Results from the MIGDAL experiment

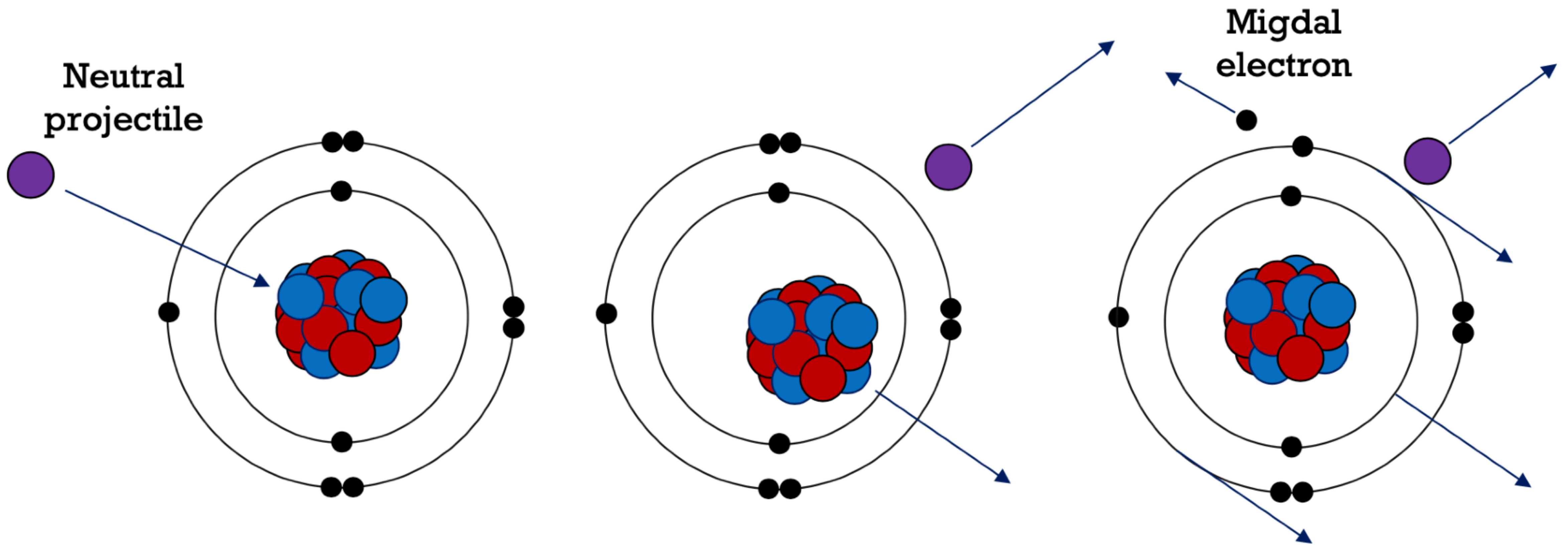
Lex Millins
University of Birmingham & STFC Rutherford Appleton Laboratory
Now at *University of Hamburg*

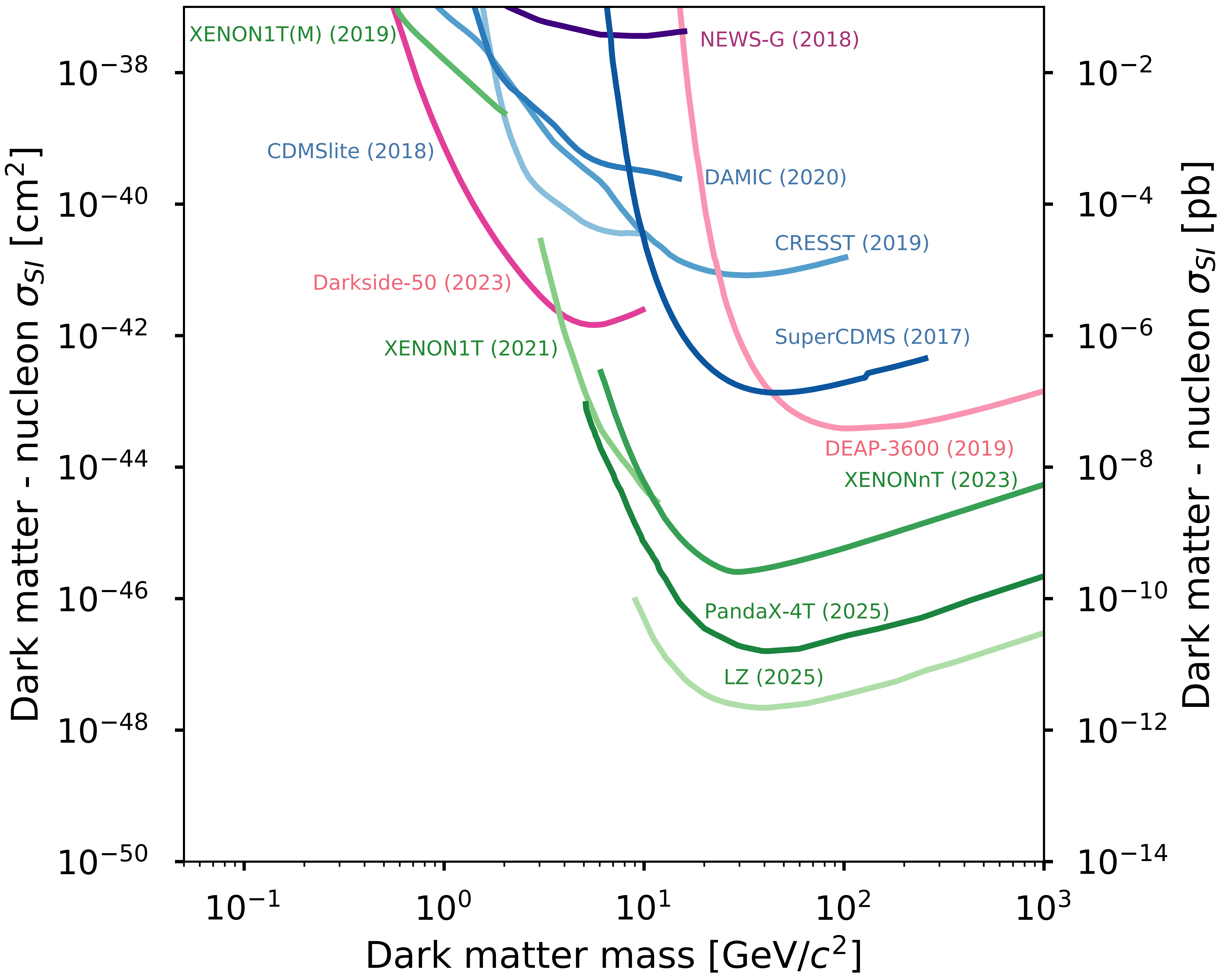
Identification of Dark Matter 2026
Zaragoza 2nd June 2026

lex.millins@cern.ch

DM direct detection and the Migdal effect

- Much progress made in search for WIMP-like DM
- Sub-GeV less explored as experimentally more challenging
- Can exploit the Migdal effect which leads to additional energy above threshold
  - Recently measured in nuclear scattering for the first time *[Nature 649, 580–583 (2026)]*

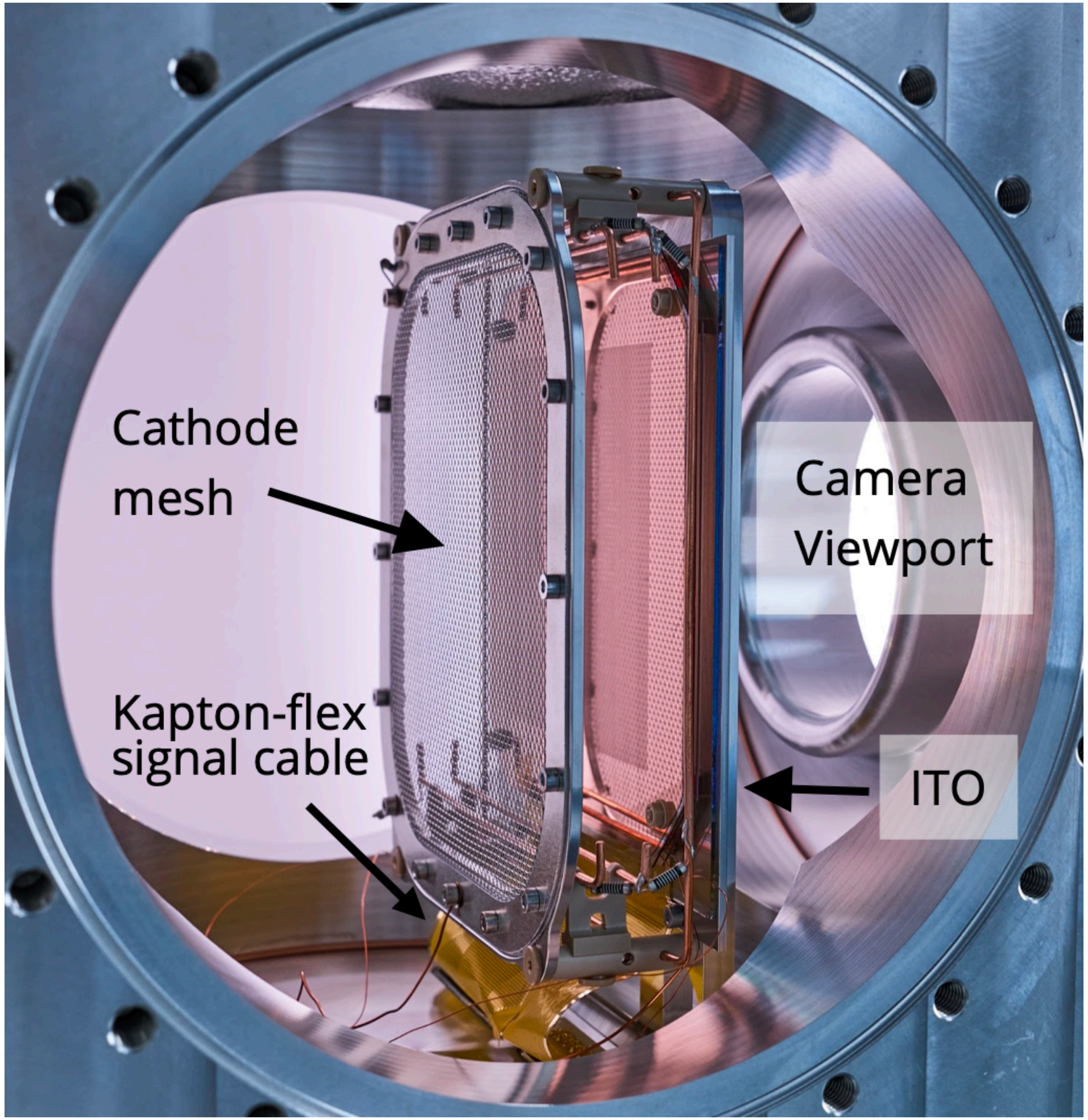




UNIVERSITY OF BIRMINGHAM

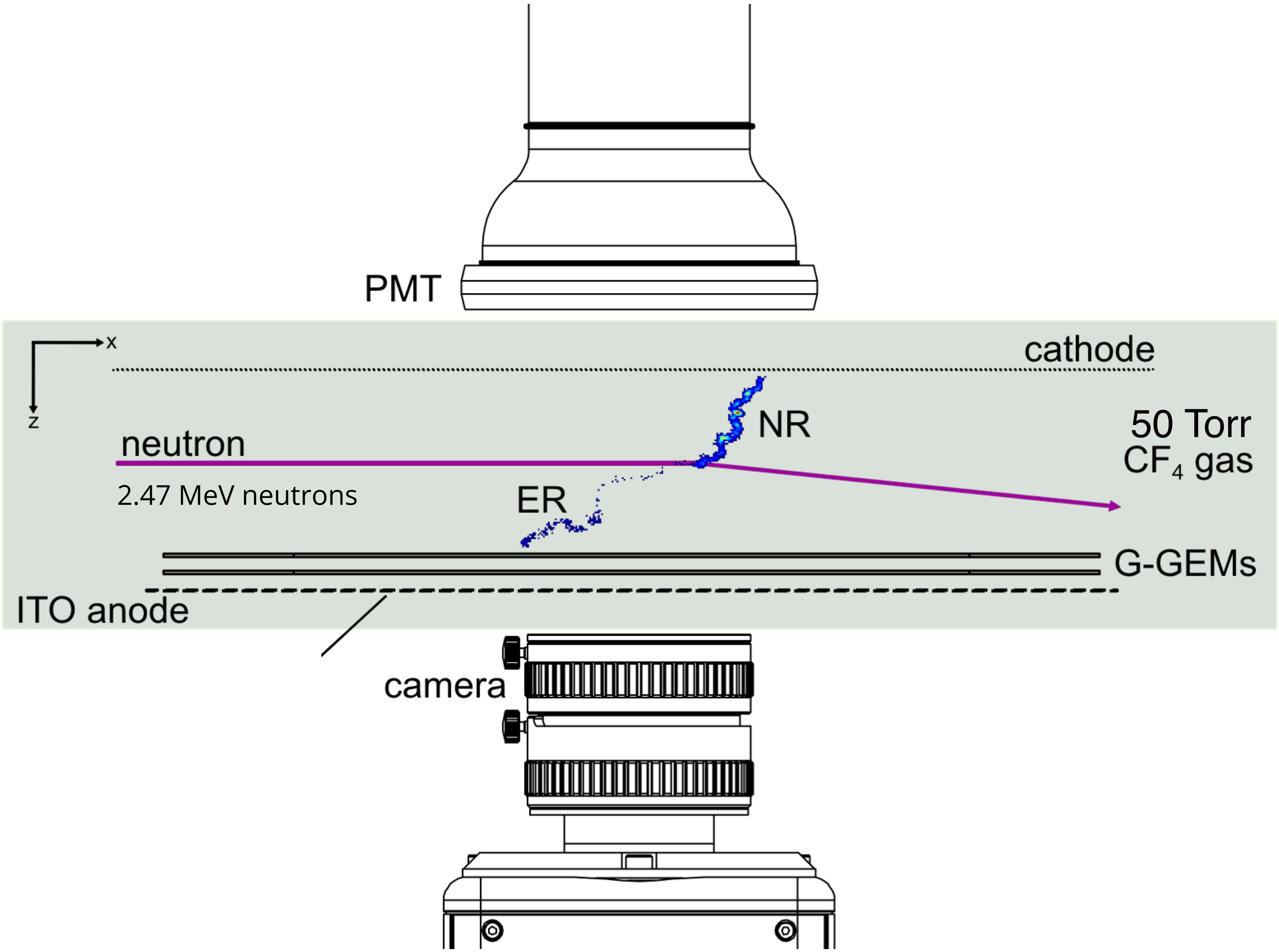
Science and Technology Facilities Council
Rutherford Appleton Laboratory

The MIGDAL Experiment



- Aim to characterise the Migdal Effect in CF_4 + noble gas mixtures
- Use a low pressure Optical Time Projection Chamber to image electron and nuclear recoil in three-dimensions

The MIGDAL Detector



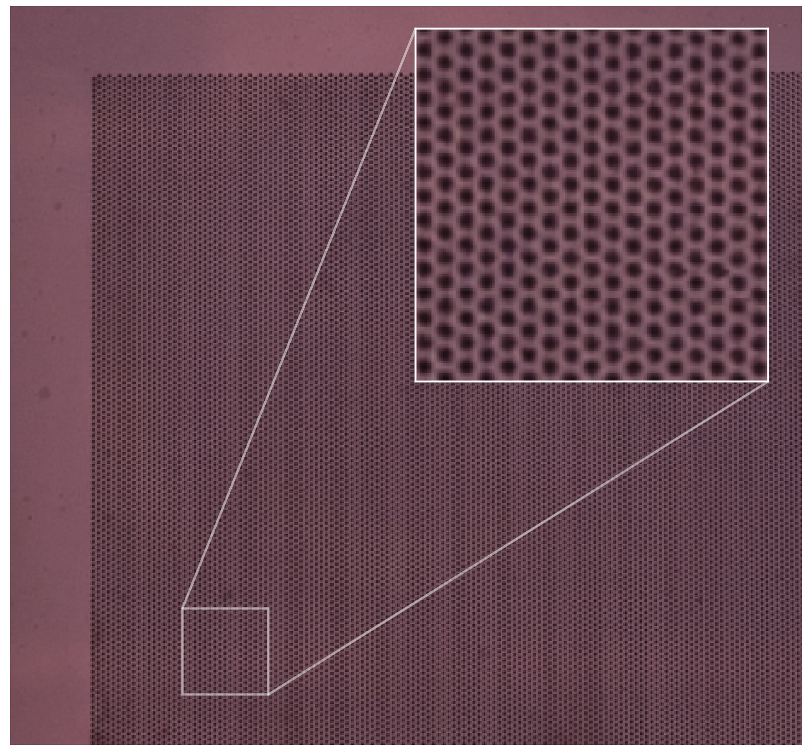
Astropart.Phys. 151 (2023) 102853

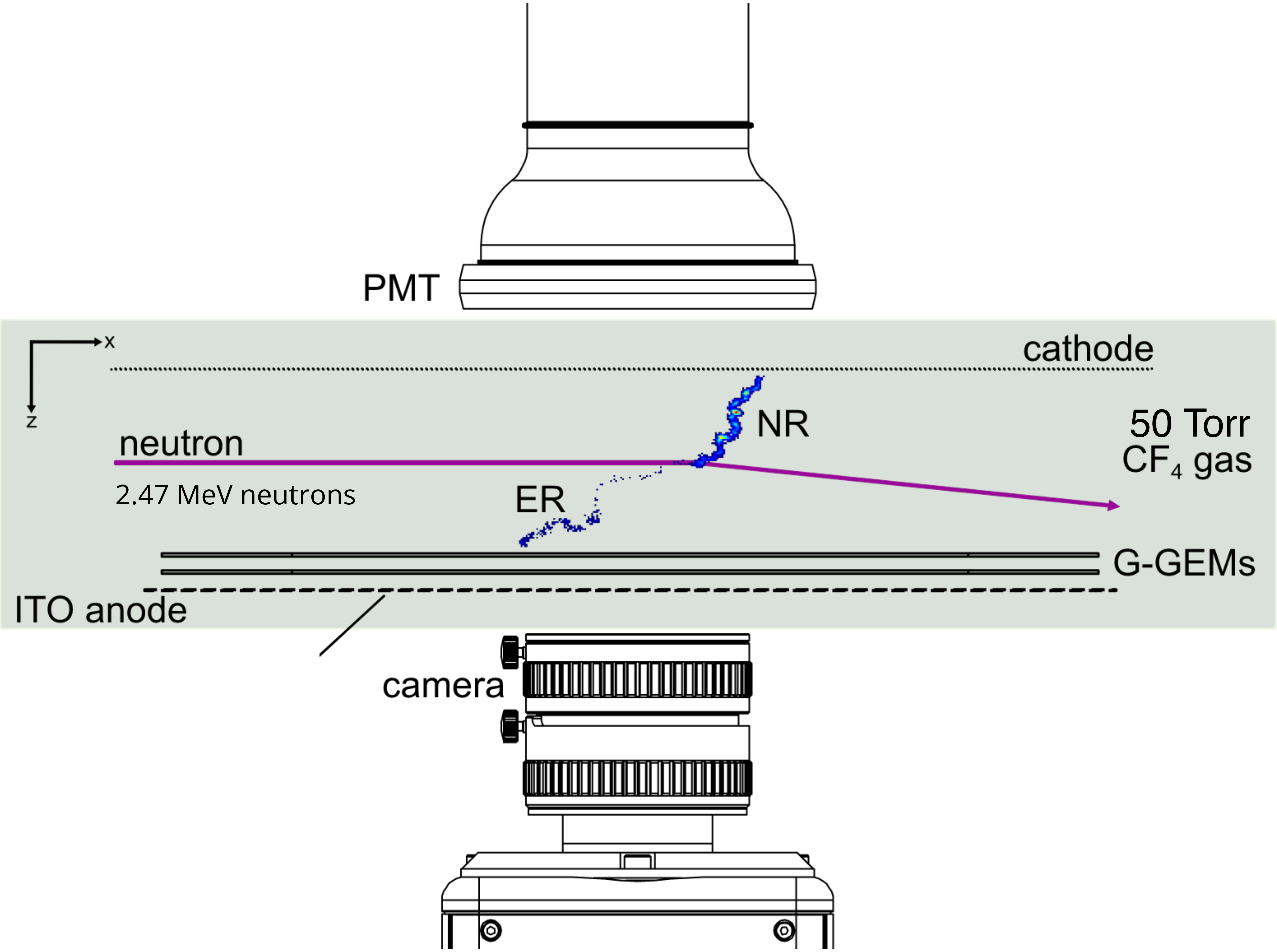
UNIVERSITY OF BIRMINGHAM

Science and Technology Facilities Council
Rutherford Appleton Laboratory

The MIGDAL Detector

Charge Amplification
Two glass GEMs



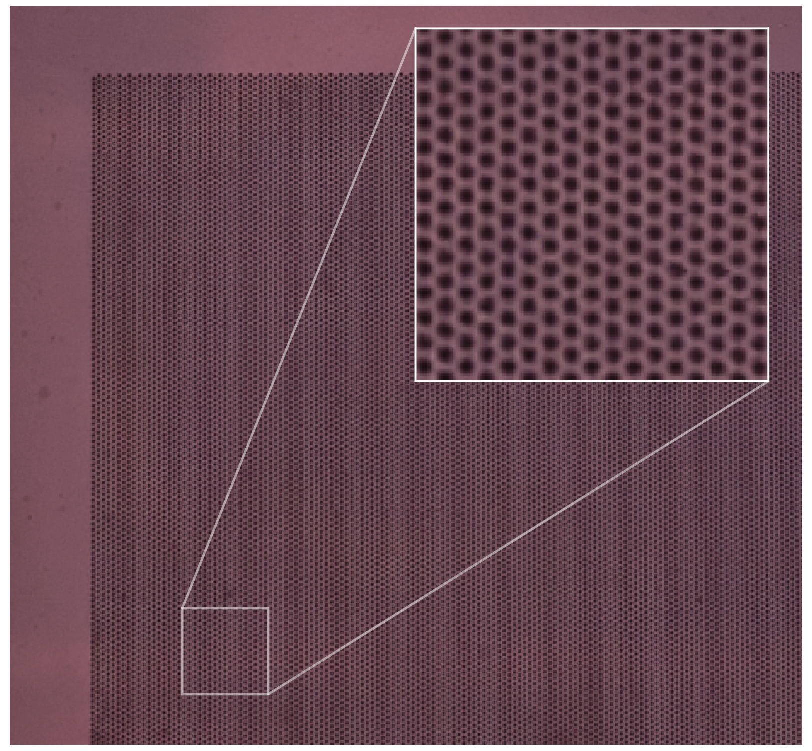


Astropart.Phys. 151 (2023) 102853

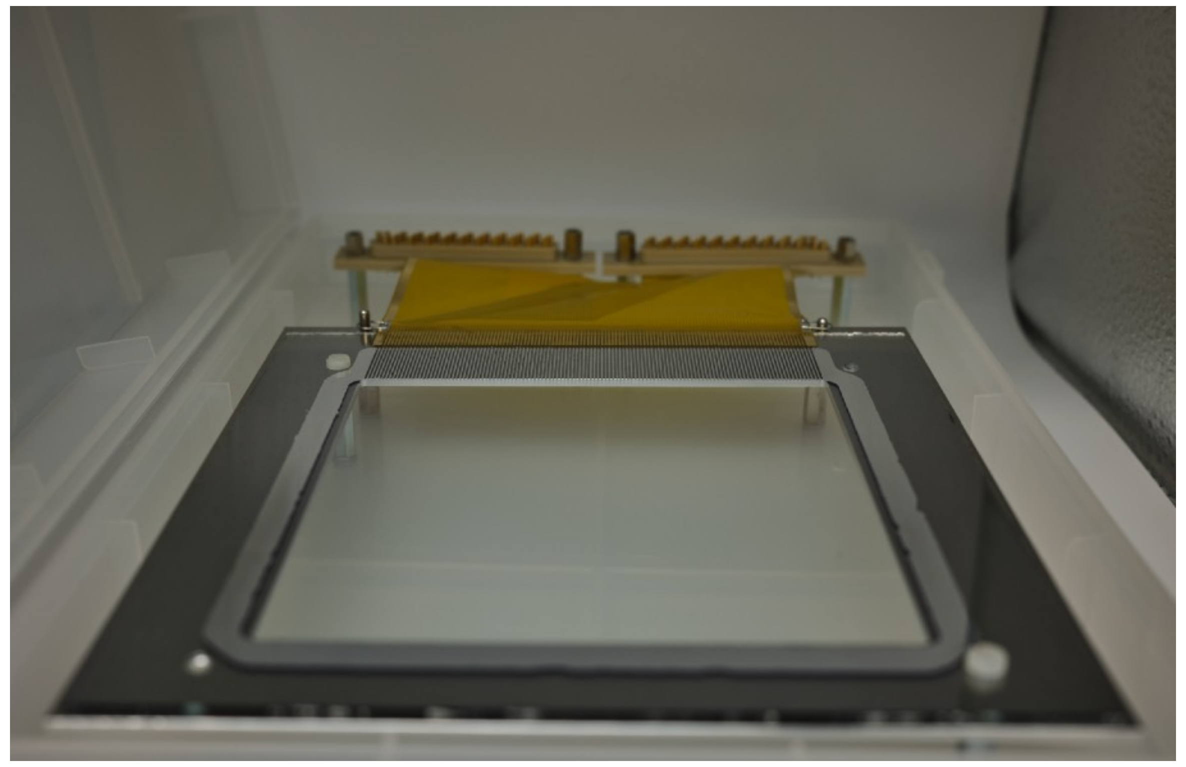
UNIVERSITY OF BIRMINGHAM
Science and Technology Facilities Council
Rutherford Appleton Laboratory

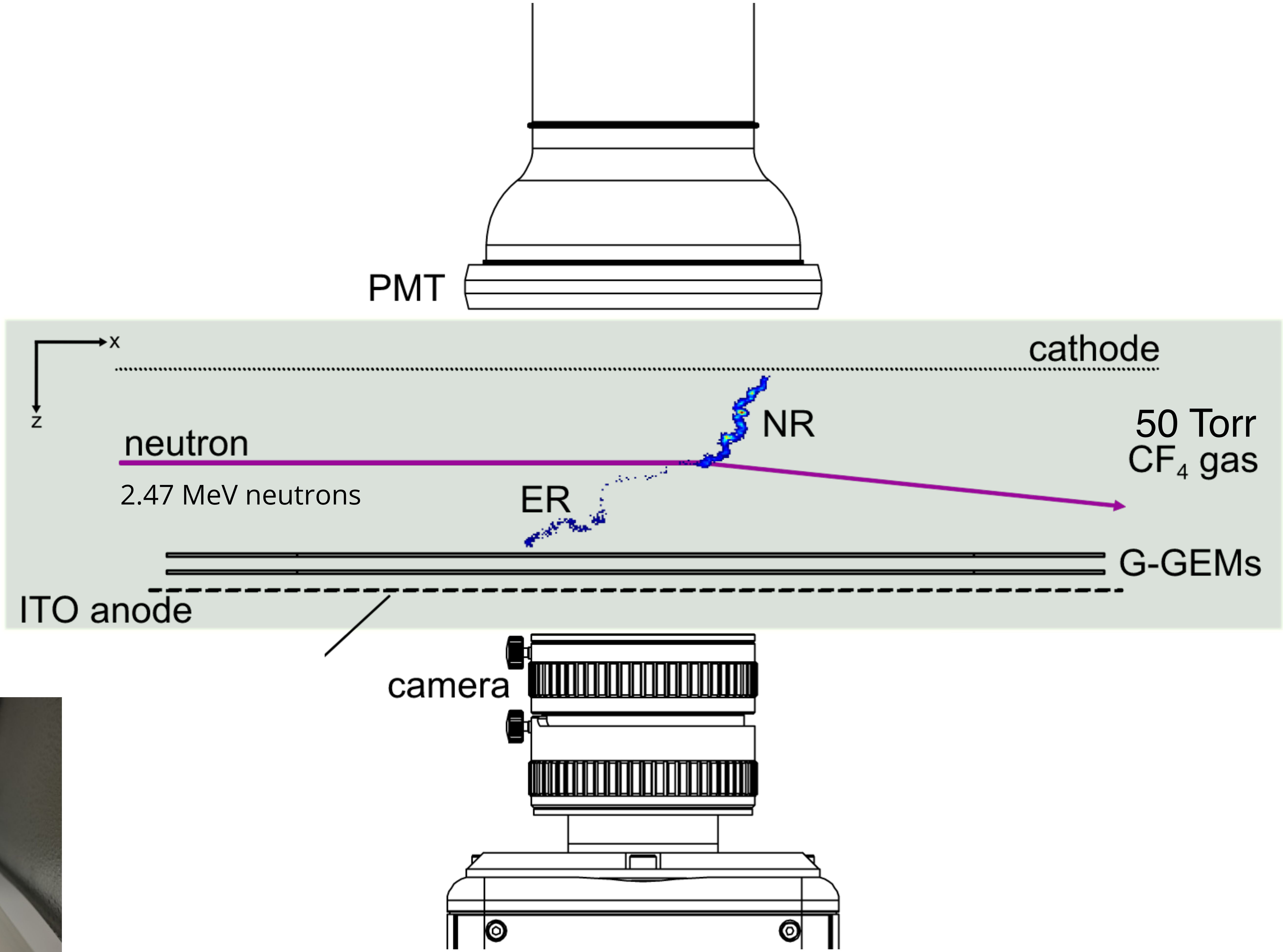
The MIGDAL Detector

Charge Amplification
Two glass GEMs



Charge read-out
anode segmented into
120 strips

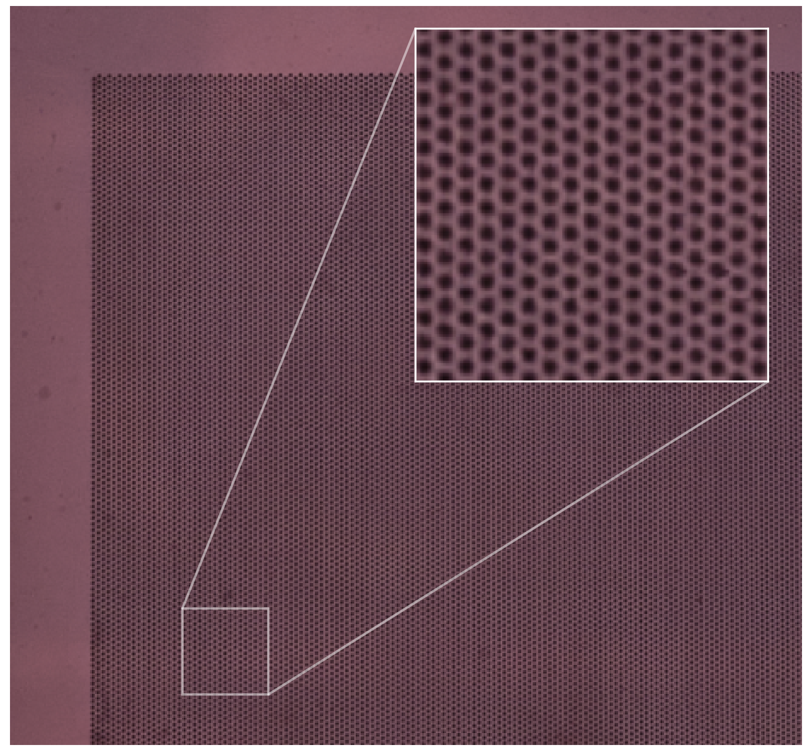




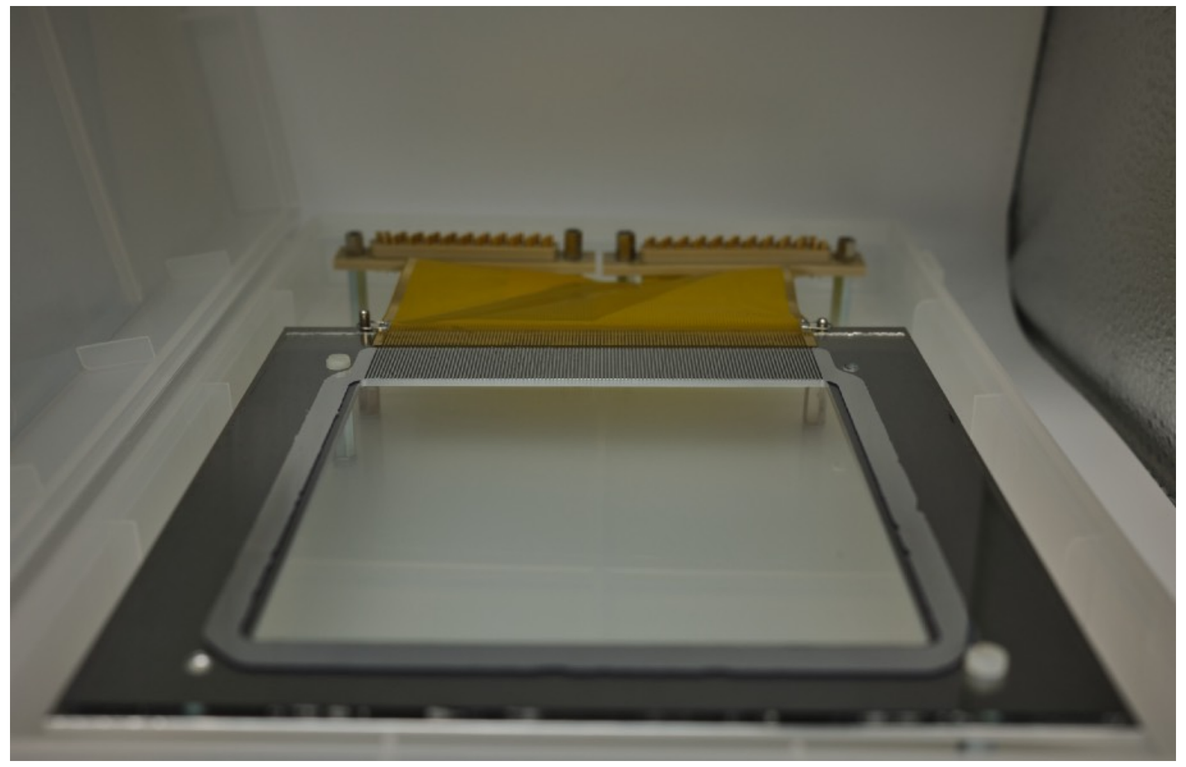
[Astropart.Phys. 151 (2023) 102853](https://doi.org/10.1016/j.astropartphys.2023.102853)

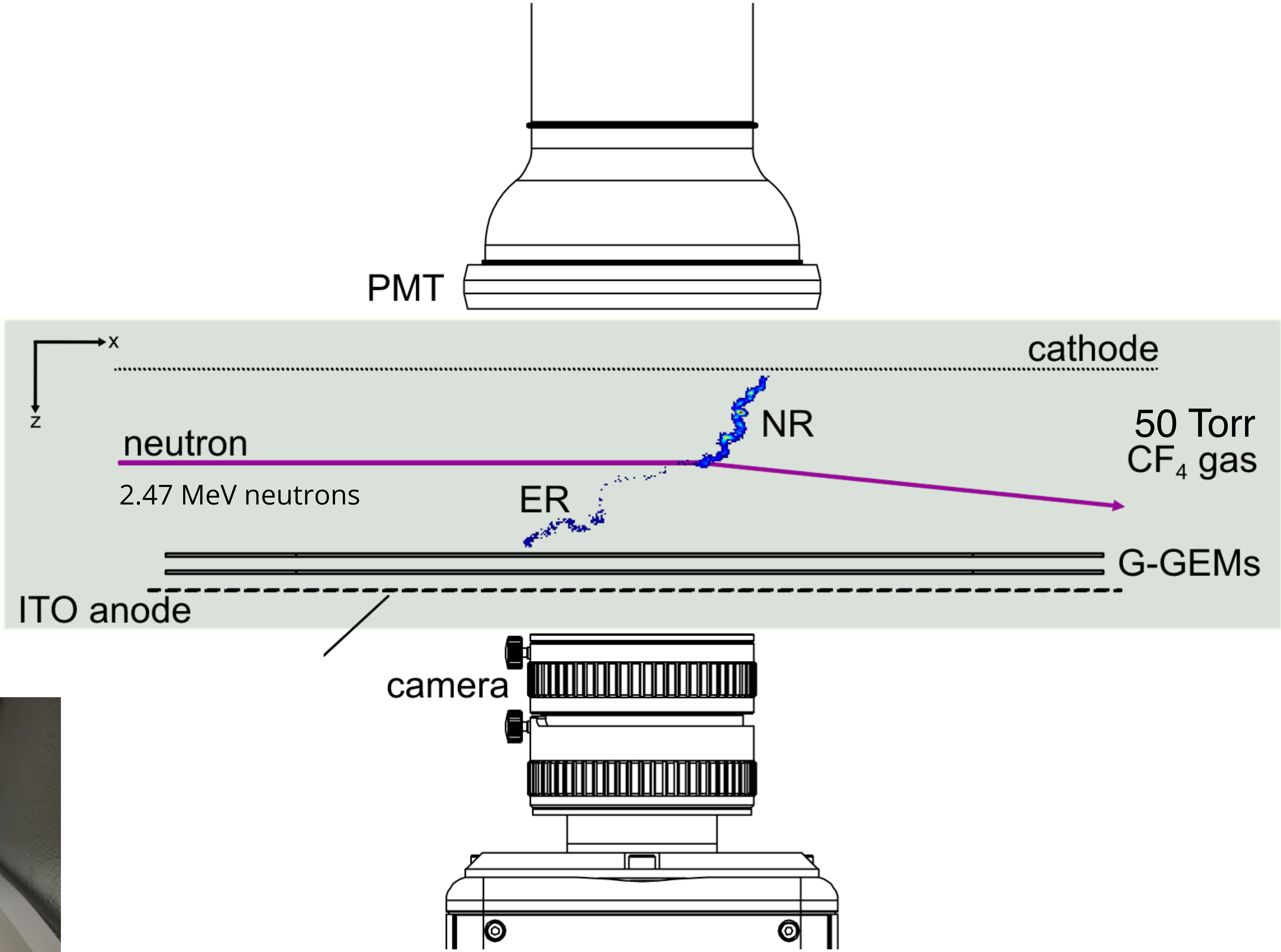
The MIGDAL Detector

Charge Amplification
Two glass GEMs



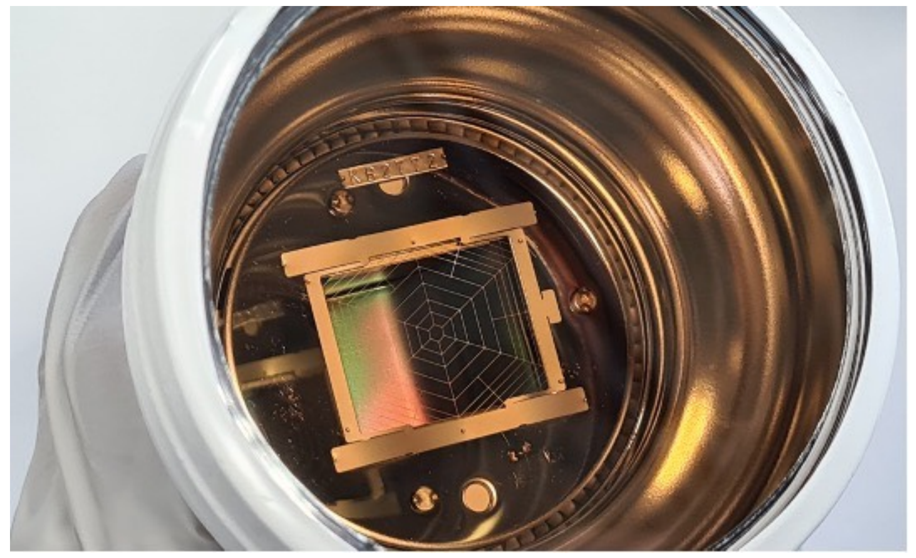
Charge read-out
anode segmented into 120 strips





Astropart.Phys. 151 (2023) 102853

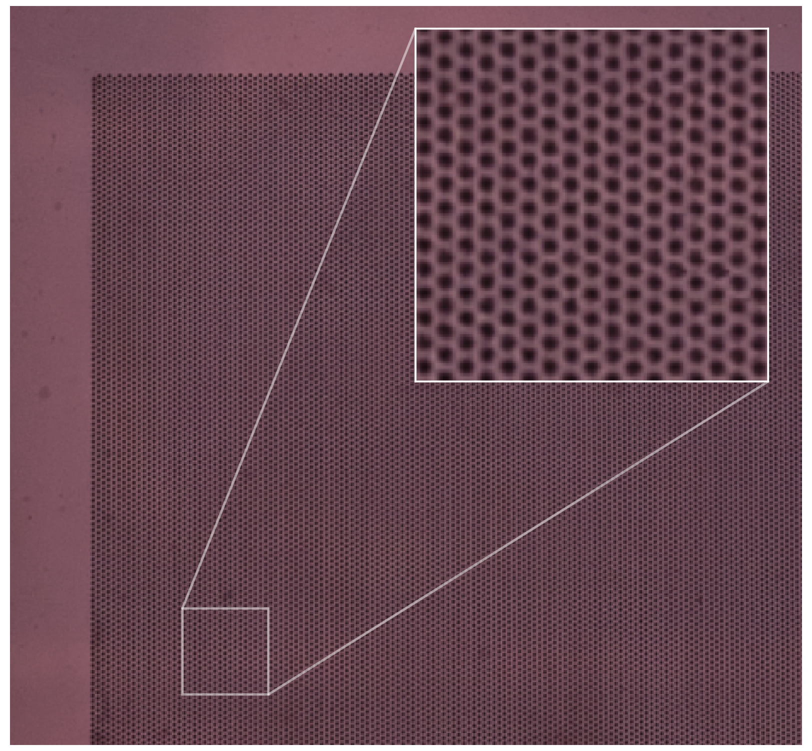
Trigger and timing
Hamamatsu R11410 VUV PMT



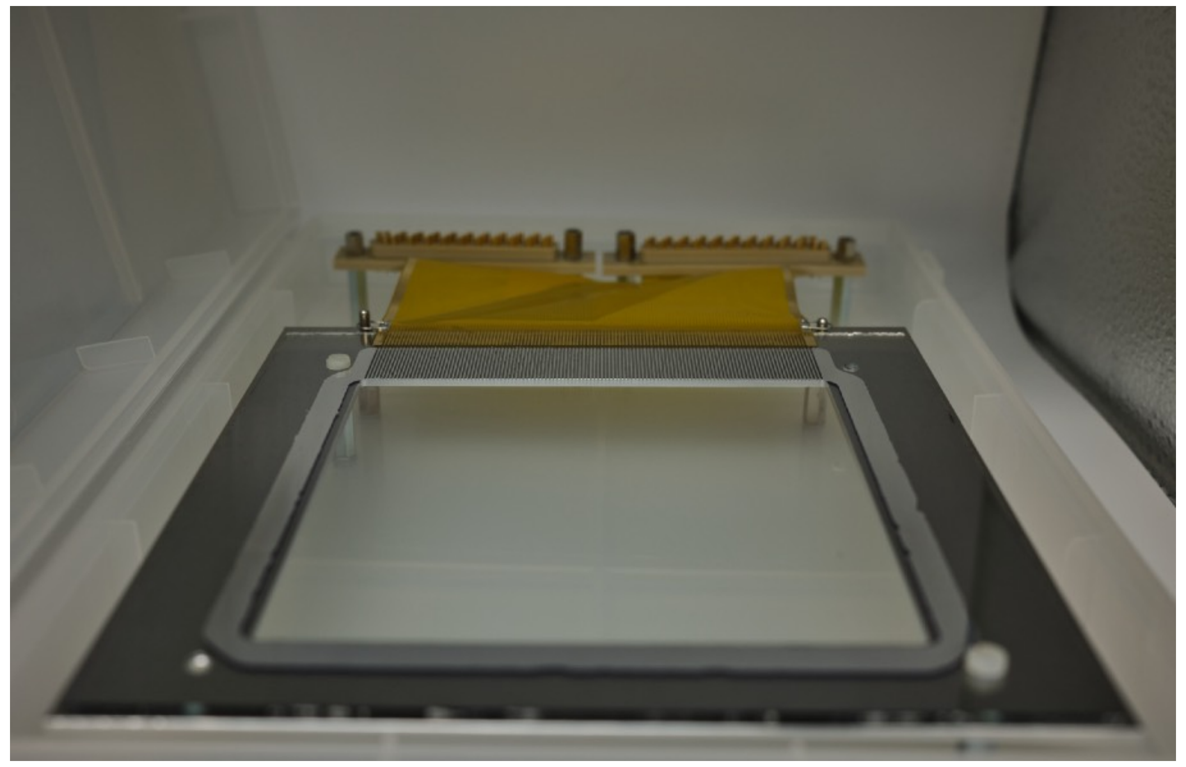
UNIVERSITY OF BIRMINGHAM
Science and Technology Facilities Council
Rutherford Appleton Laboratory

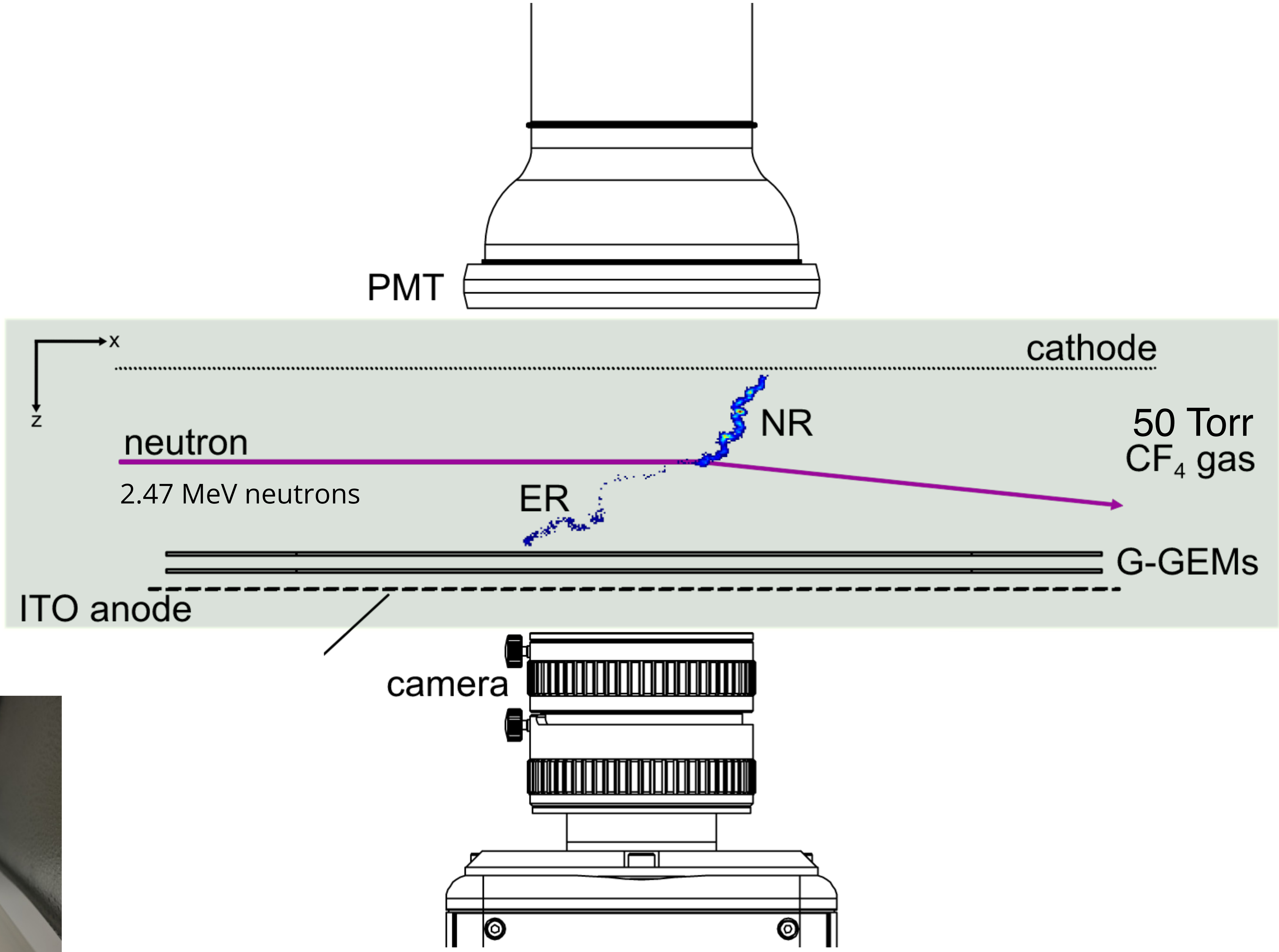
The MIGDAL Detector

Charge Amplification
Two glass GEMs



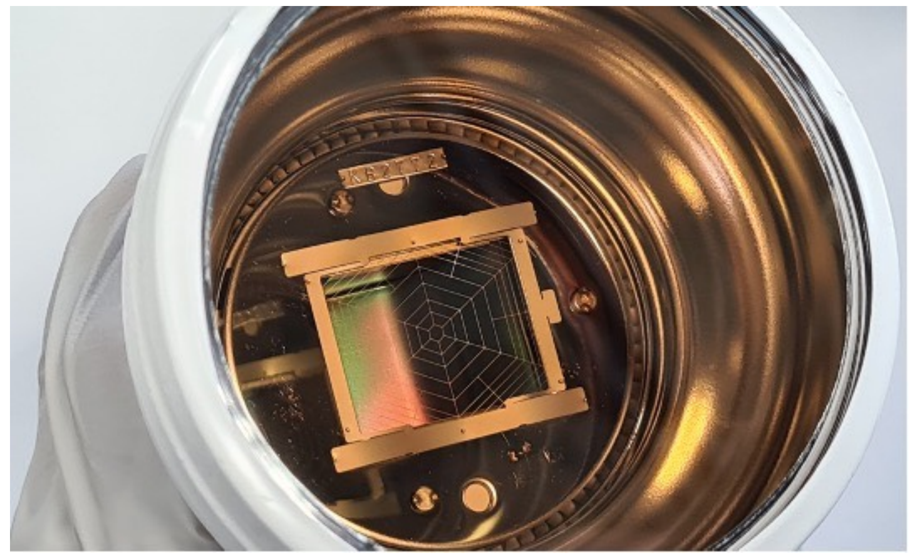
Charge read-out
anode segmented into
120 strips



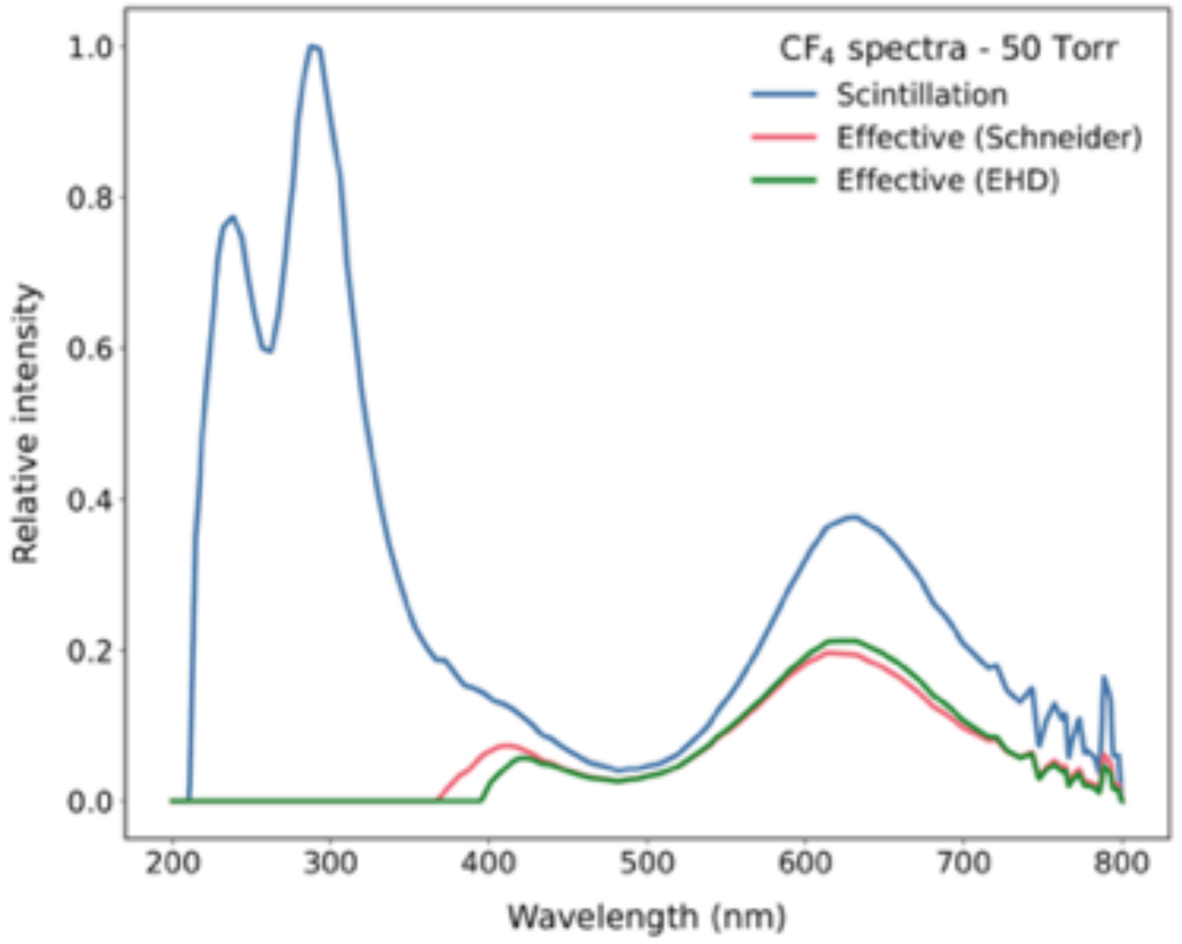


[Astropart.Phys. 151 (2023) 102853](#)

Trigger and timing
Hamamatsu R11410 VUV PMT



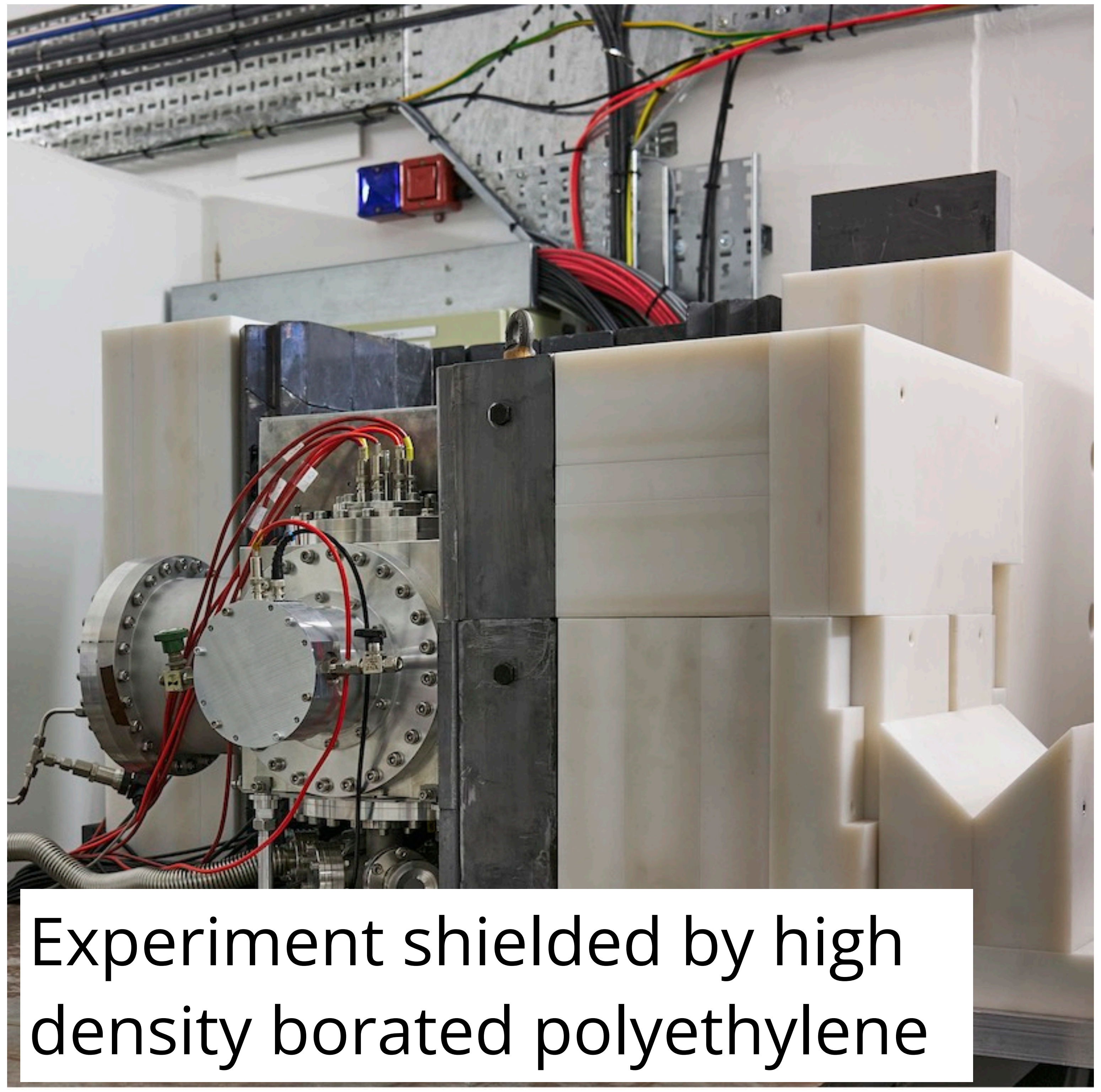
Light read-out
Orca Quest qCMOS camera
8.3 ms exposure



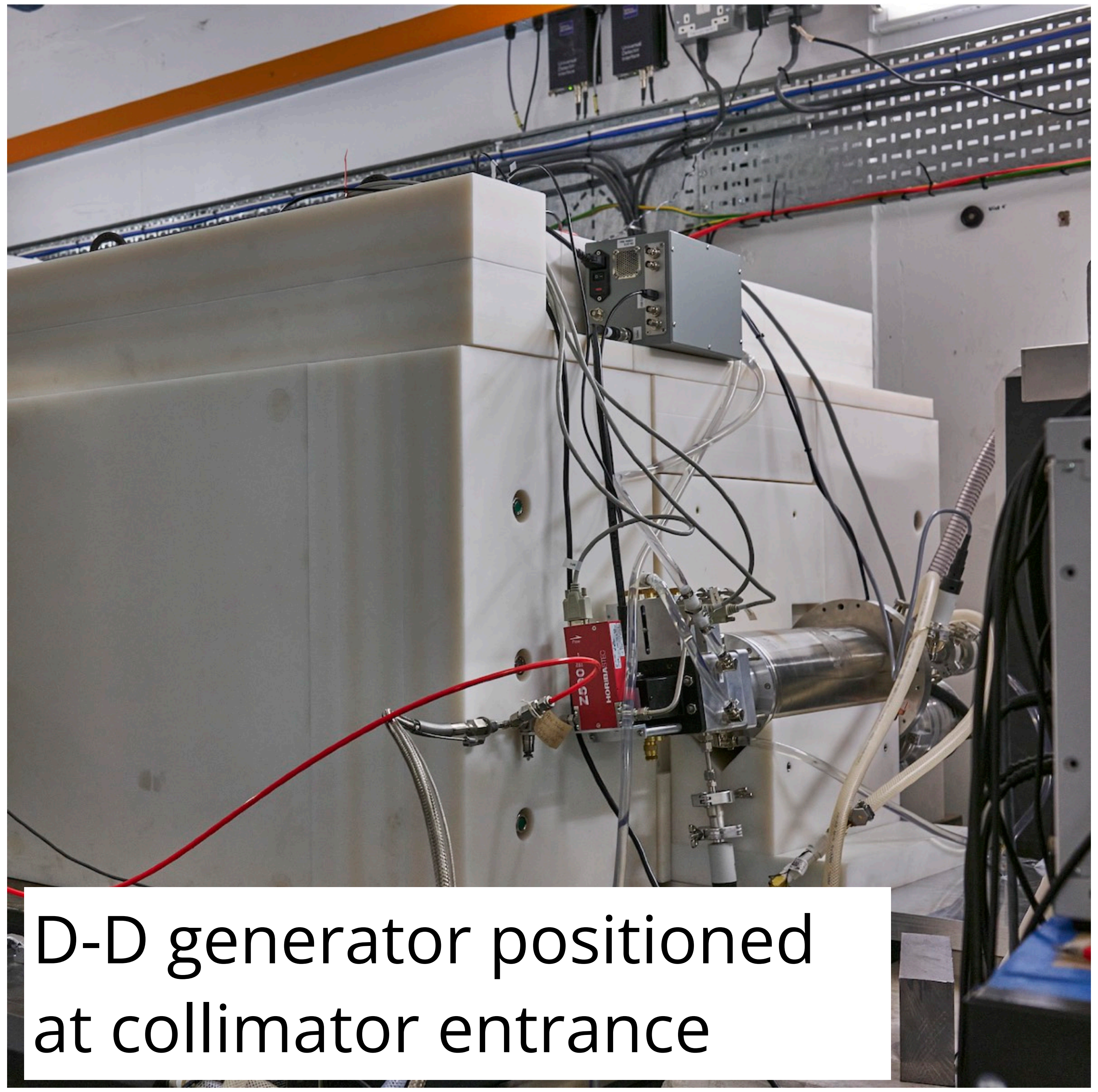
UNIVERSITY OF BIRMINGHAM
Science and Technology Facilities Council
Rutherford Appleton Laboratory

MIGDAL@NILE

- Installed summer 2023


Experiment shielded by high density borated polyethylene


Detector with lead shielding

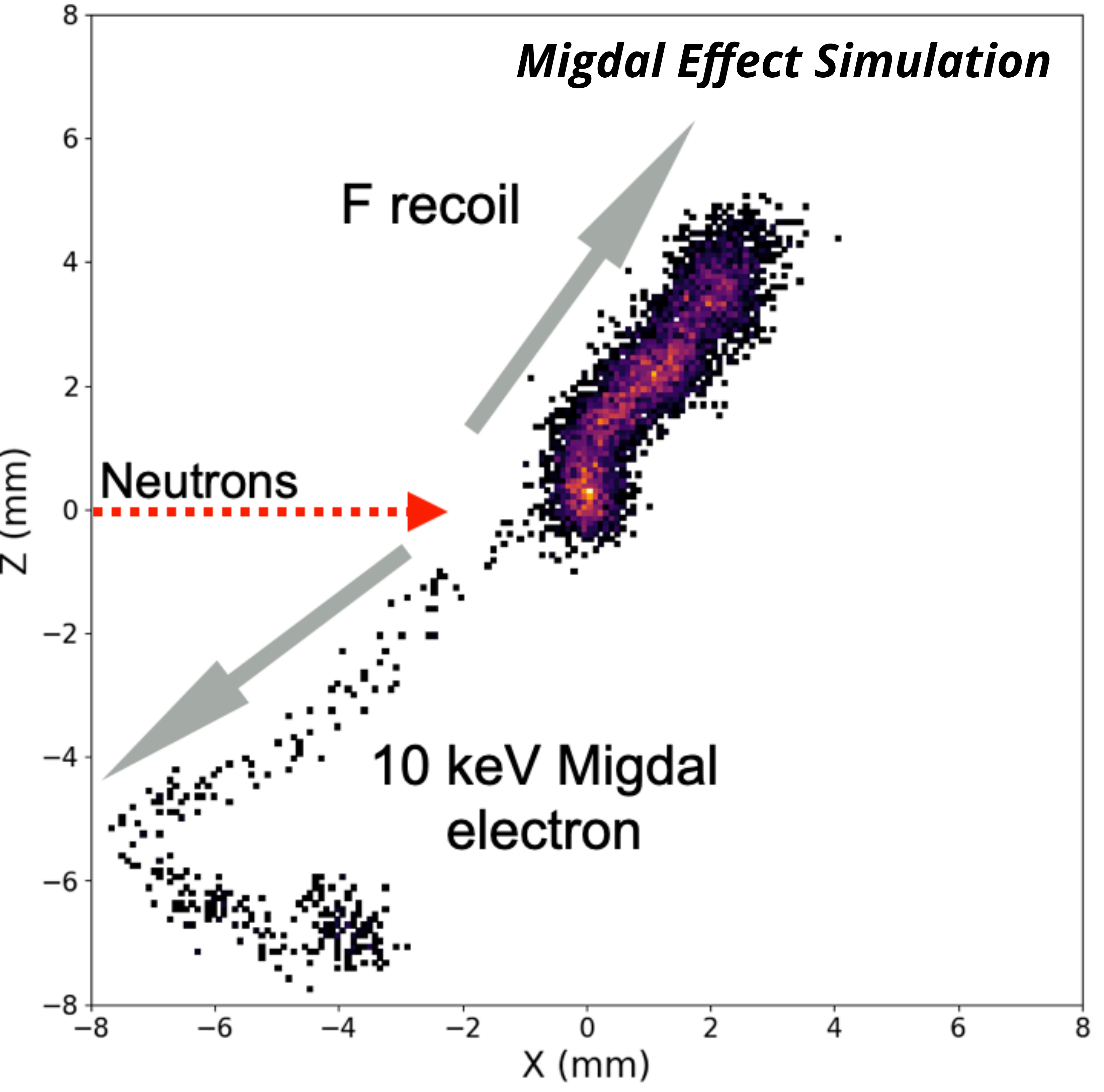

D-D generator positioned at collimator entrance

- Science run data collected from 15/01/2024 - 06/02/2024
- Gas replaced ~ every 3 days and calibration with ^{55}Fe every 3 hours
- Total exposure of 85.3 hours with ~3.6×10^5 nuclear recoils
- Initial selection criteria defined on 49% of the data

UNIVERSITY OF BIRMINGHAM
Science and Technology Facilities Council
Rutherford Appleton Laboratory

Signal and Backgrounds

- Backgrounds suppressed through energy thresholds and timing resolution
- Main source of background from gammas produced in inelastic scattering with fluorine Compton scattering near track vertex

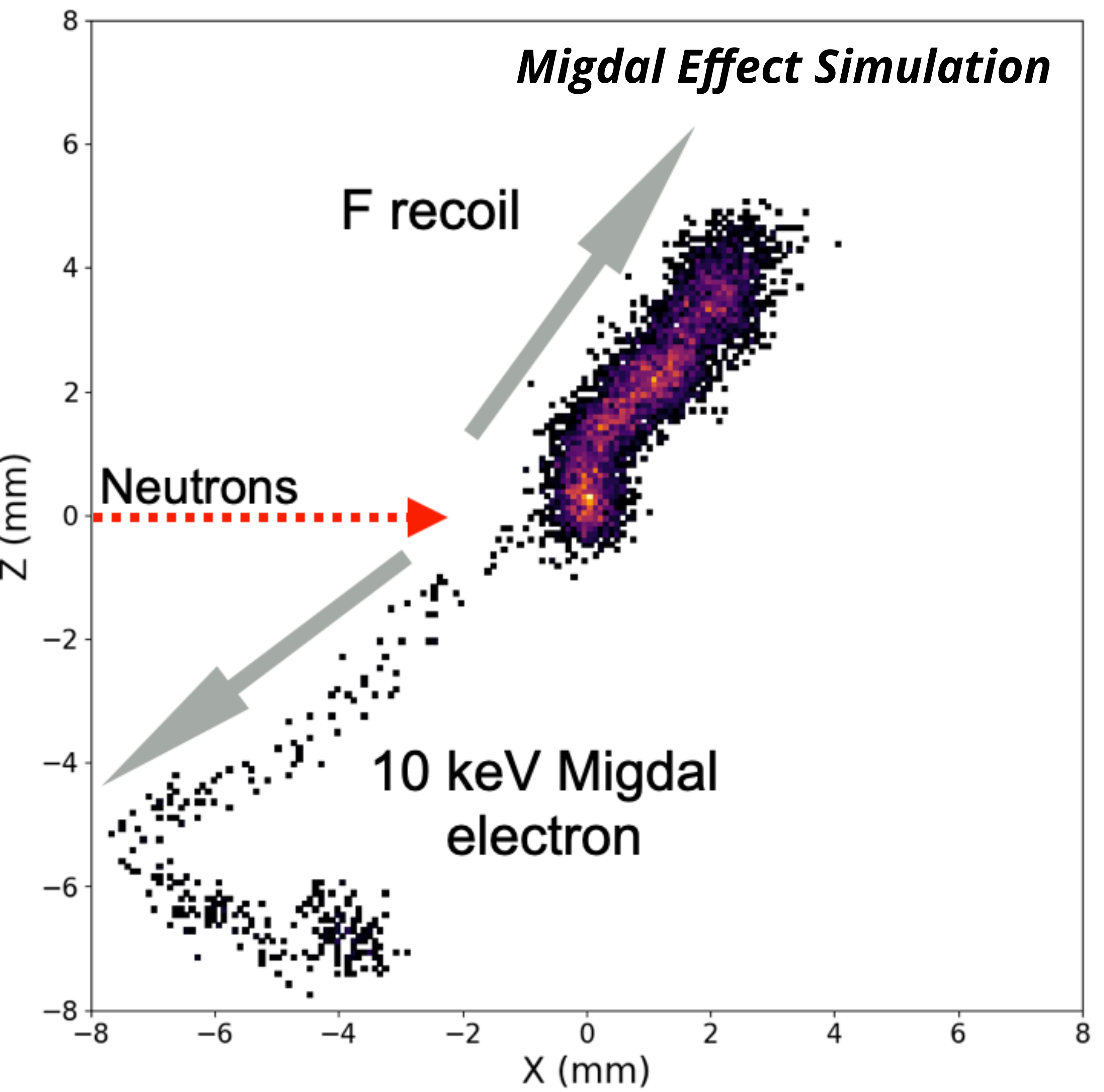


Component	Topology	D-D neutrons >0.5	5–15 keV
Recoil-induced δ-rays	Delta electron from NR track origin	≈ 0	0
Particle-Induced X-ray Emission (PIXE)			
X-ray emission	Photoelectron near NR track origin	1.8	0
Auger electrons	Auger electron from NR track origin	19.6	0
Bremsstrahlung processes†			
Quasi-Free 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

Astropart. Phys. 151 (2023) 102853

Signal and Backgrounds

- Backgrounds suppressed through energy thresholds and timing resolution
- Main source of background from gammas produced in inelastic scattering with fluorine Compton scattering near track vertex



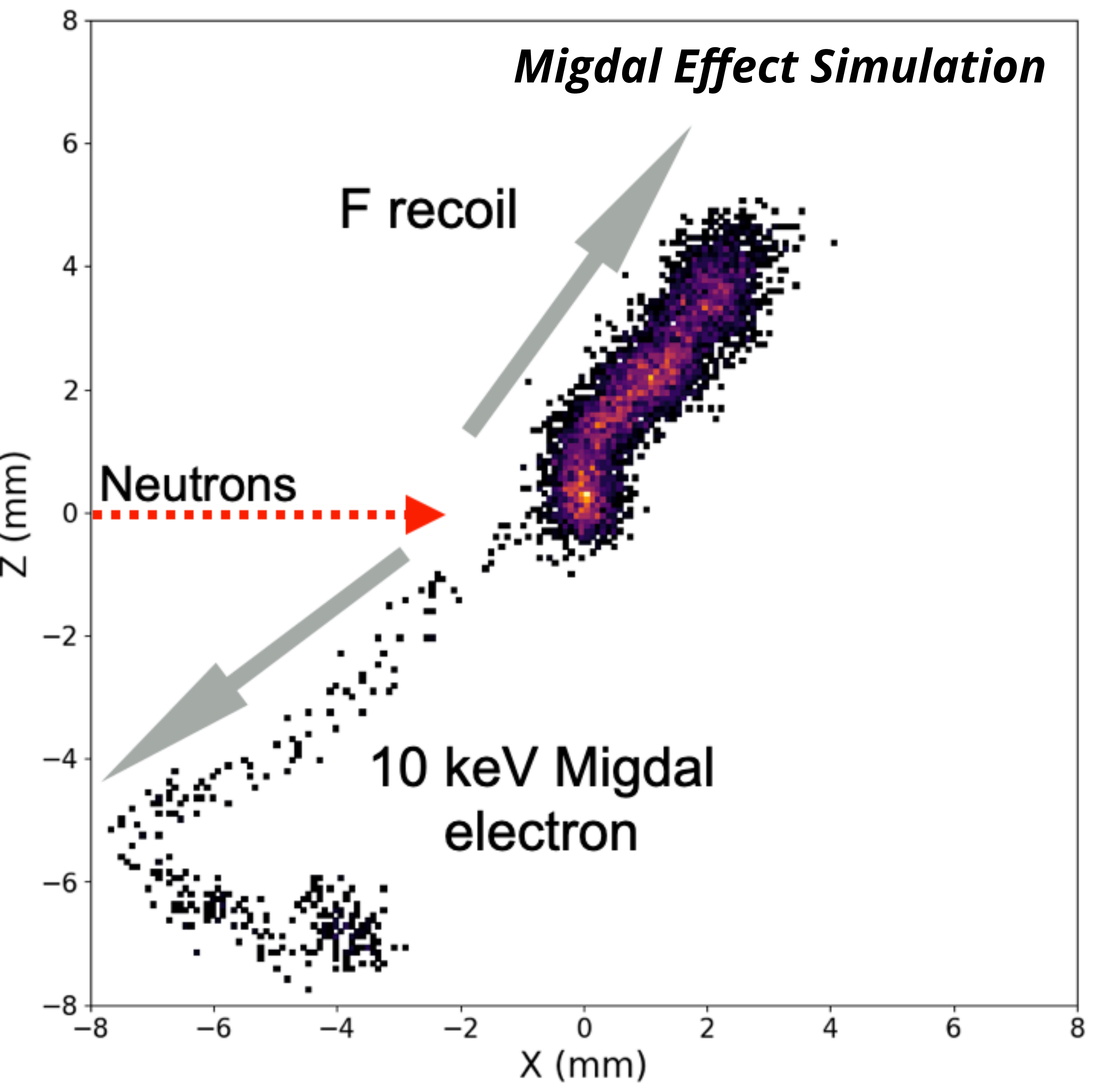
Component	Topology	D-D neutrons >0.5	5–15 keV
Recoil-induced δ-rays	Delta electron from NR track origin	$\approx$0	0
Particle-Induced X-ray Emission (PIXE)			
X-ray emission	Photoelectron near NR track origin	1.8	0
Auger electrons	Auger electron from NR track origin	19.6	0
Bremsstrahlung processes†			
Quasi-Free Electron Br. (QFEB)	Photoelectron near NR track origin	112	$\approx$0
Secondary Electron Br. (SEB)	Photoelectron near NR track origin	115	$\approx$0
Atomic Br. (AB)	Photoelectron near NR track origin	70	$\approx$0
Nuclear Br. (NB)	Photoelectron near NR track origin	$\approx$0	$\approx$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	$\approx$0	$\approx$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	$\approx$0	$\approx$0
Secondary nuclear recoil fork	NR track fork near track origin	–	$\approx$1
Total background	Sum of the above components		1.5
Migdal signal	Migdal electron from NR track origin		32.6

Astropart. Phys. 151 (2023) 102853

UNIVERSITY OF BIRMINGHAM
Science and Technology Facilities Council
Rutherford Appleton Laboratory

Signal and Backgrounds

- Backgrounds suppressed through energy thresholds and timing resolution
- Main source of background from gammas produced in inelastic scattering with fluorine Compton scattering near track vertex

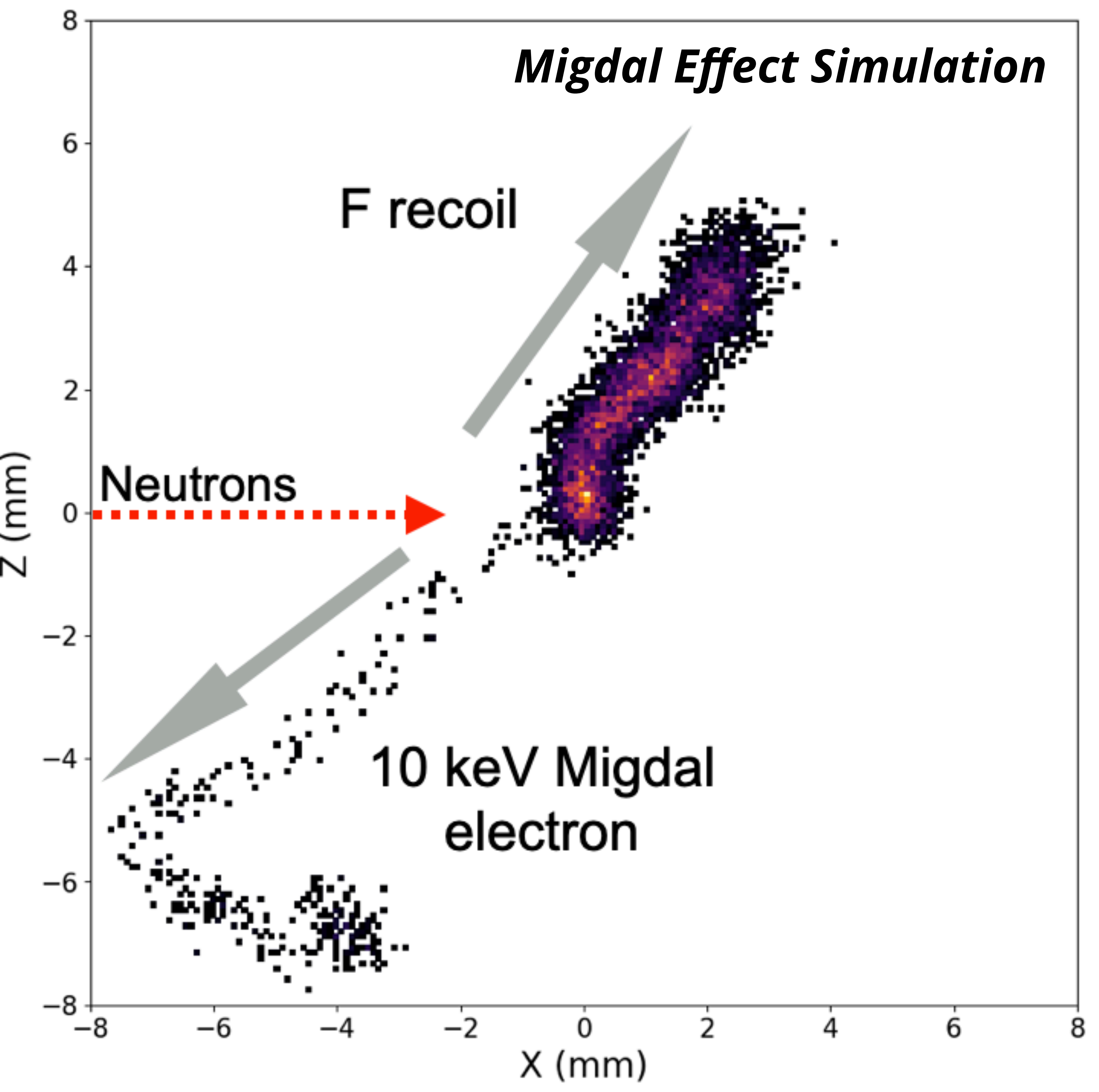


Component	Topology	D-D neutrons >0.5	D-D neutrons 5–15 keV
Recoil-induced δ-rays	Delta electron from NR track origin	≈ 0	0
Particle-Induced X-ray Emission (PIXE)			
X-ray emission	Photoelectron near NR track origin	1.8	0
Auger electrons	Auger electron from NR track origin	19.6	0
Bremsstrahlung processes†			
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

Astropart. Phys. 151 (2023) 102853

Signal and Backgrounds

- Backgrounds suppressed through energy thresholds and timing resolution
- Main source of background from gammas produced in inelastic scattering with fluorine Compton scattering near track vertex



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†			
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

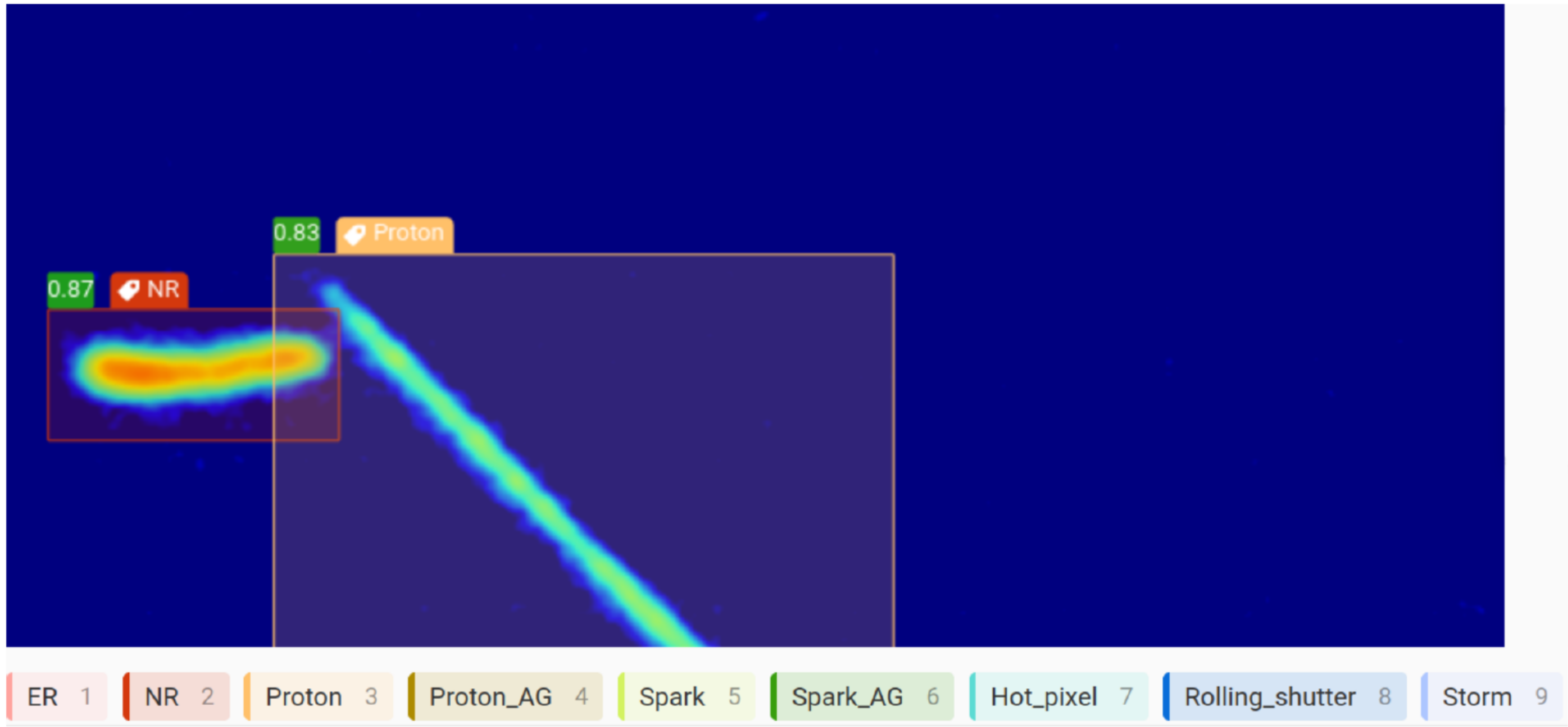
Astropart. Phys. 151 (2023) 102853

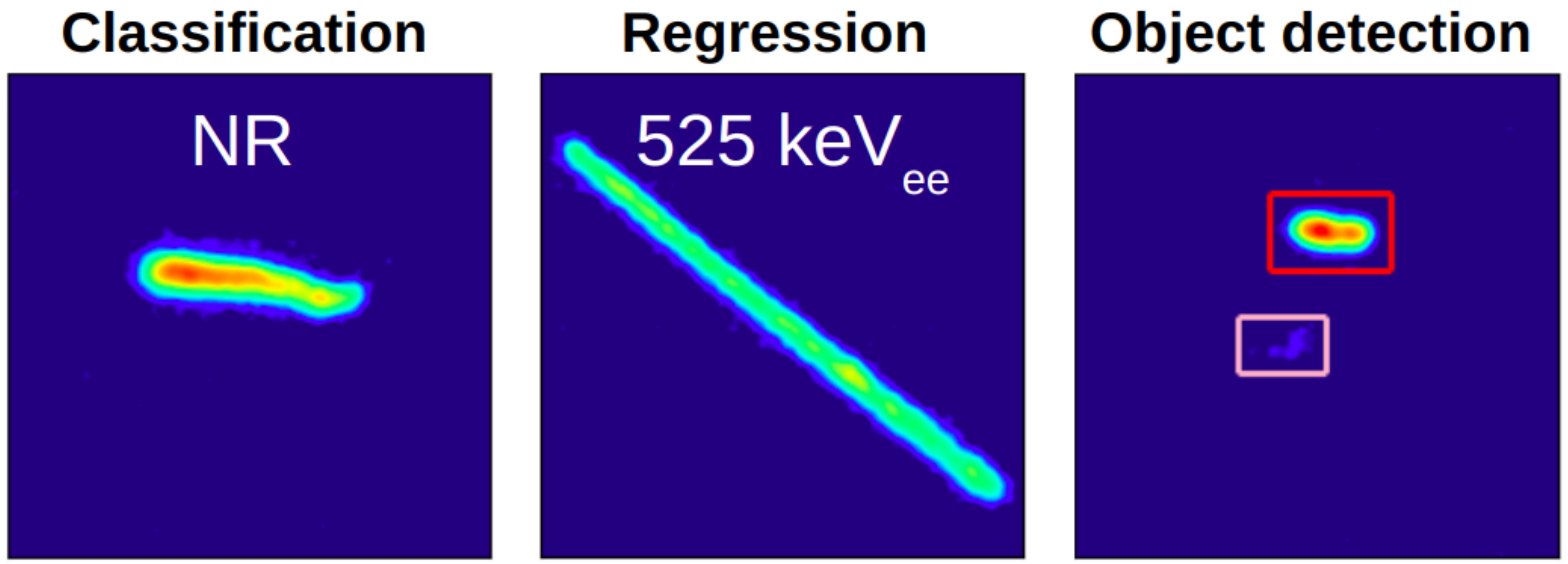
UNIVERSITY OF BIRMINGHAM
Science and Technology Facilities Council
Rutherford Appleton Laboratory

YOLOv8 for track Identification

Phys.Rev.D 111 (2025) 7

- YOLOv8 is a state-of-the-art object detection algorithm
- Localises and classifies objects within images
- Trained on real data with hand-labelled bounding boxes
  - Search for overlapping electron and nuclear recoil rather than a simulated signal topology
- Runs in real time providing mixed-field particle ID and detector performance feedback



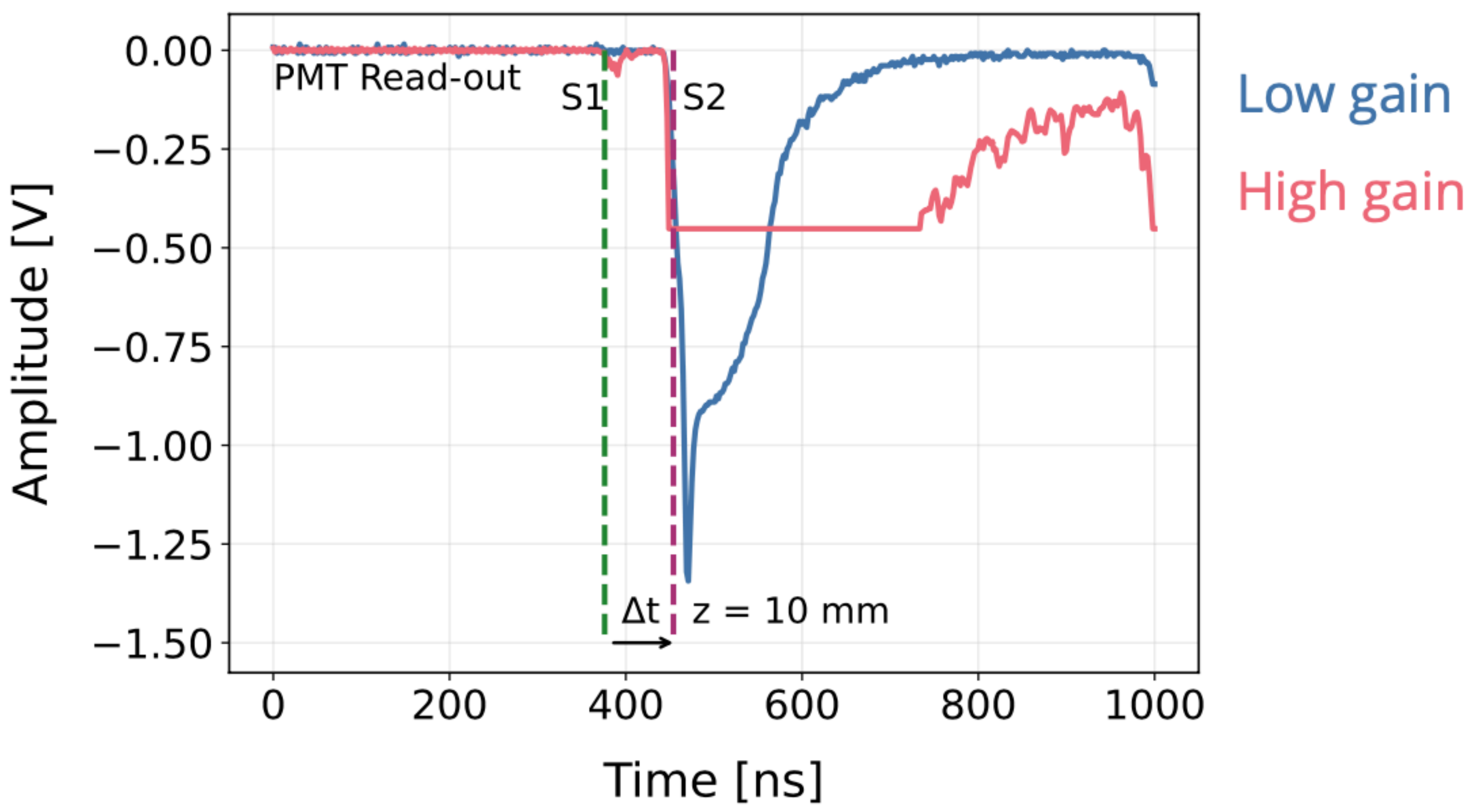


UNIVERSITY OF BIRMINGHAM
Science and Technology Facilities Council
Rutherford Appleton Laboratory

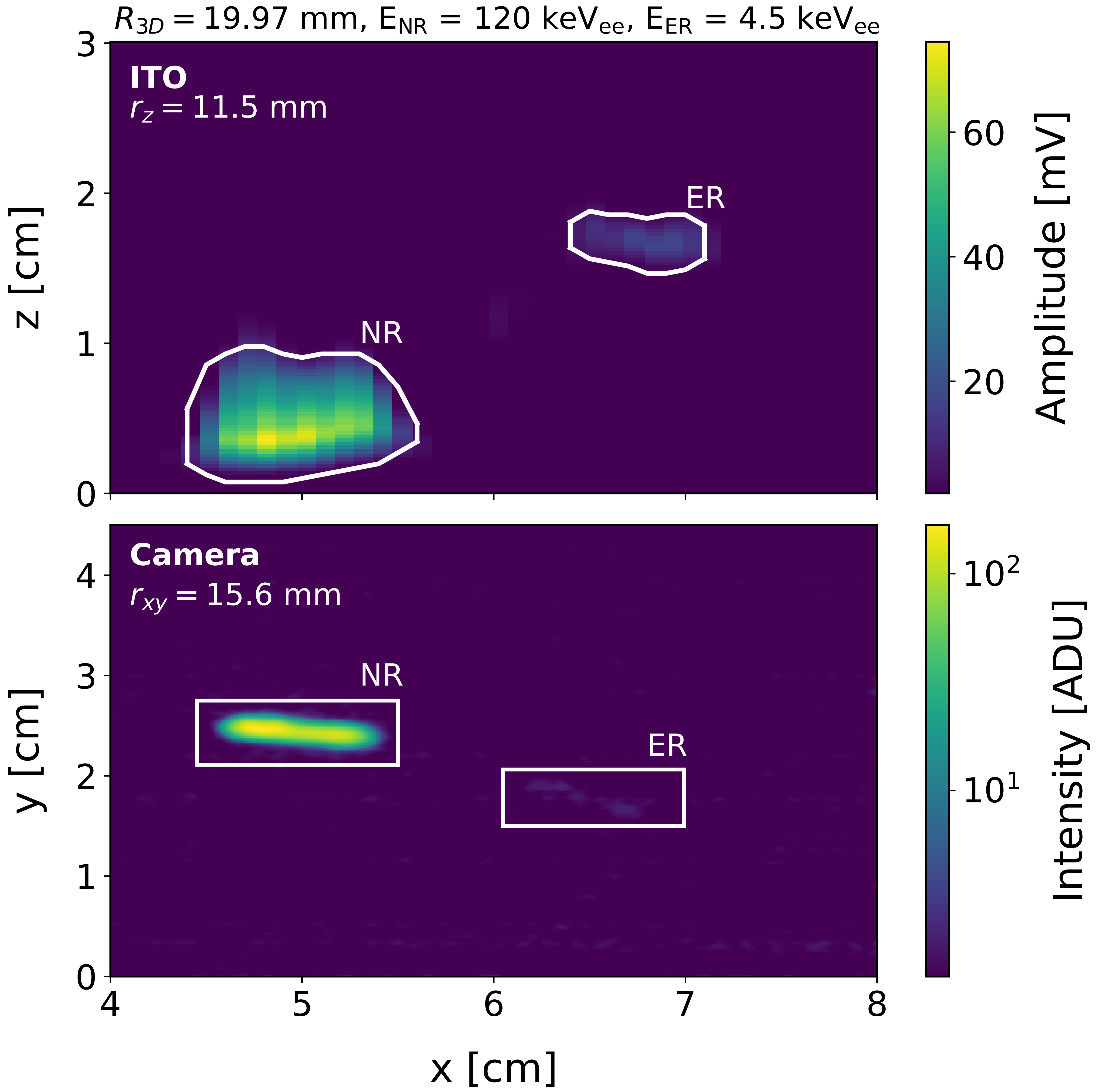
3D Reconstruction

- Tracks in the ITO anode are identified using **DBSCAN**
- Camera and DAQ events synchronised offline using timestamp information from an FPGA counter
- Timing between S1 and S2 in the PMT gives absolute depth

Nucl.Instrum.Meth.A 1069 (2024)



3D Reconstruction: JINST 18 C07013

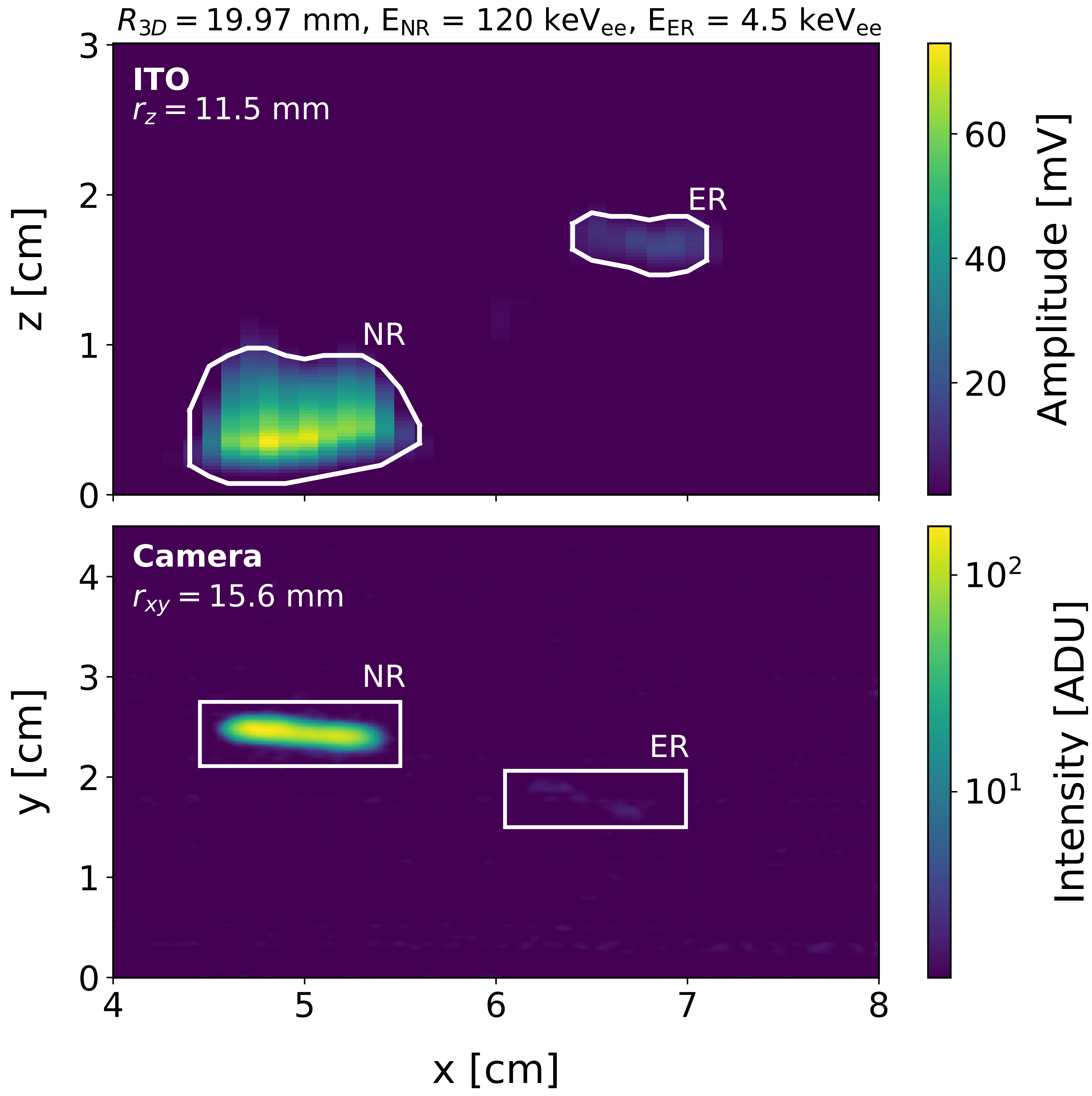


UNIVERSITY OF BIRMINGHAM

Rutherford Appleton Laboratory

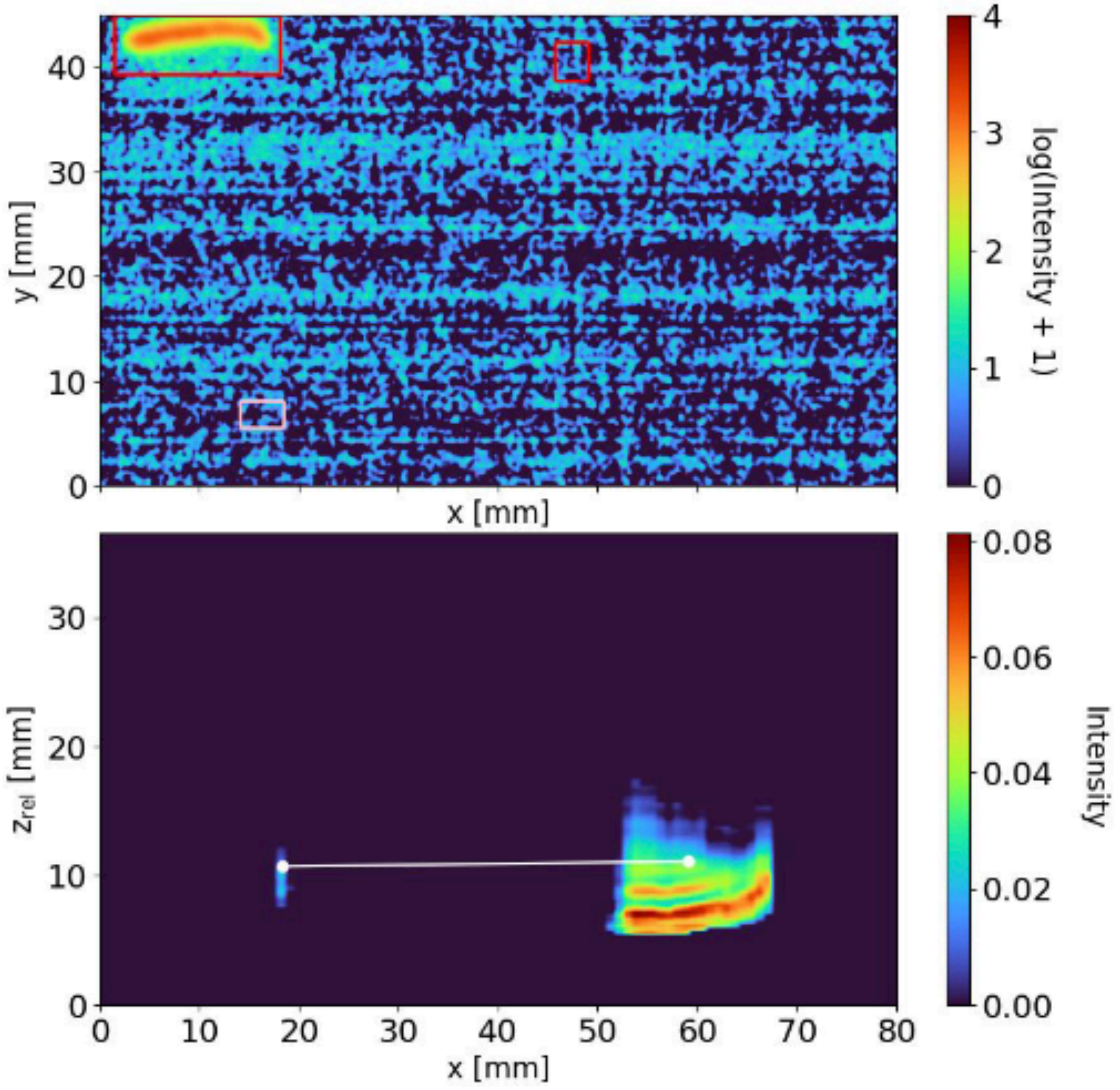
Event Selection

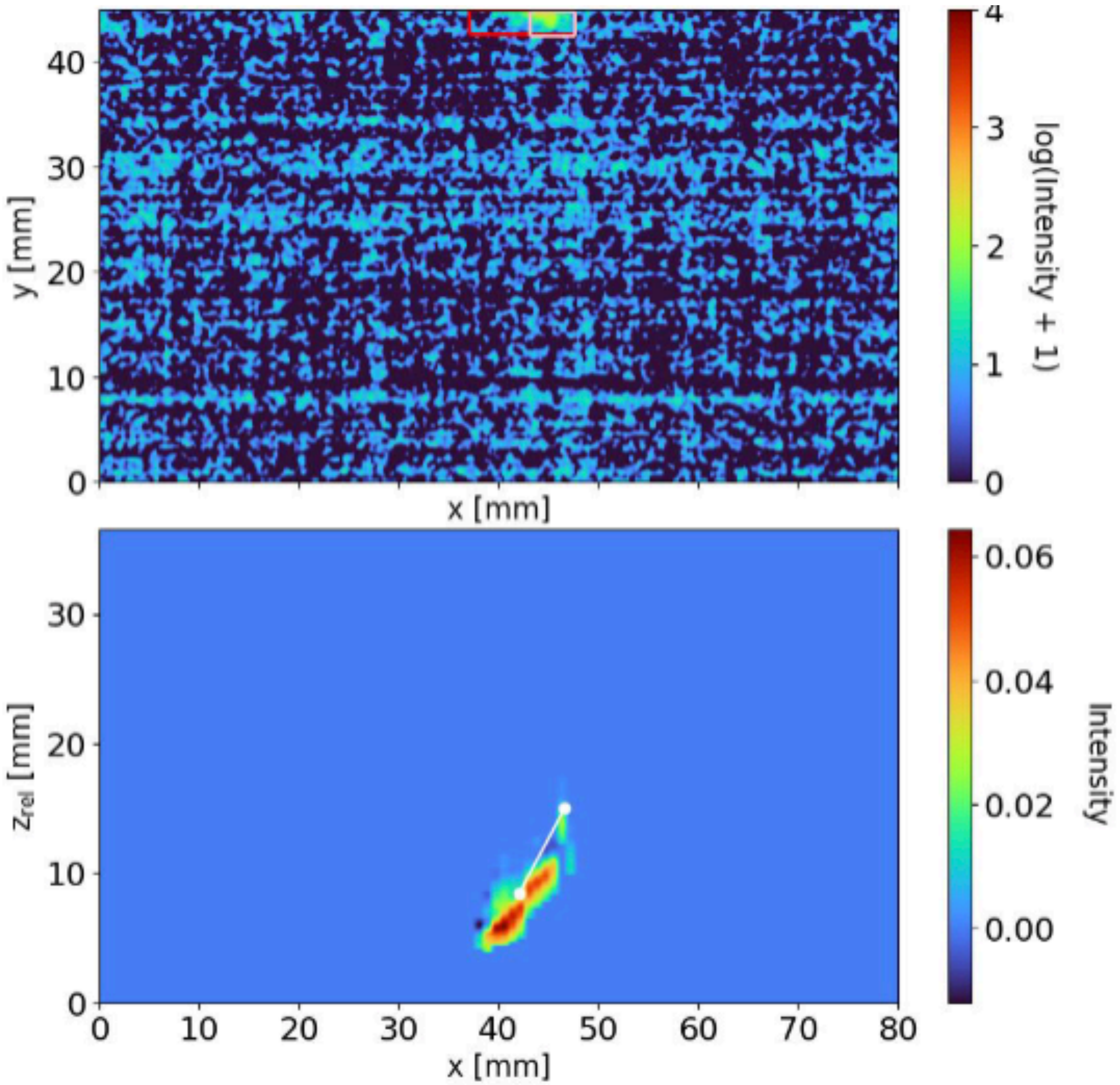
- Nuclear recoil energy in the ITO > 50 keV_{ee}, corresponding to ~150 keV (F)
- Electron energy 3 < E_{ER} < 15 keV in the ITO
- Electron and nuclear recoil both identified in image by YOLO
- Define a control region and a signal region:
  - Signal region: ER-NR separation ≤ 10mm
  - Control region: ER-NR separation 10 - 70 mm



Additional Event Selection Requirements

- After unblinding, two pathological classes of events were observed and the selection criteria were updated to target these classes of events
- Signal efficiency was reevaluated to reflect this and reduced by 1.5%

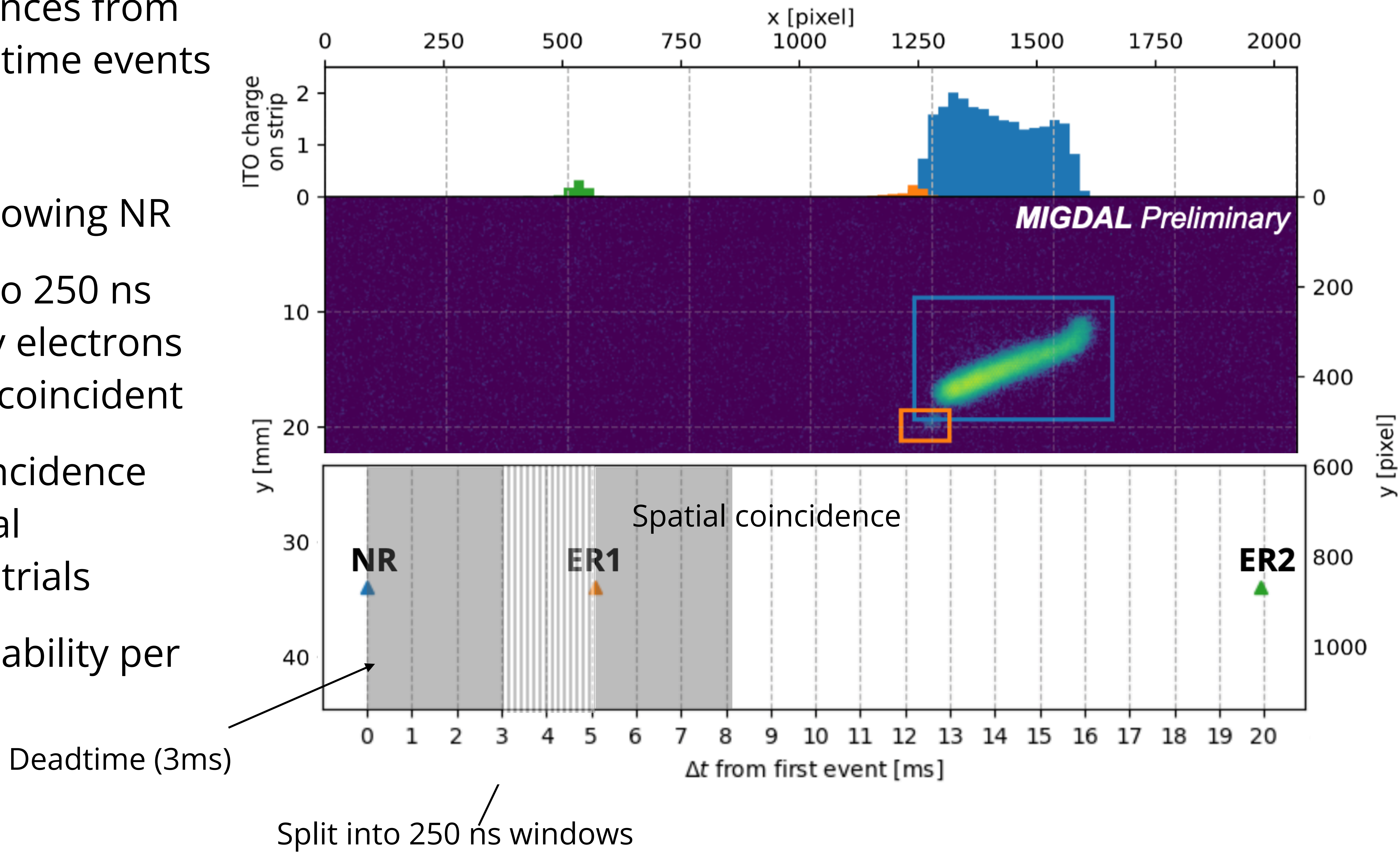




UNIVERSITY OF BIRMINGHAM
Science and Technology Facilities Council
Rutherford Appleton Laboratory

Background: Random track coincidences

- Estimate random coincidences from spatially coinciding out-of-time events
- For each NR:
  - Look for ERs 3-8 ms following NR
  - Split remaining time into 250 ns windows and count any electrons that would be spatially coincident
- Probability of random coincidence per NR = Number of spatial coincidences / Number of trials
- Random coincidence probability per NR is $\boxed{\mathbf{(1.8 \pm 0.1) \times 10^{-8}}}$
- Negligible background

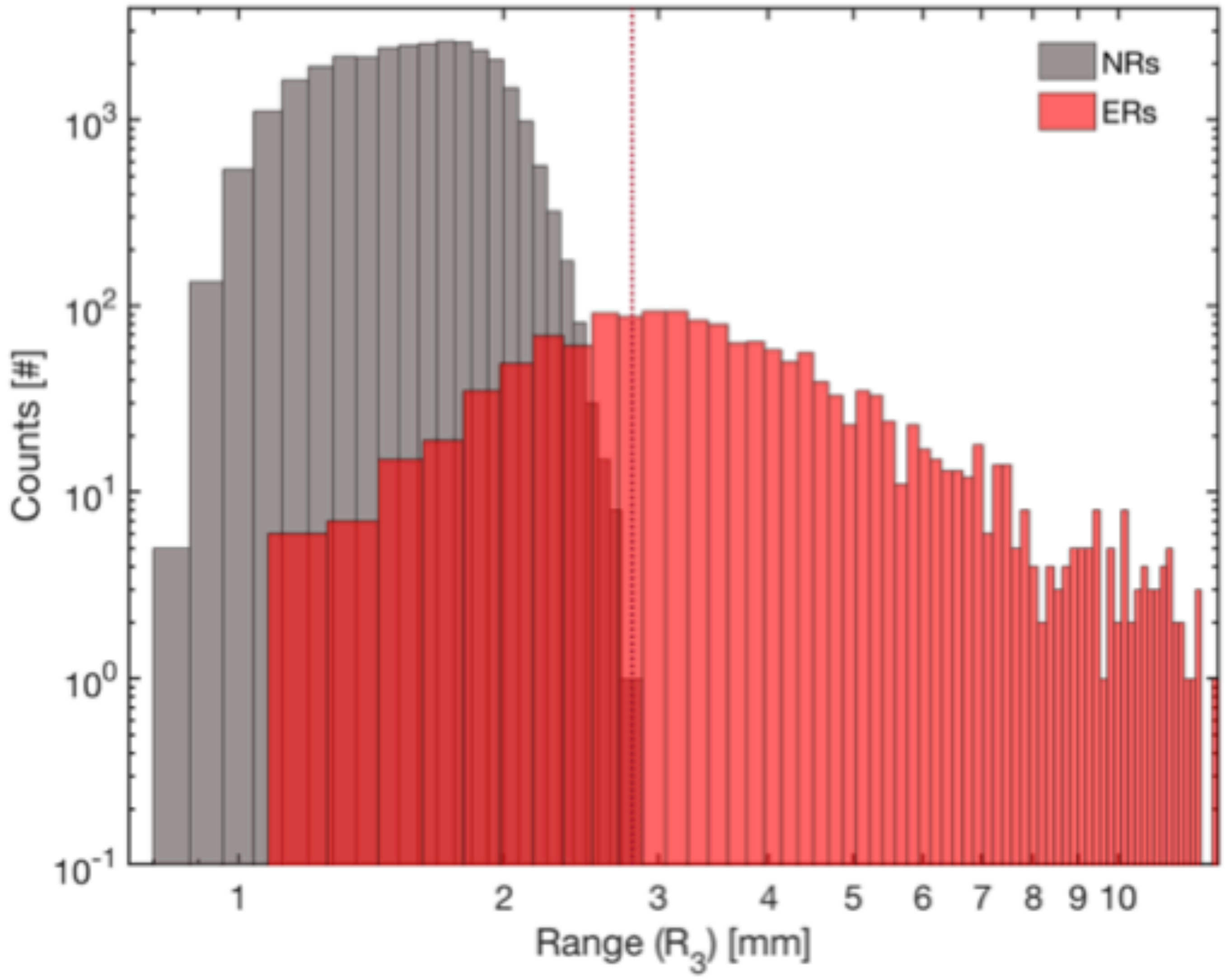


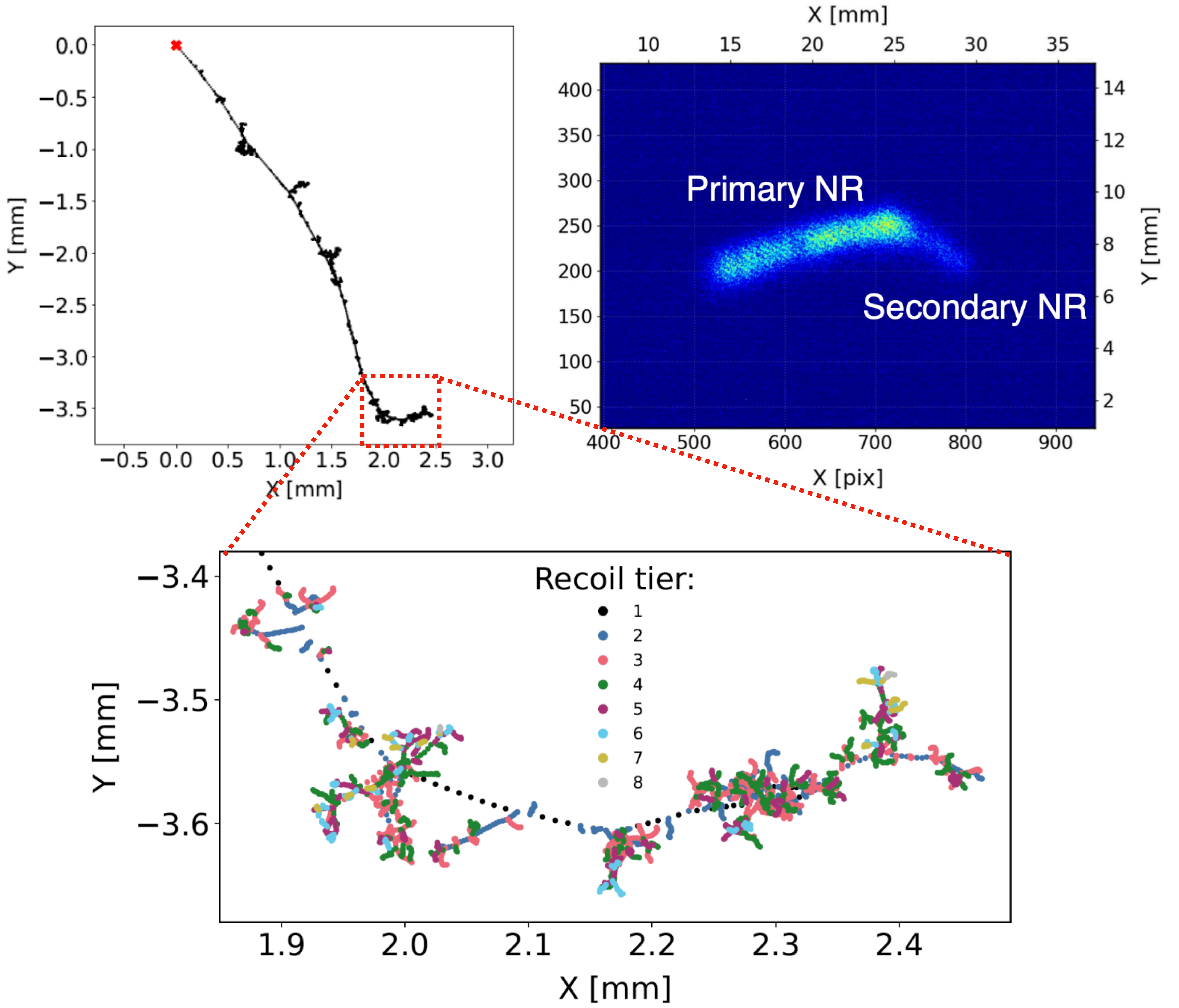
UNIVERSITY OF BIRMINGHAM

Science and Technology Facilities Council
Rutherford Appleton Laboratory

Background: Secondary Nuclear Recoils

- 7% of NRs will have secondary that is:
  - < 1mm from vertex
  - Reconstructed energy 5-15 keV_{ee}
- By requiring a track length > 3 mm expect 1 in 10^6 will mimic signal
- As the clustering is sensitive to dE/dx, expect $\boxed{< 0.1 \text{ events}}$ in our dataset - assume to be negligible

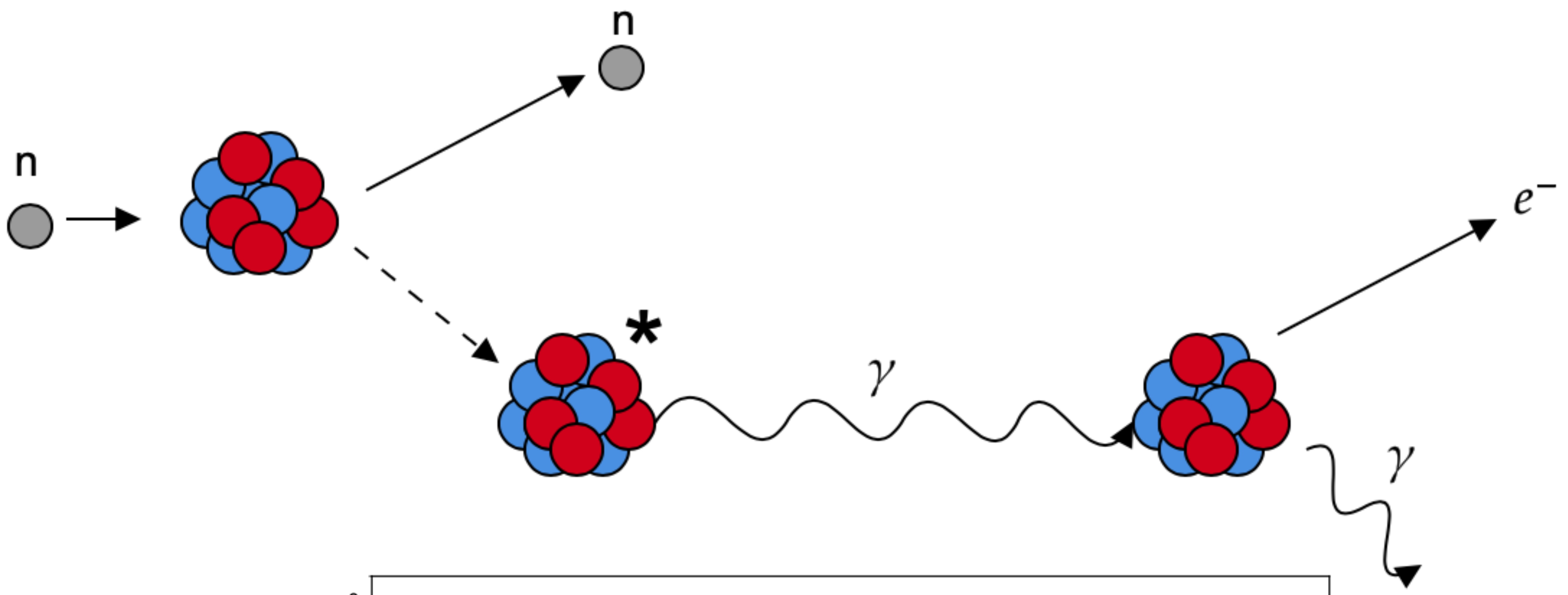


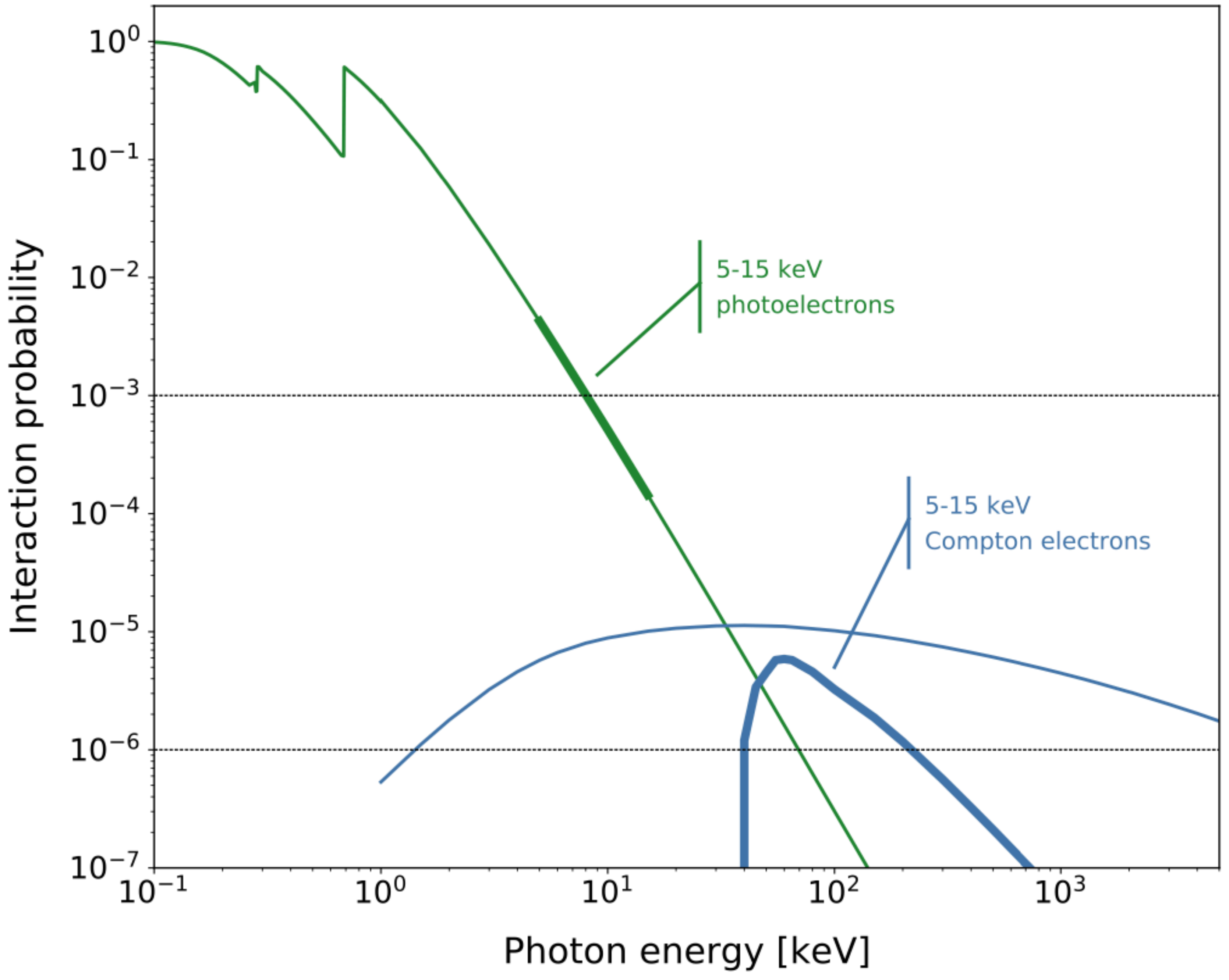


UNIVERSITY OF BIRMINGHAM
Science and Technology Facilities Council
Rutherford Appleton Laboratory

Background: Fluorine Inelastic Scattering

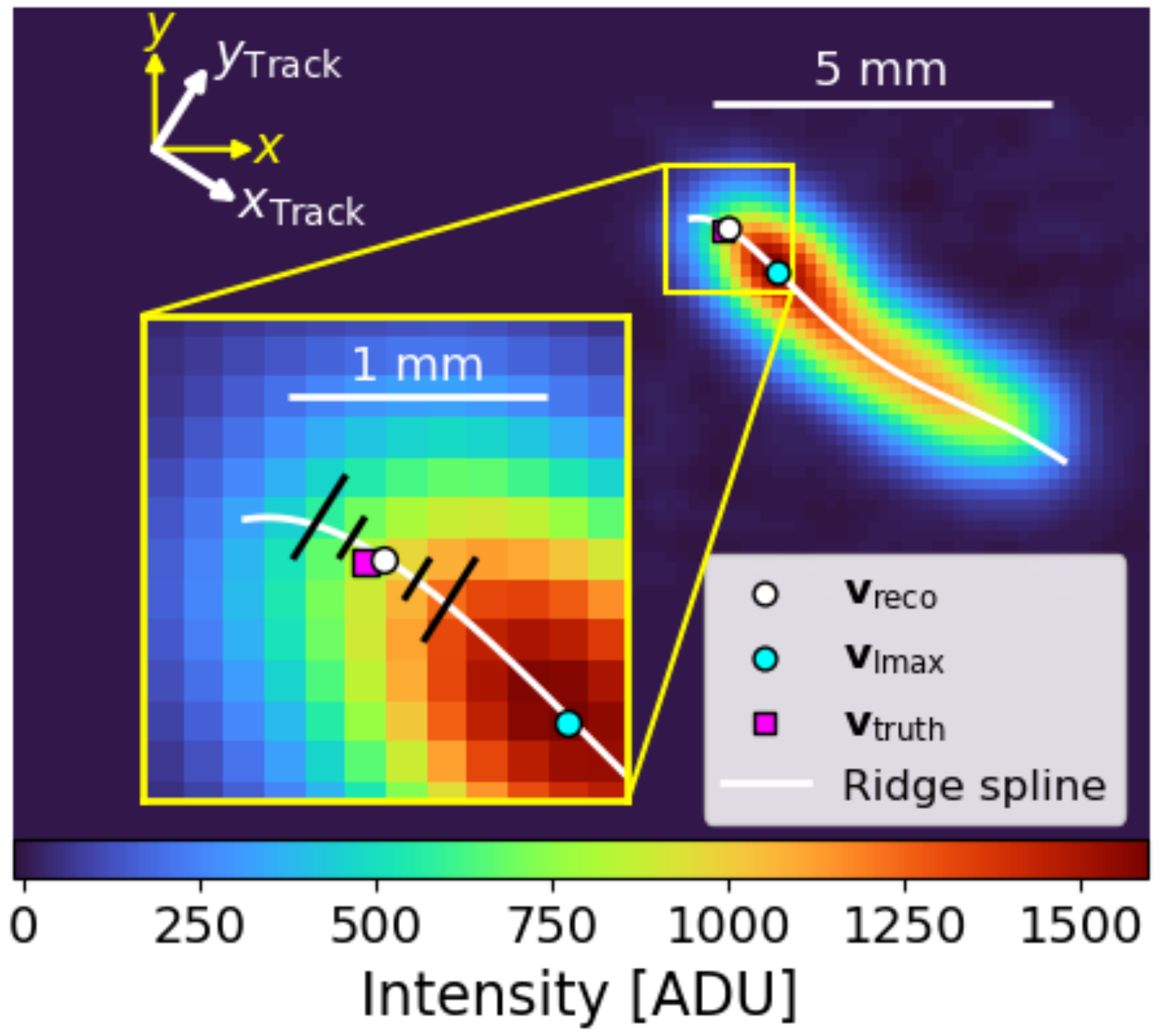
- Inelastic scattering prediction from Geant4 simulations of neutron interactions
- Validate the rate with control region
    - ER - NR separation > 10 mm
- Observe 3 events
    - Expected from simulation 5.7 ± 0.6 events
- Gives an expectation of 0.45 ± 0.05 events in the signal region

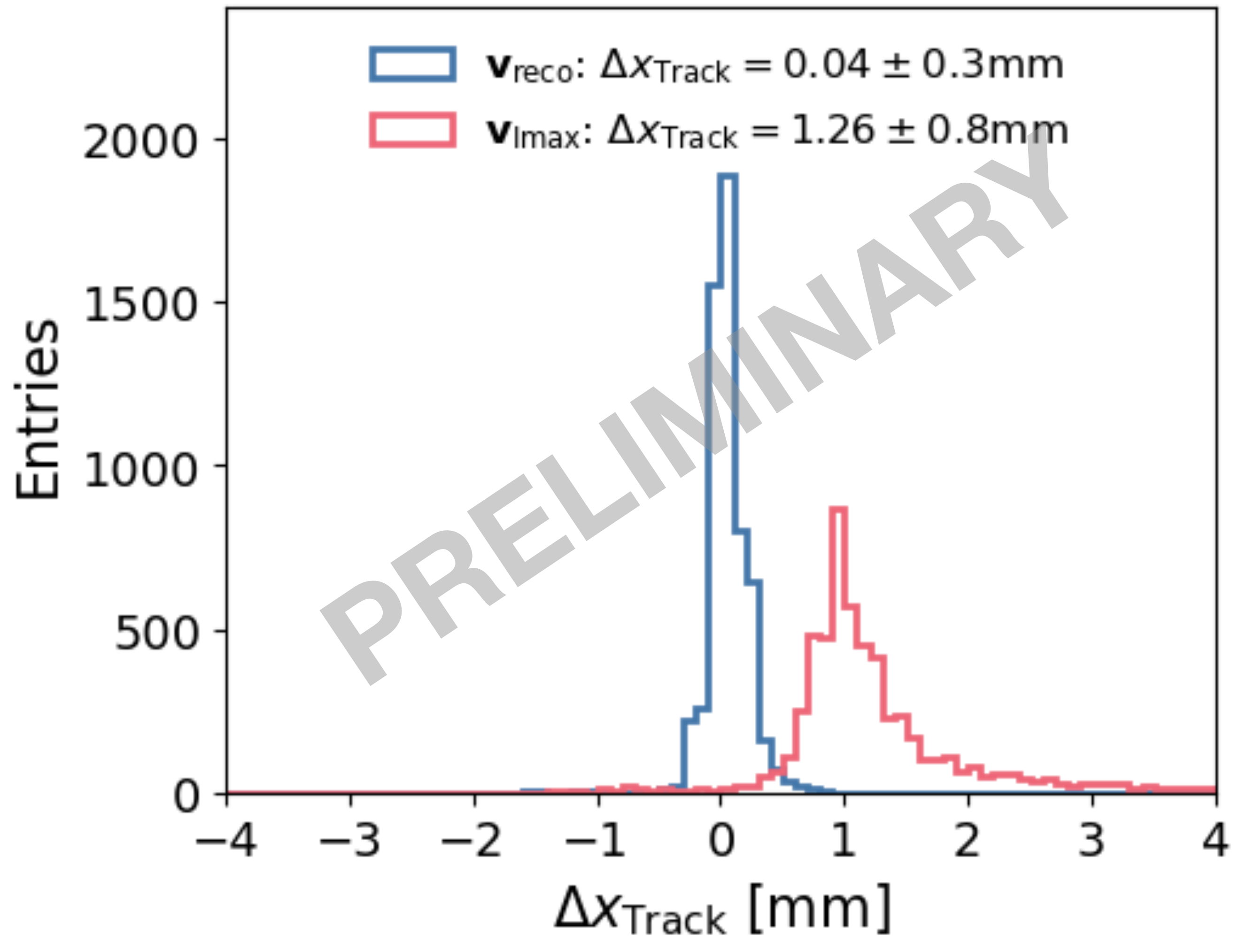


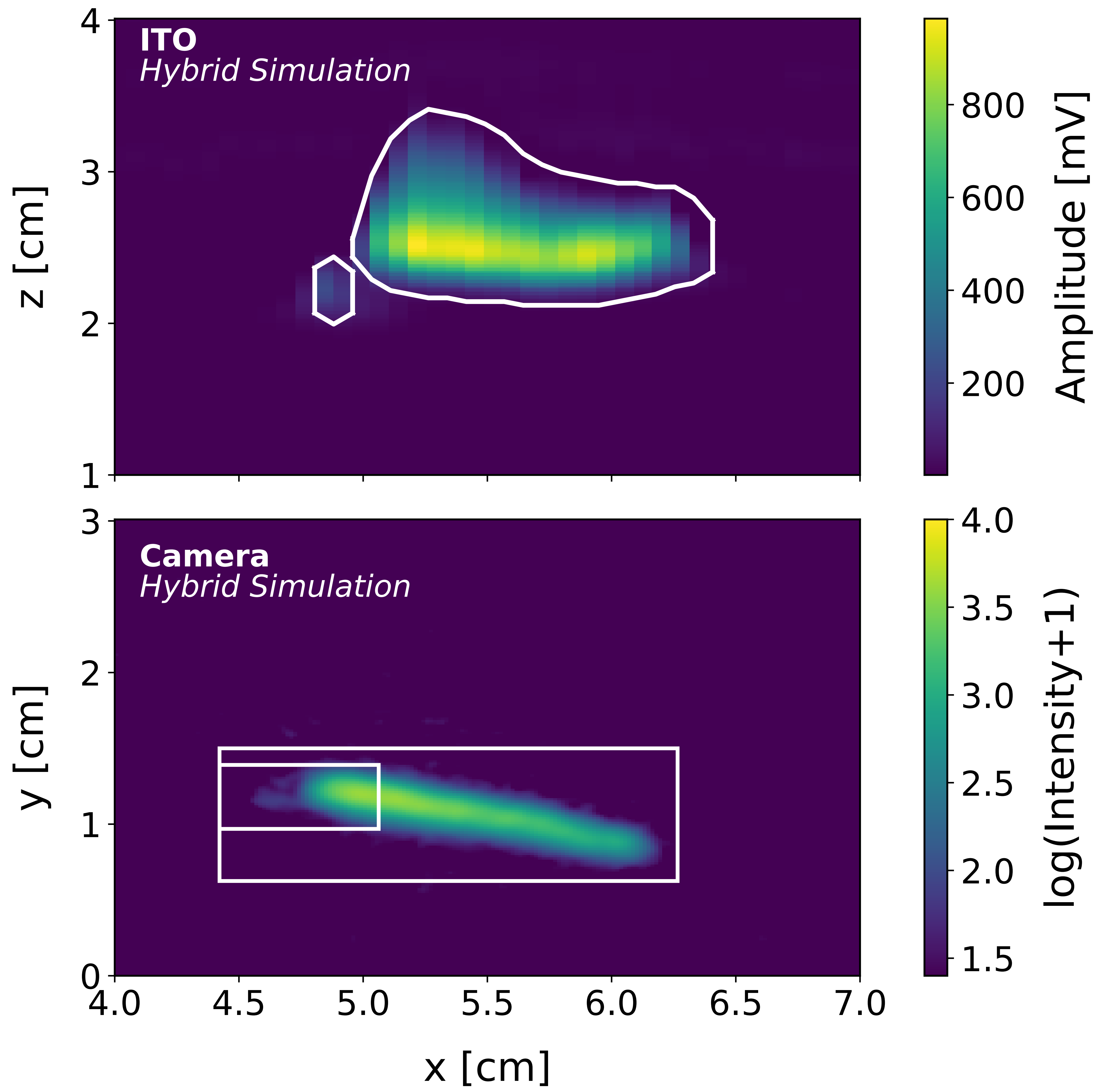


Hybrid Signal Simulations

- Migdal events are simulated by stitching nuclear recoils from data with simulated electrons
- Vertex is estimated in nuclear recoils using the Bragg intensity curve along the ridge of the track for *(x, y)*
- Use absolute depth and track extent to reconstruct z vertex



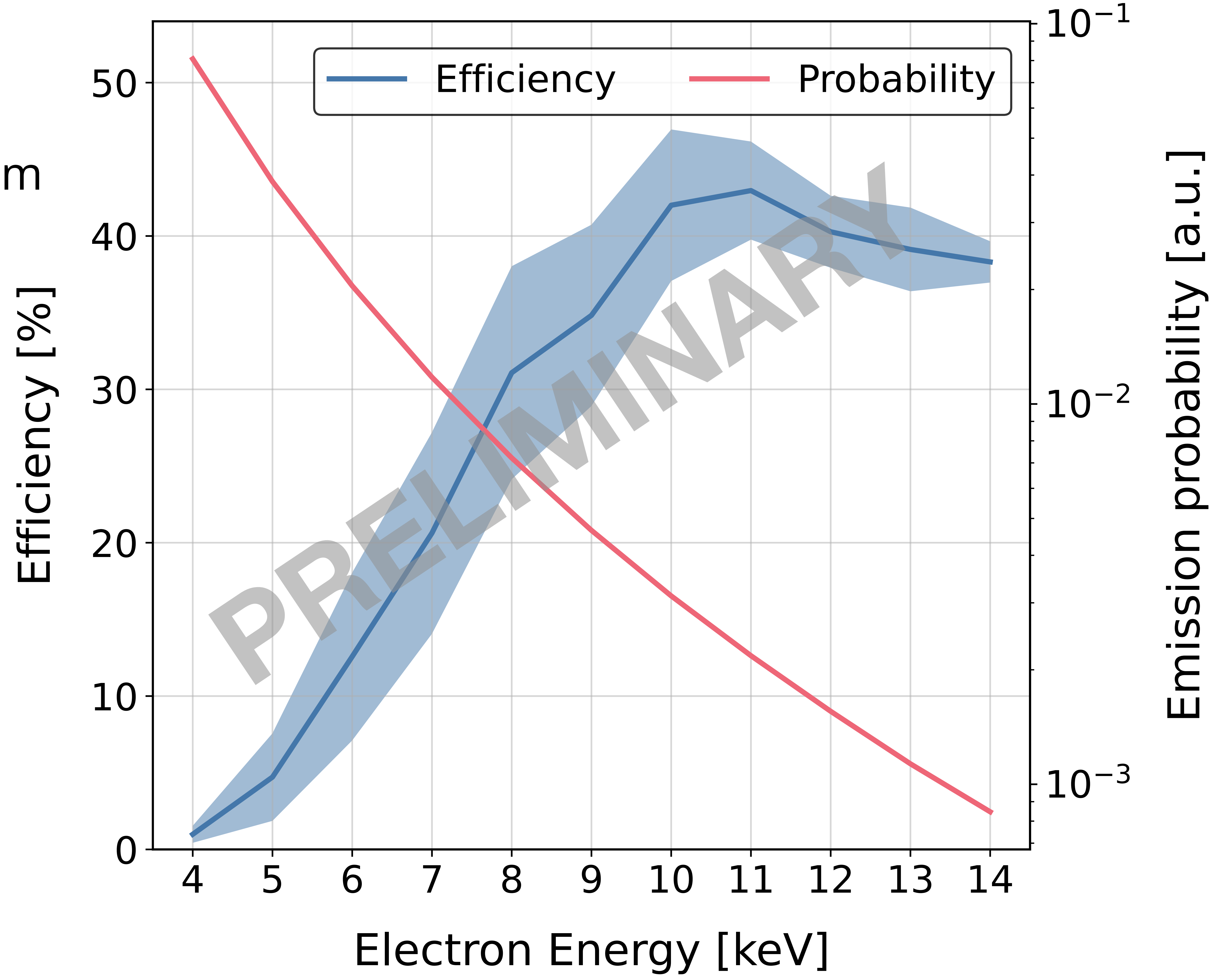




Efficiency

- Efficiencies are estimated by passing hybrid events through analysis chain
- Dominant source of systematic uncertainty from uncertainty in vertex position of nuclear recoil
- Estimate systematic uncertainty by shifting vertex in hybrids by the uncertainty in the vertex position
- Most sensitive to the *z* vertex
  - Analysis improvements are expected to reduce this uncertainty
- Overall efficiency is:

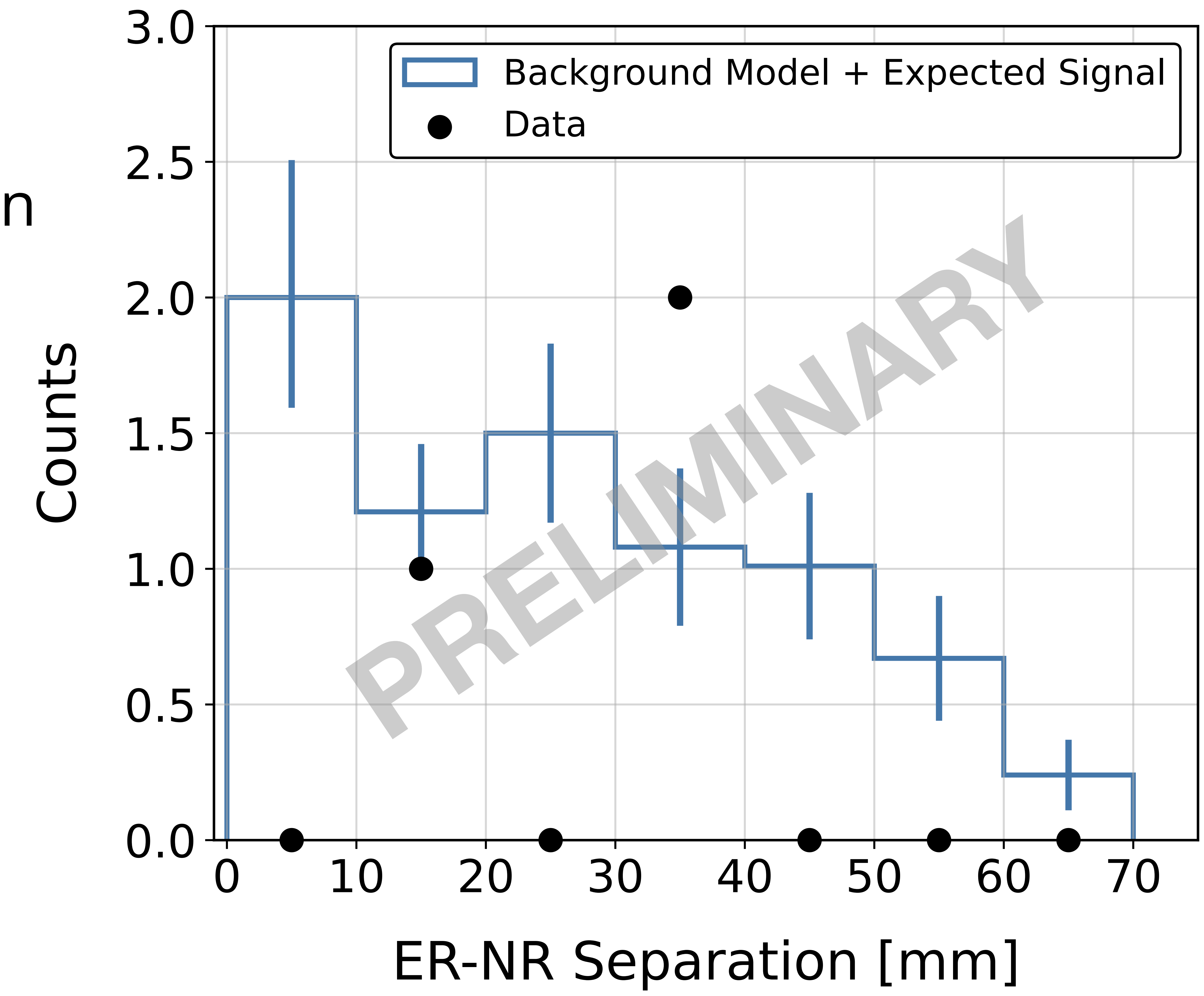
$$\boxed{\epsilon = 8.8 \pm 2.6\,\%}$$



UNIVERSITY OF BIRMINGHAM
Science and Technology Facilities Council
Rutherford Appleton Laboratory

Results

- 3 events observed in the control region
- 0 events observed in signal region
  - Expected 0.45 ± 0.05 events from background
  - Expected 1.6 ± 0.4 signal events



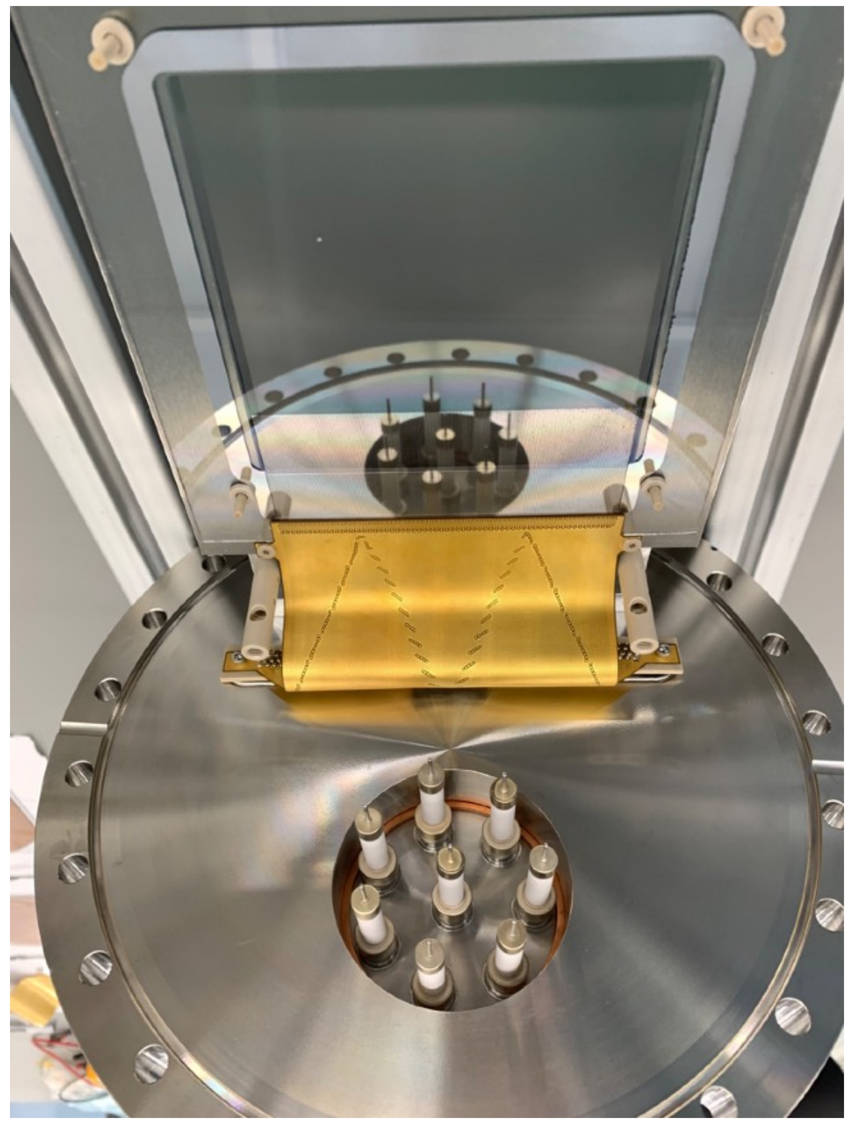
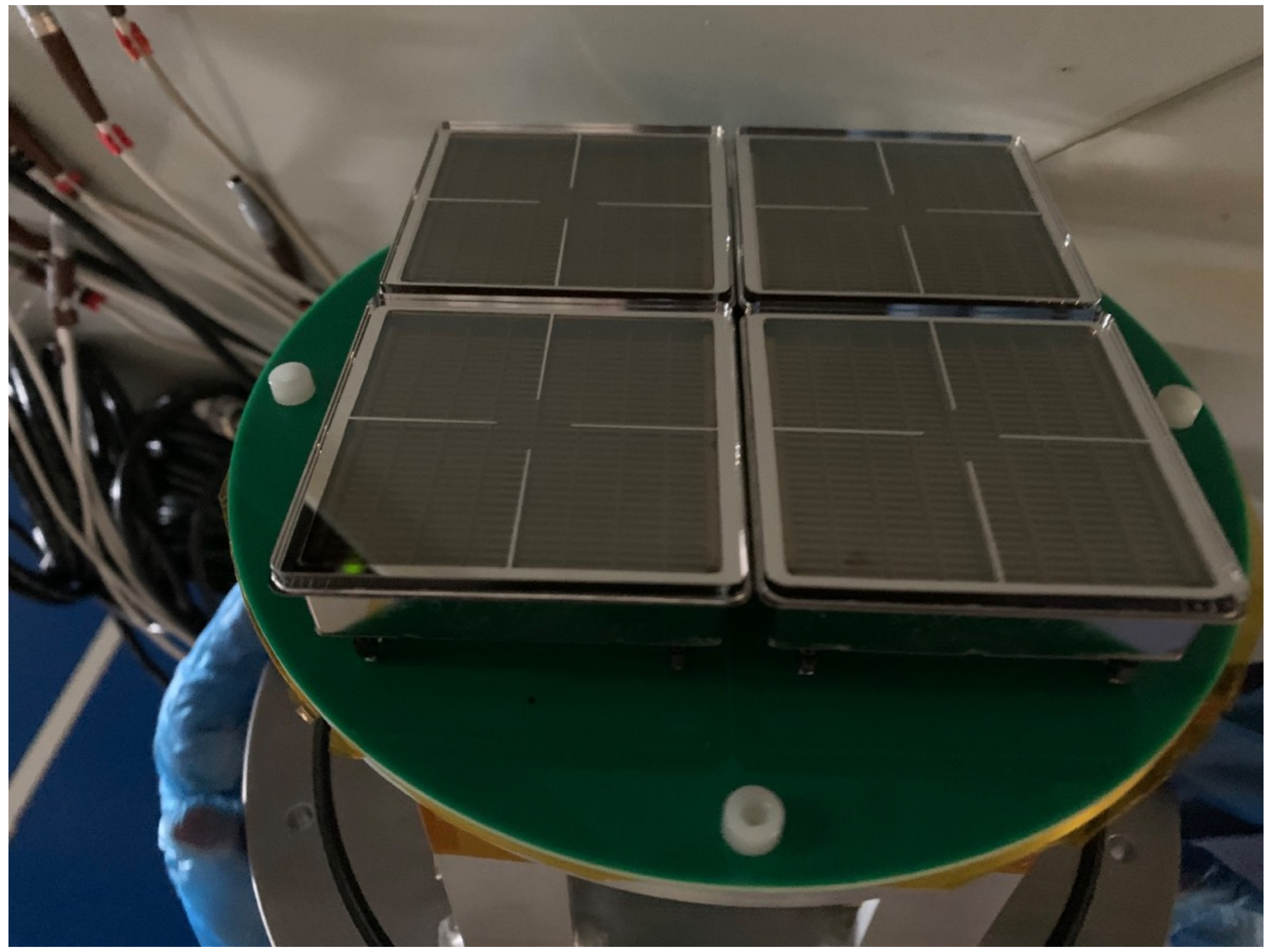
UNIVERSITY OF BIRMINGHAM
Science and Technology Facilities Council
Rutherford Appleton Laboratory

Future Plans

- A number of detector upgrades
  - Re-optimised collimator to maximise NR rate
  - Testing addition of third GEM
  - New PMT array for improved S1 efficiency
  - New 14 bit DAQ for improved dynamic range

- Exploring applying YOLO to the ITO signals
  - Initial results look promising to improve efficiency, exploring background models

- Plan to take more data and maximise nuclear recoil statistics

UNIVERSITY OF BIRMINGHAM

Science and Technology Facilities Council
Rutherford Appleton Laboratory

Summary

- The MIGDAL experiment aims to characterise the Migdal Effect in a range of species
- Performed the first search for the Migdal Effect in nuclear scattering of carbon and fluorine
- Observe 0 events in signal region
- More science data planned this year with improved beam characteristics
- Analysis ongoing, exploring improvements to efficiency

Publications:

Overlap-aware segmentation for topological reconstruction of obscured objects
MLST 10.1088/2632-2153/ae6e18 (2026)

Transforming a rare event search into a not-so-rare event search in real-time with deep learning-based object detection
Phys.Rev.D 111 (2025) 7, 072004

Commissioning of the MIGDAL detector with fast neutrons at NILE/ISIS
Nucl.Instrum.Meth.A 1069 (2024) 169971

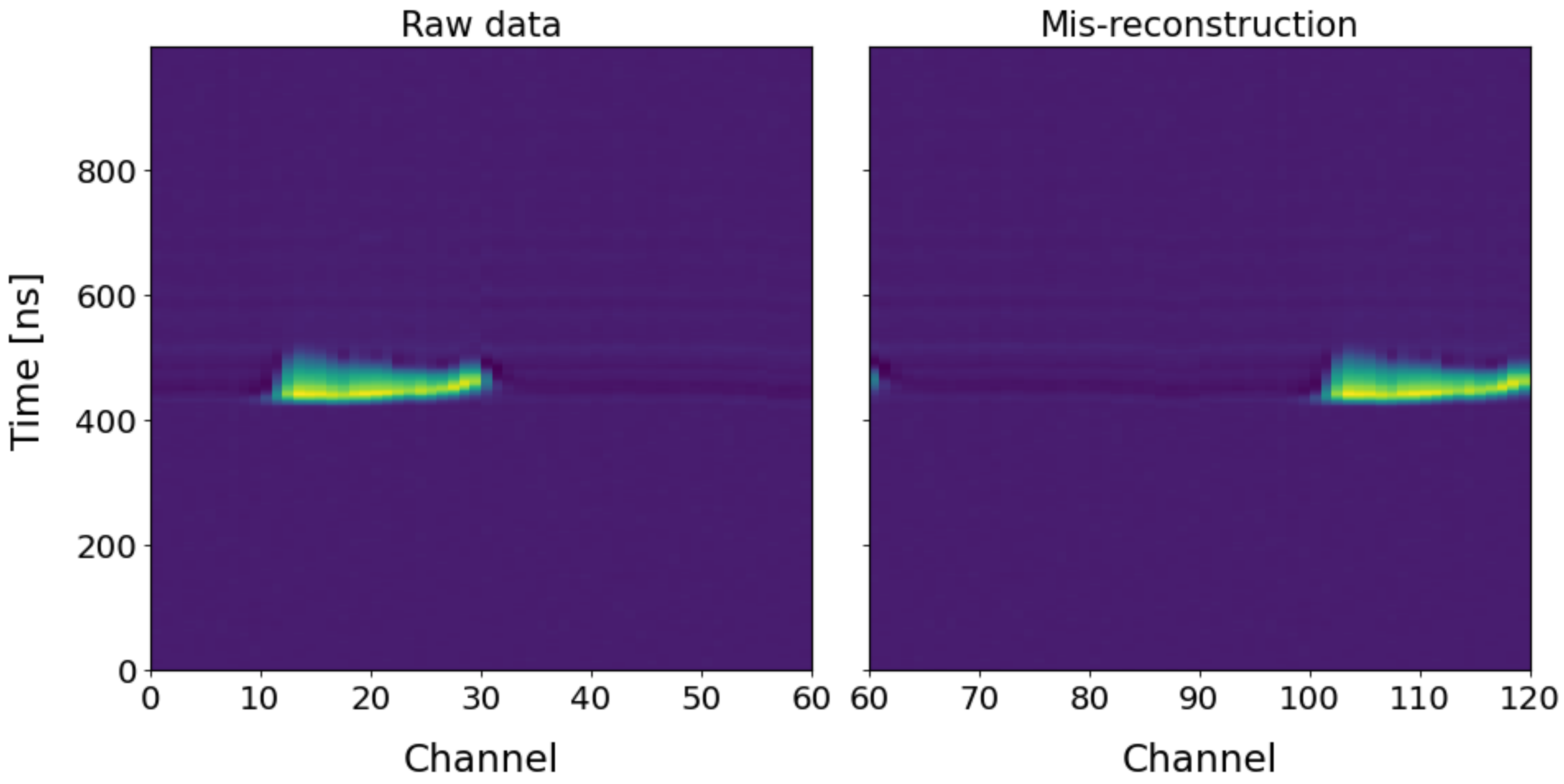
3D track reconstruction of low-energy electrons in the MIGDAL low pressure optical time projection chamber
JINST 18 (2023) 07, C07013

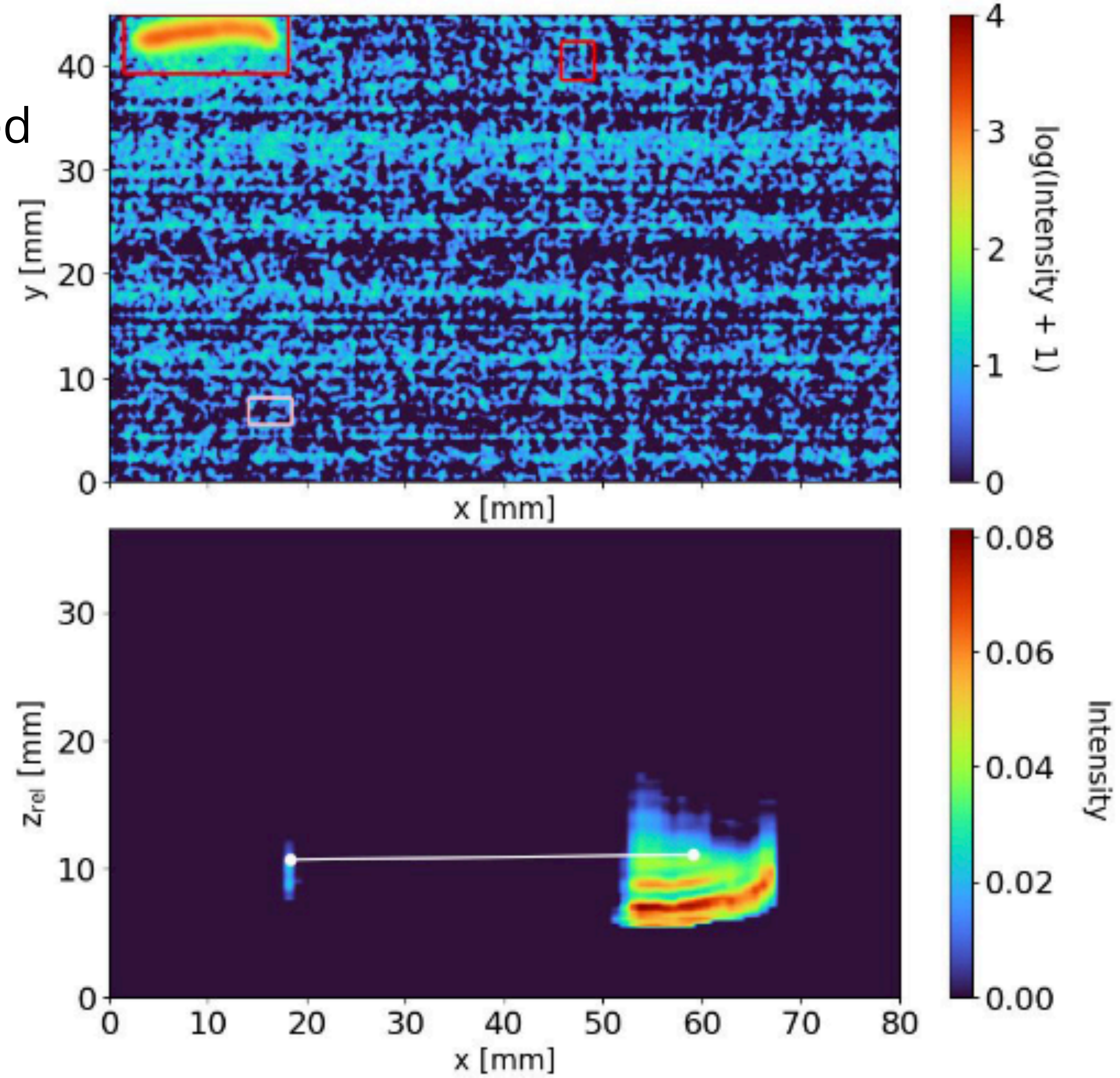
The MIGDAL experiment: Measuring a rare atomic process to aid the search for dark matter
Astropart.Phys. 151 (2023) 102853

Backup

Additional Event Selection Requirements

- Strips are read-out in pairs. When event crosses channel 0 and 59 a wrap around correction applied
- Implementation insufficient in cases where ITO signal oscillated
  - Small probability for additional cluster to be identified in the ITO
  - Requirement added to reject such clusters
- This impacts only events in the control region





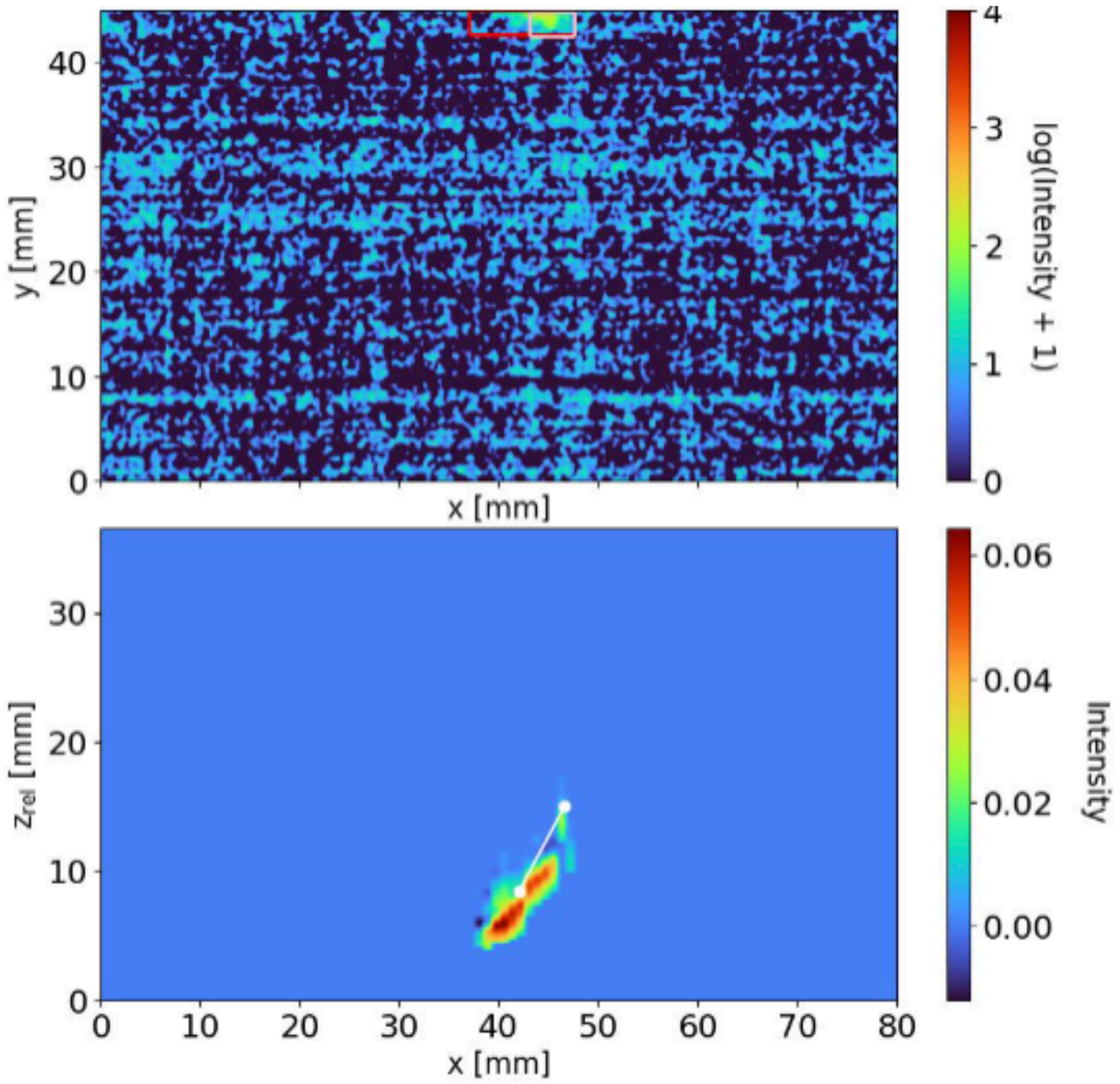
UNIVERSITY OF BIRMINGHAM

Science and Technology Facilities Council

Rutherford Appleton Laboratory

Additional Event Selection Requirements

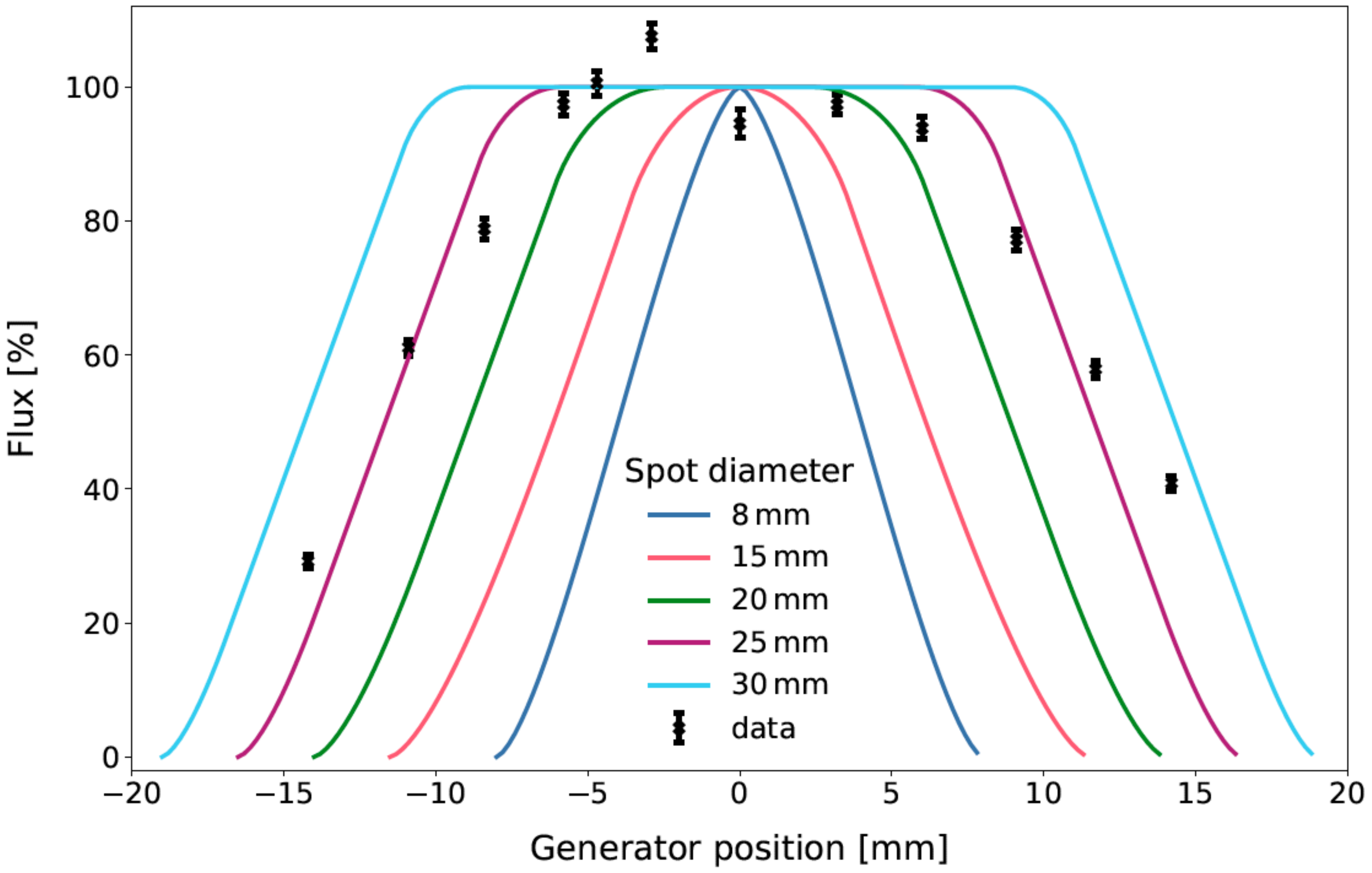
- After unblinding issue with DAQ identified
  - Affects <1% of events where single strip misaligned in time
  - Relevant for 4 specific read-out channels (out of 60)
- Additional requirement applied to reject events with non-physical dE/dx profile



UNIVERSITY OF BIRMINGHAM
Science and Technology Facilities Council
Rutherford Appleton Laboratory

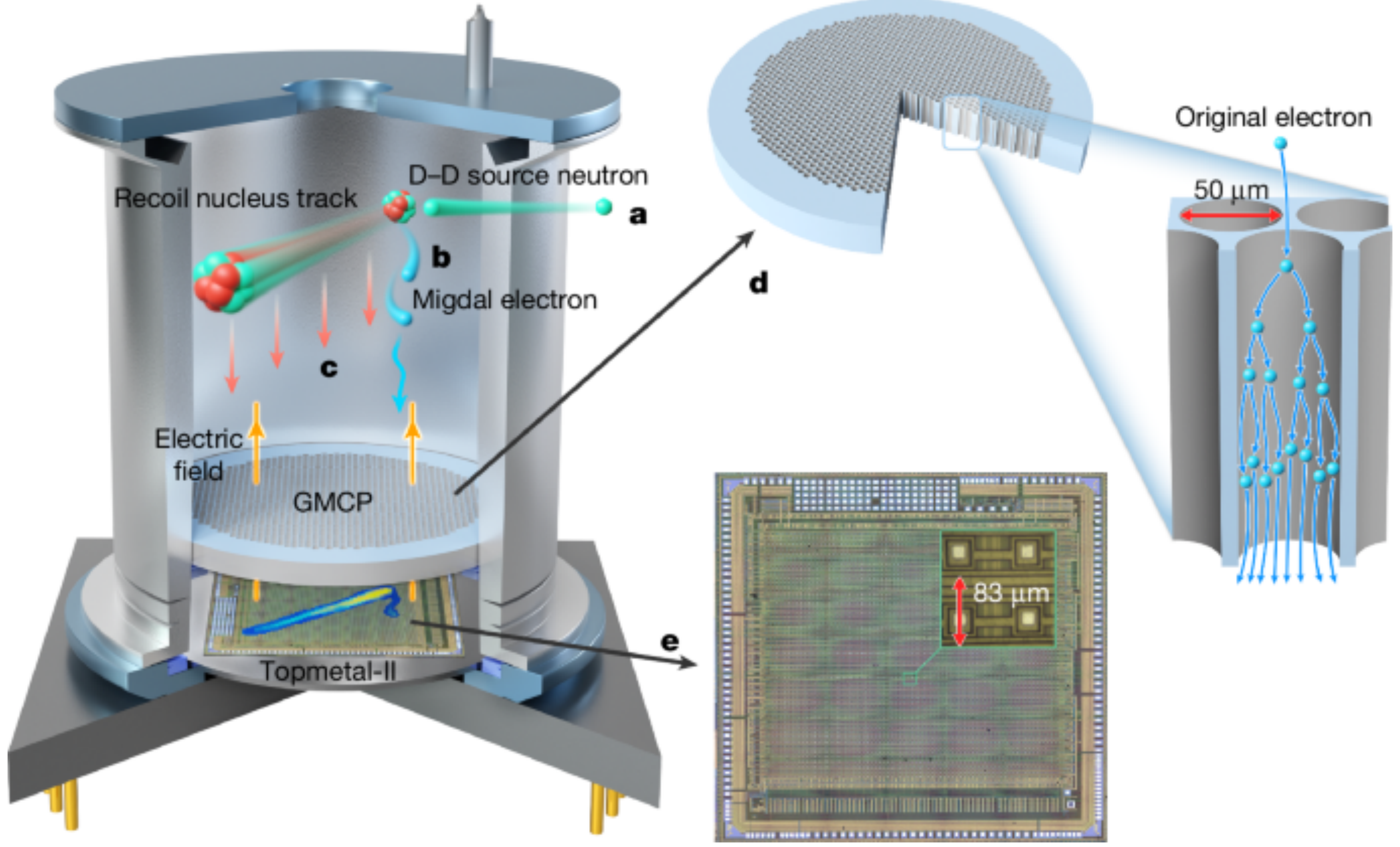
Nuclear Recoil Rate

- Collimator was designed for a D-D generator with an 8mm target spot size
- Generator actually has a 25mm target spot size
- Decrease in nuclear recoil rate by a factor of 4 compared to experiment design specifications
- Optimising collimator for next science run which will increase nuclear recoil rate

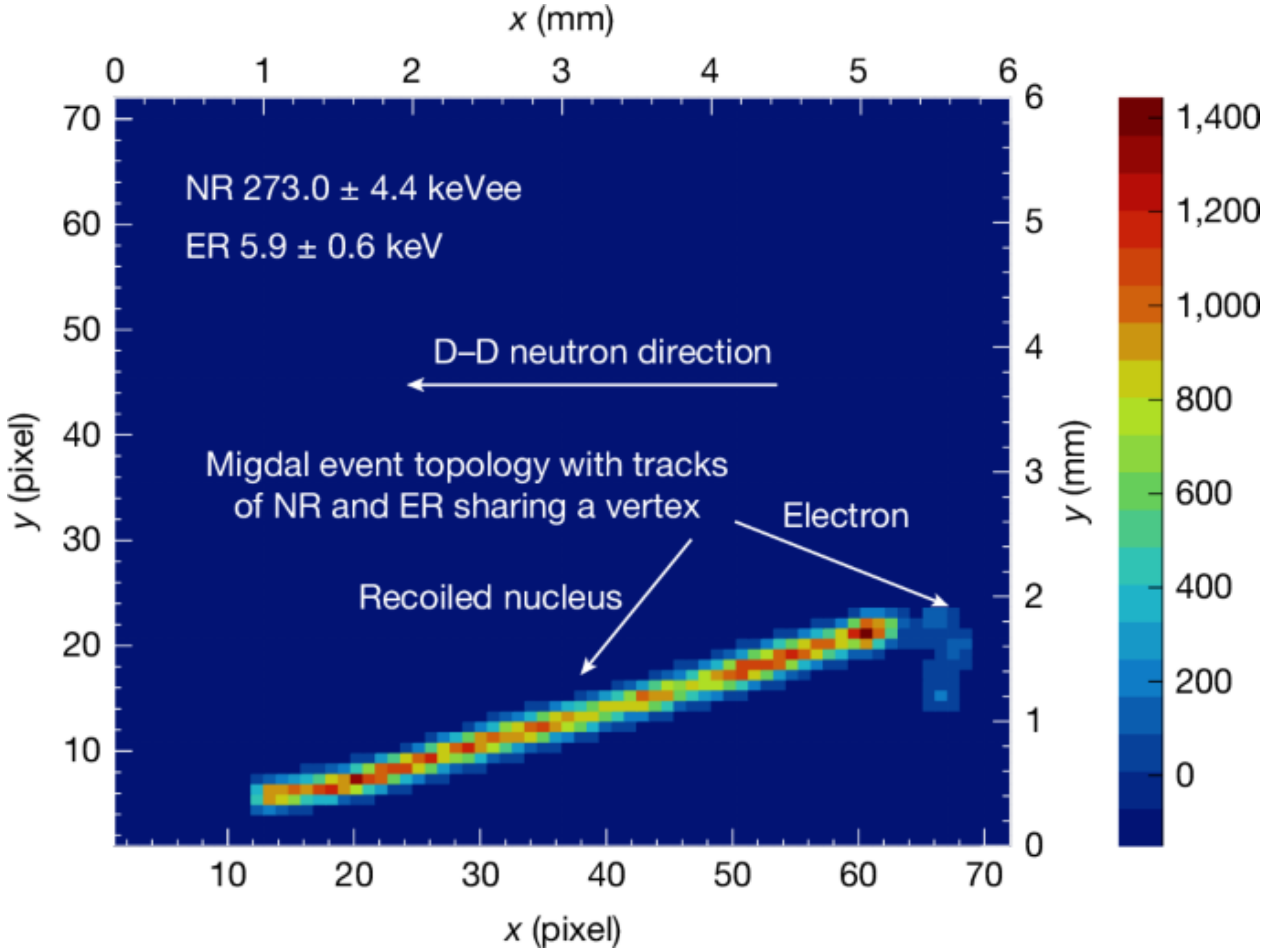


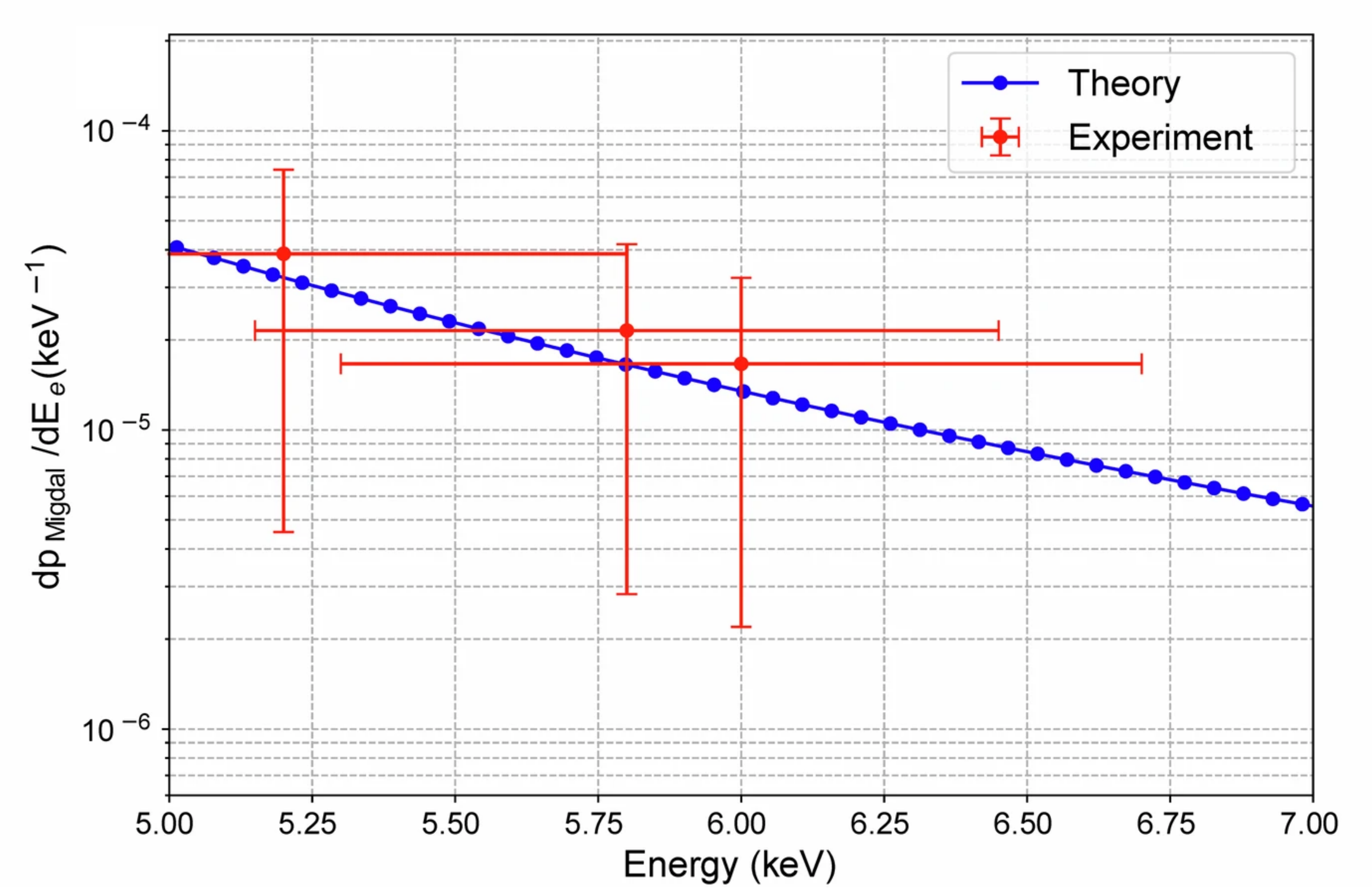
First observation of the Migdal effect in nuclear scattering

- First observation of the Migdal Effect in nuclear scattering by MARVEL (Nature 649, 580–583 (2026))
- Using a gas pixel detector with He:CH30CH3 (40:60)
- 2.45 MeV neutrons from a D-D generator



- Signal is primarily from He and H
- In agreement with theoretical predictions



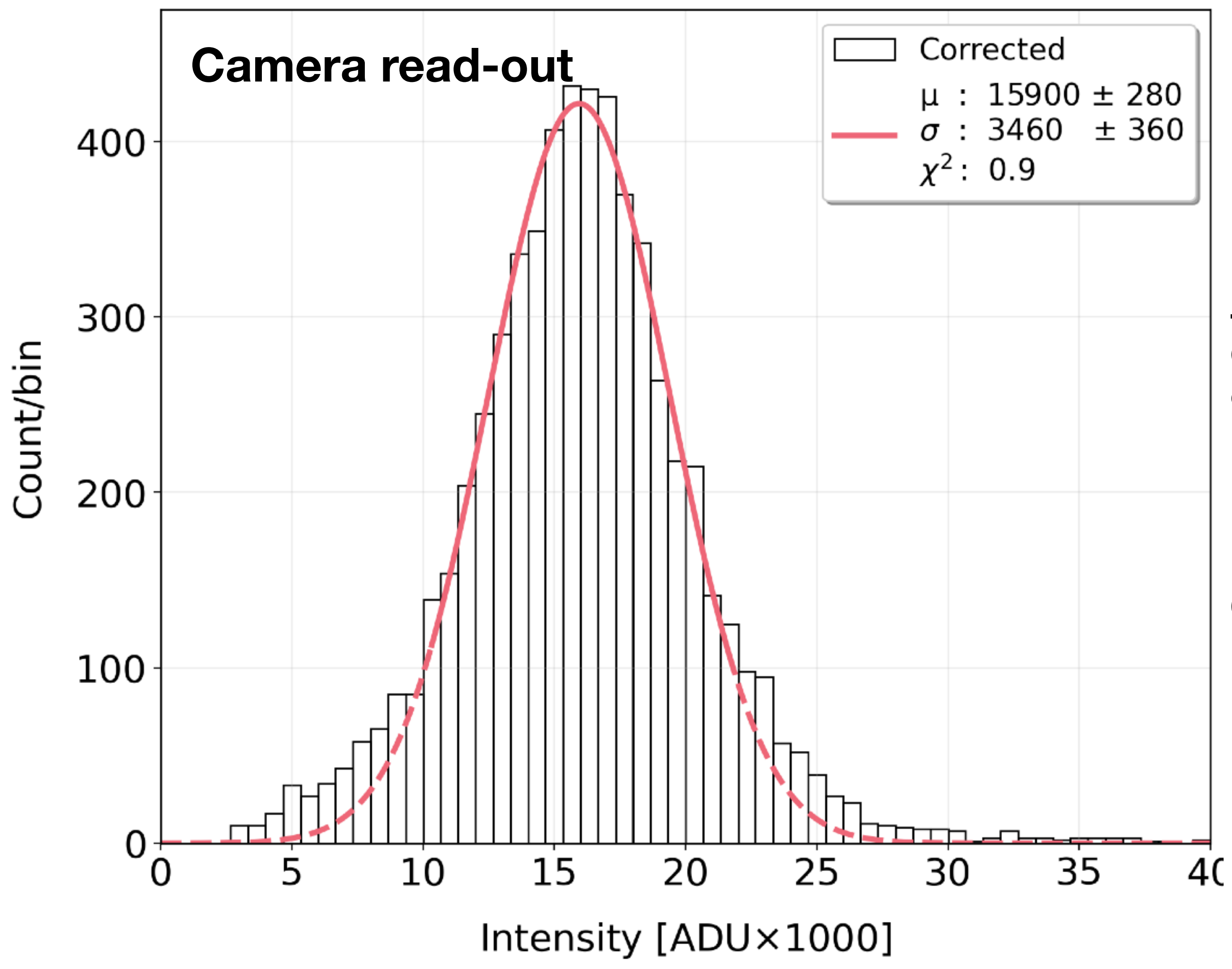


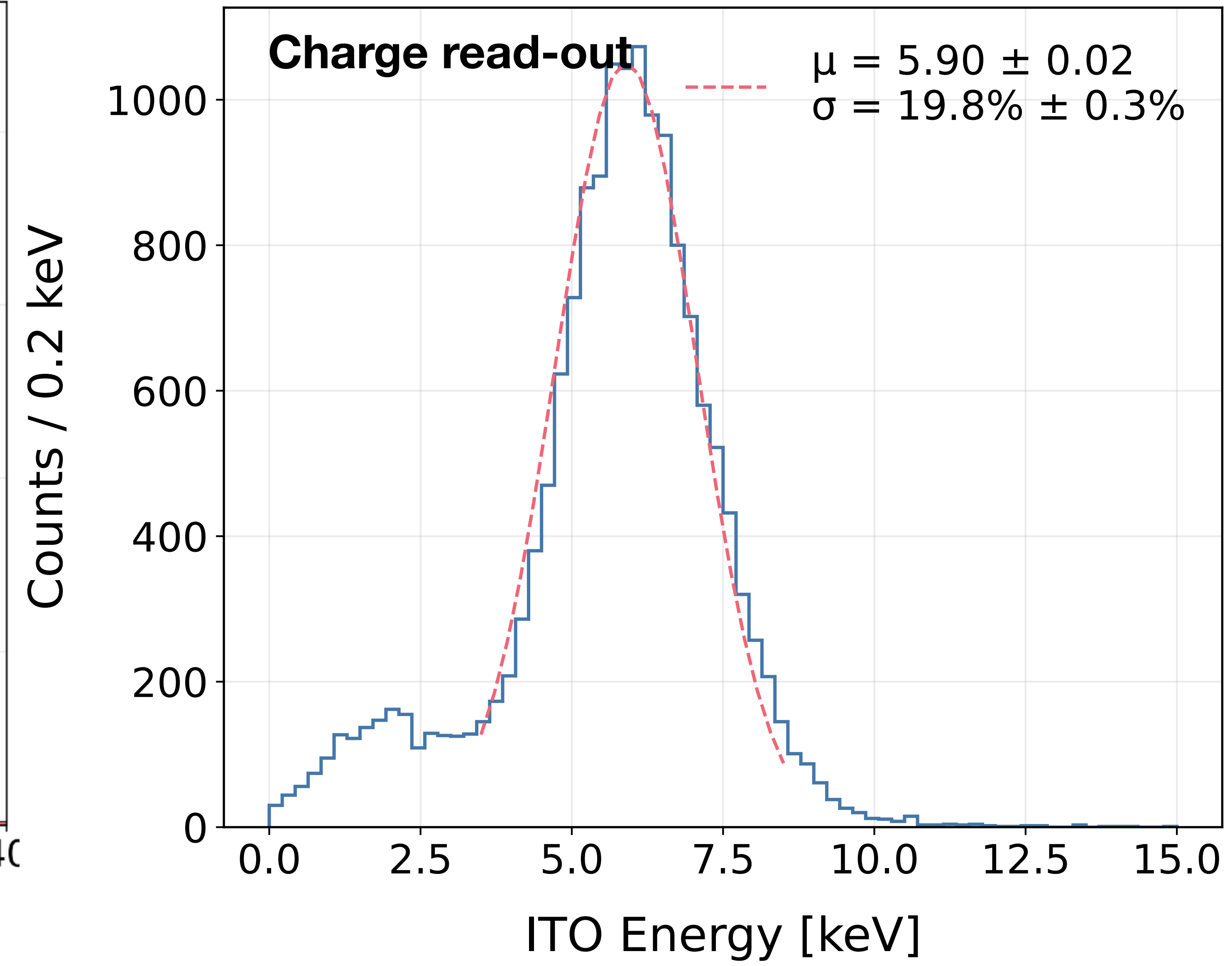
UNIVERSITY OF BIRMINGHAM

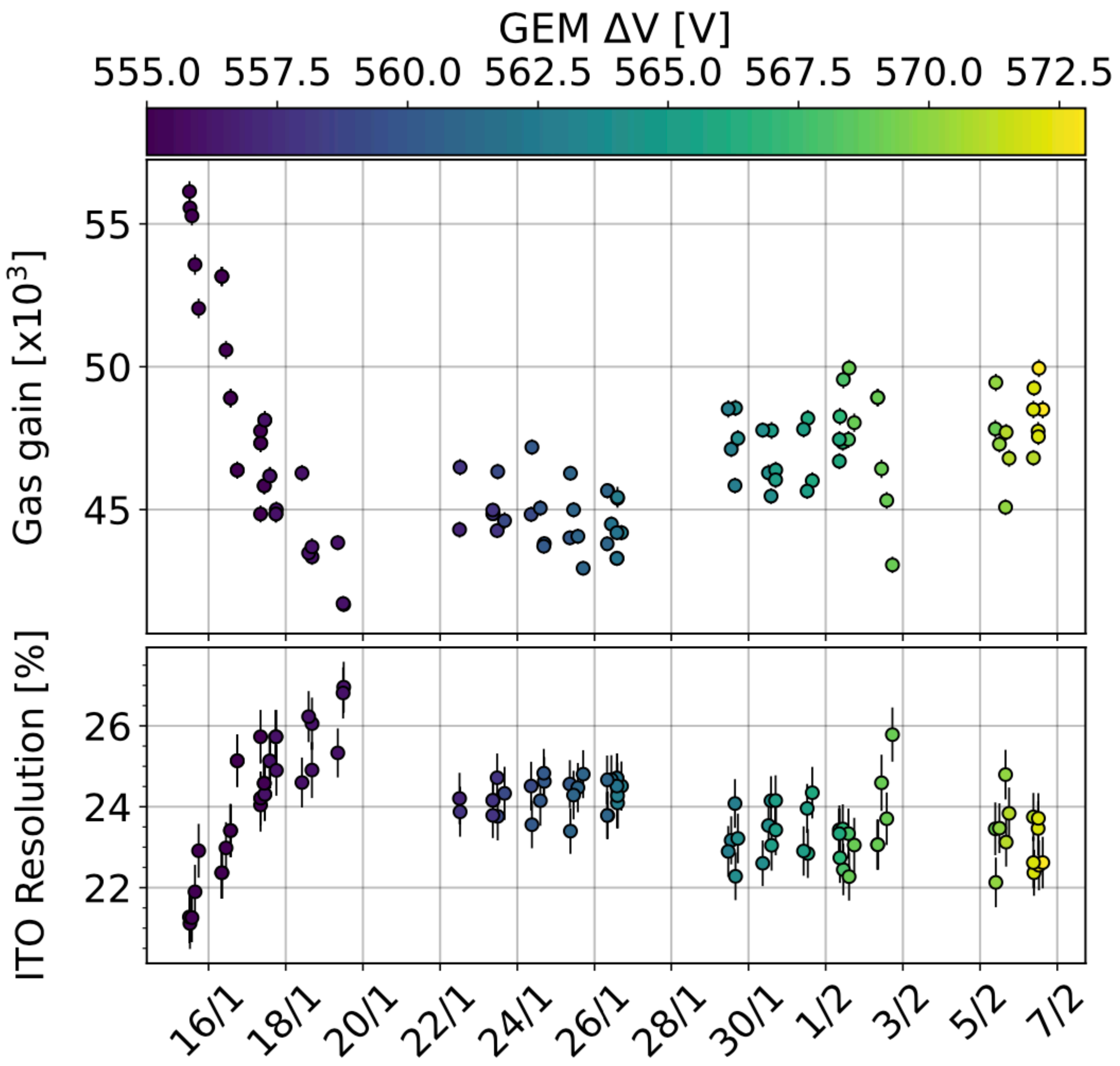
Science and Technology Facilities Council
Rutherford Appleton Laboratory

Calibration

- Calibration with ^{55}Fe source
- Operate near threshold for large stable dynamic range
- Energy resolution of ~20% in all sub-systems
- Gain and resolution monitored in all sub-systems
- GEM voltages increased ~2V per day to maintain gain







UNIVERSITY OF BIRMINGHAM

Science and Technology Facilities Council
Rutherford Appleton Laboratory