The MIGDAL Experiment

Migdal In Galactic Dark mAtter expLoration

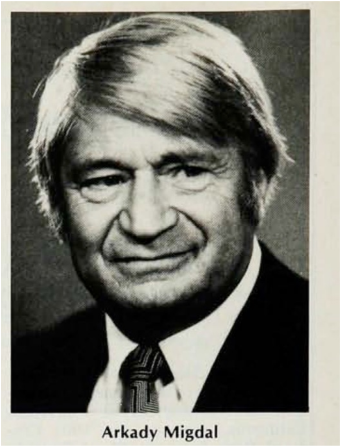
Dinesh Loomba on behalf of the MIGDAL collaboration

University of New Mexico

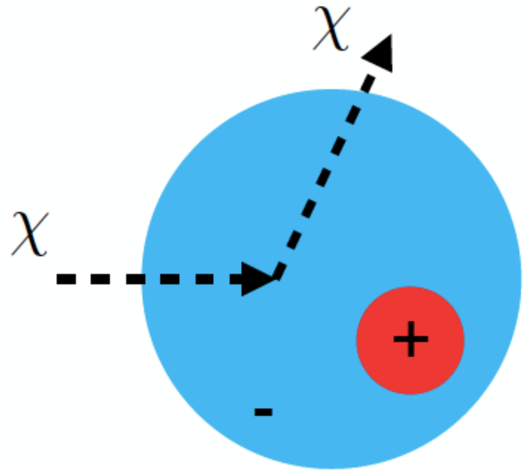
Magnificient CEvNS

13th June 2024, Valencia

The Migdal Effect



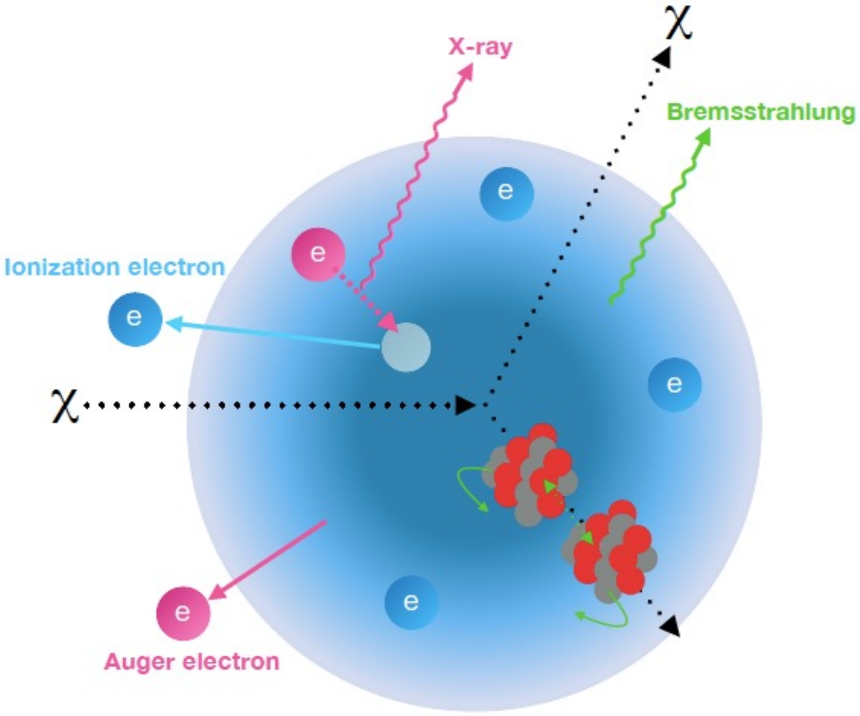
A.B. Migdal, Ionization of atoms accompanying α- and β-decay , J. Phys. USSR 4 (1941) 449



nucleus gets a nudge

$E_{\rm recoil} \lesssim 0.1~{\rm keV}$

Nuclear recoil can't be detected



Christopher McCabe
Dark Matter at the dawn of discovery? -
Heidelberg, 11th April 2018

XENON1T collab
arXiv:1907.12771

Recent application to low mass DM has led to huge interest in Migdal

Migdal effect calculations reformulated by **M. Ibe et al.** with ionisation probabilities for atoms and recoil energies relevant to Dark Matter searches.

JHEP

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Migdal effect in dark matter direct detection experiments

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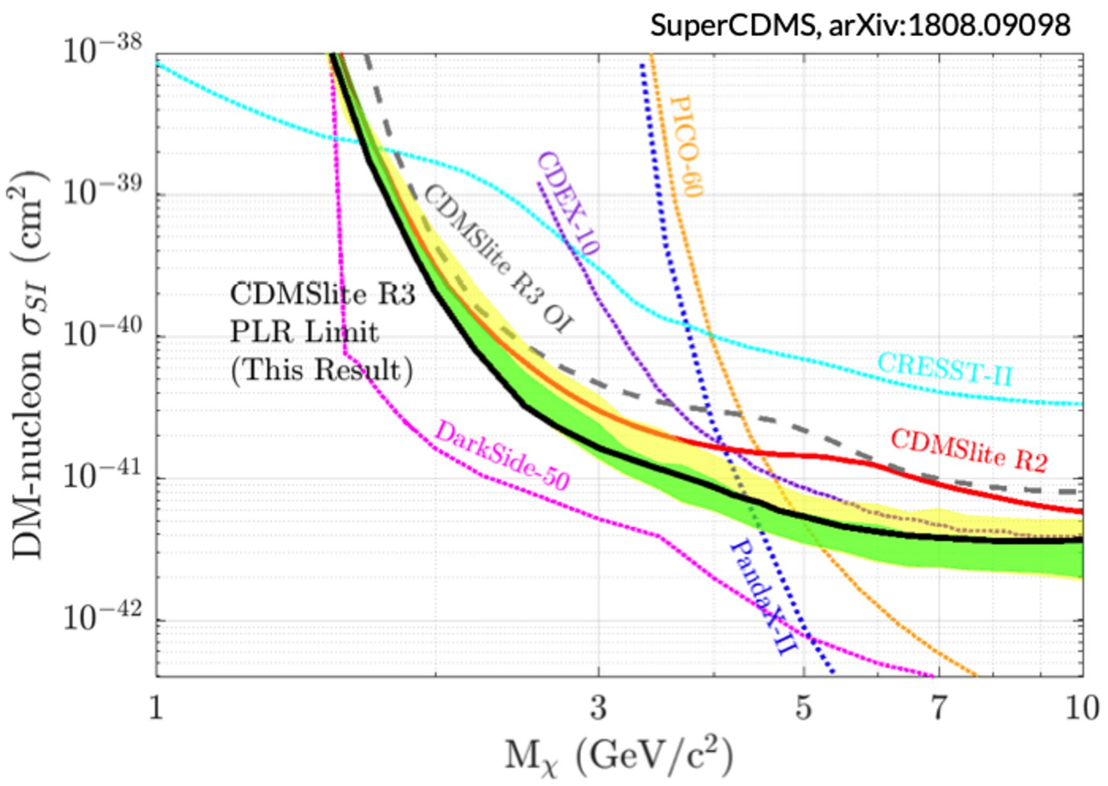
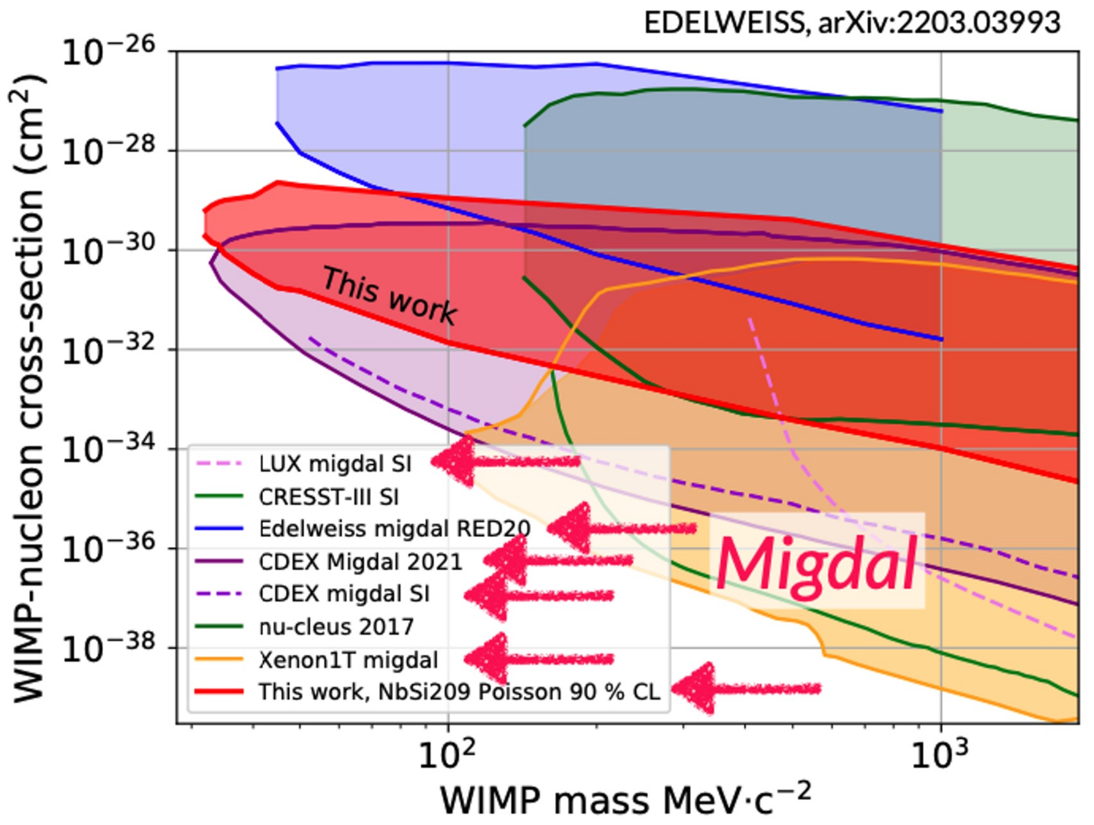
So far ~ 200 citations of Ibe et al.

Experiments using Migdal to enhance sensitivity to Light DM:

LUX, XENON1T, EDELWEISS,CDEX-1B, SENSEI, DarkSide-50…

Including targets: Ge, Si, Xe and Ar





Pre-2018
No Migdal limits

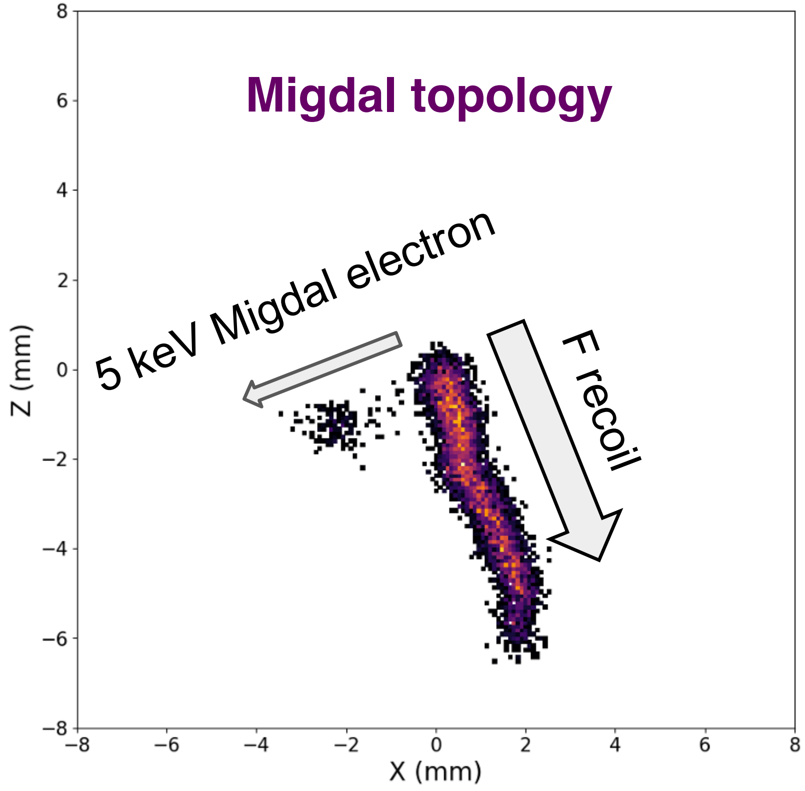
Migdal effect in dark matter direct detection experiments, Ibe et al arXiv:1707.07258

Today
Dominated by Migdal

Detecting the Migdal effect

MIGDAL
Migdal In Galactic Dark mAtter expLoration

- The Migdal effect has not been measured
  → **needs validation!**
- Many efforts underway (**see B. Lenardo's talk**)
- Our aim is to detect the **Migdal topology – electron and nuclear recoil tracks sharing a common vertex**
  → **Challenging!**

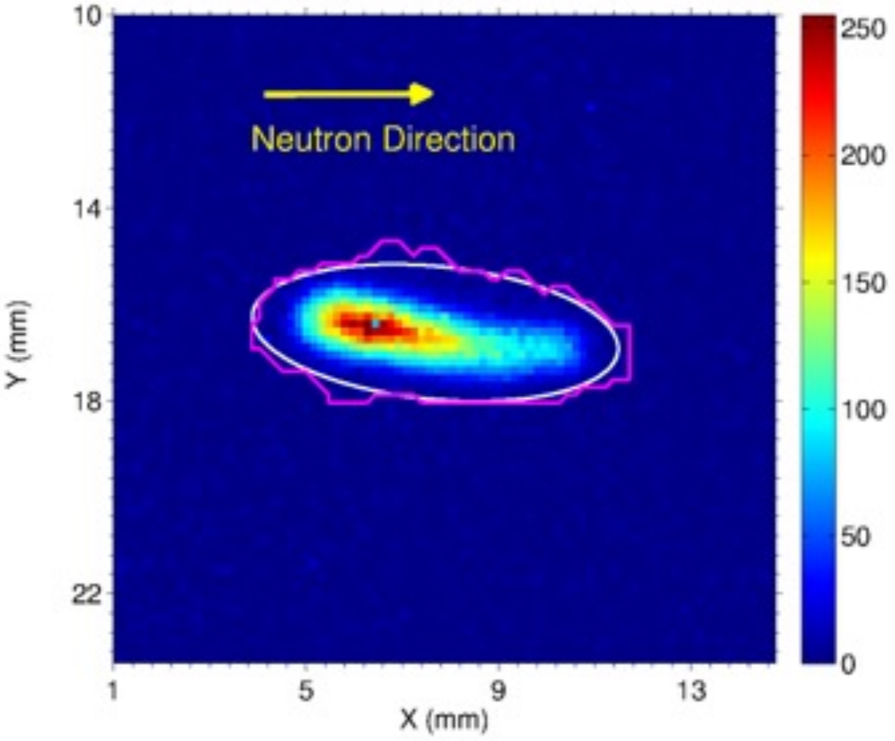


P. Majewski, "OTPC for the observation of the Migdal effect in nuclear scattering", New Horizons in Time Projection Chambers, 2020

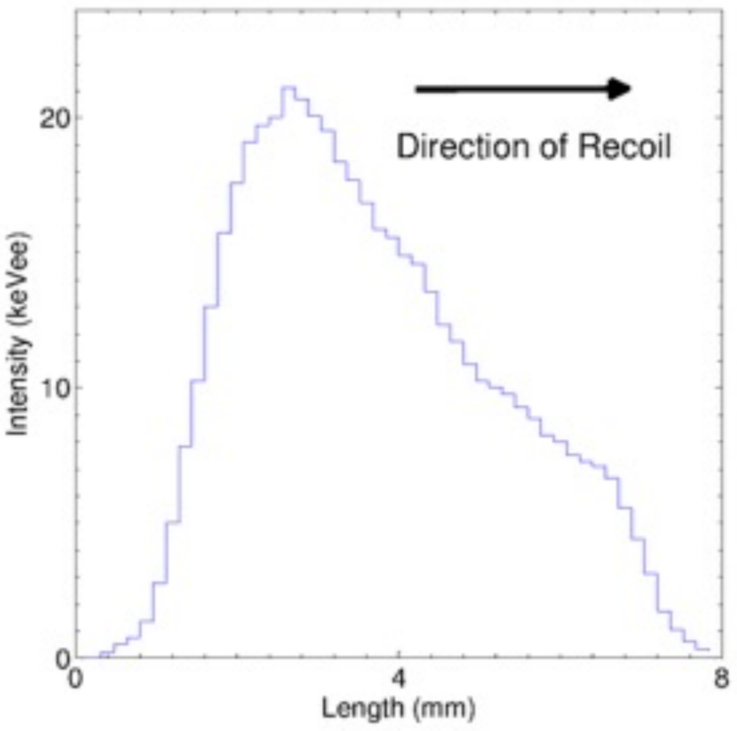
The Directional DM Community has pointed the way **for NRs**

Well resolved NR:

CCD image of Fluorine Recoil



Projected dE/dx along track



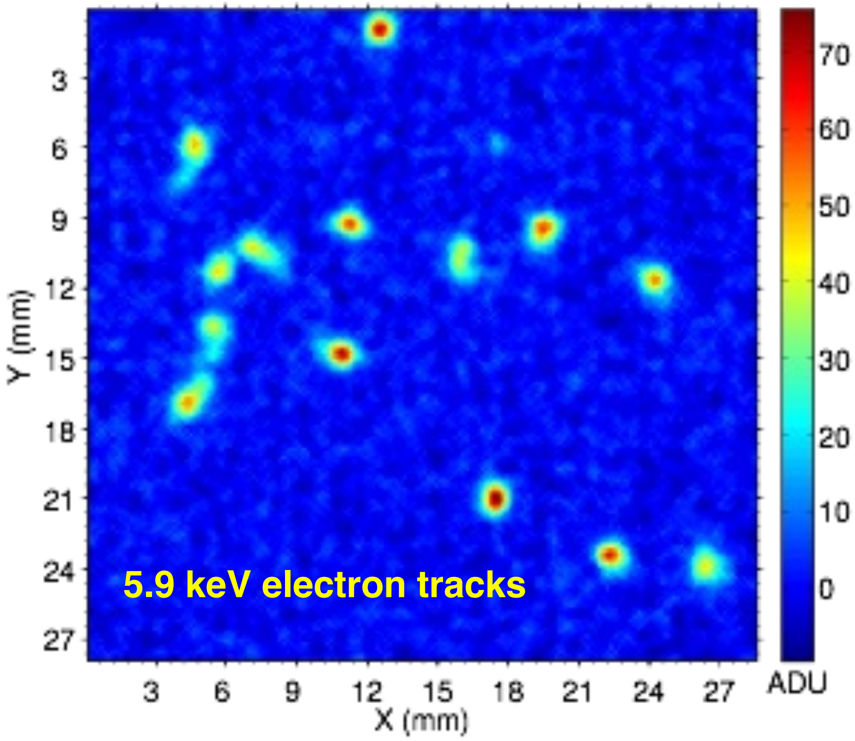
N. Phan, PhD thesis, UNM (2016)

…for Migdal we also need to resolve <10 keV electron tracks, **and** measure their direction…

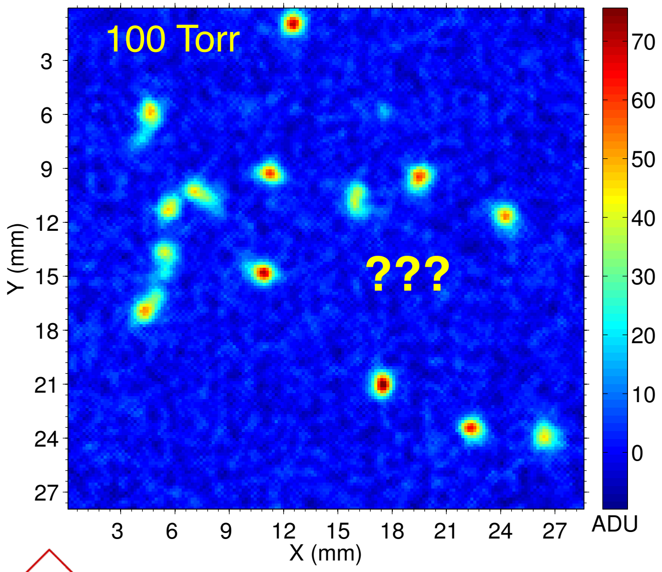
Challenging because electron tracks have **low dE/dx**, large fluctuations:

We need:

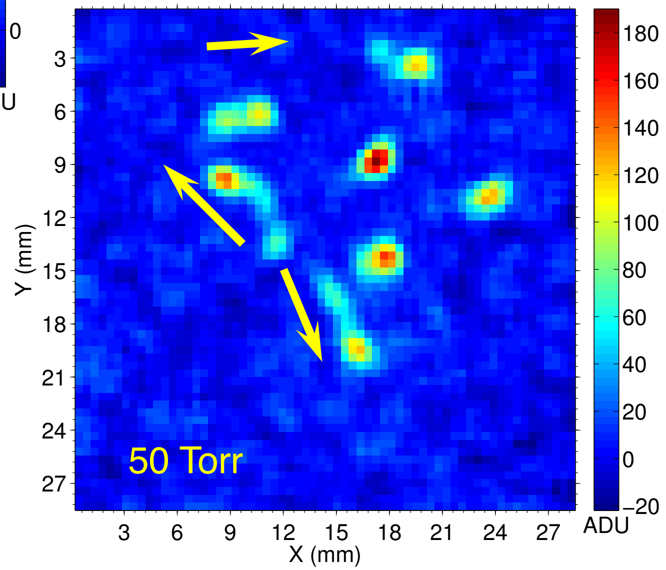
- **low pressures**
- **fine granularity readouts**
- **high S/N, and**
- **Large dynamic range!**



Phan, et al. JINST **15** P05012 (2020). arXiv:1703.09883

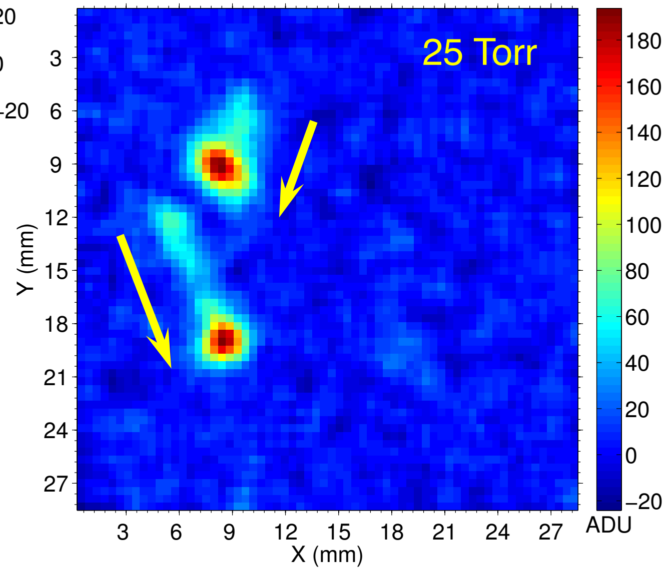


- Using **THGEMs** we can lower pressure, while maintaining:
  - S/N (gas gain) and
  - the granularity of the readouts



5.9 keV electron tracks imaged at same scale

Lower Pressure → Longer Tracks

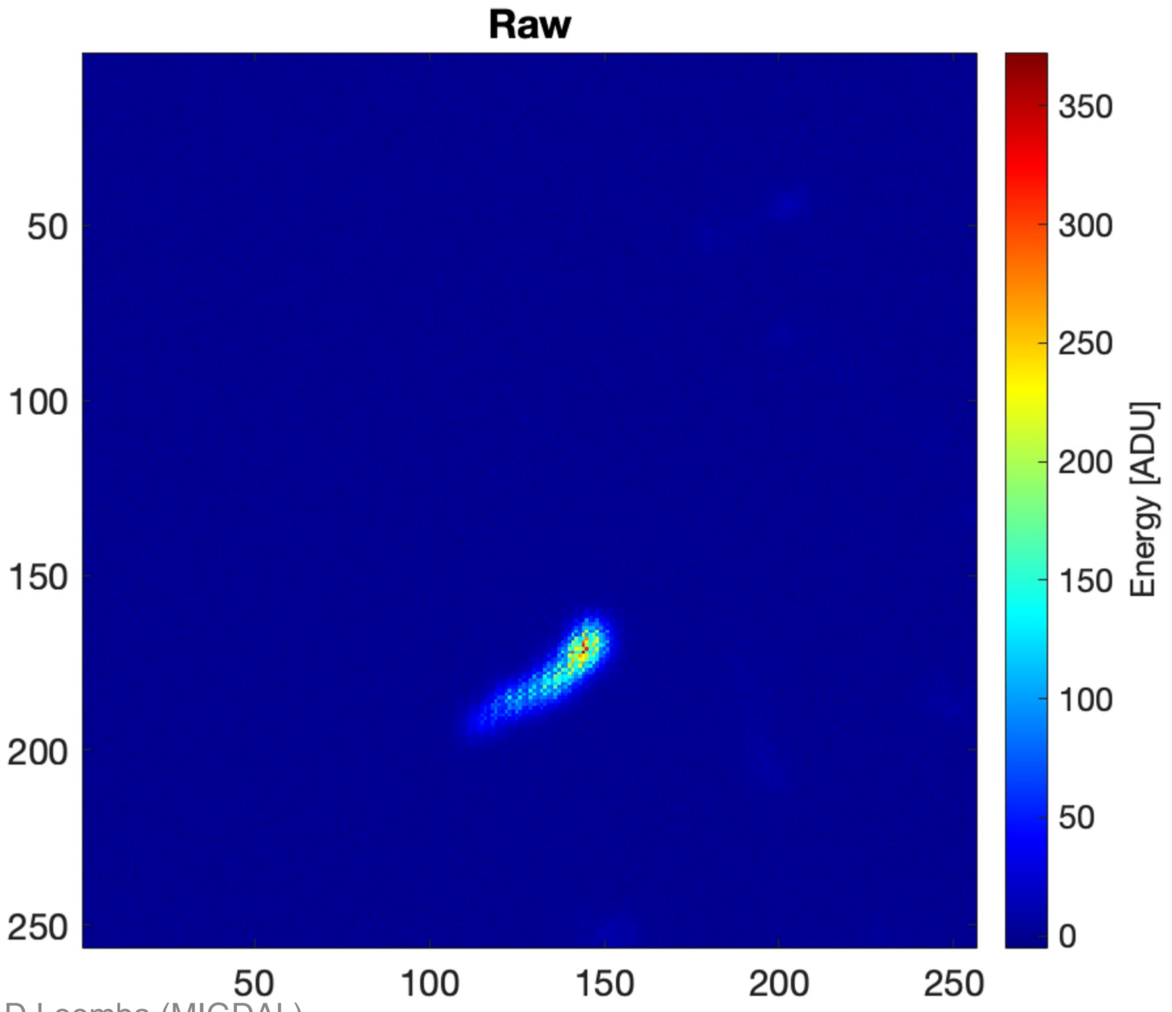


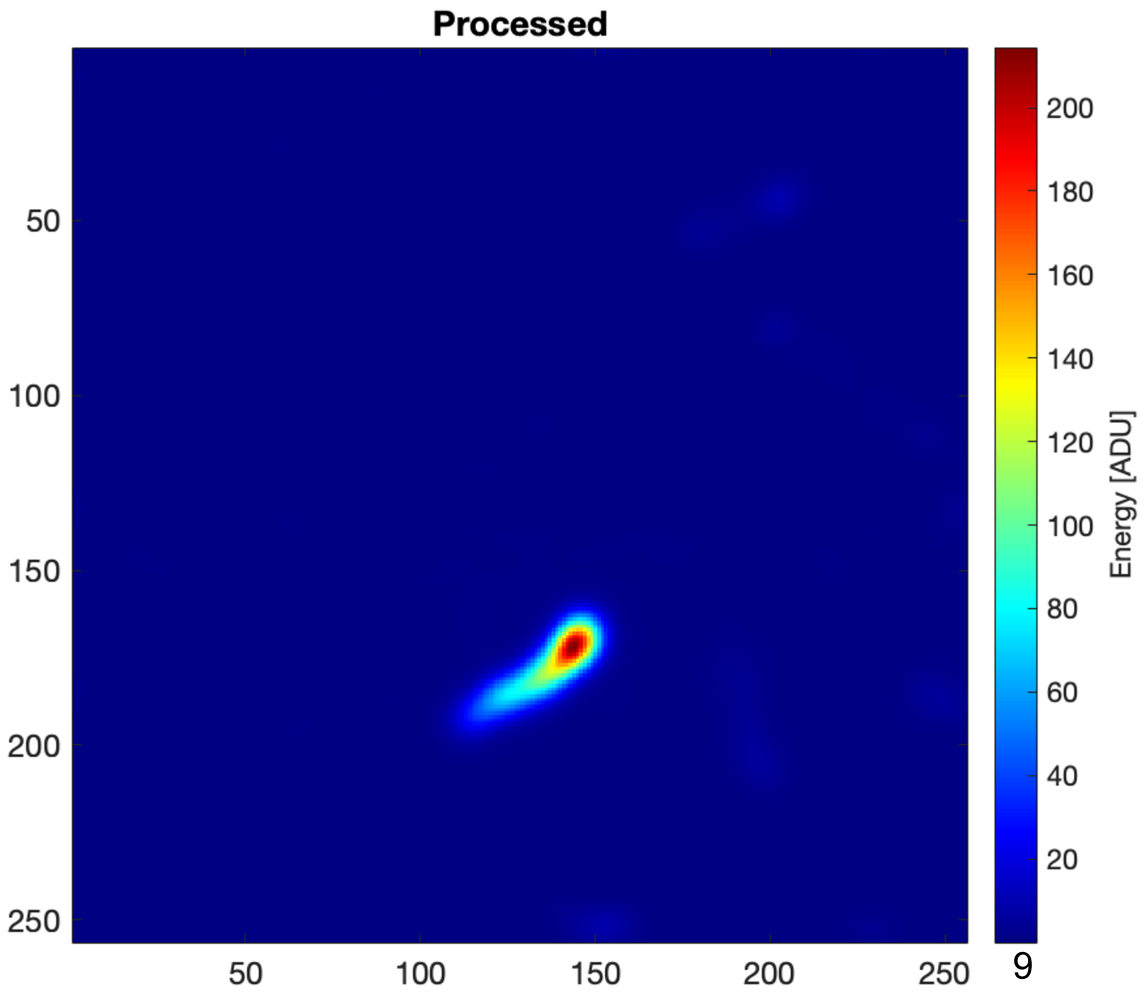
Phan, et al. JINST **15** P05012 (2020). arXiv:1703.09883

Plus we demonstrated we could cover the **huge** dynamic range:

- With GEM gain set such that DD NR's are stable:

(A. Mills, RD51, Nov 2021)





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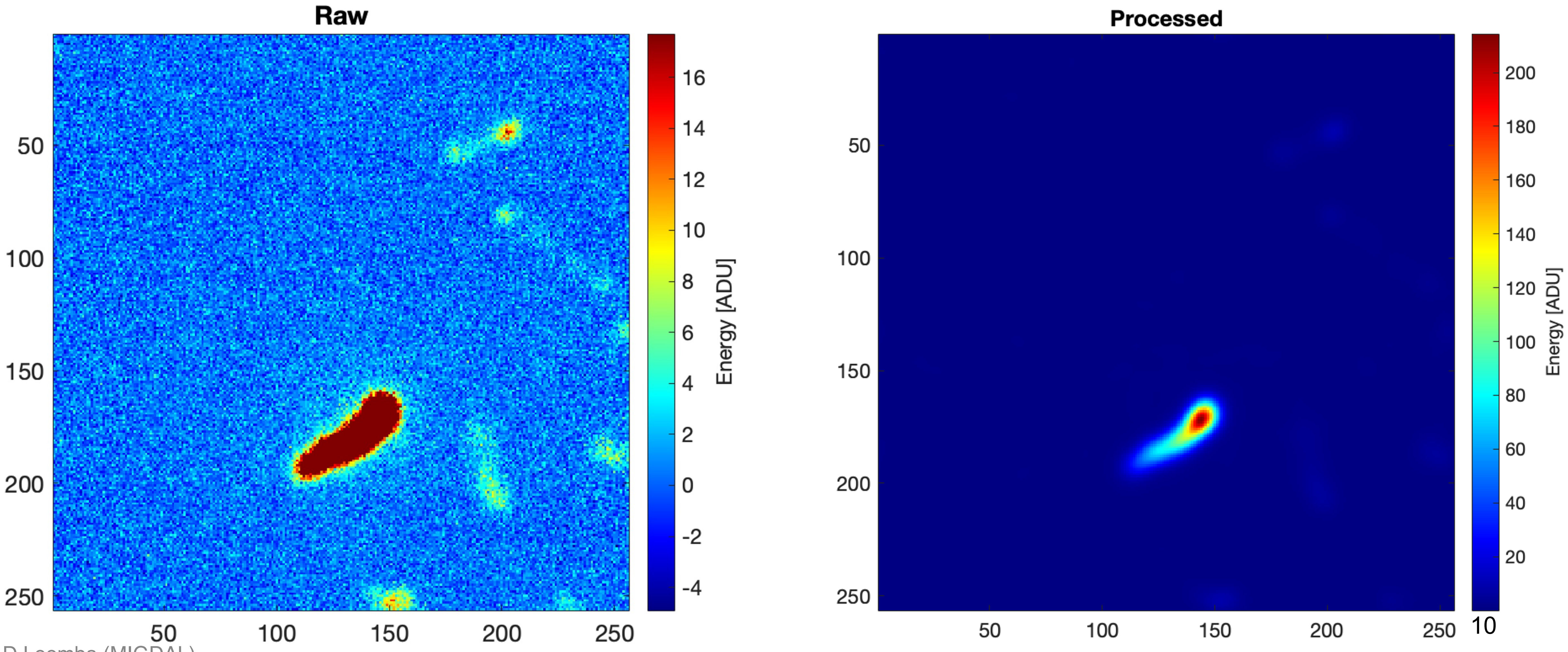
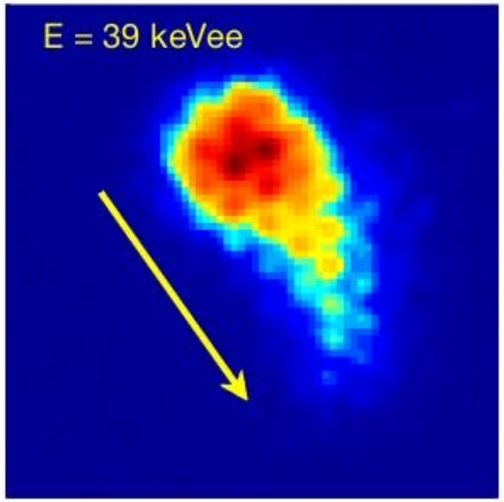


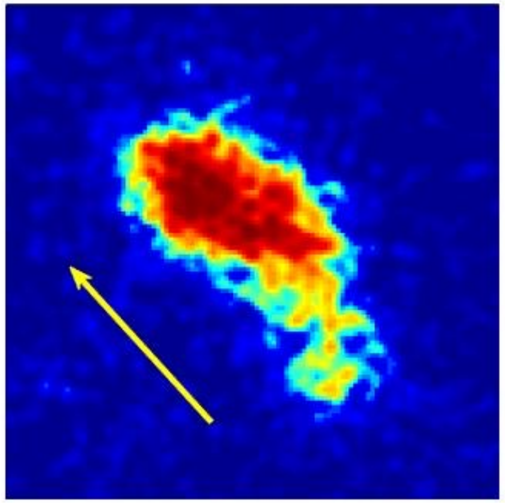
“Migdal Events”

Nuclear Recoil



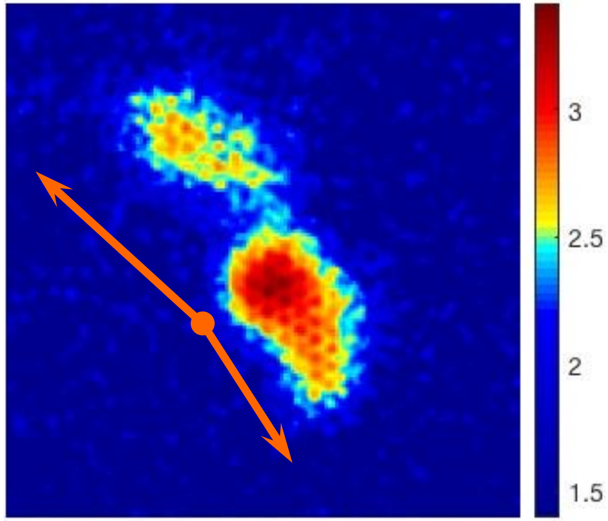
+

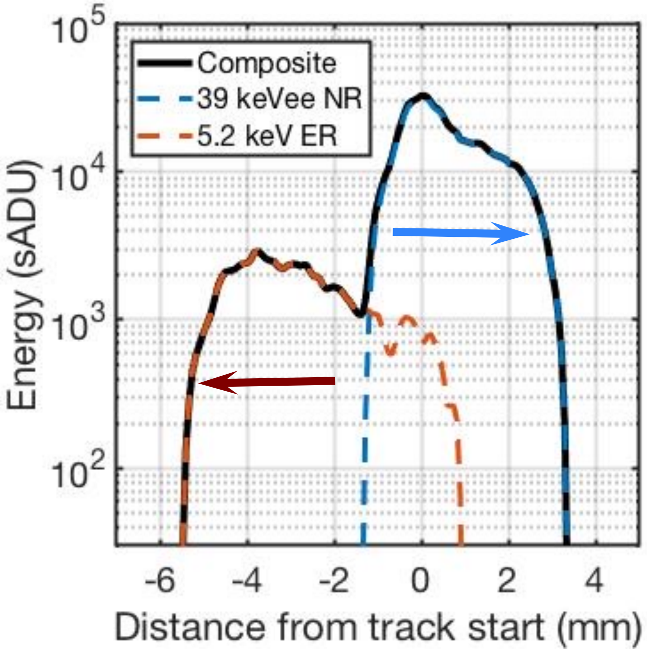
Electron



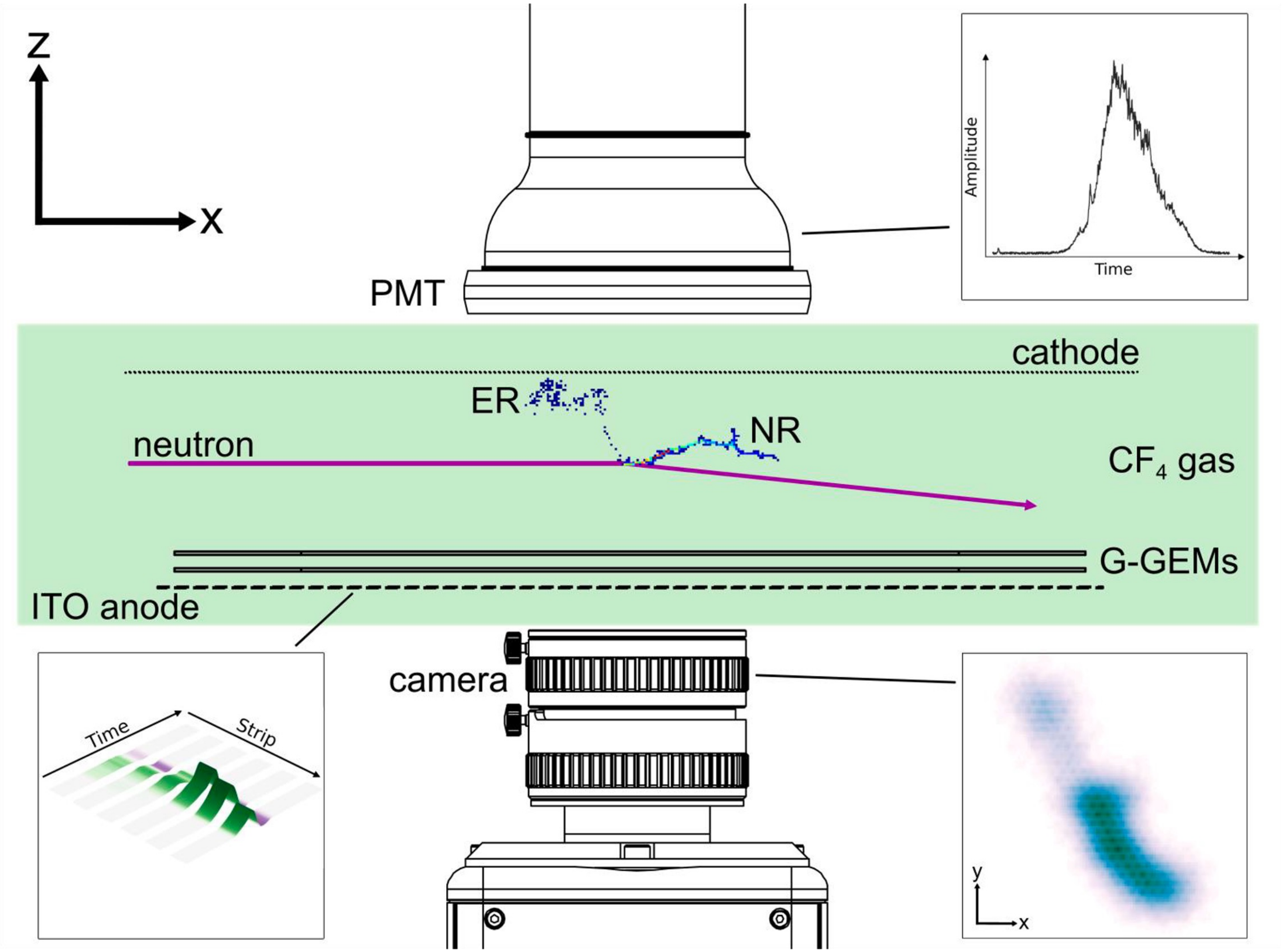
=

Migdal





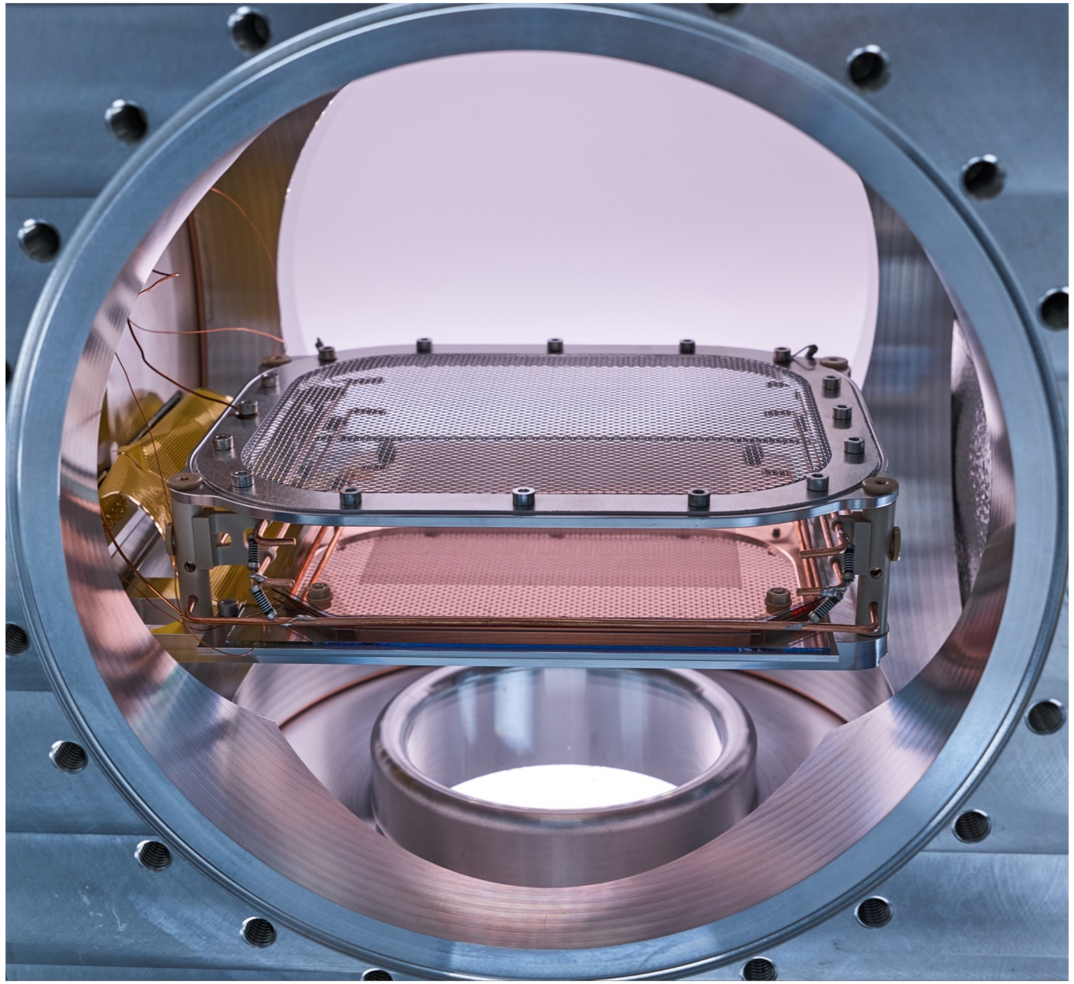
The MIGDAL experiment

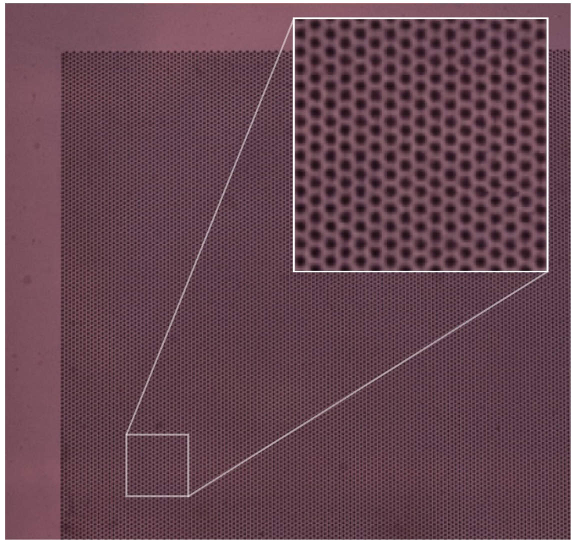


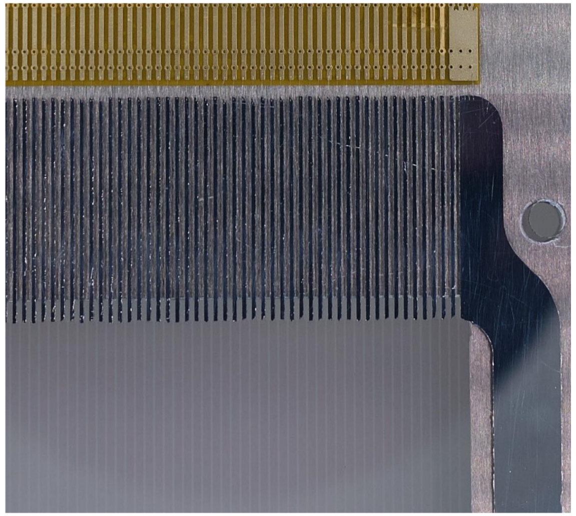
- Low-pressure gas: 50 Torr of CF_4
  - To extend particle tracks
  - Minimize gamma interactions
- Readout
  - Optical : Camera + photomultiplier tube
  - Charge: GEMs + 120 ITO anode strips
- TPC signal amplification
  - 2 x glass-GEMs (Cu or Ni cladded)
- High-yield neutron generator
  - D-D: 2.47 MeV (10^9n/s)
  - Defined beam, “clear” through TPC
- Electron and nuclear recoil tracks
  - Migdal: NR+ER tracks, common vertex
  - Cover dynamic range of NRs and ERs
  - 5 keV electron threshold
    5.9 keV X-rays from Fe-55 for calibration at threshold (5.2 keV photoelectron)

H.M. Araújo *et al* 2023 *Astropart. Phys.* **151** 102853
https://doi.org/10.1016/j.astropartphys.2023.102853

The MIGDAL optical-TPC







Two glass GEMs:

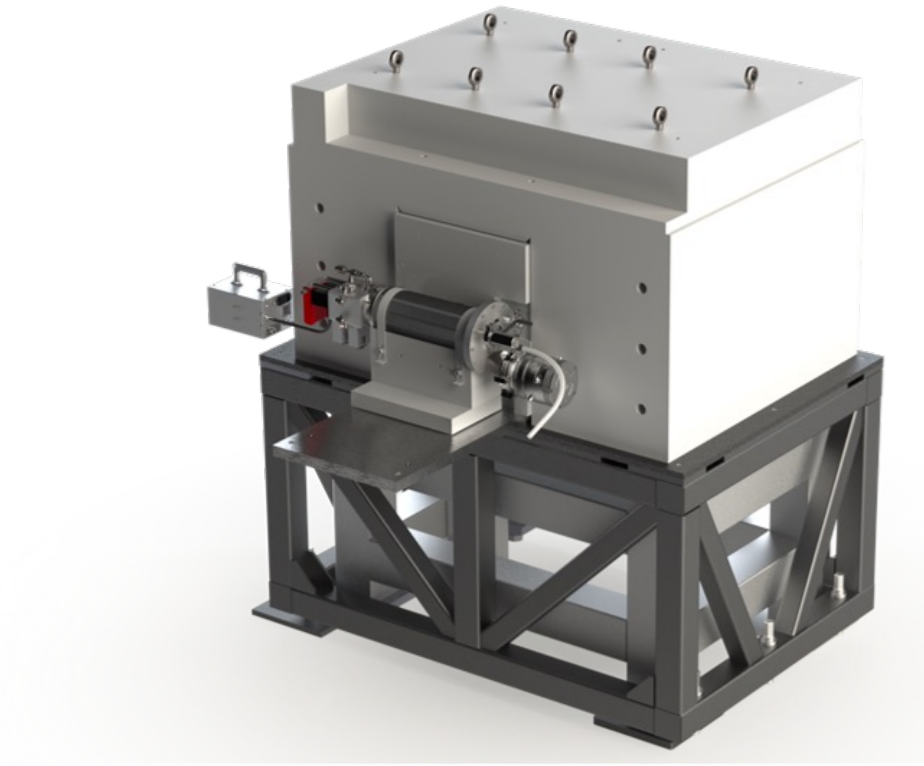
- active area: 10x10 cm^2
- thickness: 550 µm
- OD /pitch: 170/280 µm
- active area: 10x10 cm^2
- total gain ~10^5

ITO strips:

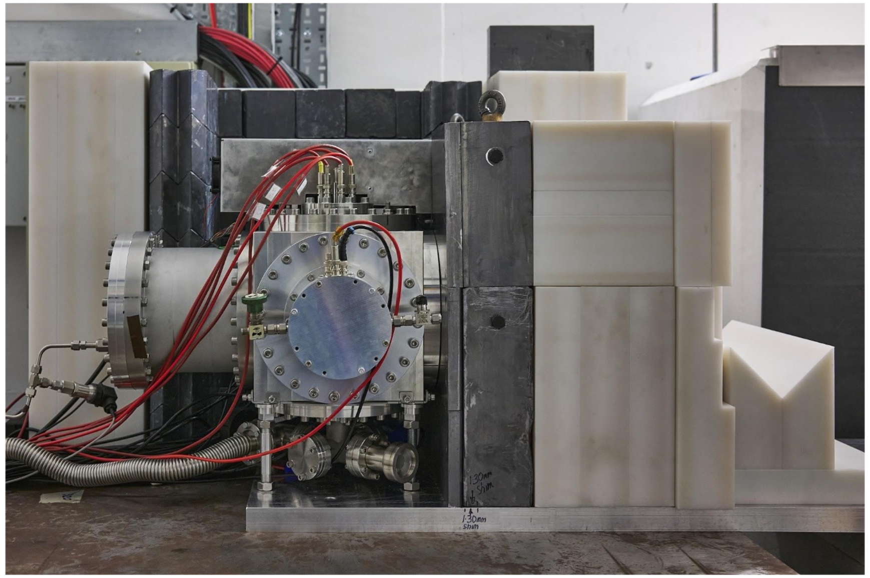
- 120 strips
- width/pitch: 0.65/0.83 mm

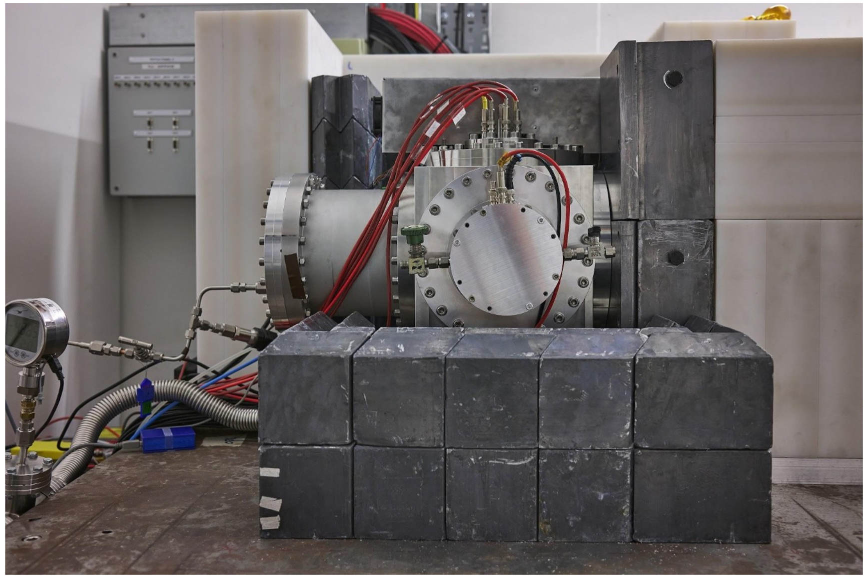
2 field shaping Cu wires

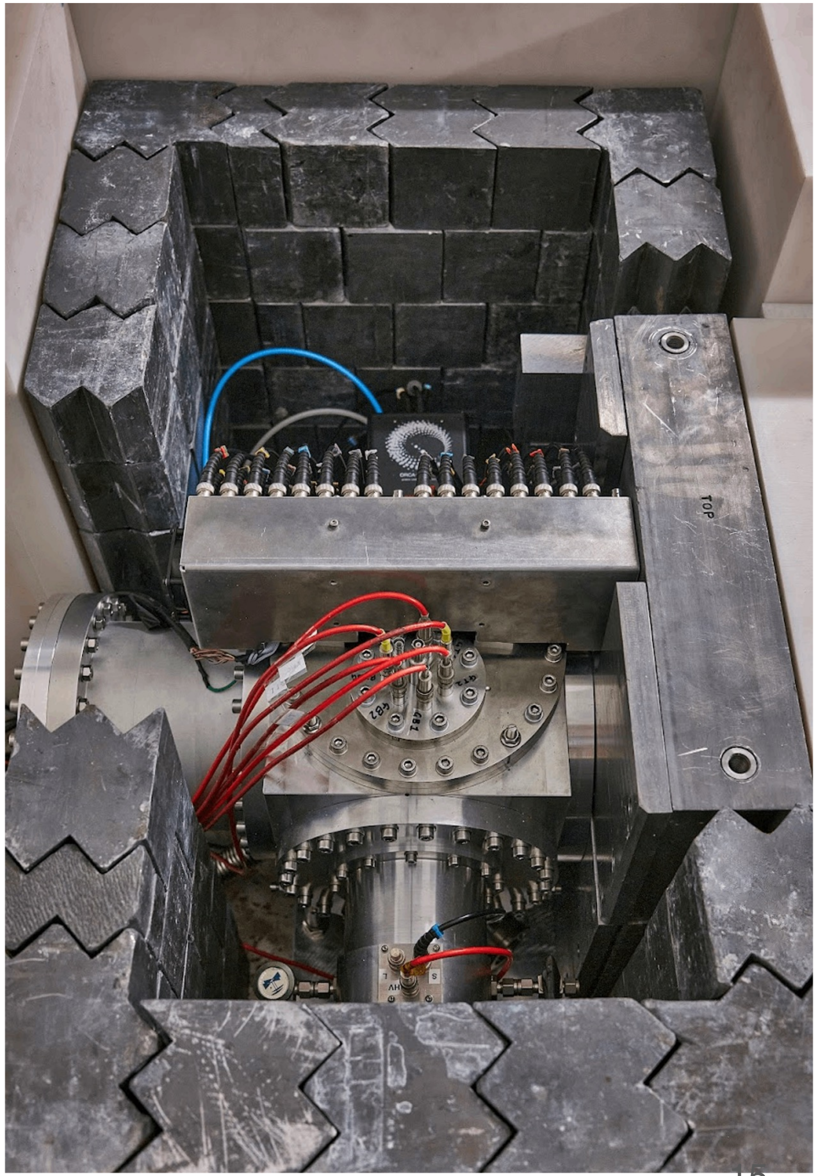
Neutron Irradiation Lab for Electronics (NILE) facility at Rutherford Appleton Lab in the UK

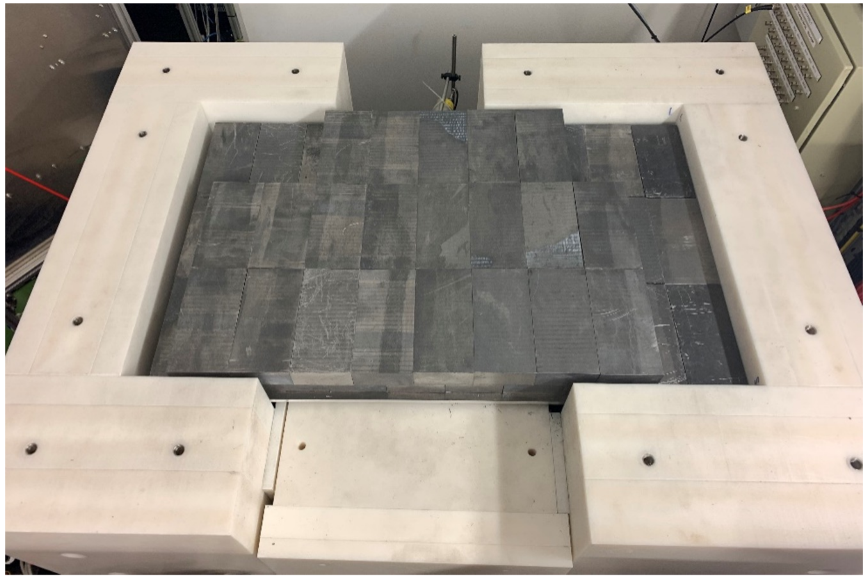


Assembling at NILE

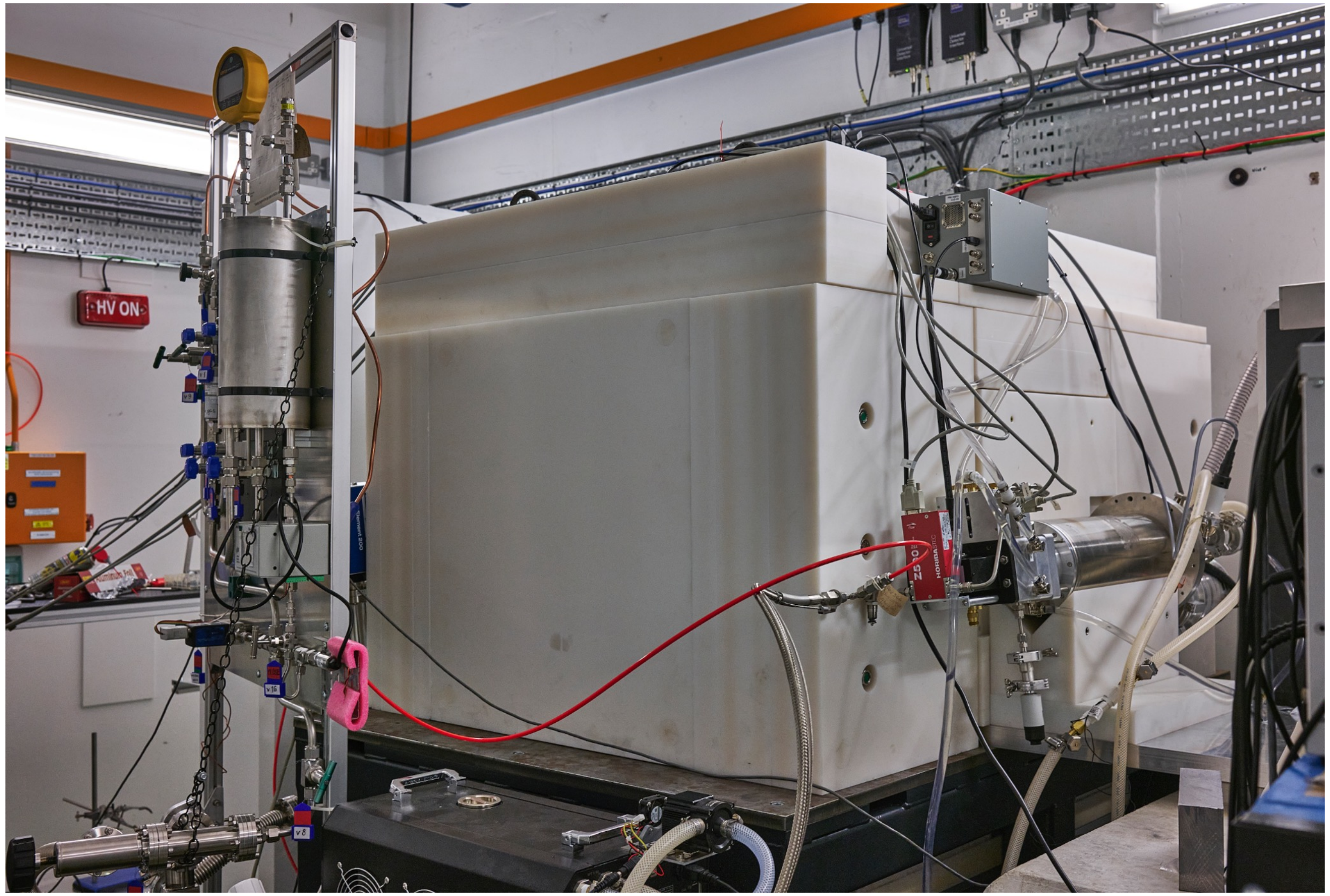








Experiment installation in the NILE bunker

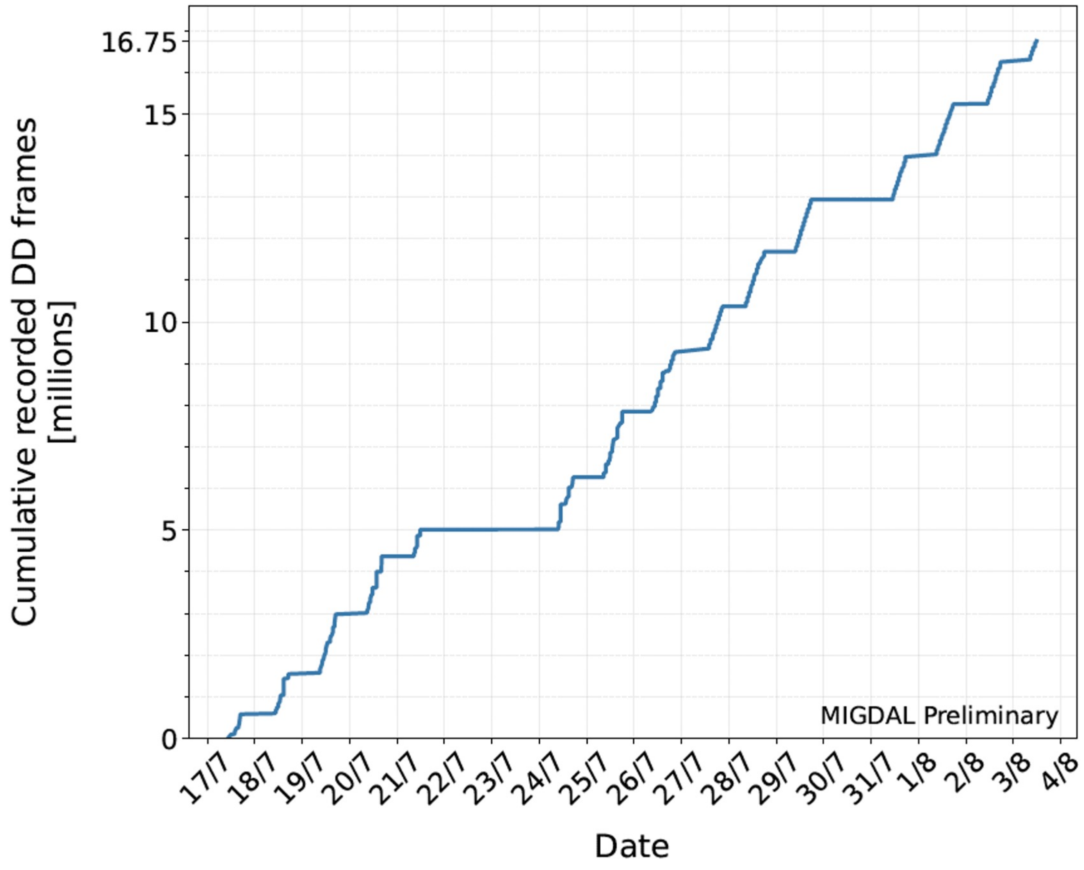


MIGDAL experiment fully assembled at NILE

- Lead shield
  - 10 cm
- Borated HDPE shield
  - 20 cm
- Collimator HDPE+ lead
  - 30 cm long

First Science Run – Summary

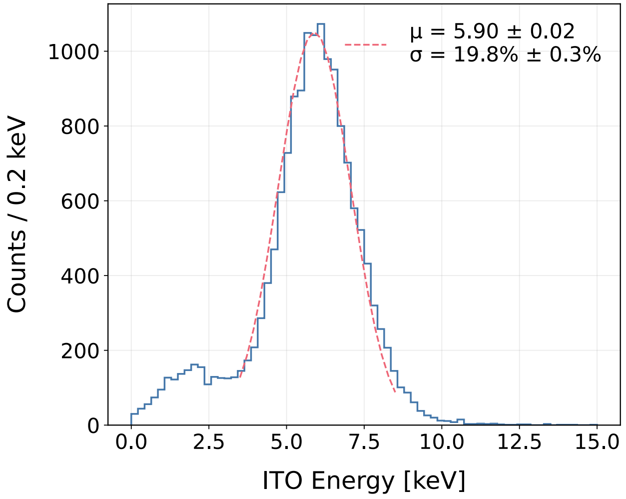
- **The First Science run took place from the 17th of July to the 3rd of August.**
- Data taken using D-D neutron generator recorded continuously during 10 hour long shifts. Significant fraction of empty frames due to low DD rate.
- Frames taken with 20 ms exposure time (vs.8.3 ms). Longer than planned due to problems with camera's Linux firmware.
- Data taking interspersed with regular calibration runs (^{55}Fe) to monitor the gain of the detector.
- GEM dV increased by a small amount each day to maintain constant gain.
- Total gain in GEMs tuned to a threshold required to fully resolved ^{55}Fe peak.
- Average spark rate ~ 7/min due to need for high dynamic range.
- **Half the data is blinded.**



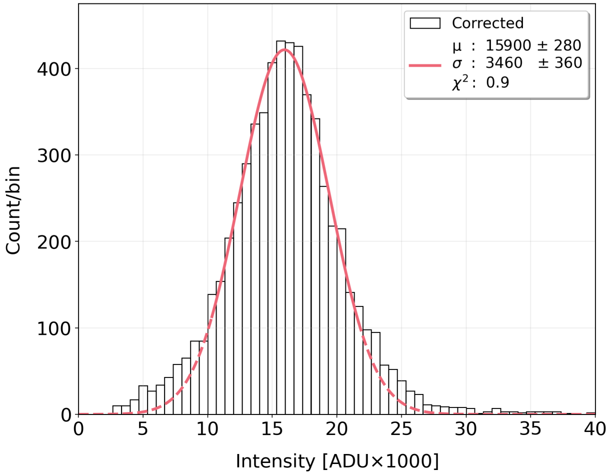
Real-time gain calibration

^{55}**Fe spectra** automatically processed at the end of calibration runs

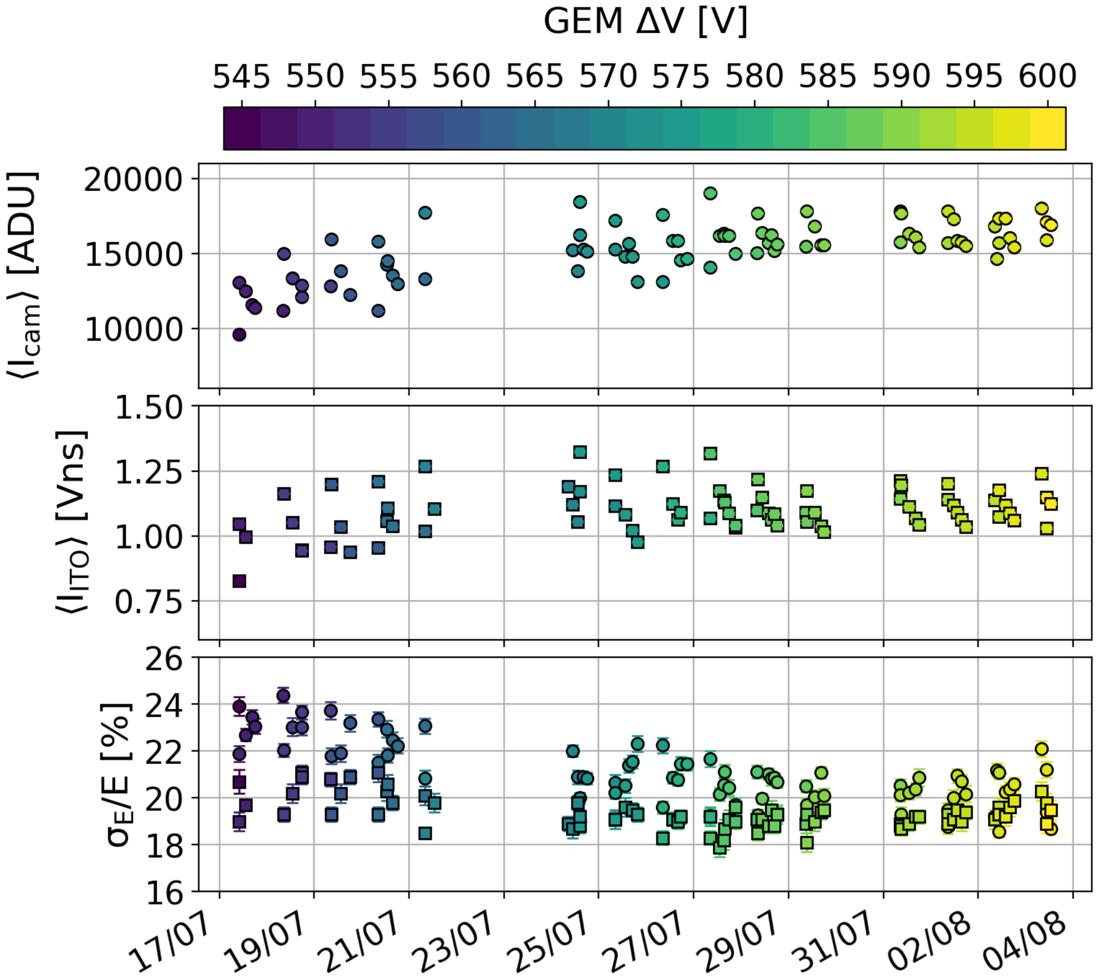
ITO



Camera

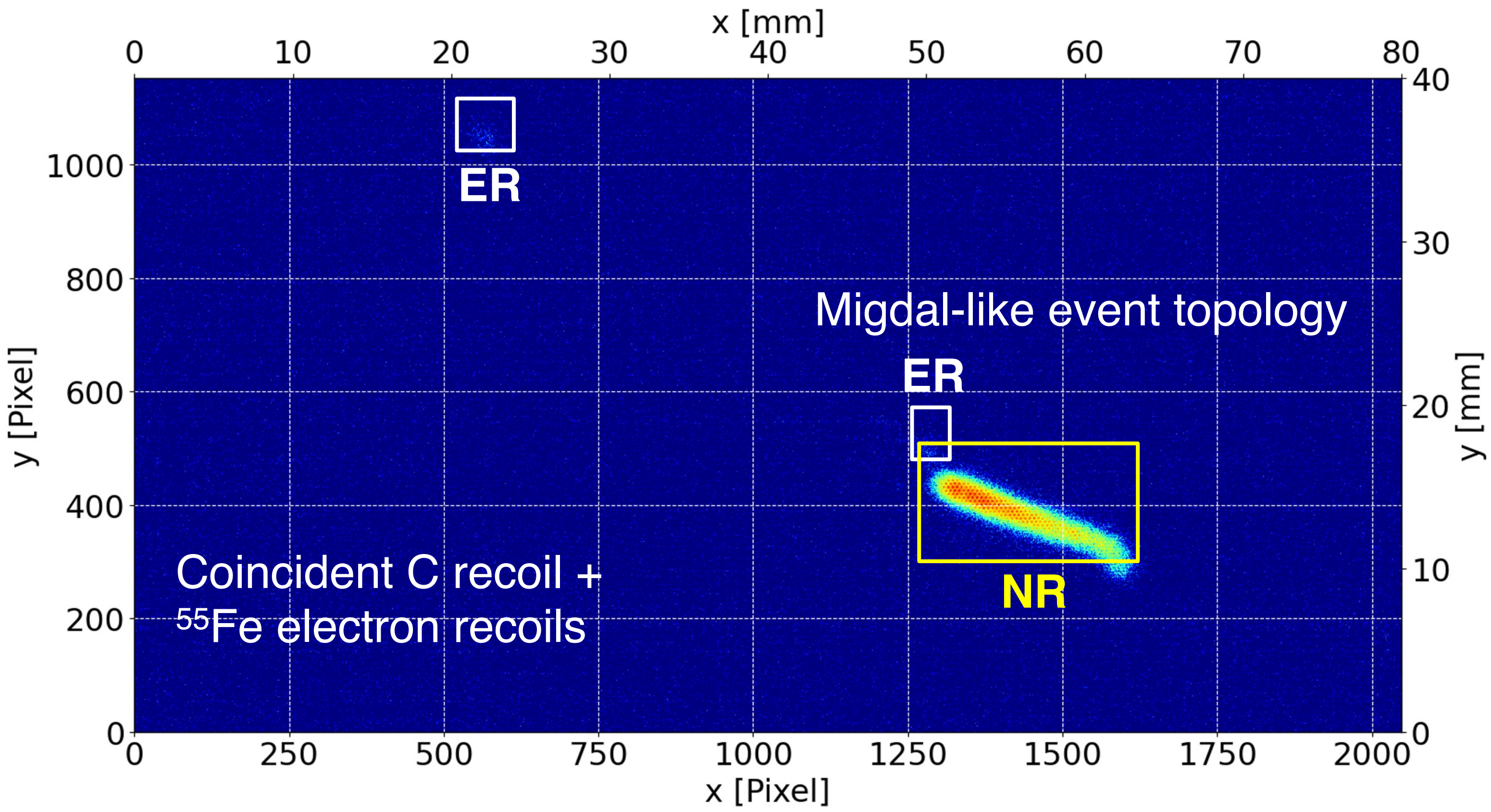


Summary of **gain** and gain **resolution** over the course of first science run from July 17th - Aug. 4th, 2023



Real-time analysis of CMOS data with YOLO (You Only Look Once)

YOLOv8 is a state of the art ***object detection*** algorithm that **simultaneously locates** (draws a bounding box) and **identifies objects** of interest in an image



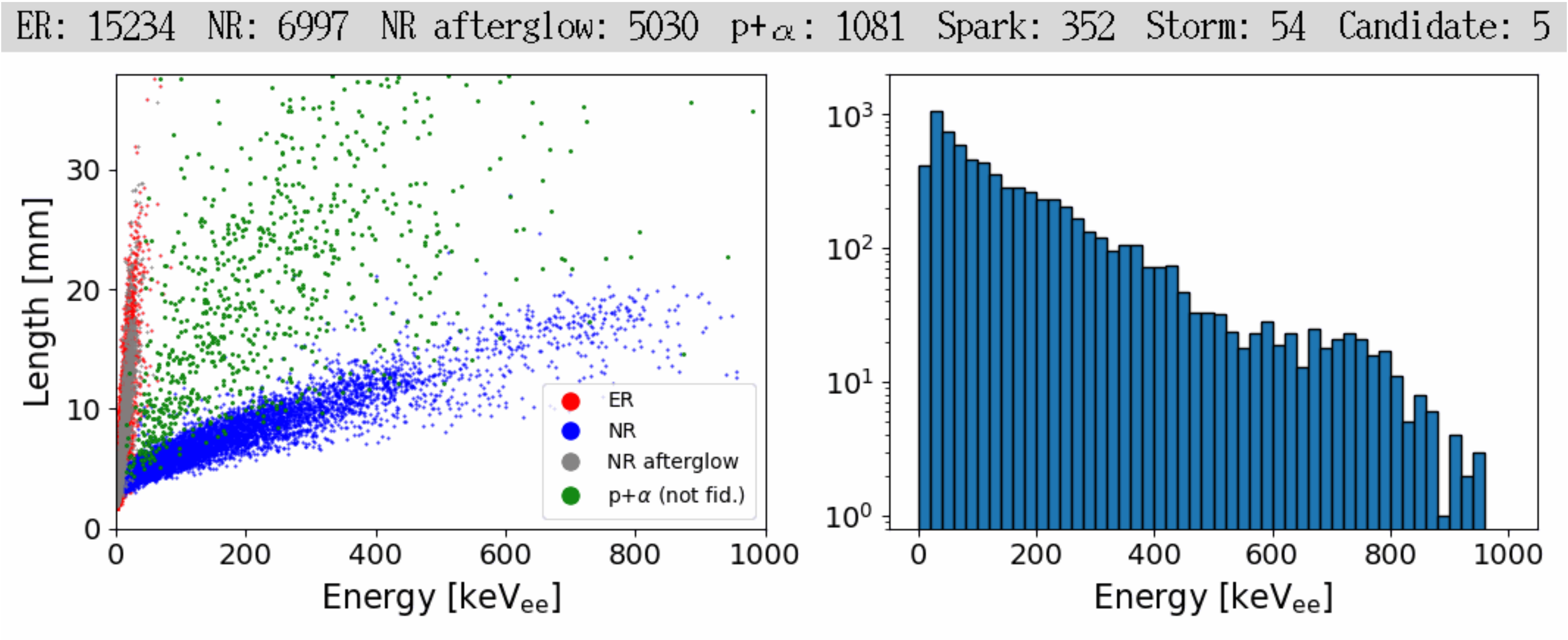
J. Schueler, et al. (MIGDAL) arXiv:2406.07528

We train YOLOv8 on measured data *to identify ERs, NRs, protons, alphas, sparks, camera afterglow, rolling shutter, etc.*

Benefits:

1. *Single-shot identification and analysis of tracks*
2. *Enables real time ^{55}Fe calibrations and ER/NR/etc event rate counting*
3. *Can identify multiple particle species within a continuous cluster*
4. ***Not trained to find Migdals*** *→ robust and doesn't need to be trained on simulation!*

Online, real-time analysis with YOLO



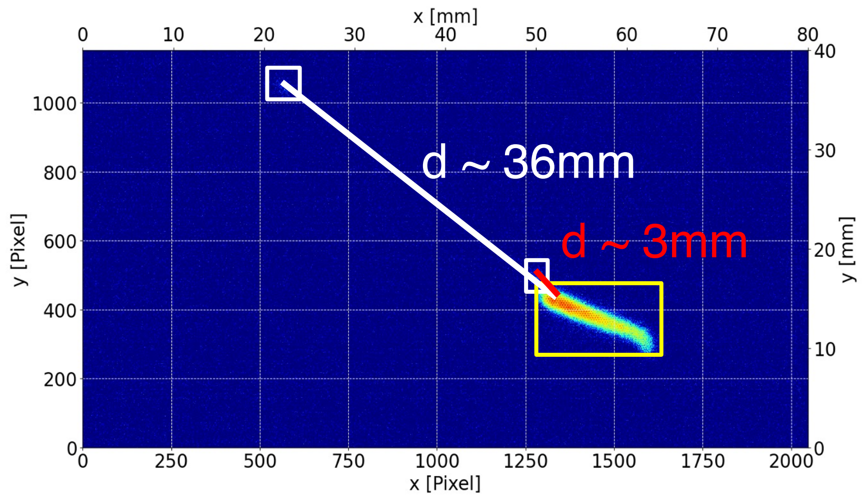
Particle species rates, dE/dx distributions, spectra, etc, automatically generated from YOLO pipeline → Detector performance monitoring

YOLO applied to Migdal search

- Applied to unblinded dataset consisting of ~20 million 2,048 x 1,152 images at 120 fps

(1) Initial sample of ***(~20 million frames)***

(2) Find frames containing at least 1 ER/NR pair ***(~25,000 frames)***



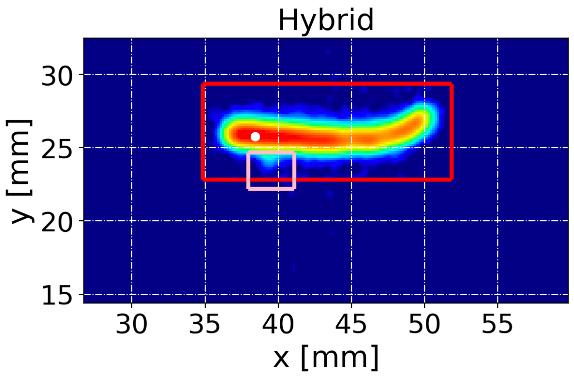
(3) Filter frames based on other criteria ***(~1,100 frames)***

→ ***No longer a rare event search! These camera-only candidates require full 3D reconstruction using the ITO+PMT to derive final Migdal candidates***

YOLO performance metrics

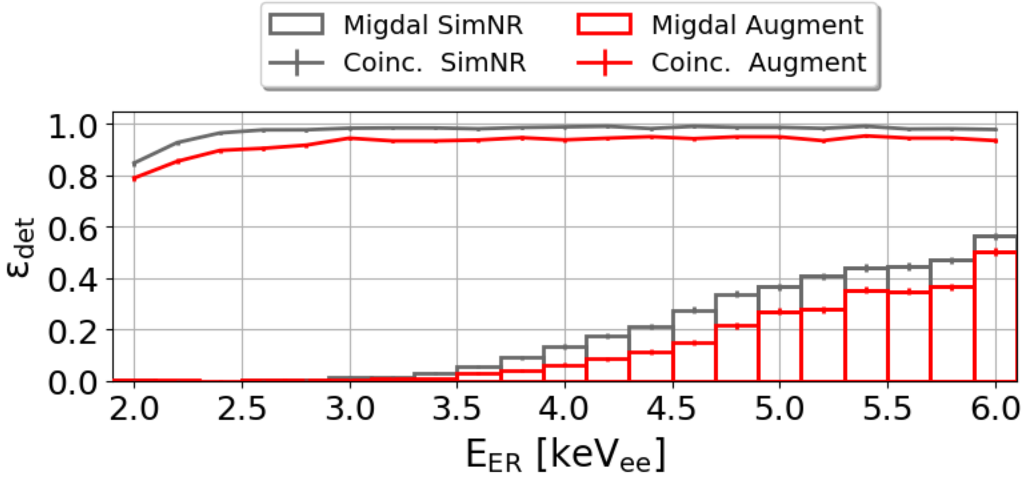
Train YOLO on **real data**, evaluate on **Migdals constructed using data NRs stitched to simulated ERs to derive efficiency.**

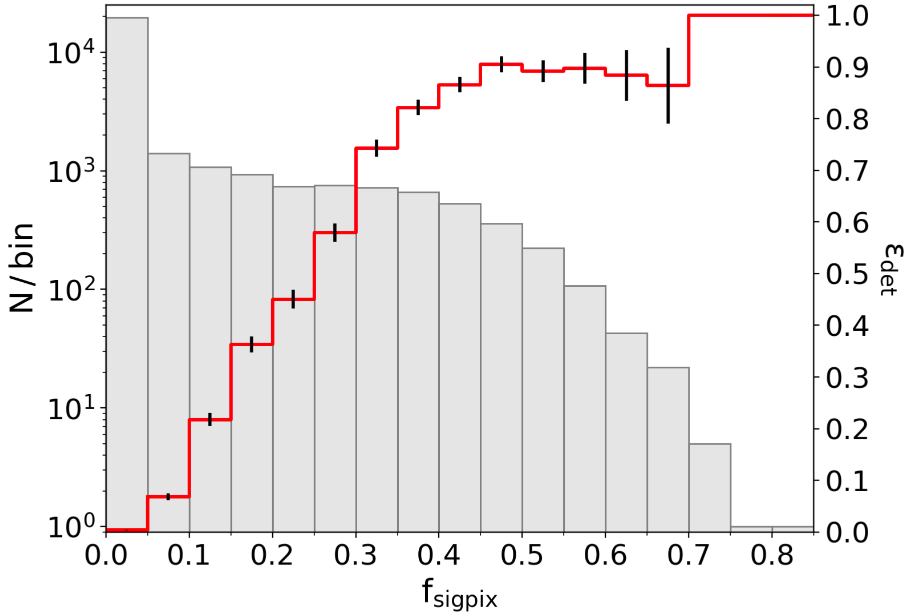
- Efficiency in MIGDAL ROI (E_e>5 keV) is **~40%**



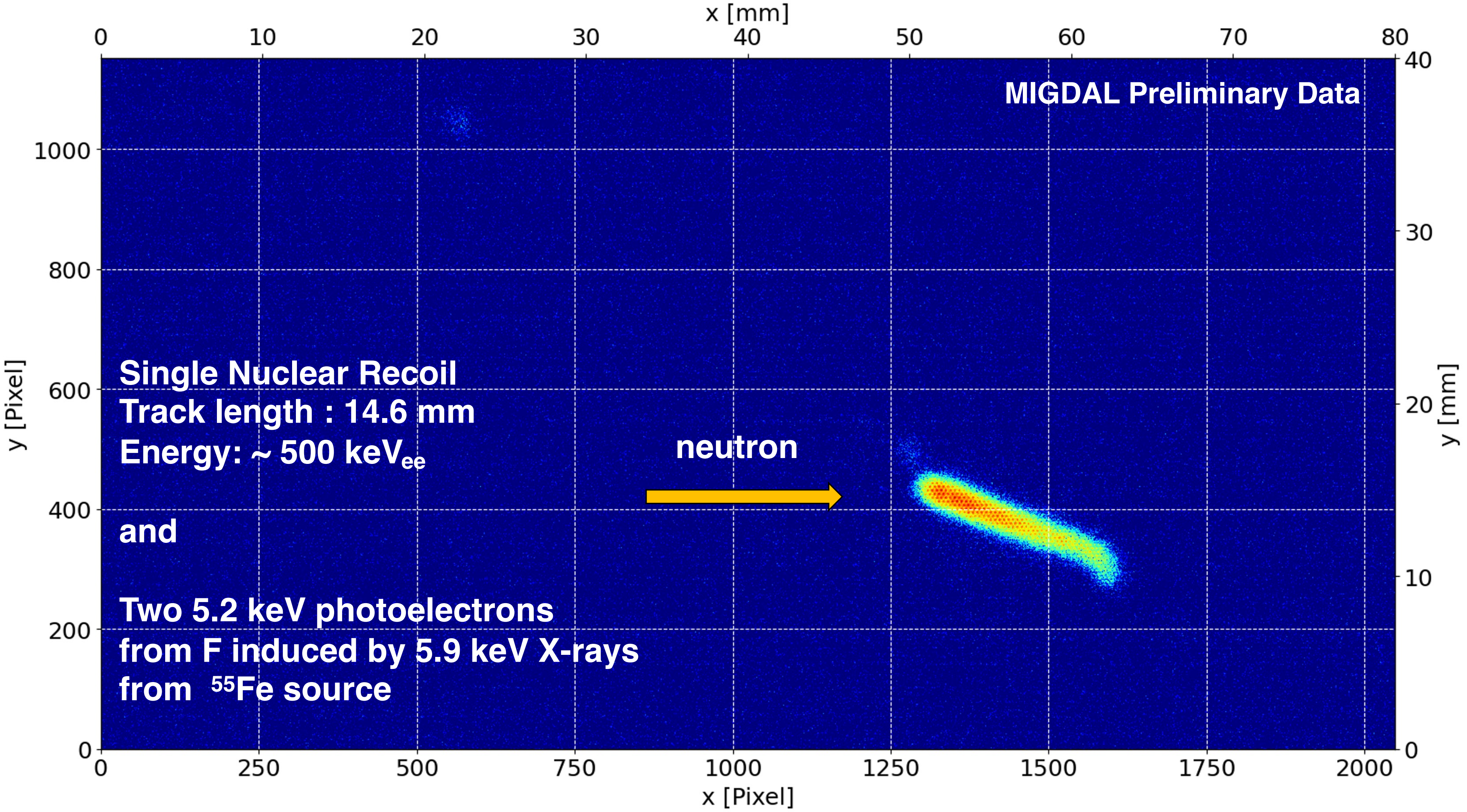
We quantify YOLO's ability to detect (faint!) ER in a Migdal event using:

- Fraction of significant pixels belonging to ER, f_{sigpix} (**sig pixel is one where >1/3 of intensity belongs to ER**)

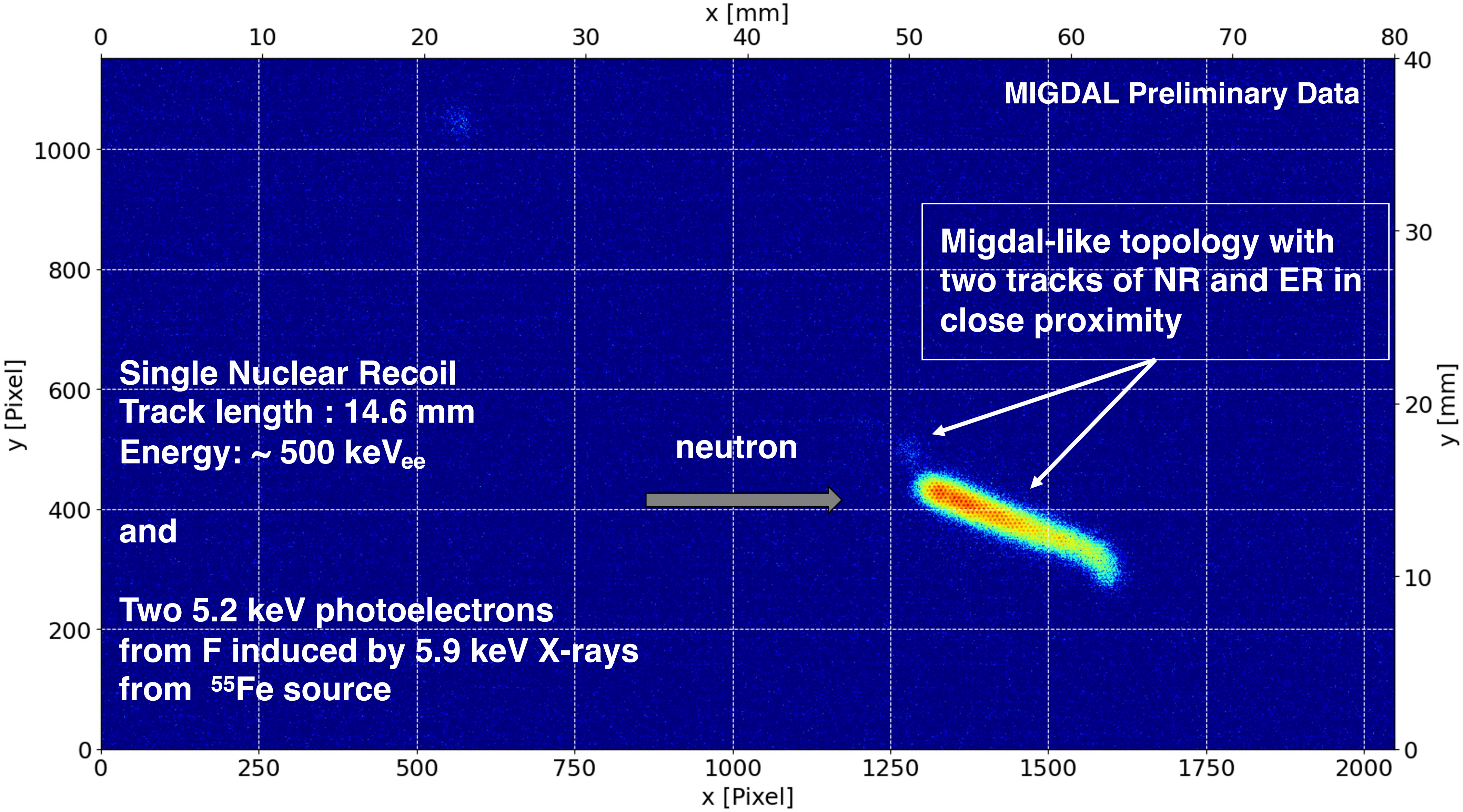




Example Migdal-like event in DD + ^{55}Fe run (or why (3+1)-dim is needed!)



Example Migdal-like event in DD + ^{55}Fe run



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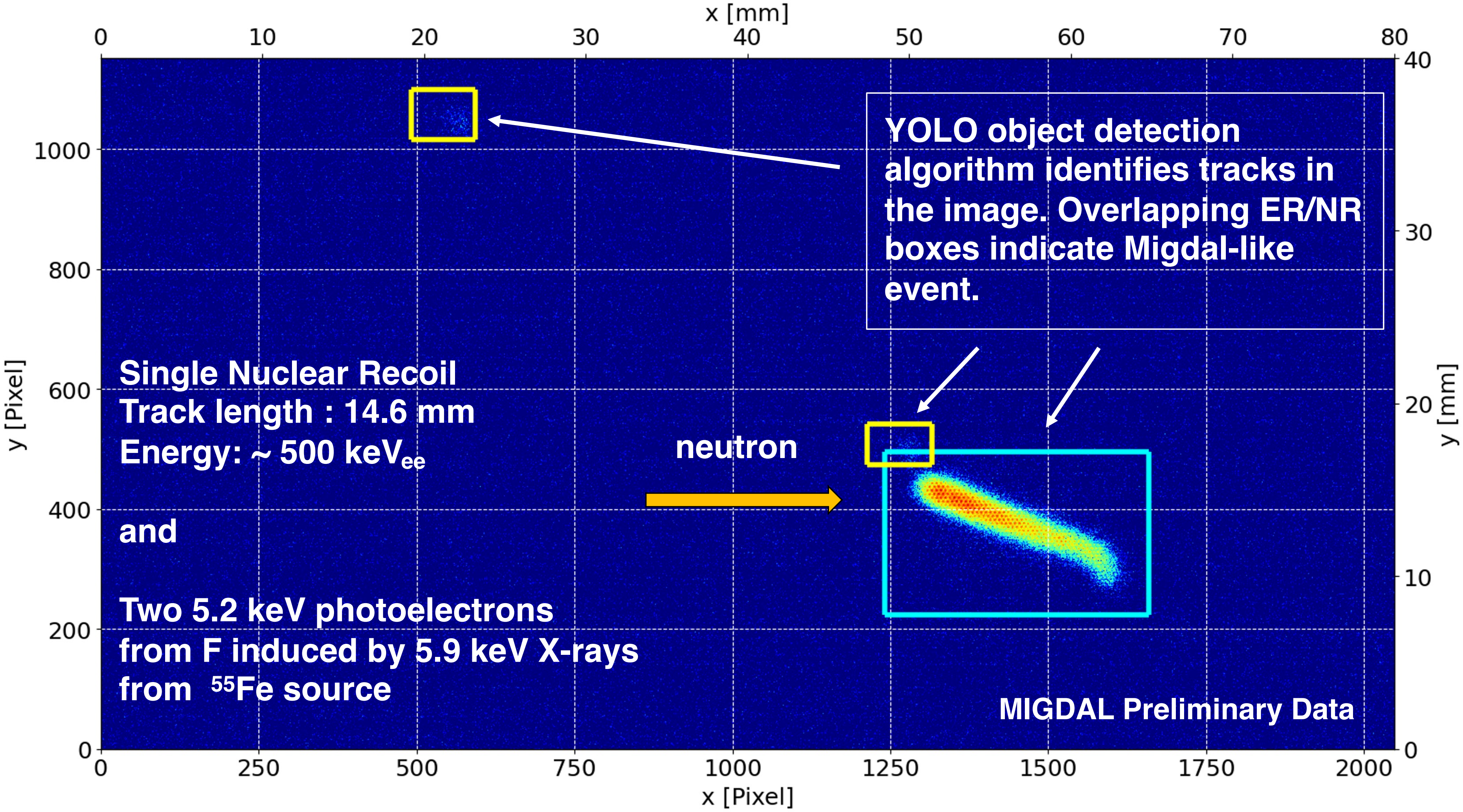
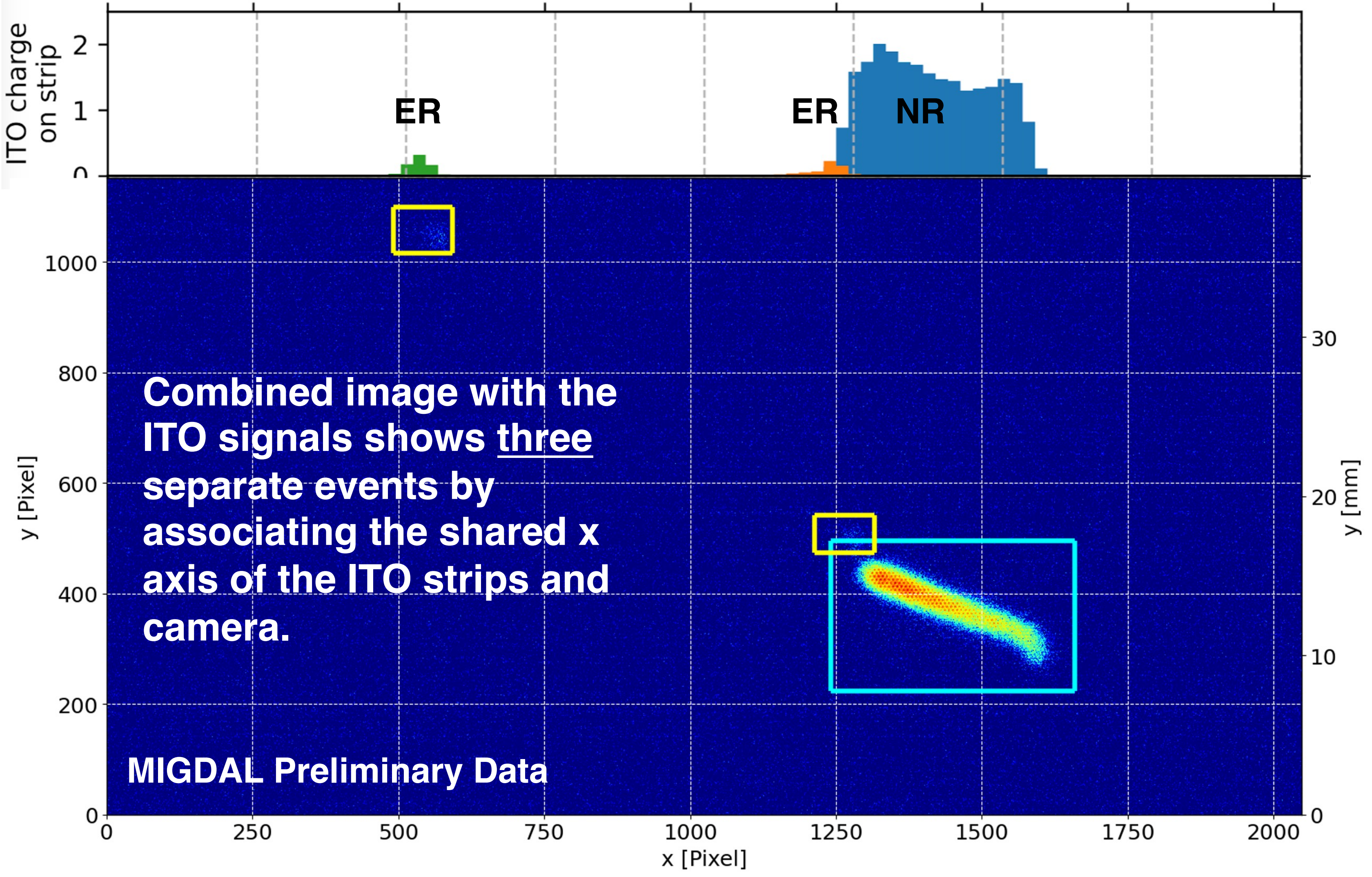


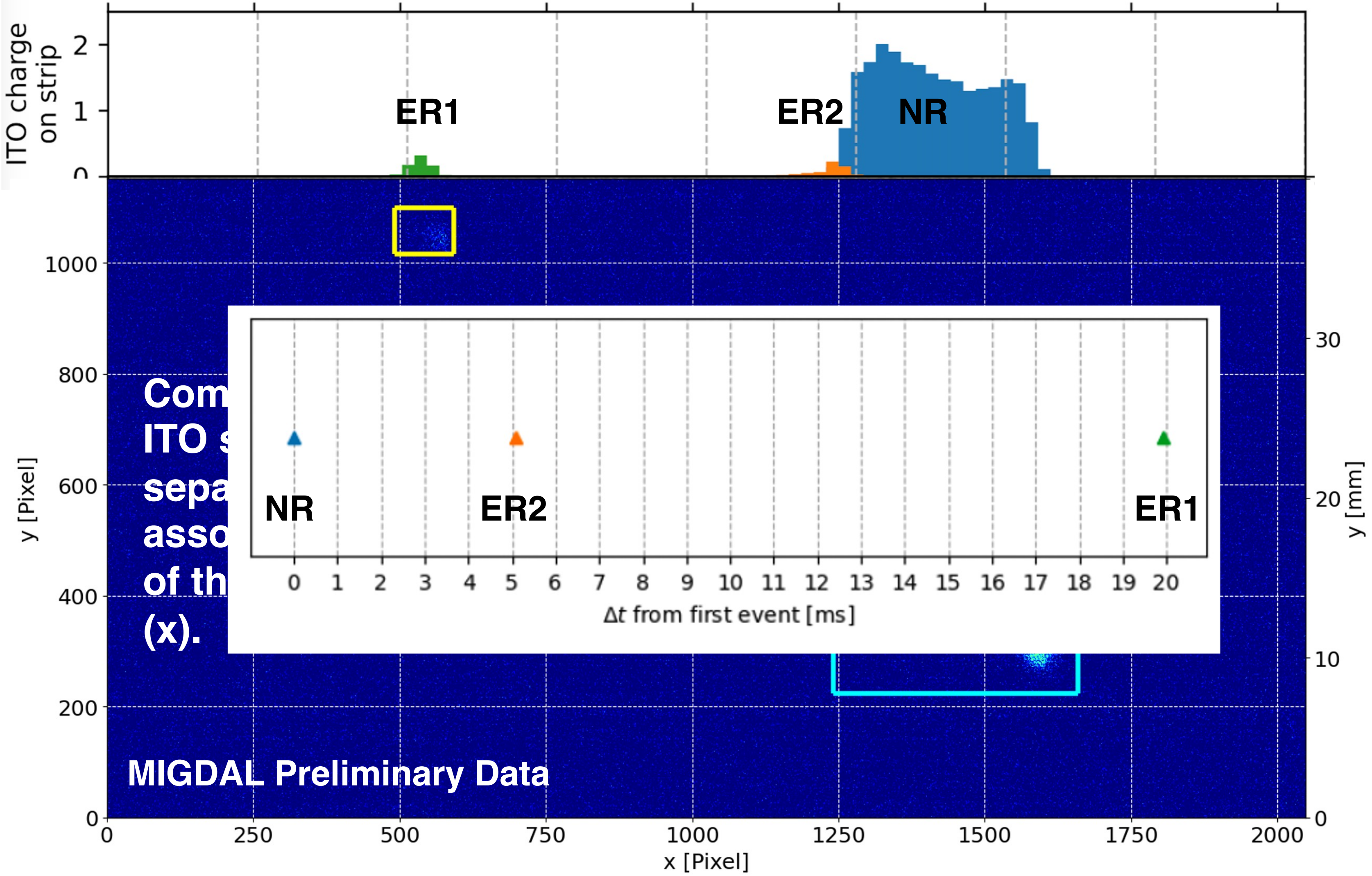
Migdal-like event…

Synchronizing with ITO signals:



Migdal-like event…

Synchronizing with ITO signals:

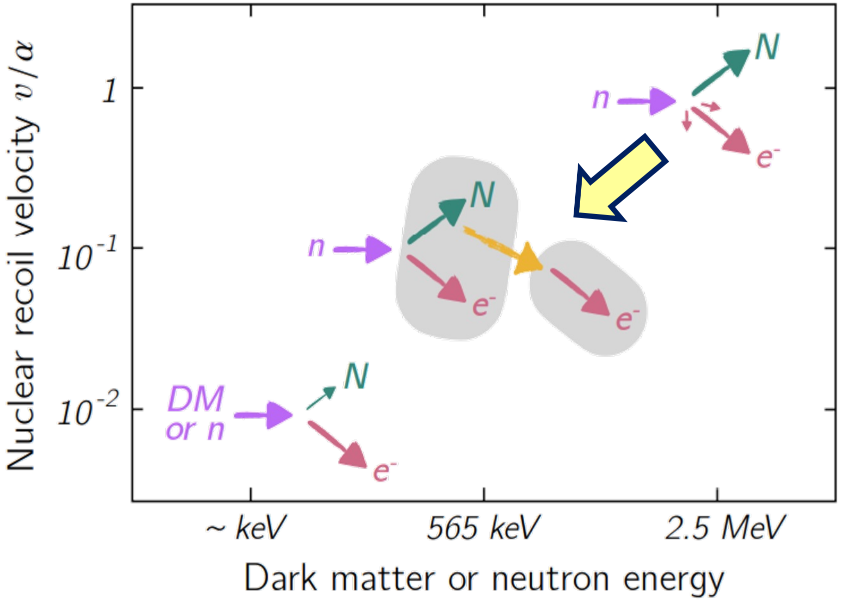


Timing information from ITO strips separates all 3 tracks in time.
→ NOT Migdal!

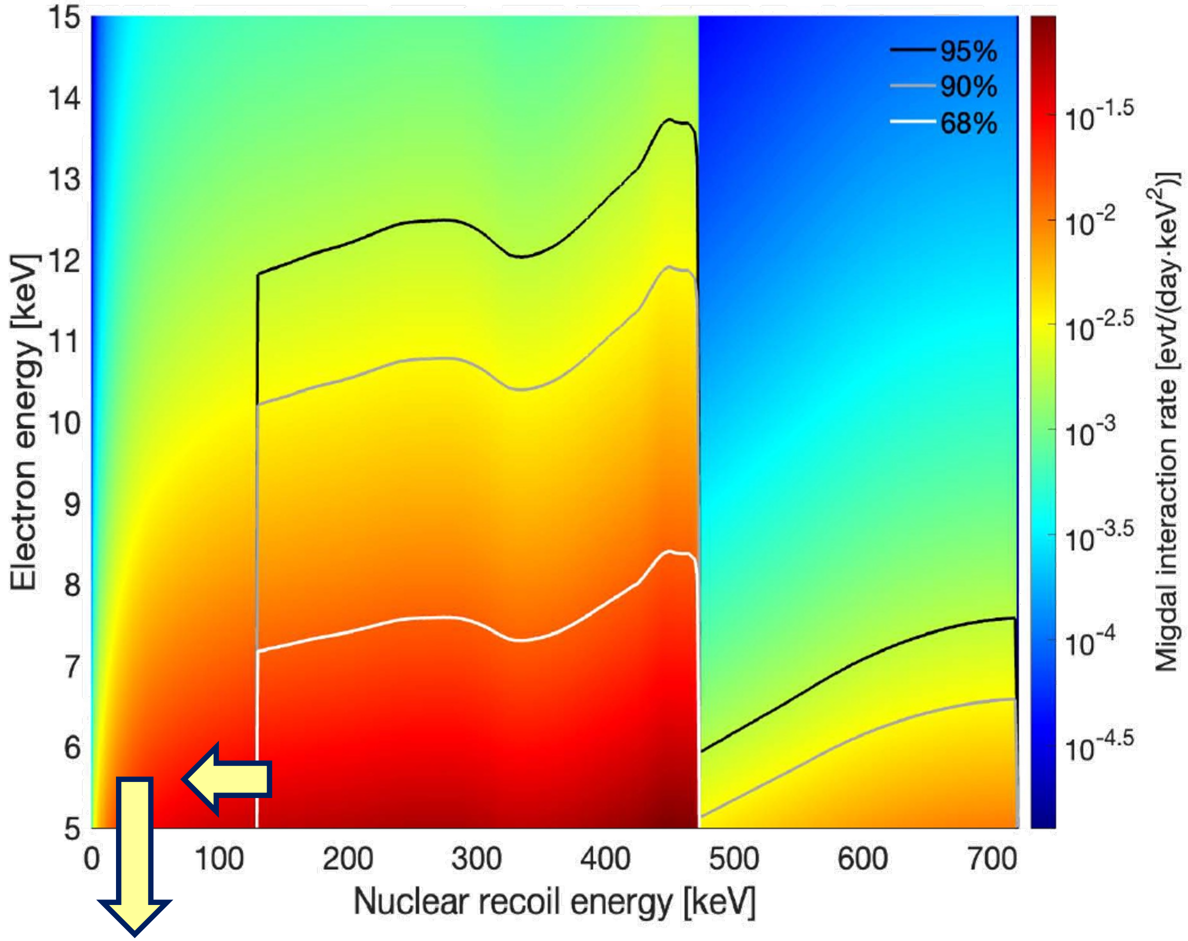
R&D for a MIGDAL Phase II

MIGDAL Phase II - Motivation

- Probe lower energies
- Attain higher rates



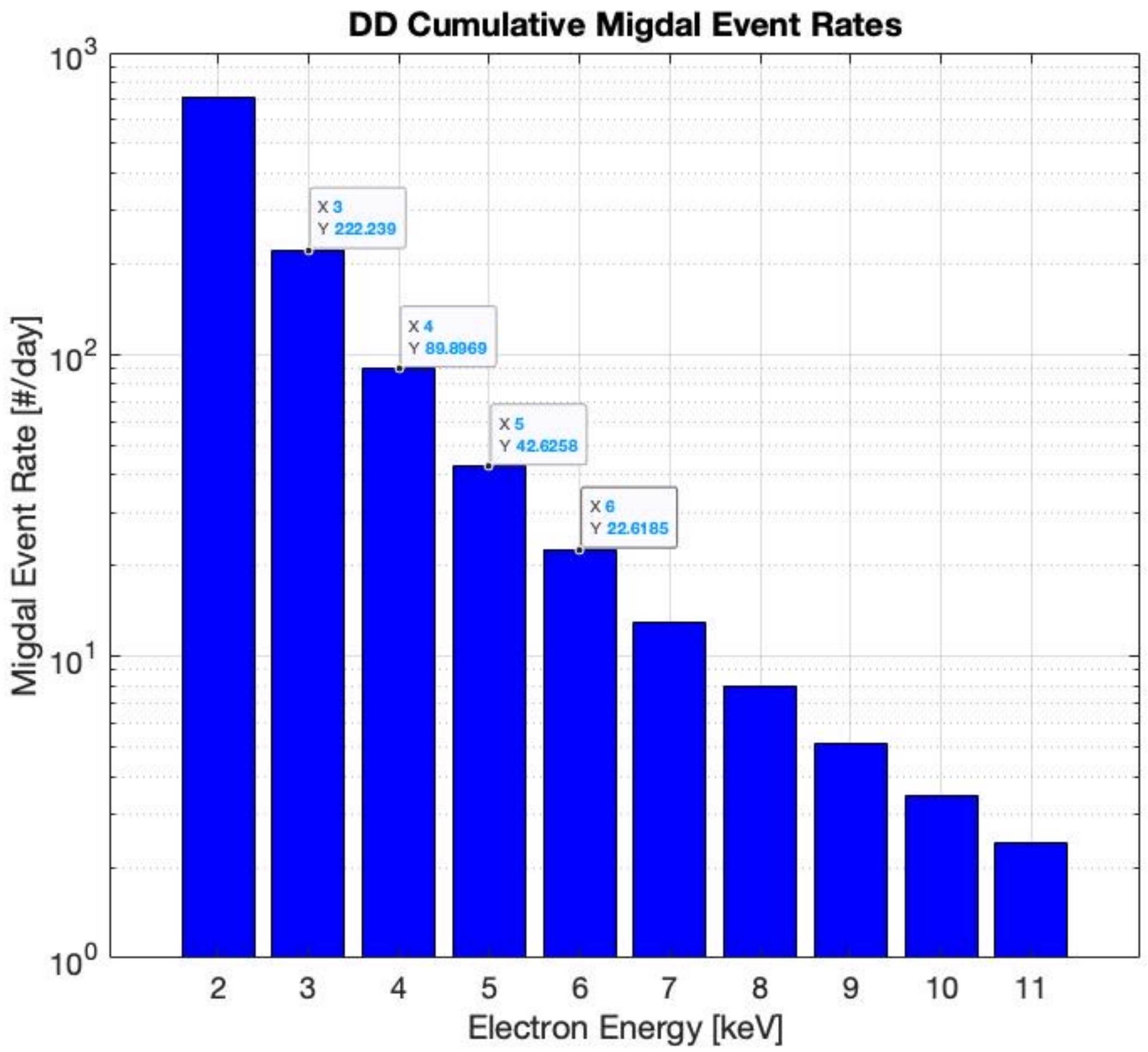
P. Cox *et al* 2023 *Phys. Rev. D* **107**, 035032
https://doi.org/10.1103/PhysRevD.107.035032



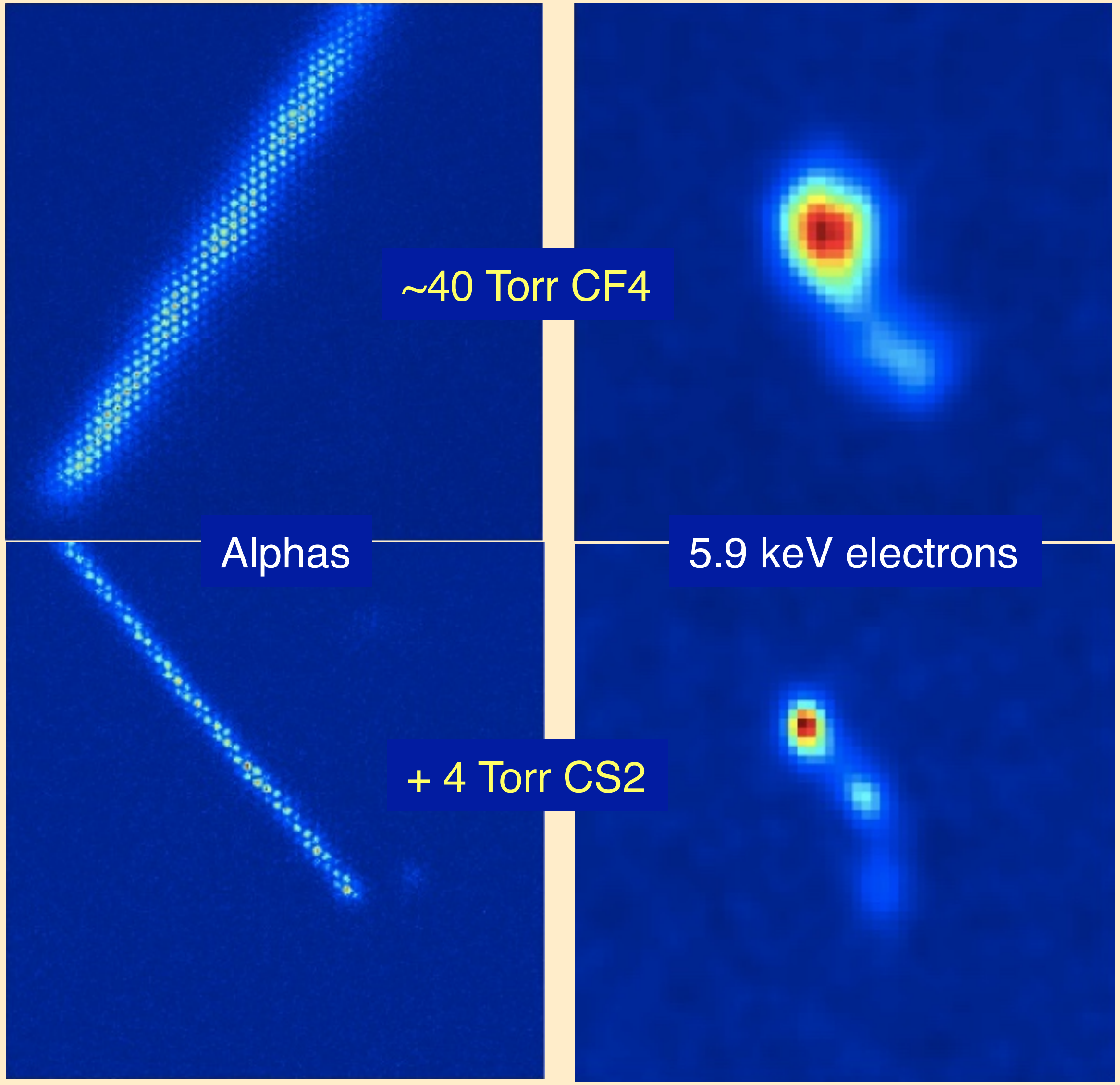
H.M. Araújo *et al* 2023 *Astropart. Phys.* **151** 102853
https://doi.org/10.1016/j.astropartphys.2023.102853

- Probing lower electron energies → **higher rates**
- Will require better spatial resolution → **NID**

→ **NI-OTPC results motivate this R&D**

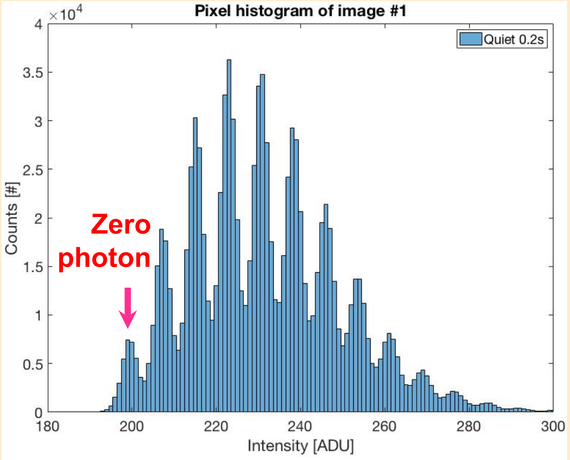


Negative-ion OTPC



Hamamatsu ORCA-Quest

- Photon Resolving Power:

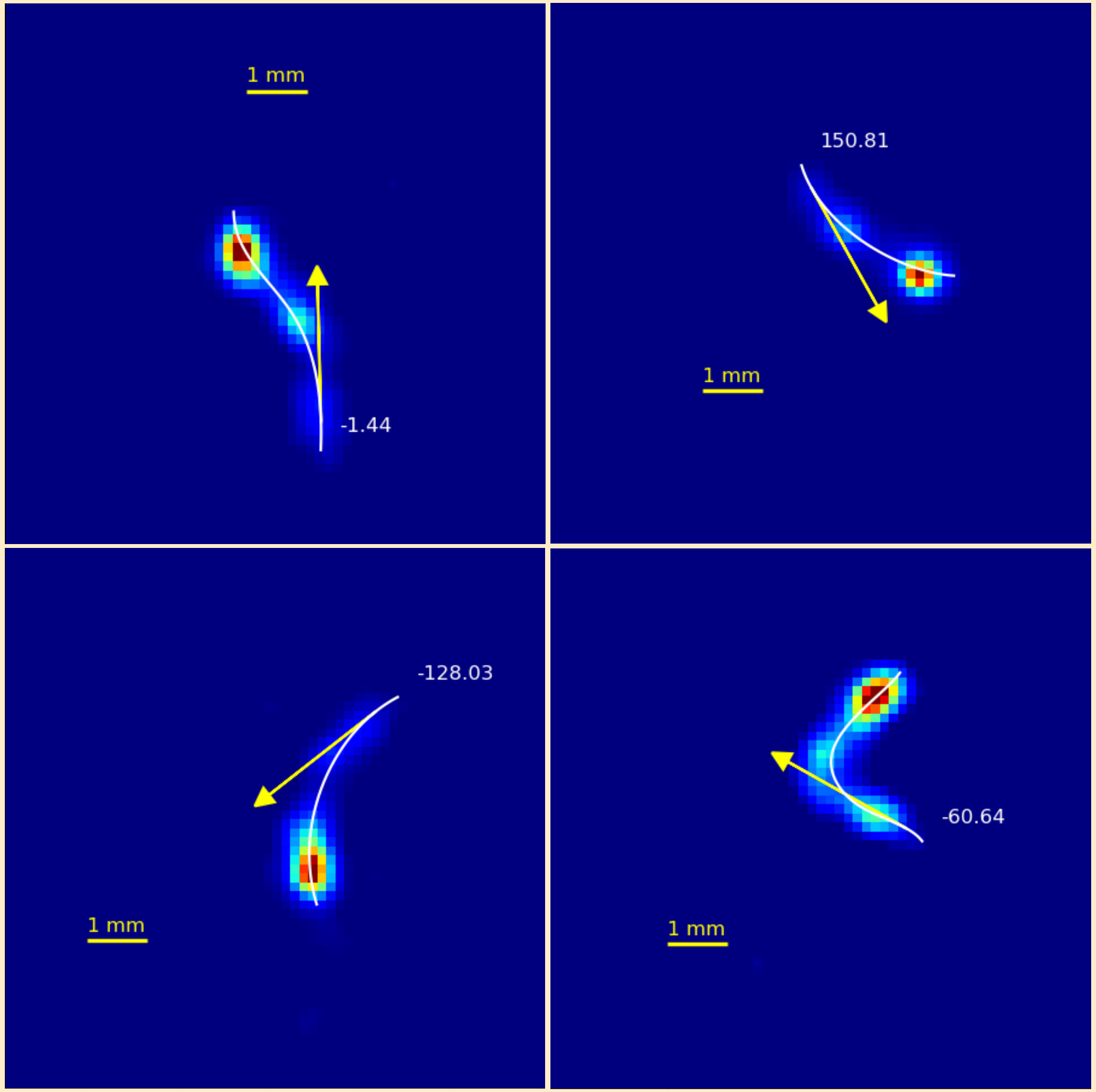


Radiment Glass-GEMs

- 270 micron pitch

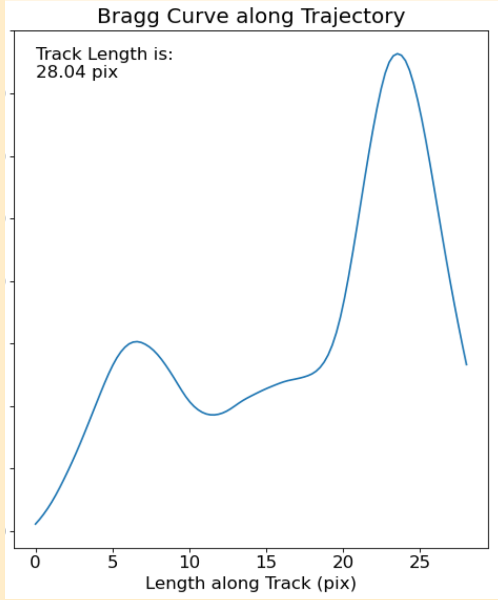
~45 Torr CF_4 + x Torr CS_2	
CS_2 (Torr)	σ(μm)
0	~500
4	~150-200

D. Loomba, UNM



Low diffusion, high spatial resolution enables detailed reconstruction of particle's trajectory:

- **Head/tail** of track
- **Initial direction**
- **Range**
- **dE/dx** (Bragg curve):



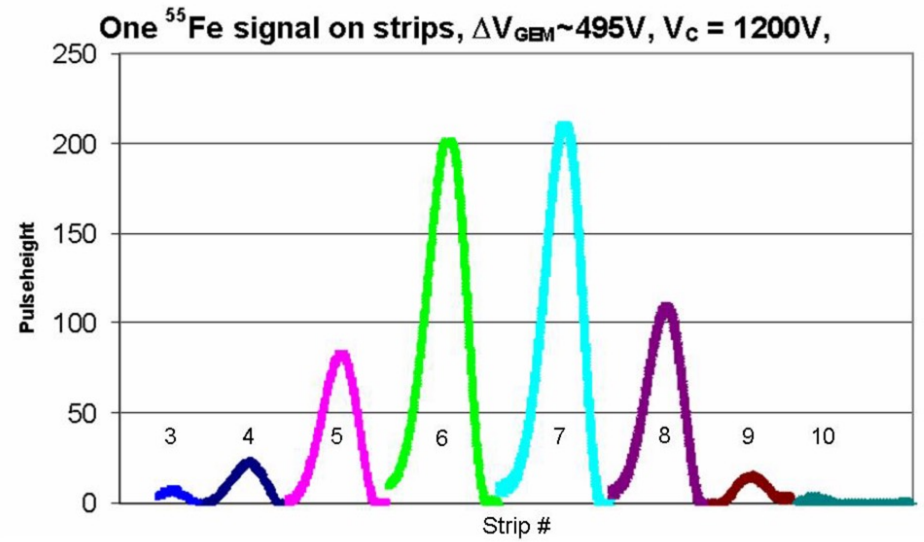
D. Loomba, UNM

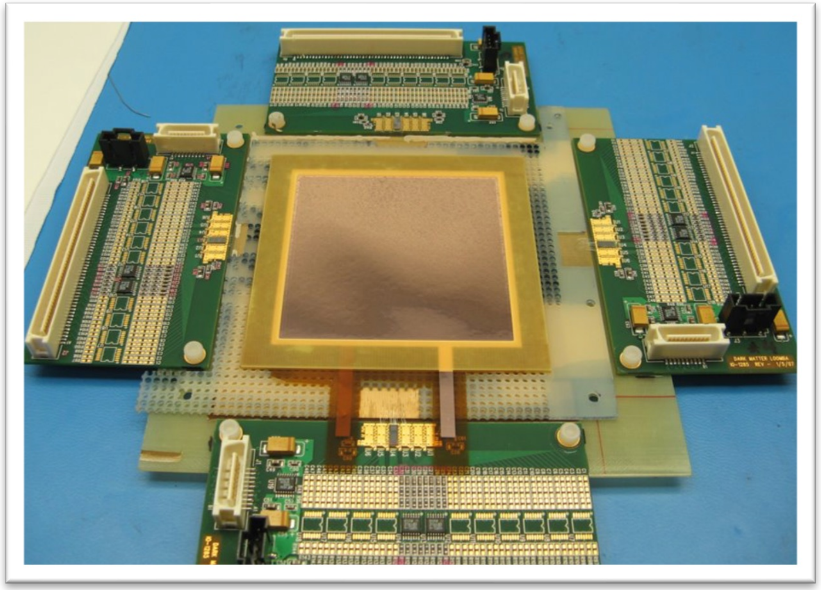
Charge readout(!) NI-TPC

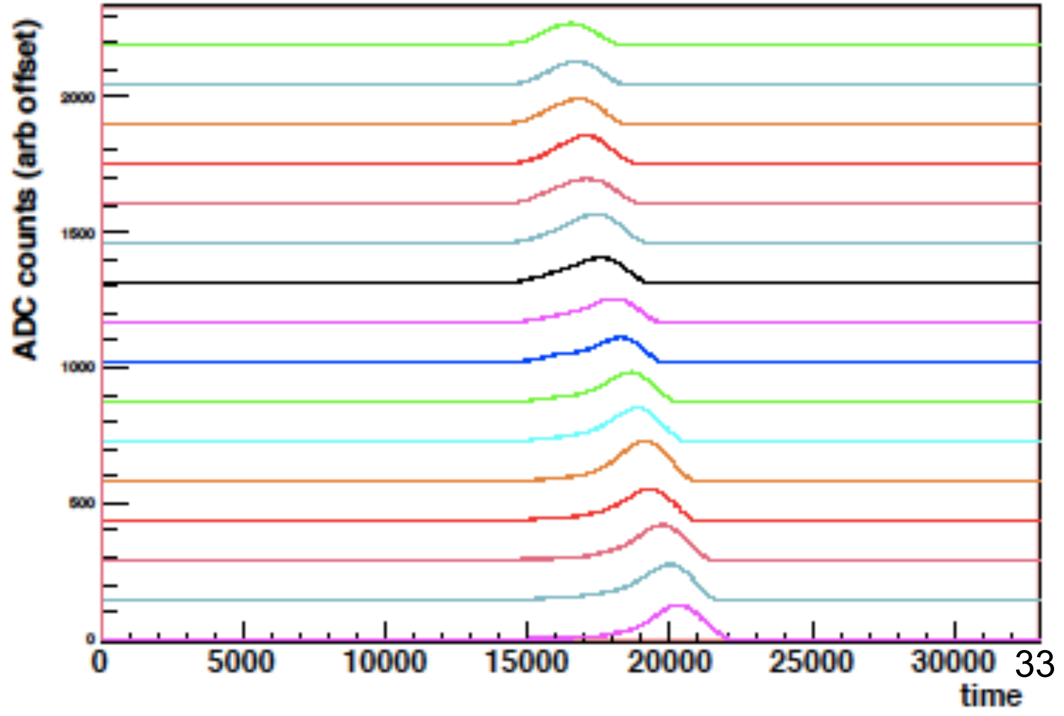
Advantages of a NI ***charge*** readout TPC:

- Achieving high dynamic range does not require high gas gains
- Gas mixtures can be optimized for target atoms w/o worrying about light yield

The detector will be built and characterized in the next year or two



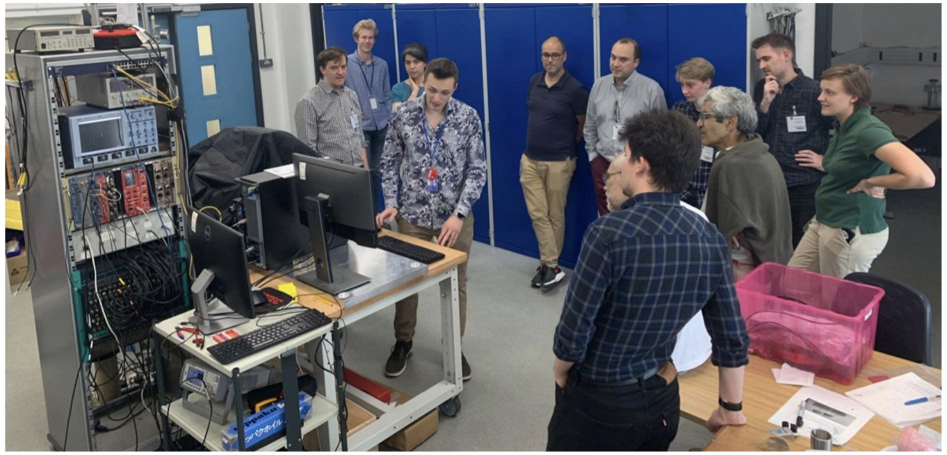


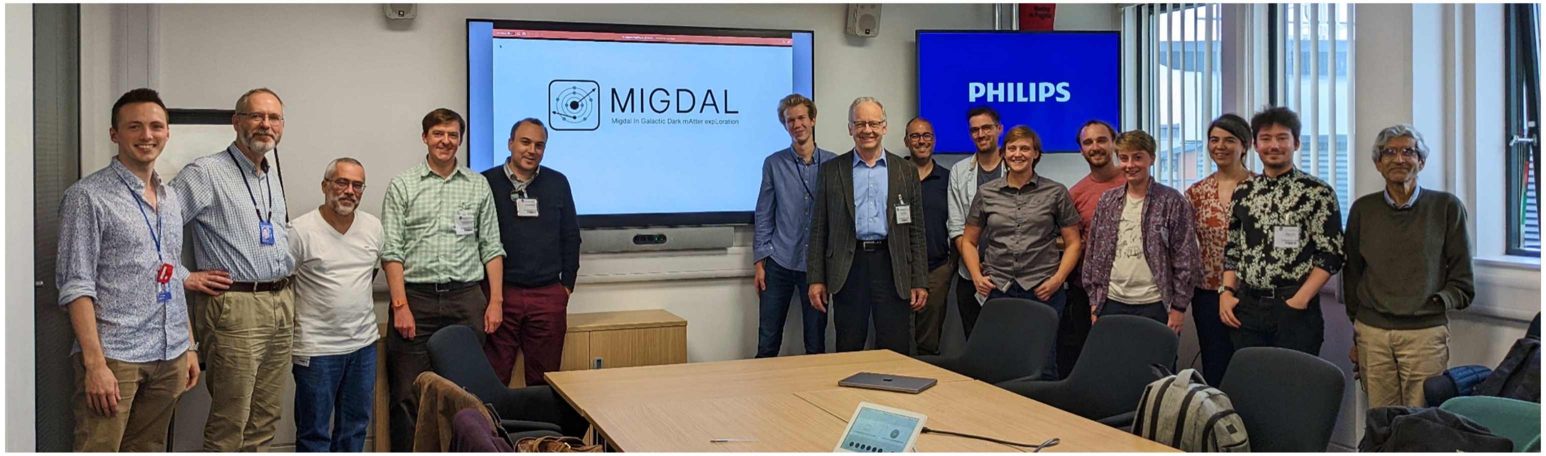


Summary

- The MIGDAL experiment aims to perform an unambiguous observation of the Migdal effect.
- Science runs with DD neutron source ongoing at the NILE facility at RAL.
- The detector performed well through the weeks of operation with highly ionizing NRs.
- Analysis of recorded data underway.
- 50% of recorded data are blinded.
- YOLOv8 pipeline for online, real-time, analysis of CMOS data including Migdal search
- Work is ongoing to create a next generation NI-TPC to probe lower energy Migdal events
- Stay tuned for results !

Thank You!



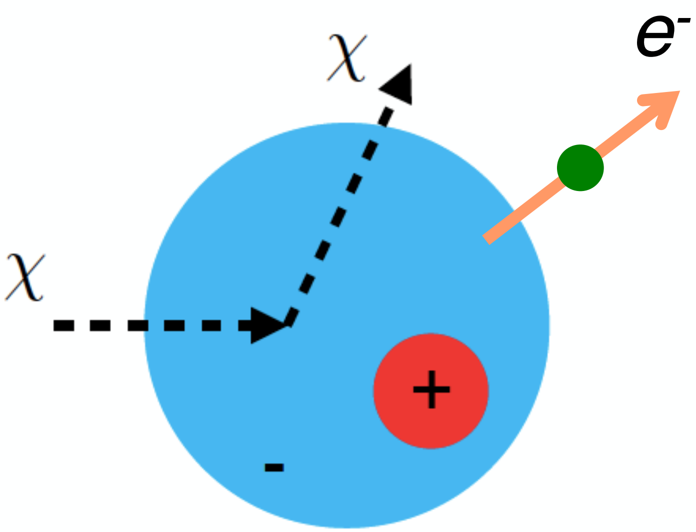


Backups

MIGDAL

Migdal In Galactic Dark mAtter expLoration

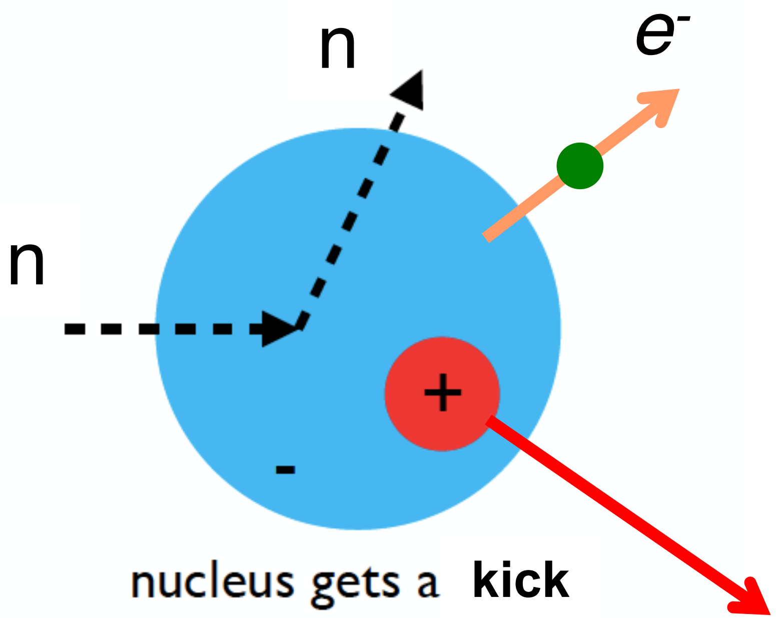
Migdal for LDM searches



nucleus gets a nudge

$E_{\mathrm{recoil}} \lesssim 0.1$ keV

Nuclear recoil can't be detected

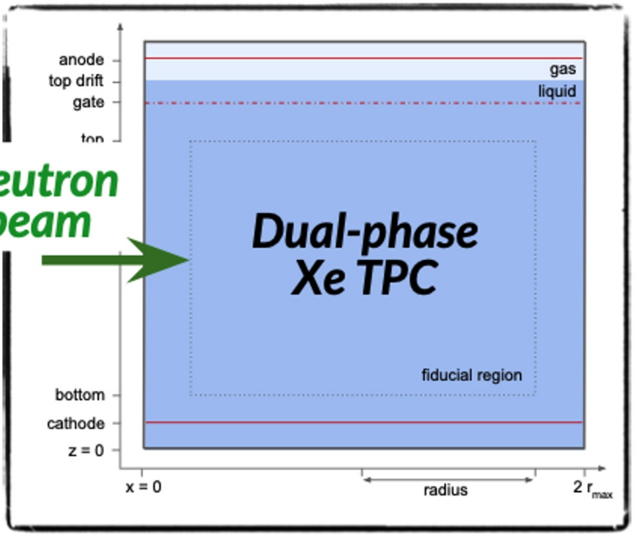


nucleus gets a **kick**

E_{recoil} >> keV

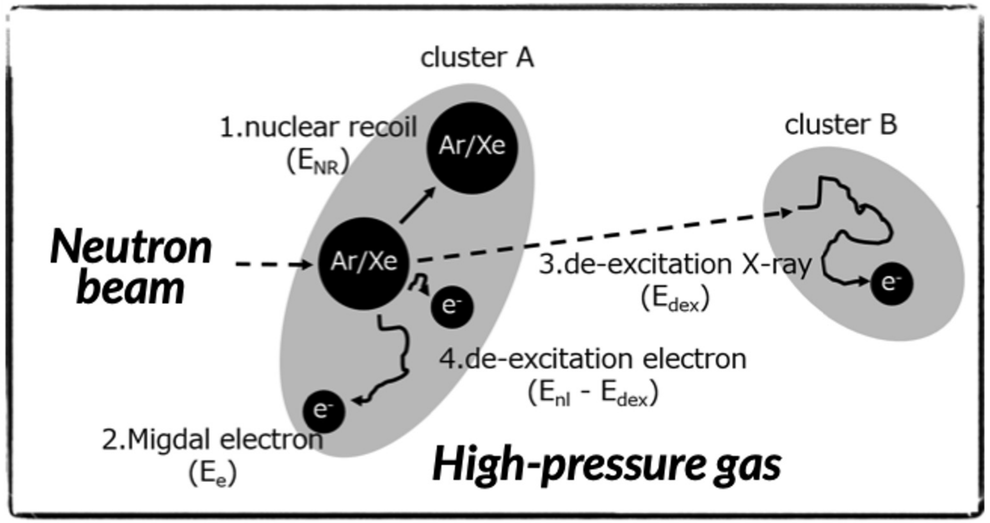
BOTH NR+ER recoils must be detected

Bell et al, arXiv:2112.08514



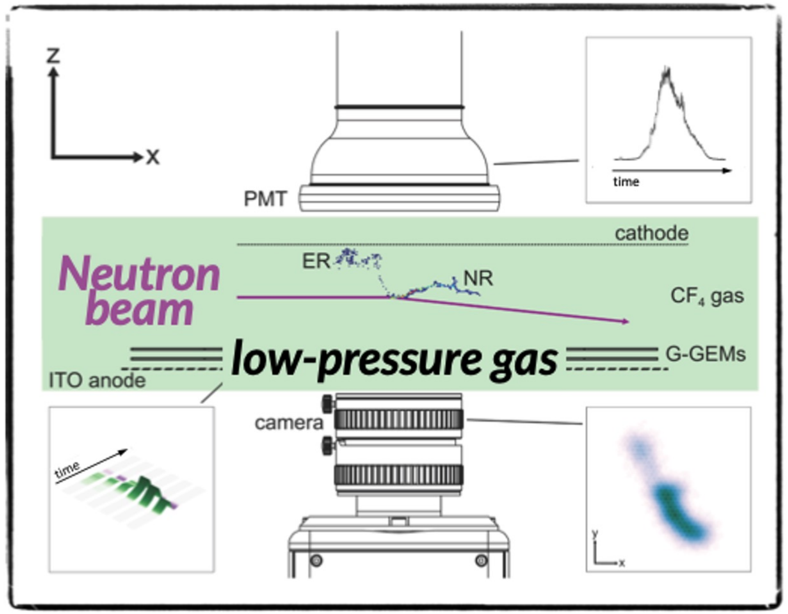
$E_{\text{neutron}} \sim 15 \text{ keV}$

Nakamura et al, arXiv:2009.05939



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

Araújo et al (MIGDAL), arXiv:2207.08284



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

MIRA CLUE

MIGDAL
Migdal In Galactic Dark mAtter expLoration

Expected Migdal backgrounds per 1 million DD-induced nuclear recoils with E > 100 keV

Component	Topology	D–D neutrons	
		>0.5	5–15 keV
Recoil-induced δ-rays	Delta electron from NR track origin	≈0	0
Particle-Induced X-ray Emission (PIXE)			
X-ray emission	Photoelectron near NR track origin	1.8	0
Auger electrons	Auger electron from NR track origin	19.6	0
Bremsstrahlung processes[a]			
Quasi-Free Electron Br. (QFEB)	Photoelectron near NR track origin	112	≈0
Secondary Electron Br. (SEB)	Photoelectron near NR track origin	115	≈0
Atomic Br. (AB)	Photoelectron near NR track origin	70	≈0
Nuclear Br. (NB)	Photoelectron near NR track origin	≈0	≈0
Neutron inelastic γ-rays	Compton electron near NR track origin	1.6	0.47
Random track coincidences			
External γ- and X-rays	Photo-/Compton electron near NR track	≈0	≈0
Trace radioisotopes (gas)	Electron from decay near NR track origin	0.2	0.01
Neutron activation (gas)	Electron from decay near NR track origin	0	0
Muon-induced δ-rays	Delta electron near NR track origin	≈0	≈0
Secondary nuclear recoil fork	NR track fork near track origin	–	≈1
Total background	Sum of the above components		1.5
Migdal signal	Migdal electron from NR track origin		32.6

Signal / background

Component	Topology	D-D neutrons		D-T neutrons	
		>0.5	5–15 keV	>0.5	5–15 keV
Recoil-induced δ-rays	Delta electron from NR track origin	≈0	0	541,000	0
Particle-Induced X-ray Emission (PIXE)					
X-ray emission	Photoelectron near NR track origin	1.8	0	365	0
Auger electrons	Auger electron from NR track origin	19.6	0	42,000	0
Bremsstrahlung processes†					
Quasi-Free Electron Br. (QFEB)	Photoelectron near NR track origin	112	≈0	288	≈0
Secondary Electron Br. (SEB)	Photoelectron near NR track origin	115	≈0	279	≈0
Atomic Br. (AB)	Photoelectron near NR track origin	70	≈0	171	≈0
Nuclear Br. (NB)	Photoelectron near NR track origin	≈0	≈0	0.013	≈0
Photon interactions					
Neutron inelastic γ-rays (gas)	Compton electron near NR track origin	1.6	0.47	0.86	0.25
Random track coincidences	Photo-/Compton electron near NR track	≈0	≈0	≈0	≈0
Gas radioactivity					
Trace contaminants	Electron from decay near NR track origin	0.2	0.01	0.03	≈0
Neutron activation	Electron from decay near NR track origin	0	0	≈0	≈0
Secondary nuclear recoil fork	NR track fork near track origin	–	≈1	–	≈1
Total background	Sum of the above components		1.5		1.3
Migdal signal	Migdal electron from NR track origin		32.6		84.2

† These processes were (conservatively) evaluated at the endpoint of the nuclear recoil spectra.

The Migdal effect has also been studied for neutrons on helium….an intriguing prediction:

Neutron-impact ionization of He

M S Pindzola[1], T G Lee[1], Sh A Abdel-Naby[1], F Robicheaux[2], J Colgan[3] and M F Ciappina[4]

J. Phys. B: At. Mol. Opt. Phys. **47** (2014) 195202

We present energy and angle differential cross sections for the neutron-impact single ionization of He at 100 keV in figure 4. The TDCC results are for single ionization leaving He^+ in the ground state, where the outgoing electron momentum $k = 2.0$ ($E = 54.4$ eV) and $\phi = 0$. We find that the electrons prefer to leave in the opposite direction to the target nucleus.

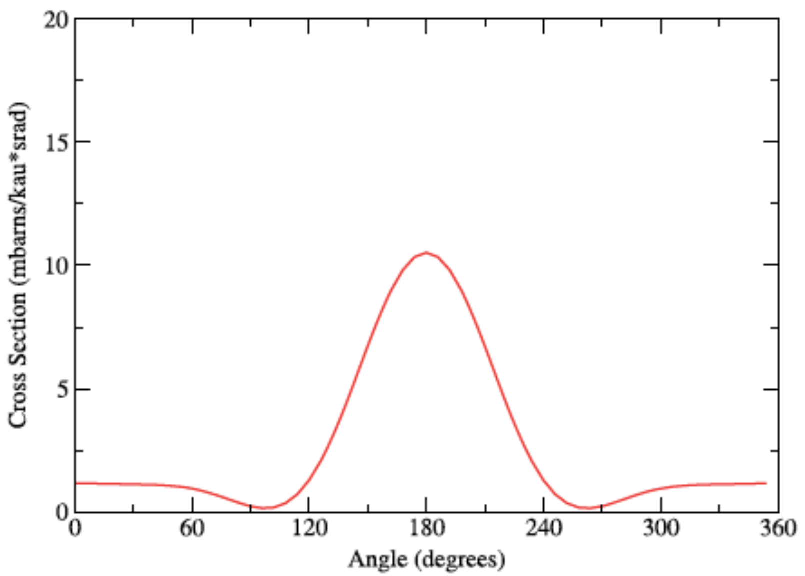
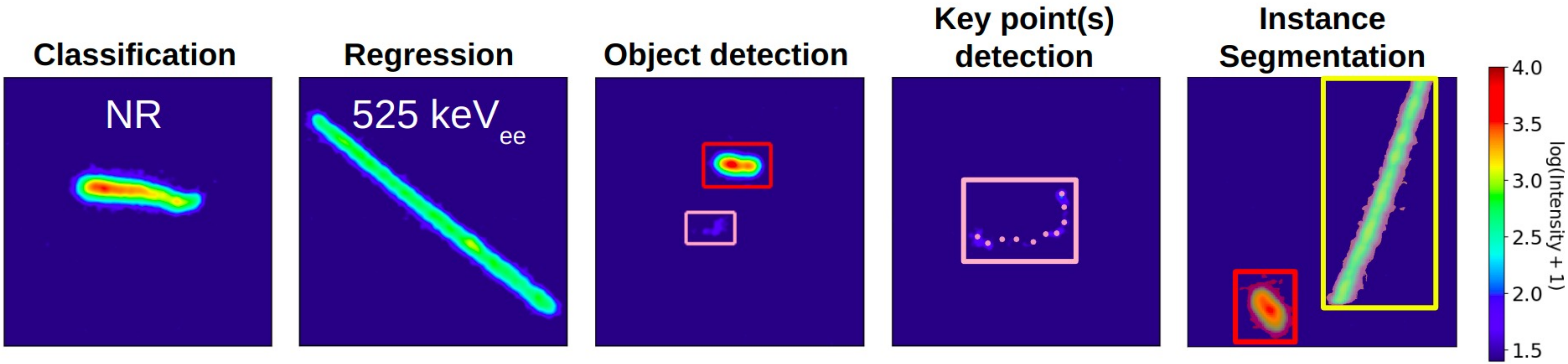


Figure 4. Neutron-impact single ionization of He at 100 keV. Solid line (red): TDCC method for the single ionization differential cross section with $k = 2.0$ and $\phi = 0$ (1.0 mbarn = 1.0×10^{-27} cm^2, kau = momentum in au, srad = solid angle in radians).

We will also be able to measure the angular distribution of the Migdal electron…

YOLO Capabilities



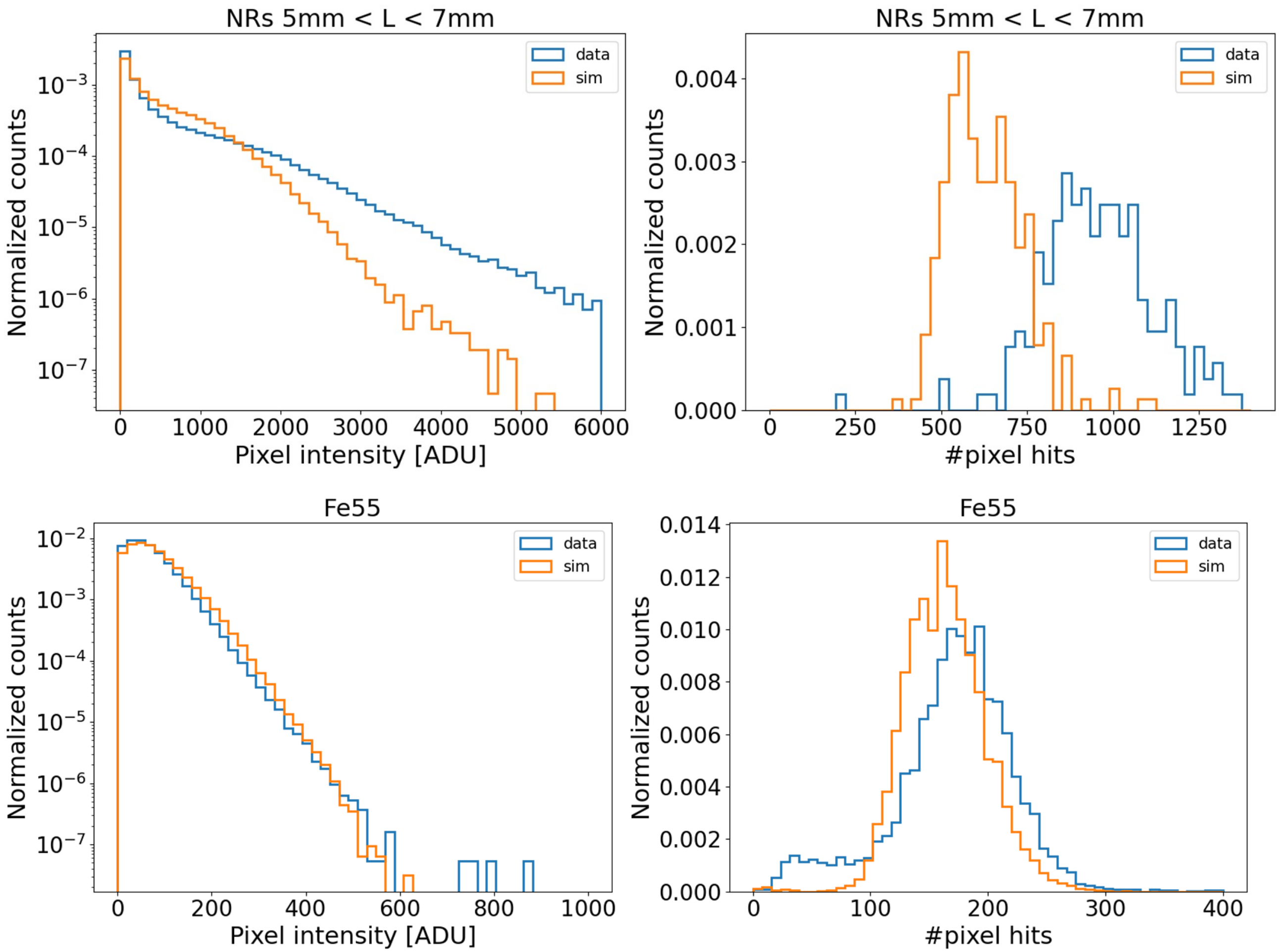
Application:
Particle ID

Application:
Rare event searches (Migdal effect)

Applications:
1. ***Directional reconstruction***
2. Energy reconstruction

Applications:
1. Vertex detection
2. Head/tail identification
3. Trajectory fitting

Simulation vs. Data

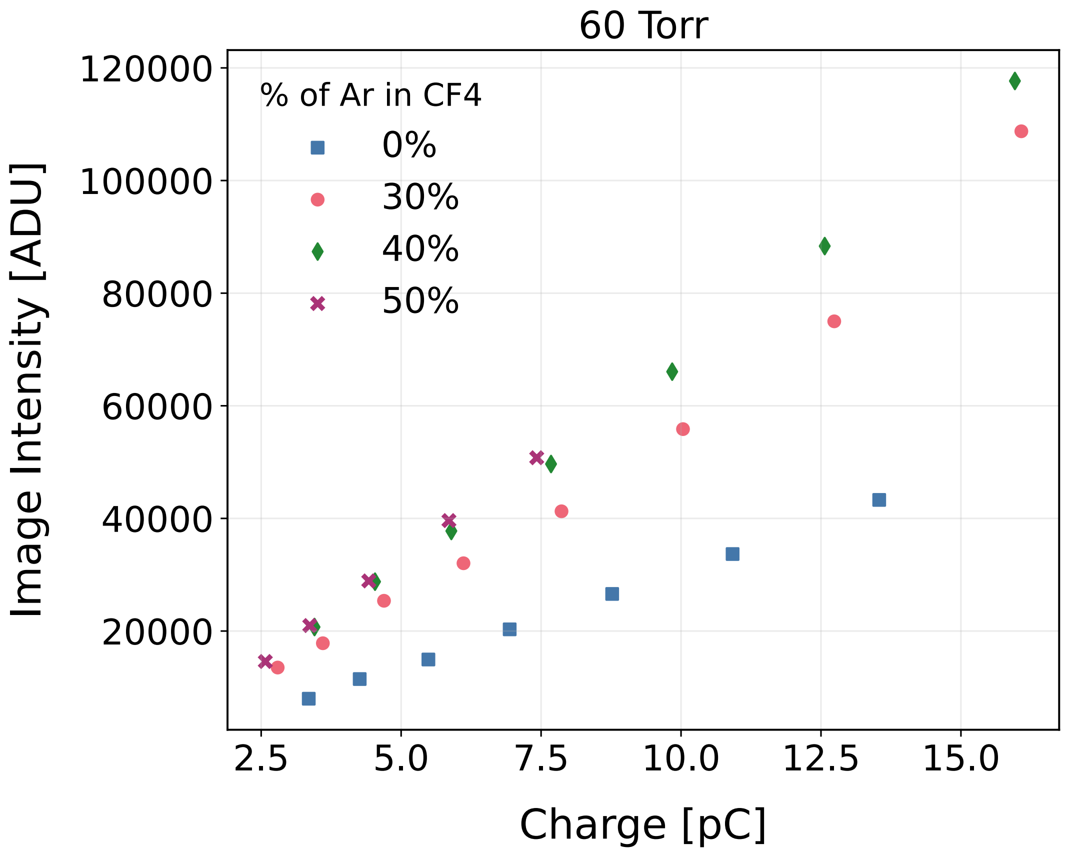


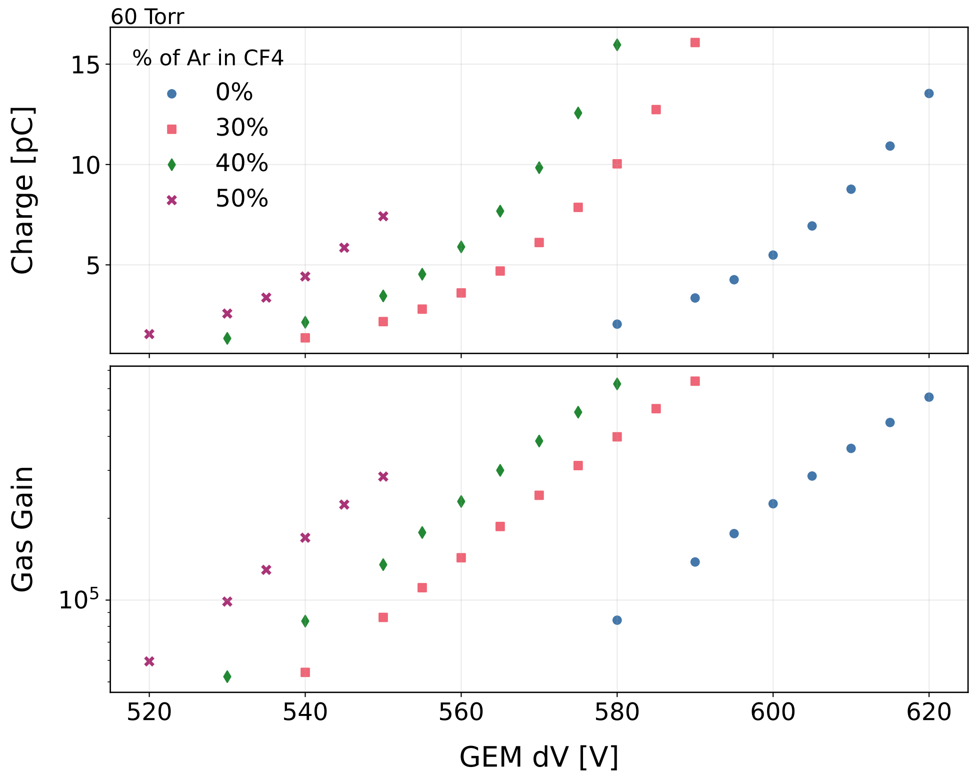
We believe that reflections are the origin of the differences between sim vs data NR distributions.

Data and simulation agree much better for simulated ERs

Simulating NRs in our optical readout is very challenging. ***Instead we stitch simulated ERs on data NRs to form Migdal signals to train and test YOLO.***

MIGDAL in nobles – Ar/CF4 mixtures

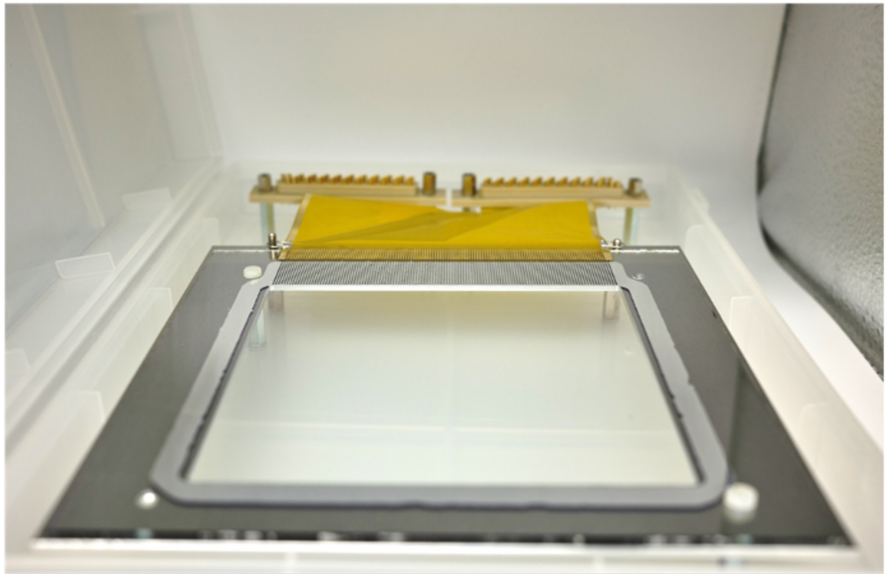


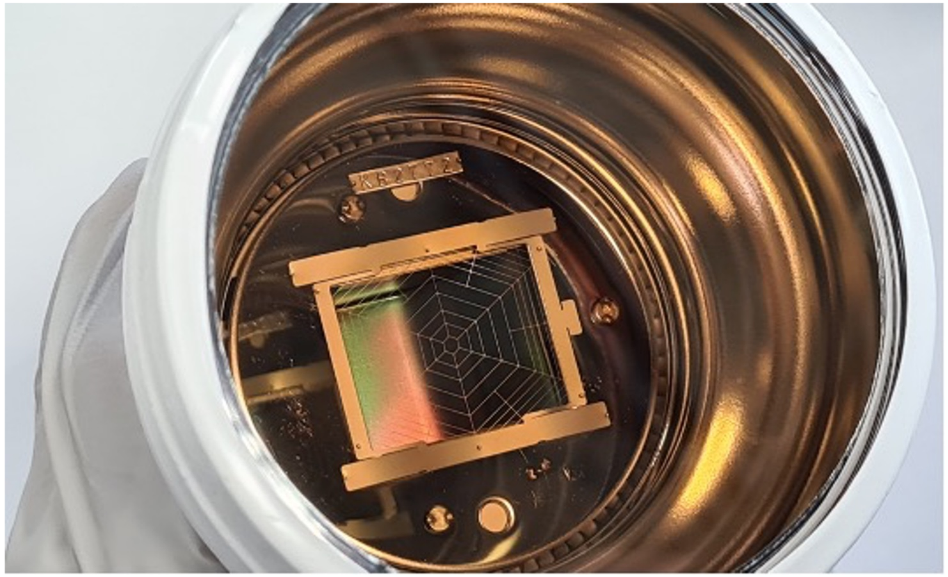


Light yield enhanced with addition of Ar.

L. Millins (MIGDAL), 16th Pisa Meeting on Advanced Detectors
May 31 2024, Isola d'Elba

Charge and Light readout



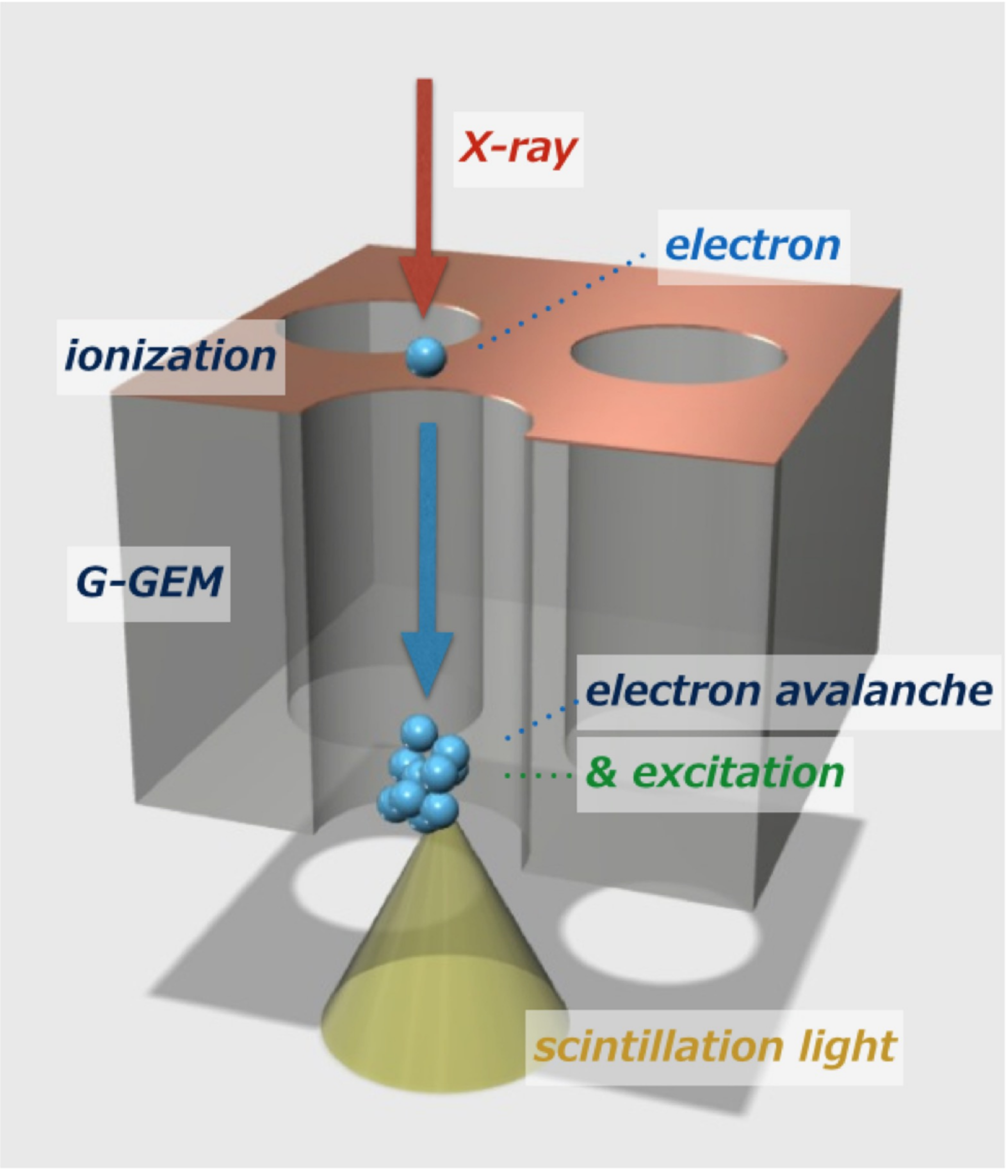


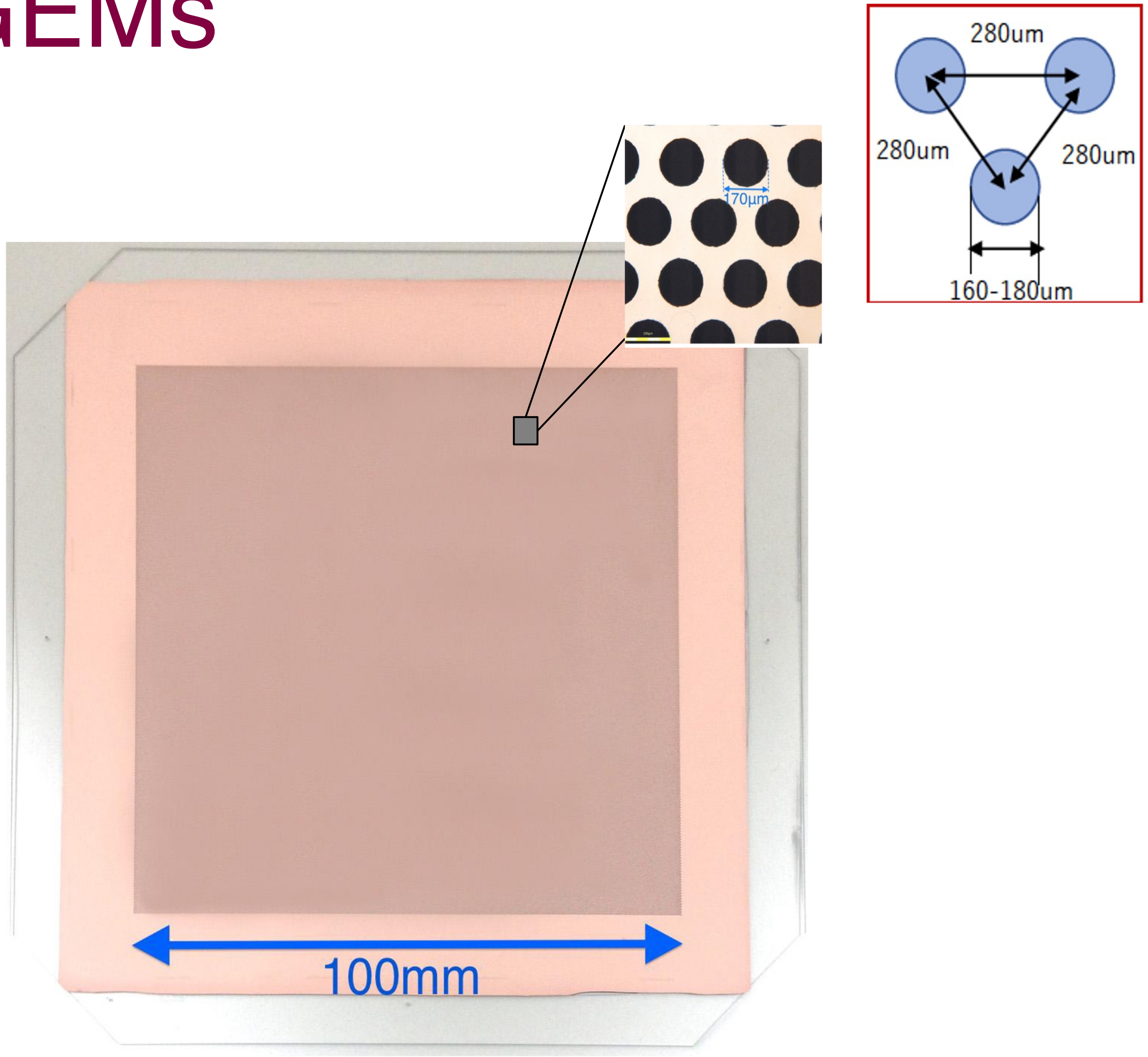
ITO anode strips
Post-GEM ionisation
Readout of (x,z) plane
Pitch: 833 μm
Digitised at 2 ns/sample
(Drift velocity: 130 μm/ns)

qCMOS camera
(Hamamatsu ORCA - QUEST)
GEM scintillation through
glass viewport behind ITO anode
Readout of (x,y) plane
Exposure: 8.33 ms/frame (~120 Hz)
(continuous)
Pixel scale: 39 μm (2 × 2 binning)
Lens: EHD-25085-C; 25mm f/0.85

VUV PMT (Hamamatsu R11410)
Detects primary (S1) and secondary
(S2 from GEM) scintillation
Absolute depth (z) coordinate
Digitised at 2 ns/sample
→ Event Trigger

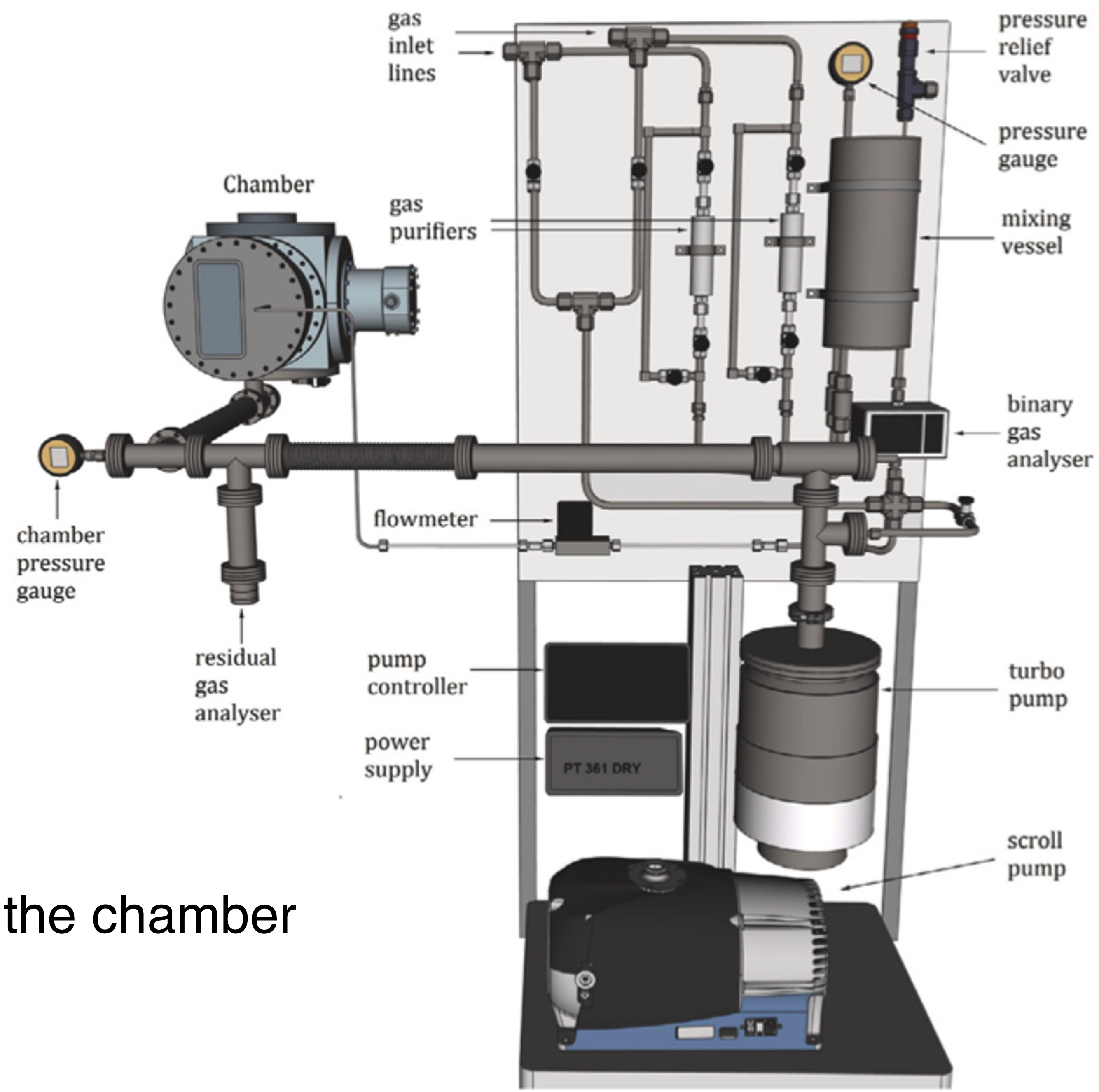
Glass-GEMs





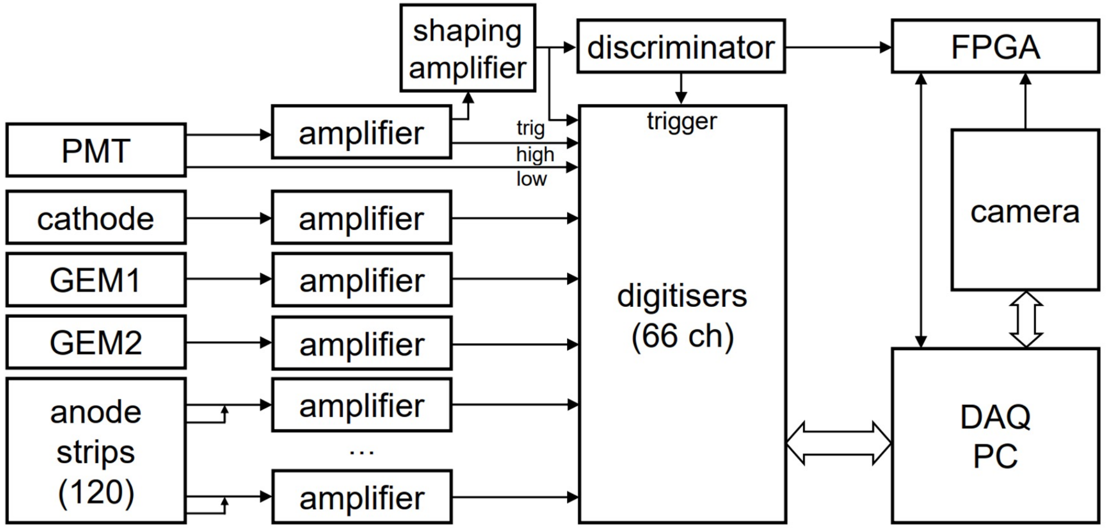
Glass thickness : 570 um

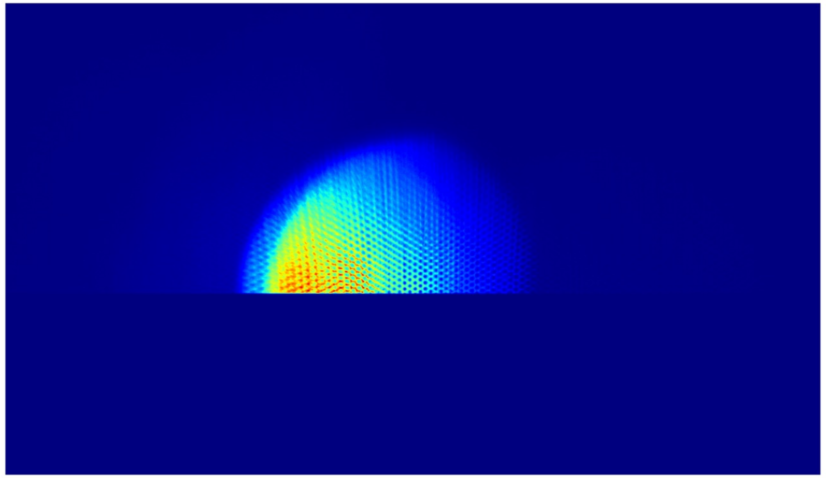
Gas System

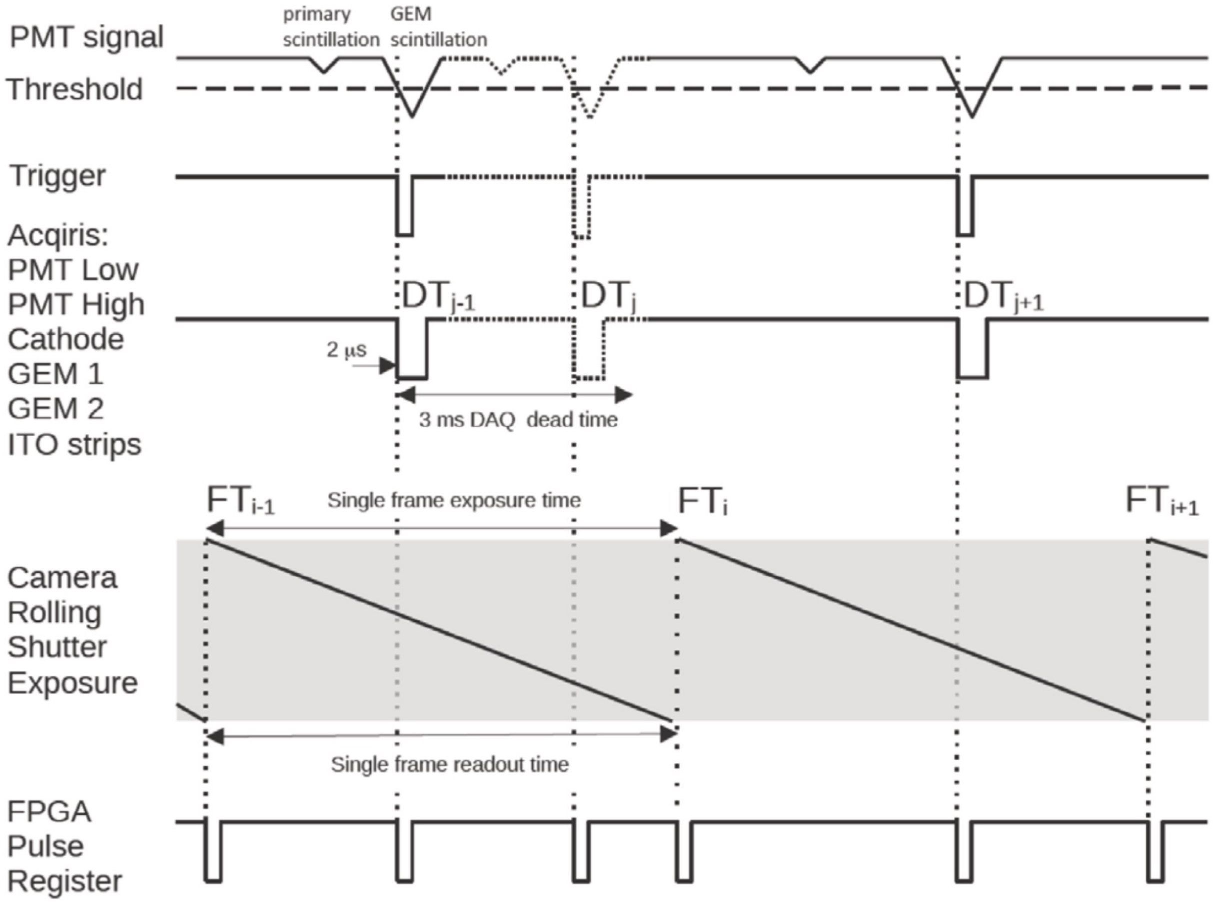


Initial vacuum in the chamber
~1E-06 mbar

DAQ





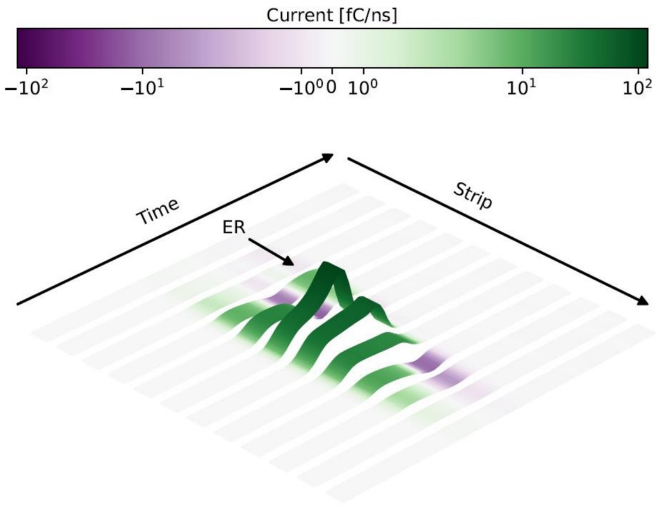


Synchronisation with LED pulse
Image cut due to a rolling shutter

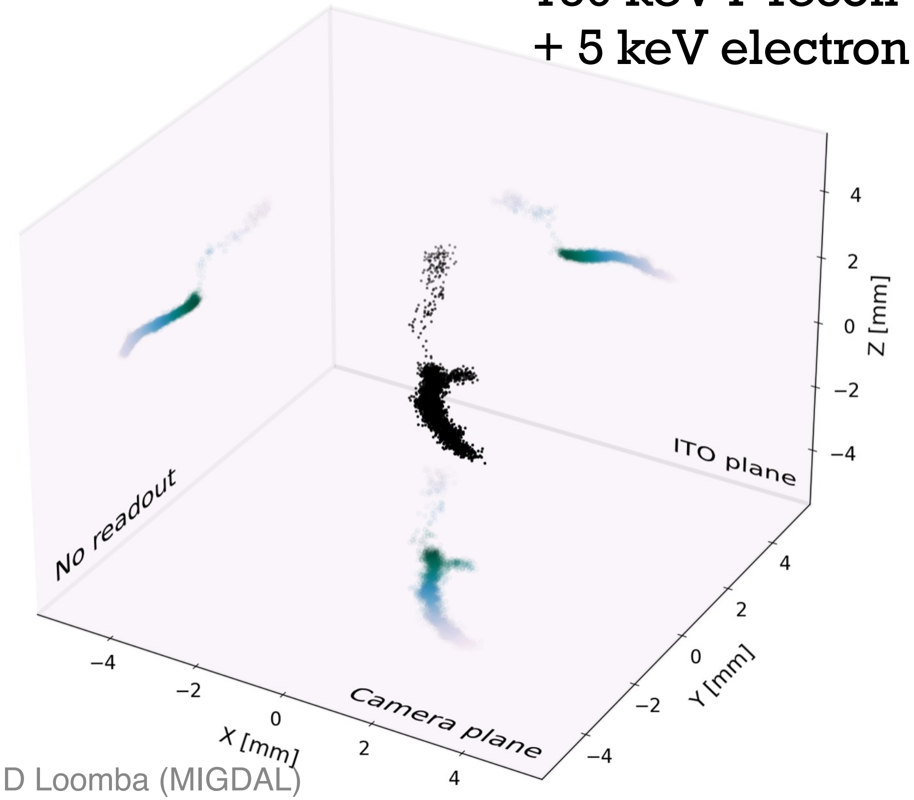
End-to-end Simulations:

- DEGRAD (electron track)
- TRIM (NR cascade and electronic dE/dx)
- Magboltz (drift properties)
- Garfield++ (GEMs)
- Gmsh/Elmer & ANSYS (ITO and E-field)

Anode strip readout
Induction/collection
(electronics
deconvolved)



Migdal event
150 keV F recoil
+ 5 keV electron



Camera readout
Diffusion + GEMs + noise

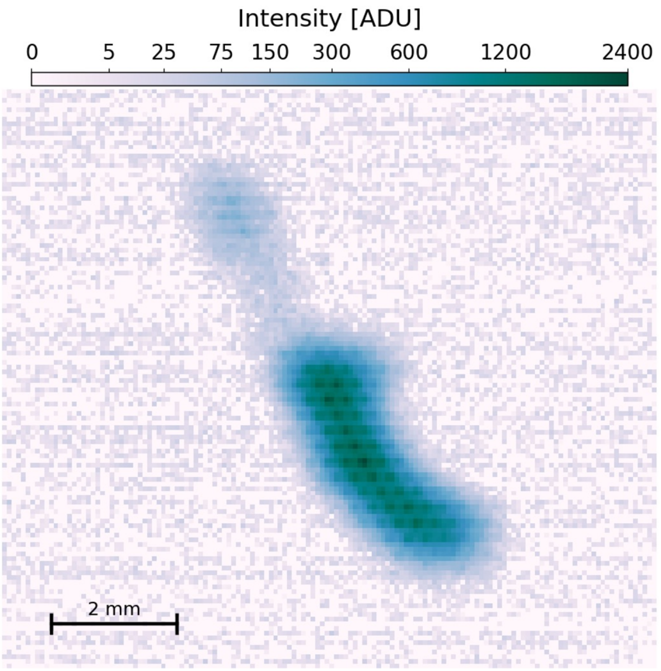
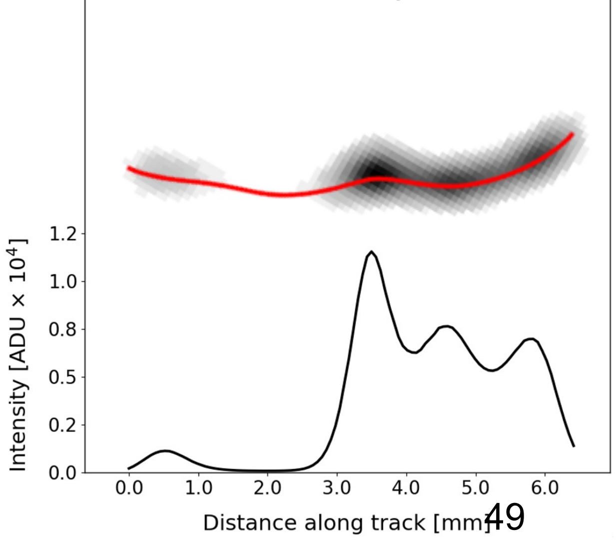
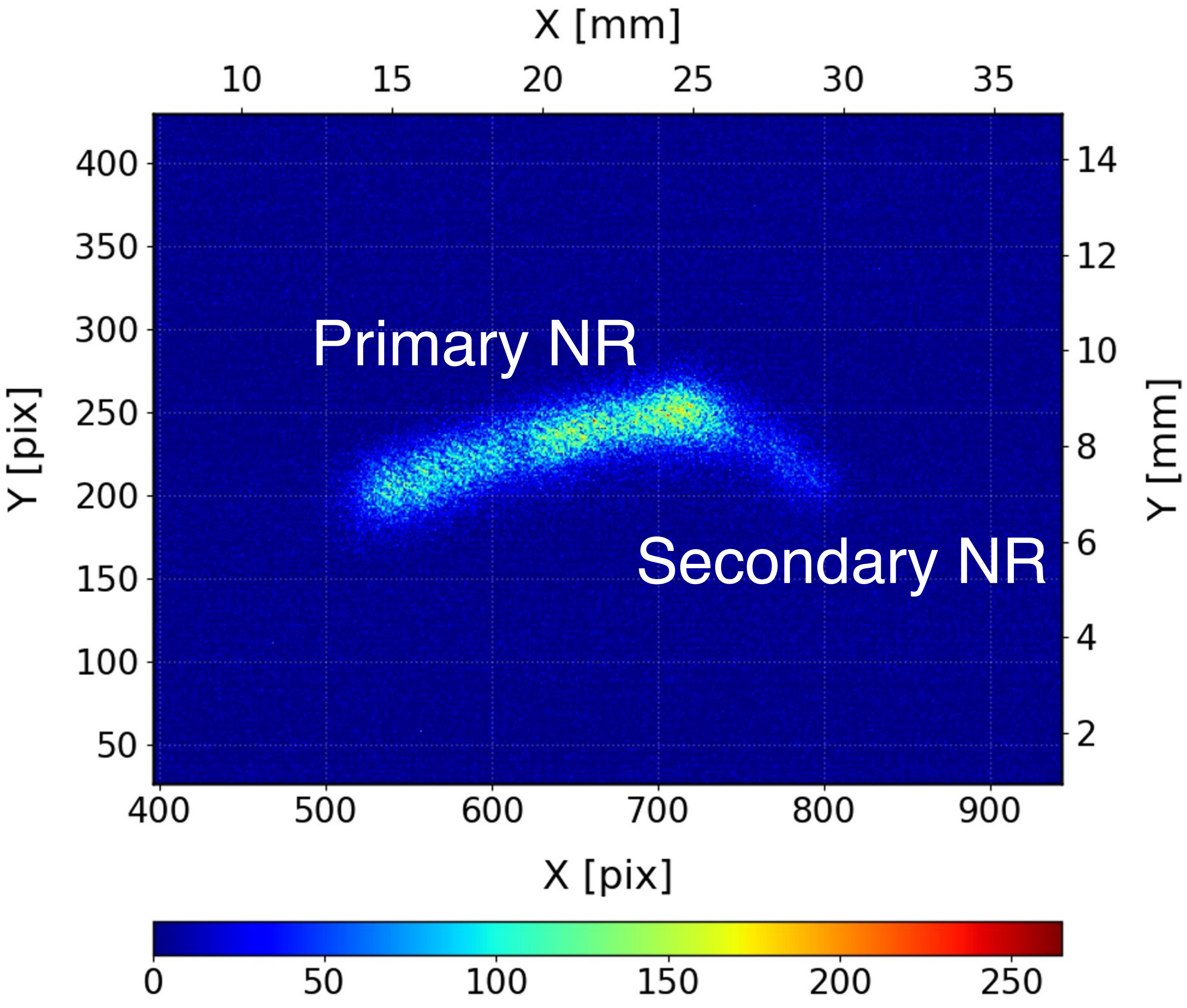
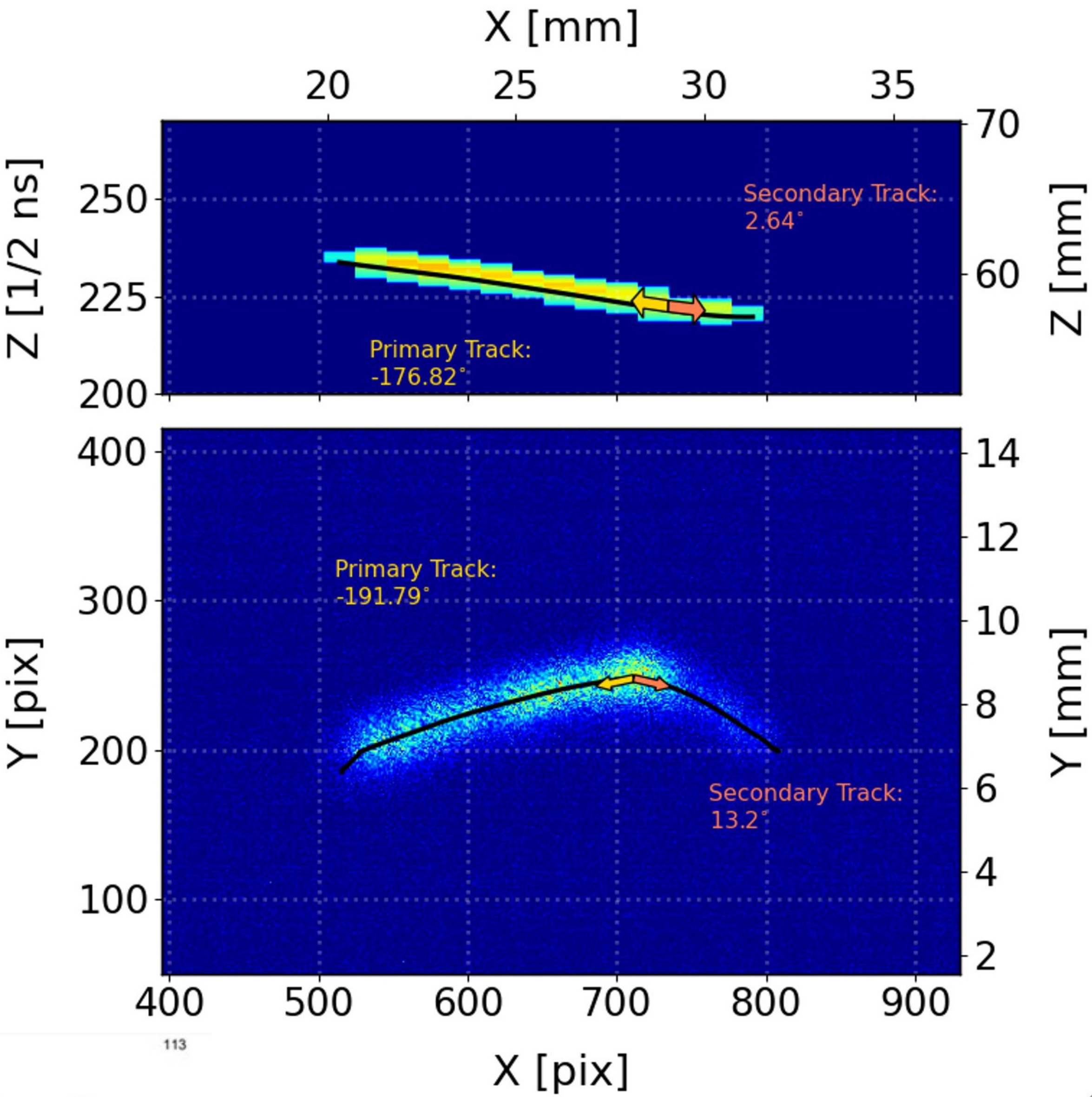


Image analysis
Deconvolution +
RidgeFinder



3D track reconstruction: Camera + ITO + PMT



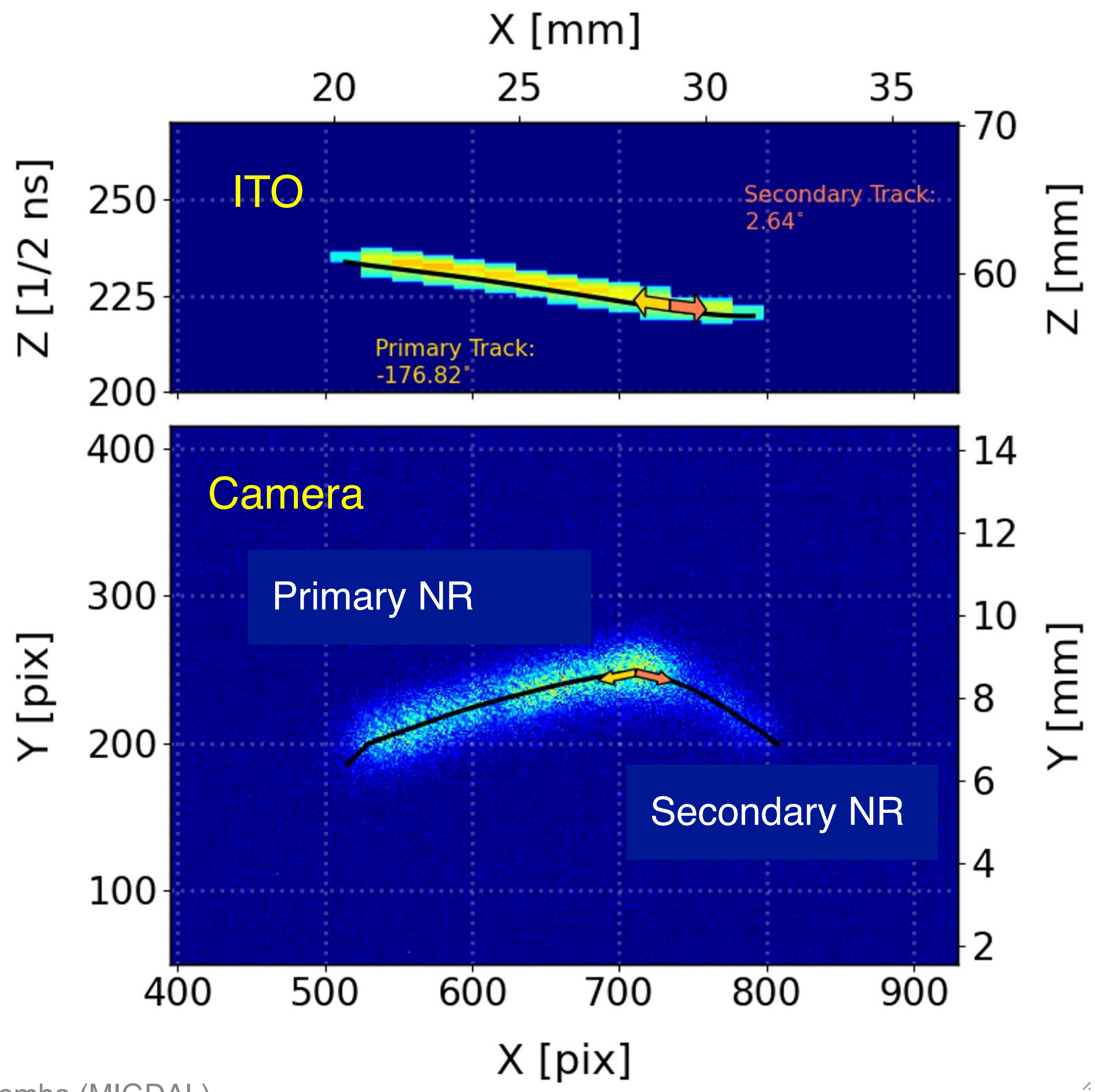


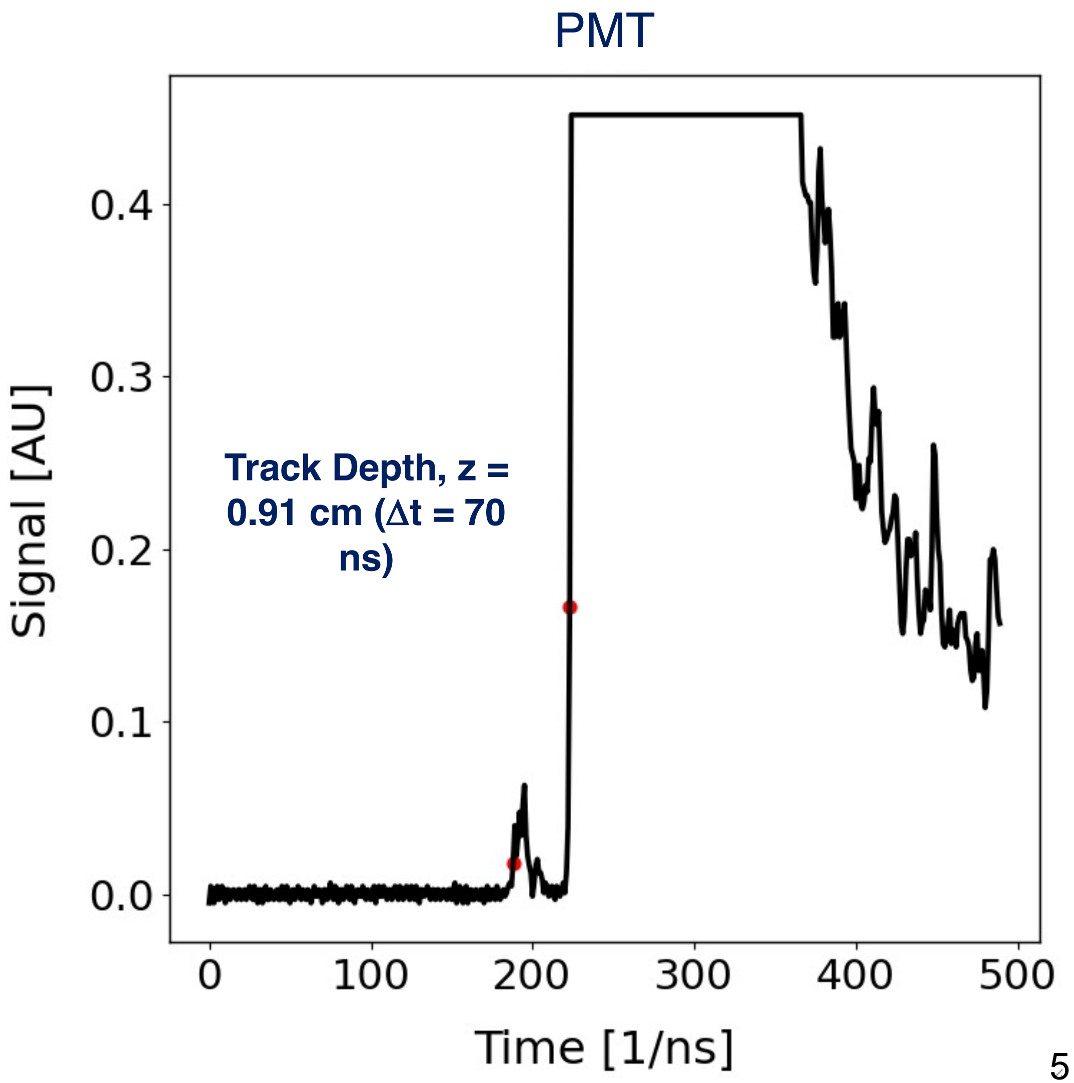
IEEE TRANSACTIONS ON PATTERN ANALYSIS AND MACHINE INTELLIGENCE, VOL. 20, NO. 2, FEBRUARY 1998 113

Ridgefinder: An Unbiased Detector of Curvilinear Structures

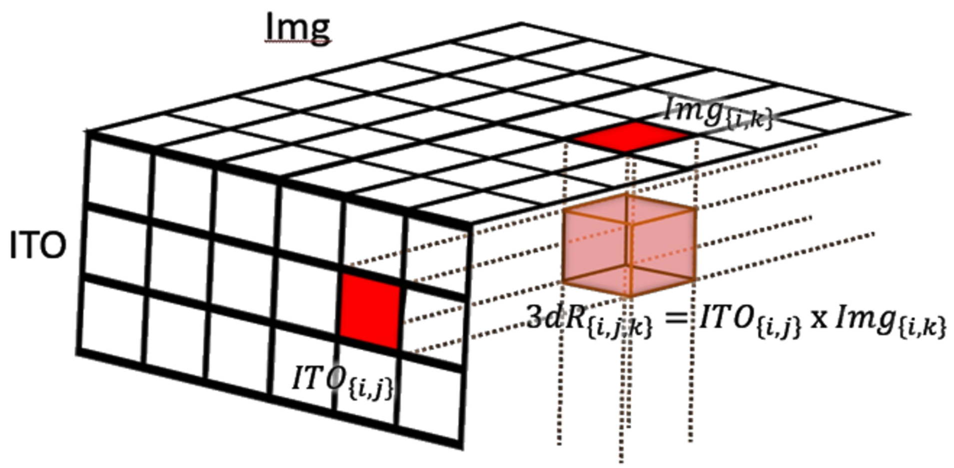
Carsten Steger

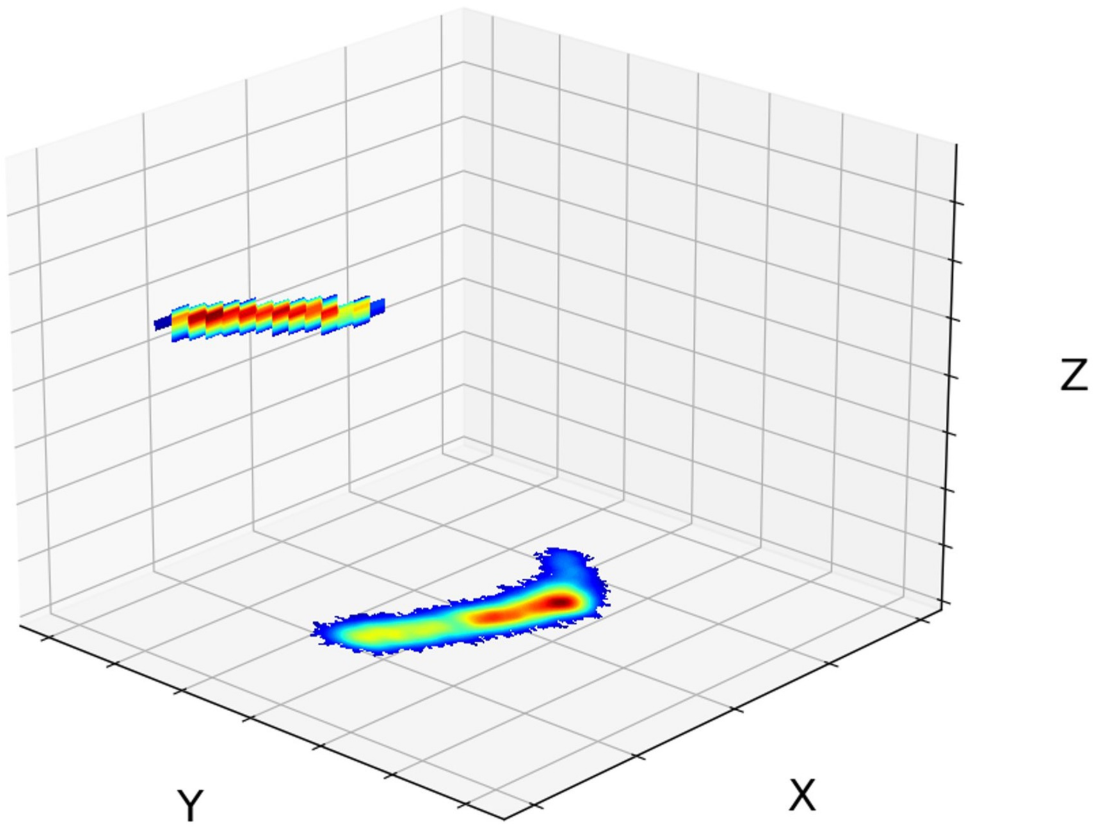
3D track reconstruction: Camera + ITO + PMT





3D track reconstruction: 3D voxels





3D track reconstruction of low-energy electrons in the MIGDAL low pressure optical time projection chamber

E. Tilly[1] and M. Handley[2,3] on behalf of the MIGDAL collaboration

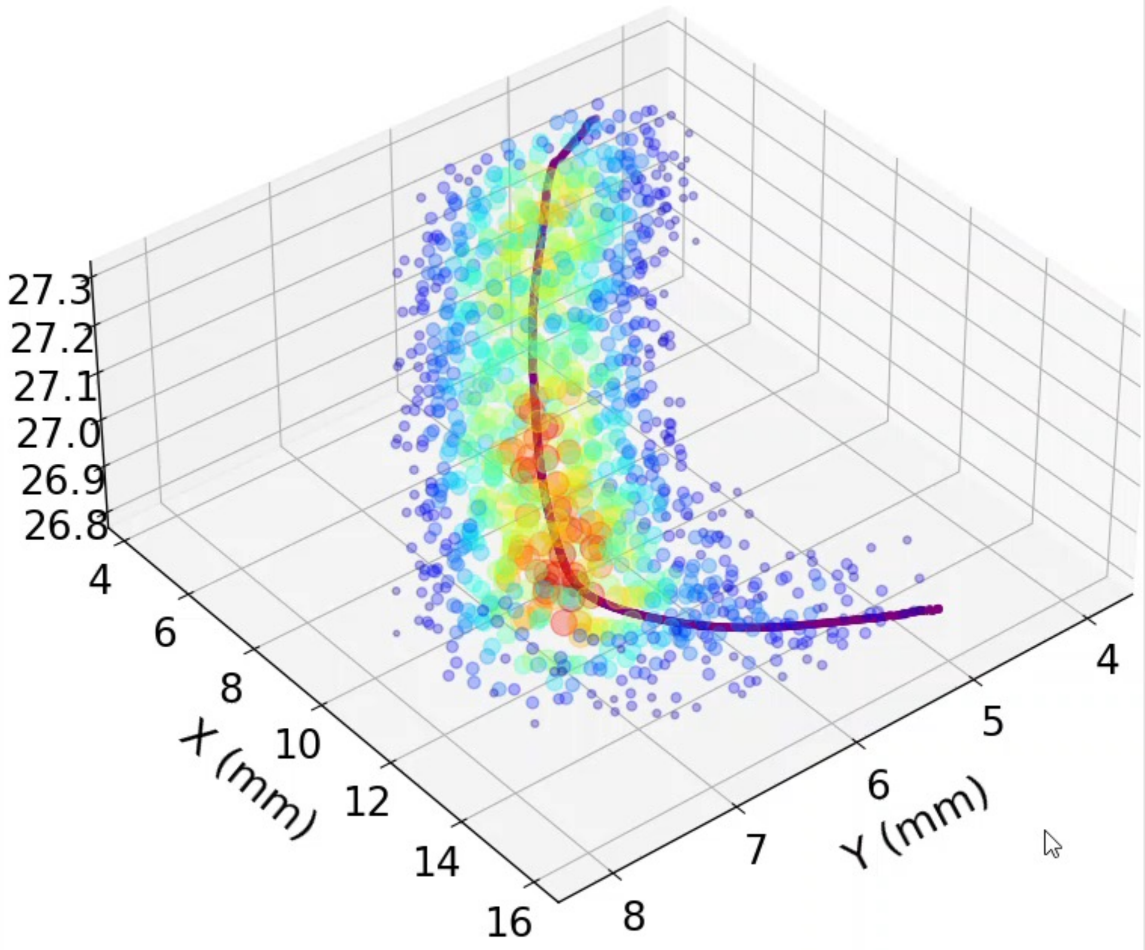
Published 17 July 2023 • © 2023 IOP Publishing Ltd and Sissa Medialab

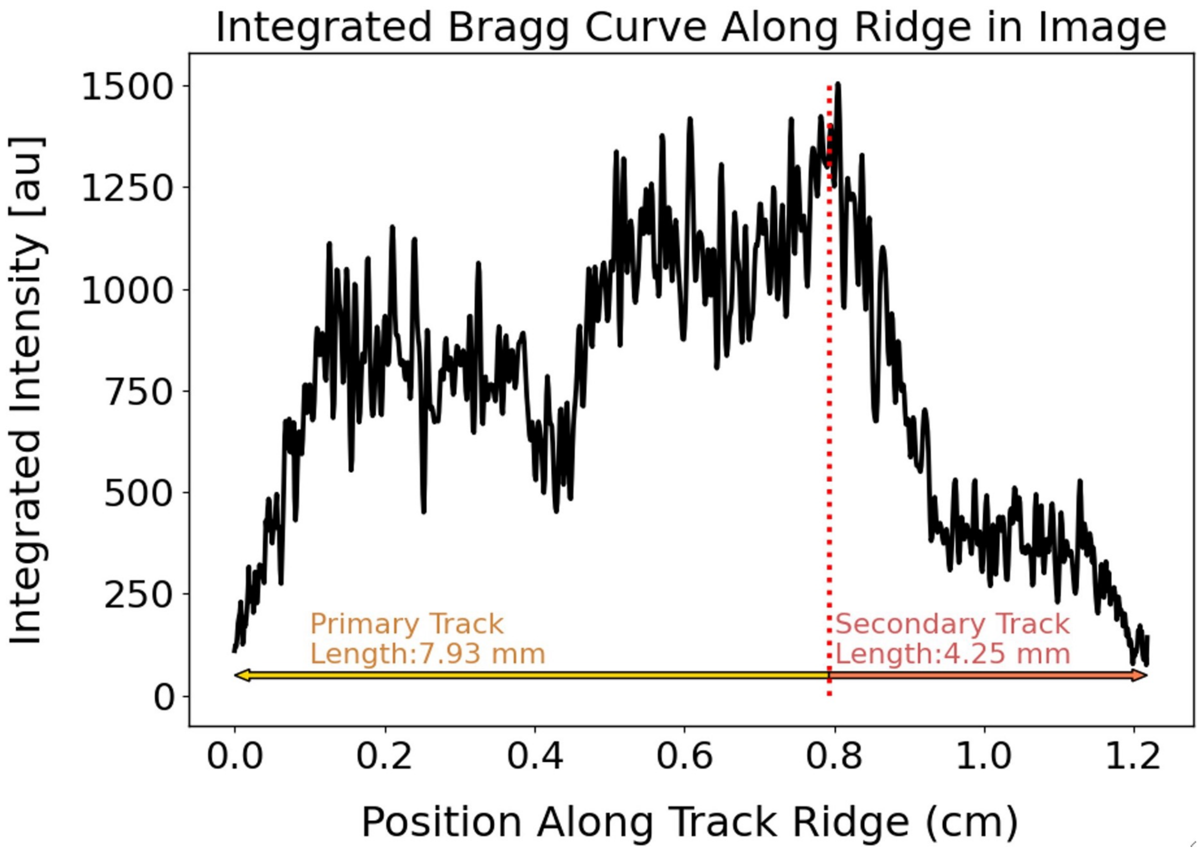
Journal of Instrumentation, Volume 18, July 2023

Citation E. Tilly *et al* 2023 *JINST* **18** C07013

DOI 10.1088/1748-0221/18/07/C07013

3D track reconstruction

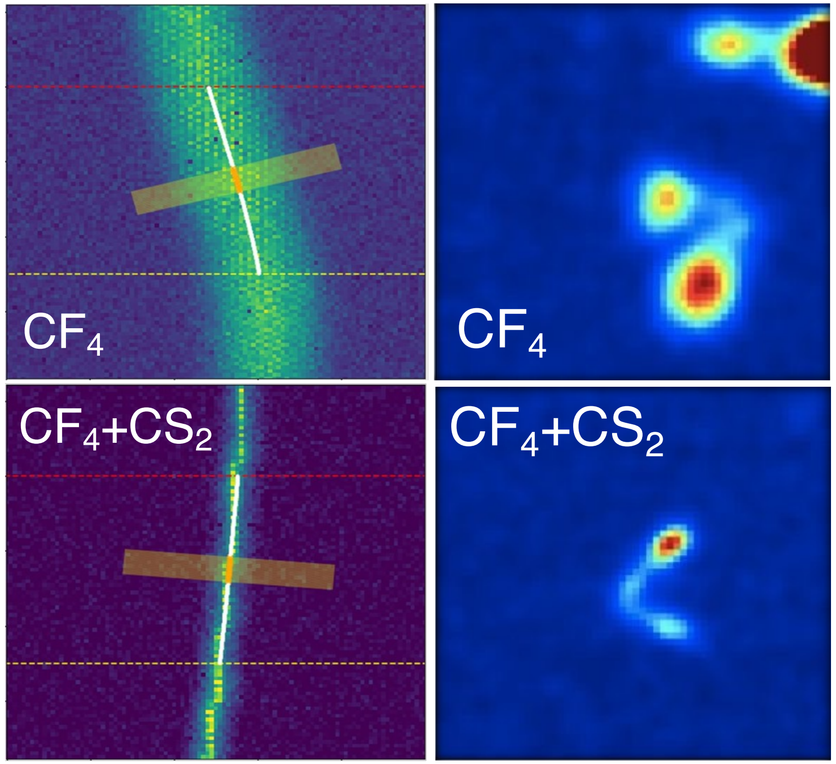




NI-OTPC Results

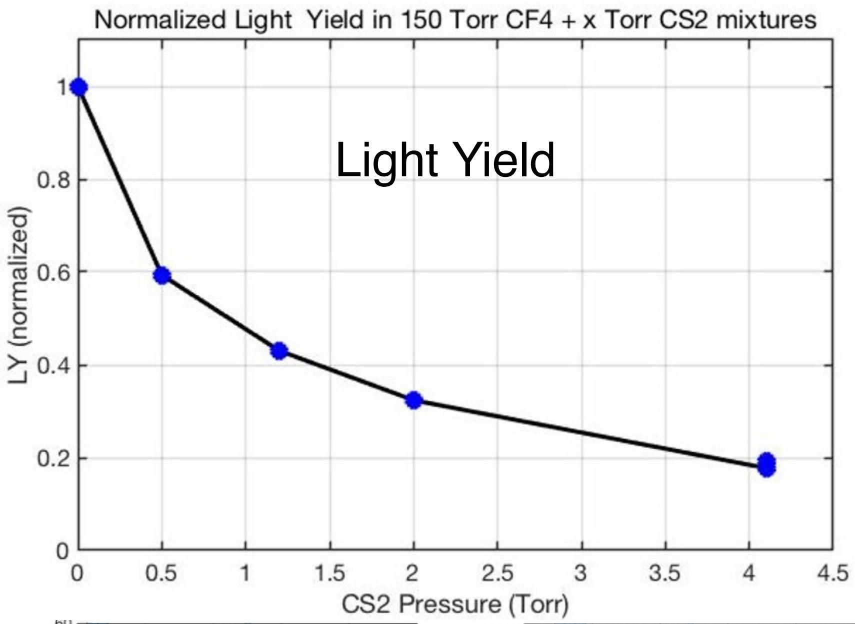
- Results show promise for NID but will be challenging in O-TPC

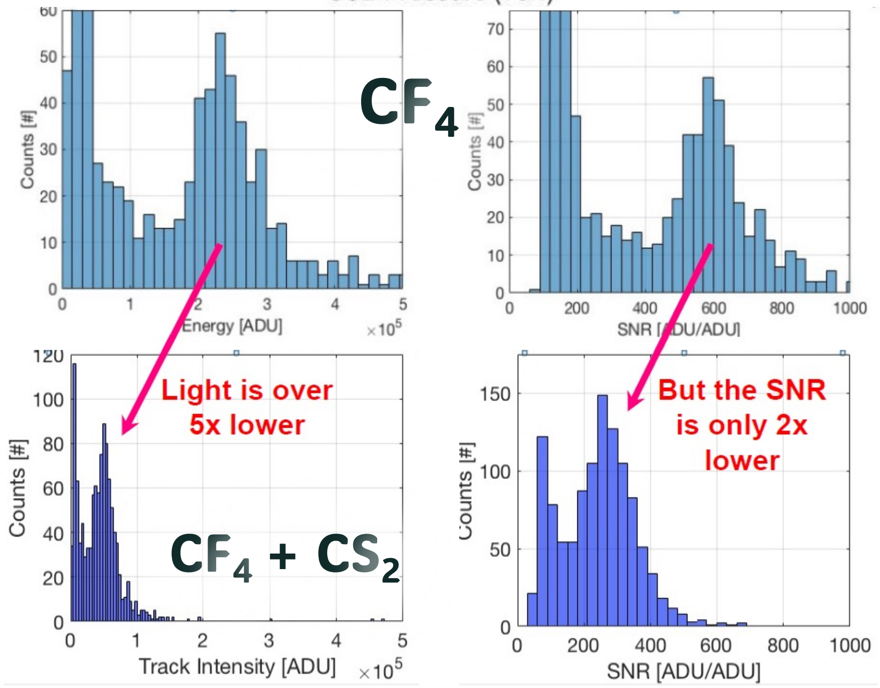
Alpha Tracks **Electron Tracks**



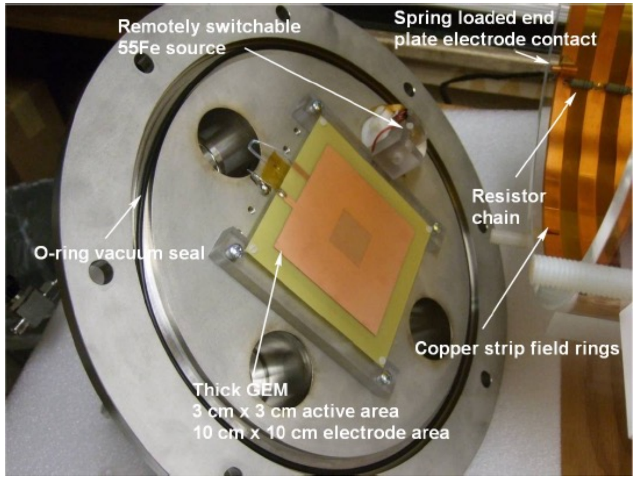
Measured Transverse Diffusion

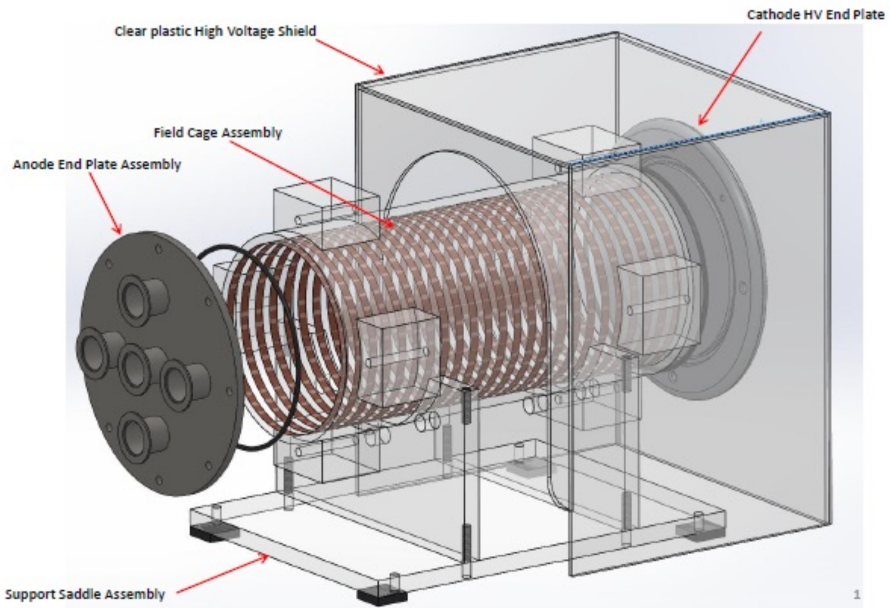
150 Torr CF_4 + X torr CS_2	
CS_2 (Torr)	σ(μm)
0	~400
2.9	133.53
4.2	126.10
5.4	125.09
45 Torr CF_4 + X torr CS_2	
0	~550
4	~150-200

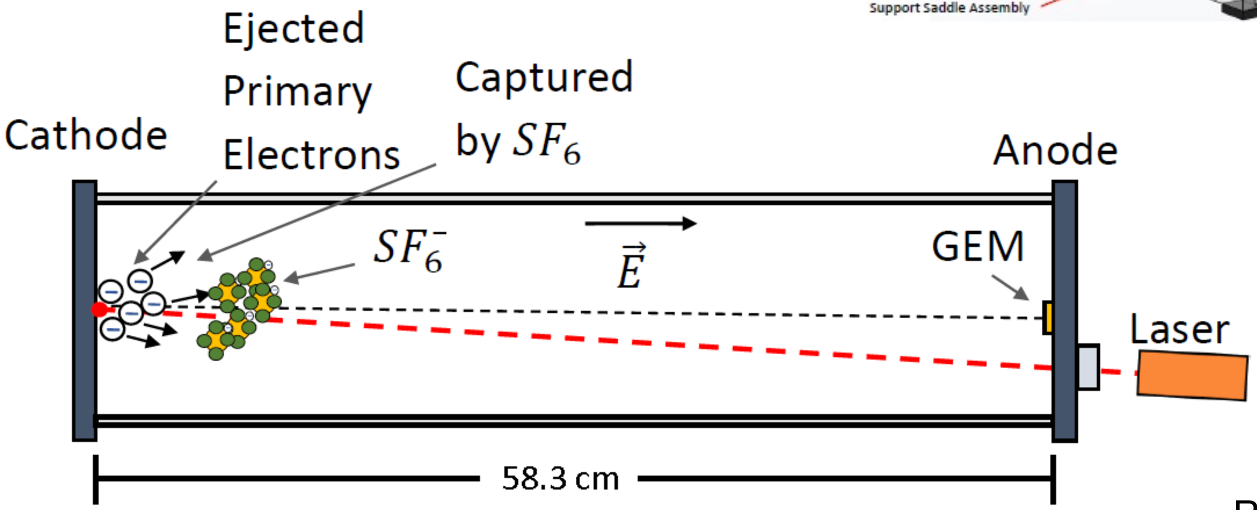




Quantify diffusion (σ_L) and find optimal NI % using charge readout:





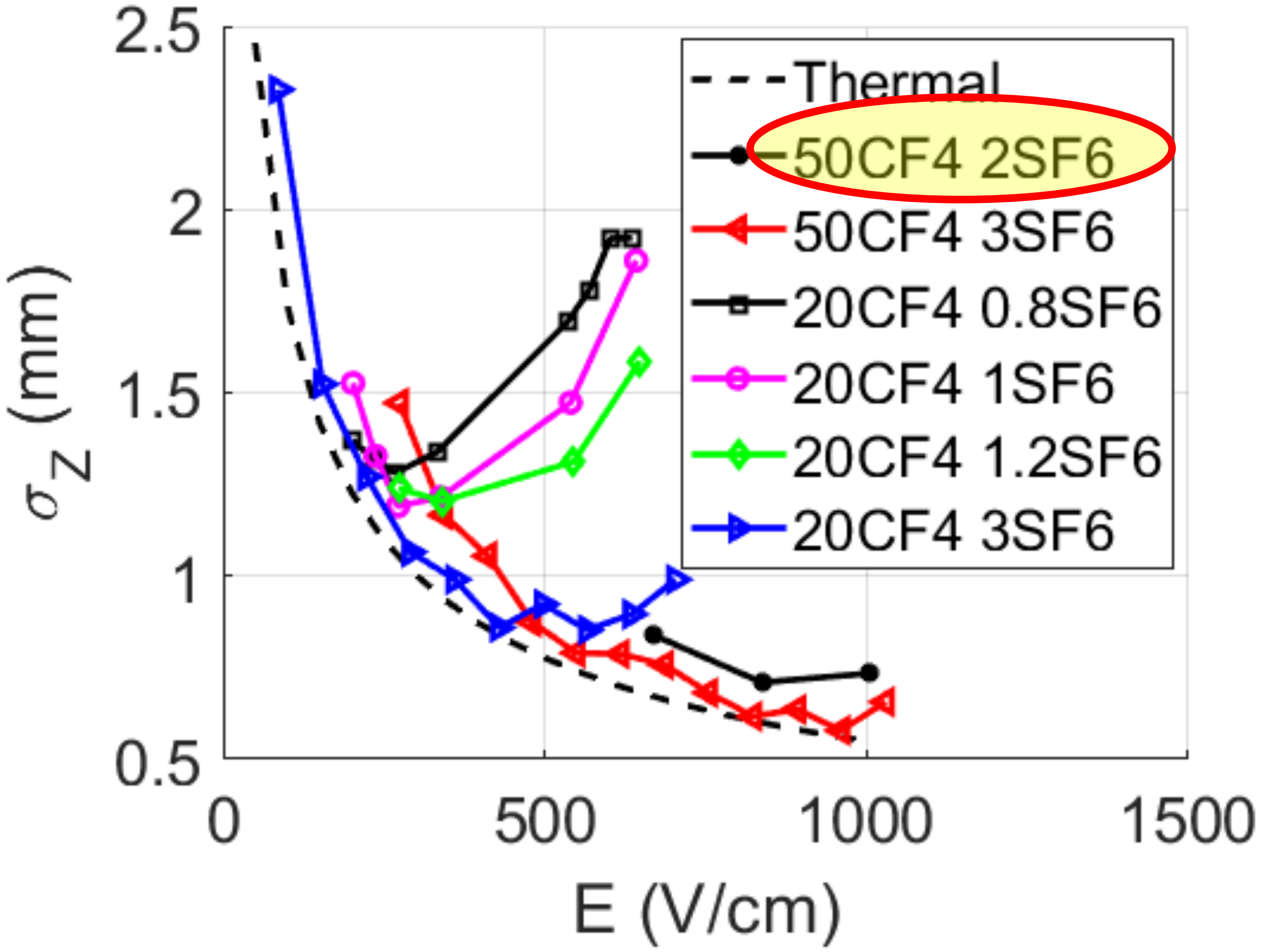


Used to measure:
- diffusion
- mobility
- waveforms

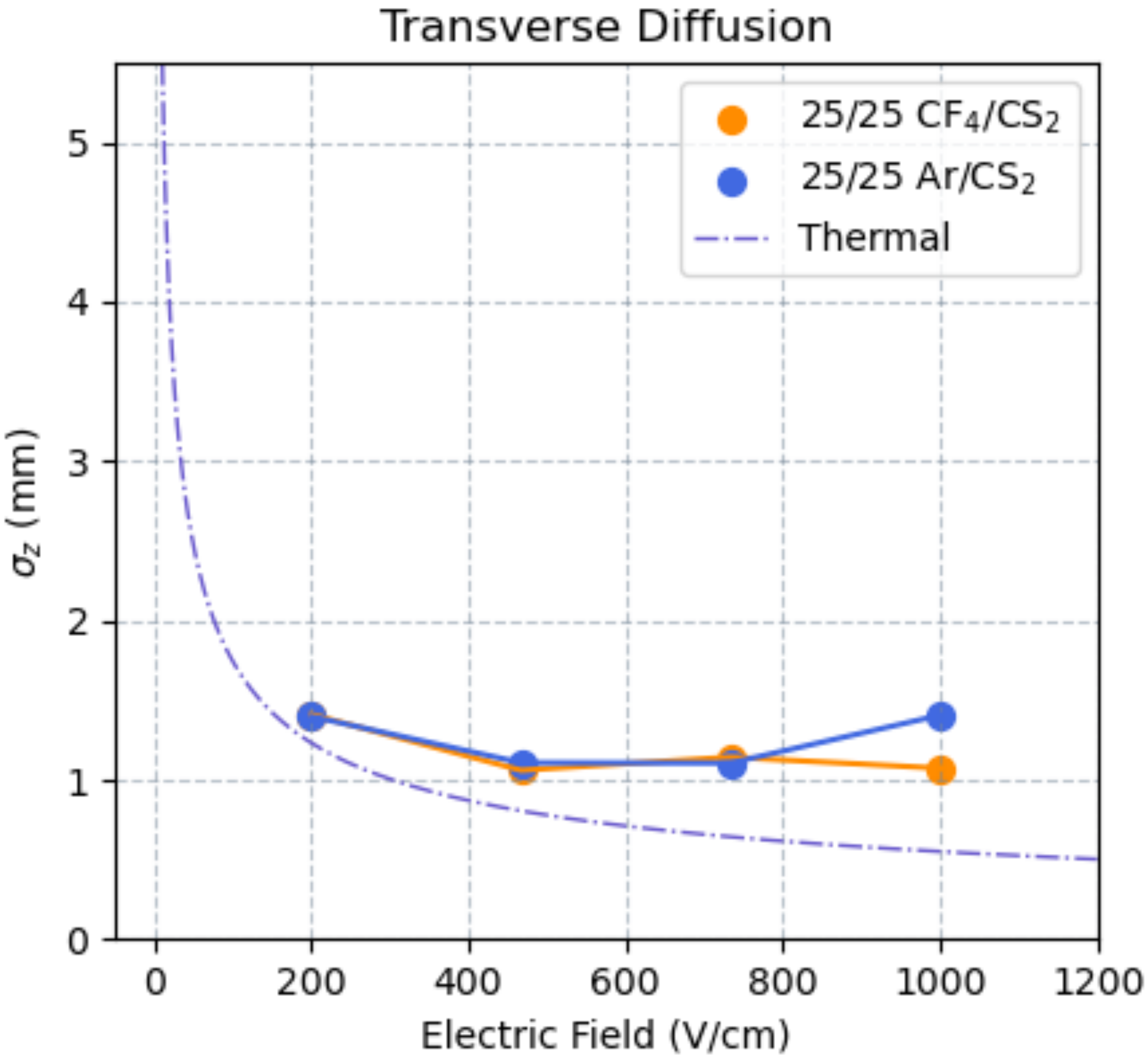
Phan et al 2017 *JINST*

R. Lafler, PhD Thesis, UNM, 2019

Results for σ_L in CF4/SF6 mixtures (60 cm drift):



R. Lafler, PhD Thesis, UNM, 2019


Transverse Diffusion
25/25 CF4/CS2
25/25 Ar/CS2
Thermal
σz (mm)
0
1
2
3
4
5
0
200
400
600
800
1000
1200
Electric Field (V/cm)