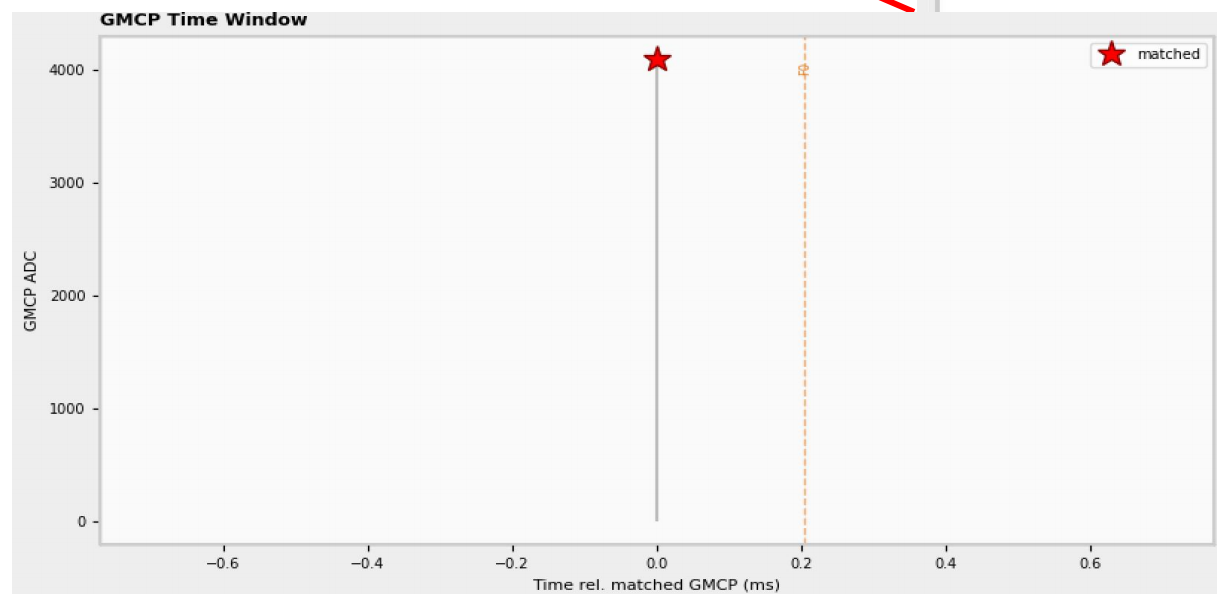
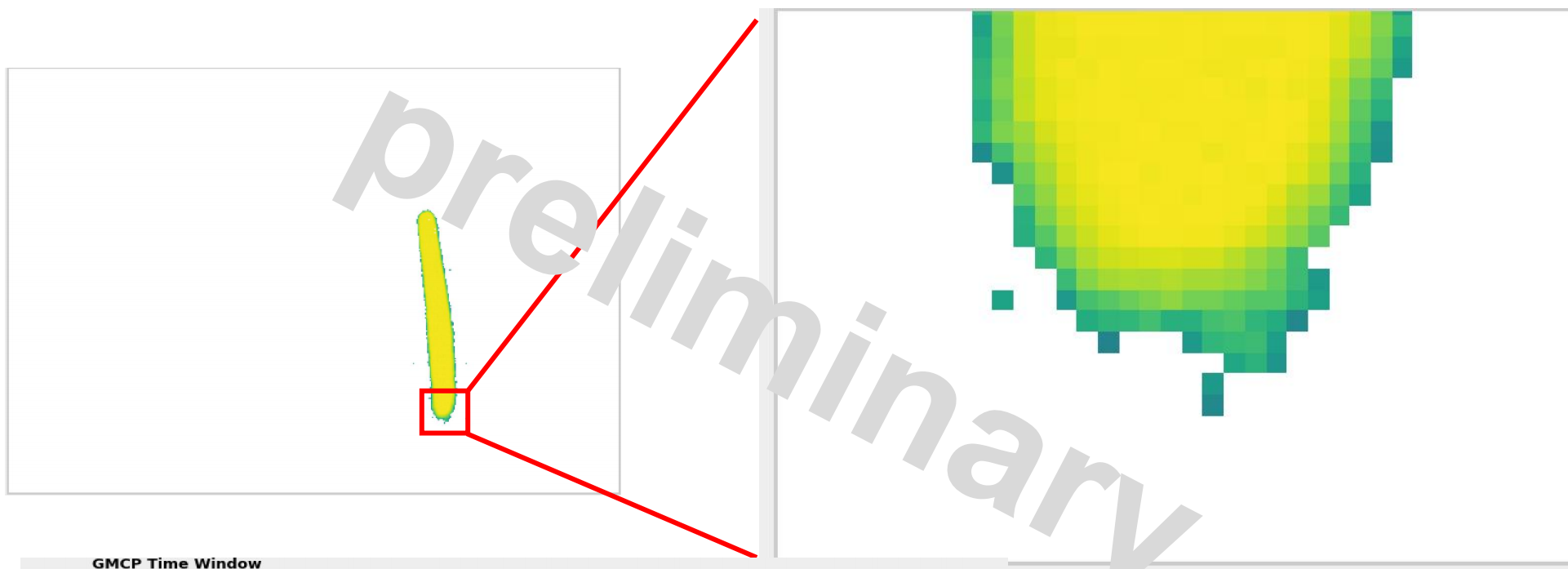
NR tracks



ER tracks



Hint for lower threshold?



With only few thousands NRs we
get new hint?

Due to better position resolution



- The Migdal effect plays a very important role in light dark matter research.
- The MARVEL experiment is dedicated to the direct detection of the Migdal effect.
- The ratio of the Migdal to the nuclear recoil cross-section to be $4.9^{+2.6}_{-1.9} \times 10^{-5}$, where nuclear recoils exceed 35 keVee and electron recoils span 5-10 keV.
- Detector upgrade is in progress.



What next?



- Single-element Migdal cross section measure.
- Shell-resolved Migdal effect measure.
- Migdal effect angular distribution measure.

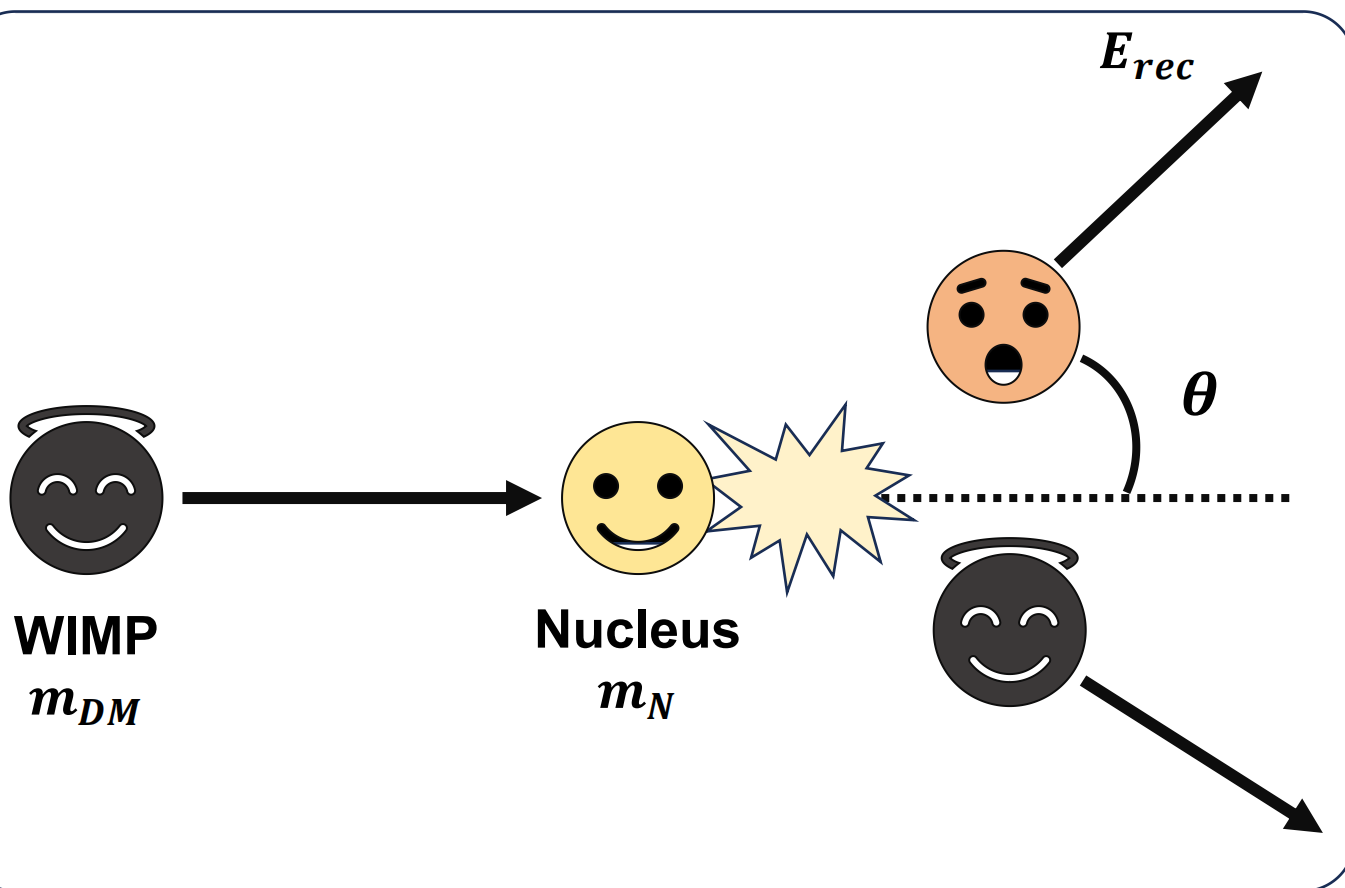
Non-relativistic elastic scattering

$$\mu = \frac{m_{DM} m_N}{m_{DM} + m_N}$$

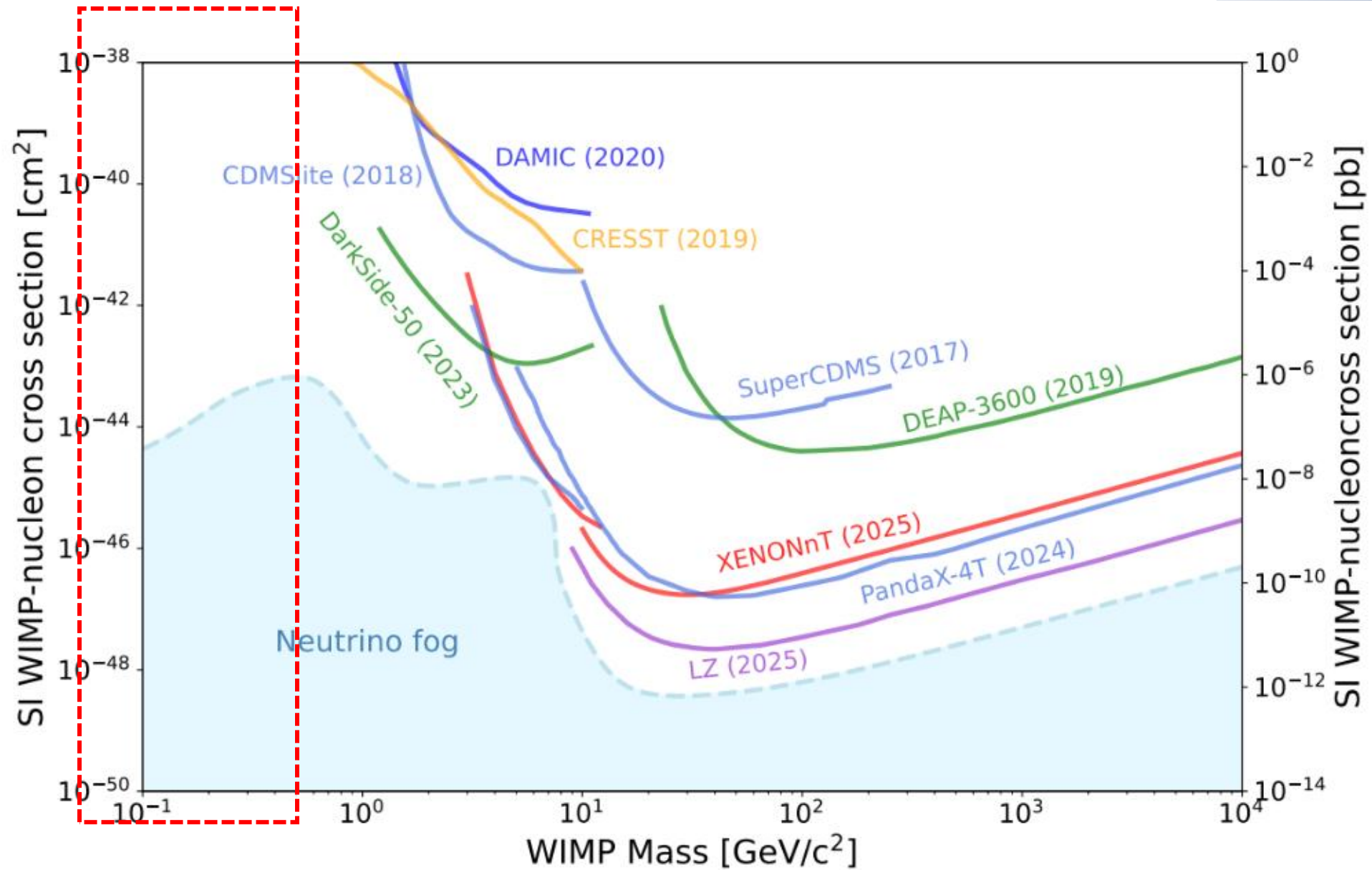
$$E_{rec} = \frac{\mu^2 v^2}{m_N} (1 - \cos\theta) \leq \frac{2\mu^2 v^2}{m_N}$$

$$m_{DM} = 10 \text{ GeV}/c^2; m_N = 131 \text{ GeV}/c^2; v = 220 \text{ km/s}$$

$$E_{rec} \leq 0.7 \text{ keV}_{nr}$$



Exp	threshold
Xenon-1T S1S2	4.9 keVnr (1.4 keVee)
Xenon-1T S2-only	0.7 keVnr (0.186 keVee)
DarkSide50 S1S2	13 keVnr (1.3 keVee)
DarkSide50 S2-only	0.6 keVnr (0.1 keVee)
CDEX:	0.64 keVnr (0.16 keVee)
CRESST-II	0.307 keVnr
SuperCDMS	0.07 KeVee



MARVEL Experiment

Scintillator ① 0°



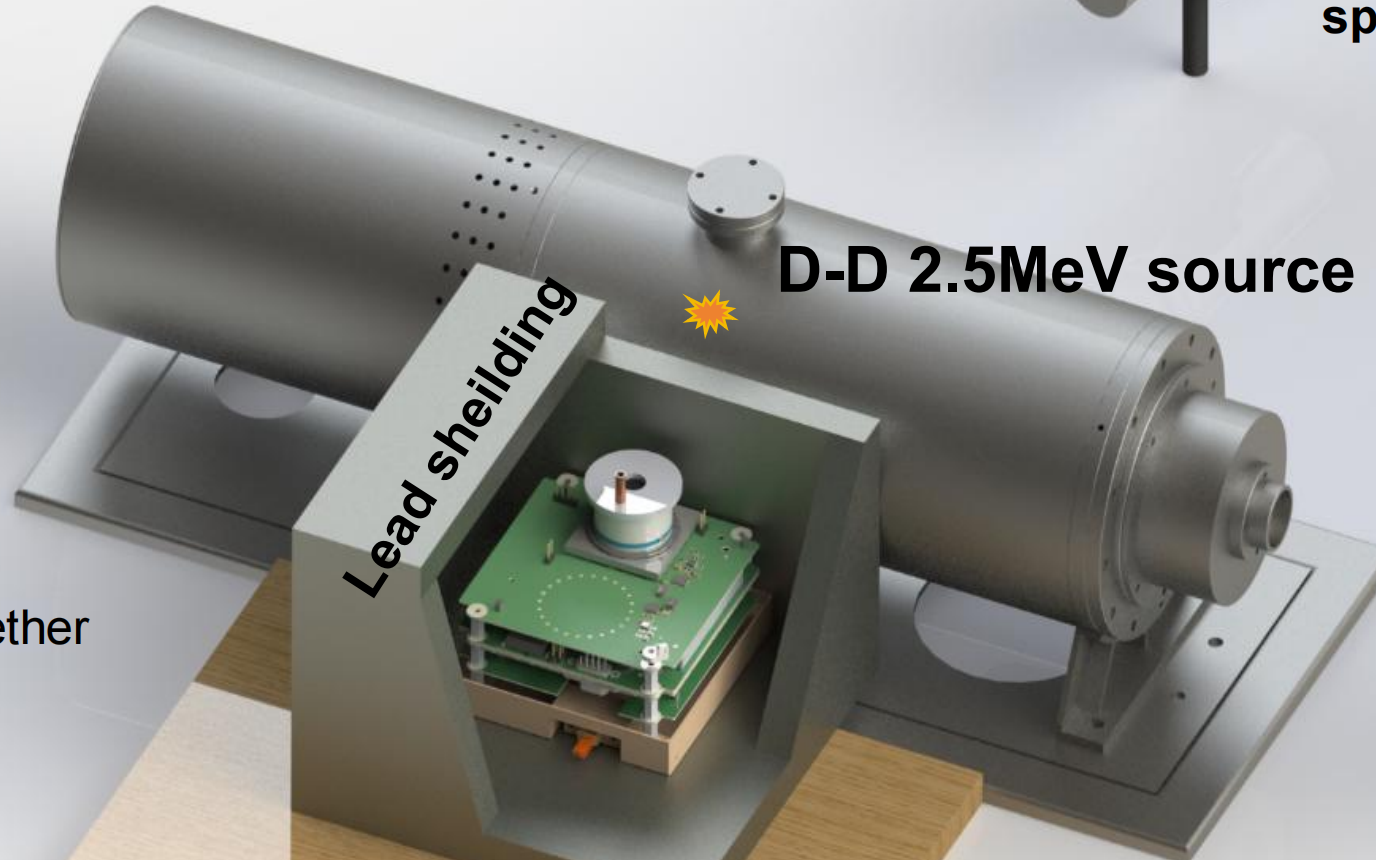
D-D source monitoring

Scintillator ② 87°



Neutron and gamma
spectrum measurement

D-D 2.5MeV source



Lead shielding

Migdal detector 270°

Working gas:

0.8 atm @ ~300 K
40% Helium + Dimethyl ether
(DME, C_2H_6O)

Neutron: 2.5 MeV
Nucleus: hundreds of keV
Electron: 5-10 keV

Scintillator ③ 180°



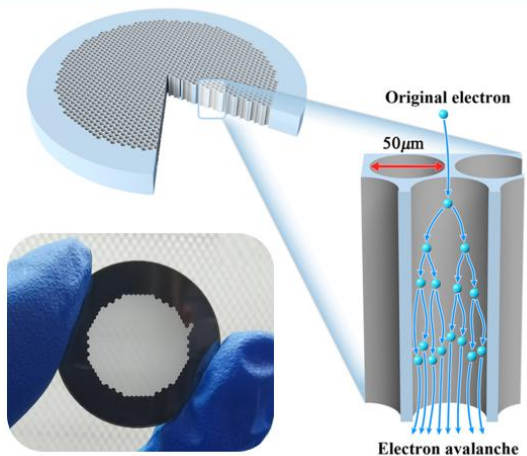
D-D source monitoring

[*Nature* 649, 580–583 \(2026\)](#)

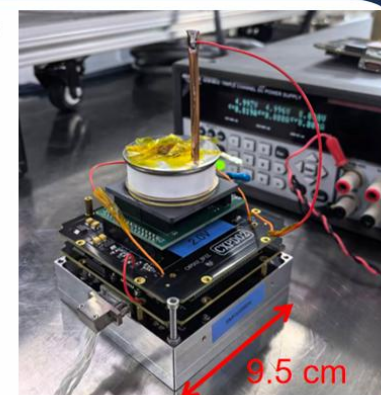
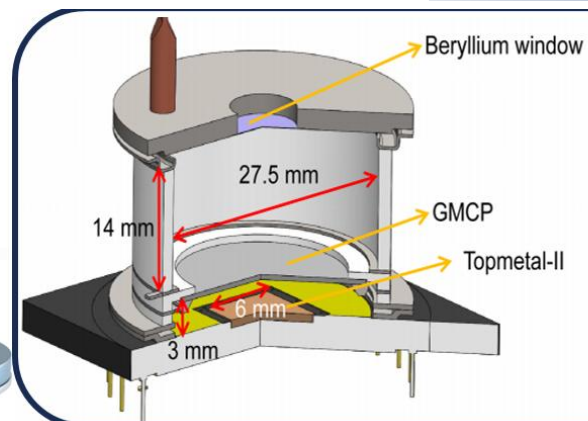
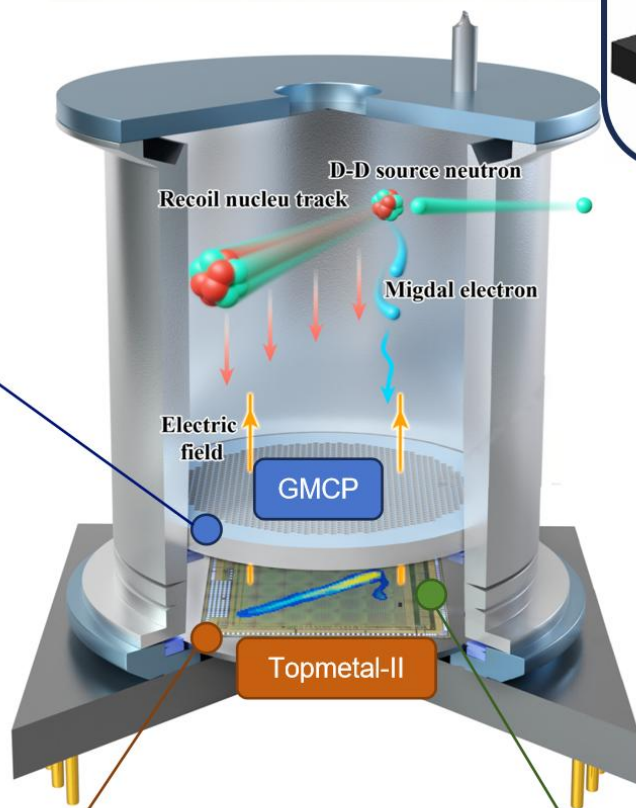
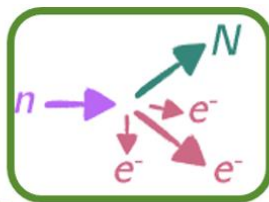
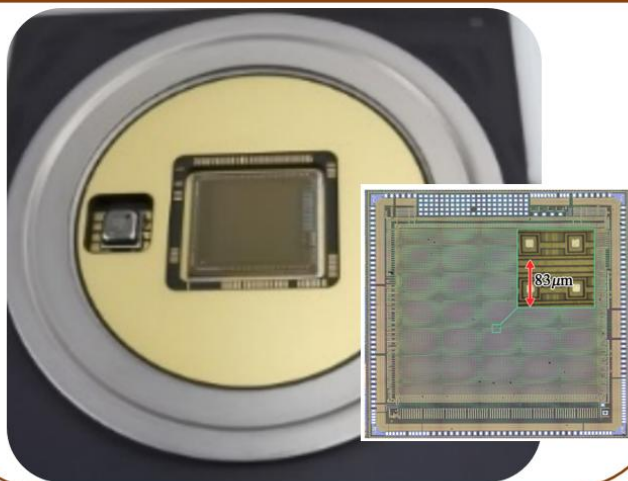
MARVEL Experiment-Detector



GMCP



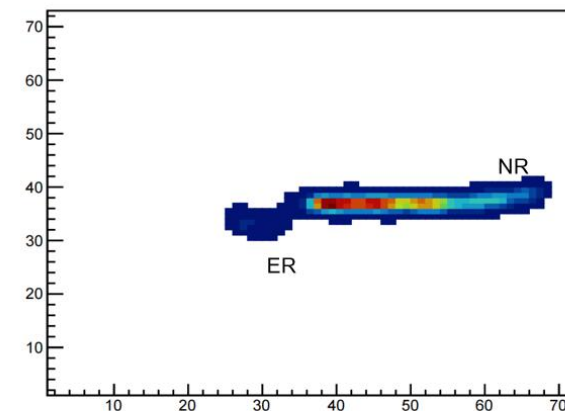
Topmetal-II



DD neutron source

Migdal topology

Electron E_k : 5.2500 keV, Ion E_k : 0.2300 MeV

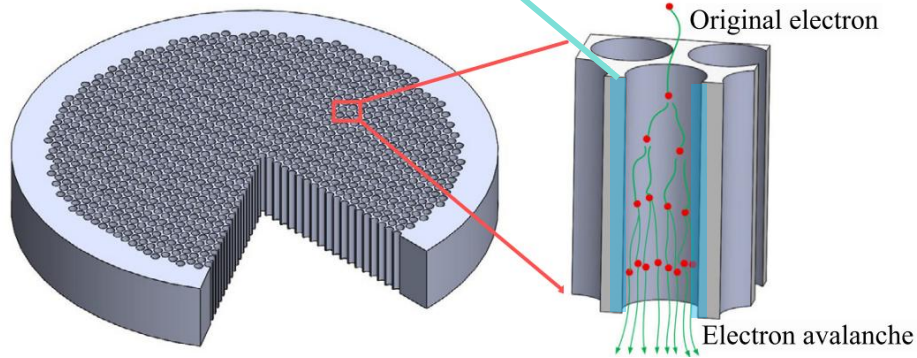


GMCP-Performance Stability

- Suppress the charge accumulation effect

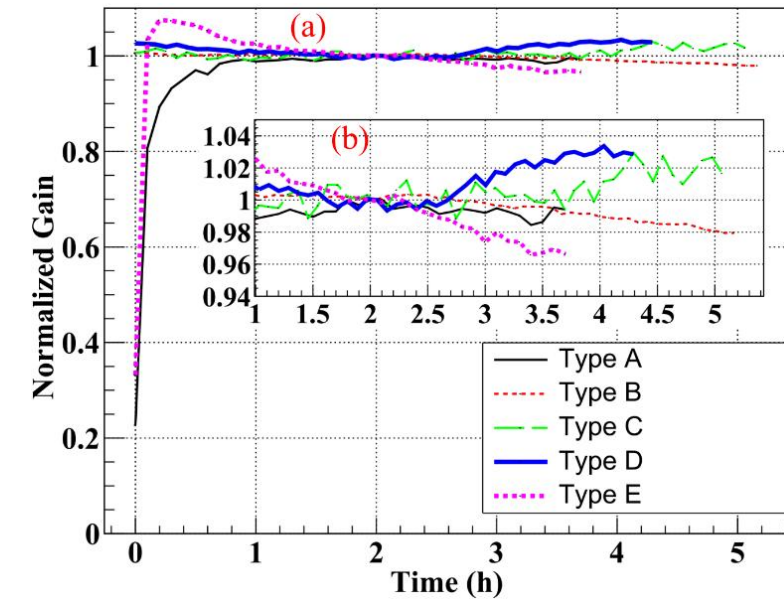
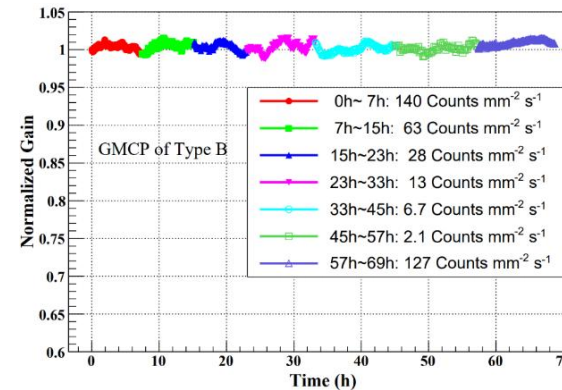
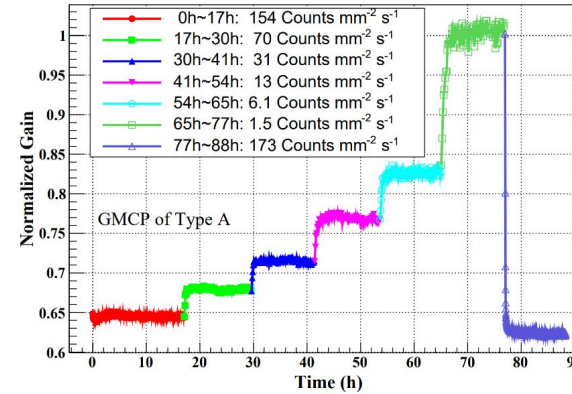
GMCP Development – Hydrogen Reduction tech for Preparing Bulk Resistance to Eliminate Charge Accumulation

Bulk Resistance



	Type A	Type B	Type C	Type D	Type E
Hole diameter	50 μm	50 μm	50 μm	60 μm	30 μm
Thickness	400 μm	400 μm	300 μm	300 μm	300 μm
Hole pitch	60 μm	60 μm	60 μm	80 μm	40 μm
GMCP resistance	∞	5 G Ω	3 G Ω	5 G Ω	∞
Hydrogen reduction	Without	With	With	With	Without

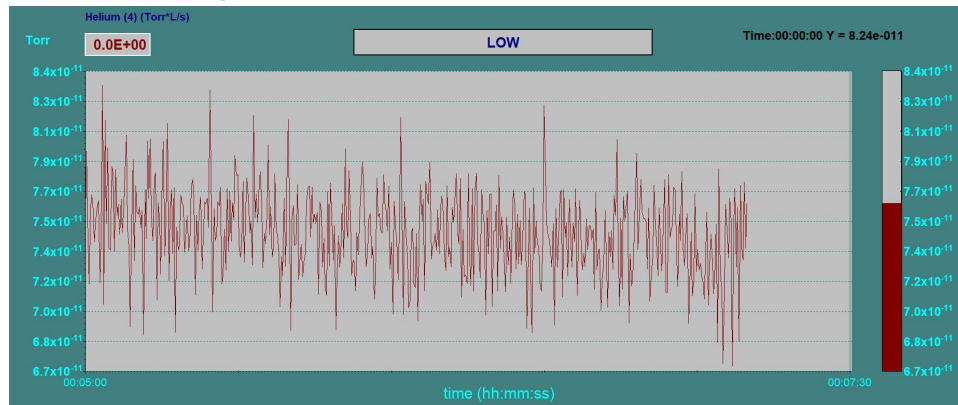
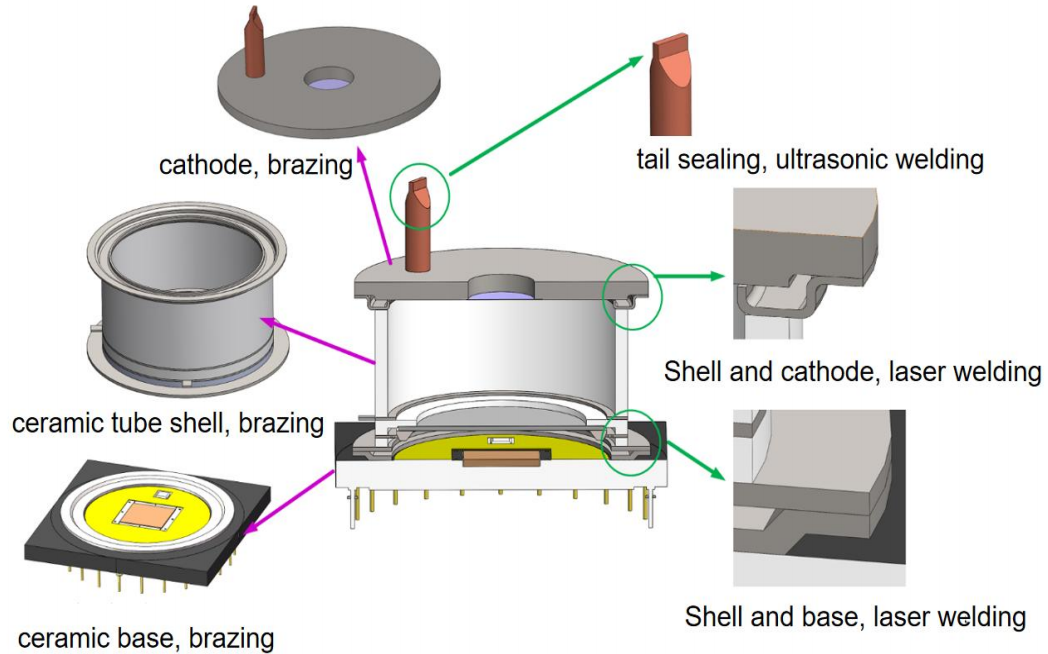
[10.1016/j.nima.2023.168499](https://doi.org/10.1016/j.nima.2023.168499)



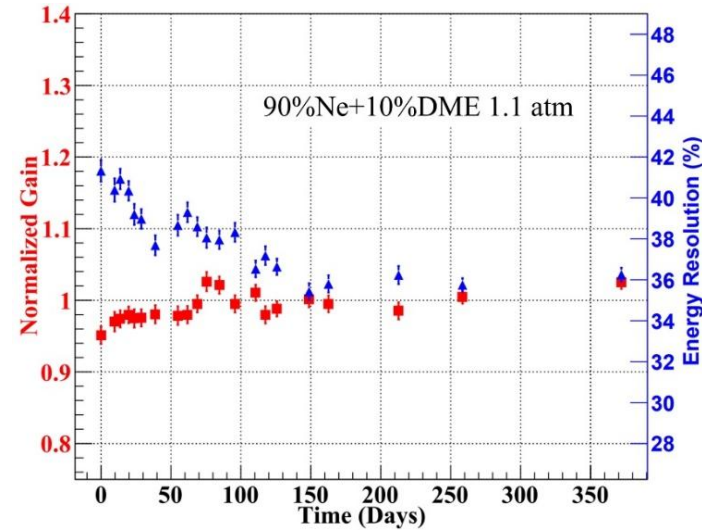
stability at different counting rates

Performance Stability/Gain

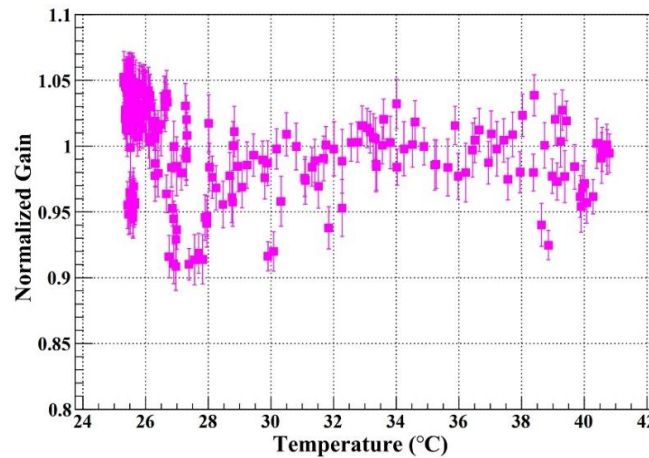
- low leakage rate and material degassing rate specifications



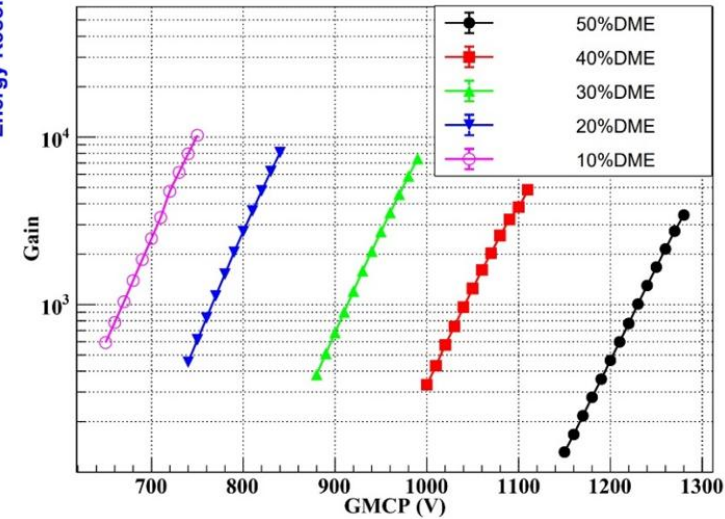
Leak rate: $\sim 7.6 \times 10^{-11}$ Torr·L/s



Long-term gain stability



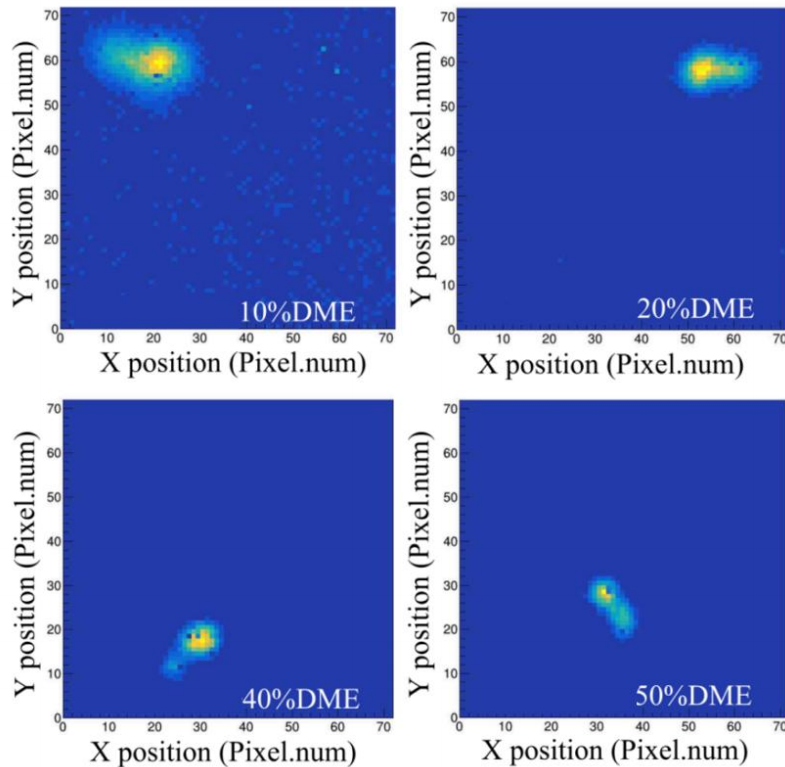
Gain variation with temperature



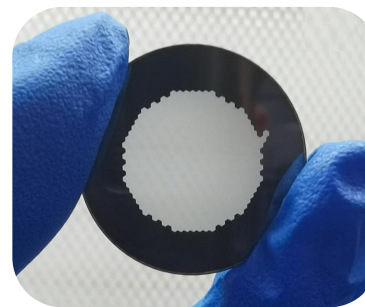
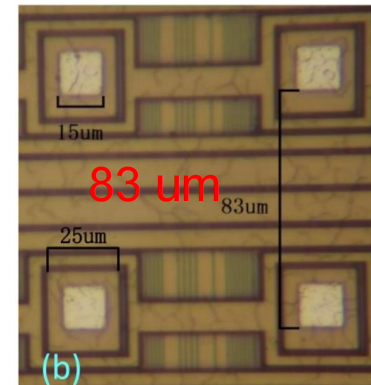
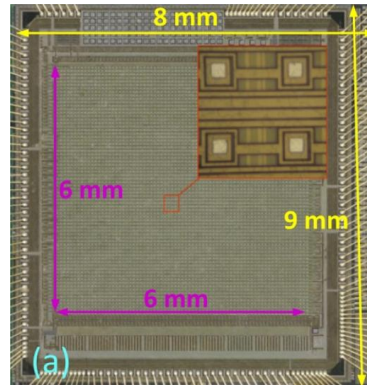
Spatial resolution

various gas mixtures:

He/Ar/Kr/Xe+CO₂/CH₄/i-C₄H₁₀/DME(C₂H₆O)/CF₄

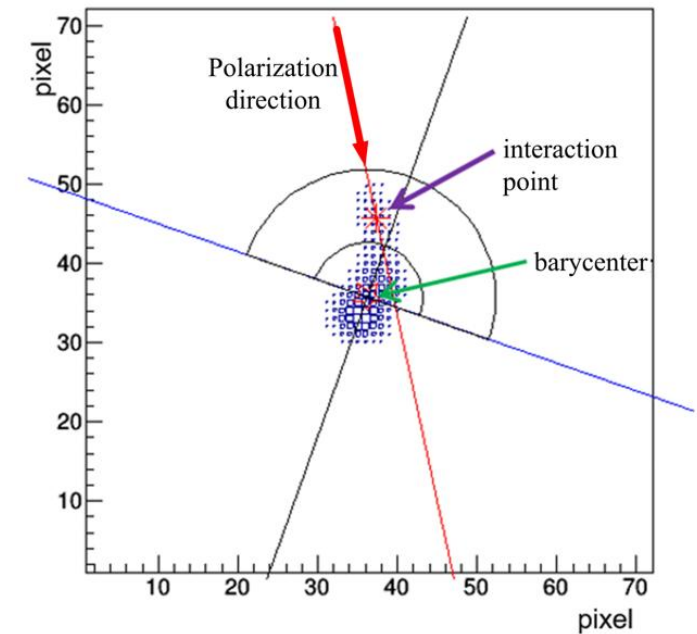


Parameter testing for various
gases and gas mixtures



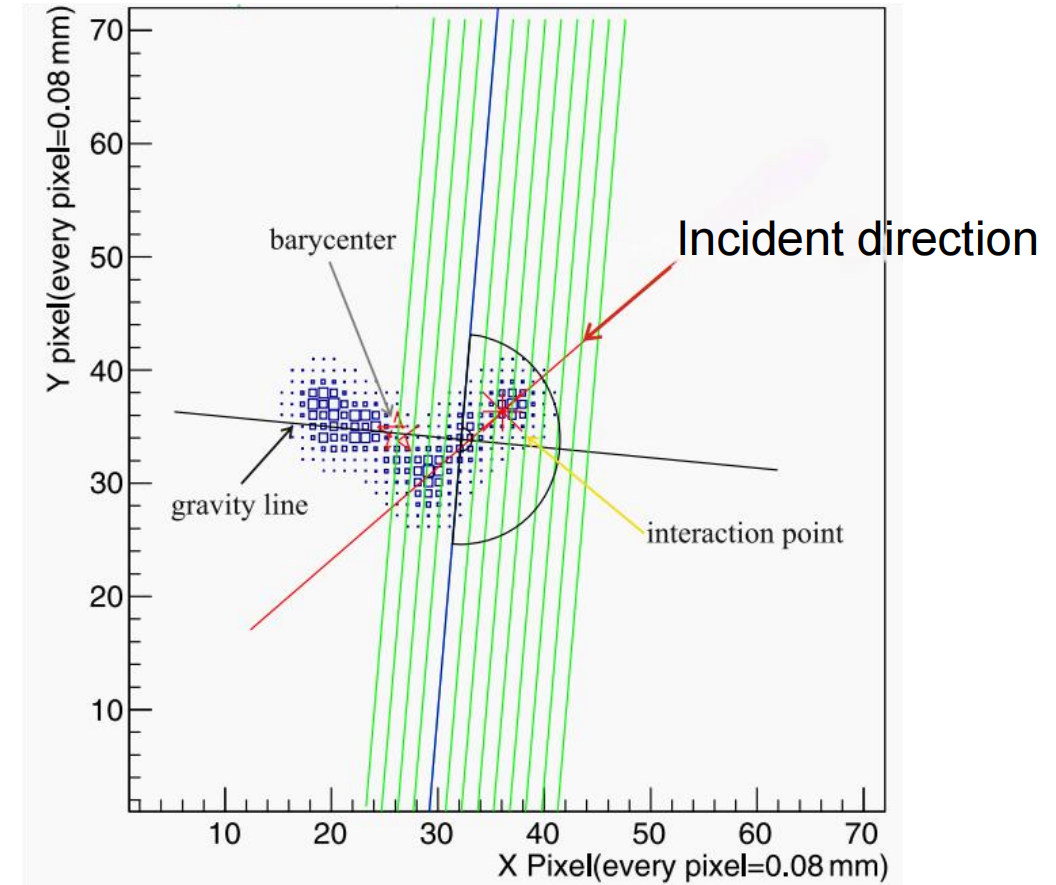
high-granularity device

[10.1007/s41365-021-00903-0](https://doi.org/10.1007/s41365-021-00903-0)



adaptive cutting
vertex reconstruction

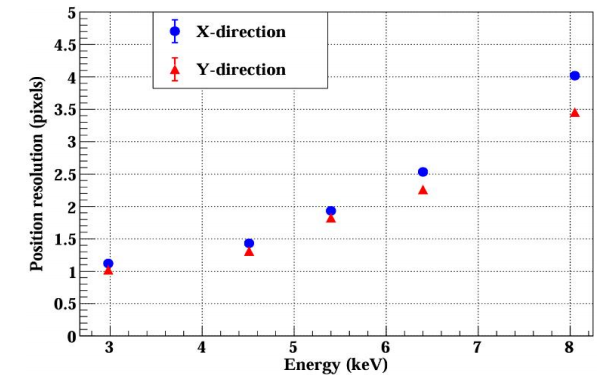
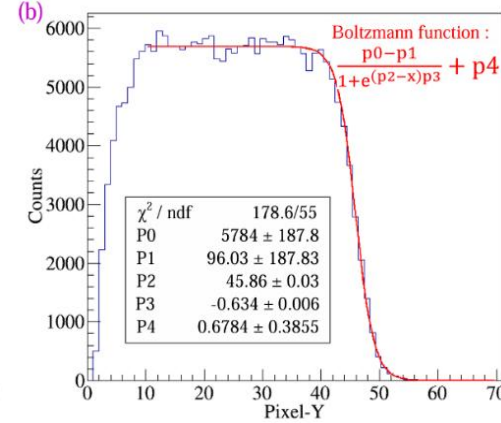
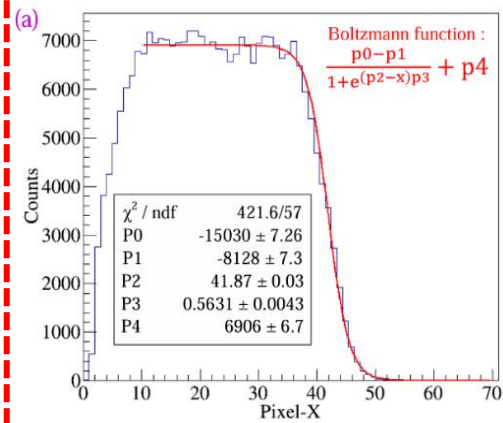
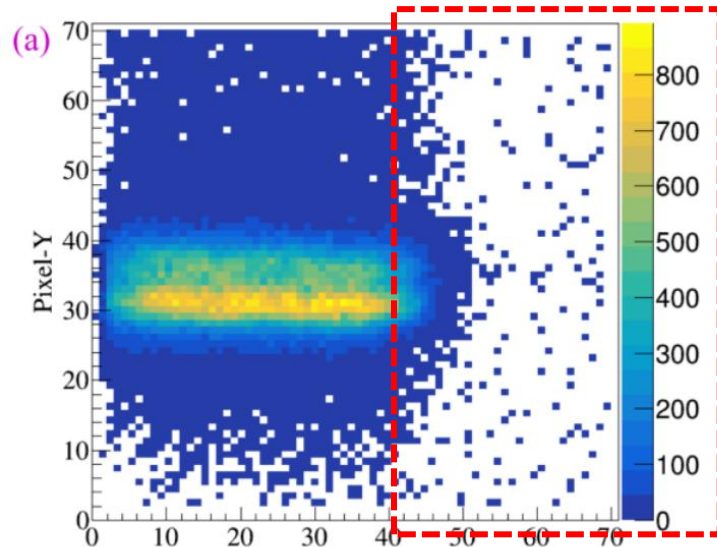
- Determine the economic center of gravity and its trajectory based on ignition point and energy deposition.
- Calculate the sign of, M_d , $M_d = \sum_{point} (d^3 \times q)$, determine the head and tail(Bragg peak) of the trajectory
- Slide a perpendicular line along the center of gravity, compute the second-order moment M_2 to measure trajectory curvature, and truncate at the point of maximum M_2 change for a straightened path.
$$M_2 = \sum_n^{pixels} (x_n - x_l)^2 + (y_n - y_l)^2$$
- Recalculate the center of gravity and its line for the truncated trajectory to identify the photoelectric interaction point and emission direction.



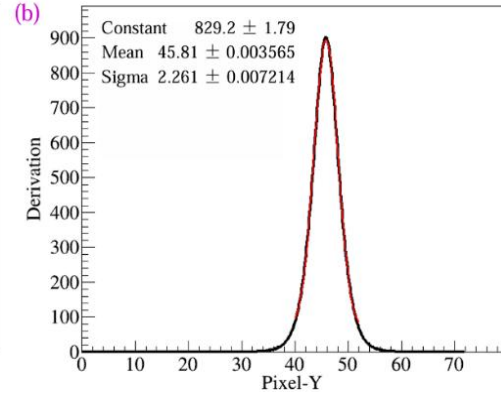
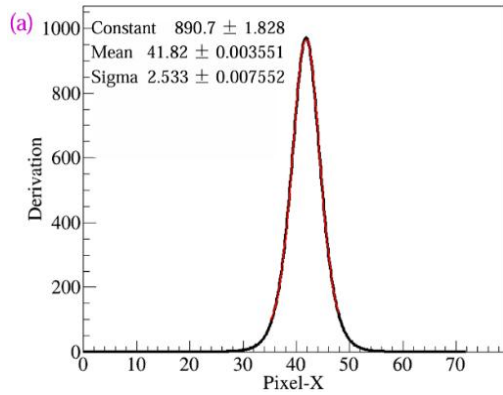
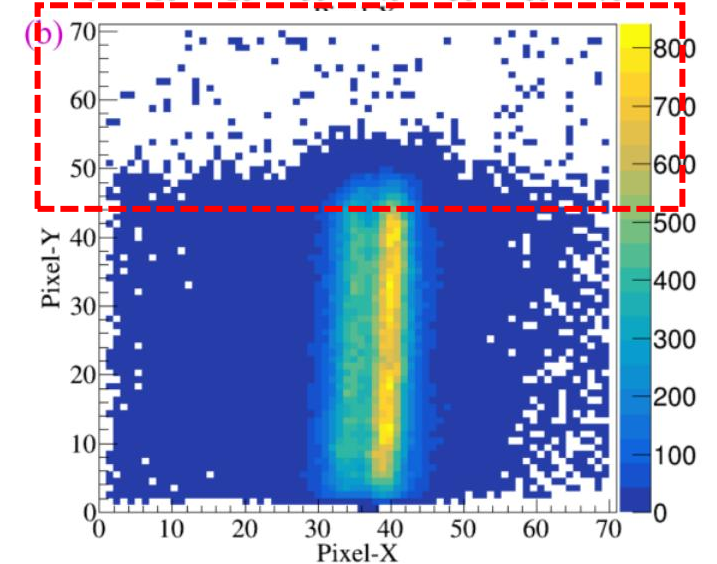
Vertex resolution

copper plate

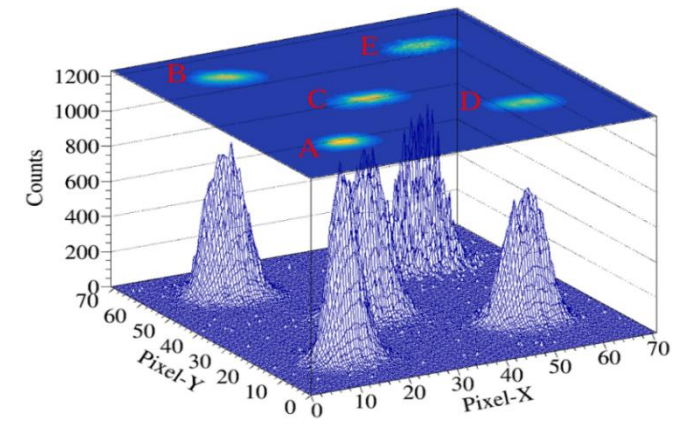
6.4 keV X-ray imaging with half the area shielded by a copper plate



position resolution at different energies



position resolution @ 6.4 keV

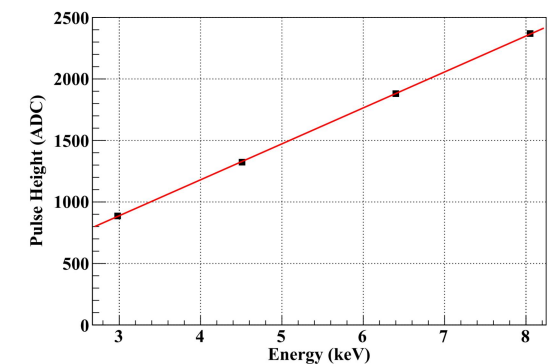
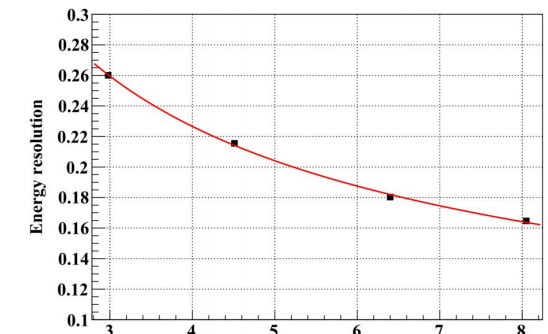
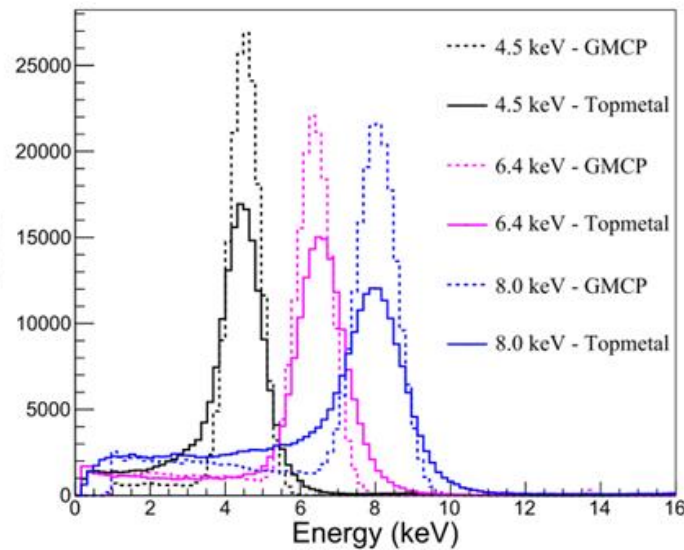
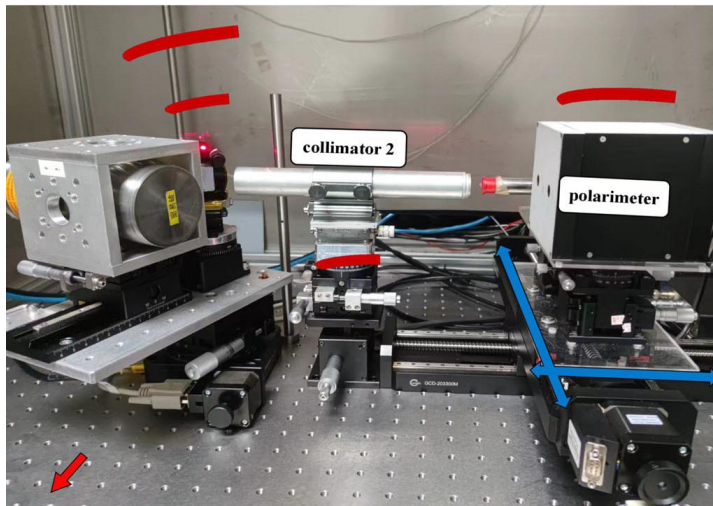
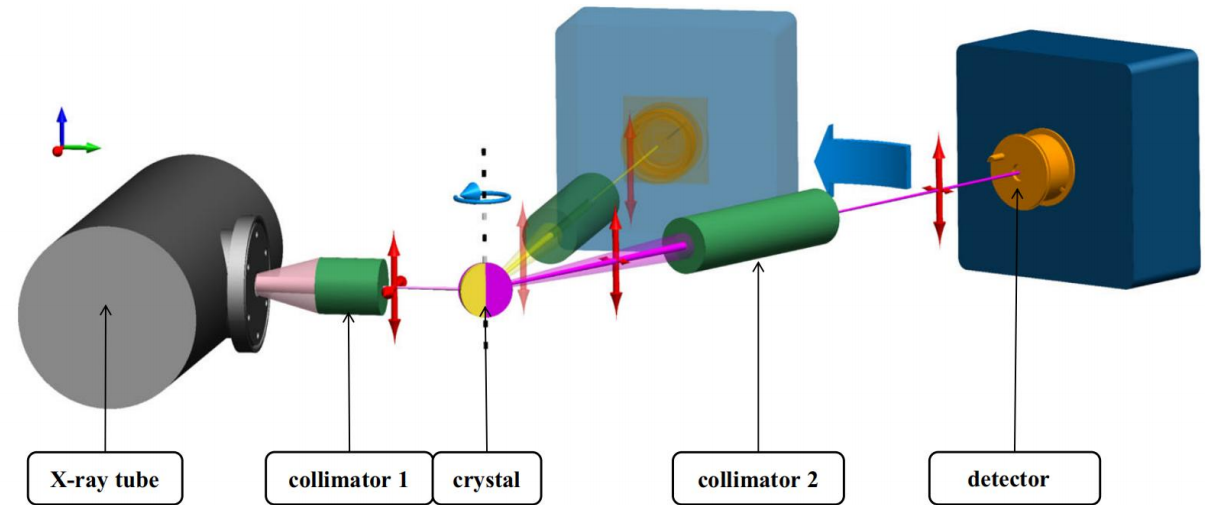


spatial resolution at different positions

[10.1088/1748-0221/19/04/P04039](https://doi.org/10.1088/1748-0221/19/04/P04039)

Energy calibration

Energy (keV)	Crystal	Incident radiation	Diffraction angle(deg)
2.98	Si(111)	Ag L $_{\alpha}$	41.6
4.51	Si(220)	Ti K $_{\alpha}$	45.8
5.40	Si(311)	Cr K $_{\alpha}$	44.5
6.40	Si(400)	Fe K $_{\alpha}$	45.5
8.05	Si(224)	Cu K $_{\alpha}$	44.1

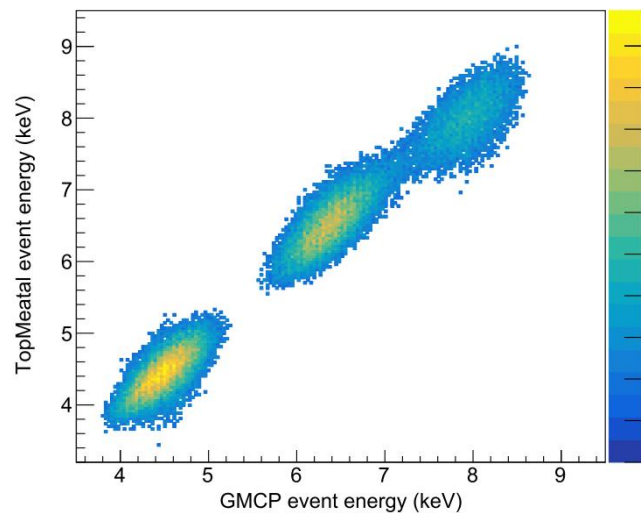
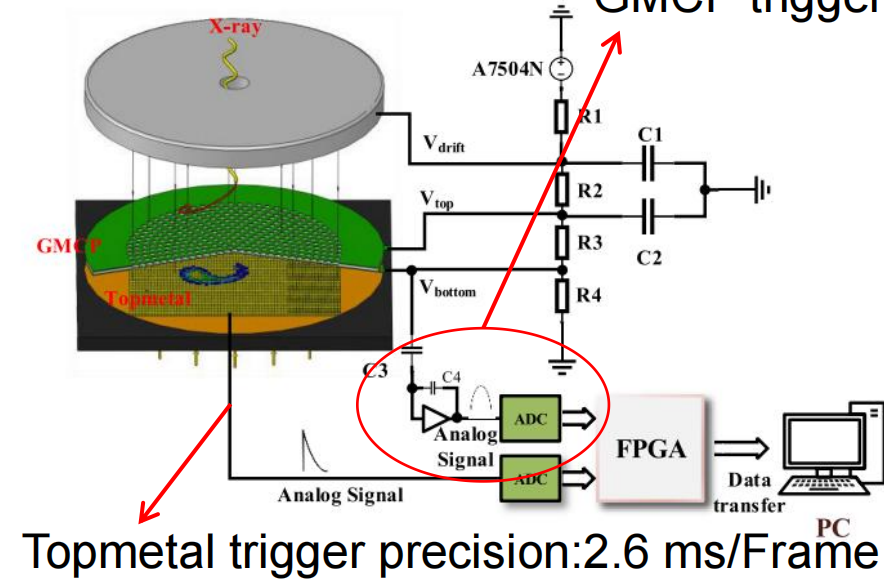


[10.1007/s10686-023-09905-9](https://doi.org/10.1007/s10686-023-09905-9)

monoenergetic X-ray platform

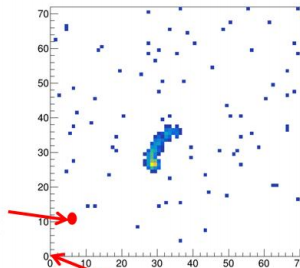
Time resolution

GMCP trigger : 100 Mhz (10 ns)



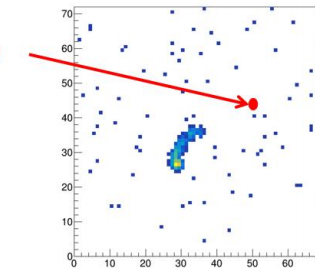
scan direction

Scanning position at signal arrival; provided by the GMCP timestamp



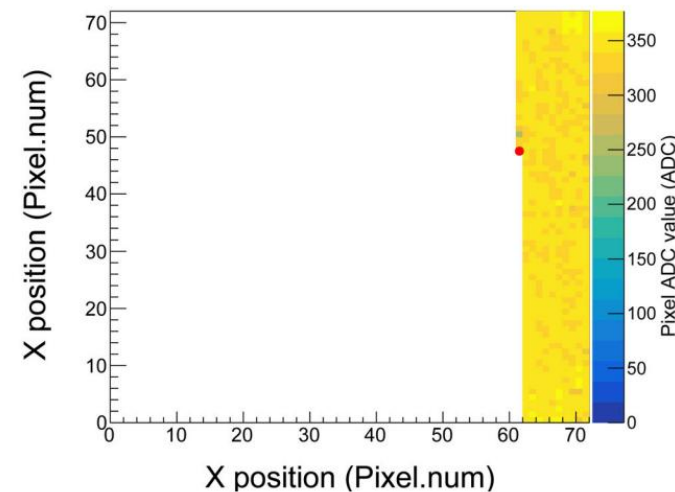
GMCP timestamp -(0, 2.592)ms

Scanning position at signal arrival



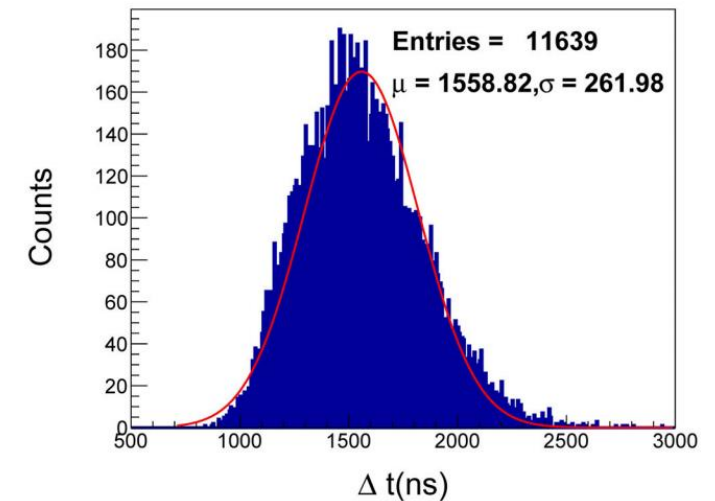
GMCP timestamp +(0, 2.592)ms

$$\Delta T = t_{\text{topmetal}} - t_{\text{GMCP}} + \text{Pixel_order} * 500\text{ns}$$



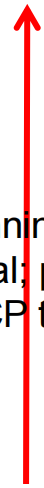
6 ms Timewindow

[IEEE Trans. Nucl. Sci., 70, 1288-1295](#)



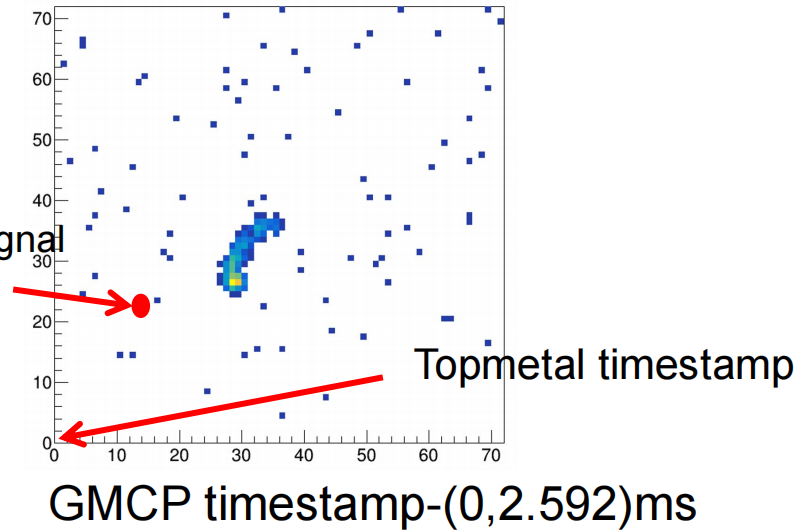
time resolution test results

Events discrimination at same frame

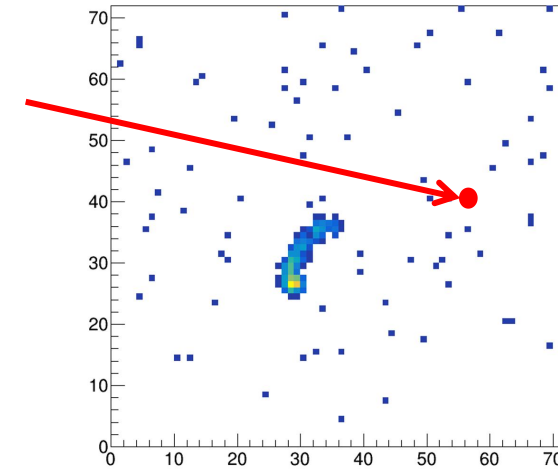


scan
direction

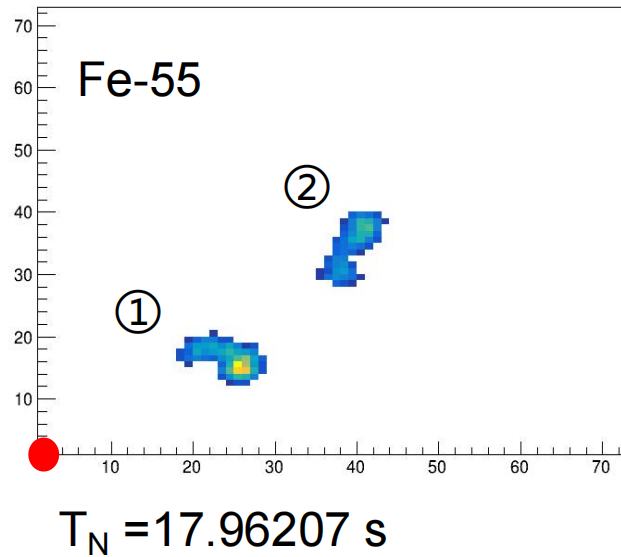
Scanning position at signal
arrival: provided by the
GMCP timestamp



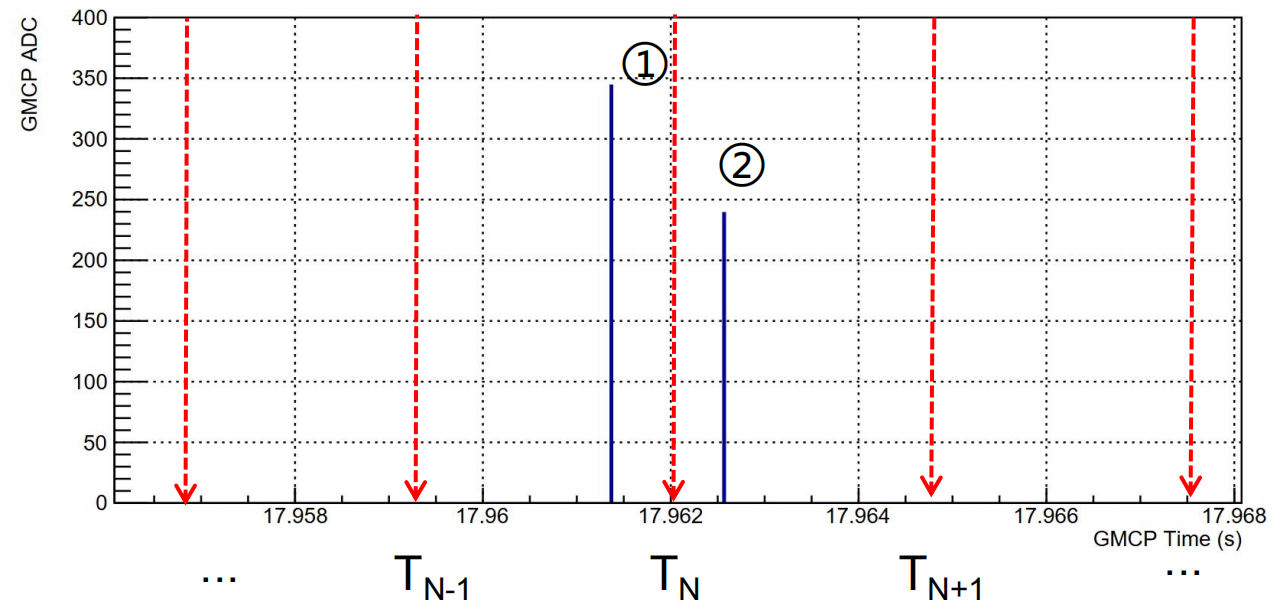
Scanning position at
signal arrival



GMCP timestamp+(0,2.592)ms

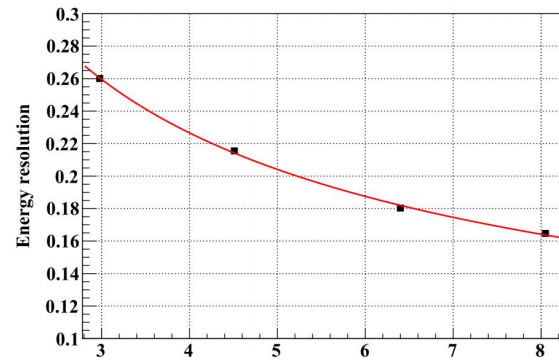
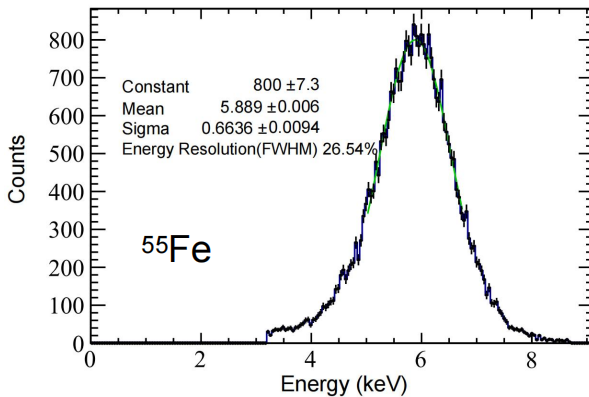


GMCP Time vs GMCP ADC



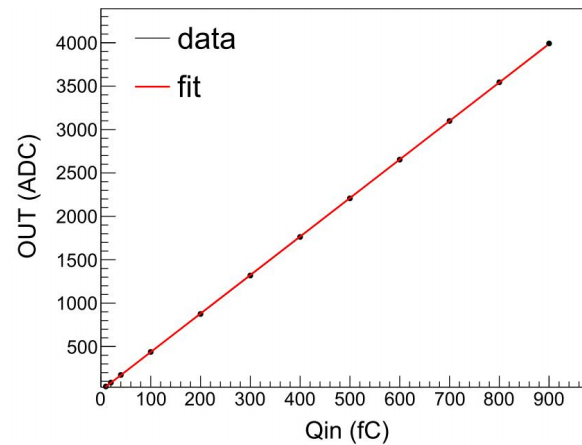
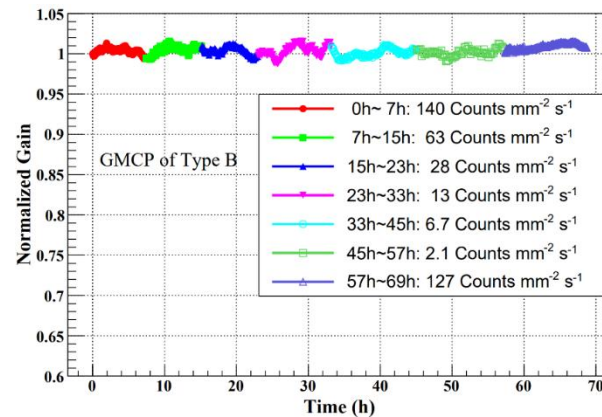
Detector performance

Energy resolution



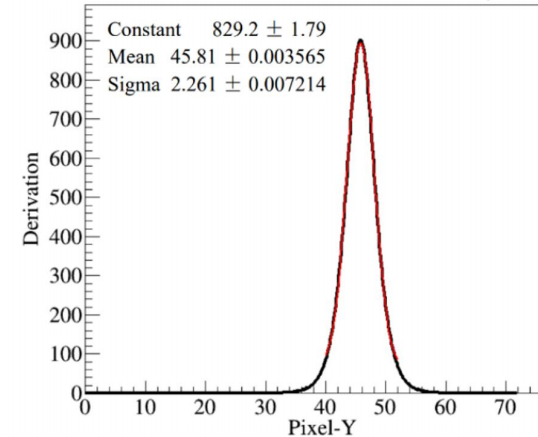
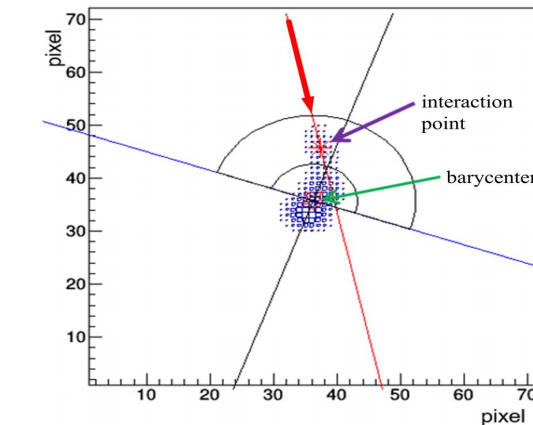
- Good linear energy response
- 20%-30% energy resolution(FWHM)
- Energy resolution follows the relationship $\sim 1/\sqrt{E}$

Dynamic range



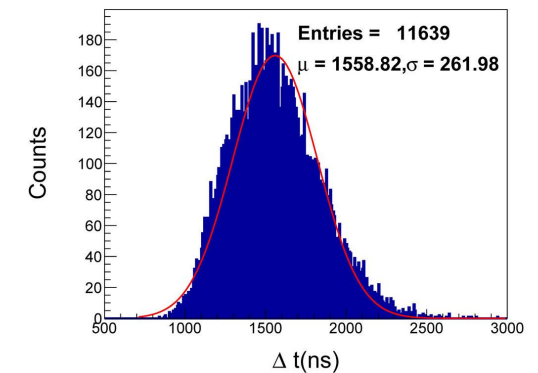
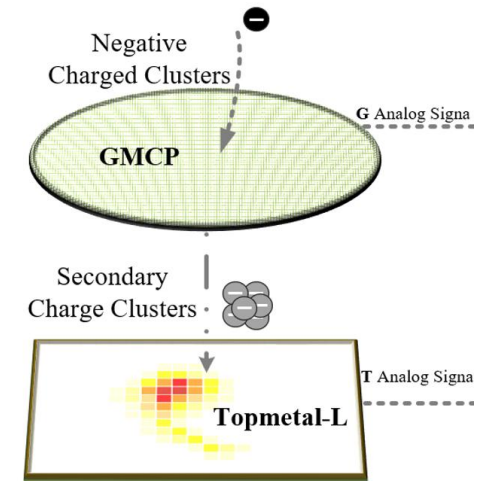
- Stable gain under different count rates(no pile up)
- Good linearity in charge response

Vertex resolution



- $\sim 200 \mu\text{m}$ vertex resolution @ 6.4 keV

Time resolution



- $\sim 262 \text{ ns}$ time resolution

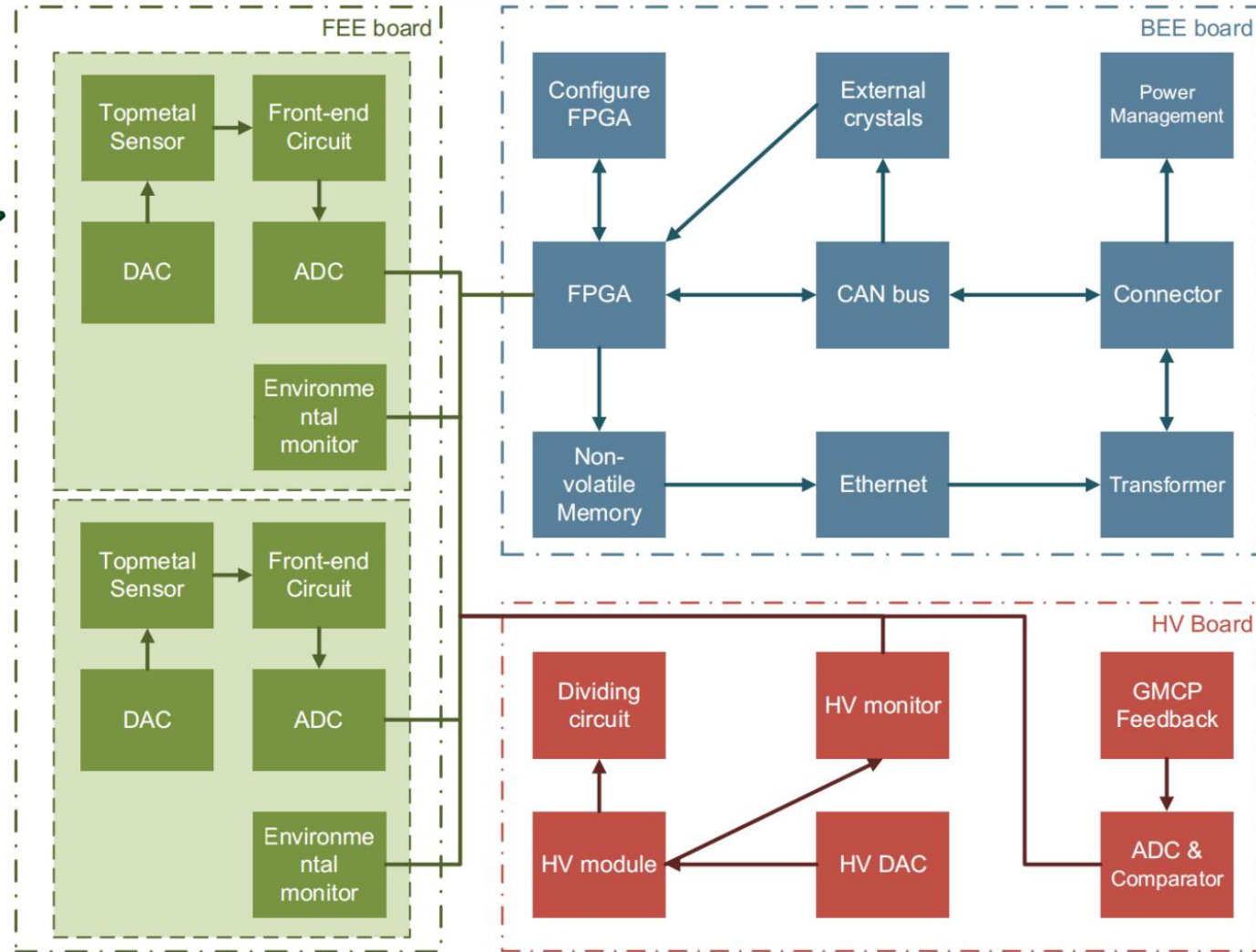
DAQ system

Detector unit

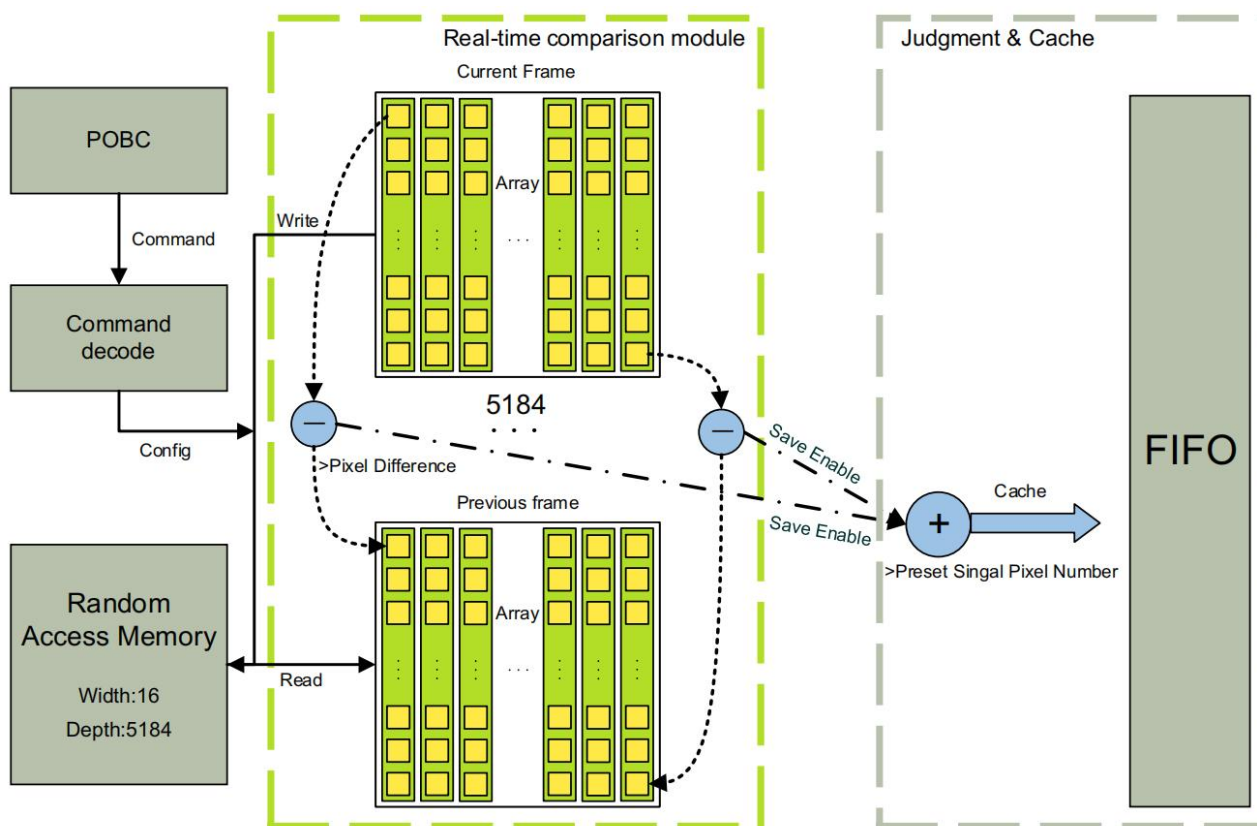
FEE board

BEE board

HV board

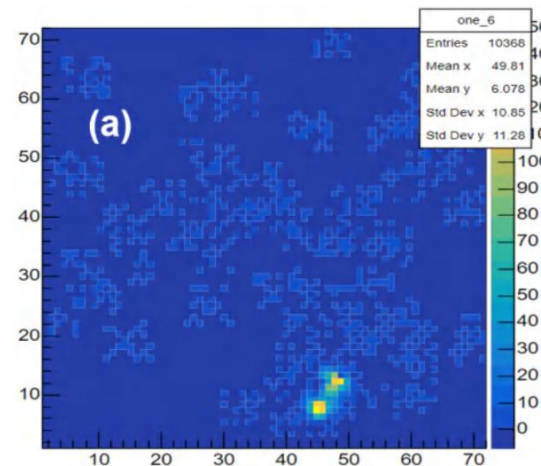


Online Data Compression

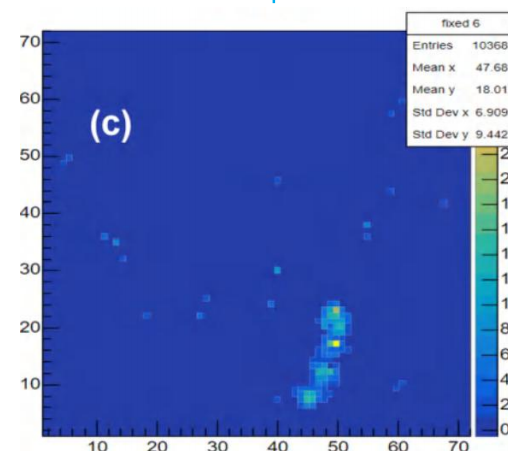
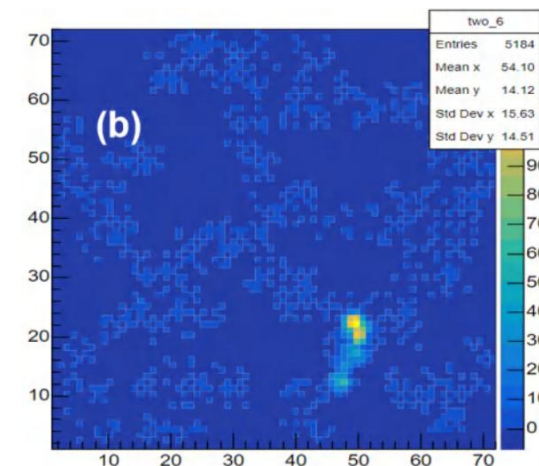


Compression ratio: 10^4

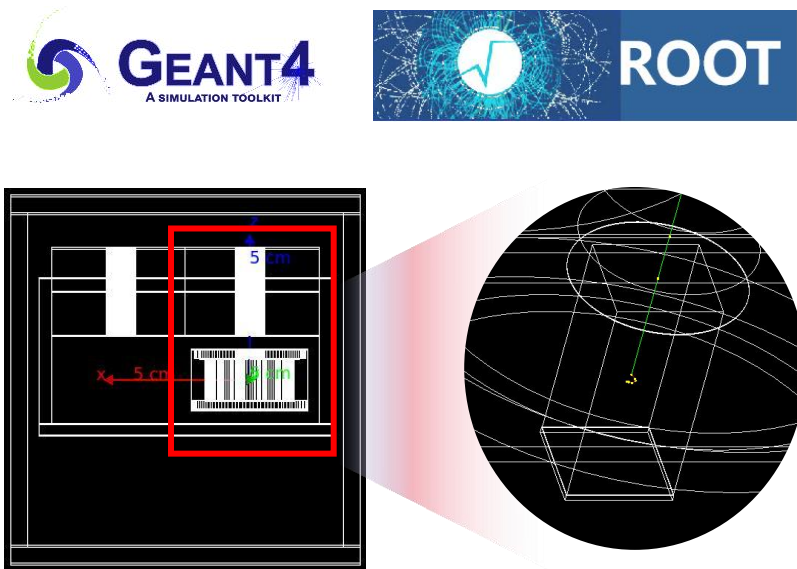
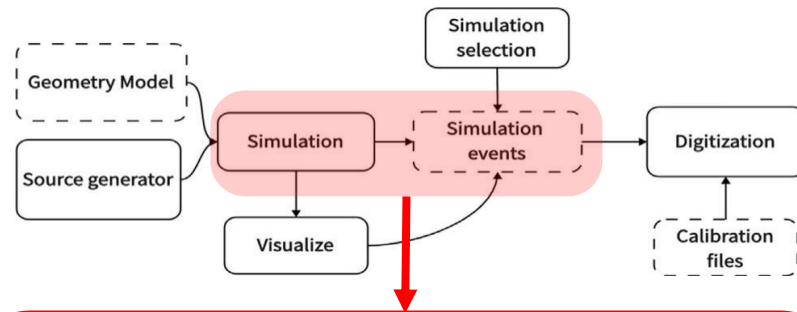
trigger frame



subsequent frame



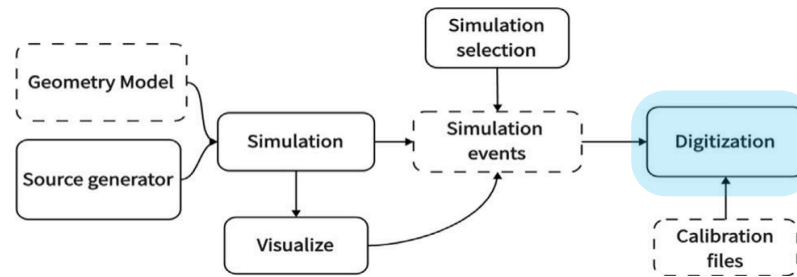
complete track



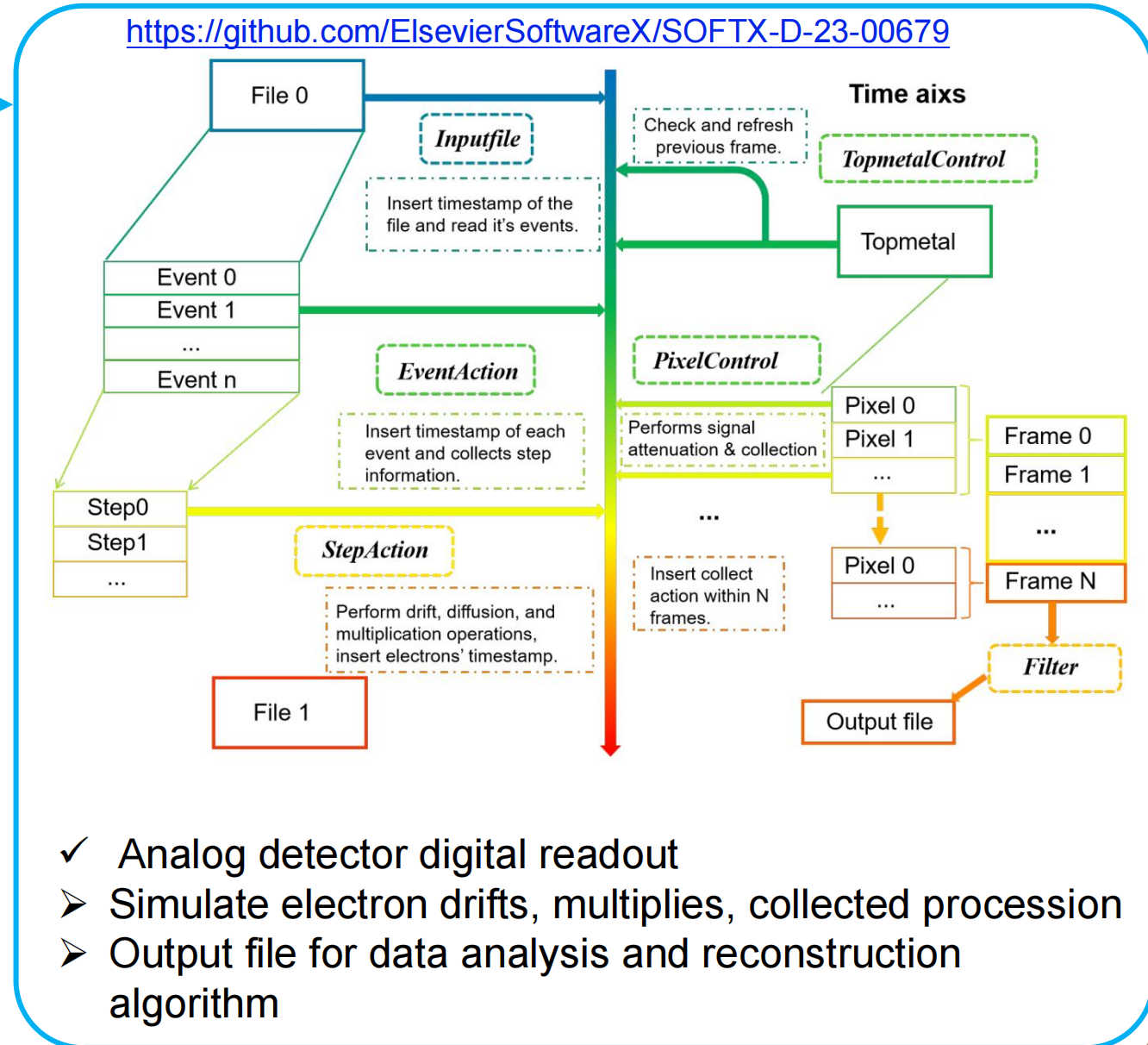
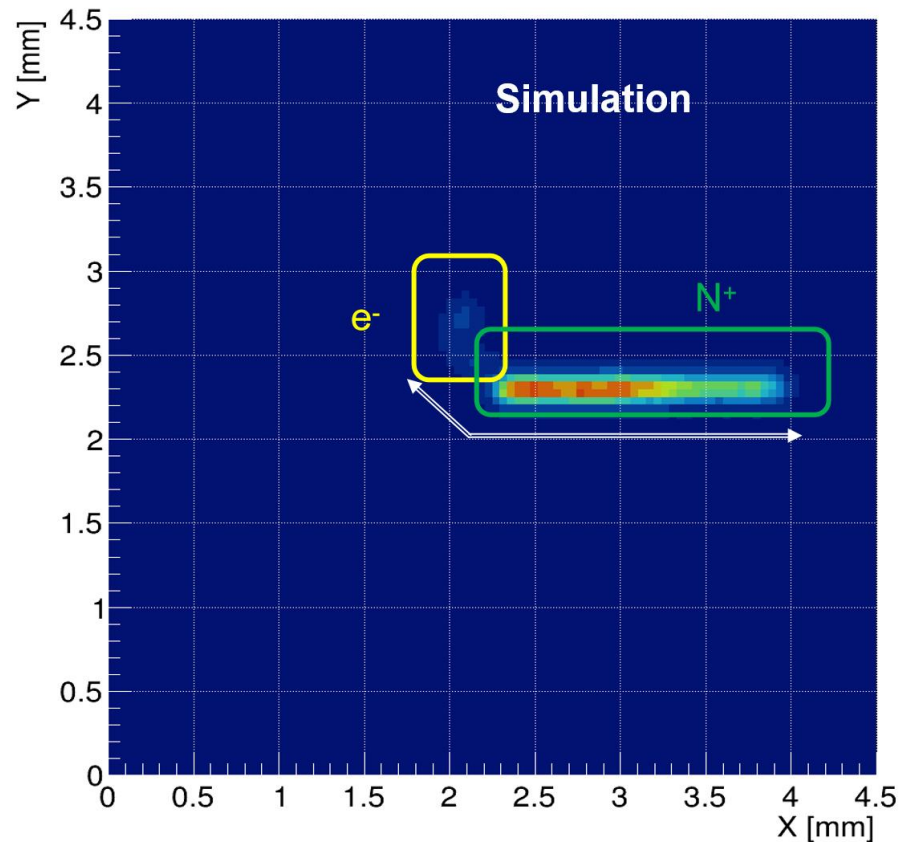
- ✓ Simulate Migdal effect interaction with detector
- Simulate different interaction
- Provide energy deposit

```
1 DetectorGDML: ./gdml/DetectorConstruction/gdml/Migdal_det_v03.xml
2 OutputFile: sim_Migdal_Oxygen.root
3 AdditionalMACCommand: AddCommand.mac
4
5 PGType: Migdal
6 IonName: Oxygen
7 IonZ: 8
8 IonA: 18
9 IonPosition: 0.0,0.,0.
10 IonMomentumDirection: 1.0,0.,0.
11 MigdalRandomSeed: 2023
12 GenValidEvents: 1000
13 #Deposit energy must higher than ValidEventEdp if chose
    GenValidEvents
14 ValidEventEdp: 0.01 #MeV
```


Simulation framework



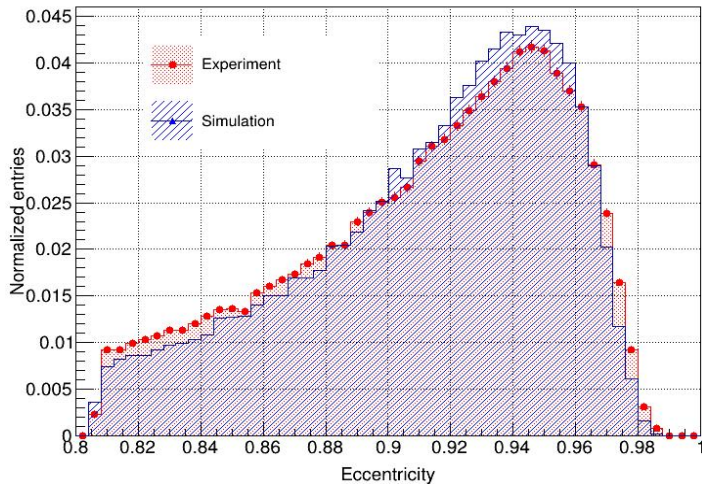
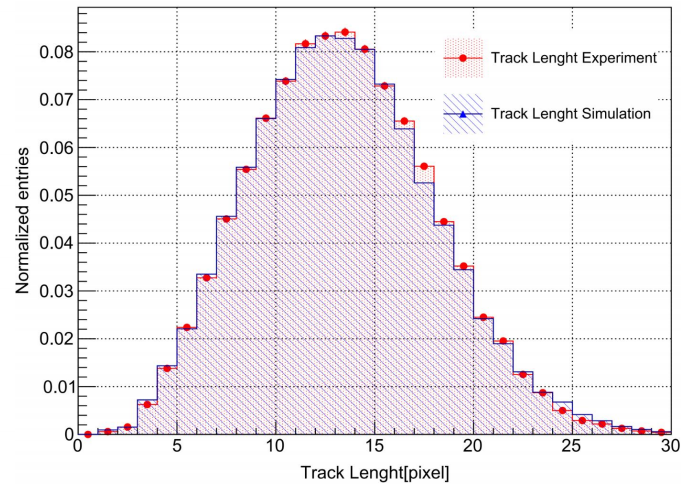
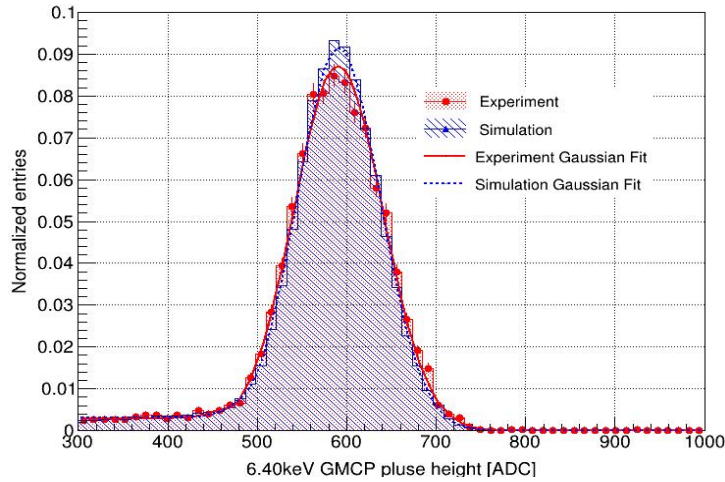
ER: 5.9 keV , NR: 300 keV



- ✓ Analog detector digital readout
- Simulate electron drifts, multiplies, collected procession
- Output file for data analysis and reconstruction algorithm

Comparison of experimental/simulation results

5-10 keV photo-electron



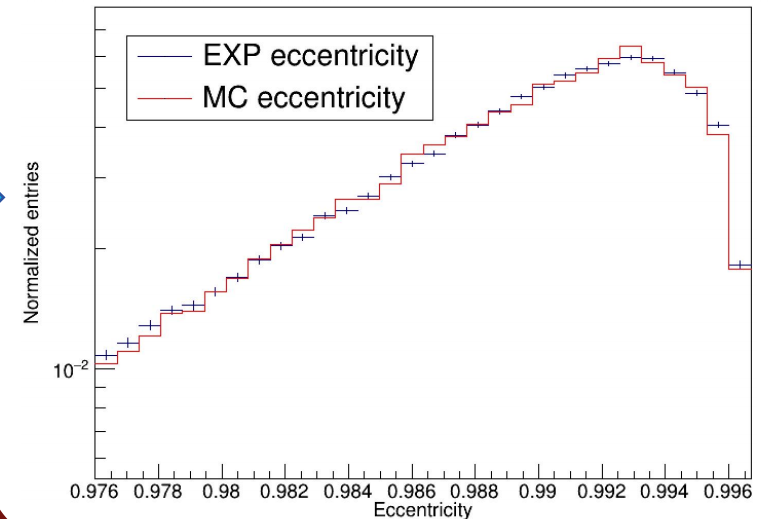
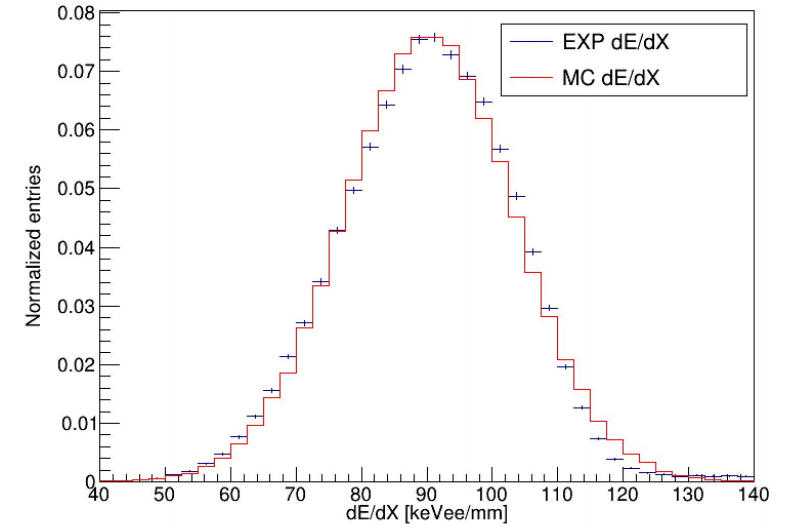
$$\mu_{ij} = \sum_x \sum_y (x - \bar{x})^i (y - \bar{y})^j Q_{xy},$$

$$M_2^{\max} = \frac{1}{2} \left[\mu_{20} + \mu_{02} + \sqrt{(\mu_{20} - \mu_{02})^2 + 4\mu_{11}^2} \right],$$

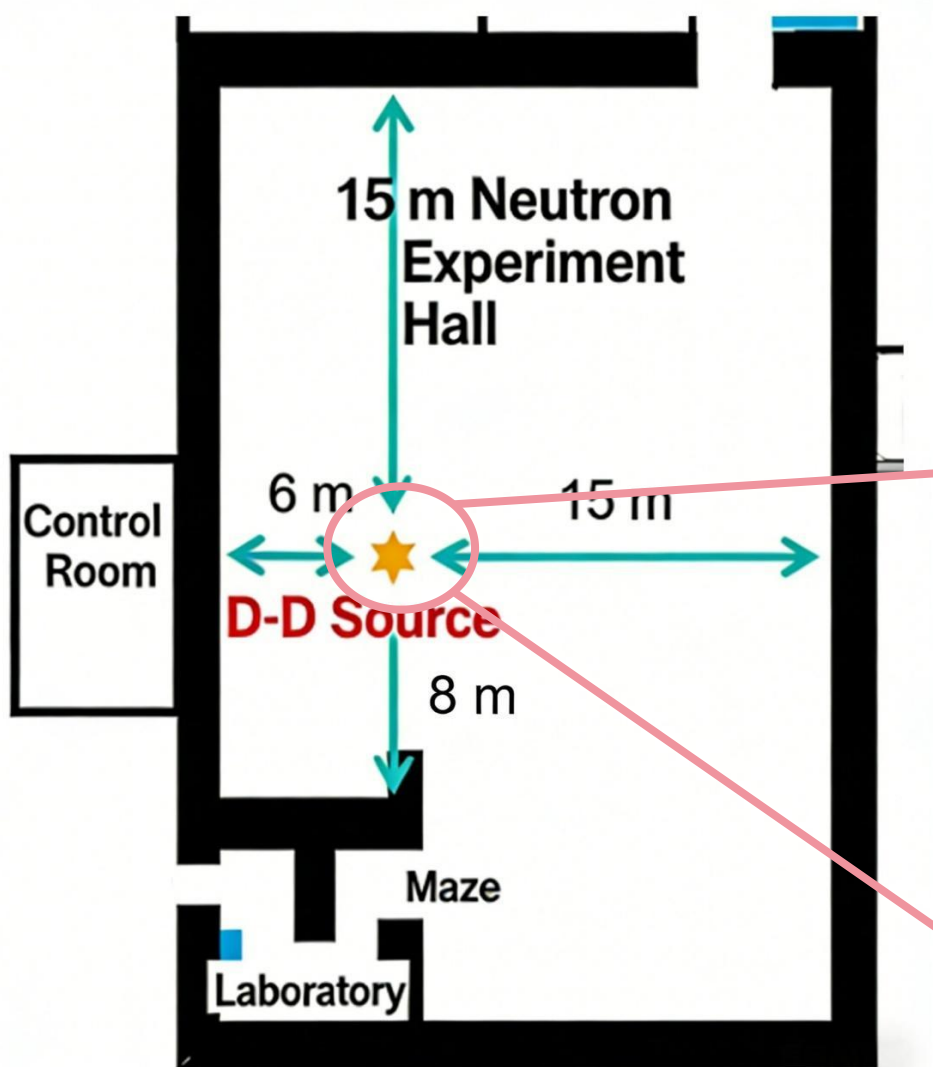
$$M_2^{\min} = \frac{1}{2} \left[\mu_{20} + \mu_{02} - \sqrt{(\mu_{20} - \mu_{02})^2 + 4\mu_{11}^2} \right],$$

$$e = \sqrt{1 - \frac{M_2^{\min}}{M_2^{\max}}}.$$

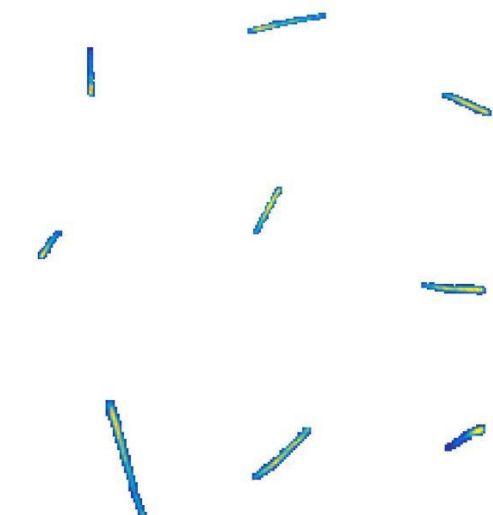
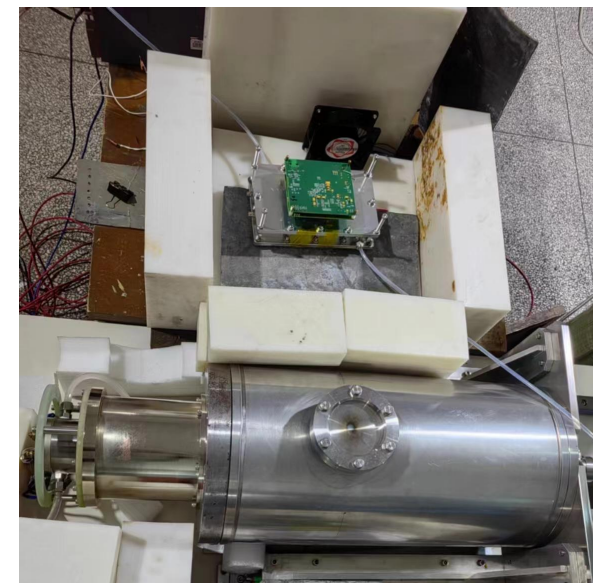
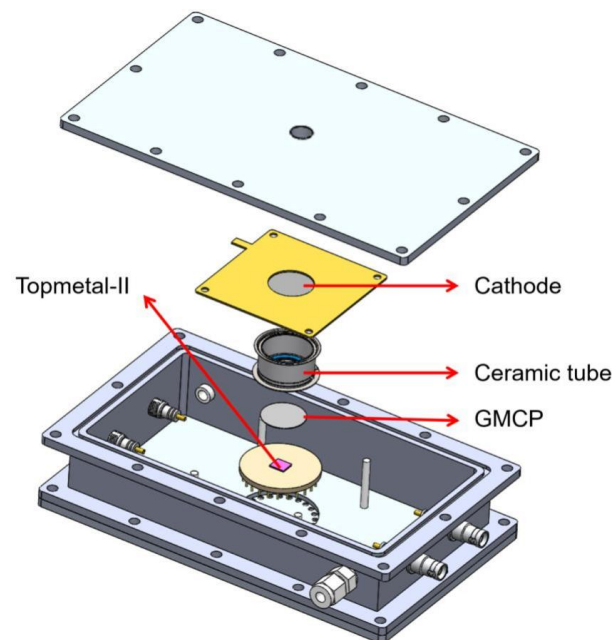
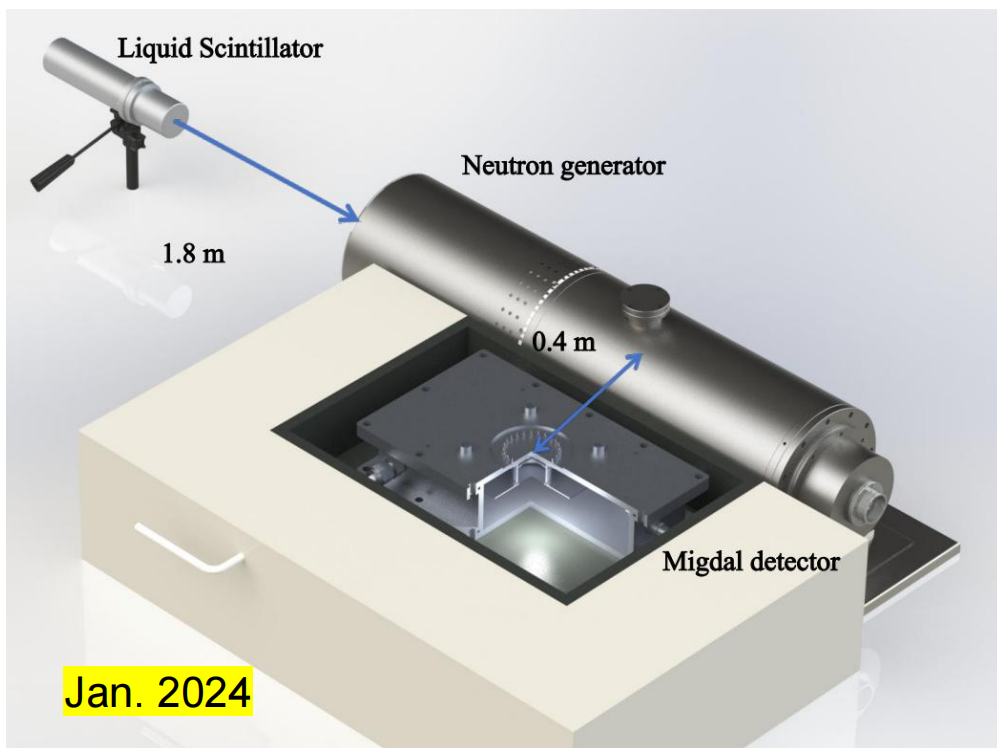
²⁴¹Am alpha source



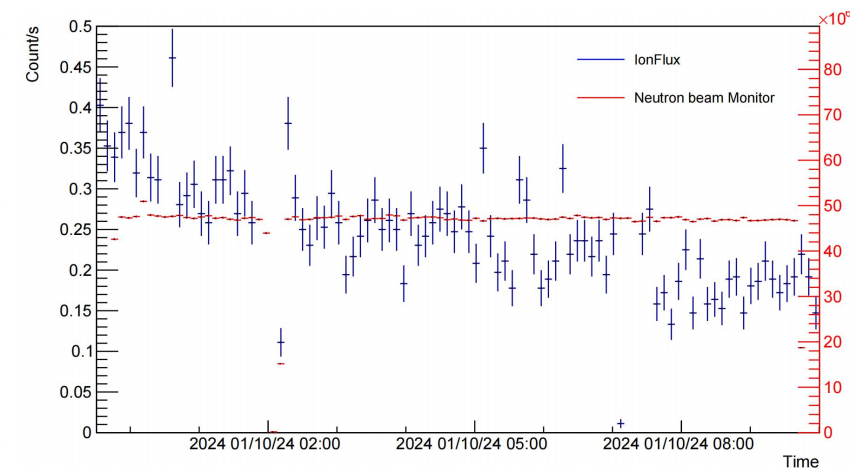
D-D neutron beam experiment



Pre-experiment

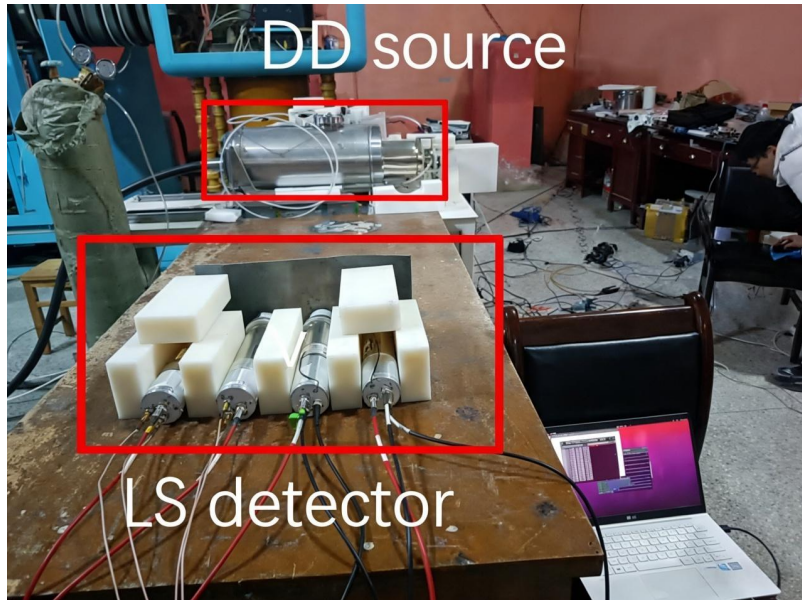


Some NR traks in pretest

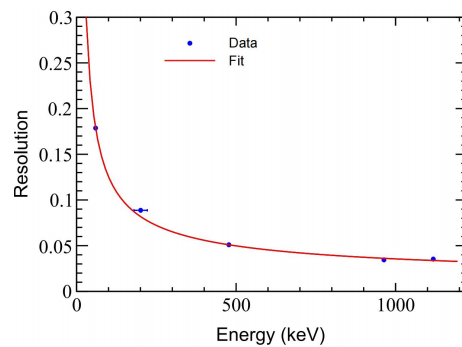
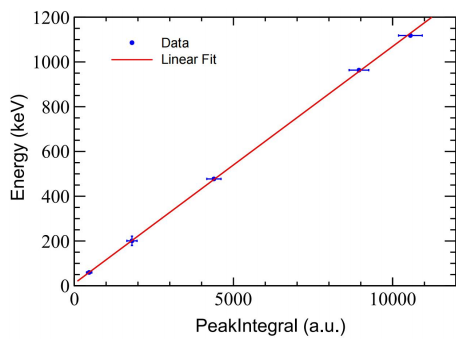


Flux monitor

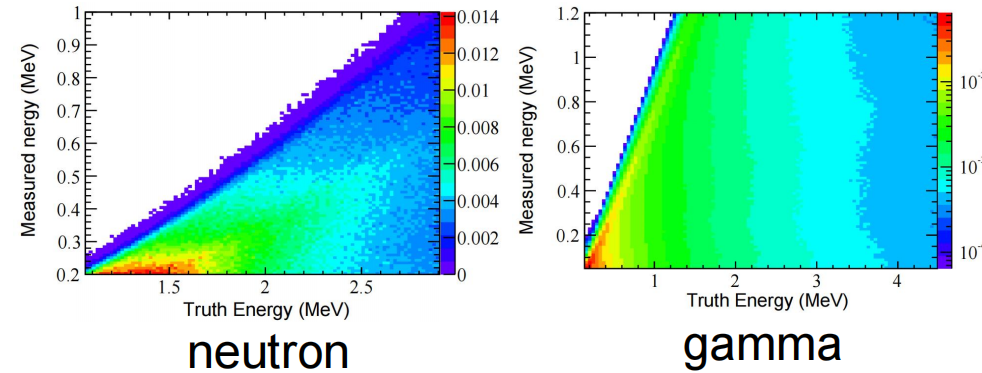
Neutron/gamma measurement



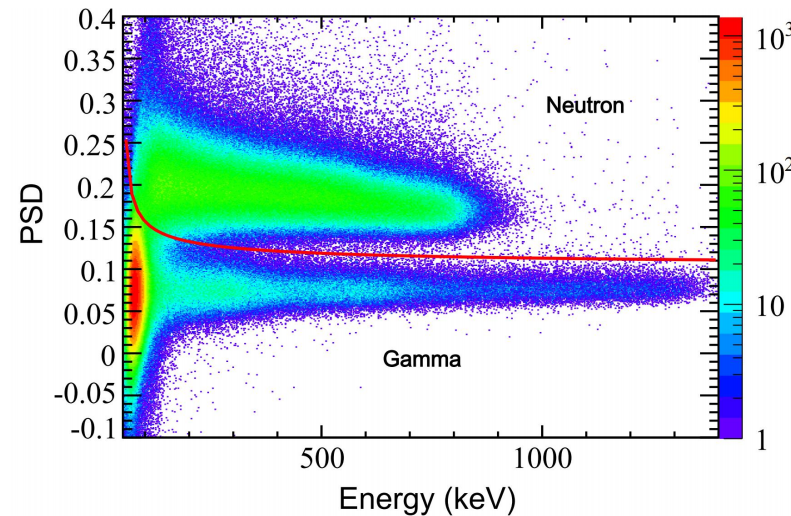
1. LS detector calibration:



2. Generate the Response matrix by GEANT4

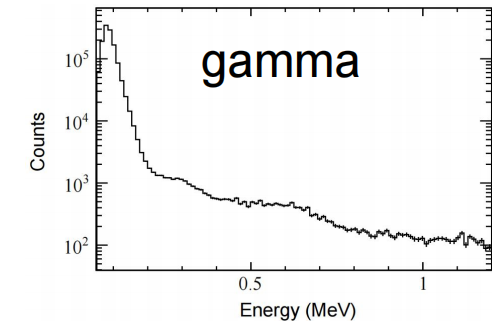
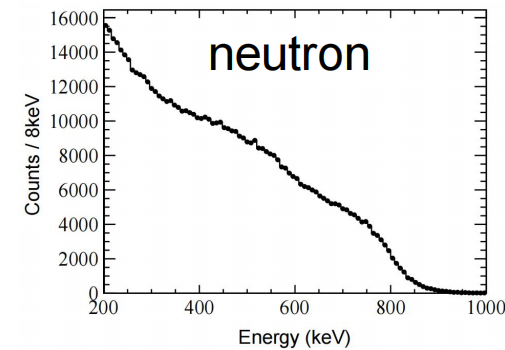


3. Neutron/gamma selection by PSD



https://gitee.com/schg_ucas/unfold-err
https://gitee.com/schg_ucas/unfold-multi

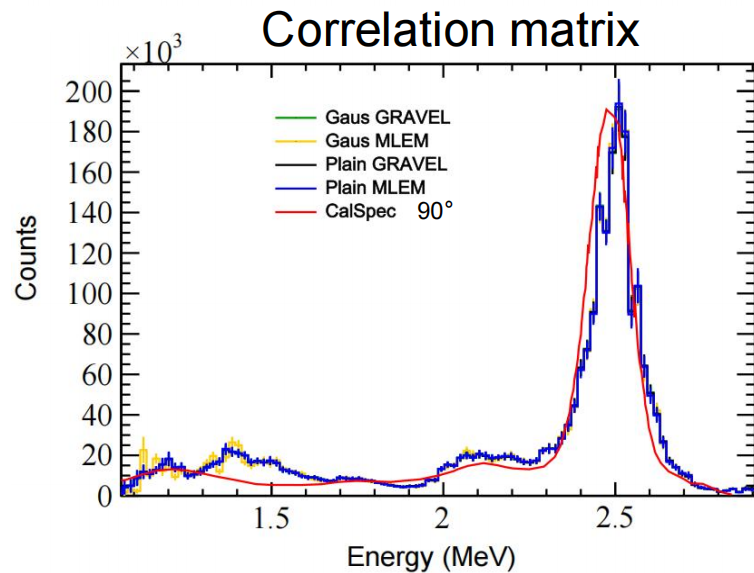
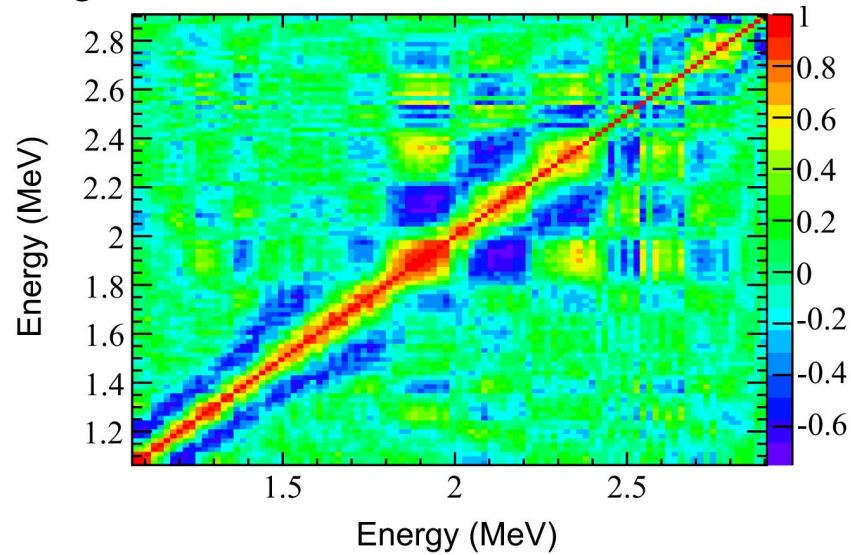
4. Do the unfolding



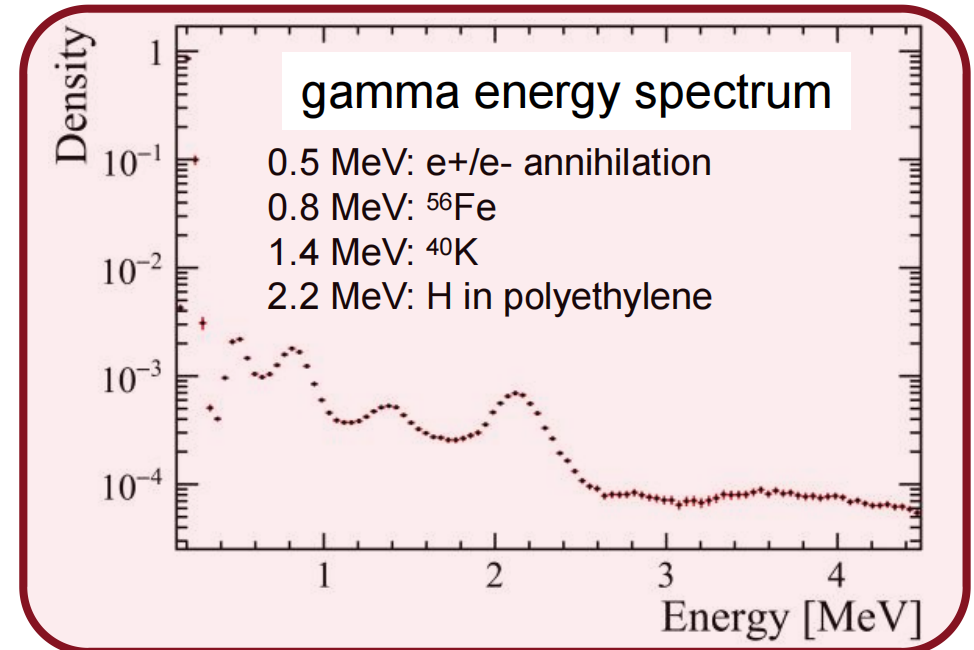
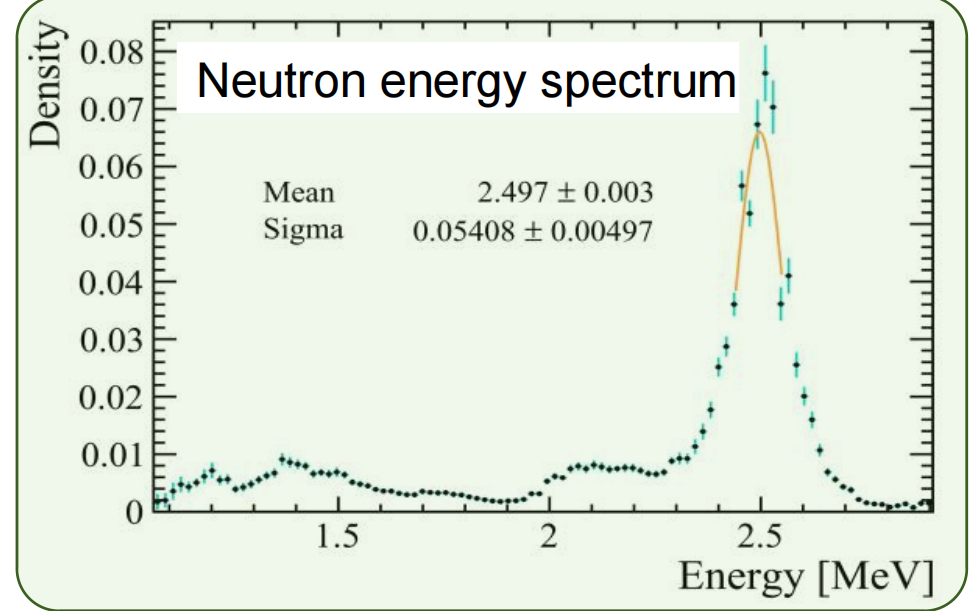
measured spectra

Neutron/gamma measurement

Unfolding result:

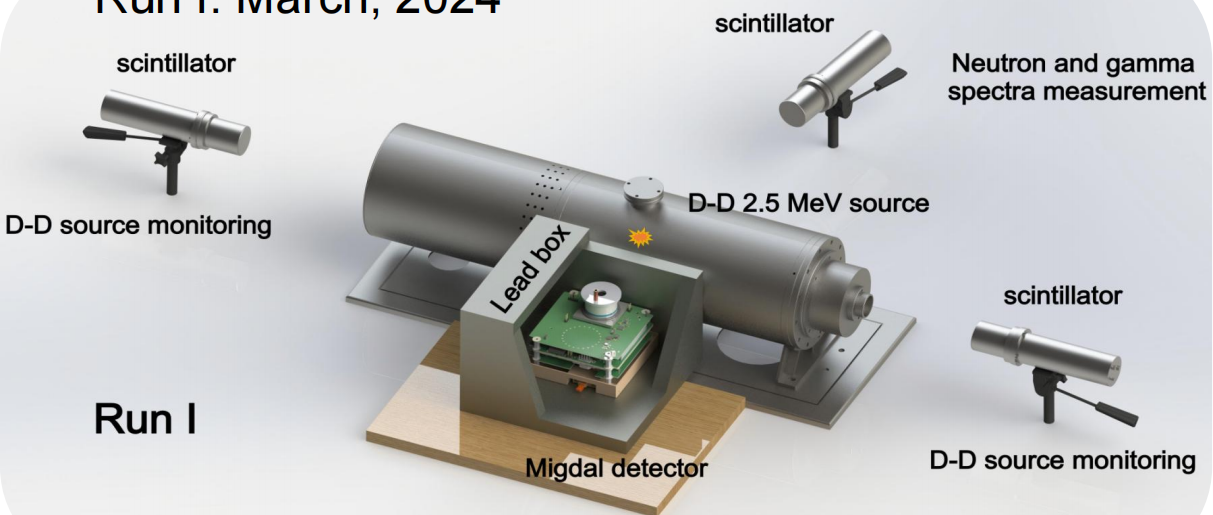


Measured at 87°, harder than 90°



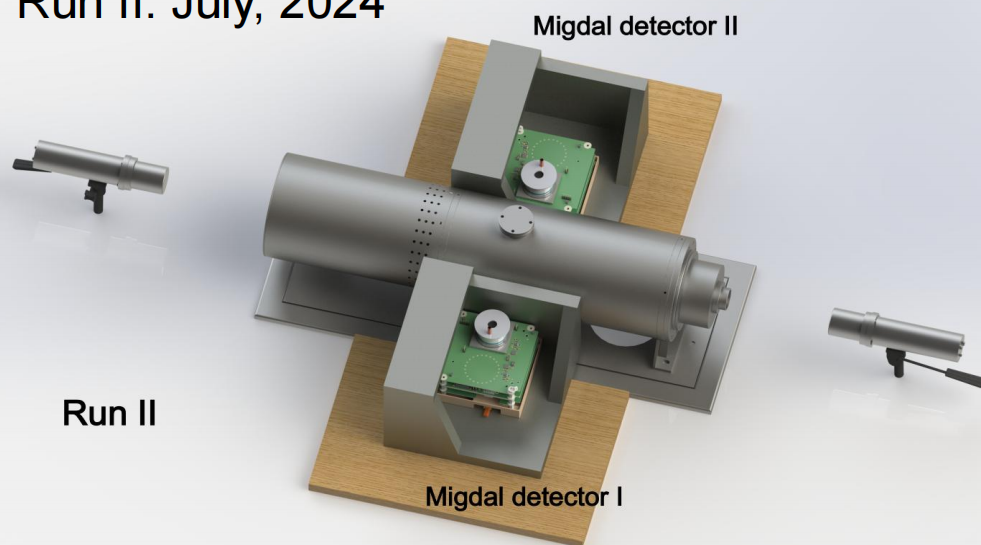
Formal experiment

Run I: March, 2024



Run I

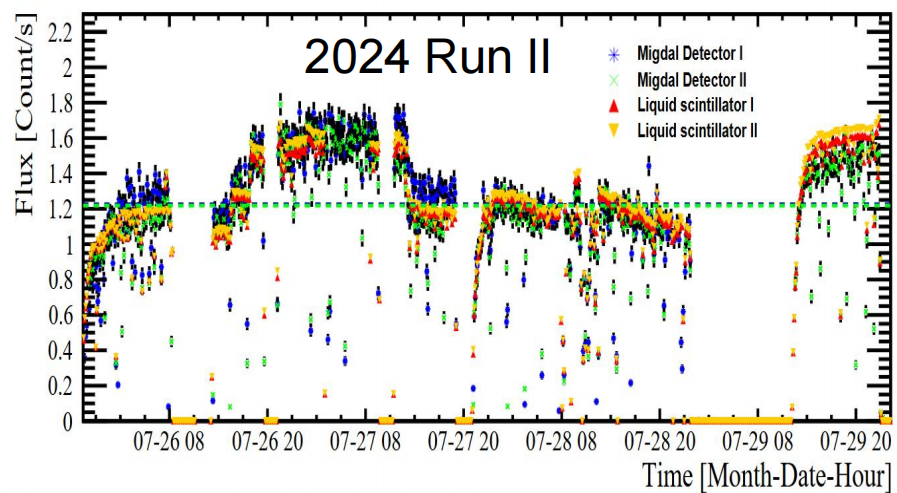
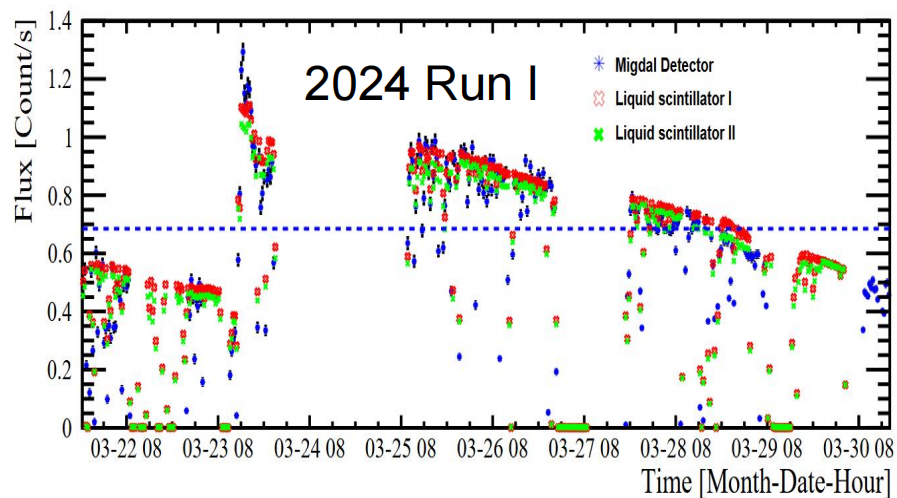
Run II: July, 2024



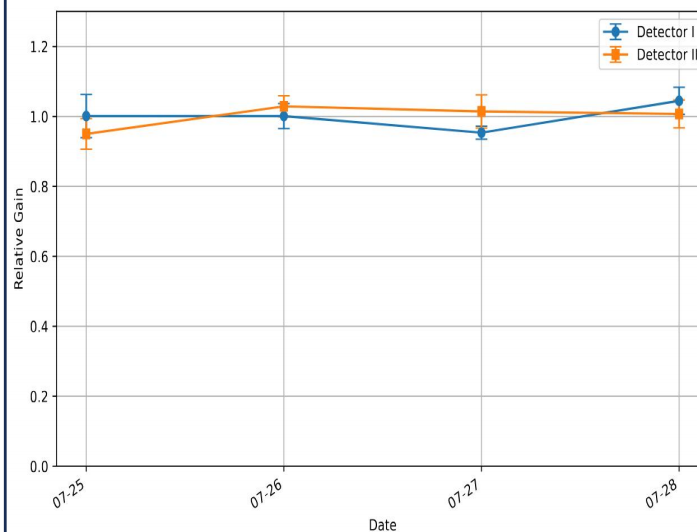
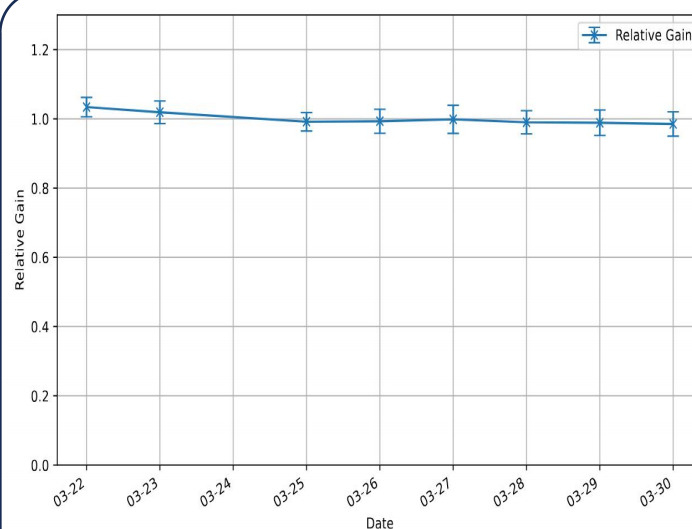
Run II



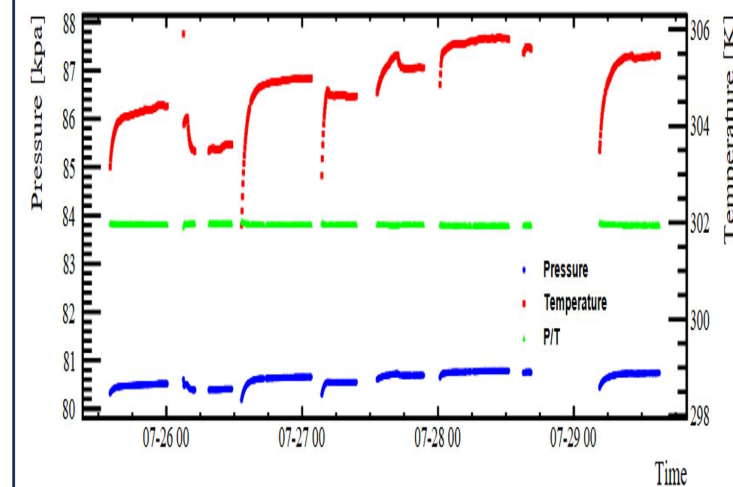
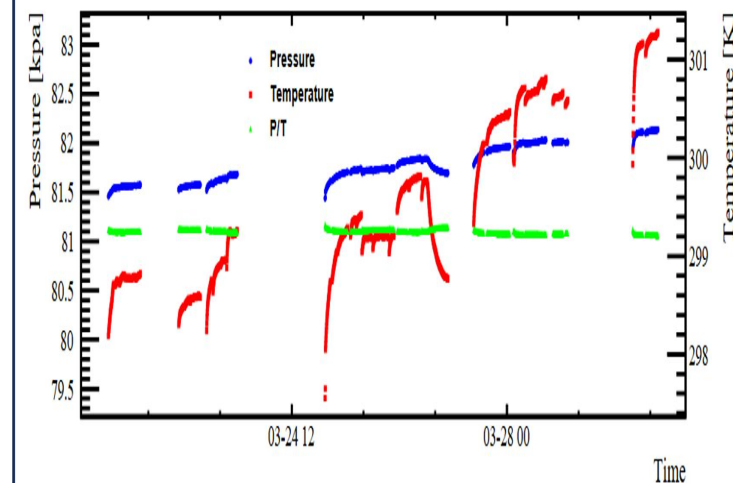
Data taking



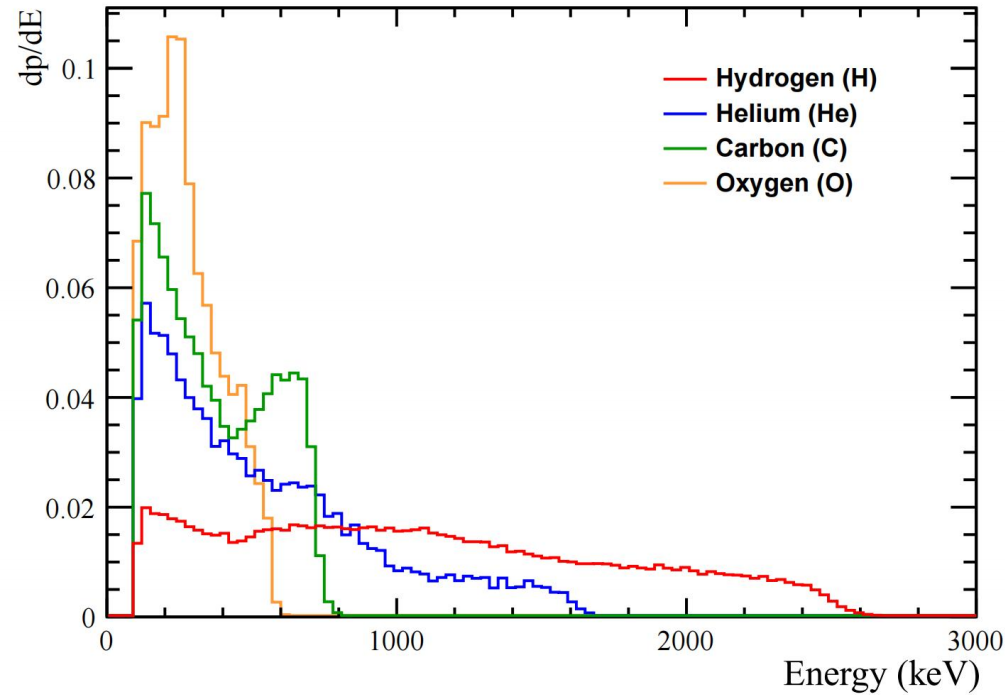
Flux



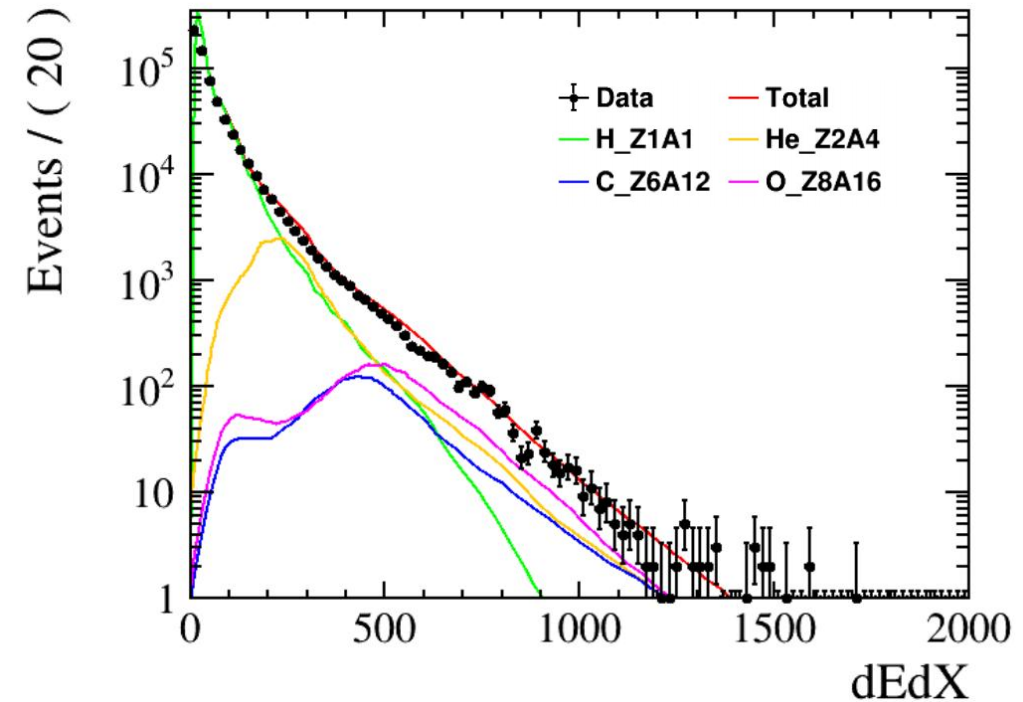
Gain



Pressure & temperature



Recoil kinetic energy distribution



dE/dX distribution

- The recoil energy range of different nucleons is mainly in the interval of hundreds of keV to MeV.
- Different nucleons exhibit differences in their distribution peak positions, and the total contribution curve shows a good fit with the experimental data.

AI-assisted event selection

Data

YOLO*1
preselection

NR
reconstruction

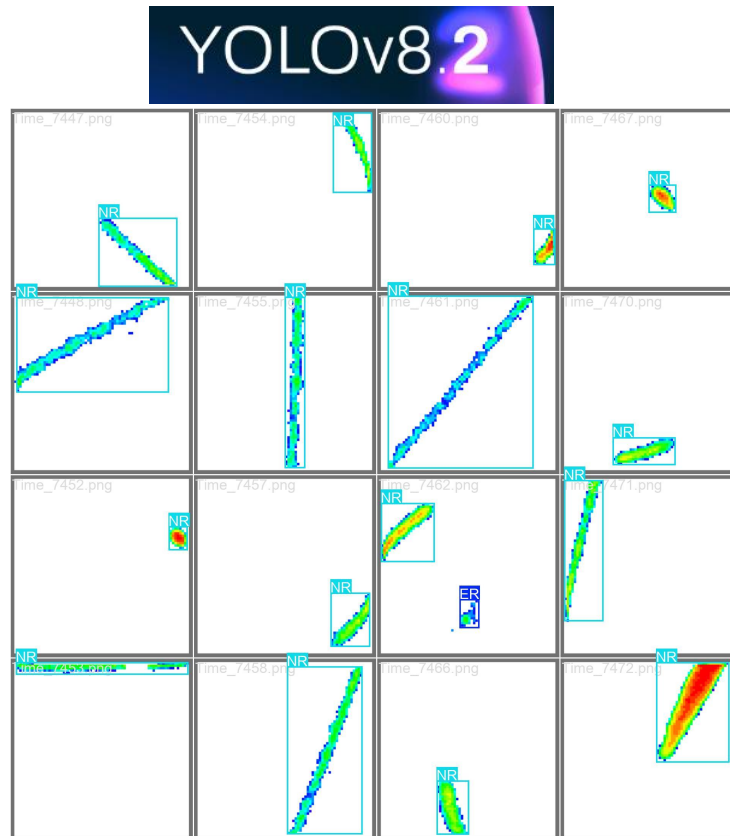
ER
reconstruction

Vertex cut

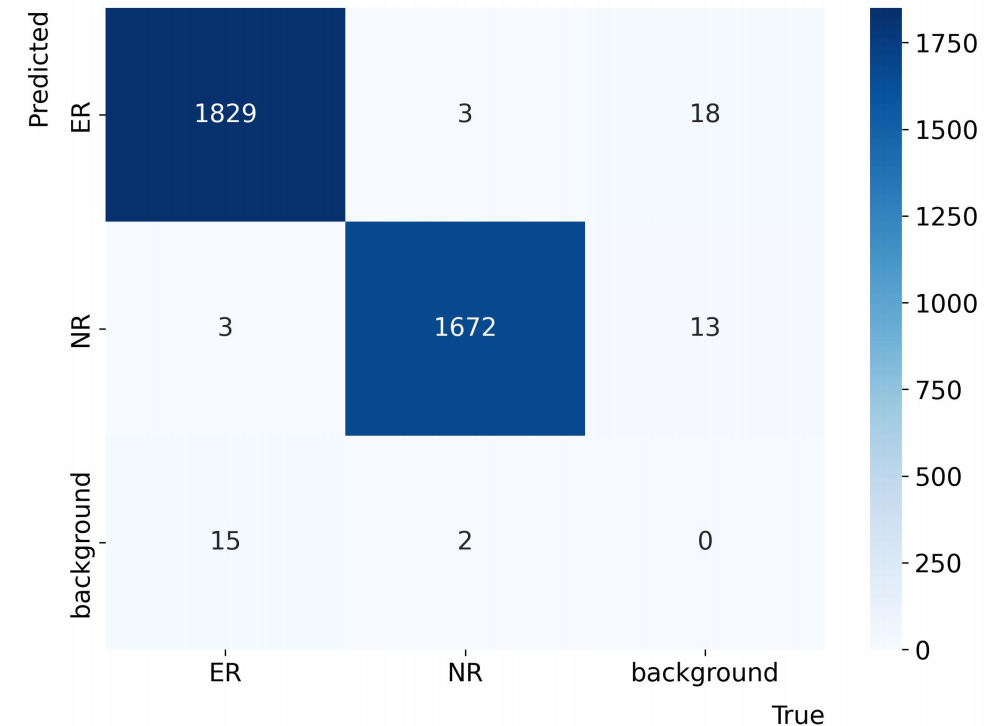
Inspired by MIGDAL collaboration's work: [10.1103/PhysRevD.111.072004](https://arxiv.org/abs/10.1103/PhysRevD.111.072004)

Labeling

Dataset		Train	Valid
Exp	⁵⁵ Fe	3000	1493
	D-D	2994	1354
Sim	ER	1200	301
	NR	1200	301
Total		8394	3449



Training



*1 <https://github.com/ultralytics/ultralytics>

Data

YOLO*1
preselection

NR
reconstruction

ER
reconstruction

Vertex cut

1. Search for the NR vertex through recursive iteration:

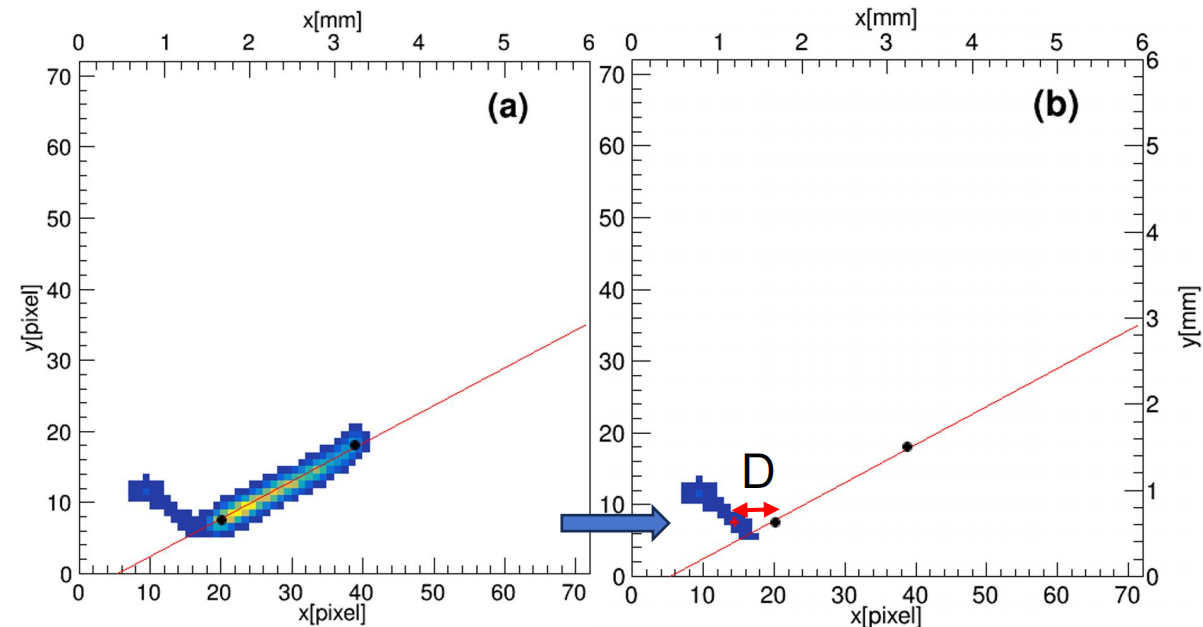
$$\begin{matrix} \text{ADC} \cdot \exp(d/d_0) \\ (x_0, y_0) \longrightarrow (x_n, y_n) \end{matrix}$$

2. Fit the NR(direction, diffusion σ) and remove it from the image.

3. Search for the electron vertex using adaptive cutting algorithm.

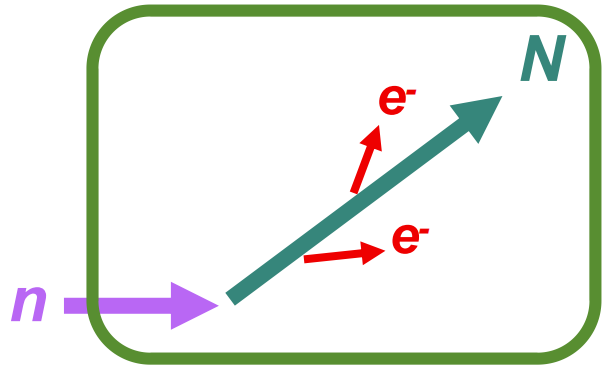
4. Determine whether the electron vertex is adjacent to the nucleon vertex.

$$R = \frac{D - 4\sigma}{L_{\text{ER}}} < 0.5$$

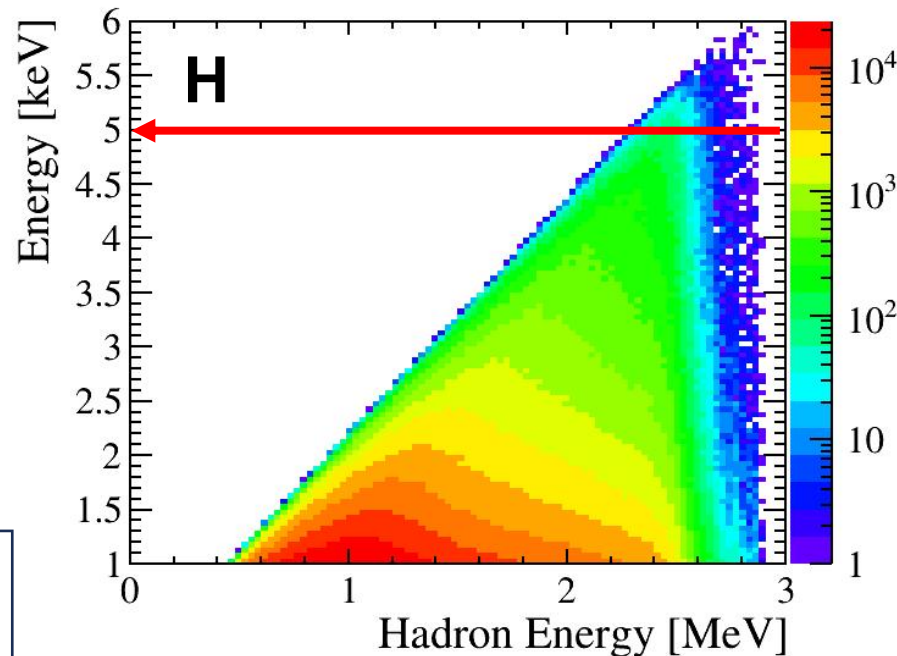
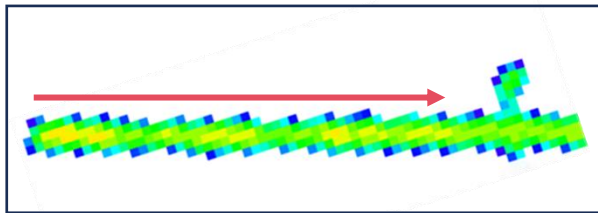


Background Component	Description
Recoil induced δ ray	δ electron near NR track origin
Particle Induced X-ray Emission	
X-ray emission	Photoelectron near NR track origin
Auger electrons	Auger electron near NR track origin
Bremsstrahlung processes	
Quasi-Free Electron (QFEB)	Photoelectron near NR track origin
Secondary Electron (SEB)	Photoelectron near NR track origin
Atomic (AB)	Photoelectron near NR track origin
Nuclear (NB)	Photoelectron near NR track origin
Random track coincidences	Photo-/Compton electron near NR track
Muon induced δ ray	δ electron near NR track origin
Gas radioactivity	
Trace contaminants	Electron from decay near NR track origin
Neutron activation	Electron from decay near NR track origin
Secondary nuclear recoil fork	NR track fork near track origin

Recoil induced δ electron

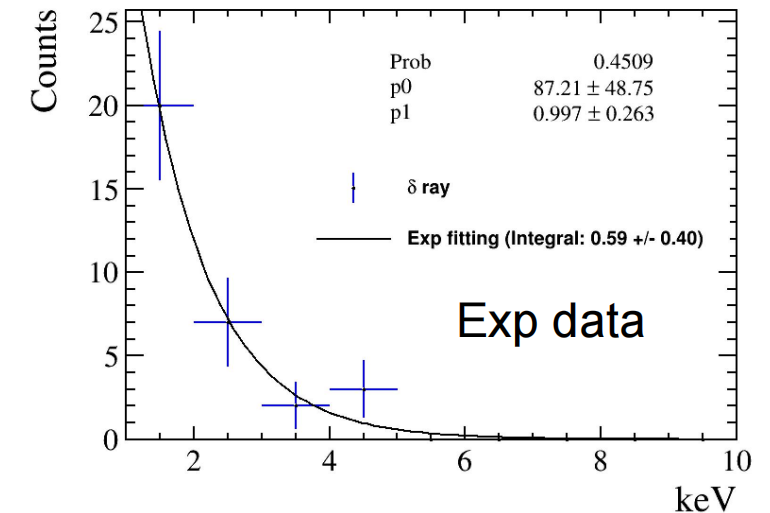
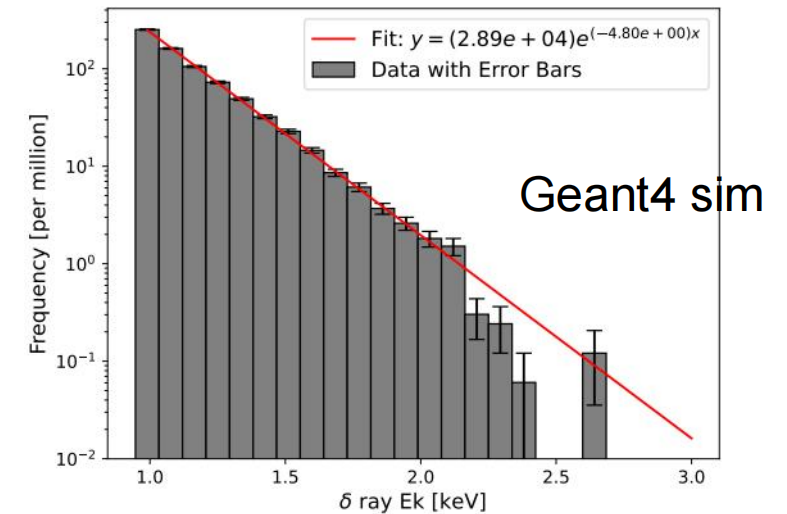


$$E_{\delta}[\text{keV}] = \frac{8.715}{(1 + A)^2} E_n[\text{MeV}]$$



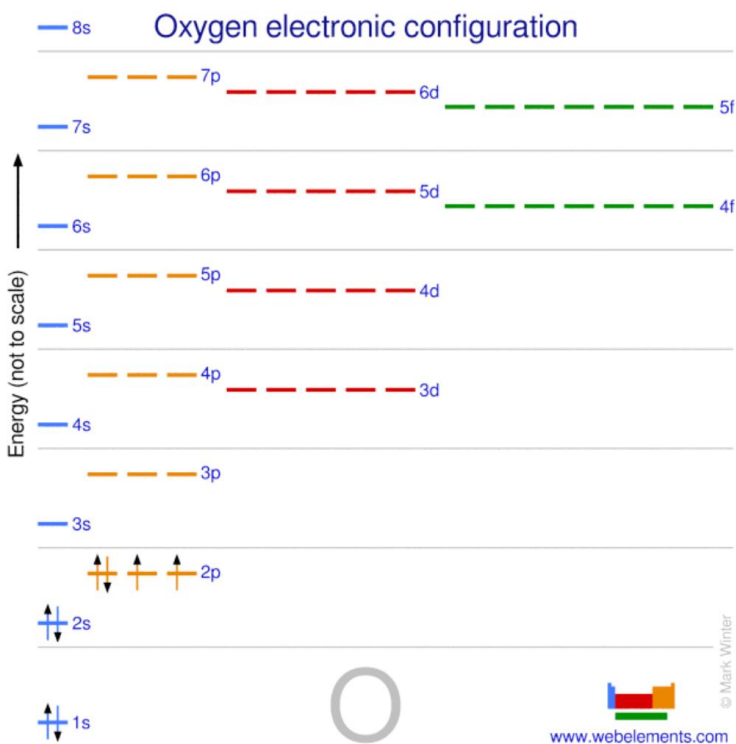
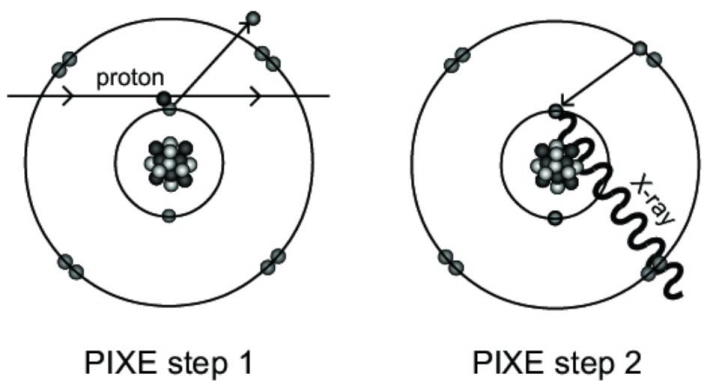
Only H has the δ electron > 5 keV.

- Consider the selection efficiency for δ -electrons.
- Finally get: $0.035 \pm 0.023(\text{stat.})$

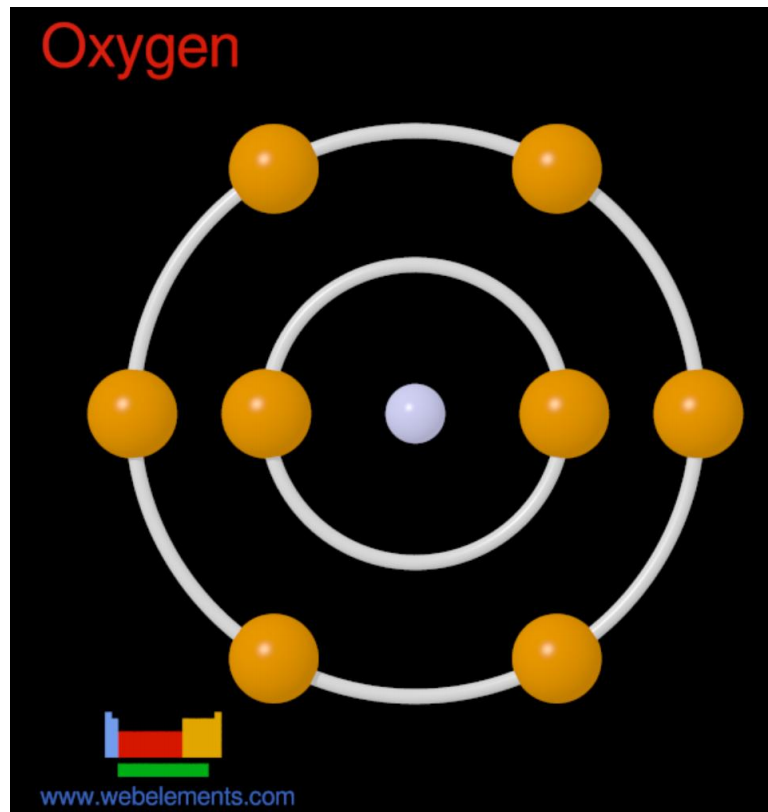


No δ above 5 keV were found.
Estimate by extrapolating from
the exponential fit

Particle Induced X-ray Emission (PIXE)



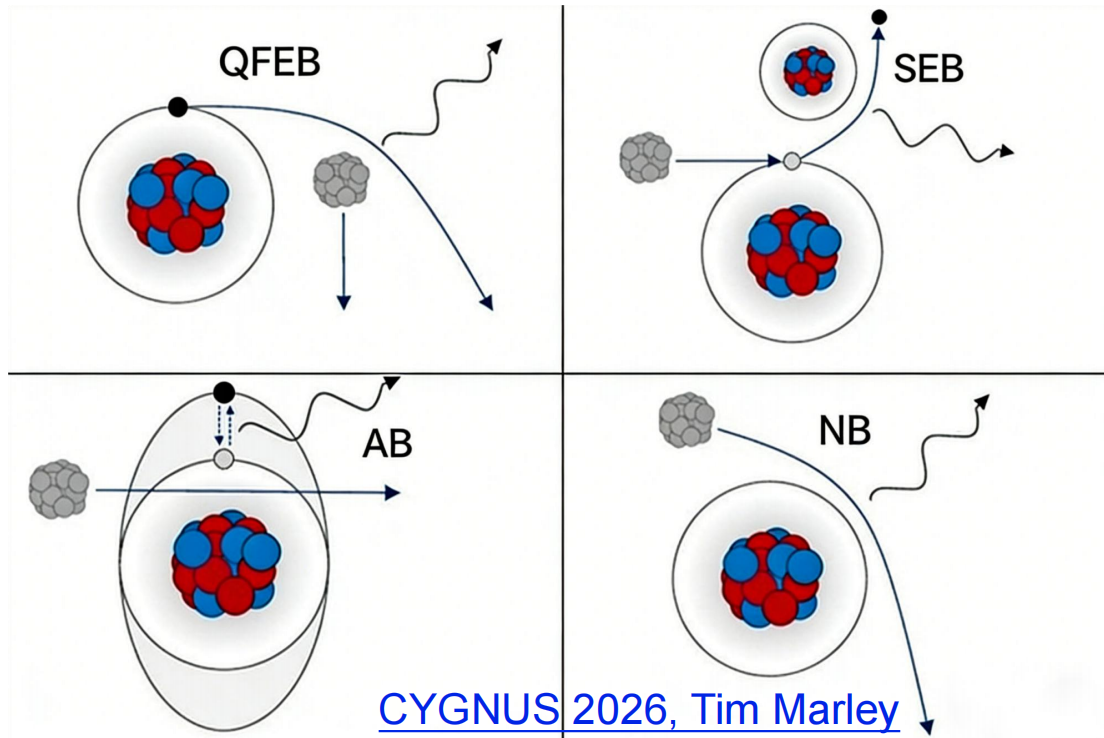
Schematic electronic configuration of oxygen.



Label	Orbital	eV [literature reference]
K	1s	543.1 [2]
L _I	2s	41.6 [2]

Bremsstrahlung processes:

Process name	Energy Region	Mechanism
Quasi-Free Electron Bremsstrahlung, QFEB	Low	The electrons are scattered in the Coulomb field of the recoiling ion.
Secondary Electron Bremsstrahlung, SEB	Intermediate	The excited electrons interact with other atoms.
Atomic Bremsstrahlung, AB	Higher	The electrons are excited to highly bound states or the continuum and then return to their initial state.
Nuclear Bremsstrahlung, NB	Highest	The Coulomb scattering between the recoiling ion and the target atoms.



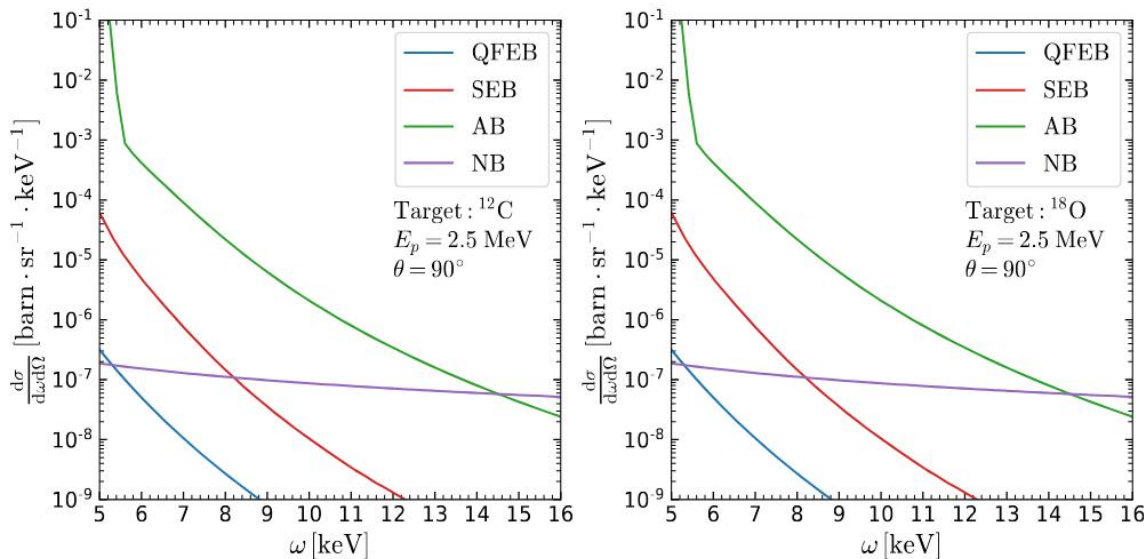
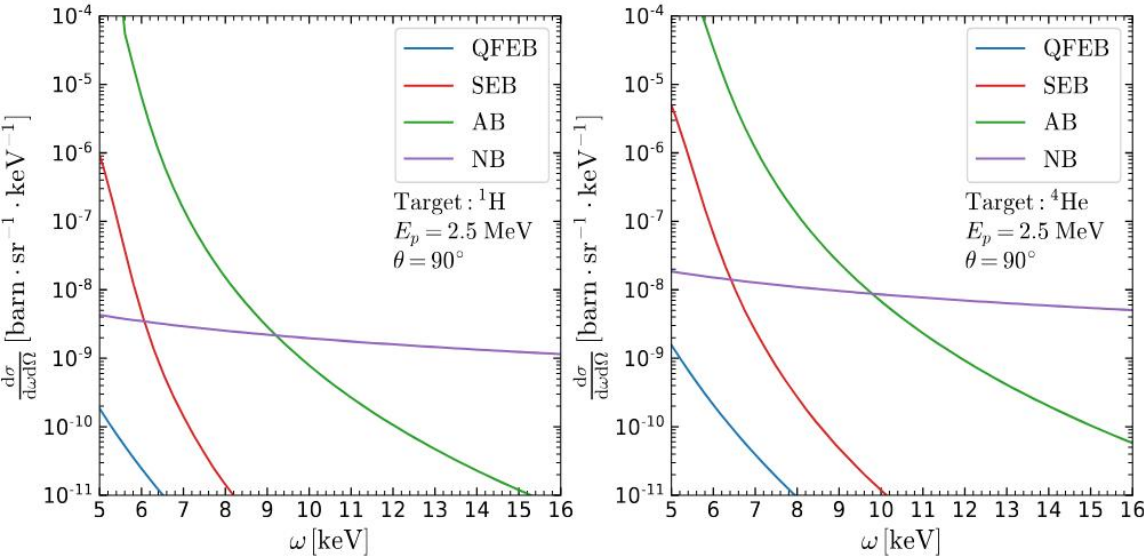
$$\omega < T_r = m_e \frac{E_p}{m_p};$$

$$T_r < \omega < T_m = 4m_e \frac{E_p}{m_p};$$

$$T_m < \omega < \omega_{AB} = \frac{2m_e \alpha Z_T v_p}{(z_p Z_T \frac{m_e}{m_p} (1 - \frac{m_p Z_T}{m_T z_p}))^{1/4}};$$

$$\omega_{AB} < \omega < \omega_{NB} = \frac{m_T}{m_T + m_p} E_p,$$

Bremsstrahlung processes:



The bremsstrahlung radiation induced by 2.5 MeV proton for differential target: H, He, C, O

Expected number of bremsstrahlung photons with energy >5 keV per million nuclear recoil:

Expected X-Ray / 1M NR		QFED	SEB	AB	NB
H	H	6.85×10^{-11}	5.15×10^{-10}	7.95×10^{-5}	2.39×10^{-5}
	He	5.18×10^{-12}	8.75×10^{-11}	4.96×10^{-6}	9.15×10^{-7}
	C	1.21×10^{-8}	5.99×10^{-7}	2.16×10^{-3}	6.54×10^{-5}
	O	6.51×10^{-9}	4.09×10^{-7}	6.84×10^{-4}	1.76×10^{-5}
C	H	3.13×10^{-18}	1.02×10^{-16}	6.30×10^{-10}	2.25×10^{-2}
	He	3.68×10^{-19}	2.72×10^{-17}	7.49×10^{-11}	1.36×10^{-3}
	C	5.61×10^{-16}	1.50×10^{-13}	1.46×10^{-7}	6.25×10^{-2}
	O	3.62×10^{-16}	1.44×10^{-13}	1.19×10^{-7}	1.95×10^{-2}



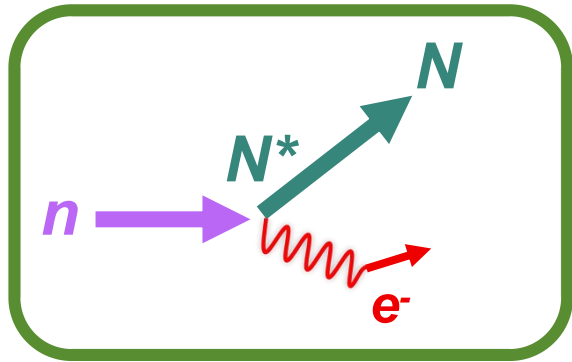
GEANT4 simulation for potonelectron

Background Photoelectron / 1M NR		QFED	SEB	AB	NB
H	H	2.47×10^{-15}	1.85×10^{-14}	4.85×10^{-9}	4.05×10^{-10}
	He	2.02×10^{-16}	3.33×10^{-15}	1.79×10^{-10}	1.92×10^{-11}
	C	3.99×10^{-13}	2.58×10^{-11}	6.71×10^{-8}	5.23×10^{-10}
	O	2.86×10^{-13}	1.72×10^{-11}	3.08×10^{-8}	2.64×10^{-10}
C	H	1.10×10^{-22}	2.96×10^{-21}	2.39×10^{-14}	2.92×10^{-7}
	He	1.62×10^{-23}	9.25×10^{-22}	1.95×10^{-15}	3.00×10^{-8}
	C	2.24×10^{-20}	3.91×10^{-18}	5.12×10^{-12}	1.06×10^{-6}
	O	1.34×10^{-20}	4.75×10^{-18}	4.51×10^{-12}	1.95×10^{-7}

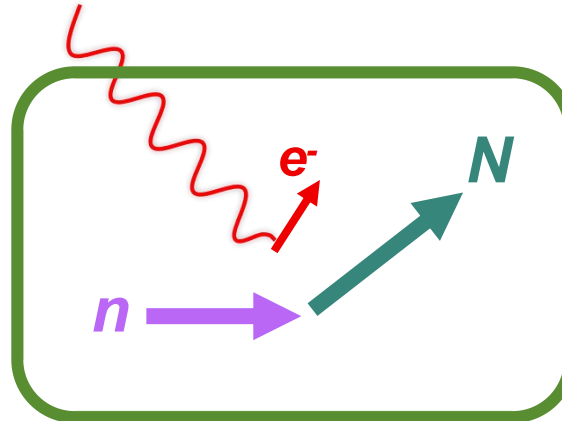
Bremsstrahlung background is negligible.

Radon track conincidence

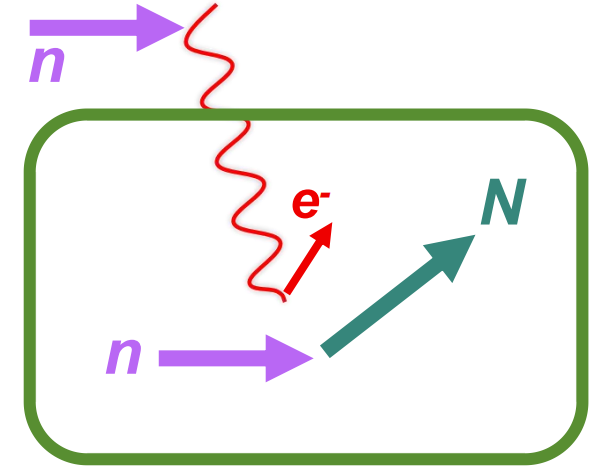
Method 1: n/γ spectrum measured by LS + GEANT4



I

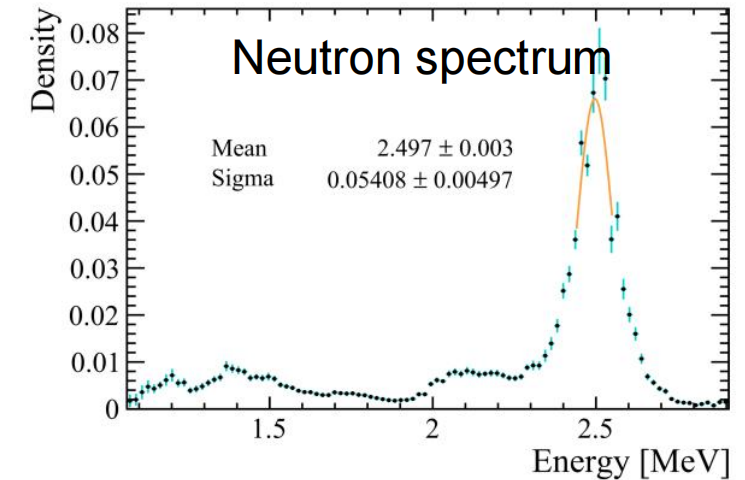
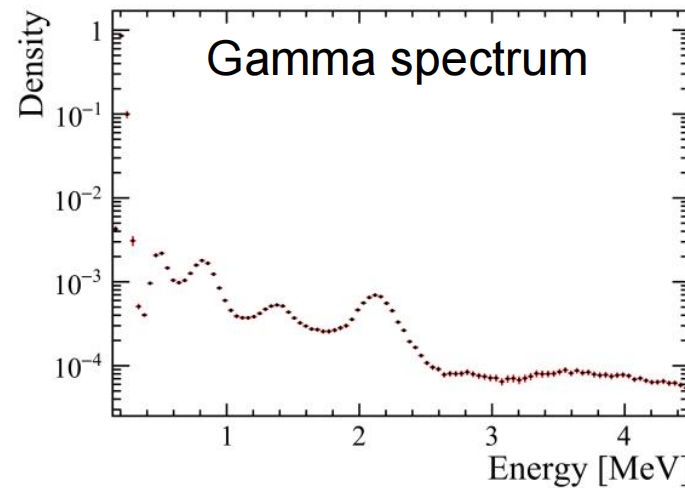


II



III

	NR	Compton e ⁻	photonEle
I	1	4.32×10^{-5}	1.06×10^{-5}
II	1	6.06×10^{-6}	$\sim 3.63 \times 10^{-8}$
III	1	3.11×10^{-6}	7.15×10^{-7}

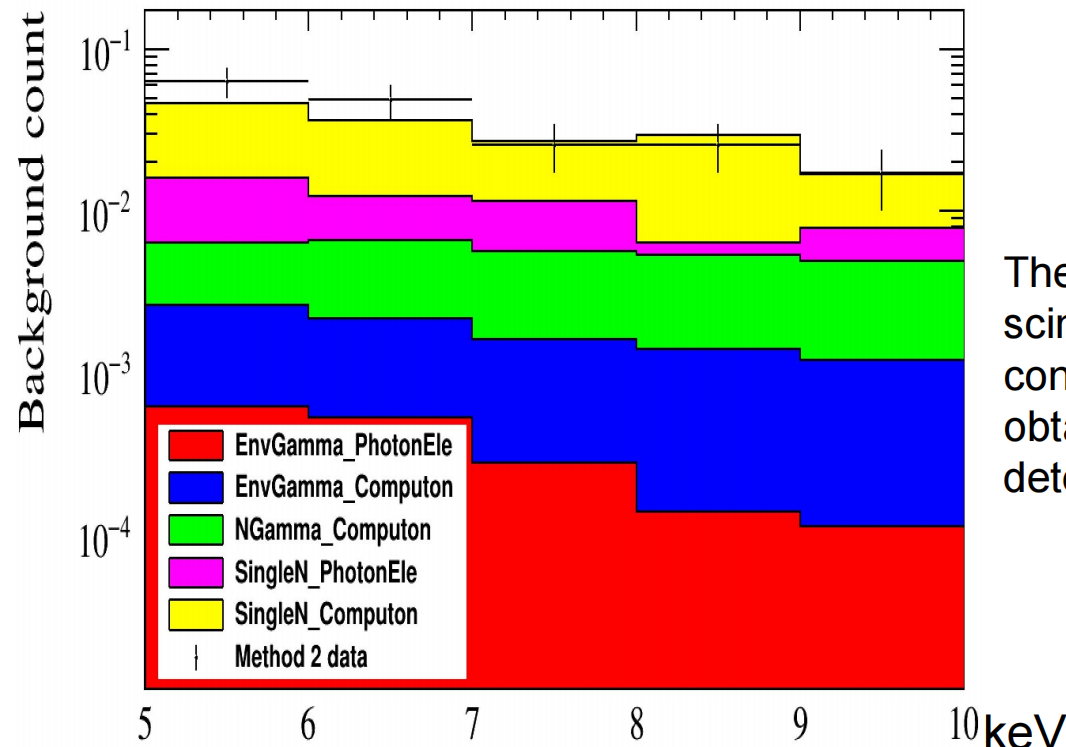
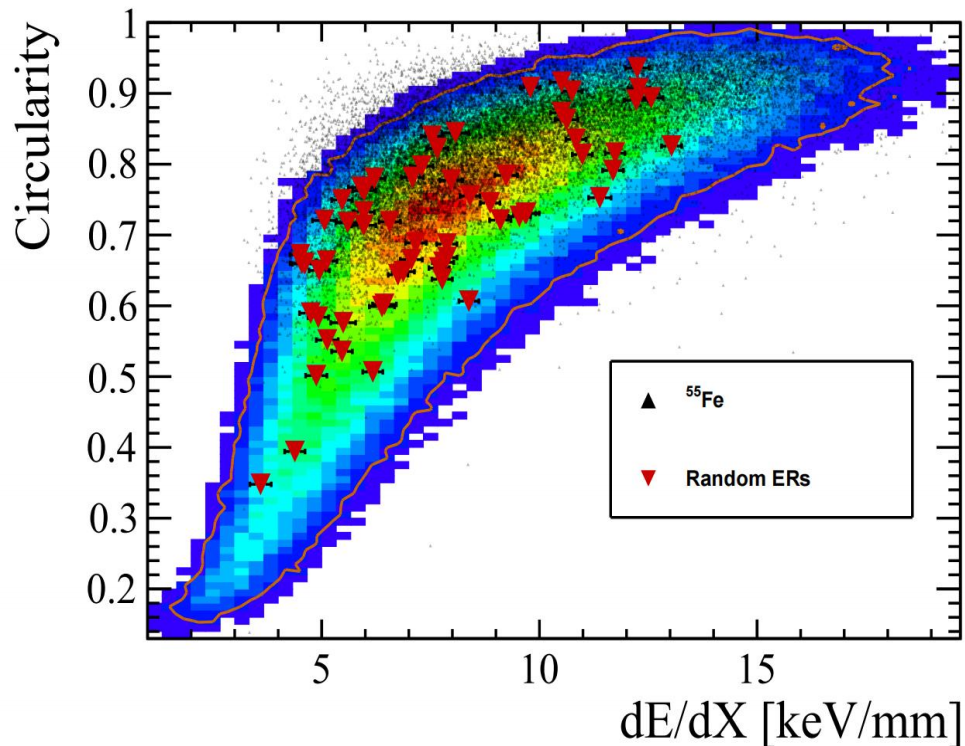


- The expected background contribution of the 3 components in total is: $0.16 \pm 0.01(\text{stat.})$

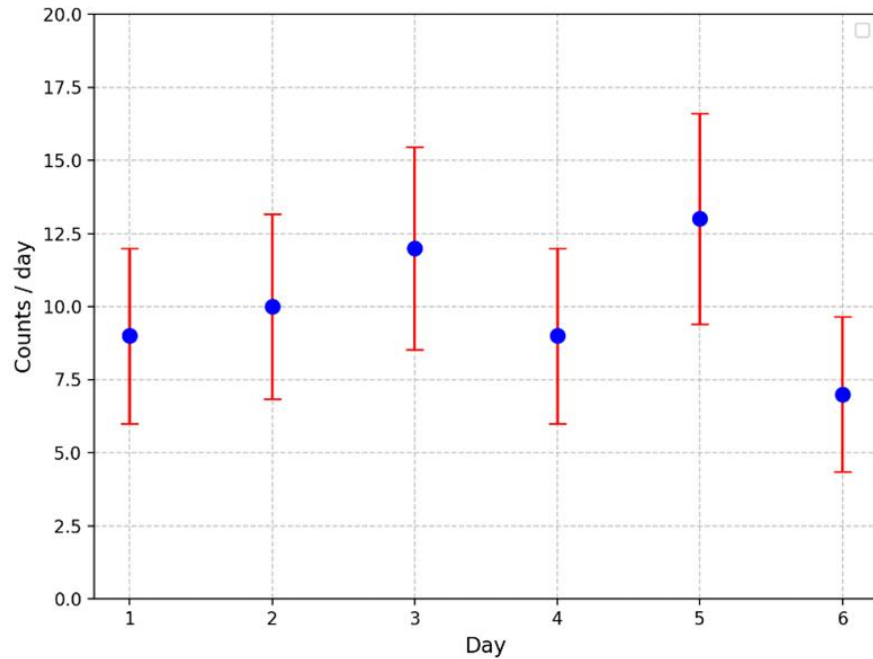
Radom track conincidence

• Method 2: Estimated from Data

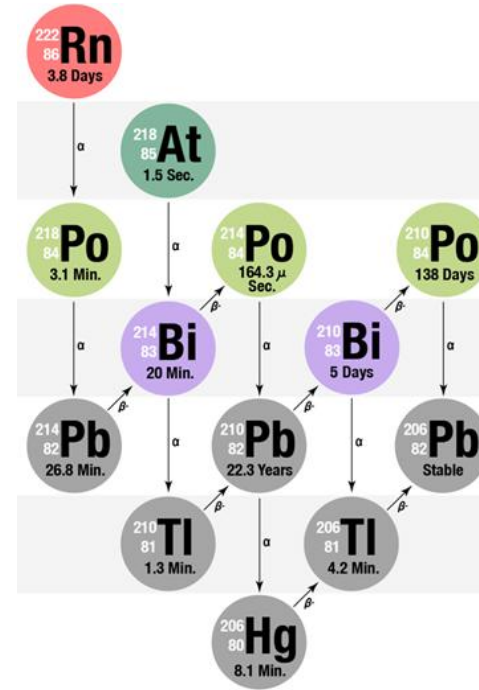
- Get the number of electron tracks within the 5-10 keV energy range that appear in the same frame as the nucleon tracks.
- Considering the accidental coincidence of NR and ER with a vertex selection efficiency,
- the final expected background value is $0.180 \pm 0.022(\text{stat.}) \pm 0.042(\text{sys.})$



The results from the liquid scintillation + GEANT4 are consistent with the data obtained from the Migdal detector.



The detector's alpha decay count rate



The decay chain of ^{222}Rn

β decay between 5-10 keV contributed by the ^{222}Rn decay chain:

- $(7.25 \pm 0.94) \times 10^{-7} / \text{s}$

Combined with the natural abundance values of the working gas:

- $(3.34 \pm 2.71) \times 10^{-6} / \text{s}$

GEANT4 simulation of trace radioactivity generating 5-10 keV pseudo-Migdal events yields a selection efficiency of 11.4%

The final expectation for the background contribution from trace radioactivity is: 0.001 ± 0.001 .

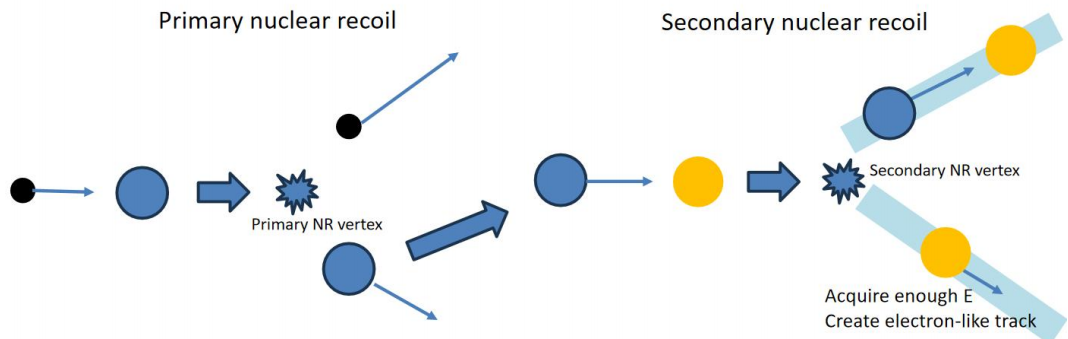
Assuming:

- All alpha rays are attributed to the decay chain of ^{222}Rn .
- The secondary nuclides with a half-life of less than 1 year have completely decayed.
- Decay process ultimately ceases at ^{210}Pb .

Secondary nuclear recoil fork

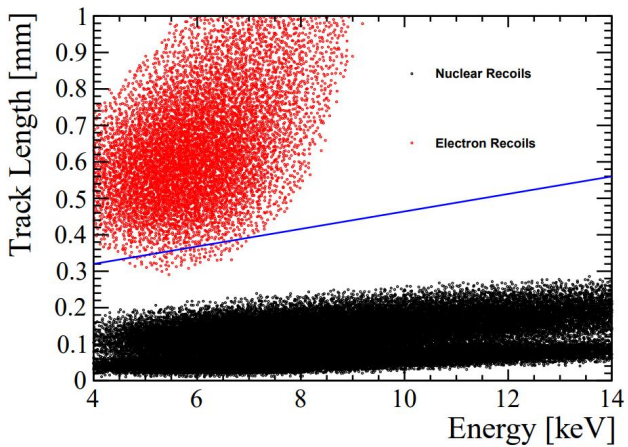
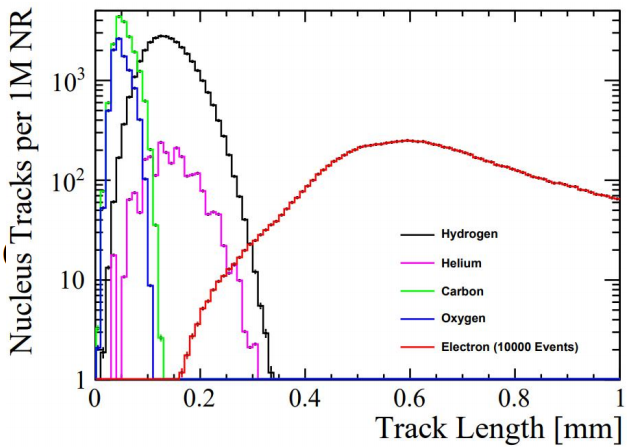
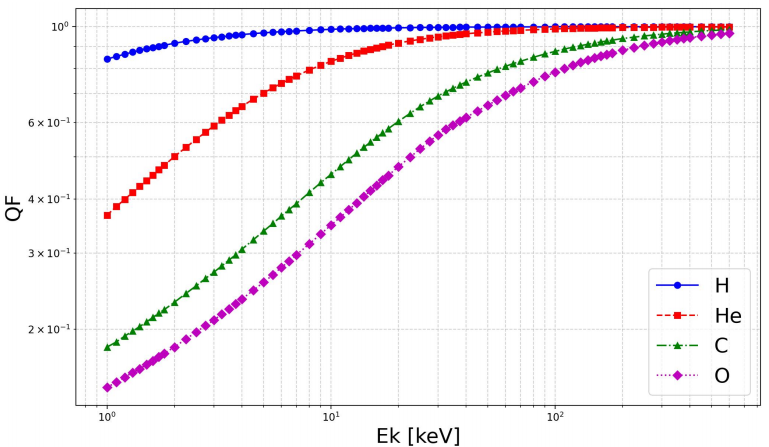


● **Definition:**



● **Method:**

- 1.Using GEANT4 to simulate the primary nucleus spectrum.
- 2.Using TRIM to simulate the cascade process of primary nucleus in the gas.
- 3.Selecting nucleus with deposited energy in the range of 5-15 keVee base on the quenching factor (QF).
- Comparing the qualified secondary nuclei with electrons



98% electron tracks remain. Secondary nuclei background nearly eliminated.

Another notable distinction: electrons exhibit a significant **Bragg peak**.

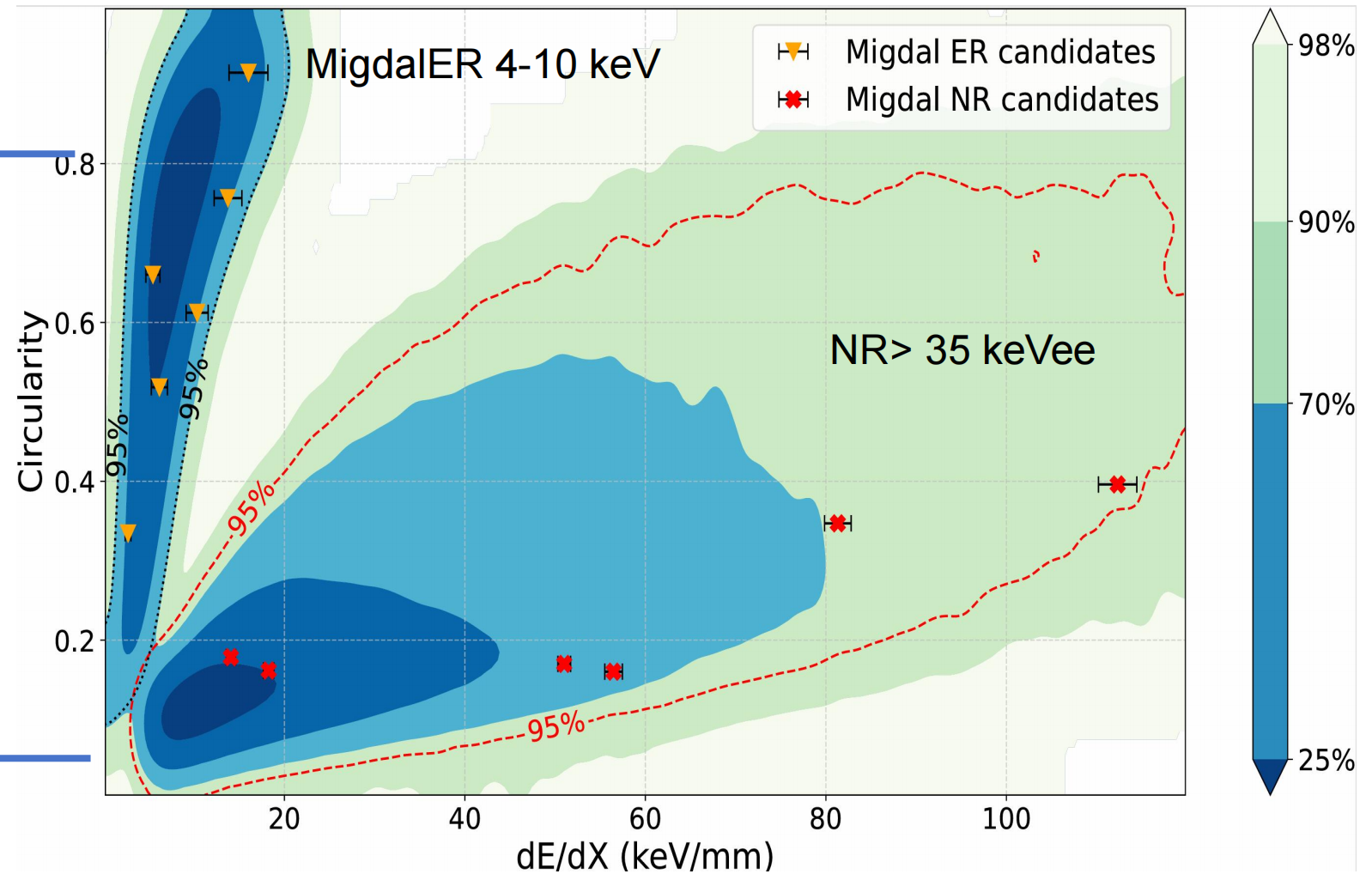
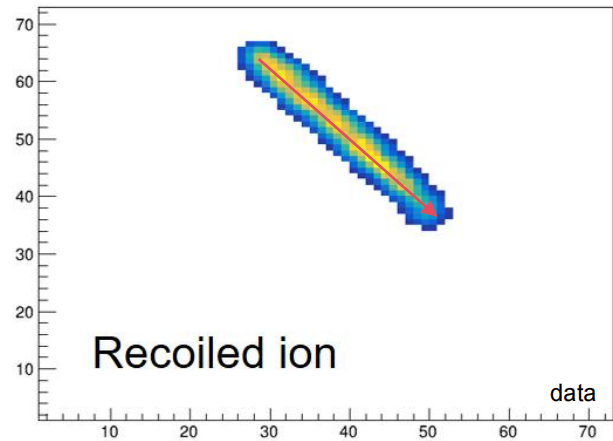
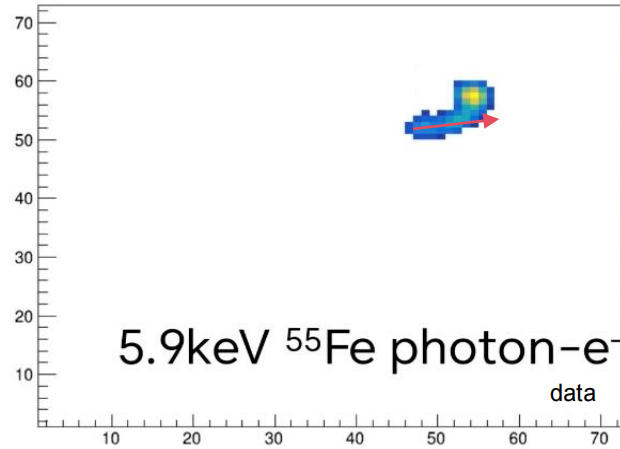
Energy cut	H	He	C	O
E / keV	5 - 16	6.5 - 17	10 - 25	12 - 30

Qualified secondary particle table

Background Component	Description	Expectation value (5 - 10 keV)
Recoil induced δ ray	δ electron near NR track origin	$0.035 \pm 0.023(\text{stat.}) \pm 0.0068(\text{sys.})$
Particle Induced X-ray Emission		
X-ray emission	Photoelectron near NR track origin	0
Auger electrons	Auger electron near NR track origin	0
Bremsstrahlung processes		
Quasi-Free Electron (QFEB)	Photoelectron near NR track origin	≈ 0
Secondary Electron (SEB)	Photoelectron near NR track origin	≈ 0
Atomic (AB)	Photoelectron near NR track origin	≈ 0
Nuclear (NB)	Photoelectron near NR track origin	≈ 0
Random track coincidences	Photo-/Compton electron near NR track	$0.180 \pm 0.022(\text{stat.}) \pm 0.042(\text{sys.})$
Muon induced δ ray	δ electron near NR track origin	0.013
Gas radioactivity		
Trace contaminants	Electron from decay near NR track origin	$0.001 \pm 0.00087(\text{sys.})$
Neutron activation	Electron from decay near NR track origin	≈ 0
Secondary nuclear recoil fork	NR track fork near track origin	≈ 0
Total background		$0.229 \pm 0.032(\text{stat.}) \pm 0.043(\text{sys.})$

Characteristic distribution of ERs and NRs

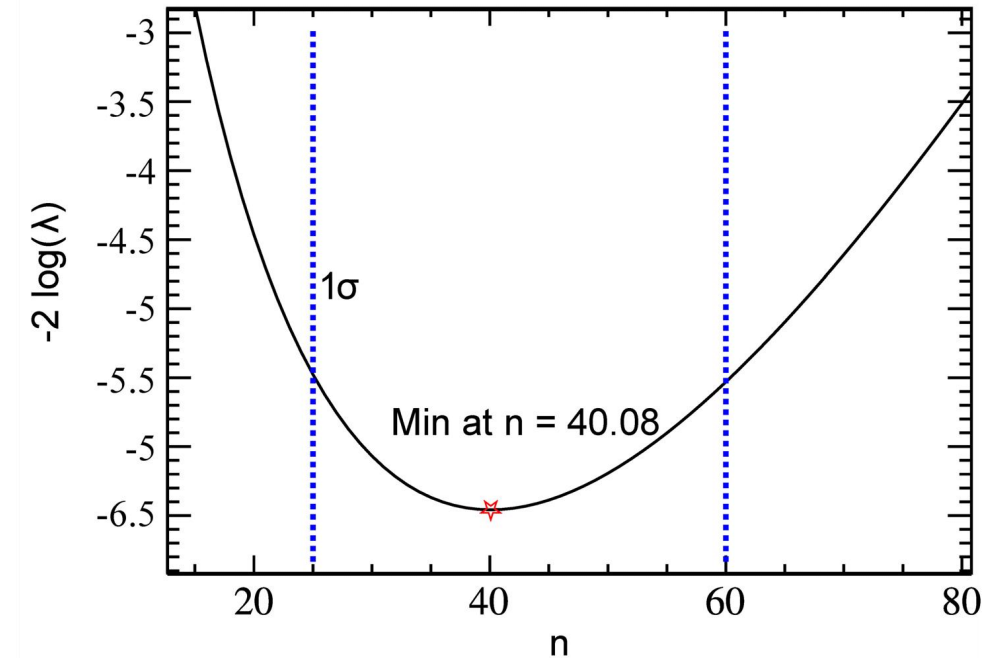
$$5 \text{ keV}_{ee} < E_e < 10 \text{ keV}_{ee}, E_{nr} > 35 \text{ keV}_{ee}$$



Cross section ratio calculation

- Probability: $P_{\text{Migdal}}(5\text{keV} < \text{ER} < 10\text{keV}, \text{NR} > 35\text{keVee}) = \frac{\left(\frac{n_{\text{obs}}^{\text{ER}} - n_{\text{obs}}^{\text{bg}}}{\varepsilon_{\text{acc}} \varepsilon_{\text{NR}} \varepsilon_{\text{ER}}} \right)}{\left(\frac{n_{\text{tot}}^{\text{NR}}}{\varepsilon_{\text{acc}} \varepsilon_{\text{NR}}} \right)} = \frac{(n_{\text{obs}}^{\text{ER}} - n_{\text{obs}}^{\text{bg}})}{\varepsilon_{\text{ER}} n_{\text{tot}}^{\text{NR}}}$
- Parameters:

	Efficiency/Count	Statistical Error	Systematic Error
Efficiency ε_{ER}	14.4% 29%(YOLO)*49%(vertex rec)	$\pm 0.1\%$	$\pm 1.9\%$
$n_{\text{tot}}^{\text{NR}}$	8.17×10^5	± 903	± 35880
$n_{\text{obs}}^{\text{ER}}$	6		
$n_{\text{obs}}^{\text{bg}}$	0.229	± 0.032	± 0.043



- upper/lower bounds: $\Delta P_{\pm} = \sqrt{\left(\frac{n_{\text{min}} - n_{\text{ul/ll}}}{n_{\text{min}}} \right)^2 + \left(\frac{n_{\text{tot}}^{\text{NR error}}}{n_{\text{tot}}^{\text{NR}}} \right)^2} \cdot \frac{n_{\text{min}}}{n_{\text{tot}}^{\text{NR}}}$

Result: $4.9_{-1.9}^{+2.6} \times 10^{-5}$

Theory: 3.9×10^{-5}

a%Ar-b%CO₂ / **a%He-b%CO₂** dual-detector combined measurement

(Assum $r_{Ar} \gg r_{He}$)

Ratio of Migdal cross section to neutron-nucleus scattering cross section:

$$r_i = \frac{\int \frac{d\sigma_i}{dE_{NR}} p(E_{NR}) dE_{NR}}{\int \frac{d\sigma_i}{dE_{NR}} dE_{NR}} = \frac{\int \frac{d\sigma_i}{dE_{NR}} p(E_{NR}) dE_{NR}}{\sigma_i}$$

$$b\sigma_C r_C + 2b\sigma_O r_O = \frac{k_B T}{\phi t LP} N_{HeMigdal} \tag{1}$$

$$a\sigma_{He} + b\sigma_C + 2b\sigma_O = \frac{k_B T}{\phi t LP} N_{HeNR} \tag{2}$$

$$a\sigma_{Ar} r_{Ar} + b\sigma_C r_C + 2b\sigma_O r_O = \frac{k_B T}{\phi t LP} N_{ArMigdal} \tag{3}$$

$$a\sigma_{Ar} + b\sigma_C + 2b\sigma_O = \frac{k_B T}{\phi t LP} N_{ArNR} \tag{4}$$



$$\sigma_{Ar} r_{Ar} = \frac{k_B T}{\phi t LP} \left(\frac{N_{ArMigdal}}{a_{Ar} \eta_{Ar}} - \frac{N_{HeMigdal}}{a_{He} \eta_{He}} \right)$$

Parameters	Description
a, b	gas composition ratio
σ	nuclear neutron scattering cross section
ϕ	flux
N	Number of events

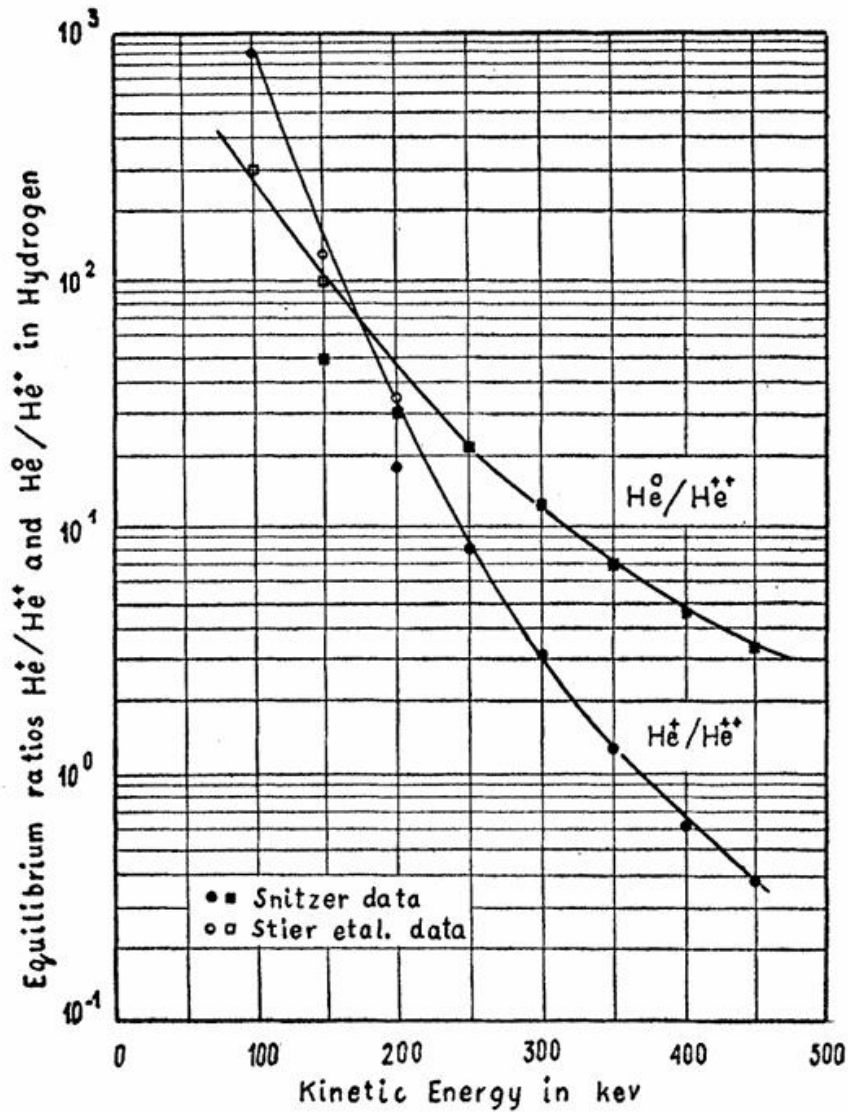
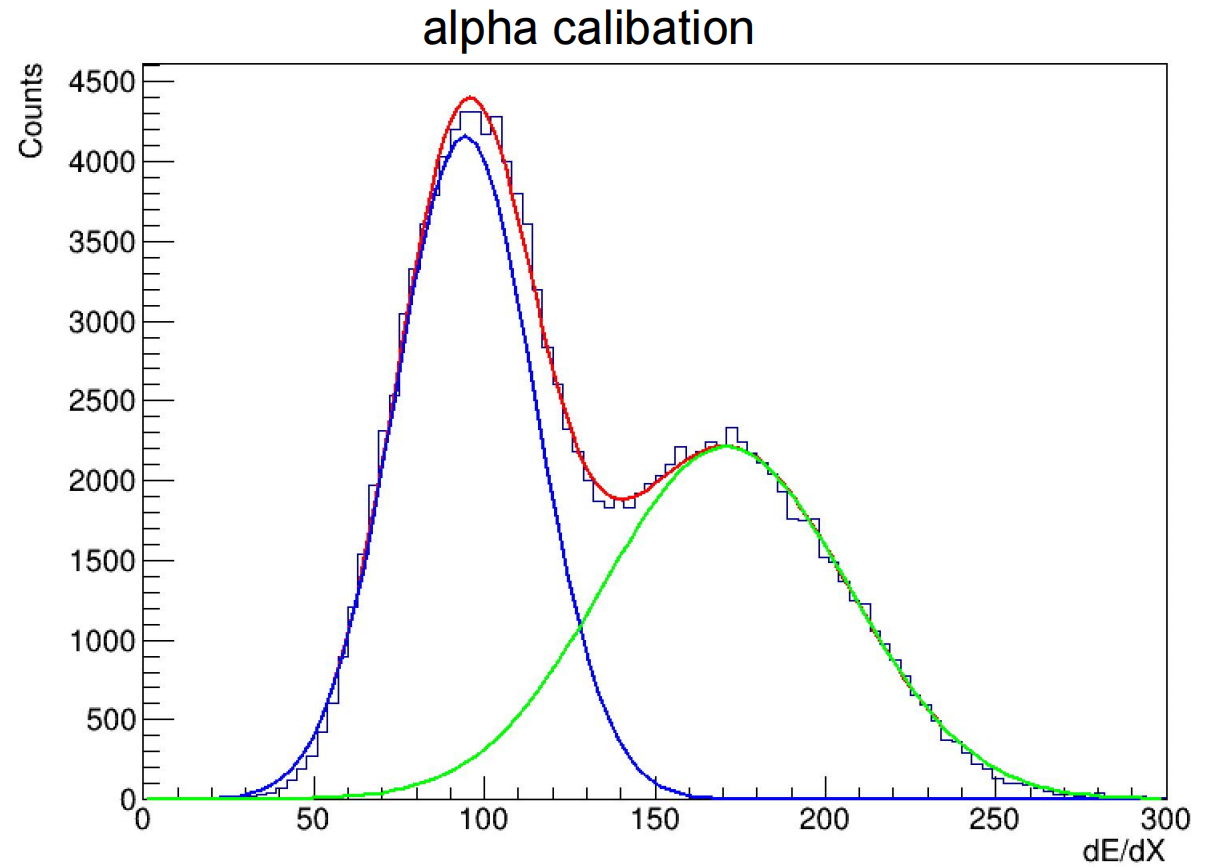


FIG. 4. Ratios He^0/He^+ and $\text{He}^0/\text{He}^{++}$ for a helium beam in a molecular hydrogen.



- **Adopt Local Cosmic Muon Flux Measurement Results**

The local cosmic muon flux measurement(Liu,G.,et al, 2024) in Lanzhou is used for estimation.

- **Set Nuclear Recoil Rate Benchmark and Calculate δ -ray Ratio**

Set the nuclear recoil rate of the D-D neutron source as 1.4 event per second, and in the 5-10 keV energy range, considering the detector's energy resolution, calculate the ratio of δ -ray production to nuclear recoil as 1.85×10^{-5} .

- **Considering random track coincidence**

- **Include detector's muon exclusion efficiency**

Normalize to the number of experimental data points and determine that δ -rays contribute 0.013 events.

- In the working gas, the naturally occurring radioactive nuclides present at natural abundance are:
 - $^3\text{H}:(6.38 \pm 6.38) \times 10^{-8} \text{ Bq}$
 - $^{14}\text{C}:(4.58 \pm 4.58) \times 10^{-5} \text{ Bq}$
- β decay between 5-10 keV:
 - $^3\text{H}:(2.29 \pm 2.29) \times 10^{-8} \text{ /s}$
 - $^{14}\text{C}:(2.59 \pm 2.59) \times 10^{-6} \text{ /s}$

- Other major trace radioactive elements in the atmosphere include:

Nuclides	specific activity	electron (5-10keV)	Weight
^{222}Rn	$10 \pm 1.0 \text{ Bq/m}^3$	0.0188	0.961
^{40}K	$62.4 \pm 32.5 \mu \text{ Bq/m}^3$	0.00220	7.02×10^{-7}
^{210}Po	$50 \mu \text{ Bq/m}^3$	0	0
^{210}Pb	$500 \mu \text{ Bq/m}^3$	0.328	8.38×10^{-4}
^{137}Cs	$1.75 \pm 1.09 \mu \text{ Bq/m}^3$	0.0172	1.54×10^{-7}
^{131}I	$20.89 \pm 34.43 \mu \text{ Bq/m}^3$	0.0172	1.84×10^{-6}
^{60}Co	$0.63 \pm 1.56 \text{ mBq/m}^3$	0.0323	1.04×10^{-4}
^{85}Kr	$0.667 \pm 0.018 \text{ Bq/m}^3$	0.0110	3.75×10^{-2}
^{39}Ar	$0.964 \text{ Bq/kg} \cdot \text{Ar}$	0.00997	6.08×10^{-4}