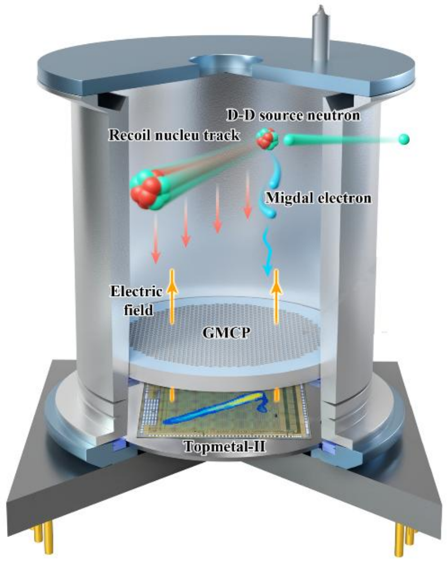
First Observation of the Migdal Effect in Neutron Nucleus Scattering



Yangheng Zheng

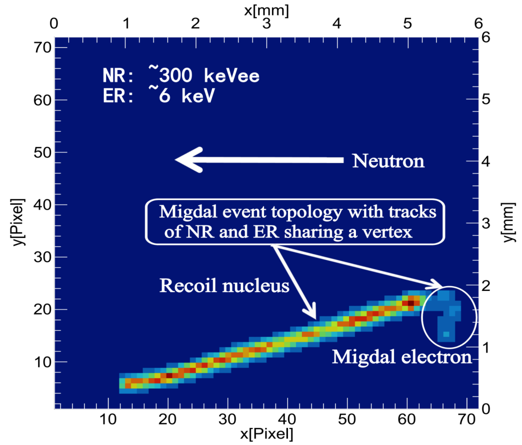
University of Chinese Academy of Sciences

On behalf of MARVEL group

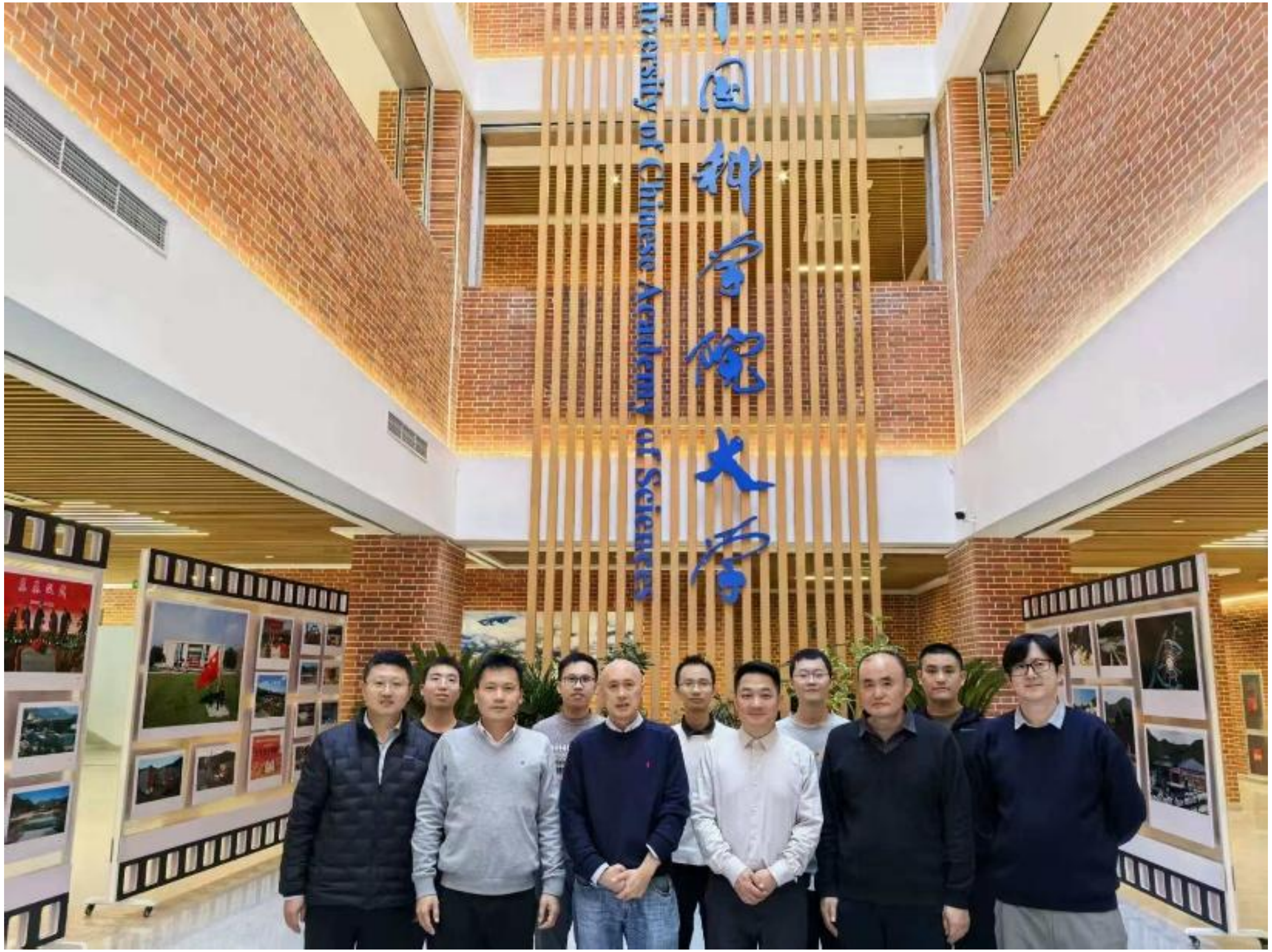
(MigdAl pRocess Validation by nEutrual scattering)

High Energy THeory Forum

March 18, 2026



MARVEL collaboration



- University of Chinese Academy of Sciences (UCAS)
- Guangxi University (GXU)
- Central China Normal University (CCNU)
- Lanzhou University (LZU)
- Nanjing Normal University (NNU)
- Yantai University (YTU)

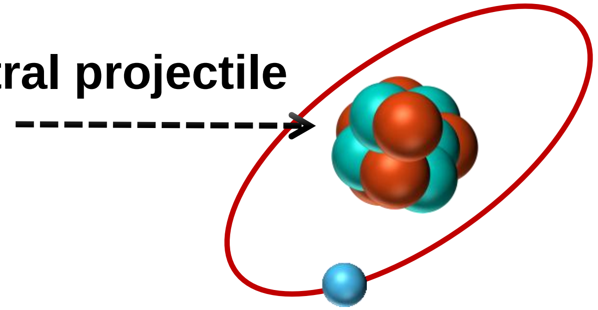
Outline

- Introduction
- MARVEL experiment & Detector performance
- Data analysis
- Results
- Detector upgrade
- Summary & outlook

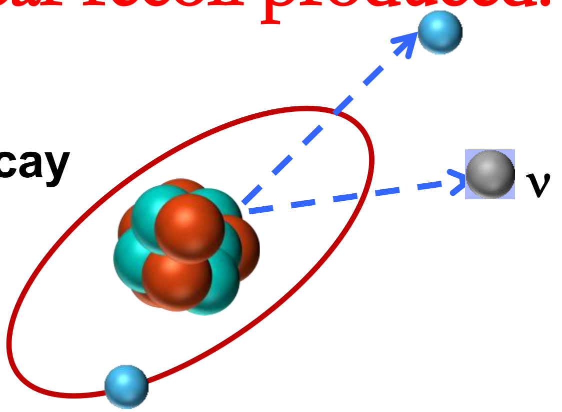
What happens in nuclear recoil?

How is nuclear recoil produced?

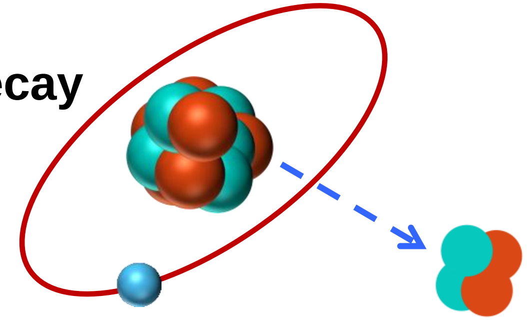
Neutral projectile



β decay



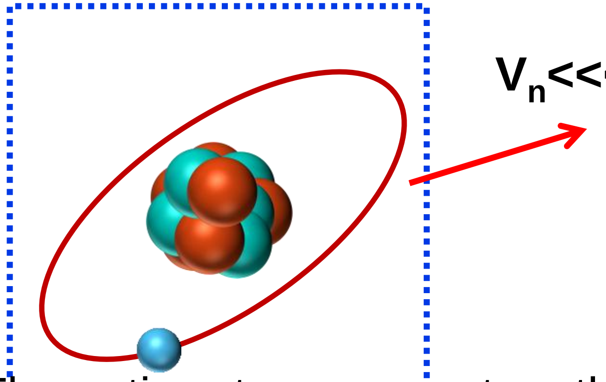
α decay



What happens following a nuclear recoil?

$\alpha = 1/137$

1. Low energy transition

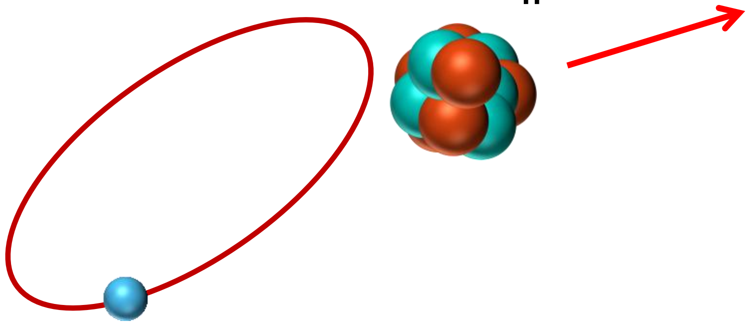


$V_n <<< \alpha c$

The entire atom moves together

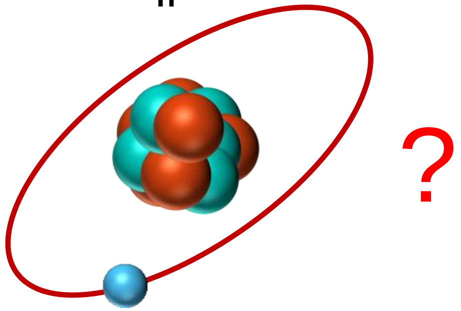
2. High energy transition

$V_n >>> \alpha c$

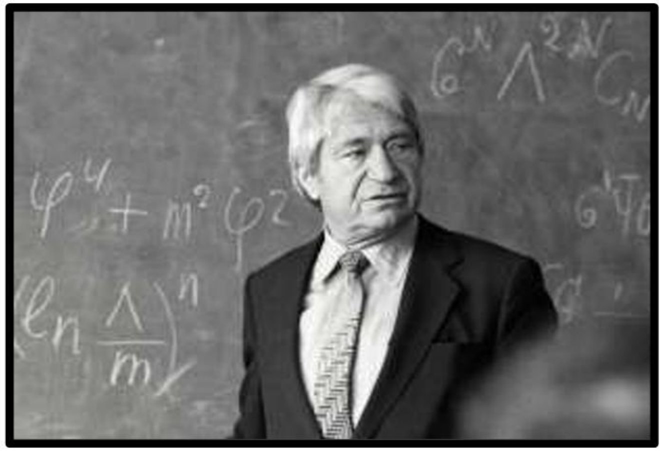


3. Middle energy transition

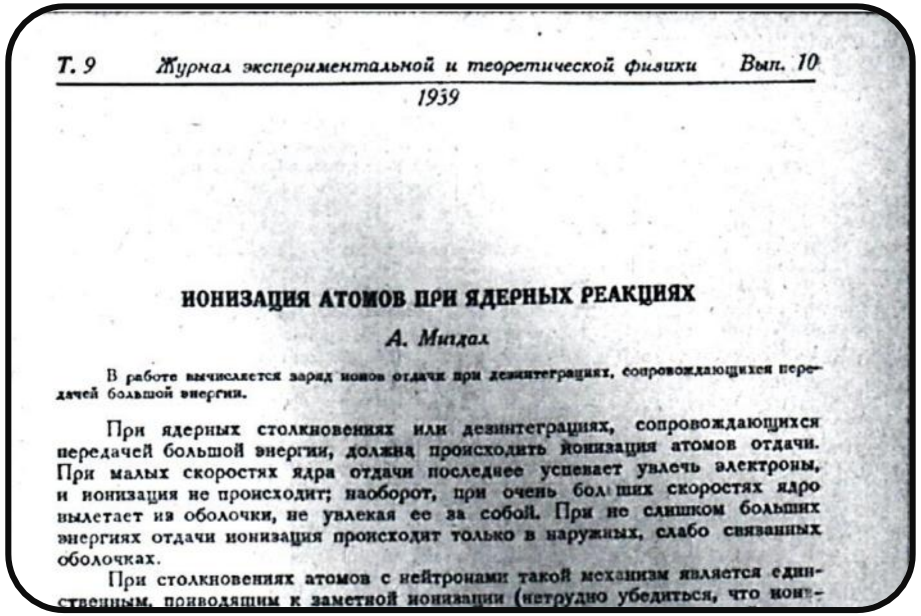
$V_n \sim \alpha c$



Migdal Effect - electron(s) shake-off



- First predicted by Migdal in 1939-1940



Т. 9 Журнал экспериментальной и теоретической физики Вып. 10

1939

ИОНИЗАЦИЯ АТОМОВ ПРИ ЯДЕРНЫХ РЕАКЦИЯХ

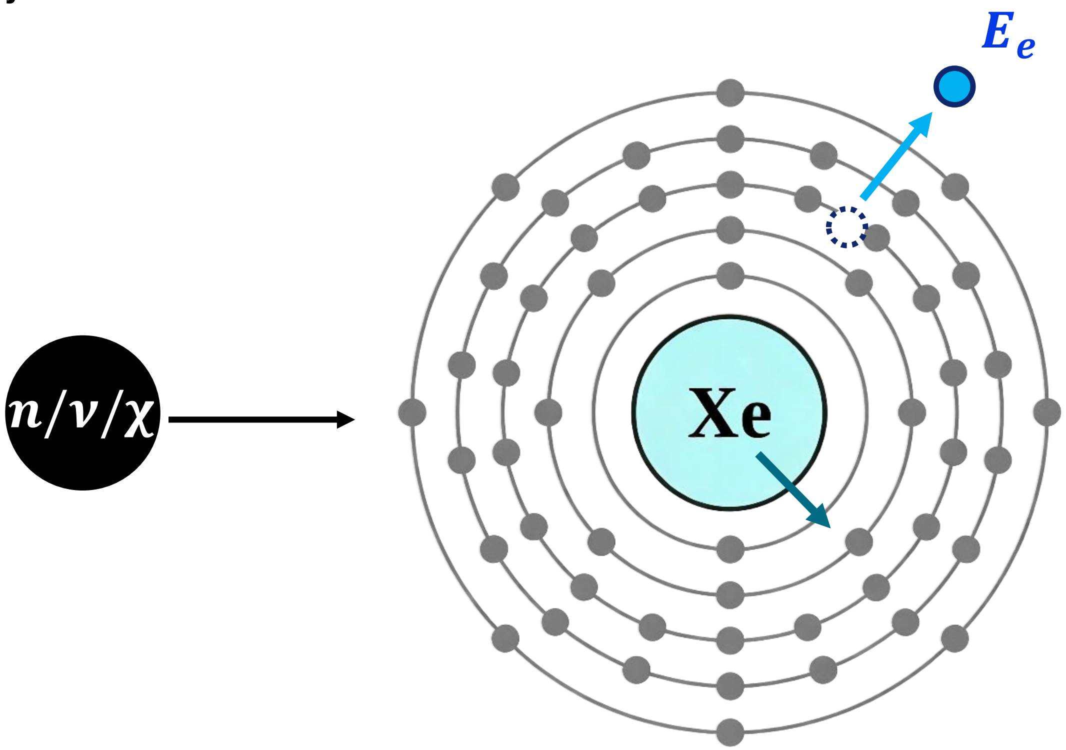
А. Мигдал

В работе вычисляется заряд ионов отдачи при дезинтеграциях, сопровождающихся передачей большой энергии.

При ядерных столкновениях или дезинтеграциях, сопровождающихся передачей большой энергии, должна происходить ионизация атомов отдачи. При малых скоростях ядра отдачи последнее успевает увлечь электроны, и ионизация не происходит; наоборот, при очень больших скоростях ядро вылетает из оболочки, не увлекая ее за собой. При не слишком больших энергиях отдачи ионизация происходит только в наружных, слабо связанных оболочках.

При столкновениях атомов с нейтронами такой механизм является единственным, приводящим к заметной ионизации (нетрудно убедиться, что иони-

Consider a rapid intranuclear process (e.g. α decay or fission) that abruptly changes Coulomb potential. The atomic electrons instantaneously experience the new potential; some electrons cannot adjust to the new potential well immediately, and are therefore excited or ejected.

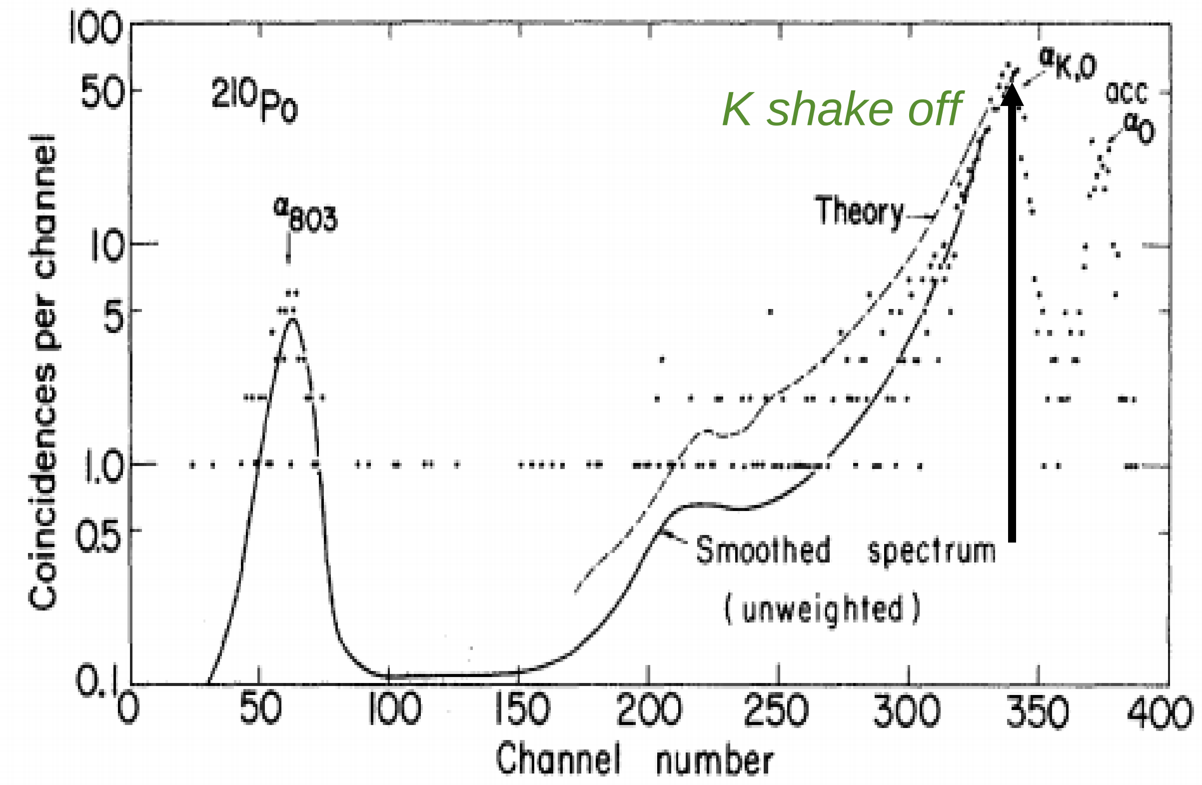


Migdal effect was predicted by A. Migdal in 1939, and observed in radioactive decays in the 70's.
– **but not observed in nuclear scattering**.

Migdal Effect: Observed in α and β decay

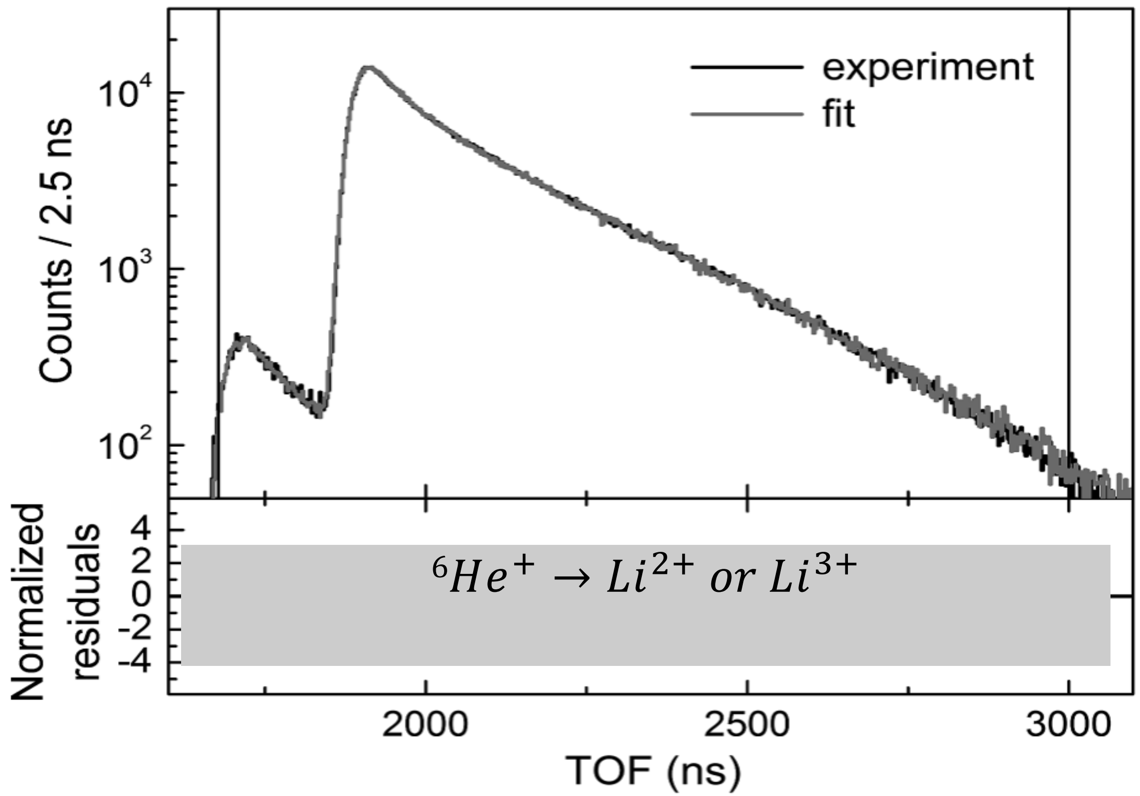
Migdal in α decay

PhysRevC.11.1740



Migdal in β decay

PhysRevLett.108.243201

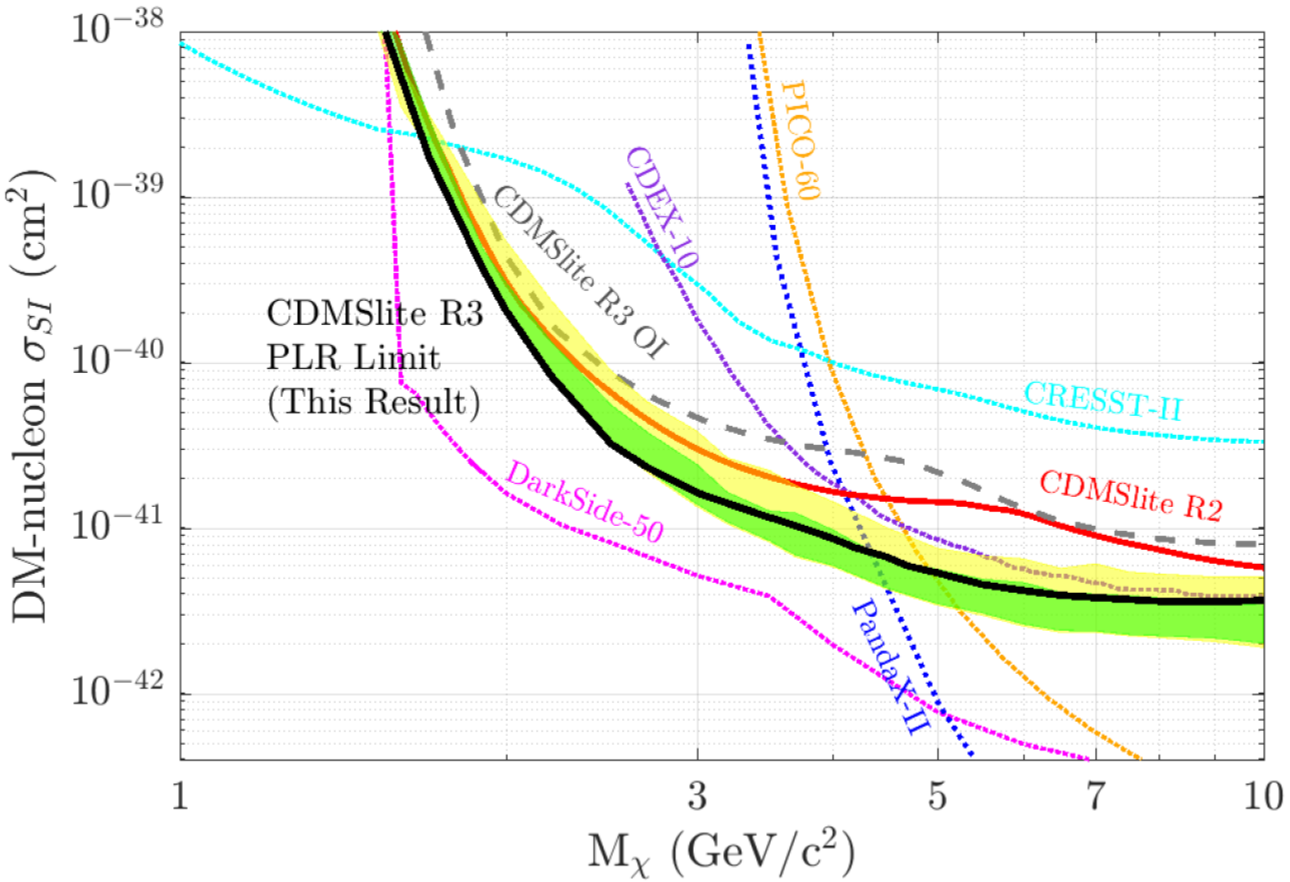


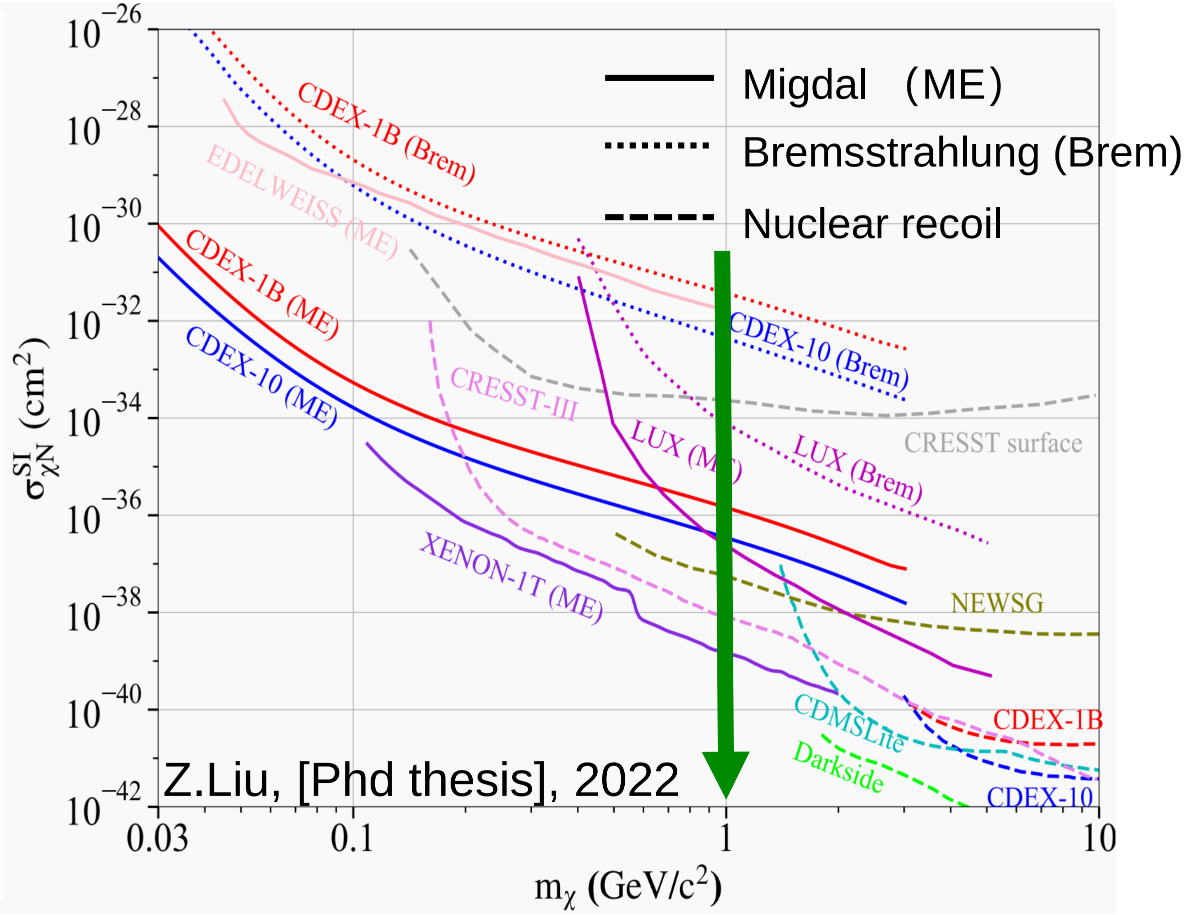
Migdal effect was observed in radioactive decays.

Migdal electron was not observed directly.

Sub-GeV DM searches dominated by Migdal

SuperCDMS, PRD 99, 062001 (2019)

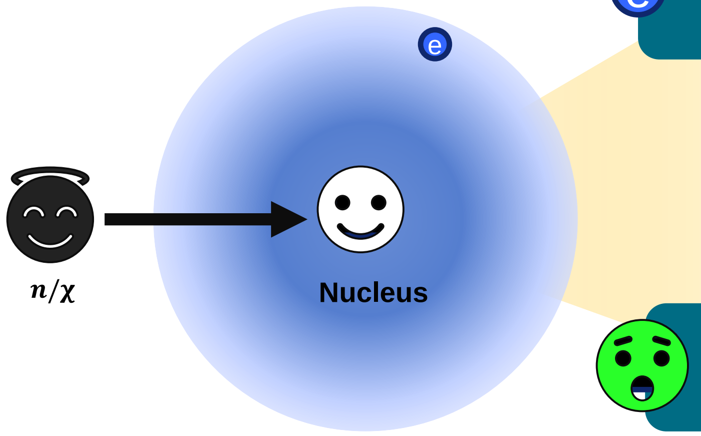




Before 2018, upper limits were set **without accounting for the Migdal effect.**

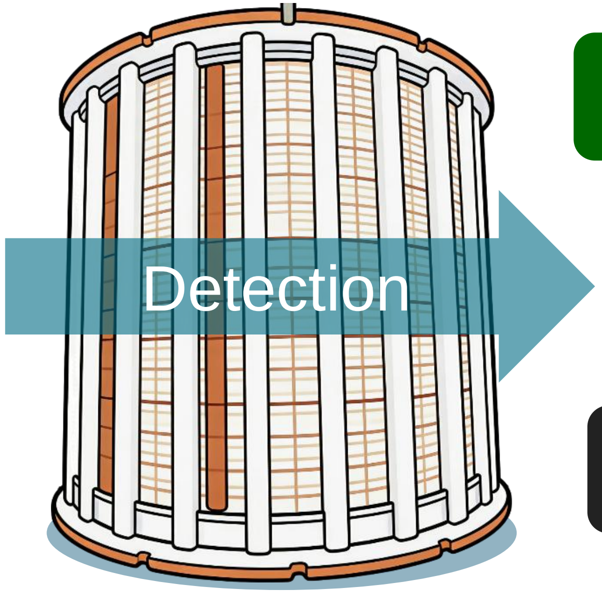
The theoretical impact of **incorporating the Migdal effect** on direct DM search: PLB 606, 313–322 (2005); NPB 727, 406–420 (2005); PLB 639, 218–222 (2006); JHEP018,194(2018)

Migdal Effect vs Nuclear Recoils



E_{er}

E_{nr}



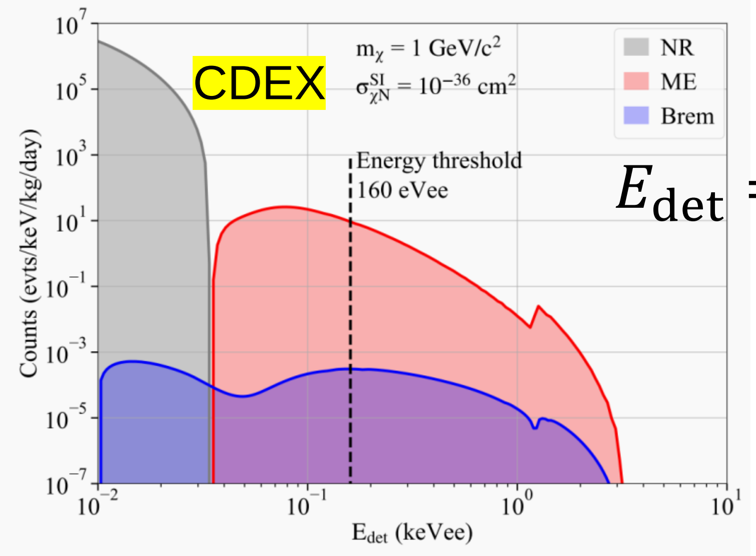
$$E_{er,obs} = E_{er} - E_{bind}$$

$+$

$$E_{nr,obs} = E_{nr} \cdot \varepsilon_{QF}$$

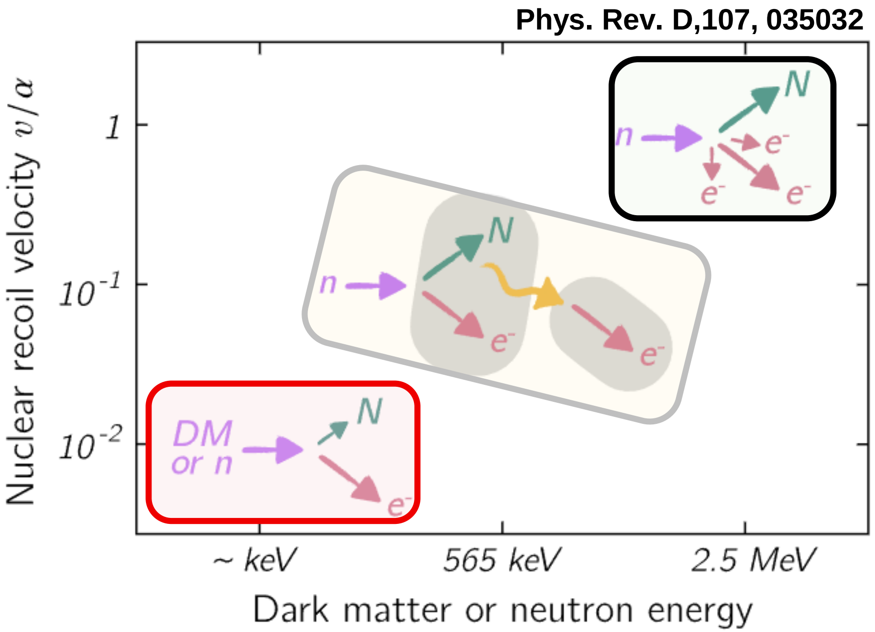
$$E_{det} = E_{er,obs} + E_{nr,obs} + \ldots$$

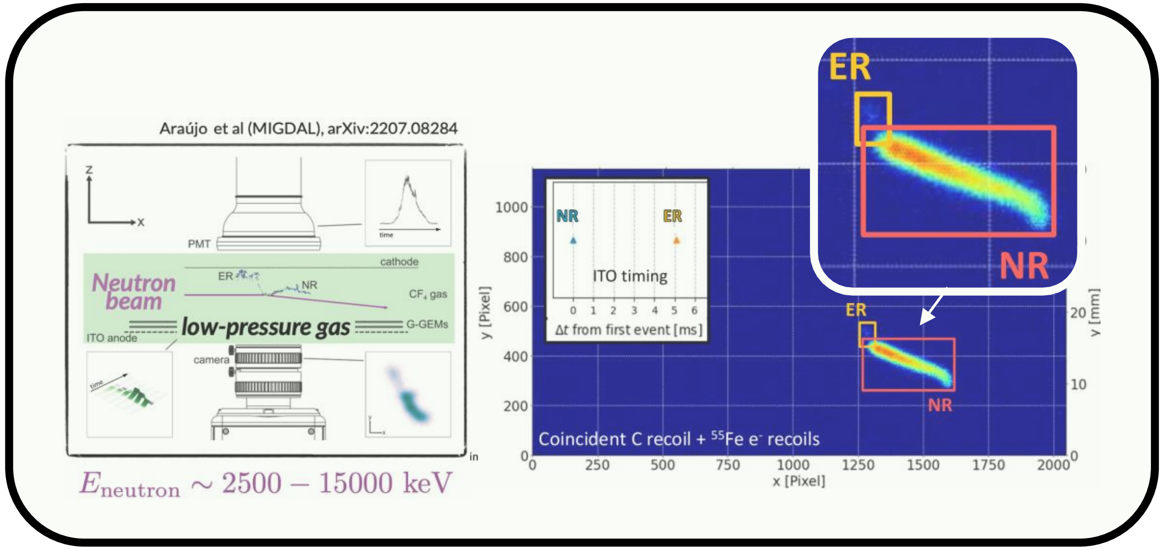
The Migdal electron aids in searching for nuclear recoils below the threshold in direct DM experiments.

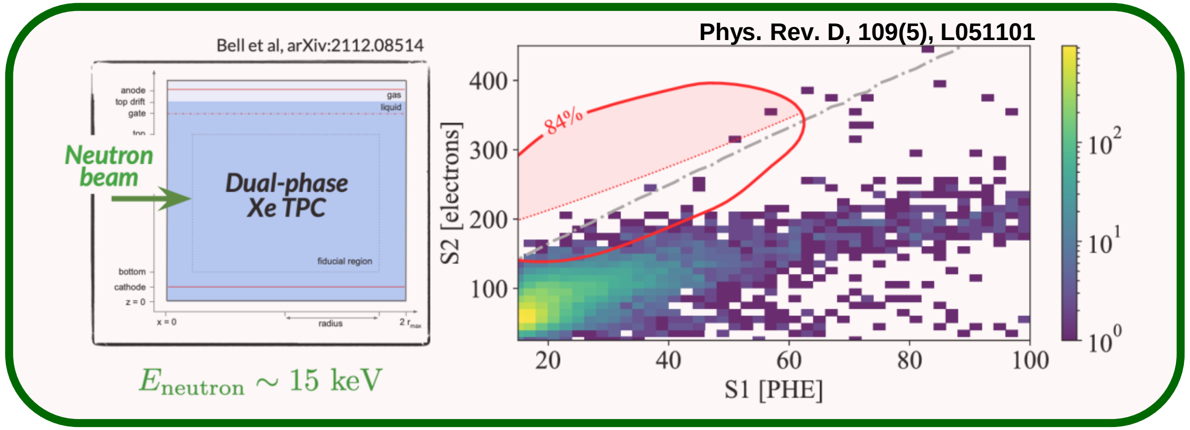


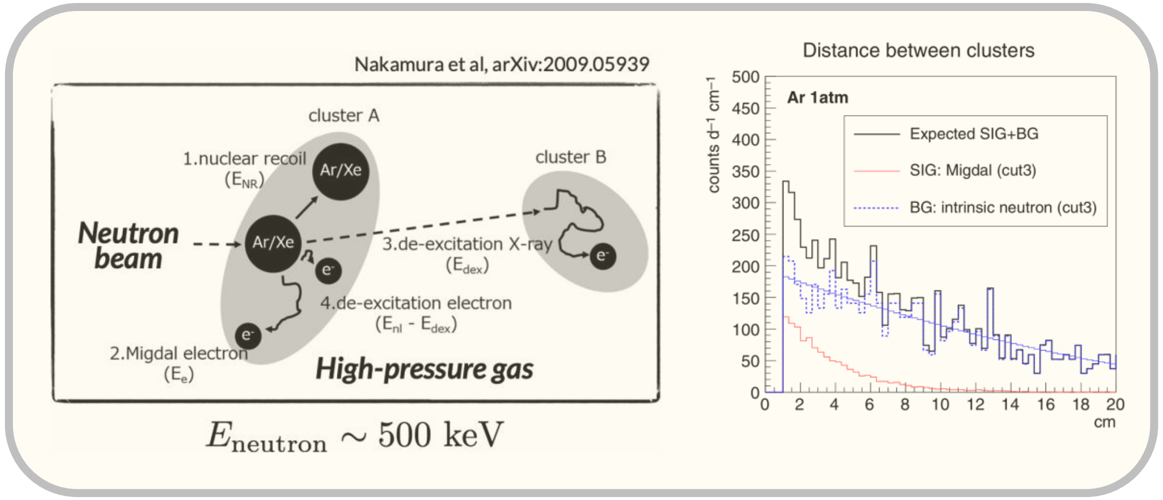
Z.Liu, [Phd thesis], 2022

Migdal effect detection Experiments

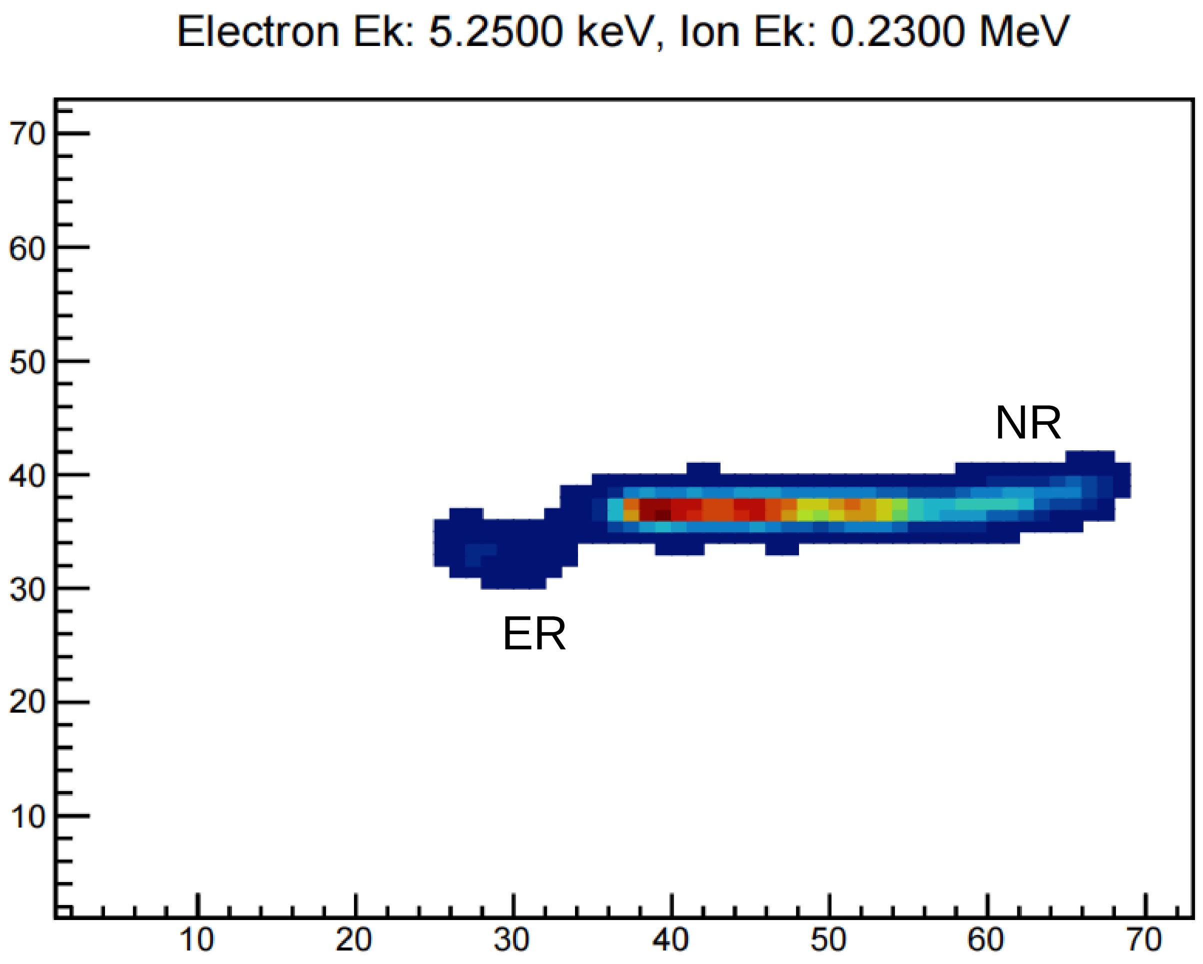








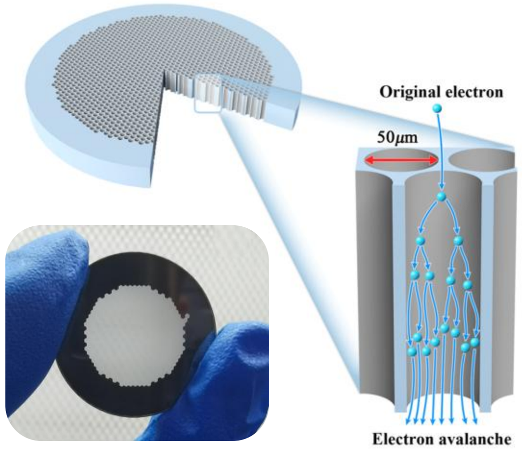
Detector Requirements



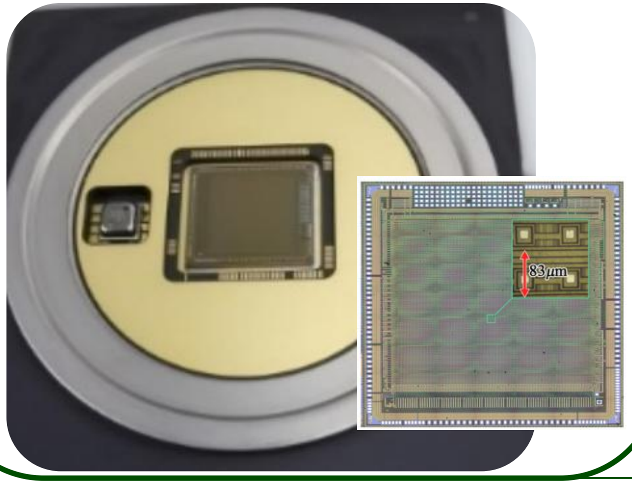
- ER~keV，NR~hundreds keV
  - Good energy resolution
  - Large dynamic range.
- ER shares vertex with NR
  - Good vertex resolution
- Reduce possible background
  - Good time resolution

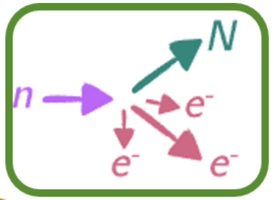
MARVEL Experiment-Detector

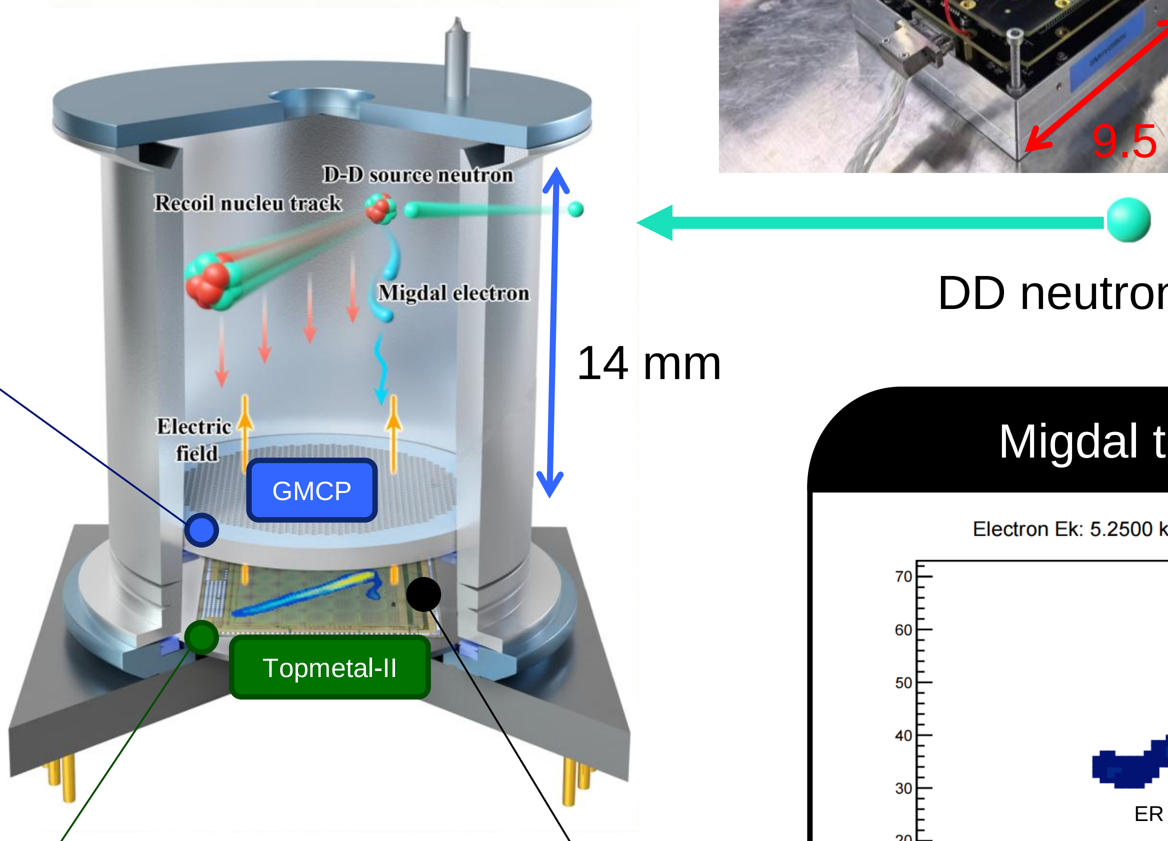
GMCP

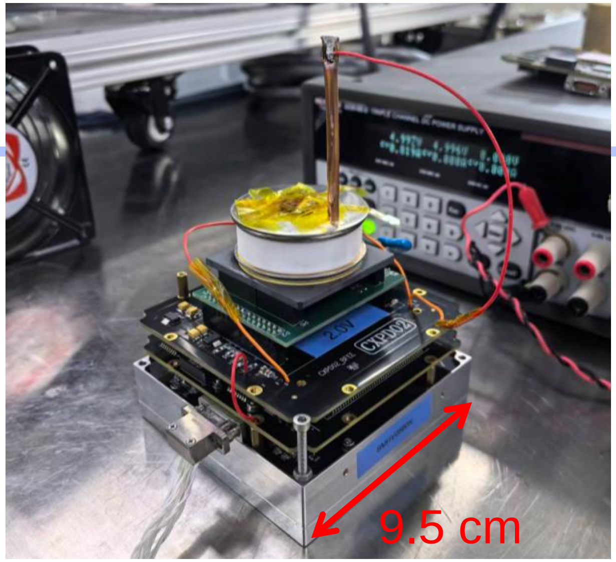


Topmetal-II

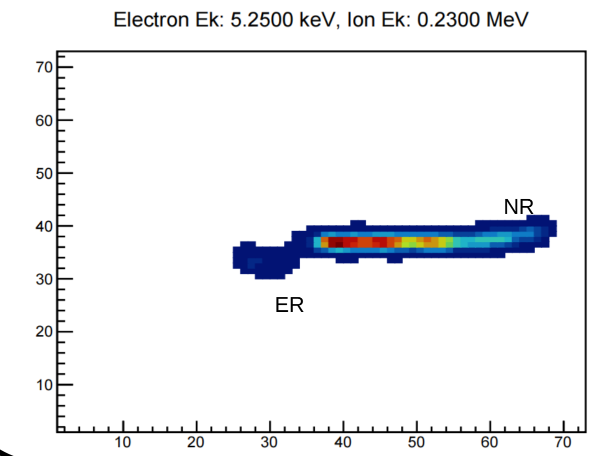






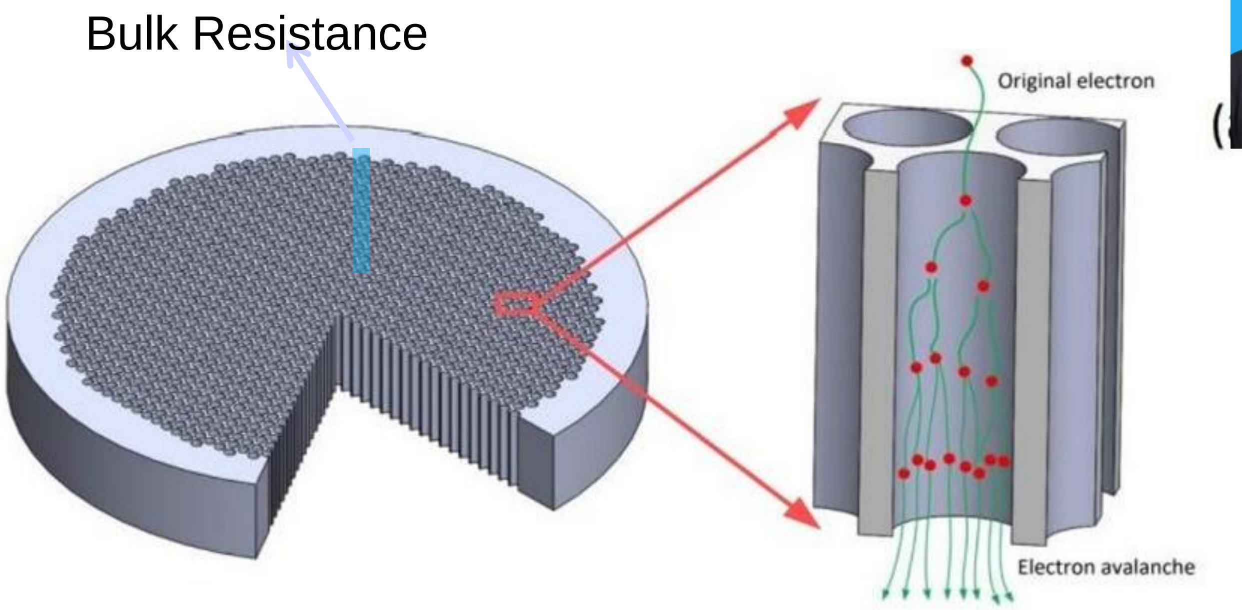


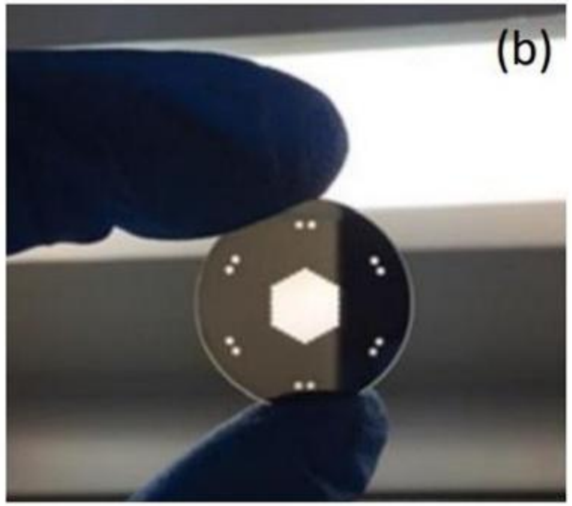
Migdal topology

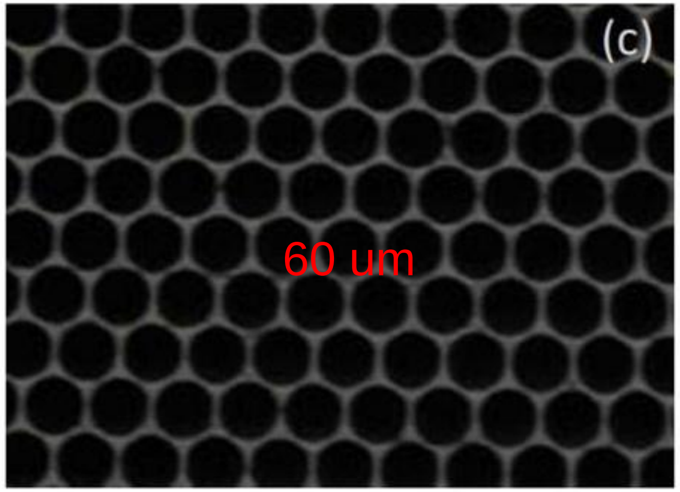


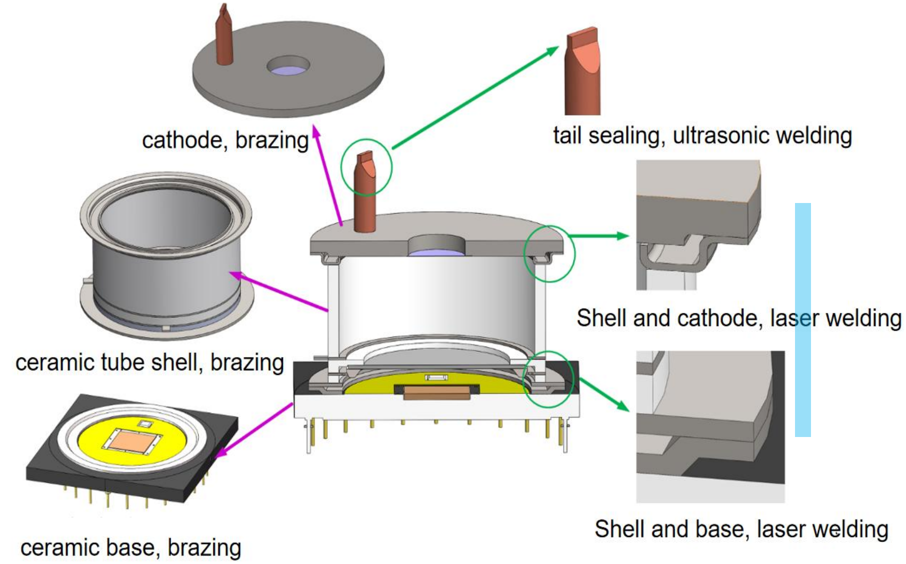
Gas Multi-Channel Plate (GMCP)

- Originally design for soft X-ray polarization detection in Space
- low leakage rate and material degassing rate specifications
- Suppress the charge accumulation effect



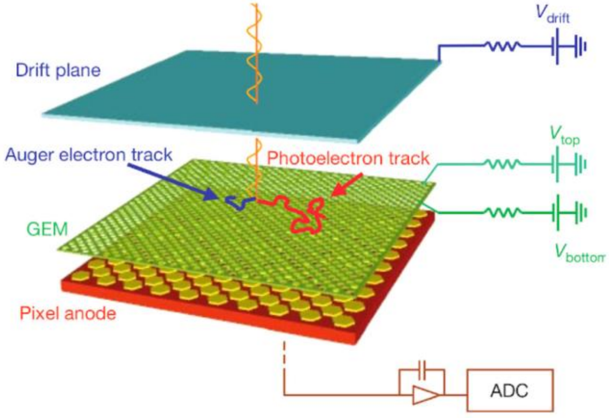


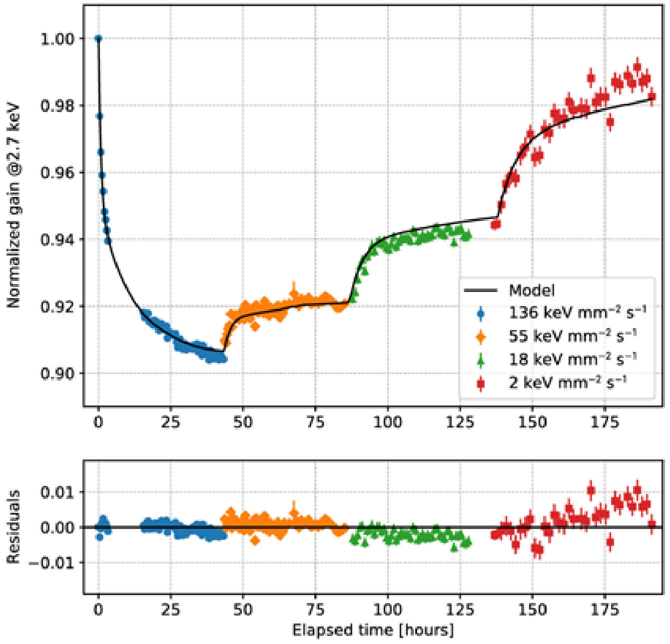




Leak rate: ~7.6^{-11} Torr·L/s

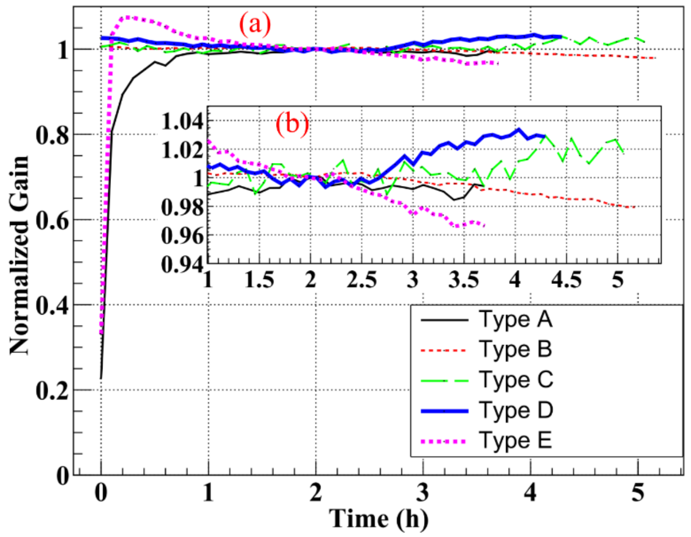
Charging-up effects for GMCP



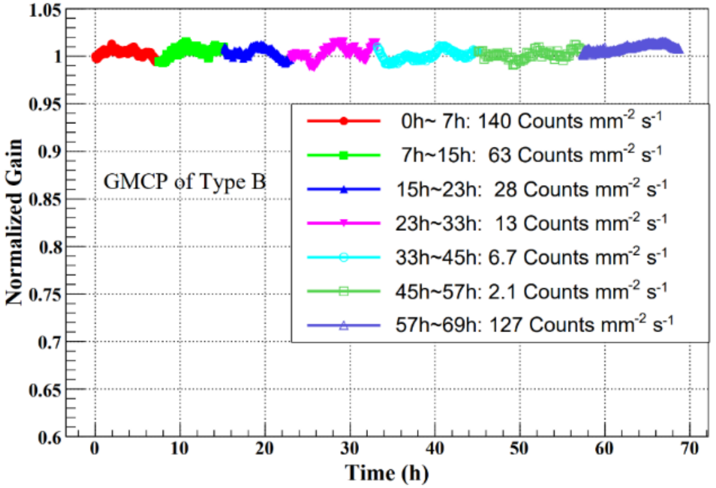


Dependence of GEM detector gain on X-ray flux

	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 GΩ	3 GΩ	5 GΩ	∞
Hydrogen reduction	Without	With	With	With	Without



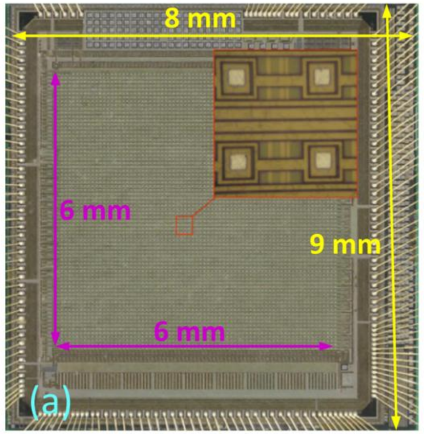
GMCP Development – Hydrogen Reduction tech for Preparing Bulk Resistance to Eliminate Charge Accumulation

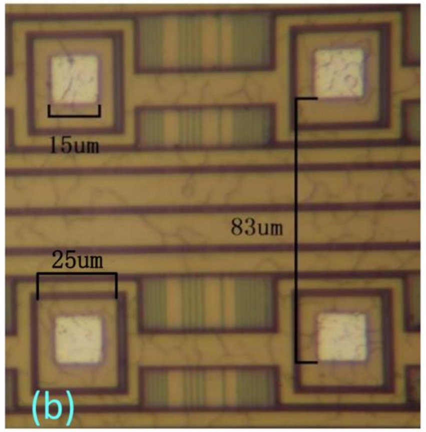


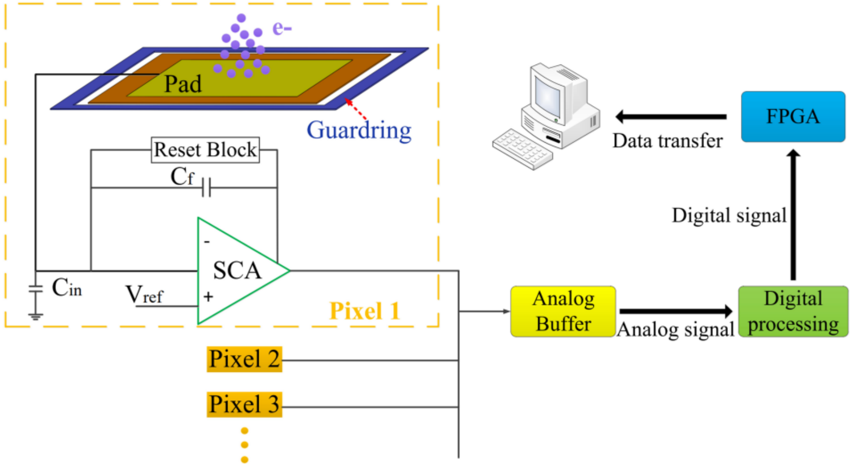
stability at different counting rates

Readout chip: Topmetal Pixel detector

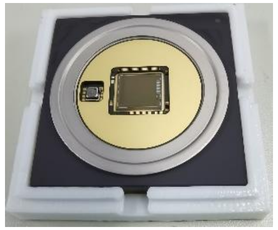
Topmetal-II

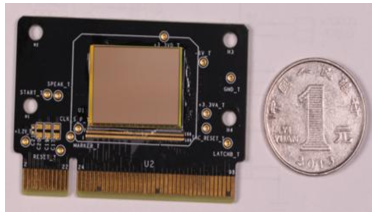


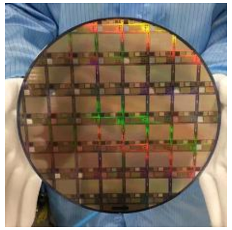




	Topmetal-II$^-$	Topmetal-M1/M2	Topmetal-L
Chip Size /mm²	6 × 6	18 × 23	17 × 24
Pixel Array	72 × 72	400 × 512	356 × 512
Pixel Size /um²	83 × 83	45 × 45	45 × 45
Pixel Electrode / um²	15 × 15	10 × 20	26 × 26
ENC	~ 13.4e-	~ 15.4e-	~ 20.0e-
Power Consumption	~ 1W @3.3V	~ 4.3W @3.3V	**~ 0.8W @3.3V**
Clock	40MHz	5MHz	20MHz
Frame Rate	2.5ms	2.4ms	0.37ms @Sentinel Readout
Readout Mode	Rolling Shutter	Rolling Shutter	Rolling Shutter **/Sentinel Readout**
Readout Channel	1	16	1

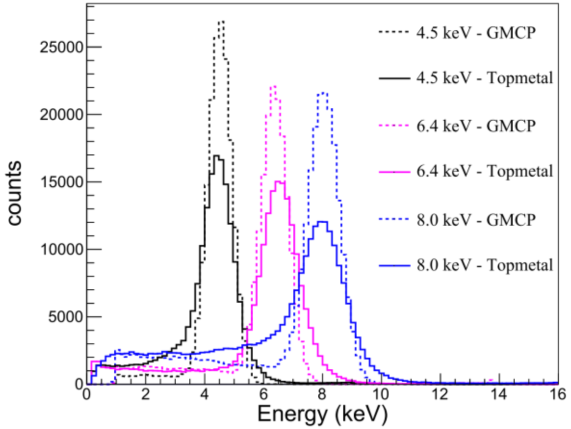


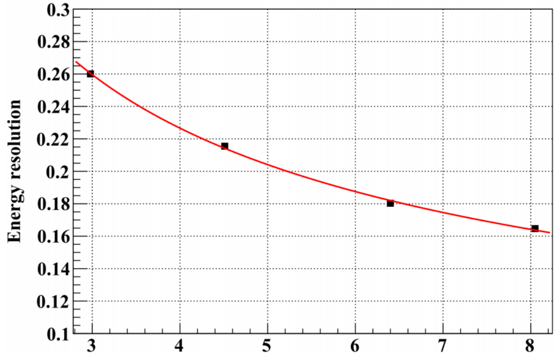




Detector performance

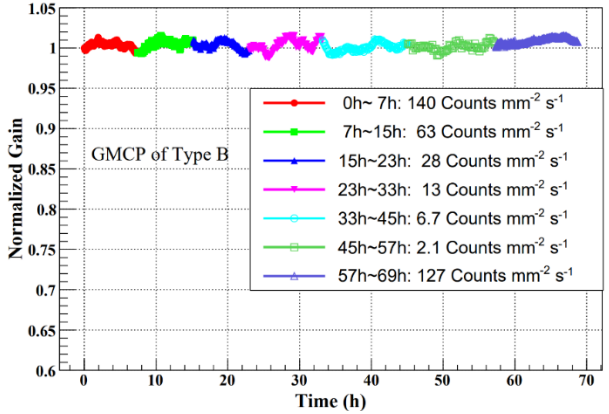
Energy resolution

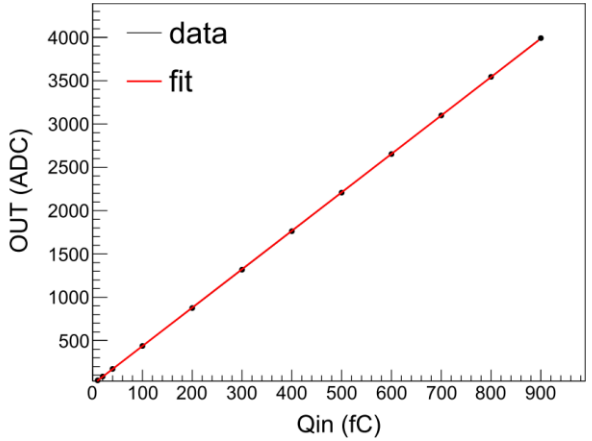




- Good linear energy response
- 20%-30% energy resolution(FWHM)
- Energy resolution follows the relationship ~ $1/\sqrt{E}$

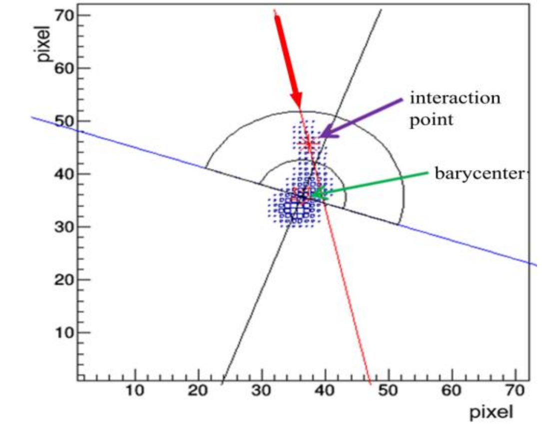
Dynamic range

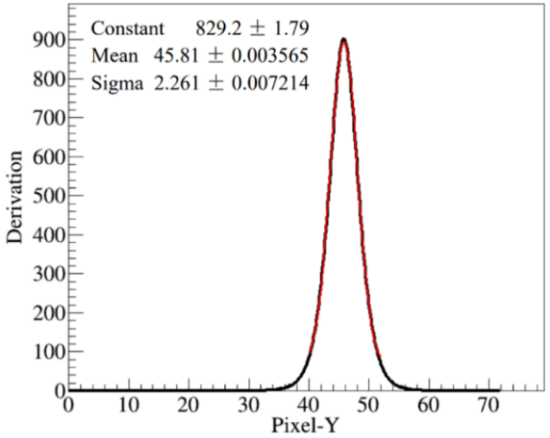




- Stable gain under different count rates(no pile up)
- Good linearity in charge response

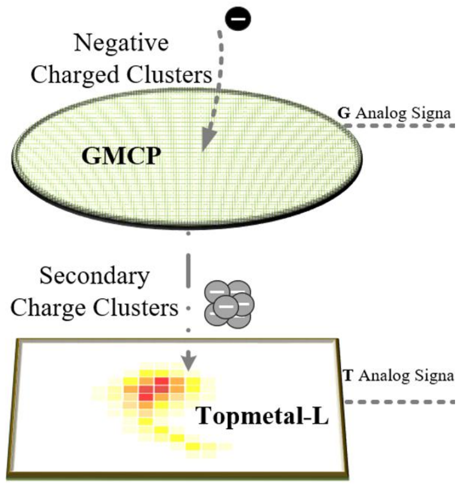
Vertex resolution

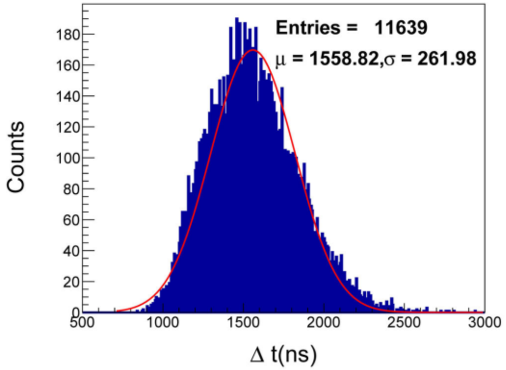




- ~200 μm vertex resolution @ 6.4 keV

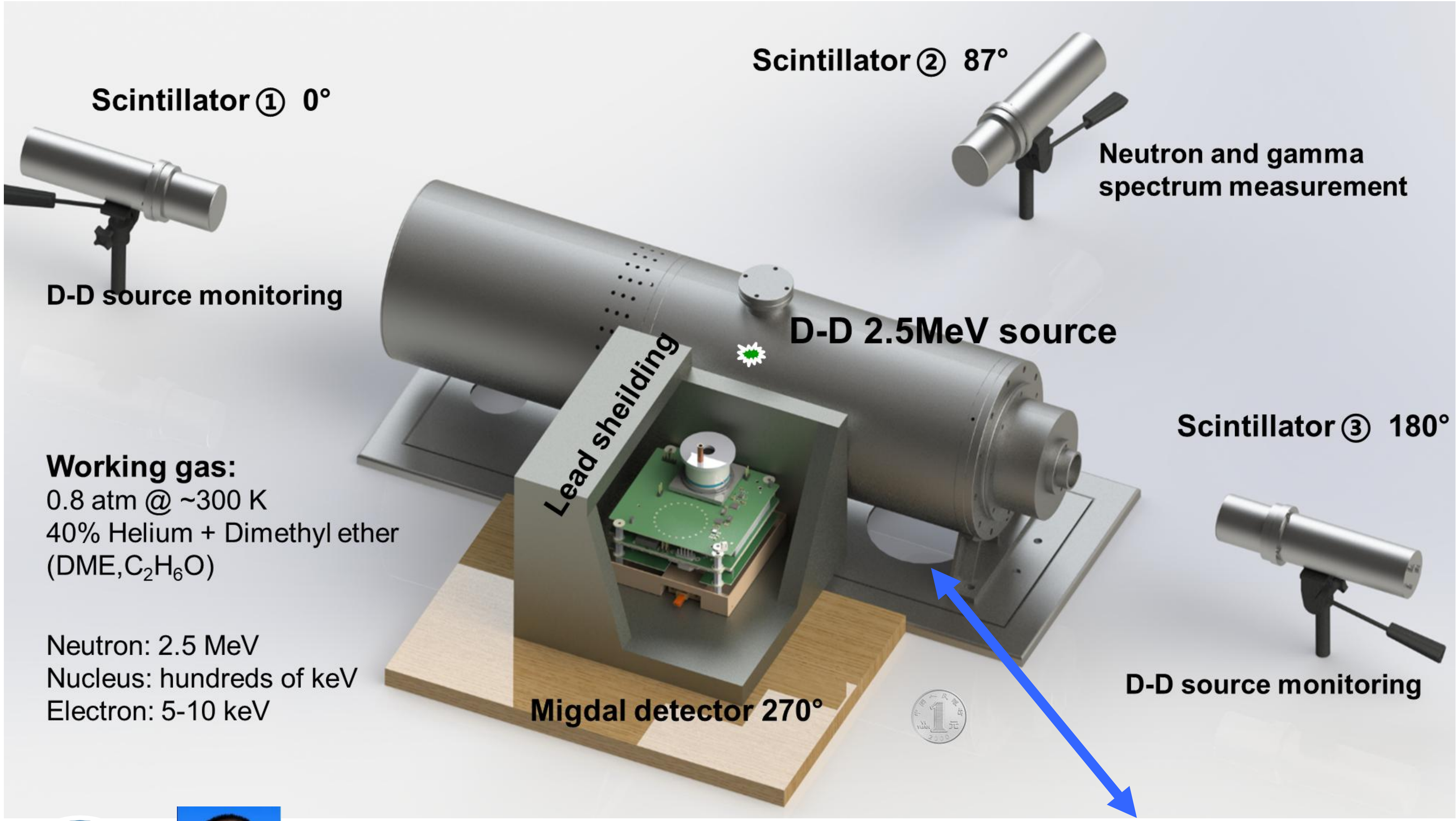
Time resolution





- ~262 ns time resolution

MARVEL Experiment setup



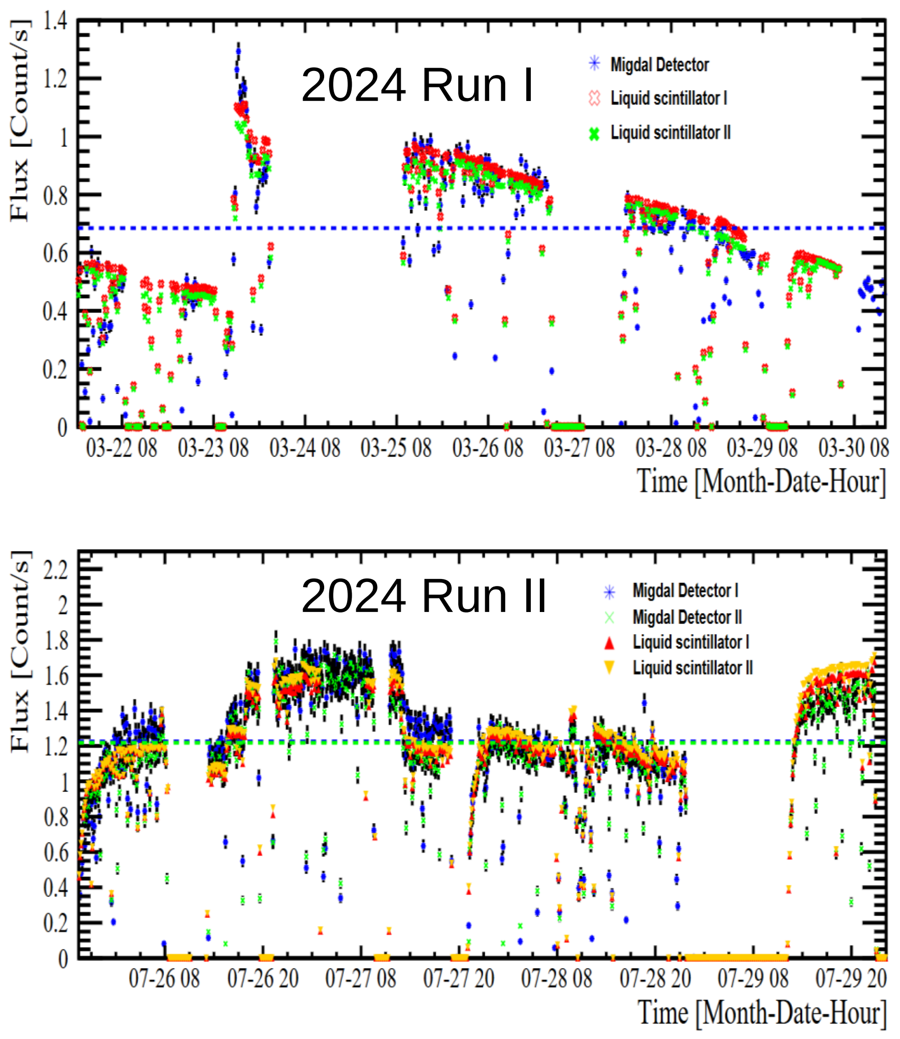
The Lanzhou University team provided the neutron source from a deuterium–deuterium (D–D) fusion-reaction accelerator

Experimental design, DAQ, and analysis team

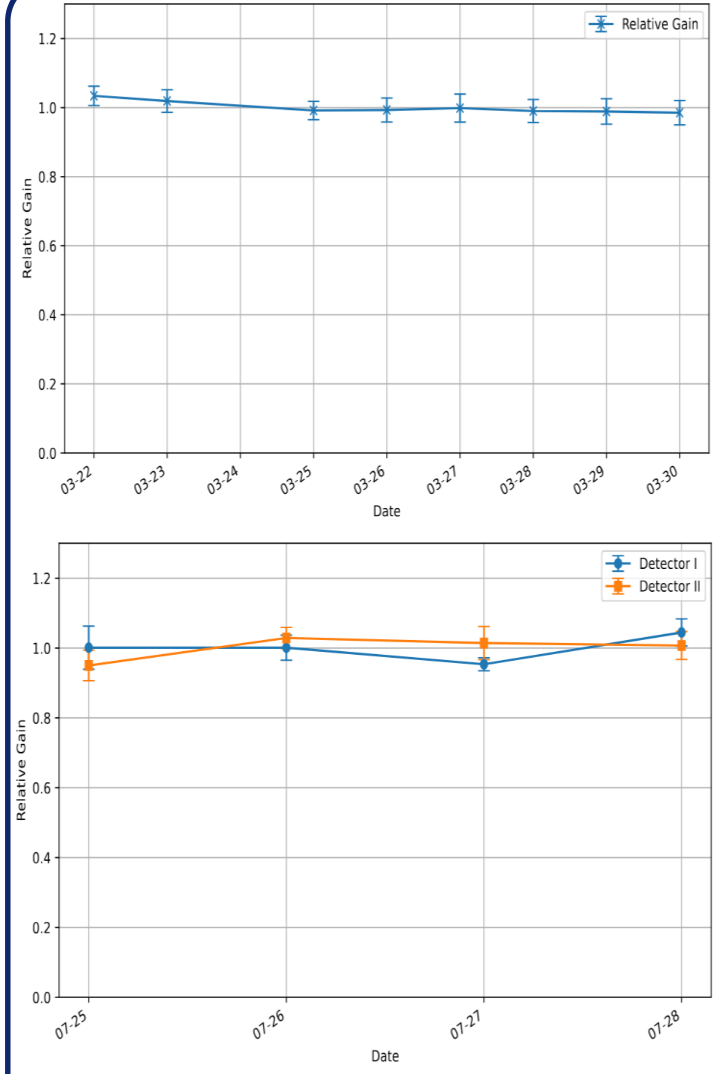
Liu Jicheng (Qian) and his young teammates (Yi Difan, Ma Ruiting, Huang Wenqian, Su Chenguang, Jing Xinmei, Kong Lingquan, Zuo Jie, Yu Yunlinchen, Chen Shi)

- **Yi Difan, Su Chenguang, Kong Lingquan, Zuo Jie, and Yu Yunlinchen are PhD students at the University of Chinese Academy of Sciences; they all joined our research team in the summer following their sophomore year of undergraduate study.**
- **Zheng Yangheng teaches "Atomic Physics" and Liu Qian teaches "Particle and Radiation Detection Technology" for undergraduate students at UCAS.**

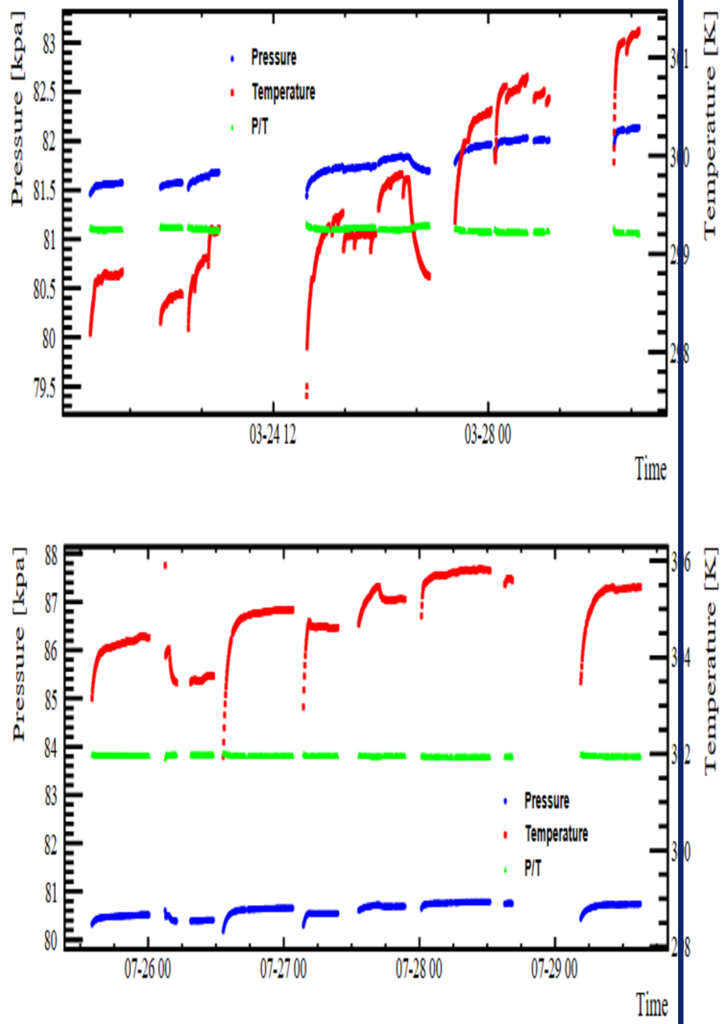
Data taking



Neutron Flux Monitoring

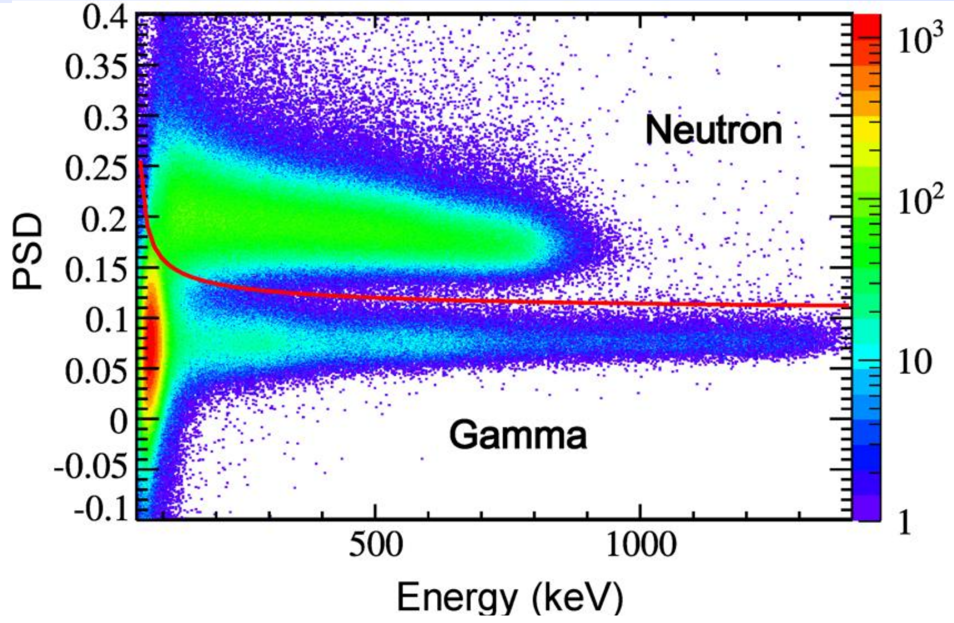


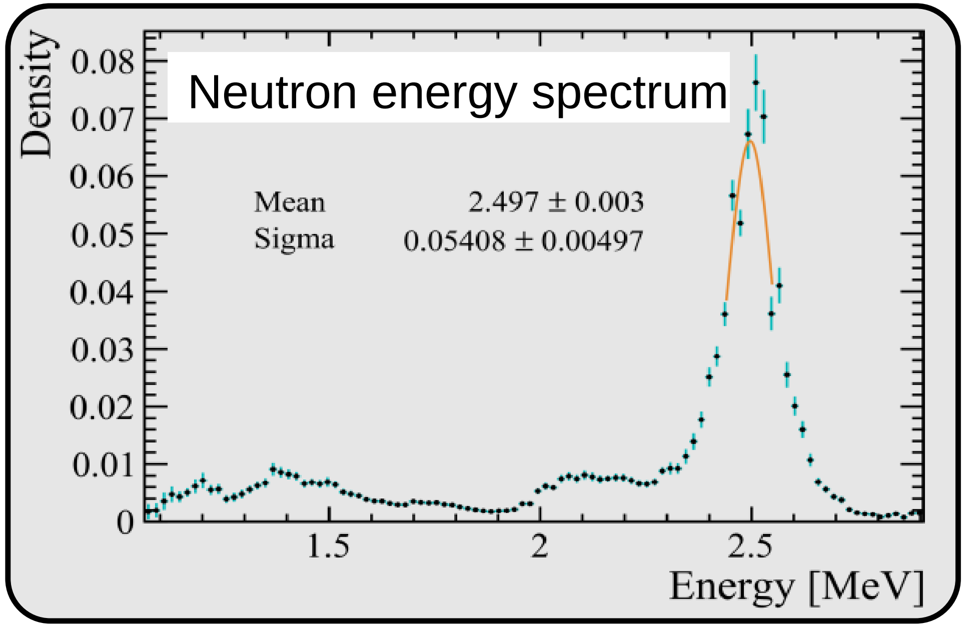
Gain

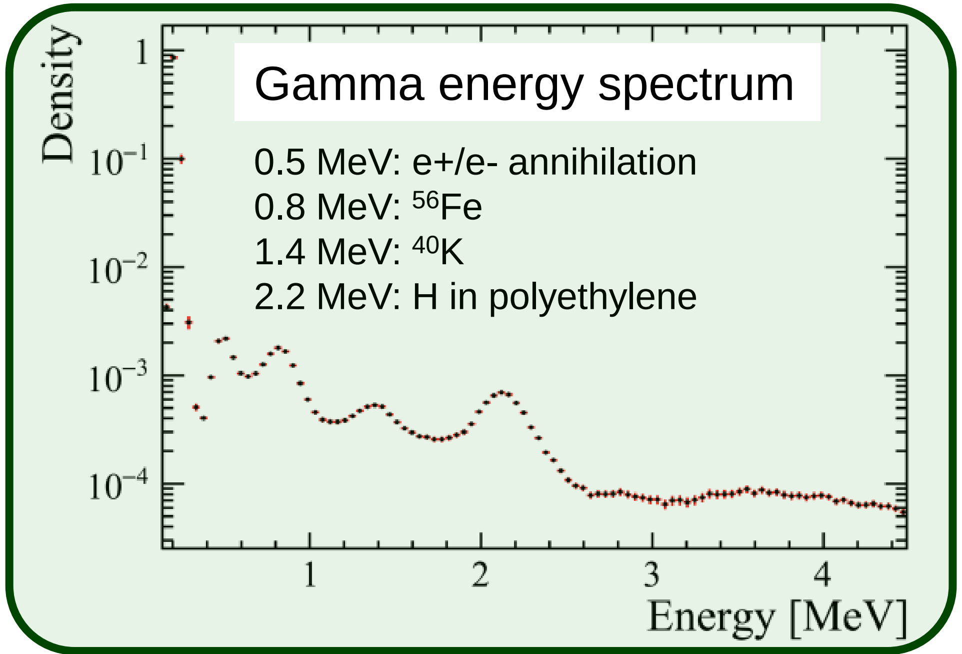


Pressure & temperature

Neutron/Gamma energy spectrum by LS

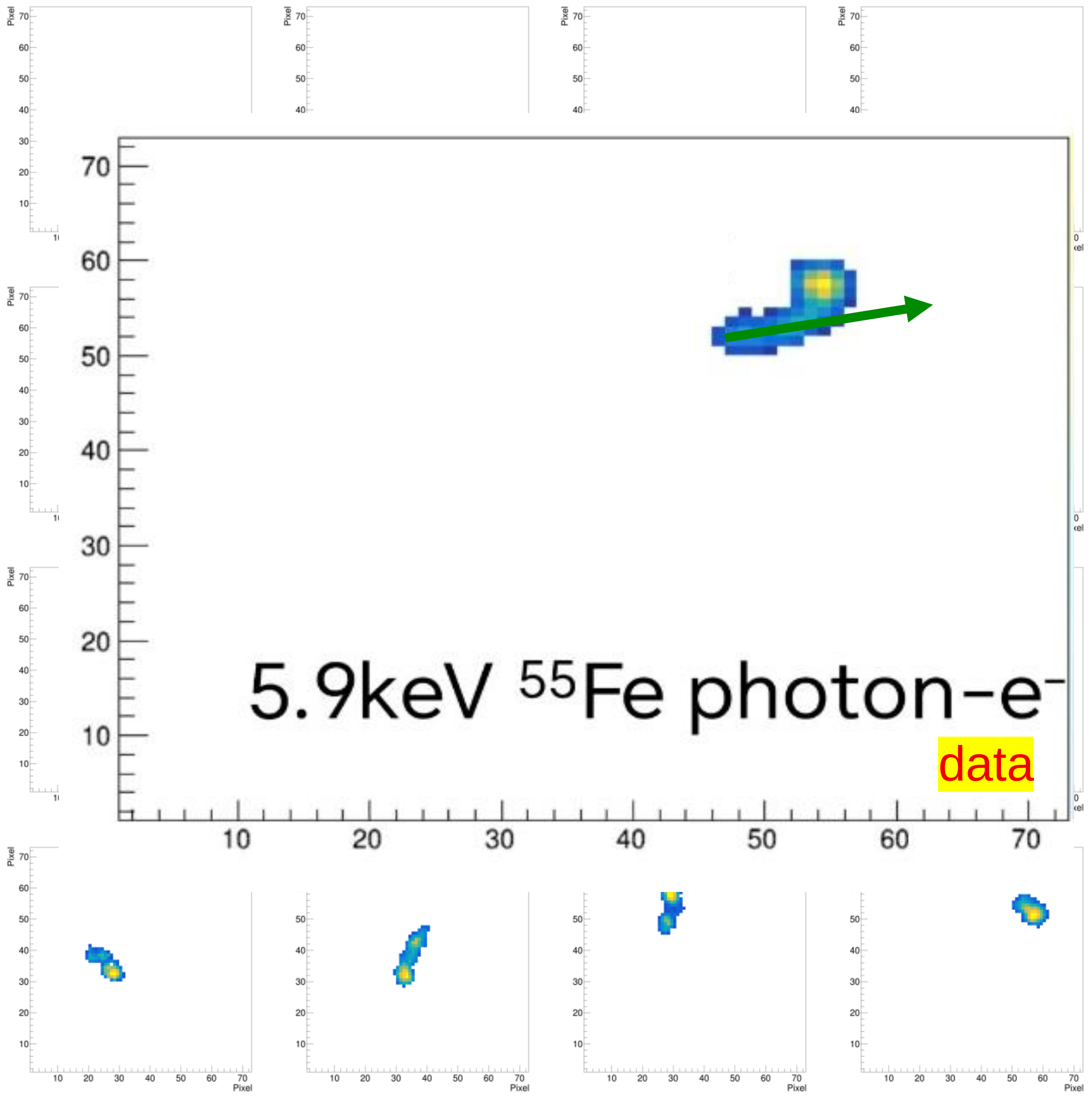


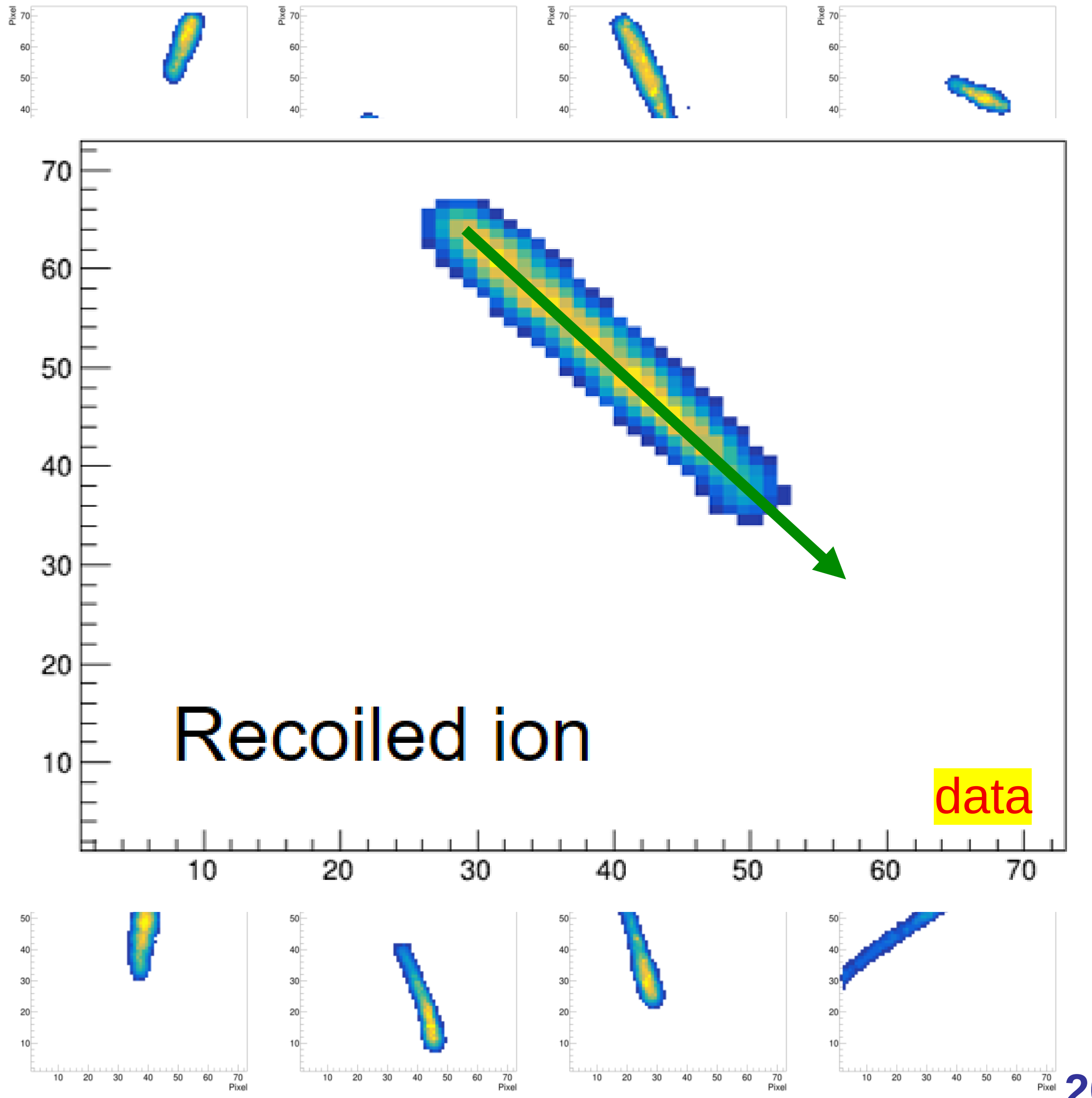




- Distinguishing neutrons from gammas using Pulse Shape Discrimination (PSD)
- Obtaining energy spectra via unfolding: using the response matrix of the LS, which is validated through calibration and simulation

Electron & ion tracks

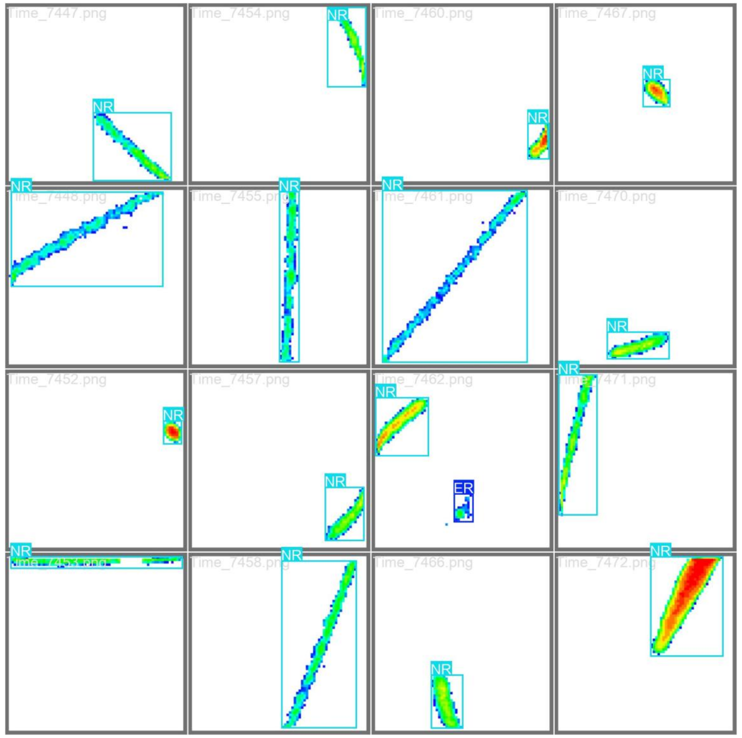




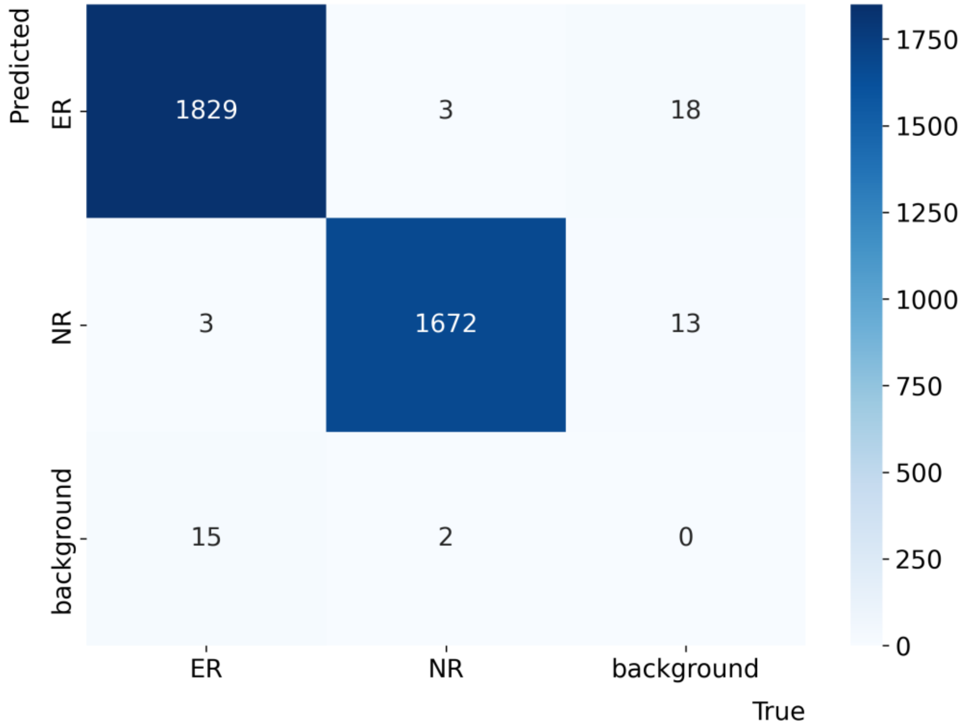
AI-assisted event selection

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

AI-assisted event selection

Data → YOLO[*1] preselection → NR reconstruction → ER reconstruction → Vertex cut

1. Search for the NR vertex through recursive iteration:

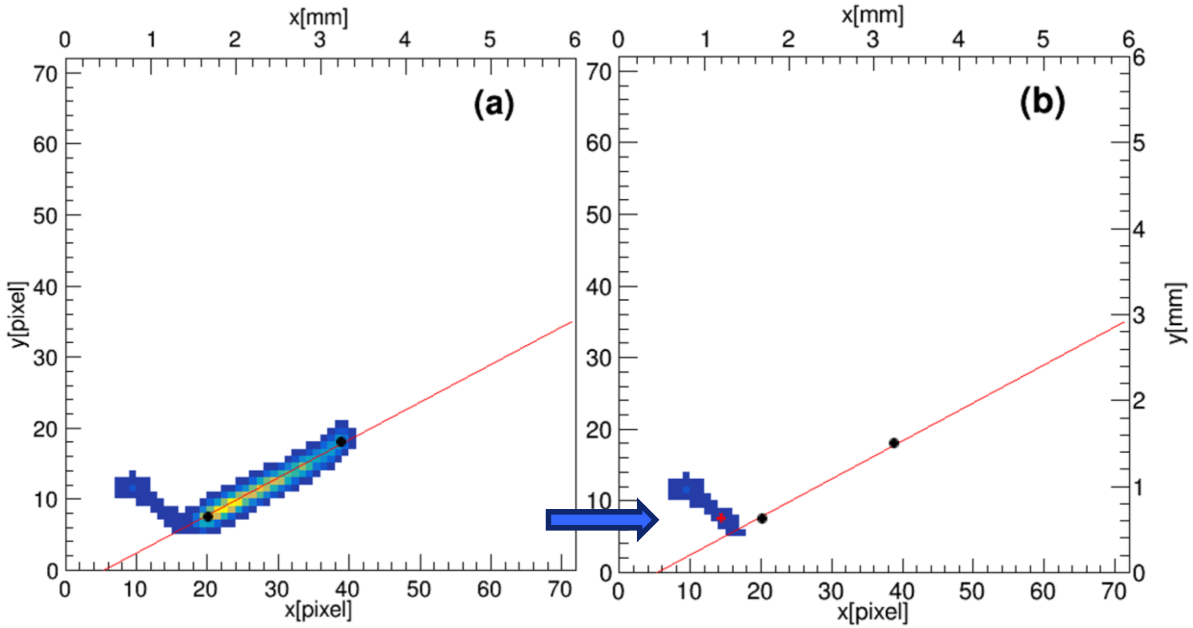
$$(x_0,y_0) \xrightarrow{\text{ADC}\cdot exp\,(d/d_0)} (x_n,y_n)$$

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

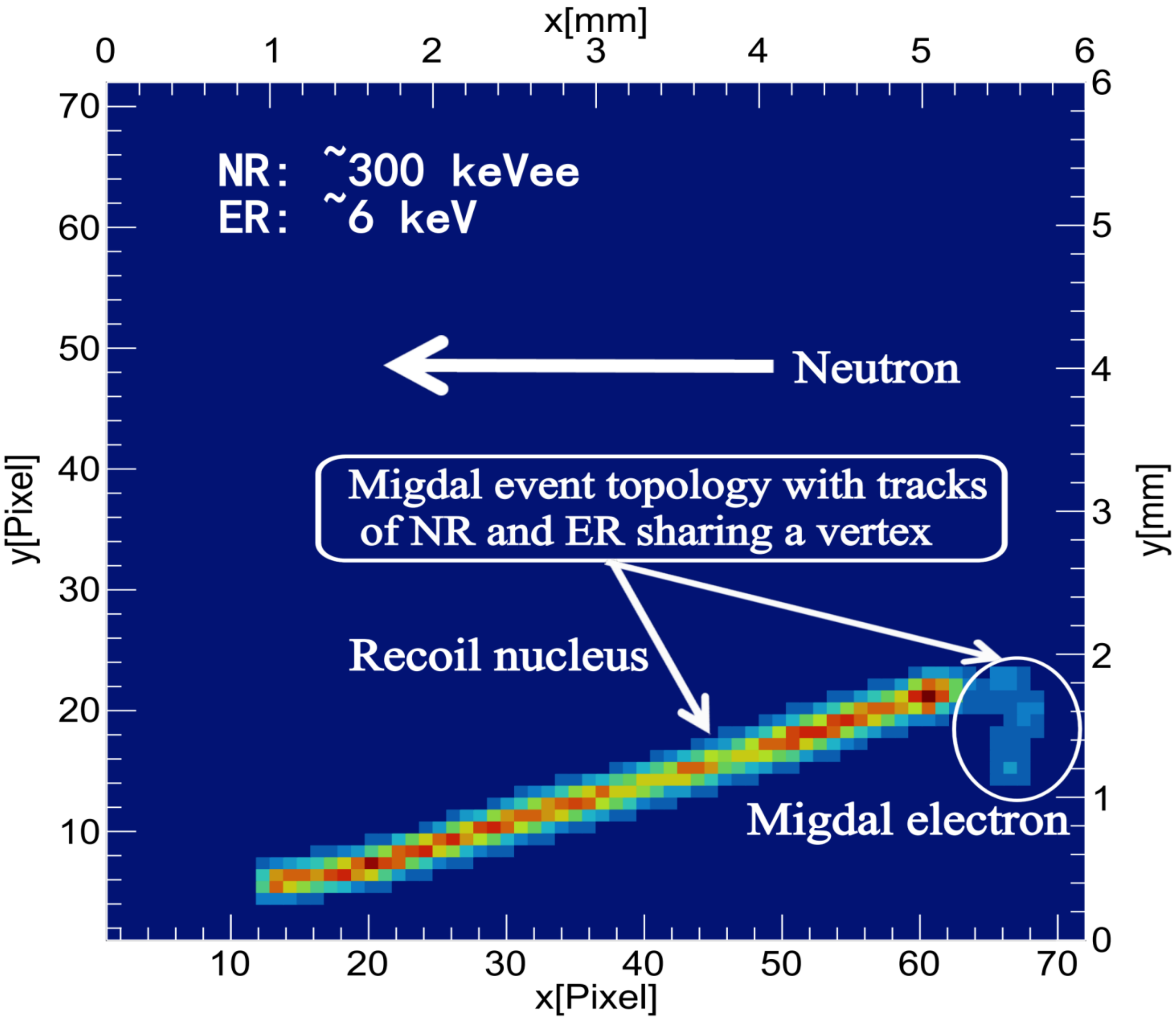
3. Search for the electron vertex using **adaptive cutting algorithm**(Nucl. Sci. Tech.doi:10.1007/s41365-021-00903-0).

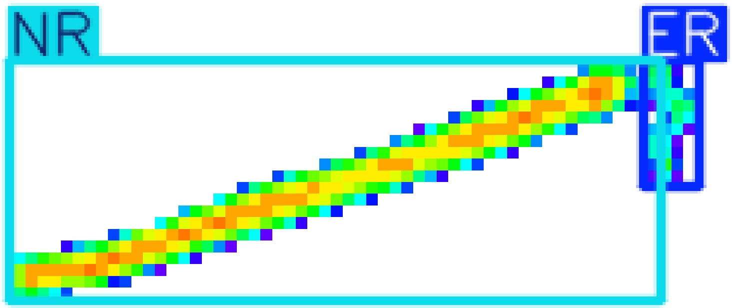
4. Determine whether the electron vertex is adjacent to the nucleon vertex.

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

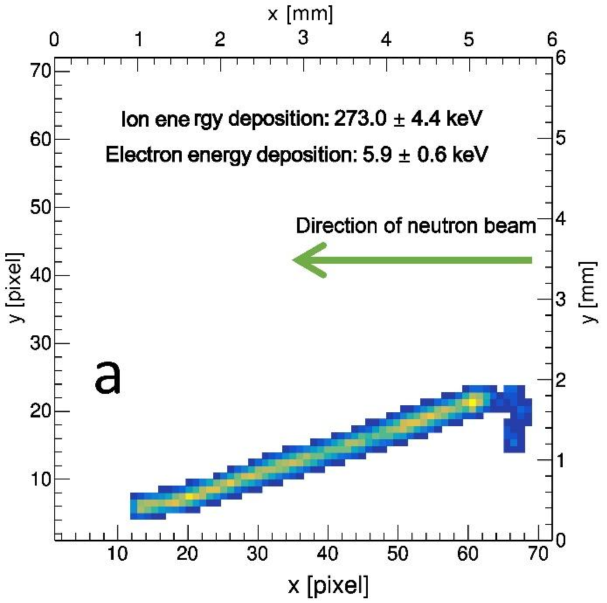


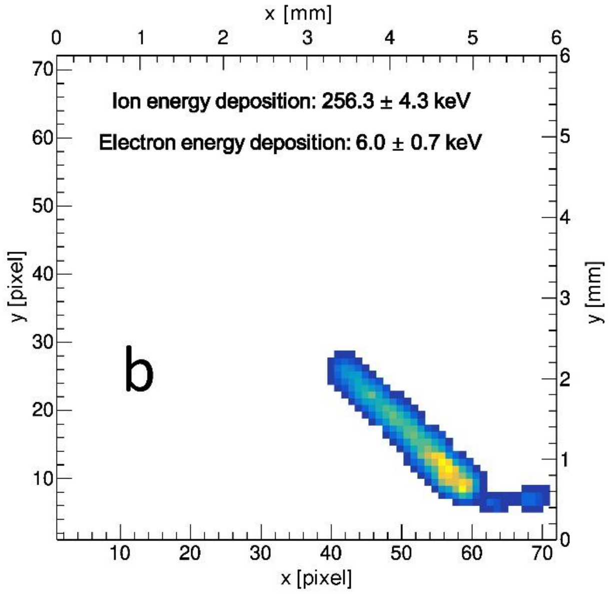
The first observed Migdal candidate!

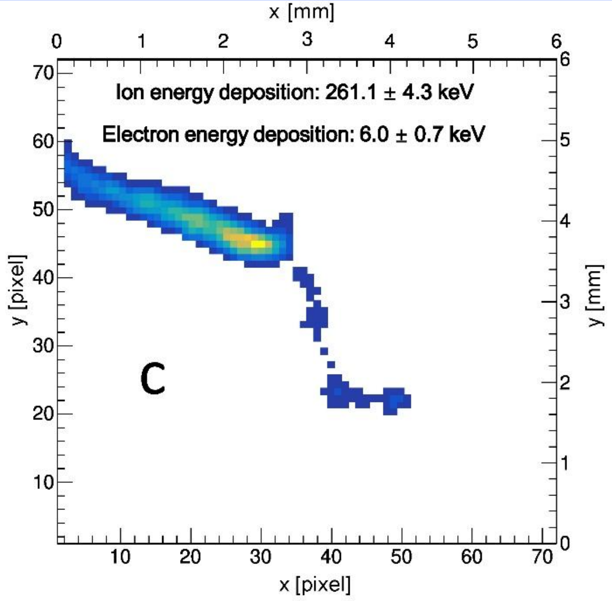


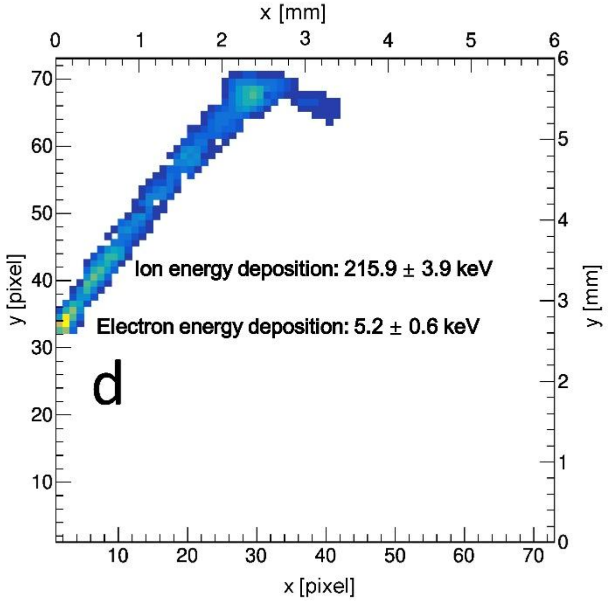


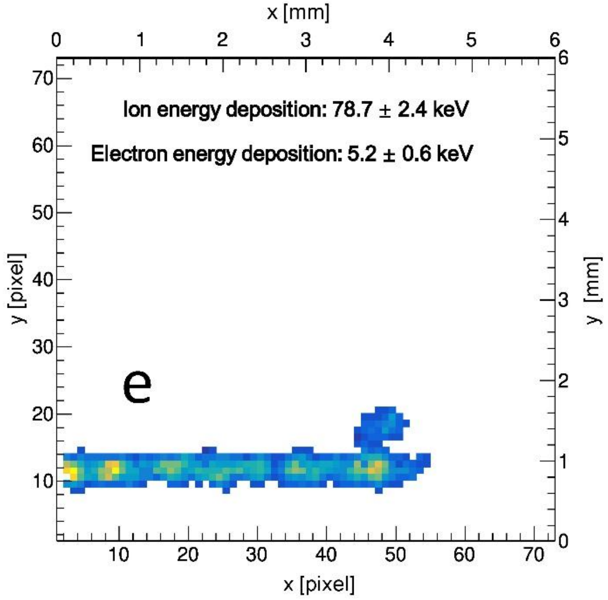
And more!

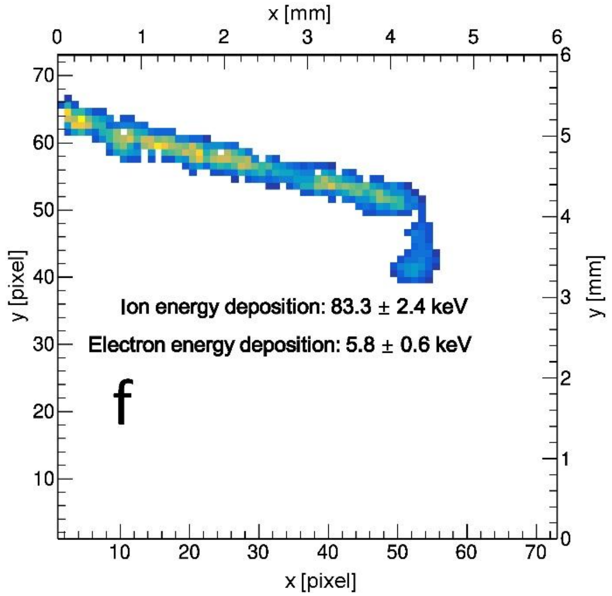

Ion ene rgy deposition: 273.0 ± 4.4 keV
Electron energy deposition: 5.9 ± 0.6 keV
Direction of neutron beam
a
x [mm]
y [mm]
x [pixel]
y [pixel]


Ion energy deposition: 256.3 ± 4.3 keV
Electron energy deposition: 6.0 ± 0.7 keV
b
x [mm]
y [mm]
x [pixel]
y [pixel]

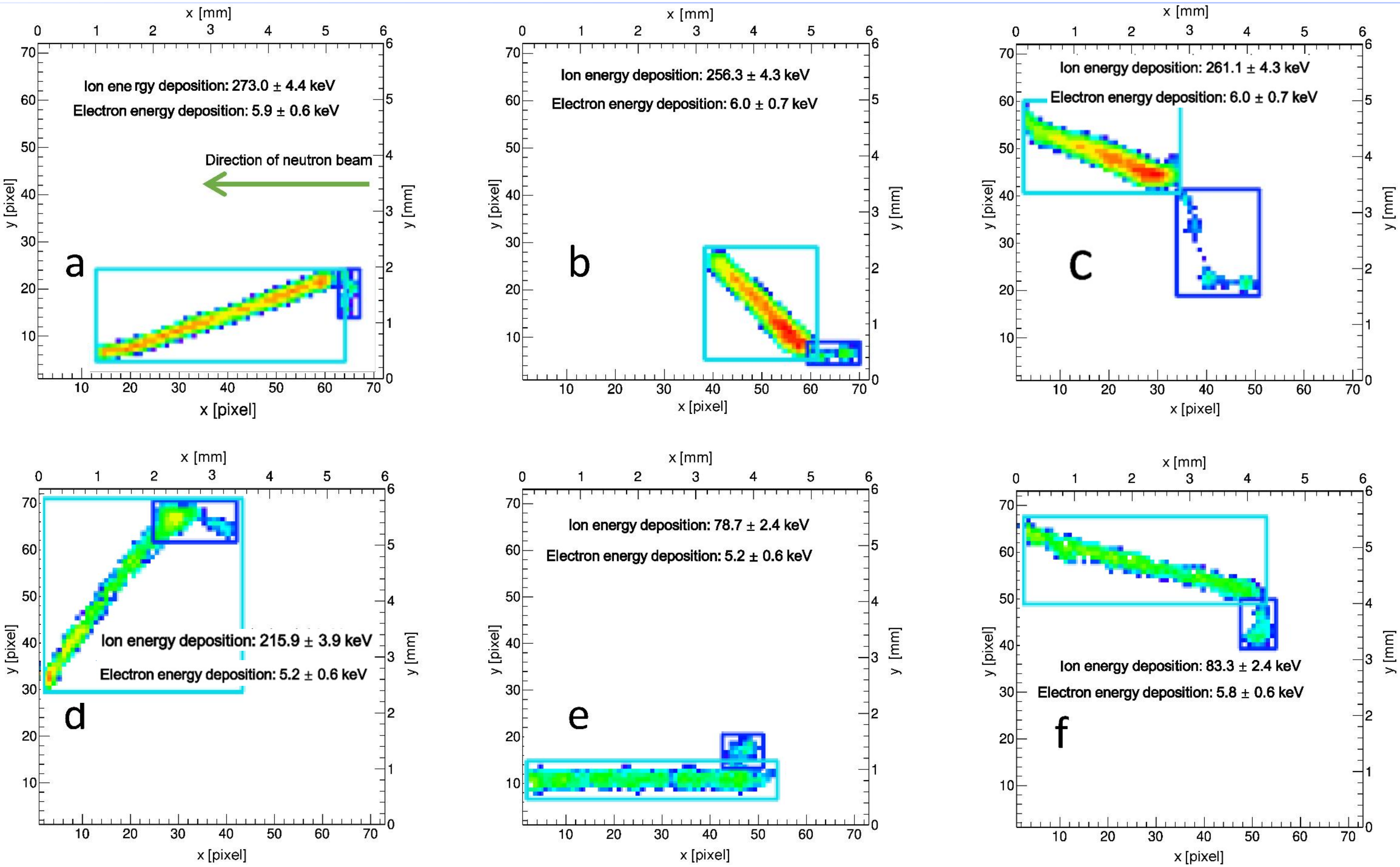

Ion energy deposition: 261.1 ± 4.3 keV
Electron energy deposition: 6.0 ± 0.7 keV
c
x [mm]
y [mm]
x [pixel]
y [pixel]


Ion energy deposition: 215.9 ± 3.9 keV
Electron energy deposition: 5.2 ± 0.6 keV
d
x [mm]
y [mm]
x [pixel]
y [pixel]


Ion energy deposition: 78.7 ± 2.4 keV
Electron energy deposition: 5.2 ± 0.6 keV
e
x [mm]
y [mm]
x [pixel]
y [pixel]


Ion energy deposition: 83.3 ± 2.4 keV
Electron energy deposition: 5.8 ± 0.6 keV
f
x [mm]
y [mm]
x [pixel]
y [pixel]

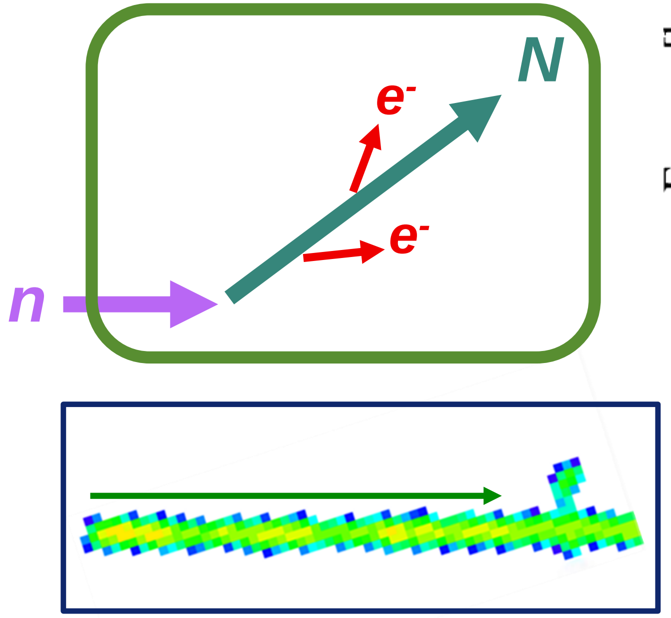
Migdal candidates recognized by YOLO

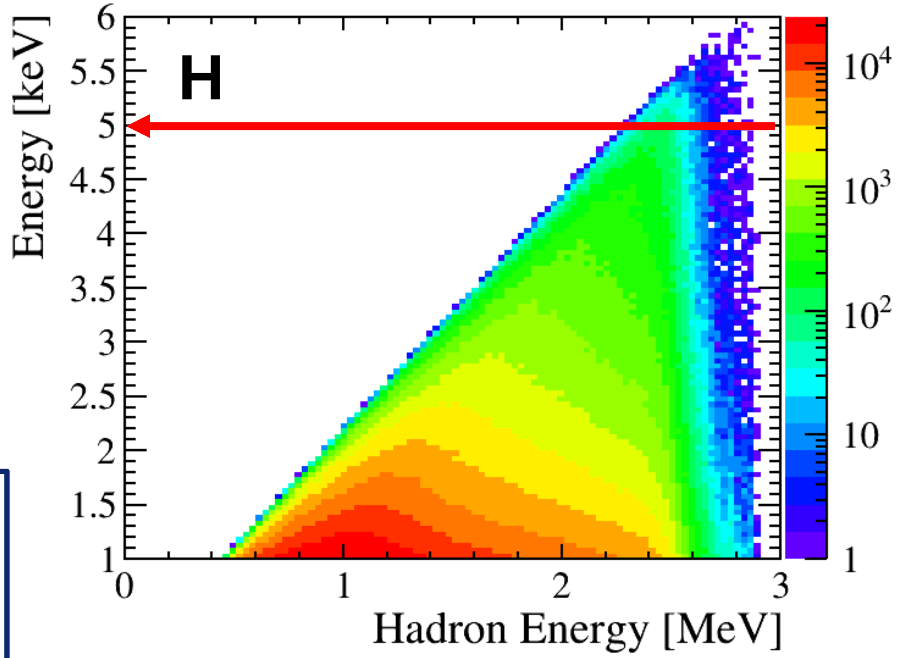


Background estimation

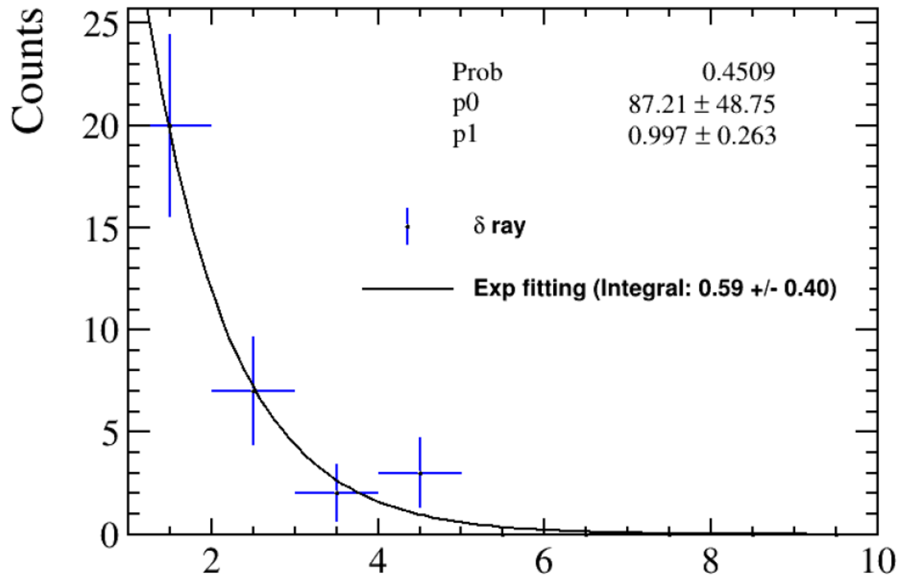
Background Component	Description	Expectation value (5 - 10 keV)	Method
Recoil induced δ ray	δ electron near NR track origin	0.035±0.023(stat.)±0.0068(sys.)	Data driven
Particle Induced X-ray Emission			
X-ray emission	Photoelectron near NR track origin	0	
Auger electrons	Auger electron near NR track 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±0.022(stat.)±0.042(sys.)	Data driven
Muon induced δ ray	δ electron near NR track origin	0.013	MC
Gas radioactivity			
Trace contaminants	Electron from decay near NR track origin	0.001±0.00087(sys.)	Data driven
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±0.032(stat.)±0.043(sys.)	

Recoil induced δ ray





Only H has the **δ electron >** 5 keV.

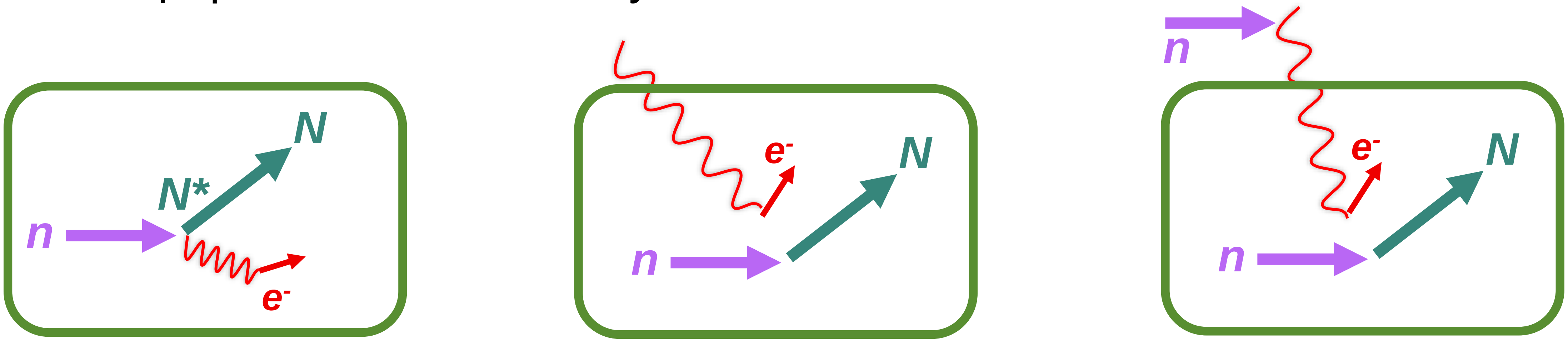


No δ above 5 keV were found.
Estimate by extrapolating from the exponential fit

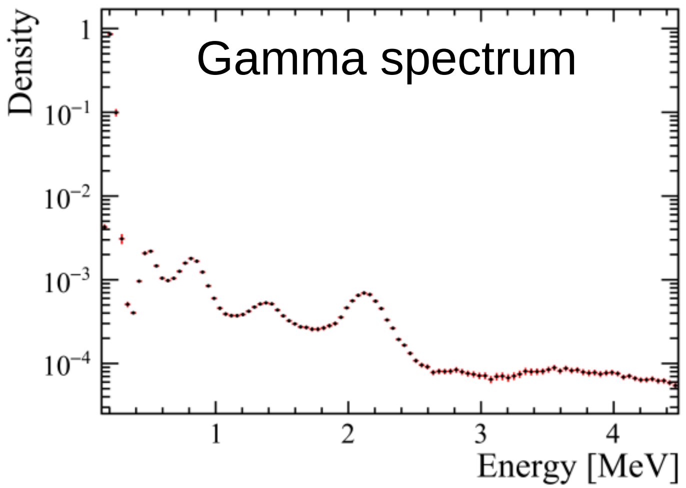
- **Consider the selection efficiency for δ-electrons.**
- **Finally get: 0.035±0.023(stat.)**

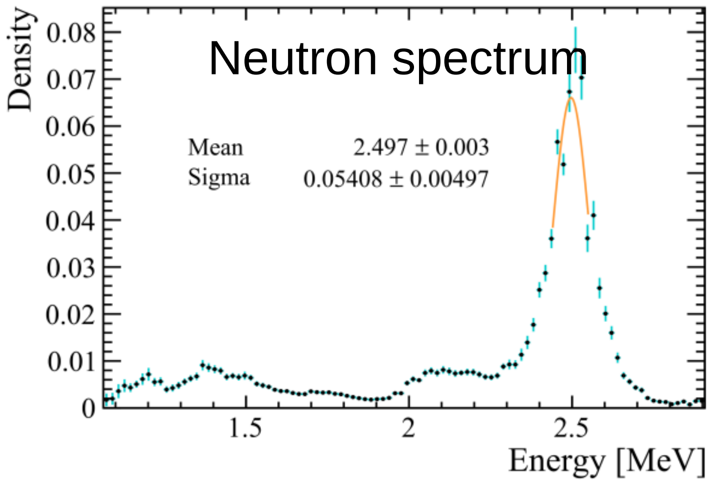
Radom track conincidence

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



	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}

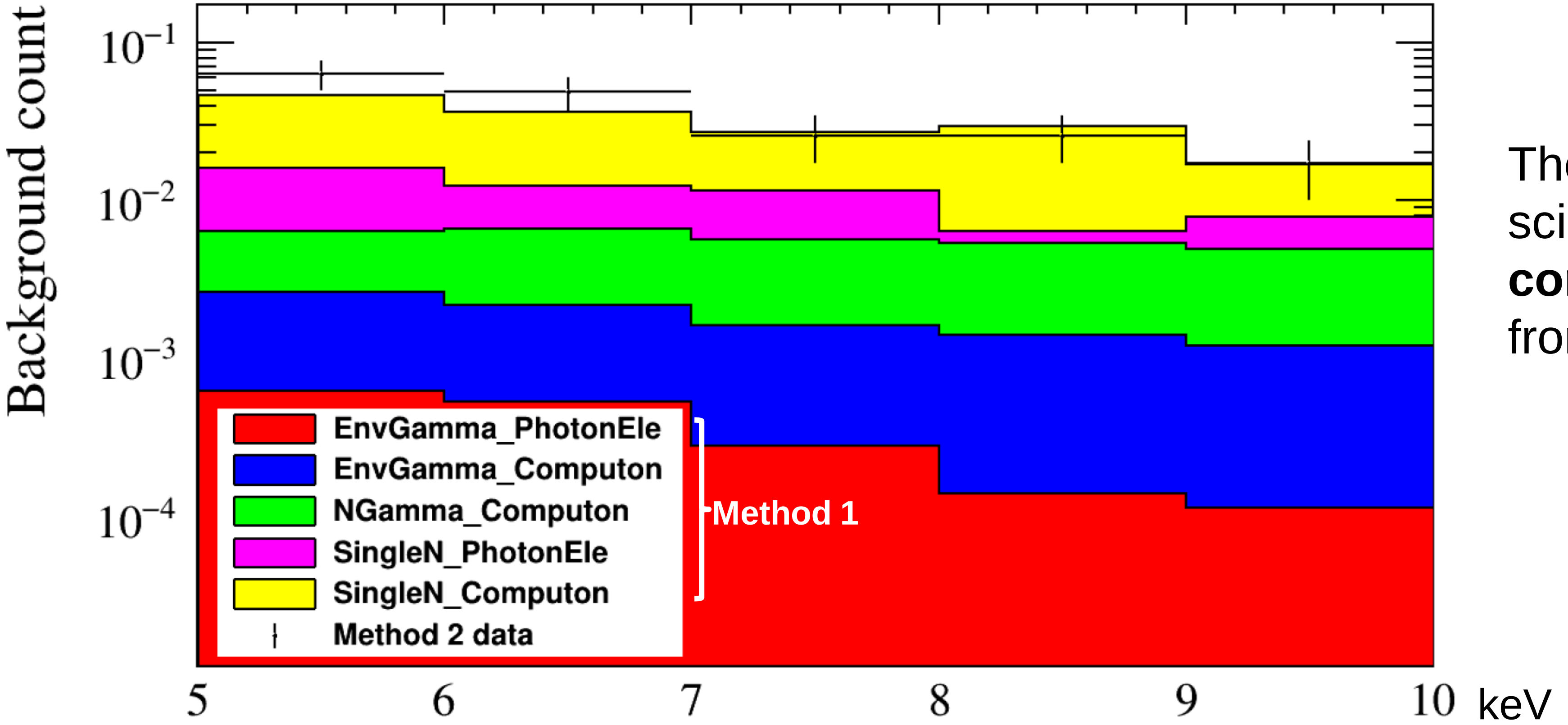




- **The expected background contribution of the 3 components in total is: 0.16±0.01(stat.)**

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±0.022(stat.)±0.042(sys.)**



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

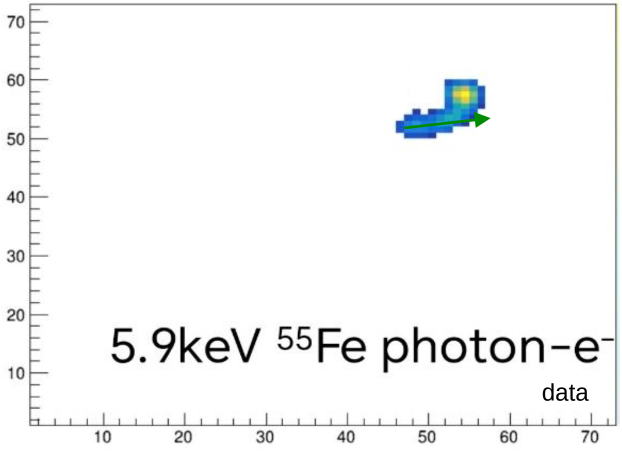
Muon induced δ ray

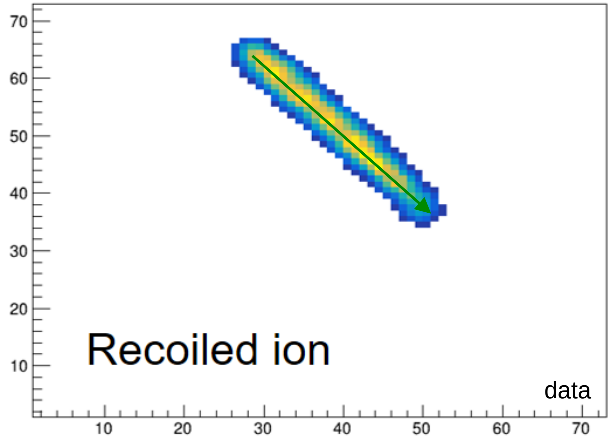
- **Adopt Local Cosmic Muon Flux Measurement Results**
  - **The local cosmic muon flux measurement(Liu,G.,et al, 2024) in Lanzhou is used for estimation.**
- **Set Nuclear Recoil Rate Benchmark and Calculate δ-ray Ratio**
  - **Set the nuclear recoil rate of the D-D neutron source as 1.4 event per second, 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**

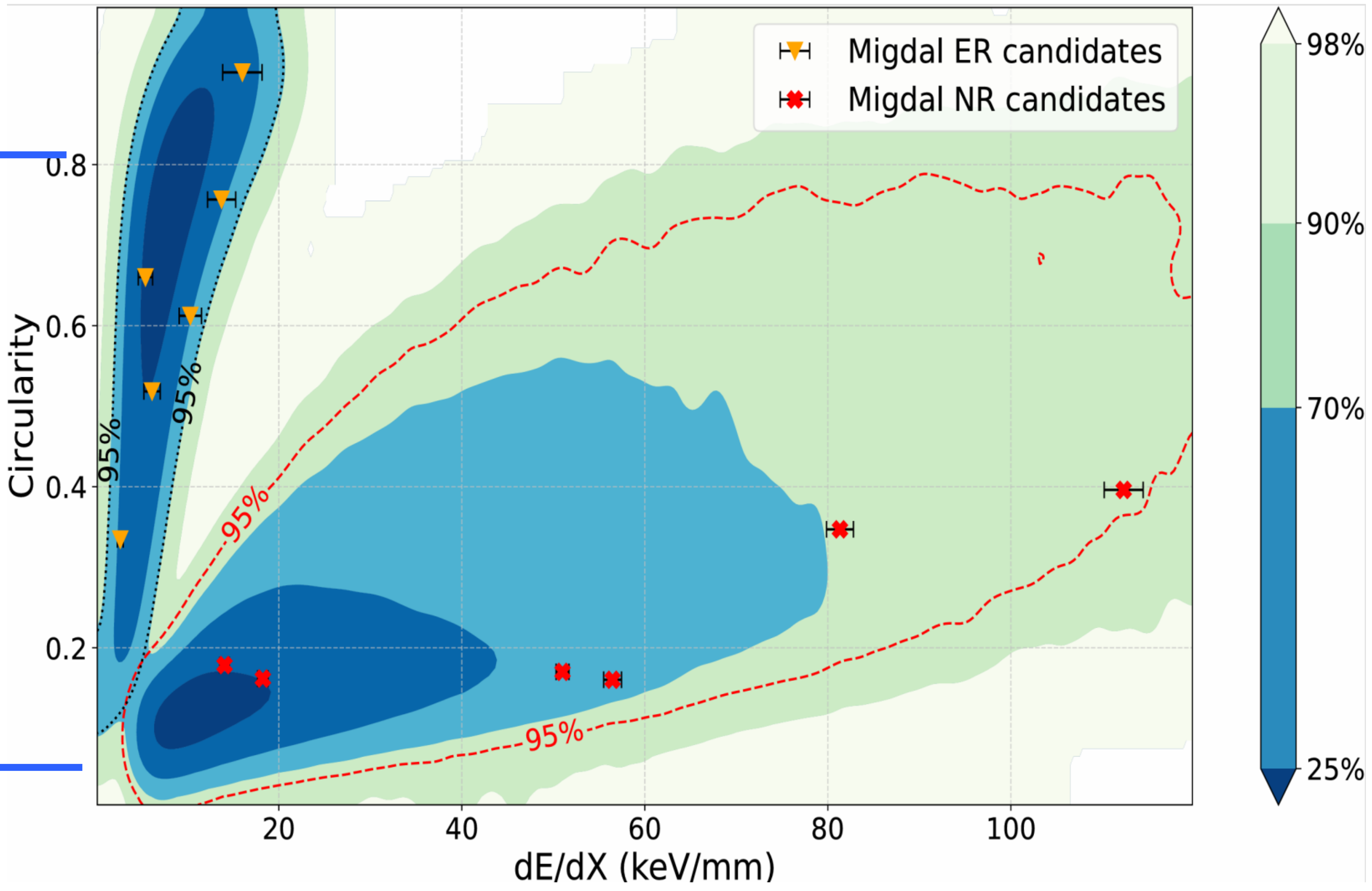
Normalize to the number of experimental data points and determine that δ-rays contribute 0.013 events.

Characteristic distribution of ERs and NRs

$5\ keV_{ee} < Ee < 10\ keV_{ee}, E_{nr} > 35keV_{ee}$



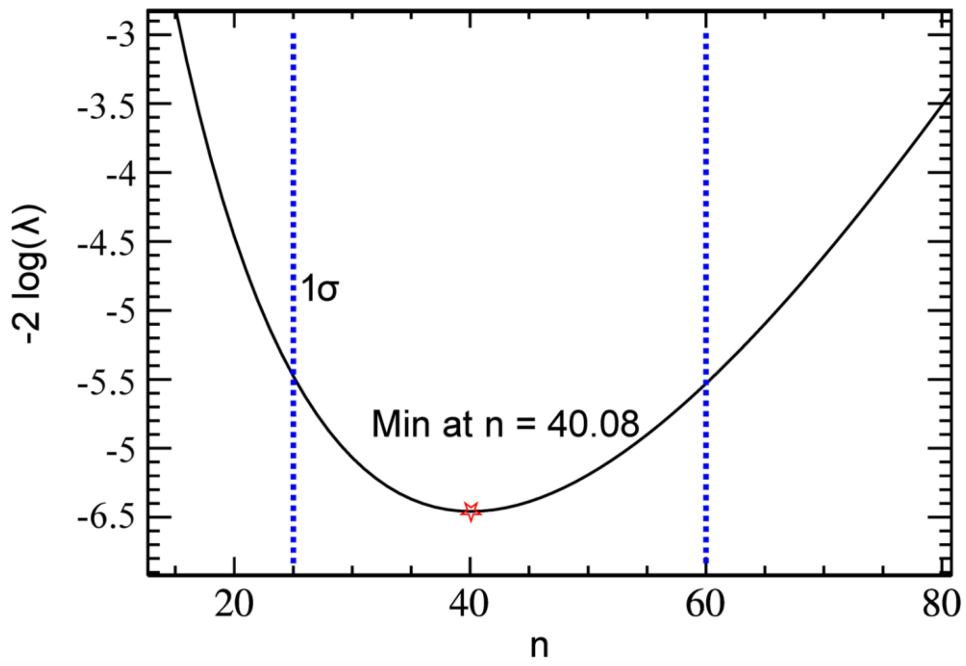




Cross section ratio calculation

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

	Efficiency/Count	Statistical Error	Systematic Error
Efficiency ε_{ER}	14.4%	±0.1%	±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: $$\Delta P_{\pm}=\sqrt{\left(\frac{n_{min}-n_{ul/ll}}{n_{min}}\right)^2+\left(\frac{n_{\text{tot}\,\text{error}}^{\text{NR}}}{n_{\text{tot}}^{\text{NR}}}\right)^2}\cdot\frac{n_{min}}{n_{\text{tot}}^{\text{NR}}}$$

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

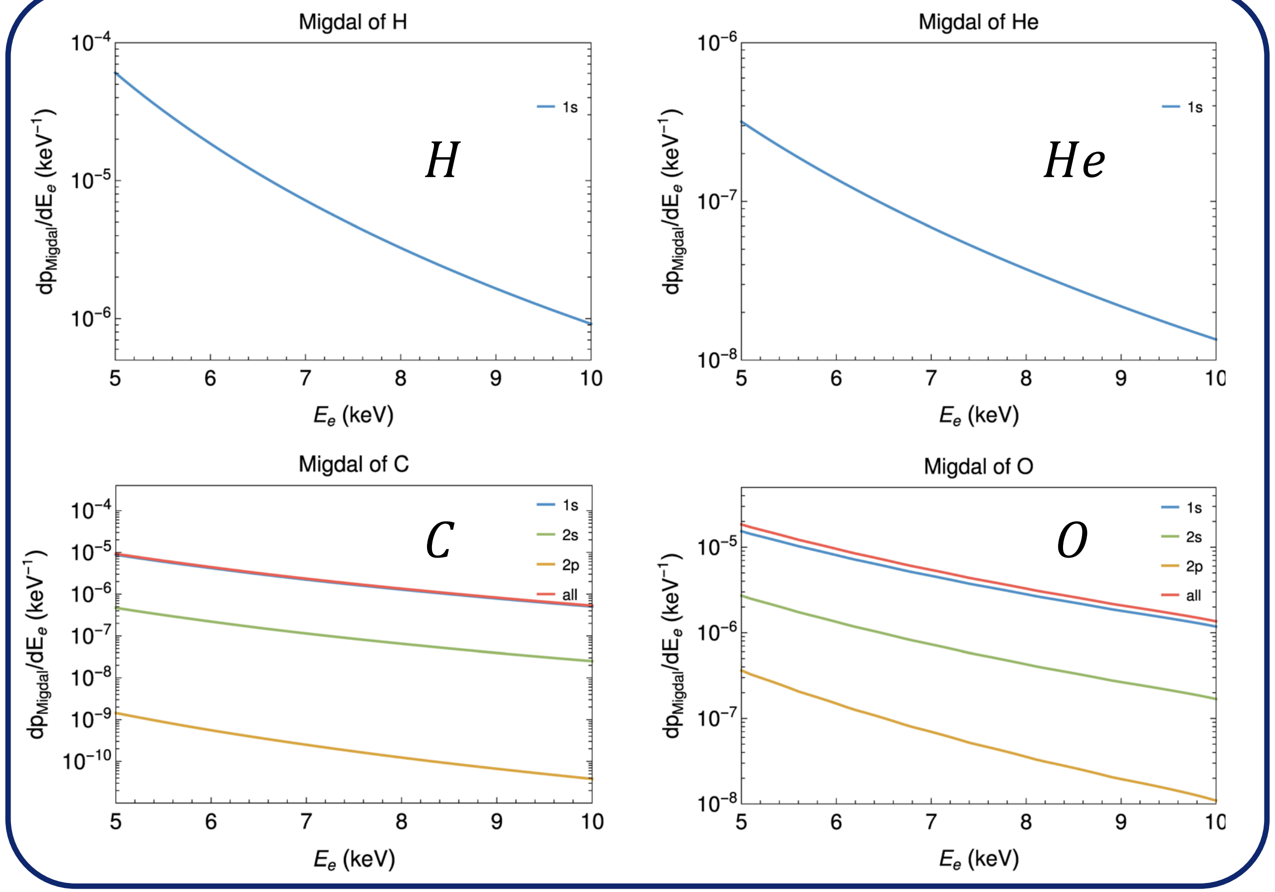
Theory: 3.9×10^{-5}

Nature 649(2026)580-583

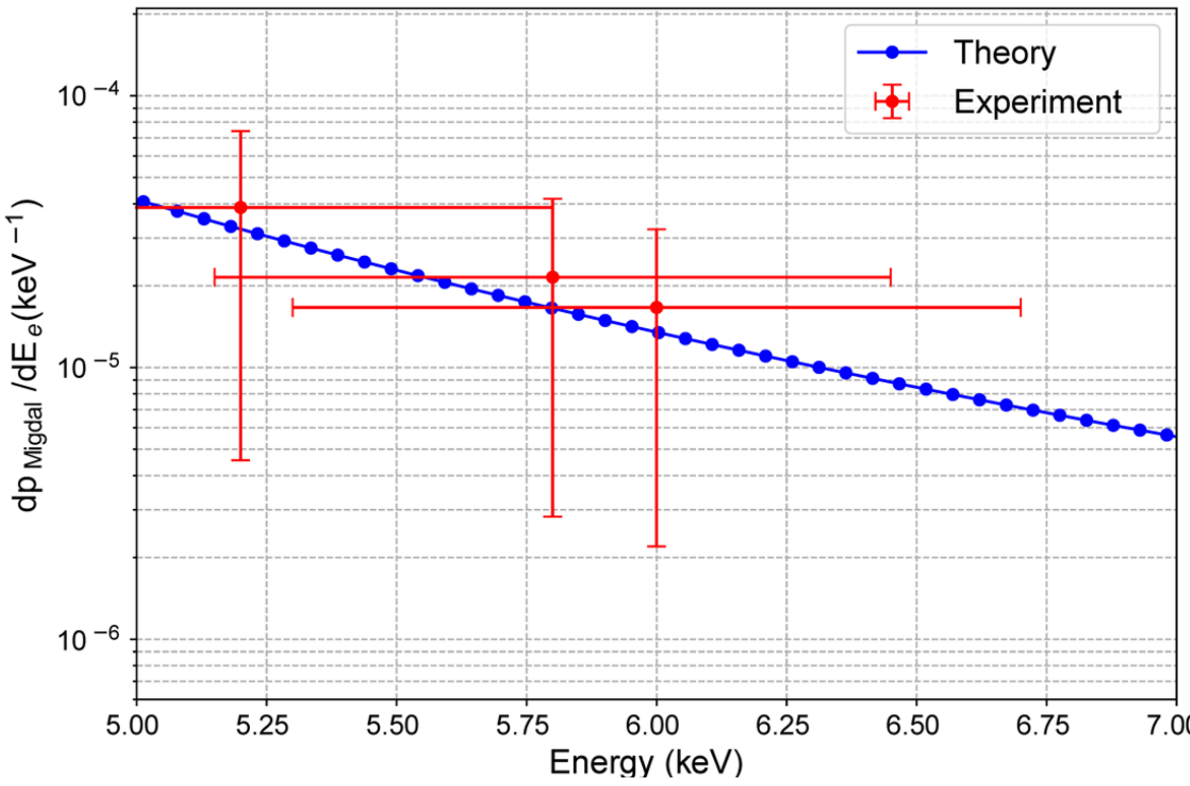
The total transition probability

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

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



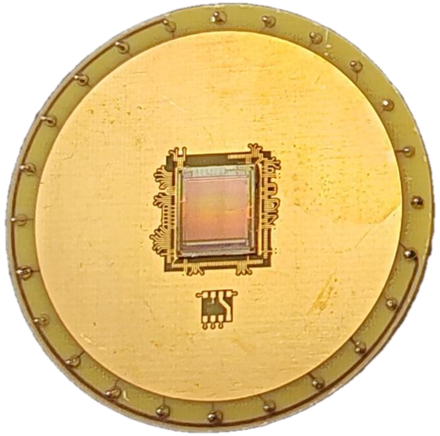
Transition probability of each element



Total Transition probability

Nature 649(2026)580-583

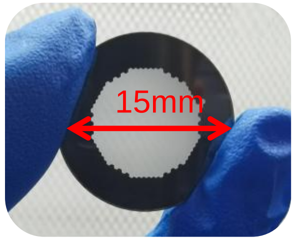
Upgrade in progress

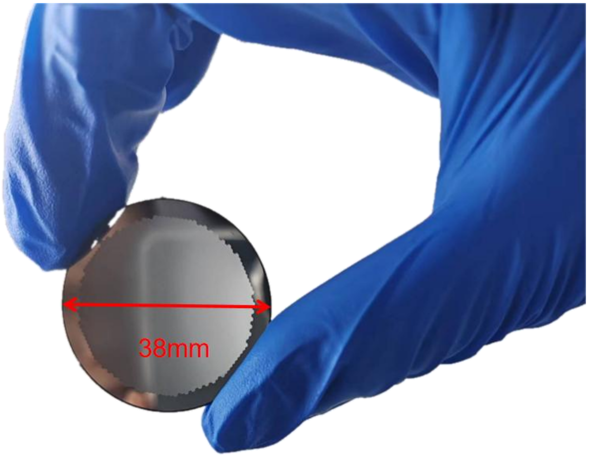


Topmetal-II

Topmetal-L

	Topmetal-II$^-$	Topmetal-L
Chip size [mm^2]	8×9	17×24
Active area [mm^2]	6×6	16.02×23.04
Pixel array	72×72	356×512
Pixel density [pixels/mm^2]	145	494
Power density [W/cm^2]	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



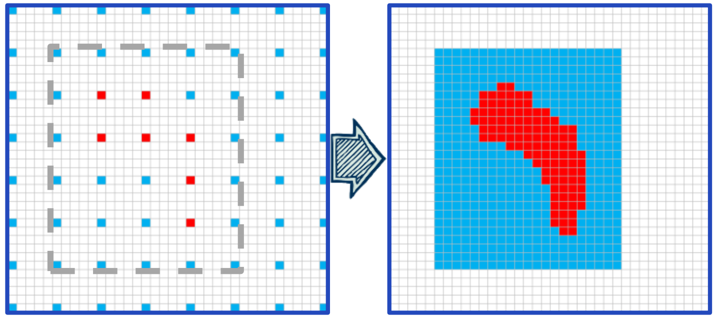


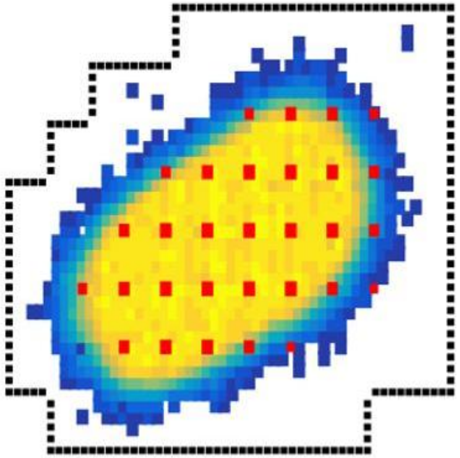
Larger GMCP

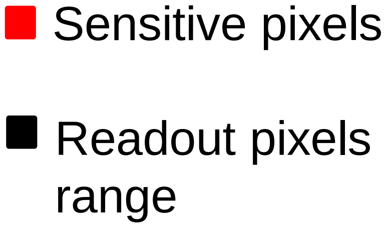
- 6x6 mm, 83 um in pitch -> 2.3x1.5 cm, 45 um in pitch
- Fresh time: 2.6 ms/Frame -> 0.7 ms/Frame
- Readout logic: Rolling Shutter -> Sensitive area

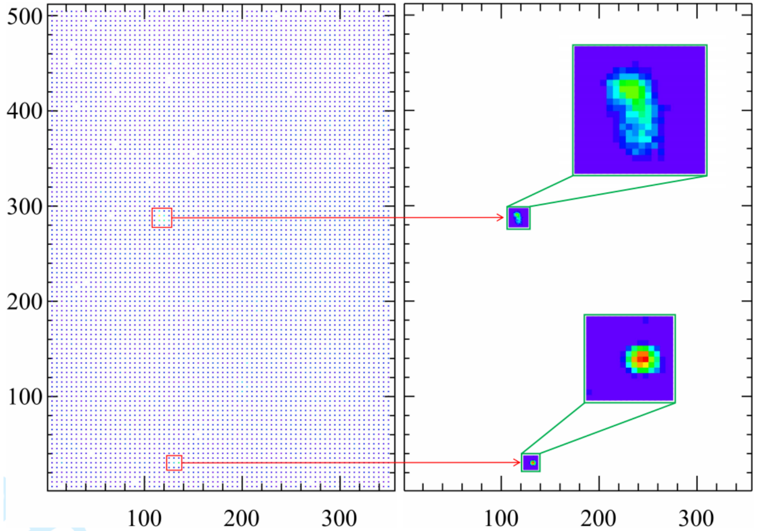
Upgrade in progress

Sensitive area readout:

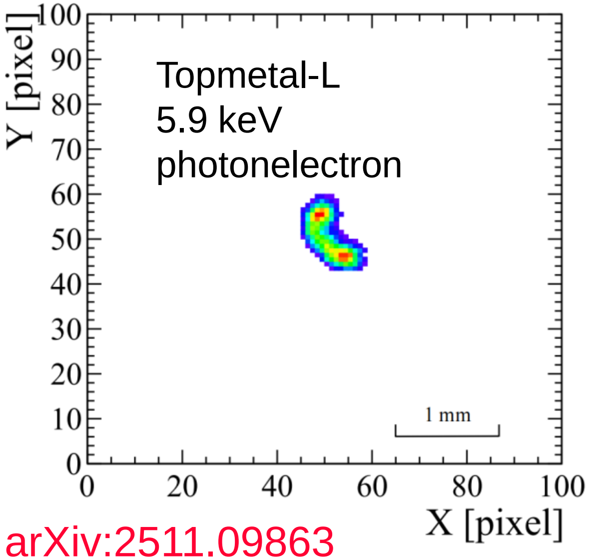


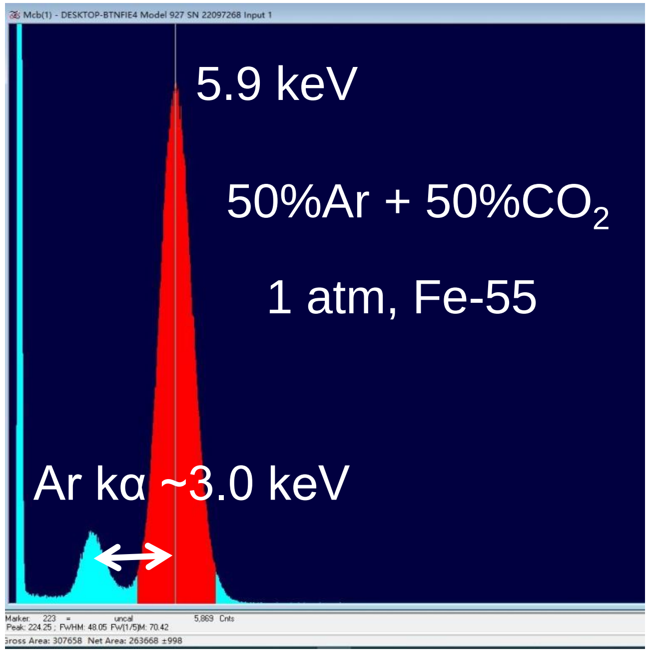


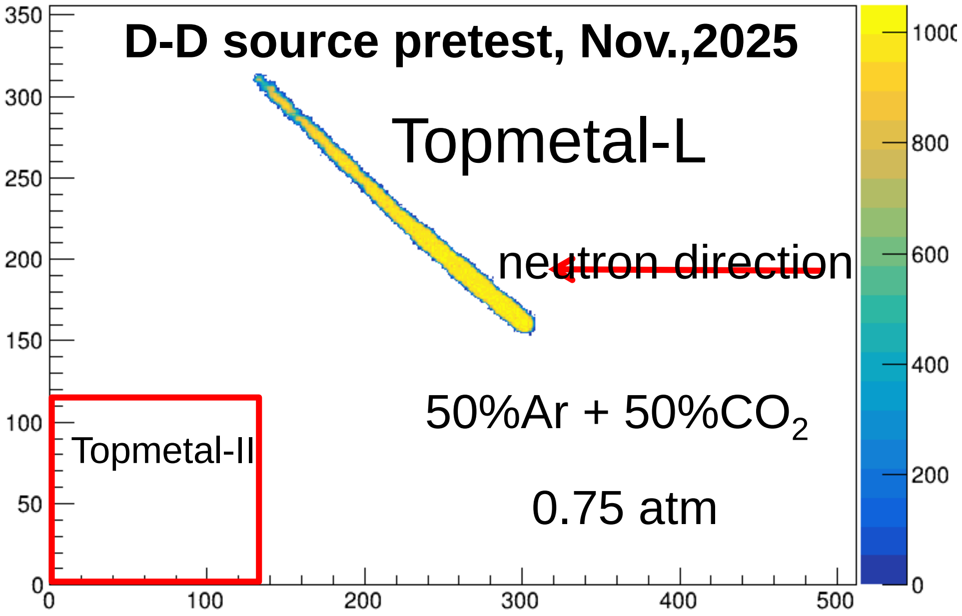




arXiv:2511.15130







arXiv:2511.09863

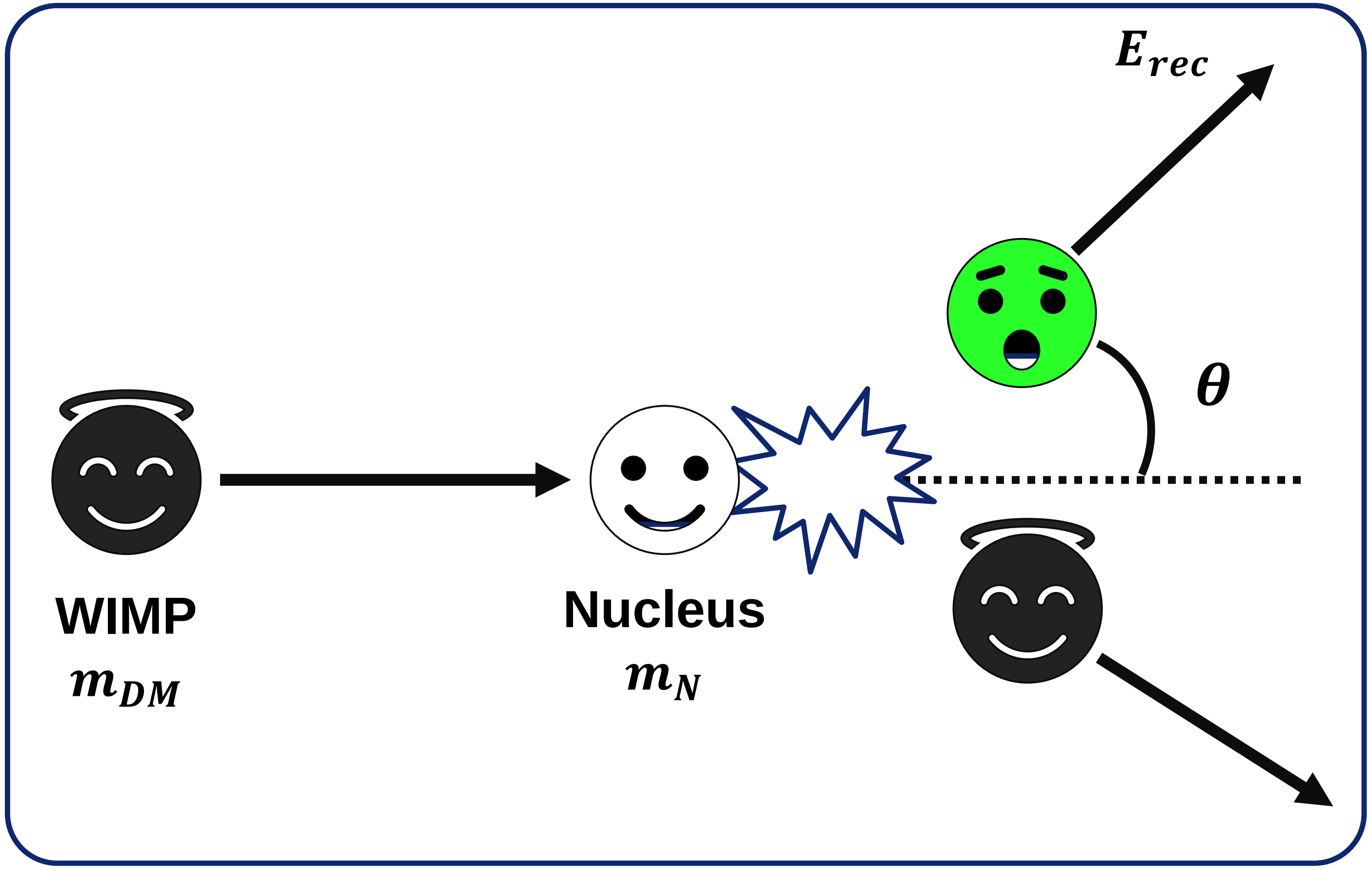
Summary and outlook

- The Migdal effect (electron shake-off) 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.
- The Detector with larger sensor area is in preparation, precise measurement for more elements relevant to dark matter experiments.
- 3D imaging detector will be consider.

Thanks for your attention!

Backup

DM-nucleus elastic scattering



Non-relativistic elastic scattering

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

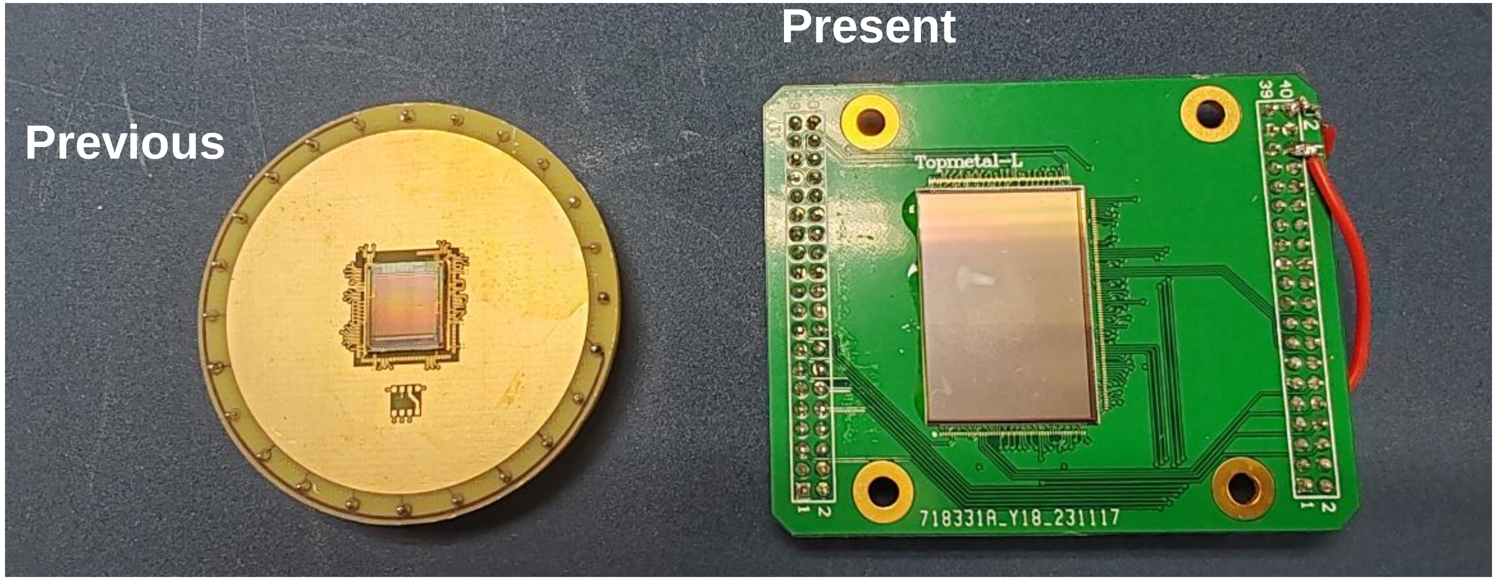
$$E_{rec} = \frac{\mu^2 v^2}{m_N}(1 - \cos\theta) \leq \frac{2\mu^2 v^2}{m_N}$$

$m_{DM} = 10\ \mathrm{GeV/c^2}$; $m_N = 131\ \mathrm{GeV/c^2}$; $v = 220\ \mathrm{km/s}$
$E_{rec} \leq 0.7\ \mathrm{keV_{nr}}$

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

Upgrade in progress

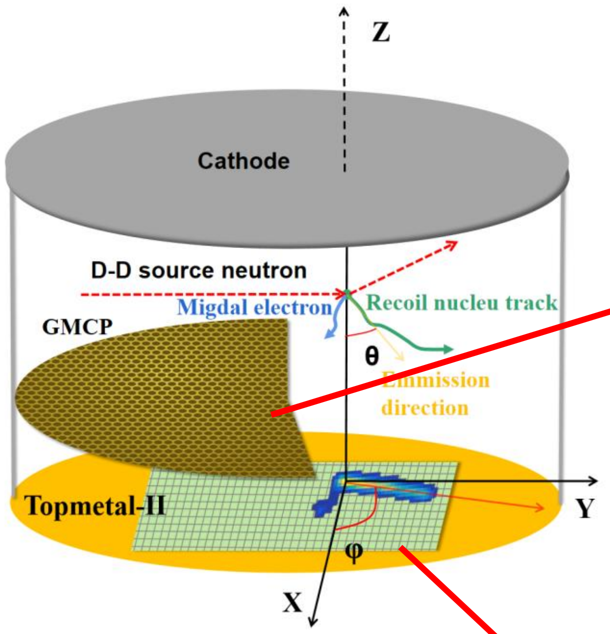
- Chip update: 6x6mm, 83um in pitch -> 2.3x1.5 cm, 45um in pitch

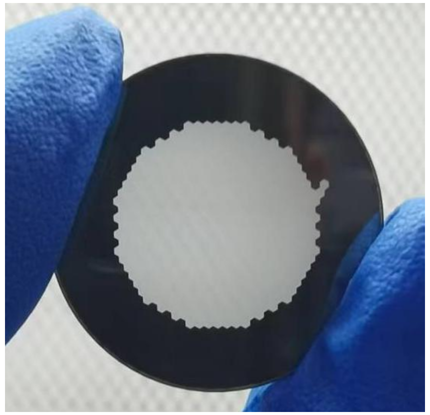


- Time resolution: 2.5ms -> 700us or less 1 us using GMCP

- Gas: He+DME -> Ne(Ar)+CO_2

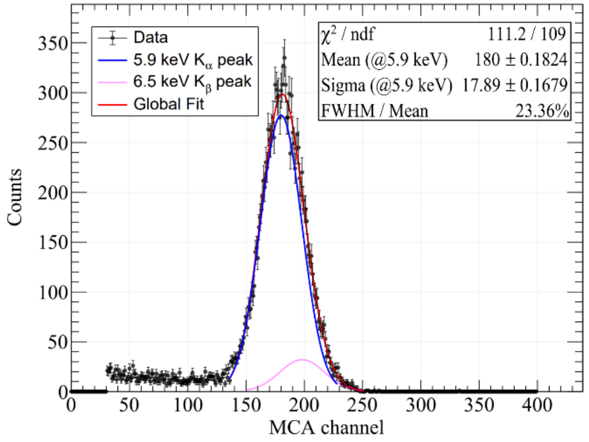
Working principle

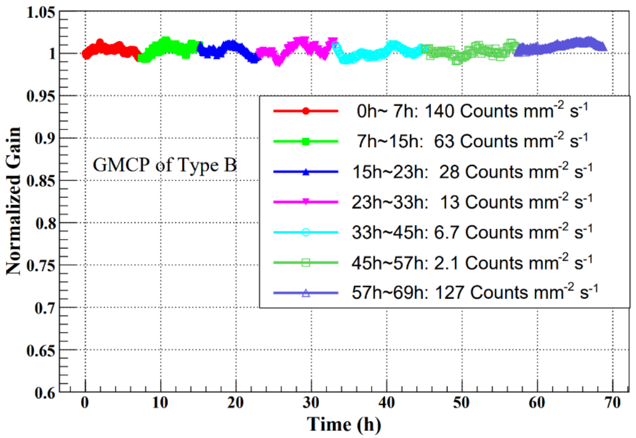


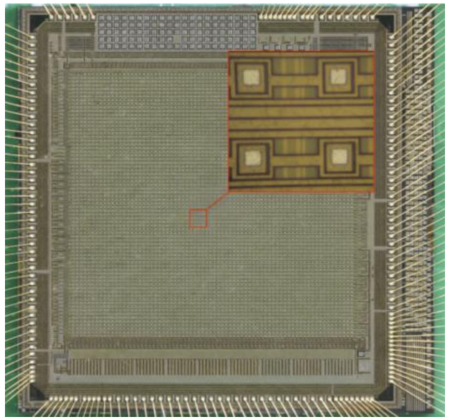


GMCP:

- 50 um diameter, 60 um pitch
- High energy resolution
- Stable gain coefficient

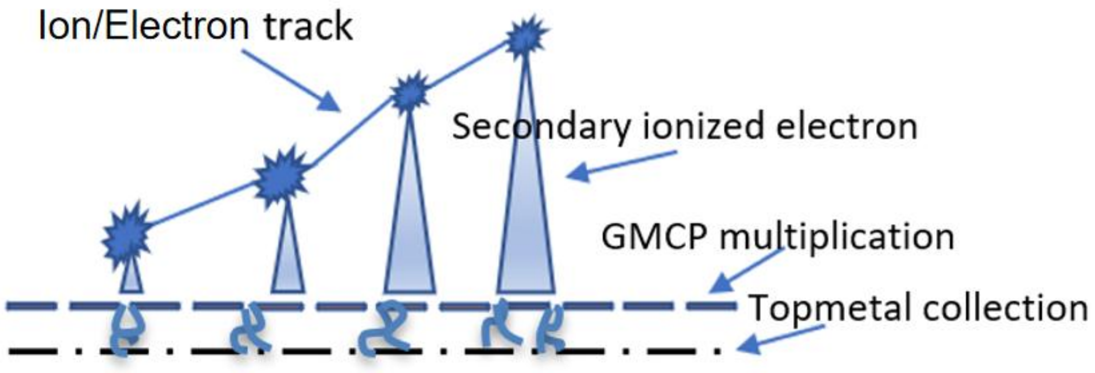






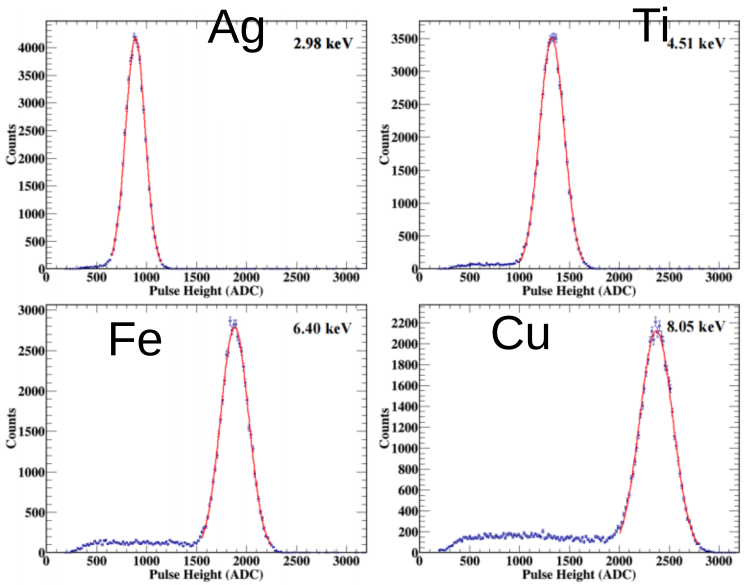
Topmetal-II-:

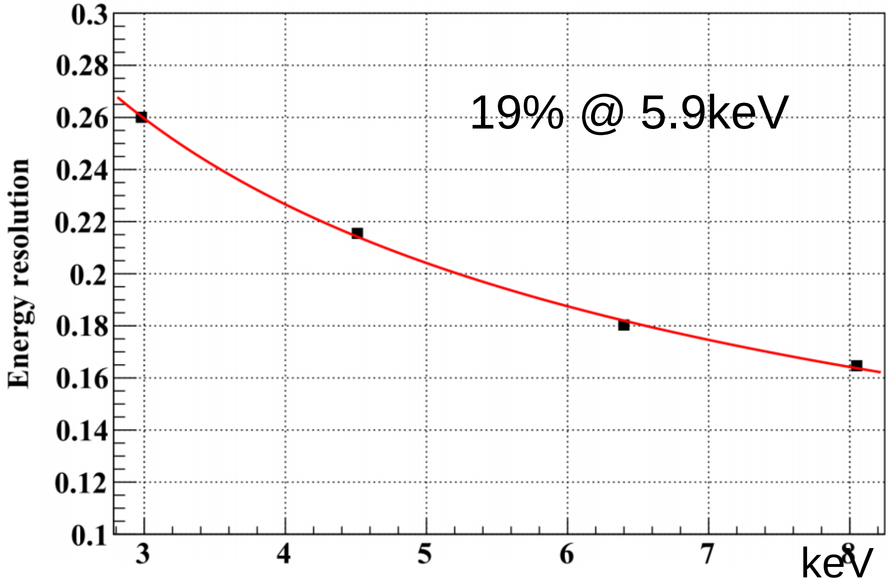
- 83 um pitch
- 2.5 ms time resolution
- noise 13.9e-



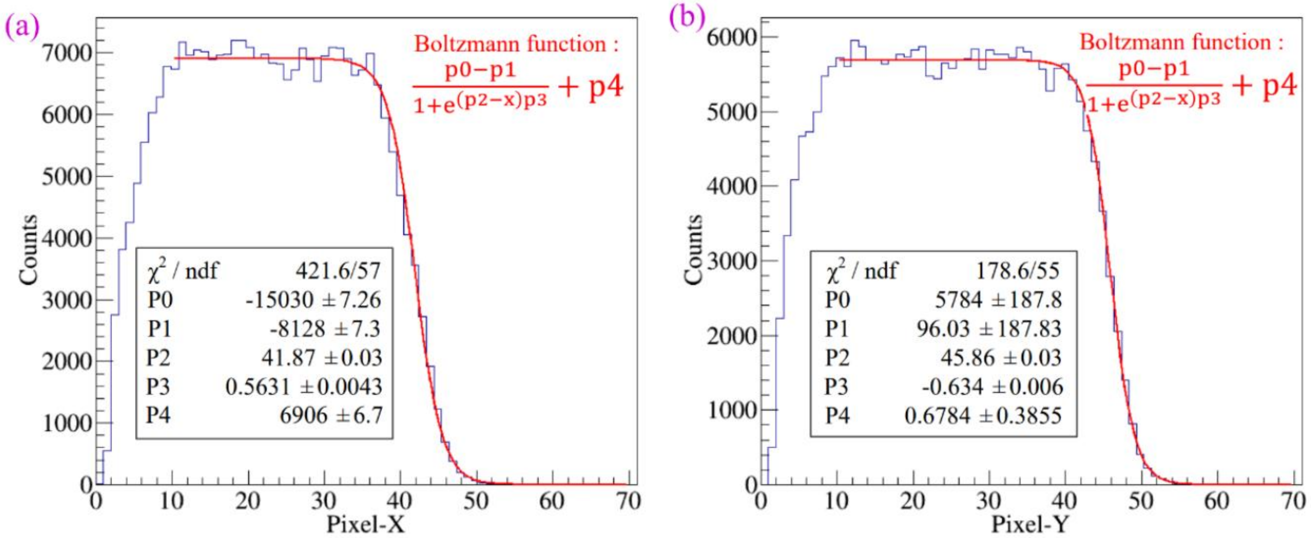
Detector Calibration

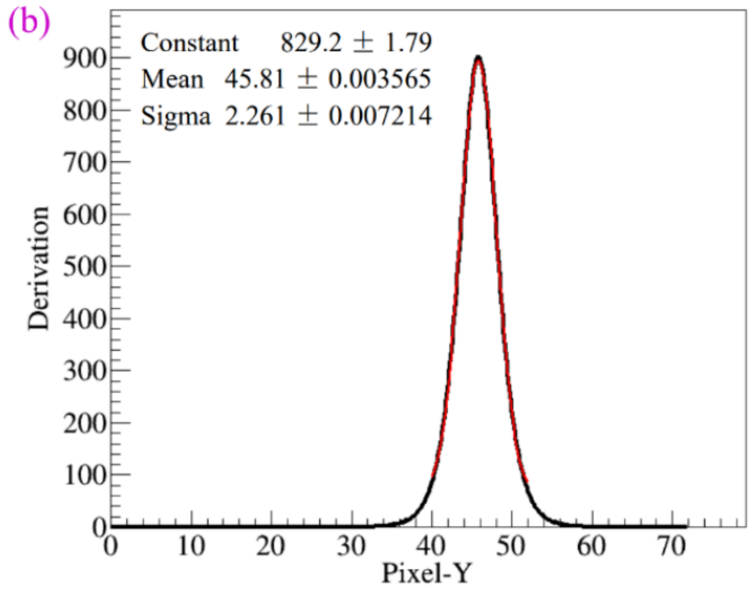
Energy resolution:





Position resolution:





~180 um position resolution

Simulation Framework

- **Motivation:**

  Establish a framework for Migdal electron and Ion measurement simulation and offline data analysis

✓ **Simulate Migdal effect interaction with detector**

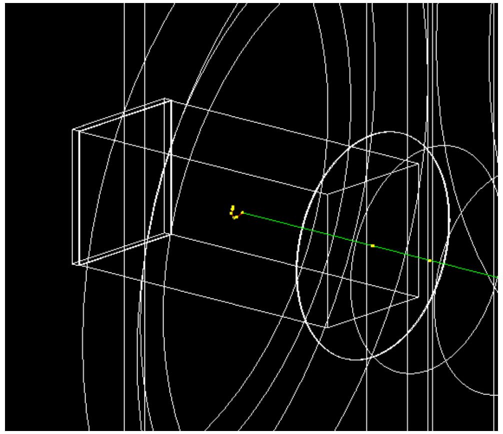
➢ **Simulate different interaction**

➢ **Provide energy deposit**

✓ **Analog detector digital readout**

➢ **Simulate electron drifts, multiplies, collected procession**

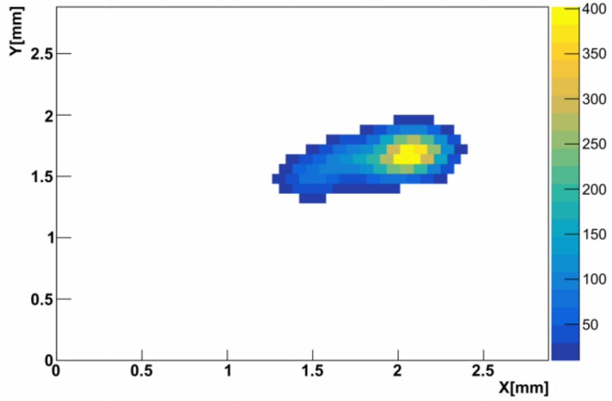
➢ **Output file for data analysis and reconstruction algorithm**



Detector modeling

Simulation parameters:

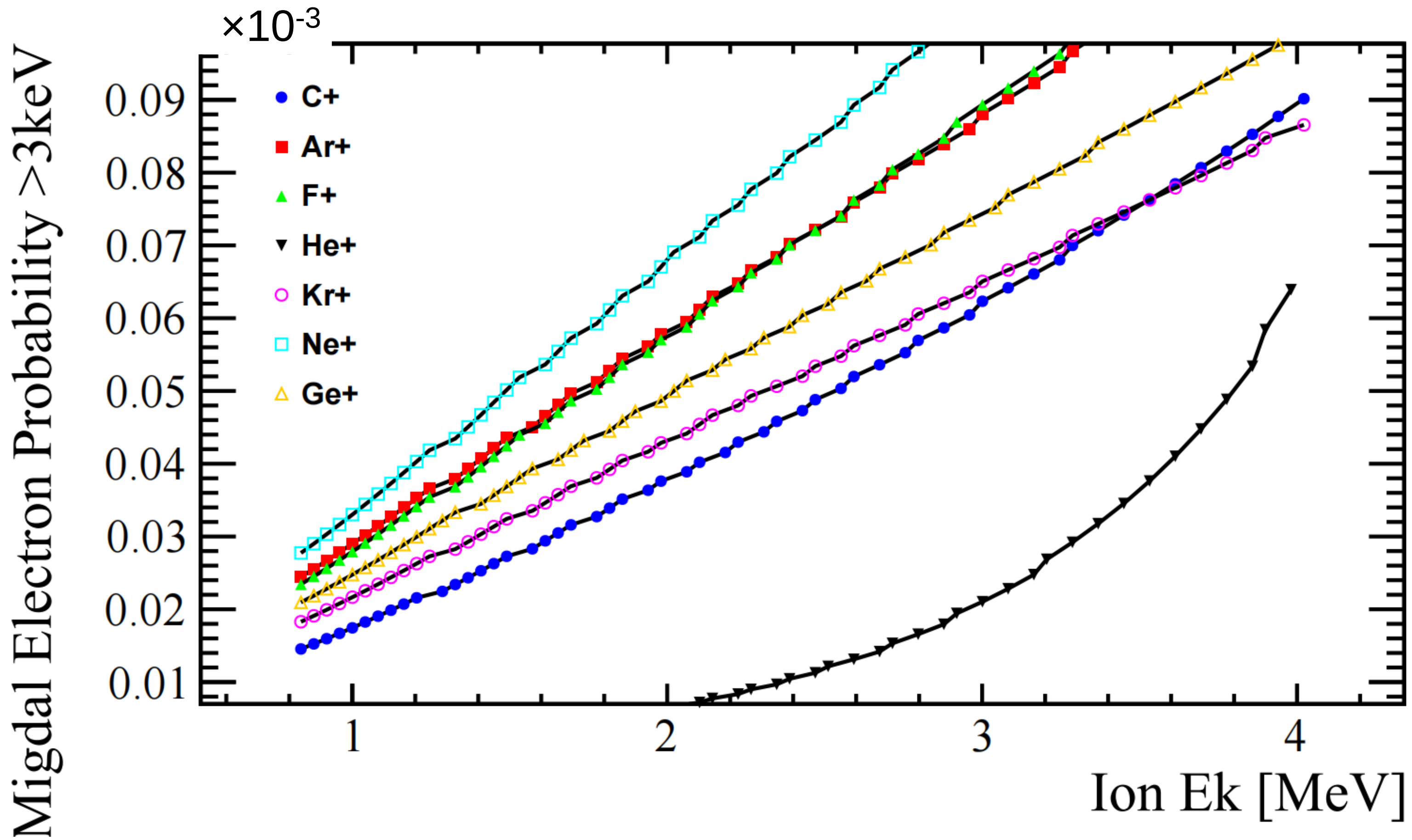
Parameters	Description	Value
D_{Drift}	Transverse diffusion coefficent within drift region	$0.0084\sqrt{\text{cm}}$ @ $1\,\text{kV/cm}$
D_{Induce}	Transverse diffusion coefficent within induce region	$0.0177\sqrt{\text{cm}}$ @ $2\,\text{kV/cm}$
v_{Drift}	Drift velocity within drift region	$3.4E+03\,\text{m/s}$ @ $1\,\text{kV/cm}$
v_{Induce}	Drift velocity within induce region	$6.8E+03\,\text{m/s}$ @ $2\,\text{kV/cm}$
$W_{Average}$	Average ionization energy	$28\,\text{eV(He)}/41\,\text{eV(DME)}$
f	Fano factor[P+97]	0.3(DME)
η_{Hole}	Hole entry efficiency	0.96
η_{Bottom}	Bottom surface adsorption rate of GMCP	0.26
η_{Collect}	Charge collection efficiency	0.11 for Topmetal-II$^-$
δ_{GMCP}	Electron multiplication factor	2×10^3 @ $37.5\,\text{kV/cm}$



Track simulation

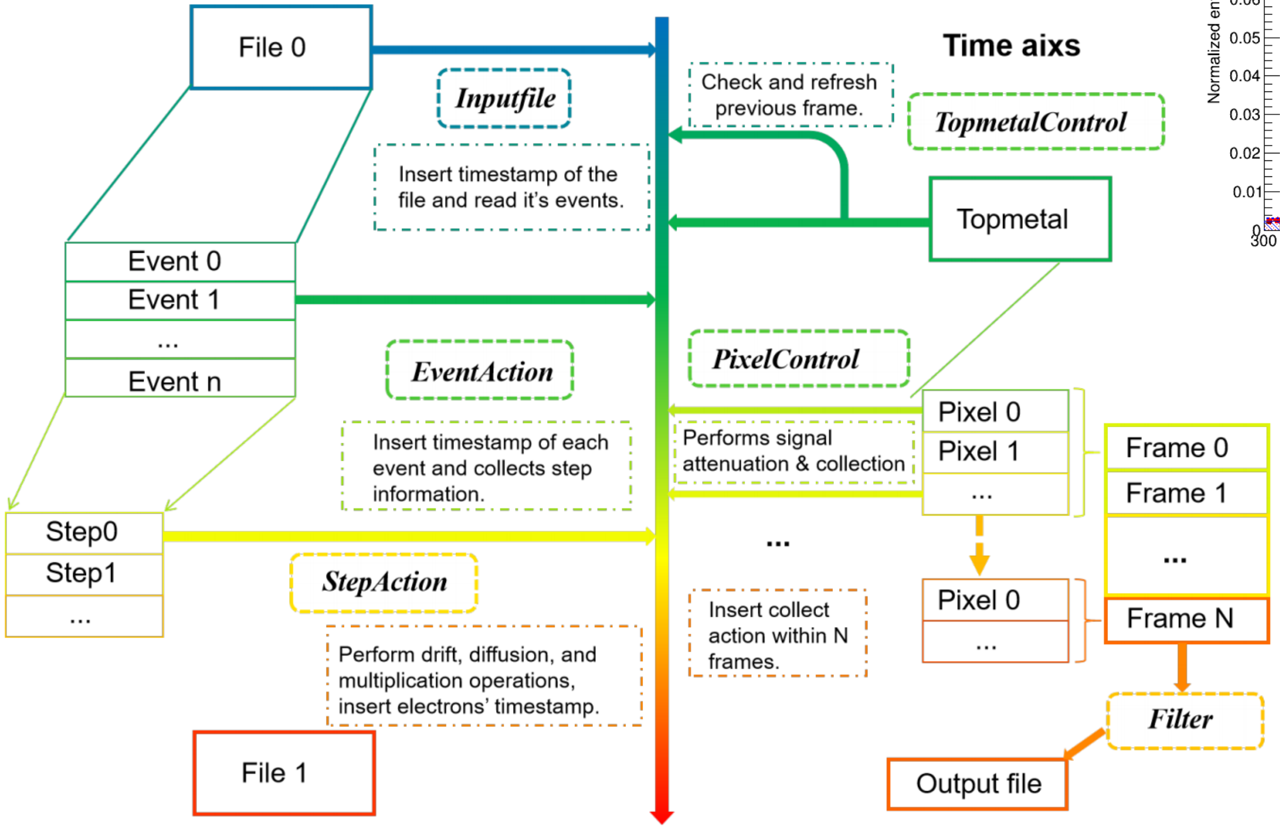
Simulation

- The cross sections for nuclear interaction and electromagnetic interaction are from Geant4
- The theoretical Migdal cross sections for Ar/C/F/Ge/He/Kr/Ne/Si/Xe nuclei are available.

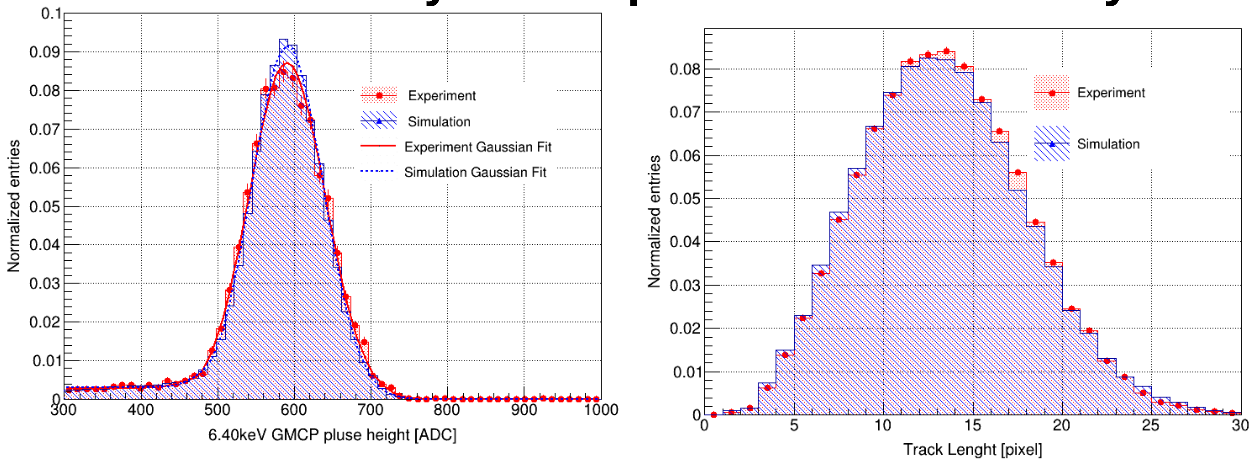


Digitization

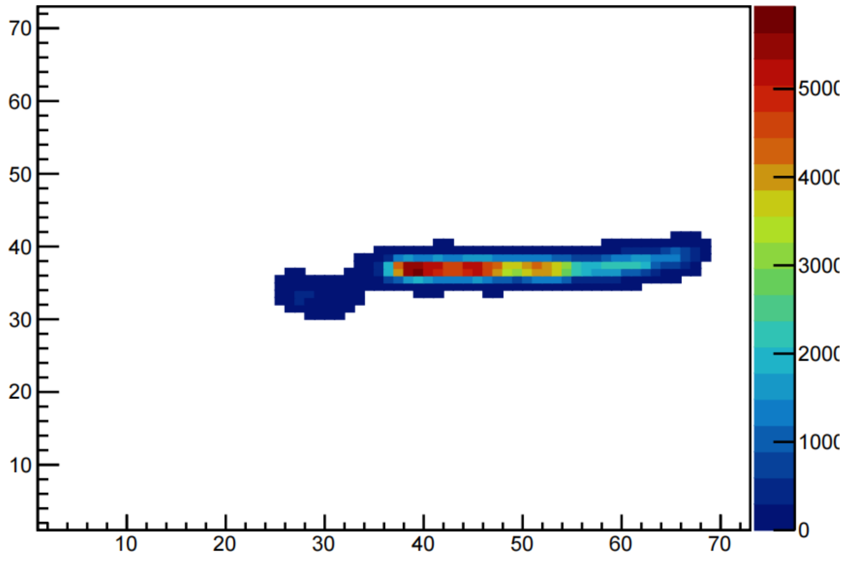
- **The digitization is entirely based on the electronic readout logic design.**



The consistency with experimental data nicely



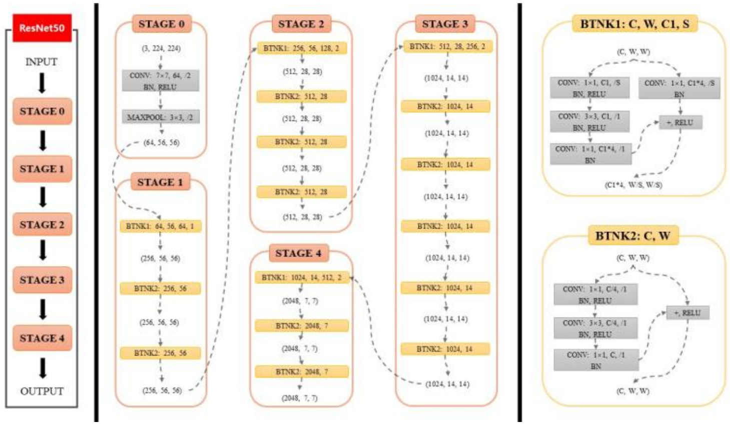
Electron Ek: 5.2500 keV, Ion Ek: 0.2300 MeV

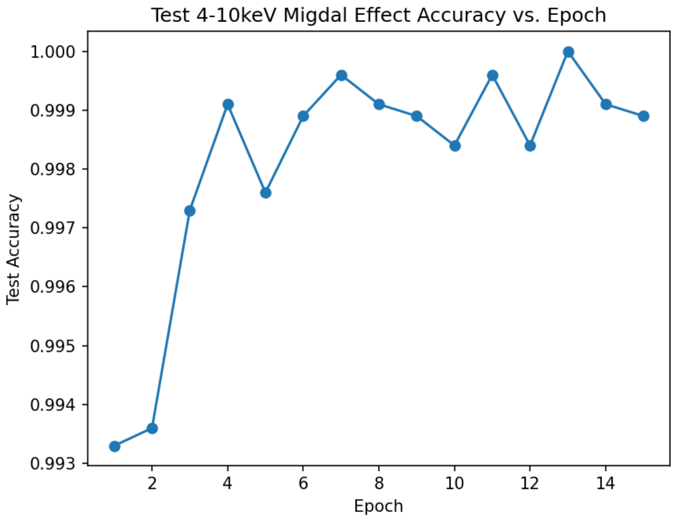


A simulation example

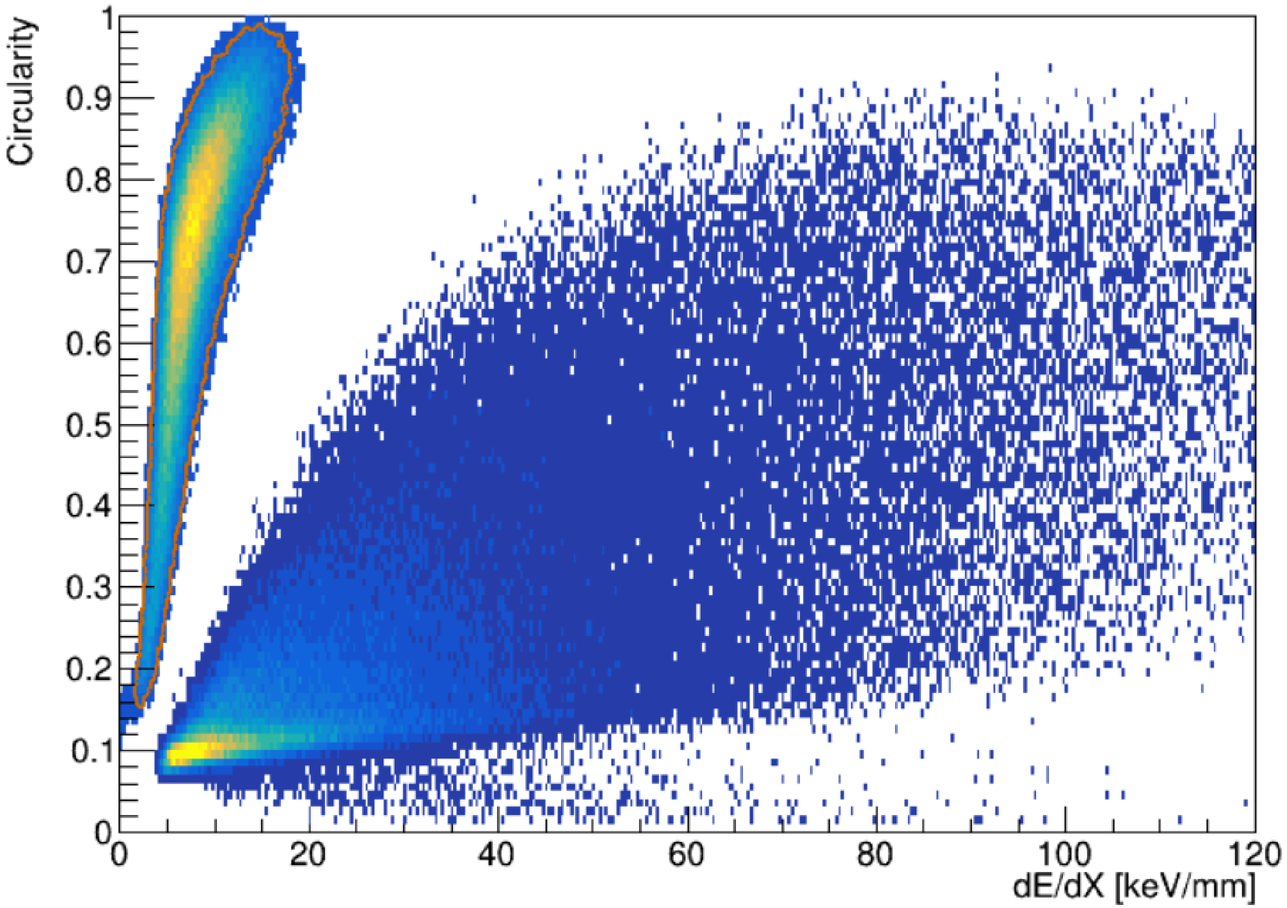
Reconstruction & Selection

- ✦ **ResNet50 neural network trained based on simulated data for Migdal instance identification.**

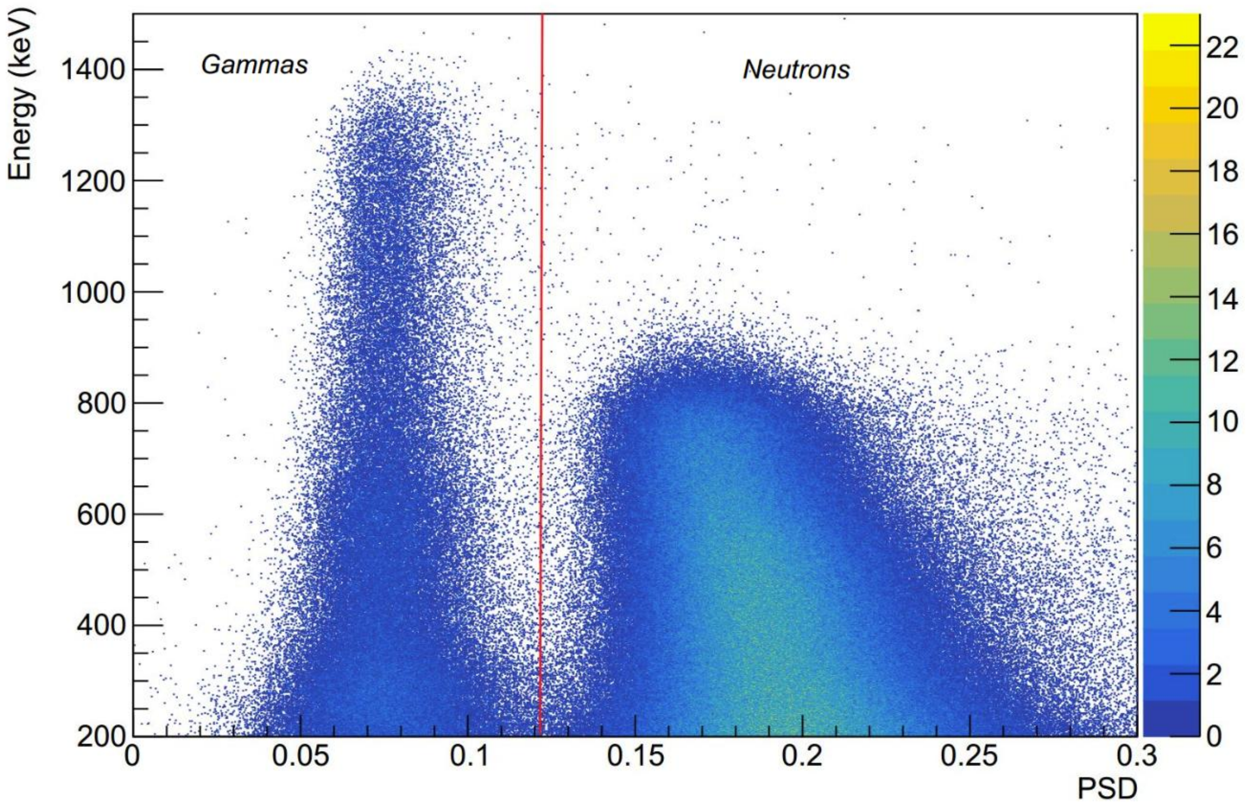




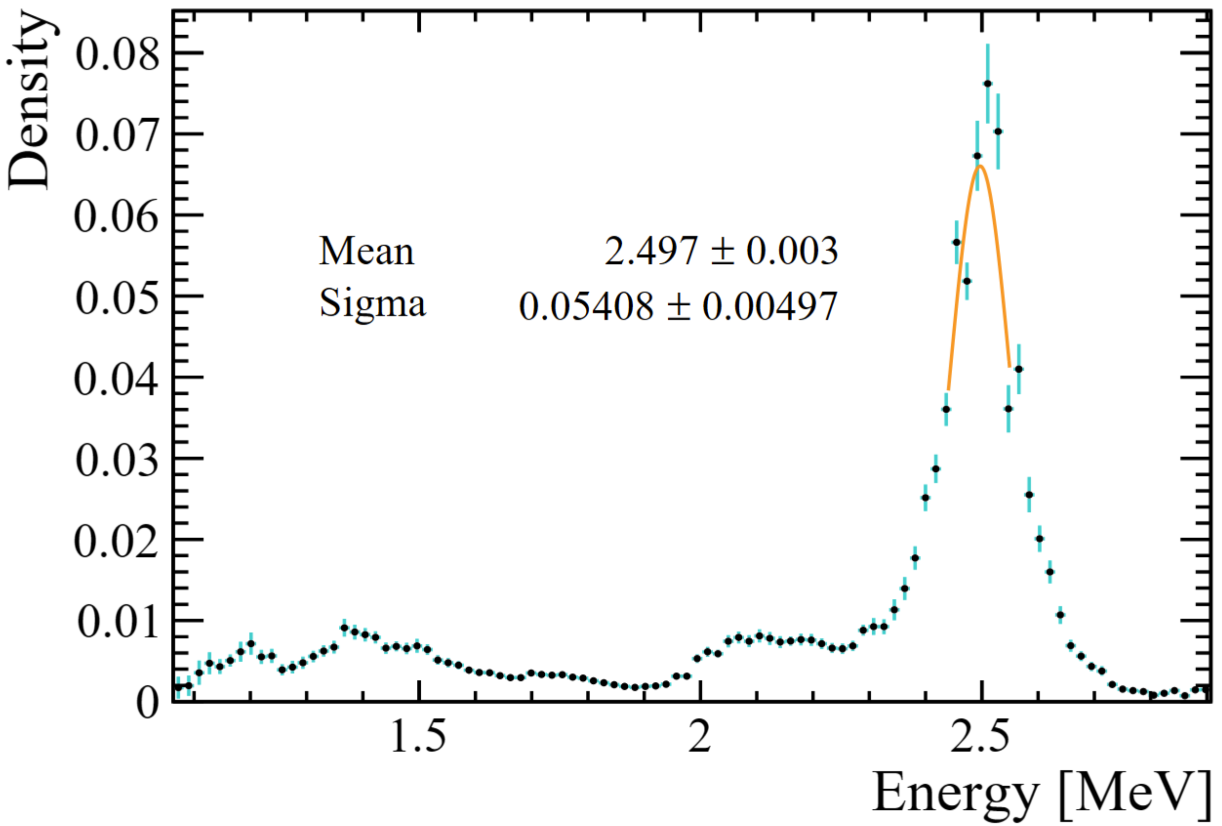
- A few keV electrons and recoiling nuclei bear distinguished features in circularity and dE/dx.



D-D source Monitor

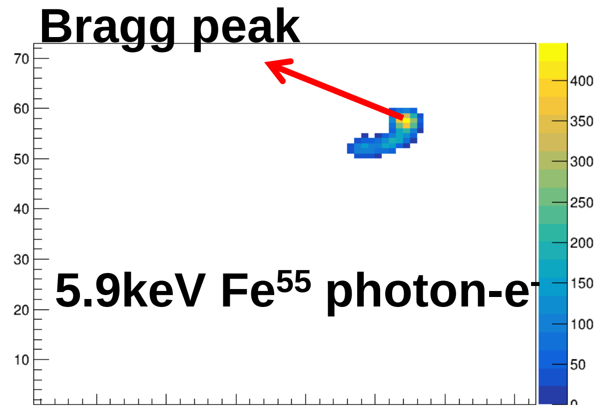


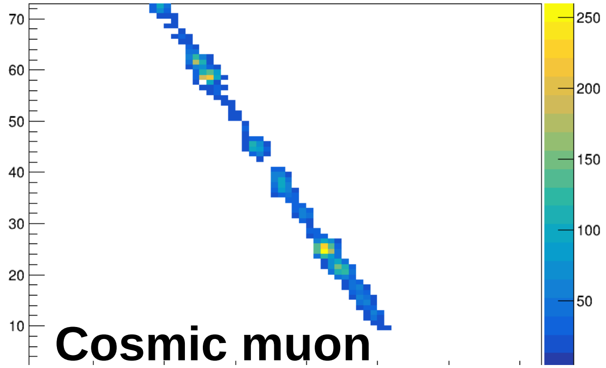
Environmental gamma and neutron identification.

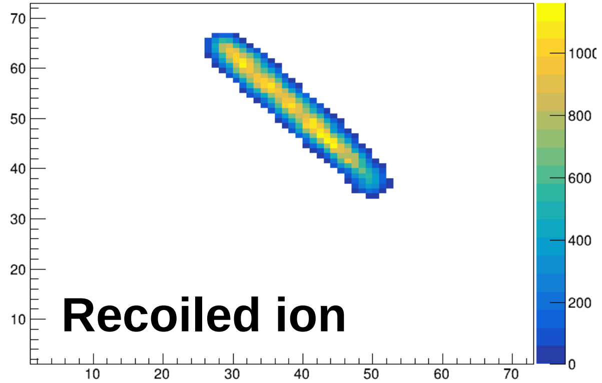


The results of neutron spectrum analysis.

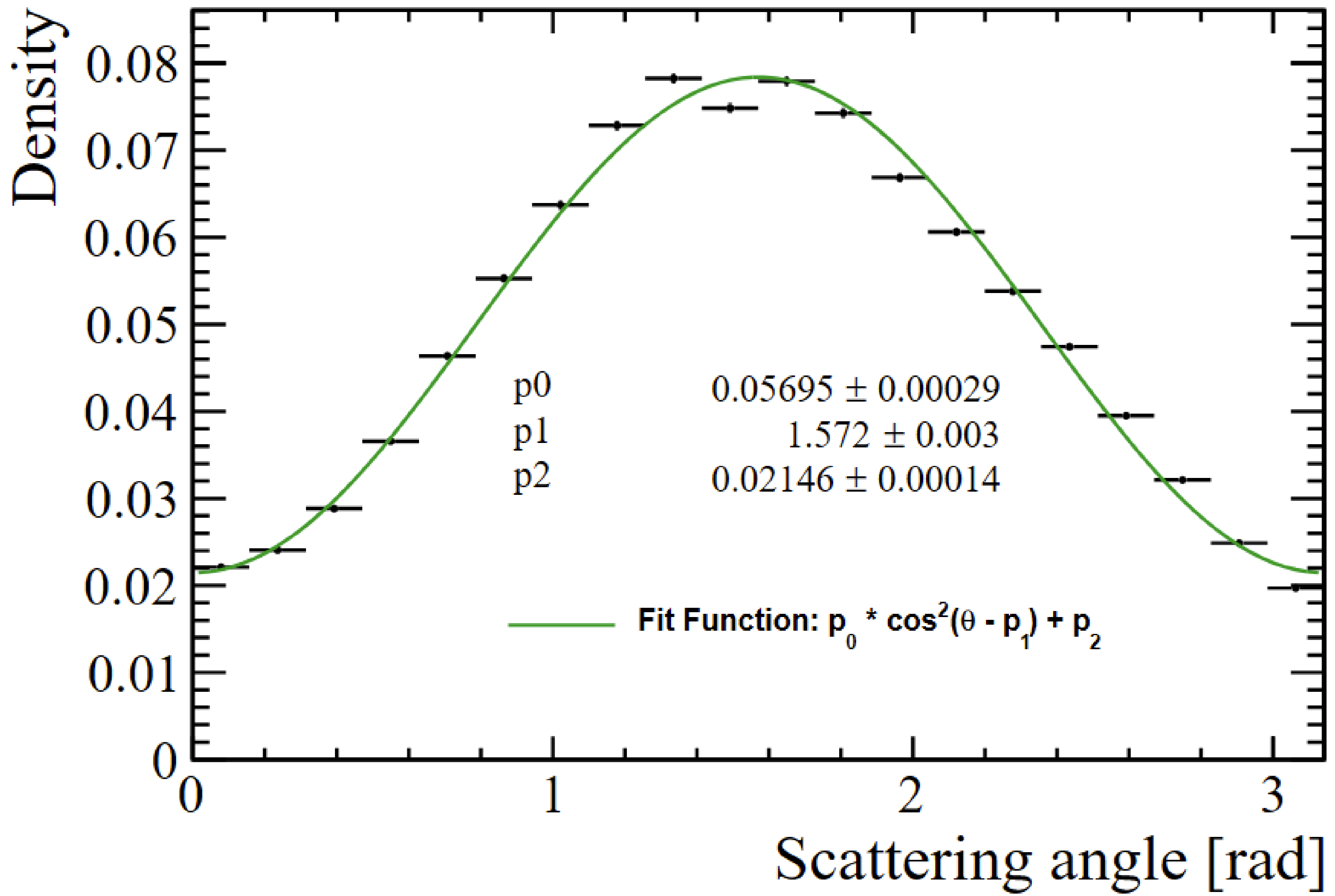
Track Imaging



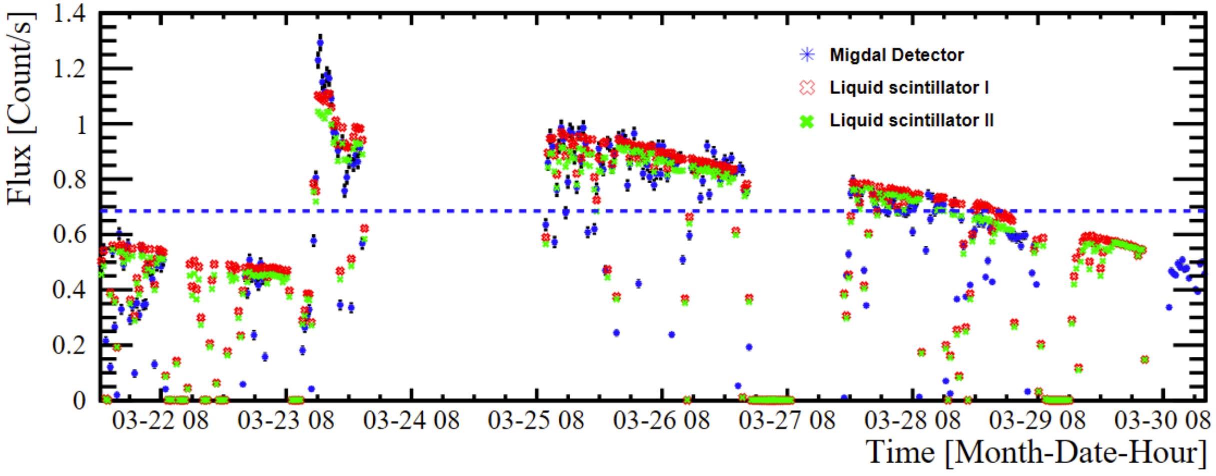


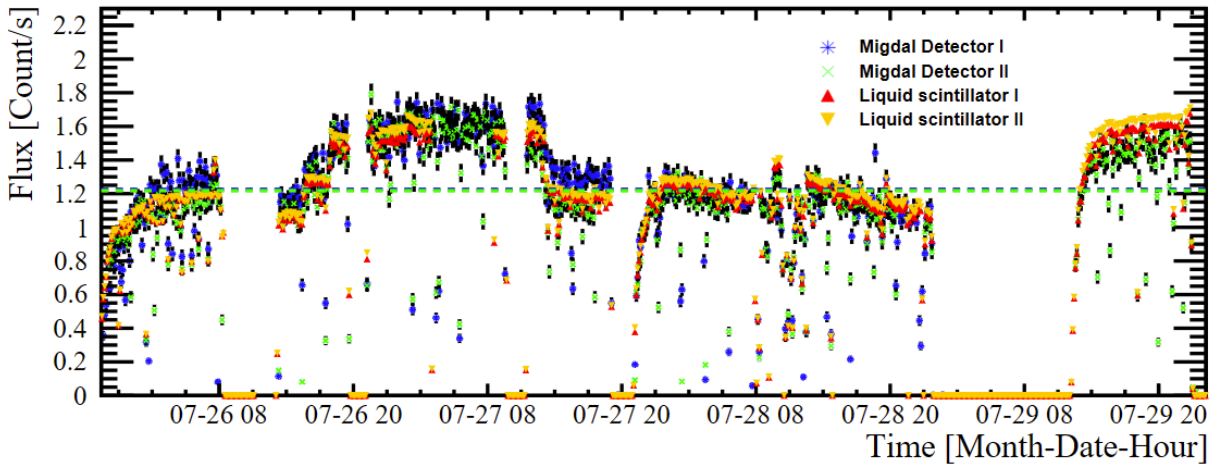


The angular distribution of recoil nuclei scattering

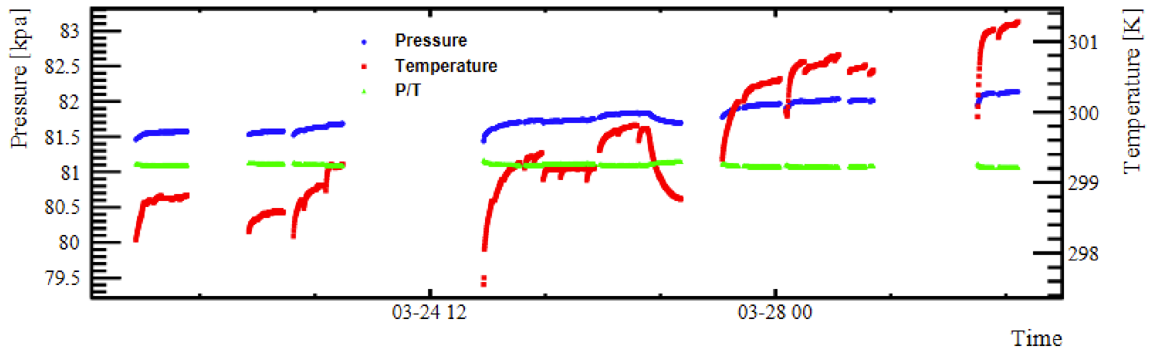


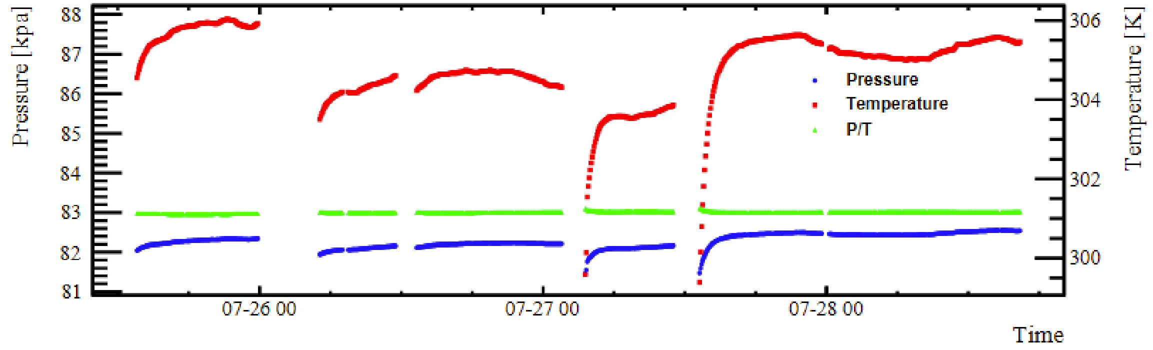
D-D flux monitor

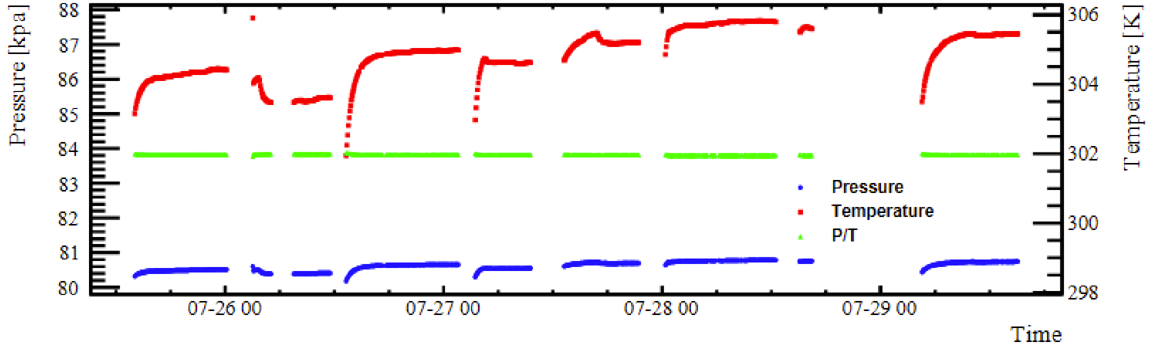




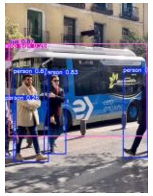
Detector gas monitoring

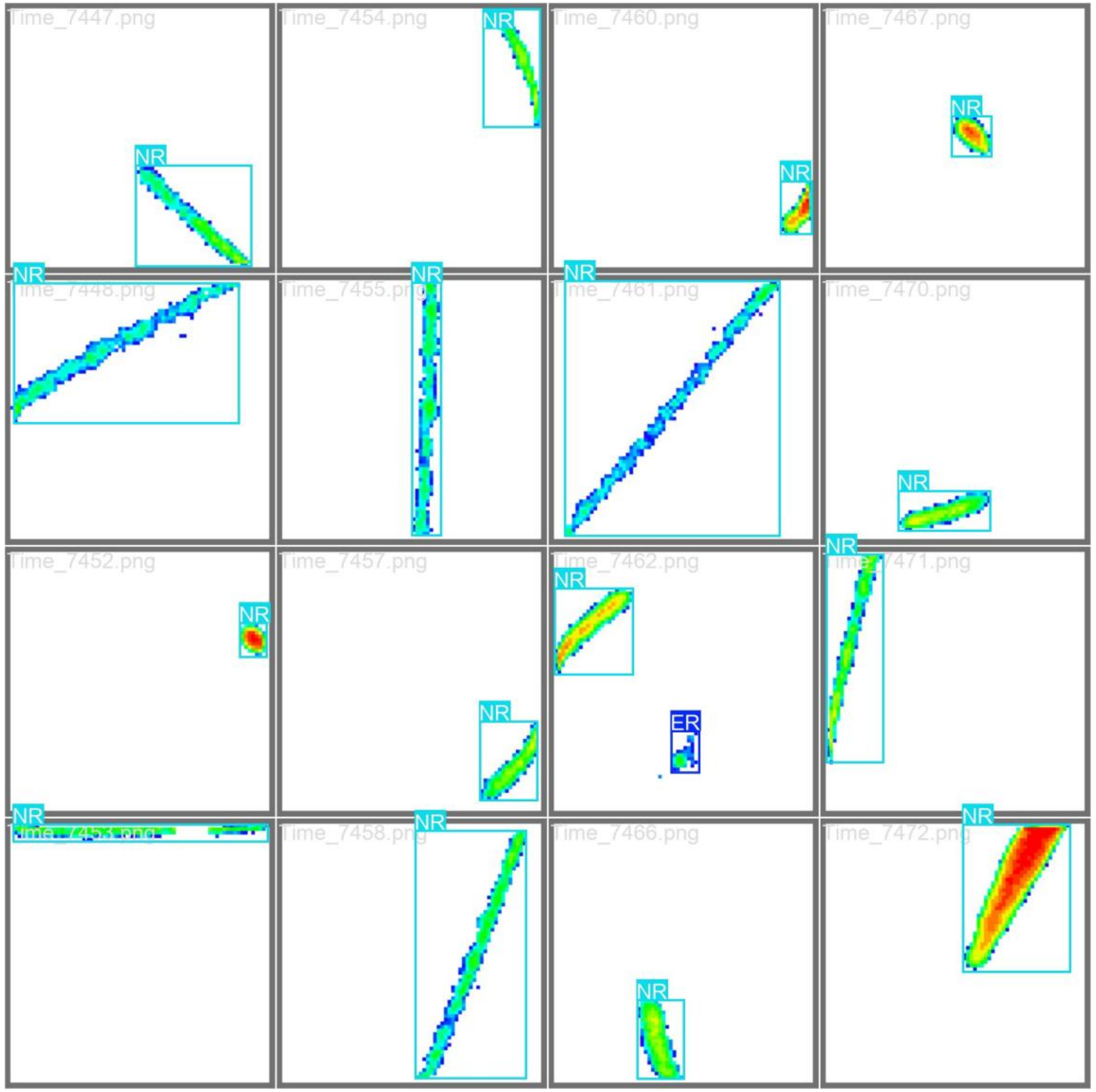






Track identify-YOLOv8

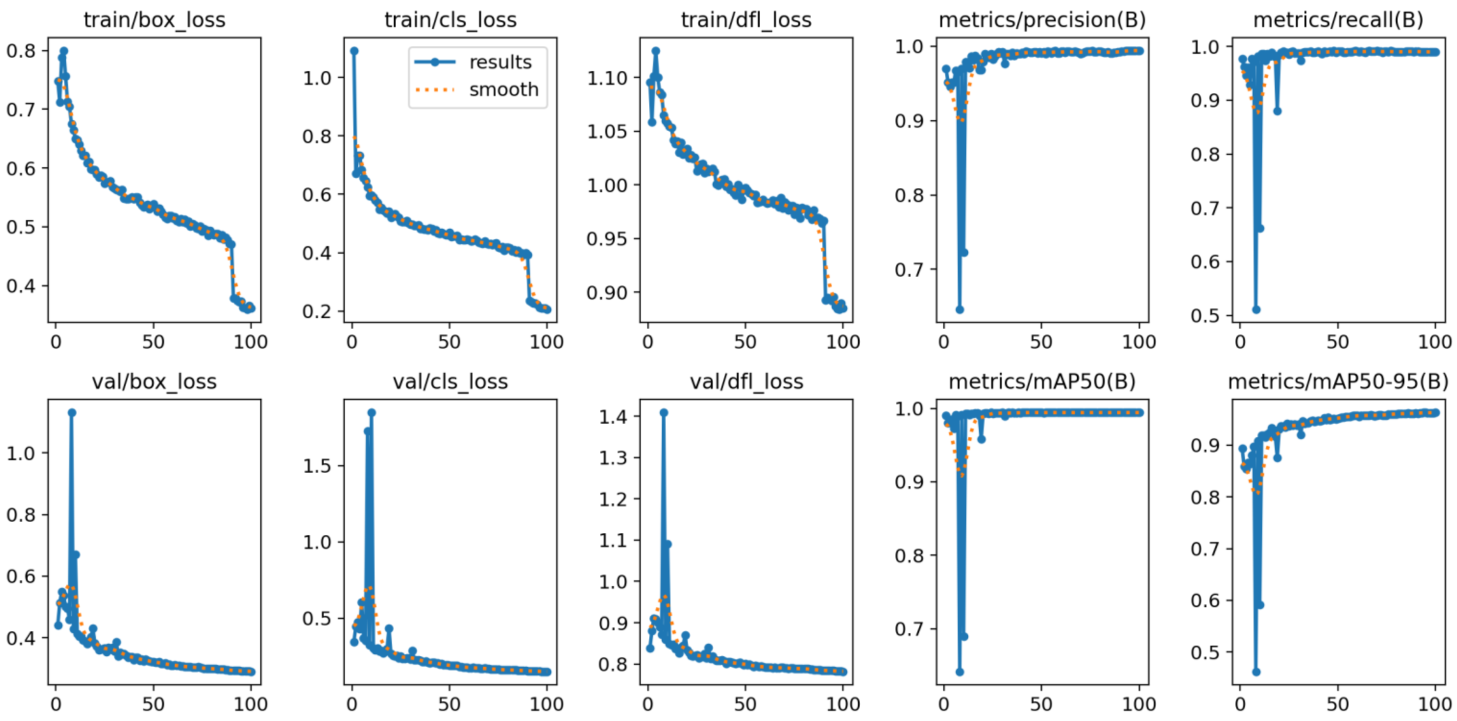


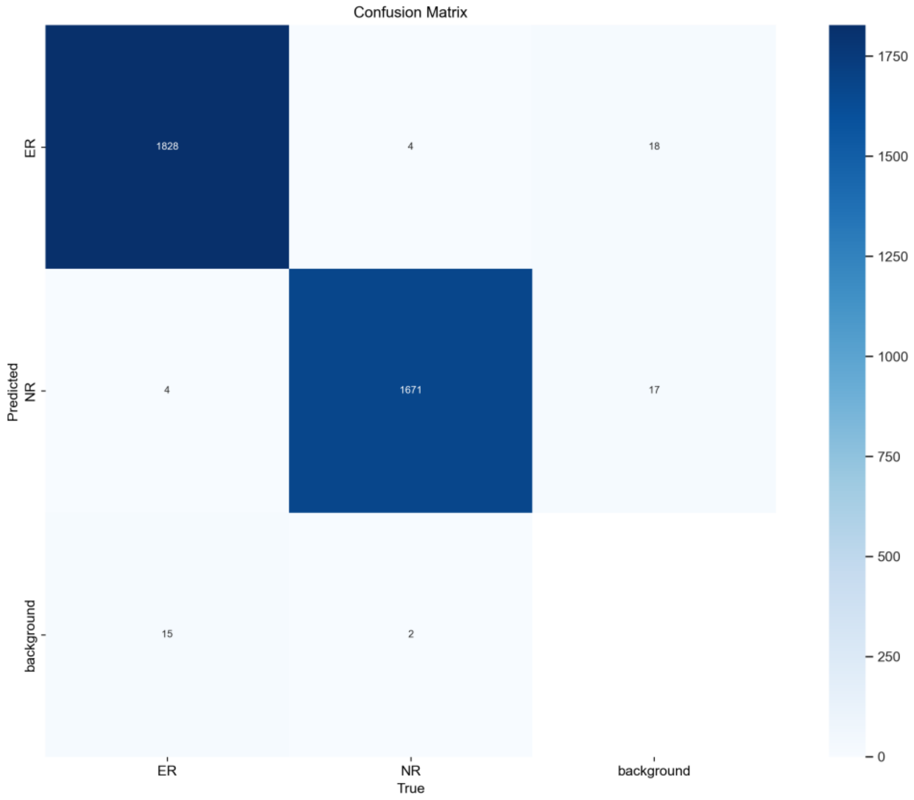


Track PID and Segmentation

YOLOv8 performance

We train YOLO with experimental data of 1500 iron track images and 1500 NR track images.



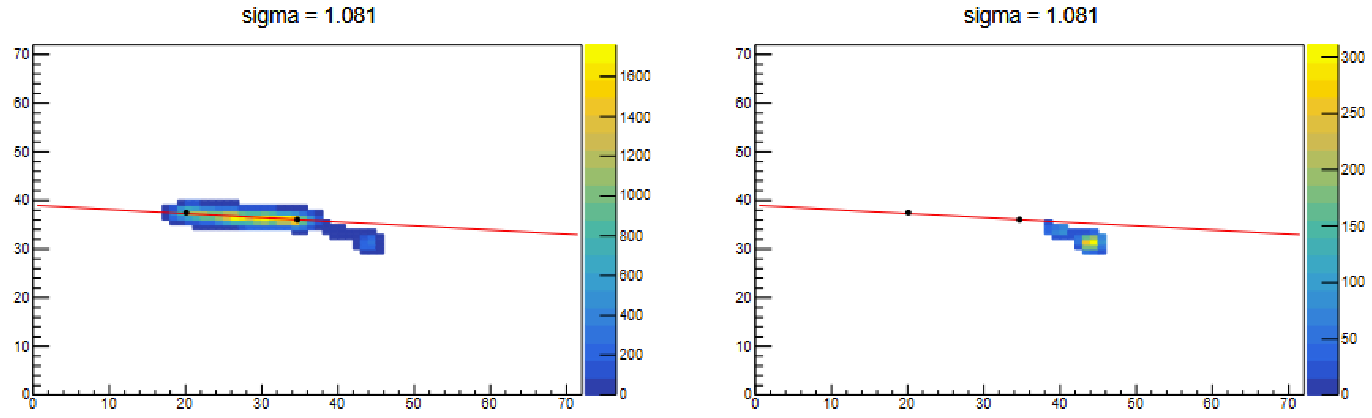


Training Convergence

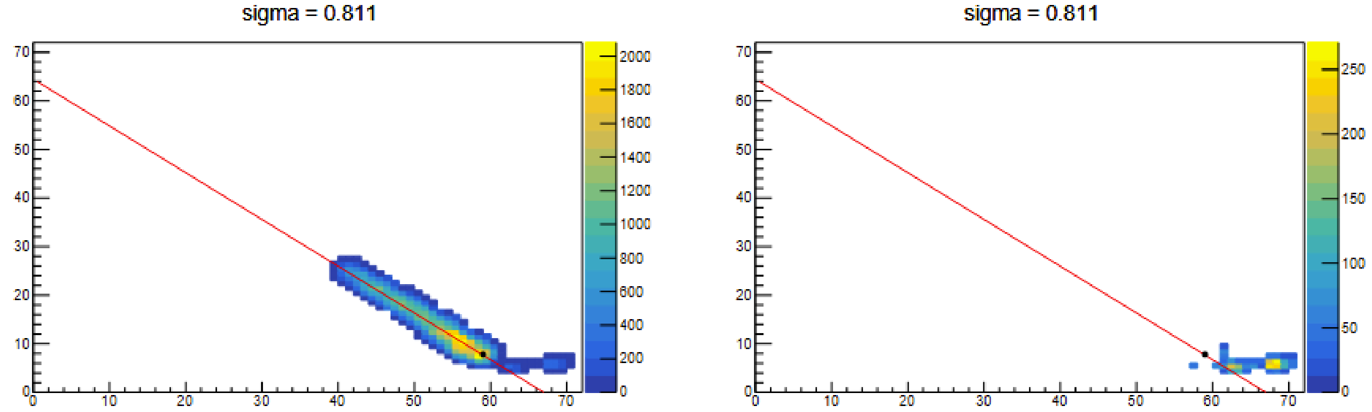
High Accuracy

Migdal event selection algorithm

1. Search for the nucleon vertex through recursive iteration.
2. Fit the nucleon tracks and subtract them from the image.
3. Search for the electron vertex through recursive iteration.
4. Determine whether the electron vertex is adjacent to the nucleon vertex.



a. Simulated event (before remove NR track) b. Simulated event (after remove NR track)

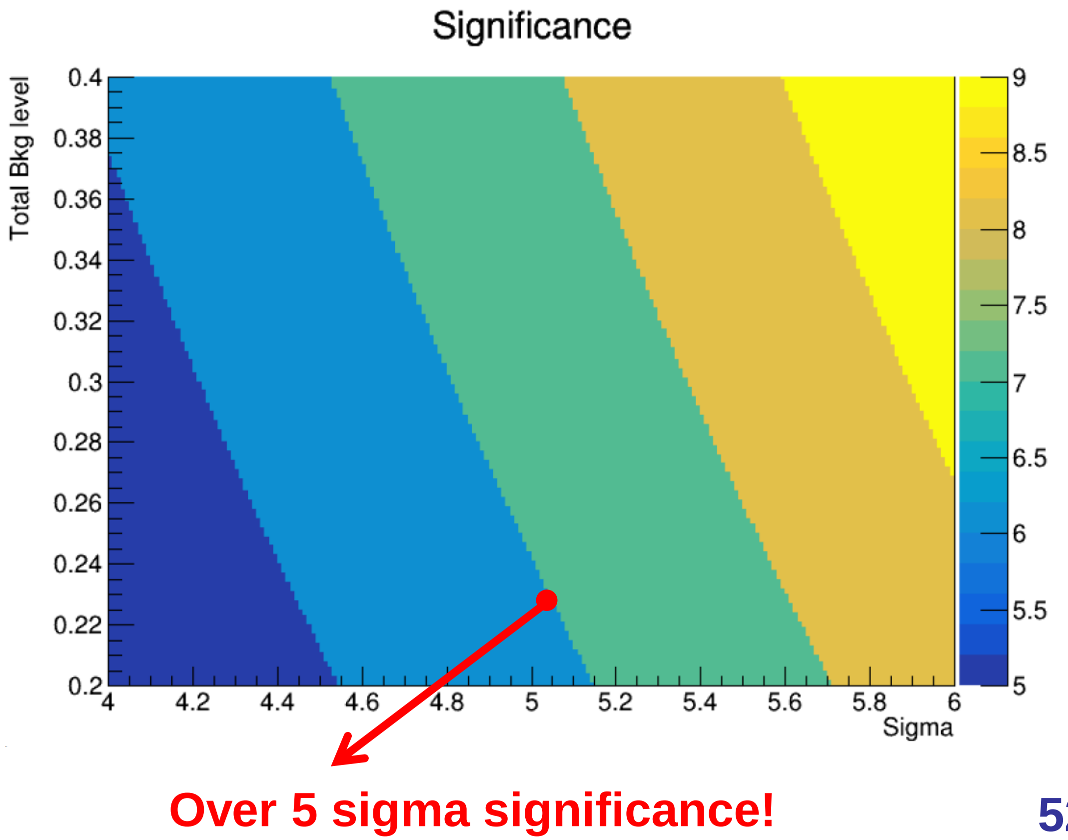


Cross-Section calculation and significance estimation

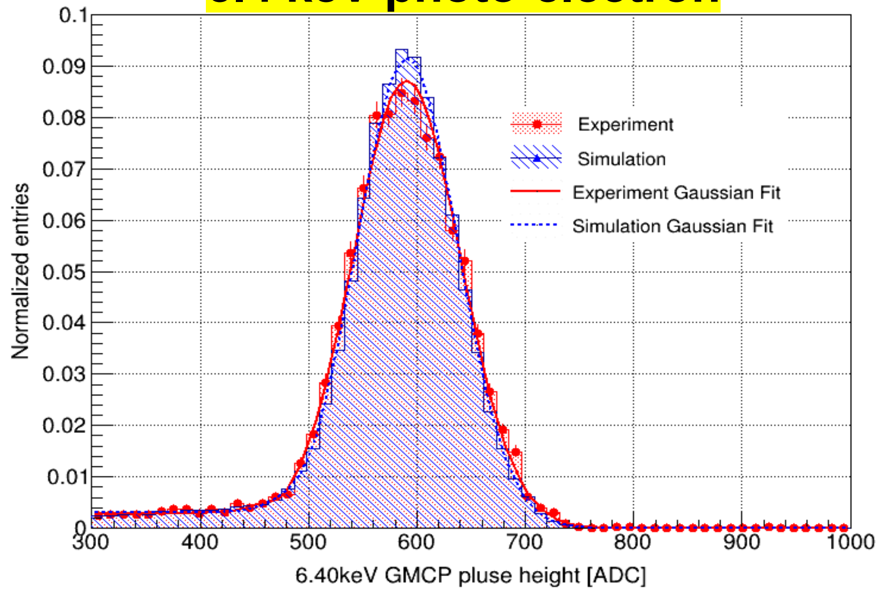
$$P_{Migdal}(5\text{keV} < \text{ER} < 10\text{keV}, \text{NR} > 35\text{keVee}) = \frac{\left(\frac{n_{obs} - n_{bg}}{\varepsilon_{acc}\varepsilon_{NR}\varepsilon_{ER}}\right)}{\left(\frac{n_{tot}^{NR}}{\varepsilon_{acc}\varepsilon_{NR}}\right)} = \frac{(n_{obs} - n_{bg})}{\varepsilon_{ER} n_{tot}^{NR}}$$

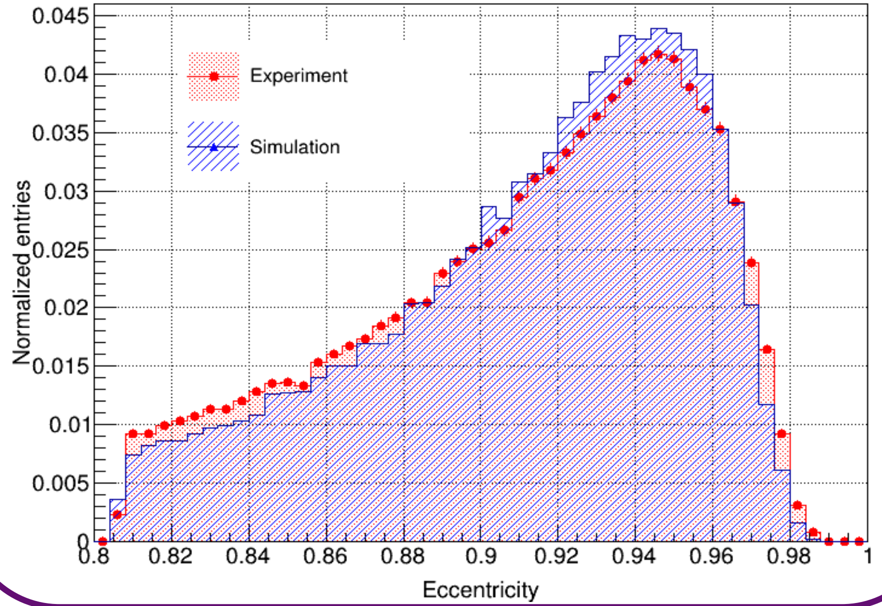
	Efficiency/Count	Statistical Error	Systematic Error
Efficiency ε_{ER}	14.4%	±0.1%	±1.9%
n_{tot}^{NR}	8.17×10^5	±903	±35880
n_{obs}^{ER}	6	±2.449	
n_{obs}^{bg}	0.229	±0.032	±0.043

Cross-section: $4.91^{+2.56}_{-1.87} \times 10^{-5}$

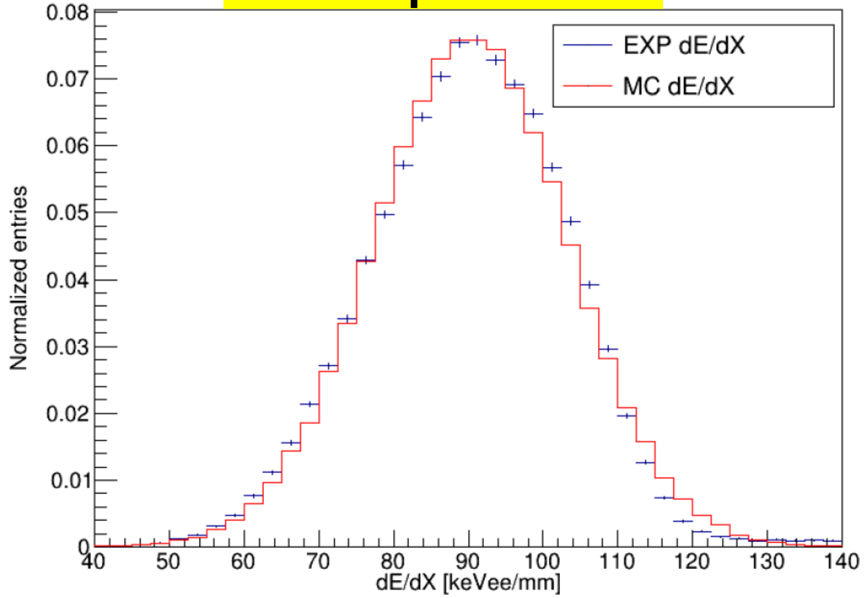


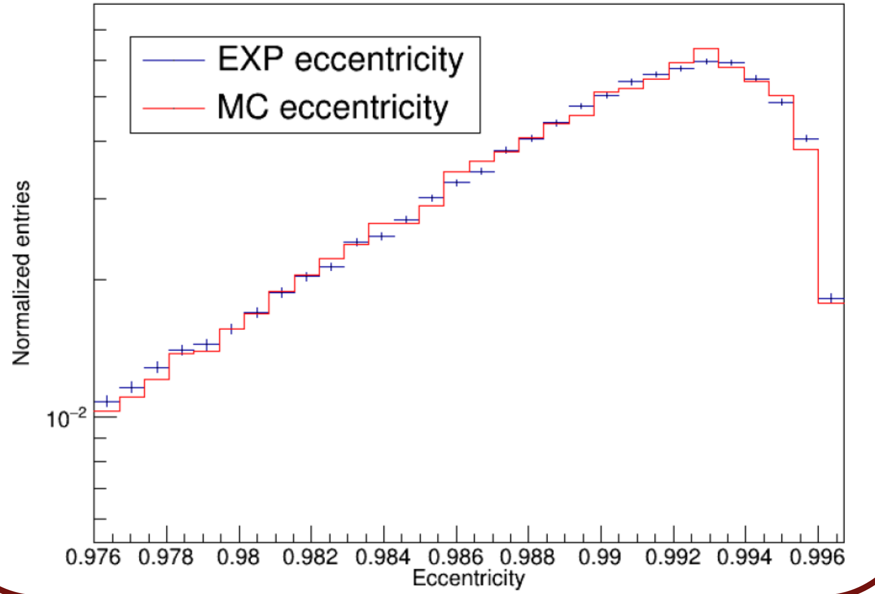
6.4 keV photo-electron





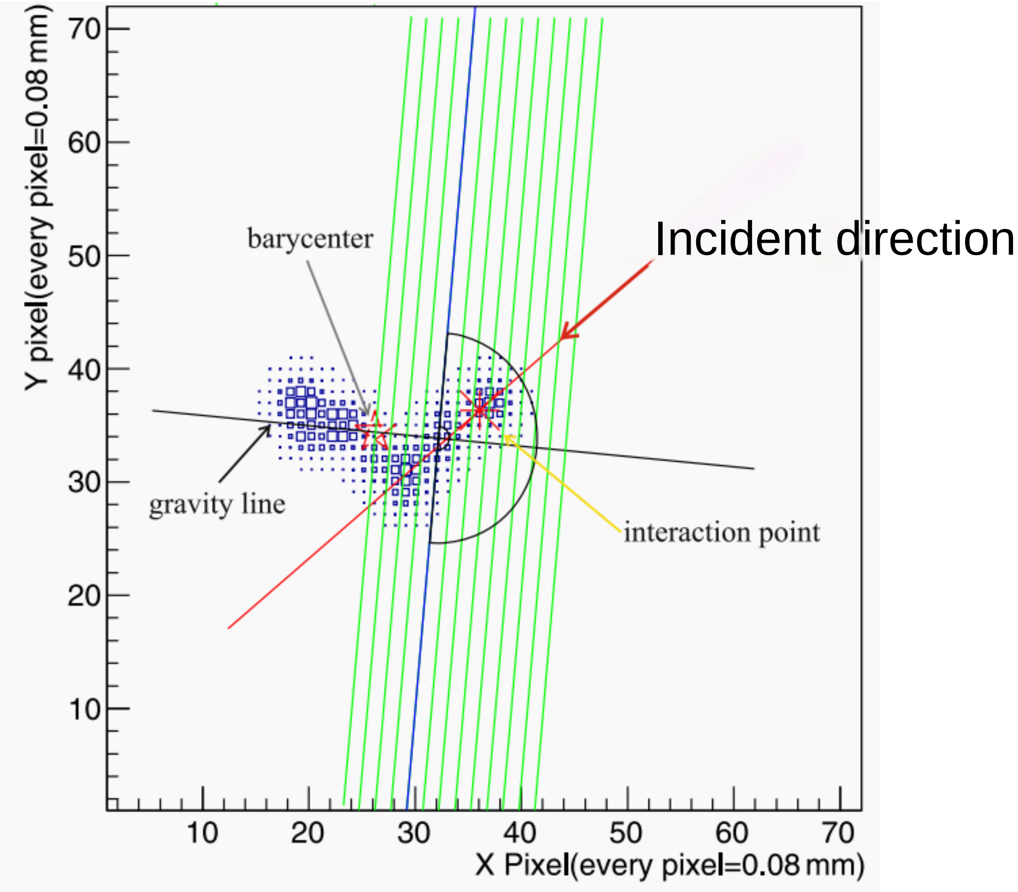
^{241}Am alpha source



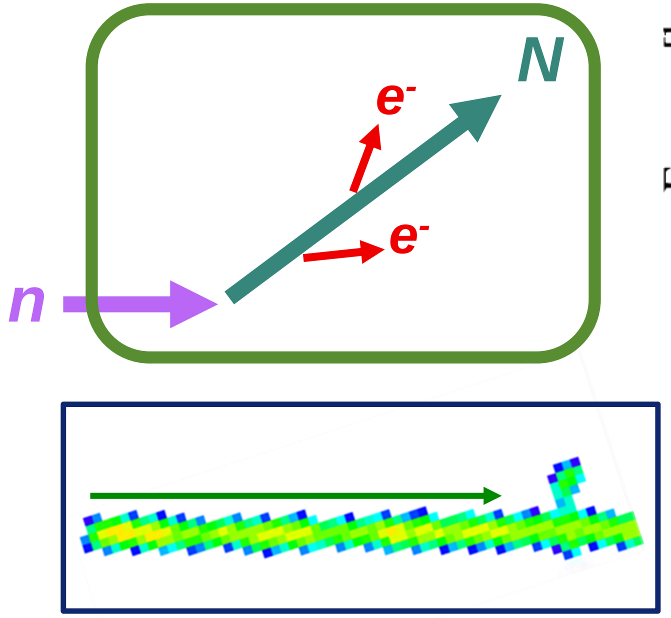


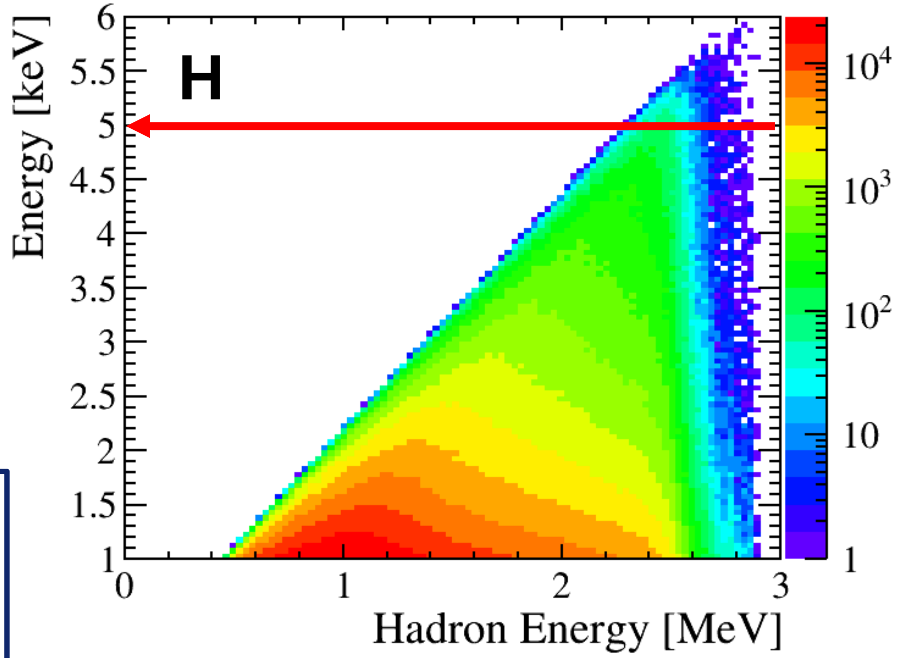
Adaptive cutting algorithm

- Determine the economic center of gravity and its trajectory based on ignition point and energy deposition.
- Calculate the sign of, M_d, $M_d = \sum_{point}(d^3 \times$

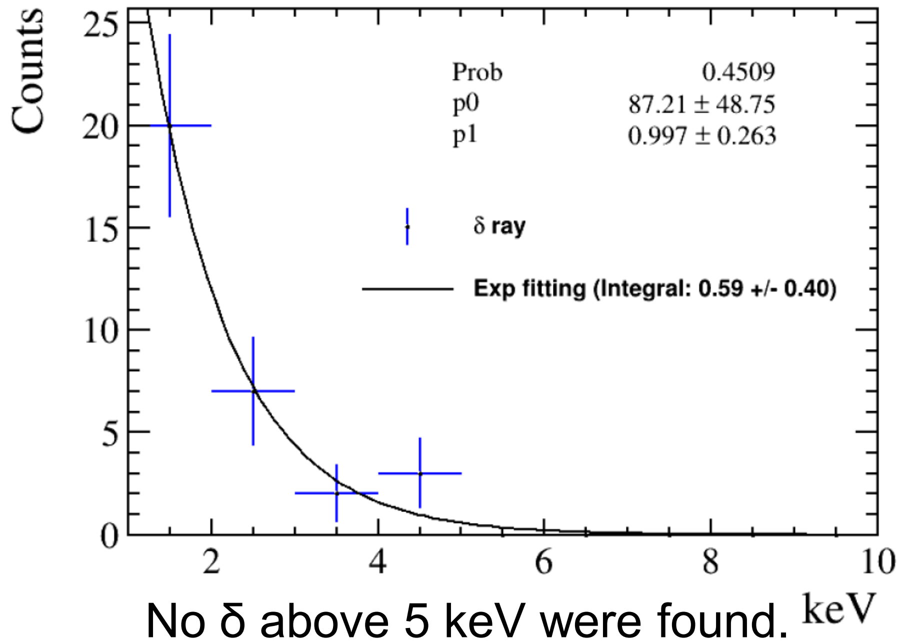


Recoil induced δ electron





Only H has the **δ electron >** 5 keV.

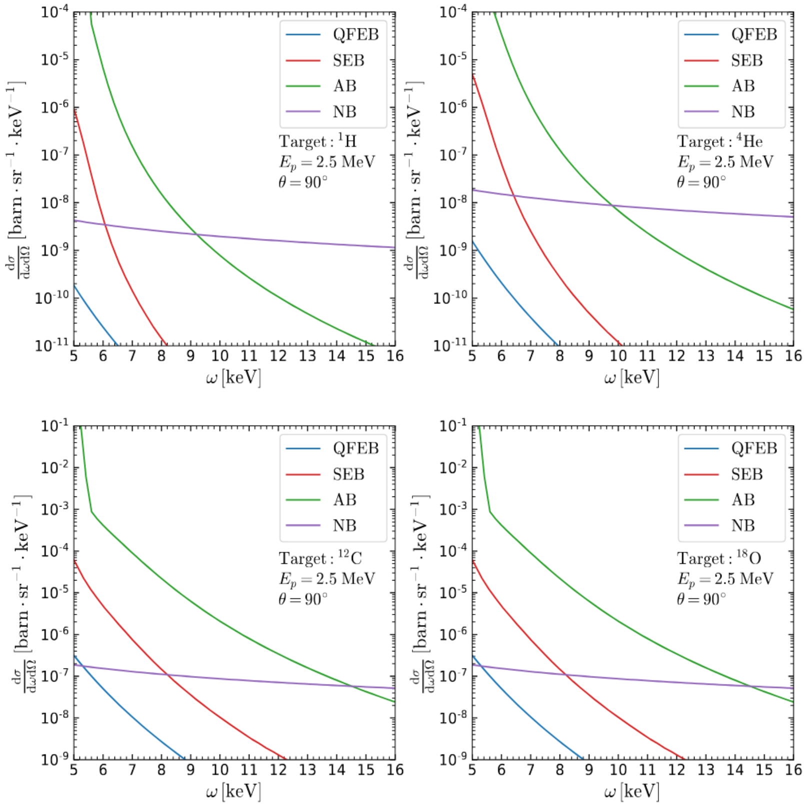


No δ above 5 keV were found.
Estimate by extrapolating from the exponential fit

- **Consider the selection efficiency for δ-electrons.**
- **Finally get: 0.035±0.023(stat.)**

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.



ratio of brem photons(E>5keV) and NR

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}

Numb of photoelectron from simulation

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.

Muon induced δ ray

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

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

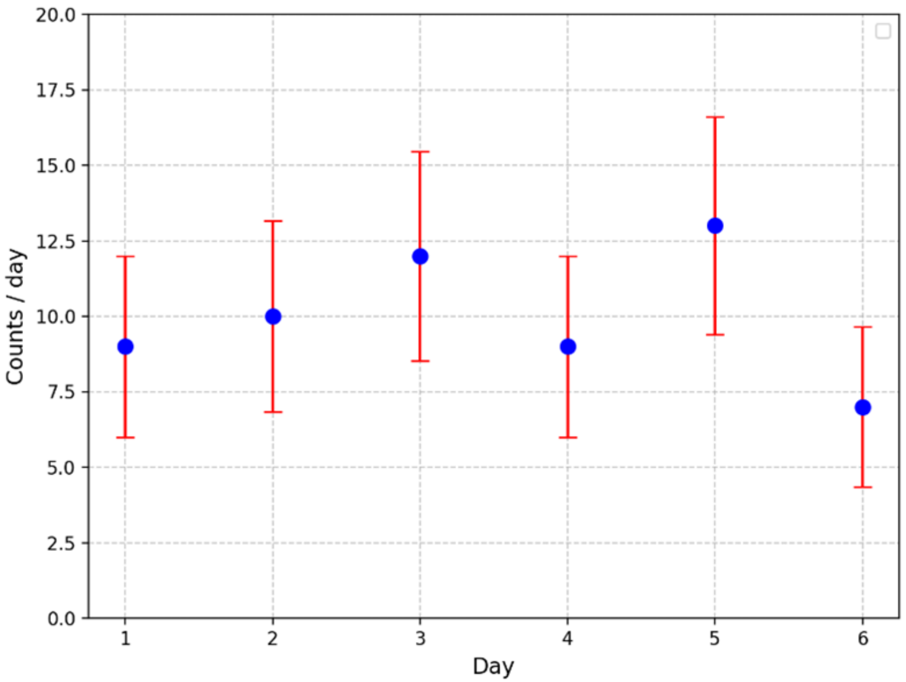
- **Set Nuclear Recoil Rate Benchmark and Calculate δ-ray Ratio**

  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}.

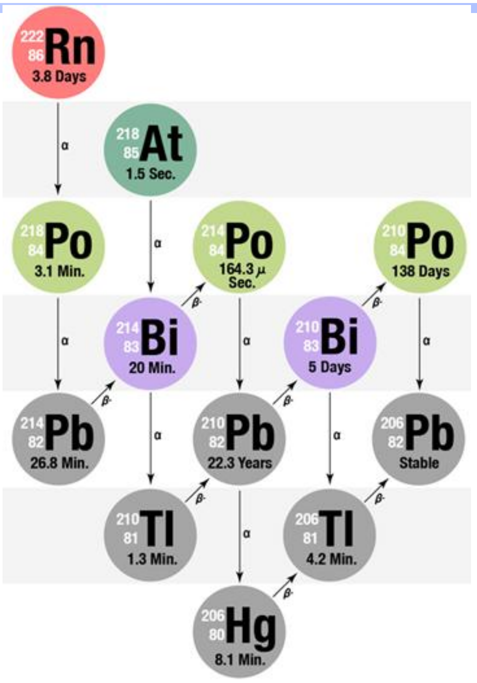
- **Considering random track coincidence**
- **Include detector's muon exclusion efficiency**

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

Trace contaminants



The detector's alpha decay count rate



The decay chain of ^{222}Rn

- The working natural abundance:
  - ^{3}H:$(6.38 \pm 6.38) \times 10^{-8}$ Bq
  - ^{14}C:$(4.58 \pm 4.58) \times 10^{-5}$ Bq
- β decay between 5-10 keV:
  - ^{3}H:$(2.29 \pm 2.29) \times 10^{-8}$ /s
  - ^{14}C:$(2.59 \pm 2.59) \times 10^{-6}$ /s

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

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

Combined with the natural abundance values of the working gas:

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

Electron momentum transfer models

✦ a. The approximate treatment of the Original Migdal's method

Nuclear rest frame, the electronic cloud state: $|\Phi'_{ec}\rangle = e^{-im_e \sum_i \mathbf{v}\cdot\hat{\mathbf{x}}_i} |\Phi_{ec}\rangle$

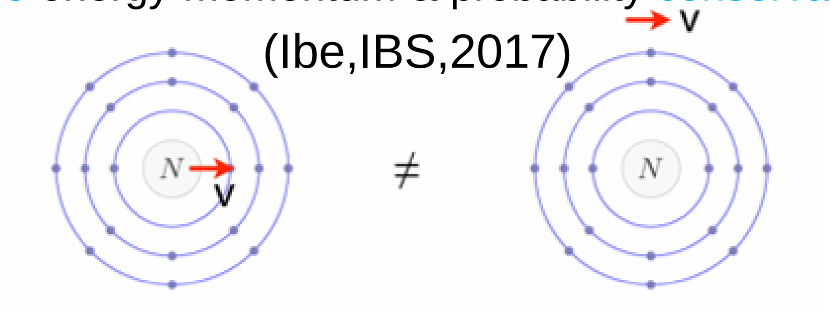
Nucleus recoil

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

Ionized eigenstate

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

(Ibe,IBS,2017)



- b. From Nuclear Recoil to Atomic Recoil (Ibe, 2023)

$$iT_{FI} \simeq F_A(q_A^2)\mathcal{M}(q_A^2) \times Z_{FI}(\mathbf{q}_e) \times i(2\pi)^4 i(p_F - p_I)$$

Electron cloud transition

Nuclear scattering

- Atom scattering coherently
- Manifested conservation relation

Ionization probability

✦Under Dirac-Hartree-Fock approximation:

$$Z_{FI}(\mathbf{q}_e) \sim \sum_{\sigma \in S_{N_e}} \mathrm{sgn}(\sigma) \prod_{i=1}^{N_e} \sum_{\alpha_i=1}^{4} \int d^3\,\mathbf{x}_i \phi^{\alpha_i *}_{o^F_{\sigma(i)}}(\mathbf{x}_i) e^{-i\mathbf{q}_e\cdot\mathbf{x}_i} \phi^{\alpha_i}_{o^I_i}(\mathbf{x}_i)$$

Orthogonality:

$$\sum_{\alpha=1}^{4} \int d^3\,\mathbf{x} \phi_o(\mathbf{x})^{\alpha *} \phi^{\alpha}_{o'}(\mathbf{x}) = \begin{cases} \delta_{nn'}\delta_{\kappa\kappa'}\delta_{mm'} & \text{(bounded)} \\ (2\pi)\delta(E-E')\delta_{\kappa\kappa'}\delta_{mm'} & \text{(unbounded)} \end{cases}$$

- Differential ionization probability

$$\frac{d}{dE_e} p^{\mathrm{i}}_{q_e}(nl \to E_e) = \frac{\omega_{n,l}}{\omega_{\max}} \sum_{\text{spins}} \left| -i\mathbf{q}_e \cdot \langle E_e \kappa' m' | \mathbf{x} | n\kappa m \rangle \right|^2$$

Migdal cross section

- Under the soft limit, the neutron migdal effect scattering cross section can be factorized into two parts:

$$\frac{d\sigma_{Migdal}}{dE_r dE_e} = \sum_i \left[\frac{d\sigma_s^i}{dE_r} \cdot \sum_{nl} \frac{dp^i(nl \to E_e)}{dE_e} \right]$$

Migdal transition probability

neutron-nucleus cross-sections
mainly elastic scattering @ 2.5MeV

Sum up for each atom
Single atom approximation for E_n

- The experiment detects the ratio of the Migdal cross-section to the neutron scattering cross-section.

$$\frac{dp_{Migdal}}{dE_r dE_e} = \frac{1}{\sigma_{tot}} \sum_i \left[\frac{d\sigma_{elastic}^i}{dE_r} \cdot \sum_{nl} \frac{dp^i(nl \to E_e)}{dE_e} \right]$$

Total cross section for n scattering

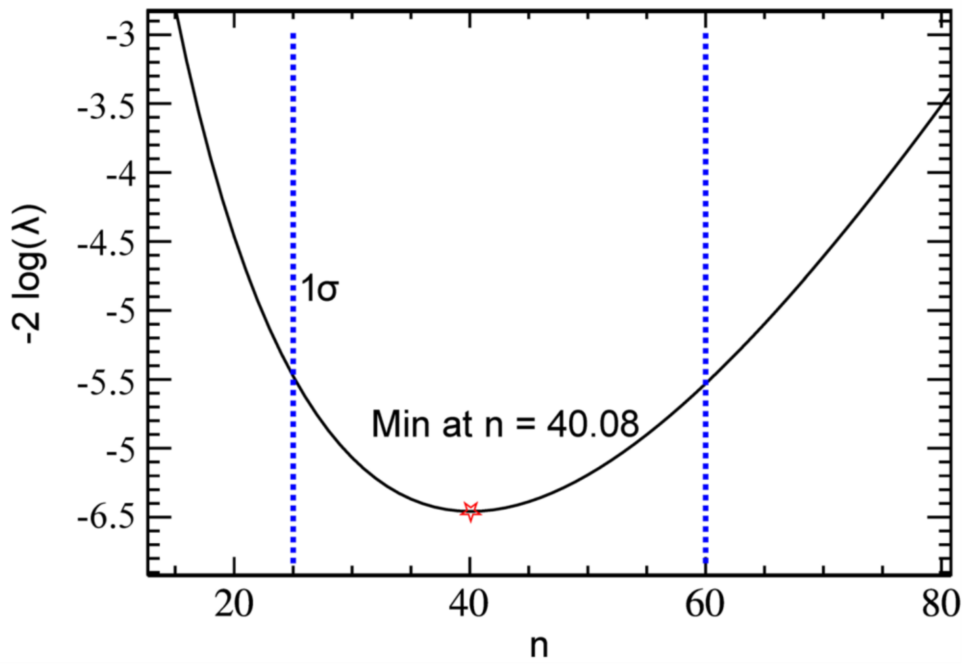
Cross Section calculation

- 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:

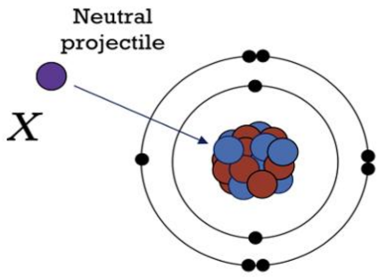
	Efficiency/Count	Statistical Error	Systematic Error
Efficiency ε_{ER}	14.4%	±0.1%	±1.9%
$n_{\text{tot}}^{\text{NR}}$	8.17×10^5	±903	±35880
$n_{\text{obs}}^{\text{ER}}$	6	±2.449	
$n_{\text{obs}}^{\text{bg}}$	0.229	±0.032	±0.043

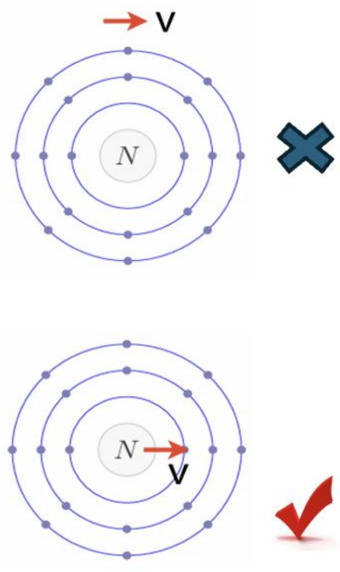


- upper/lower bounds: $\Delta P_{\pm}=\sqrt{\left(\frac{n_{min}-n_{ul/ll}}{n_{min}}\right)^2+\left(\frac{n_{\text{tot error}}^{\text{NR}}}{n_{\text{tot}}^{\text{NR}}}\right)^2}\cdot\frac{n_{min}}{n_{\text{tot}}^{\text{NR}}}$

Cross-section: $4.91^{+2.56}_{-1.87}\times 10^{-5}$

Migdal effect

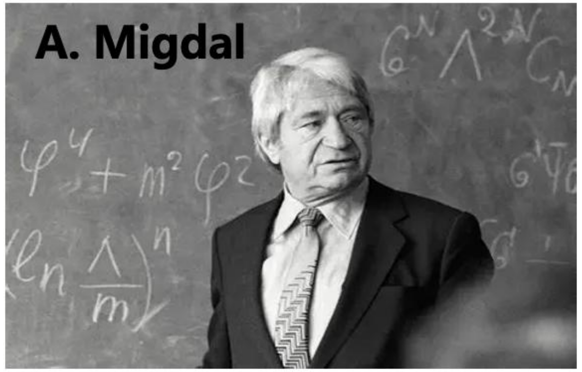




$$m_X = 1\ \text{GeV}, \quad q_N \sim 1\ \text{MeV}, \quad m_N = 100\ \text{GeV}$$

$$\Delta E_N \sim q_N^2/(2\mu_{NX}) \sim 1\ \text{keV}, \qquad \Delta t_N \sim \hbar/\Delta E_N \sim 10^{-19}\ \text{s}$$

$$\Delta E_e \sim 10\ \text{eV}, \qquad \Delta t_e \sim \hbar/\Delta E_e \sim 10^{-17}\ \text{s}$$



If a particle gives a sudden jolt to the nucleus of an atom, there is a probability that the atom will emit a high-energy electron.

- A. Migdal, Ionizatsiya atomov pri yadernykh reaktsiyakh. Sov. Phys. JETP 9, 1163 (1939).
- A. Migdal, Ionization of atoms accompanying α-and β-decay. J. Phys. USSR 4, 449 (1941).