The MIGDAL Experiment

Migdal In Galactic Dark mAtter expLoration

Dinesh Loomba on behalf of the MIGDAL collaboration
University of New Mexico

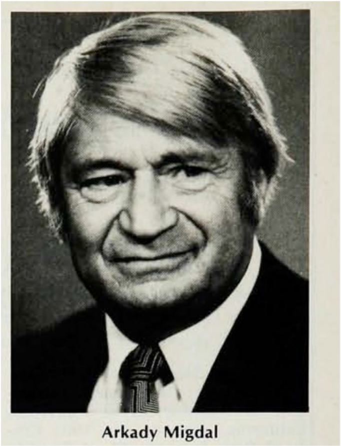
8th CYGNUS Workshop on Directional Recoil Detection

12th December 2023, Sydney

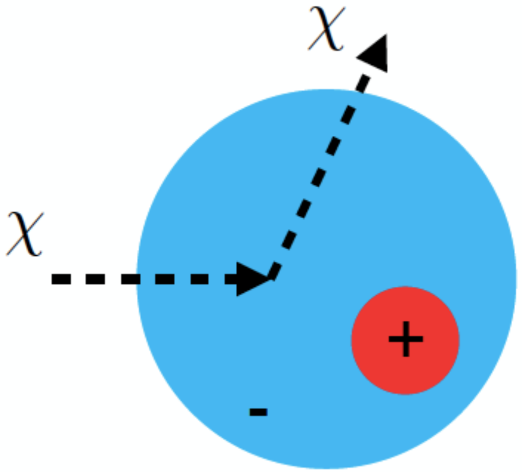
University of Birmingham, UAM Universidad Autónoma de Madrid, GDD Gas Detectors Development Group, Helsinki Institute of Physics, Imperial College London, King's College London, LIP, The University of New Mexico, University of Oxford, Royal Holloway University of London, Science & Technology Facilities Council Rutherford Appleton Laboratory, The University Of Sheffield

Funding: UKRI Science and Technology Facilities Council; U.S. Department of Energy; FCT Fundação para a Ciência e a Tecnologia; Horizon 2020 European Union Funding for Research & Innovation; NSF National Science Foundation; Marie Curie Actions

The Migdal Effect



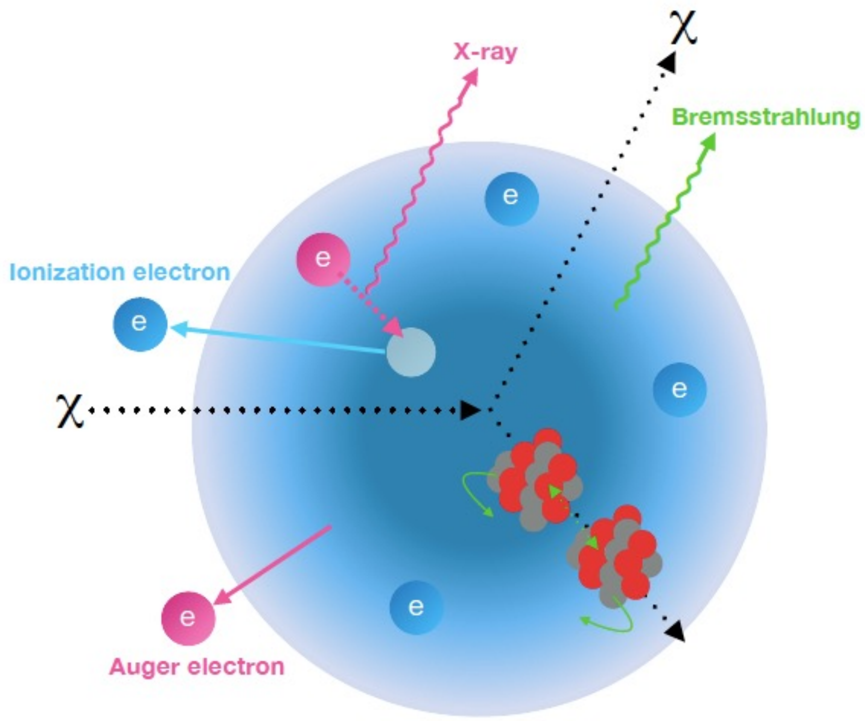
A.B. Migdal, Ionization of atoms accompanying α- and β-decay , J. Phys. USSR 4 (1941) 449



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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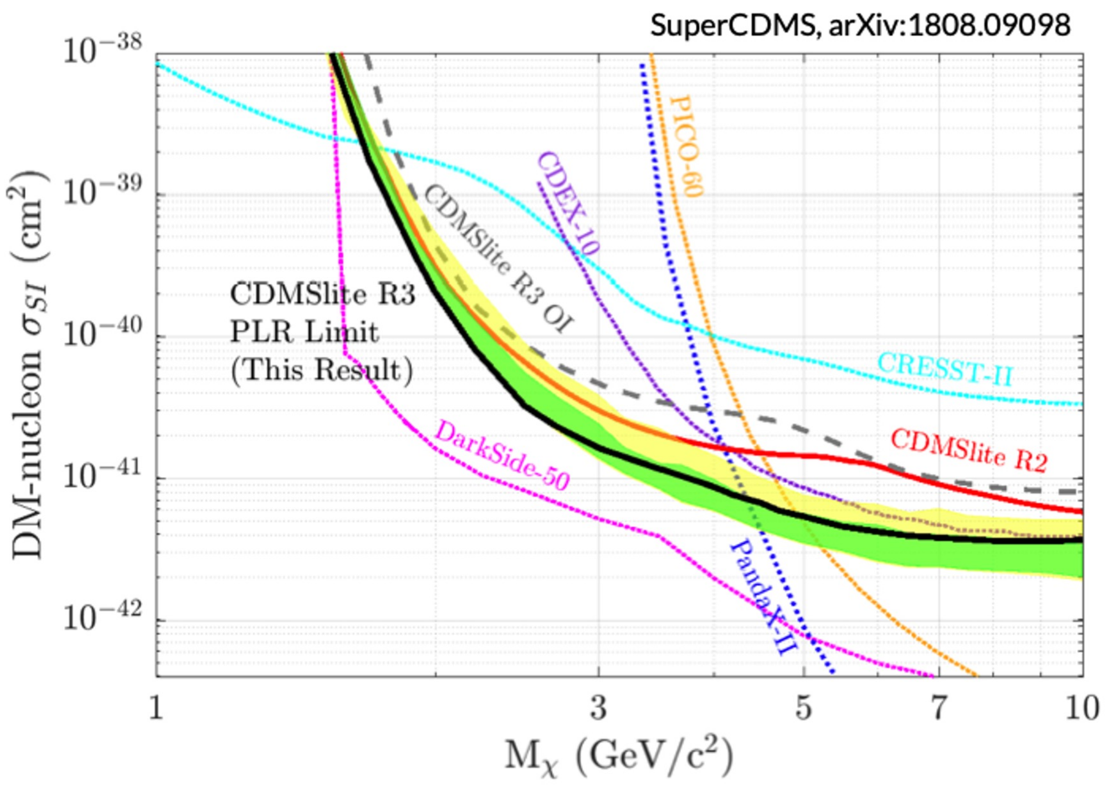
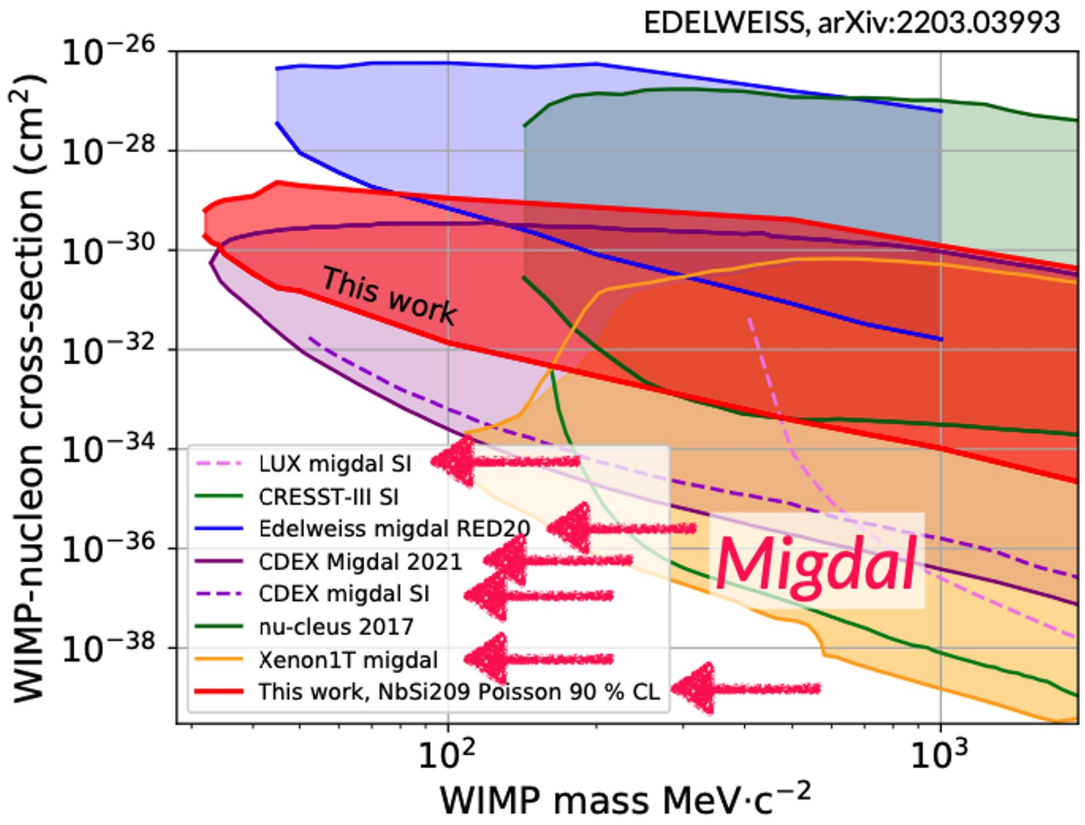
So far ~ 200 citations of Ibe et al.

Experiments using Migdal to enhance sensitivity to LDM:

LUX, XENON1T, EDELWEISS,CDEX-1B, SENSEI

Including targets: Ge, Si, Xe and Ar





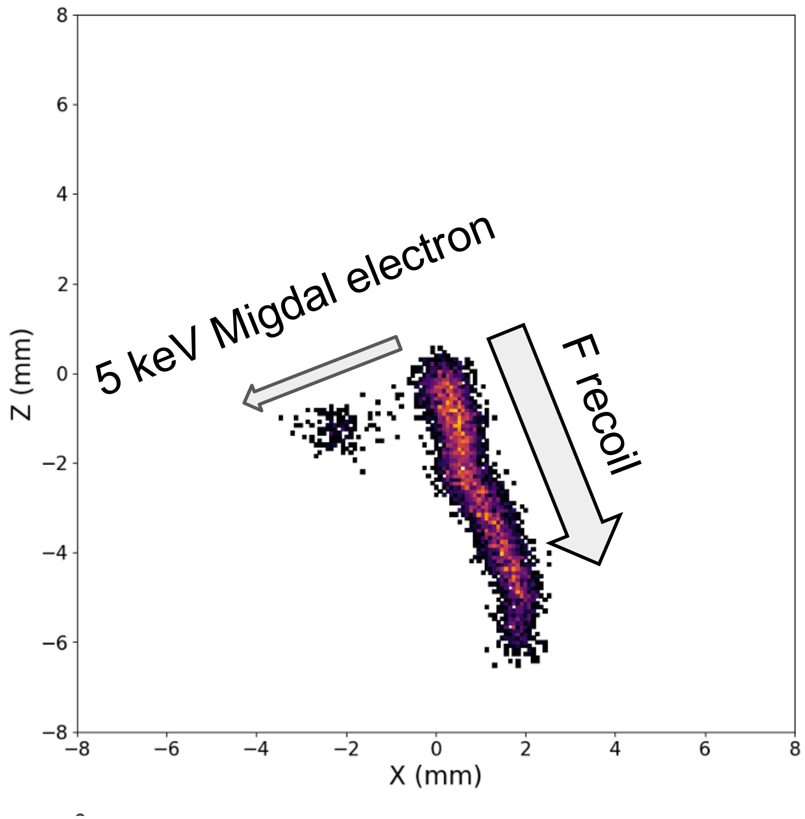
Pre-2018
No Migdal limits

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

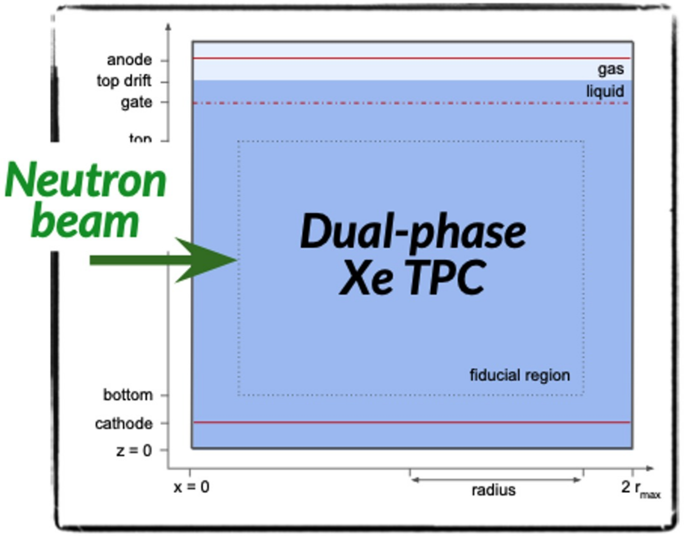
Today
Dominated by Migdal

Detecting the Migdal Effect

- The Migdal effect has not been measured in this regime
  → **needs validation!**
- Many efforts/techniques underway (**see Kentaro's talk!**)
- Here we focus on detecting the **electron and nuclear recoils – the Migdal topology**
  → **Challenging!**

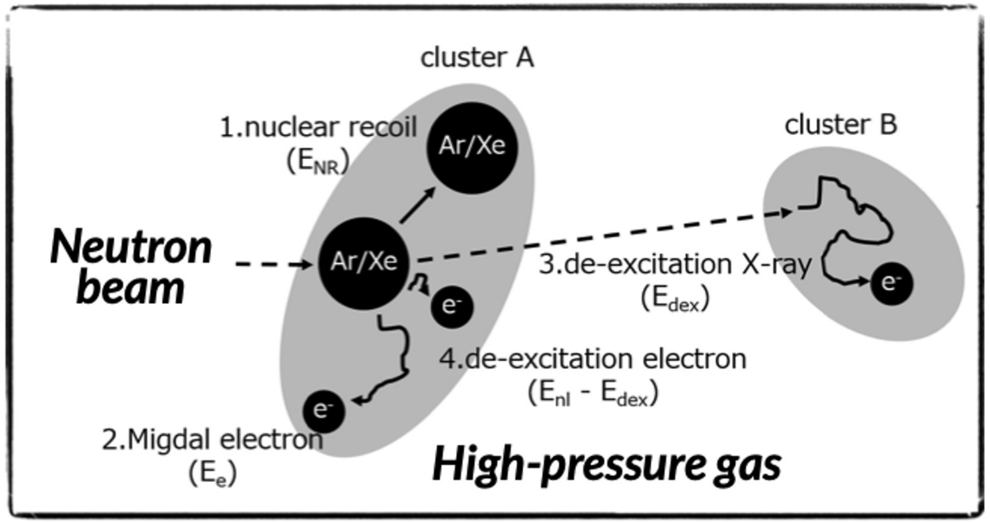


Bell et al, arXiv:2112.08514



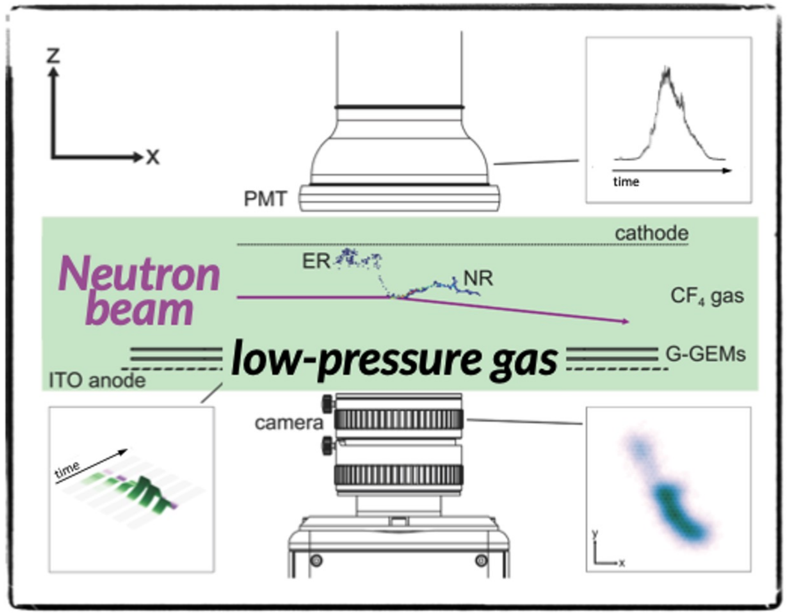
$E_{\mathrm{neutron}} \sim 15$ keV

Nakamura et al, arXiv:2009.05939



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

Araújo et al (MIGDAL), arXiv:2207.08284



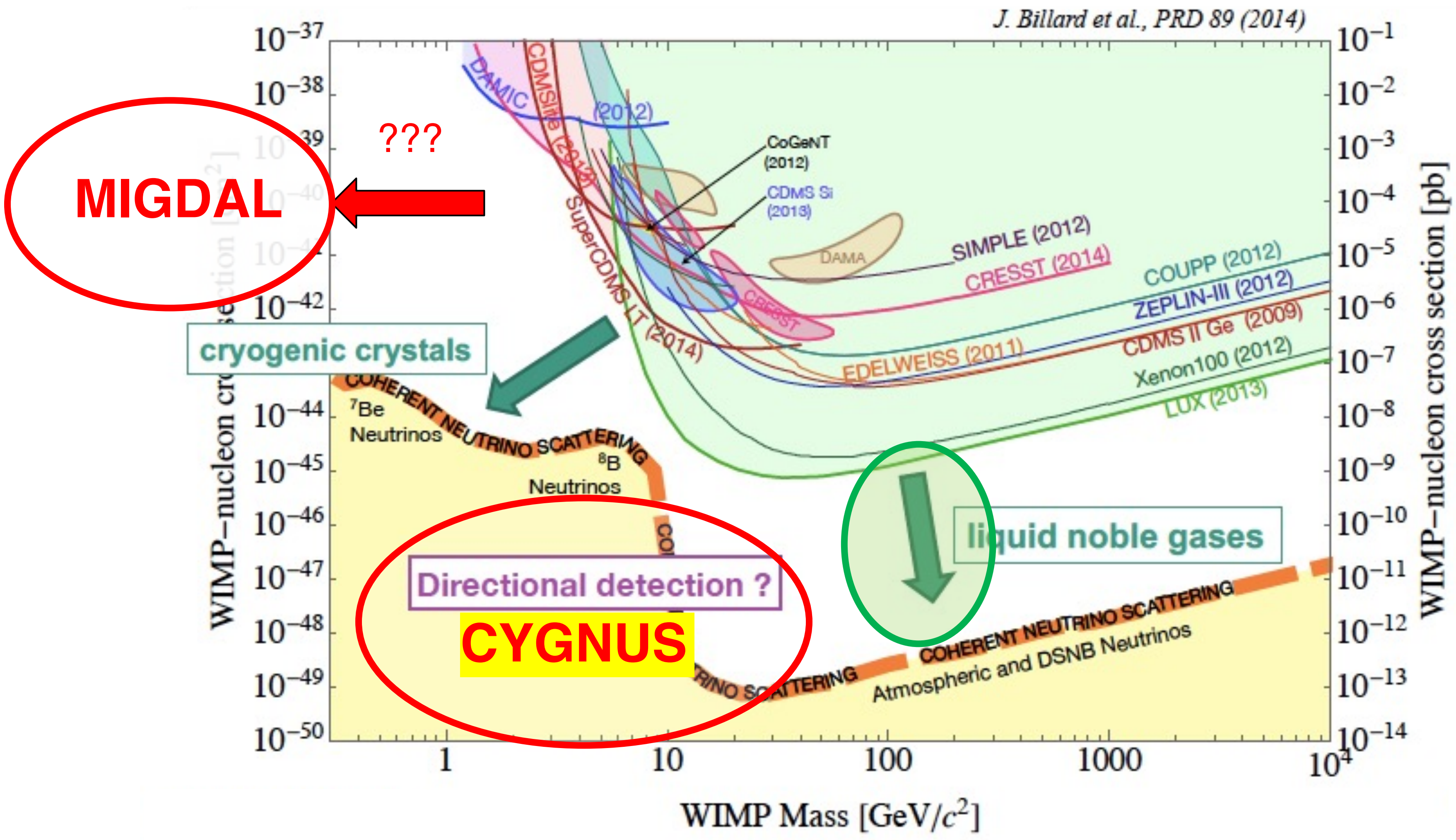
$E_{\mathrm{neutron}} \sim 2500 - 15000$ keV

MIRA CLUE

See Kentaro's talk!

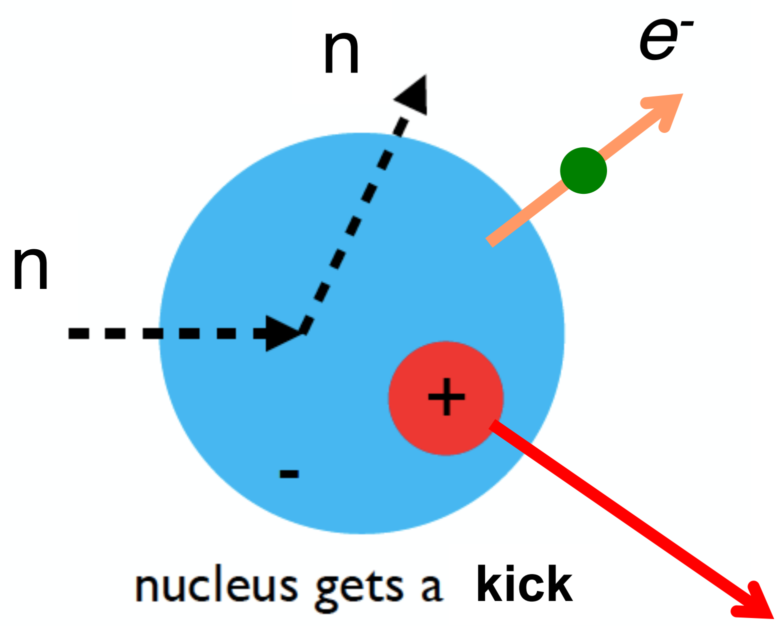
MIGDAL
Migdal In Galactic Dark mAtter expLoration

Directional Detectors



Courtesy of J. Billard

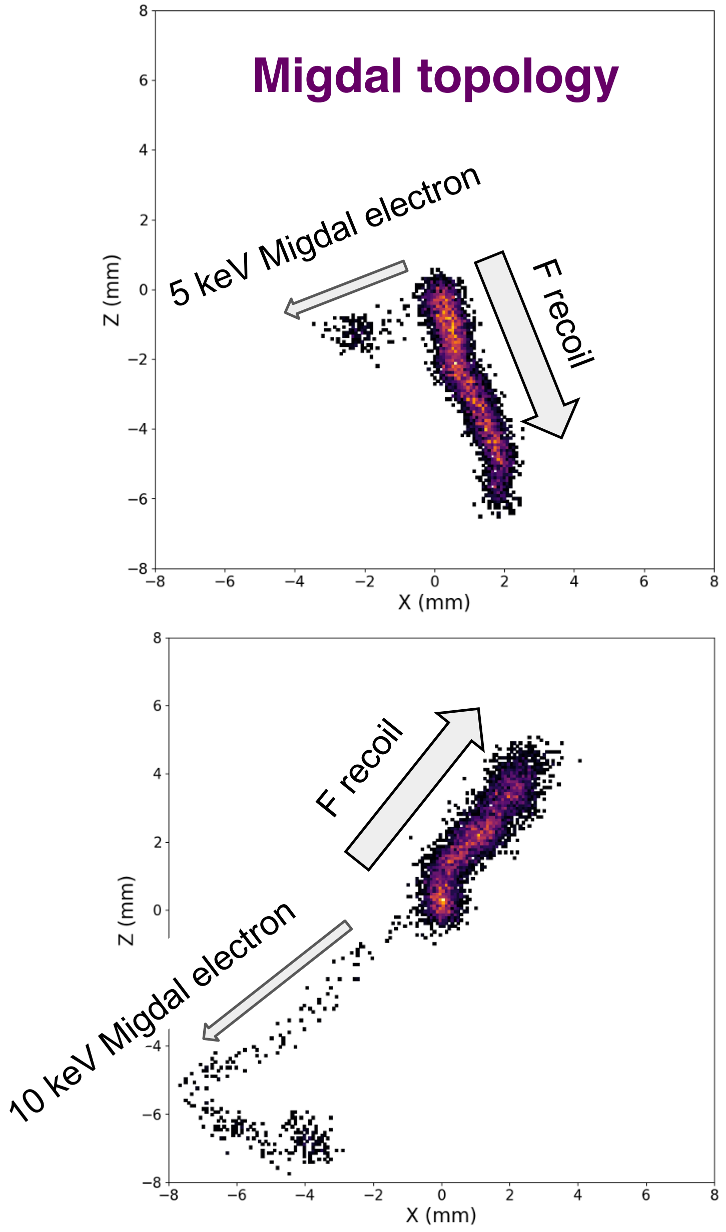
Measure Migdal event topology



nucleus gets a **kick**

$E_{recoil} >> keV$

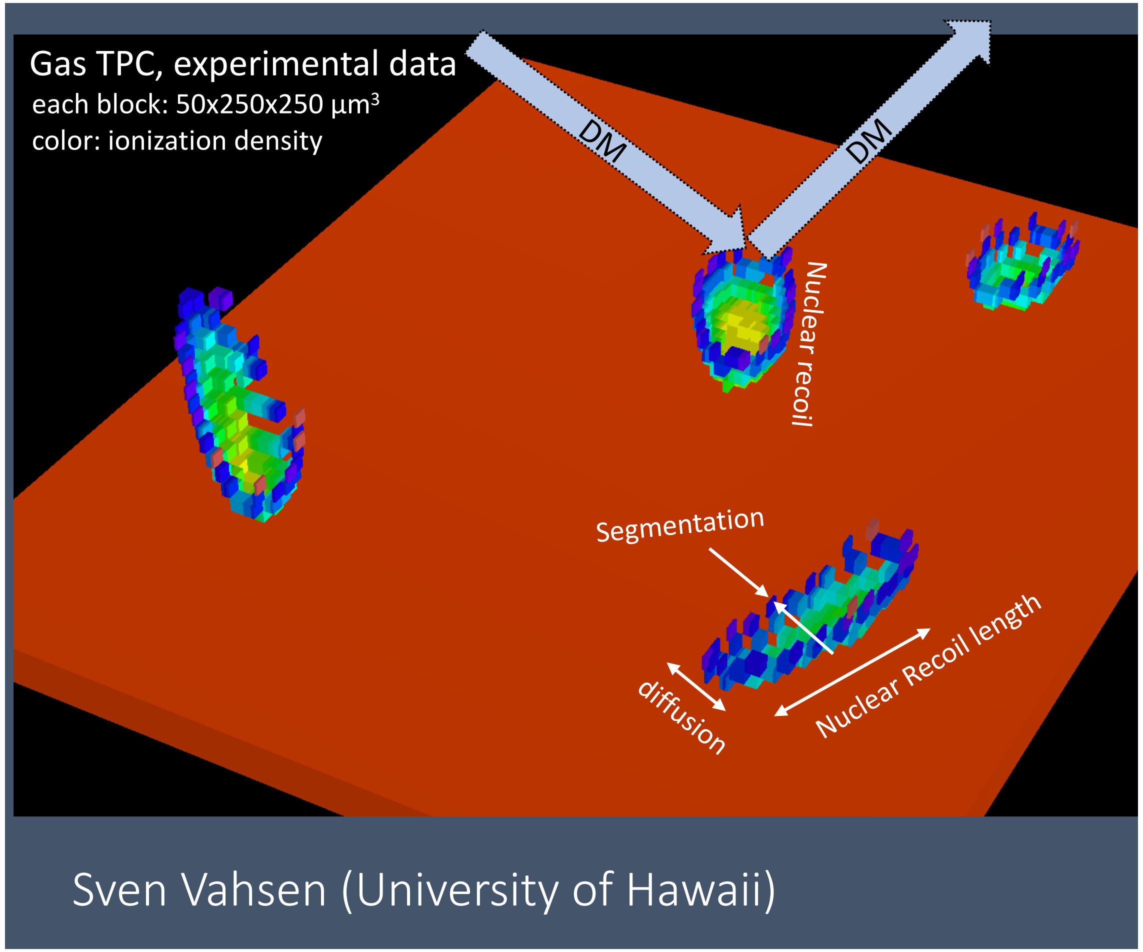
Both NR+ER recoils must be detected



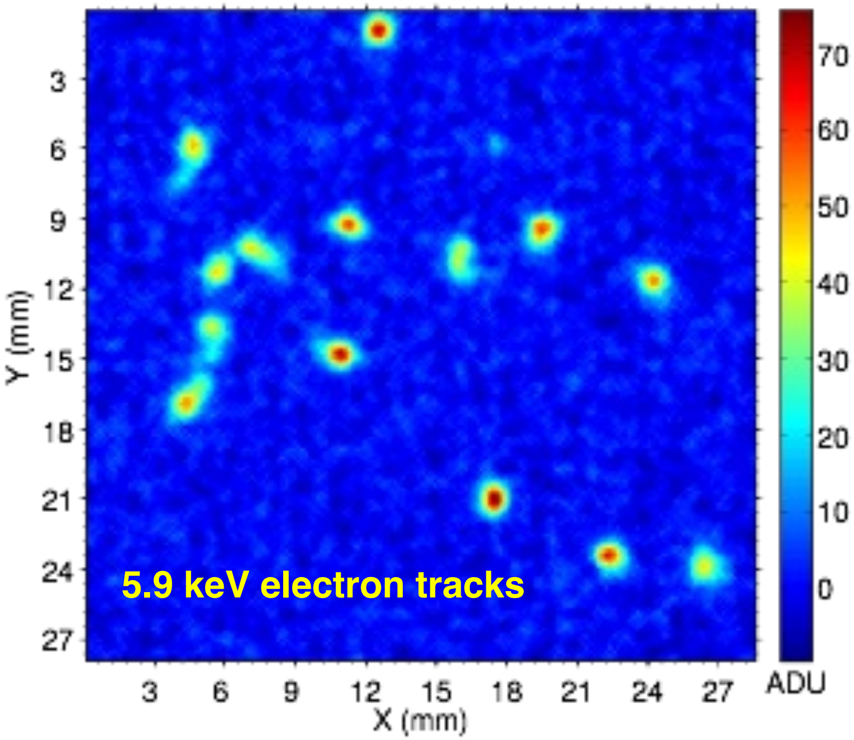
P. Majewski, "OTPC for the observation of the Migdal effect in nuclear scattering", New Horizons in Time Projection Chambers, 2020

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

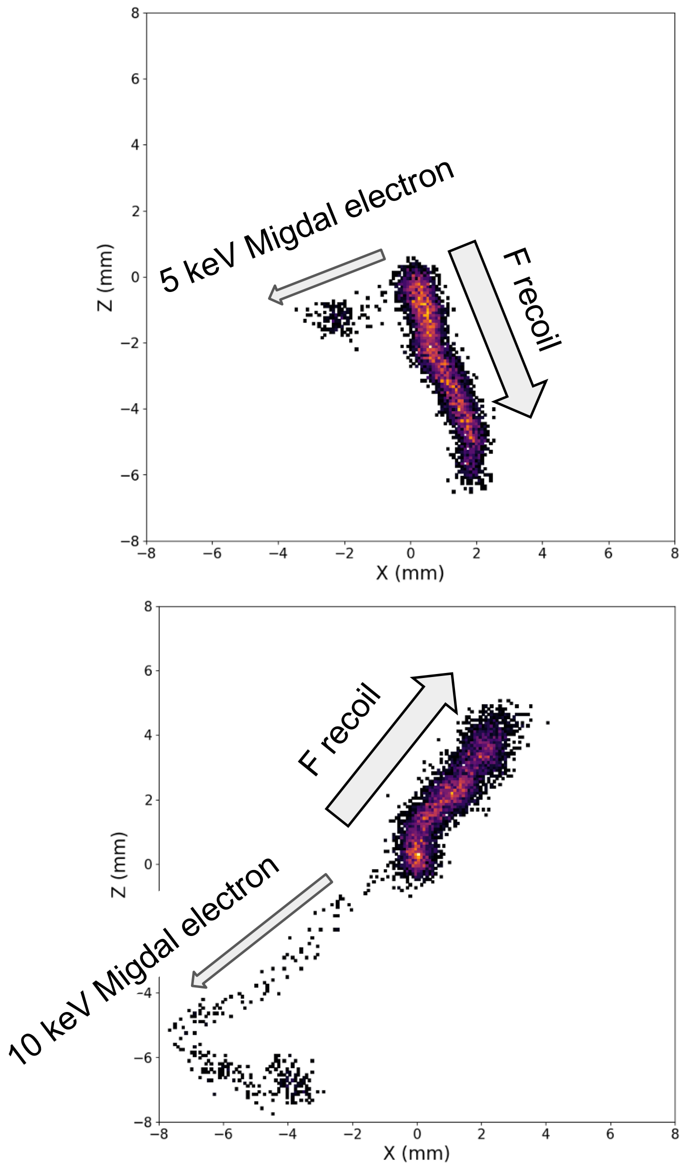
Well resolved NRs:



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



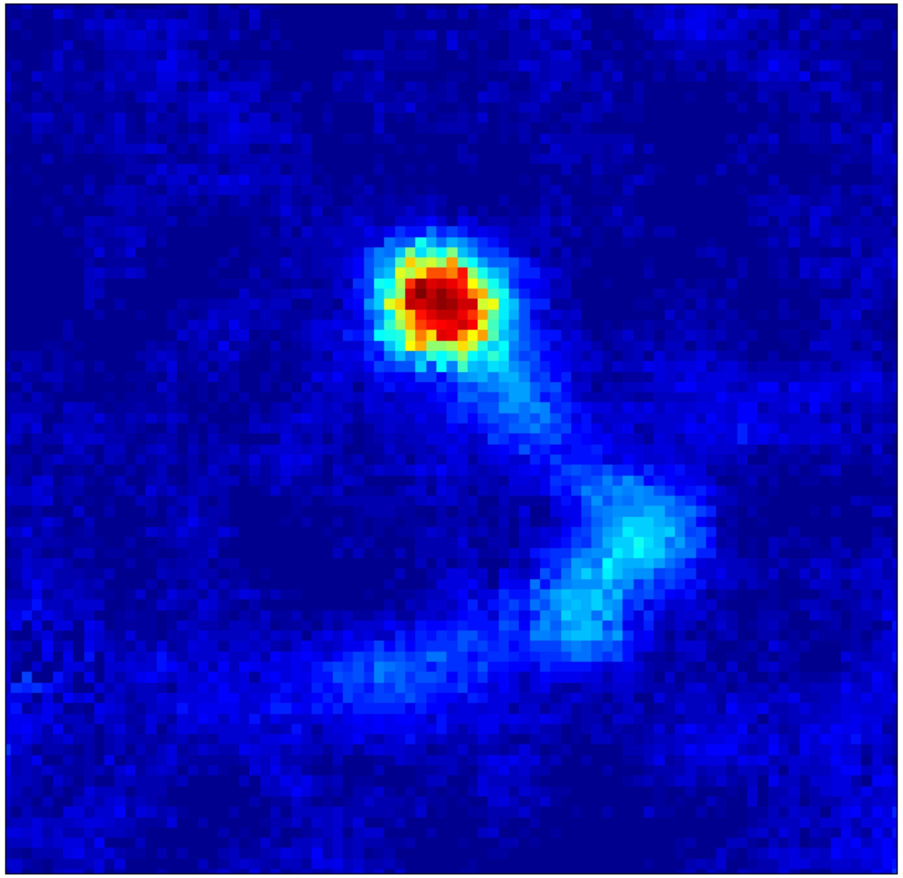
Phan, et al. JINST **15** P05012 (2020). arXiv:1703.09883



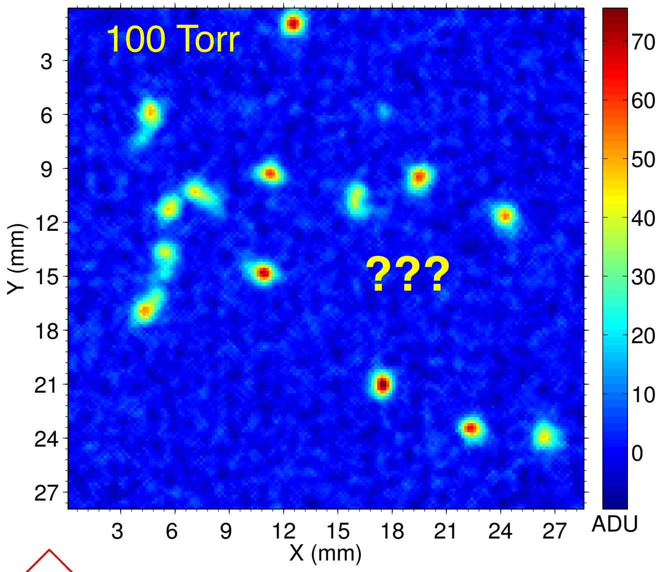
The challenge: electron tracks have **low dE/dx**, large fluctuations:

We need:

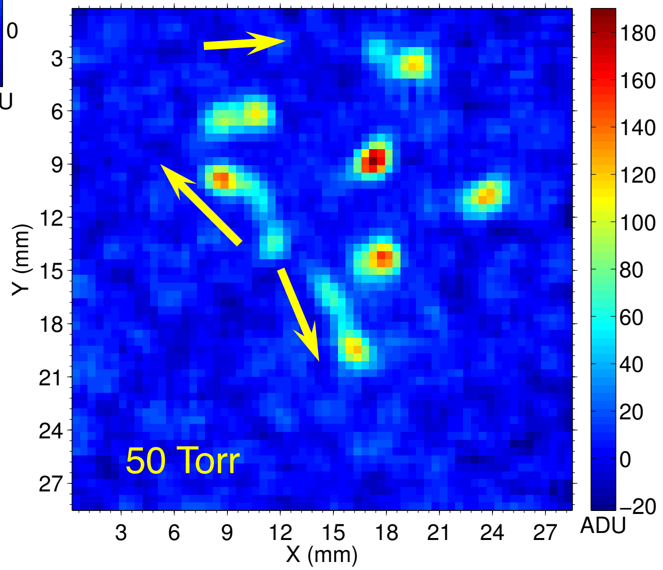
- low pressures
- fine granularity readouts
- high S/N, and
- **Large dynamic range!**



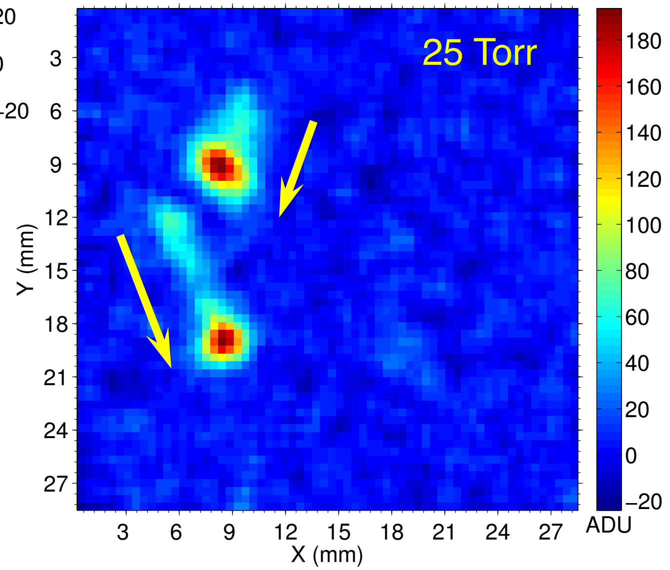
pre-lbe:



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



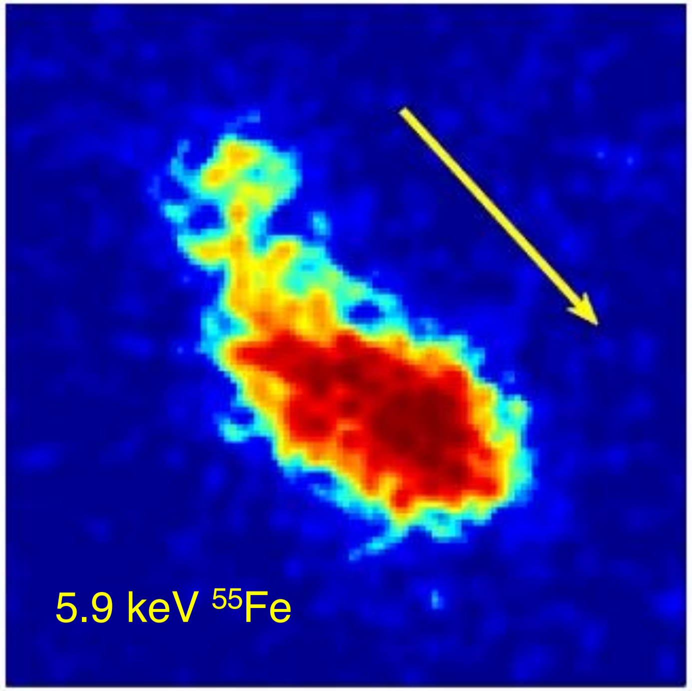
5.9 keV electron tracks imaged at same scale



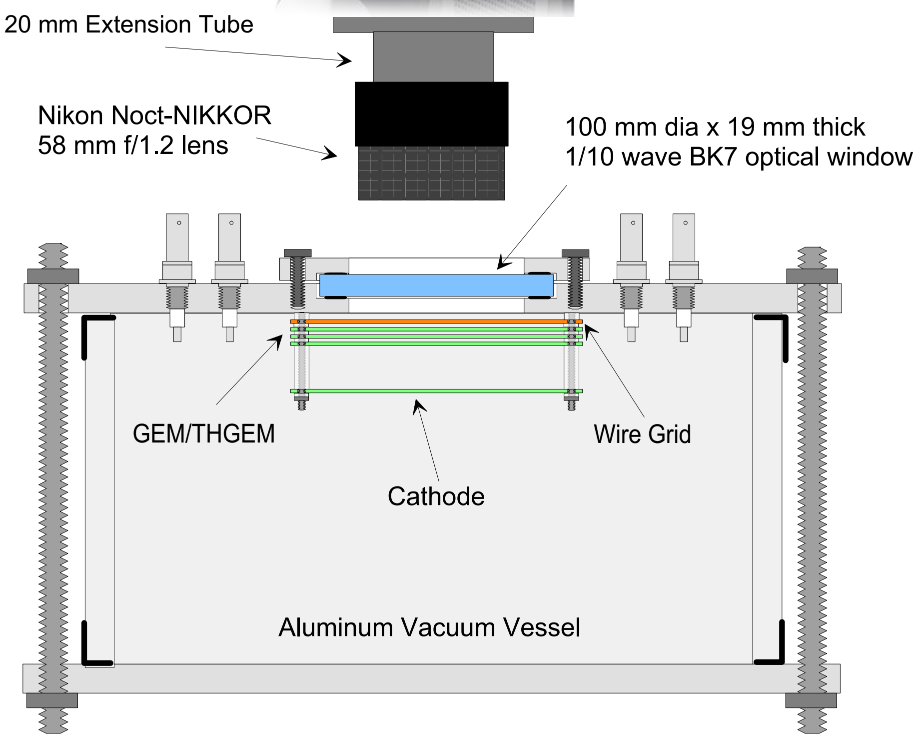
Lower Pressure → Longer Tracks

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

Post-Ibe: higher S/N and resolution of ERs using next-gen MPGDs, CCDs & CMOS

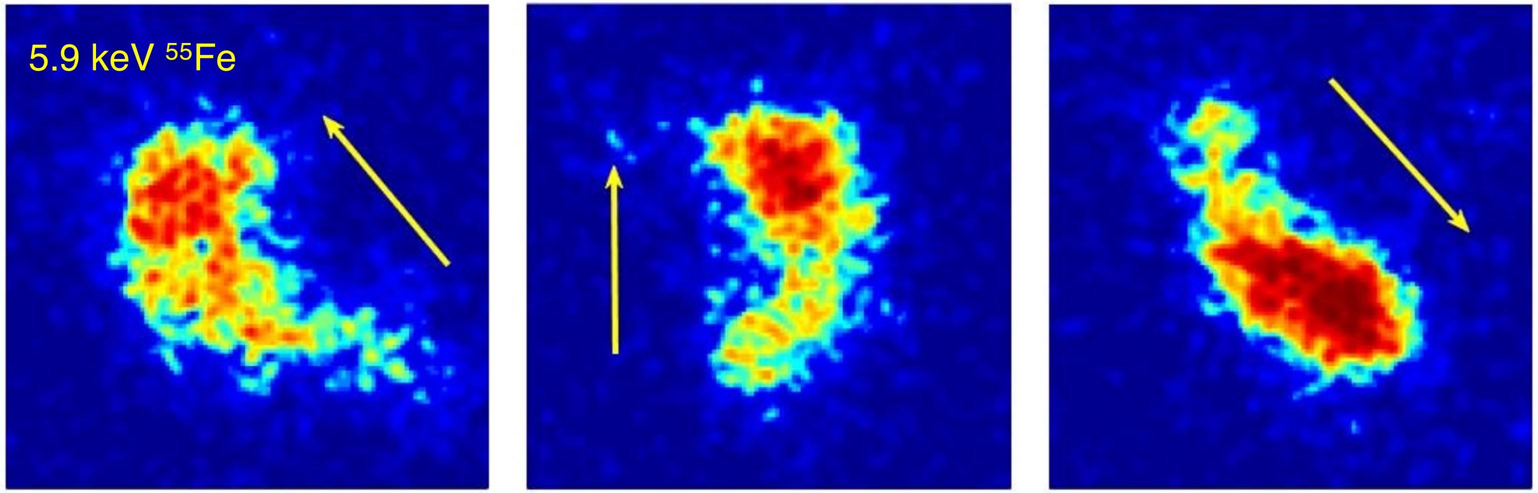


Hamamatsu EMCCD camera + Others

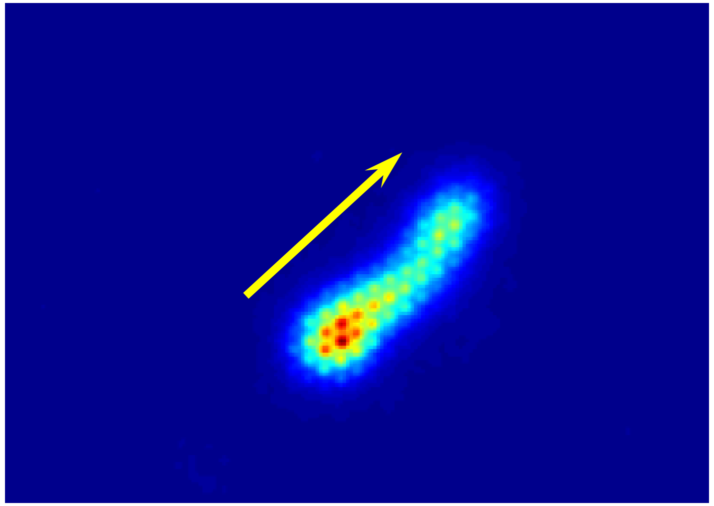


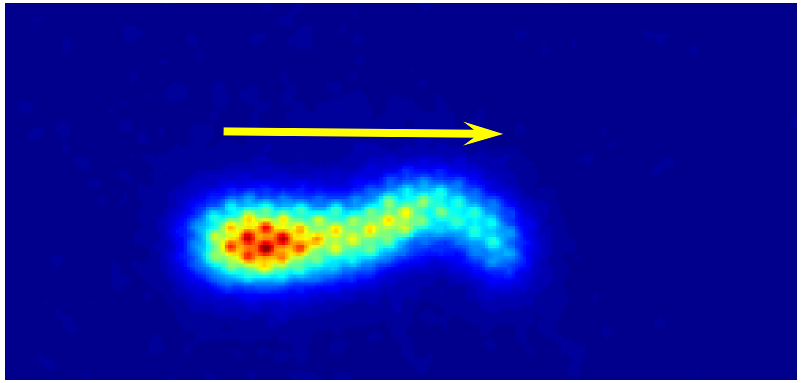
Results:

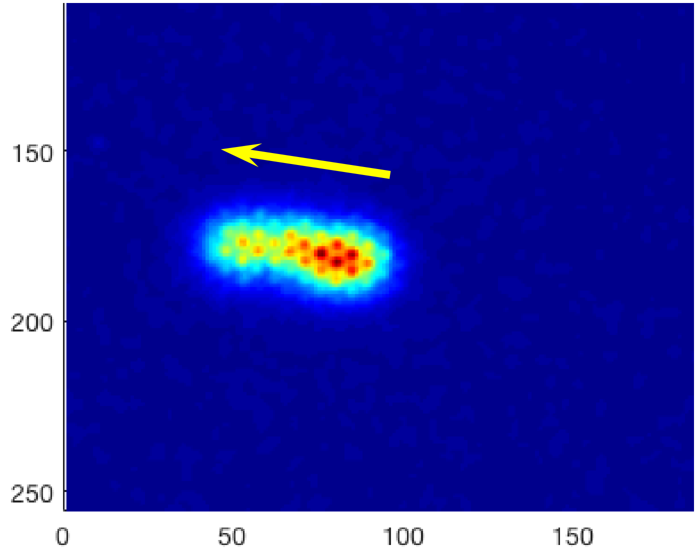
5.9 keV ER tracks



~100-300 keV NR tracks





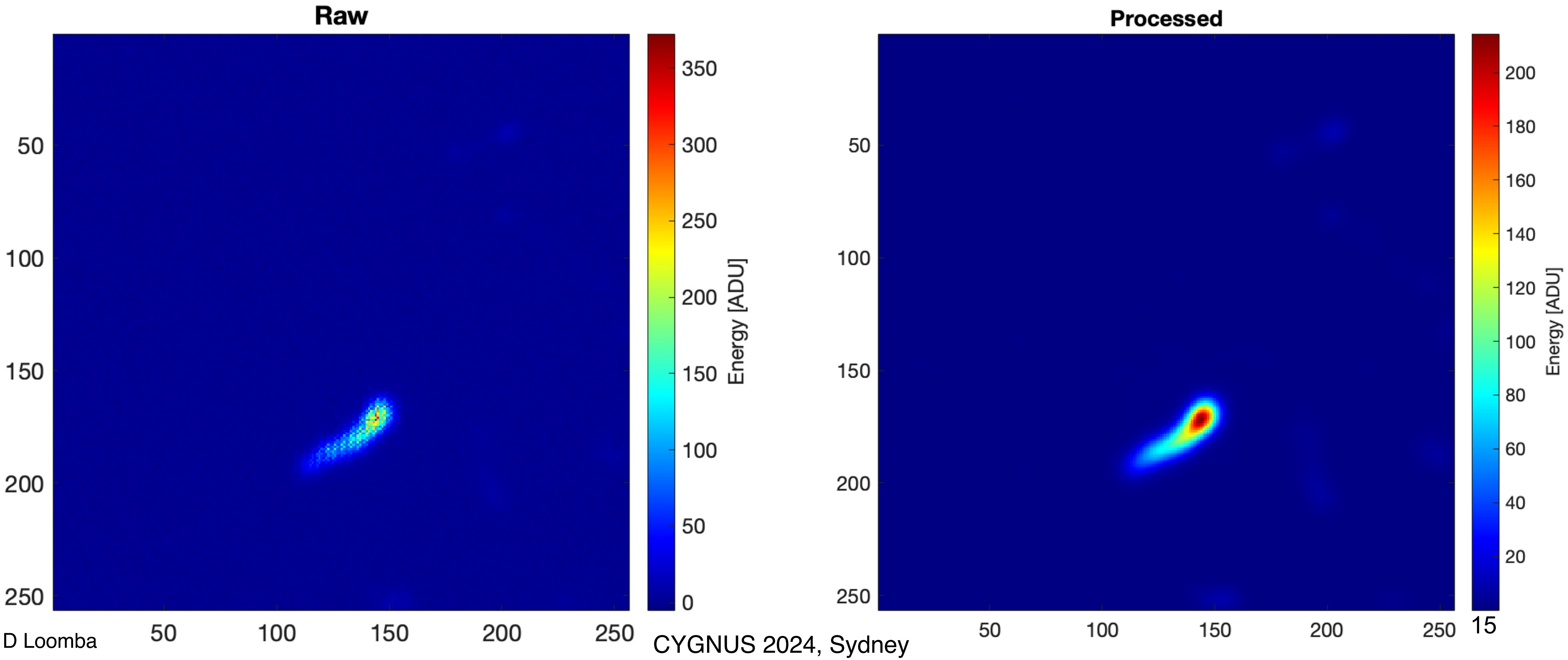


At 30 Torr, these tracks are well resolved with clear directionality (arrows)

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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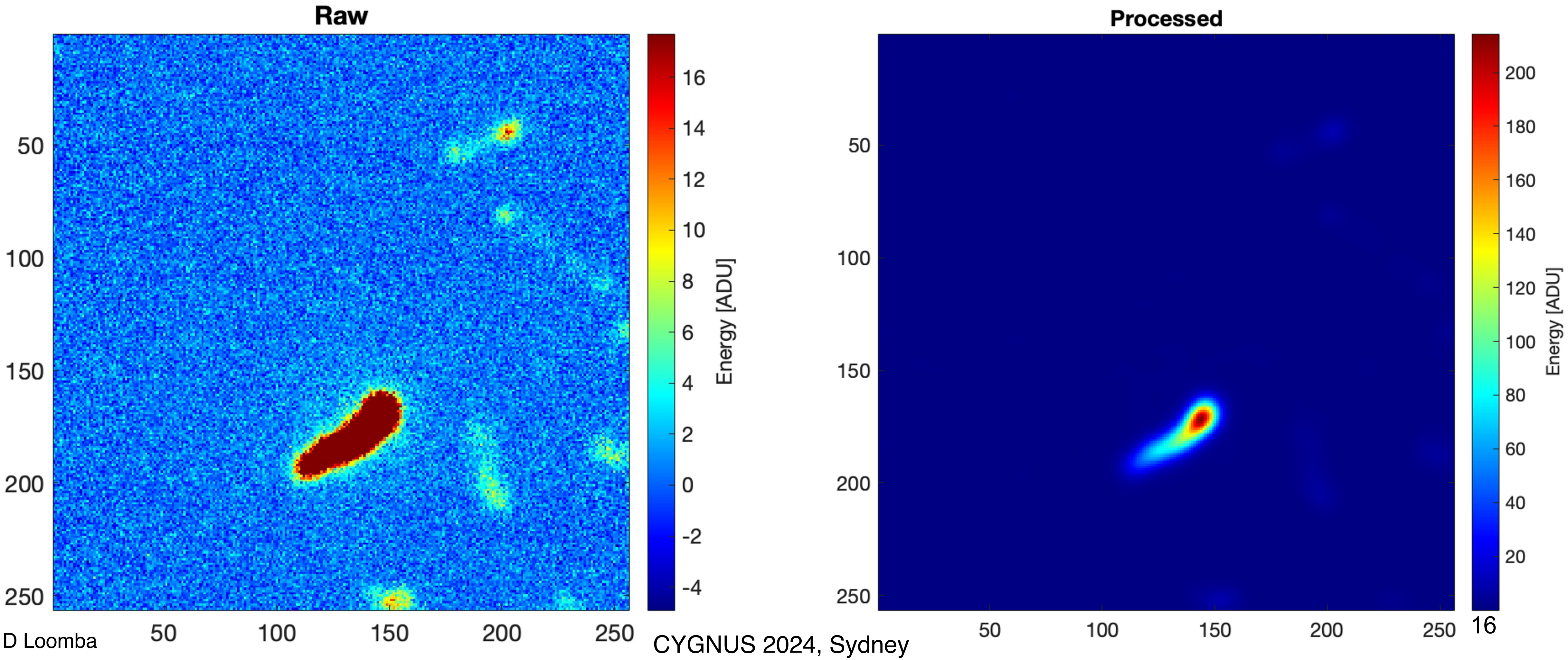
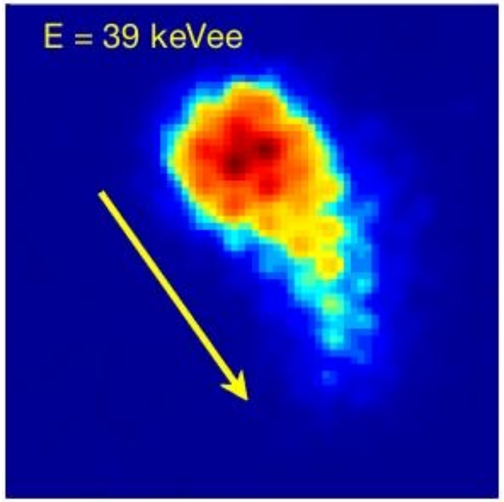


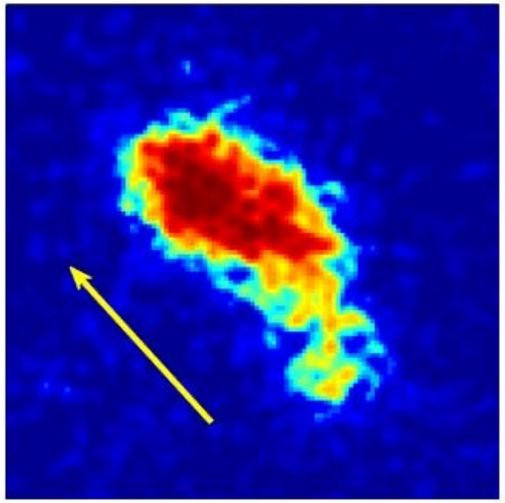
"Migdal Events"

Nuclear Recoil



+

Electron



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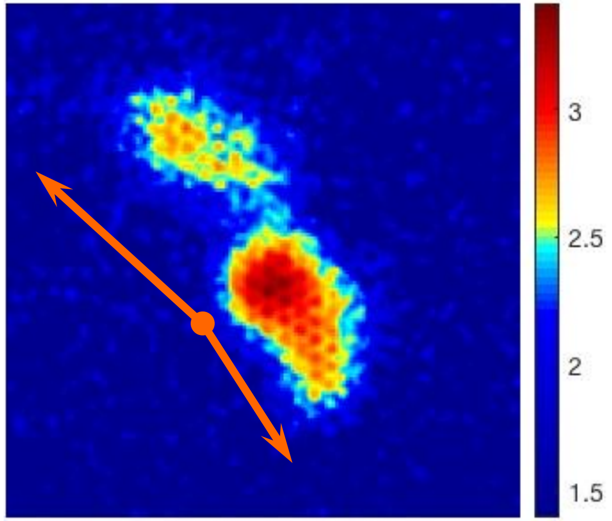
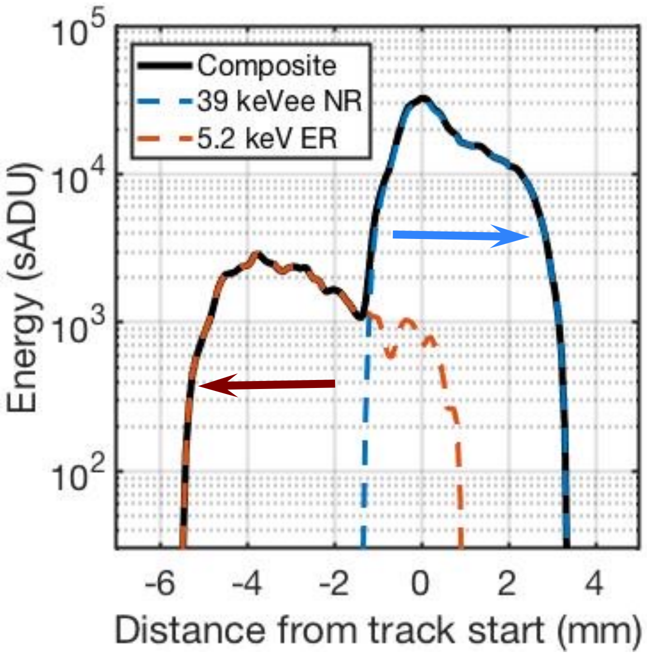


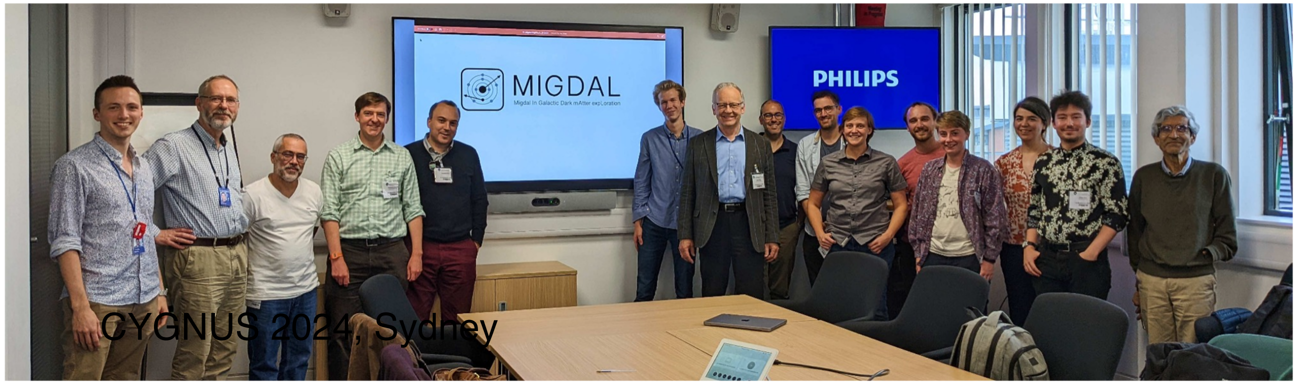


Migdal

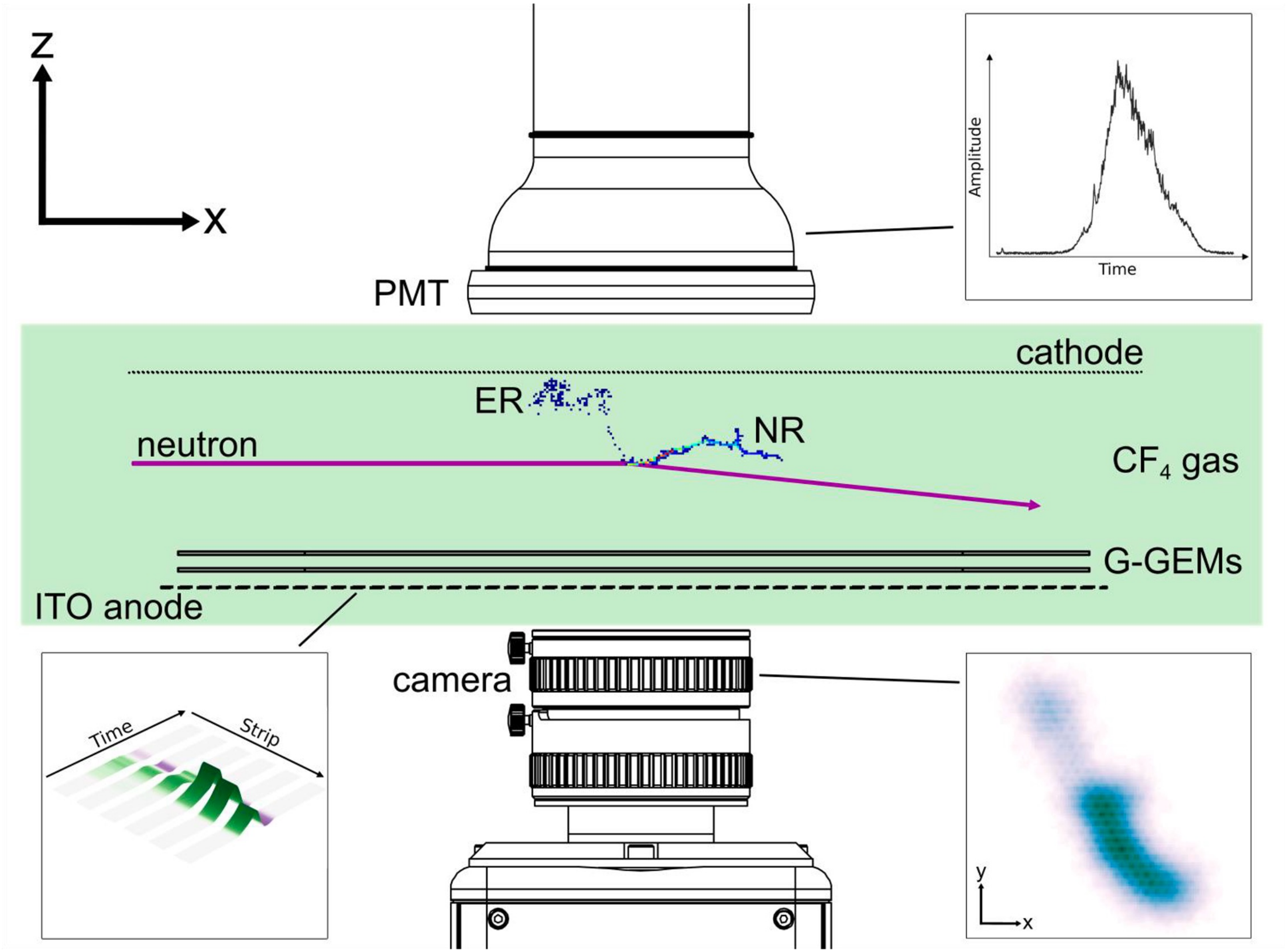
The MIGDAL Collaboration

- Over 35 physicists and engineers from 14 institutions across 6 countries
- At Rutherford Appleton Lab at the NILE facility

UKRI Science and Technology Facilities Council
U.S. DEPARTMENT OF ENERGY
FCT Fundação para a Ciência e a Tecnologia
Horizon 2020 European Union Funding for Research & Innovation
NSF National Science Foundation
MARIE CURIE ACTIONS



The MIGDAL experiment



- Low-pressure gas: 50 Torr of CF_4
  - To extend particle tracks
  - Minimize gamma interactions
- TPC signal amplification
  - 2 x glass-GEMs (Cu or Ni cladded)
- Readout
  - Optical : Camera + photomultiplier tube
  - Charge: GEMs + 120 ITO anode strips
- High-yield neutron generator
  - D-D: 2.47 MeV (10^9n/s)
  - D-T: 14.7 MeV (10^{10}n/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

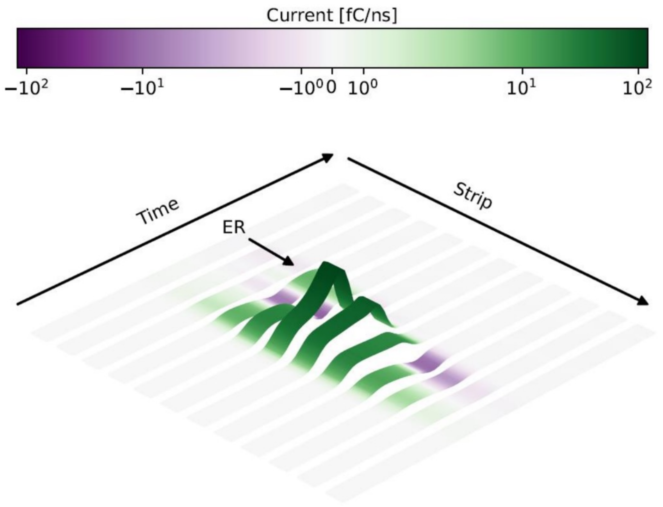
Expected Migdal signal/backgrounds per 1 million DD-induced nuclear recoils with E > 100 keV

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

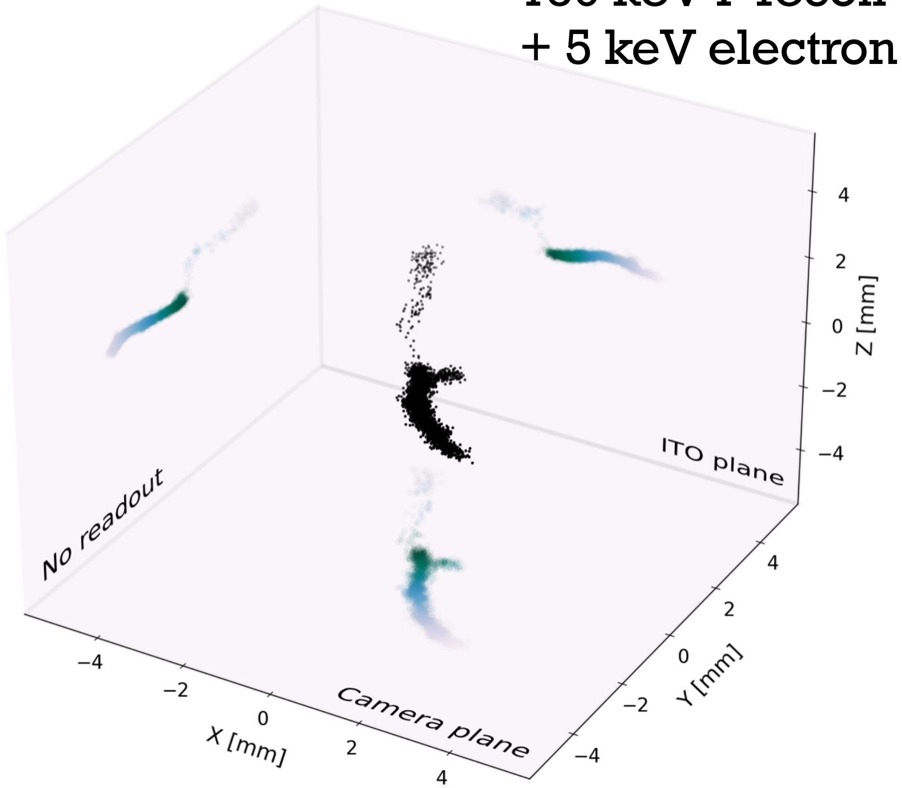
End-to-end Simulations:

- 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

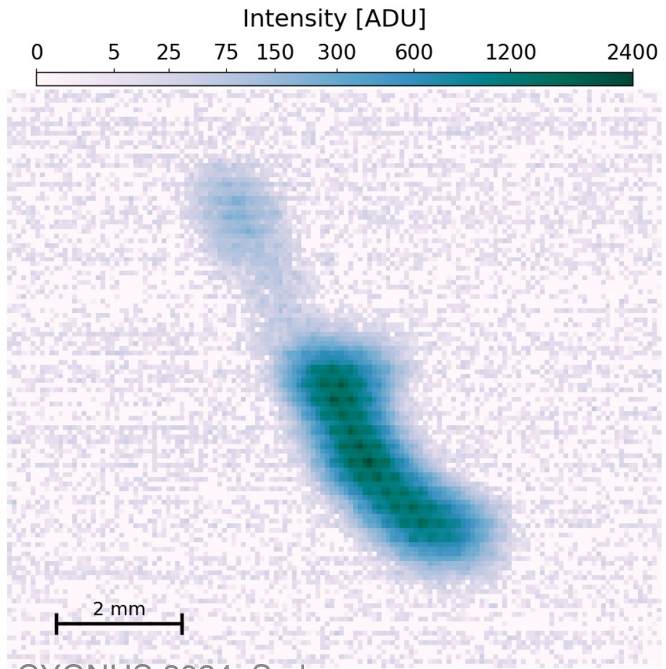
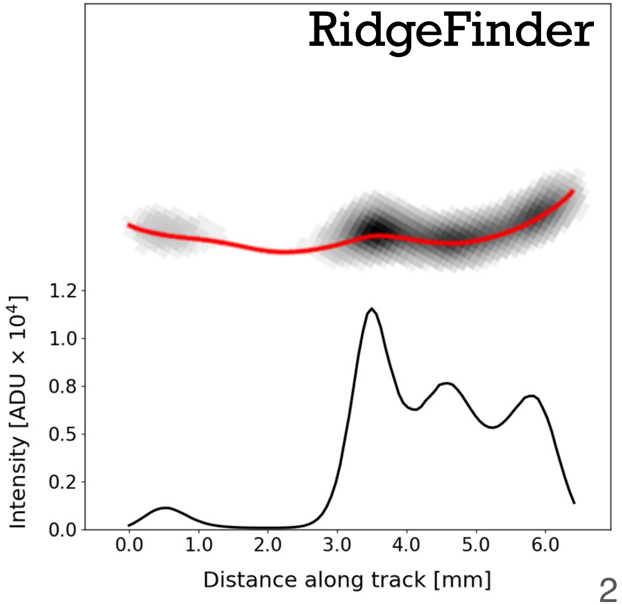
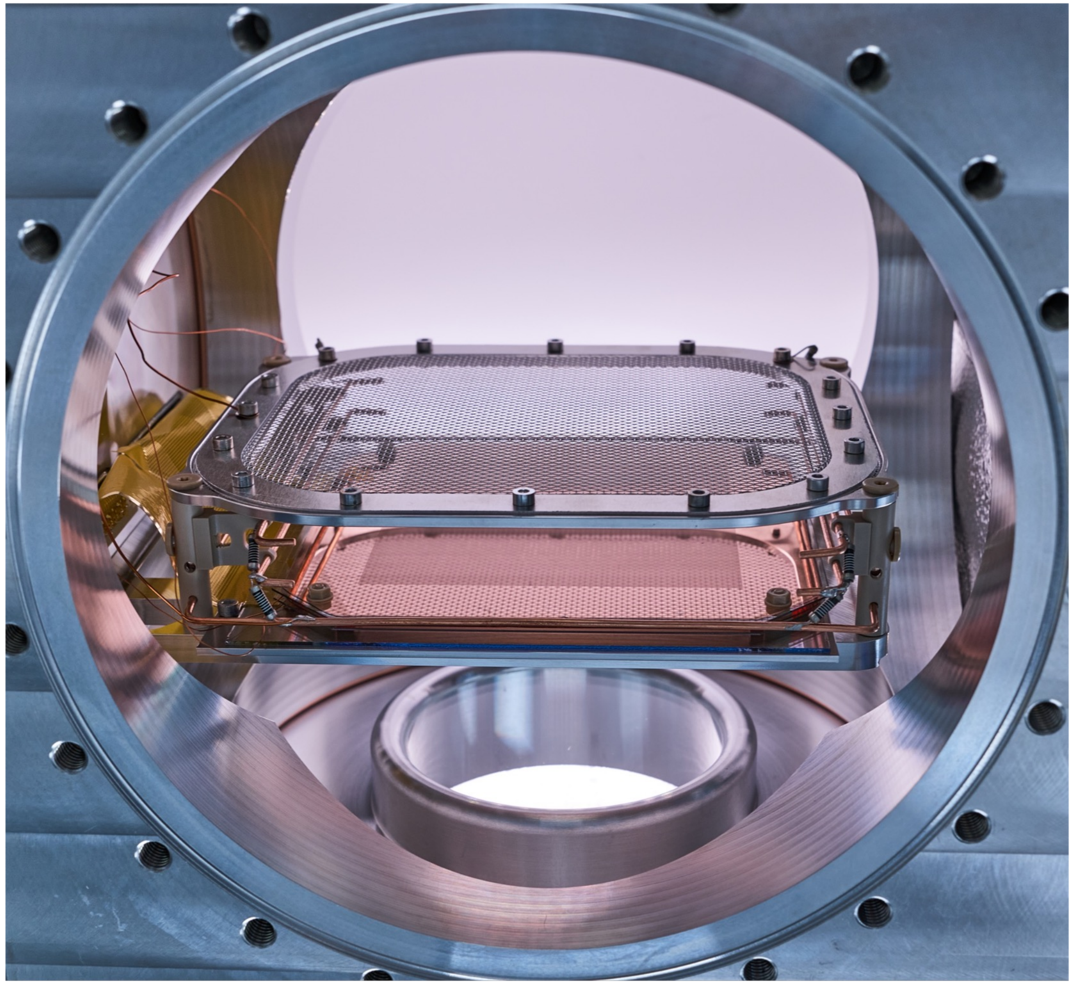
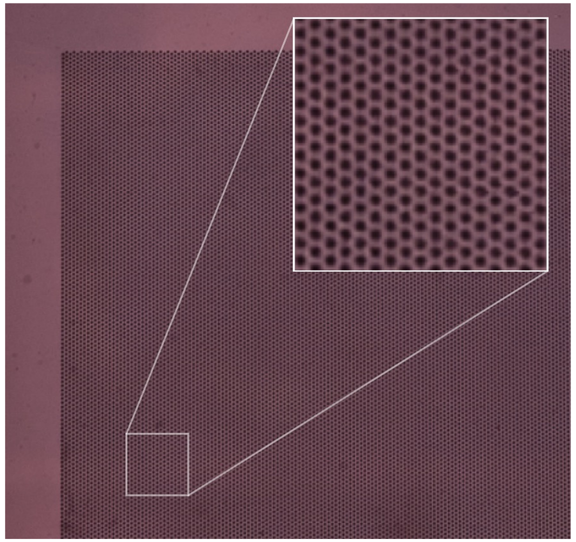


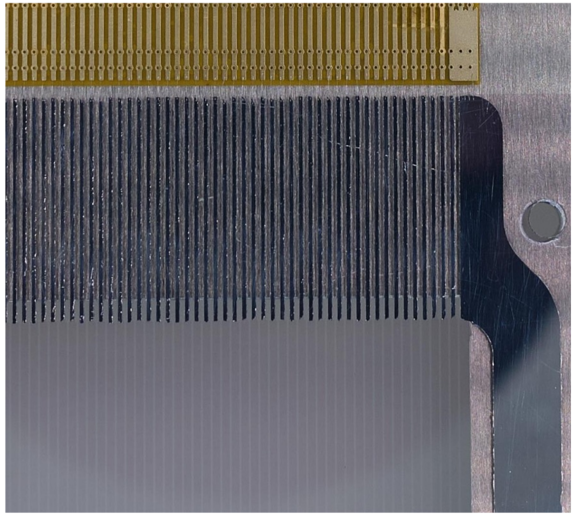
Image analysis
Deconvolution + RidgeFinder



The MIGDAL optical-TPC







Two glass GEMs one Cu- and one Ni-cladded :

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

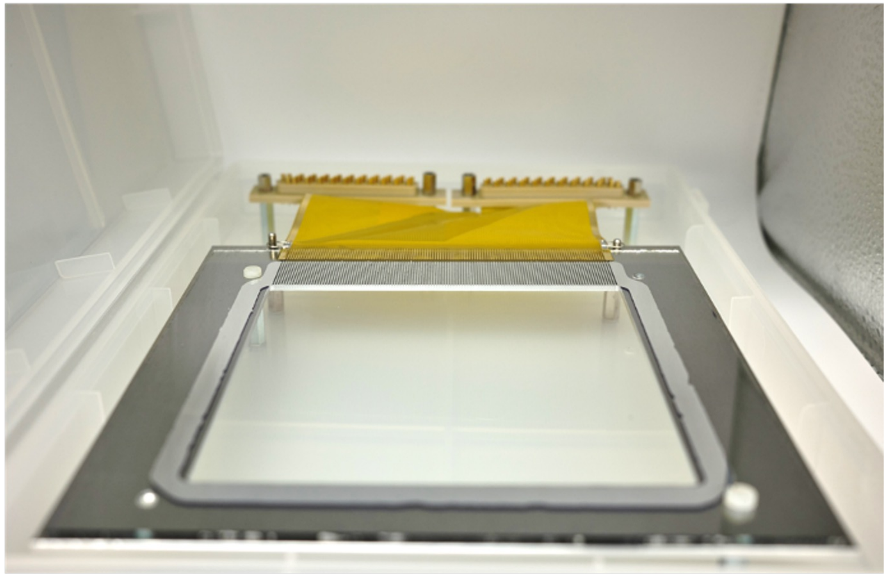
ITO strips wire bonded to readout:

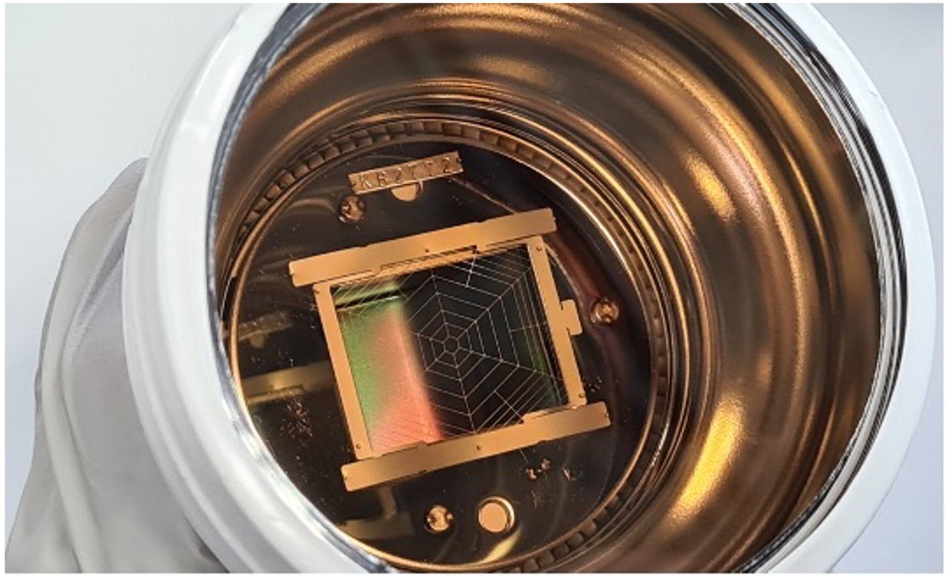
- 120 strips
- width/pitch: 0.65/0.83 mm

Two field shaping copper wires

- TPC inside aluminium cube vacuum vessel
- Drift gap: 3 cm between woven mesh cathode and cascade of two glass-GEMs (E_{DRIFT}=200 V/mm for min. electron diffusion)
- Transfer and signal induction gaps : 2 mm
- Low outgassing materials; vacuum before fill $2x10^{-6}$ mbar; vacuum unchanged several days after fill

Charge and Light readout



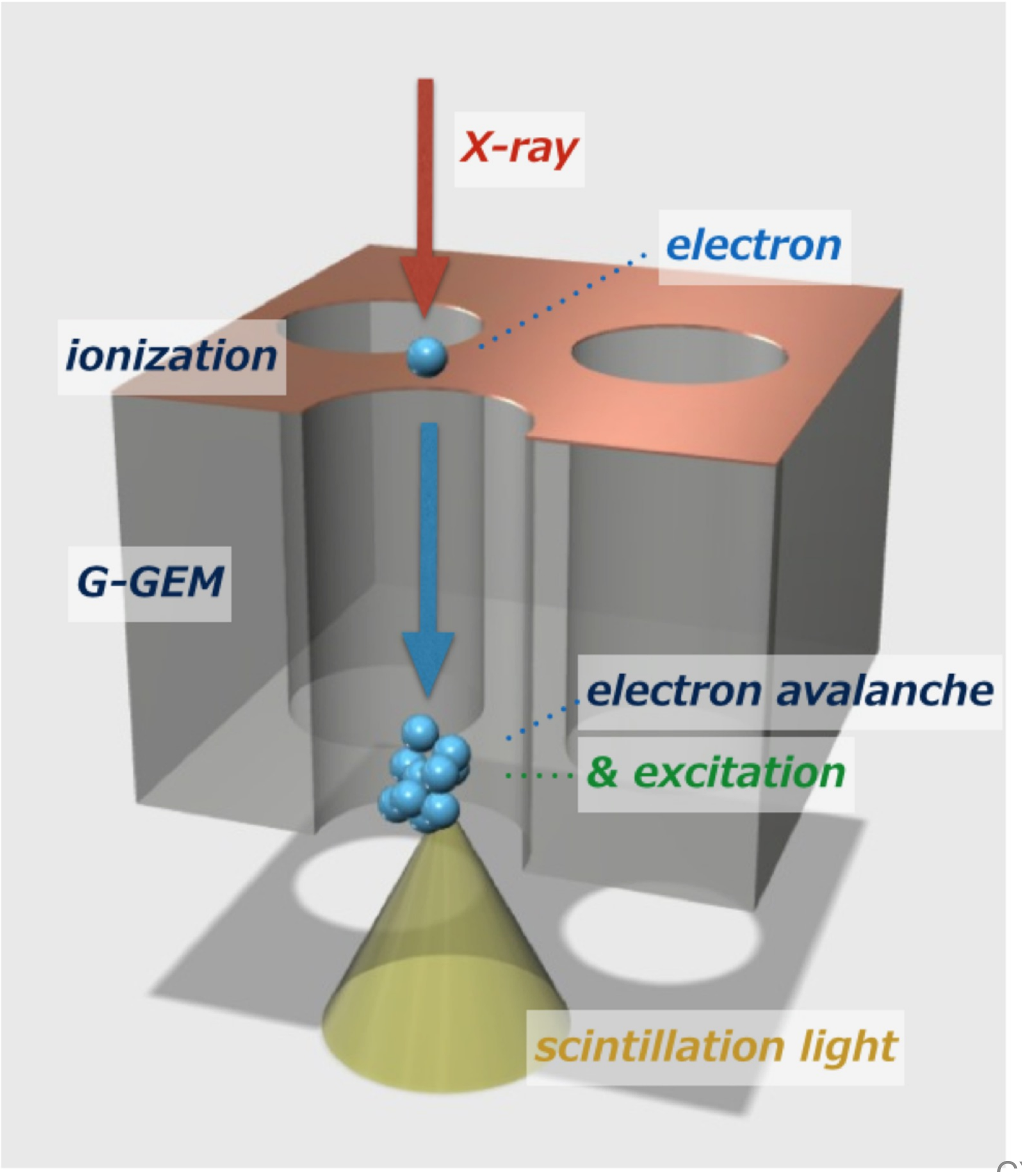


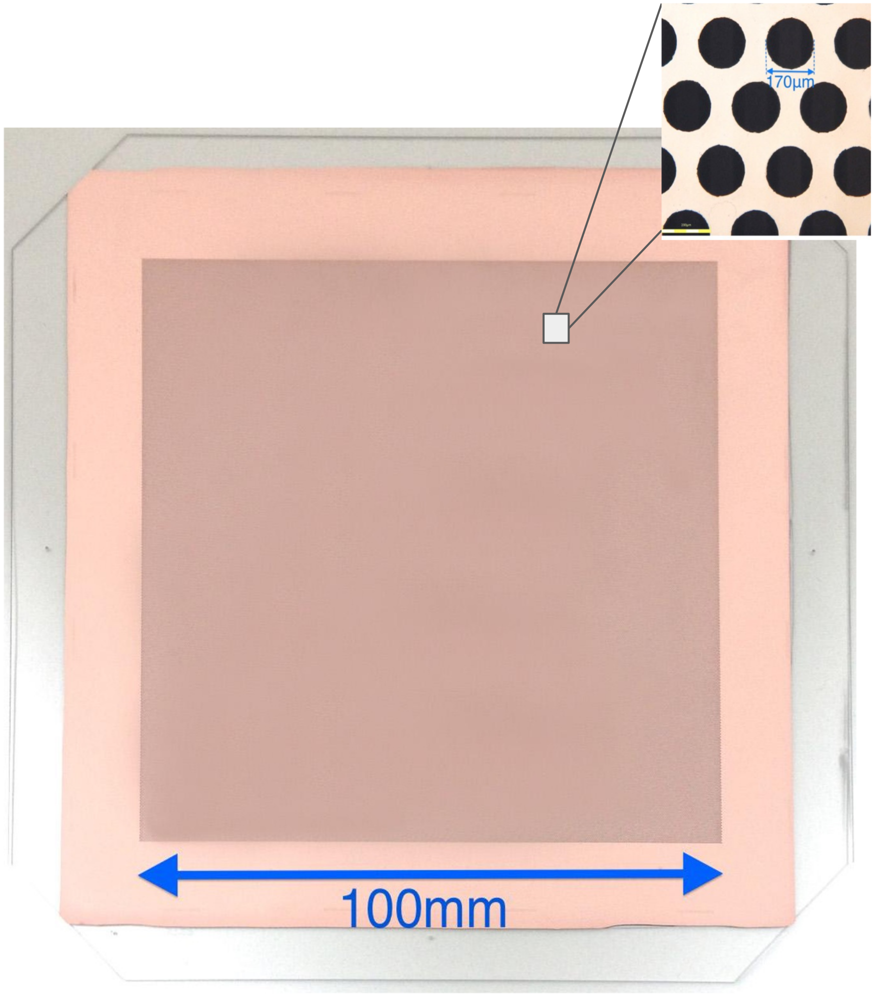
ITO anode strips
Post-GEM ionisation
Readout of (x,z) plane
Pitch: 833 μm
Digitised at 2 ns/sample
(Drift velocity: 130 μm/ns)

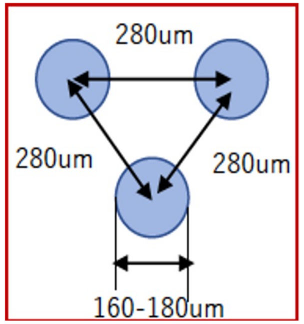
qCMOS camera
(Hamamatsu ORCA - QUEST)
GEM scintillation through
glass viewport behind ITO anode
Readout of (x,y) plane
Exposure: 8.33 ms/frame (~120 Hz)
(continuous)
Pixel scale: 39 μm (2 × 2 binning)
Lens: EHD-25085-C; 25mm f/0.85

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

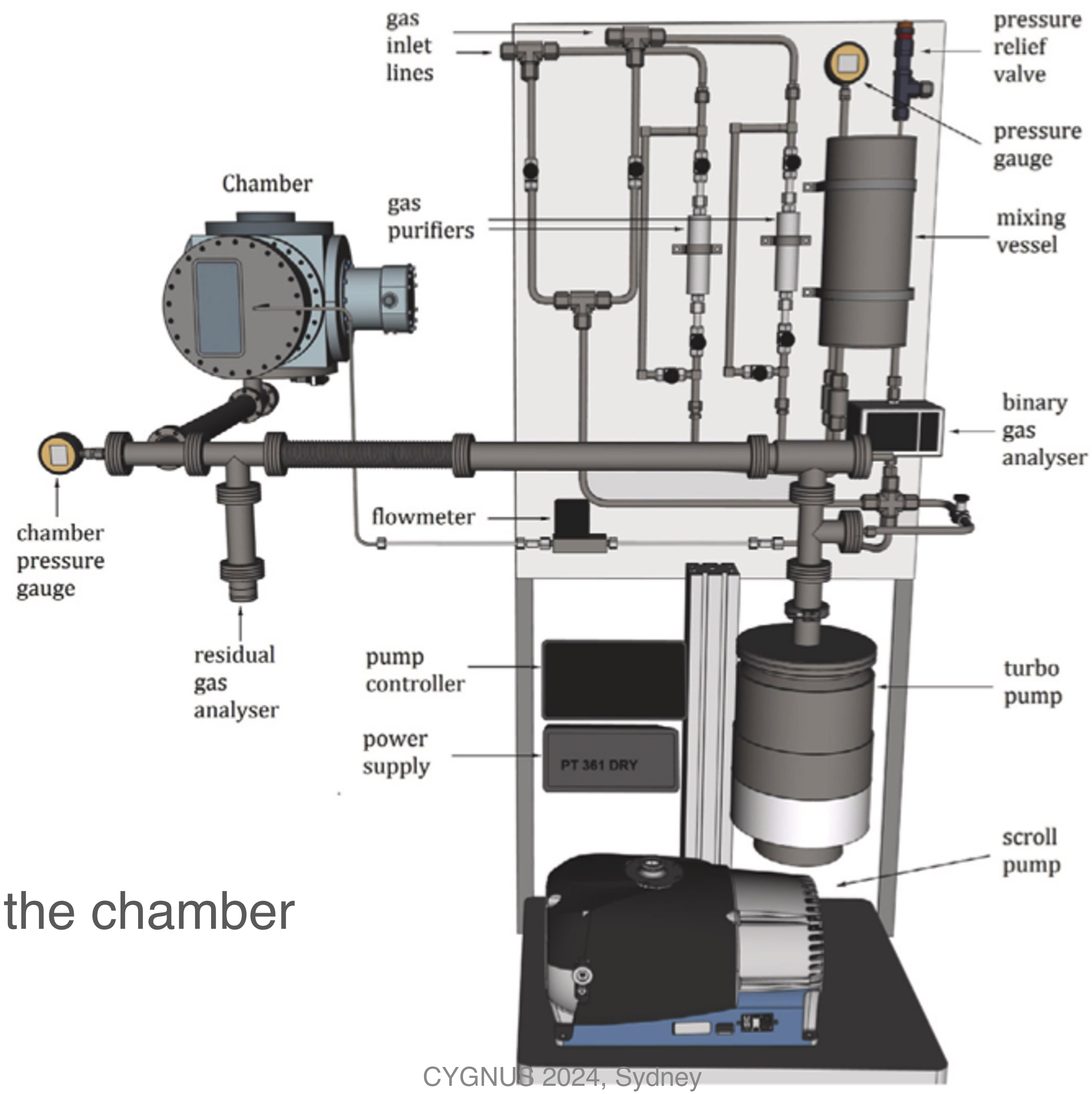






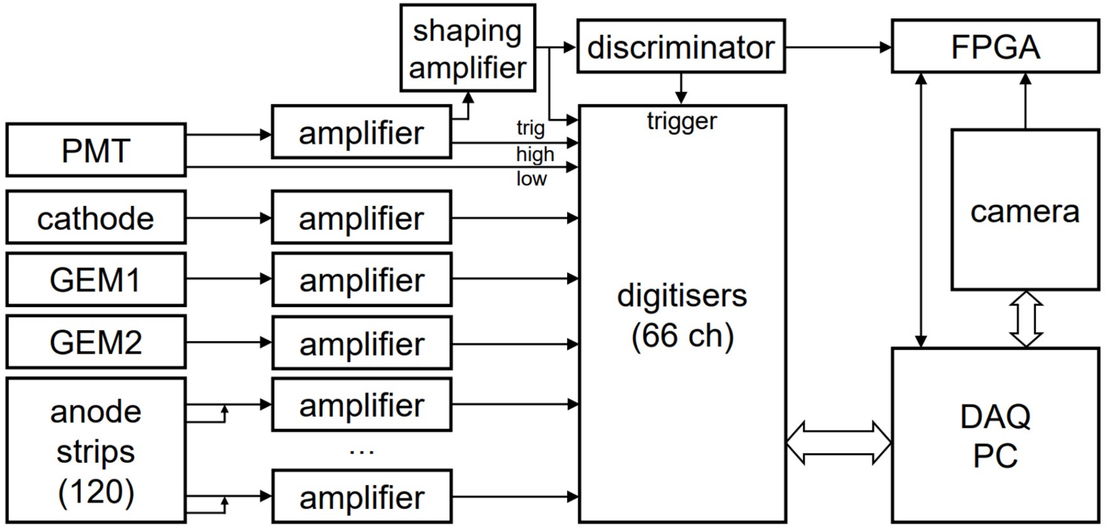
Glass thickness : 570 um

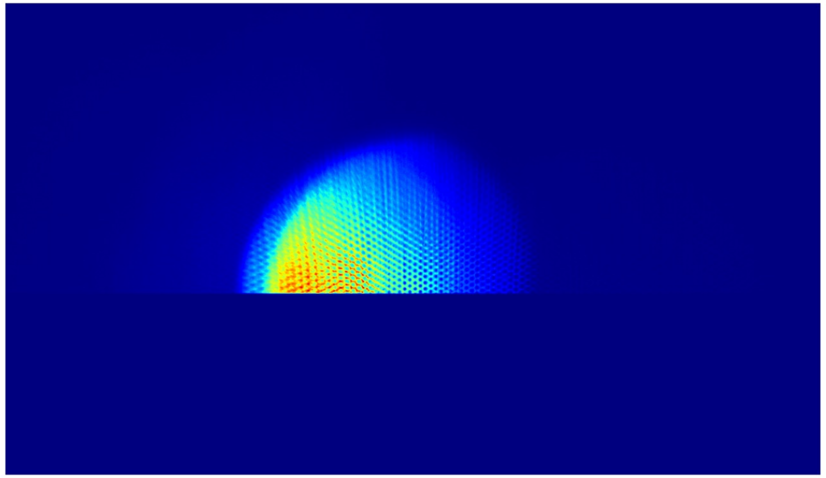
Gas System

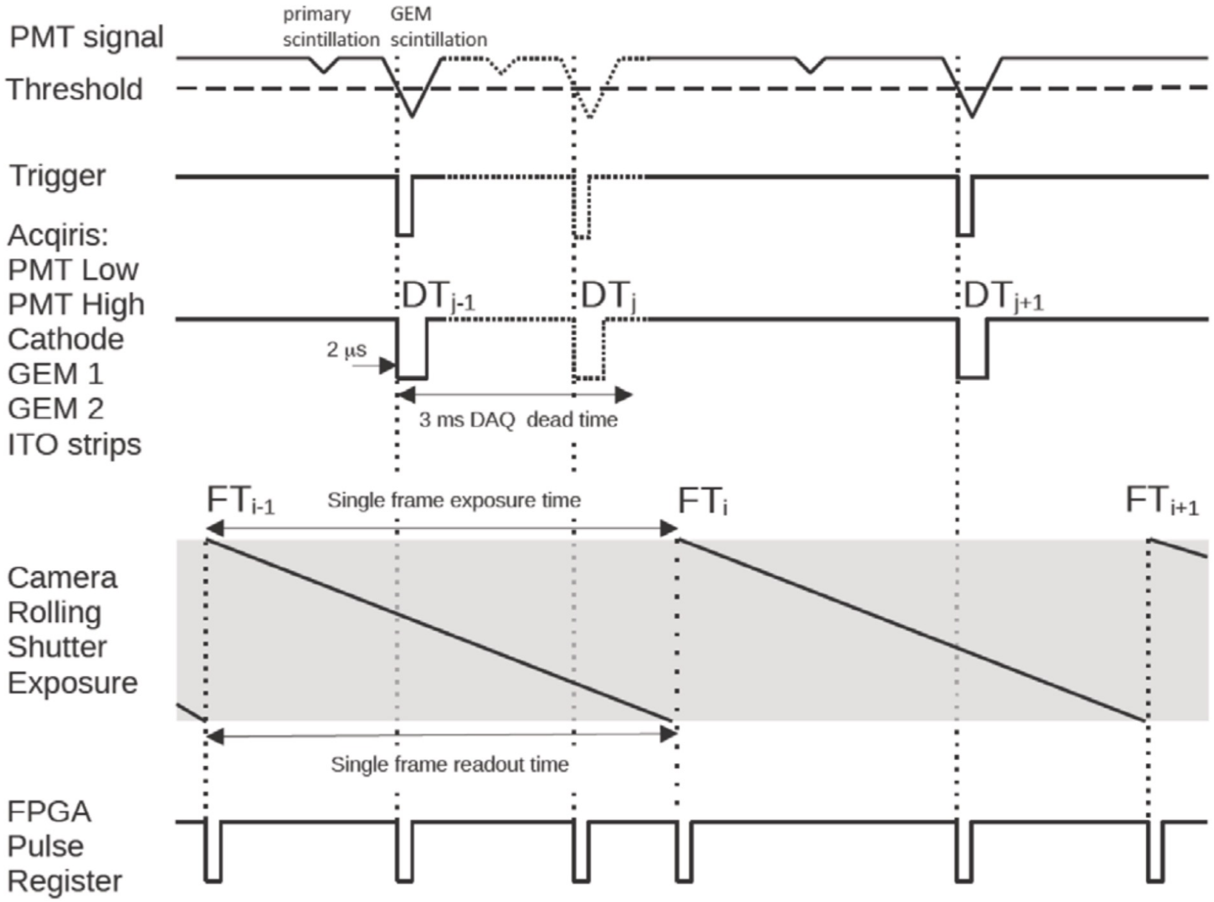


Initial vacuum in the chamber
~1E-06 mbar

DAQ





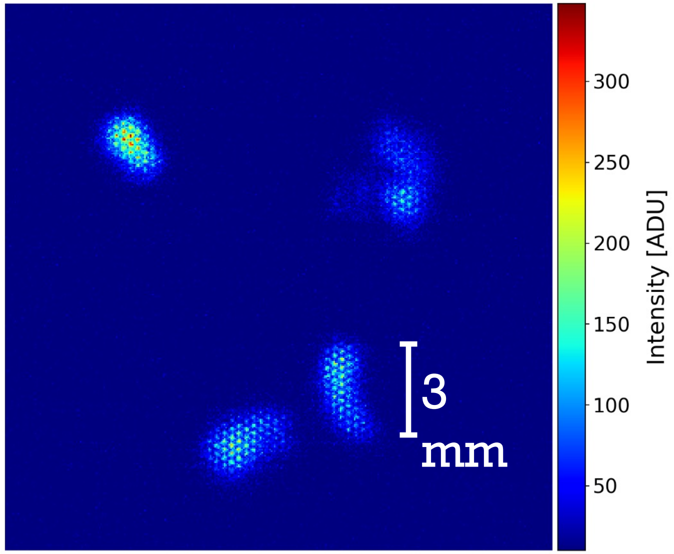


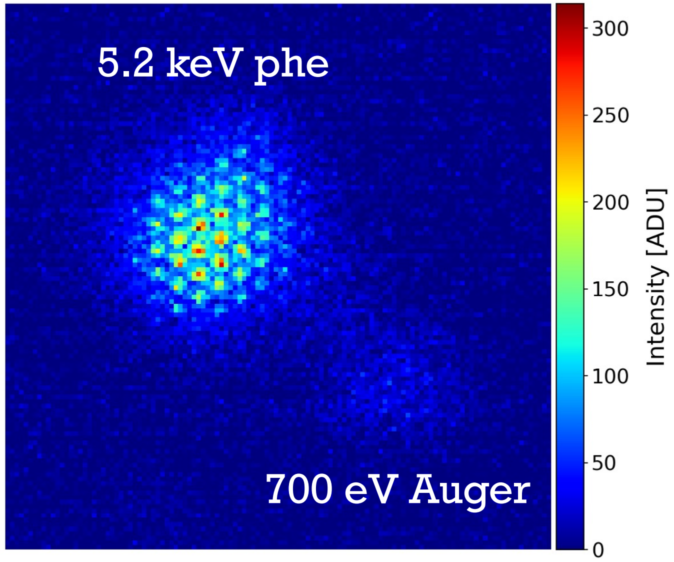
Synchronisation with LED pulse
Image cut due to a rolling shutter

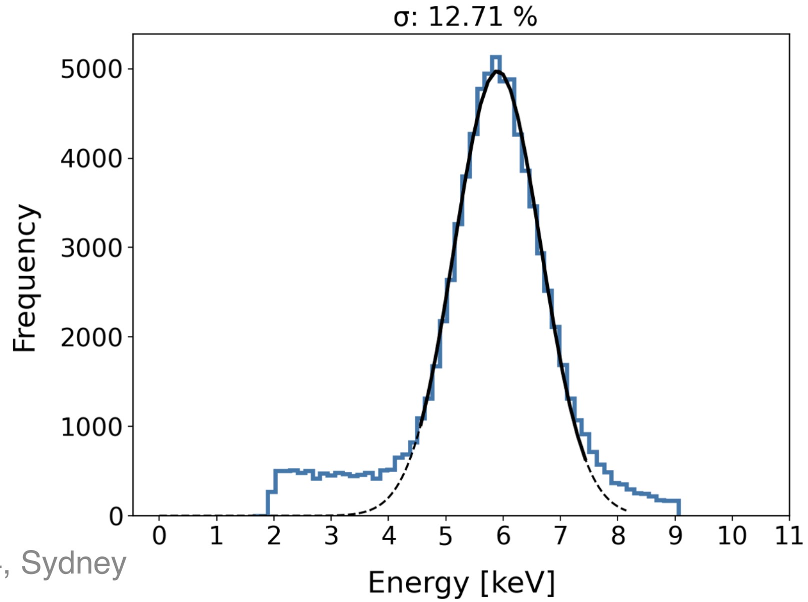
Pre-run Calibrations

Calibration with ^{55}Fe – Pure CF_4

- Tests were performed with ^{55}Fe (5.9 keV x-ray).
- The gain was maximum achievable with ^{55}Fe.
- Achievable energy resolution is excellent ($\sigma/\mu \sim 12.7\%$).
- Head & tail is clearly resolved.
- 700 eV Auger electron from fluorine is visible.

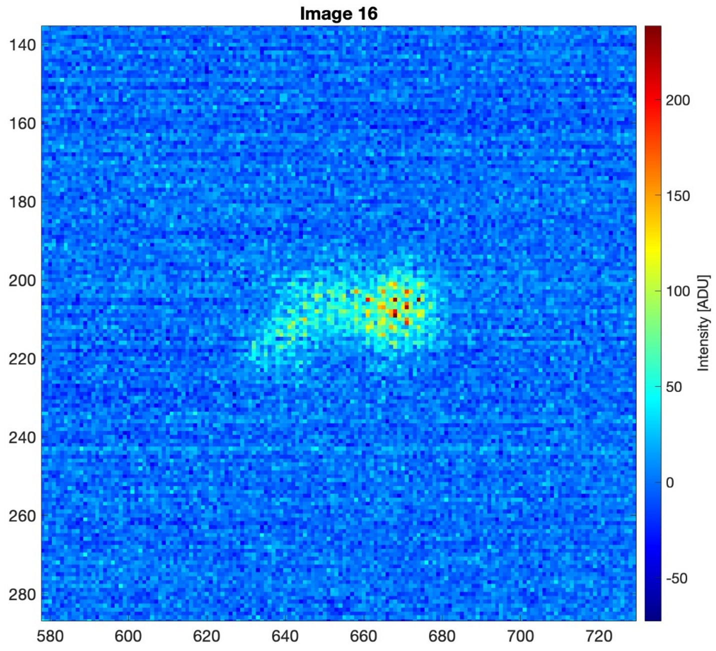


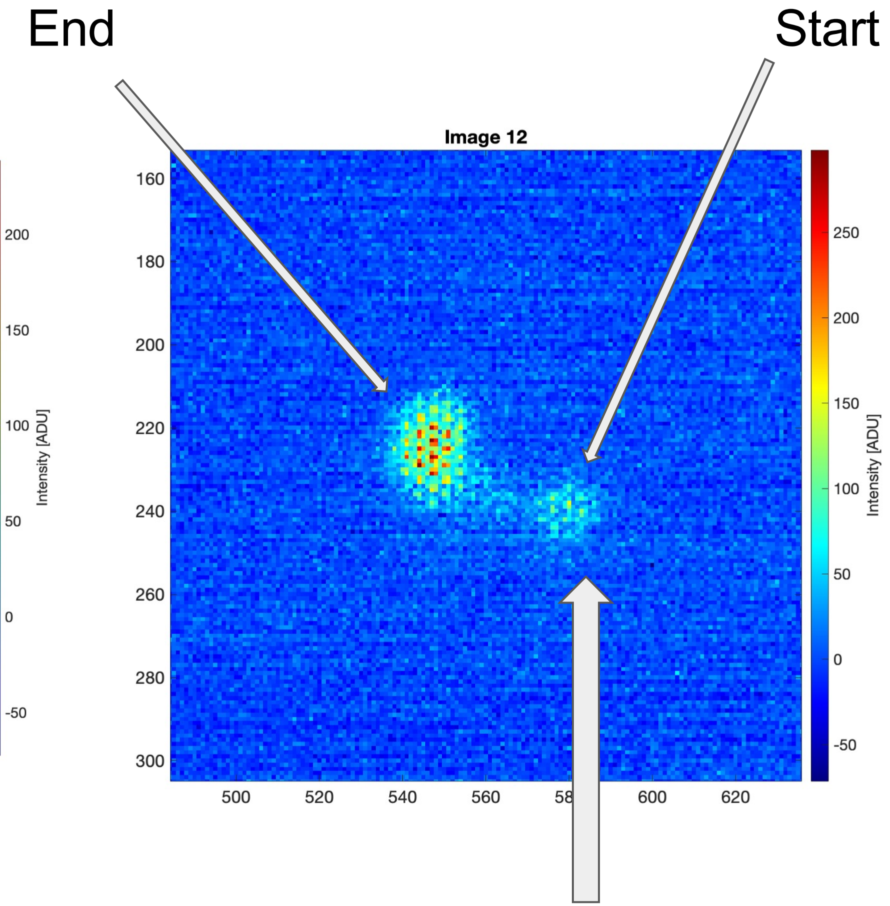


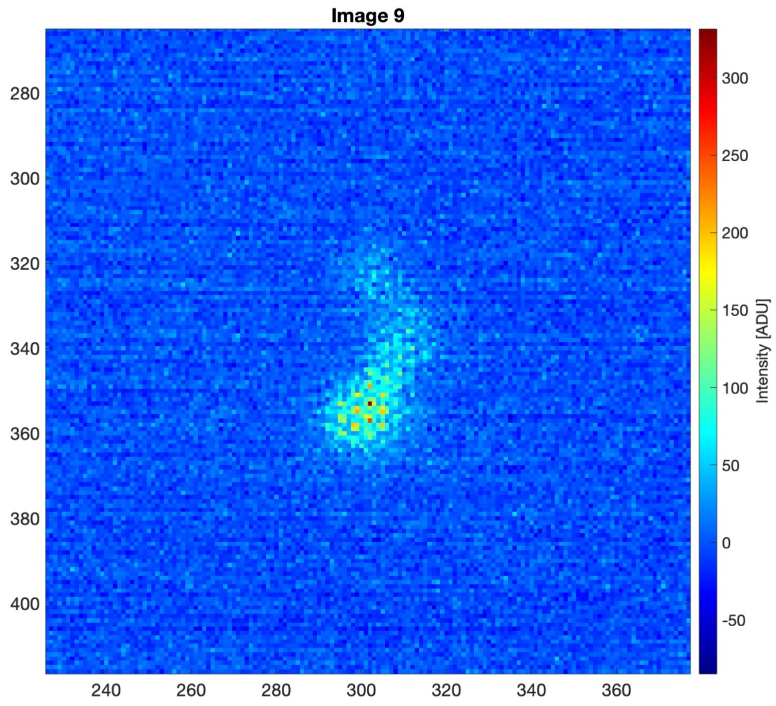


Example images from 5.9 keV X-ray conversions using Fe-55 source

5.2 keV electrons



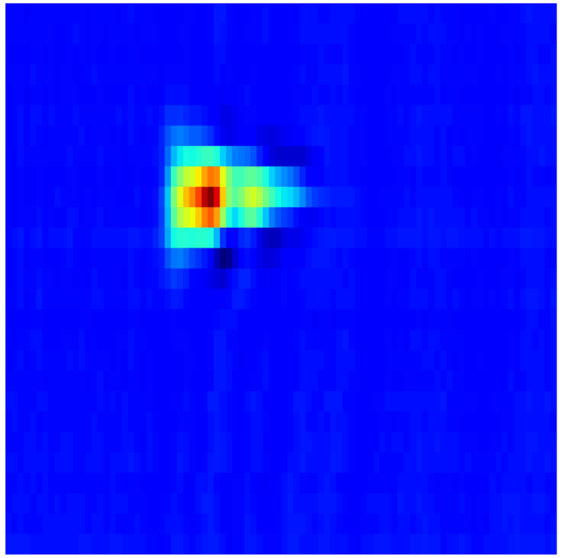


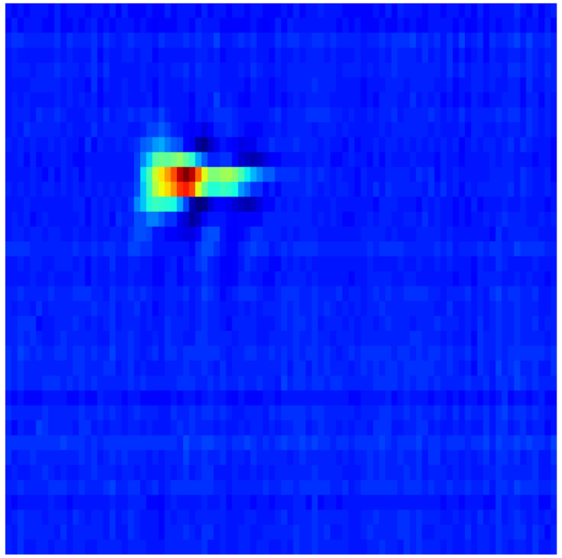


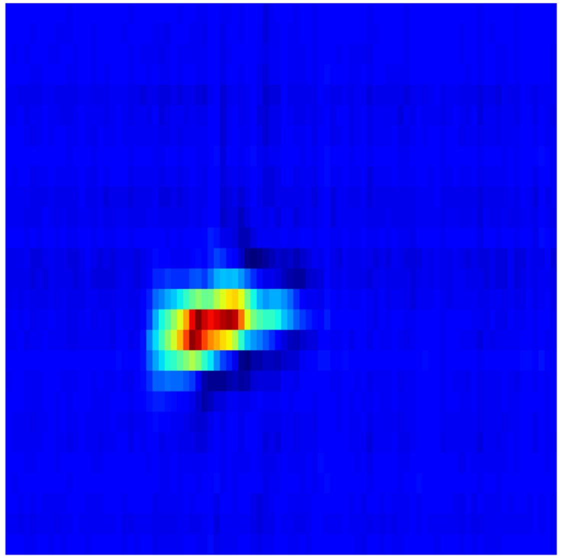
Extra charge at the start from
Fluorine 650 eV Auger Electron

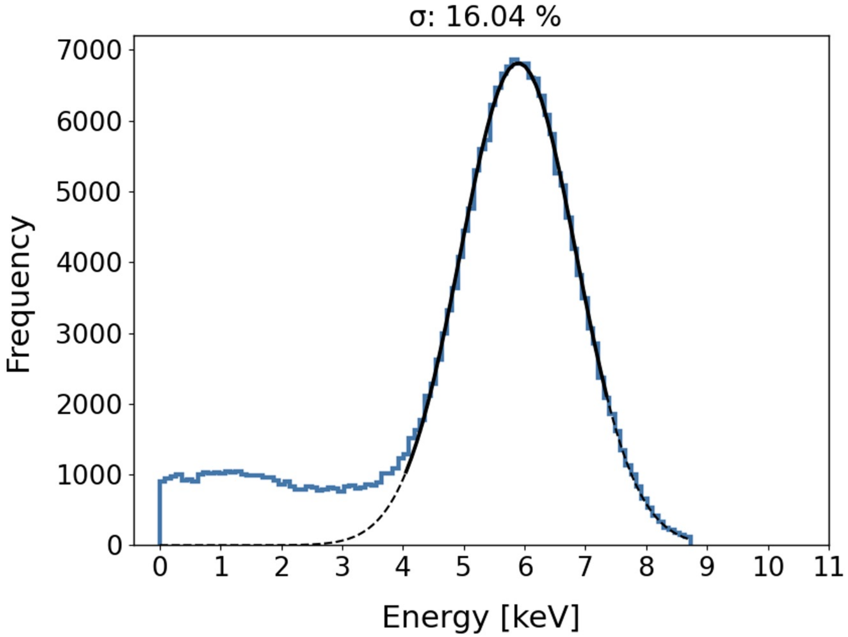
ITO (Pure CF_4)

- Very good signal to noise.
- Spatial resolution is not as good as camera (~0.83 mm pitch).
- Good energy resolution even with no flat fielding correction.
- Analysis of ITO images is ongoing, methods are still being refined.



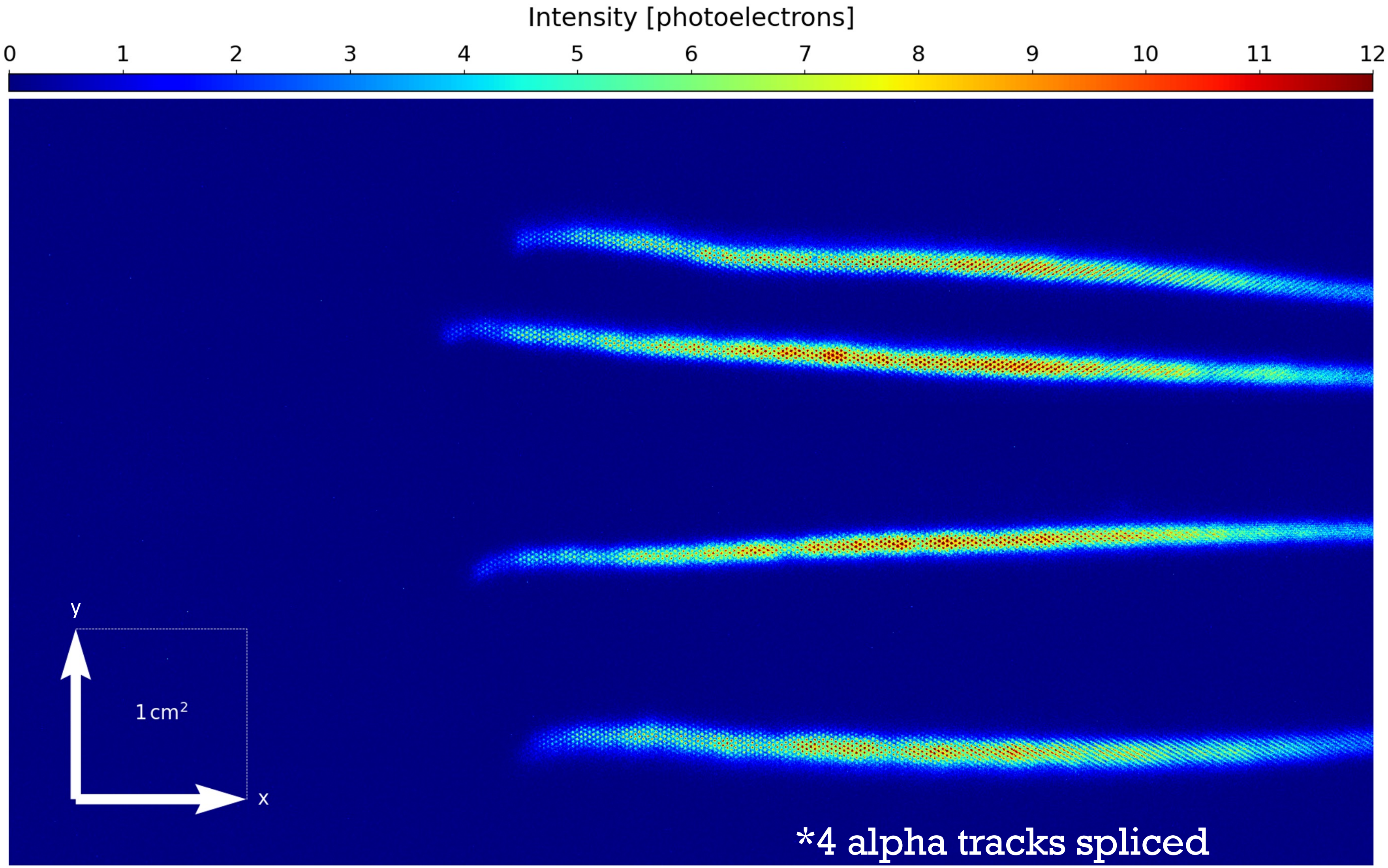






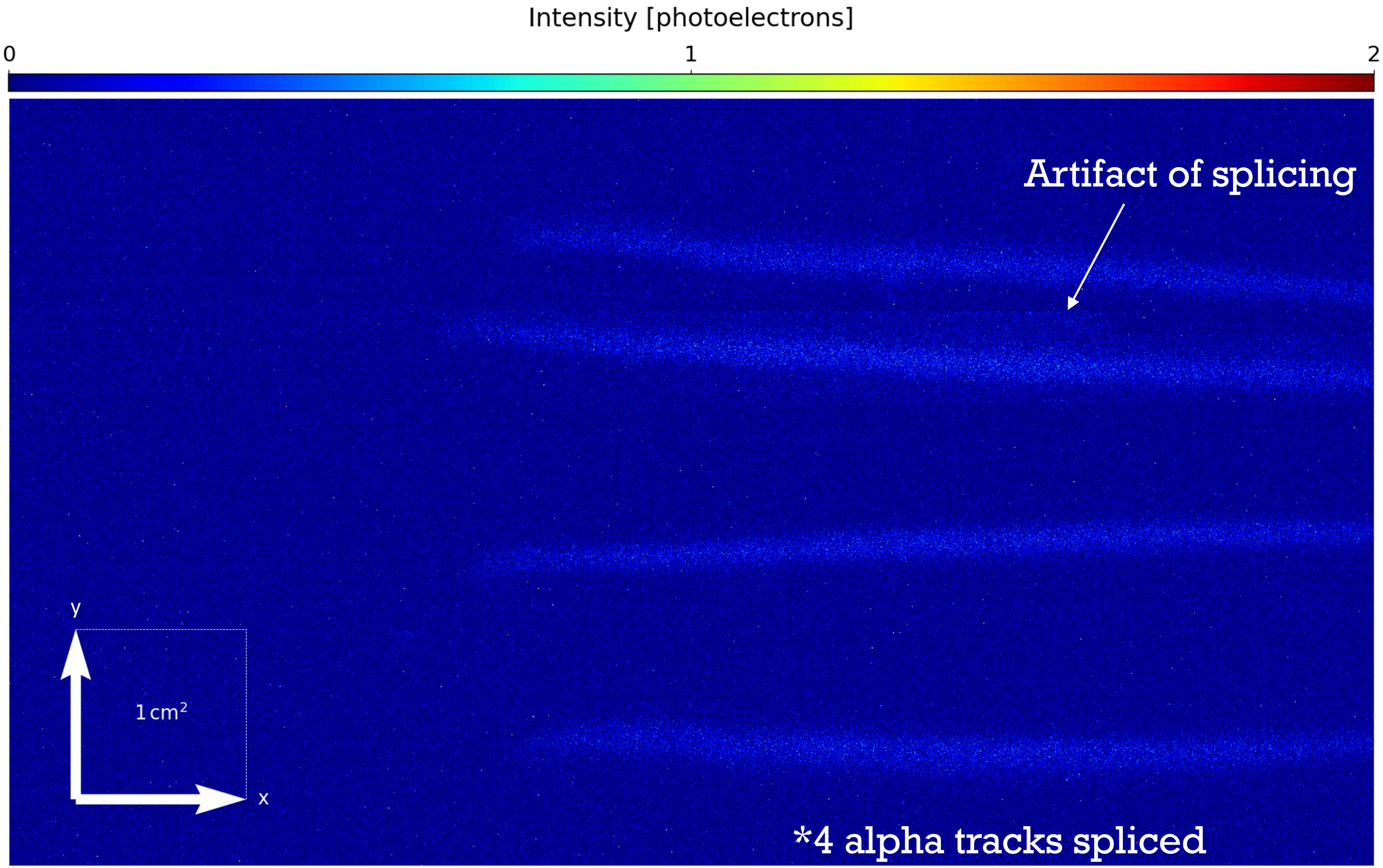
Alphas:

- Testing operational stability with 37 Bq ^{252}Cf source in 50 Torr CF_4.
- The new camera produces very good-looking images!
- The optical distortion and lens field curvature are visible towards the edges of the image.



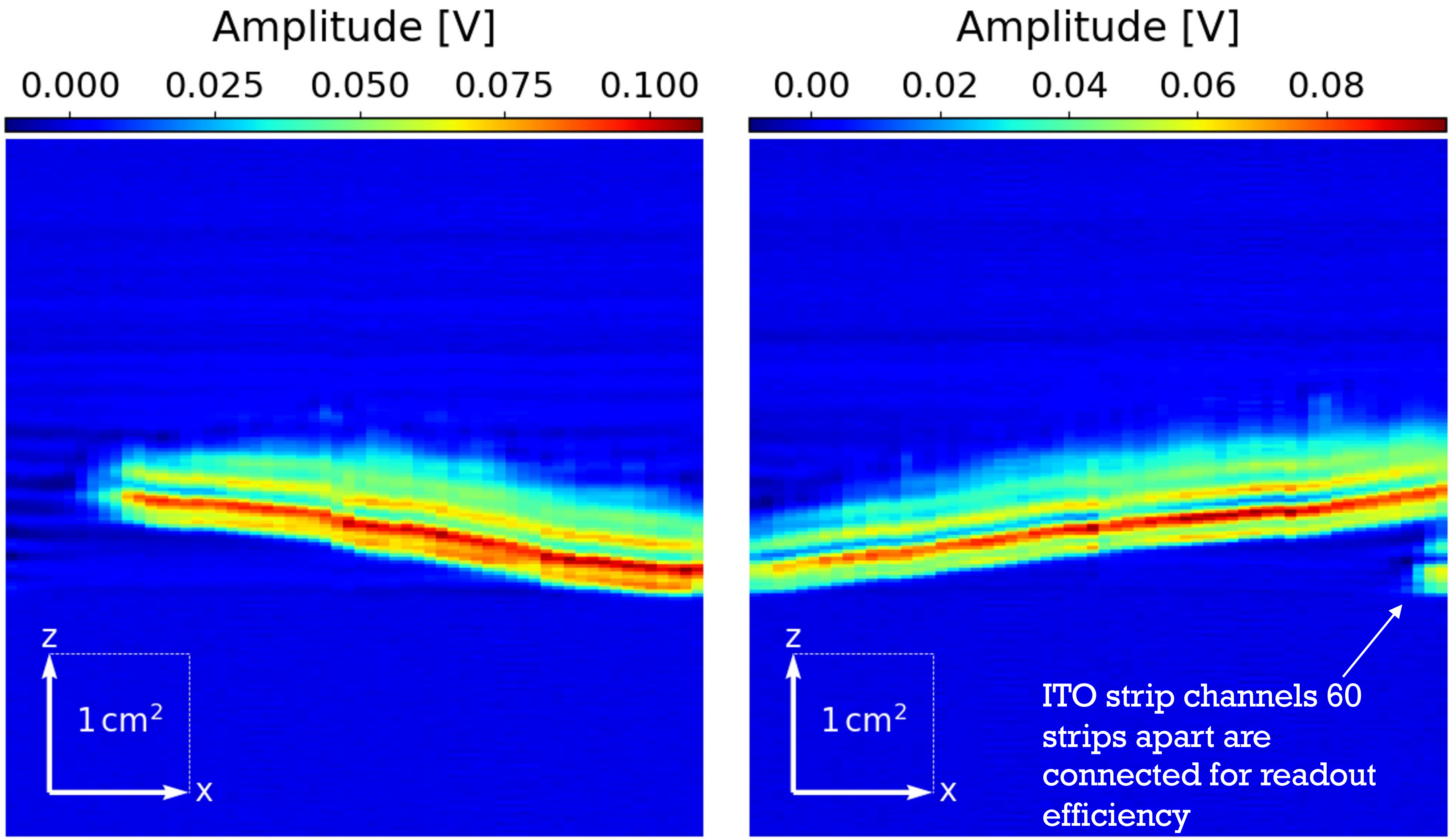
Afterglow (Ghosts!) with ORCA Quest

- In frames following alpha tracks (any bright track), we see an afterglow of ~1 photoelectron in many pixels.
- This does not seem to vary with exposure time.
- We are in contact with Hamamatsu.



Alphas in the ITO strips

- The signals from alpha tracks create a ‘ripple’ in the ITO strips. (under investigation)
- ITO strips 1 & 61, 2 & 62 etc. are connected. This is ok for nuclear recoils as no tracks will be longer than 5 cm.



First Science/Commissioning Run at NILE

NILE facility at RAL, UK

- NILE facility is at TS2, ISIS
- Chamber packed and moved from lab to NILE mid-May.

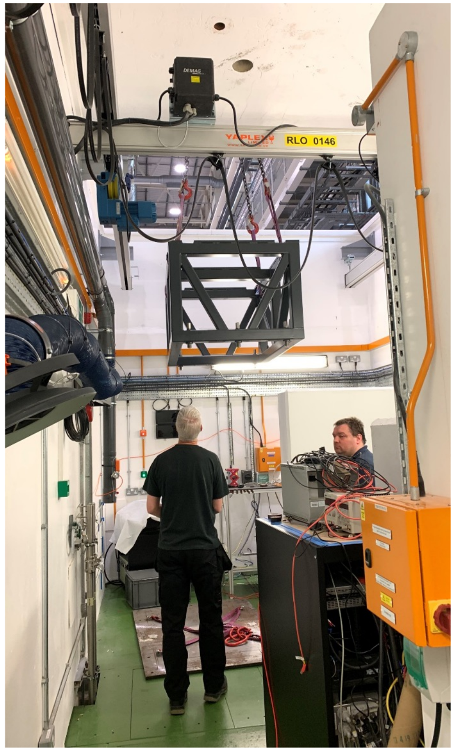
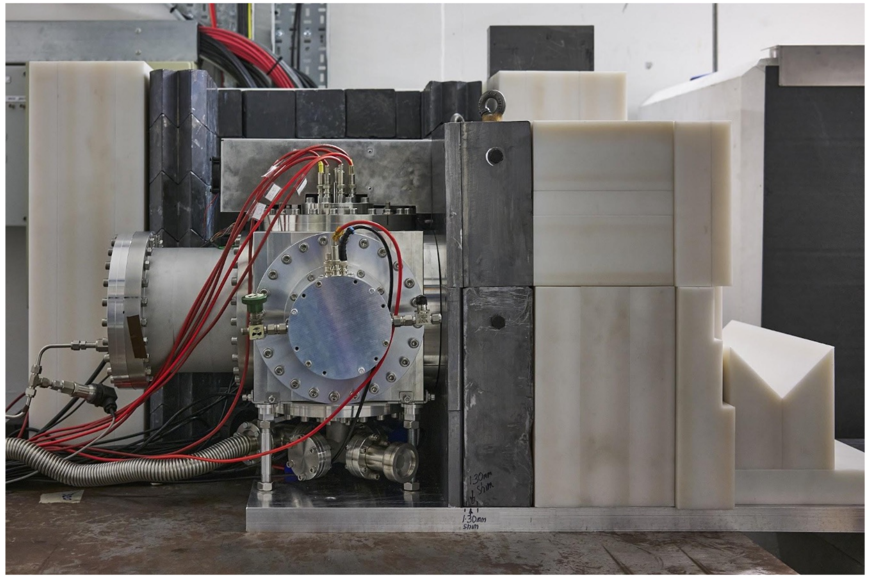
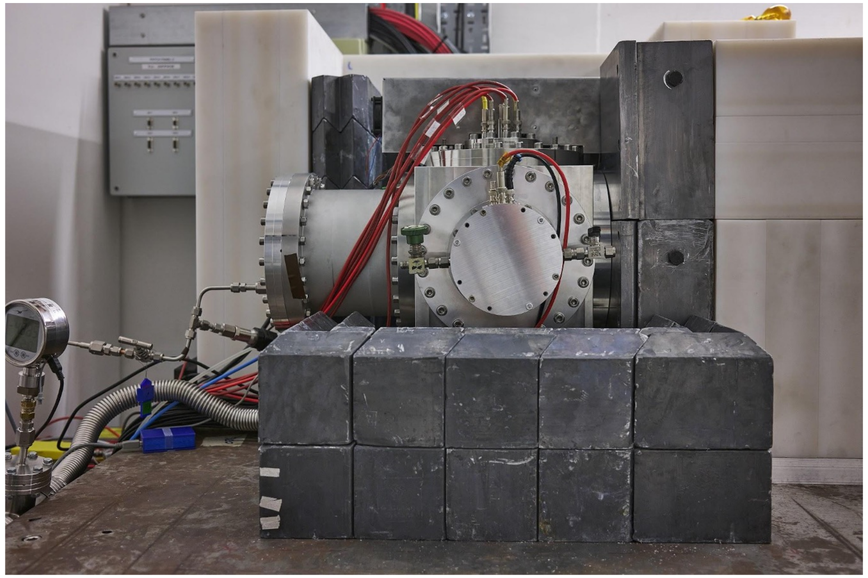


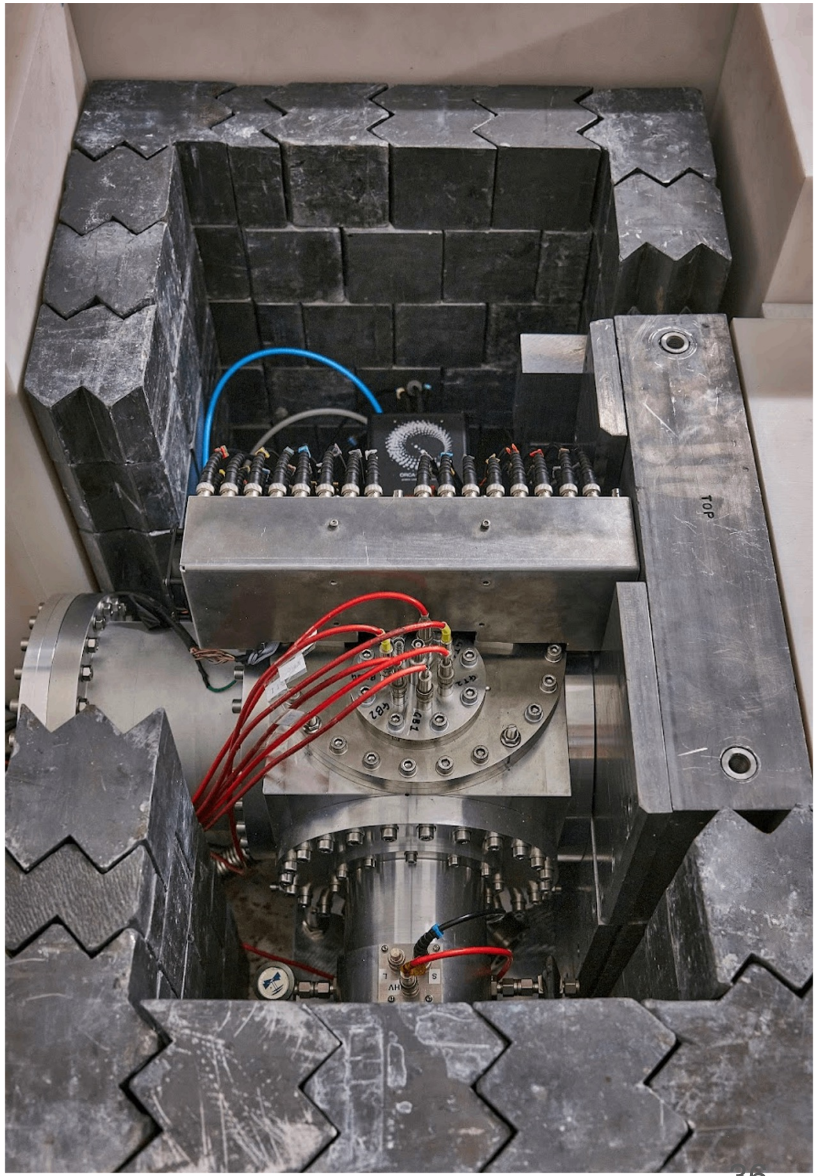
Table installed with lead under-shield

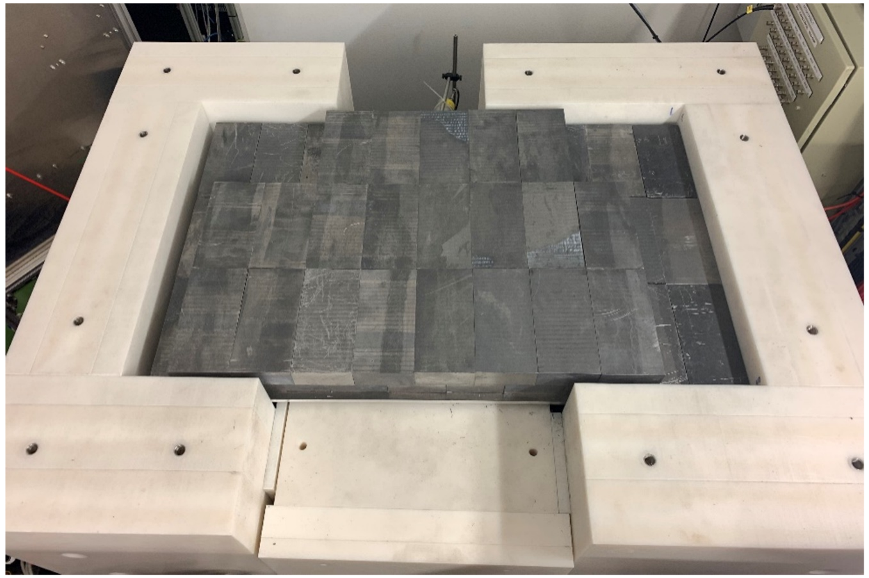
Chamber driven over to NILE

Assembling at NILE







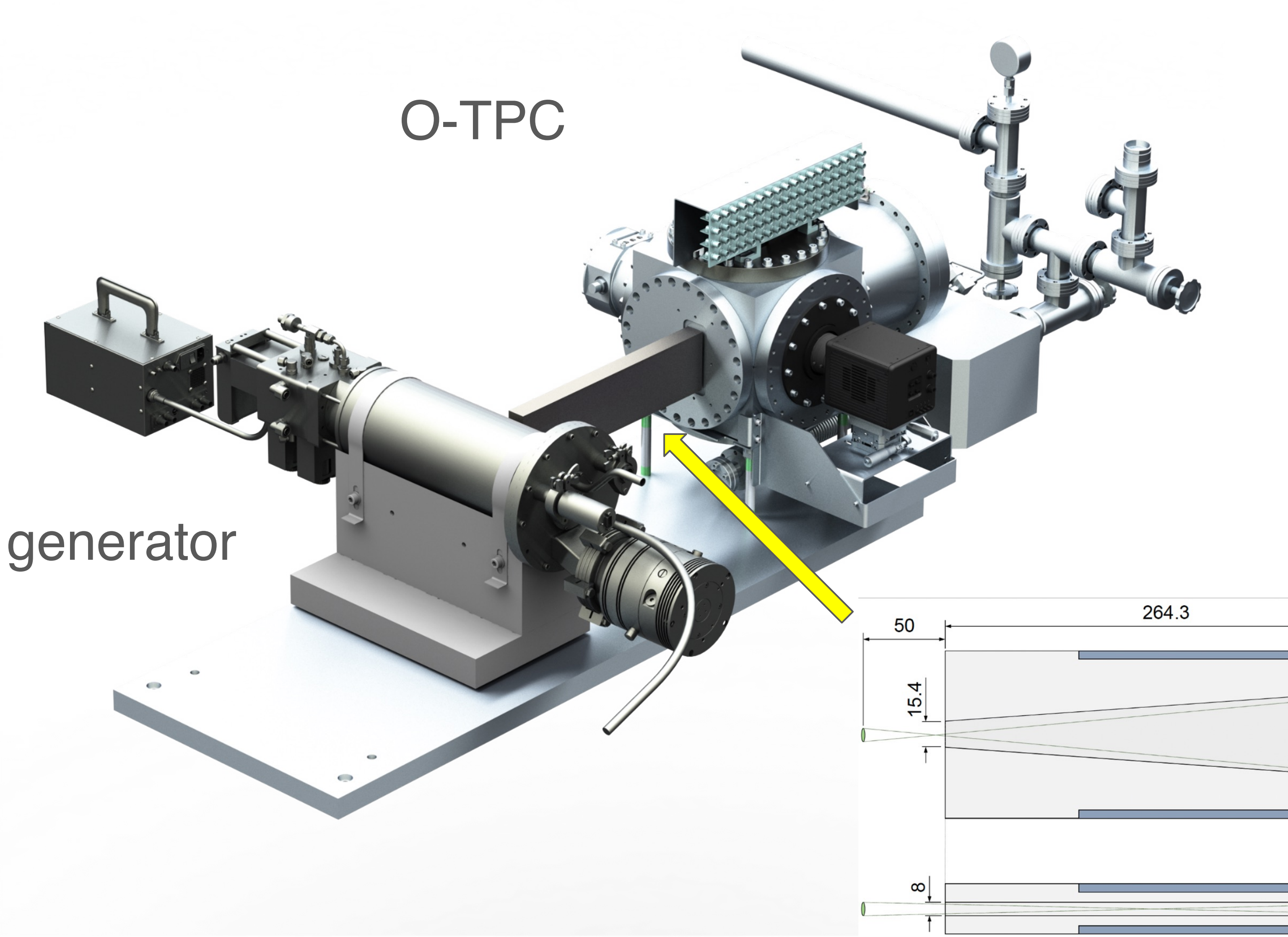


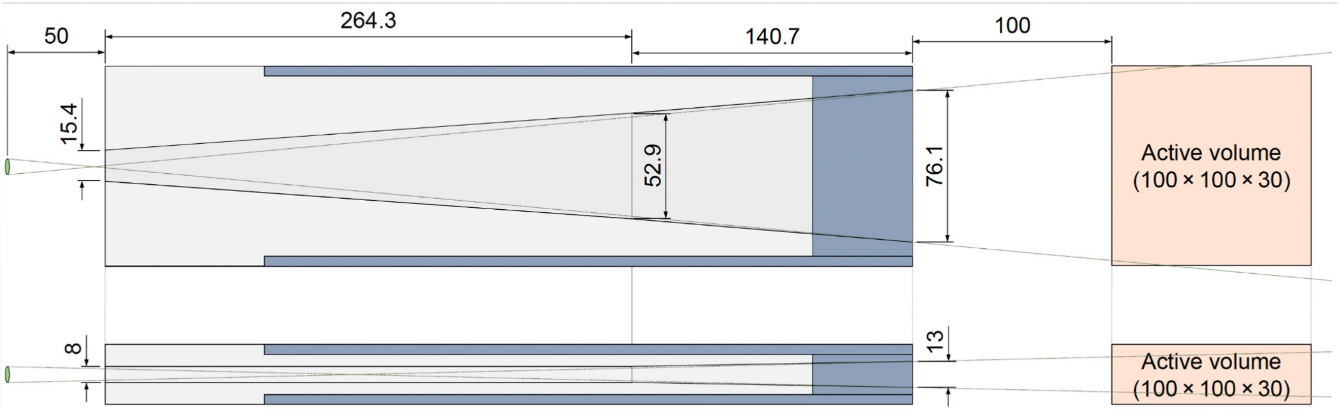
Assembling at NILE

To Gas System

O-TPC

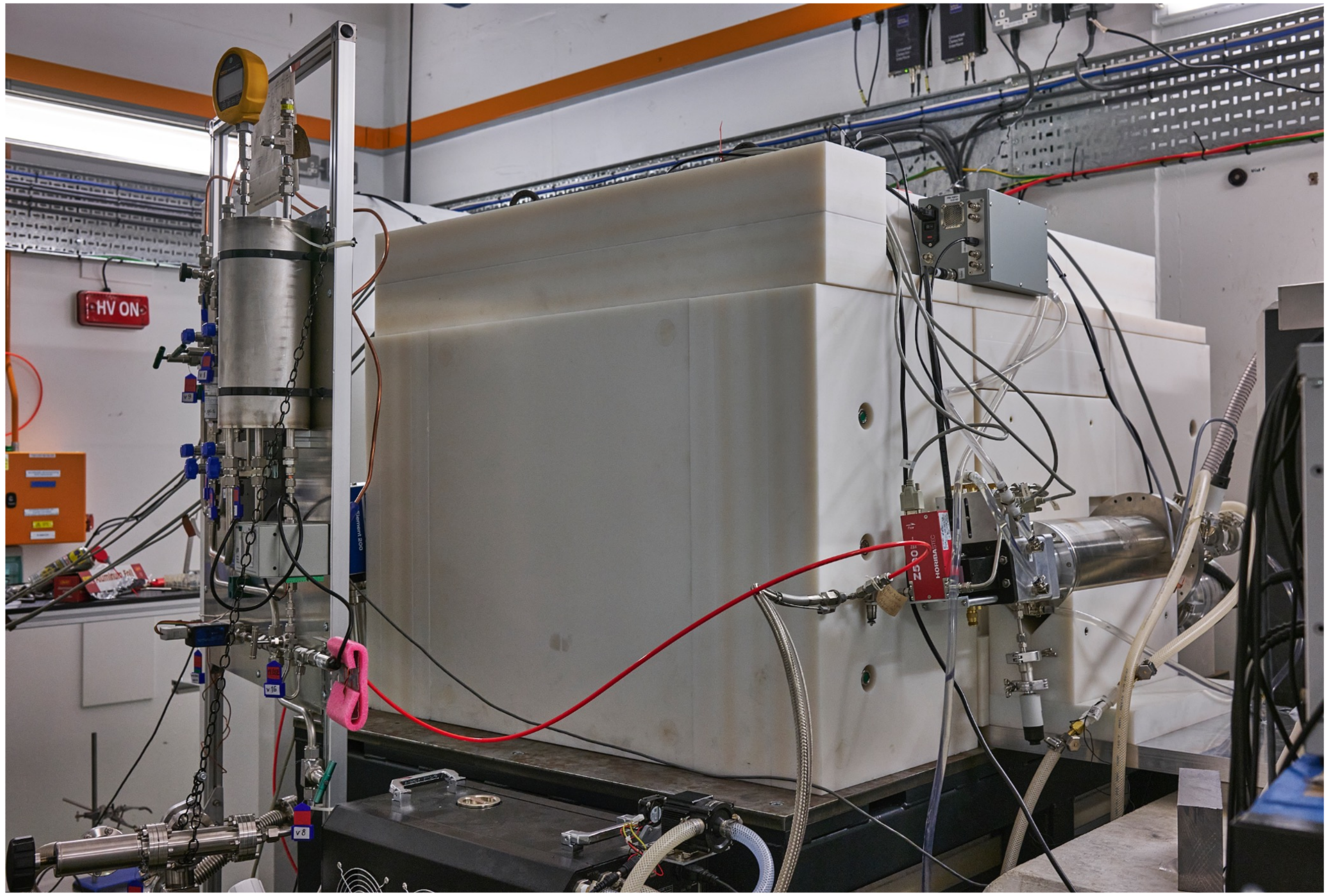
DD generator





30 cm long collimator

Experiment installation in the NILE bunker

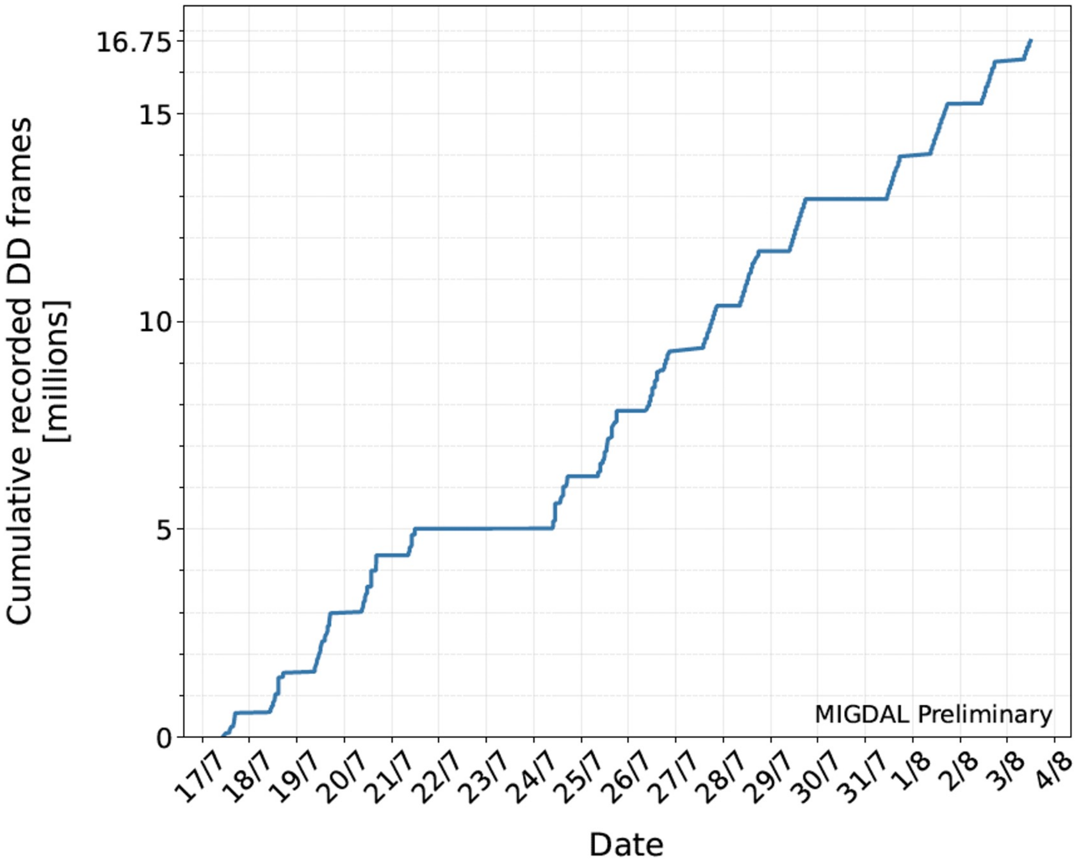


MIGDAL experiment fully assembled at NILE

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

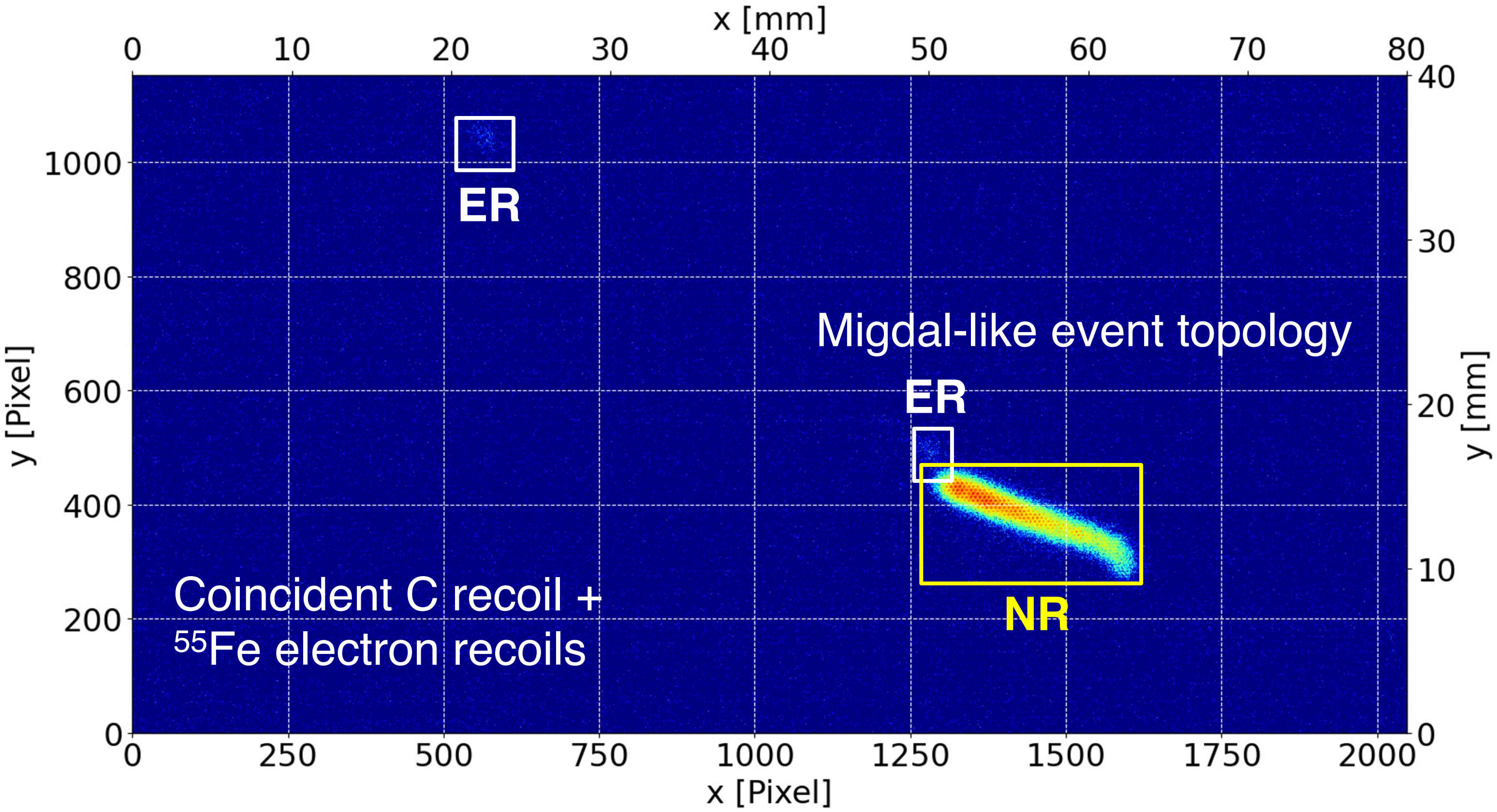
First Science Run – Summary

- **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. Longer than planned (8 ms) 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 keep 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 to cover high dynamic range.
- **Half the data is blinded.**



Real-time analysis 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



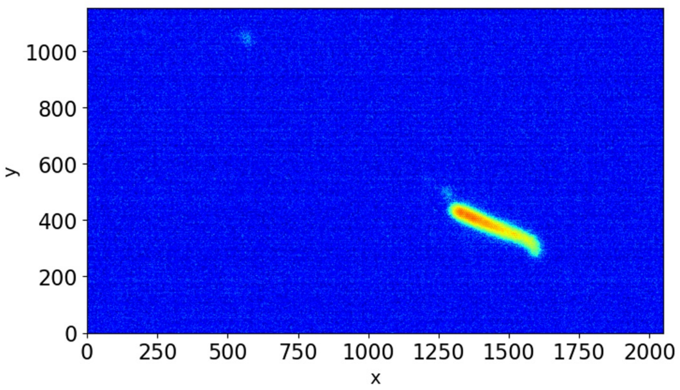
***We train YOLOv8 on measured data** to identify ERs, NRs, protons, alphas, sparks, camera afterglow, rolling shutter, etc.*

Benefits:

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

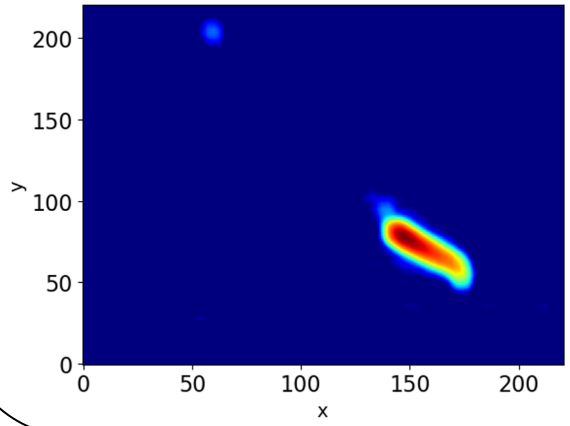
The data processing pipeline

(1) Dark subtracted image



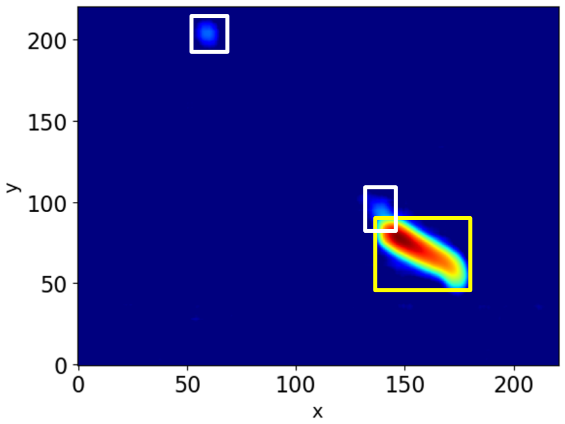
(2) Downsample

At this stage we train YOLOv8 by hand labeling bounding boxes



(3) YOLOv8 predicts bounding boxes

Retrain as needed



(4) Perform analysis on each bounding box, computing qtys such as: Intensity, track length, angle (with head/tail), bounding box centroid

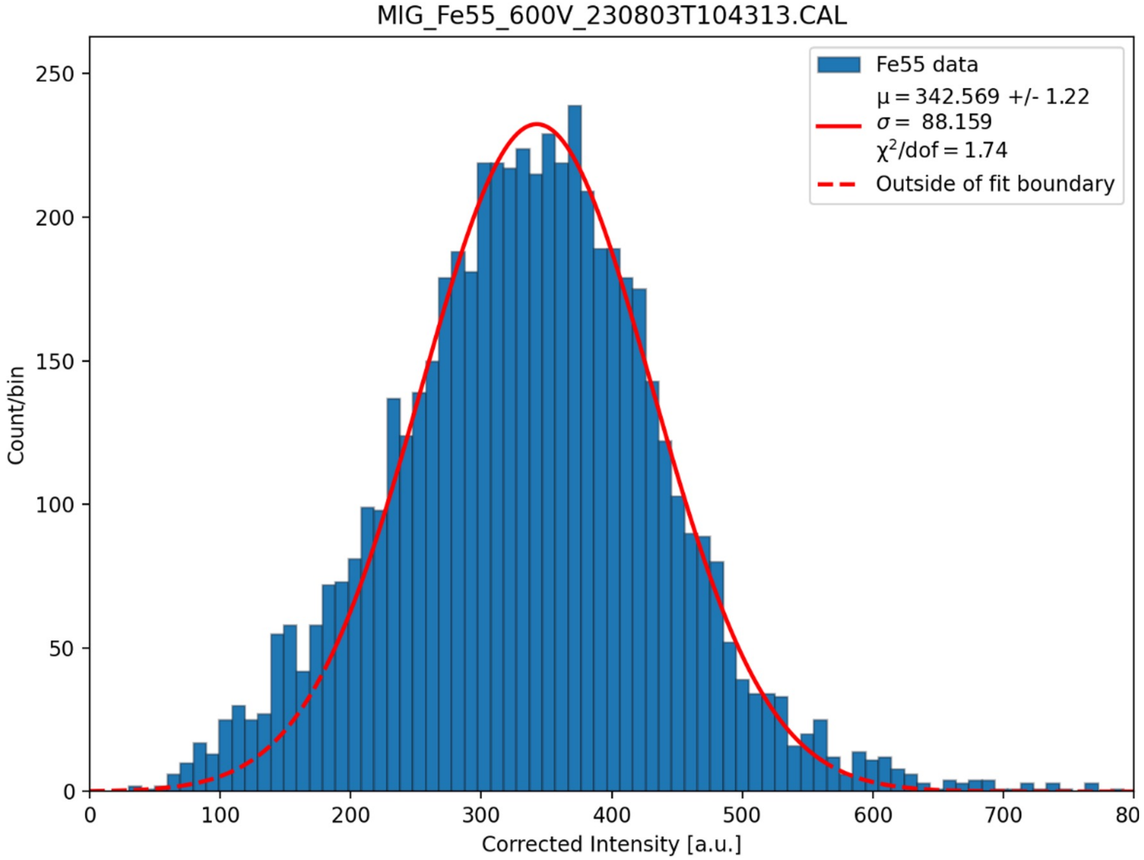
(5) Save coordinates of each bounding box, as well as extracted physics information

This entire pipeline reduces data size by a factor of ~5,000, runs at 200 fps on a consumer desktop GPU, and is integrated with the MIGDAL DAQ

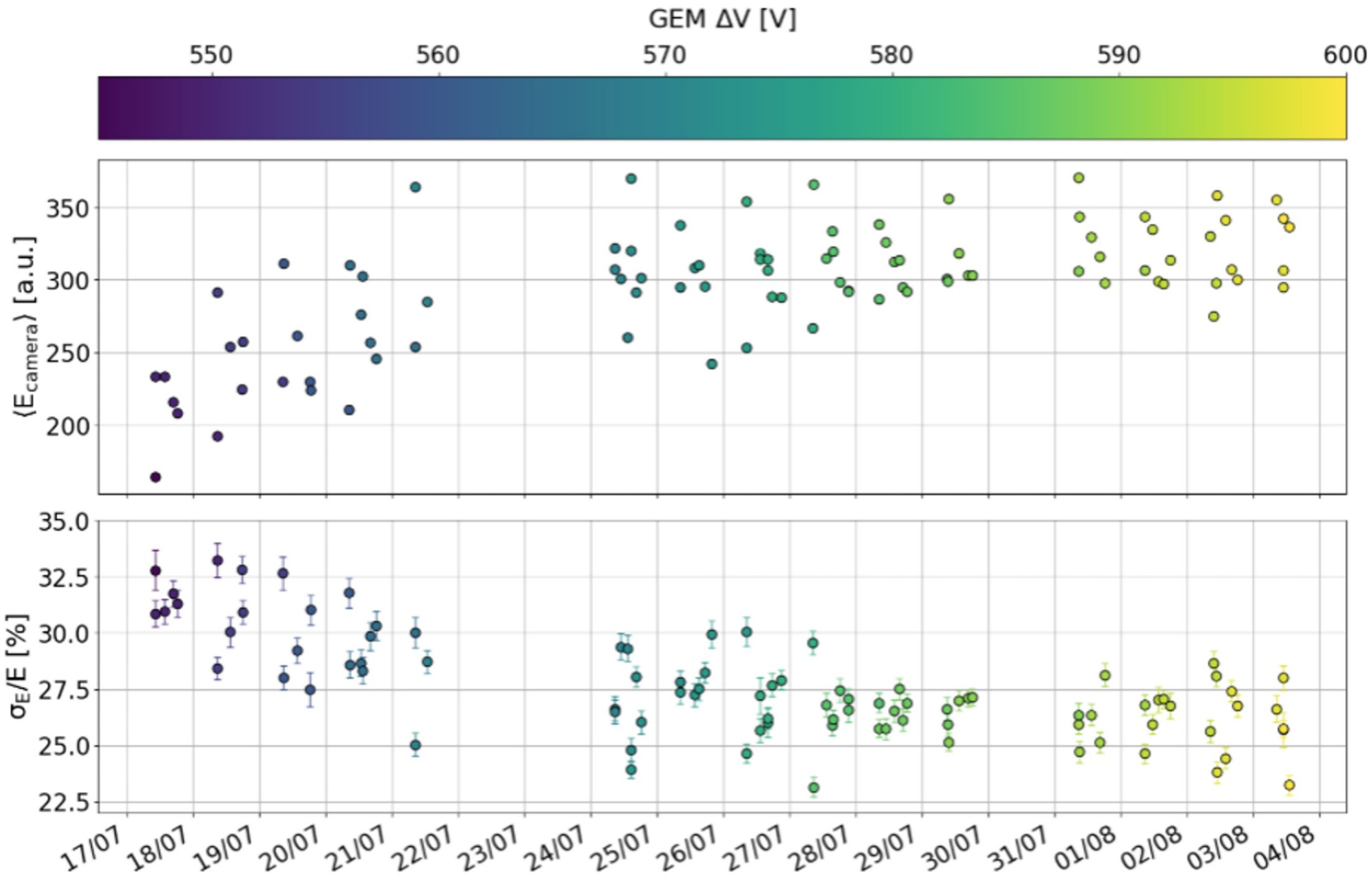
→ Real time feedback!

Real-time gain calibration with YOLO

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

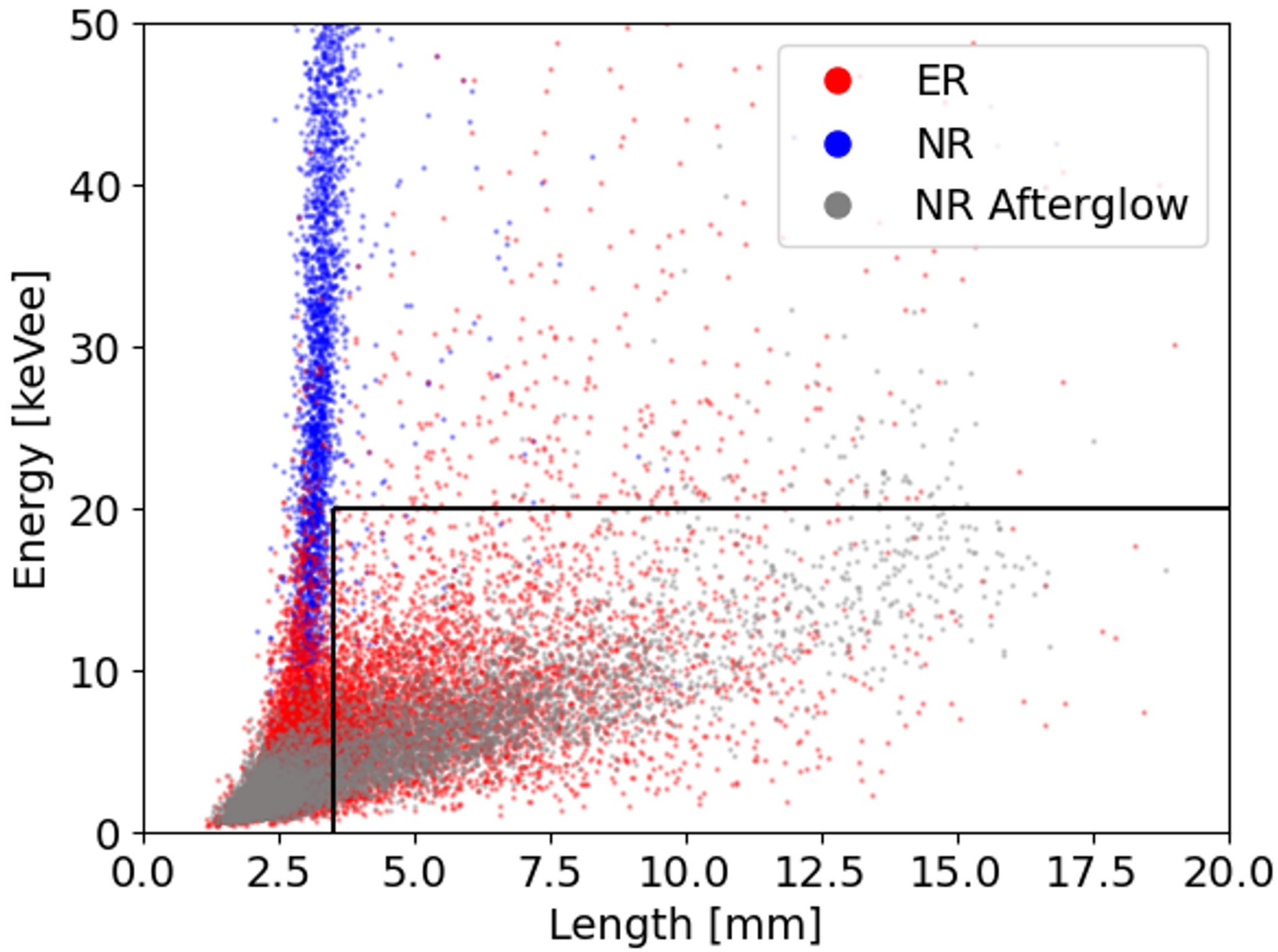


Summary of gain and gain resolution over the course of our science run from July 17th - Aug. 4th, 2023



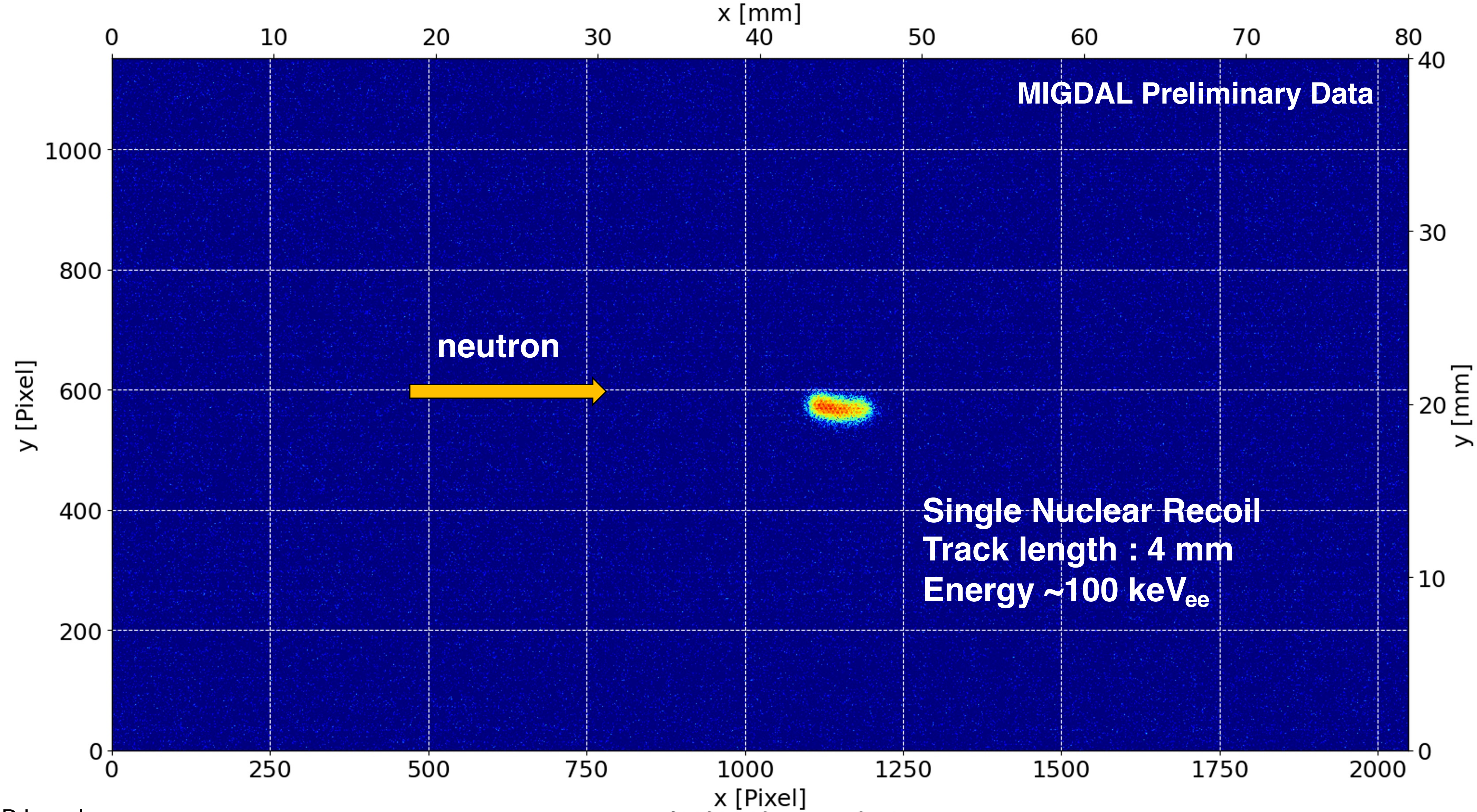
D Loomba

Real-time E vs R2 from YOLO



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

Example events - single Nuclear Recoil

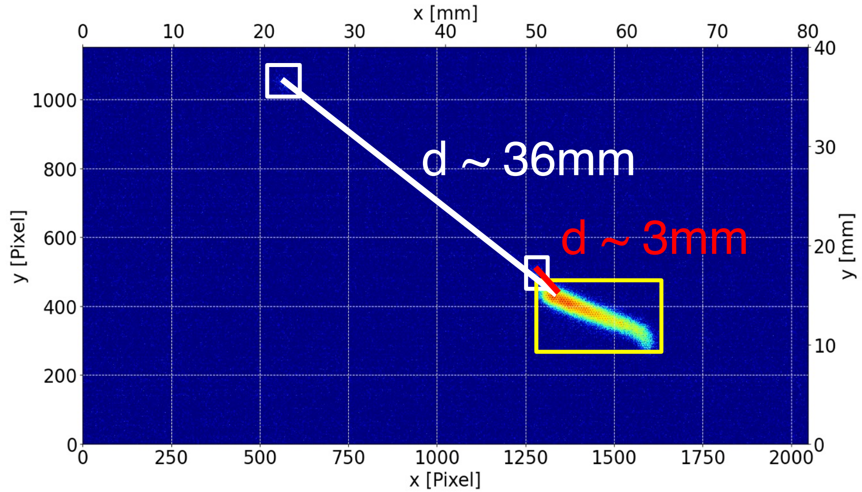


YOLO applied to Migdal search

- Initial science run recorded from July 17th 2023 - August 4th 2023
- Collected an unblinded dataset consisting of 10 million 2,048 x 1,152 images

(1) Initial sample of ***(10 million frames)***

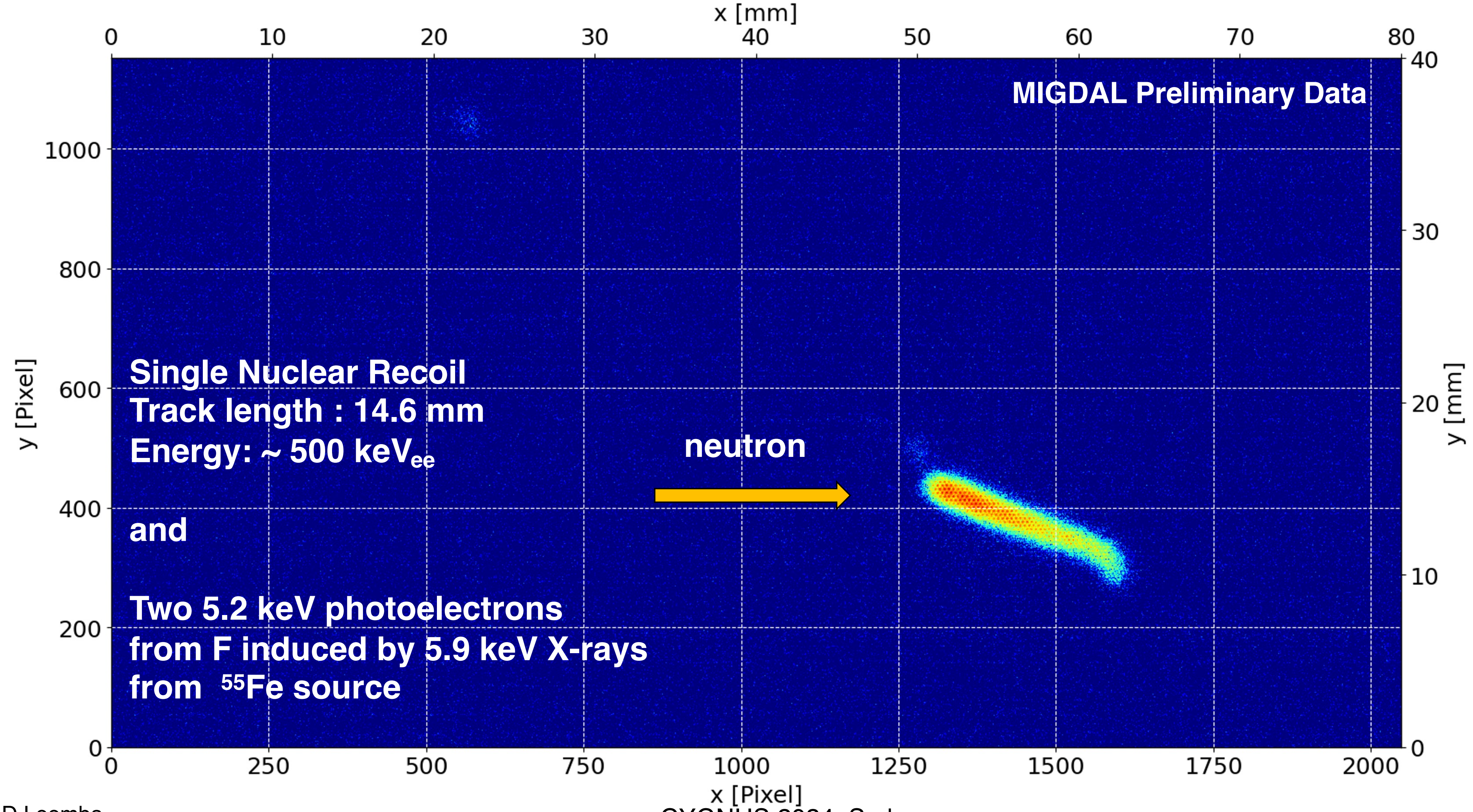
(2) Find frames containing at least 1 overlapping ER/NR ***(~16,000 frames)***



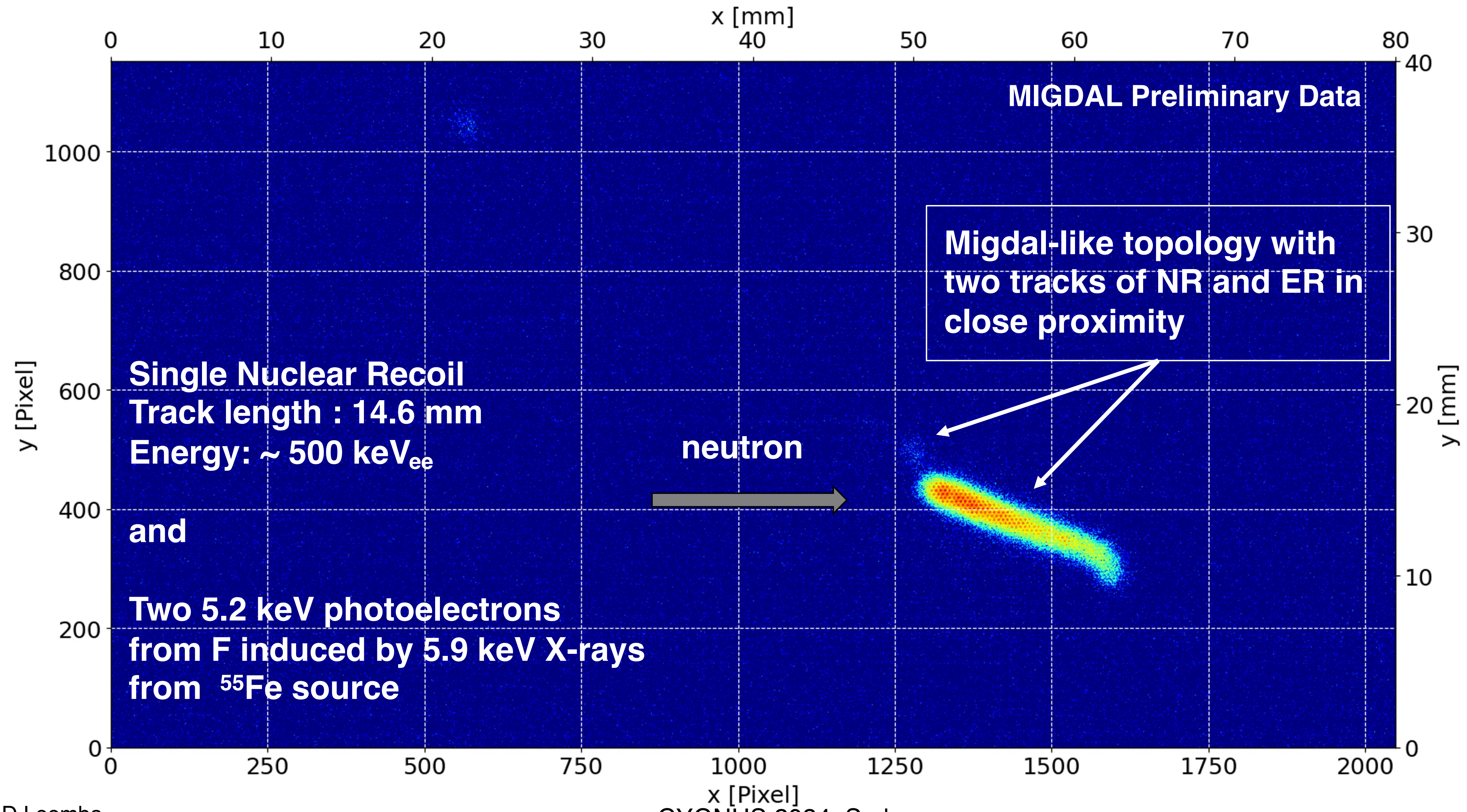
(3) Filter frames based on other criteria ***(~1,500 frames)***

YOLOv8 bounding box analysis takes us from 10's of millions of frames to a few 1000 frames → No longer a rare event search! We can use other techniques to optimize signal purity

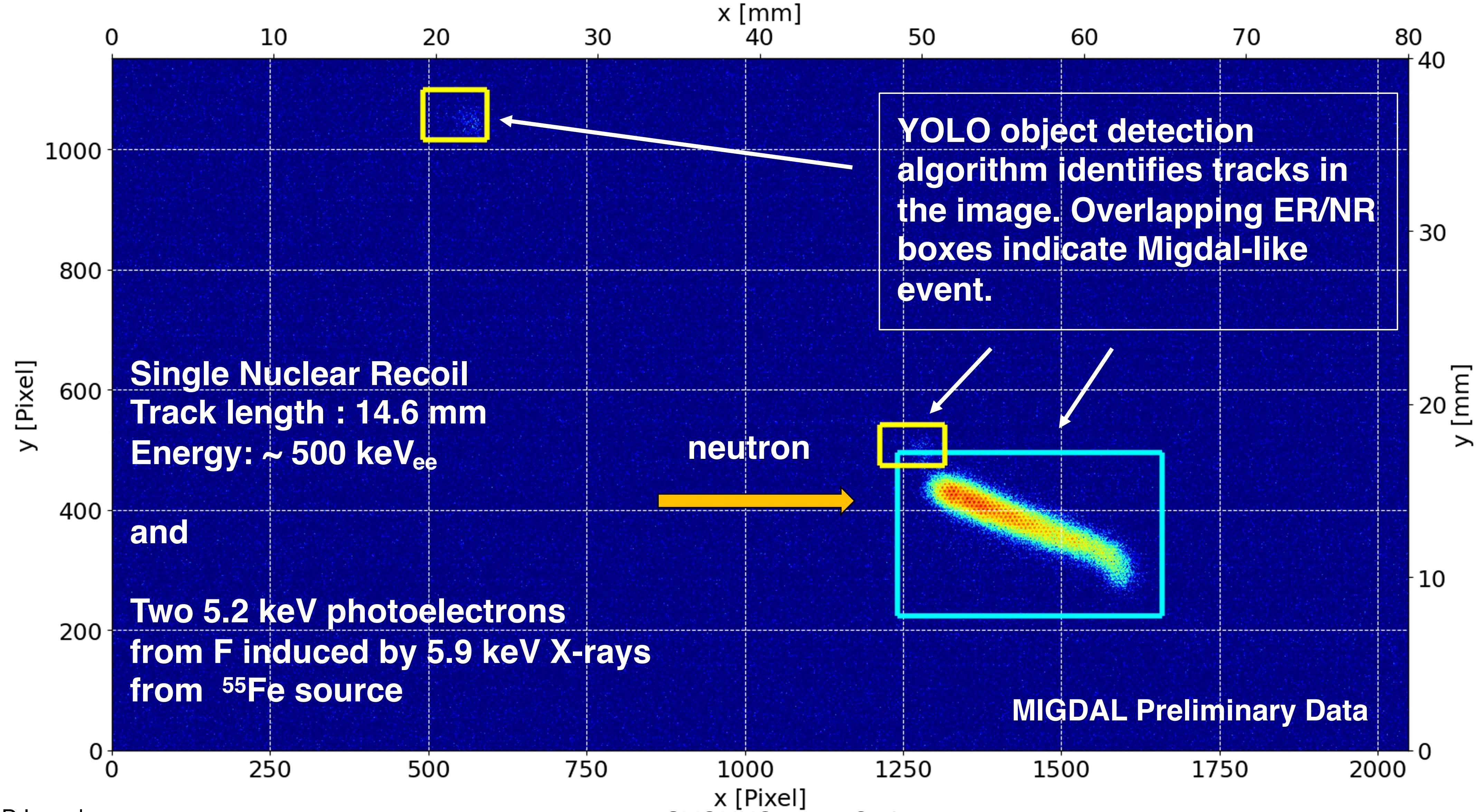
Example event - Migdal-like



Example event - Migdal-like

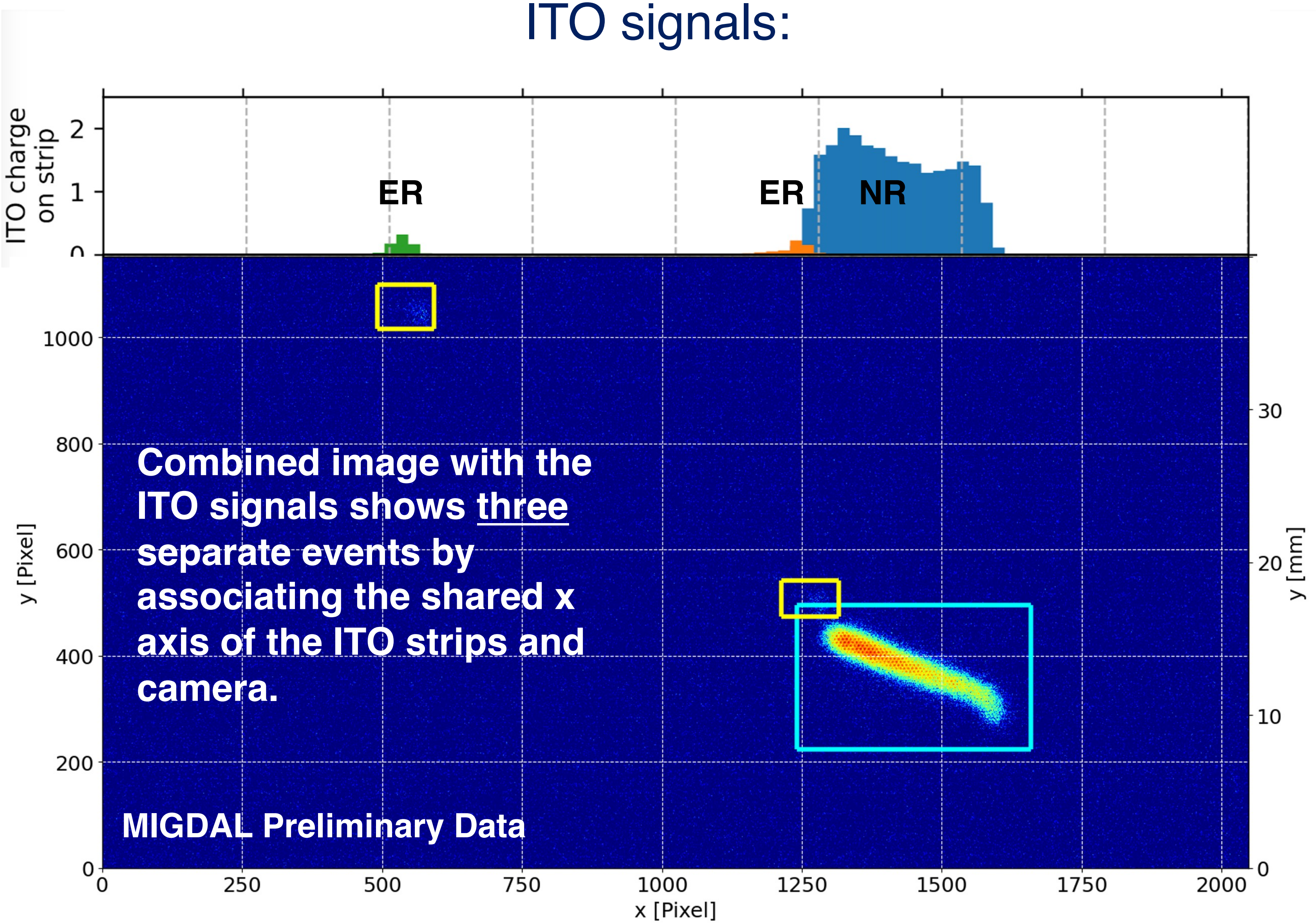


Example event - Migdal-like



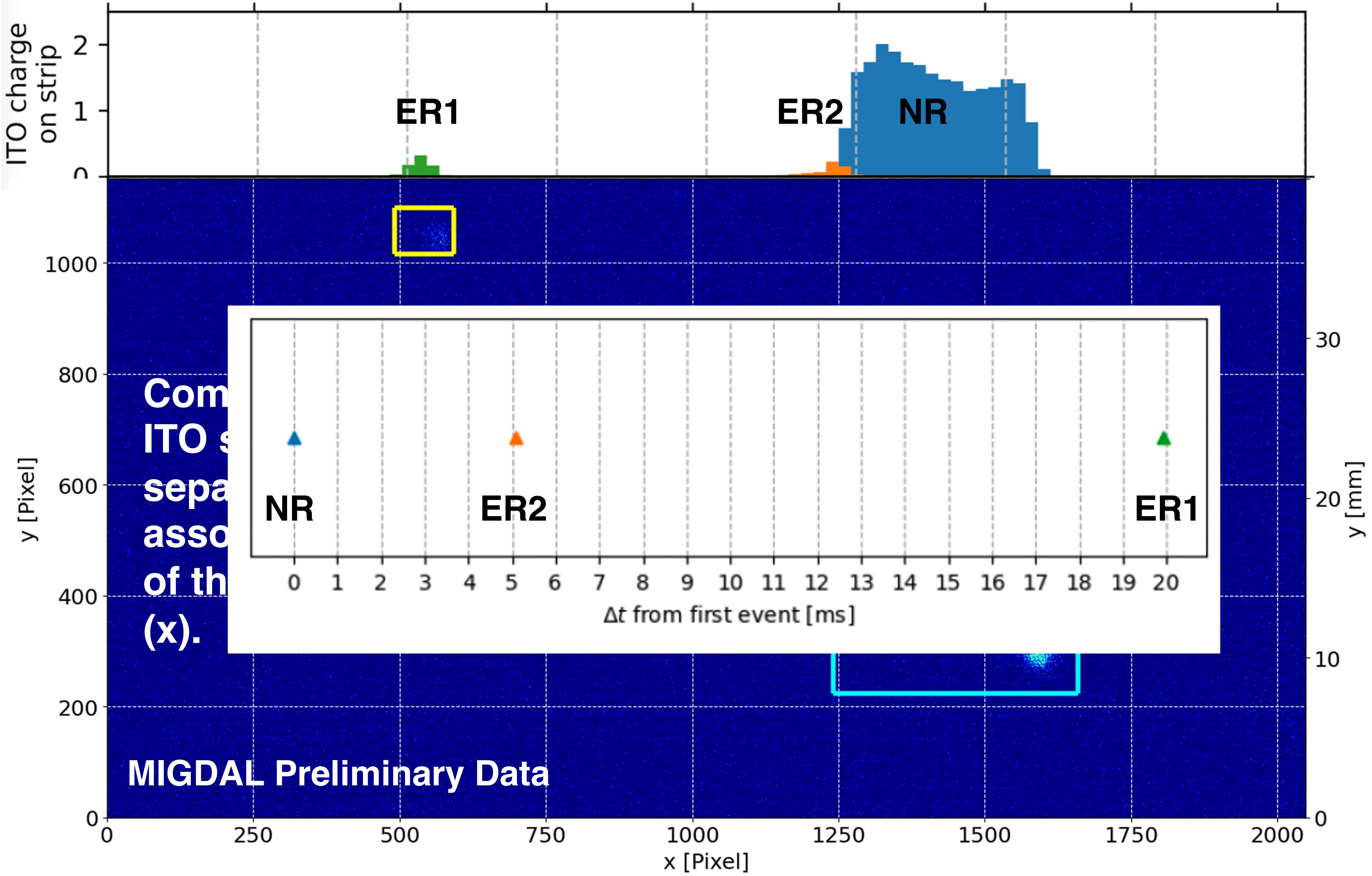
Migdal-like event

Synchronizing with ITO signals:



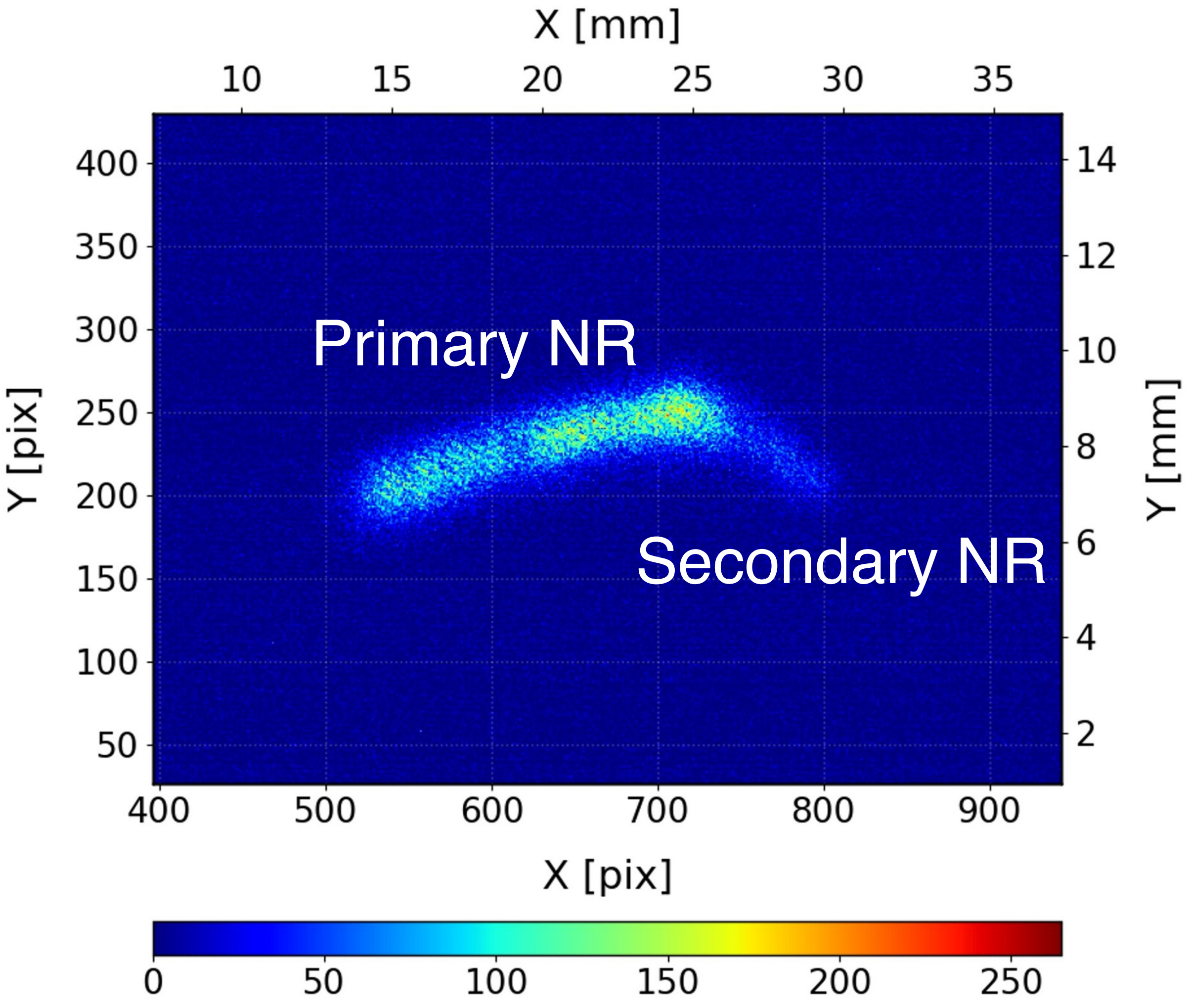
Migdal-like event

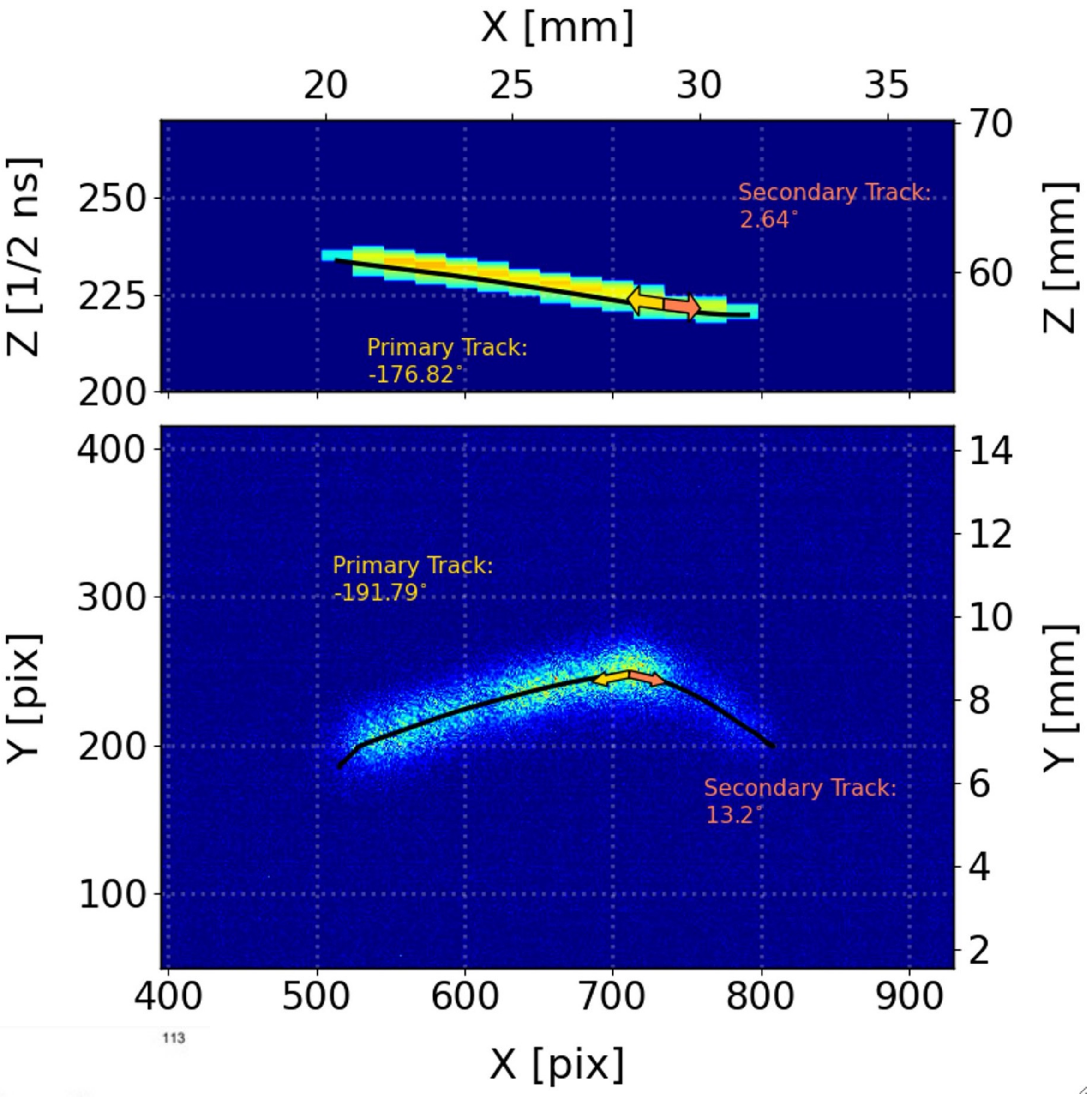
Synchronizing with ITO signals:



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

3D track reconstruction: Camera + ITO + PMT



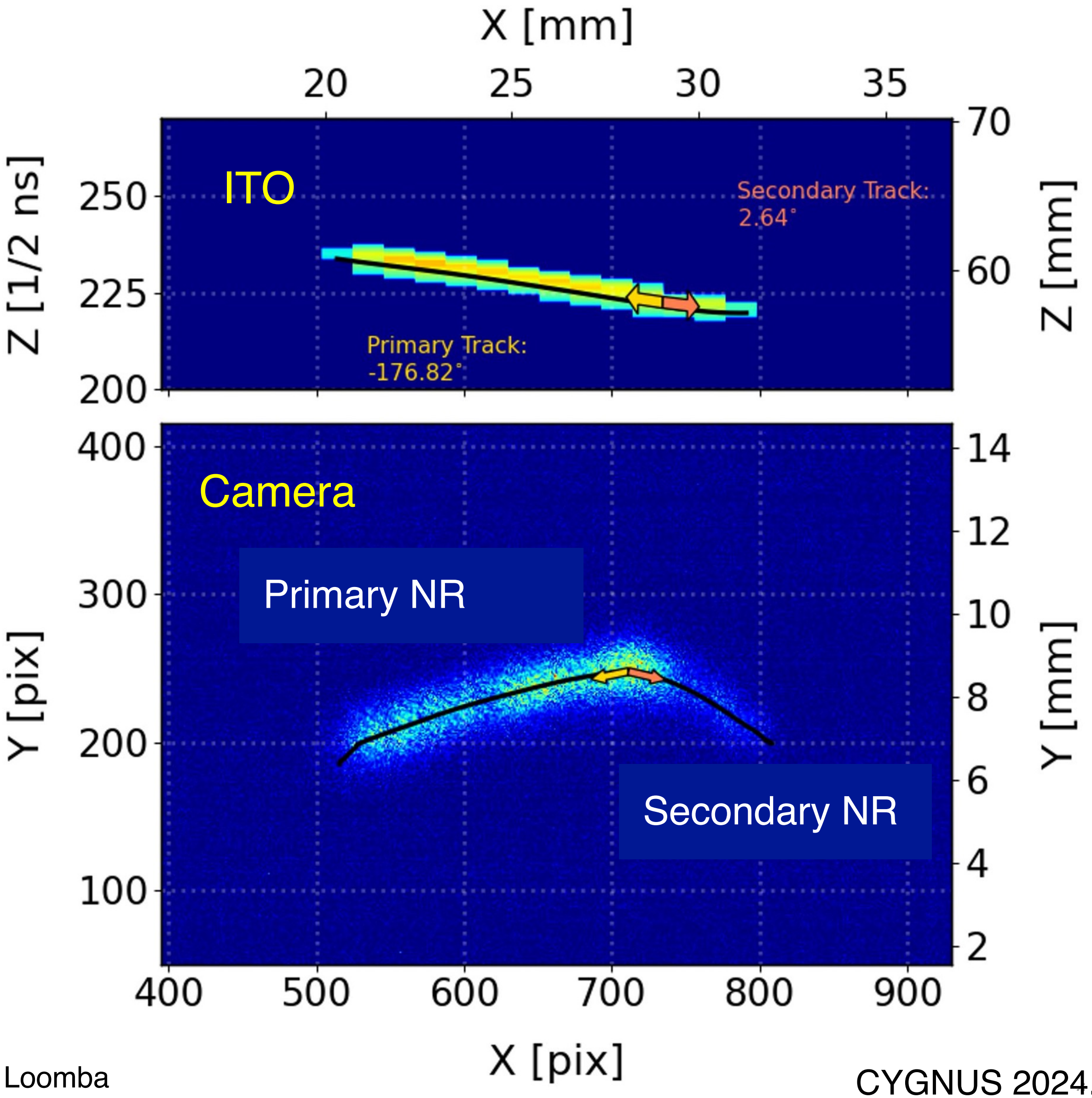


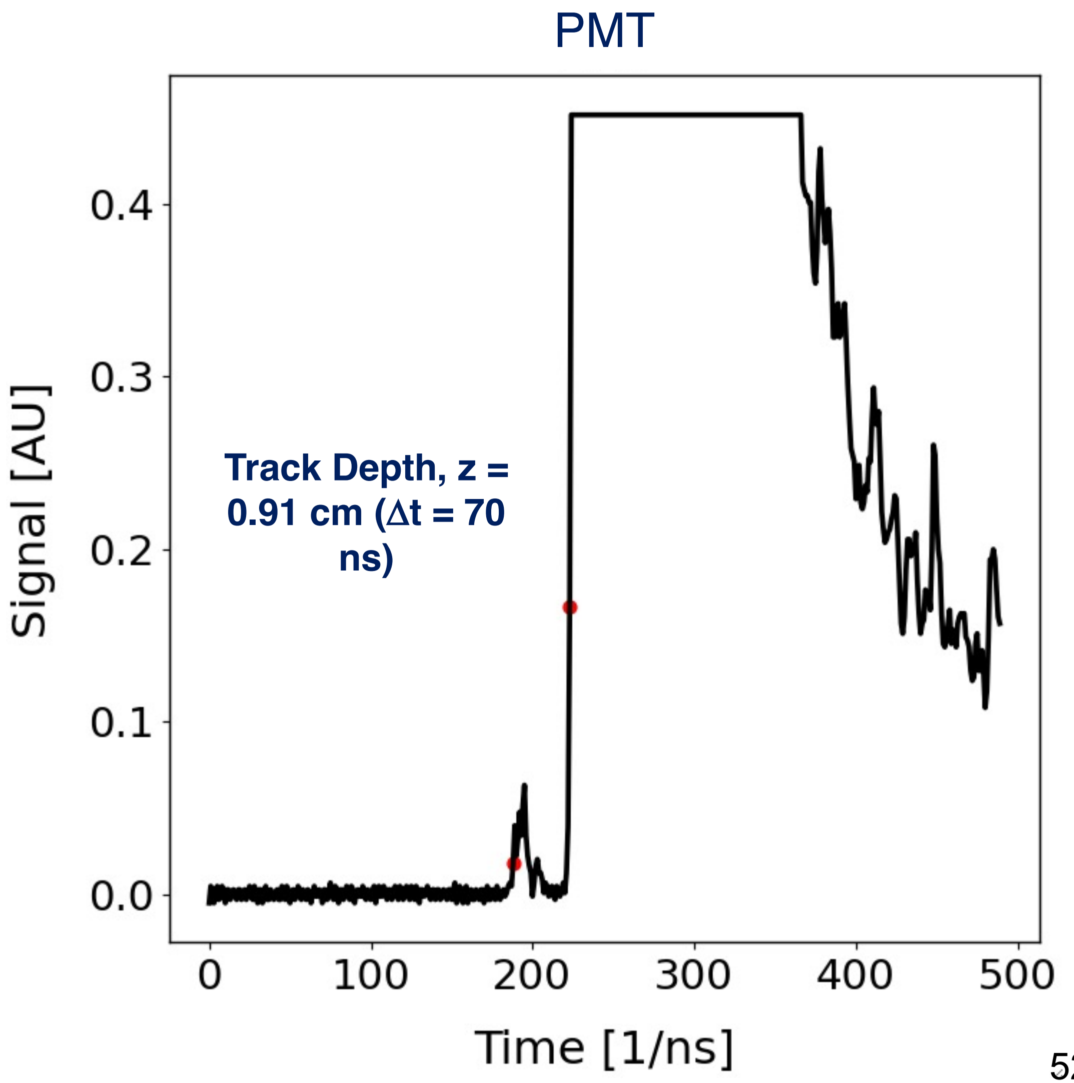
IEEE TRANSACTIONS ON PATTERN ANALYSIS AND MACHINE INTELLIGENCE, VOL. 20, NO. 2, FEBRUARY 1998 113

Ridgefinder: An Unbiased Detector of Curvilinear Structures

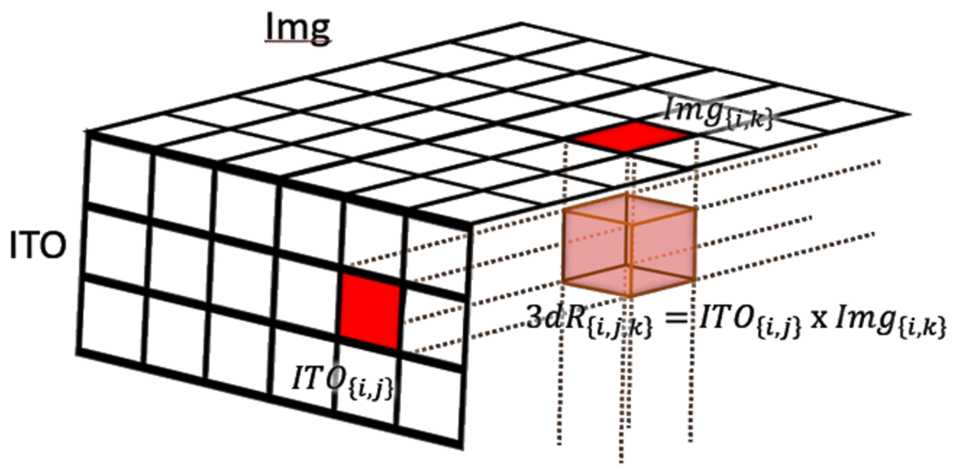
Carsten Steger

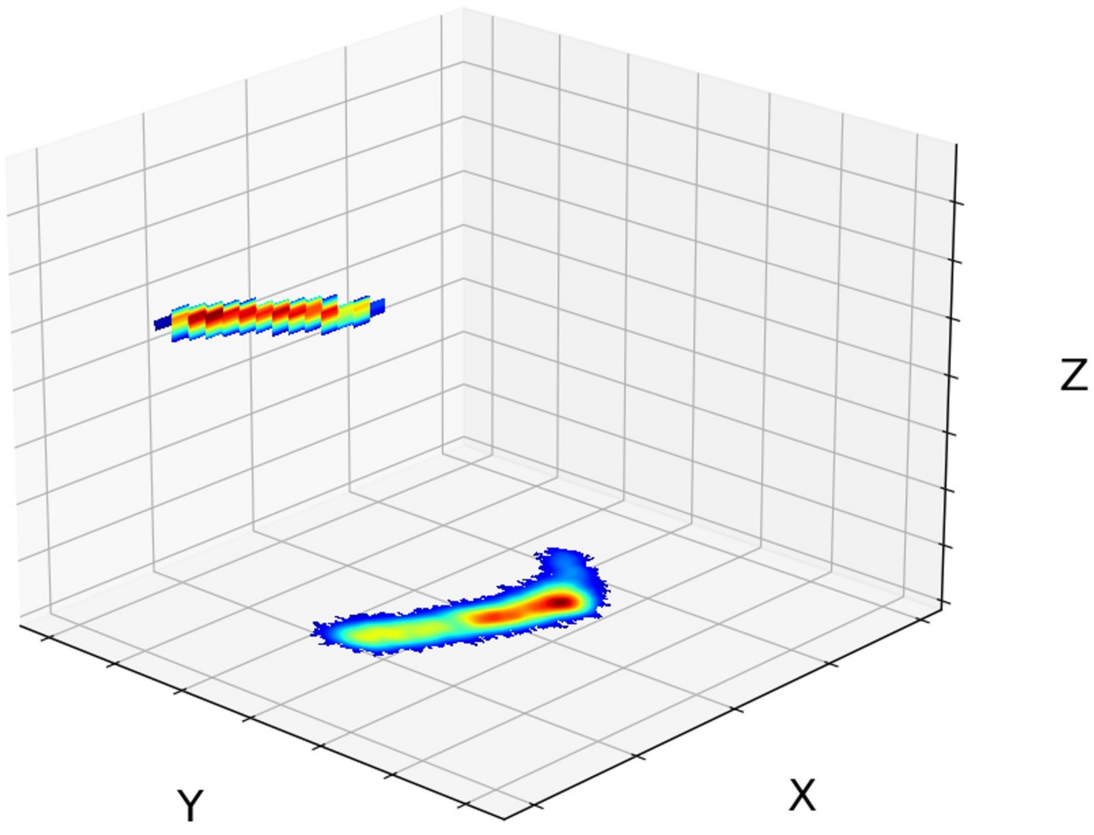
3D track reconstruction: Camera + ITO + PMT





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

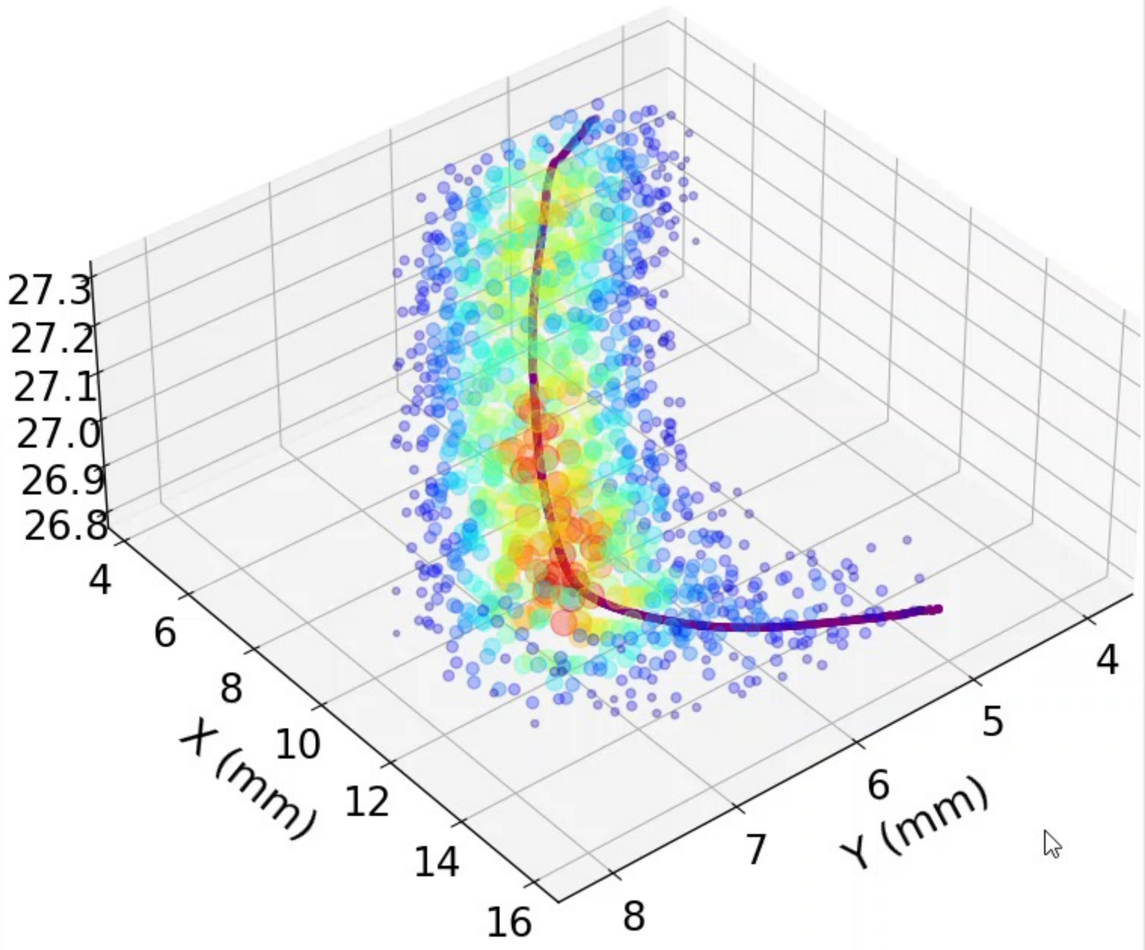
Published 17 July 2023 • © 2023 IOP Publishing Ltd and Sissa Medialab

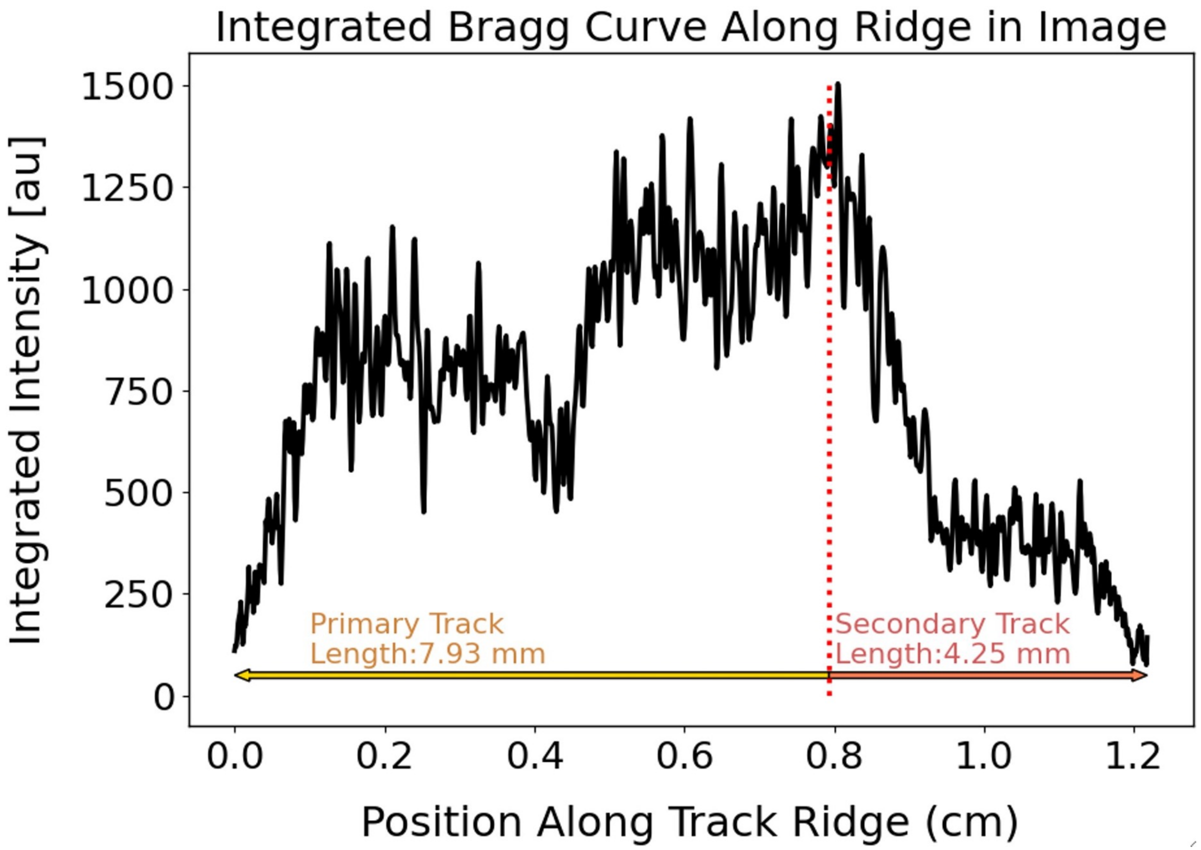
Journal of Instrumentation, Volume 18, July 2023

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

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

3D track reconstruction





Preparations for the Second Science RUN

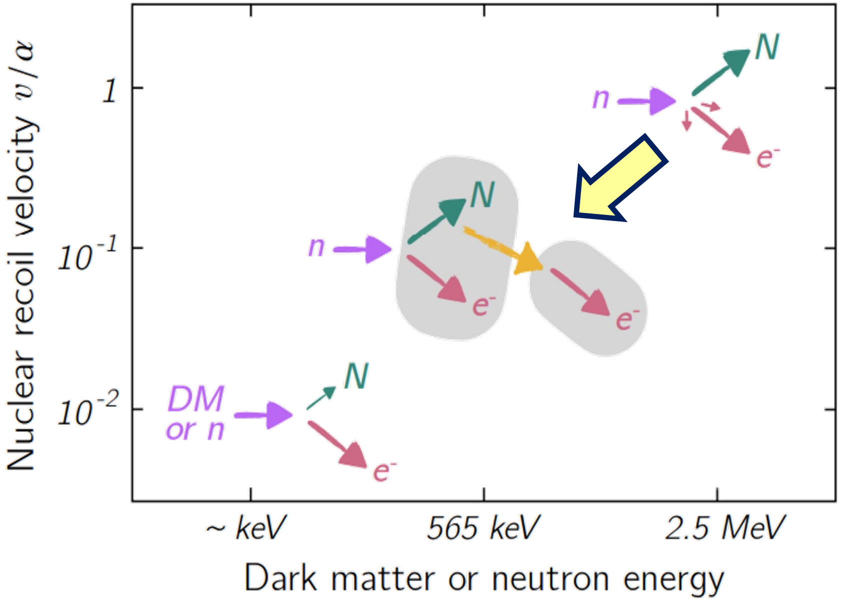
Improvements for the Second Science Run (SSR):

1. Fixed communication between DAQ PC and camera - use CoaXPress instead of USB decreasing exposure time from 20 ms to 8.3 ms - less chance for coincidence events.
2. Fixed missing bonded connection to central ITO strips.
3. Use FPGA to record timing information of every trigger also within 3 ms of DAQ dead time.
4. New GEMs w/o metallisation around mounting holes
5. Use of mask to provide better overlap of ITO and camera field-of-view
6. At the later stage of the SSR - a new collimator increasing NR rate x3.

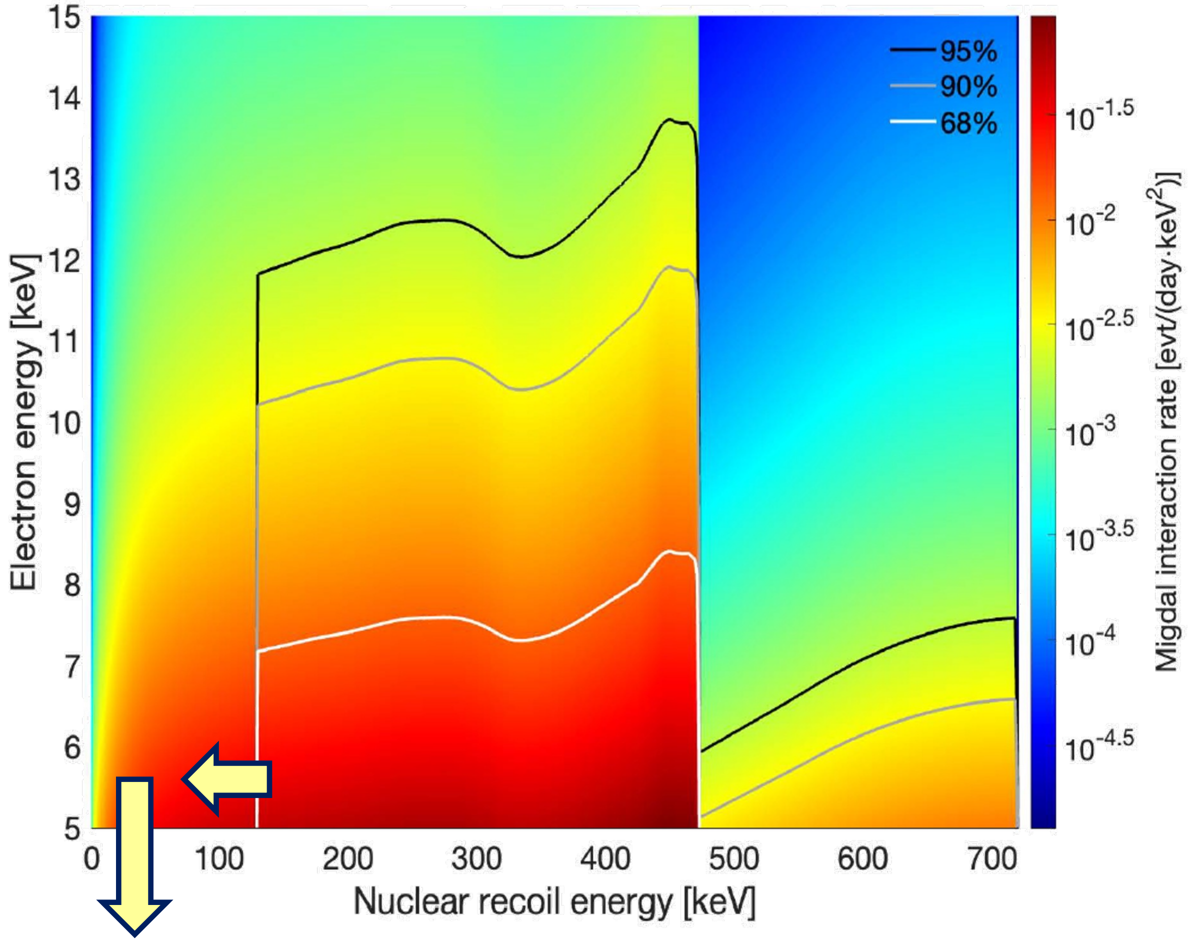
R&D for a MIGDAL Phase II

MIGDAL Phase II - Motivation

- Probe lower energies
- Attain higher rates



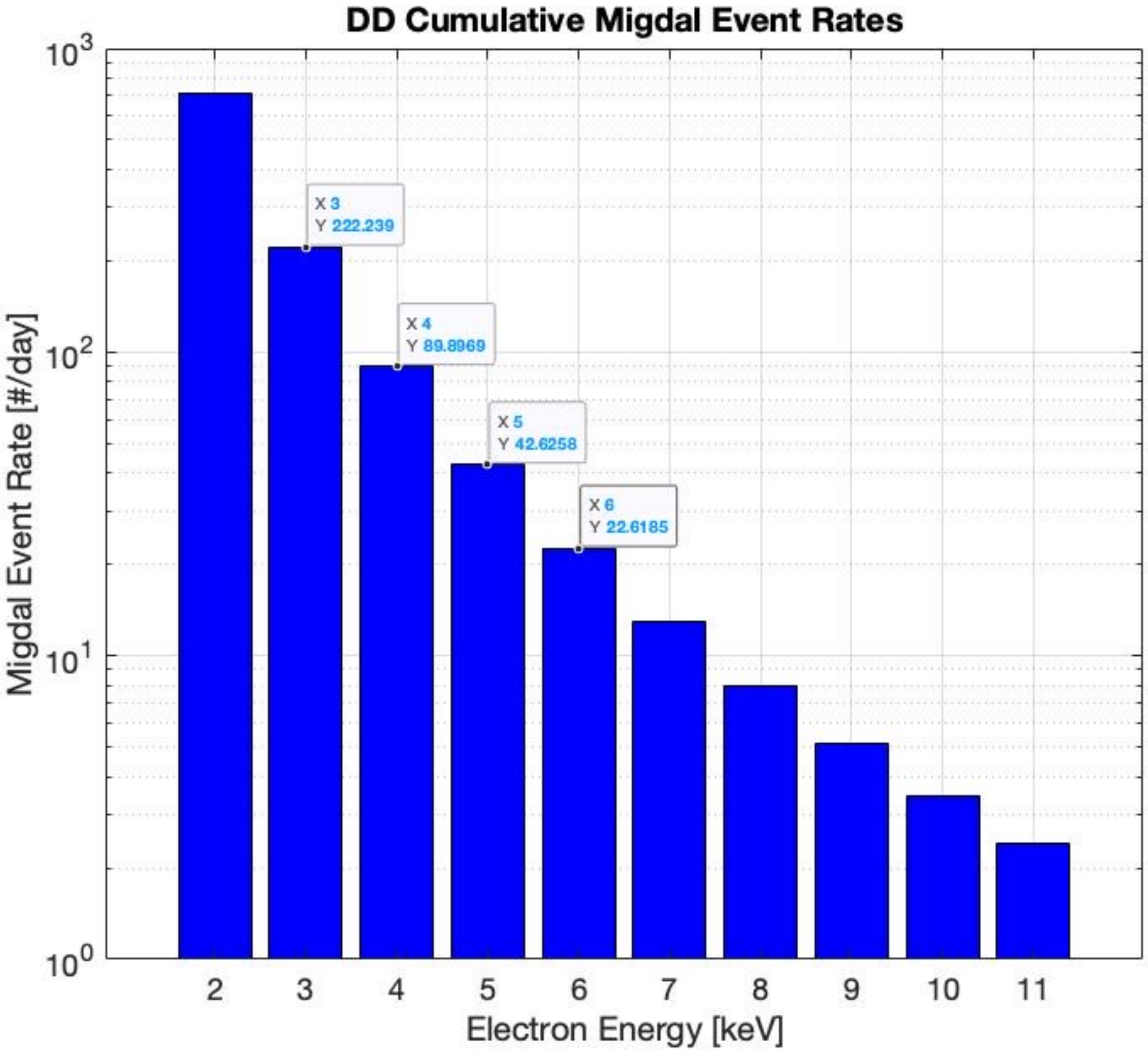
P. Cox *et al* 2023 *Phys. Rev. D* **107**, 035032
https://doi.org/10.1103/PhysRevD.107.035032



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

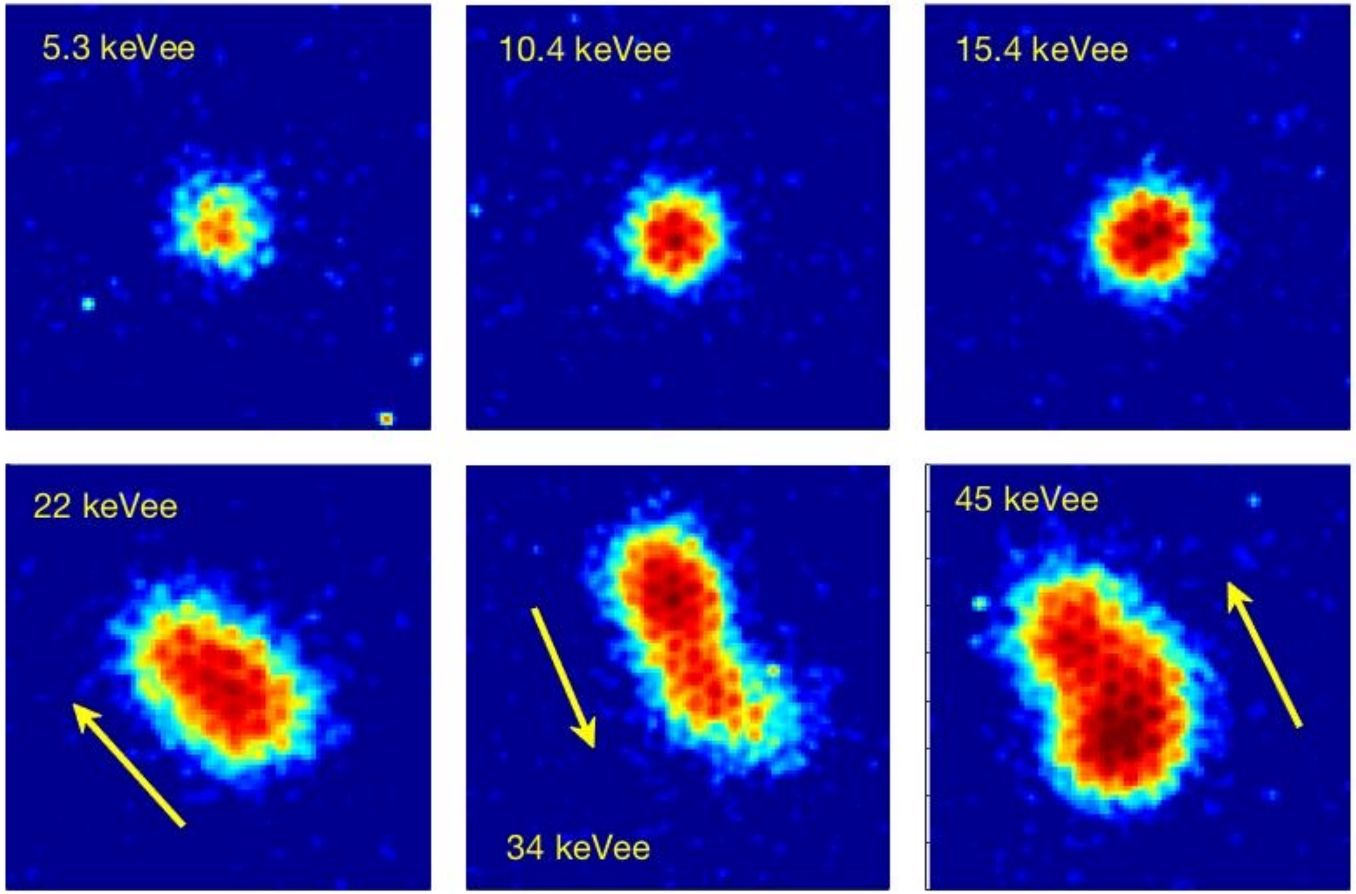


Pure CF4

- $E_{discrimination}$ ~ 4 keVee
- $E_{directionality}$ ~ 20 keVee NR*
- $E_{directionality}$ ~ a few keVee ER

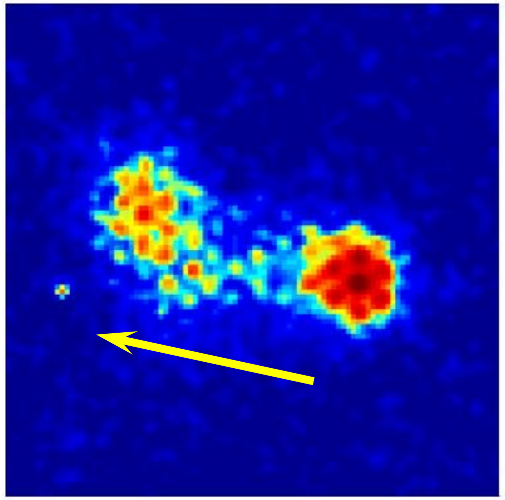
*Disappointing, due to σ~0.7 mm

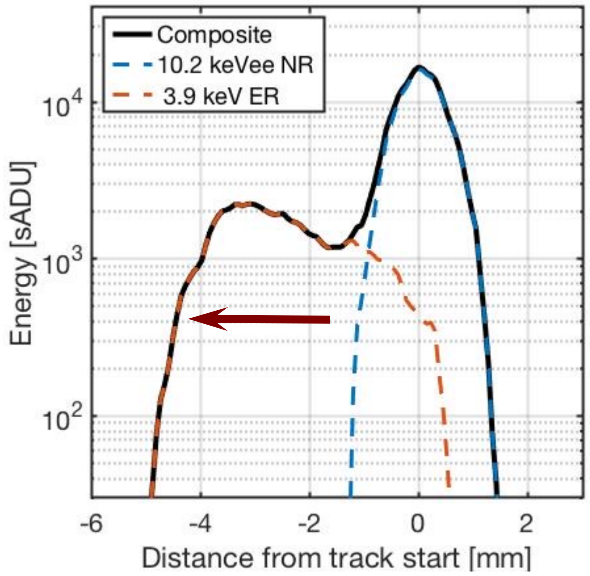
Nuclear Recoils

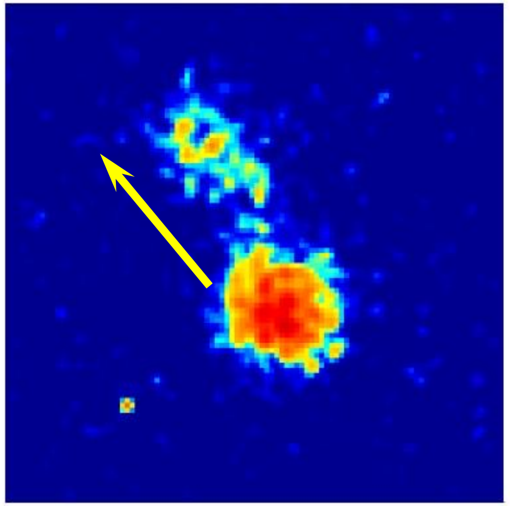


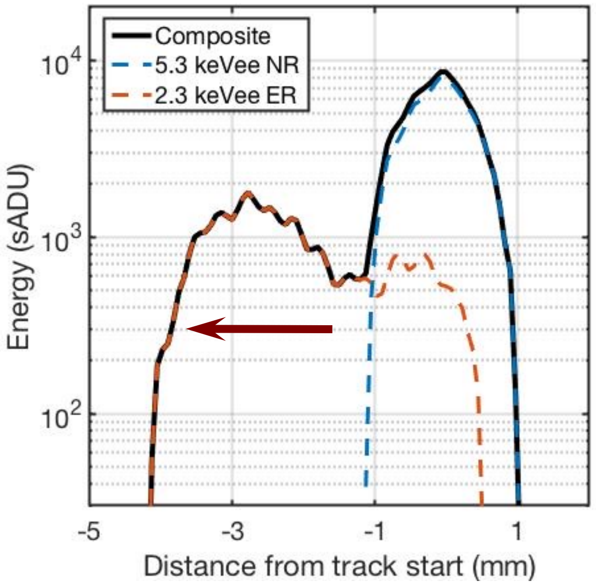
Low energy “Migdal Events”??

- **3D and lower diffusion will help**
- **Backgrounds?**





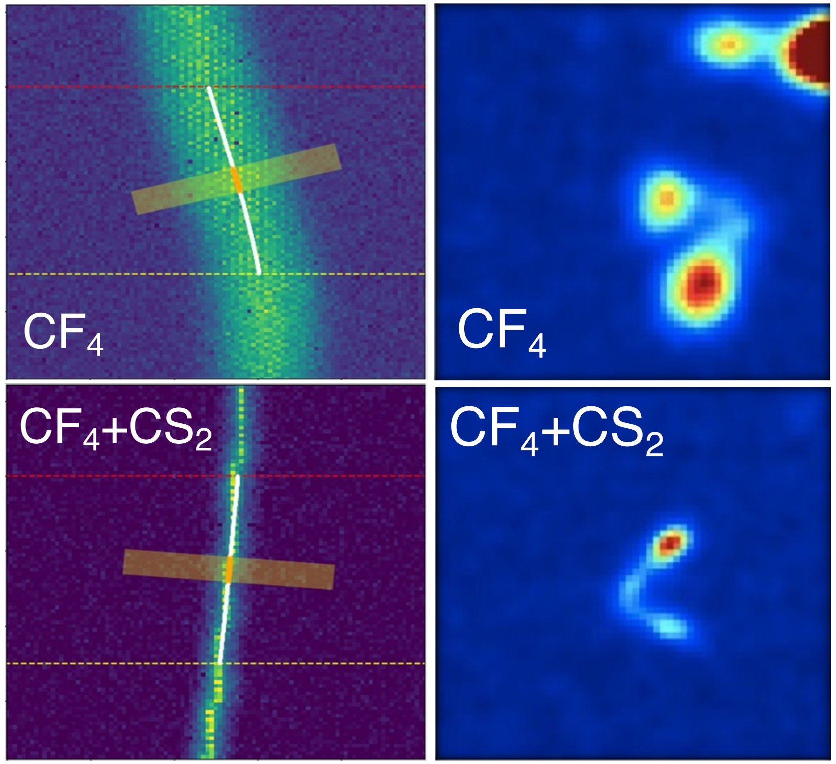




NI-OTPC Results

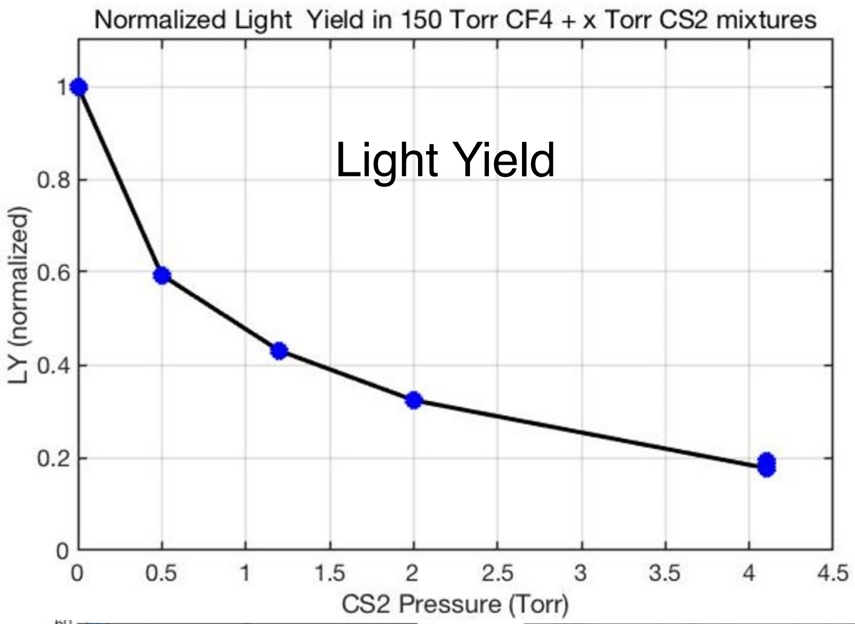
- Results show promise for NID but will be **challenging in O-TPC**

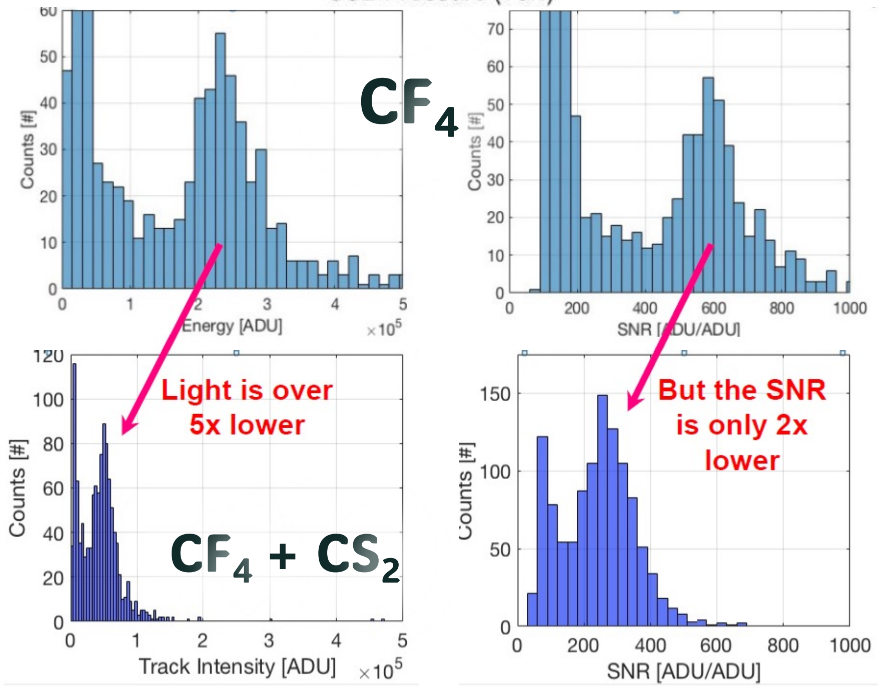
Alpha Tracks **Electron Tracks**



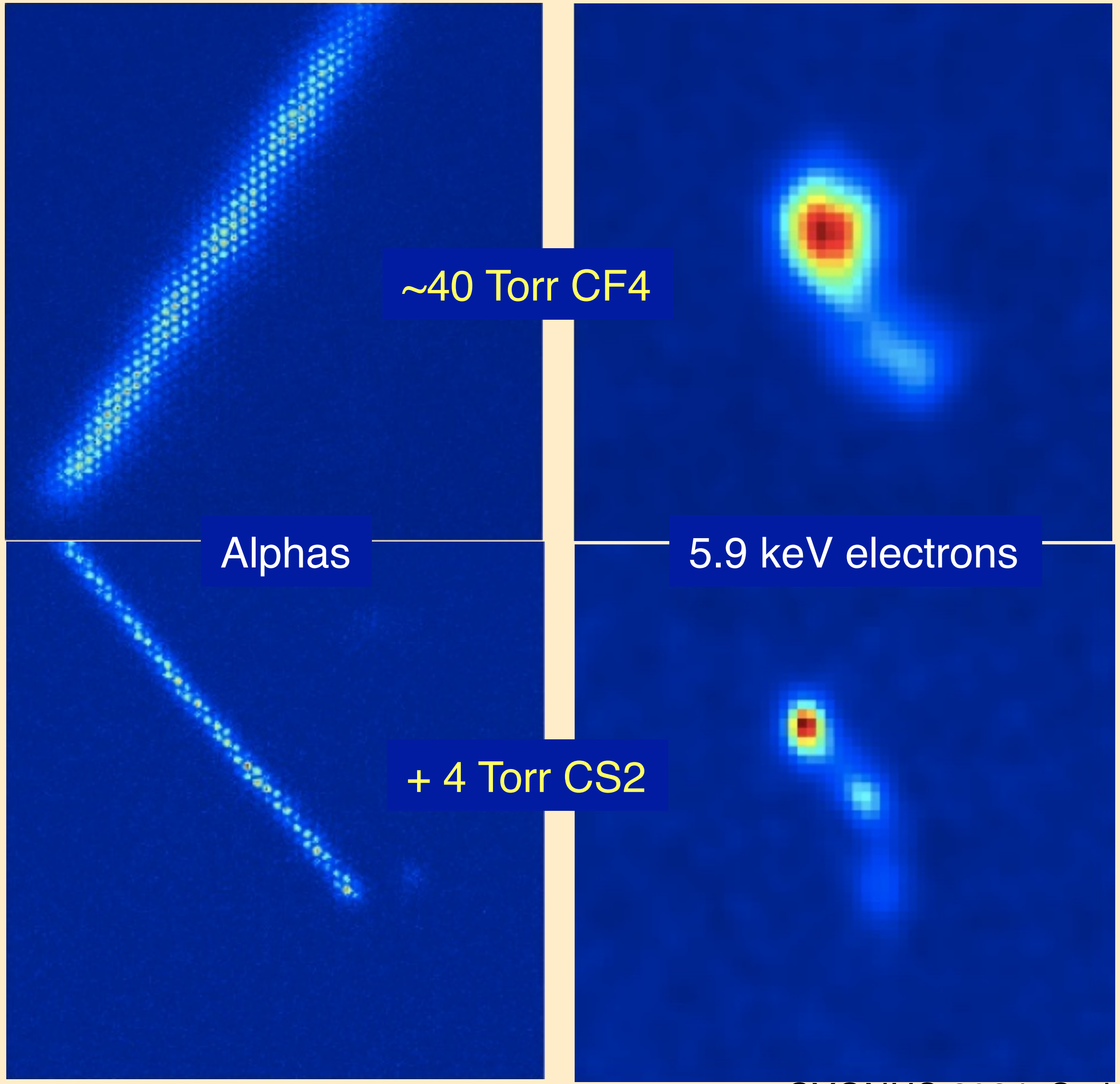
Measured Transverse Diffusion

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



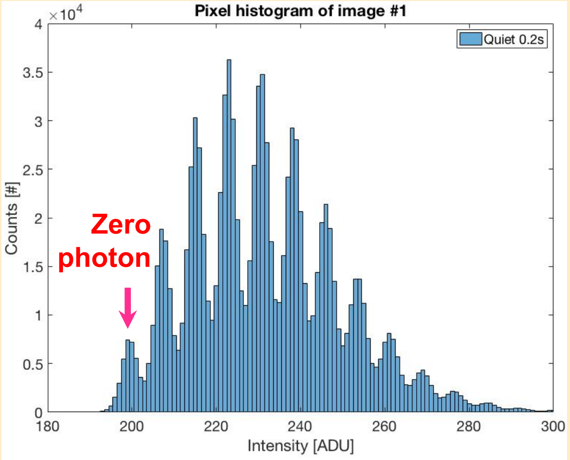


Negative-ion OTPC



Hamamatsu ORCA-Quest

- Photon Resolving Power:

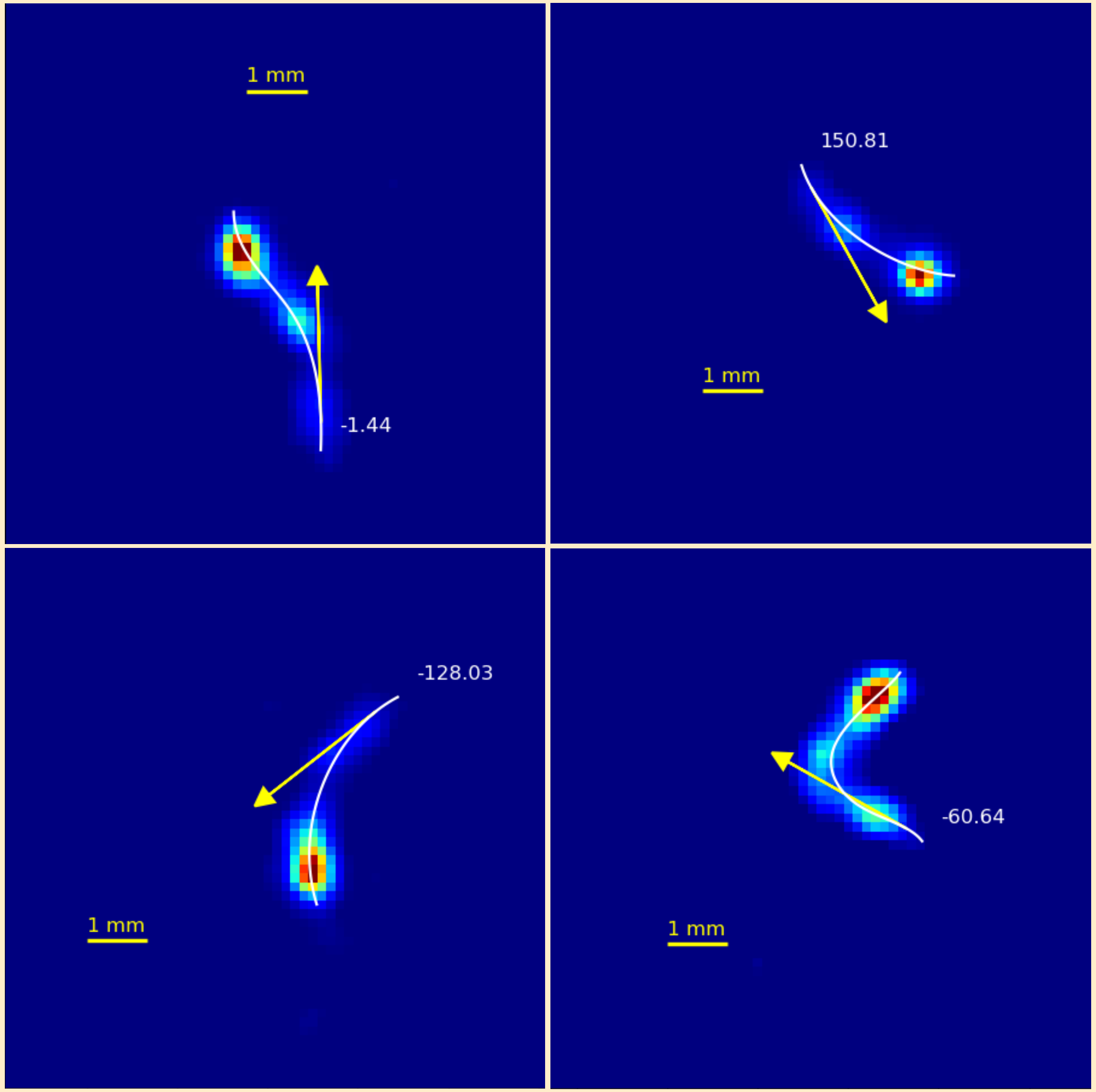


Radiment Glass-GEMs

- 270 micron pitch

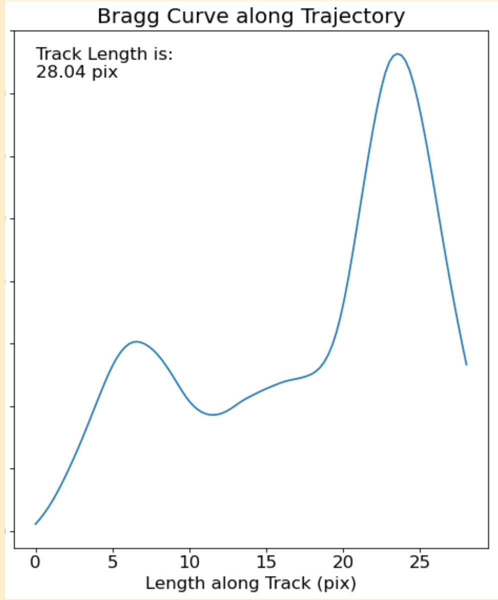
~45 Torr CF_4 + x Torr CS_2

CS_2 (Torr)	σ(μm)
0	~500
4	~150-200



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

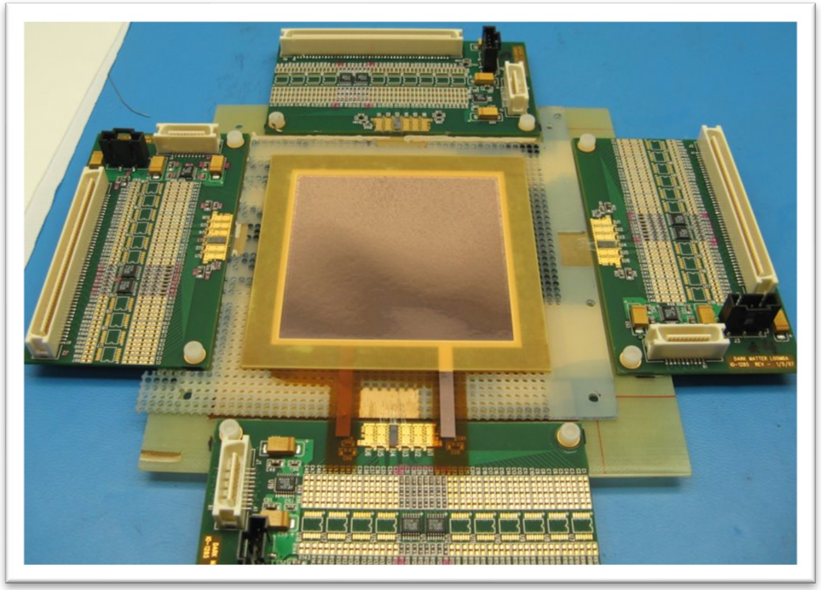
- **Head/tail** of track
- **Initial direction**
- **Range**
- **dE/dx** (Bragg curve):

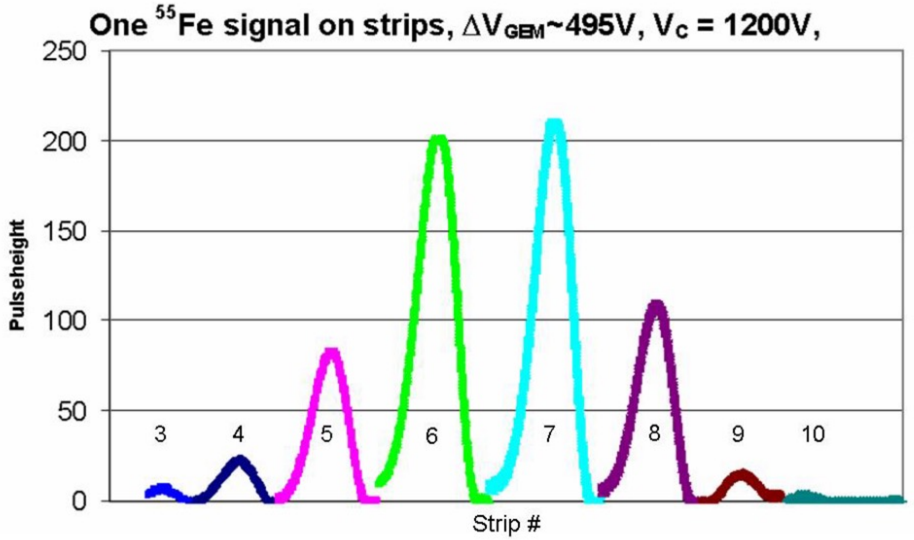


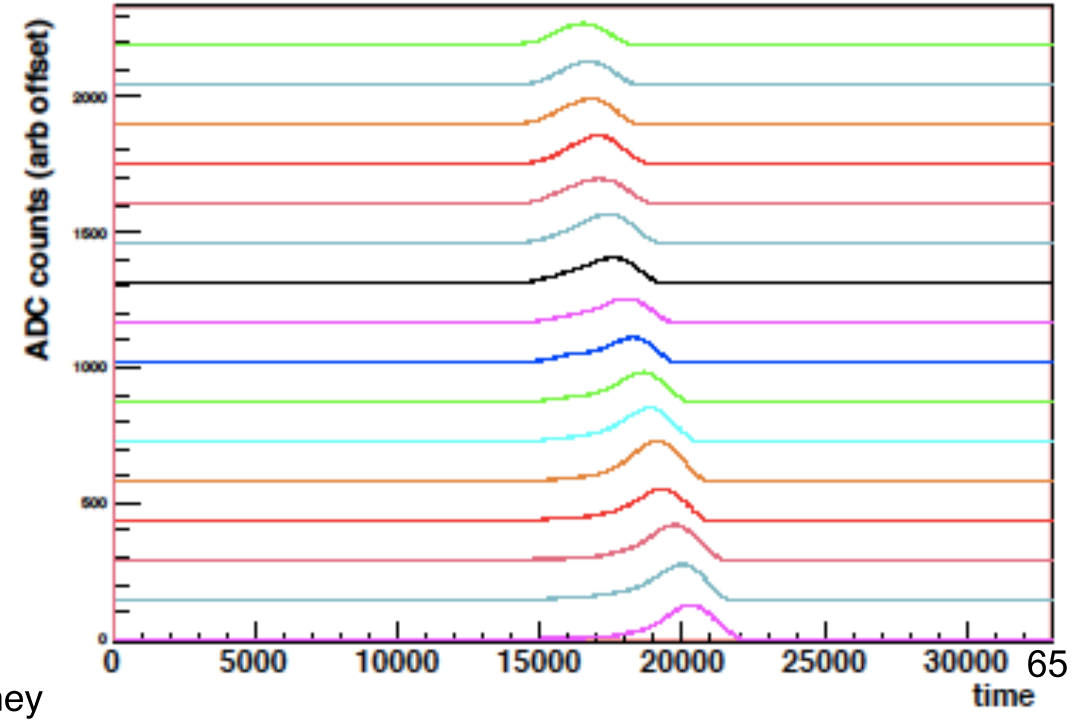
Charge readout(!) NI-TPC

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

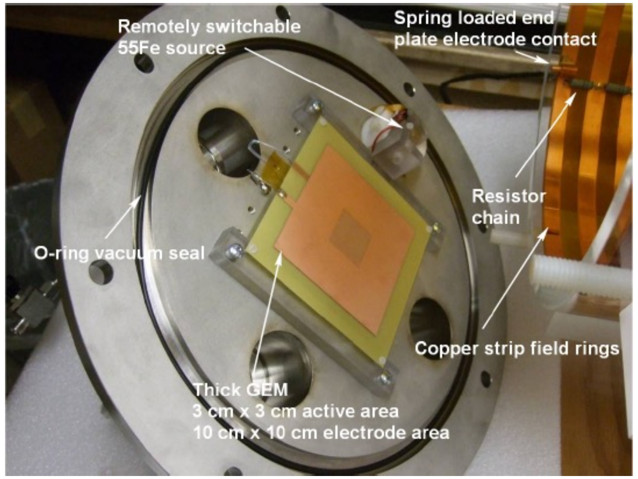
- Achieving high dynamic range does not require high gas gains
- Gas mixtures can be optimized for target atoms w/o worrying about light yield
- The detector will be built and characterized in the next year or two

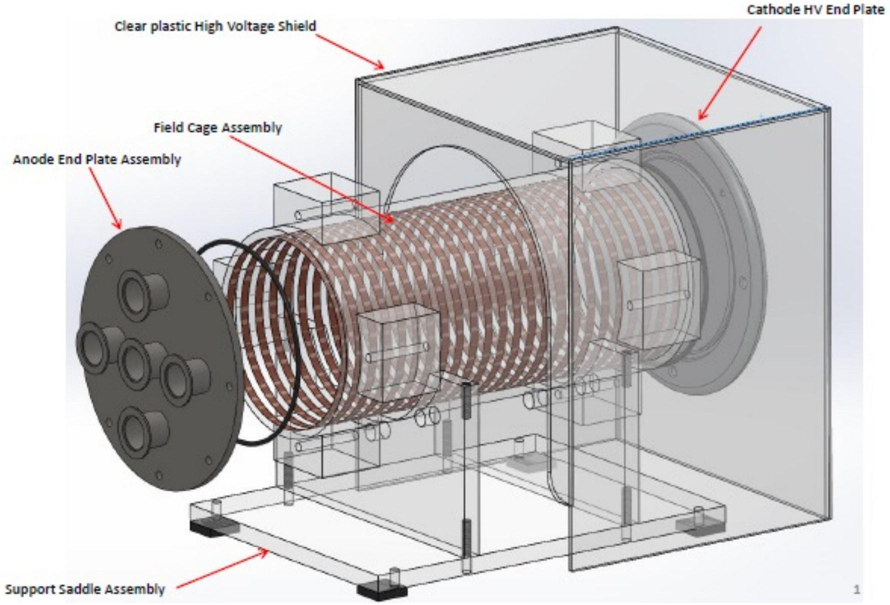


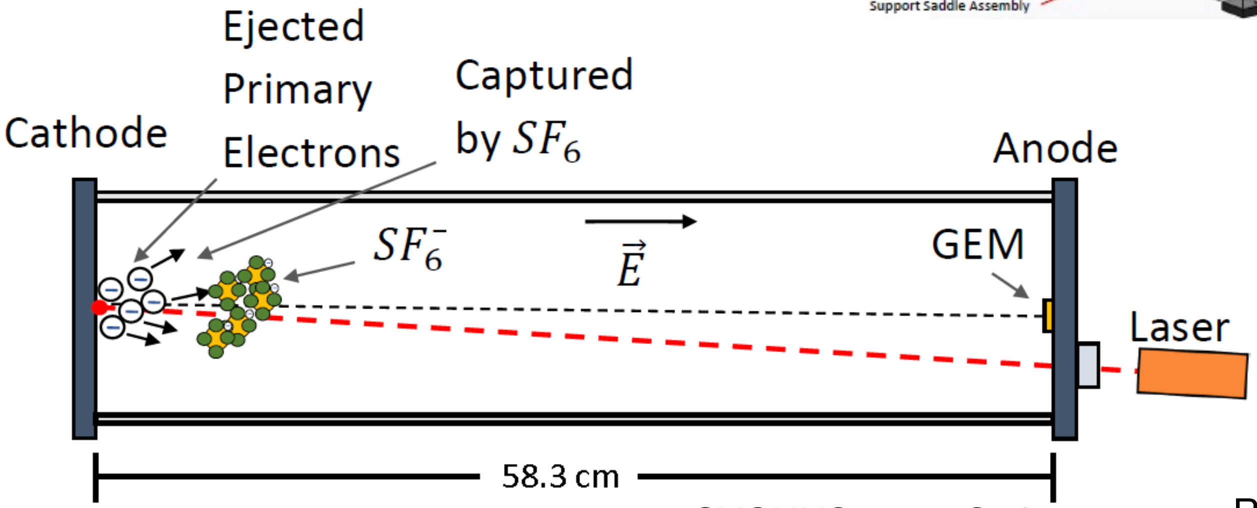




R&D program to measure/optimize NI+noble gas properties







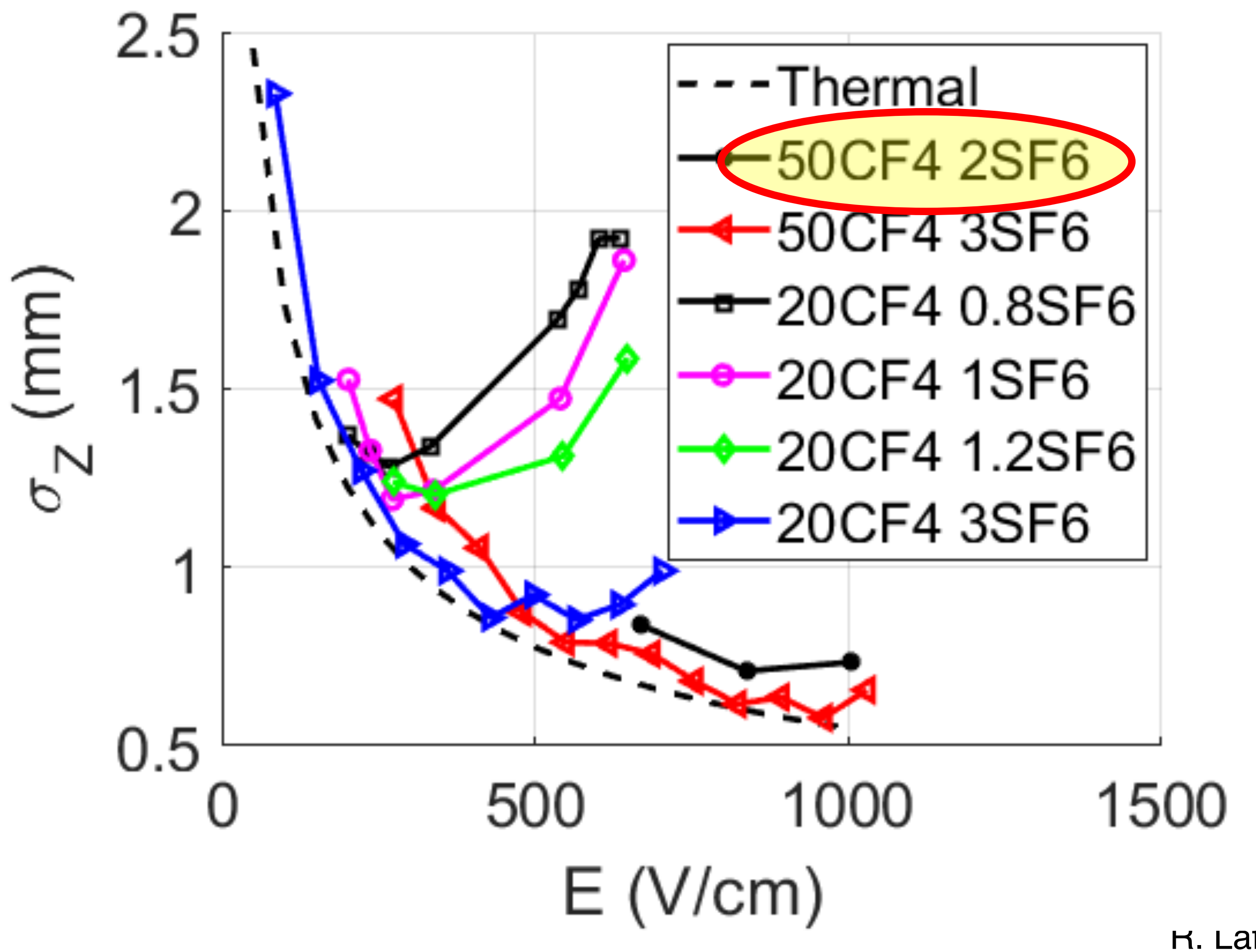
Used to measure:

- diffusion
- mobility
- waveforms

Phan et al 2017 *JINST*

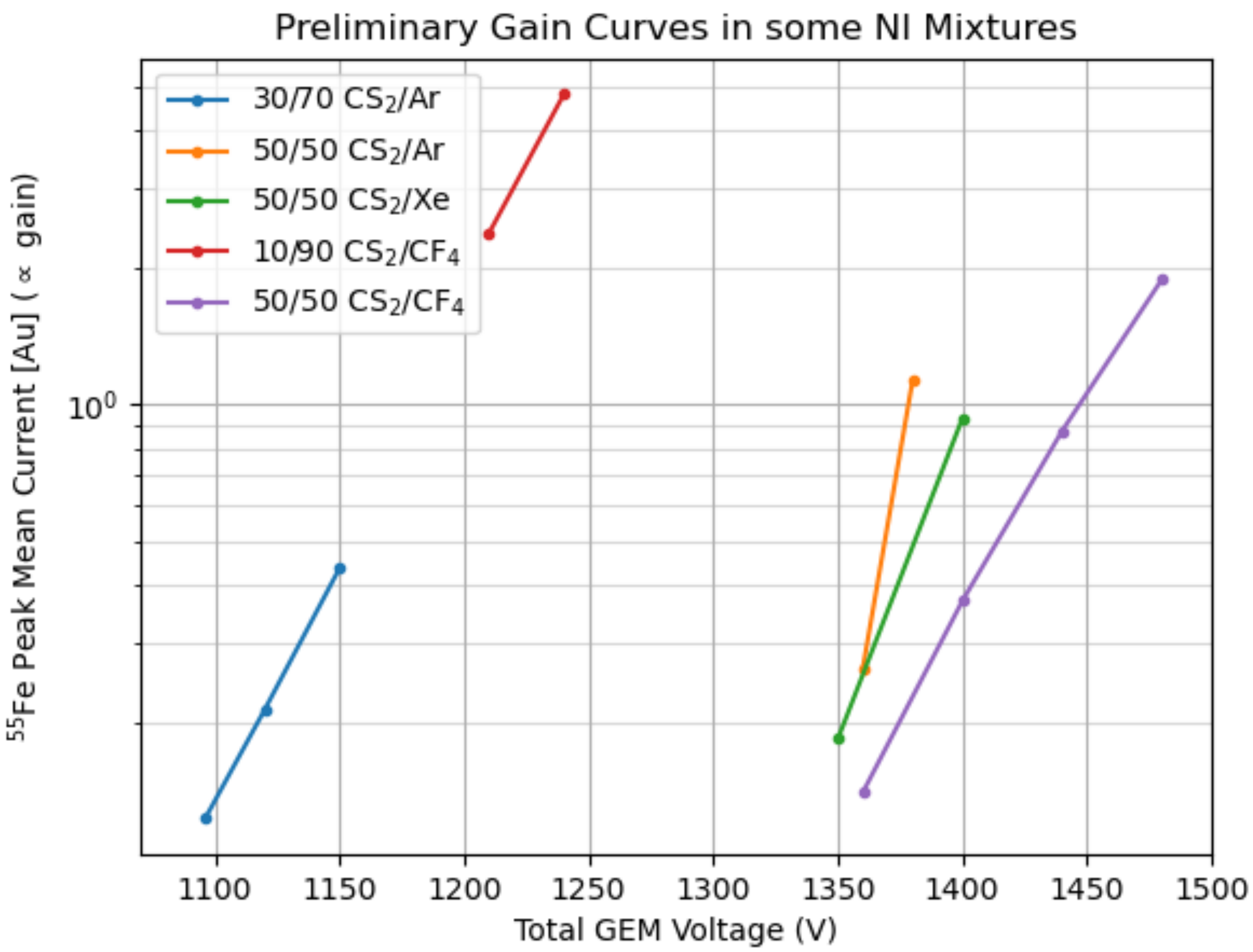
R. Lafler, PhD Thesis, UNM, 2019

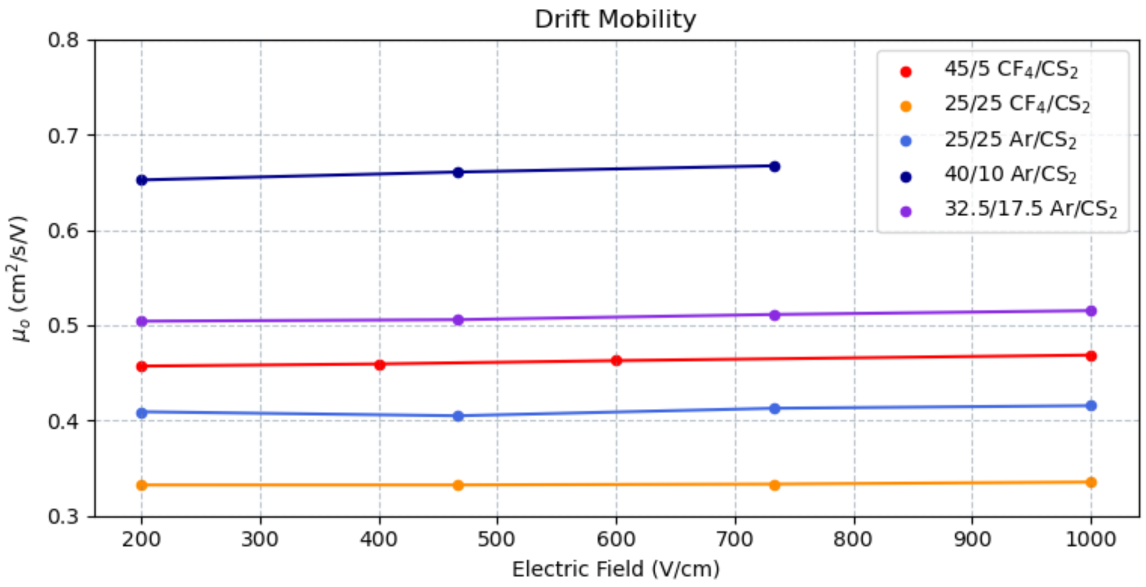
Results for σ_L in CF4/SF6 mixtures (60 cm drift):

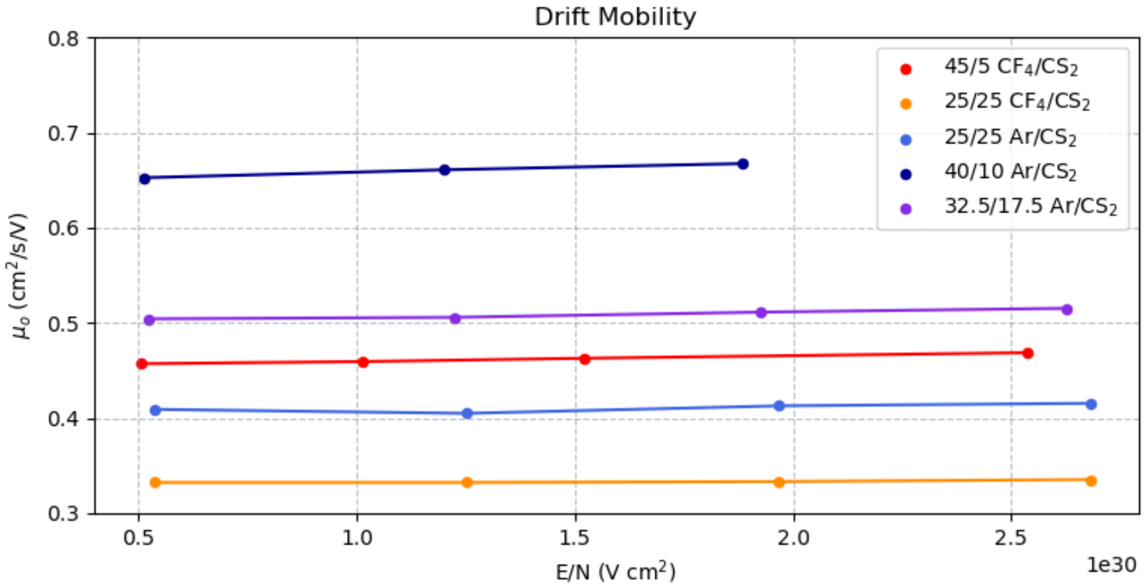


R. Lafler, PhD Thesis, UNM, 2019

Preliminary results in CS2+nobles







Summary

- The MIGDAL experiment aims to perform an unambiguous observation of the Migdal effect.
- First science run took place with DD neutron source 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.
- Second science run starting soon.
- Work is ongoing to create a next generation NI-TPC to probe lower energy Migdal events
- Stay tuned for results !

Thank You!

UNIVERSITY OF BIRMINGHAM | UAM | GDD Gas Detectors Development Group | Helsinki Institute of Physics | Imperial College London | King's College London | LIP | The University of New Mexico | University of Oxford | Royal Holloway University of London | Science & Technology Facilities Council Rutherford Appleton Laboratory | The University Of Sheffield.

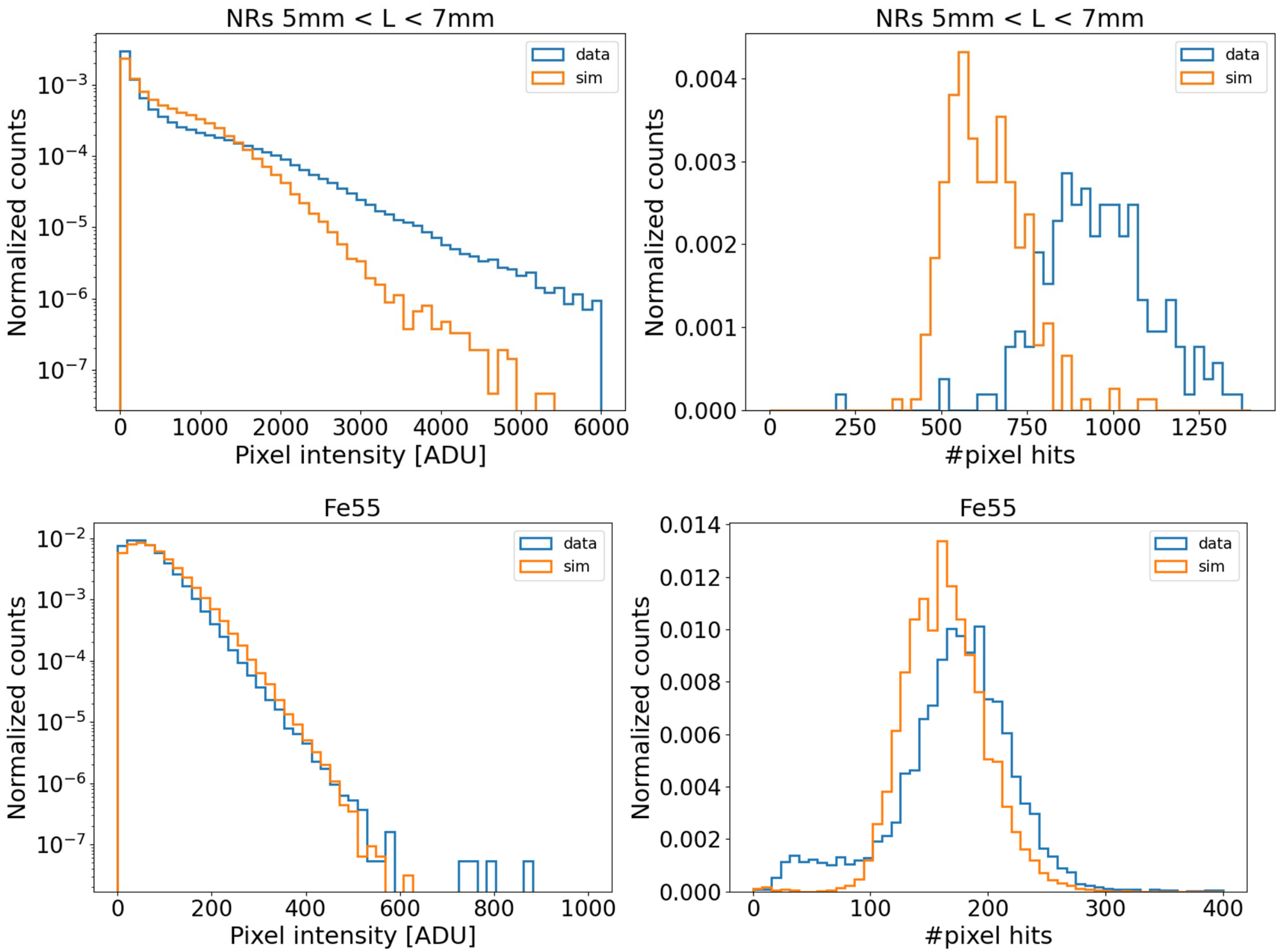
Funding: UKRI Science and Technology Facilities Council | U.S. DEPARTMENT OF ENERGY | FCT Fundação para a Ciência e a Tecnologia | Horizon 2020 European Union Funding for Research & Innovation | NSF National Science Foundation | MARIE CURIE ACTIONS

Backups

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

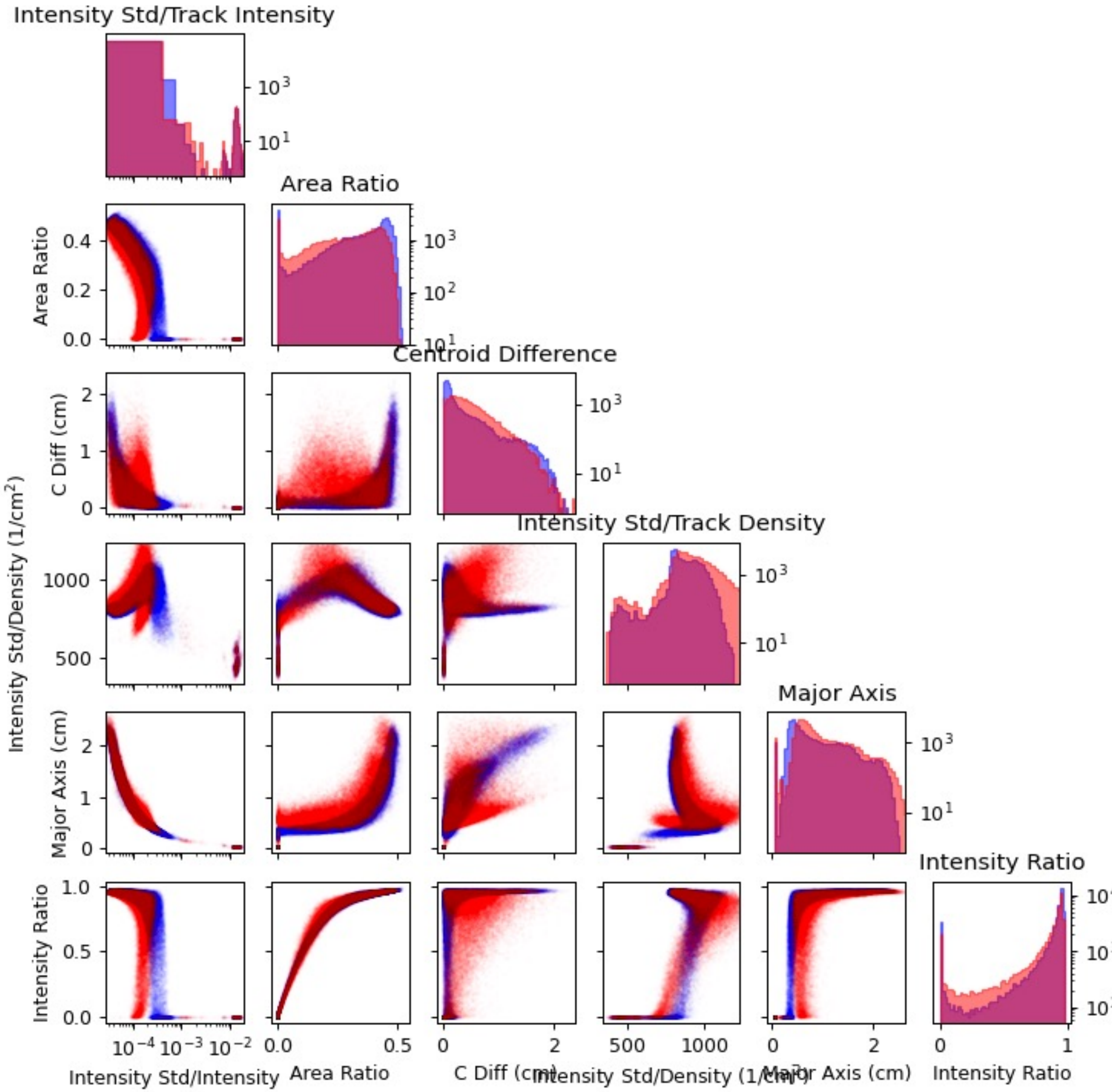
Simulation vs. Data



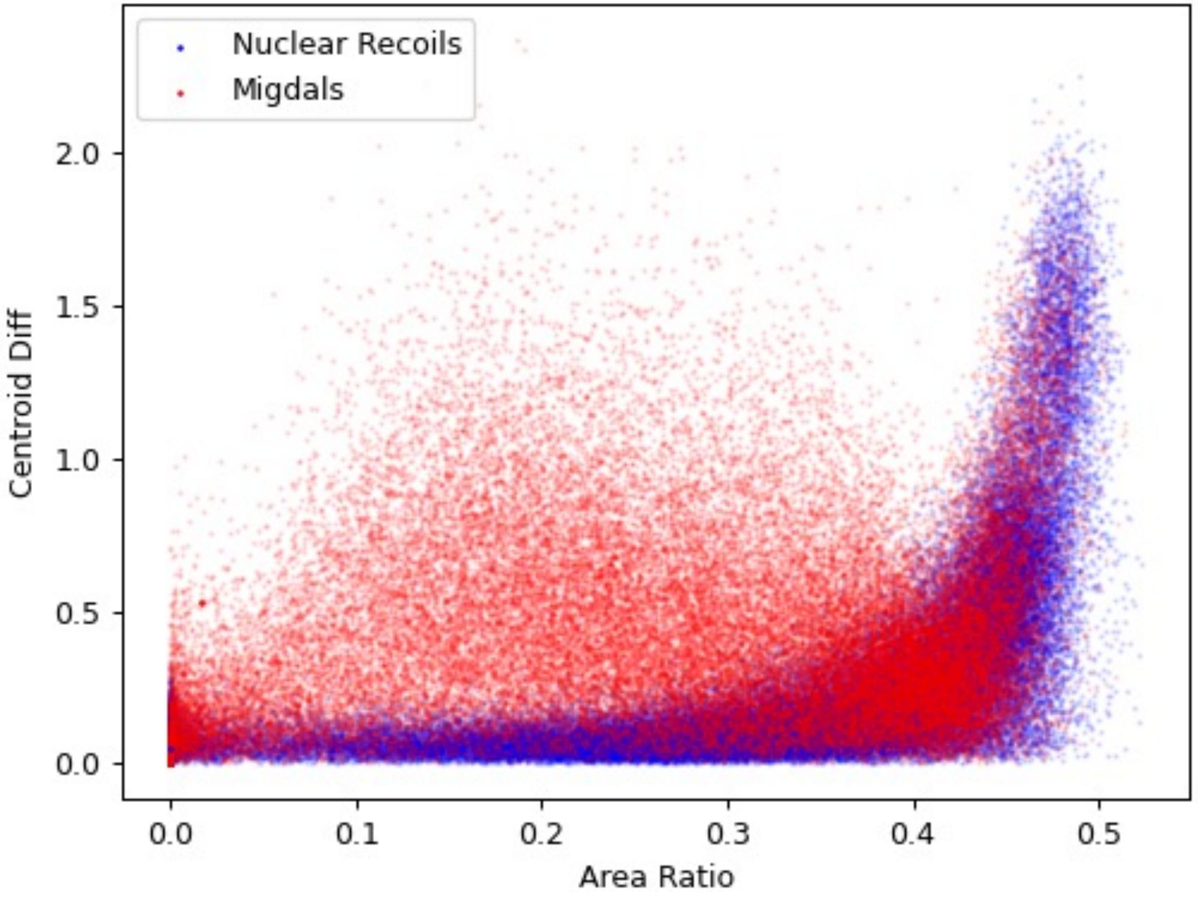
We believe that reflections are the origin of the differences between sim vs data NR distributions.

Data and simulation agree much better for simulated ERs

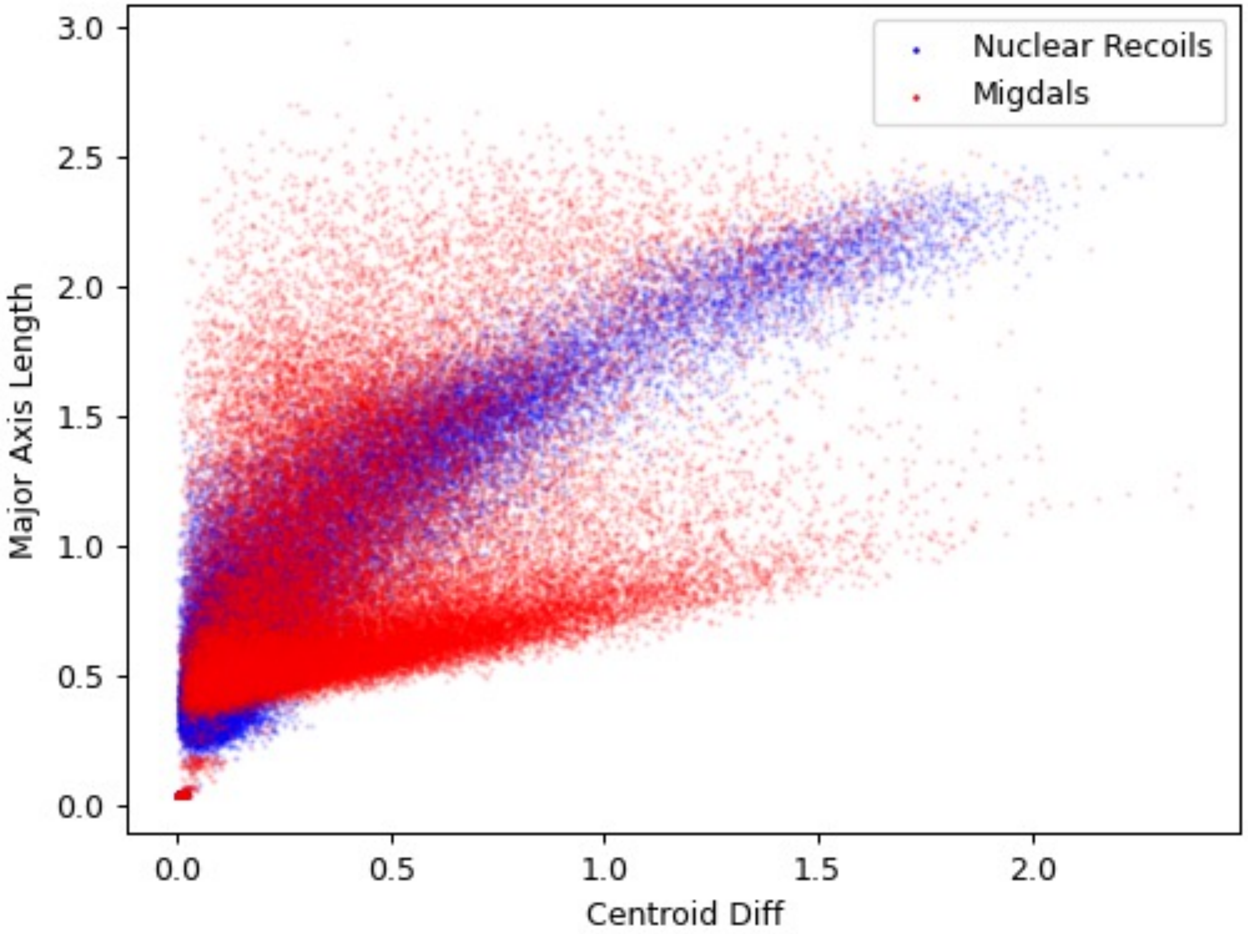
The main problem is that simulating NRs in our optical readout is very challenging. ***We plan to pursue an idea to stitch simulated ERs on data NRs to form Migdal signals for YOLO (or CNN!) to be trained and tested on.***



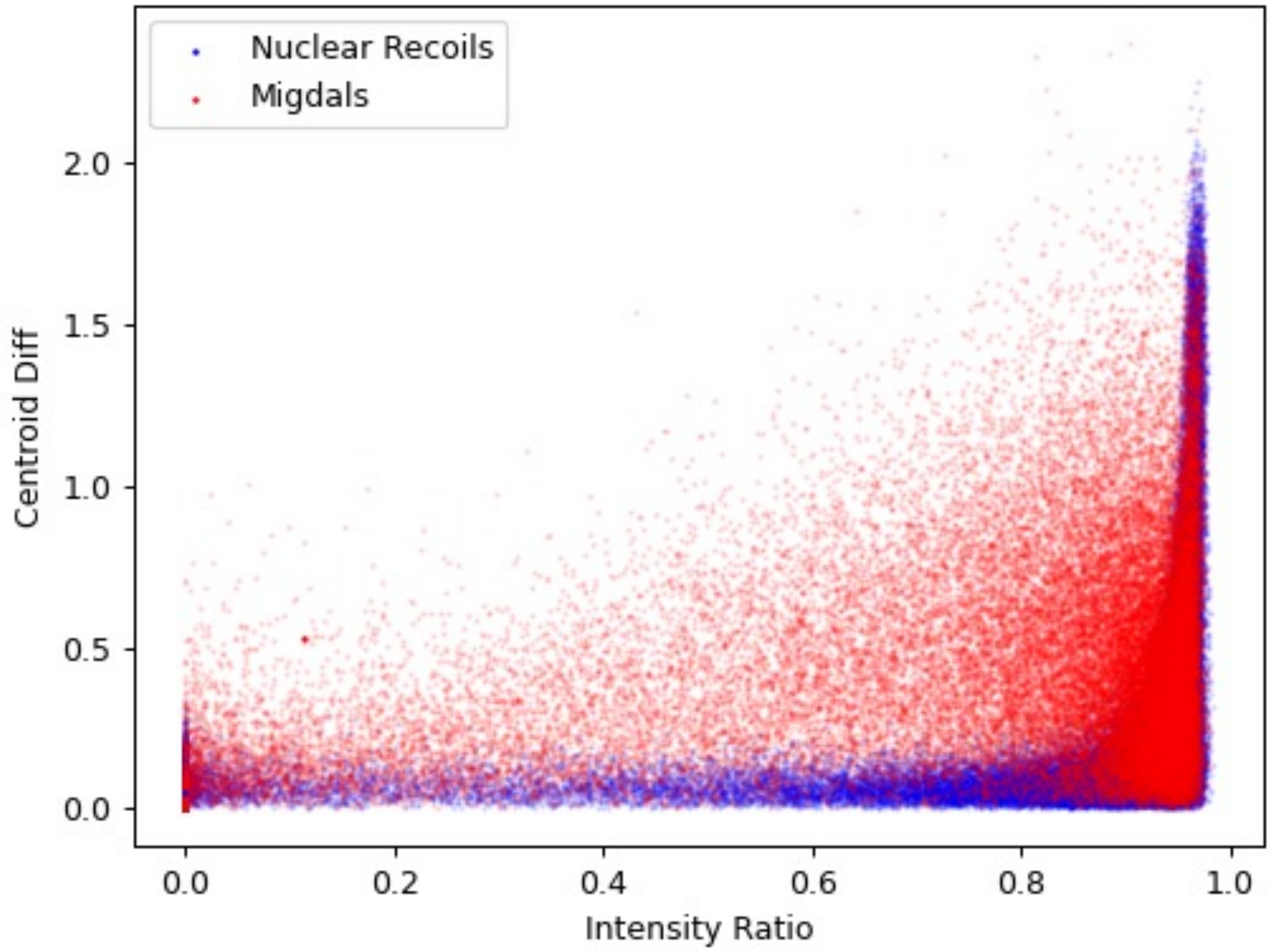
Intensity Std/Track Intensity
Area Ratio
Centroid Difference
Intensity Std/Track Density
Major Axis
Intensity Ratio
Area Ratio
C Diff (cm)
Intensity Std/Density (1/cm^2)
Major Axis (cm)
Intensity Ratio
Intensity Std/Intensity
Area Ratio
C Diff (cm)
Intensity Std/Density (1/cm^2)
Major Axis (cm)
Intensity Ratio



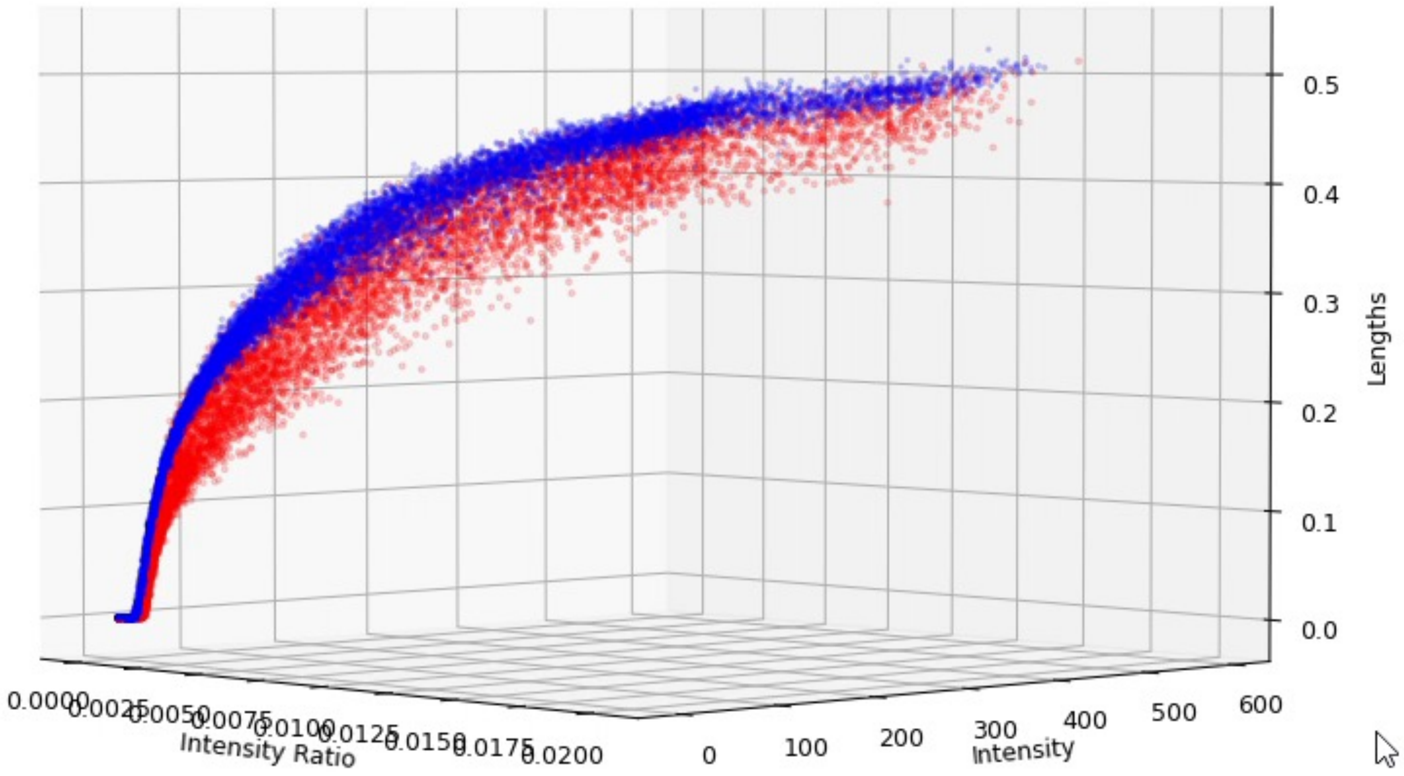
Nuclear Recoils
Migdals
Centroid Diff
0.0
0.5
1.0
1.5
2.0
0.0
0.1
0.2
0.3
0.4
0.5
Area Ratio



Nuclear Recoils
Migdals
Major Axis Length
Centroid Diff
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0

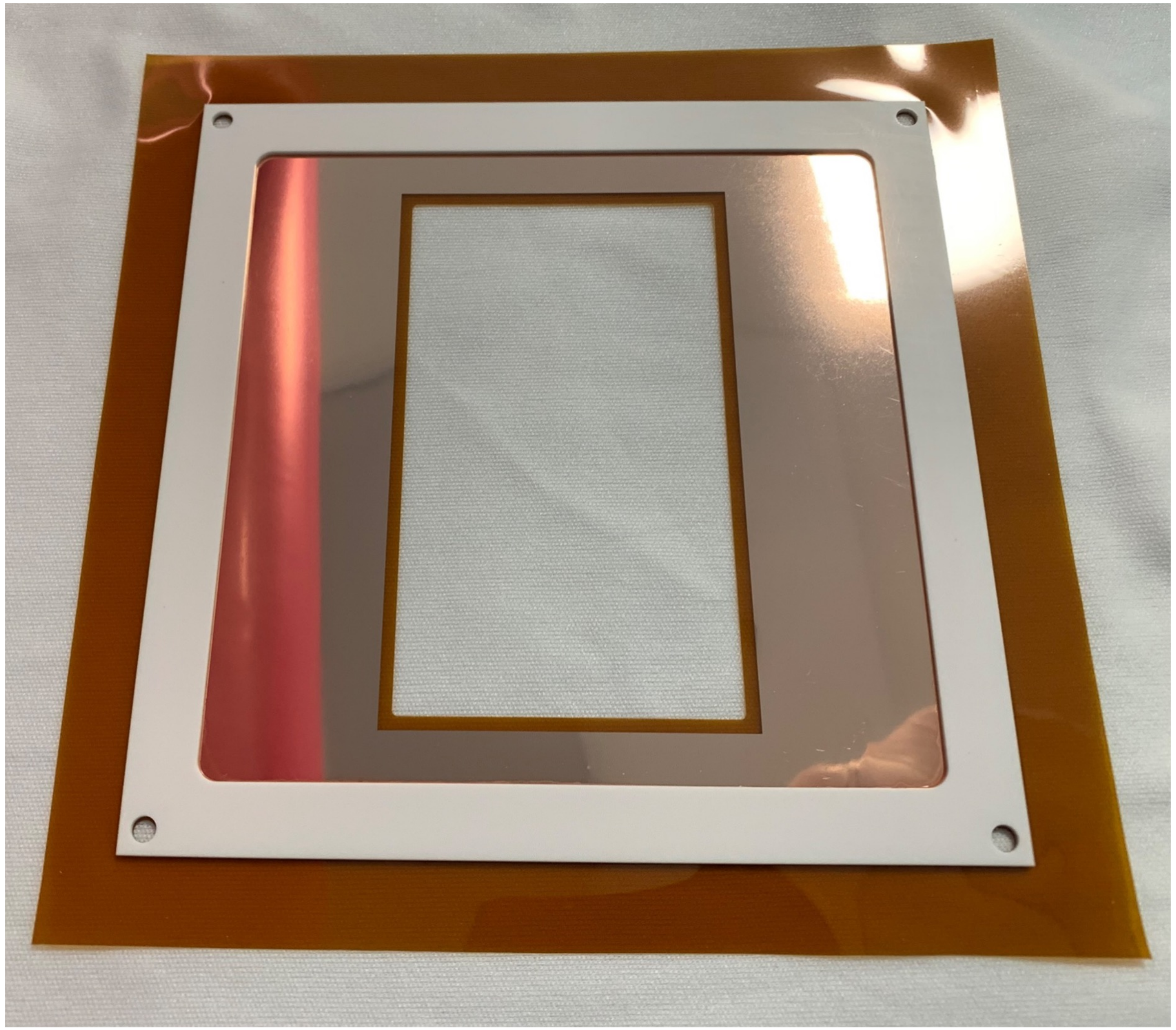


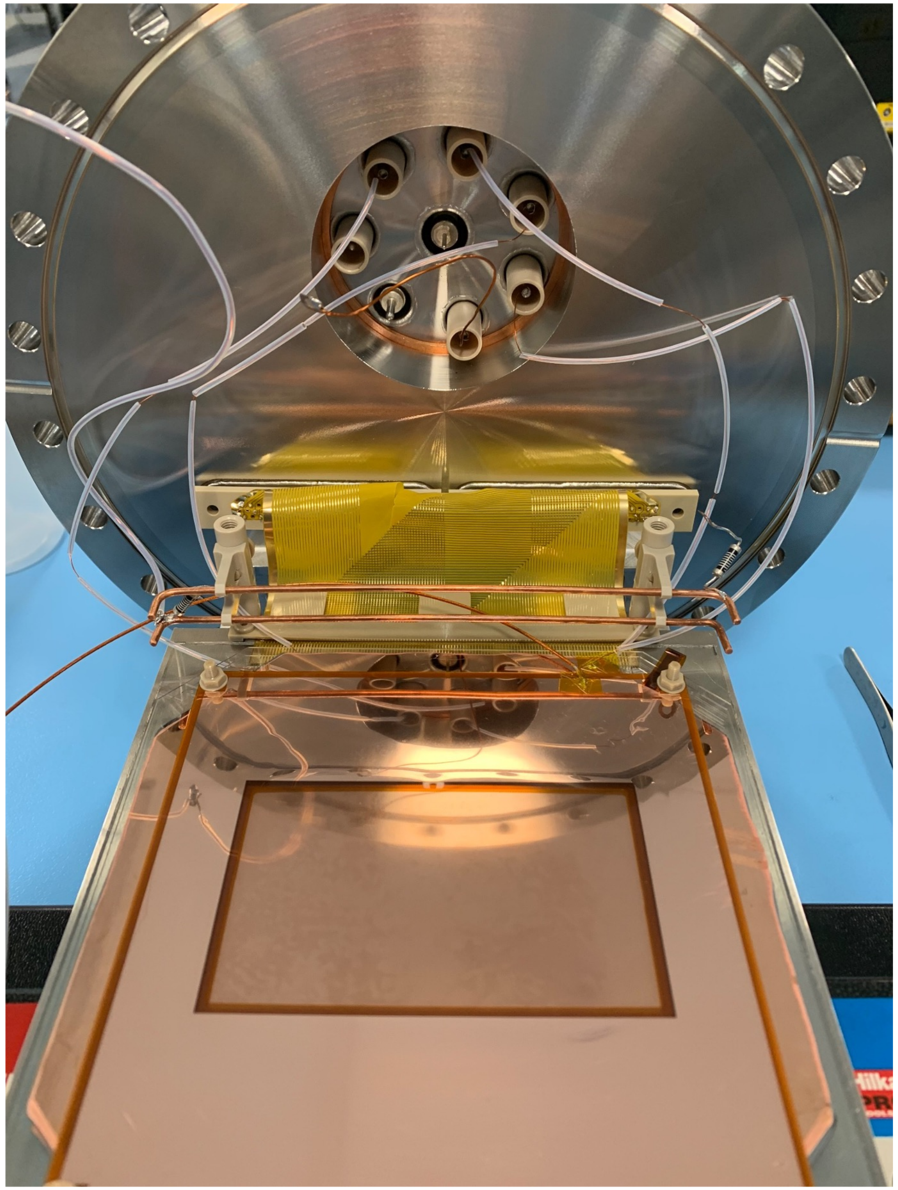
Nuclear Recoils
Migdals
Centroid Diff
0.0
0.5
1.0
1.5
2.0
0.0
0.2
0.4
0.6
0.8
1.0
Intensity Ratio



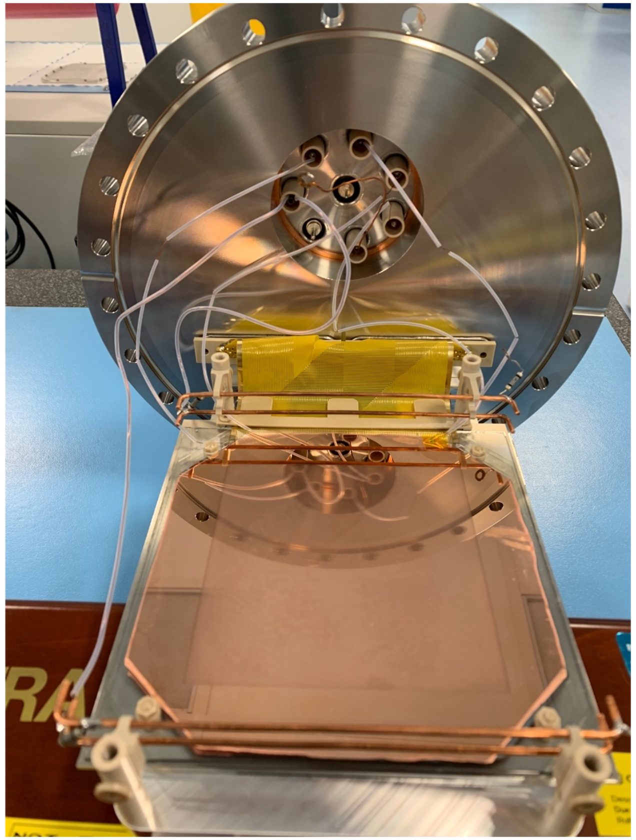
0.0
0.1
0.2
0.3
0.4
0.5
Lengths
0.0000
0.0025
0.0050
0.0075
0.0100
0.0125
0.0150
0.0175
0.0200
Intensity Ratio
0
100
200
300
400
500
600
Intensity

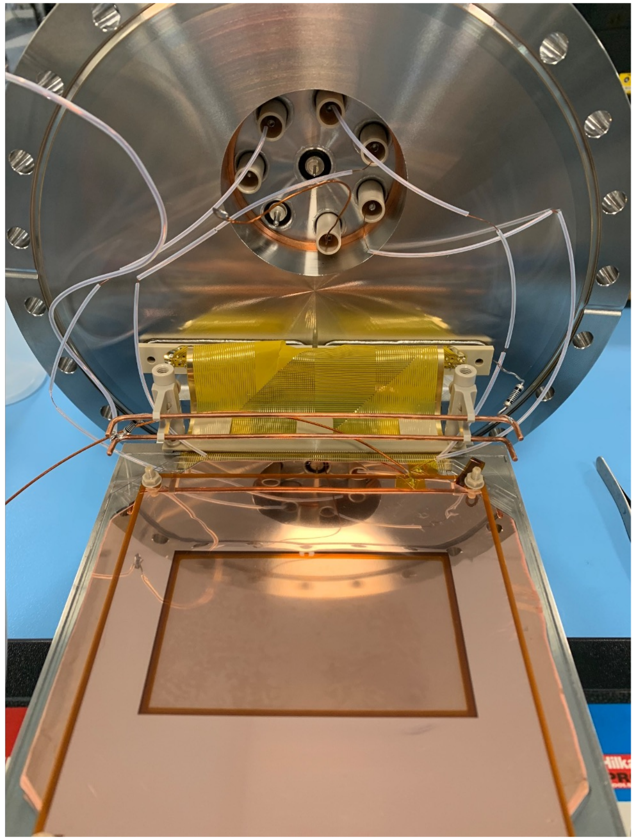
Mask assembly

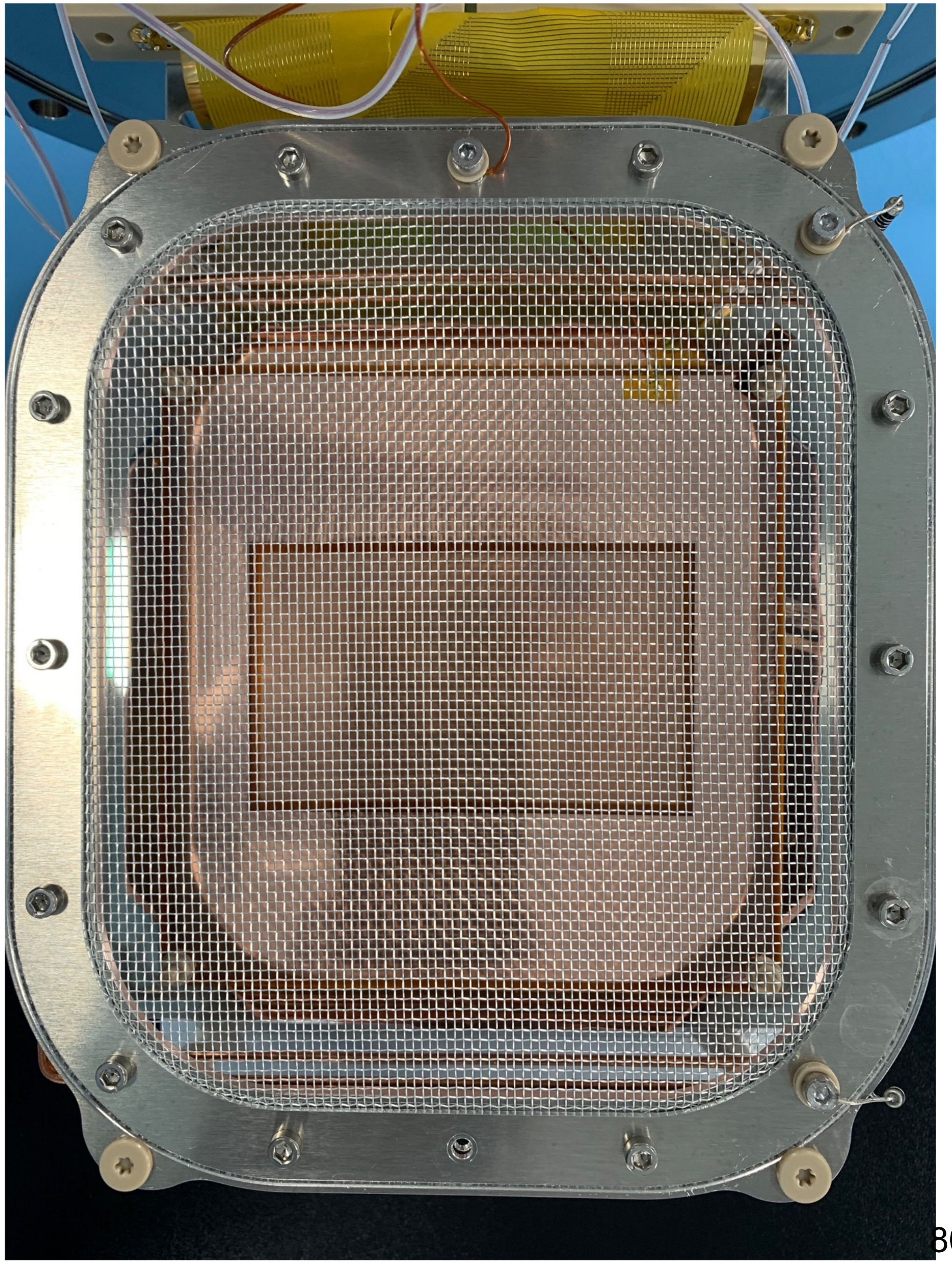




Mask assembly







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.

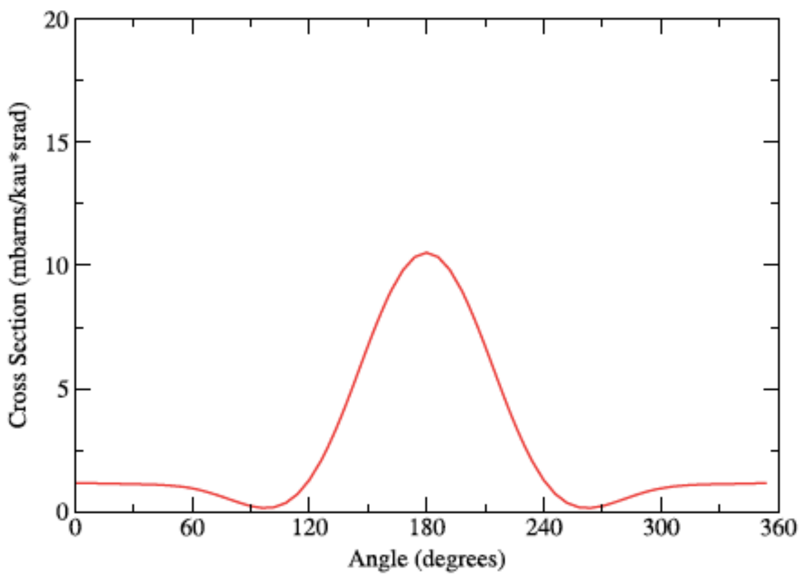


Figure 4. Neutron-impact single ionization of He at 100 keV. Solid line (red): TDCC method for the single ionization differential cross section with $k = 2.0$ and $\phi = 0$ (1.0 mbarn = 1.0×10^{-27} cm^2, kau = momentum in au, srad = solid angle in radians).

We would also like to measure the angular distribution of the Migdal electron…

Punch line is that only 10-20% of the NR energy is measured by XENON in the region of interest.

→ This means ~0.01 – 0.02 keV for 1 GeV WIMP!

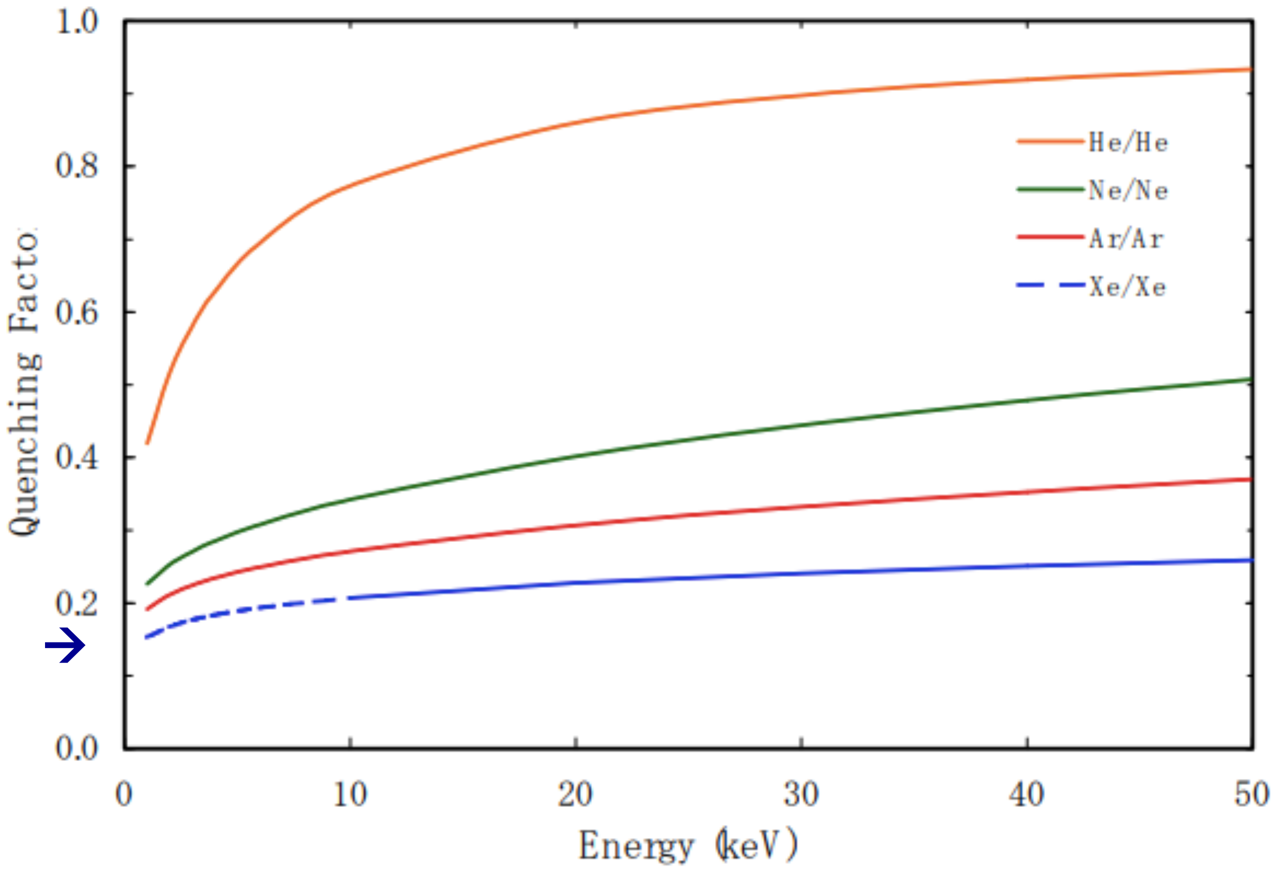


Figure 2. The nuclear quenching factor q_{nc} for recoil ions in, from top to bottom, He, Ne, Ar and Xe as a function of the recoil energy at 1-50 keV.

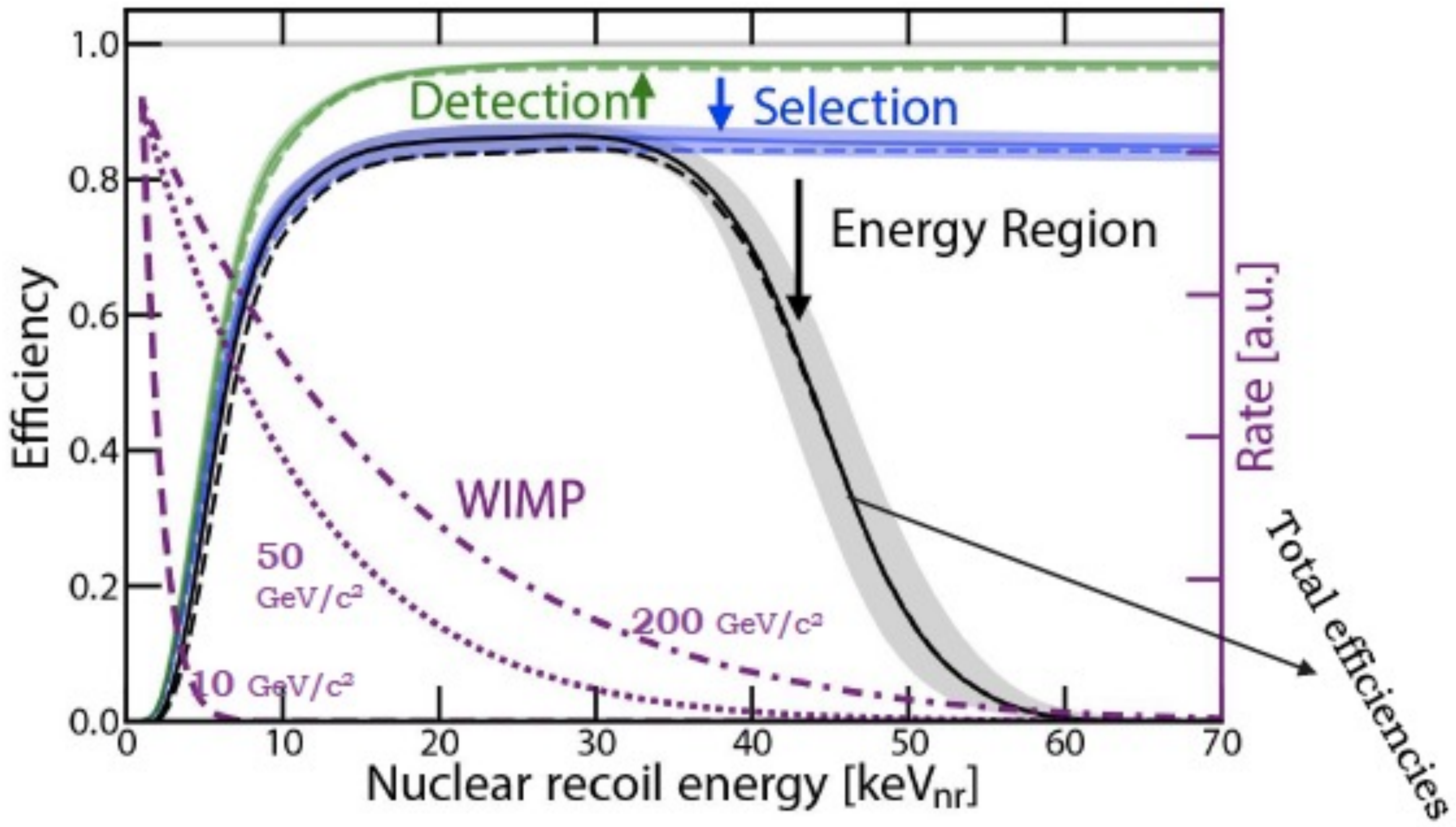
From Akira Hitachi 2007 J. Phys.: Conf. Ser. 65 012013

Summarizing the reasons for XENON's insensitivity to low mass WIMPs:

1. Maximum recoil energy for a 1 GeV/c² WIMP:

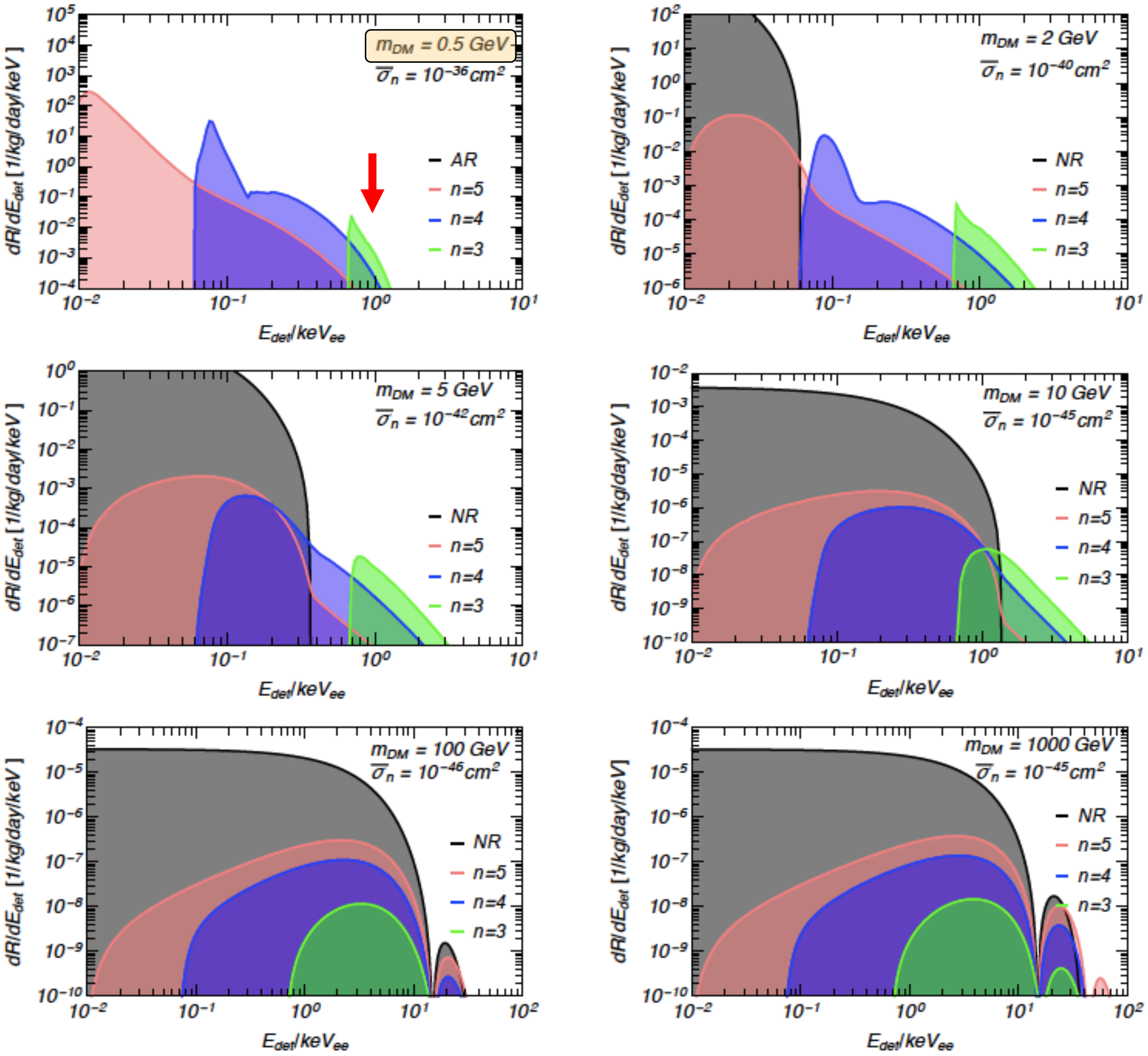
2. d

3. C
d



From Giovanni Volta's talk at the Swiss Physics Society Annual Meeting, August 29, 2019

Differential event rate as a function of **detected** energy

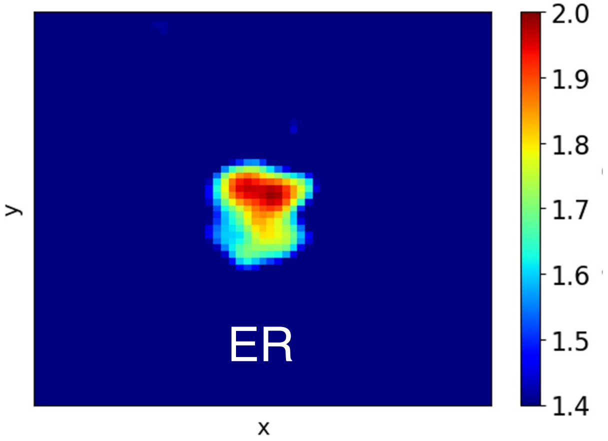


Ibe et al., JHEP, arXiv:1707.07258

D Loomba

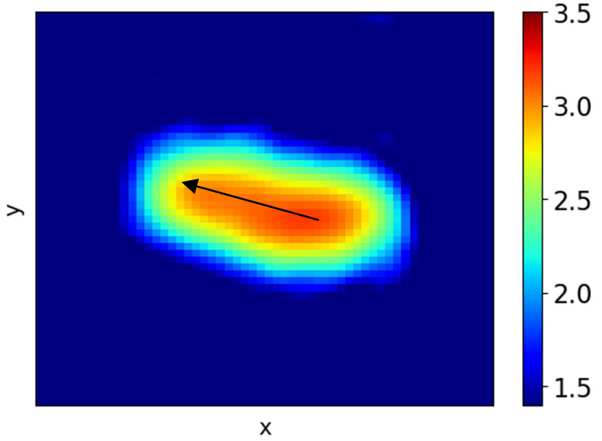
YOLO Capabilities

Classification



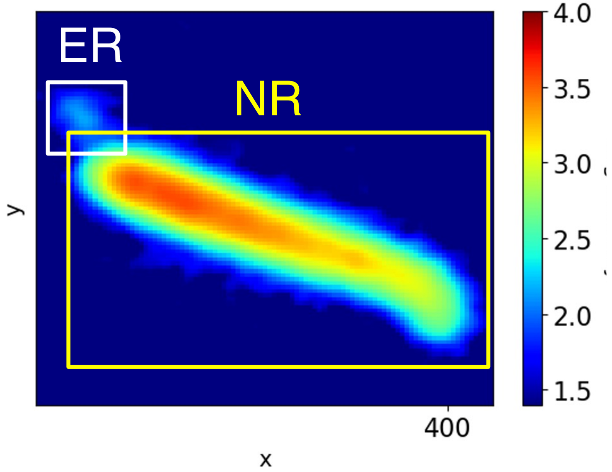
Application:
Particle ID

Regression



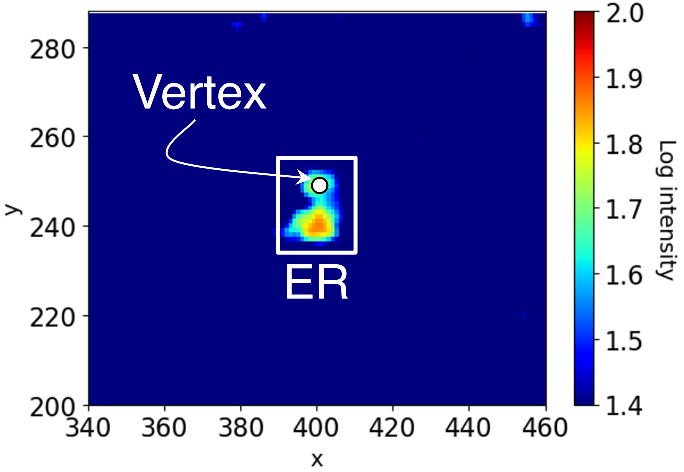
Applications:
*1. **Directional reconstruction***
2. Energy reconstruction

Object detection



Application:
Rare event searches (Migdal effect)

Key point(s) detection



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

Many implementations of algorithms for object detection and key point detection already exist (see here and here), and there are many tools for developing custom classification and regression models for 2D and 3D image data (PyTorch tutorial, TensorFlow tutorial, spconv for sparse 3D convolutional neural networks). ***Today I'll highlight examples of (1) directional reconstruction for a CYGNUS prototype BEAST TPC and (2) object detection for the rare event Migdal search***