Design and Testing of a Gaseous Pixel Detector for the Migdal Effect

University of Chinese Academy of Sciences

Difan Yi

MigdAl pRocess Validation by nEutruaL scattering

on behalf of MARVEL group

08, 22, 2025

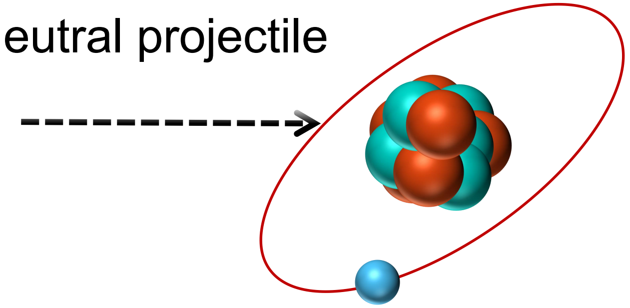
Shanghai

Outline

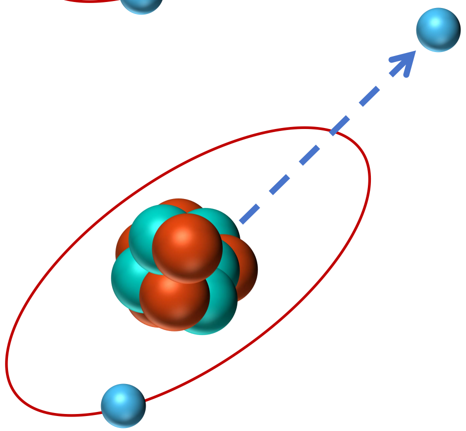
- **Motivation**
- **Detector design and performance**
- **Simulation & reconstruction**
- **Pretest on D-D souce**
- **Summary and outlook**

What happens in neuclear recoil?

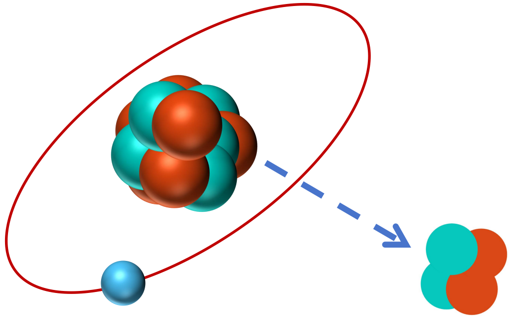
Neutral projectile



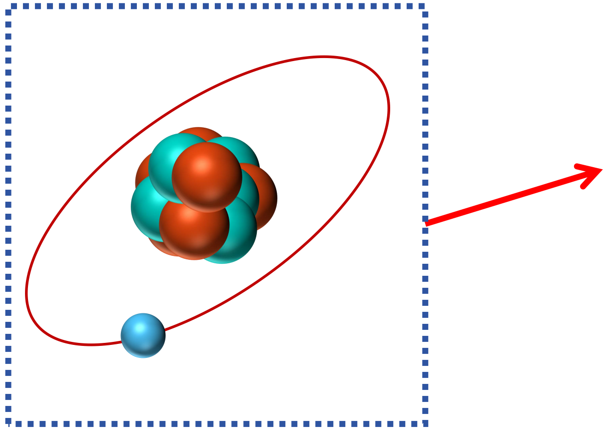
β decay



α decay



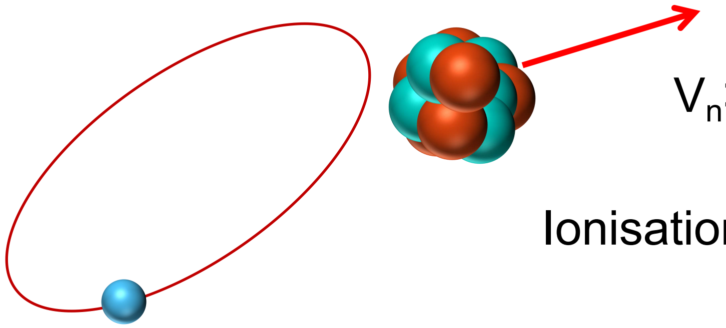
1. Low energy transition



$V_n << \alpha c$

The entire atom moves together

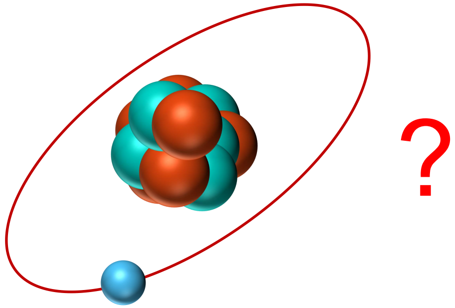
2. High energy transition



$V_n >> \alpha c$

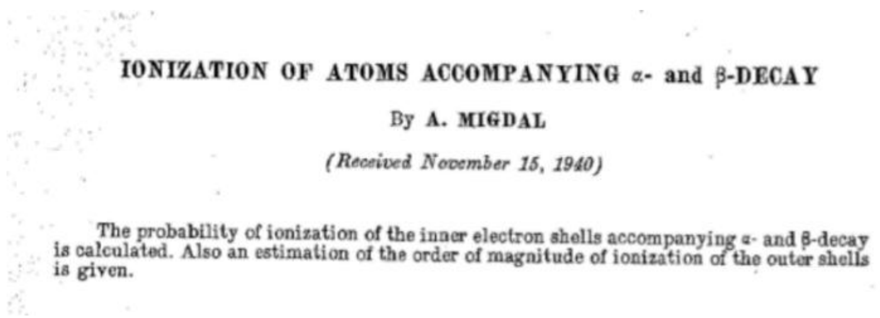
Ionisation

3. Middle energy transition



$V_n \approx \alpha c$

The Migdal effect?



IONIZATION OF ATOMS ACCOMPANYING α- and β-DECAY

By A. MIGDAL

(Received November 15, 1940)

The probability of ionization of the inner electron shells accompanying α- and β-decay is calculated. Also an estimation of the order of magnitude of ionization of the outer shells is given.

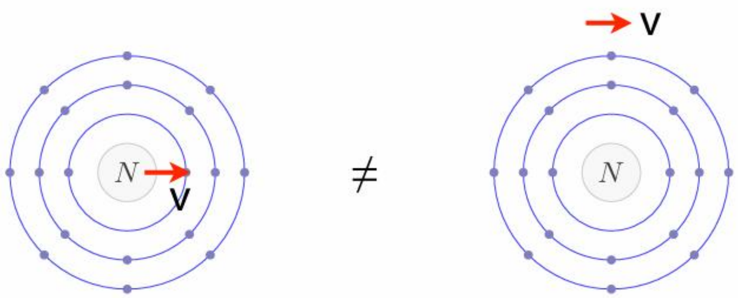
The Migdal effect describes the ionization or excitation of atomic electrons caused by a sudden nuclear recoil during interactions such as dark matter collisions, where electrons lag behind the rapidly moving nucleus.

Predicted by A.B.Migdal date back to the 1940s

Predicted effect in:

1. α， β decay
2. Neutral scattering

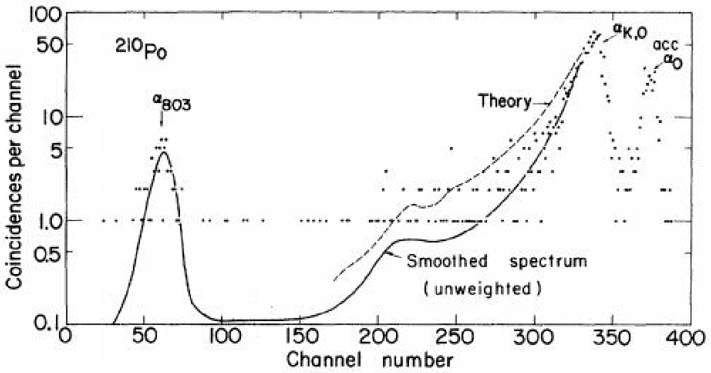
✔ In reality, it takes some time for the electrons to catch up…



✔ The process to catch up causes electron excitations/ionizations!

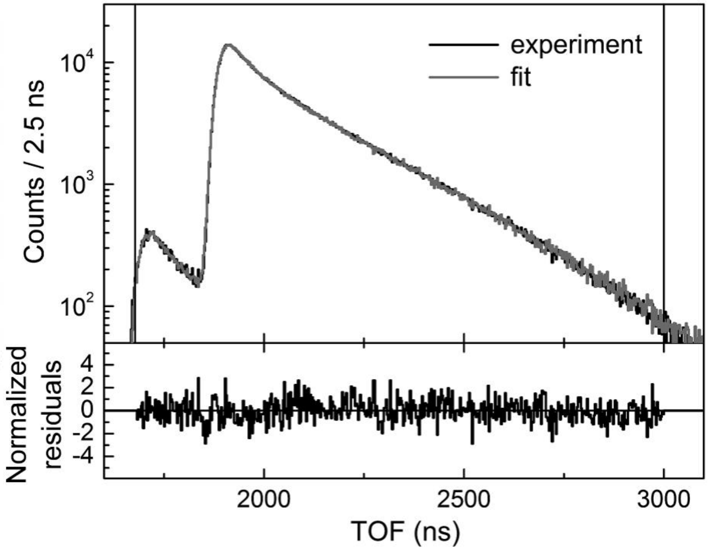
(Ibe,IBS,2017)

oberved in β decay



PhysRevC.11.1740

oberved in α decay

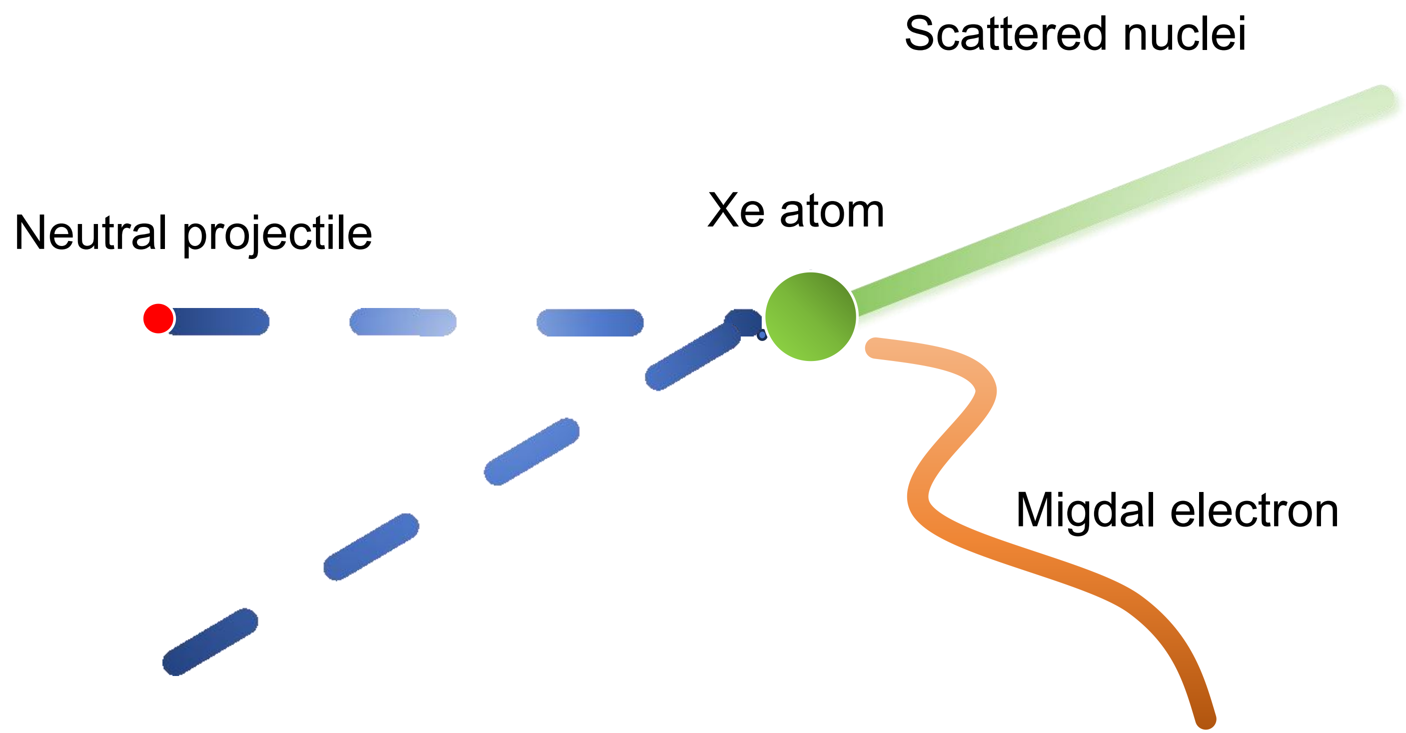


PhysRevLett.108.243201

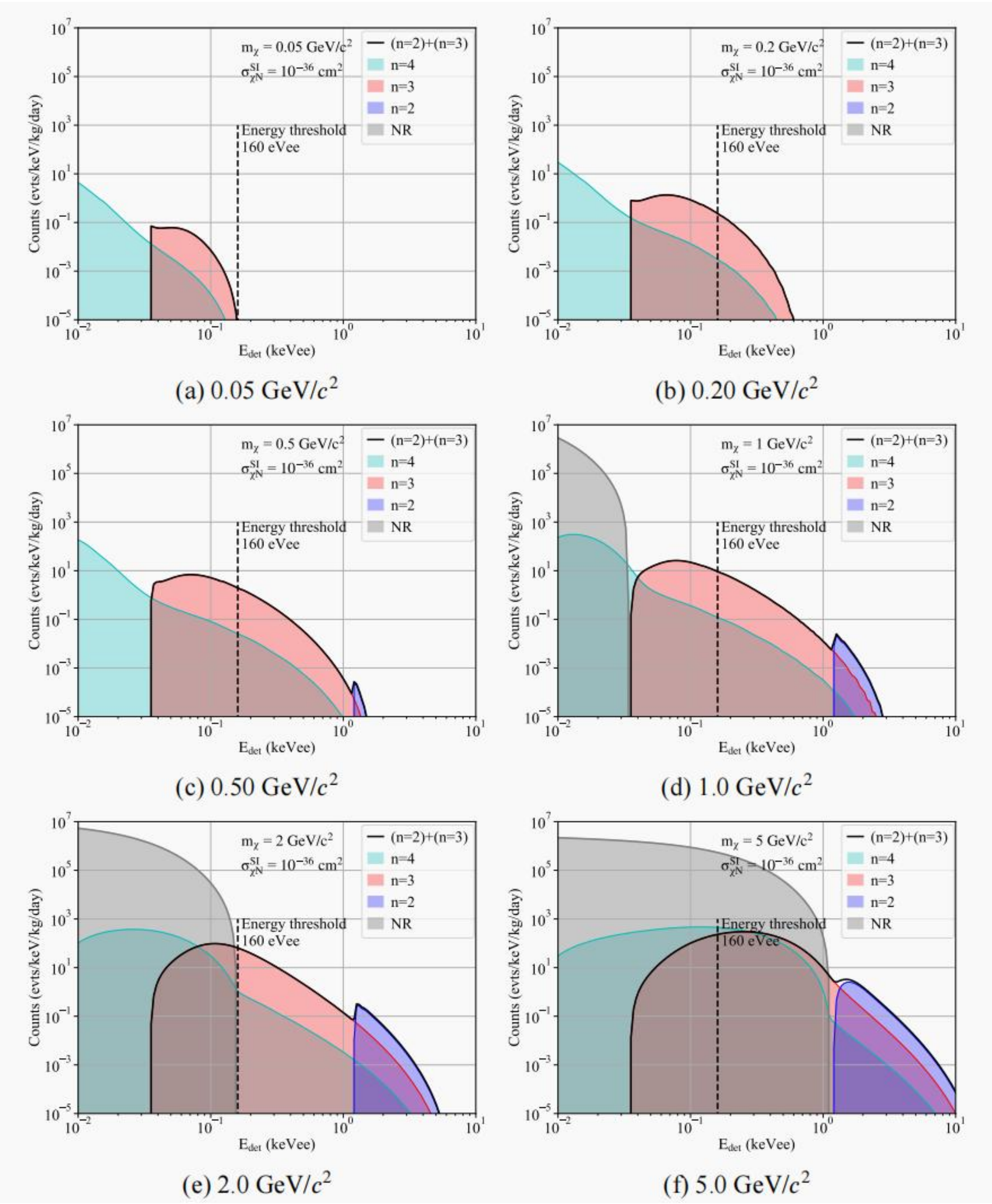
Haven't been oberved in Neutral scattering

Migdal electron haven't been oberved directly

The Migdal effect?

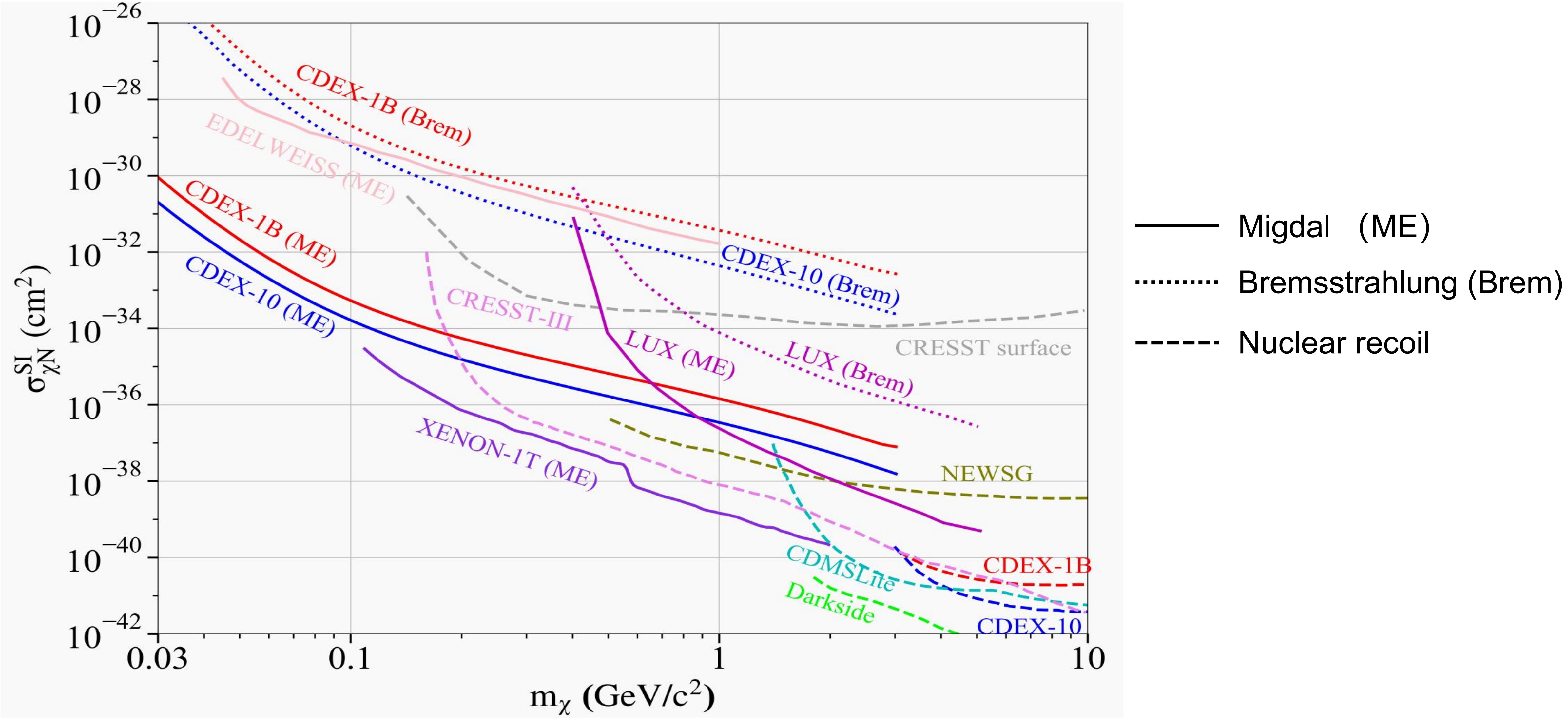


Migdal effect for CDEX experiment



- Energy deposition = nuclear scattering + Migdal effect electron
- Without the uncertainty of quenching factor

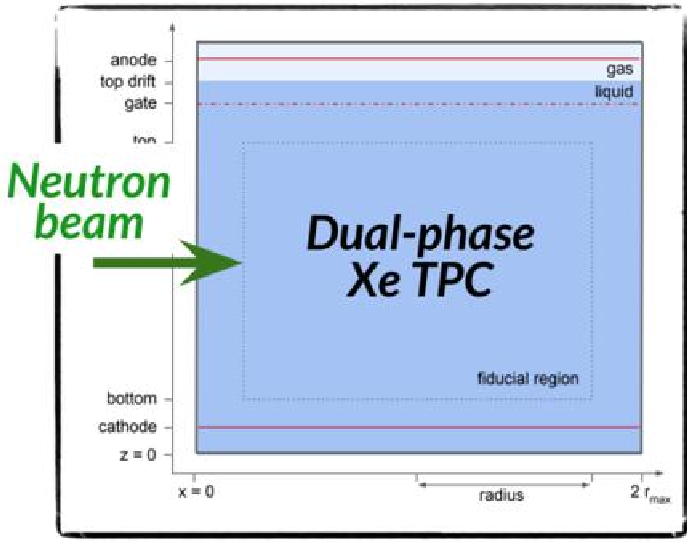
Sensitivity with & without Migdal effect



The Migdal effect has enhanced the sensitivity of many existing direct dark matter detection experiments to the sub-GeV range

Proposed MIGDAL experiment

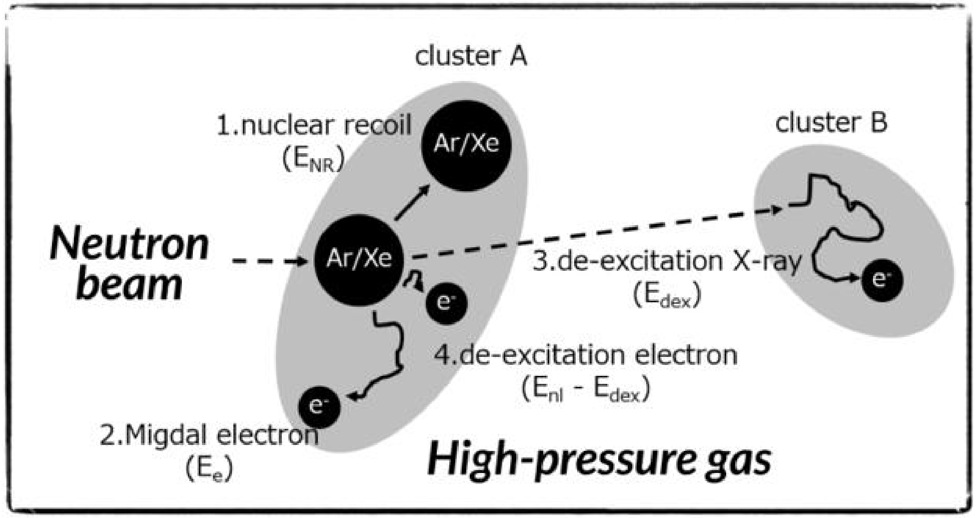
Bell et al, arXiv:2112.08514
Xu et al, arXiv:2307.12952



$E_{\mathrm{neutron}} \sim 15 - 15000\ \mathrm{keV}$

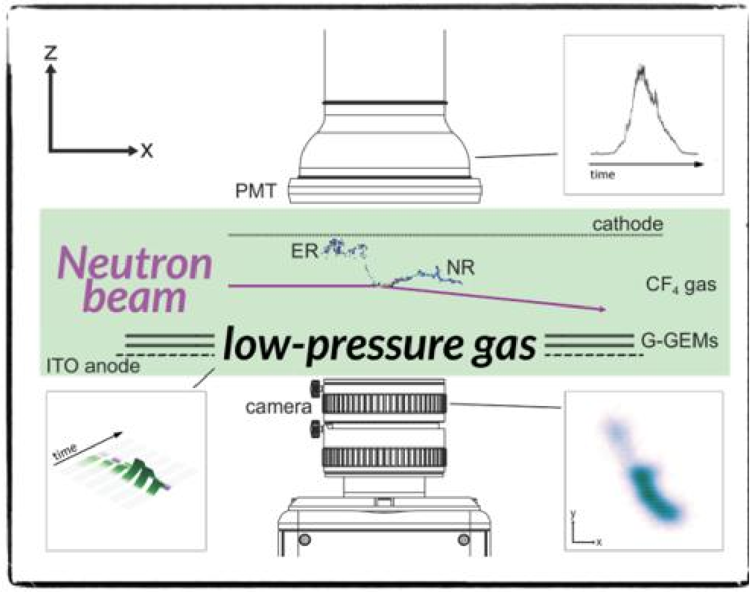
S1/S2

Nakamura et al, arXiv:2009.05939



$E_{\mathrm{neutron}} \sim 500\ \mathrm{keV}$

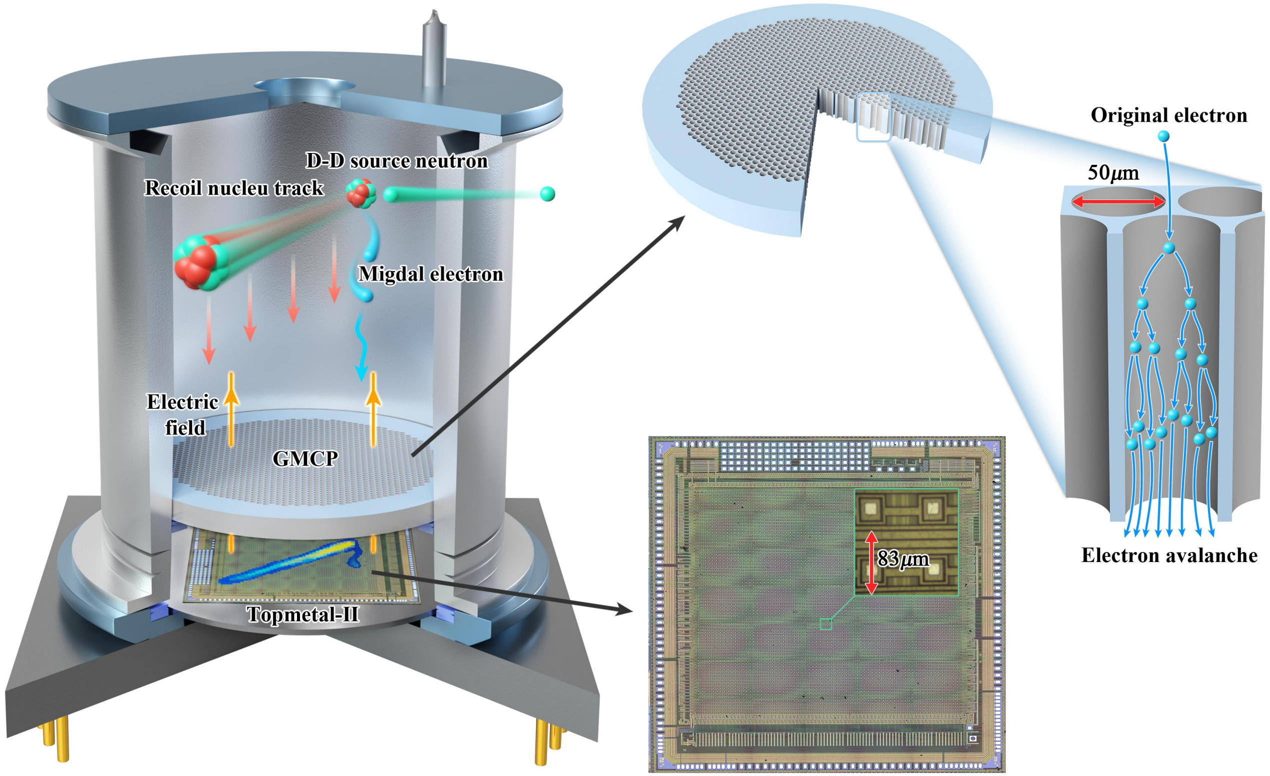
Araújo et al (MIGDAL), arXiv:2207.08284

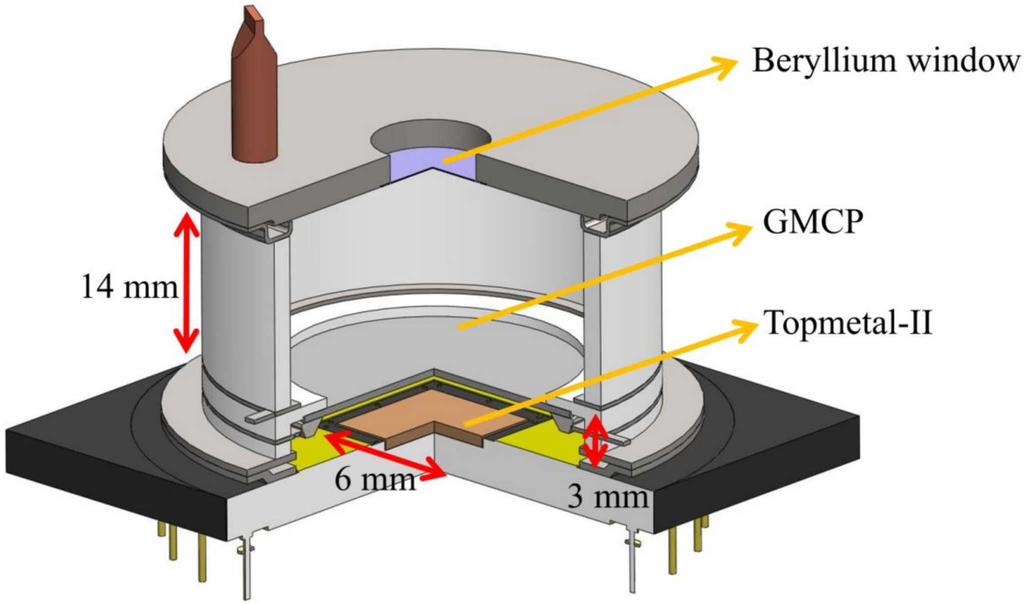


$E_{\mathrm{neutron}} \sim 2500 - 15000\ \mathrm{keV}$

Optical TPC

Detector construction





Working gas:

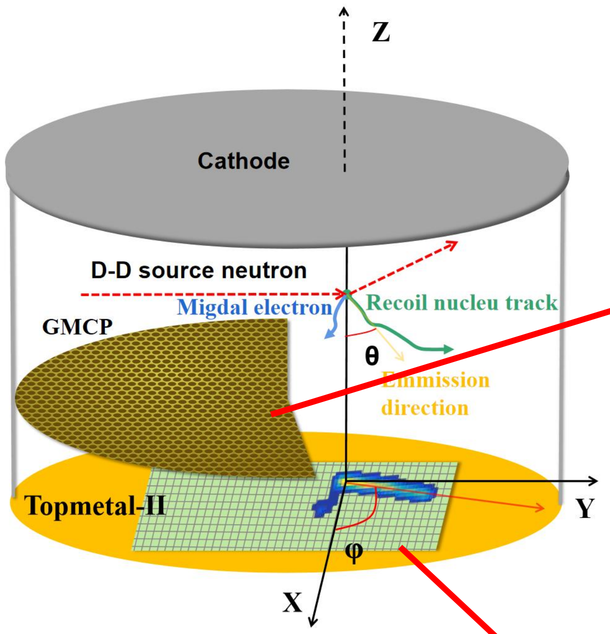
0.8 atm

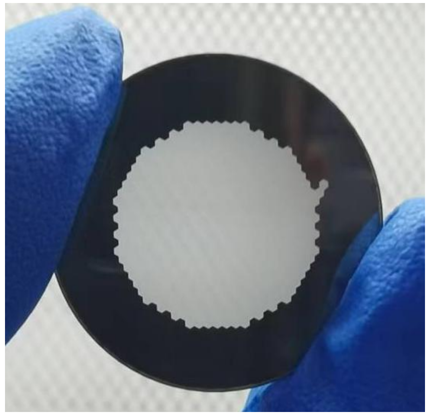
40% Helium + Dimethyl ether (DME,C_2H_6O)

Purpose: direct observation of the Migdal effect using the gas micropixel detector during neutron nuclear recoil processes

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

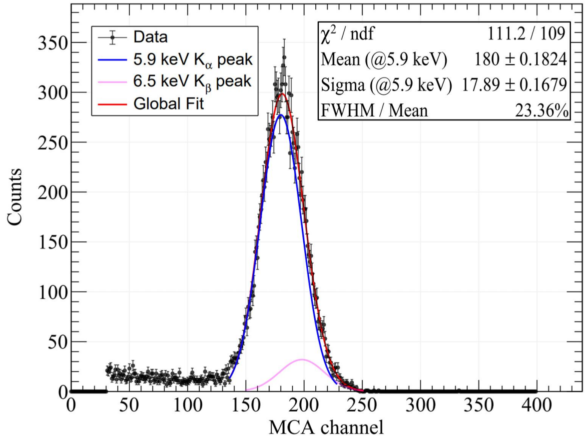
关键器件组件

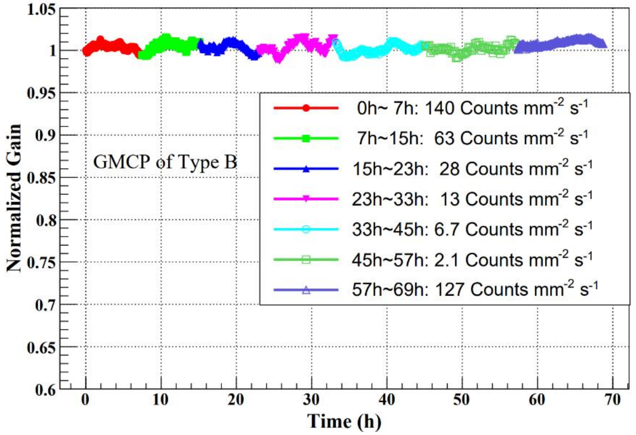




GMCP:

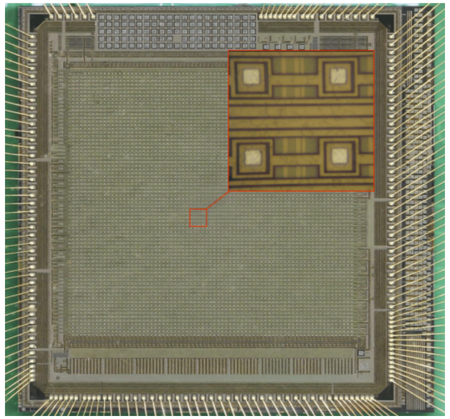
- 50 um diameter, 60 um pitch
- High energy resolution
- Stable gain coefficient

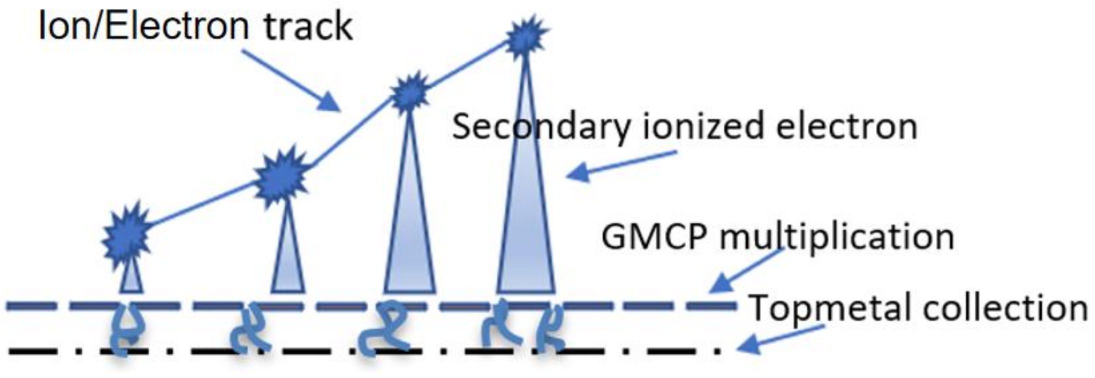




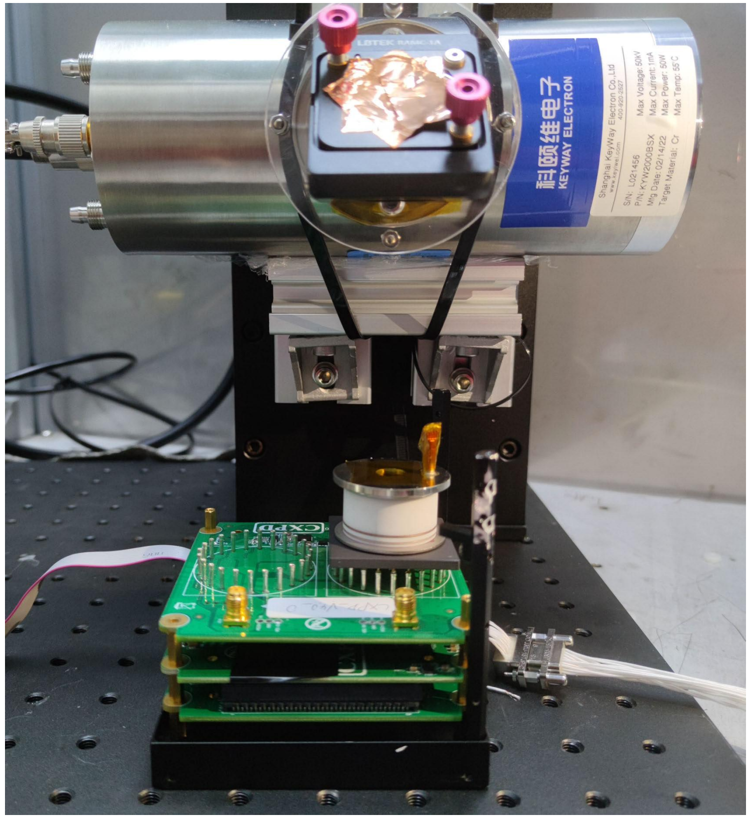
Topmetal-II-:

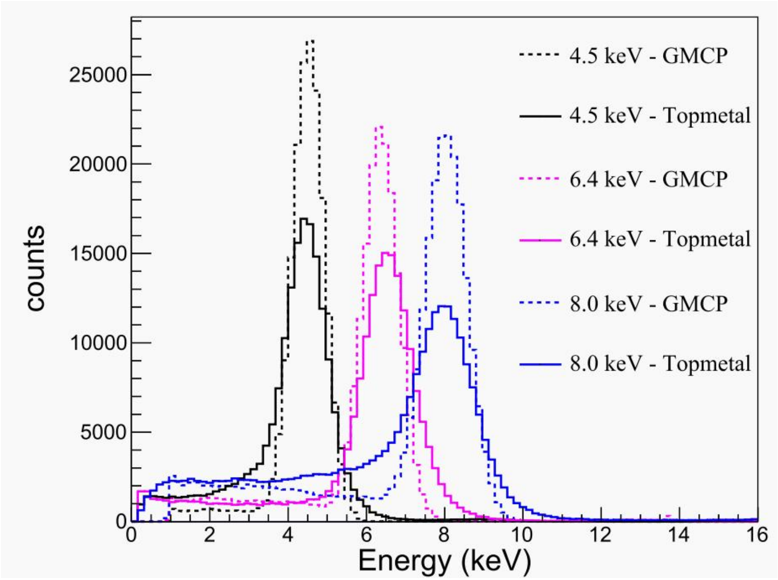
- 83 um pitch
- 2.5 ms time resolution
- noise 13.9e-

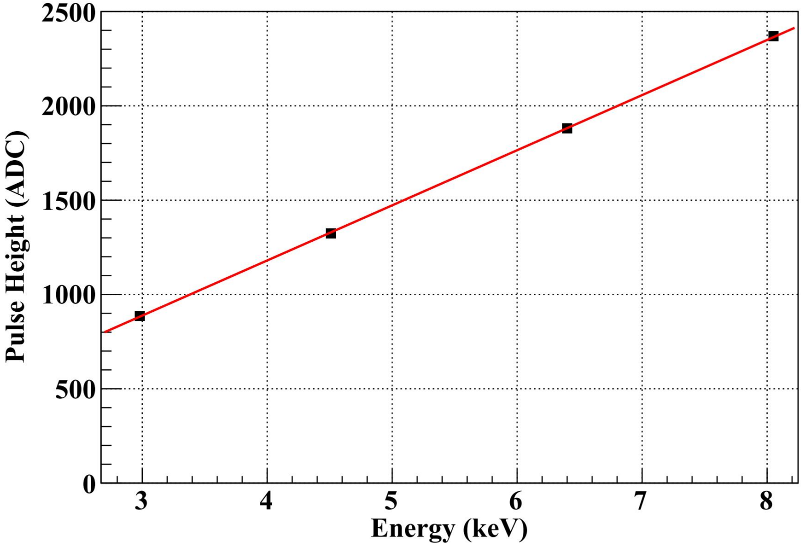




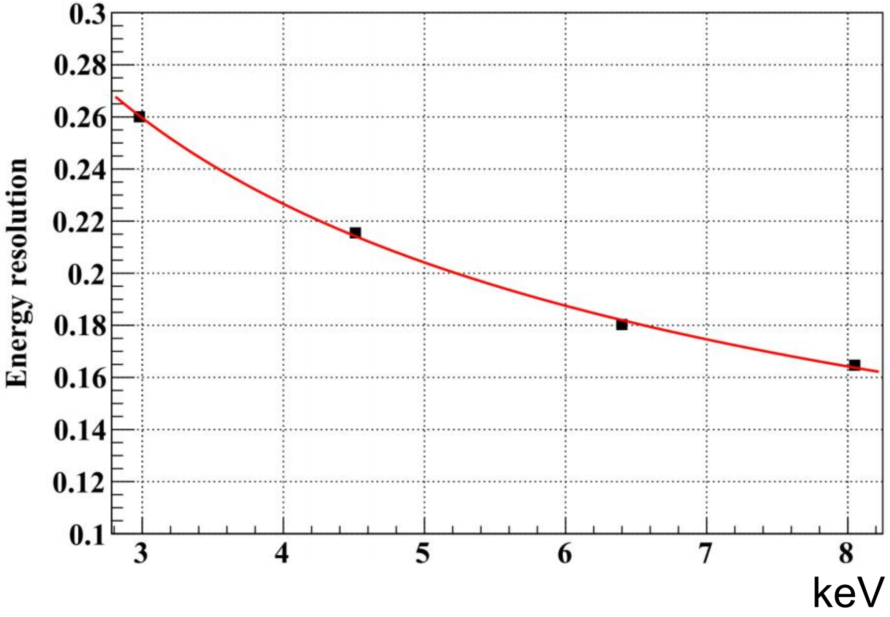
Detector performance： energy





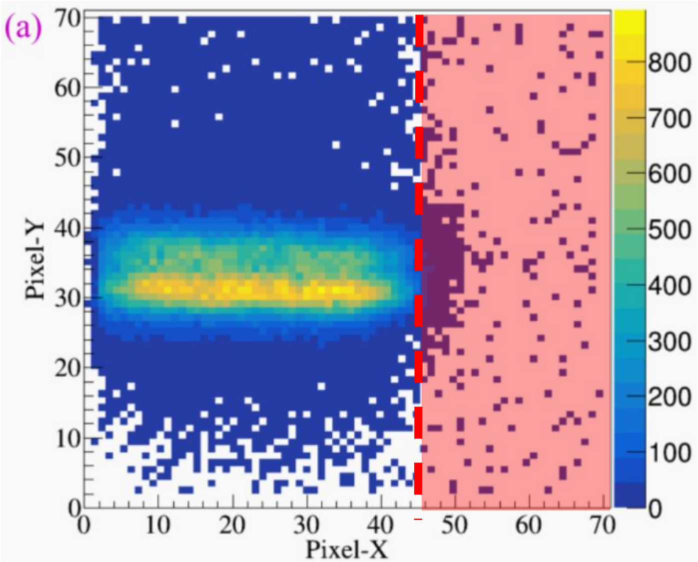


Energy(keV)	Crystal	Incident radiation	Diffraction angle (deg)
2.98	Si(111)	Ag	41.6
4.51	Si(220)	Ti	45.8
6.40	Si(400)	Fe	45.5
8.05	Si(224)	Cu	45.1

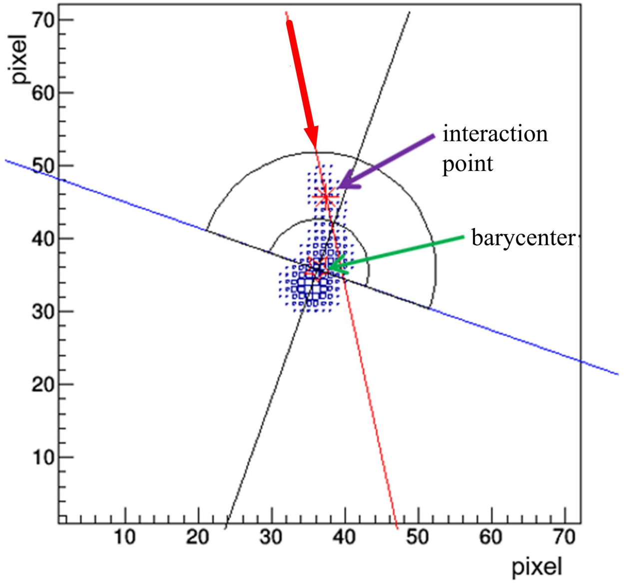


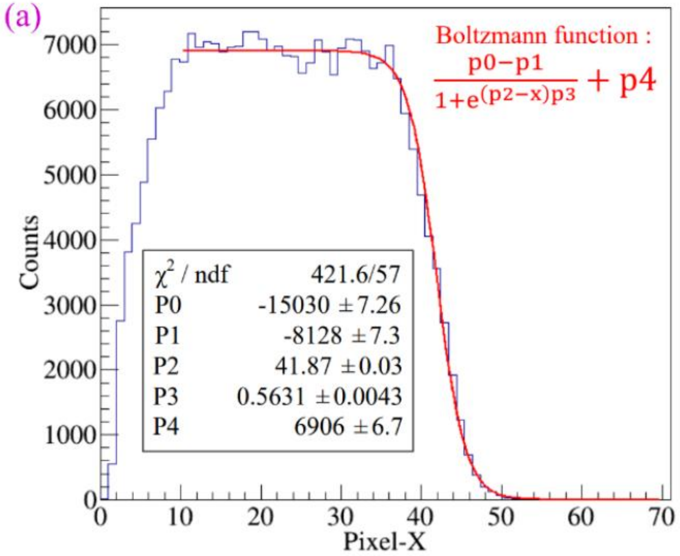
- Good linear energy response
- 20%-30% energy resolution
- Energy resolution follows the relationship ~ $1/\sqrt{E}$

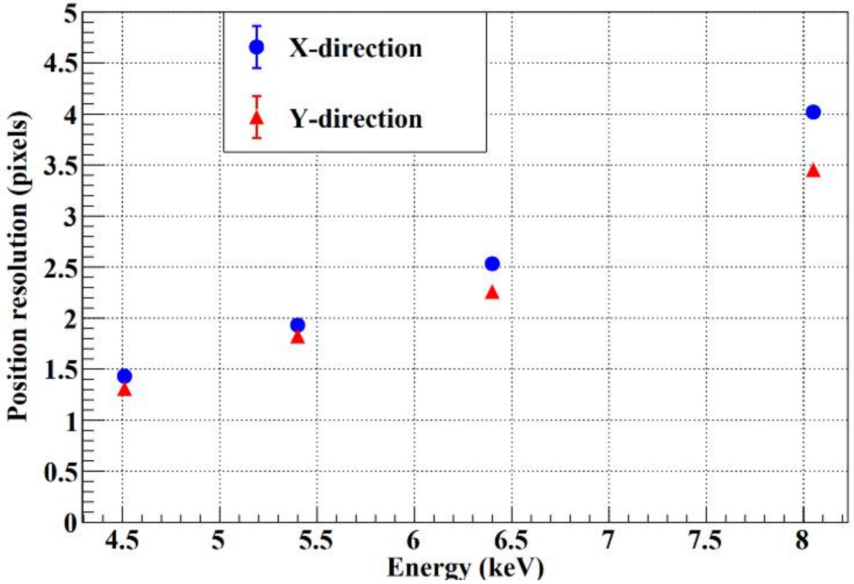
Detector performance: position resolution

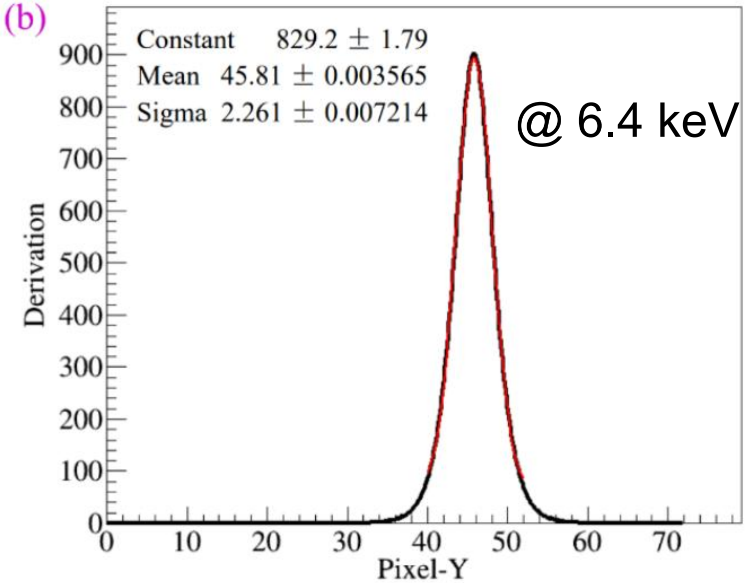


Shadowing Method





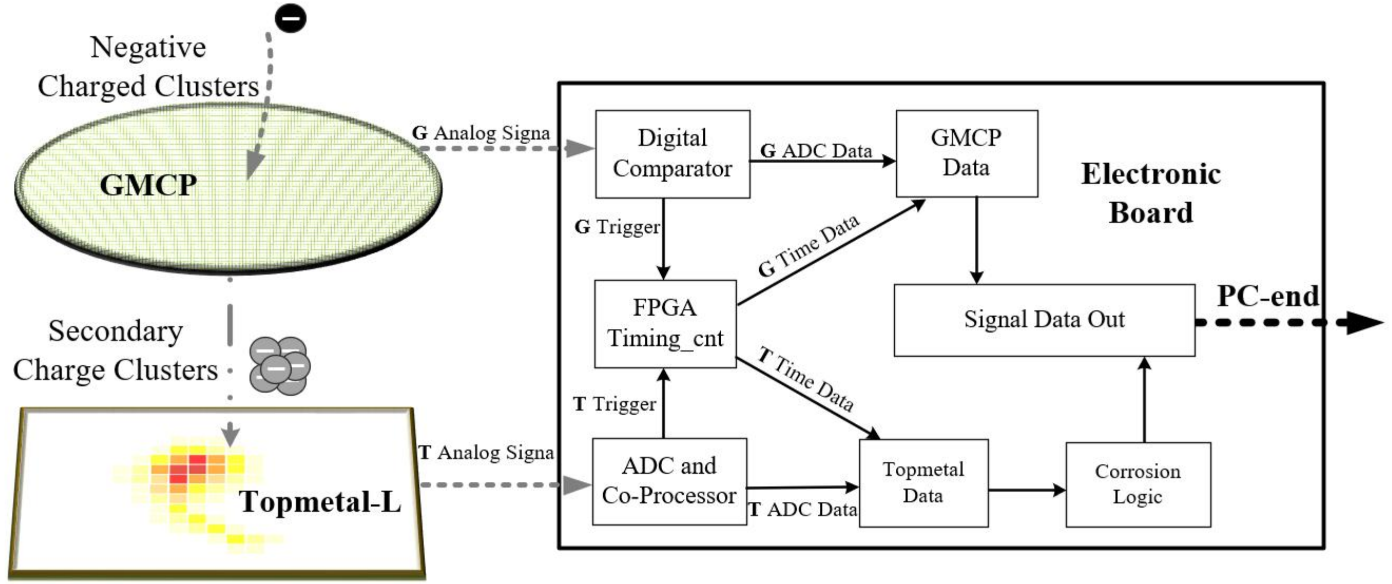


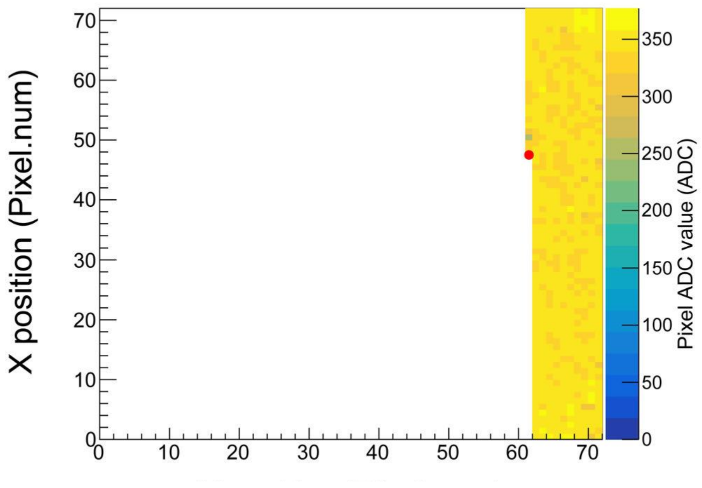


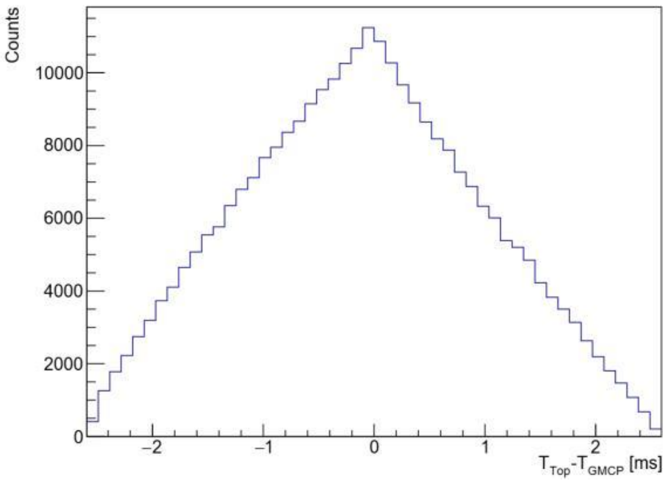
@ 6.4 keV

~200 um
position resolution

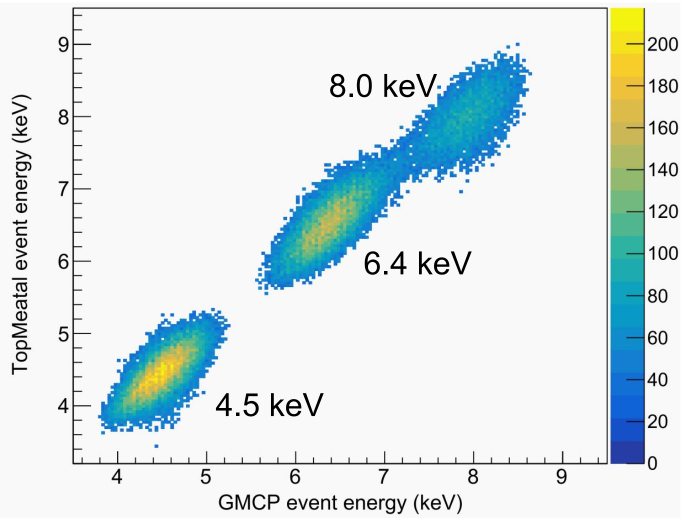
Detector performance: time resolution



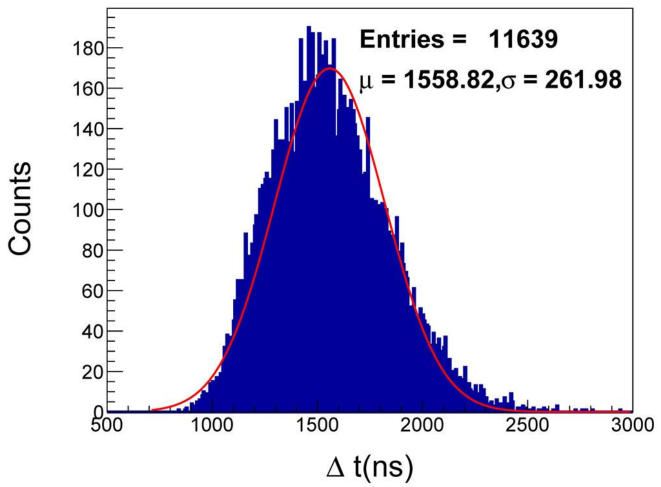




GMCP and Topmetal Time Coincidence



Energy Spectrum Correlation

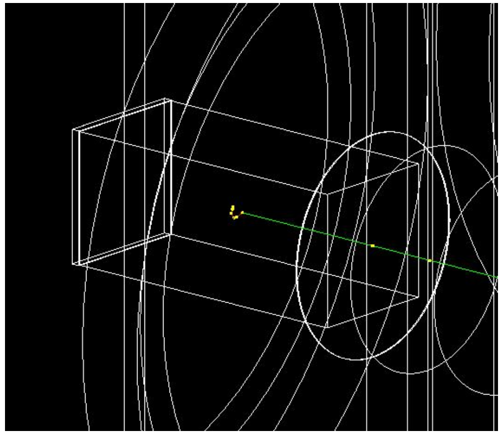


By combining data from GMCP and Topmetal, a time resolution capability at 262 ns can be achieved.

Simulation Framework

- Motivation:

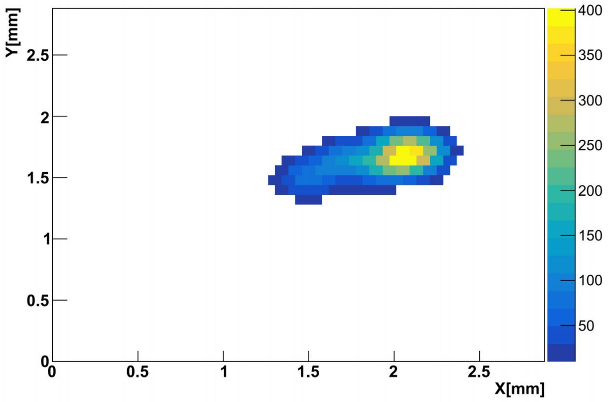
  Establish a framework for Migdal electron and Ion measurement simulation and offline data analysis



Detector modeling

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

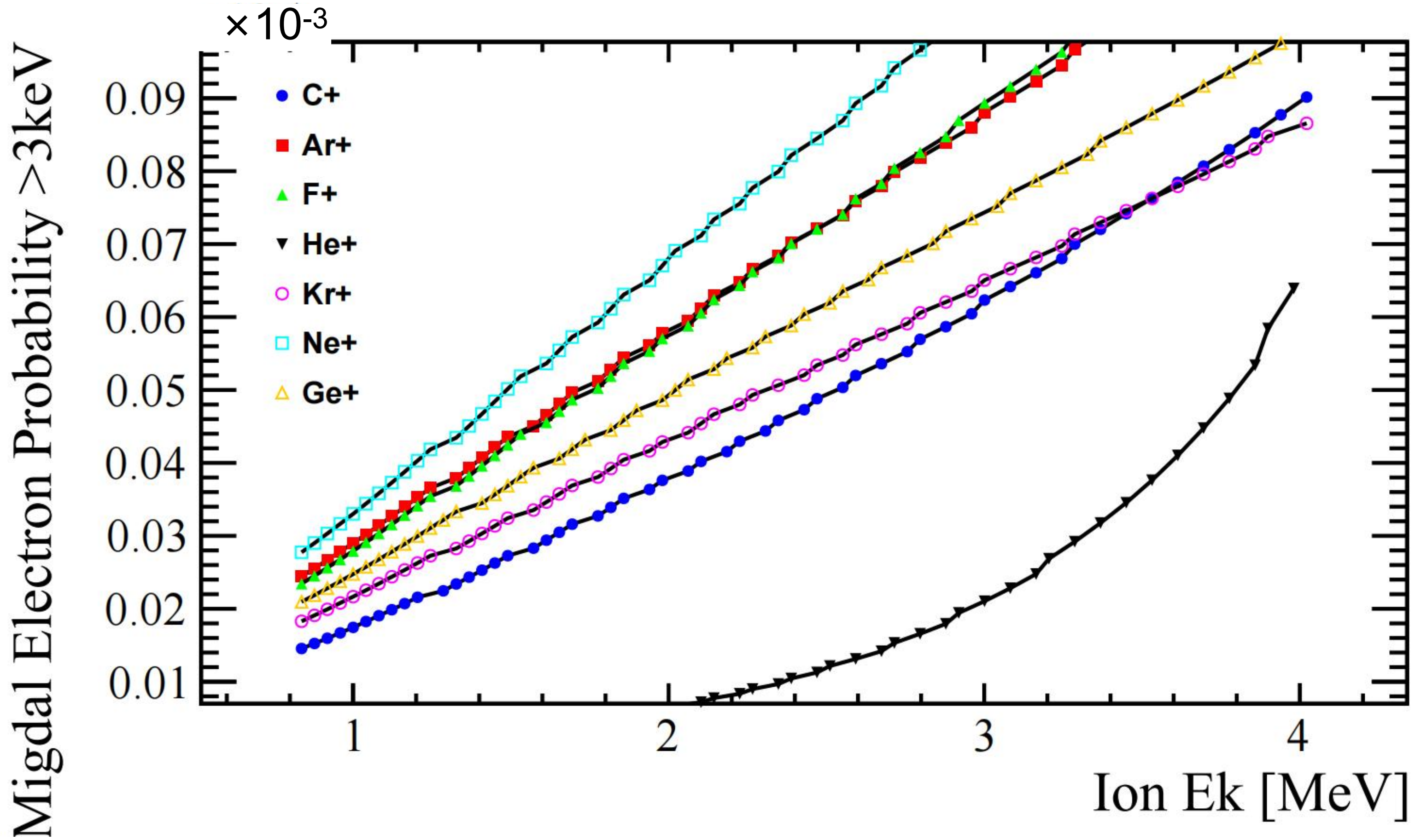
✓ Analog detector digital readout
- ➢ Simulate electron drifts, multiplies, collected procession
- ➢ Output file for data analysis and reconstruction algorithm



Track simulation

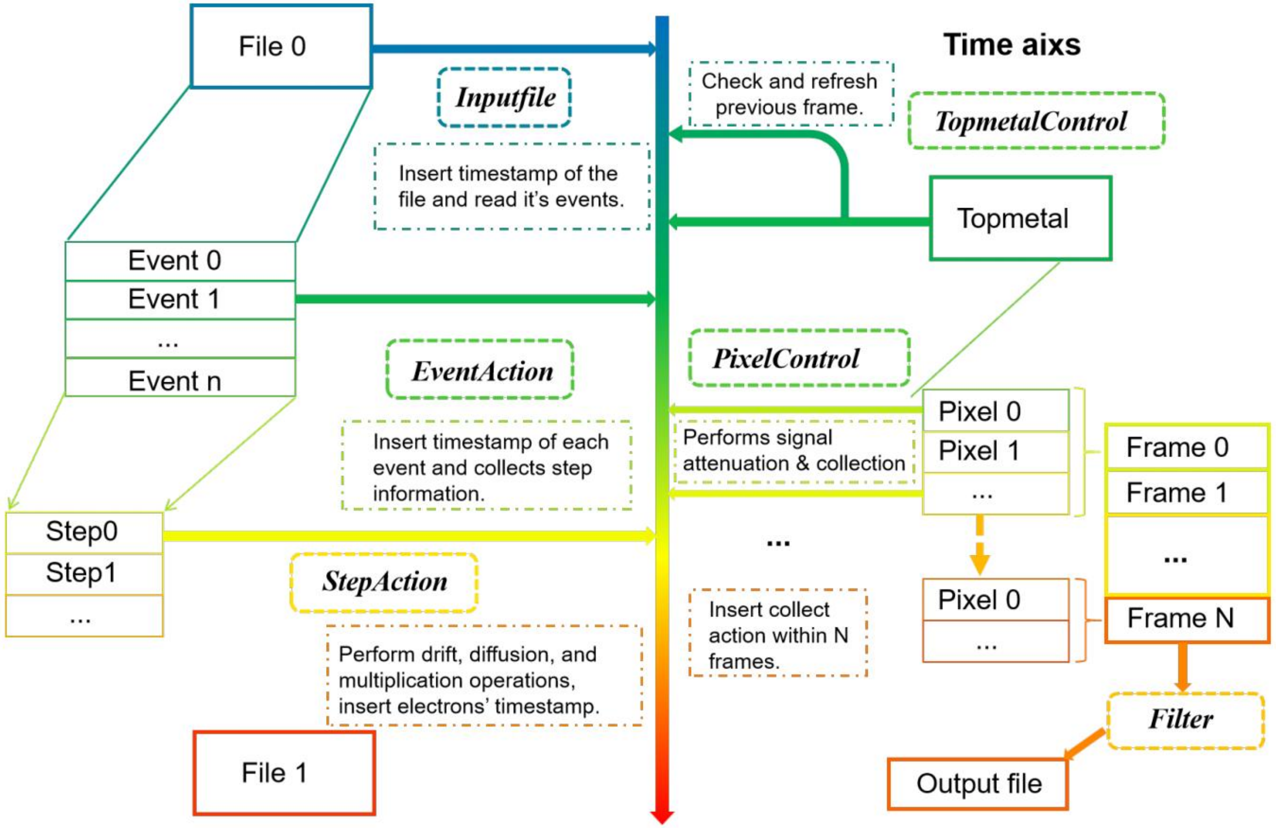
Simulation

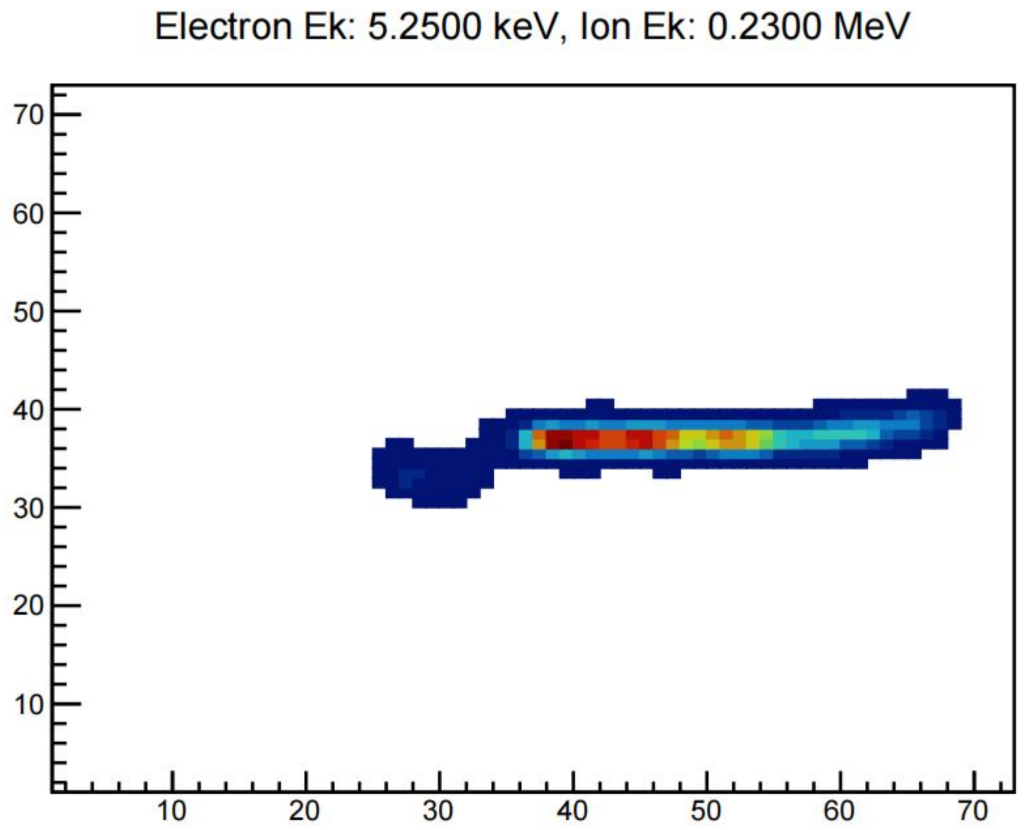
- **The cross sections for nuclear interaction and electromagnetic interaction are from Geant4**
- **The theoretical Migdal cross sections for Ar/C/F/Ge/He/Kr/Ne/Si/Xe nuclei are available.**



Digitization

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



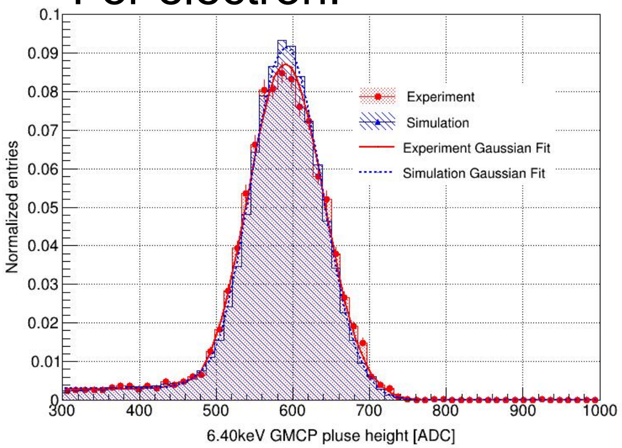


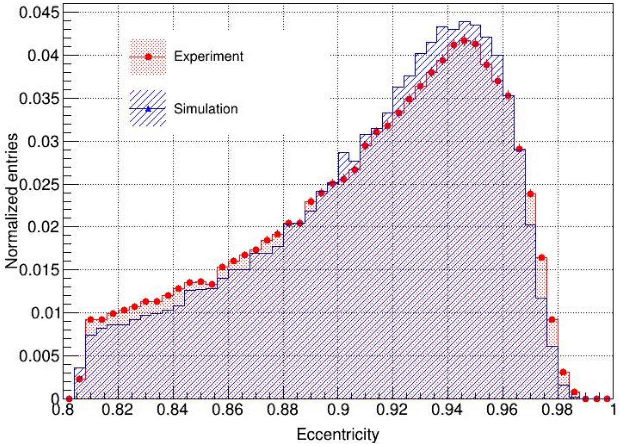
A simulation example

Consistency Between Simulation and Experiment

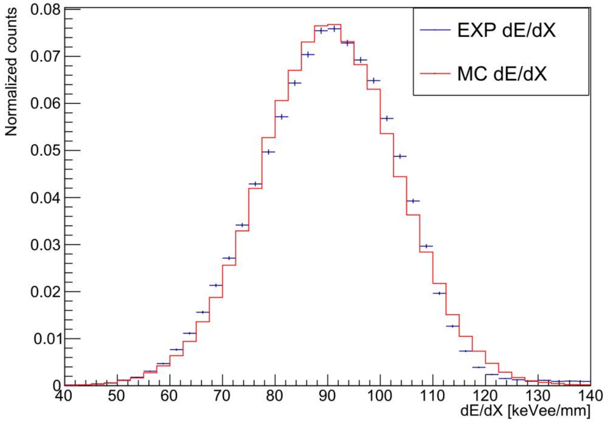
The consistency with experimental data nicely

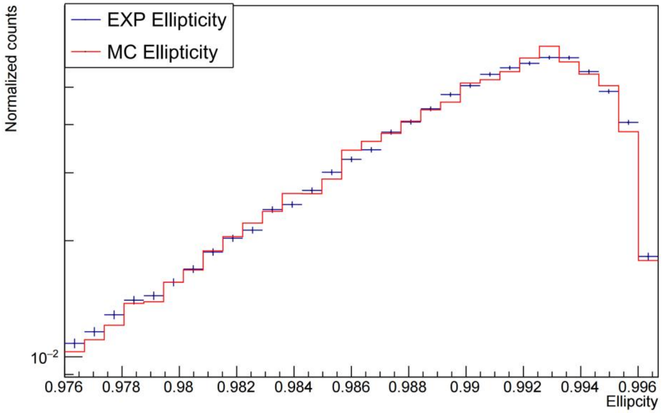
For electron:



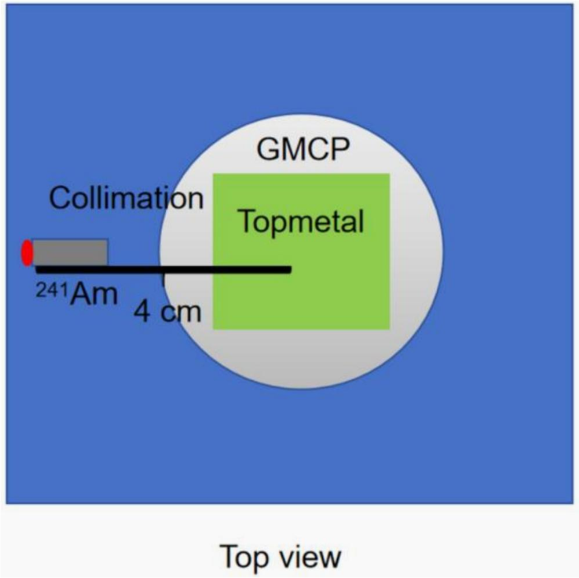


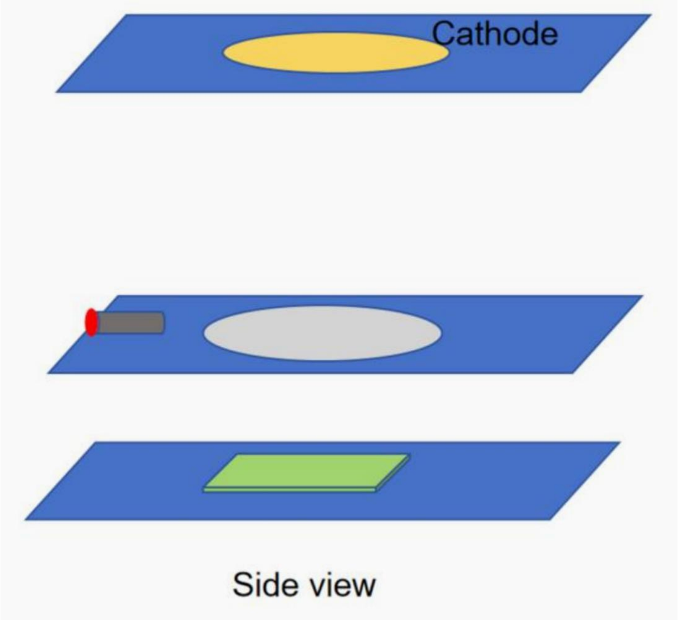
For ion(Alpha ray):



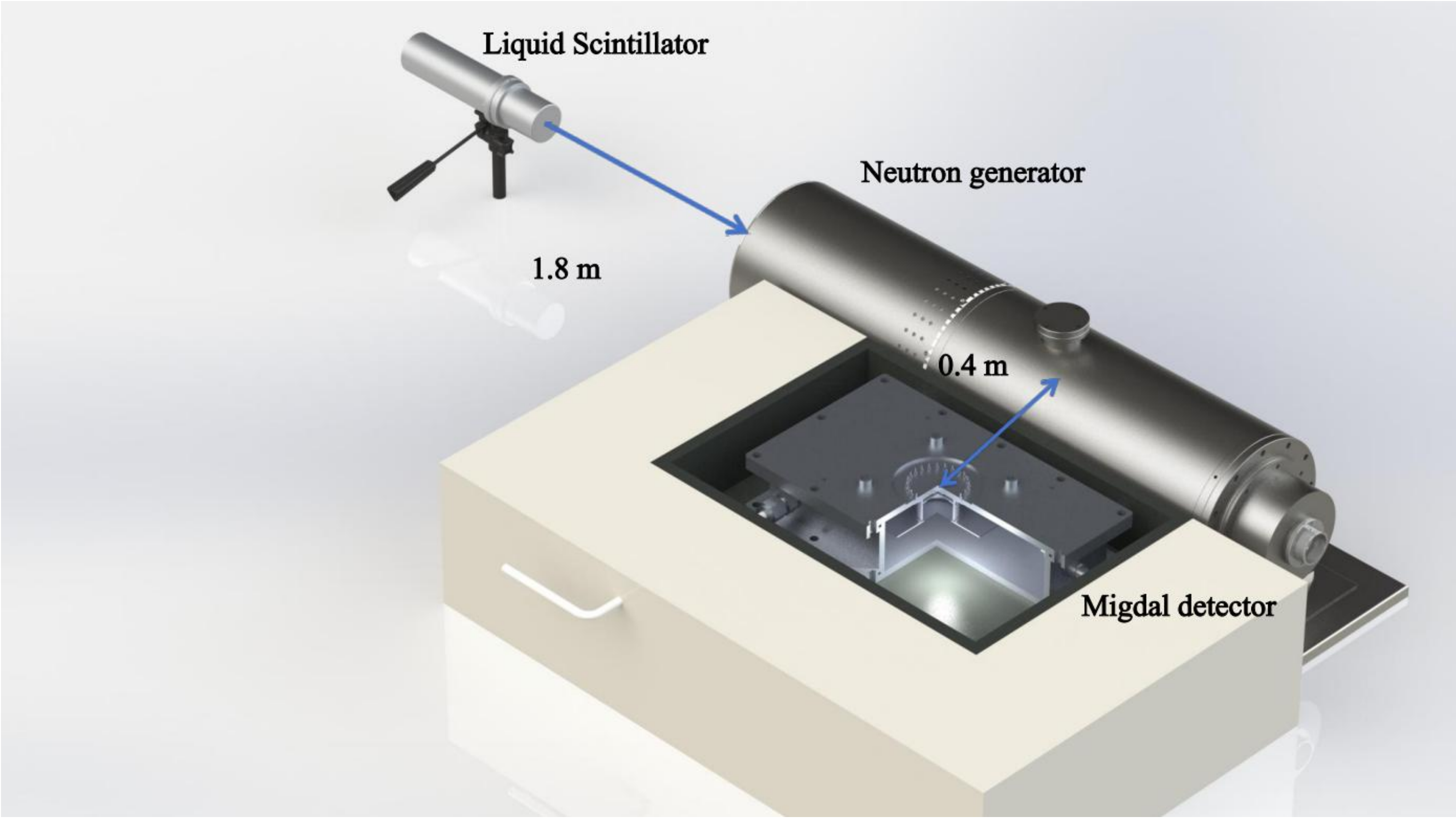


Alpha Source Placement:



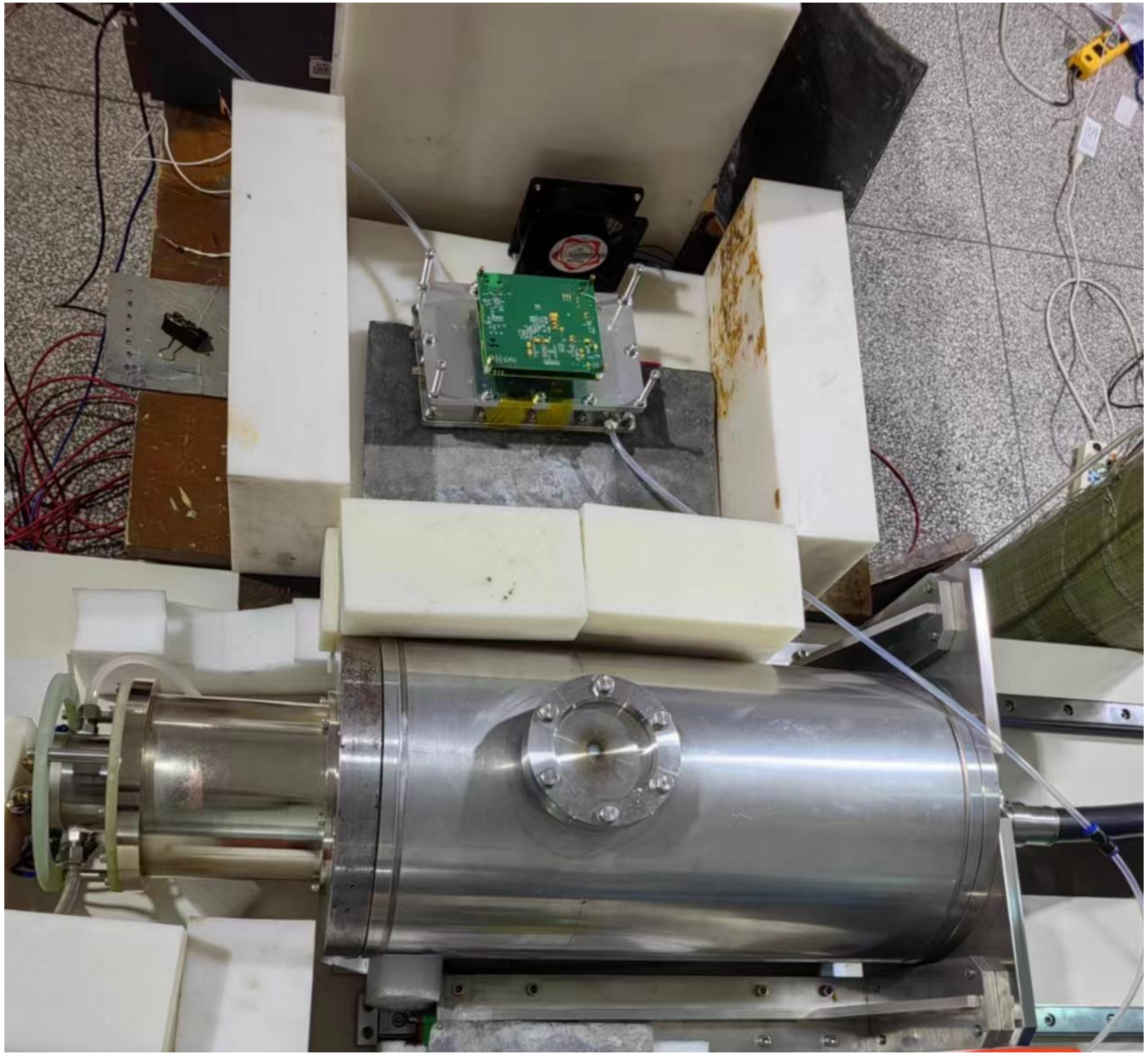


preliminary experiment @ Lanzhou

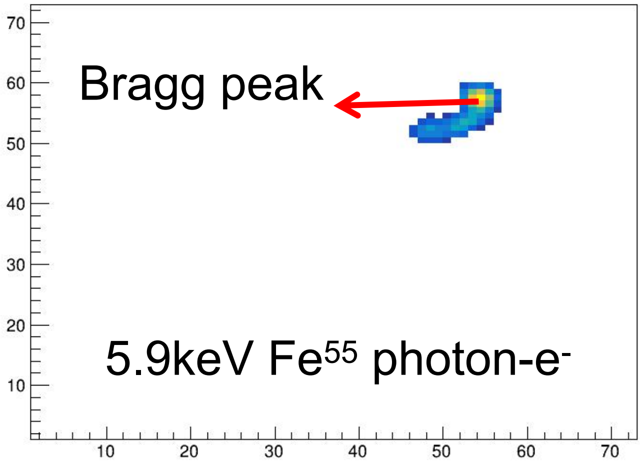


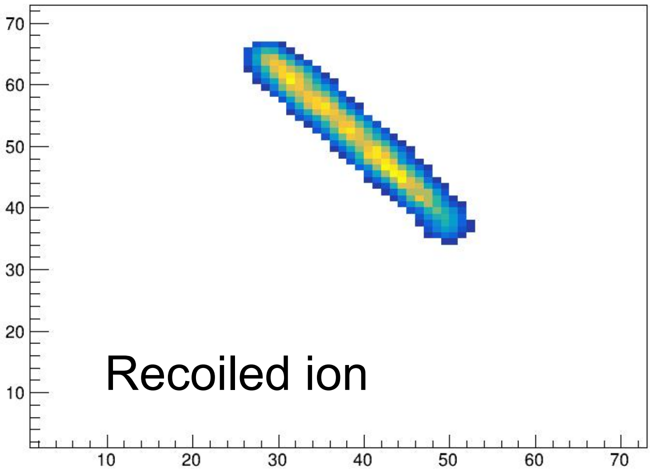
- Mixture of dimethyl ether(DME,C_2H_6O) and helium gas at 1 atm
  - High efficency
  - low diffusion coefficient
  - relativly long electron track
- Gas Microchannel Plate(GMCP) amplification
  - High gain upto~10^4
  - Fine granularity
  - Stable gain coefficient
- Topmetal Charge-sensitive chip imaging
  - Fine granularity
  - High resolution

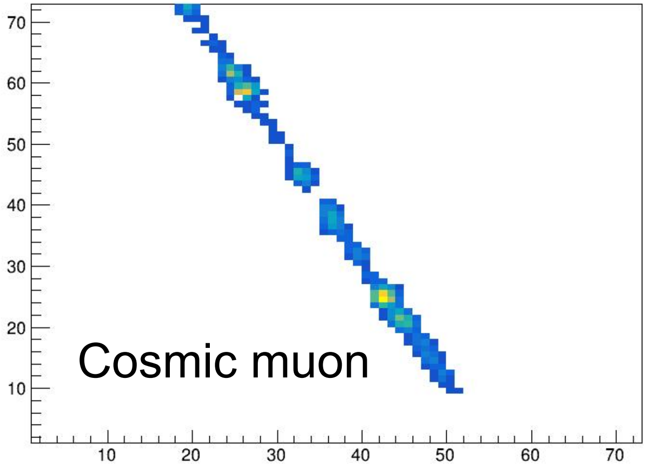
Pretest & Placement

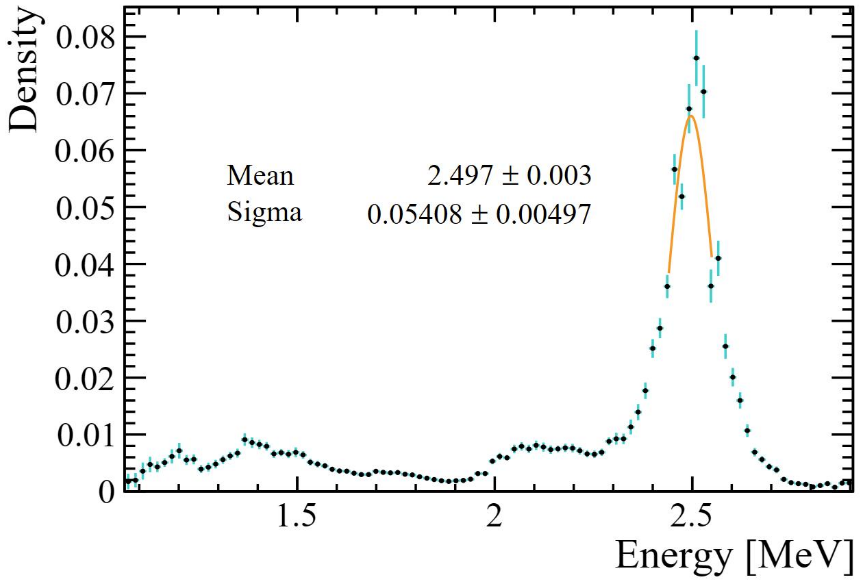


Track Imaging



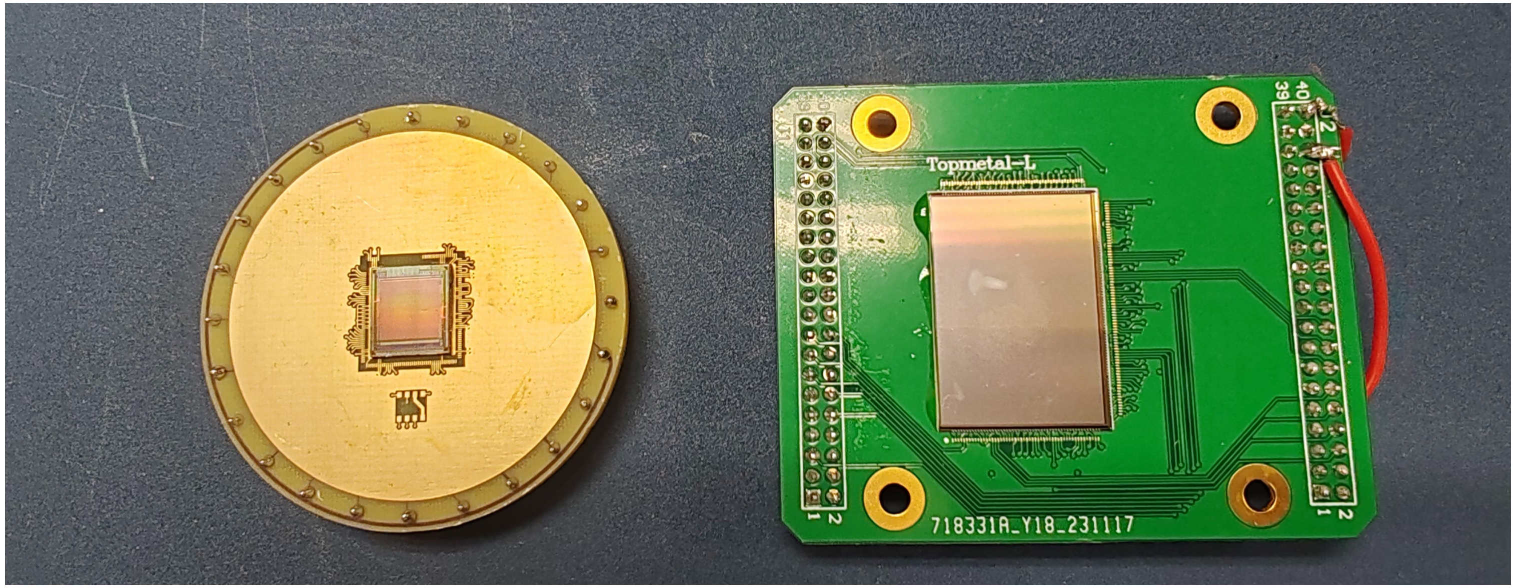


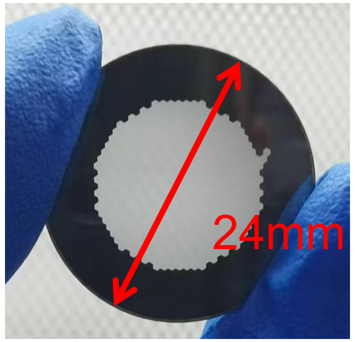


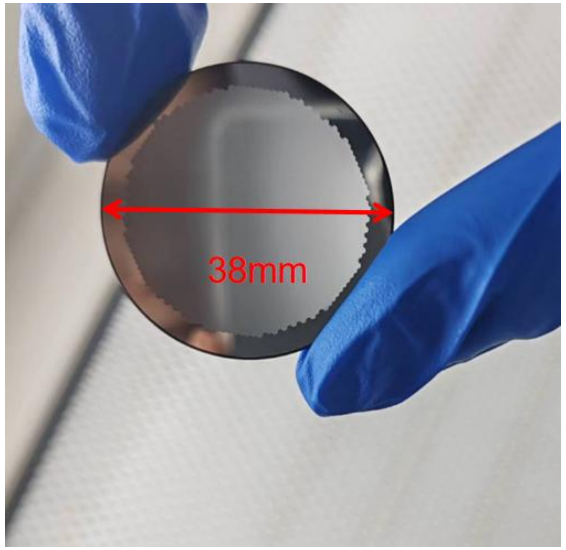


Upgrade in progress

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

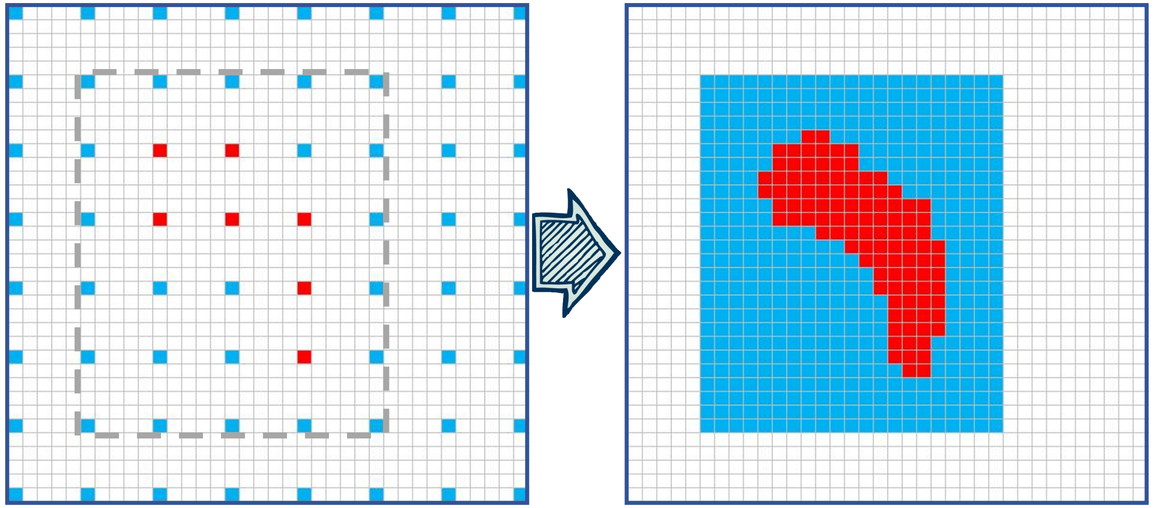


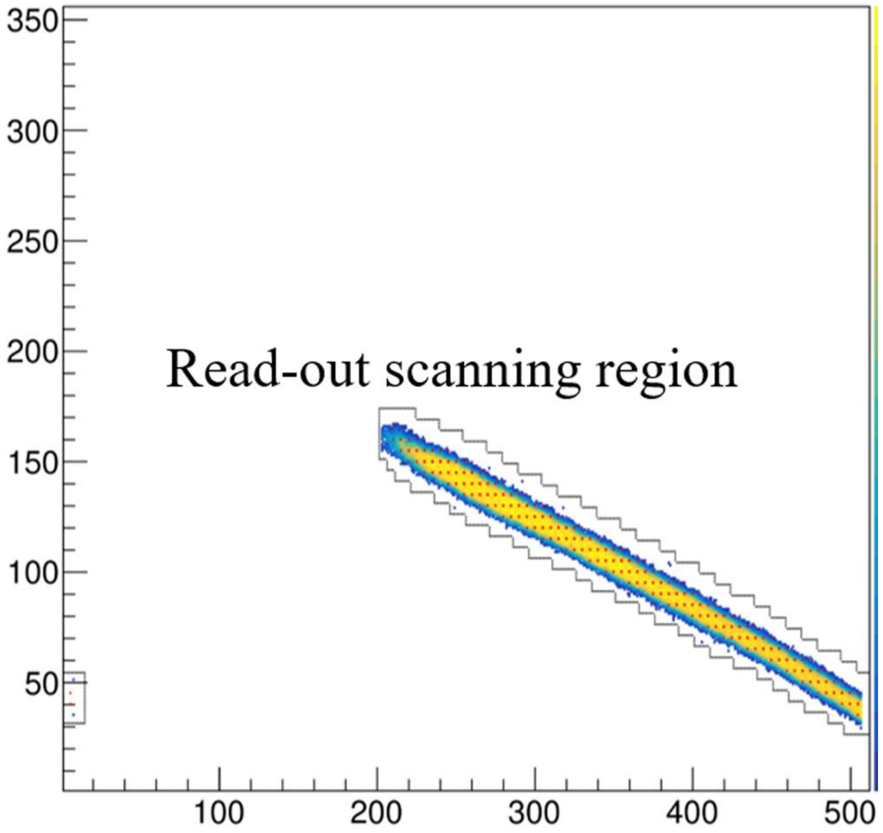




- Frame Refresh Time: 2.5ms -> 700us
- Gas: He+DME -> He(Ne)+CO_2

Sentinel Point Readout: For a large array, an interval point scanning method is employed, where the scanned pixels are designated as sentinel points. The regions corresponding to the sentinel points that exceed the threshold are scanned and read out.





White pixels: Pixels that are not read.
Blue pixels: Pixels that need to be read but did not receive a signal.
Red pixels: Pixels that need to be read and successfully received a signal.

- The Migdal effect plays a very important role in light dark matter research.
- However this effect has not been observed with the neutral projectile.
- Many experiments have been proposed.
- The capability of the GMCP detector to measure the Migdal effect is being discussed.
- Simulation and reconstruction is ready.
- More work is currently in progress.

Experiment is ready,
Looking forward to results!

Thanks for your attention!