



UNIVERSITY OF BIRMINGHAM



Rutherford Appleton Laboratory

The MIGDAL experiment:

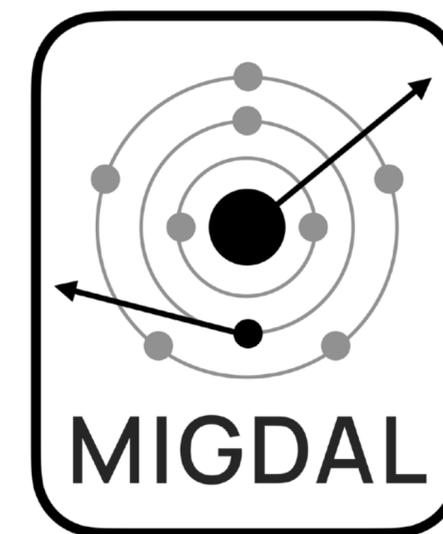
Measuring a rare atomic process to aid the search for dark matter

Lex Millins

University of Birmingham & STFC Rutherford Appleton Laboratory

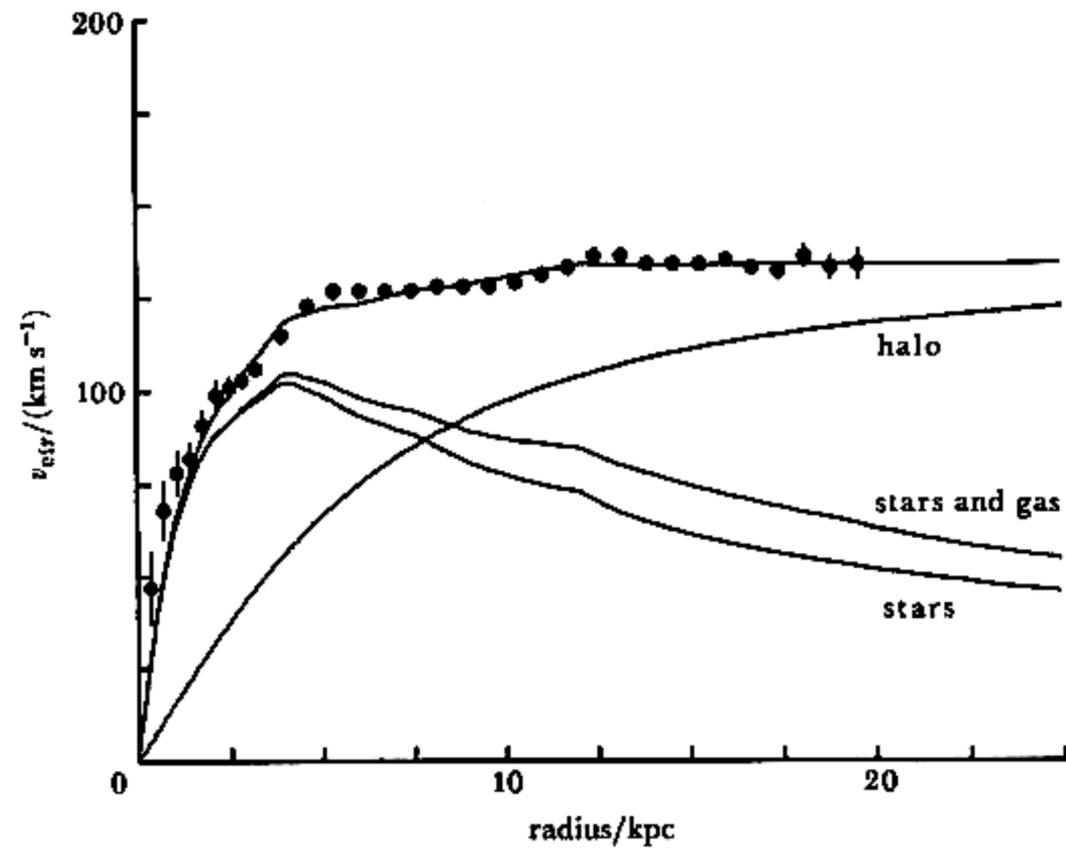
University of Liverpool, Particle Physics Seminar

24th March 2026

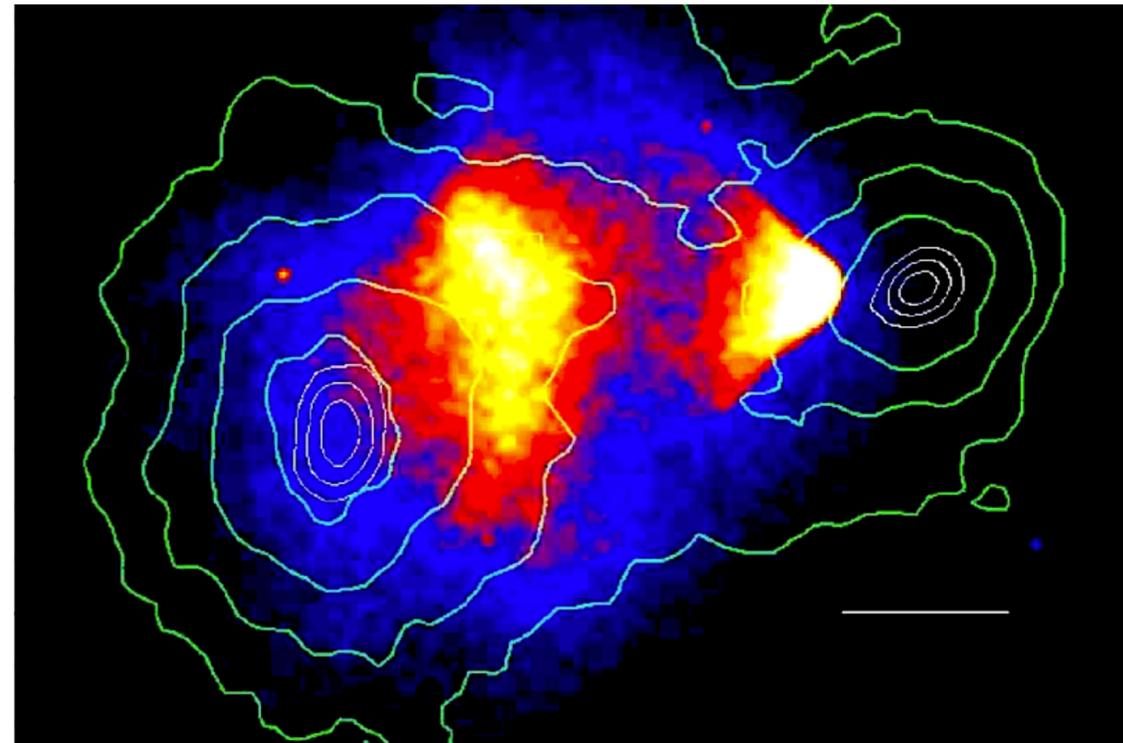


lkm892@student.bham.ac.uk

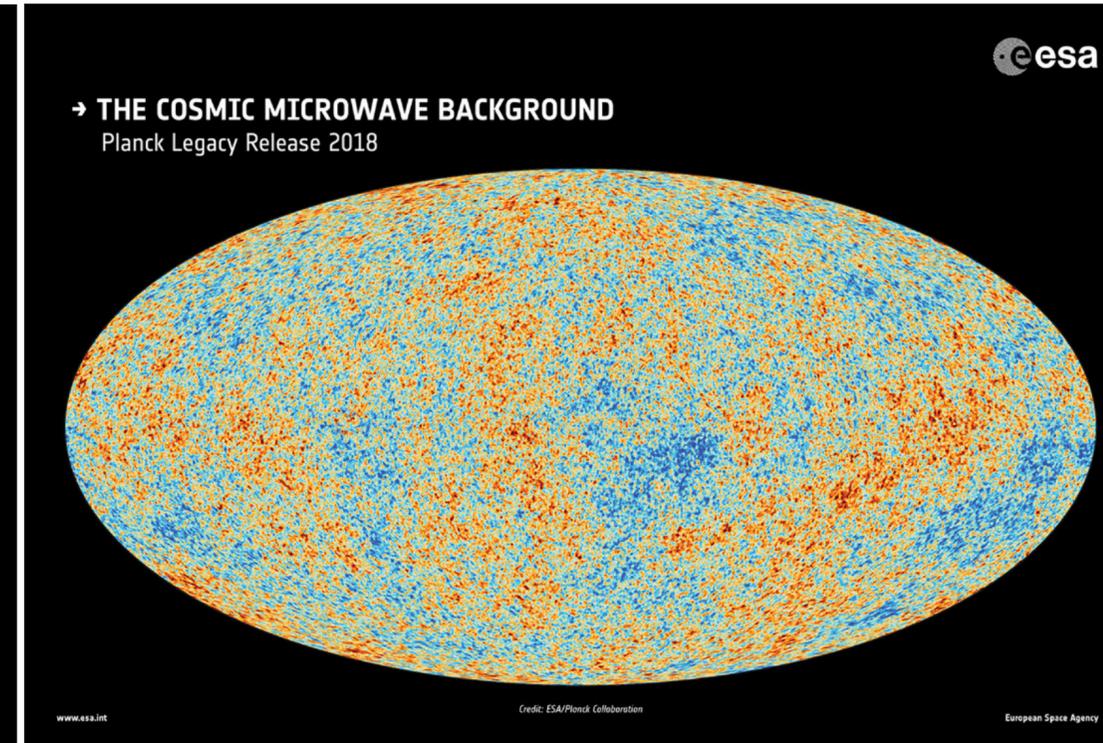
- Wealth of astrophysical evidence for existence of DM
- Inferred through it's gravitational effects
- Makes up 27% of the mass-energy content of the universe



[Phil. Trans. Roy. Soc. Lond. A 320.1156 \(1986\)](#)

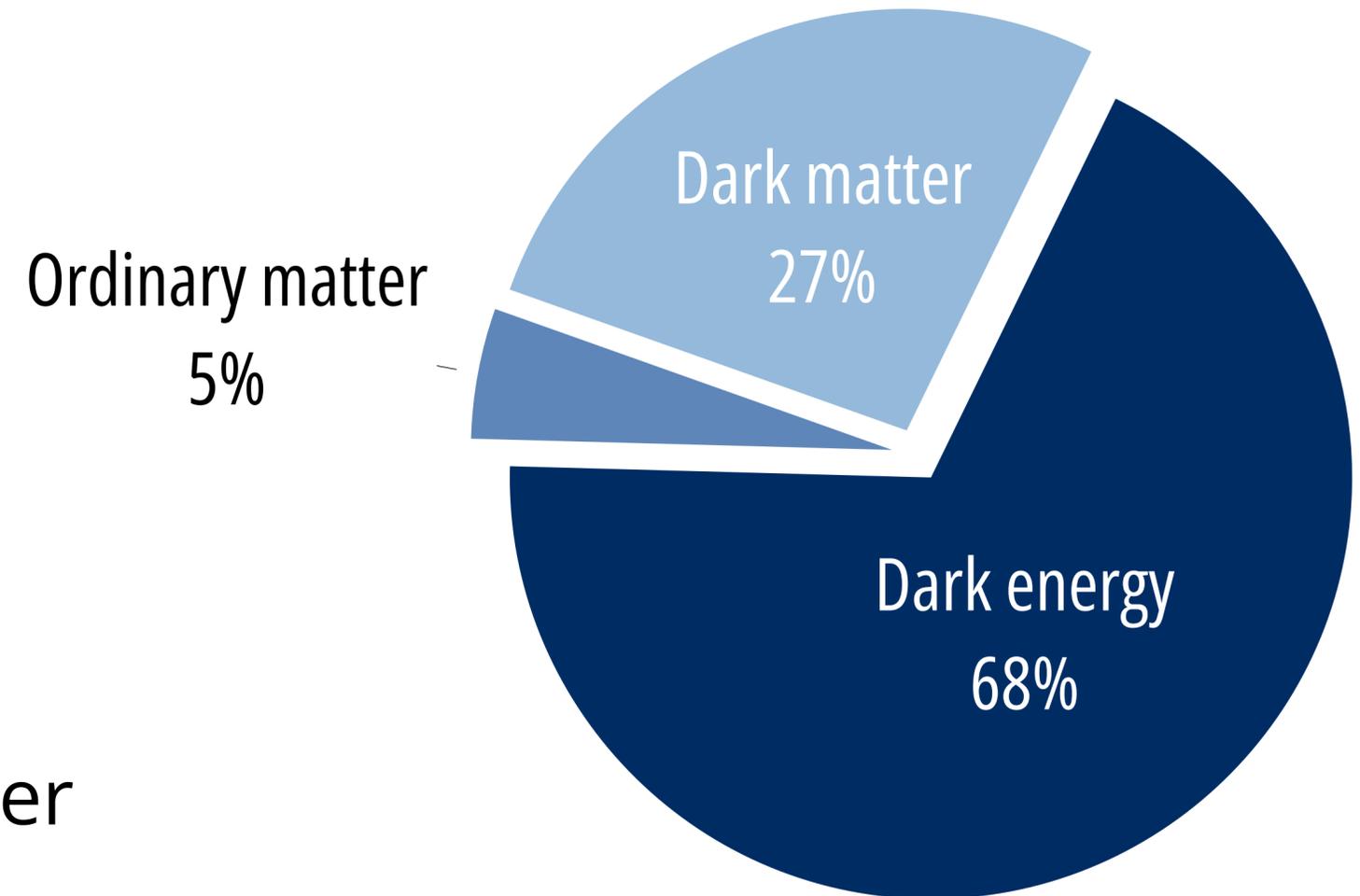


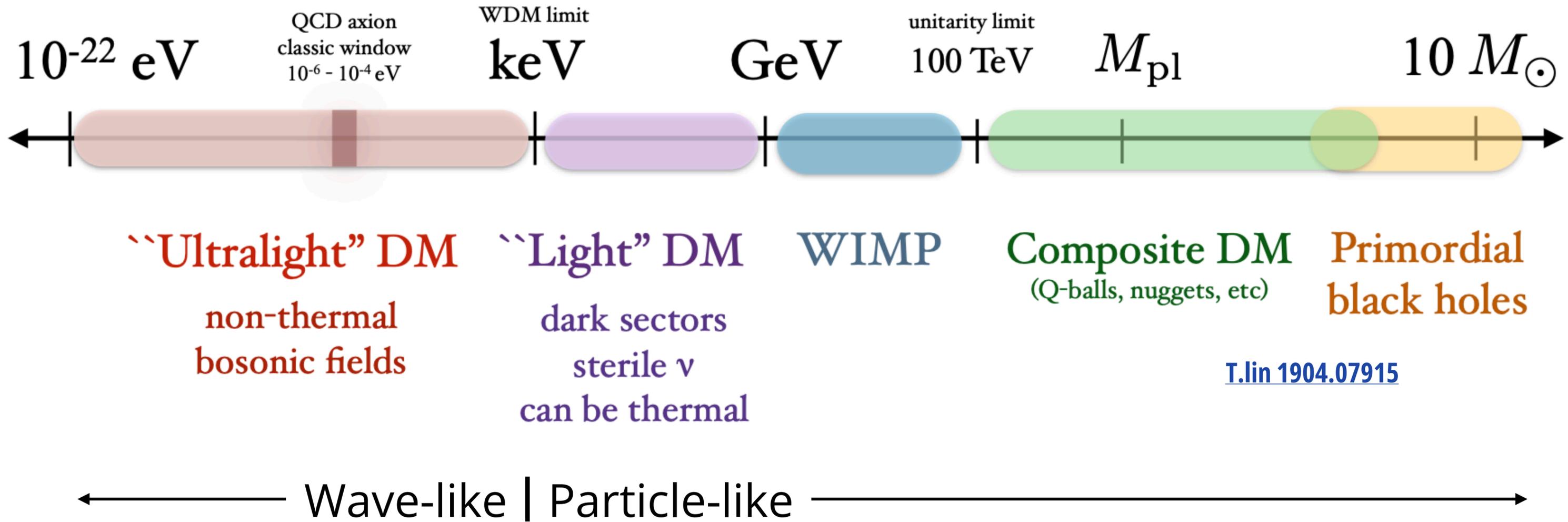
[Astrophys. J. Lett. 648 \(2006\)](#)



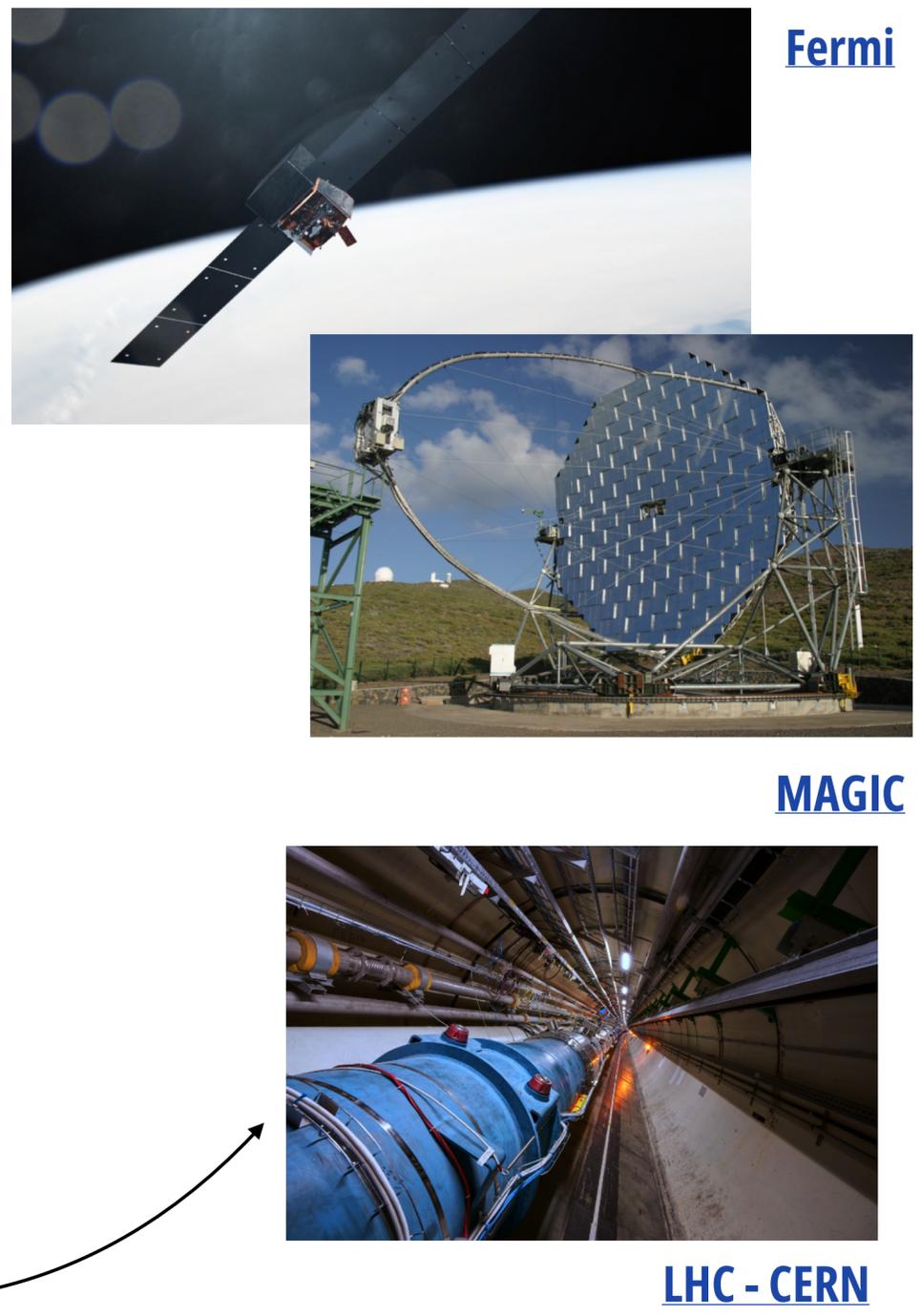
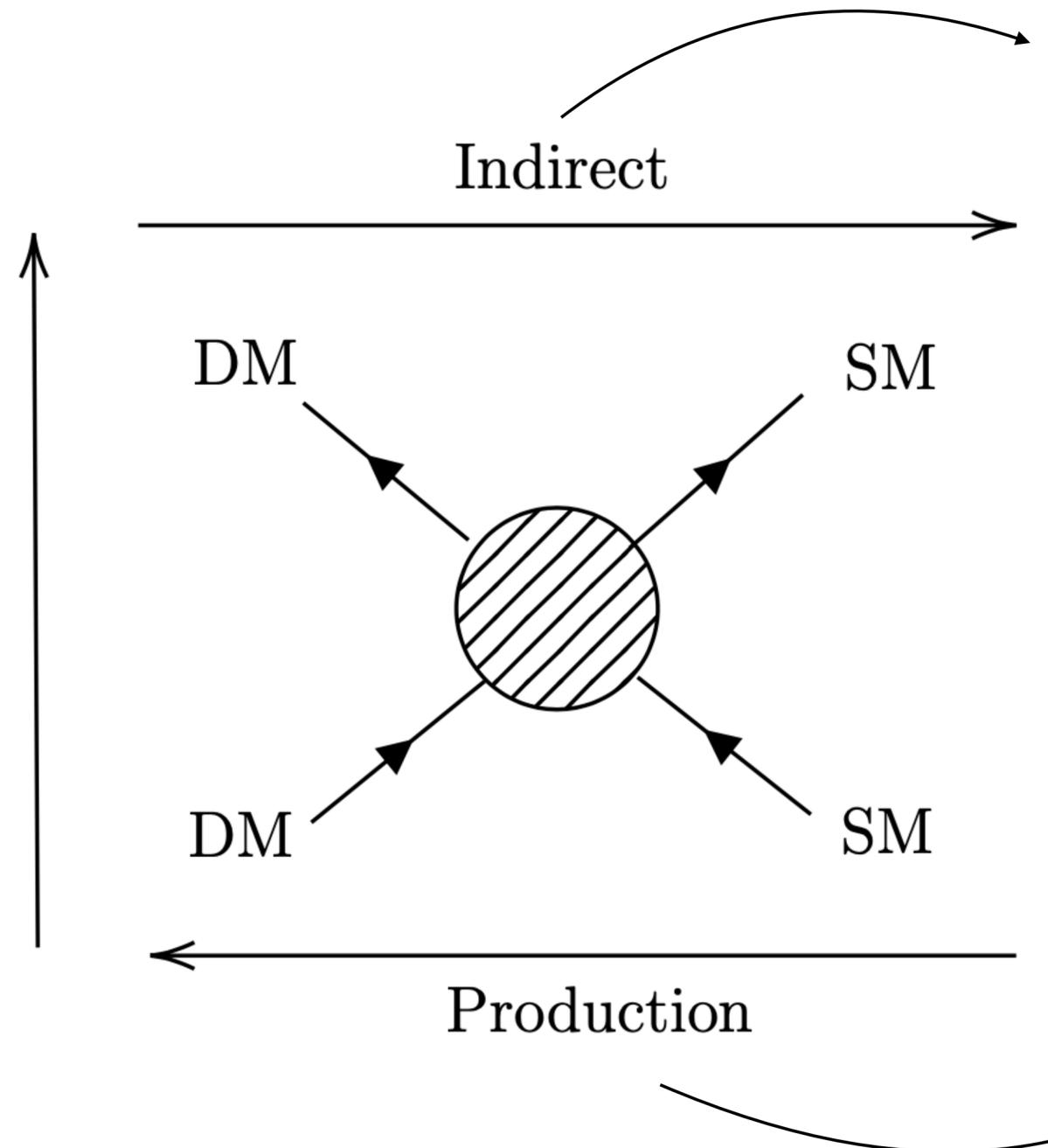
[Astron.Astrophys. 641 \(2020\) A6](#)

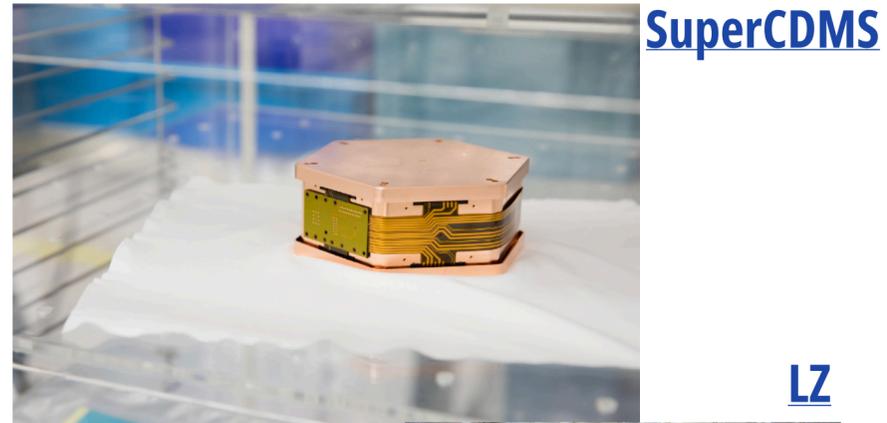
- 85% of the total mass of the universe
- A typical candidate may be
 - No (or very small) electric charge
 - Non-baryonic
 - Non-relativistic at freeze-out
 - Stable on scale of age of universe
 - No/little interaction with ordinary matter
- No standard model particle fits the bill!



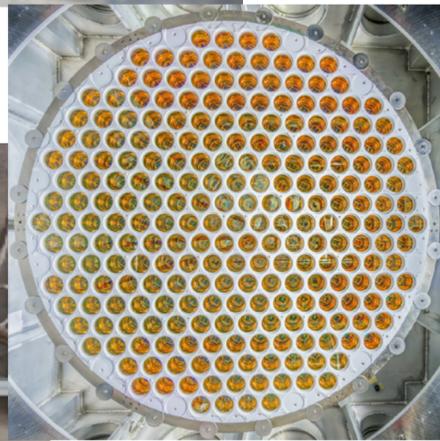


[T.lin 1904.07915](mailto:T.lin@liverpool.ac.uk)





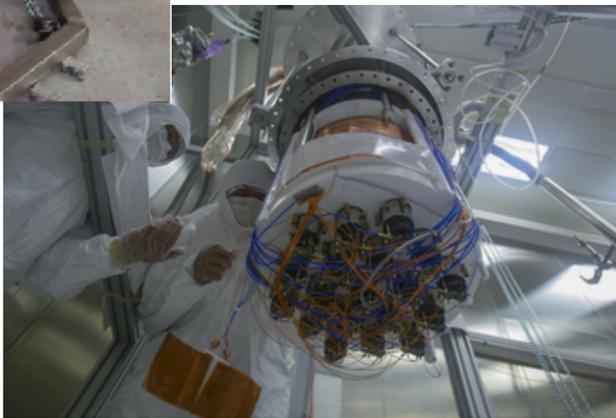
SuperCDMS



LZ

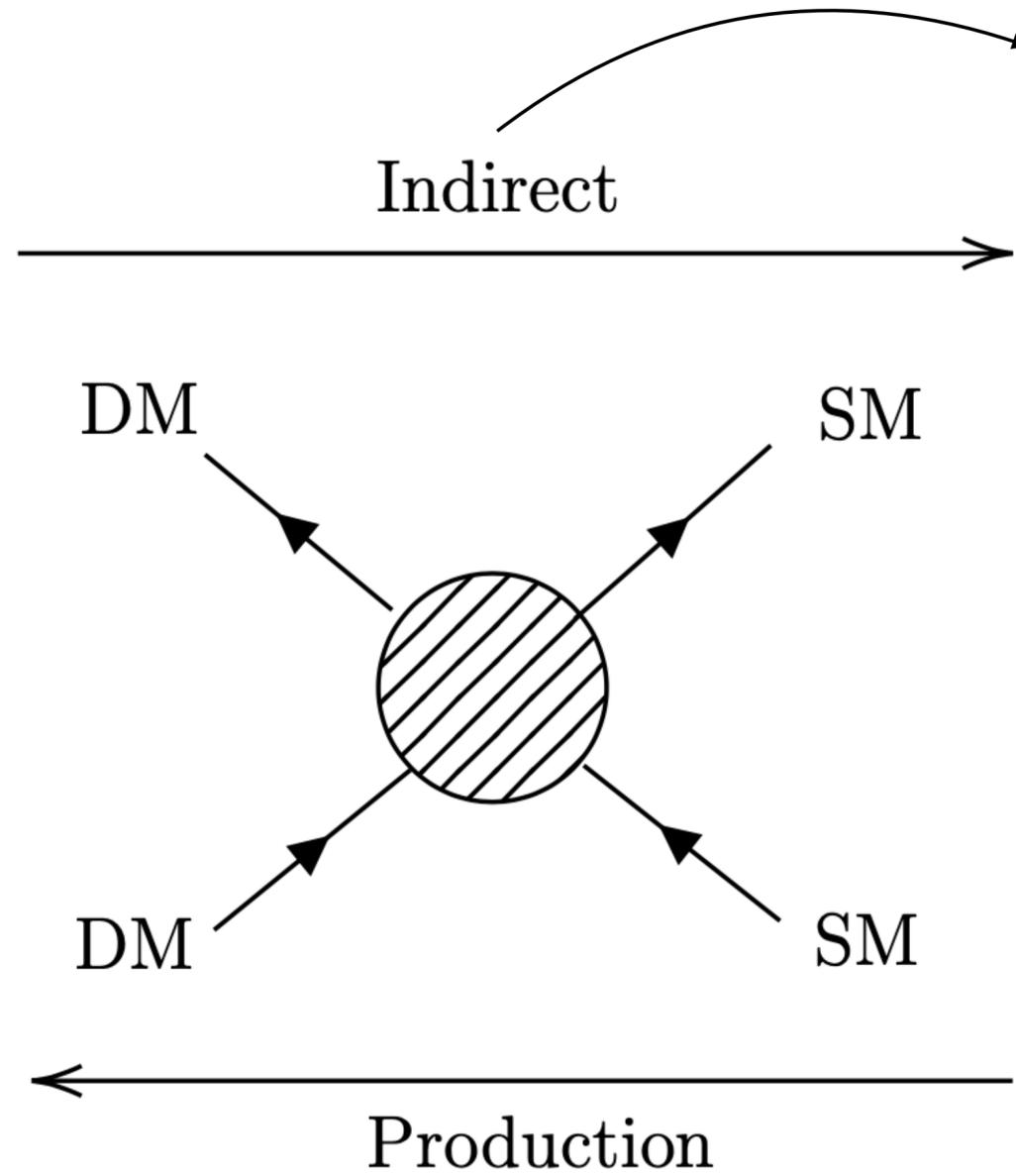


NEWS-G

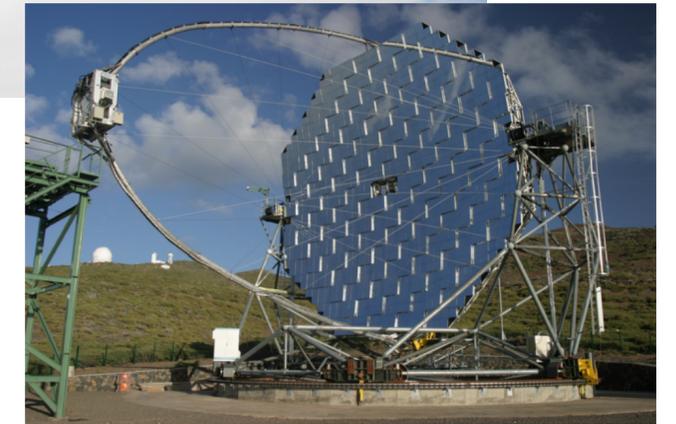


DarkSide

Direct



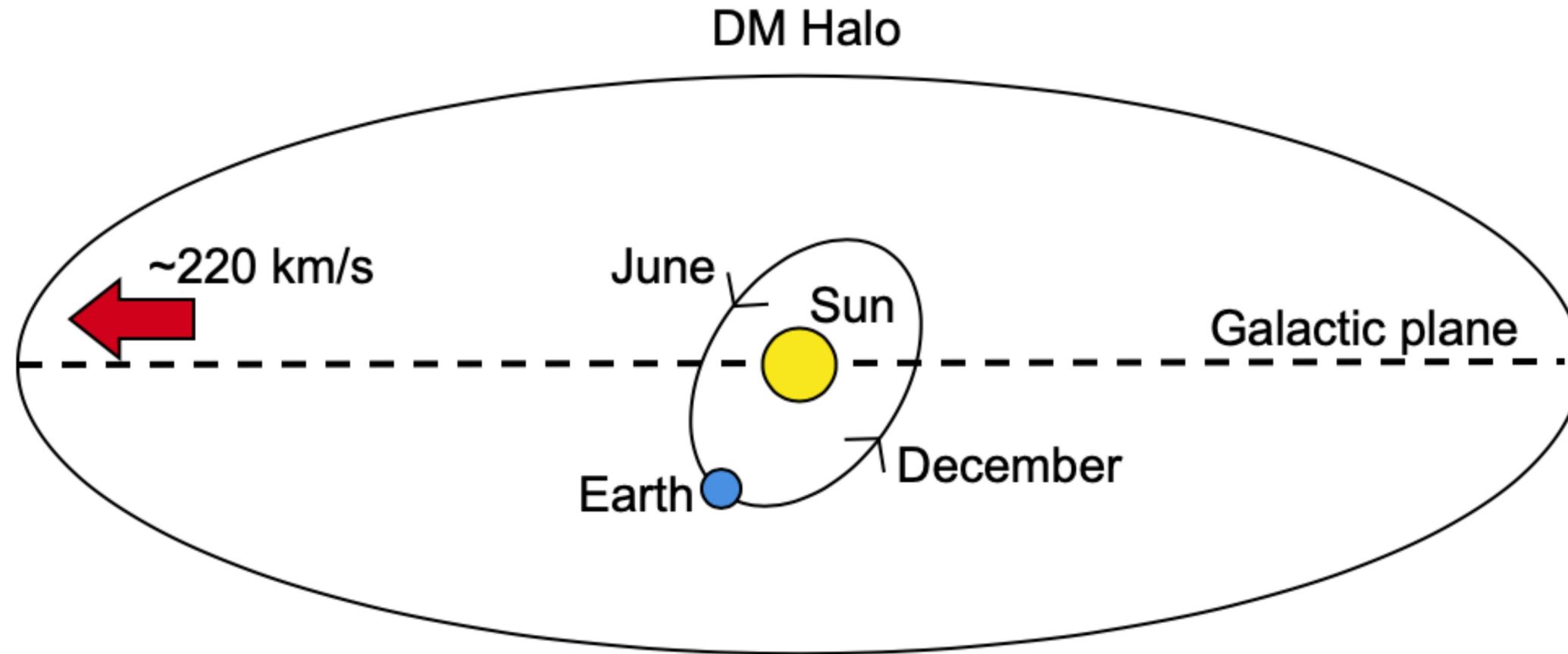
Fermi



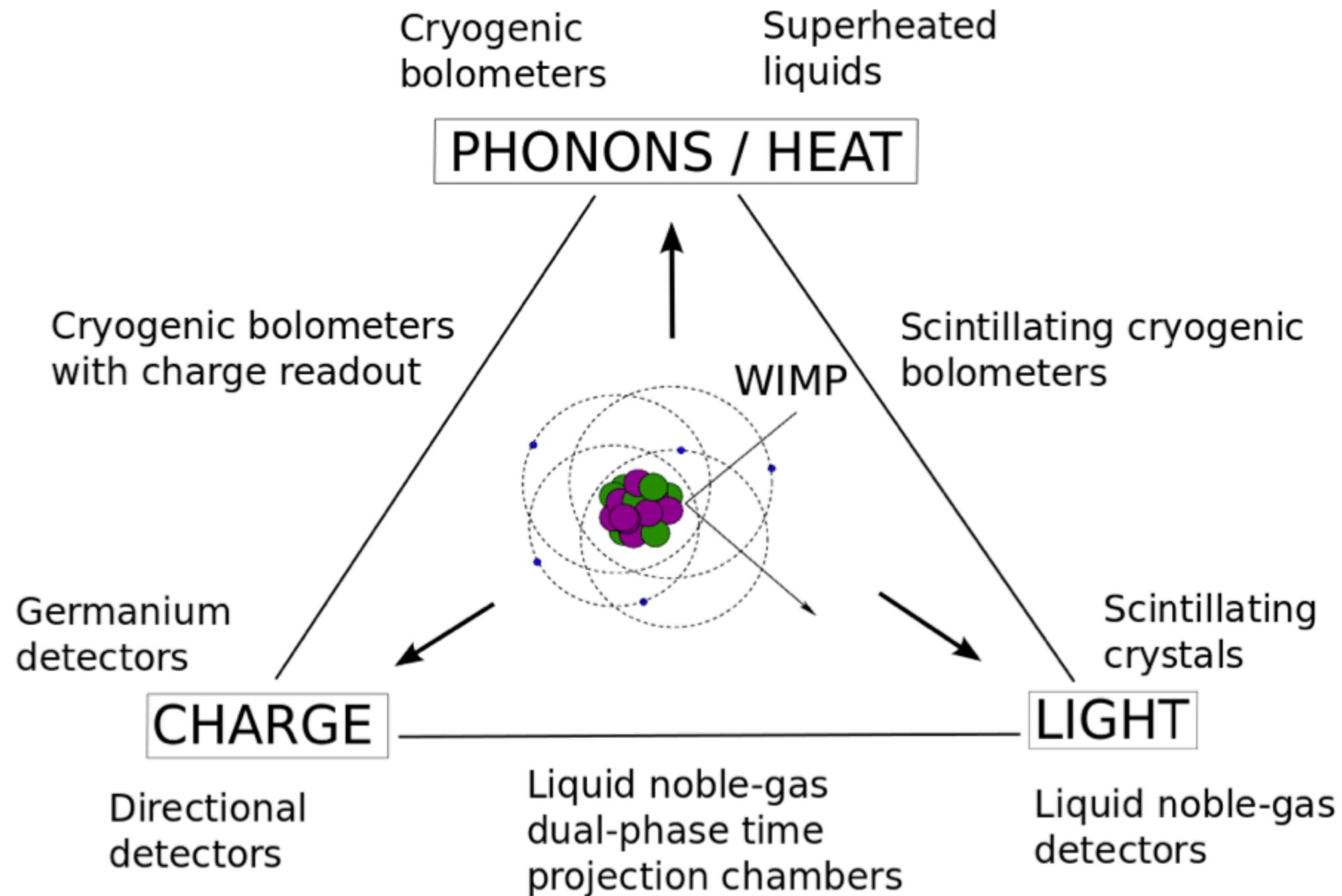
MAGIC



LHC - CERN

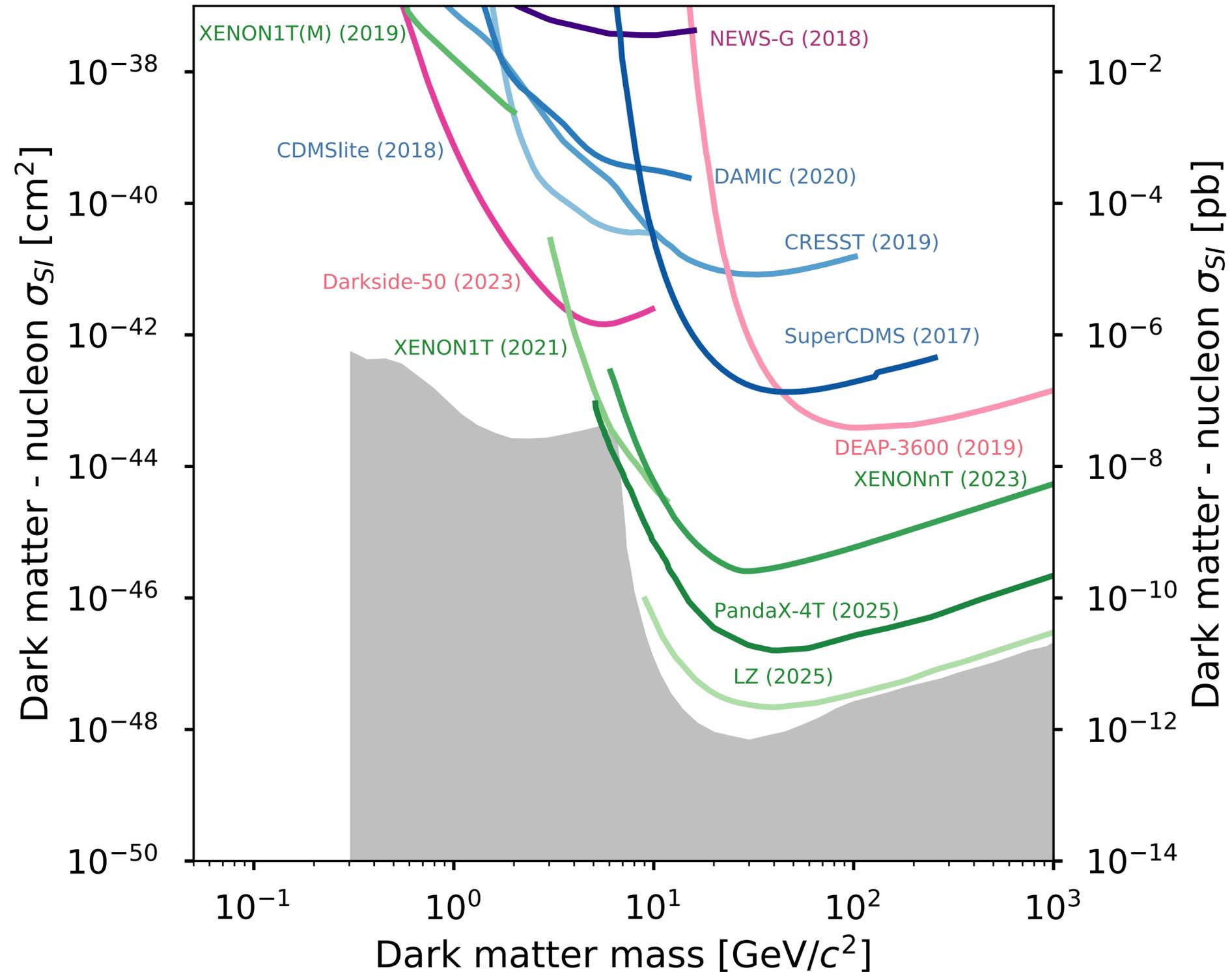


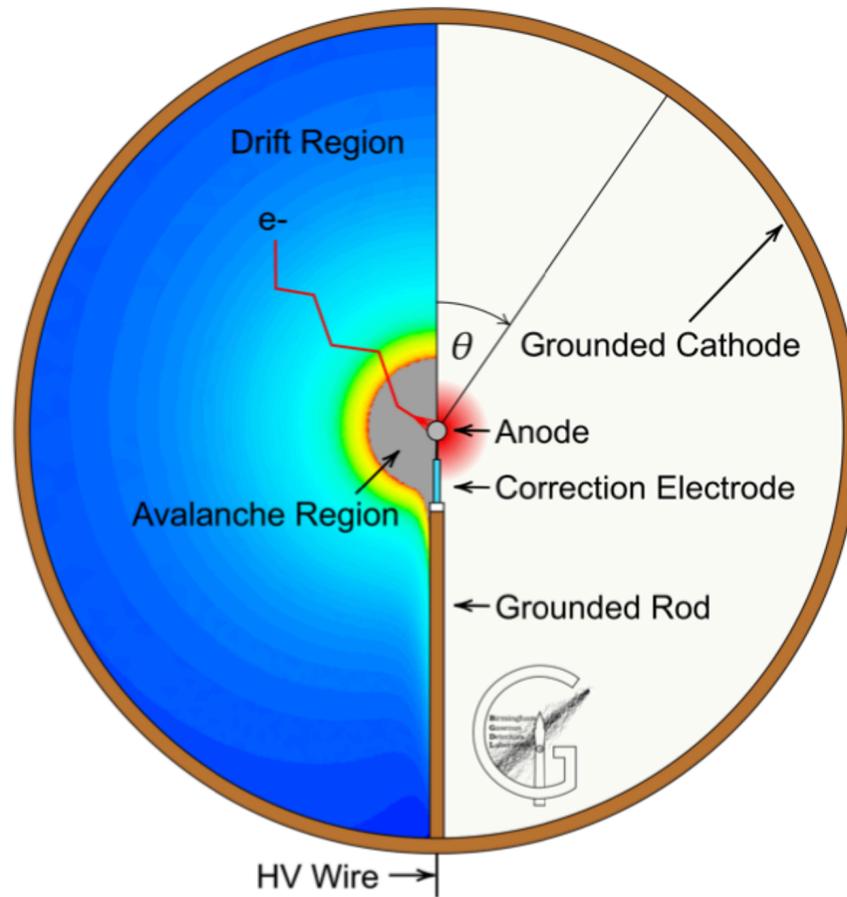
- Moving through DM halo with a velocity of $\sim 220 \text{ km/s}$
- Local DM density $\sim 0.3 \text{ GeV/cm}^3$
- Model as collisionless gas - from Maxwell-Boltzmann velocity distribution
local flux of $\sim (10^7/m_\chi) \text{ GeV/cm}^2\text{s}$
- Motion of Earth induces annual signal modulation



[J.Phys.G 43 \(2016\) 1, 013001](#)

- 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





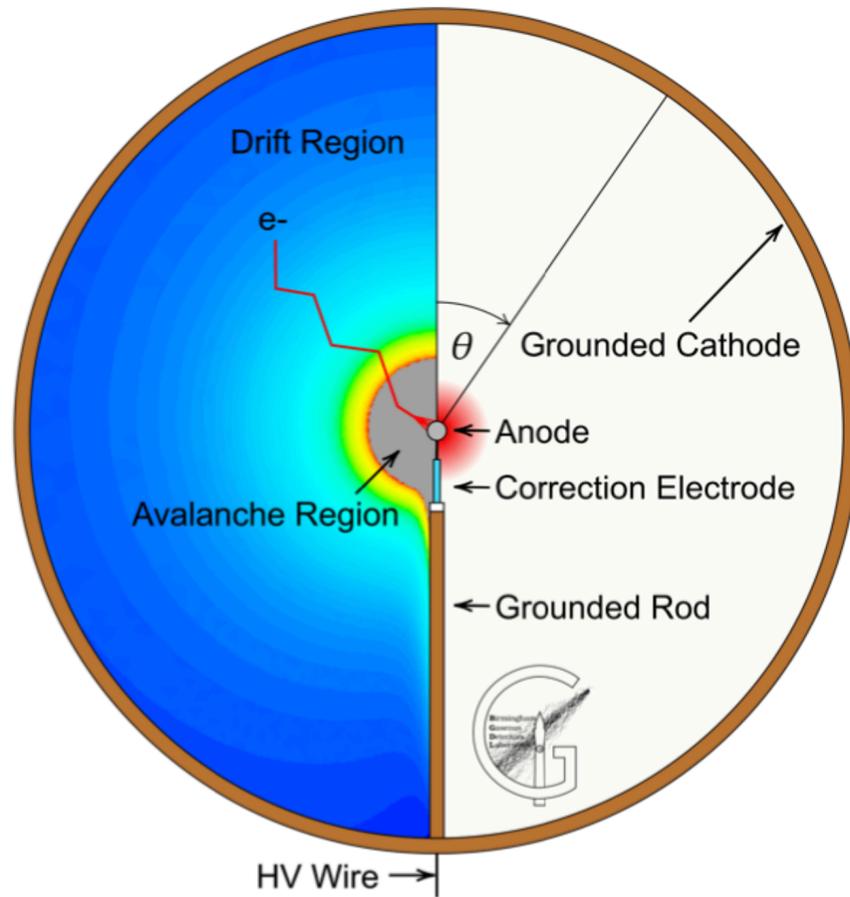
NEWS-G [arxiv:2407.12769](https://arxiv.org/abs/2407.12769)

Light gaseous target

Choice of target and pressure

Low capacitance

- ▶ Single electron detection



NEWS-G [arxiv:2407.12769](https://arxiv.org/abs/2407.12769)

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Choice of target and pressure

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SuperCDMS [arxiv:2302.09115](https://arxiv.org/abs/2302.09115)

Semiconducting calorimeter

Phonon and ionisation
detection

- ▶ Low energy thresholds

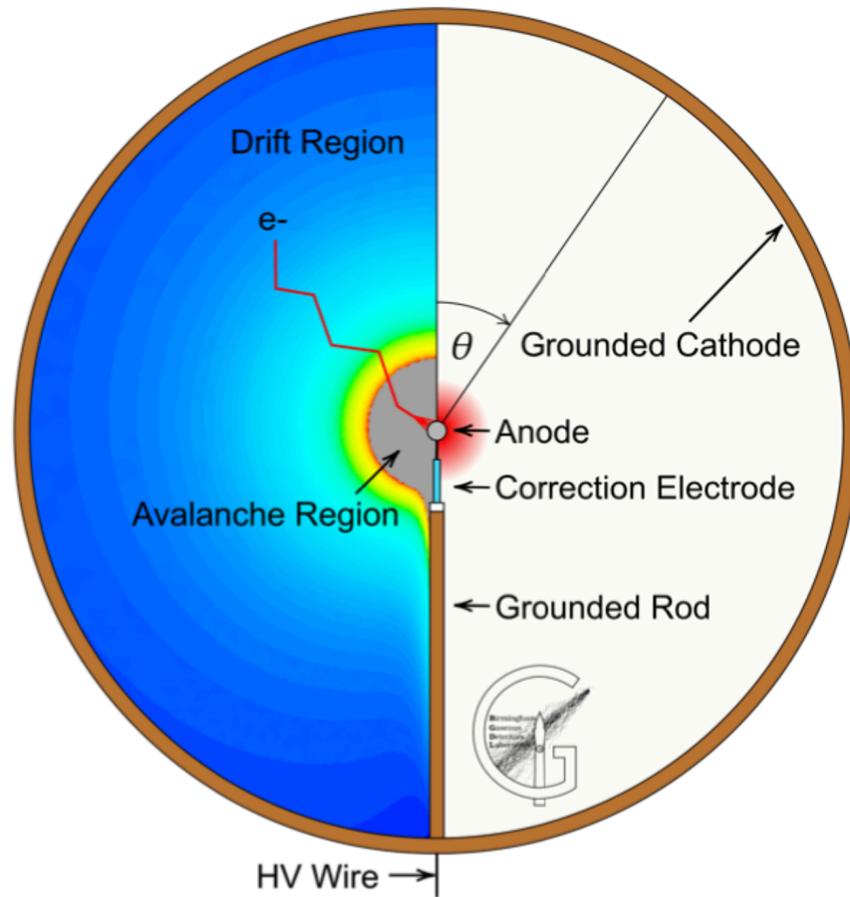
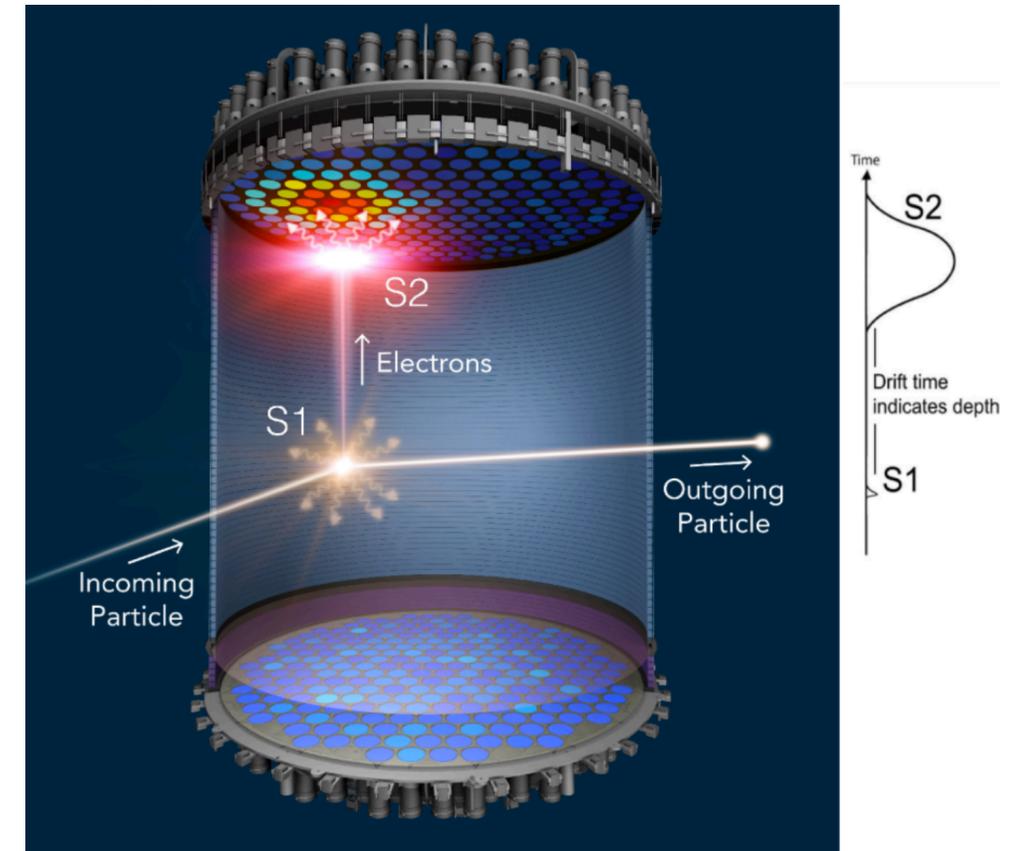


Image: VA Kudryavtsev ICNFP 2018



NEWS-G [arxiv:2407.12769](https://arxiv.org/abs/2407.12769)

- Light gaseous target
- Choice of target and pressure
- Low capacitance
 - ▶ Single electron detection

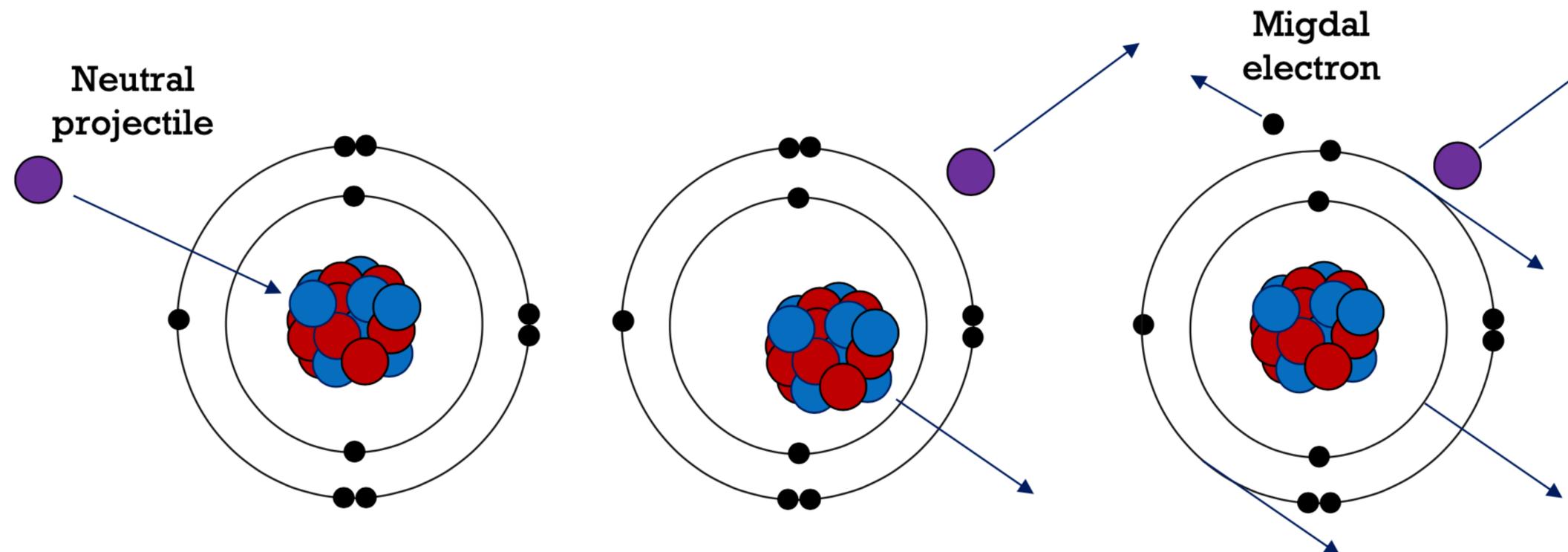
SuperCDMS [arxiv:2302.09115](https://arxiv.org/abs/2302.09115)

- Semiconducting calorimeter
- Phonon and ionisation detection
 - ▶ Low energy thresholds

Liquid noble element TPCs

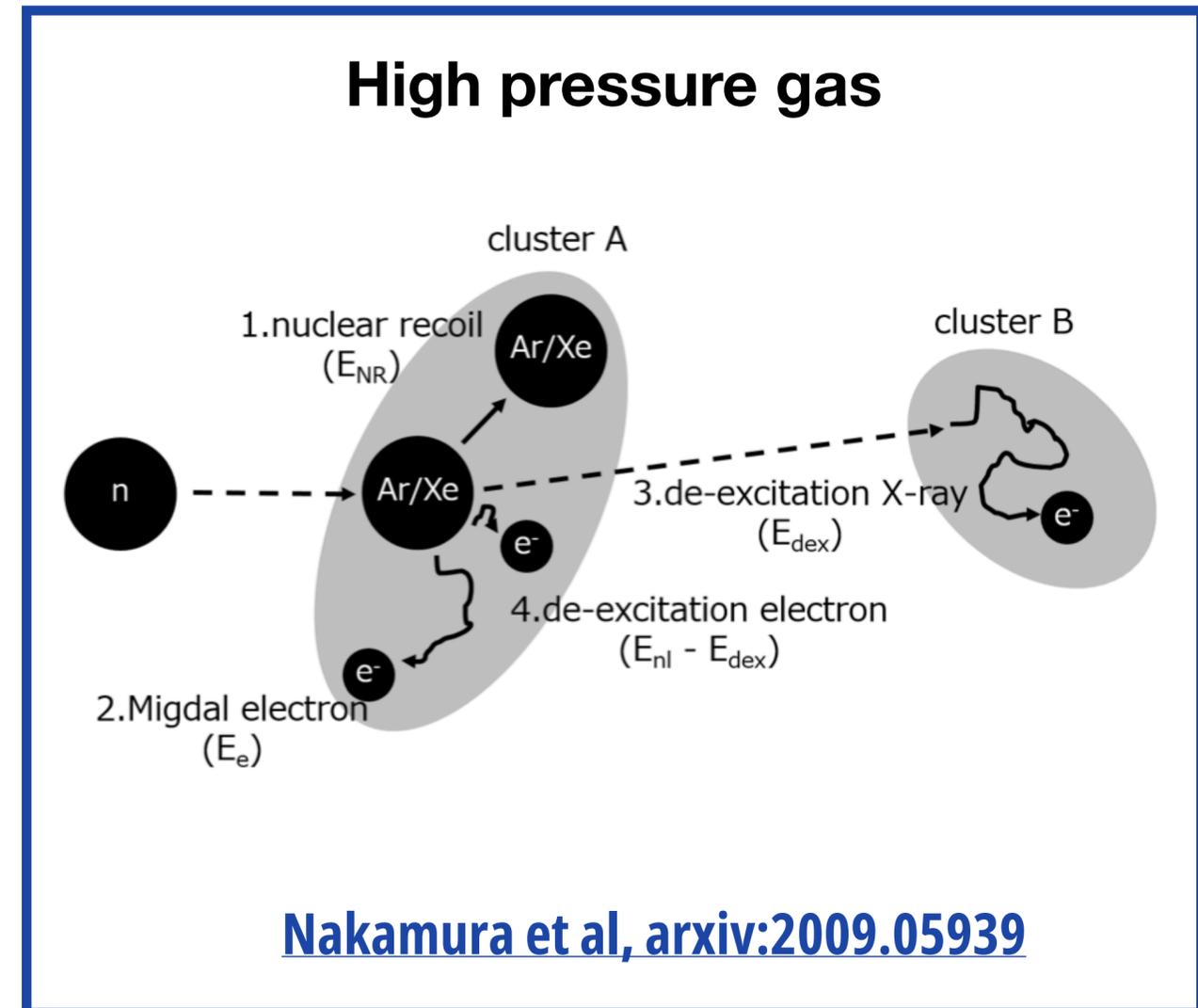
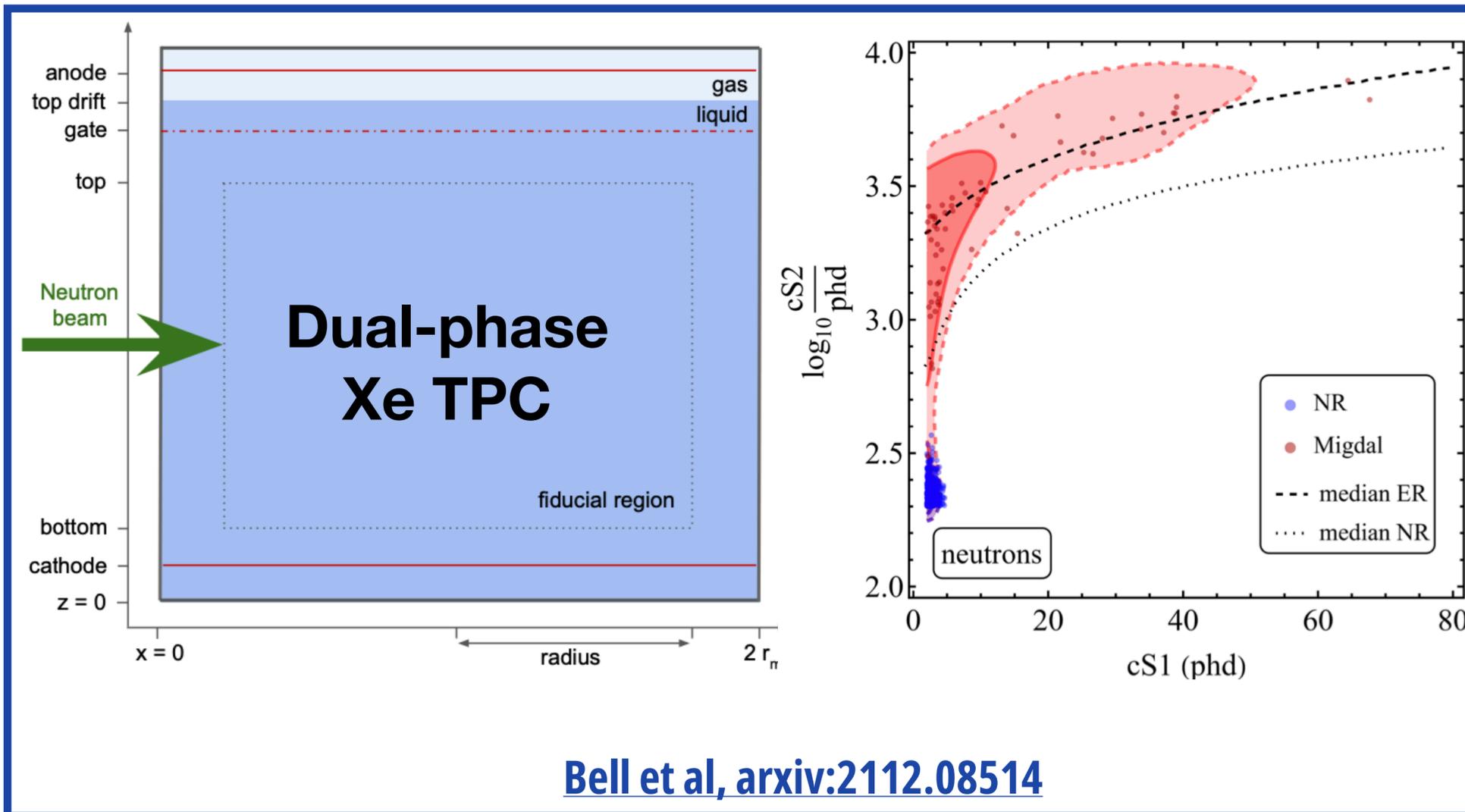
- S2 only searches (lower threshold) [PhysRevD.106.022001](https://arxiv.org/abs/1006.022001)
- H doped Xe [HydroX](https://arxiv.org/abs/1006.022001)

- During nuclear recoil sudden displacement of nucleus with respect to atomic electron cloud excites the atom
- De-excitation can result in emission of one or more Migdal electrons (with low probability)
- Observed in α , β decay ([Phys. Rev. C 11 \(1975\), 1740-1745 & 1746-1754](#), [Phys. Rev. 93 \(1954\), 518-523](#), [Phys. Rev. A 97 \(2018\), 023402](#))
- For low mass WIMP-like DM energy deposited by electron can exceed $O(\text{keV})$ nuclear recoil
- Recently observed for the first time in nuclear scattering ([Nature 649, 580–583 \(2026\)](#))



Migdal experimental efforts

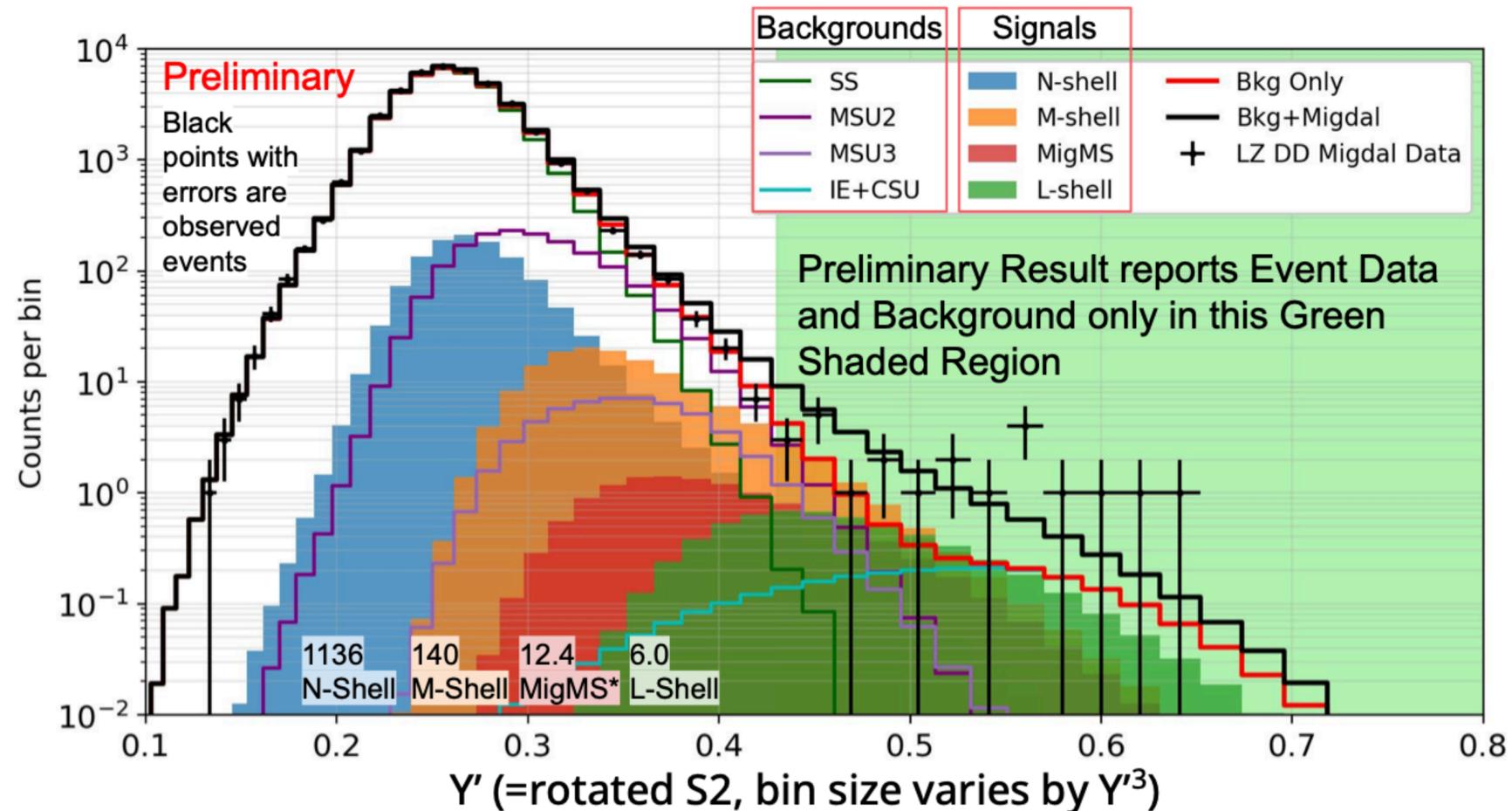
- Searches for Migdal in nuclear scattering induced by neutrons
- Detect nuclear recoil and simultaneously Migdal electron or associated de-excitation x-ray



- Dual-phase Xe TPC results

LZ: Observe excess in high S2 region consistent with Migdal Analysis to be finalised

[J.Bang, UCLA Dark Matter 2023](#)



Xu et al: Signal suppressed due to recombination

[Phys.Rev.D 109 \(2024\) 5, L051101](#) [arXiv 2503.07562](#)

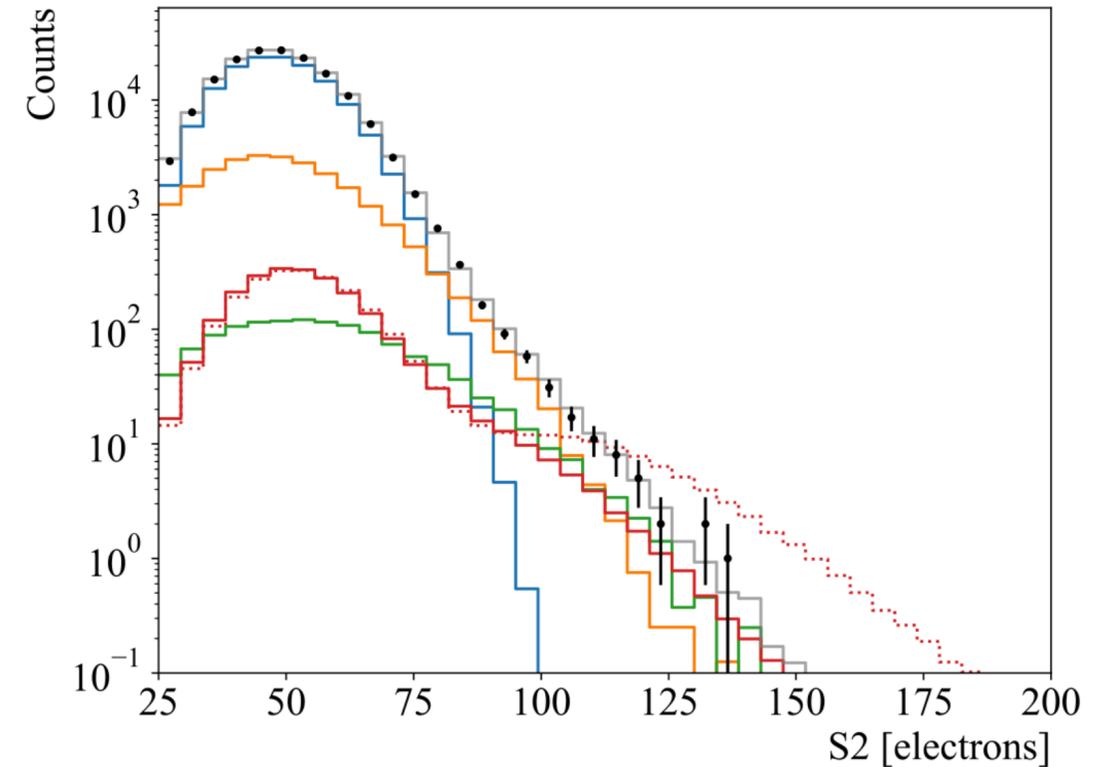
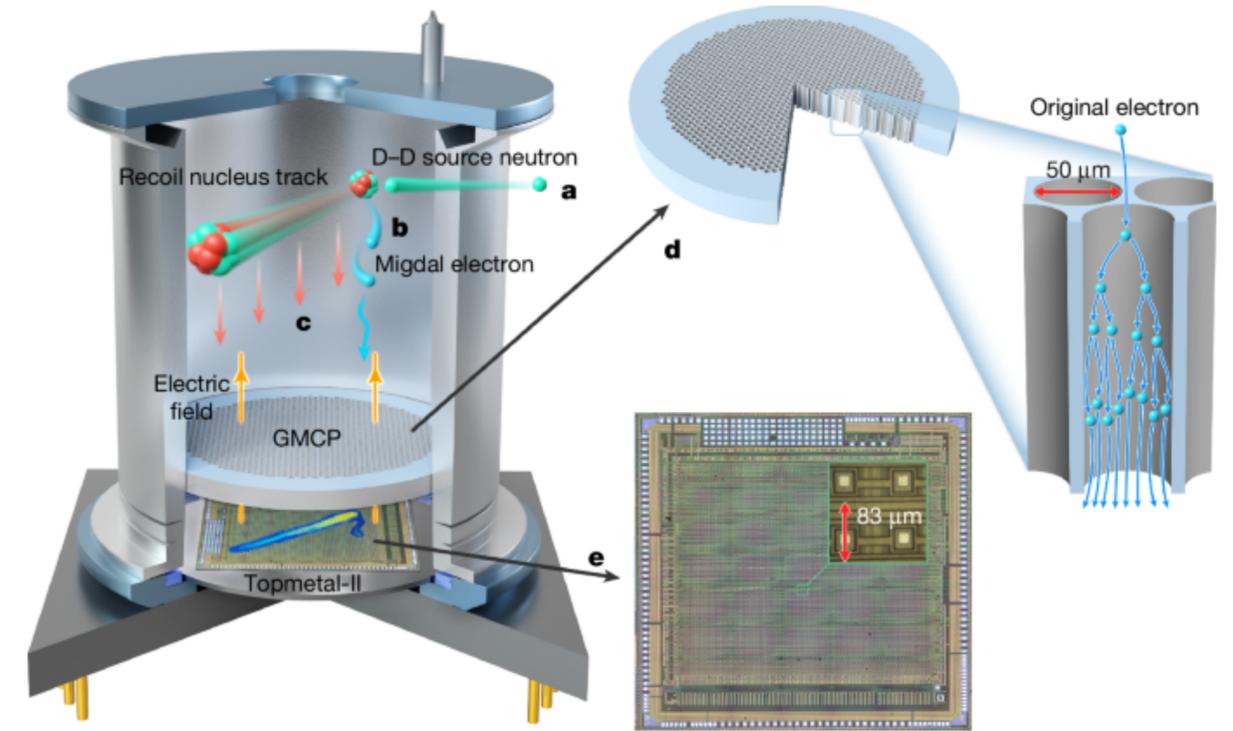


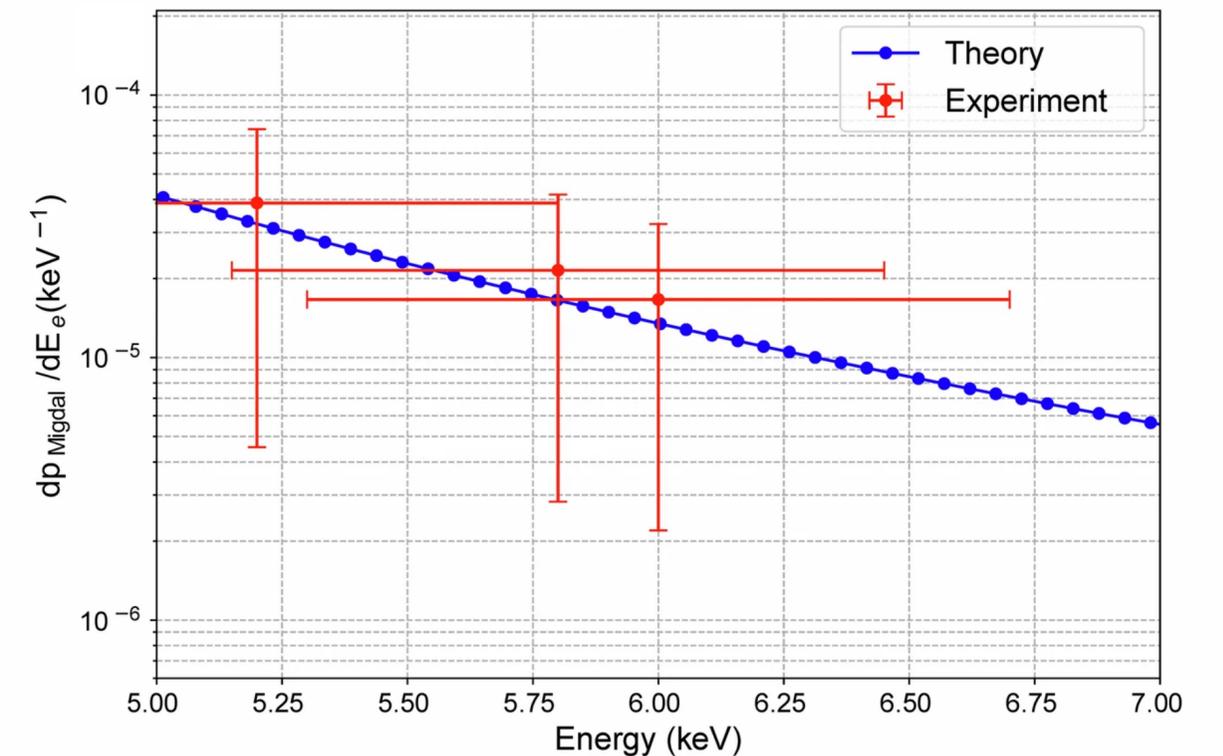
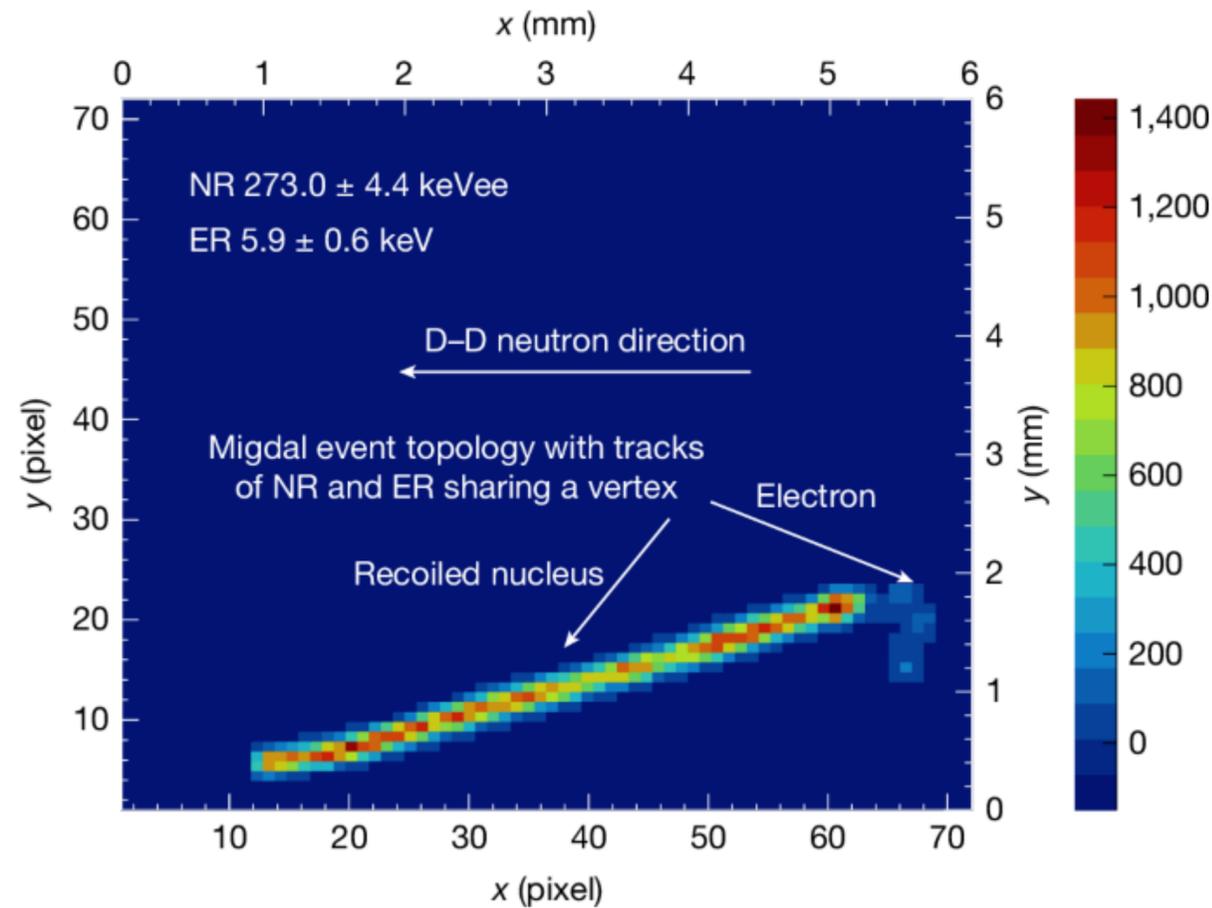
FIG. 5. Reanalysis of Migdal search data in [28] using a Migdal signal yield from this work. The electron spectrum with scintillation signals between 4 and 10 photoelectrons is compared with the best-fit signal and background models: Migdal signal at the nominal strength (solid red), single-scatter NR (blue), neutron multi-scatters in xenon (green) and in passive materials (orange), and the sum of all components (grey); the Migdal signal model that simply adds the NR and ER yields without considering recombination enhancement is also shown (dotted red).

First observation of the Migdal effect in nuclear scattering

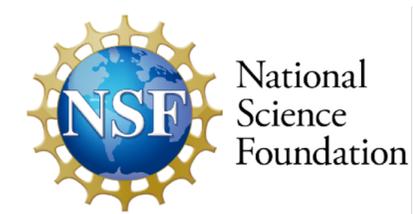
- First observation of the Migdal Effect in nuclear scattering by MARVEL (*Nature* 649, 580–583 (2026))
- Using a gas pixel detector with He:CH₃OCH₃ (40:60)
- 2.45 MeV neutrons from a D-D generator



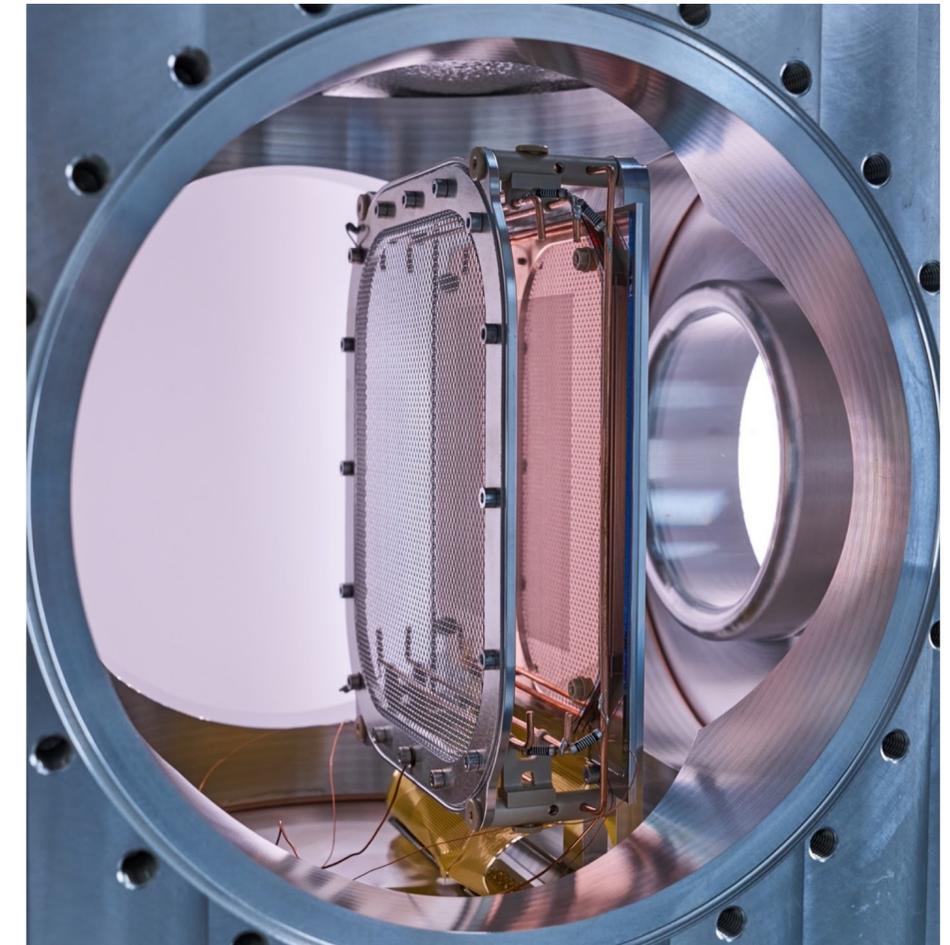
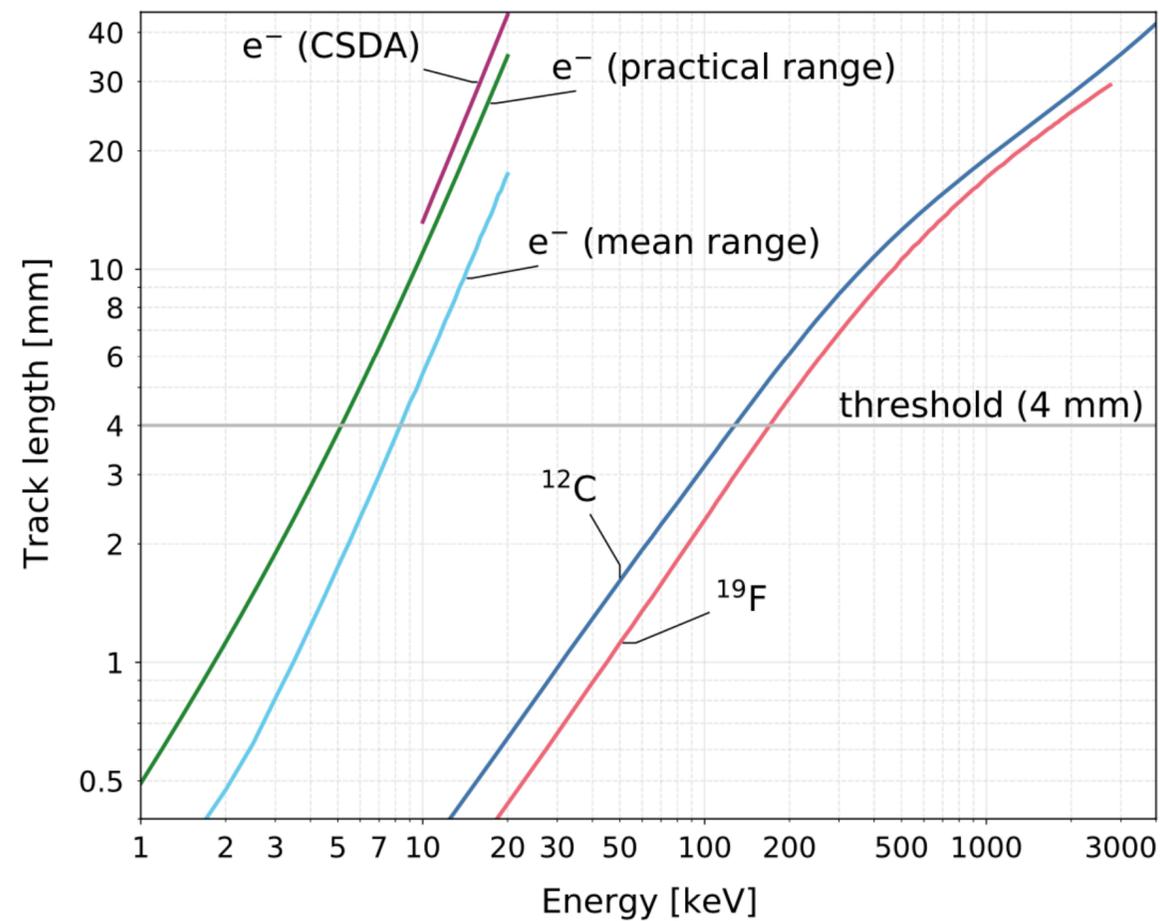
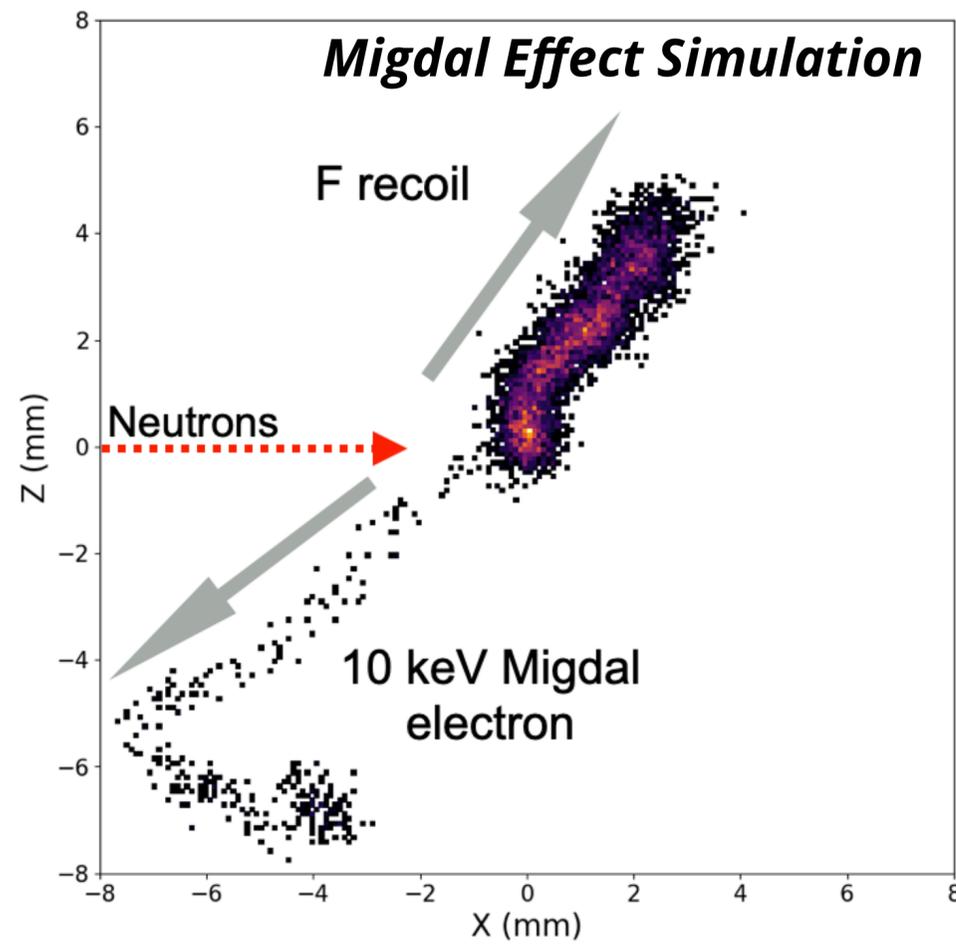
- Signal is primarily from He and H
- In agreement with theoretical predictions



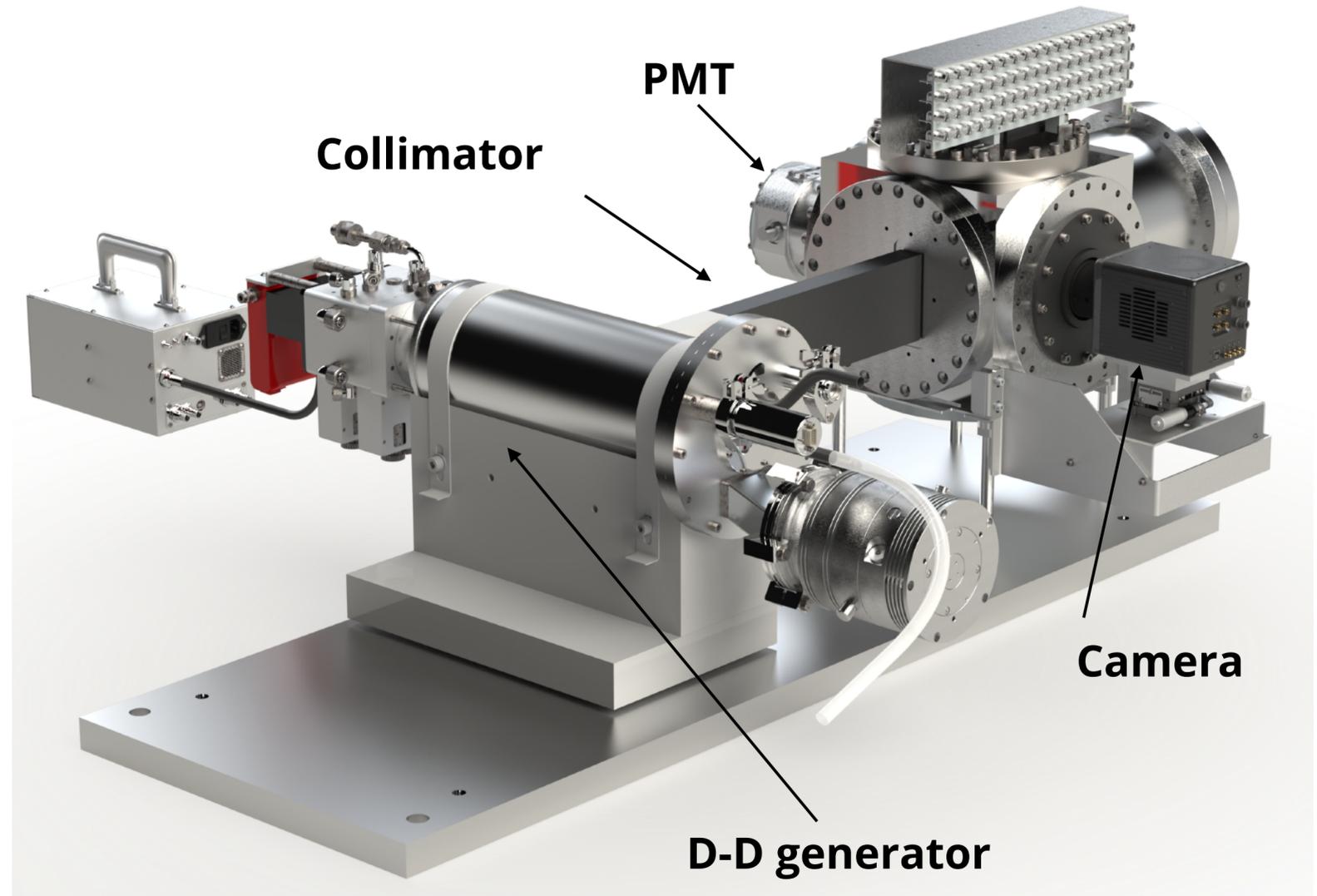
- Aim to characterise the Migdal Effect in CF_4 + noble gas mixtures
- Use a low pressure Optical Time Projection Chamber to image electron and nuclear recoil in three-dimensions
- Over 35 physicists and engineers from 14 institutions and 8 countries

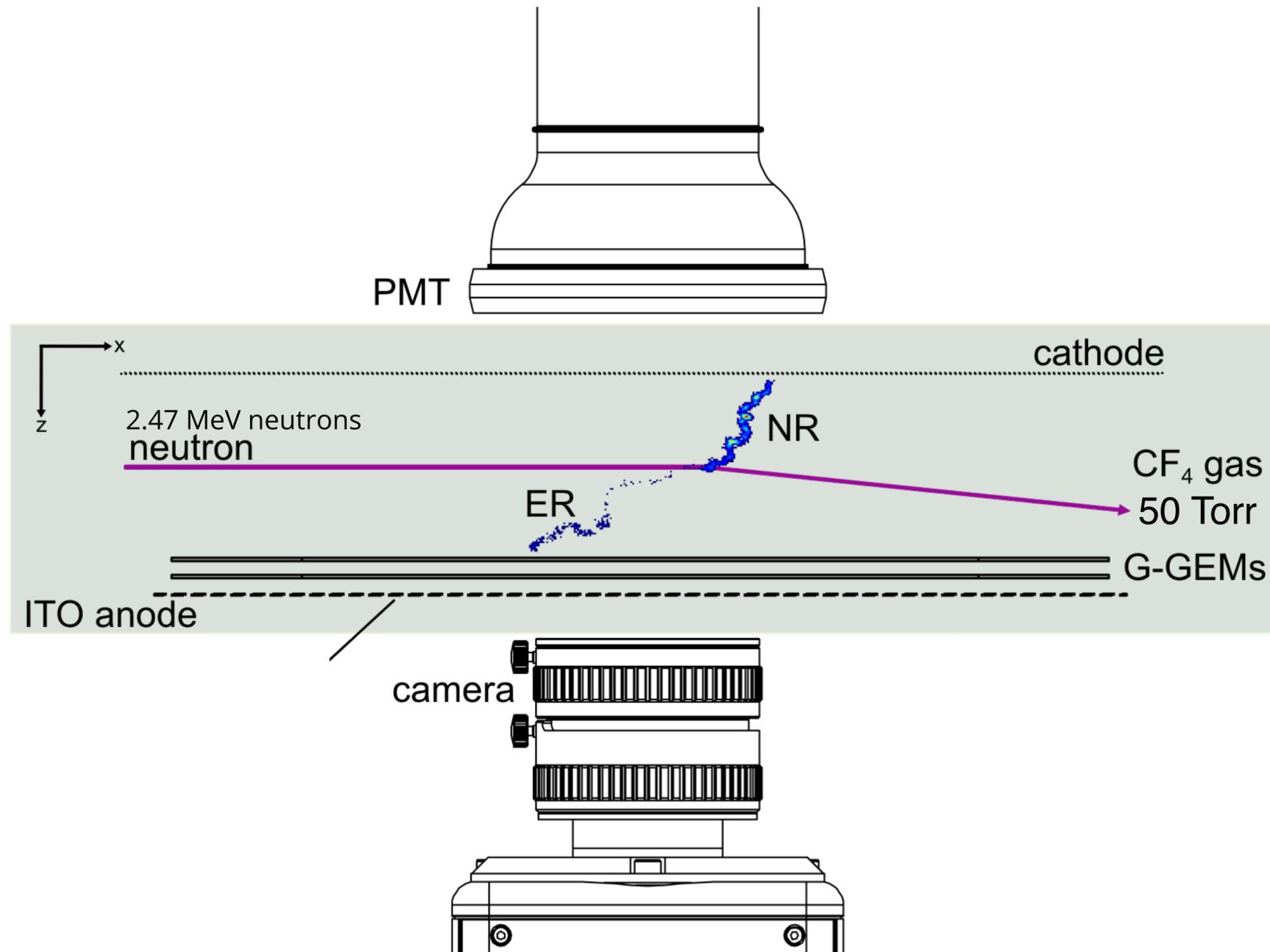


- Aim to characterise the Migdal Effect in a range of species
- Low pressure Optical Time Projection Chamber (OTPC) with **50 Torr CF₄**
- Unambiguous measurement of electron and nuclear recoil from common vertex



- Event signature is nuclear recoil and an electron sharing a common vertex
- Nuclear scattering induced by 2.47 MeV neutrons from a D-D generator

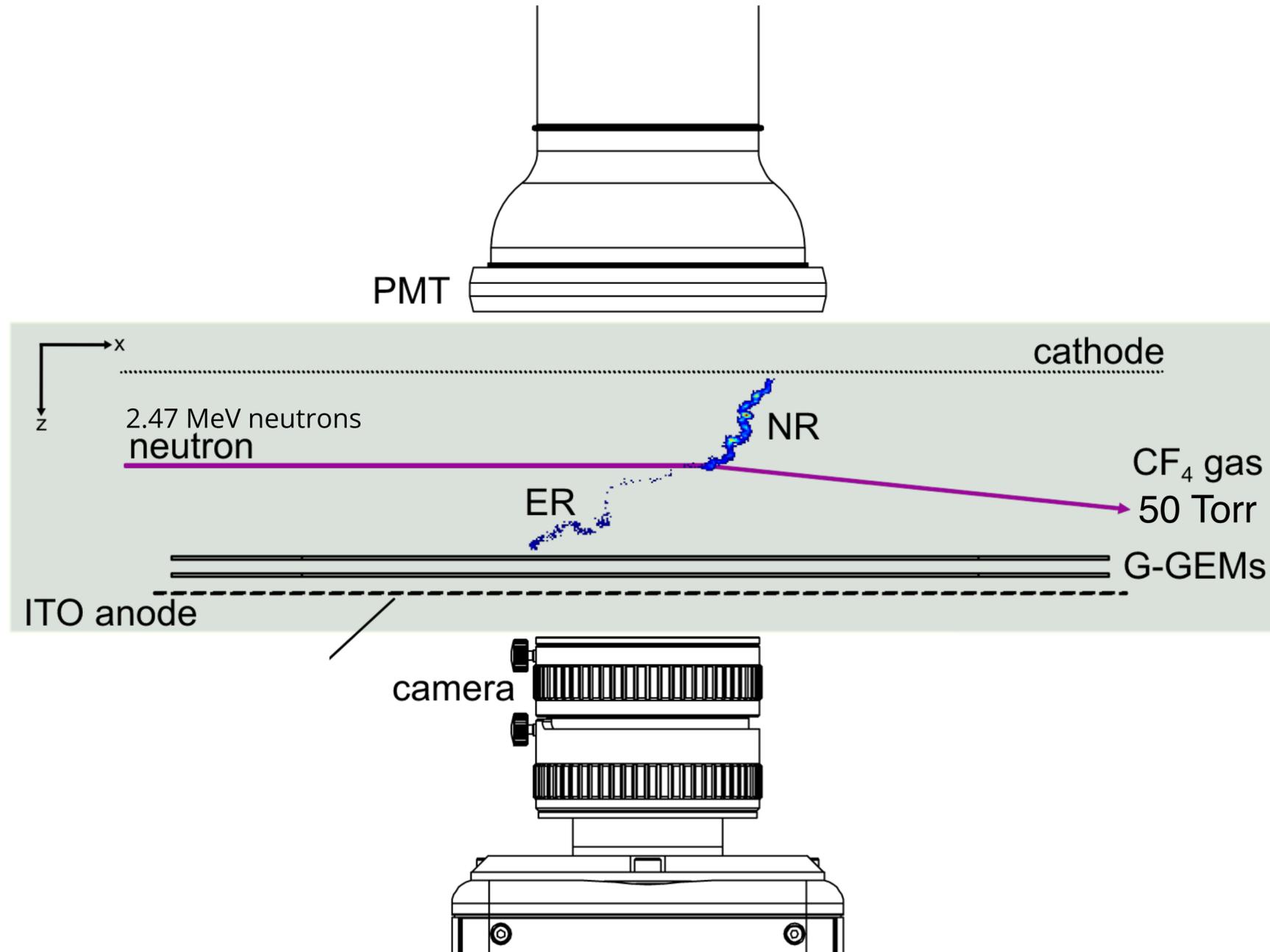
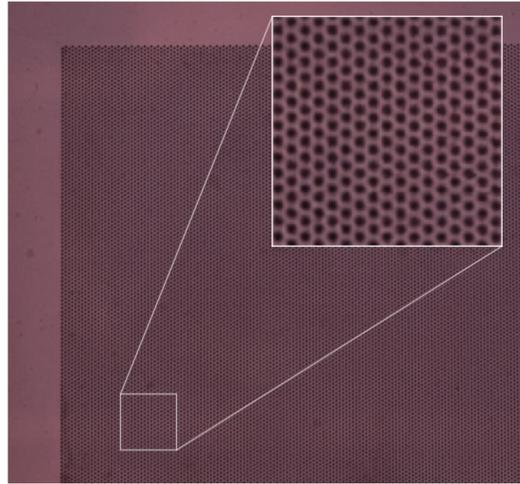




[Astropart.Phys. 151 \(2023\) 102853](#)

Charge Amplification

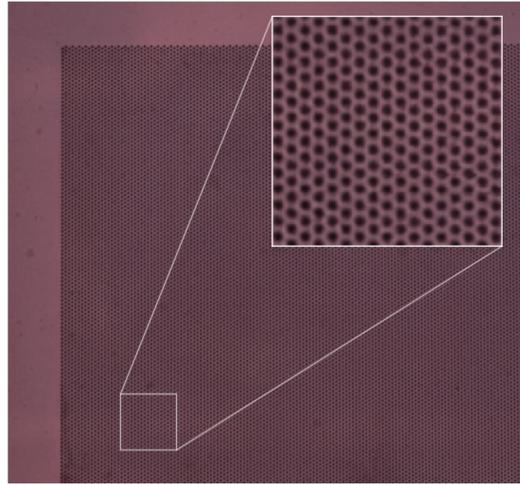
Two glass GEMs



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

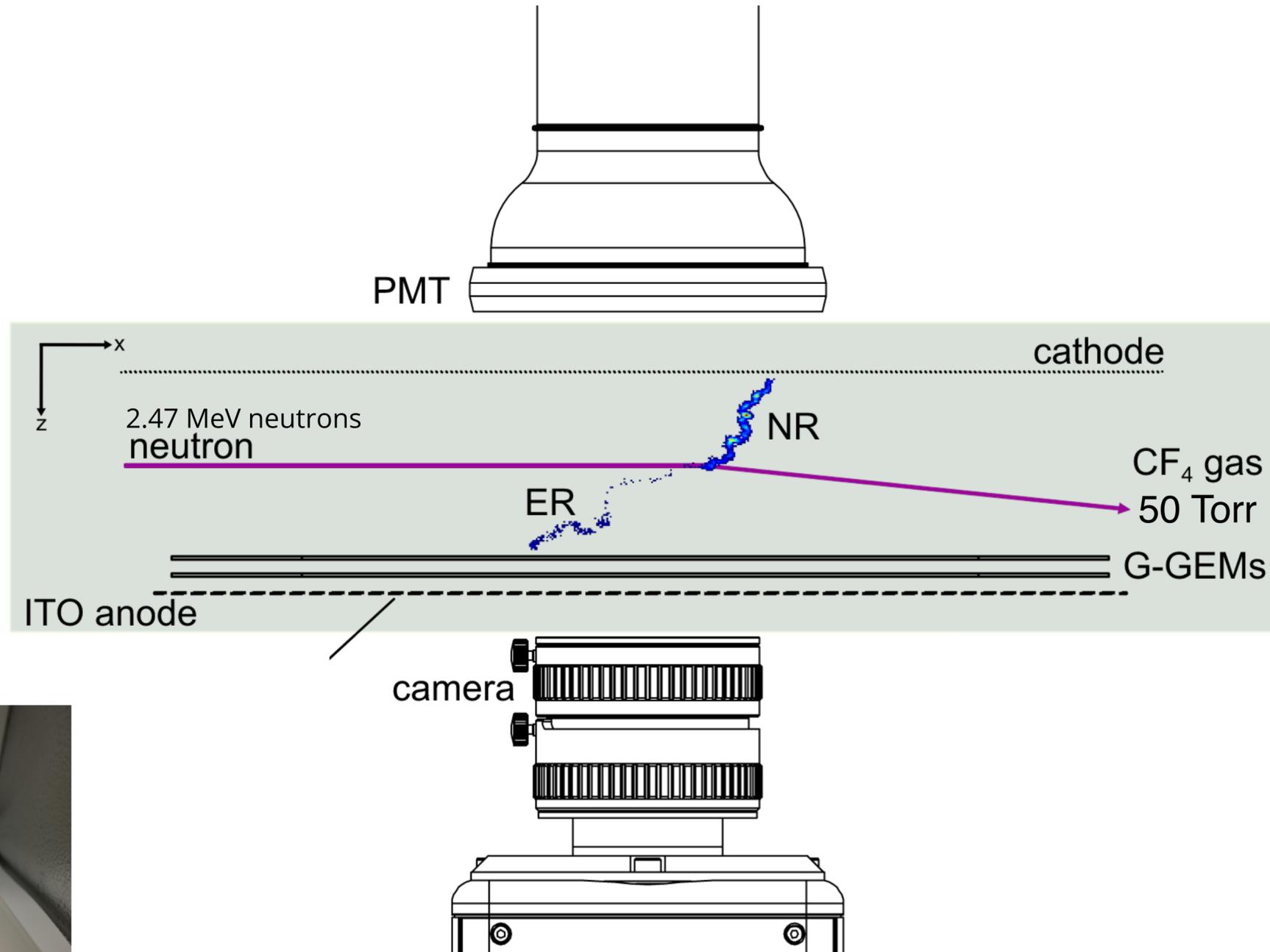
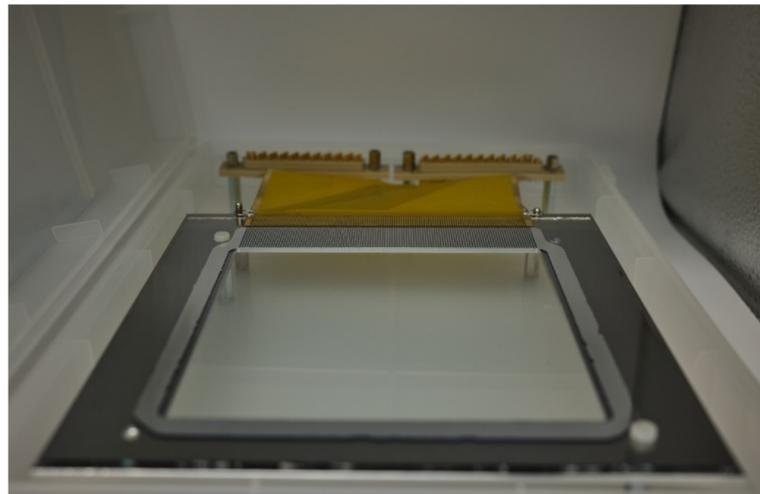
Charge Amplification

Two glass GEMs



Charge read-out

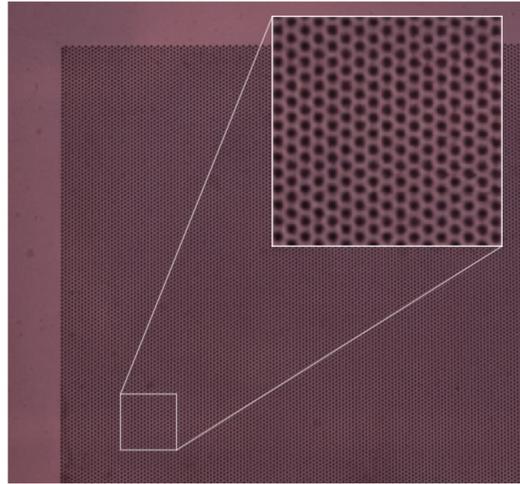
anode segmented into 120 strips



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

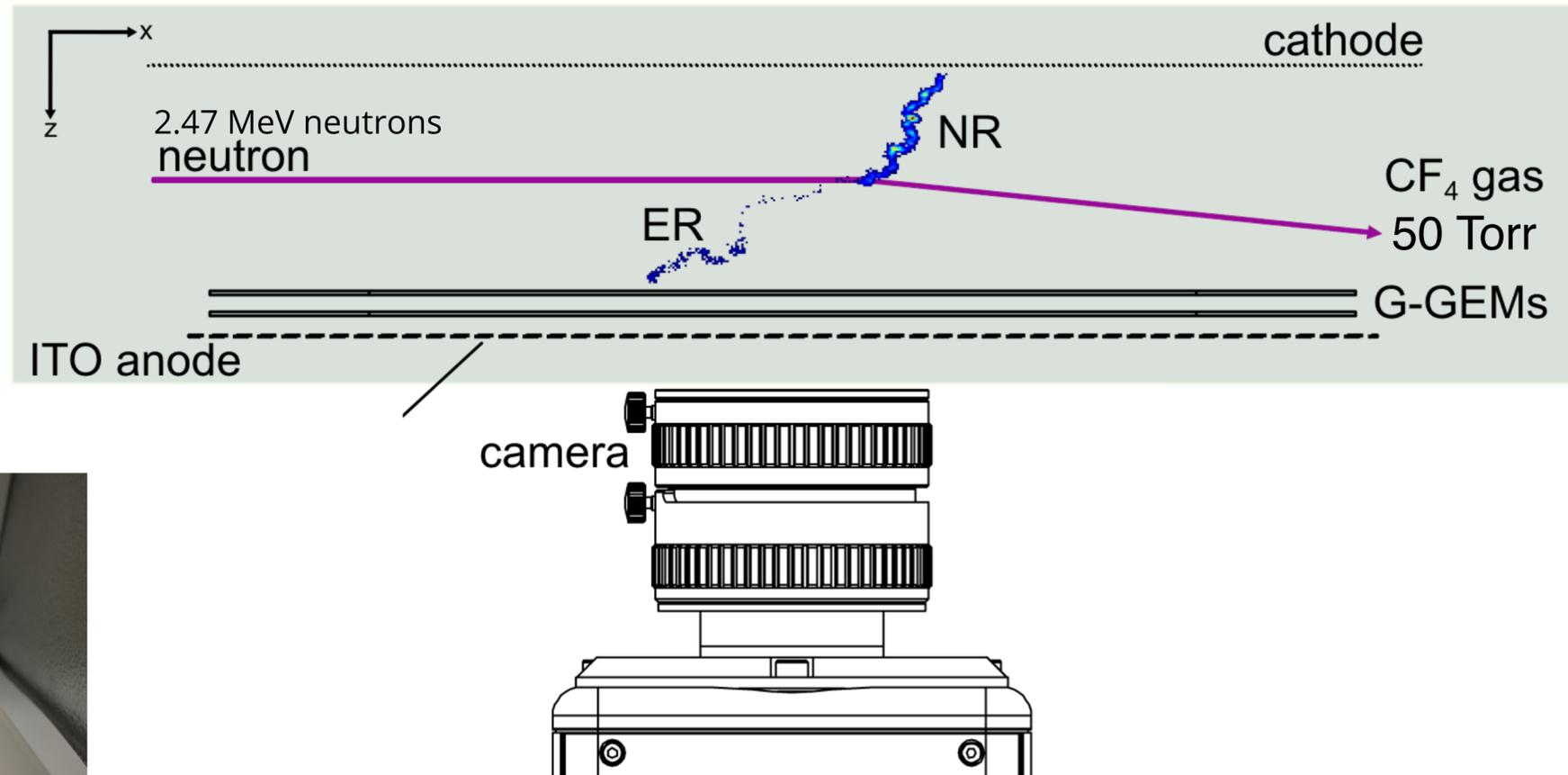
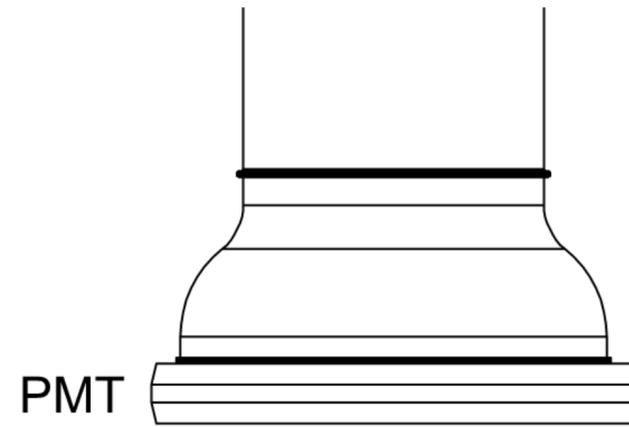
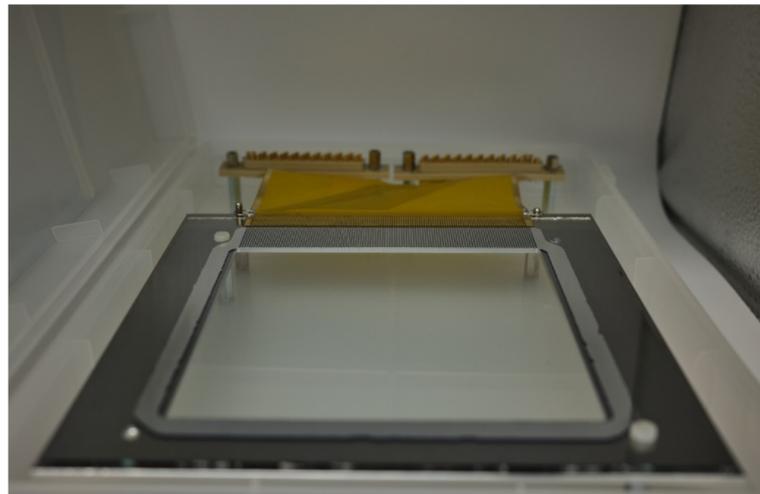
Charge Amplification

Two glass GEMs



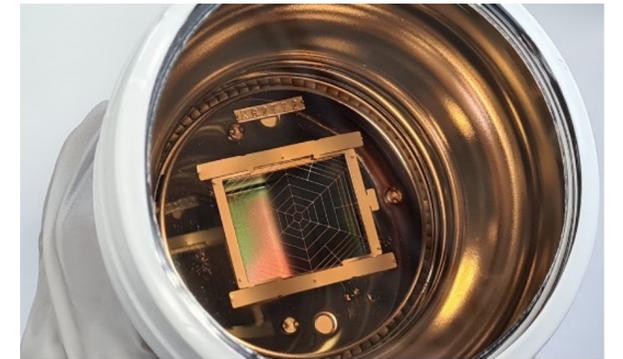
Charge read-out

anode segmented into 120 strips



Trigger and timing

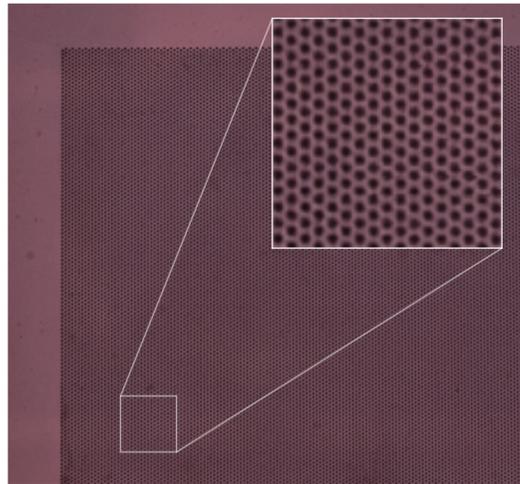
Hamamatsu R11410 VUV PMT



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

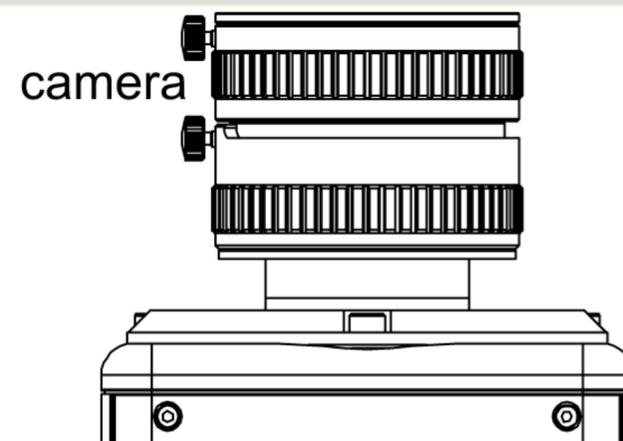
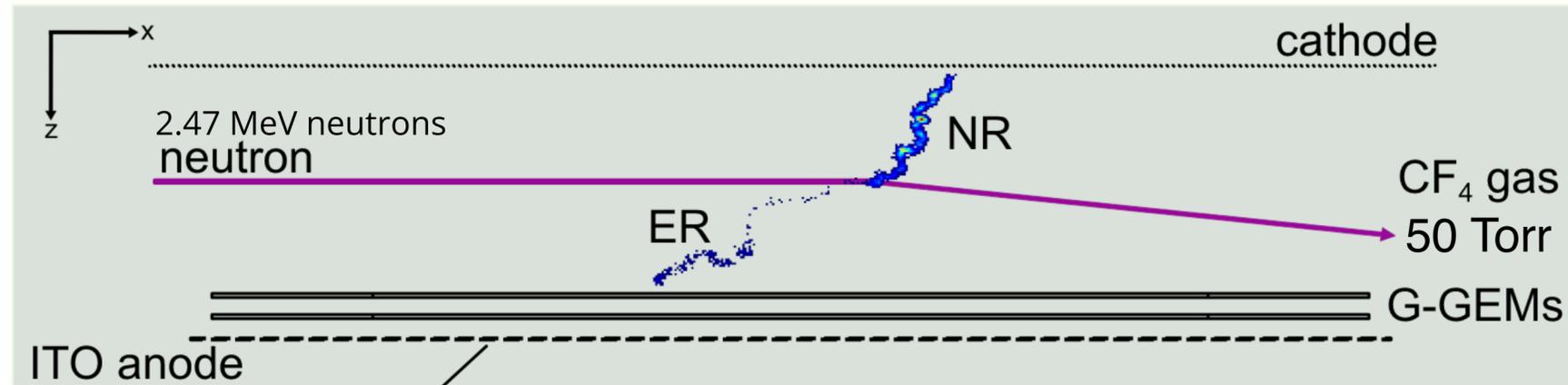
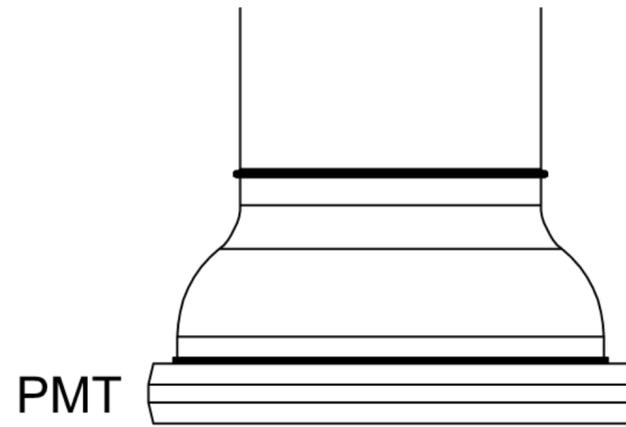
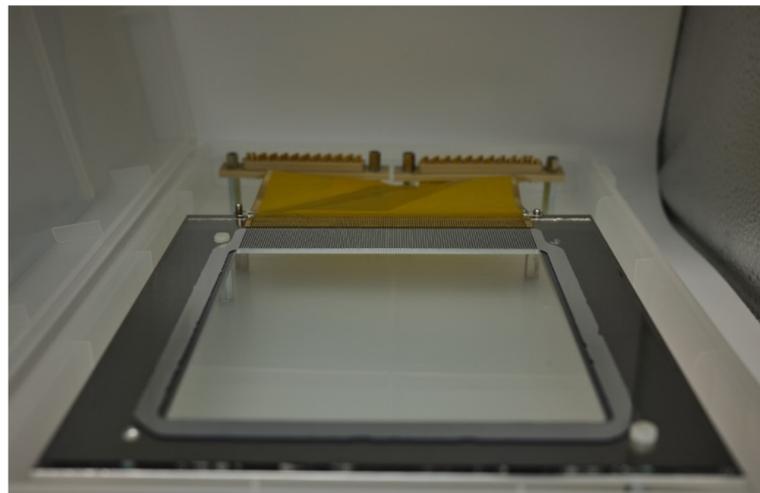
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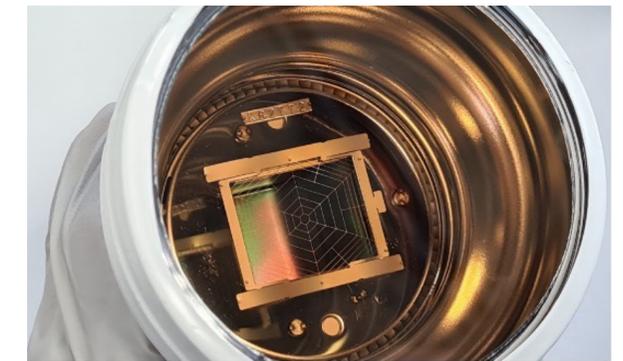
Charge read-out

anode segmented into 120 strips



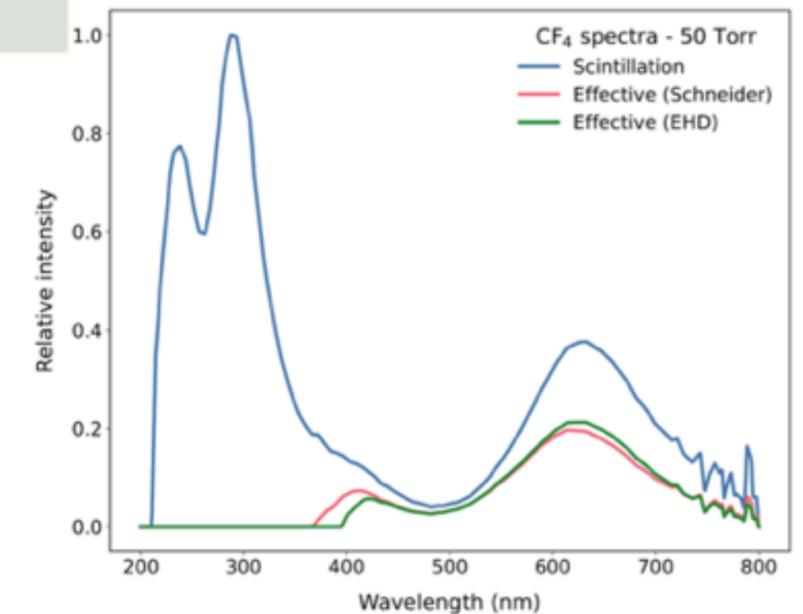
Trigger and timing

Hamamatsu R11410 VUV PMT

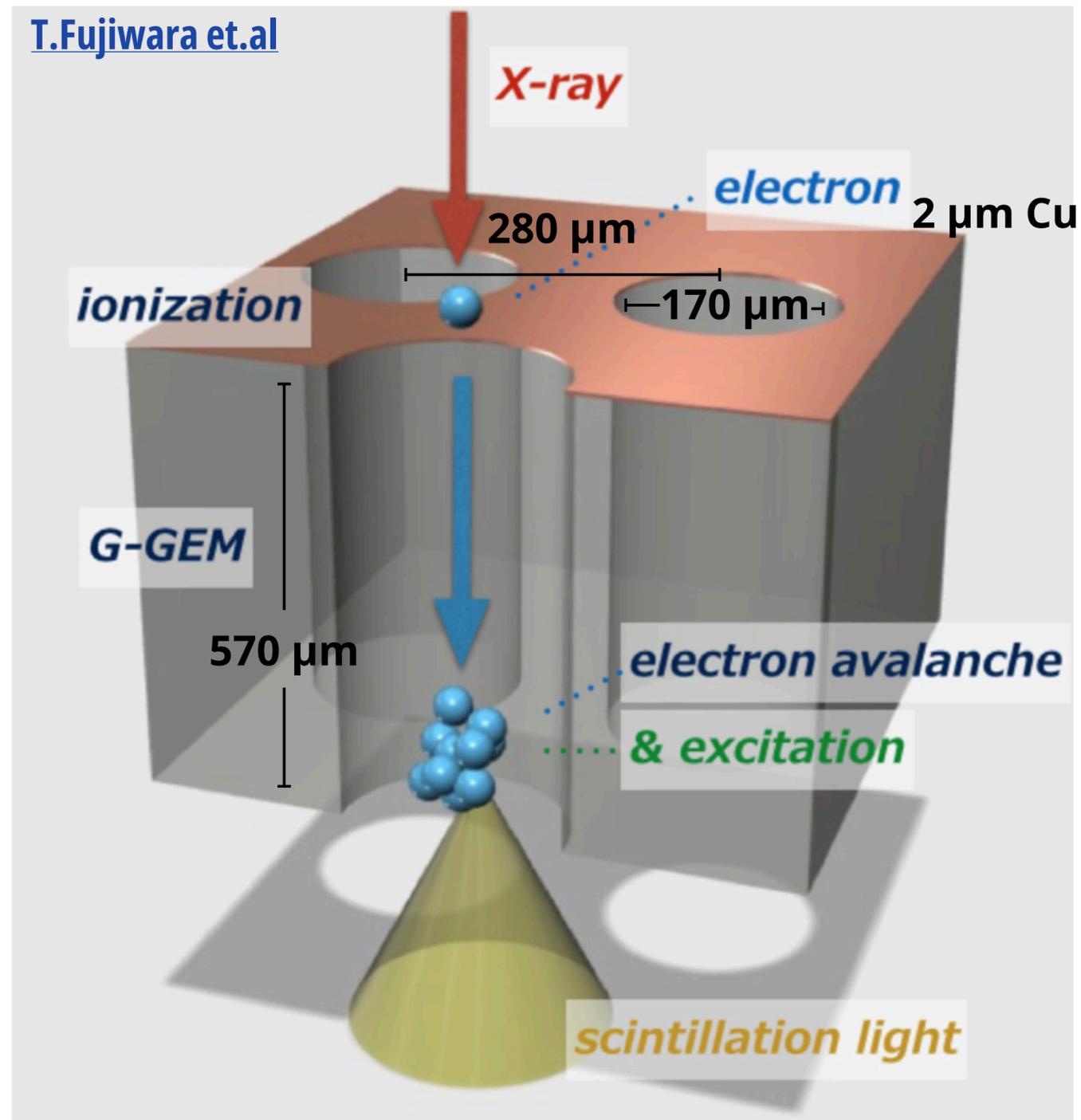


Light read-out

Orca Quest qCMOS camera
8.3 ms exposure

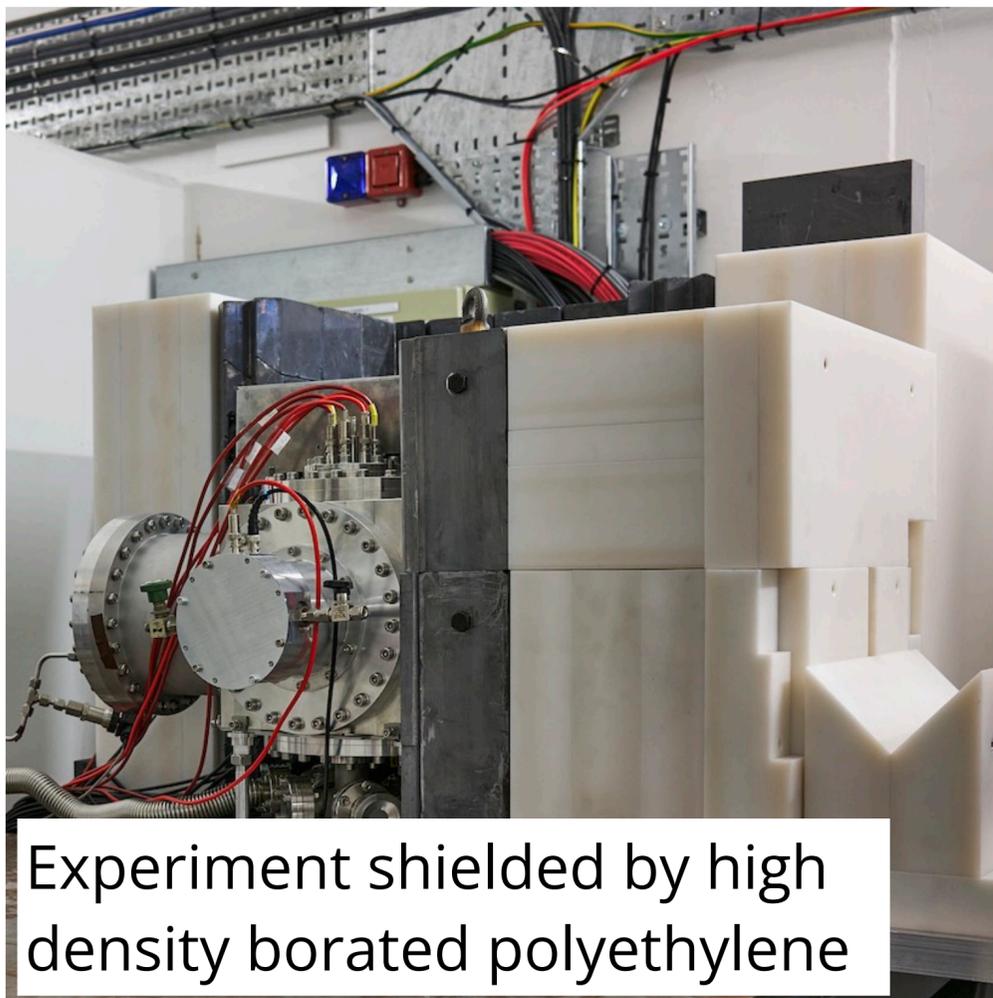


[Astropart.Phys. 151 \(2023\) 102853](#)

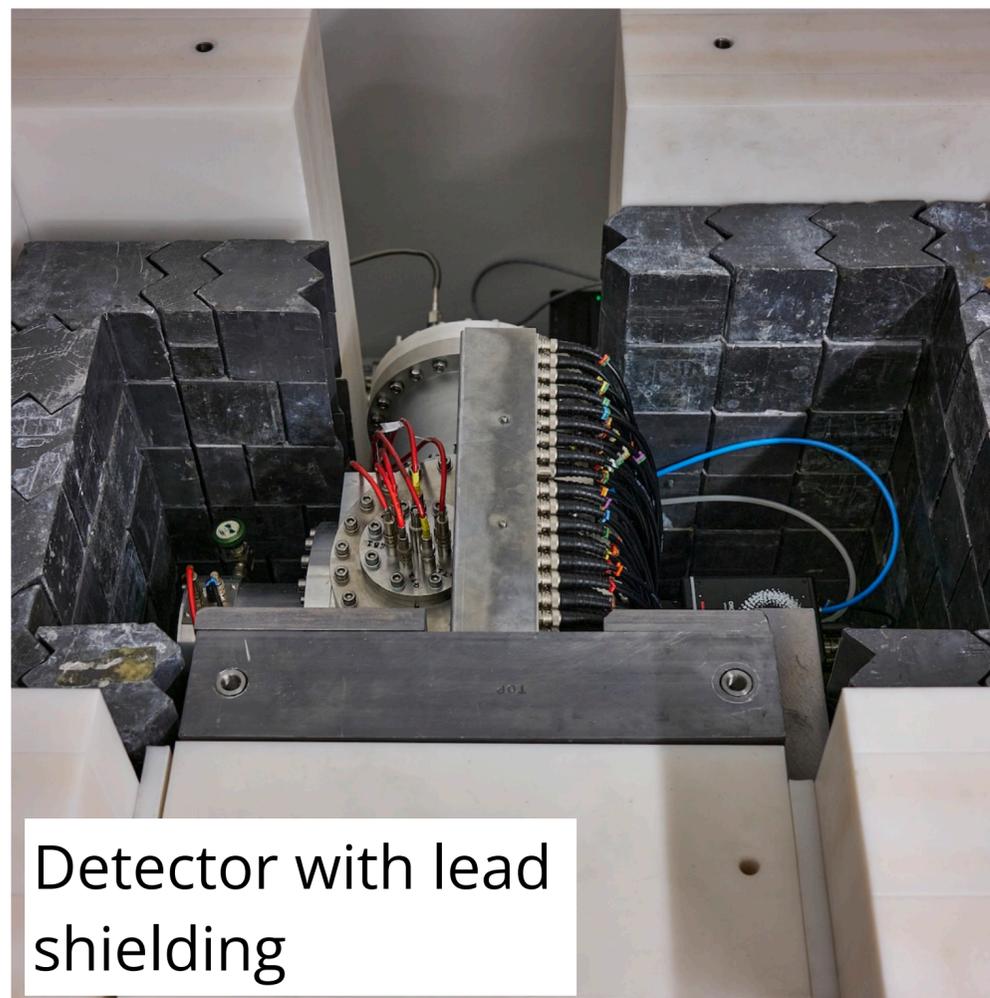


- Voltage applied across dielectric
- Electrons funnelled through holes
- Strong field results in avalanche
- Charge multiplication and scintillation
- Use two glass GEMs for gas gains $\sim 10^5$

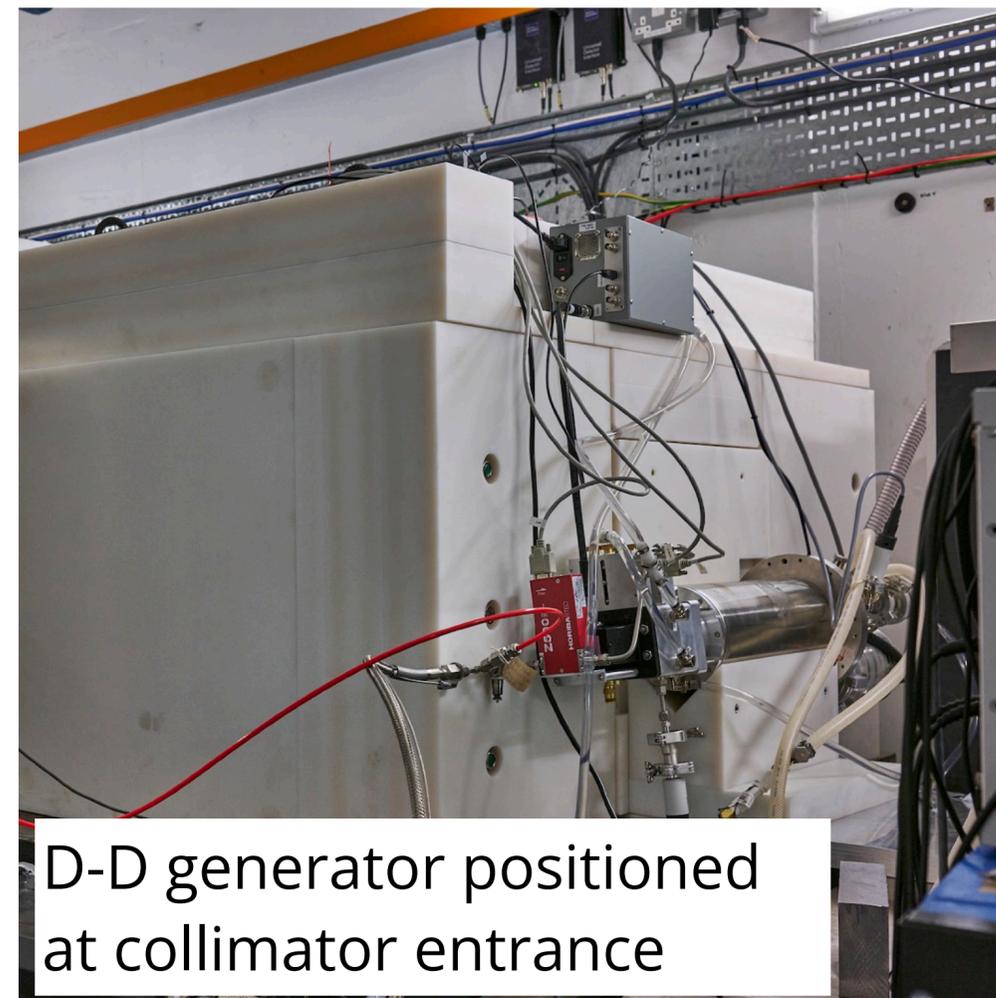
- Installed summer 2023



Experiment shielded by high density borated polyethylene



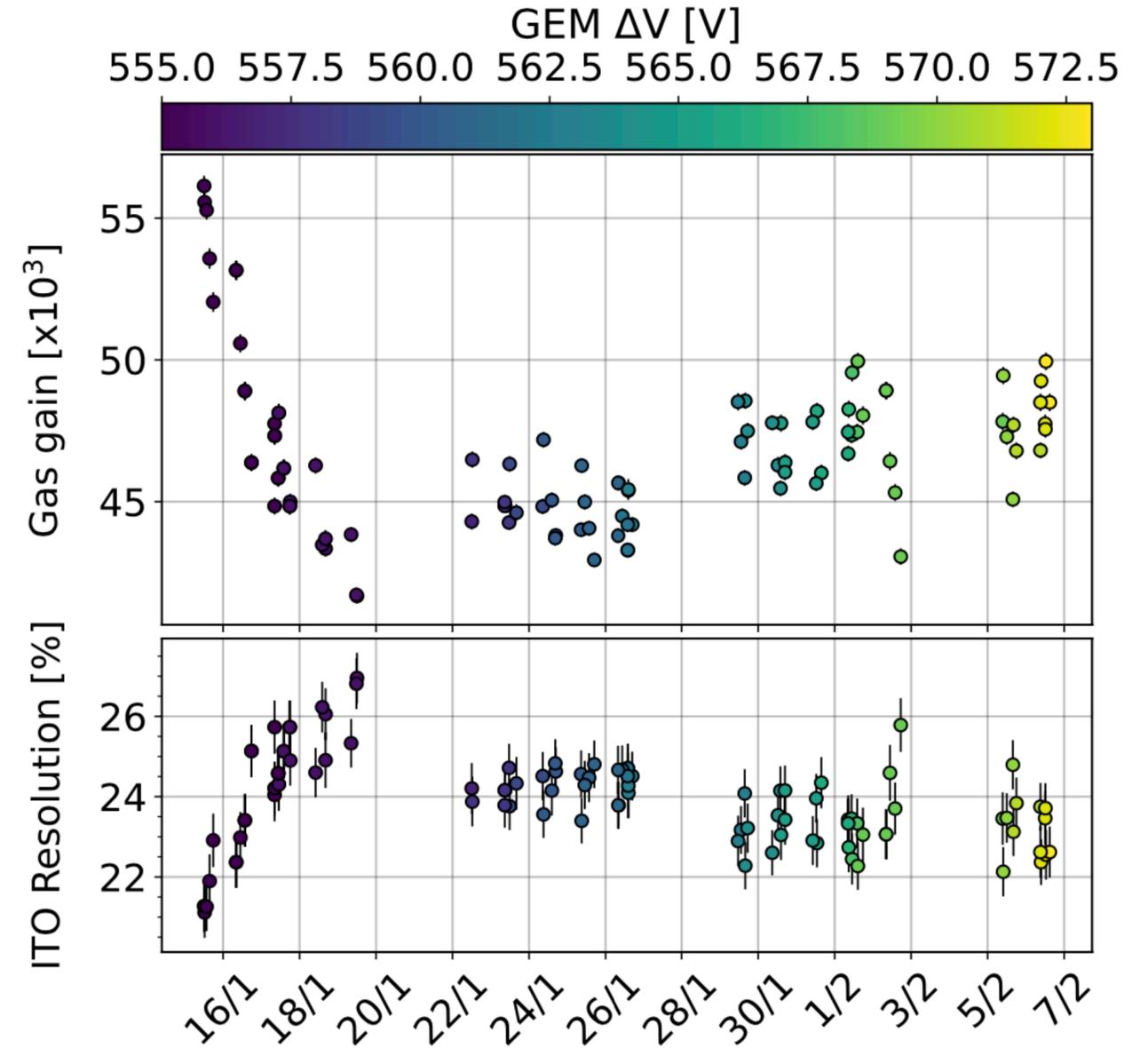
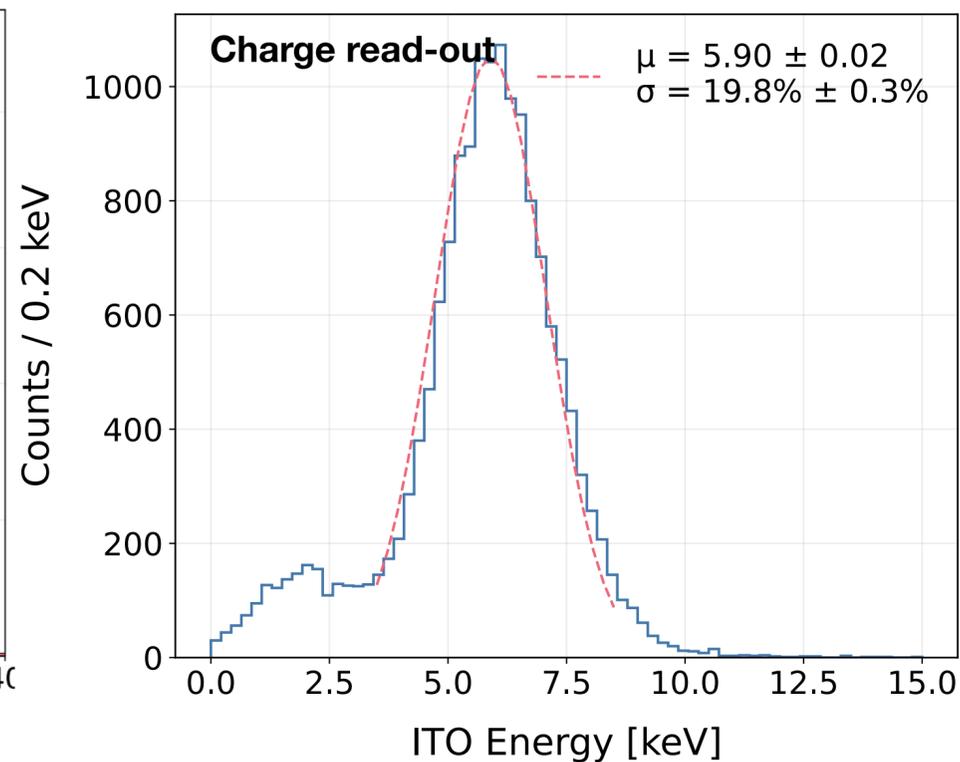
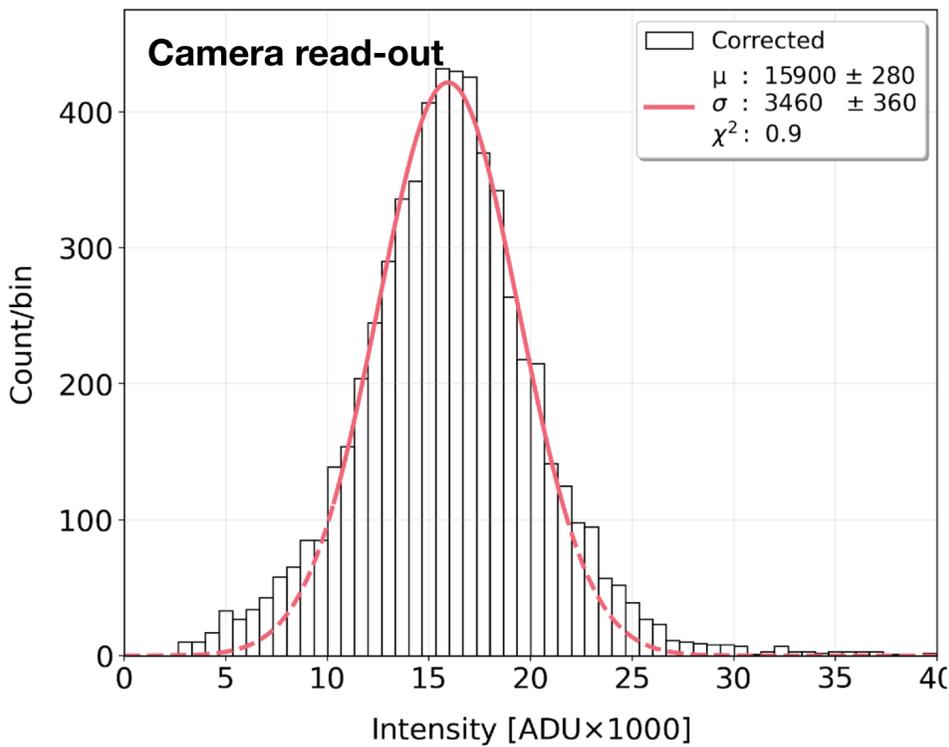
Detector with lead shielding



D-D generator positioned at collimator entrance

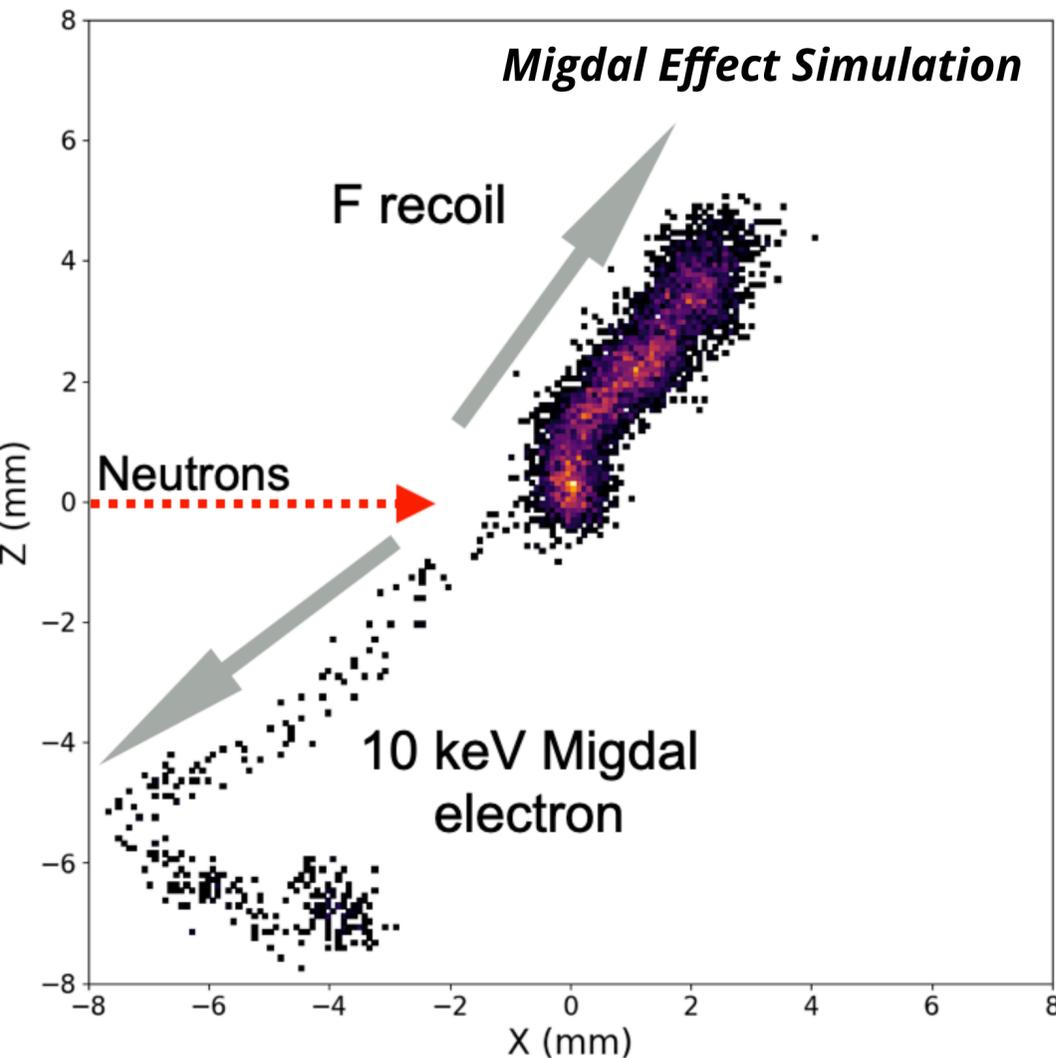
- Science run data collected from 15/01/2024 - 06/02/2024
- Gas replaced ~ every 3 days and calibration with ^{55}Fe every 3 hours
- Total exposure of 85.3 hours with $\sim 3.6 \times 10^5$ nuclear recoils
- Initial selection criteria defined on 49% of the data

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



Signal and Backgrounds

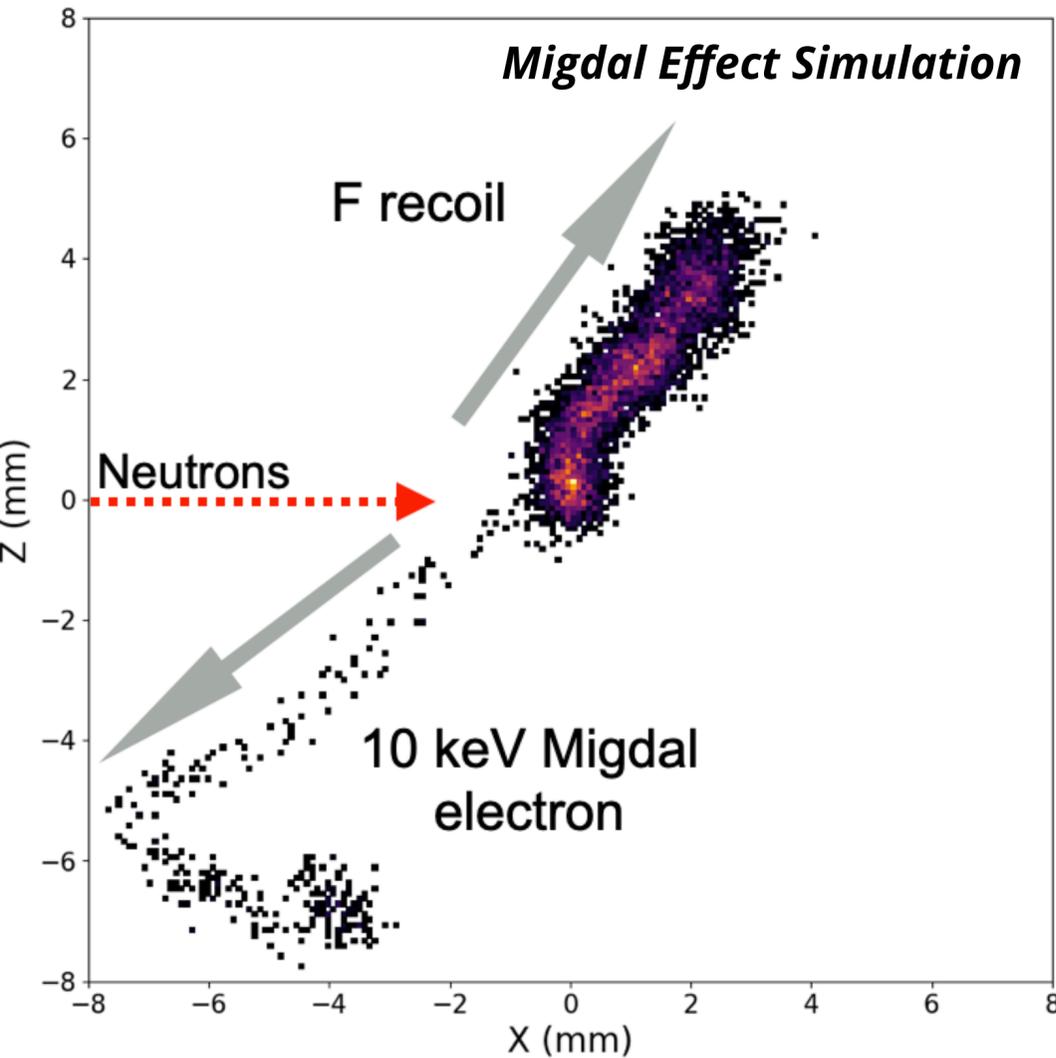
- Backgrounds suppressed through energy thresholds and timing resolution
- Main source of background from gammas produced in inelastic scattering with fluorine Compton scattering near track vertex



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](#)

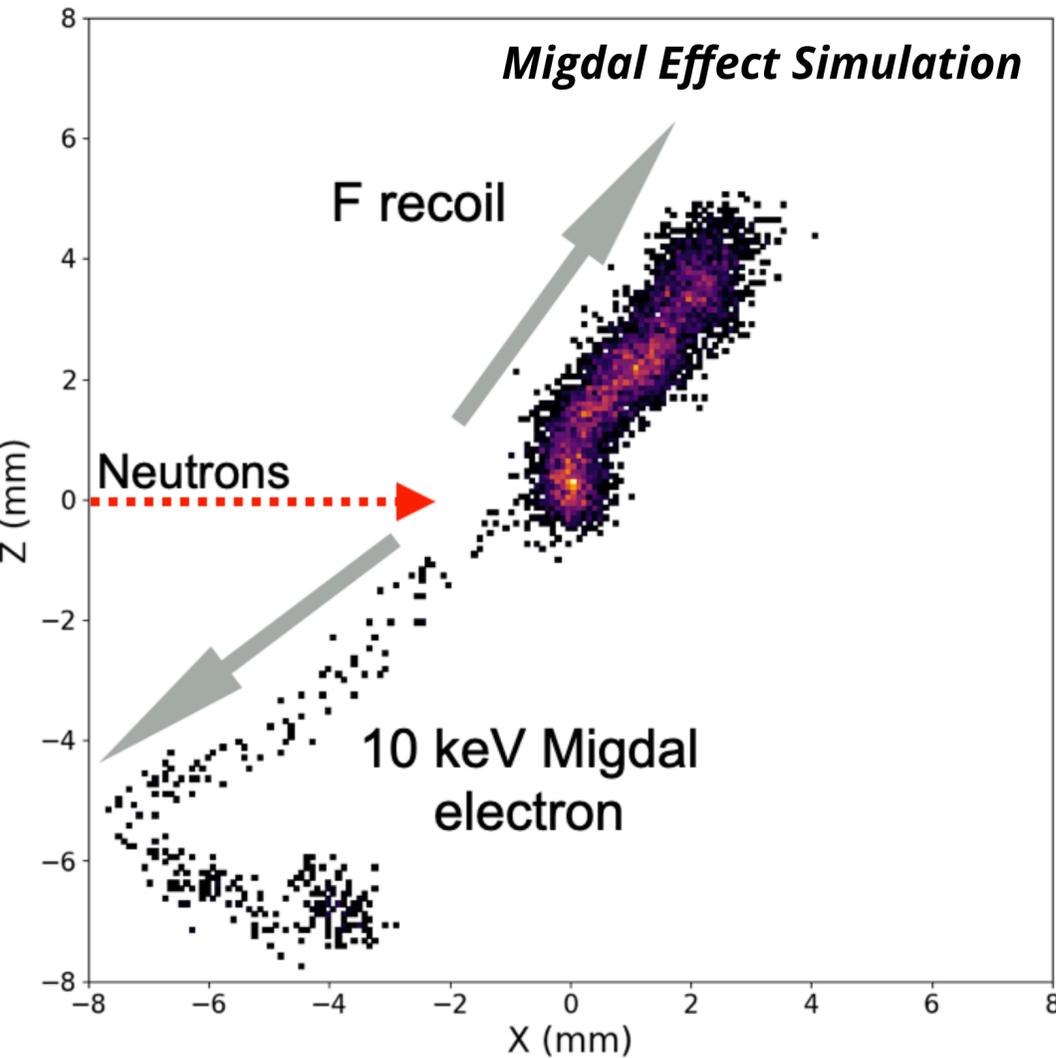
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Particle-Induced X-ray Emission (PIXE)			
X-ray emission	Photoelectron near NR track origin	1.8	0
Auger electrons	Auger electron from NR track origin	19.6	0
Bremsstrahlung processes [†]			
Quasi-Free Electron Br. (QFEB)	Photoelectron near NR track 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](#)

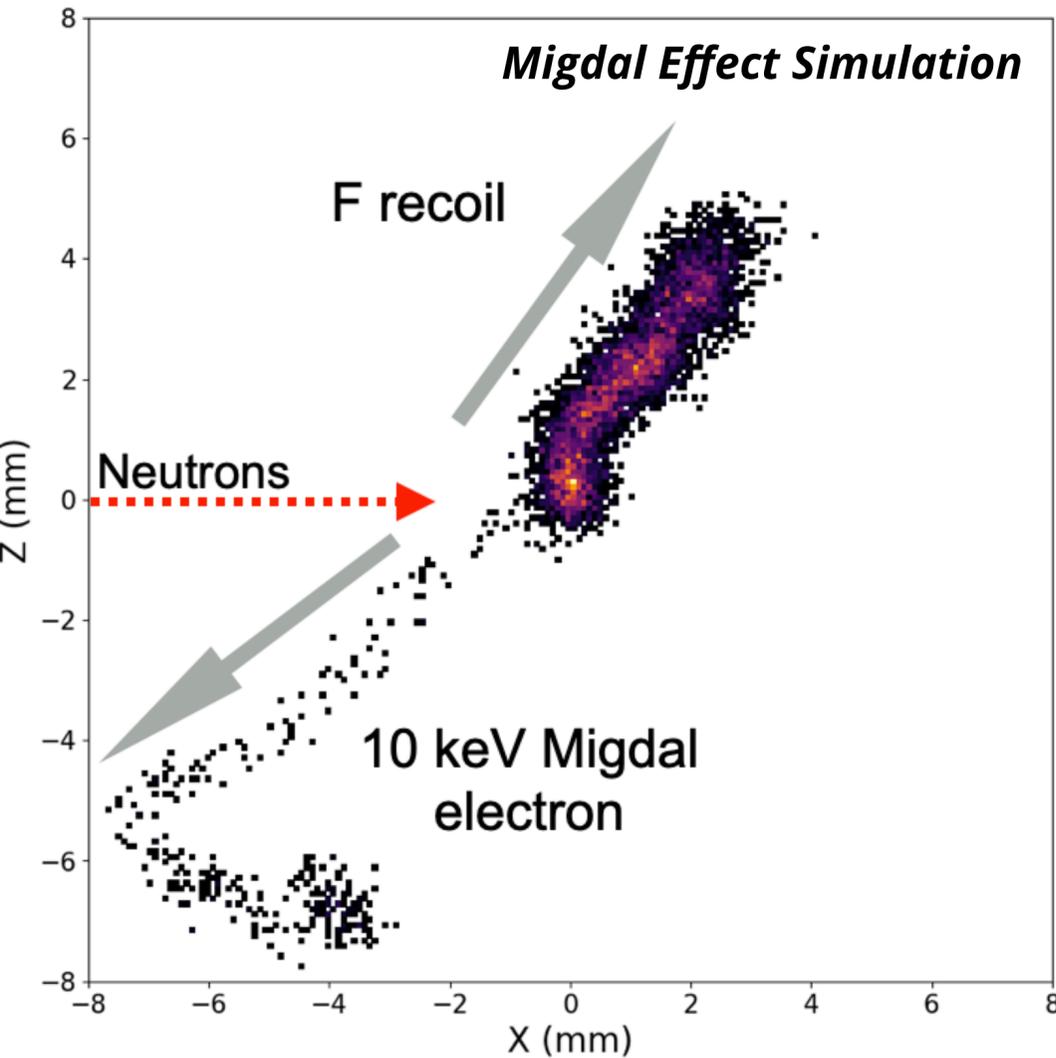
- Backgrounds suppressed through energy thresholds and timing resolution
- Main source of background from gammas produced in inelastic scattering with fluorine Compton scattering near track vertex



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 [†]			
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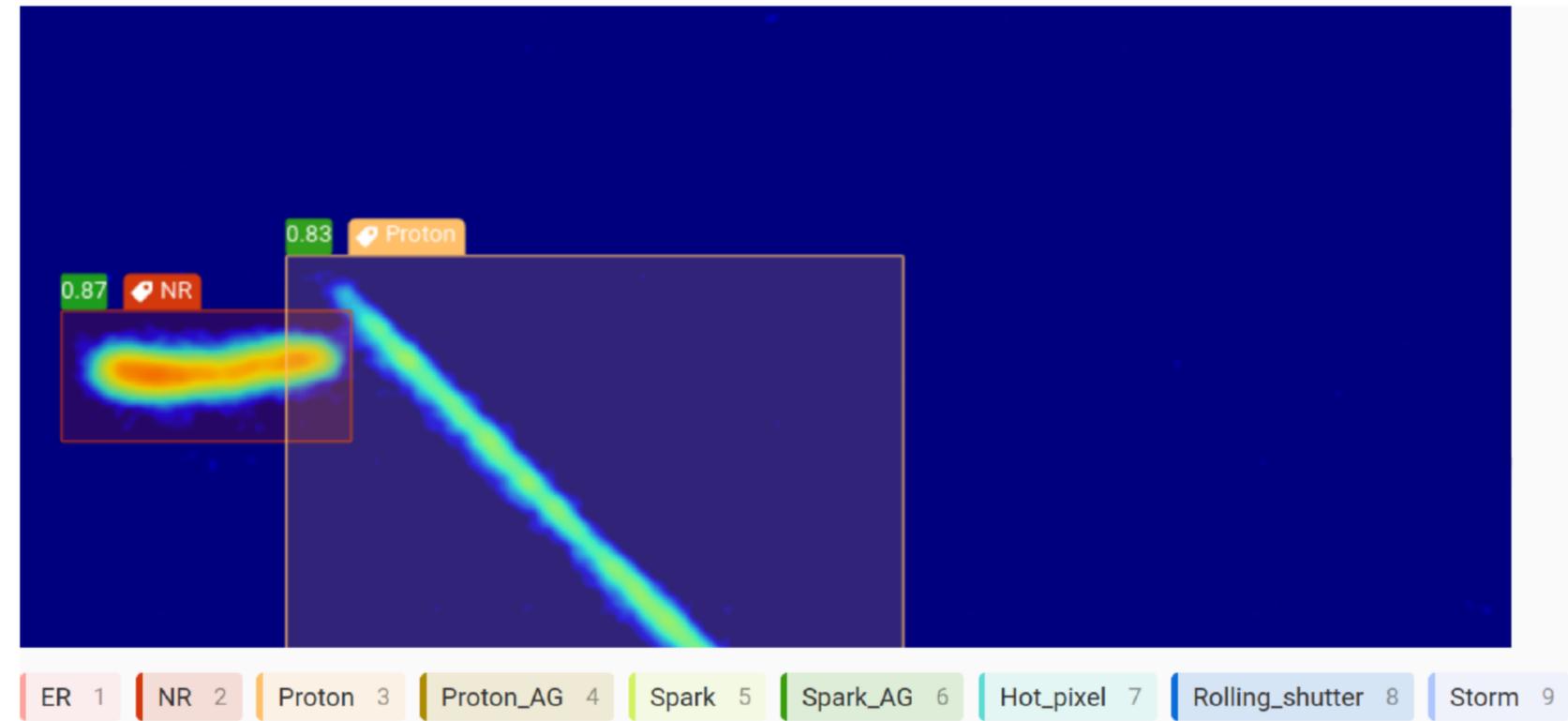


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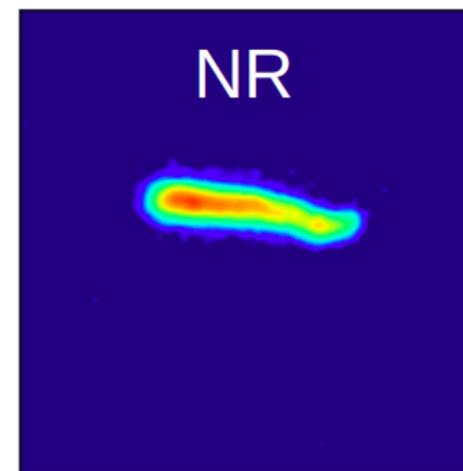
[Astropart. Phys. 151 \(2023\) 102853](#)

Phys.Rev.D 111 (2025) 7

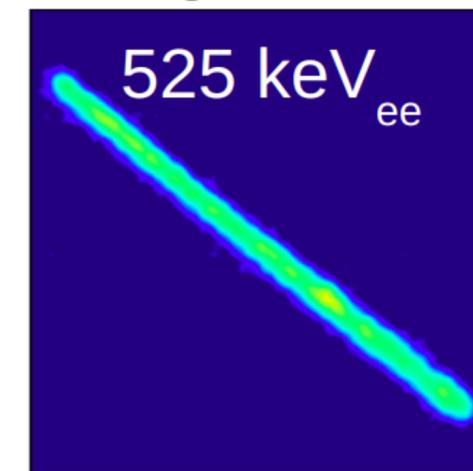
- YOLOv8 is a state-of-the-art object detection algorithm
- Localises and classifies objects within images
- Trained on real data with hand-labelled bounding boxes
 - Search for overlapping electron and nuclear recoil rather than a simulated signal topology
- Runs in real time providing mixed-field particle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



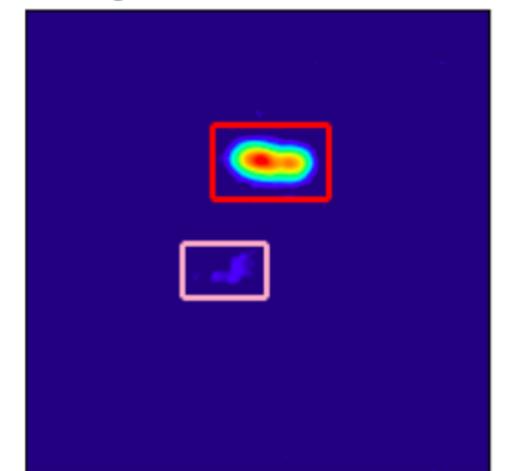
Classification



Regression

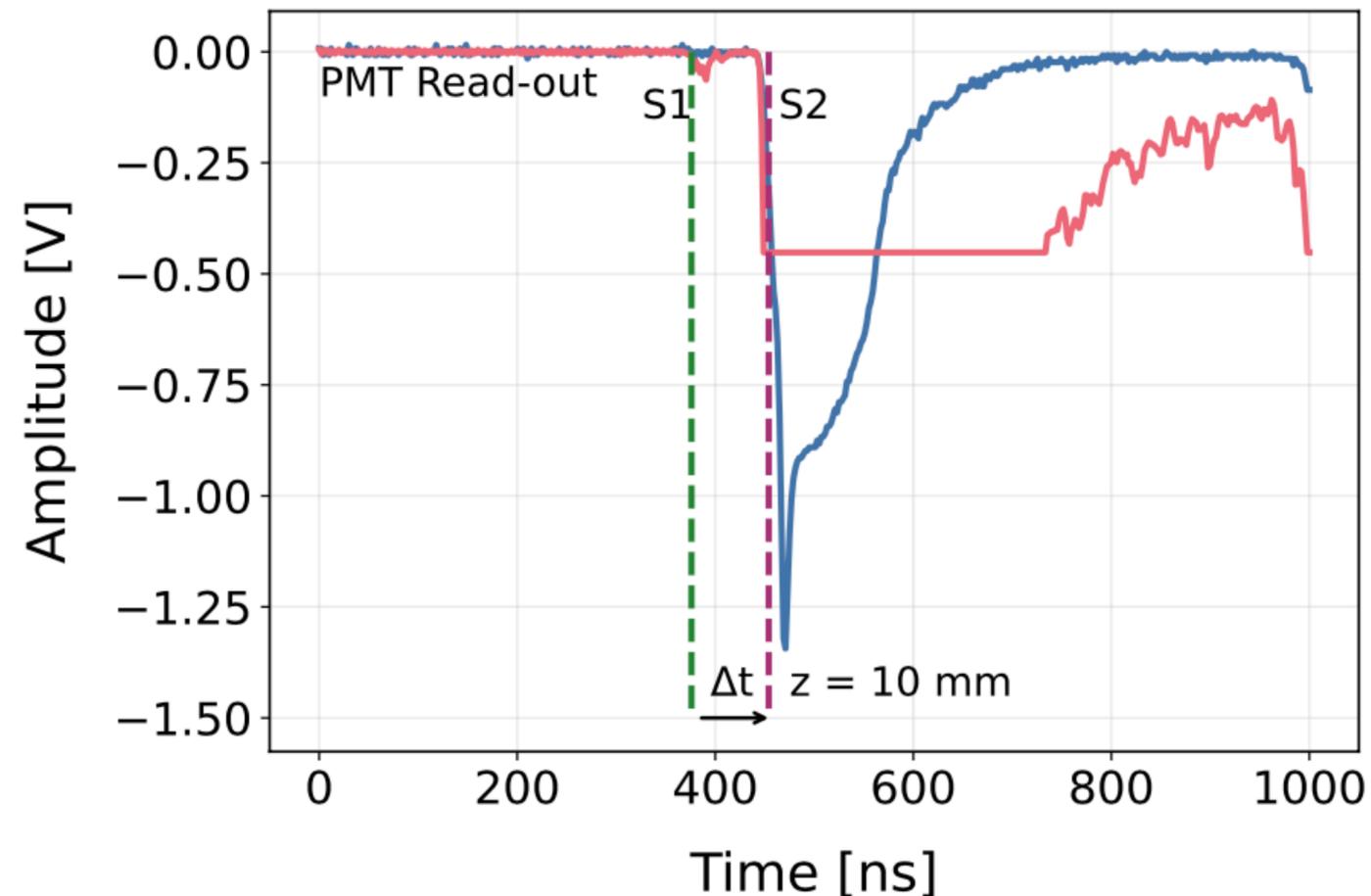


Object detection

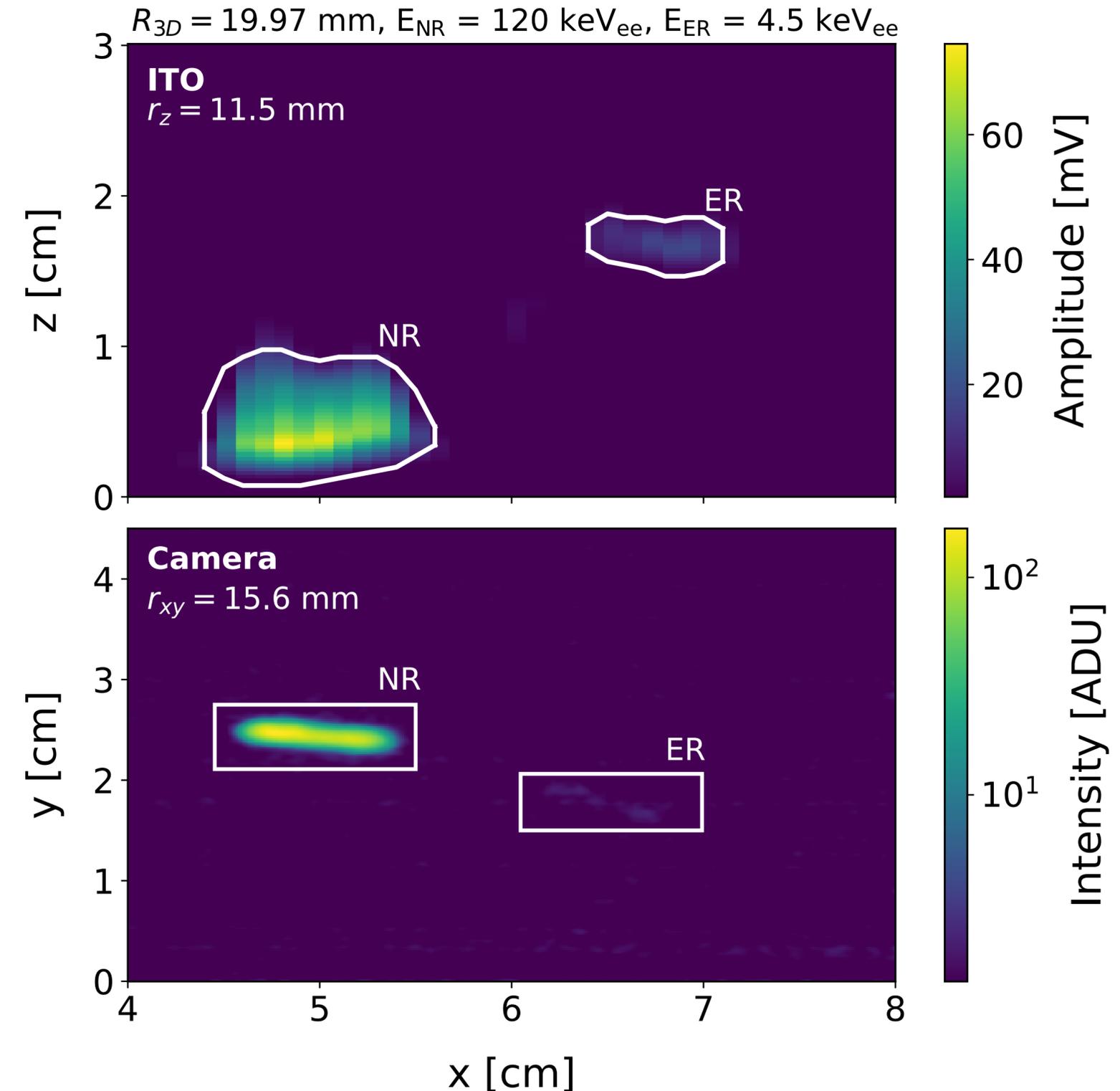


- Tracks in the ITO anode are identified using [DBSCAN](#)
- Camera and DAQ events synchronised offline using timestamp information from an FPGA counter
- Timing between S1 and S2 in the PMT gives absolute depth

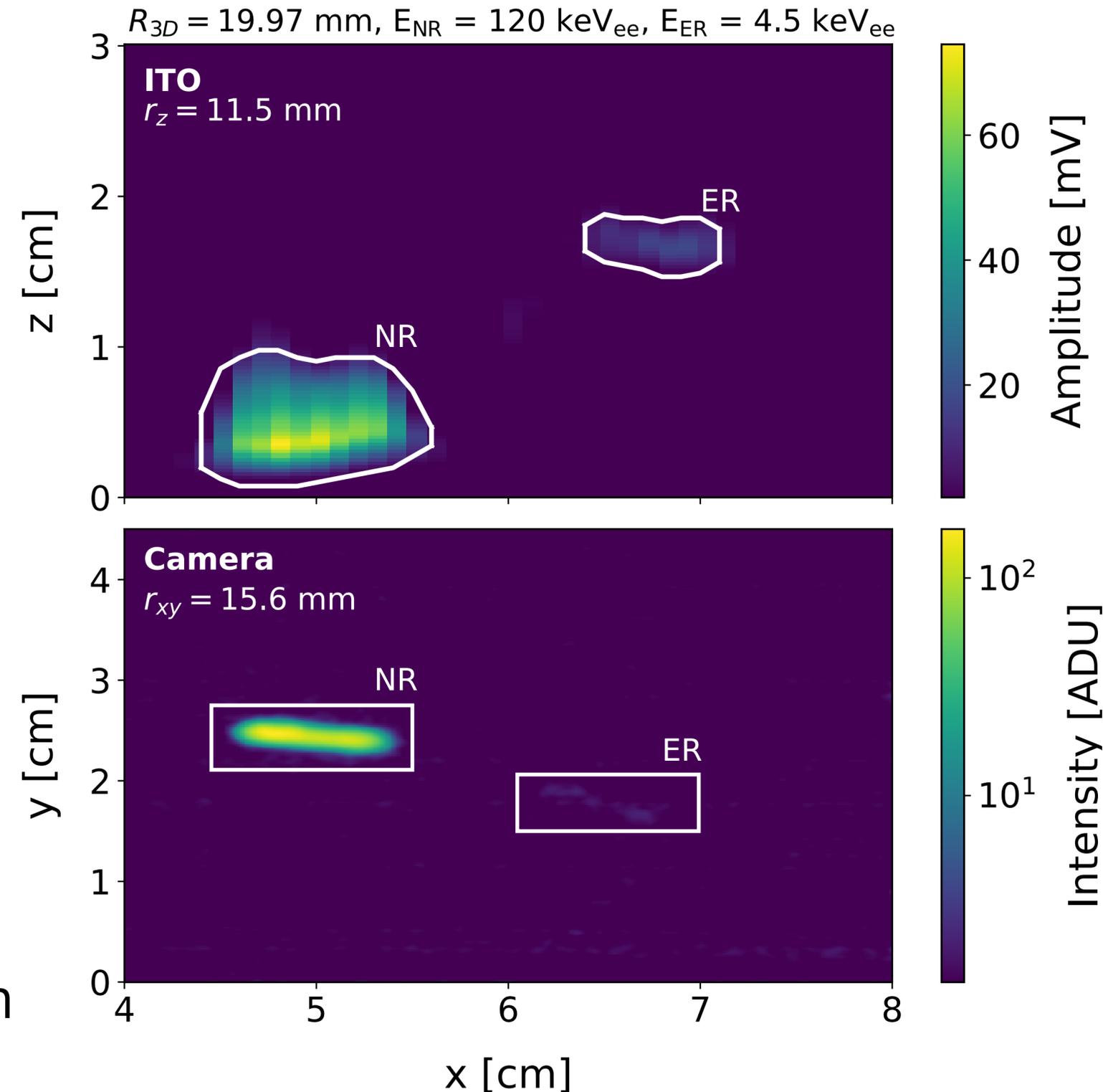
[Nucl.Instrum.Meth.A 1069 \(2024\)](#)



3D Reconstruction: [JINST 18 C07013](#)

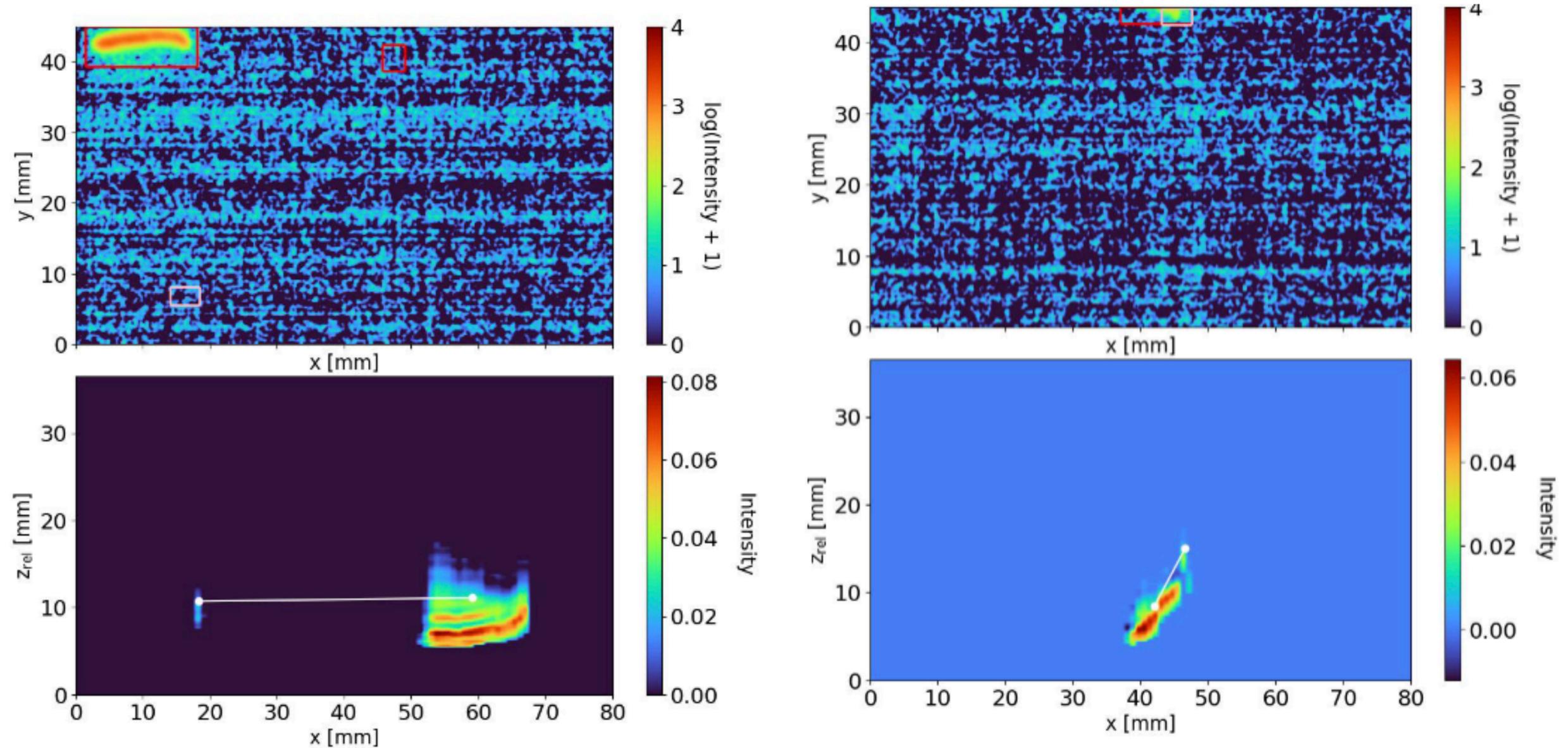


- Nuclear recoil energy in the ITO $> 50 \text{ keV}_{ee}$, corresponding to $\sim 150 \text{ keV}$ (F)
- Electron energy $3 < E_{ER} < 15 \text{ keV}$ in the ITO
- Electron and nuclear recoil both identified in image by YOLO
- Define a control region and a signal region:
 - Signal region: ER-NR separation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

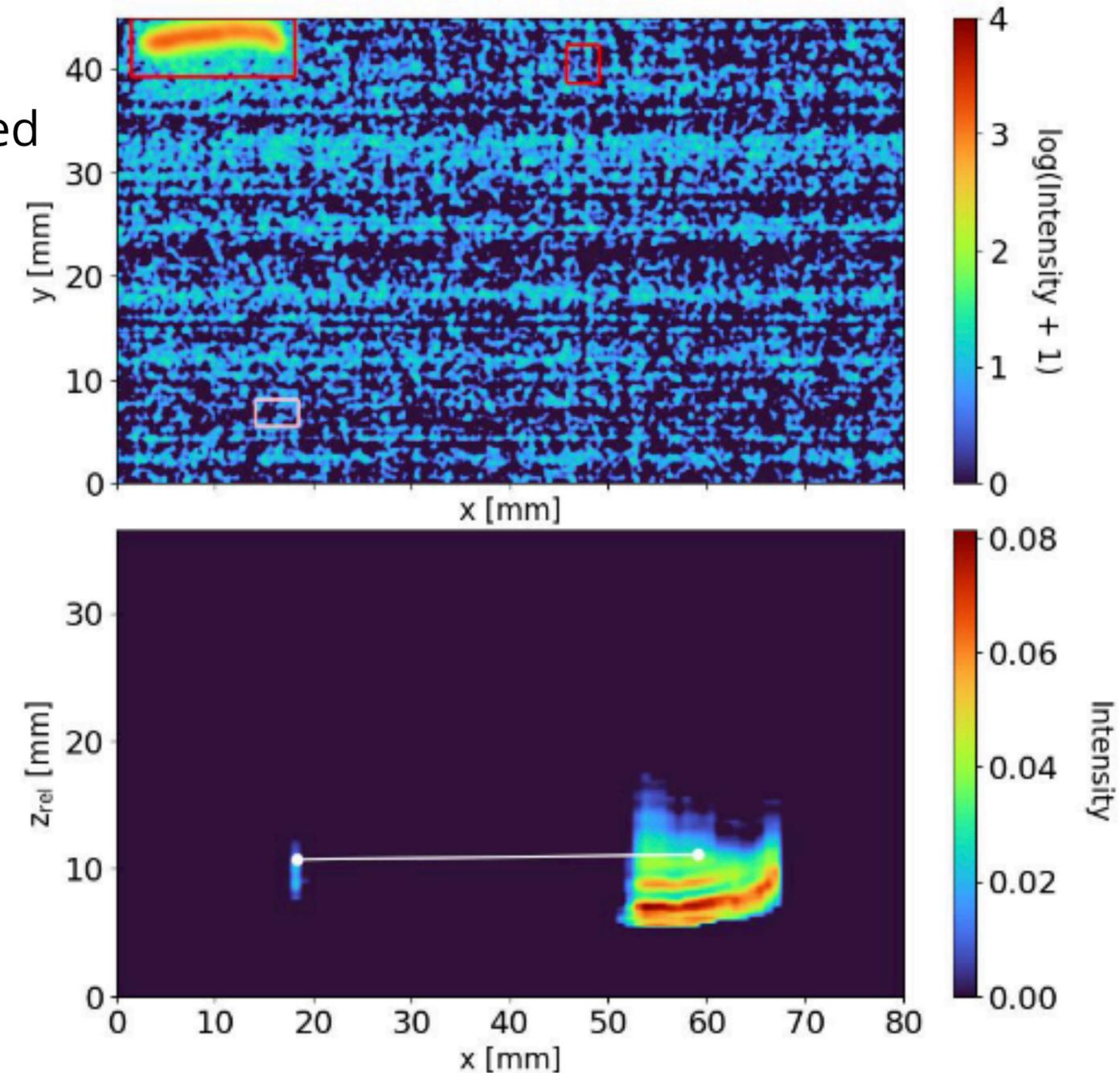
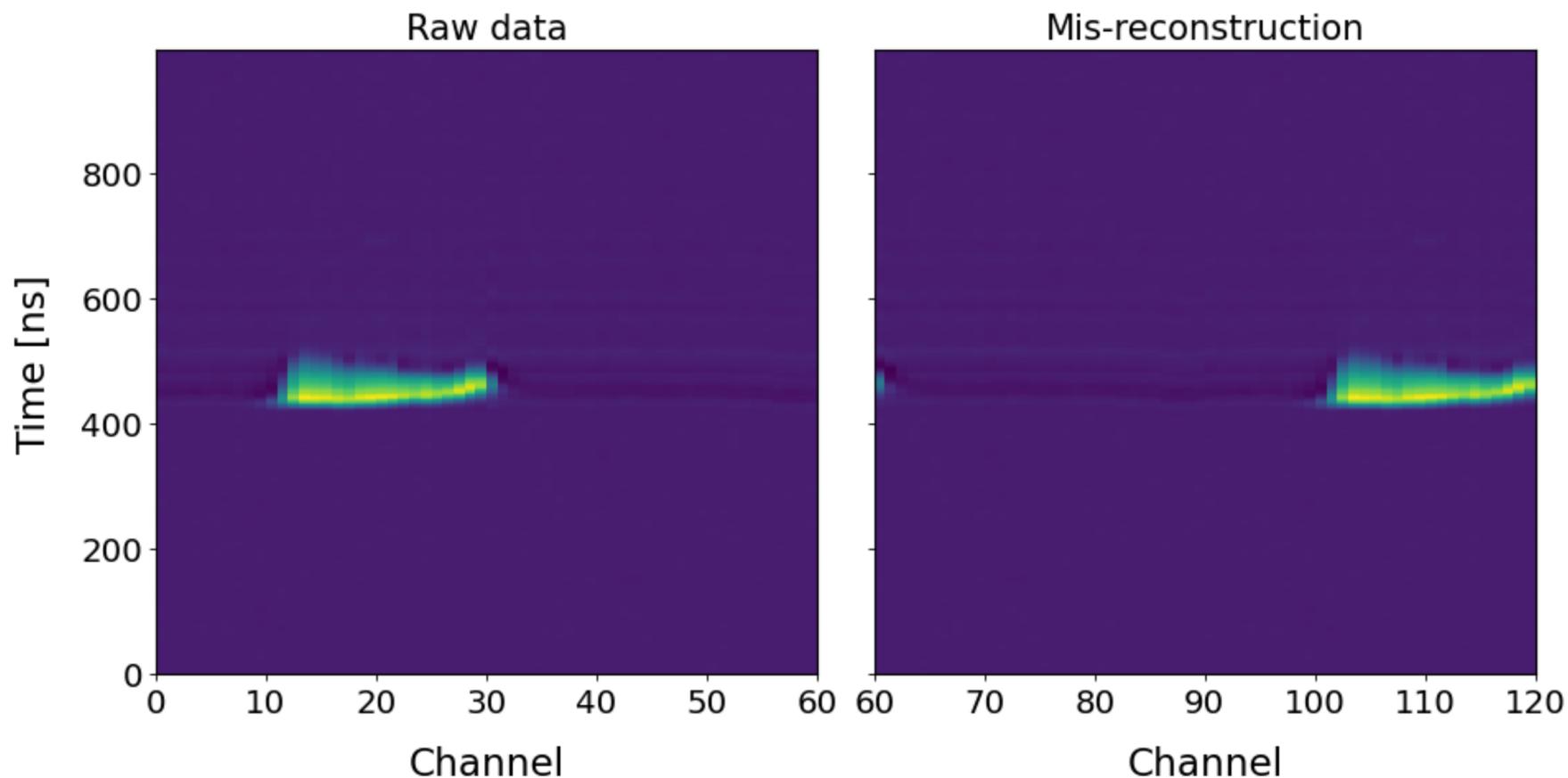


Additional Event Selection Requirements

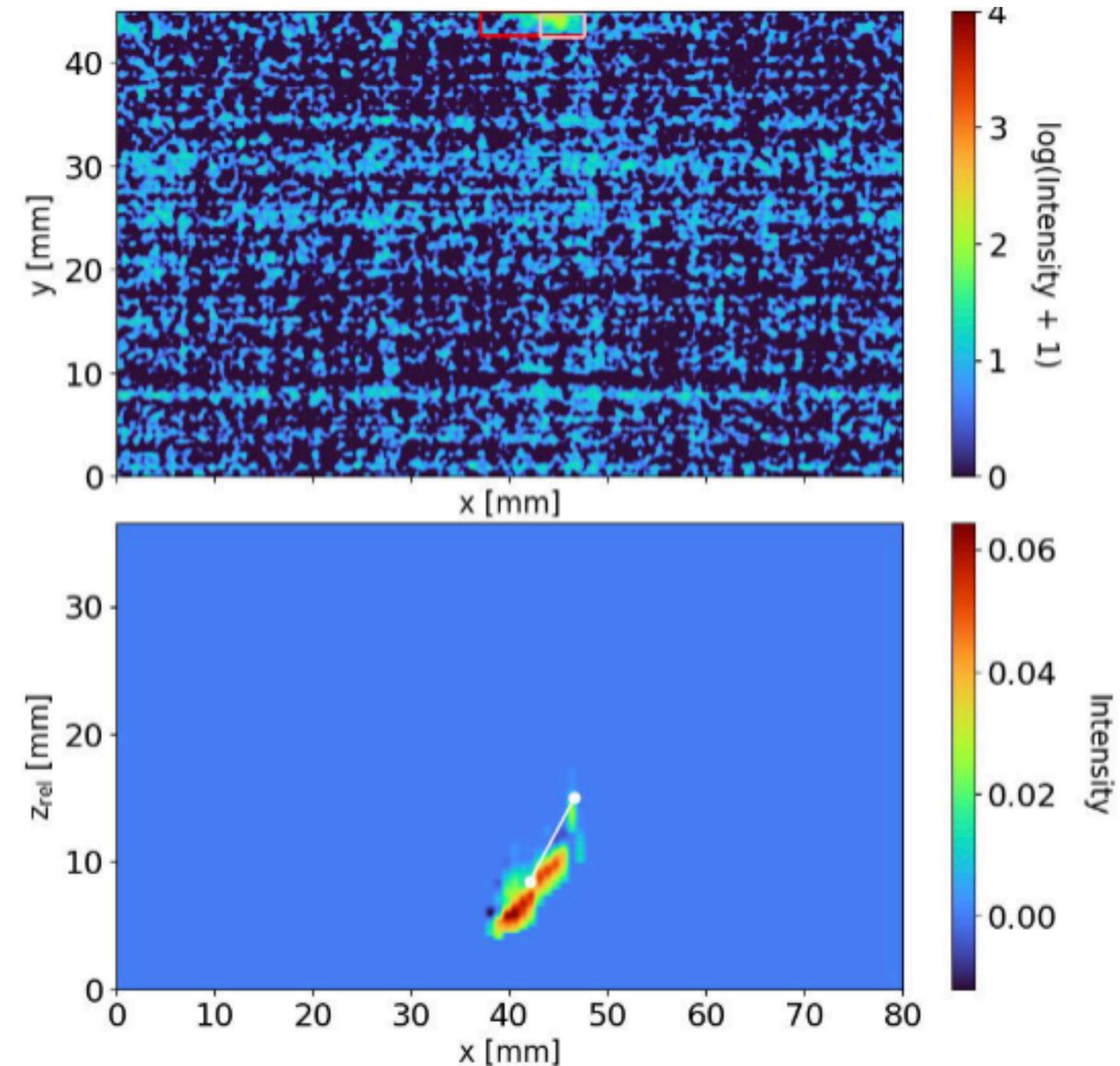
- After unblinding, two pathological classes of events were observed and the selection criteria were updated to target these classes of events
- Signal efficiency was reevaluated to reflect this and reduced by 1.5%



- 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

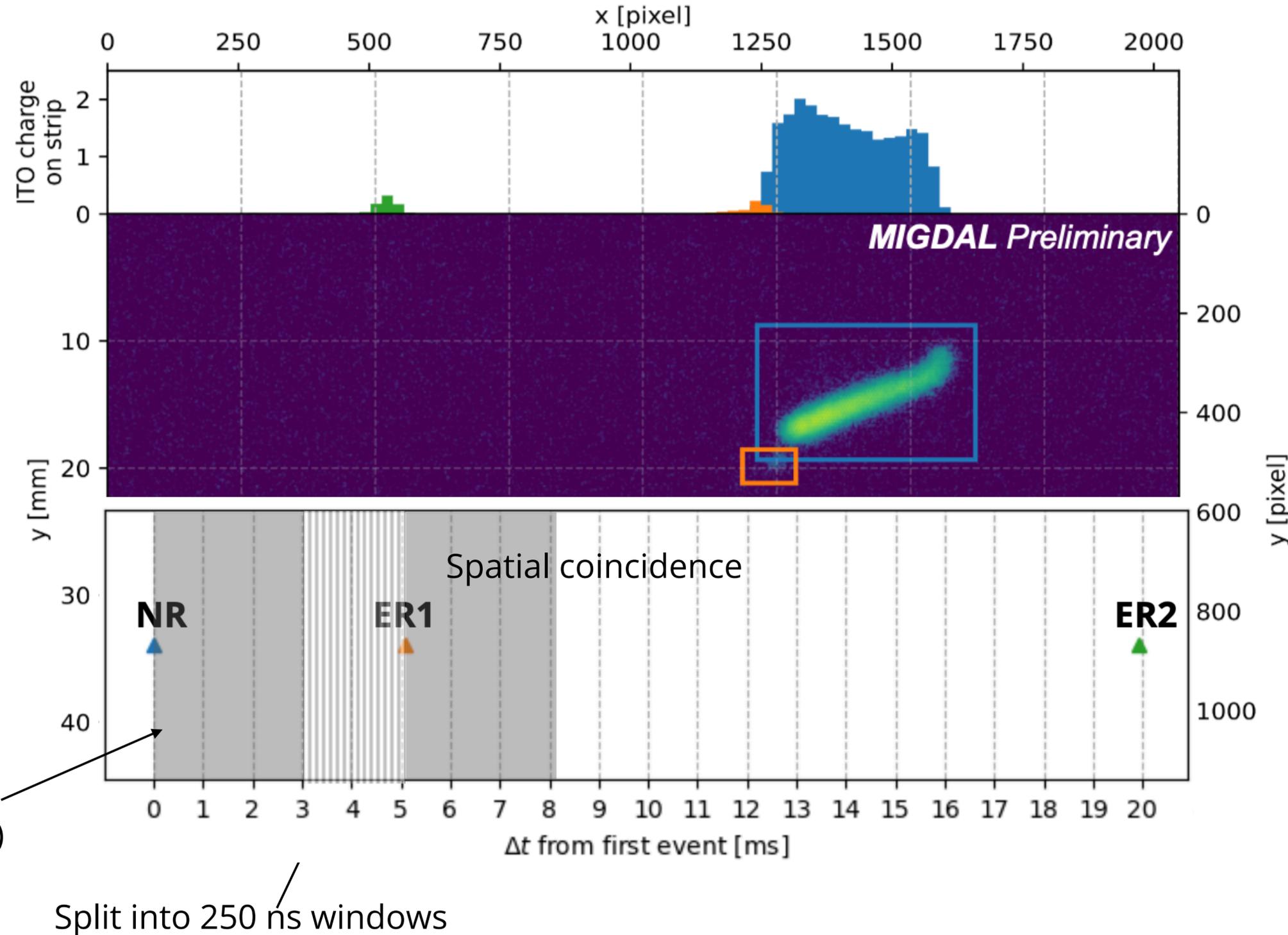


- After unblinding issue with DAQ identified
 - Affects $<1\%$ of events where single strip misaligned in time
 - Relevant for 4 specific read-out channels (out of 60)
- Additional requirement applied to reject events with non-physical dE/dx profile

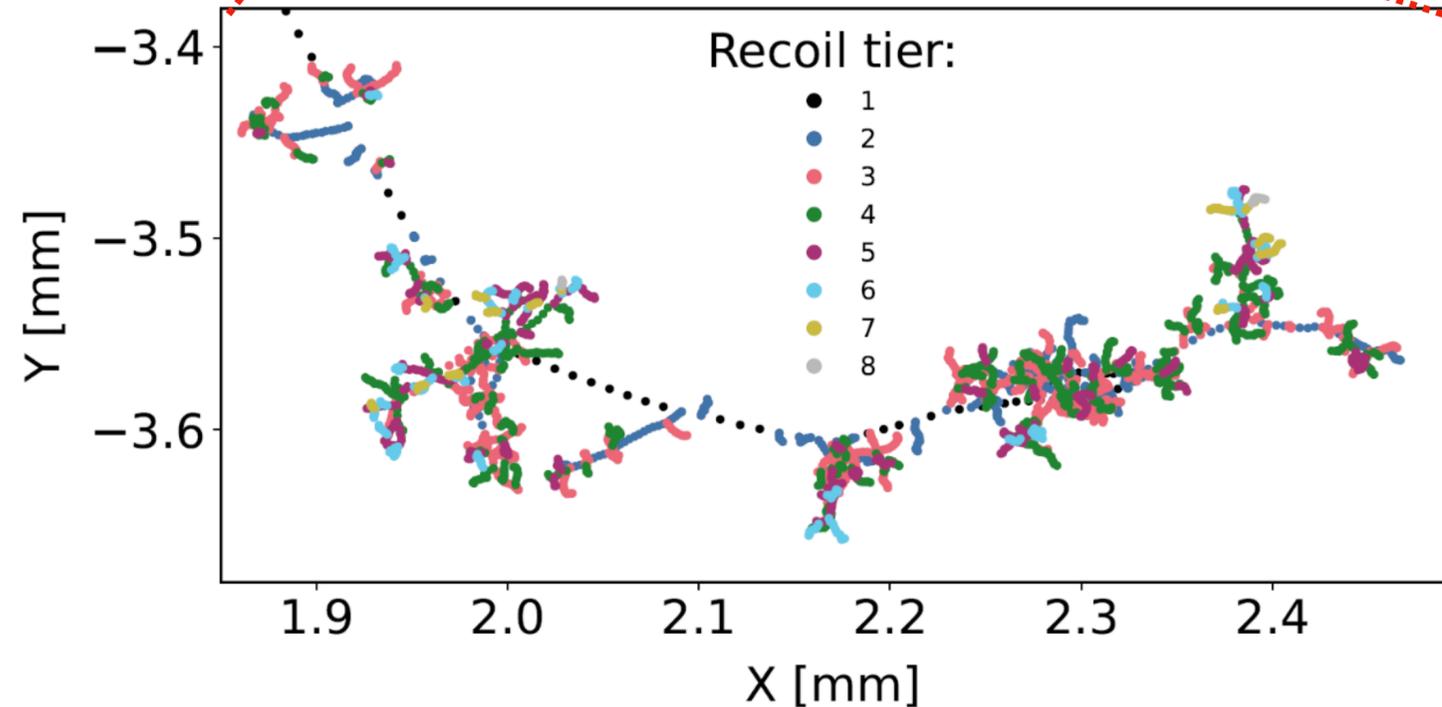
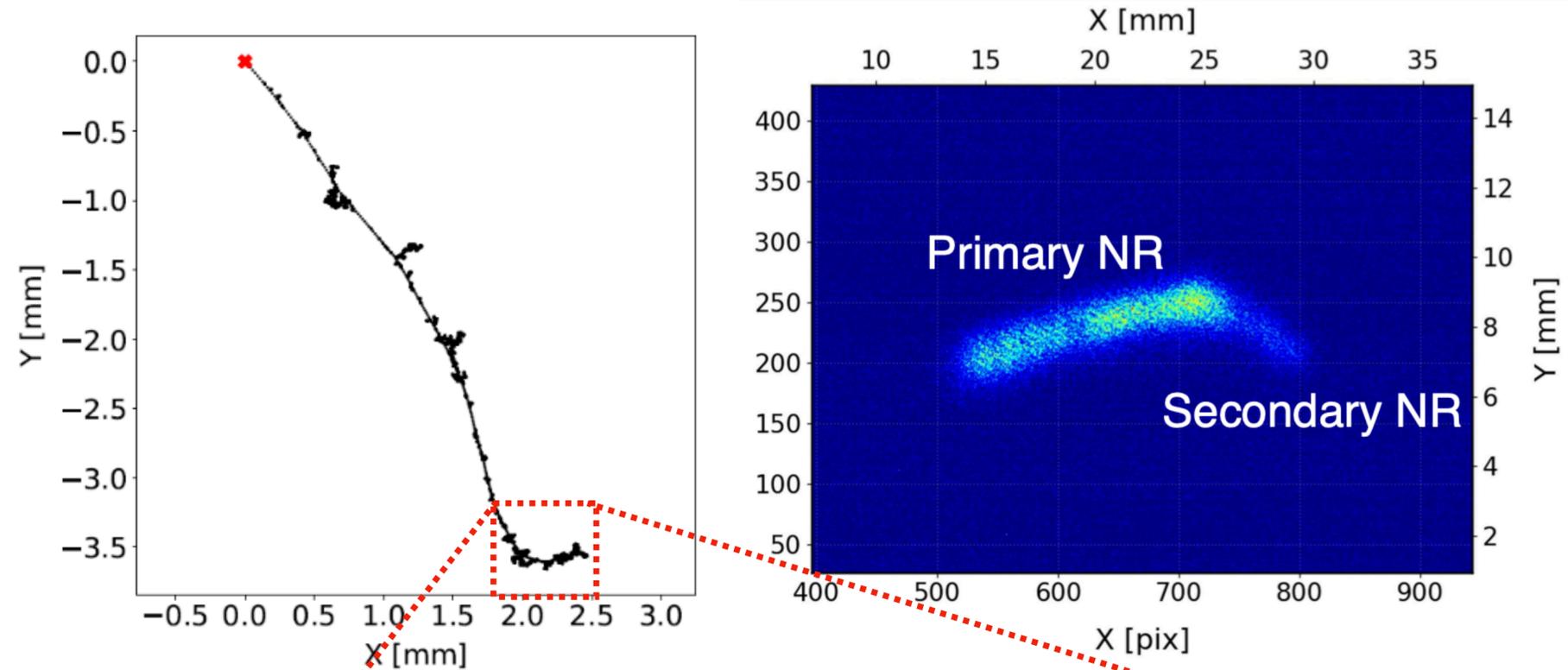
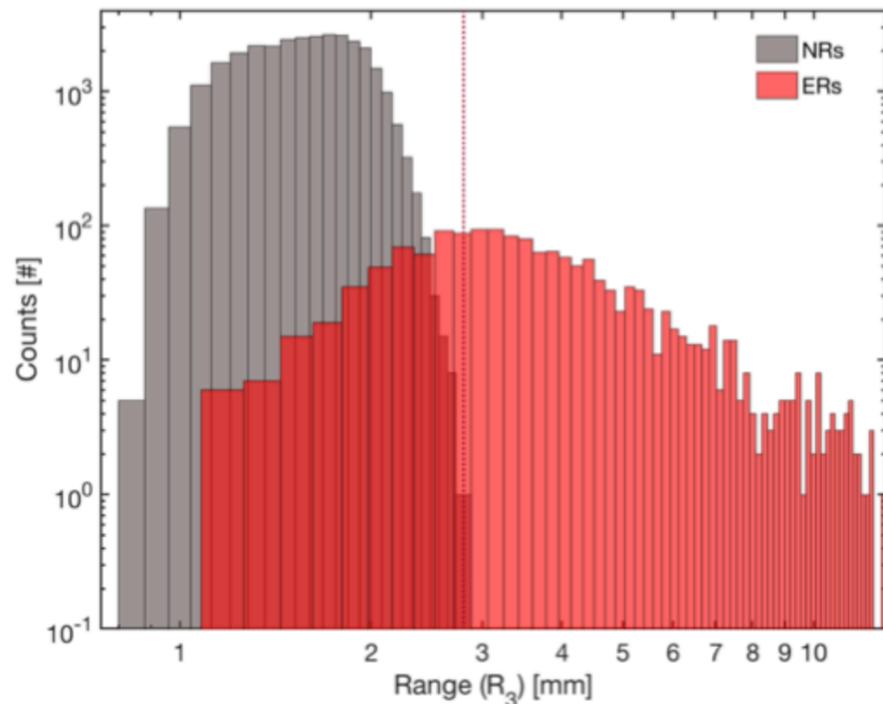


Background: Random Track Coincidences

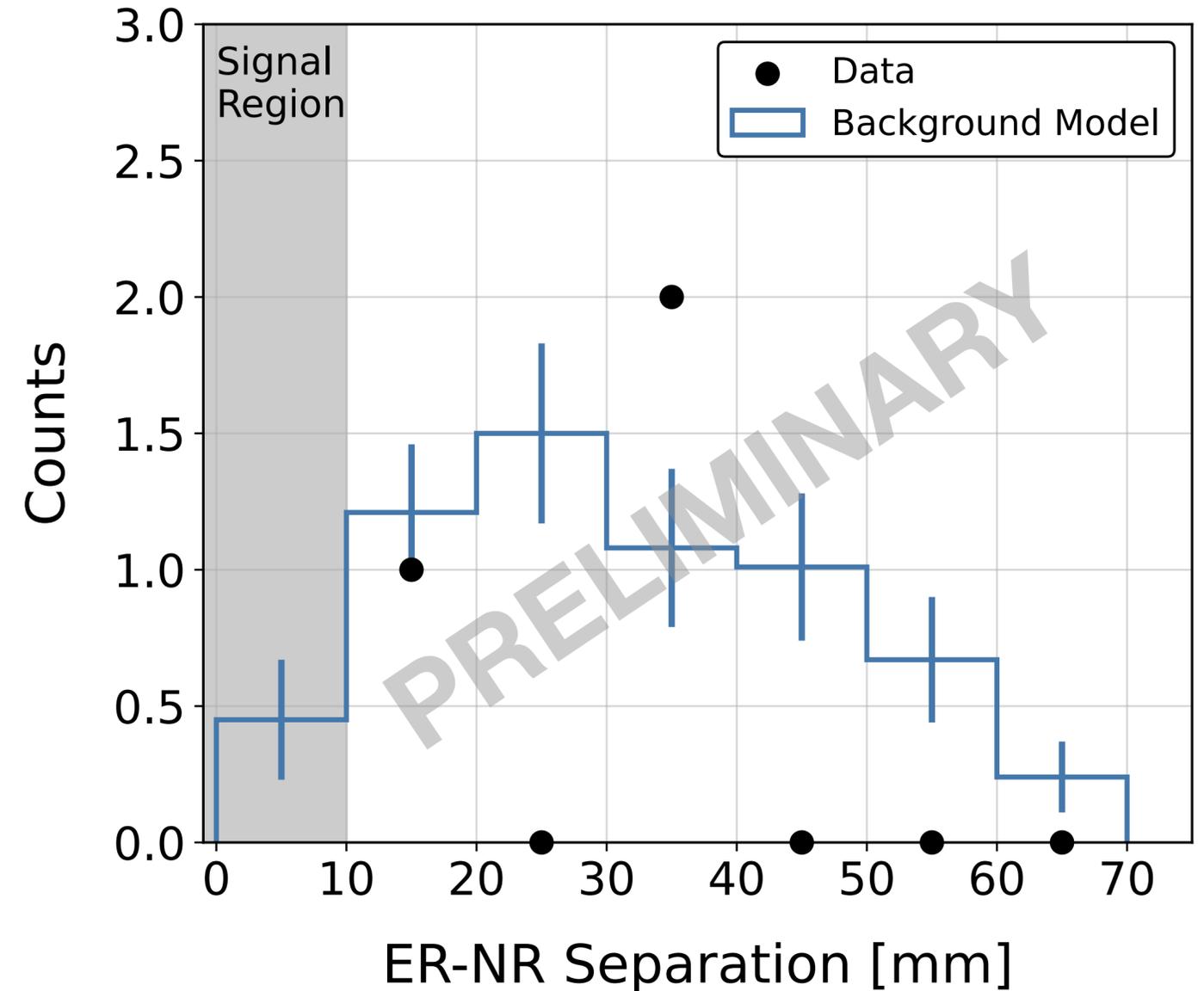
- Estimate random coincidences from spatially coinciding out-of-time events
- For each NR:
 - Look for ERs 3-8 ms following NR
 - Split remaining time into 250 ns windows and count any electrons that would be spatially coincident
- Probability of random coincidence per NR = Number of spatial coincidences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



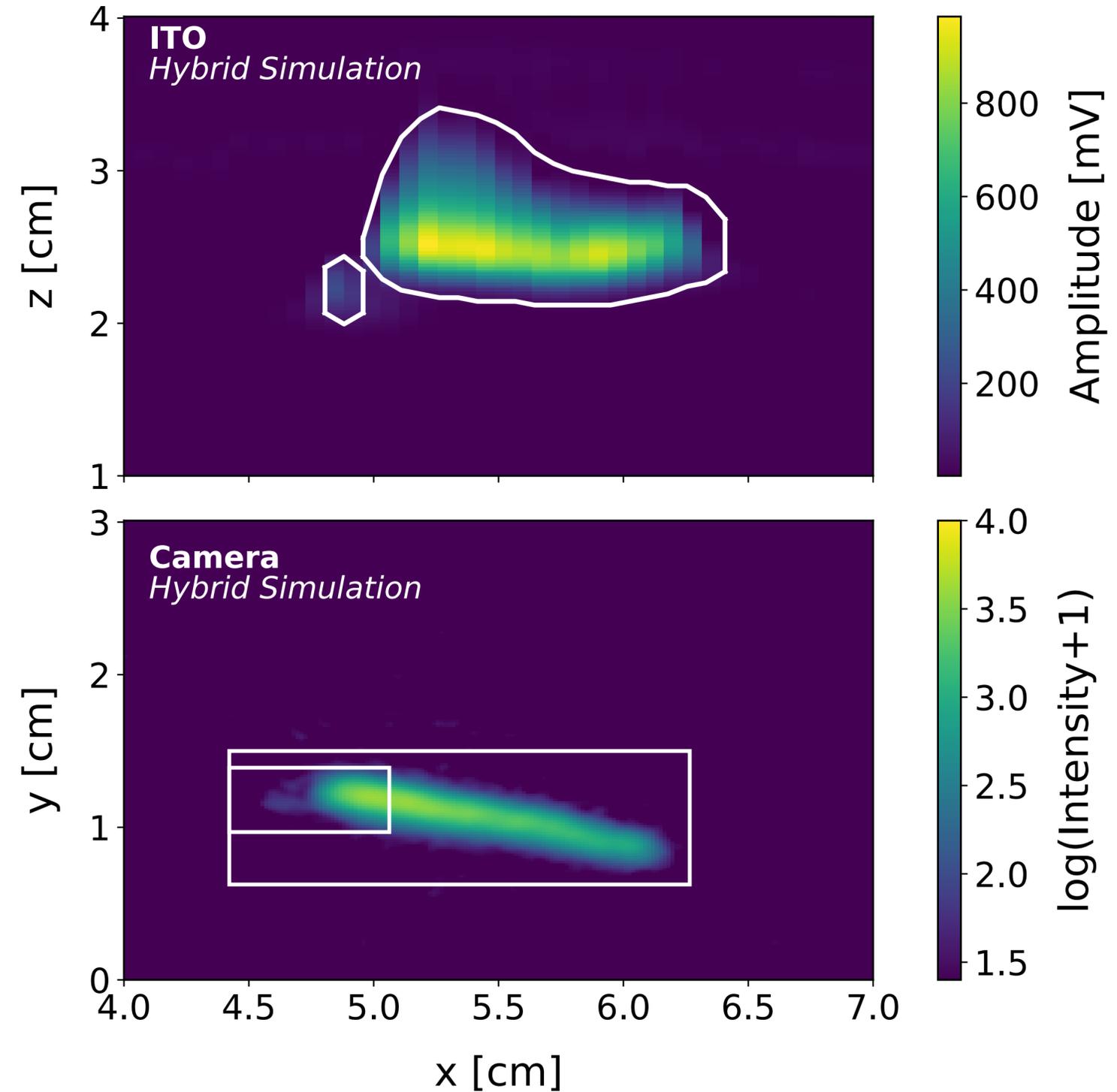
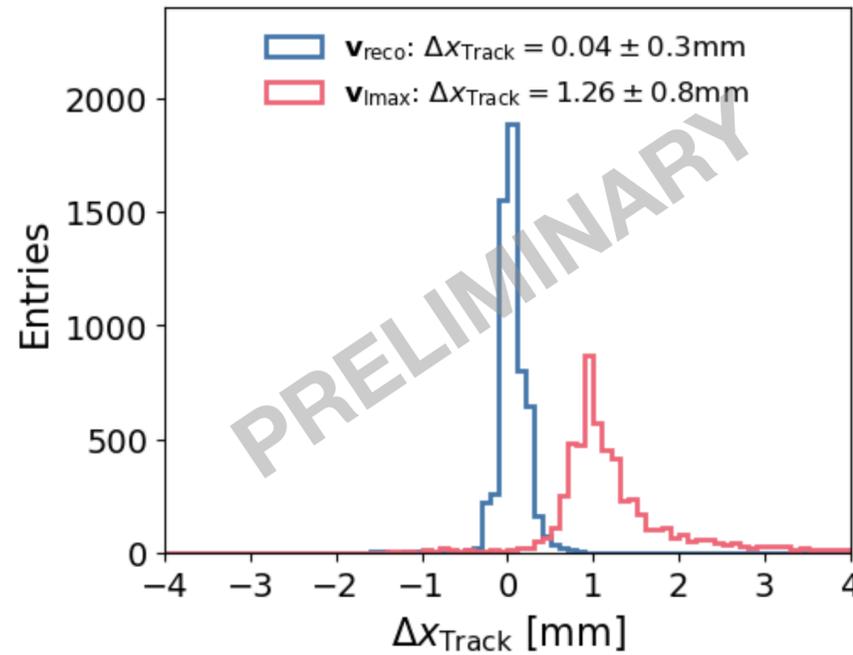
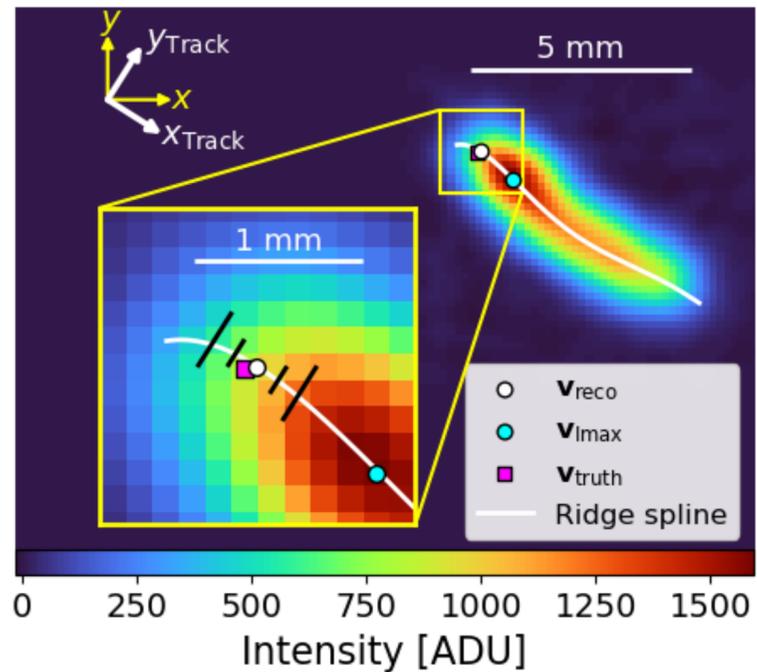
- 7% of NRs will have secondary that is:
 - < 1 mm from vertex
 - Reconstructed energy 5-15 keV_{ee}
- By requiring a track length > 3 mm expect 1 in 10^6 will mimic signal
- As the clustering is sensitive to dE/dx , expect < 0.1 events in our dataset - assume to be negligible



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

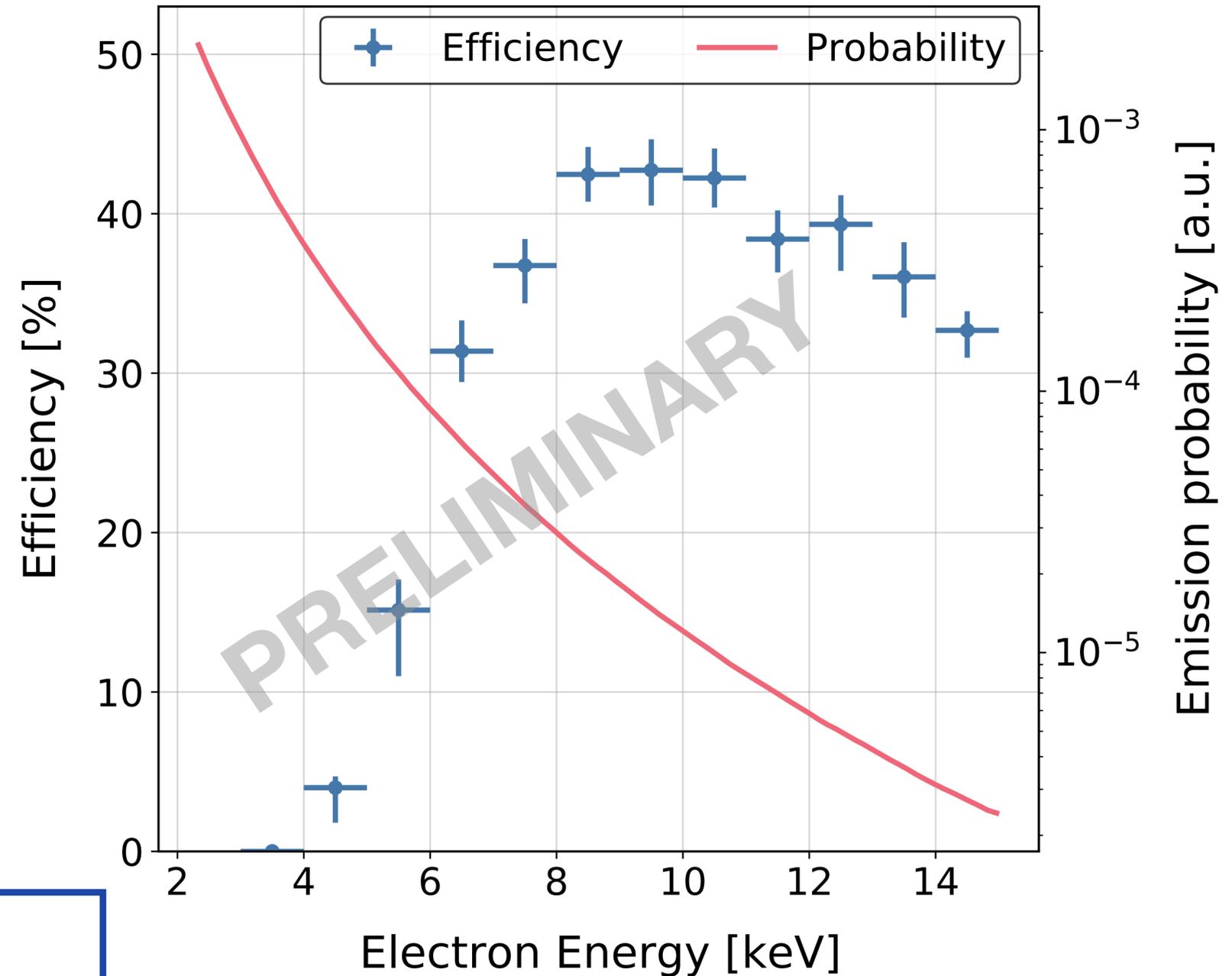


- Migdal events are simulated by stitching nuclear recoils from data with simulated electrons
- Vertex is estimated in nuclear recoils using the Bragg intensity curve along the ridge of the track for (x, y)
- Use absolute depth and track extent to reconstruct z vertex

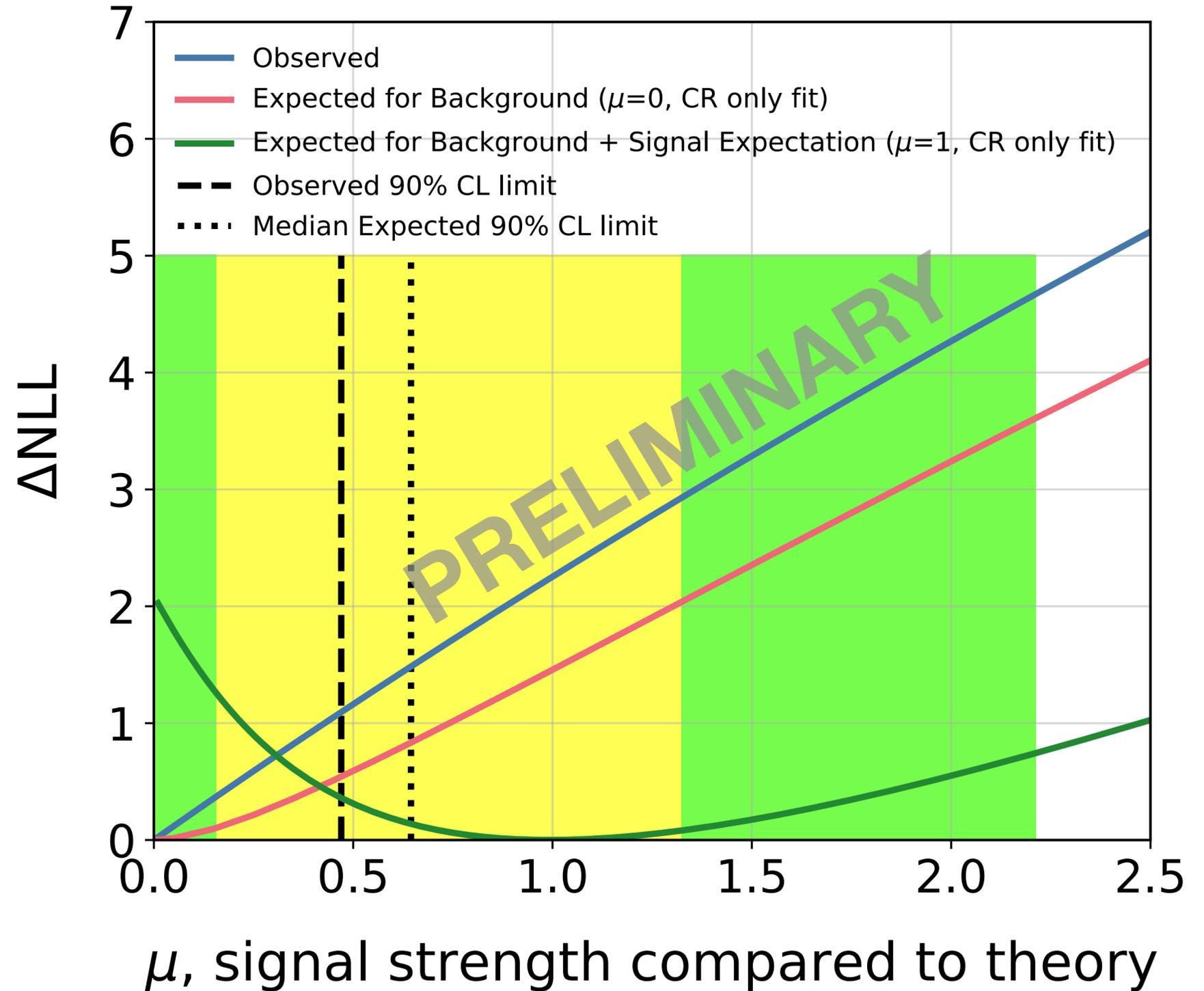
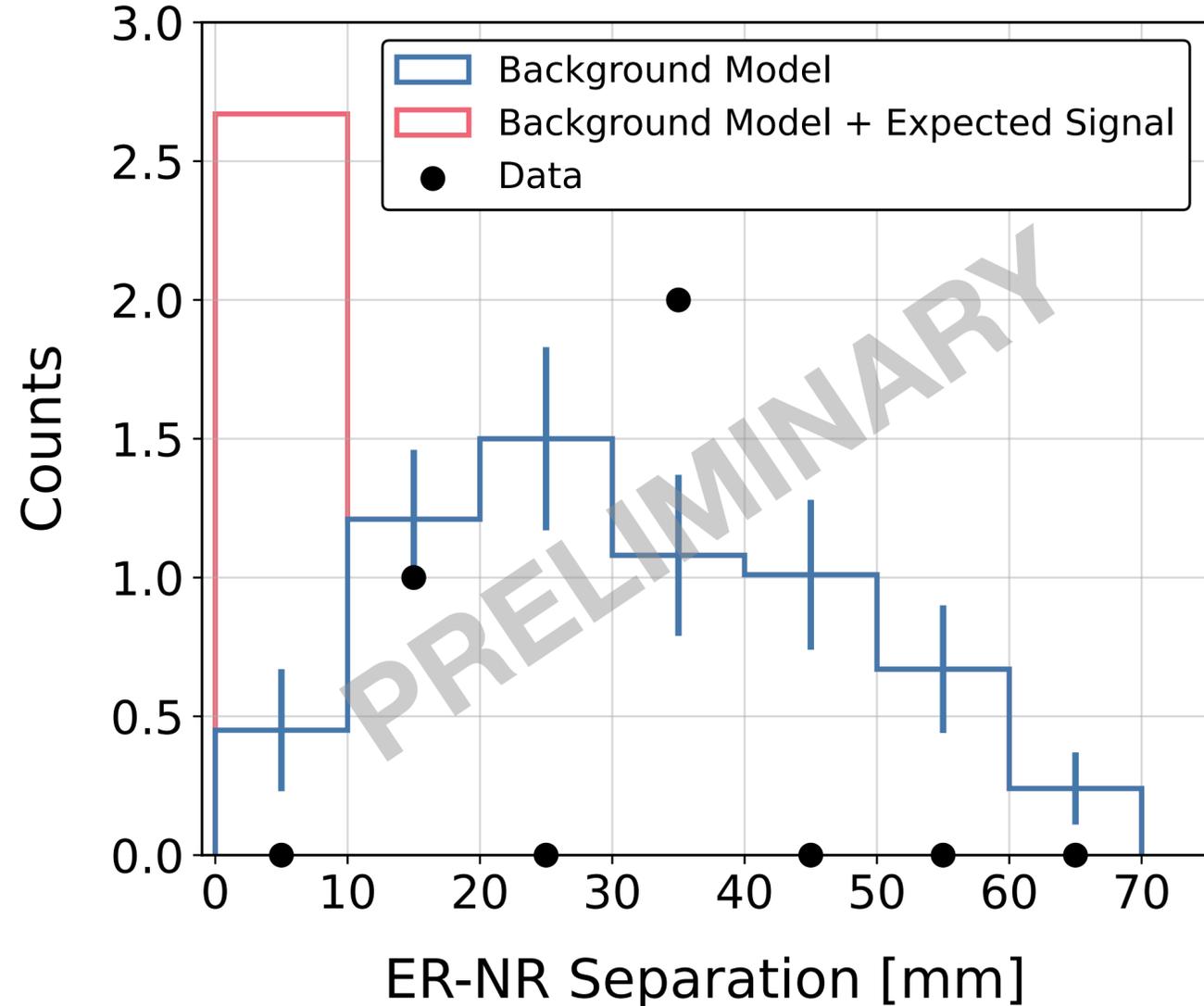


- Efficiencies are estimated by passing hybrid events through analysis chain
- Dominant source of systematic uncertainty comes from uncertainty in vertex position of nuclear recoil
- Estimate systematic uncertainty by shifting vertex in hybrids by the uncertainty in the (x, y) position and the expected diffusion length in z
- Overall efficiency is:

$$\epsilon = 14.9 \pm (1.0)_{stat.} \pm \begin{pmatrix} +0.1 \\ -0.9 \end{pmatrix}_{xy,syst} \pm \begin{pmatrix} +1.9 \\ -0.4 \end{pmatrix}_{z,syst}$$



- 0 events observed in signal region
 - Expected 0.45 ± 0.05 events from background
- Observed (Expected) 90% CL upper limit in multiples of theory cross section = 0.45 (0.65)



- 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
- We set a 90% CL limit of 0.45 times the theory cross section
- More science data planned this year with improved beam characteristics

Publications:

Overlap-aware segmentation for topological reconstruction of obscured objects

[*Preprint: 2510.06194 \(2025\)*](#)

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

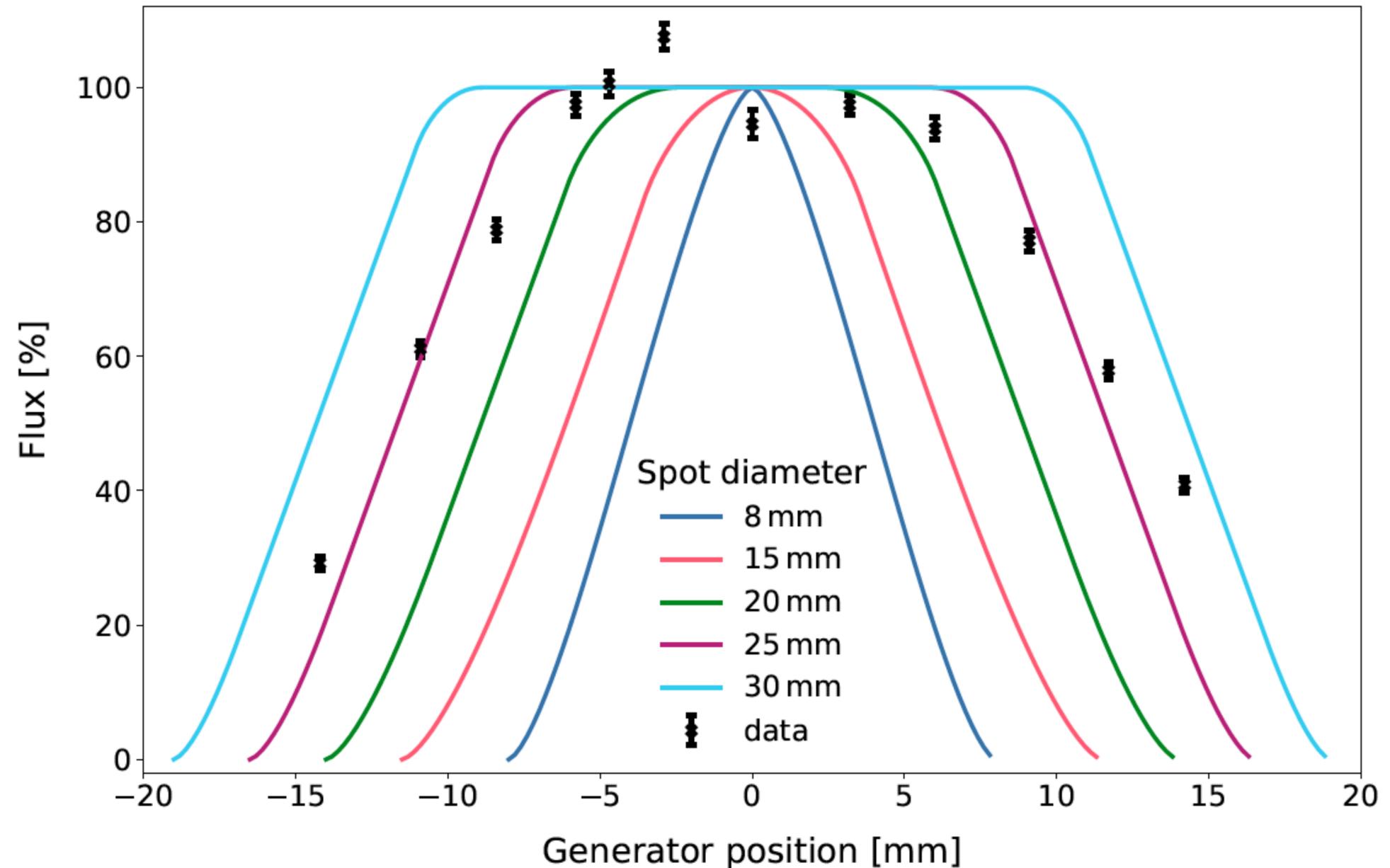
[*JINST 18 \(2023\) 07, C07013*](#)

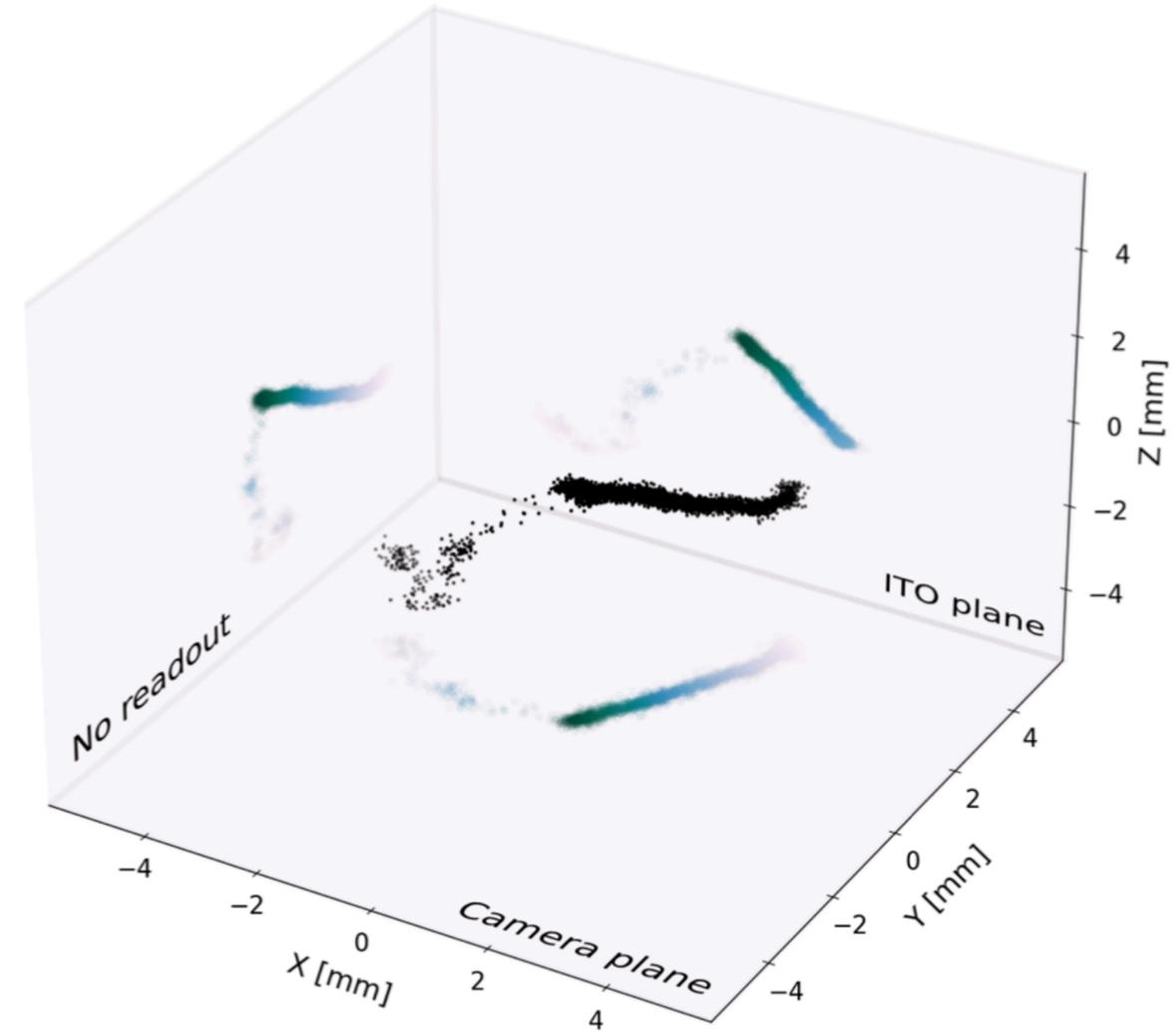
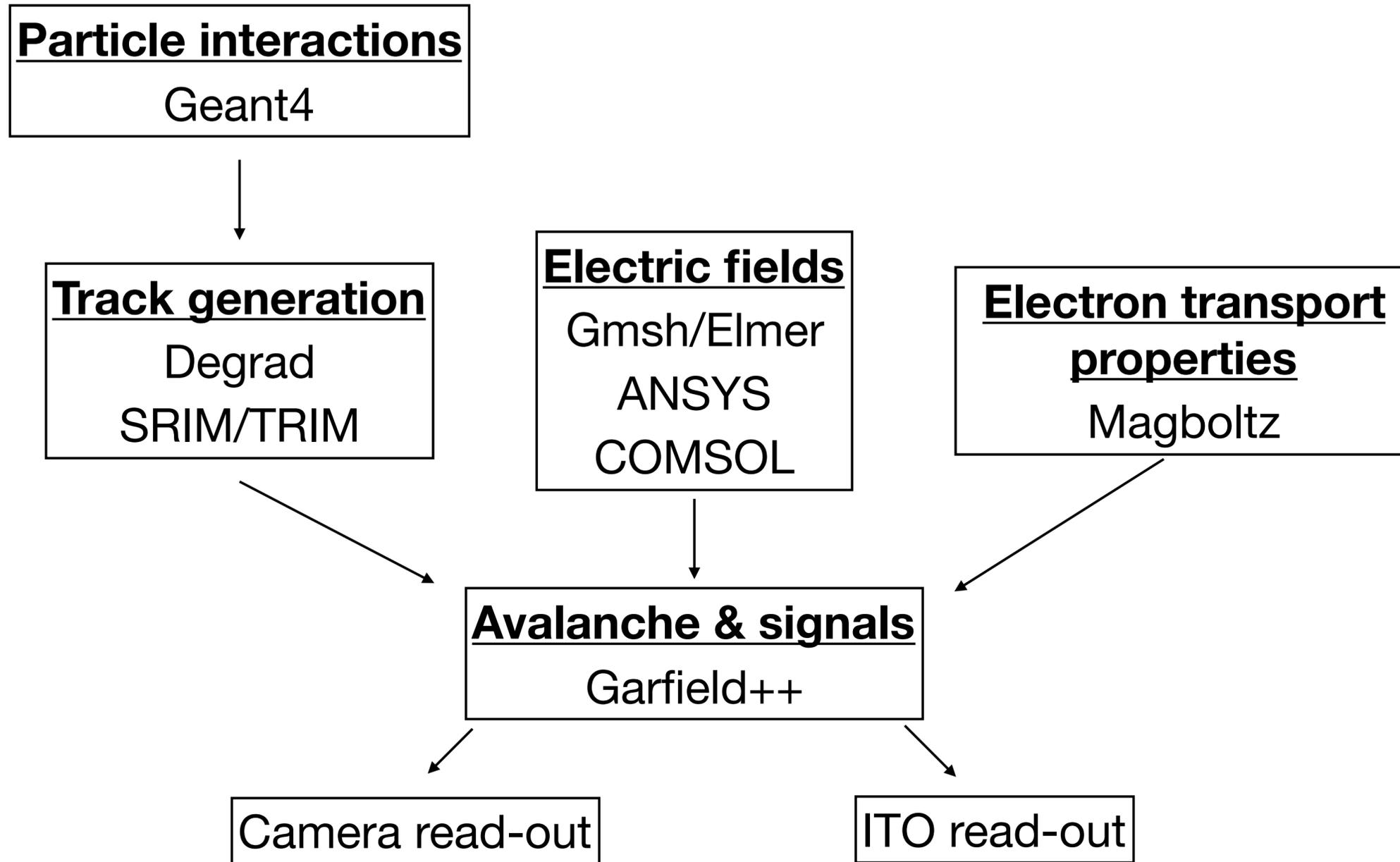
The MIGDAL experiment: Measuring a rare atomic process to aid the search for dark matter

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

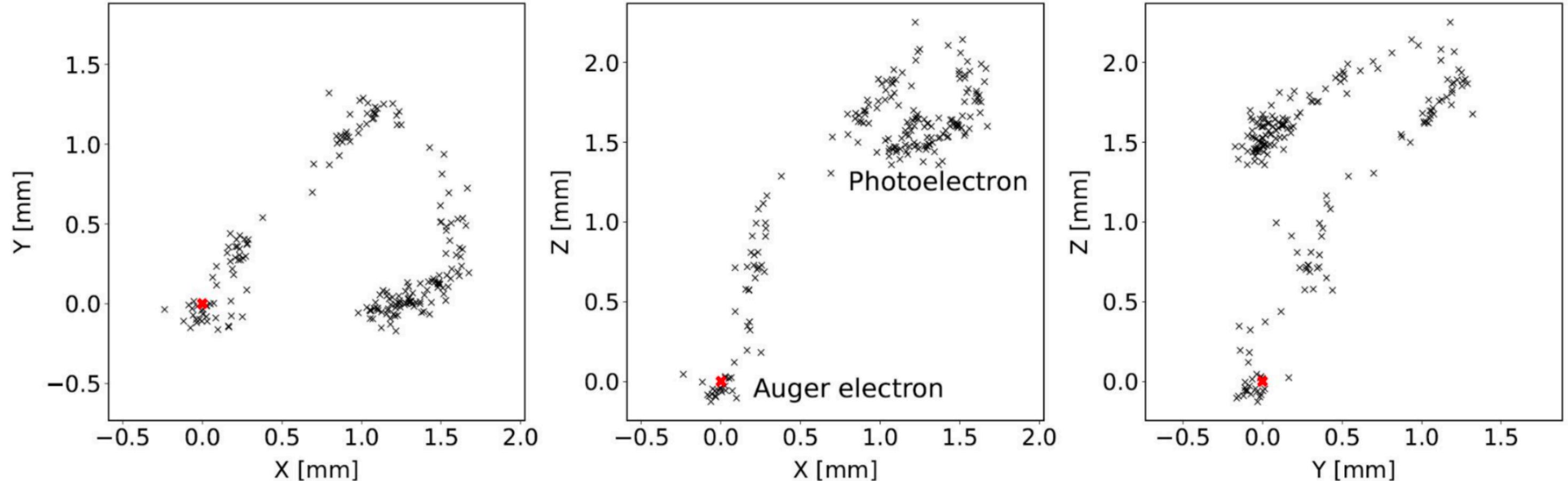
Backup

- 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

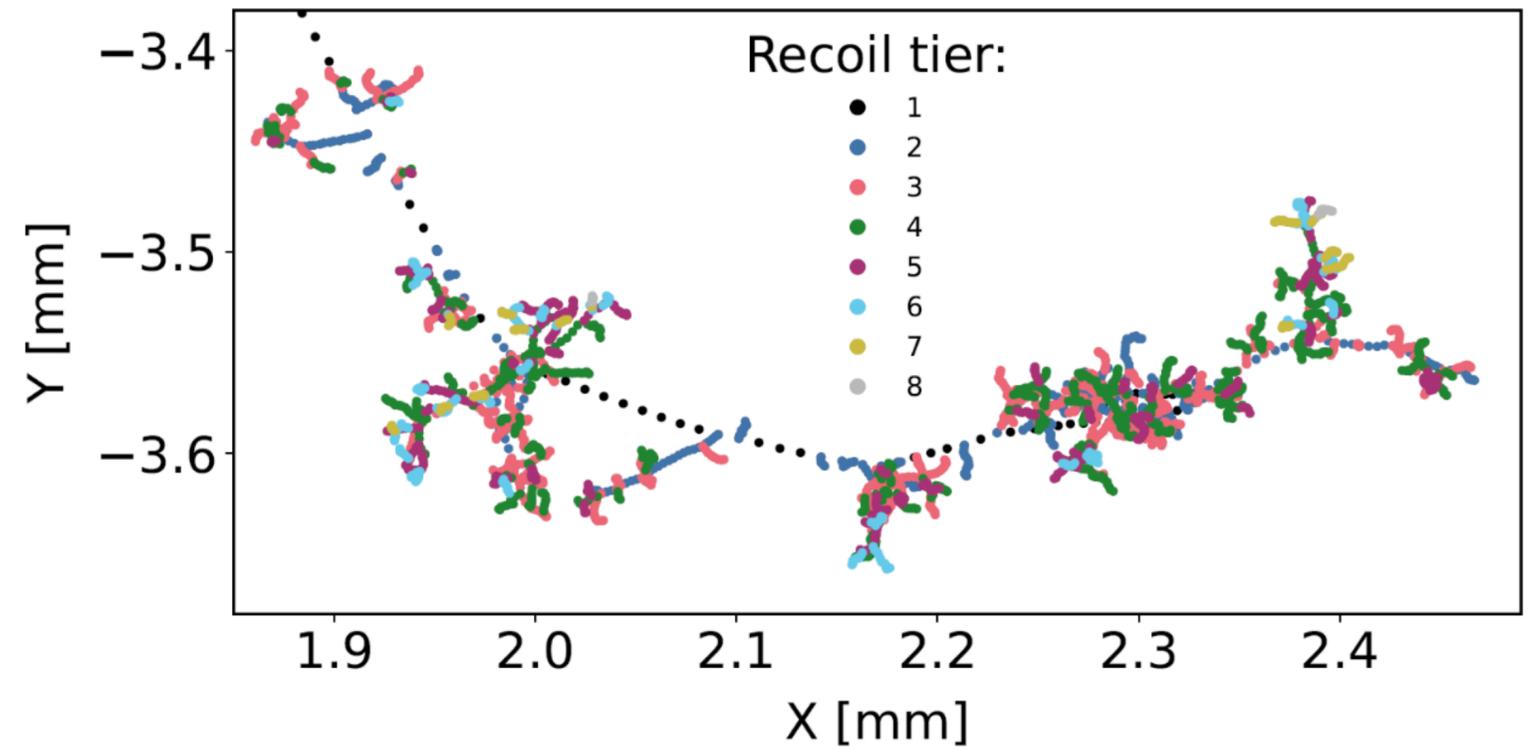
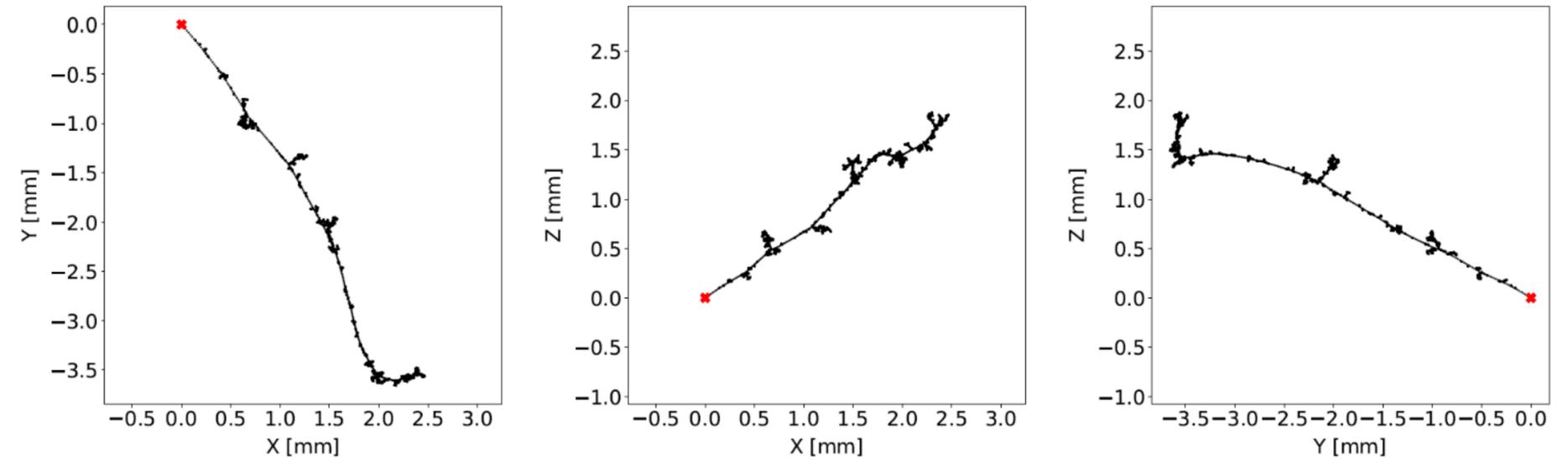
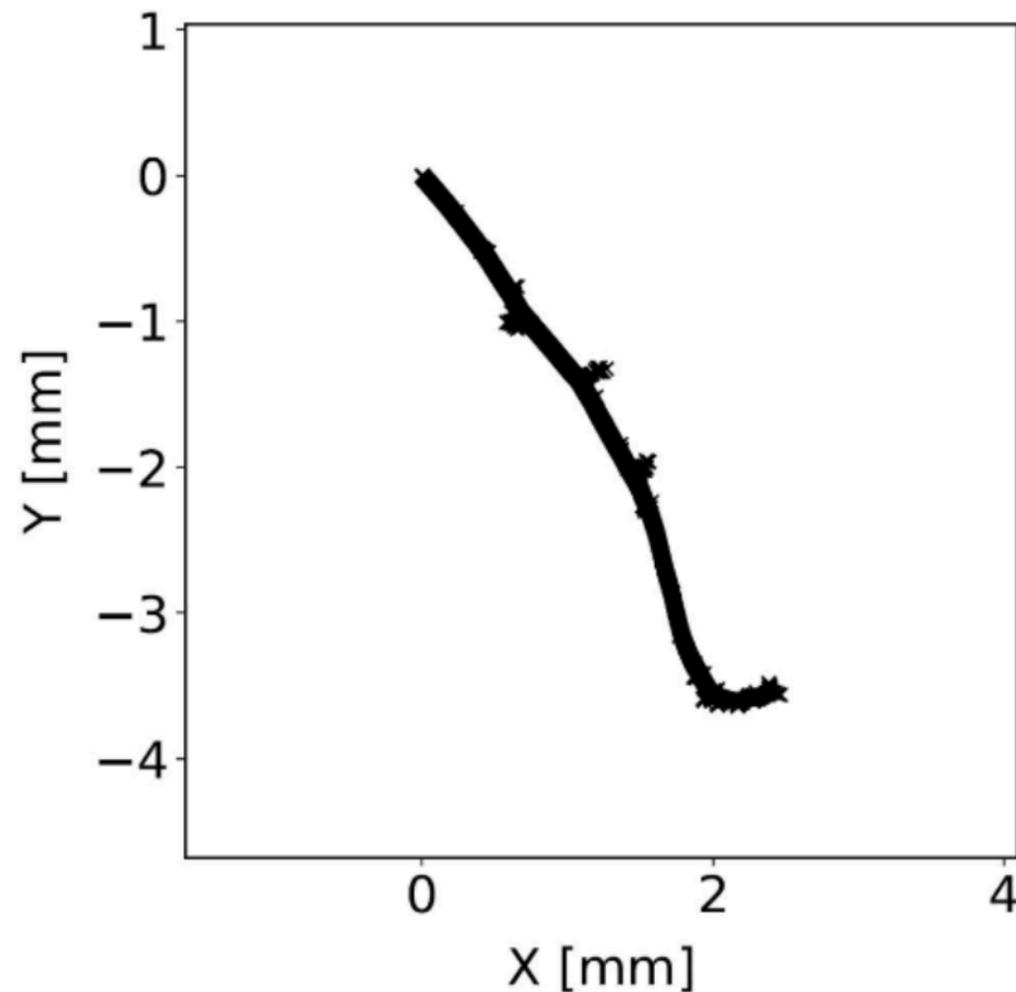


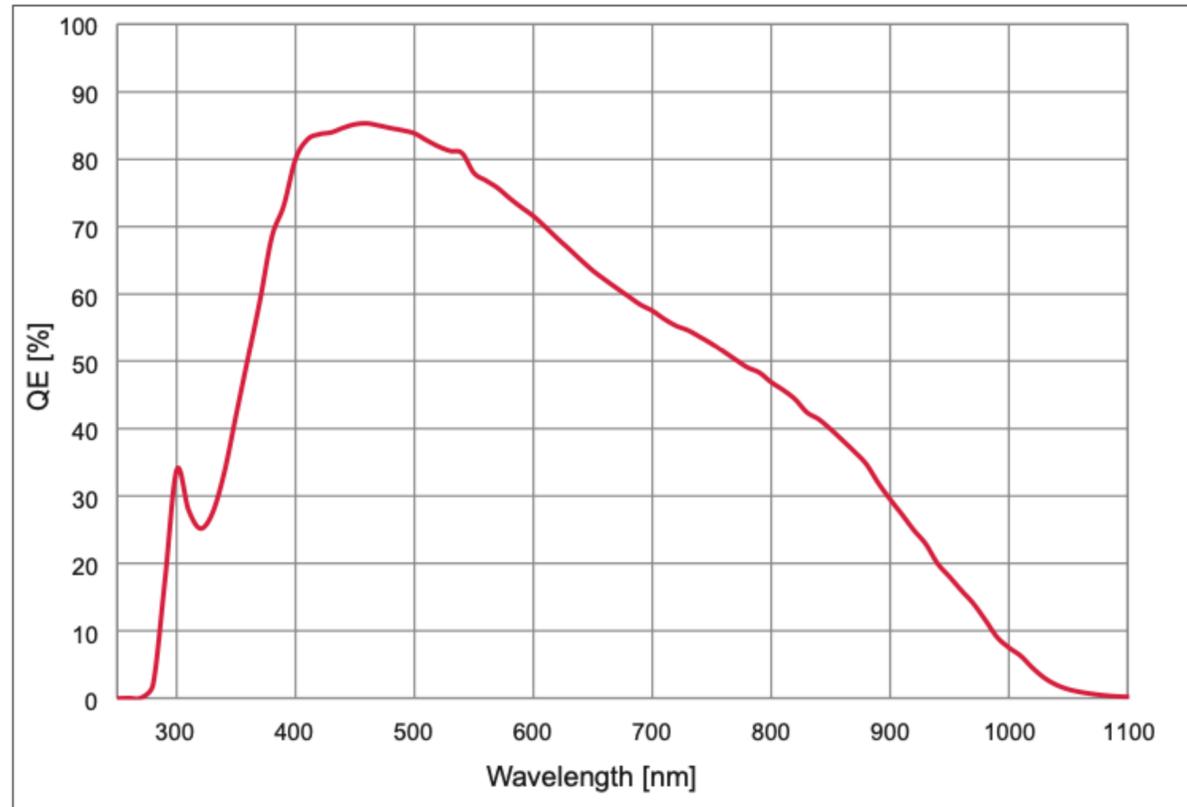


- Ionisation of electron tracks from DEGRAD
- Plots show ^{55}Fe X-ray interaction producing Auger and photoelectron



- Nuclear recoil tracks and atomic recoil cascades from TRIM with bespoke code for cascades
- Ionisation from Poisson distribution of energy losses



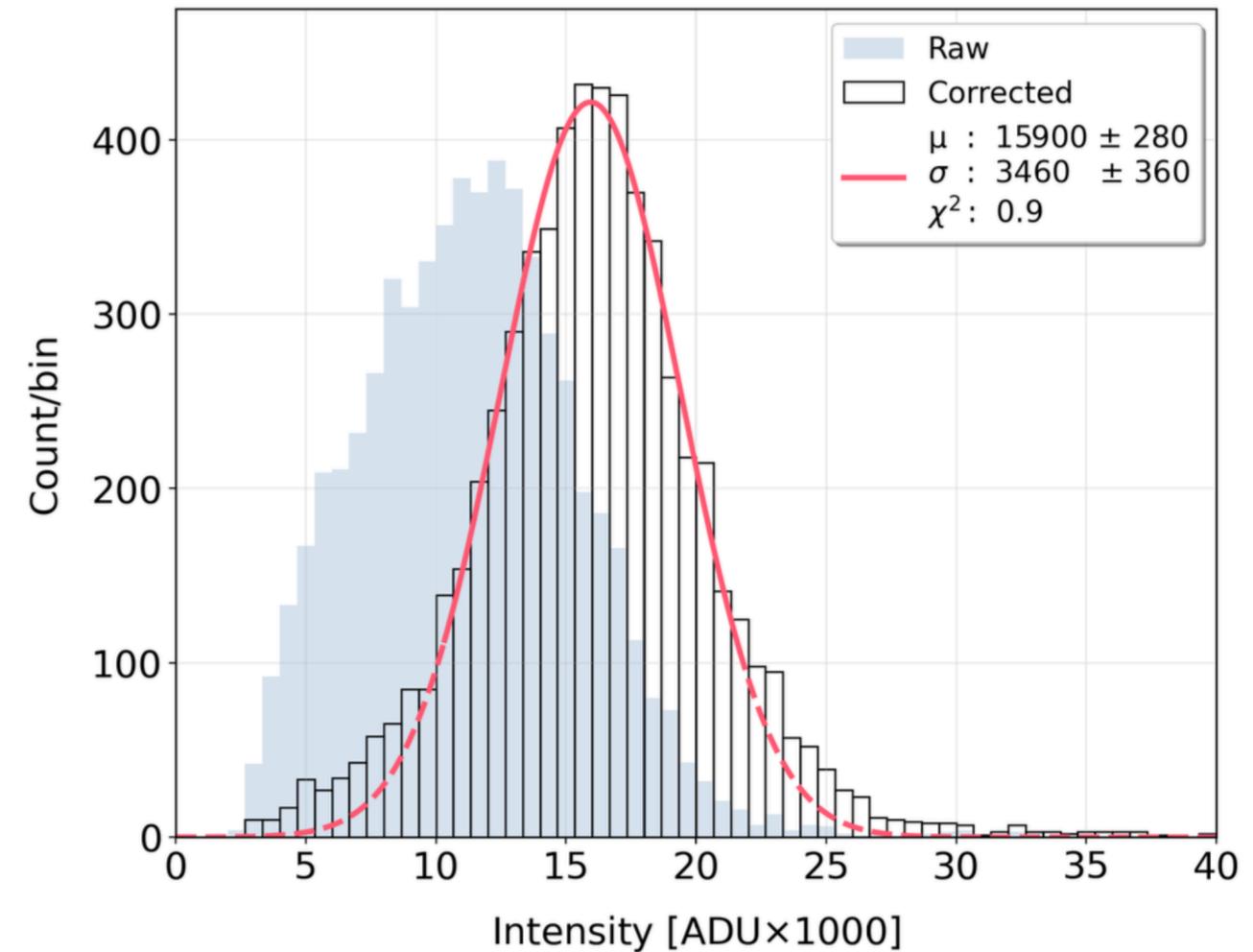
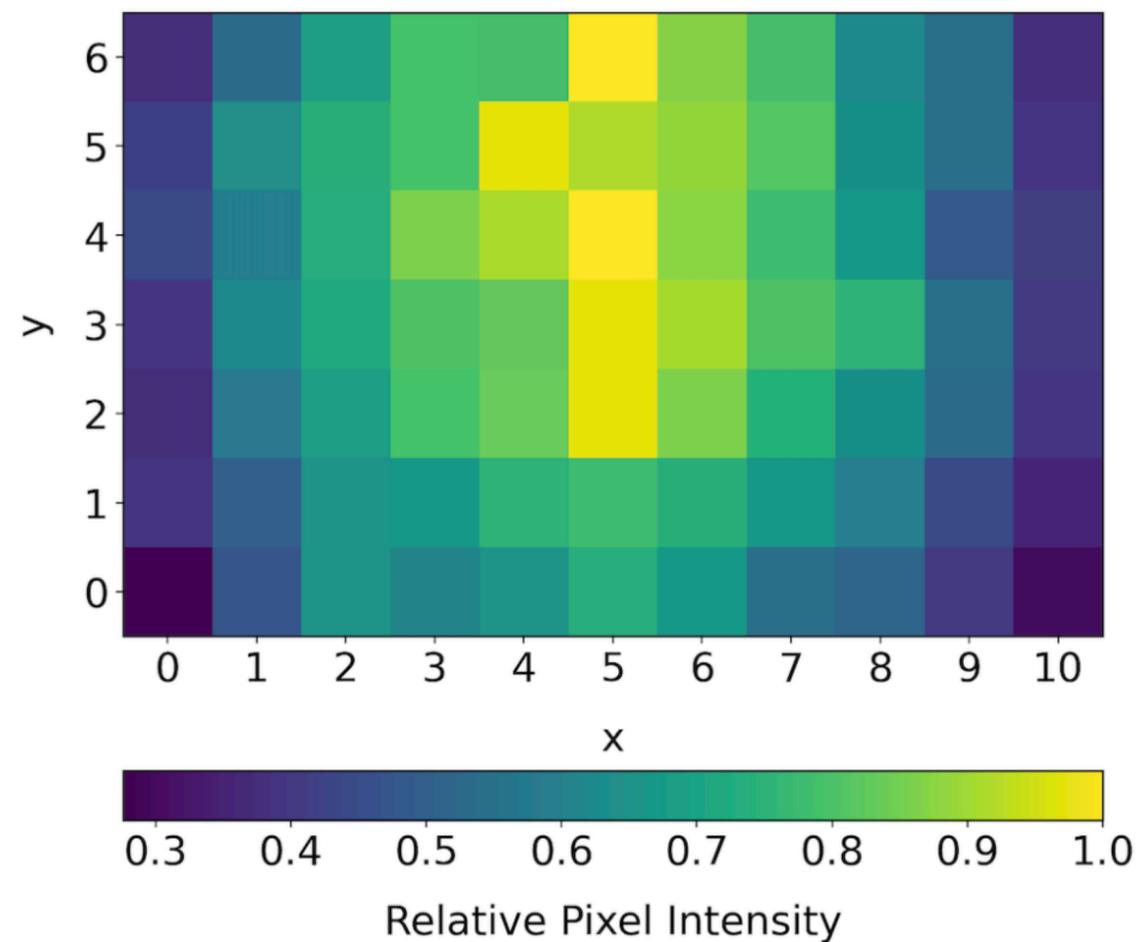


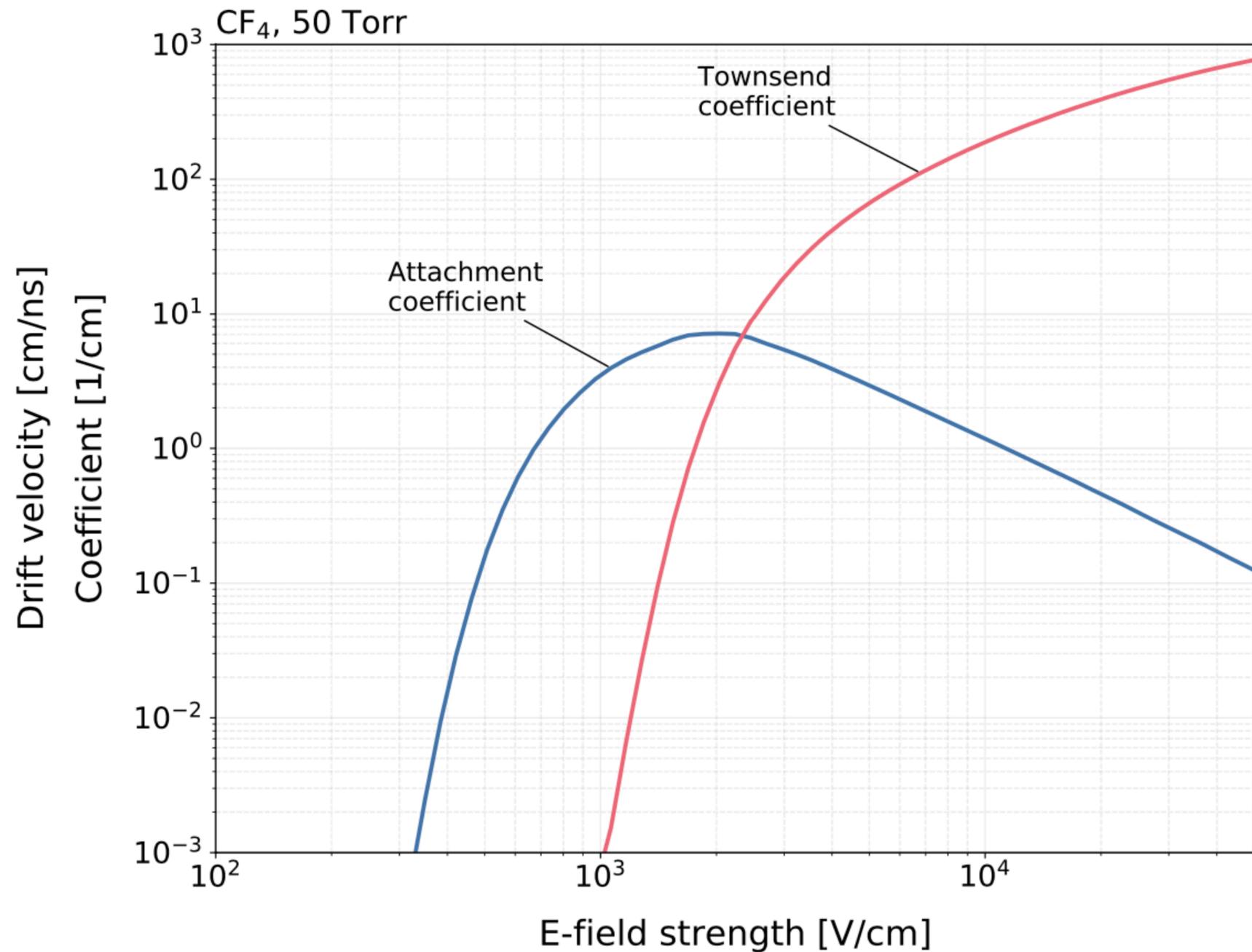
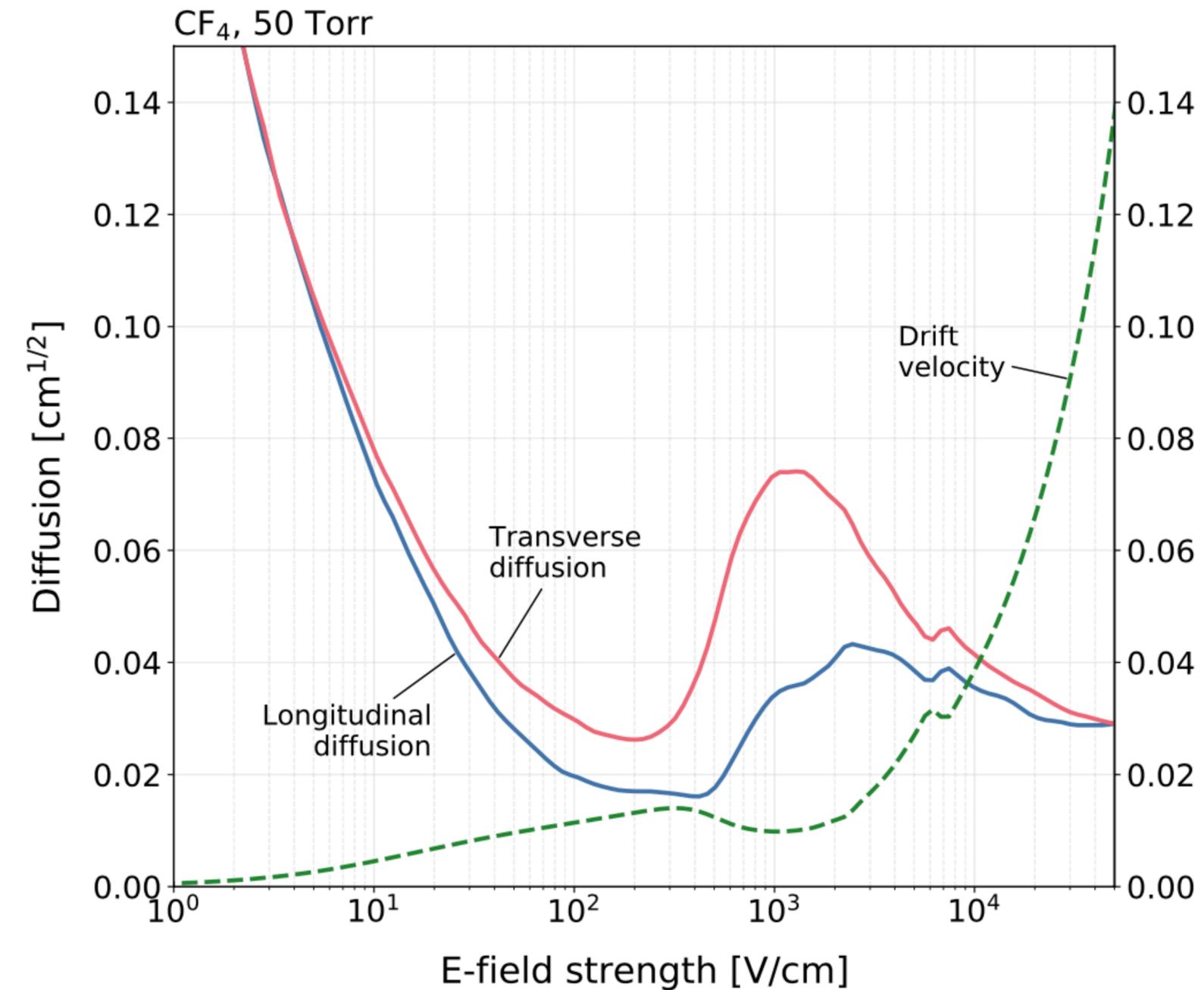
Hamamatsu Orca Quest

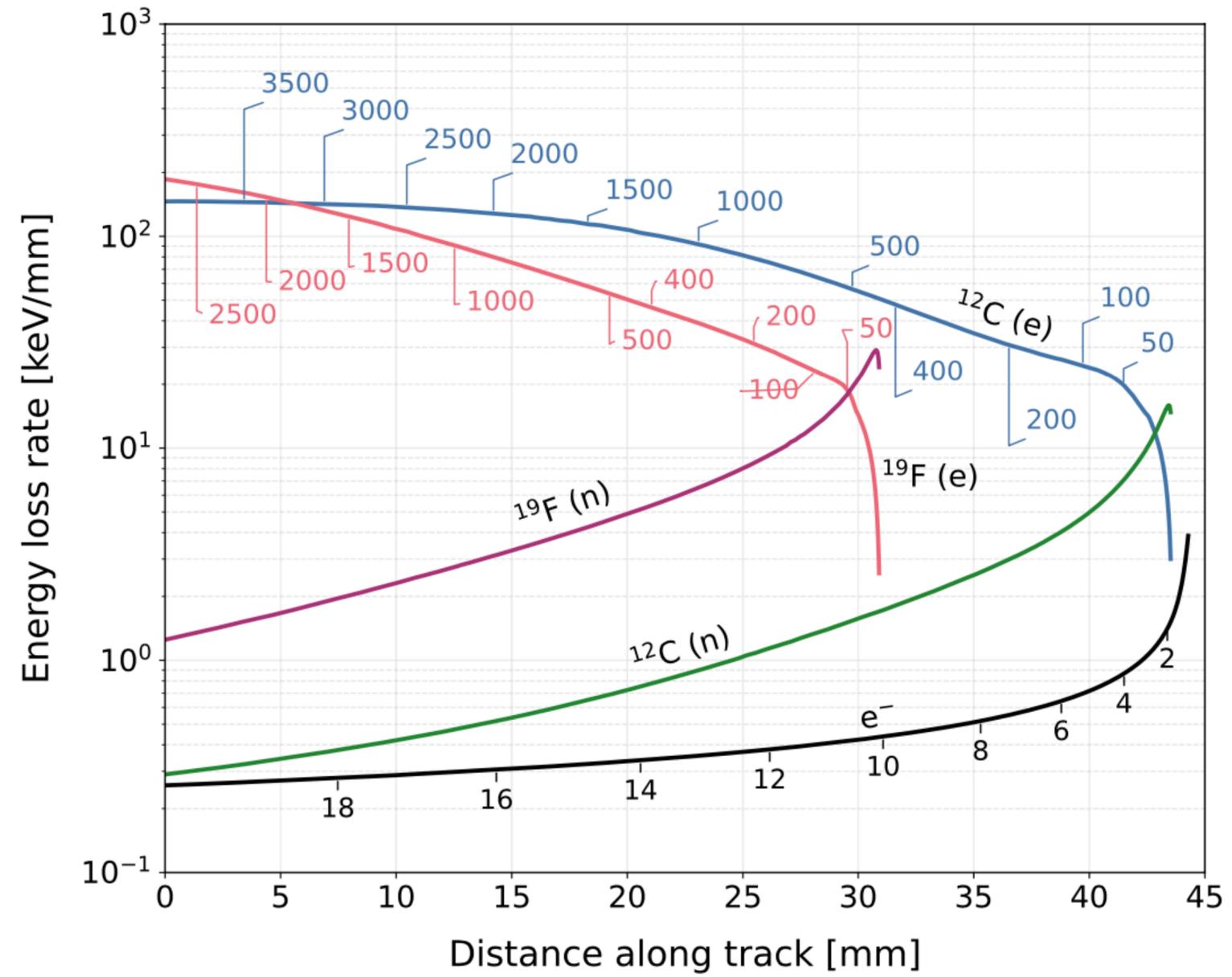


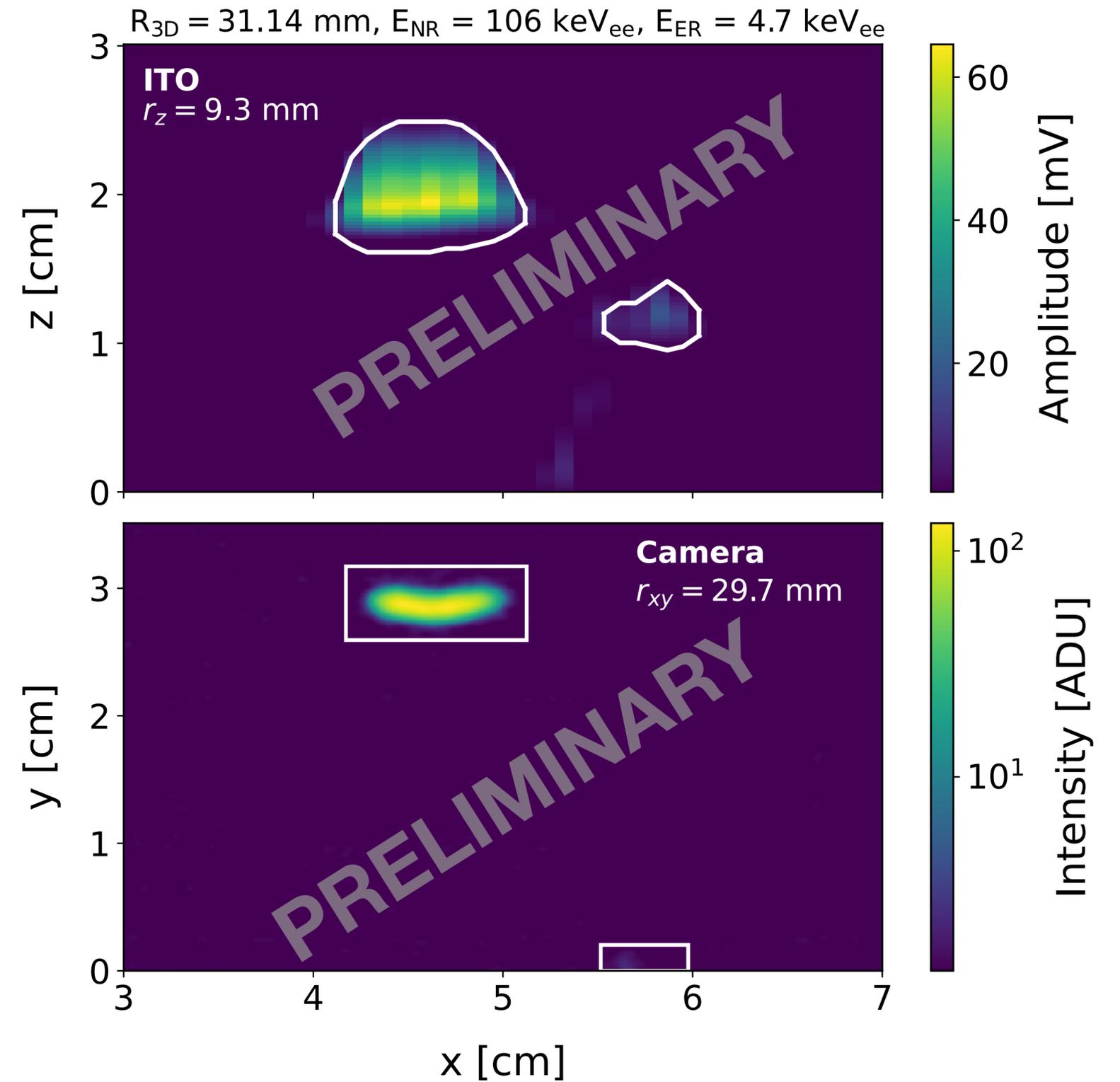
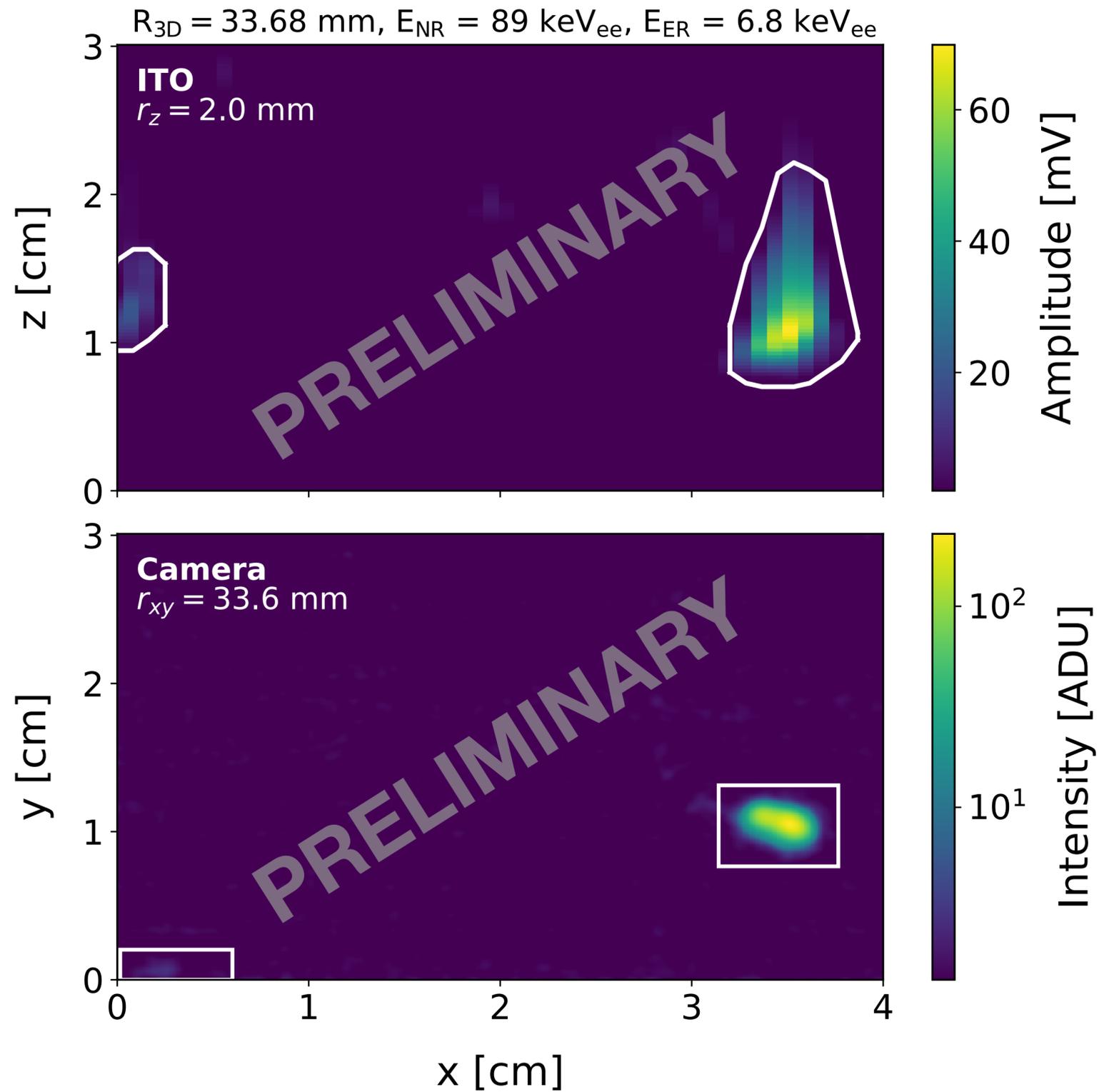
- Orca quest low noise CMOS camera
- Continuous 120 fps read-out with rolling shutter
- Synchronise offline using FPGA recorded timestamp information
- 39 μm pixel size (2x2 binning)
- EHD-25985 f/0.85 lens
- 0.43 electron RMS noise

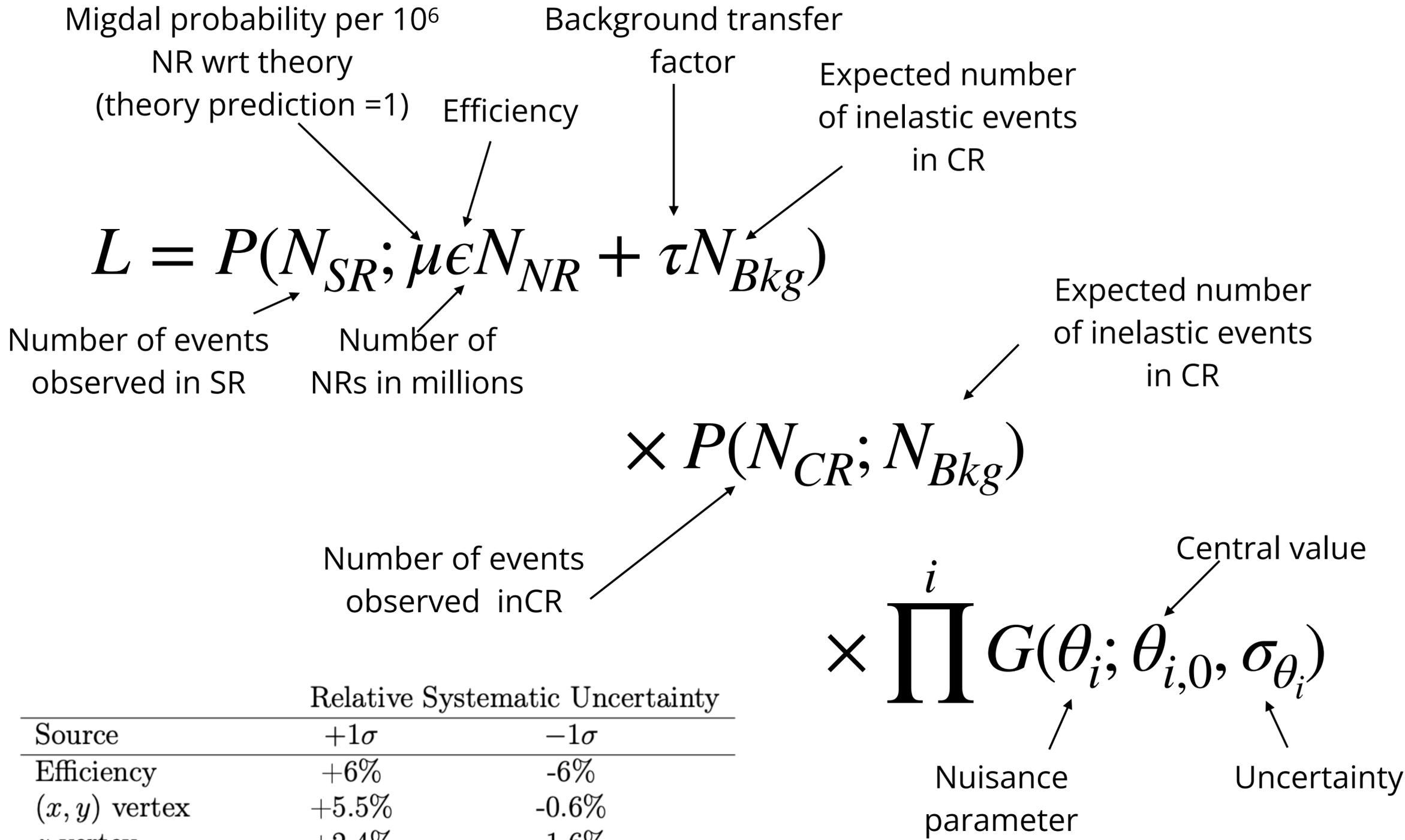
- Vignetting correction applied to account for decrease in intensity at edges of frame











Signal Region

Control Region

Nuisance Parameters

Source	Relative Systematic Uncertainty	
	+1σ	-1σ
Efficiency	+6%	-6%
(x, y) vertex	+5.5%	-0.6%
z vertex	+2.4%	-1.6%
Theory uncertainty	+20%	-20%