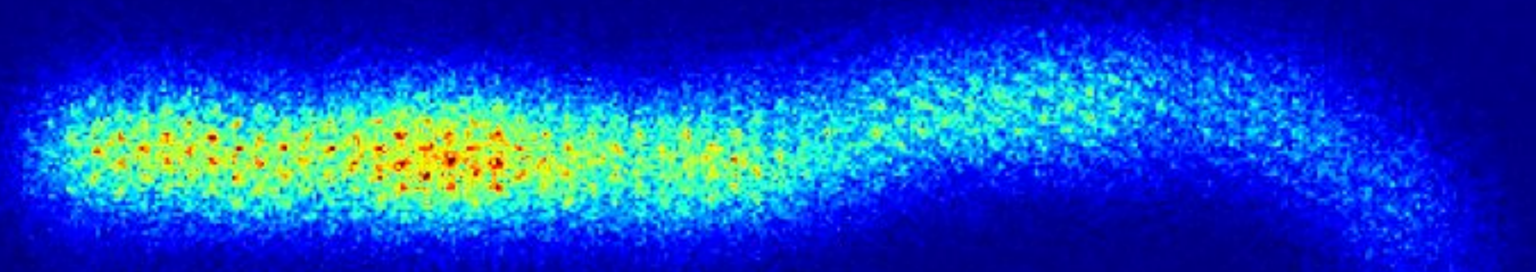
Results from the MIGDAL experiment's commissioning using fast neutrons from a D-D generator



Pawel Majewski

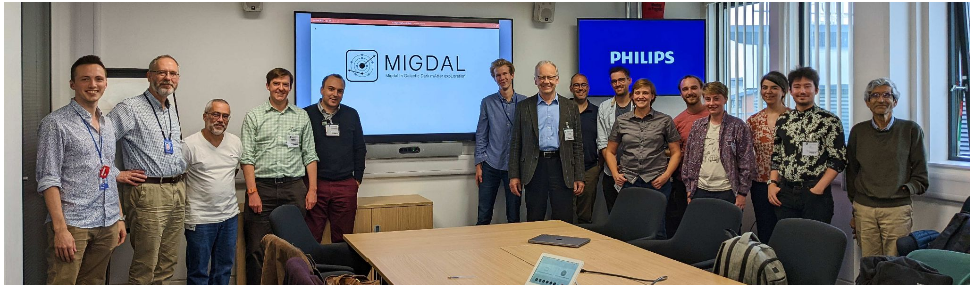
STFC/Rutherford Appleton Laboratory

on behalf of the MIGDAL collaboration

The MIGDAL Collaboration

- Over 35 physicists and engineers from 14 institutions across 6 countries
- Supported by the ISIS/NILE team
- At RAL we combine the strengths of PPD, Technology, and ISIS/NILE

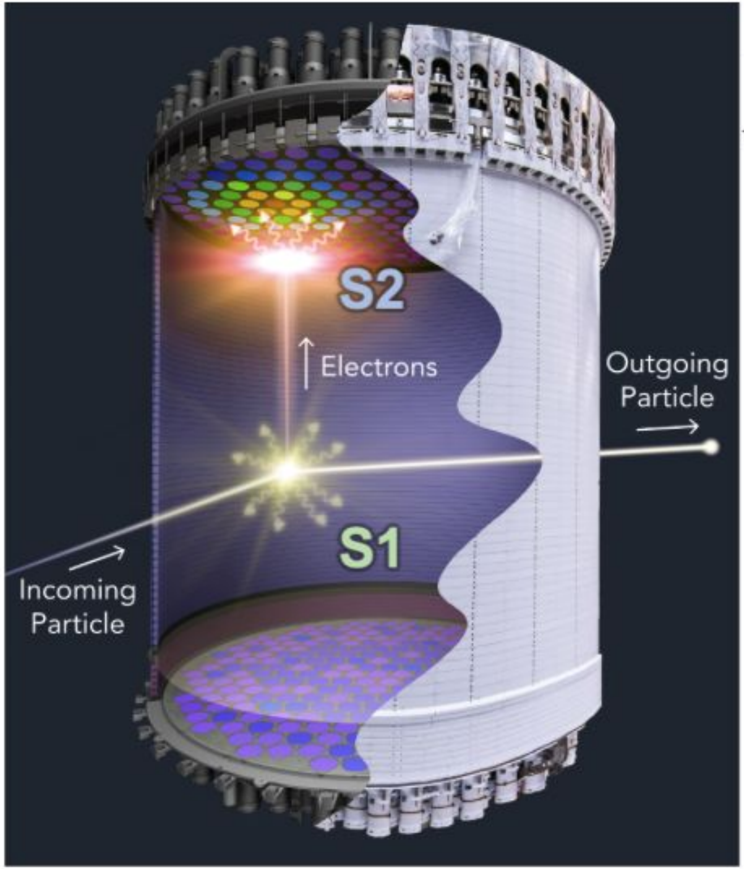
Science and Technology Facilities Council | U.S. DEPARTMENT OF ENERGY | FCT Fundação para a Ciência e a Tecnologia | Horizon 2020 European Union Funding for Research & Innovation | National Science Foundation | MARIE CURIE ACTIONS

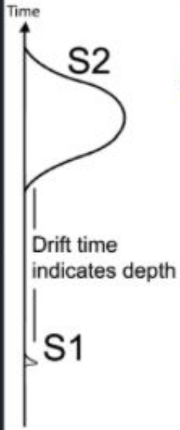


Outline

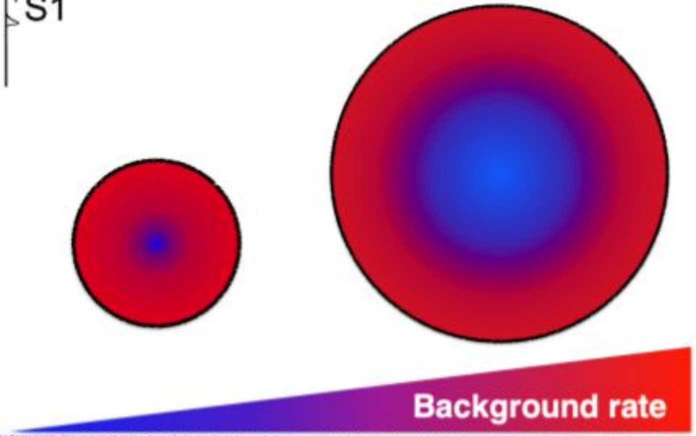
1. Migdal effect in Dark Matter searches - why it is important ?
2. Migdal effect - what do we know so far ?
3. Migdal effect in nuclear scattering and its searches in different media
4. MIGDAL experiment at NILE
5. MIGDAL's First Science Run
6. Conclusions

Dual Phase Xenon TPC



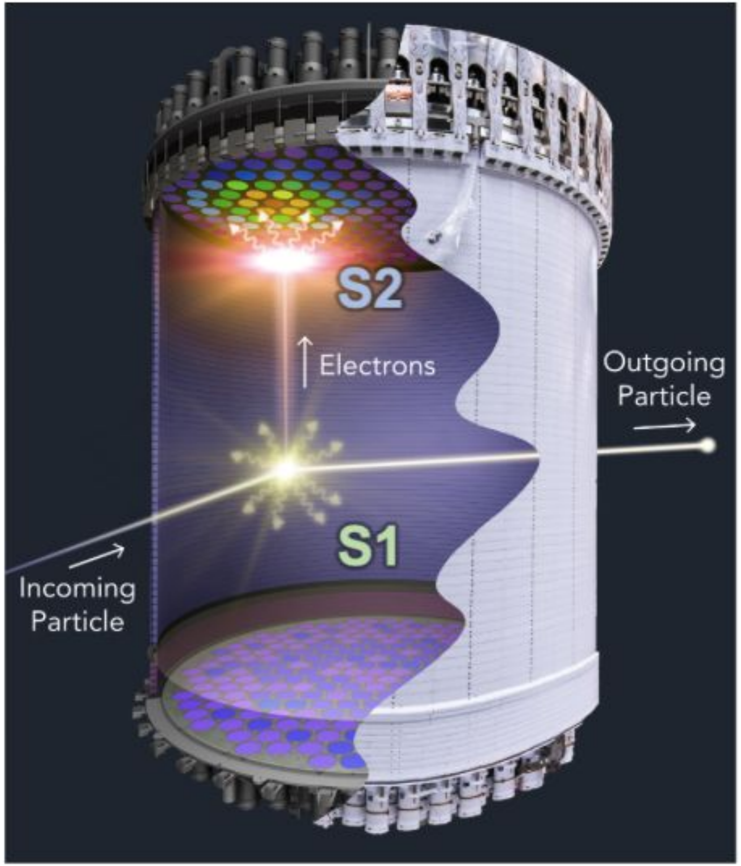


- Excellent 3D imaging capability
  - Z position from S1 - S2 timing
  - XY positions from S2 light pattern
- Xenon is easily purified
- Xenon is DENSE!

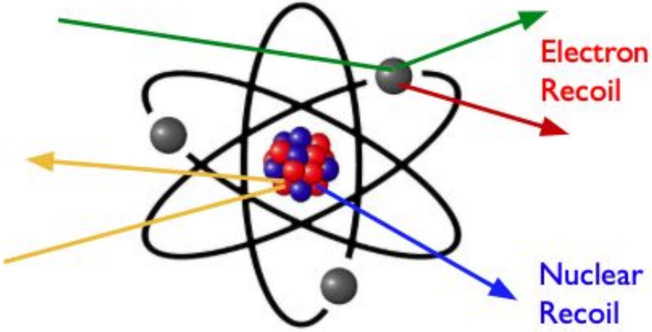


From LZ FSR
talk by H.L

Dual Phase Xenon TPC

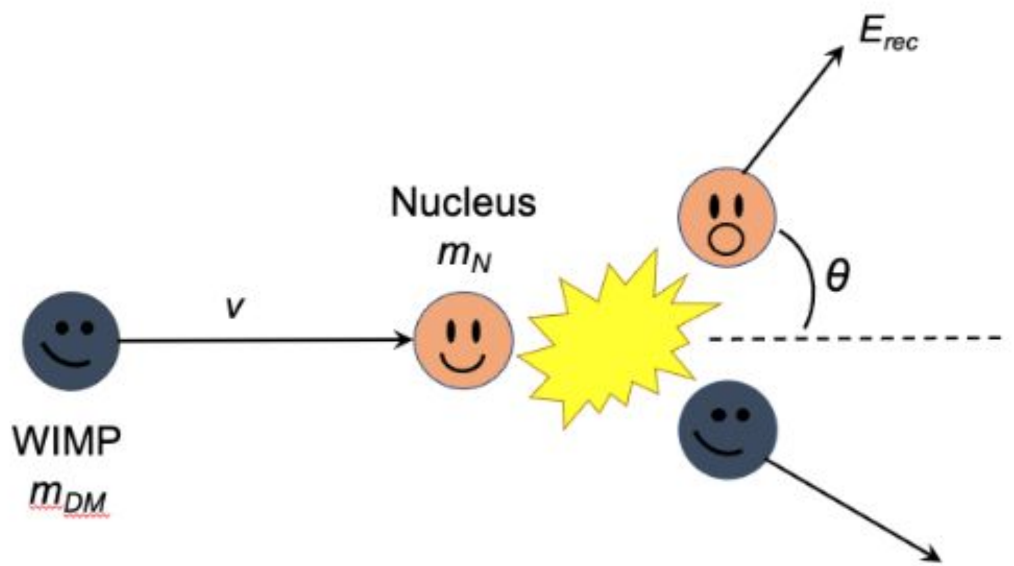


- Charge (S2) / light (S1) ratio
  => Signal vs Background discrimination



- ✦ Electrons and gammas interact with atomic electrons, produce electron recoils (ER)
- ✦ WIMPs (and neutrons) interact with Xe nuclei, produce nuclear recoils (NR)

From LZ FSR
talk by H.L



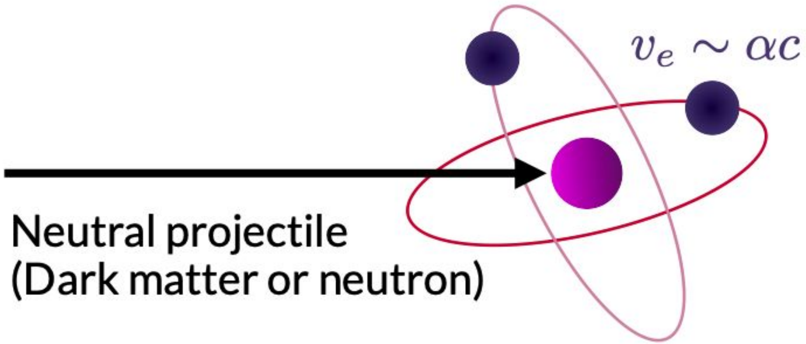
Courtesy Alissa Monte

Non-relativistic elastic scattering

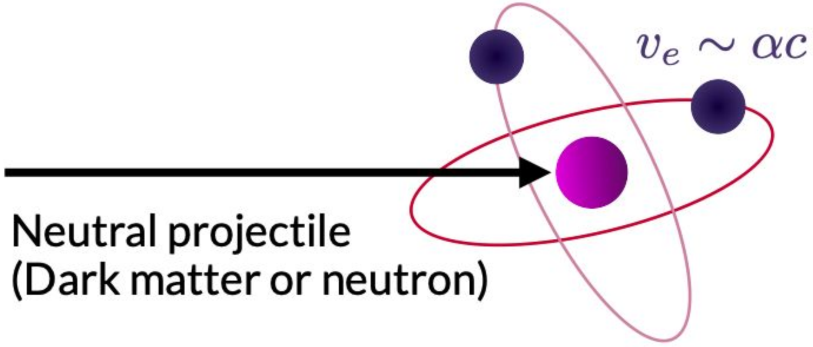
$$\mu = \frac{m_{DM} m_N}{m_{DM} + m_N}$$

$$E_{rec} = \frac{\mu^2 v^2}{m_N}(1 - cos\theta)$$

m_{DM} = 100 GeV/c²
m_N = 131 GeV/c²
v = 220 km/s
E_{rec} = 3 keV



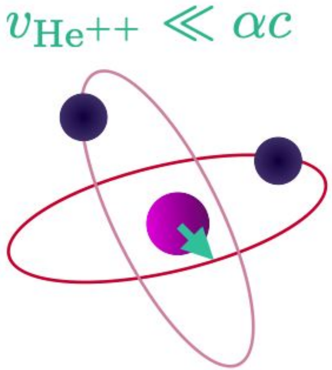
Fine-structure constant: $\alpha = 1/137$



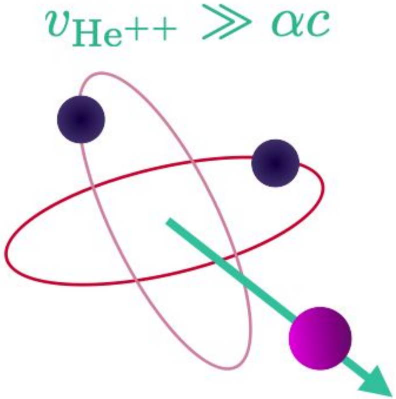
Helium atom

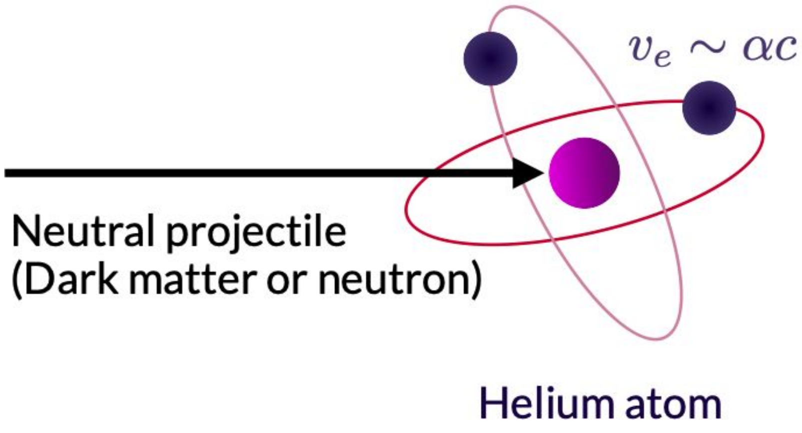
Fine-structure constant: $\alpha = 1/137$

1. Low speed recoil:
   - *remain in ground state*

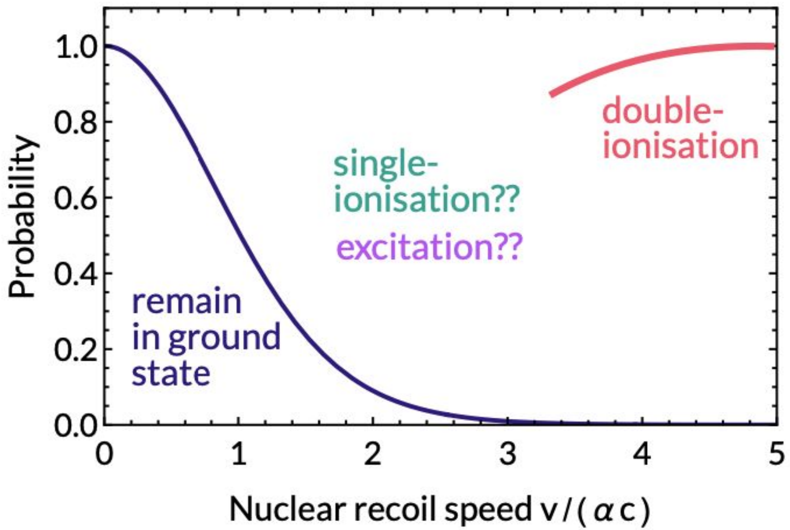


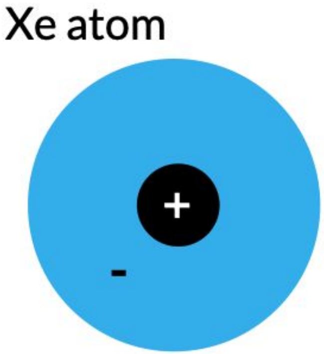
2. High speed recoil:
   - *double ionisation (electrons 'left behind')*

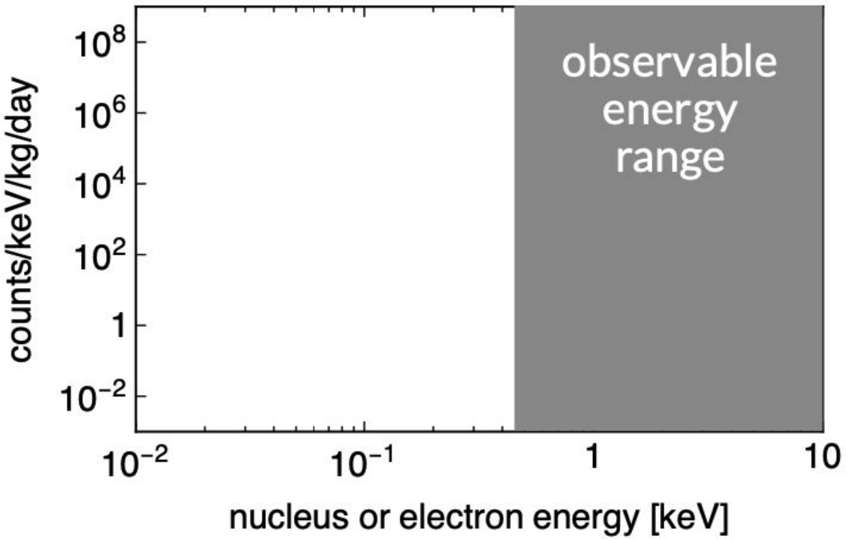


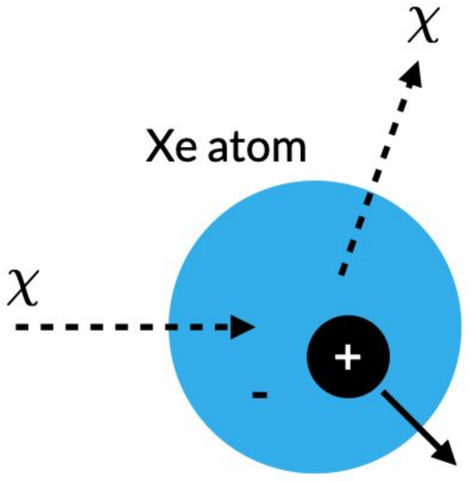


Fine-structure constant: $\alpha = 1/137$

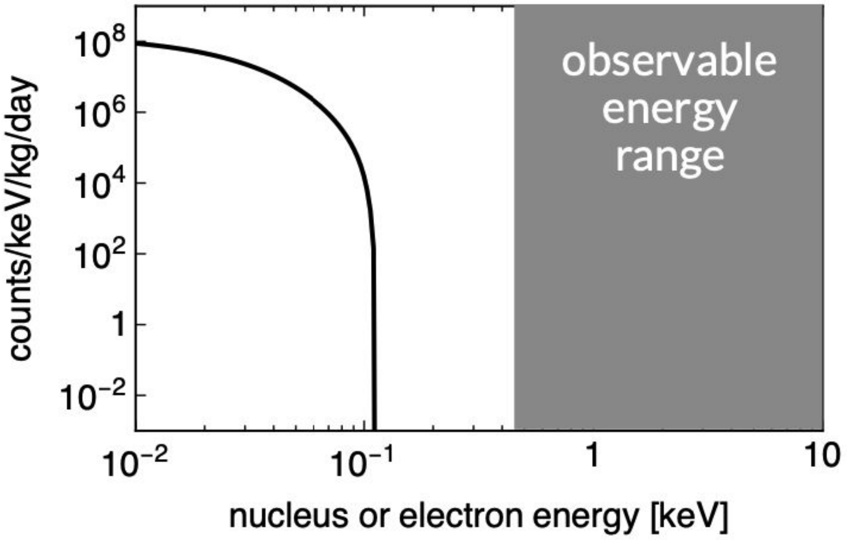


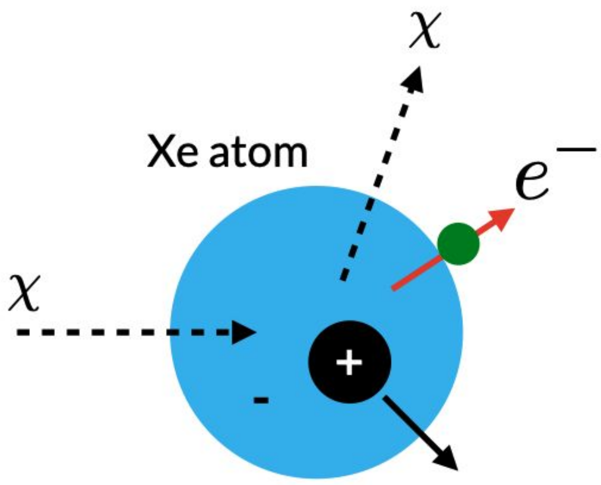

Xe atom
+
-


observable energy range
counts/keV/kg/day
10^8
10^6
10^4
10^2
1
10^{-2}
10^{-2}
10^{-1}
1
10
nucleus or electron energy [keV]

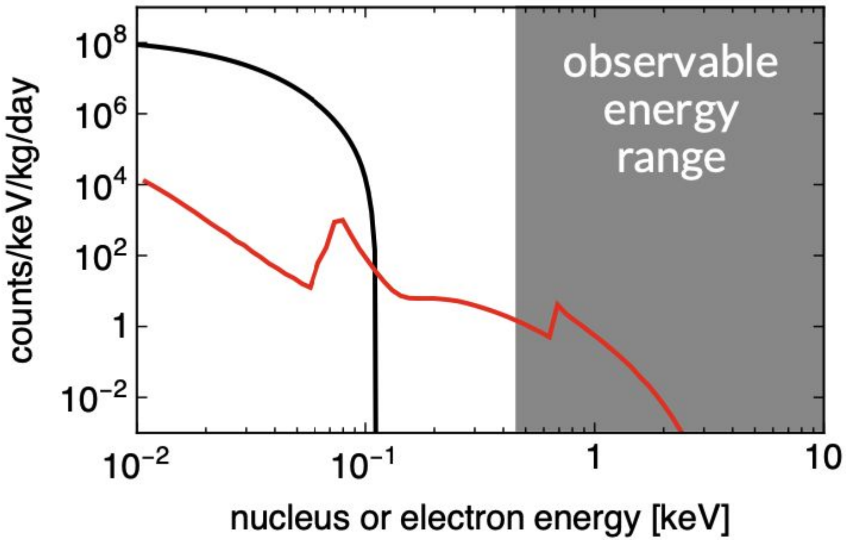


m_{DM} = 1 GeV
'Normal' nuclear scattering



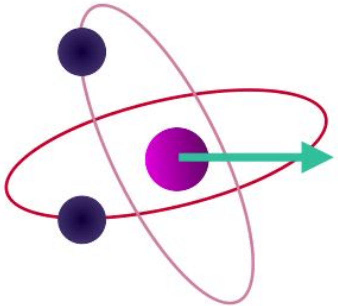


m_{DM} = 1 GeV
'Normal' nuclear scattering
+ Migdal effect (ionisation of 1 electron)



Required matrix element is given by:

$$\left\langle \Psi_f^{\{k\}} \middle| e^{im_e \mathbf{v} \cdot \sum_a \mathbf{r}_a} \middle| \Psi_i^{\{j\}} \right\rangle$$

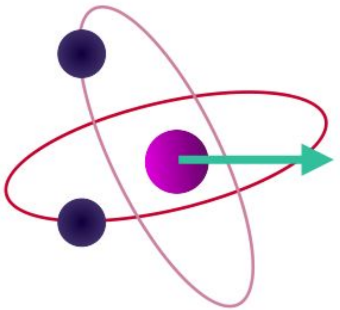


$|\Psi_i^{\{j\}}\rangle$ describes the bound atomic-electrons wavefunction

$\mathbf{v} = \mathrm{Nuclear\ recoil\ velocity}$

$|\Psi_f^{\{k\}}\rangle$ describes the final state wavefunction (excitation, ionisation, etc)

$$\left\langle \Psi_f^{\{k\}} \middle| e^{im_e \mathbf{v}\cdot\sum_a \mathbf{r}_a} \middle| \Psi_i^{\{j\}} \right\rangle$$



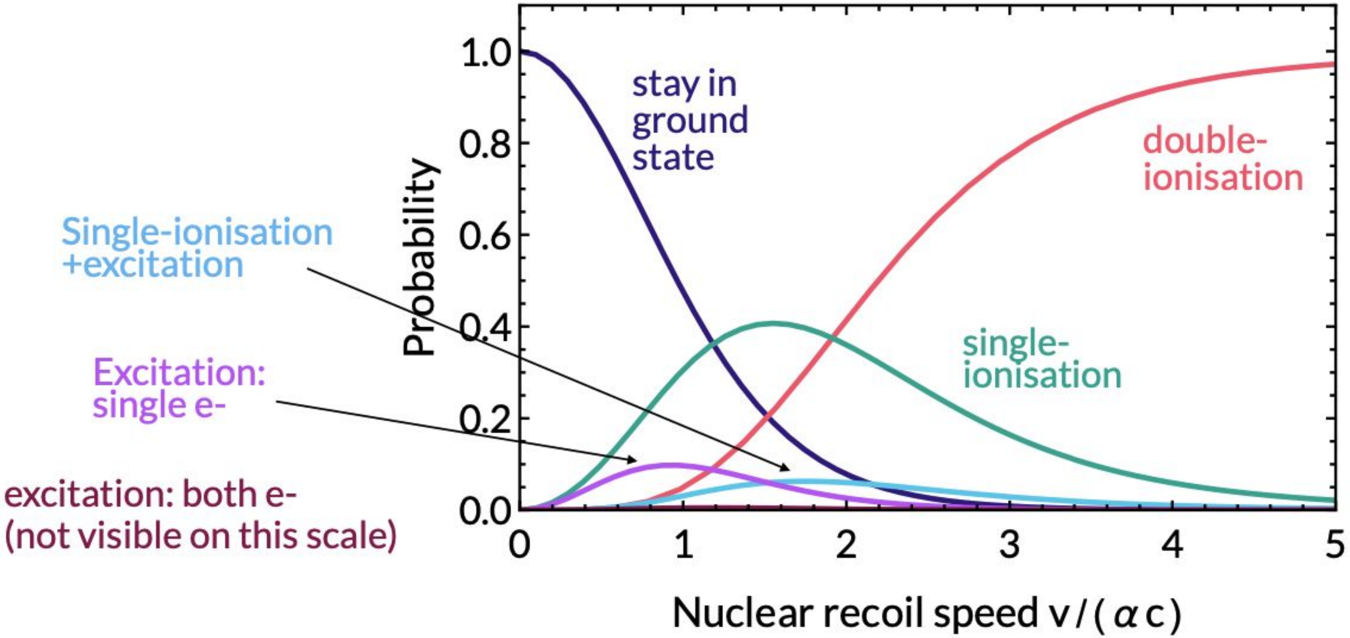
Previous calculations made the ‘dipole approximation’:

$$\exp\left(im_e\mathbf{v}\cdot\sum_{a=1}^{N}\mathbf{r}_a\right) \approx 1 + im_e\mathbf{v}\cdot\sum_{a=1}^{N}\mathbf{r}_a$$

Unclear if dipole approximation holds for neutron scattering processes (high **v**) — and only allows for single ionisation processes to be accounted for

We keep the full exponential factor (sounds easy but lots of extra work!)

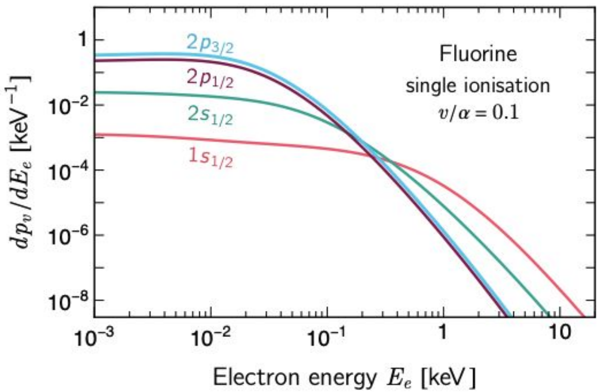
Cox, Dolan, CM, Quiney, arXiv:2208.12222

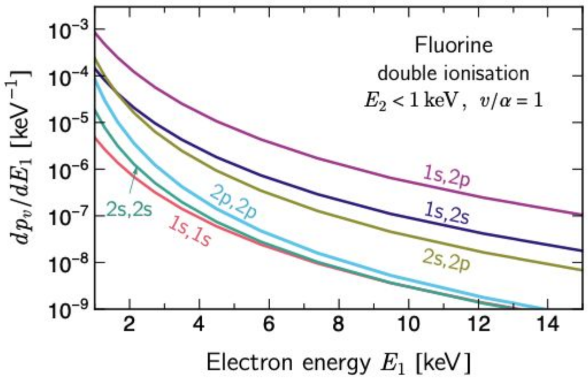


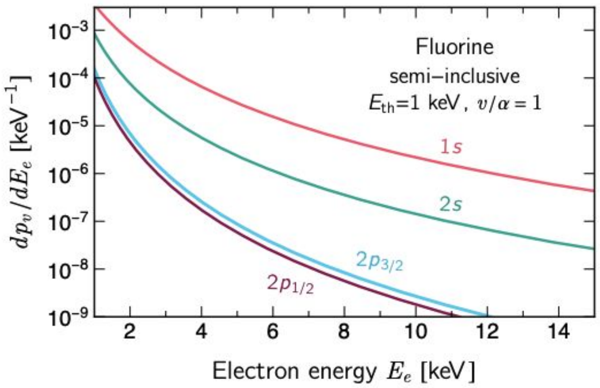
Previous calculations could only give the single-ionisation curve for $v/\alpha \ll 1$

Most likely configuration for single-ionisation:
Hard electron from inner-shell
Soft-electron from valence-shell

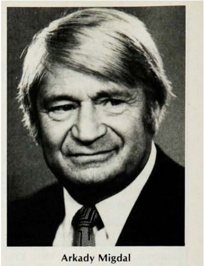
Most likely configuration for ionisation scenario with 1 hard- and soft-electrons:
Hard-electron from inner-shell with soft-electron from valence-shell

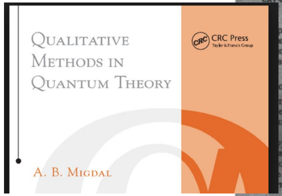


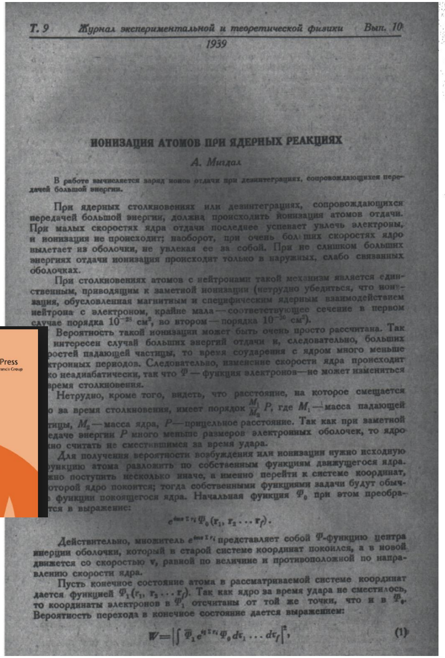




What do we already know about the Migdal effect ?



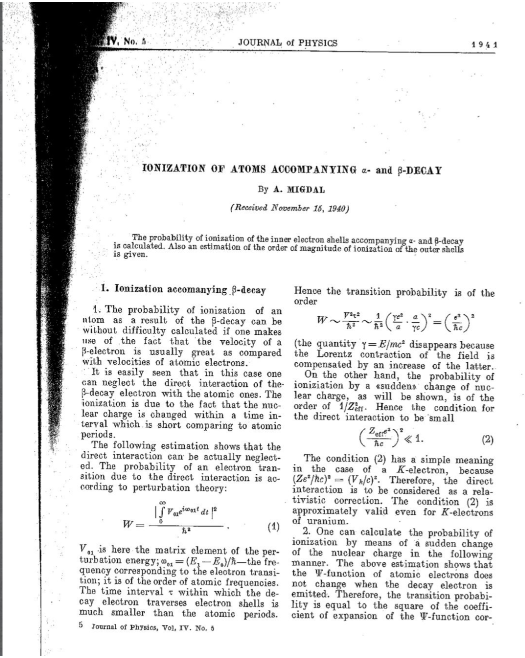




Т. 9 Журнал экспериментальной и теоретической физики Вып. 10
1939

ИОНИЗАЦИЯ АТОМОВ ПРИ ЯДЕРНЫХ РЕАКЦИЯХ

А. Мигдал



IV, No. 5 JOURNAL of PHYSICS 1941

IONIZATION OF ATOMS ACCOMPANYING α- and β-DECAY

By A. MIGDAL

(Received November 15, 1940)

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

1. Ionization accompanying β-decay

1. The probability of ionization of an atom as a result of the β-decay can be without difficulty calculated if one makes use of the fact that the velocity of a β-electron is usually great as compared with velocities of atomic electrons.

It is easily seen that in this case one can neglect the direct interaction of the β-electron with the atomic ones. The ionization is due to the fact that the nuclear charge is changed within a time interval which is short comparing to atomic periods.

The following estimation shows that the direct interaction can be actually neglected. The probability of an electron transition due to the direct interaction is according to perturbation theory:

$$W = \frac{\left|\int_0^\infty V_{01} e^{i\omega_{01} t}\, dt\right|^2}{\hbar^2}. \quad (1)$$

V_{01} is here the matrix element of the perturbation energy; $\omega_{01} = (E_1 - E_0)/\hbar$ — the frequency corresponding to the electron transition; it is of the order of atomic frequencies. The time interval τ within which the decay electron traverses electron shells is much smaller than the atomic periods.

5 Journal of Physics, Vol. IV. No. 5

Hence the transition probability is of the order

$$W \sim \frac{V^2 \tau^2}{\hbar^2} \sim \frac{1}{\hbar^2}\left(\frac{\gamma e^2}{a}\cdot\frac{a}{\gamma c}\right)^2 = \left(\frac{e^2}{\hbar c}\right)^2$$

(the quantity $\gamma = E/mc^2$ disappears because the Lorentz contraction of the field is compensated by an increase of the latter.

On the other hand, the probability of ionization by a «sudden» change of nuclear charge, as will be shown, is of the order of $1/Z^2_{eff}$. Hence the condition for the direct interaction to be small

$$\left(\frac{Z_{eff}e^2}{\hbar c}\right)^2 \ll 1. \quad (2)$$

The condition (2) has a simple meaning in the case of a K-electron, because $(Ze^2/\hbar c)^2 = (V_k/c)^2$. Therefore, the direct interaction is to be considered as a relativistic correction. The condition (2) is approximately valid even for K-electrons of uranium.

2. One can calculate the probability of ionization by means of a sudden change of the nuclear charge in the following manner. The above estimation shows that the Ψ-function of atomic electrons does not change when the decay electron is emitted. Therefore, the transition probability is equal to the square of the coefficient of expansion of the Ψ-function cor-

A. Migdal publications:

- Ionisation in nuclear reactions [1]
- Ionisation in radioactive decays [2]

First observations of the Migdal effect in :

- Alpha decay [3,4]
- Beta decay [5]
- Positron decay [6]
- Nuclear scattering [ ]

[1] A. Migdal *Ionizatsiya atomov pri yadernykh reaktsiyakh, ZhETF, 9, 1163-1165 (1939)*
[2] A. Migdal *Ionizatsiya atomov pri α- i β- raspade, ZhETF, 11, 207-212 (1941)*
[3] M.S. Rapaport, F. Asaro and I. Pearlman *K-shell electron shake-off accompanying alpha decay, PRC 11, 1740-1745 (1975)*
[4] M.S. Rapaport, F. Asaro and I. Pearlman *L- and M-shell electron shake-off accompanying alpha decay, PRC 11, 1746-1754 (1975)* [5] C. Couratin et al. , *First Measurement of Pure Electron Shakeoff in the β Decay of Trapped $^6He^+$ Ions, PRL 108, 243201 (2012)* [6] X. Fabian et al., *Electron Shakeoff following the β^+ decay of Trapped $^{19}Ne^+$ and $^{35}Ar^+$ trapped ions, PRA, 97, 023402 (2018)*

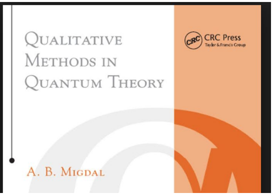
What do we already know about the Migdal effect ?

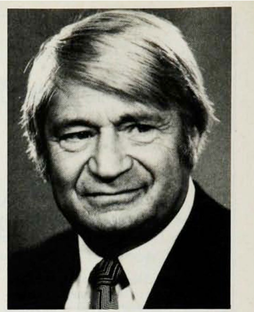
- Observation of the Migdal effect in α decay
    - Measured in ^{210}Po and ^{238}Pu decays measuring α particles in coincidence with X-rays emitted from K, $L_{I,II,III}$ and M-shell due to electron shake-off effect (emission of Migdal electron)
- Observation of the Migdal effect in β and β+ decay
    - Measured in $^{6}He^{+}$ (β- decay) and also in $^{19}Ne^{+}$ and $^{35}Ar^{+}$ (β+ decay) using an ion trap coupled to a TOF recoil-ion spectrometer detecting recoils of $^{6}Li^{2+}$ and also $^{19}F^{q+}$ and $^{35}Cl^{q+}$

None of the experiments was actually observing Migdal electrons.

- Migdal effect in nuclear scattering
    - Extremely challenging and awaiting for its first observation

What do we already know about the Migdal effect ?




Arkady Migdal

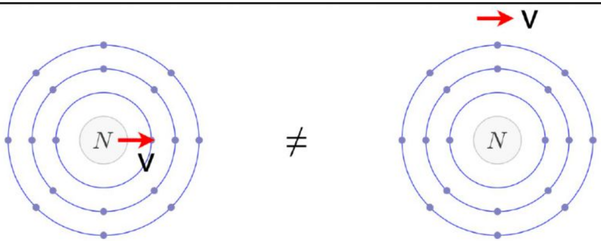
Ionization of an Atom in Nuclear Reactions

In nuclear collisions involving large energy transfer there must occur ionization of the recoil atoms. If the velocity acquired by the nucleus is not too large, then it can carry its electrons off with it, and ionization takes place only in the outer, weakly bound shells. For large velocities, on the other hand, the nucleus recoils right out of its electronic shells instead of carrying them with it.

We shall calculate the probability of ionization when a neutron collides with the nucleus (Migdal 1939). The duration of the neutron-nucleus collision is of order $\tau \sim R/v$, where R is the nuclear radius and v the neutron velocity. This time is much less than the electronic periods τ_{el}, so that the electron wave function is practically unchanged over the duration of the collision.

A.B. Migdal
"Qualitative Methods in Quantum Theory"
Advanced Book Classics CRC Press, 2000

Conventionally the recoiling nucleus is treated as a recoiling neutral atom however as described by Migdal in reality it takes some time for the electrons to catch up … and this may lead to atomic ionisation !



A long time ago, Migdal (1941, 1977) gave a rather simple formula for this ionisation probability. The transition probability P_i from an initial electron state i to a final electron state f is given by

$$P_i = |\langle\varphi_f(\mathbf{r})|\ \exp[\mathrm{i}(m_e/\hbar)\mathbf{v}_f \cdot \mathbf{r}]|\varphi_i(\mathbf{r})\rangle|^2$$

G. Baur, F. Rosel and D. Trautmann
"Ionisation induced by neutrons"
J. Phys. B: At Mol. Phys. 16 (1983) L419-L423

PROBLEM 2. The nucleus of an atom in the normal state receives an impulse which gives it a velocity v; the duration τ of the impulse is assumed short in comparison both with the electron periods and with a/v, where a is the dimension of the atom. Determine the probability of excitation of the atom under the influence of such a "jolt" (A. B. MIGDAL 1939).

L. Landau and E. Lifshitz
"Quantum Mechanics : Non-relativistic Theory"
Volume 3

Huge attention of the DM community to the Migdal Effect

JHEP
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ACCEPTED: March 8, 2018
PUBLISHED: March 30, 2018

Migdal effect in dark matter direct detection experiments

Masahiro Ibe,[a,b] Wakutaka Nakano,[a] Yutaro Shoji[a] and Kazumine Suzuki[a]
[a] *ICRR, The University of Tokyo, Kashiwa, Chiba 277-8582, Japan*
[b] *Kavli IPMU (WPI), UTIAS, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan*
E-mail: ibe@icrr.u-tokyo.ac.jp, m156077@icrr.u-tokyo.ac.jp, yshoji@icrr.u-tokyo.ac.jp, ksuzuki@icrr.u-tokyo.ac.jp

So far ~ 200 citations of the Ibe's paper.

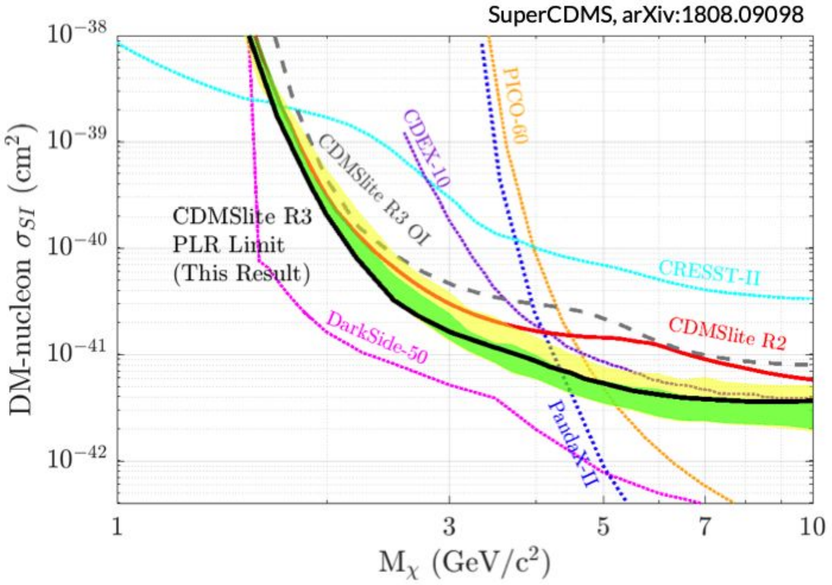
Migdal effect calculations reformulated by M. Ibe et al. with ionisation probabilities for atoms and recoil energies relevant to Dark Matter searches.

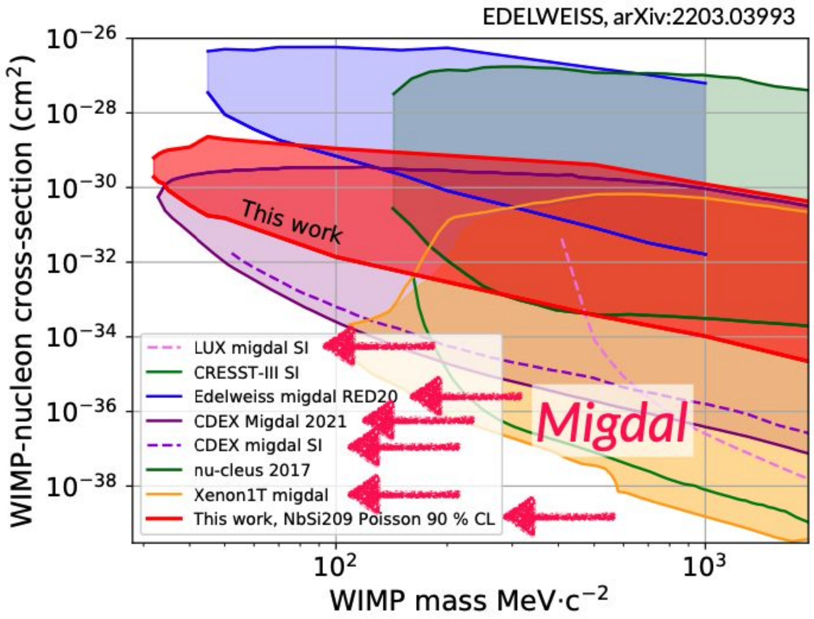
Papers in the past from: LUX, XENON1T, EDELWEISS,CDEX-1B, SENSEI

Including targets:

Ge, Si, Xe and Ar

and claiming sensitivity to WIMPs with mass below 1 GeV



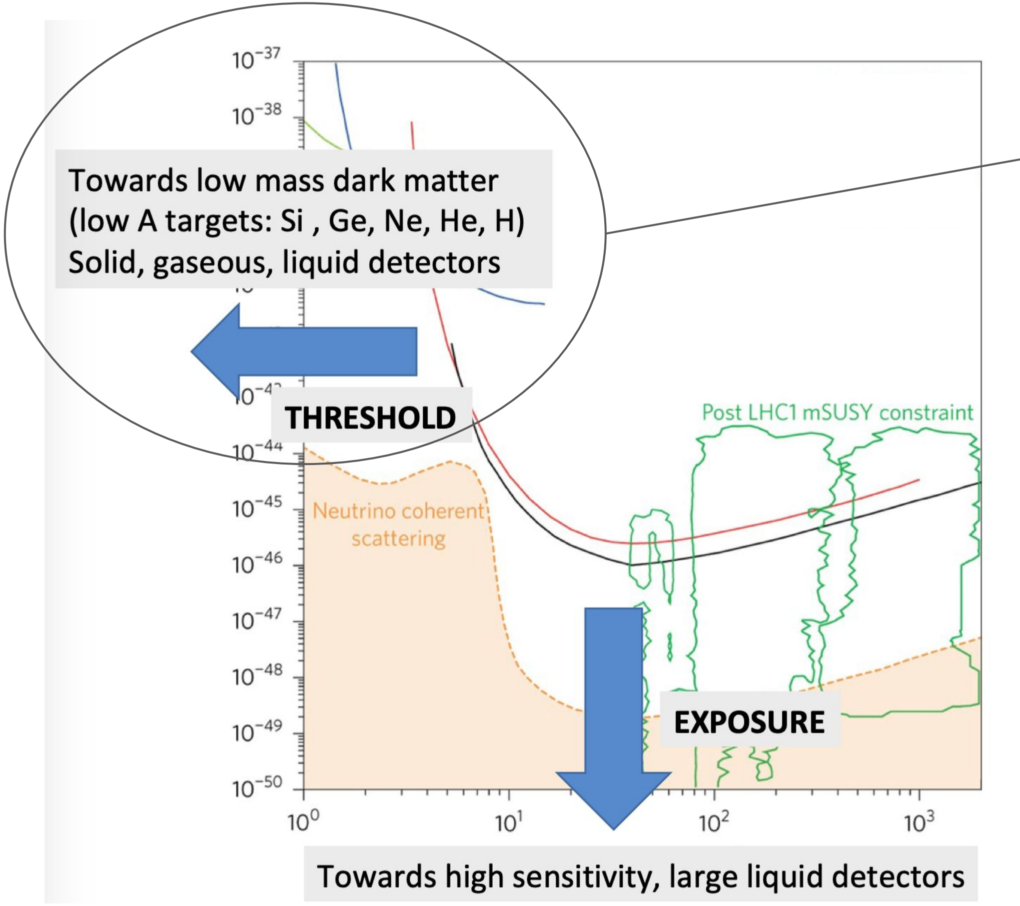


Pre-2018
No Migdal limits

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

Today
Dominated by Migdal

Why Migdal effect matters in DM searches ?



Parameter space reachable exclusively by the detectors with a low mass target material

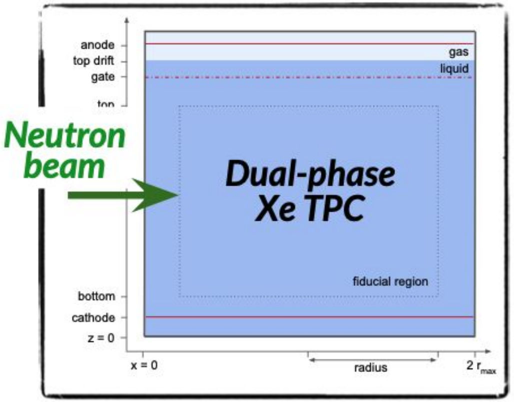
BUT not any longer

if the Migdal experimentally is confirmed in elements such as Xe and Ar

and as a bonus it comes for free !

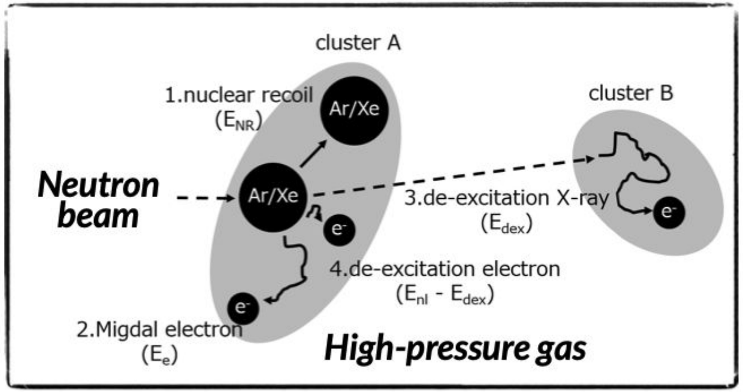
Ionisation electrons treated so far as background can contribute to subthreshold signal from the low mass dark matter particles making them detectable.

Bell et al, arXiv:2112.08514



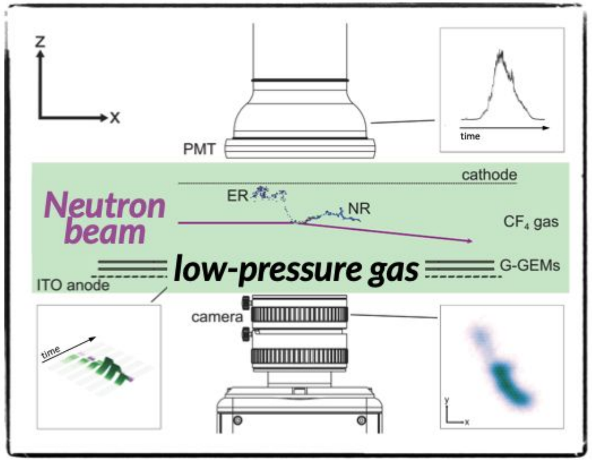
$E_{\mathrm{neutron}} \sim 15$ keV

Nakamura et al, arXiv:2009.05939



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

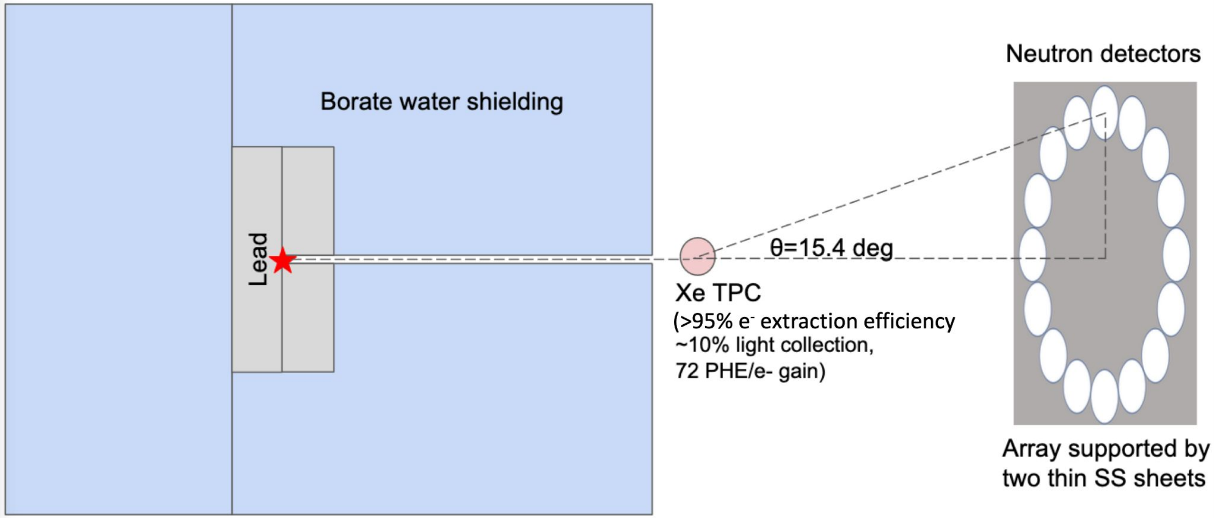
Araújo et al (MIGDAL), arXiv:2207.08284

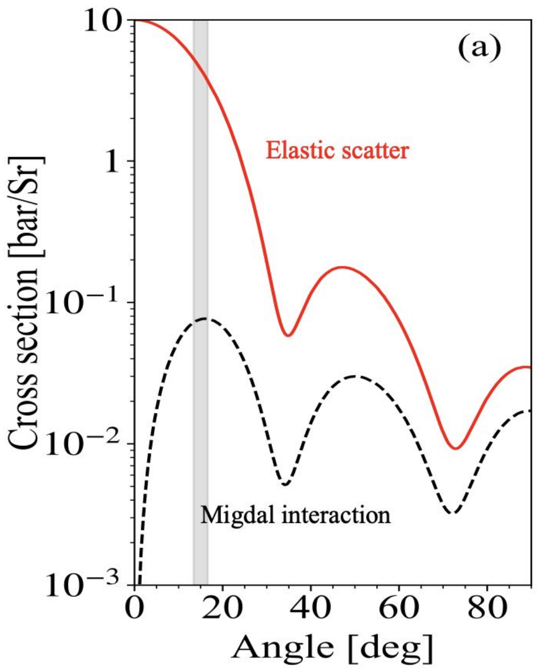


$E_{\mathrm{neutron}} \sim 2500 - 15000$ keV

Experimental search for the Migdal effect with keV-level xenon nuclear recoils at LLNL

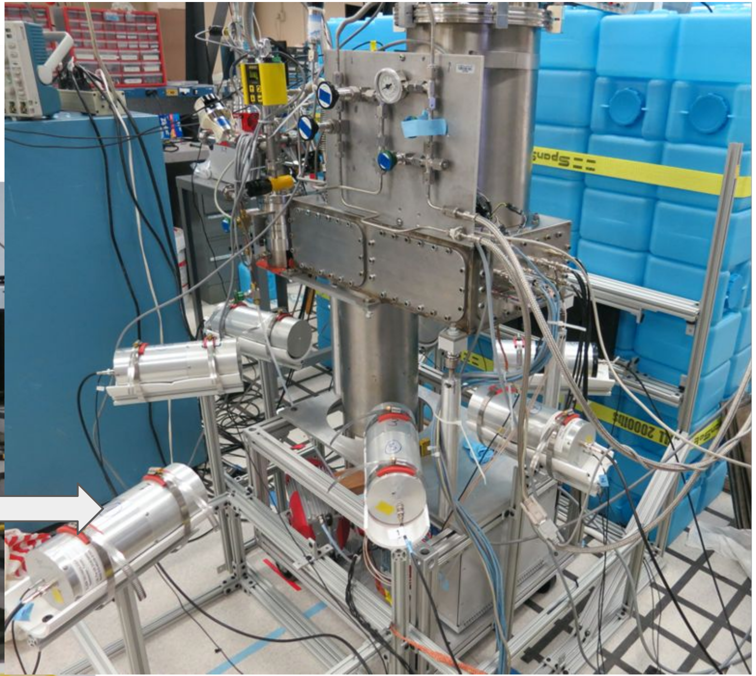
- **High energy neutrons (14.1 MeV):** enhance Migdal cross section, reduce neutron multi-scatter (NMS)
- **Tag scattered neutrons:** obtain interaction time, reduce background with neutron time of flight (TOF)
- **Quasi-mono-energetic NR:** reduce signal rate uncertainties from nuclear cross section and efficiency
- **Low scatter angle:** reduce NR energy, separate Migdal events from pure NRs



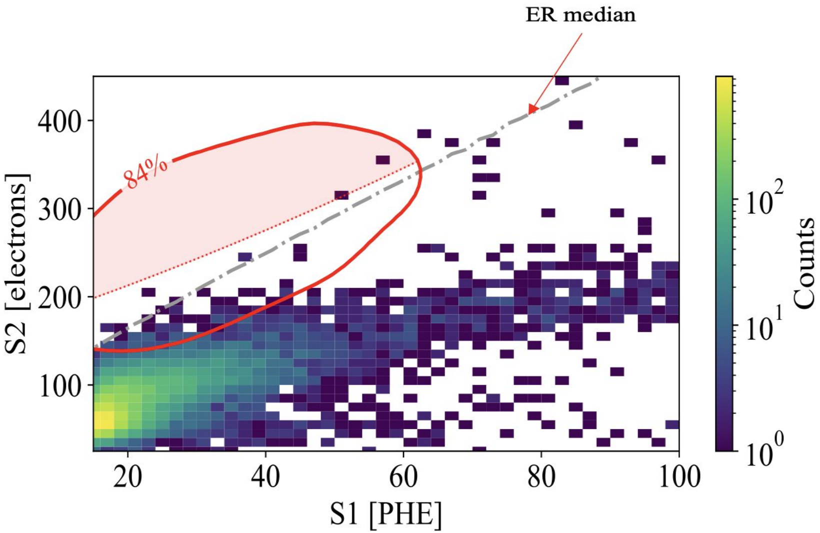


Experimental search for the Migdal effect with keV-level xenon nuclear recoils at LLNL

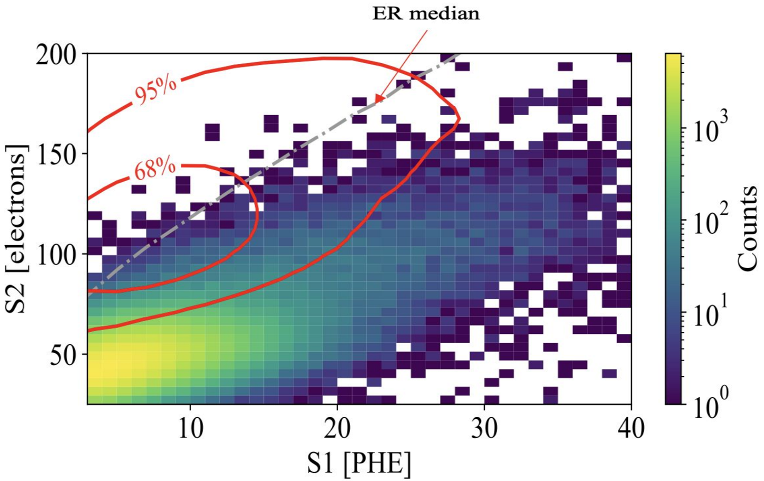
Experimental setup at LLNL



Experimental search for the Migdal effect with keV-level xenon nuclear recoils at LLNL



Data set used for the L-shell Migdal interaction (E_{ER}>0.5keV) search



Data set used for the M-shell Migdal interaction (E_{ER}>0.5keV) search

5.7+/-1.2 signals expected

2 events observed

2.1+/0.9 backgrounds expected

~10 times fewer Migdal events estimated by fit than prediction, statistically consistent with 0 signals

Two cluster event topology to find the Migdal effect

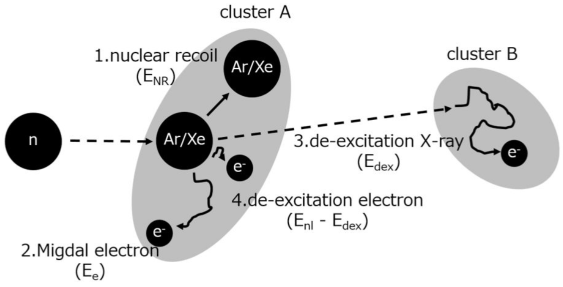


Fig. 1 Shcematis mechanism of the reactions related to the Migdal effect.

Emitted Migdal electron creates a vacancy which triggers EL de-excitation emitting characteristic X-rays and Auger Electrons. Good in heavier atoms like Ar and Xe with multiple electron shells.

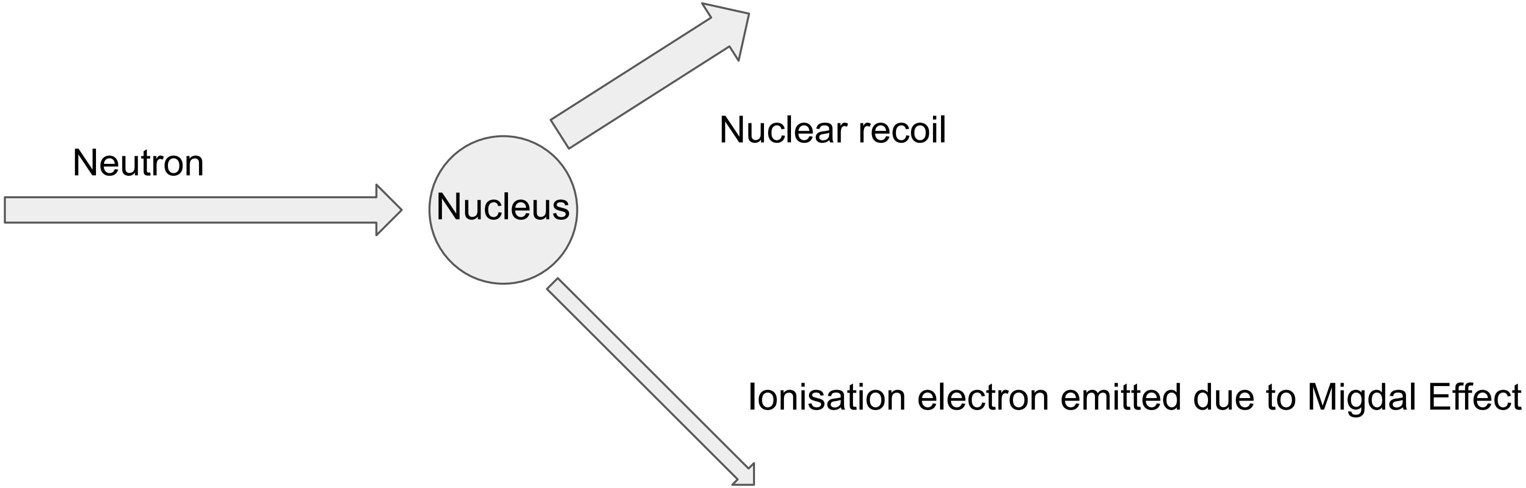
<u>Two spatially separated clusters:</u>

A - from NR, Migdal electron, Auger electrons
B - from characteristic X-ray with well defined, fixed energy
Distance between clusters : 2.95 and 2.19 cm for Ar and Xe

- Experiment is focused on the reaction associated with the emission of the characteristic X-rays
- Electric signal can be spatially separated from NR with a choice of gas and pressure
- Requires TPC with good energy resolution and segmented charge (or light) readout.

Experimental Goal of MIGDAL

Observation of two simultaneously created tracks of the ionisation electron and the nuclear recoil originating from the same vertex



We propose first observation of the Migdal effect with detection of the Migdal electrons.

ER and NR tracks in 50 Torr CF_4

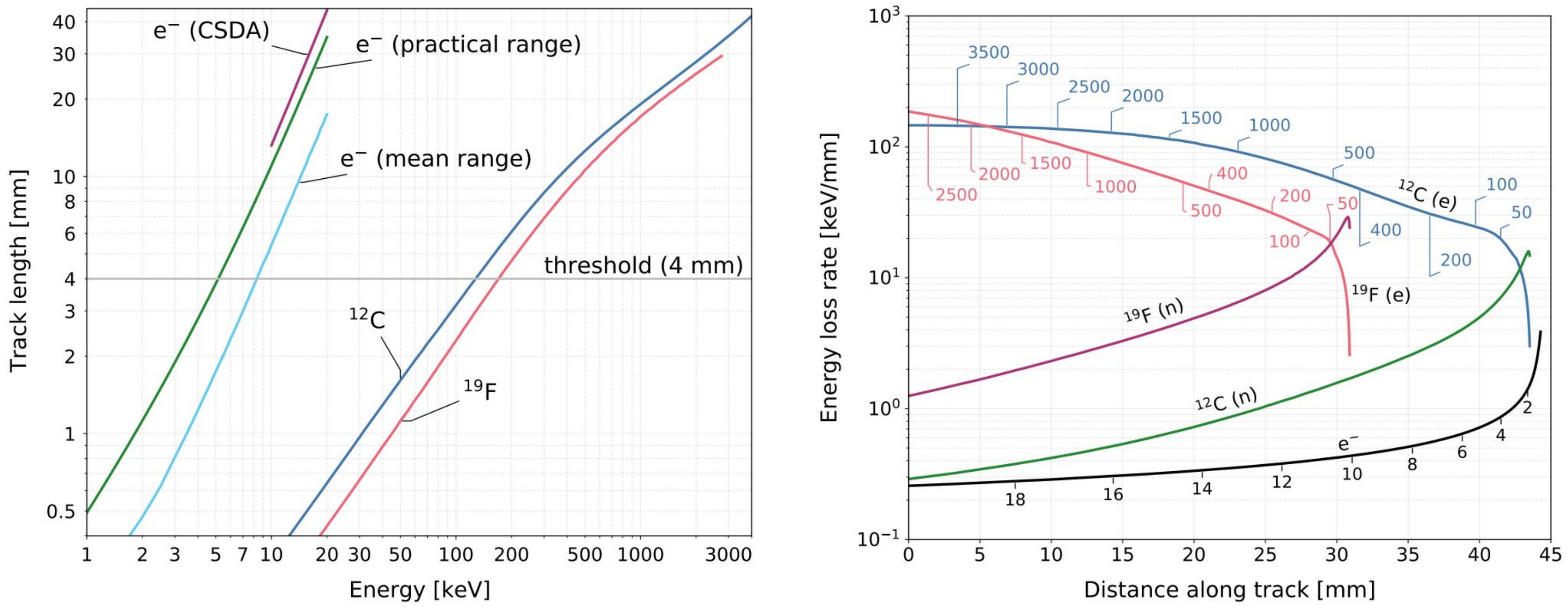


Figure 2: Left – Track length in CF_4 at 50 Torr for electrons (mean projected range calculated with Degrad [48], CSDA range with ESTAR [51], and the practical range formula from Ref. [52]), and mean projected range for carbon and fluorine ions from SRIM [49]). Right – Electronic and nuclear energy loss rates (CSDA) along carbon and fluorine ion tracks in CF_4 at 50 Torr, calculated with SRIM and electronic energy loss for 20 keV electrons obtained with ESTAR; called out values are interim particle energies (in keV) remaining at that point in the track.

Electron transport in 50 Torr CF_4

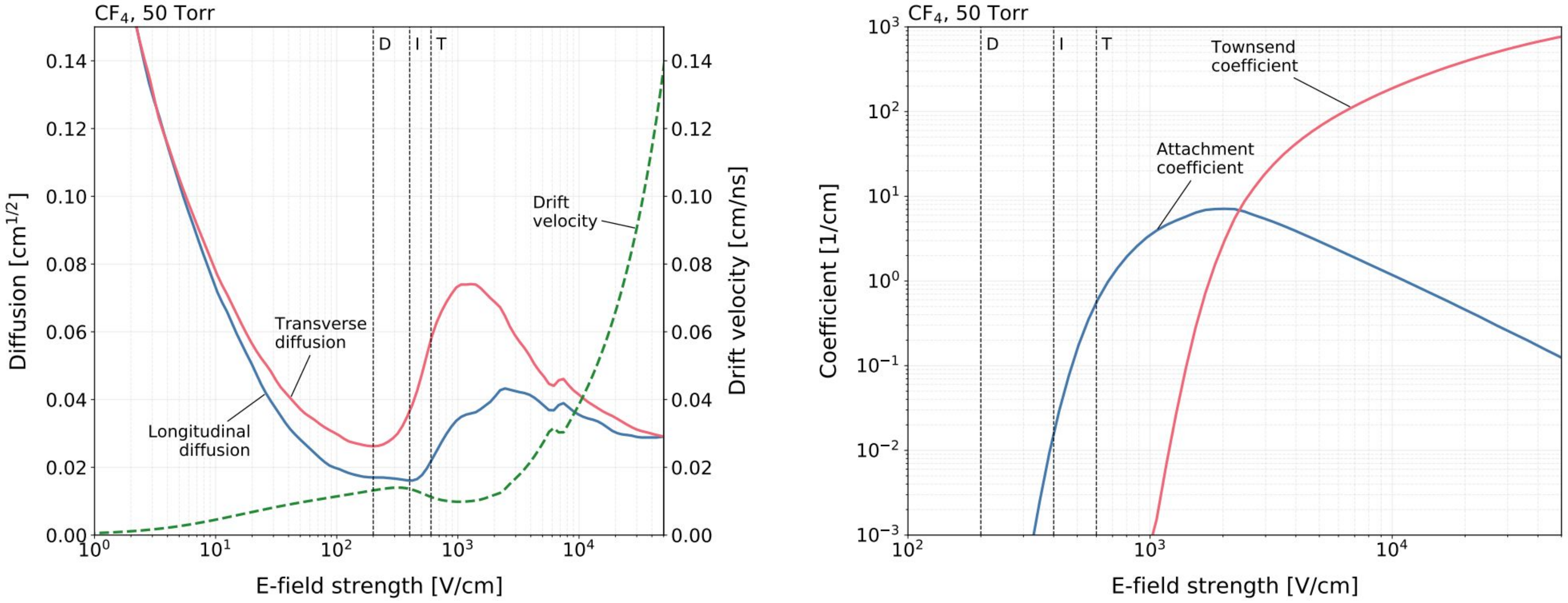
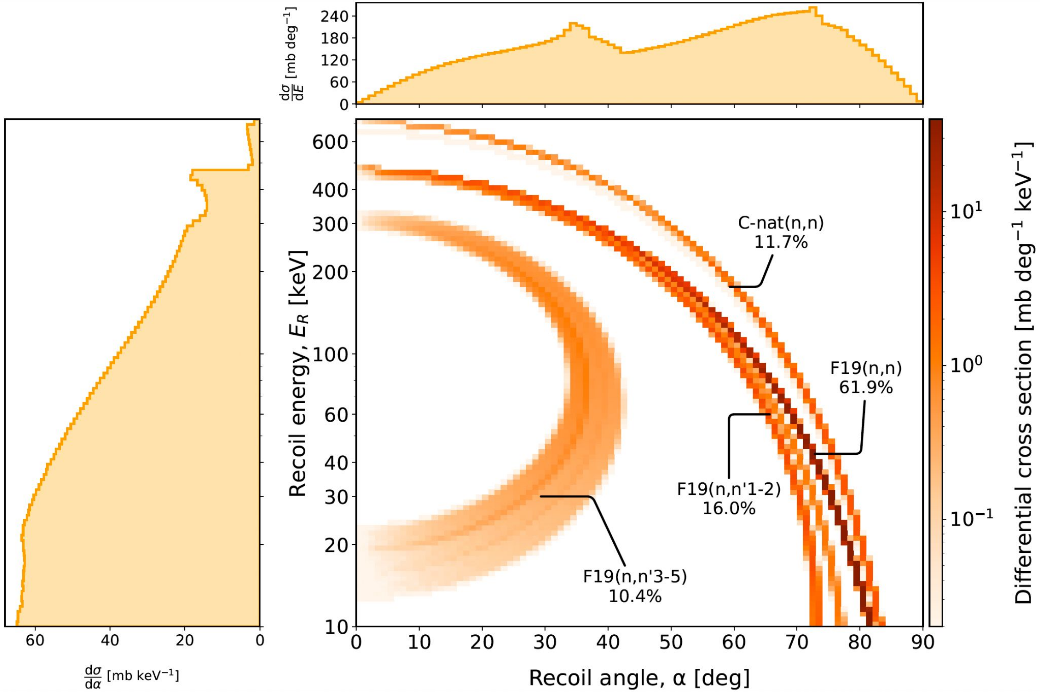


Figure 17: Electron transport properties of CF_4 at 50 Torr. Left – Drift velocity and diffusion. Right – Attachment and Townsend coefficients. Nominal fields in the drift (D), transfer (T) and induction (I) regions are indicated.

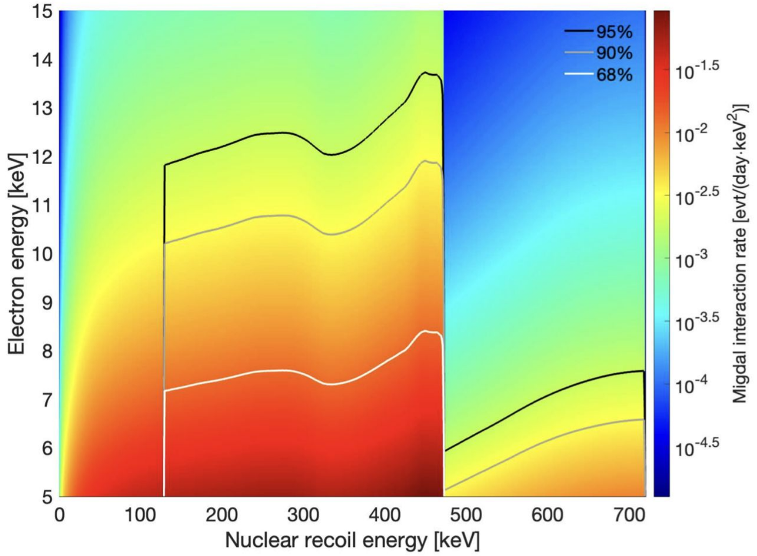
Energy-angle relation for D-D neutron scattering in CF_4 and Migdal rates



Migdal search ROI:

ER and NR tracks longer than 4 mm

5-15 keV electron; >130/170 keV F/C NRs

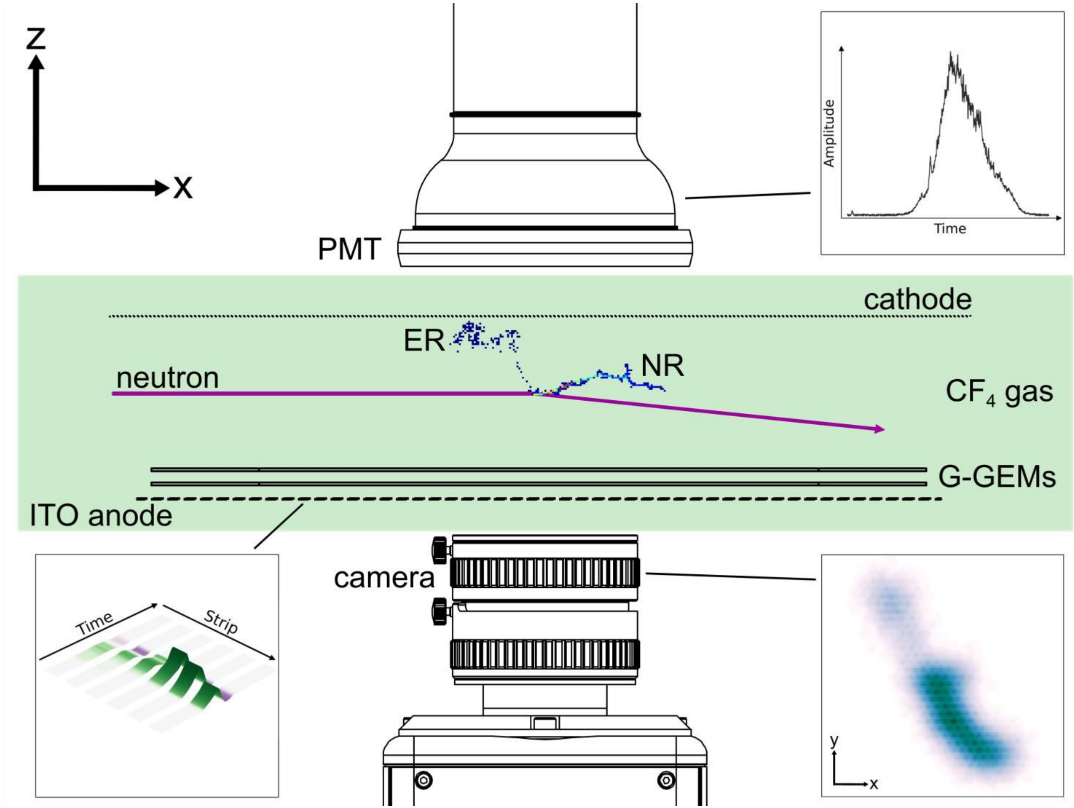


DD source: 8.9 Migdal events/day

DT source 29.3 Migdal events/day

After duty cycle, efficiencies, single-event frames …

The MIGDAL experiment

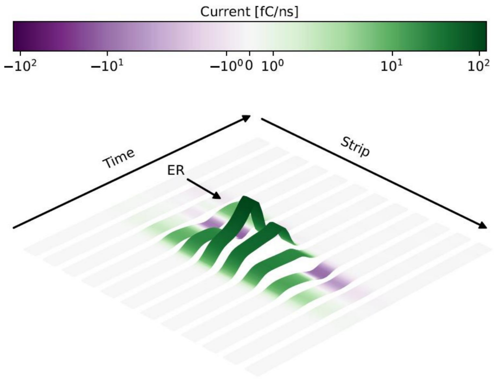


- Low-pressure gas: 50 Torr of CF_4
  - Extended particle tracks
  - Avoid gamma interactions
  - Can stably work with fraction of Ar
- TPC Signal amplification
  - 2 x glass-GEMs (Cu + Ni cladded)
- Readout :
  - Optical : Camera + photomultiplier tube
  - Charge: GEMs + 120 ITO anode strips
- High-yield 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
  - NR and ER have very different dE/dx
  - 5 keV electron threshold

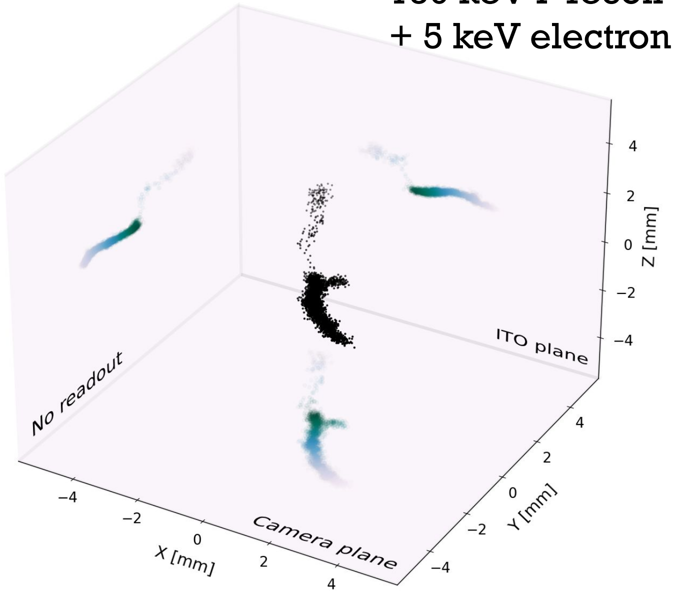
    5.9 keV X-rays from Fe-55 induce 5.2 keV photoelectrons from F for calibration at threshold.

- 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

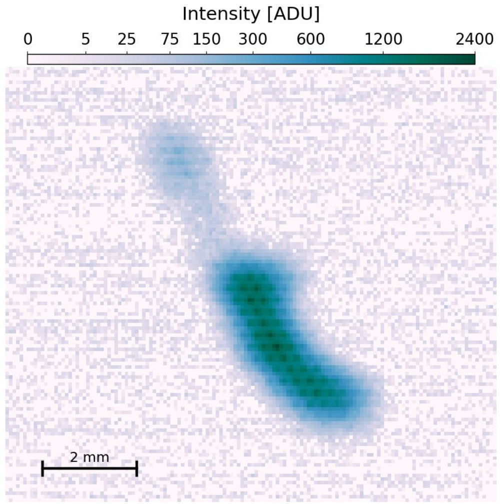
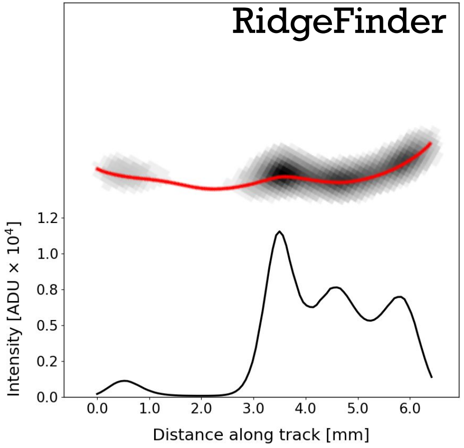
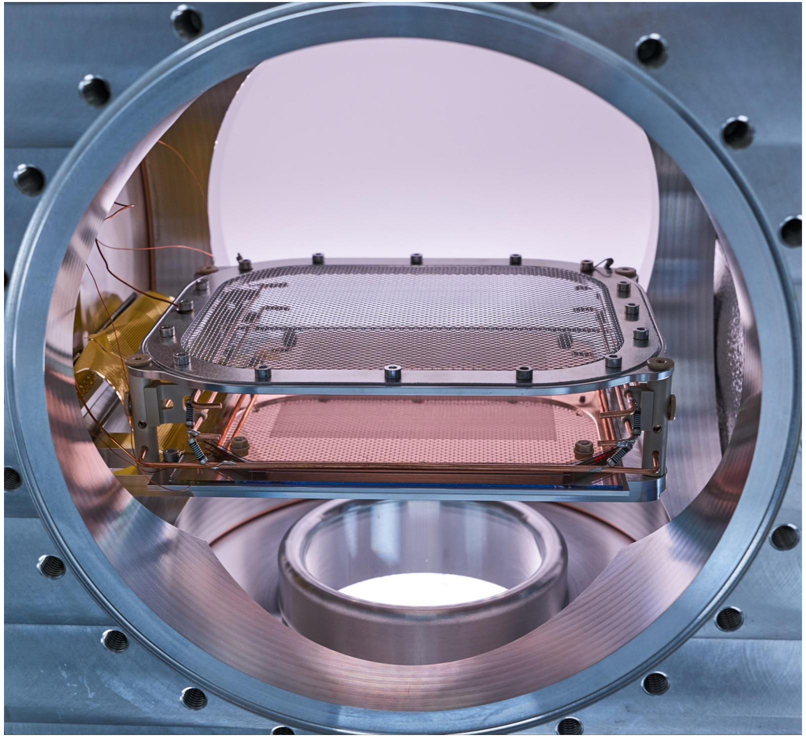
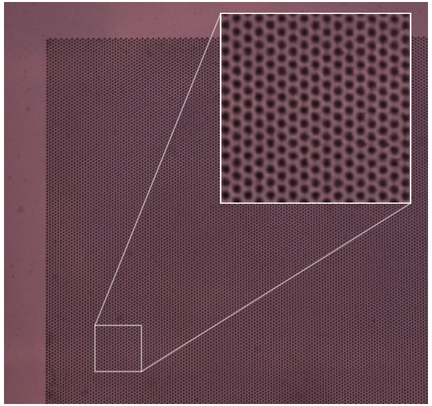


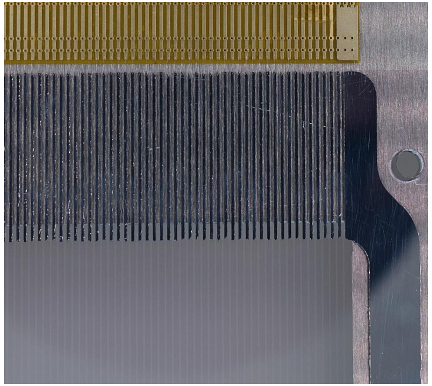
Image analysis
Deconvolution +
RidgeFinder



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

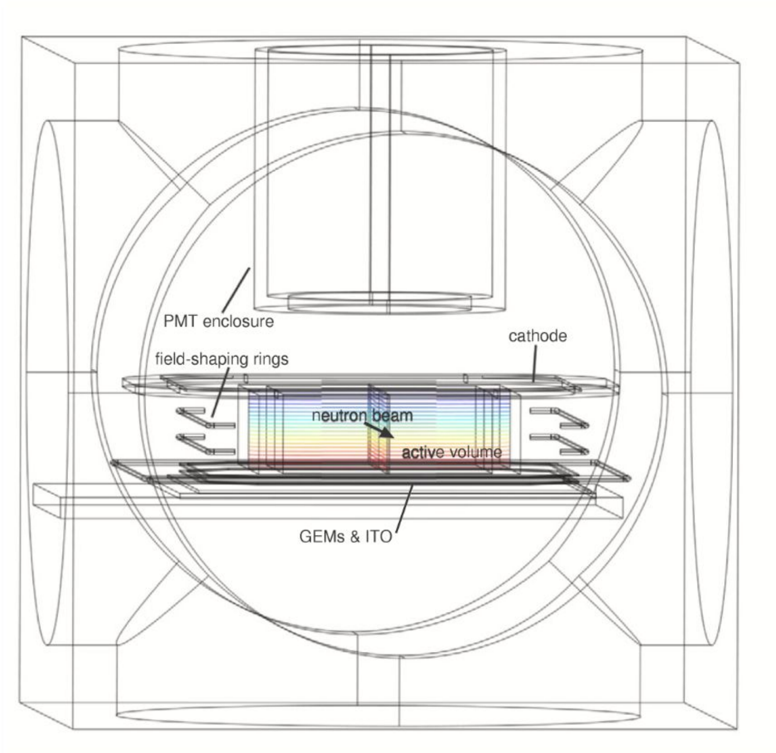
- 120 strips

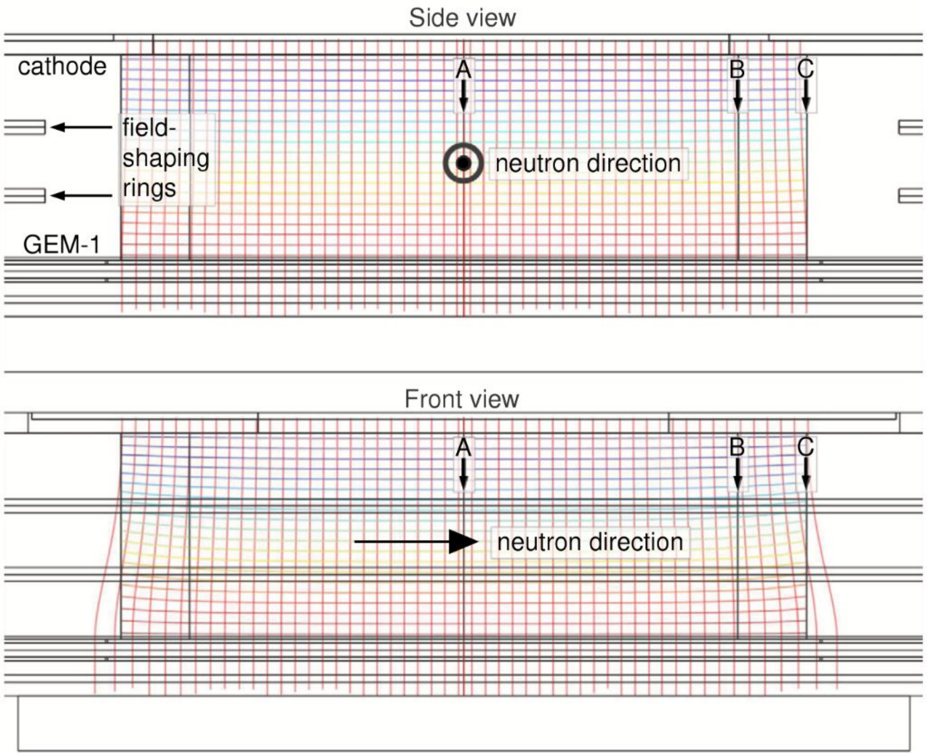
- width/pitch: 0.65/0.83 mm

Two field shaping copper wires

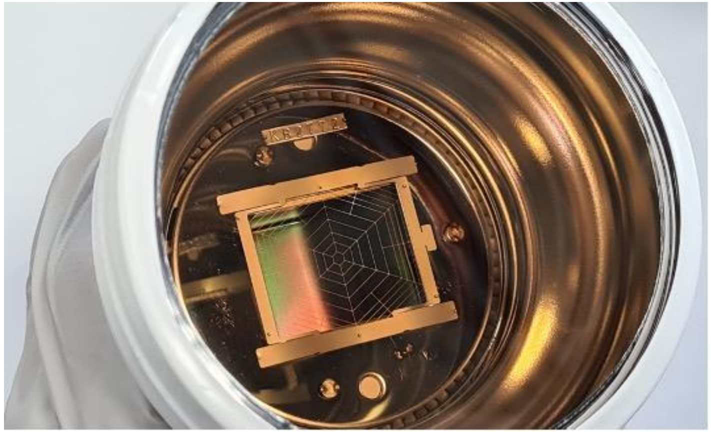
- TPC inside of the central aluminium cube
- Drift gap: 3 cm between woven mesh and cascade of two glass-GEMs (E_{DRIFT}=200 V/mm for minimum electron diffusion)
- Transfer and signal induction gaps : 2 mm
- Low outgassing materials; vacuum before fill $2*10^{-6}$ mbar; signal unchanged several days after fill

Electric field in the TPC - modelling with COMSOL





Light and charge readout

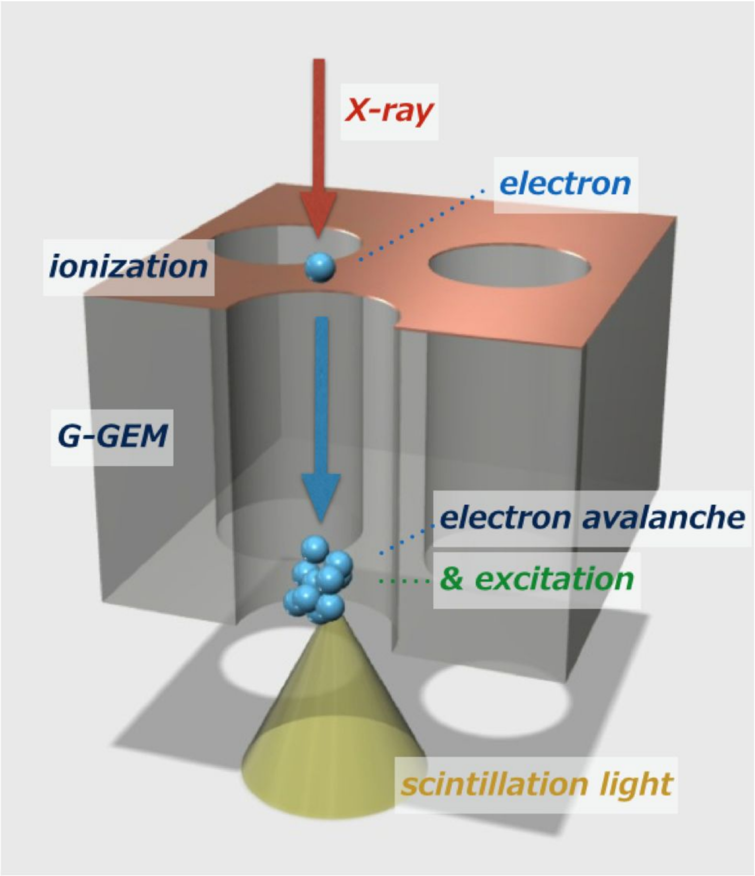


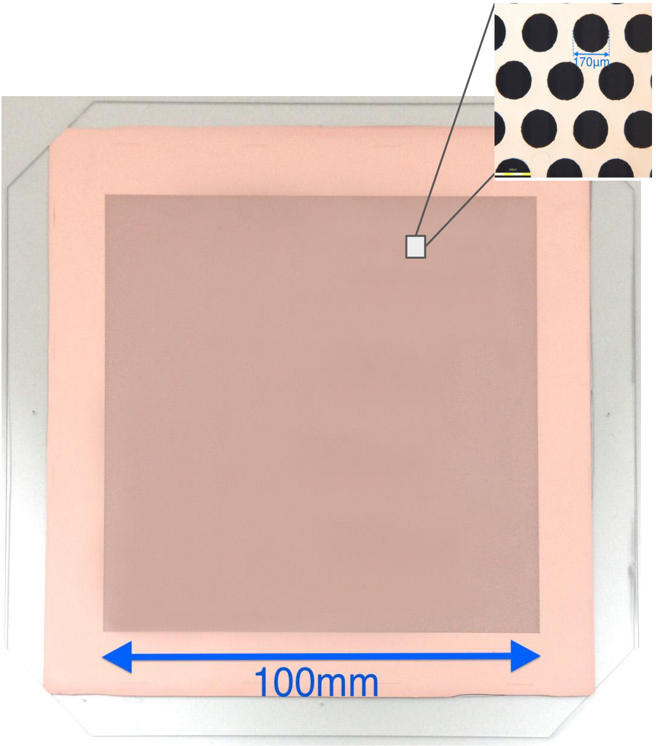
ITO anode strips
Post-GEM ionisation
Readout of (x,z) plane
Pitch: 833 µm
Digitised at 2 ns/sample
(Drift velocity: 130 µm/ns*)*

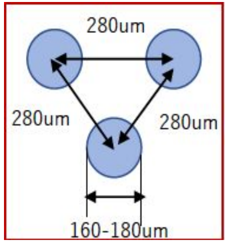
qCMOS camera
(Hamamatsu ORCA - QUEST)
Detects GEM scintillation through glass viewport behind ITO anode
Readout of (x,y) plane
Exposure: 8.33 ms/frame (continuous)
Px scale: 39 µm (2×2 binning)
Lens: EHD-25085-C; 25mm f/0.85

VUV PMT (Hamamatsu R11410)
Detects primary and secondary (GEM) scintillation
Absolute depth (z) coordinate
Digitised at 2 ns/sample [Trigger]

Glass-GEMs

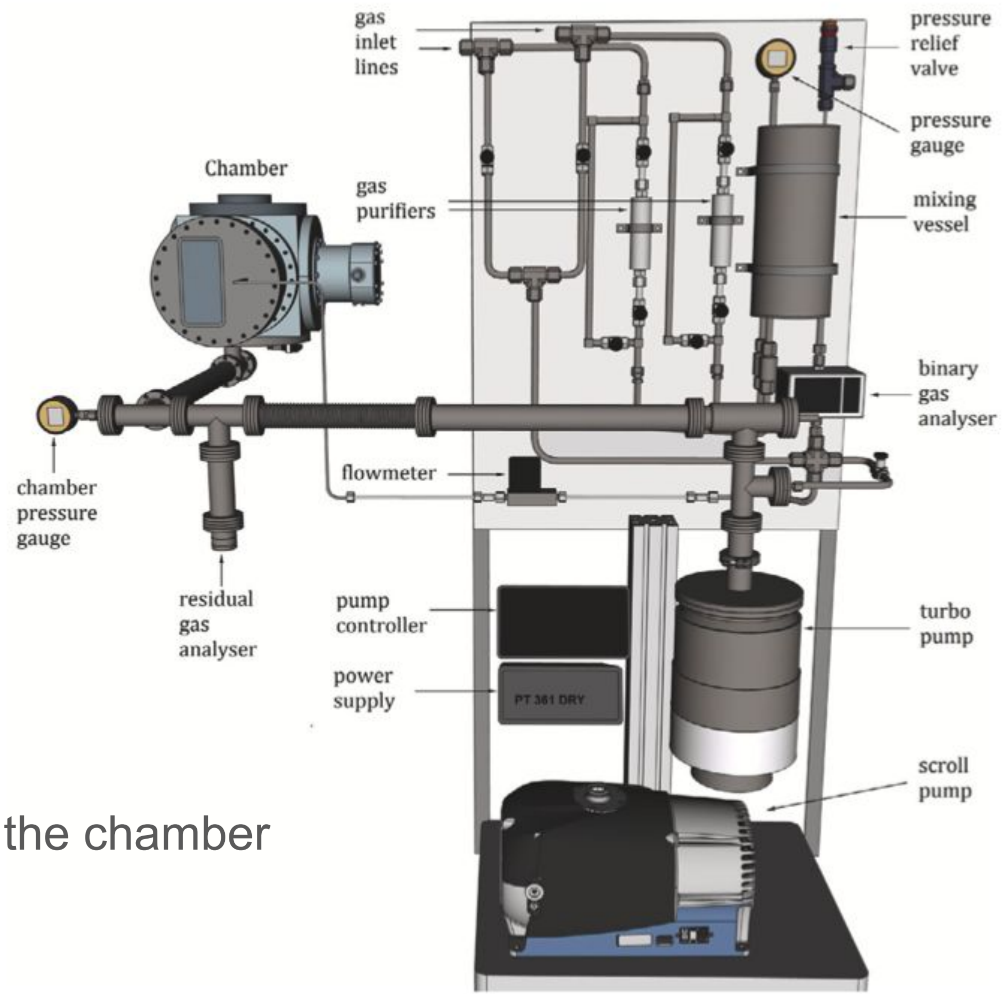






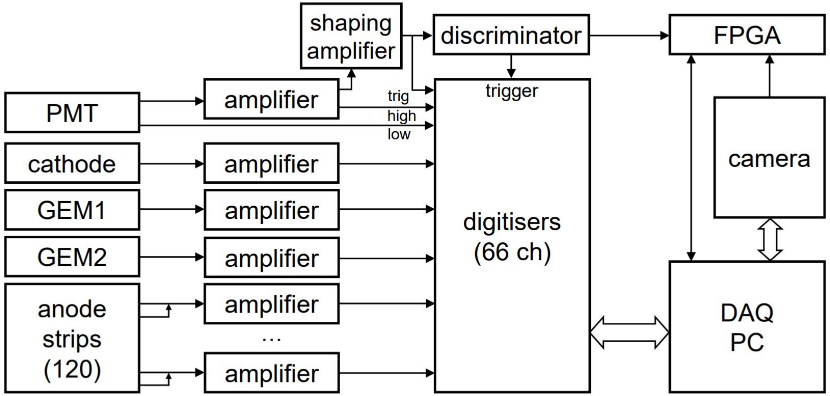
Glass thickness : 570 um

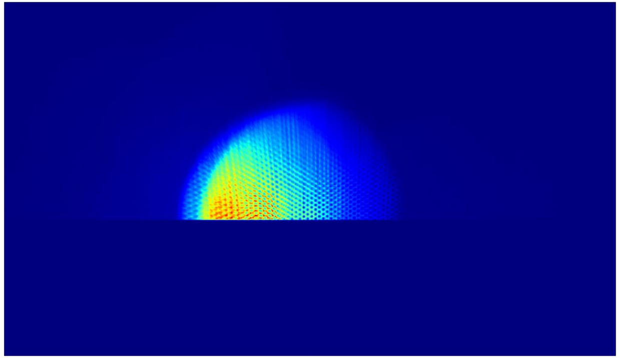
Gas System

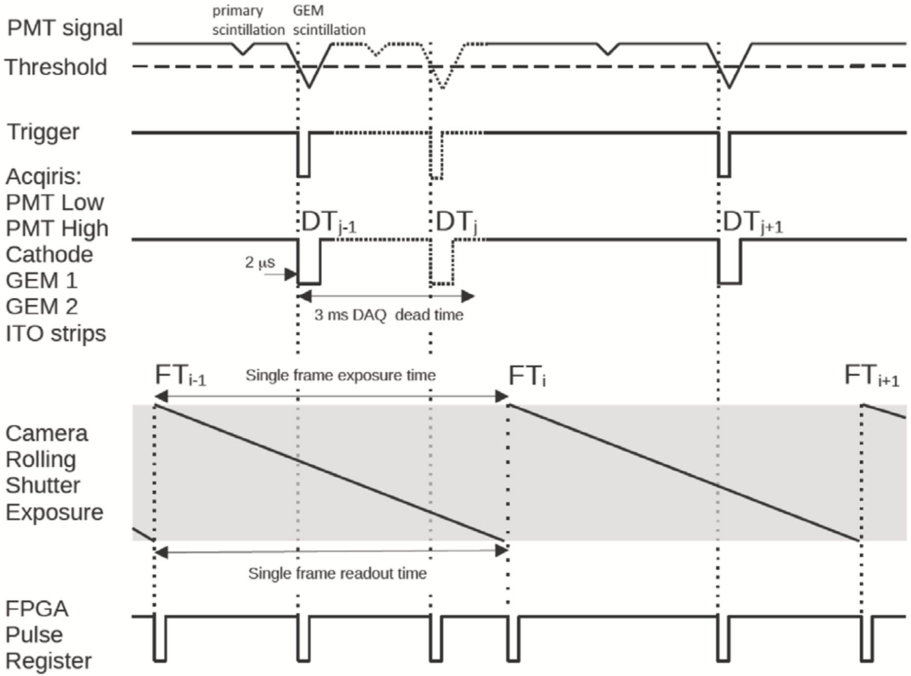


Initial vacuum in the chamber
~1E-06 mbar

DAQ



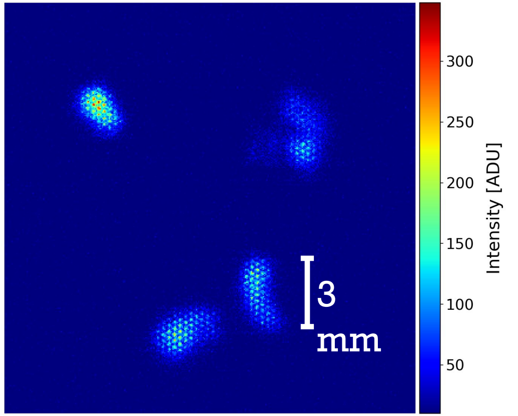


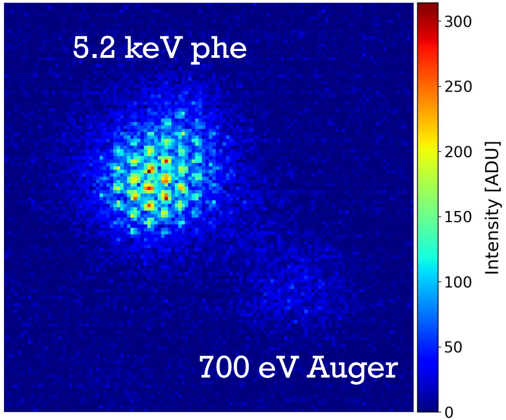


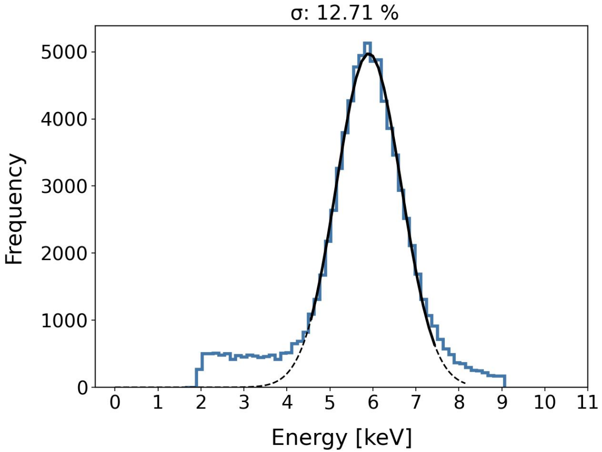
Synchronisation with LED pulse
Image cut due to a rolling shutter

Calibration with ^{55}Fe – Pure CF_4

- Tests were performed with ^{55}Fe (5.9 keV x-ray).
- The gain was pushed high.
- Head & tail is clearly resolved.
- 700 eV Auger electron from fluorine is visible.
- Achievable energy resolution is high (σ/μ ~ 12.7%).

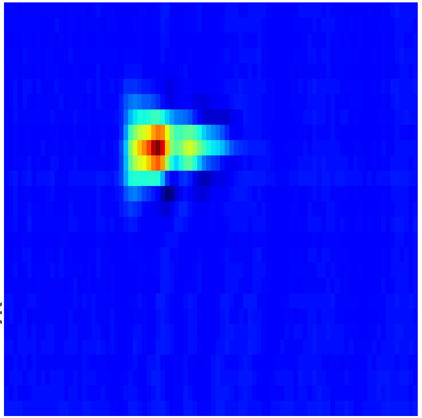


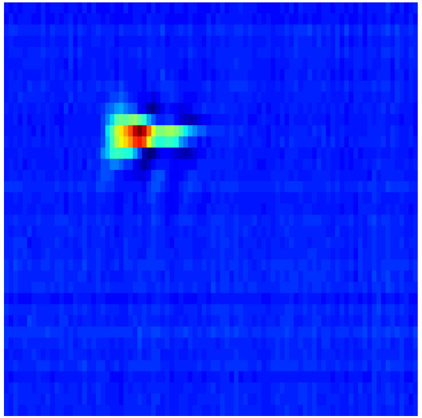


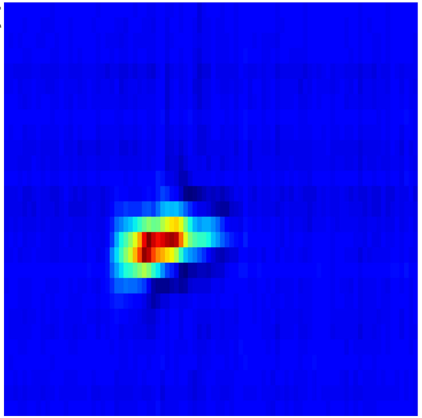


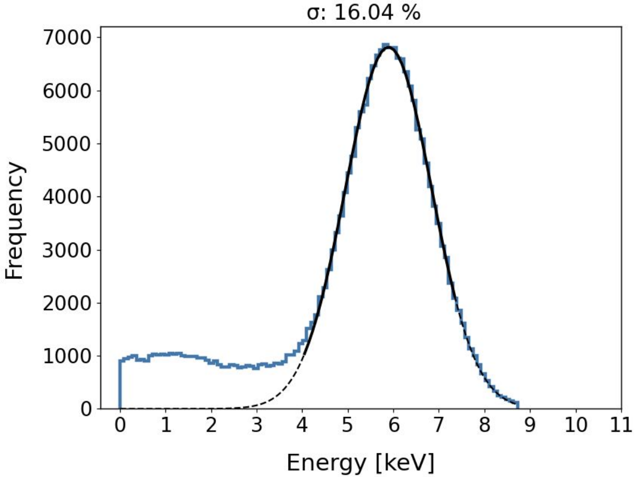
ITO (Pure CF_4)

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



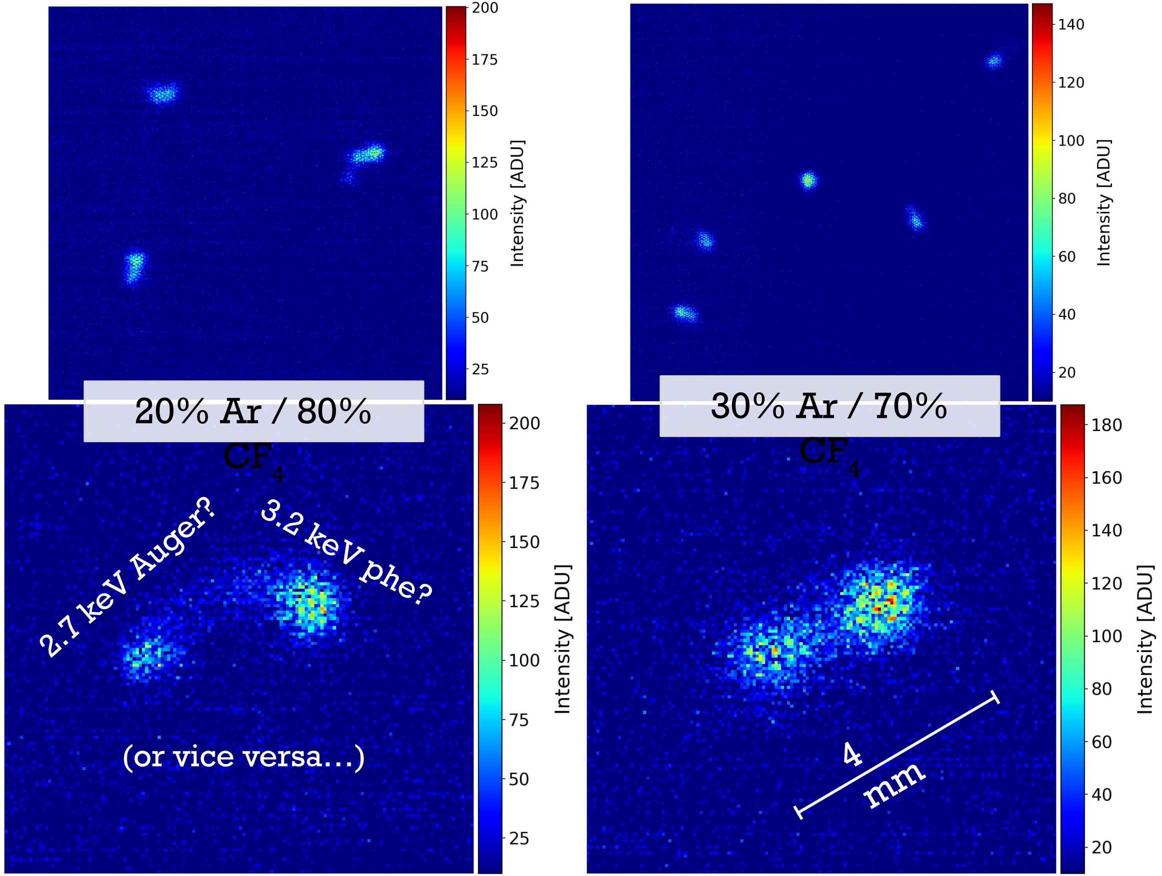






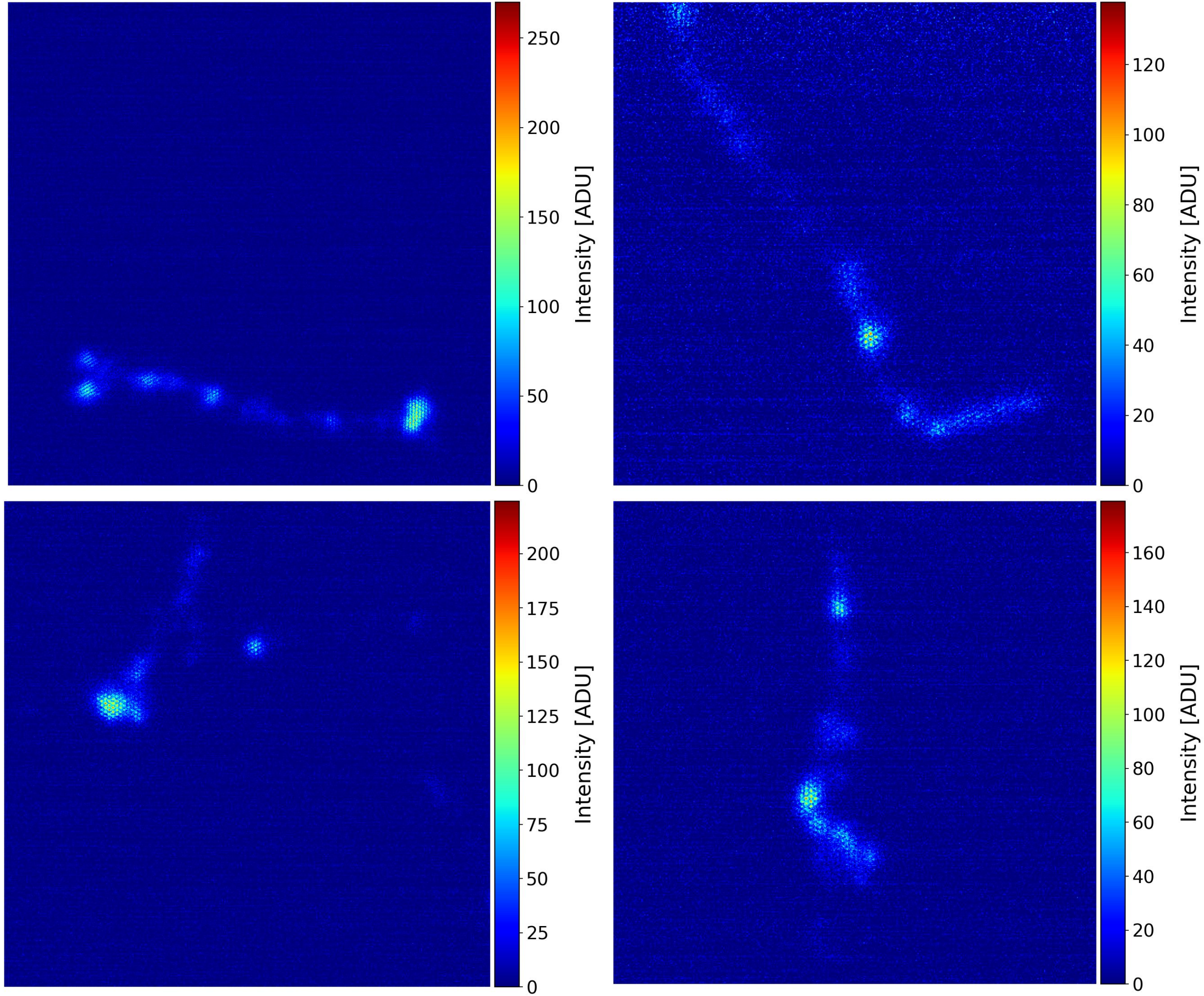
Calibration with ^{55}Fe – Ar / CF_4

- The chamber was tested with a fraction of argon at 50 Torr.
  - 20 % Ar / 80% CF_4
  - 30 % Ar / 70% CF_4
  - 40 % Ar / 60% CF_4
- Diffusion is greater.
- Tracks are in general longer.
- Stability is lower at high fractions of Ar.



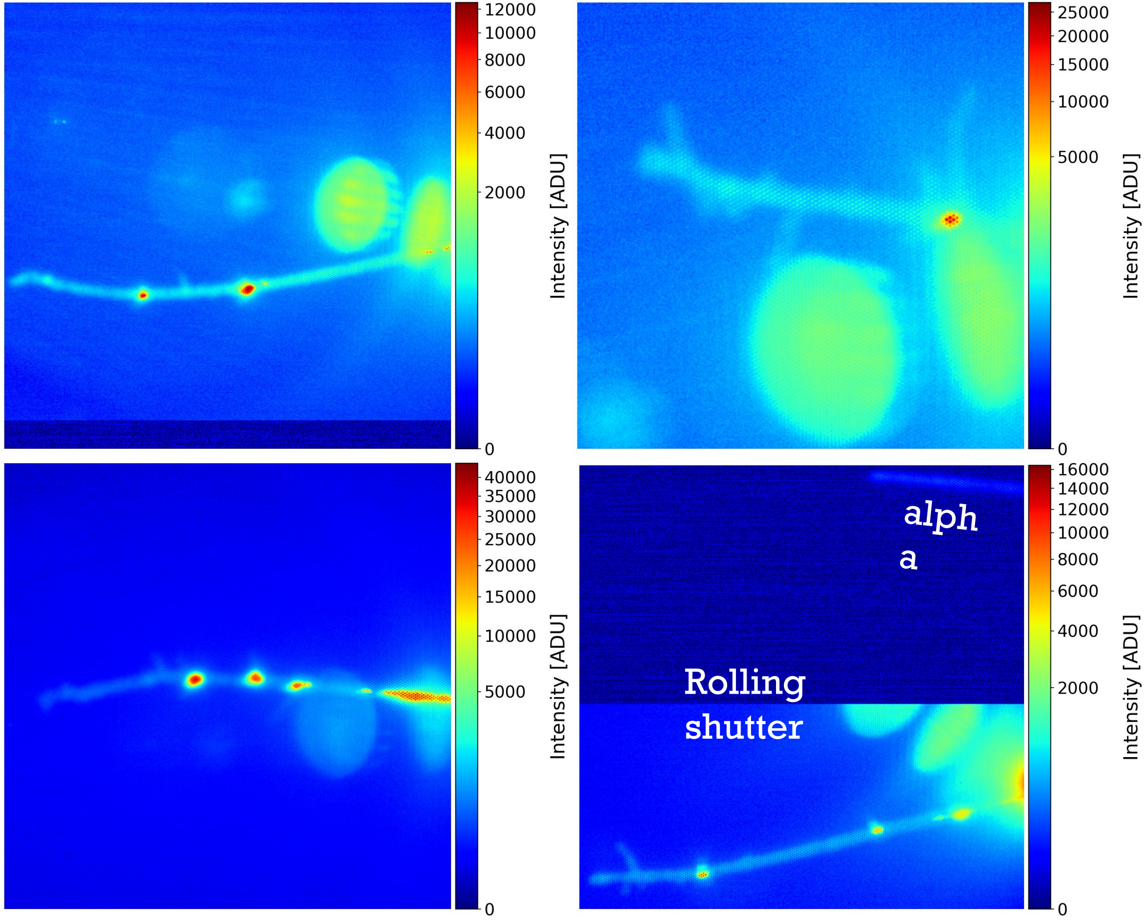
No source

- The detector sees high energy electrons with frequency ~1 Hz.
- Almost none of these tracks terminate in the active volume.
- Can see delta electrons emitted along the track.
- What is the source of these events? Electron shower?



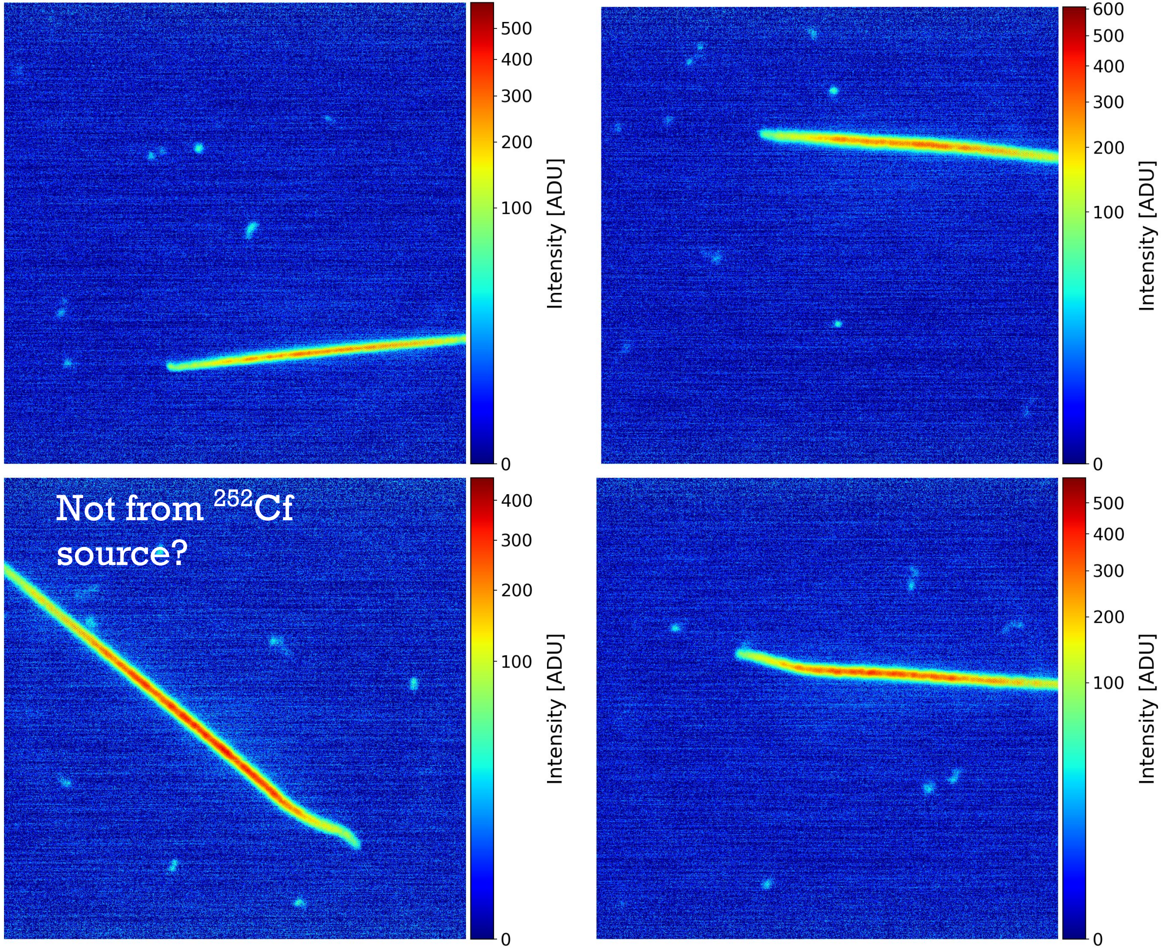
Fission fragments

- 37 Bq ^{252}Cf source was placed internally ~10 cm from active volume.
    - 6.2 MeV α
    - 80 MeV Nd
    - 105 MeV Pd
- Testing the dynamic range limits of the detector.
- At this distance the Nd/Pd have dE/dx comparable to nuclear recoil tracks produced by **DT (14.7 MeV)** neutron scattering.
- All fission fragment tracks produced sparks.



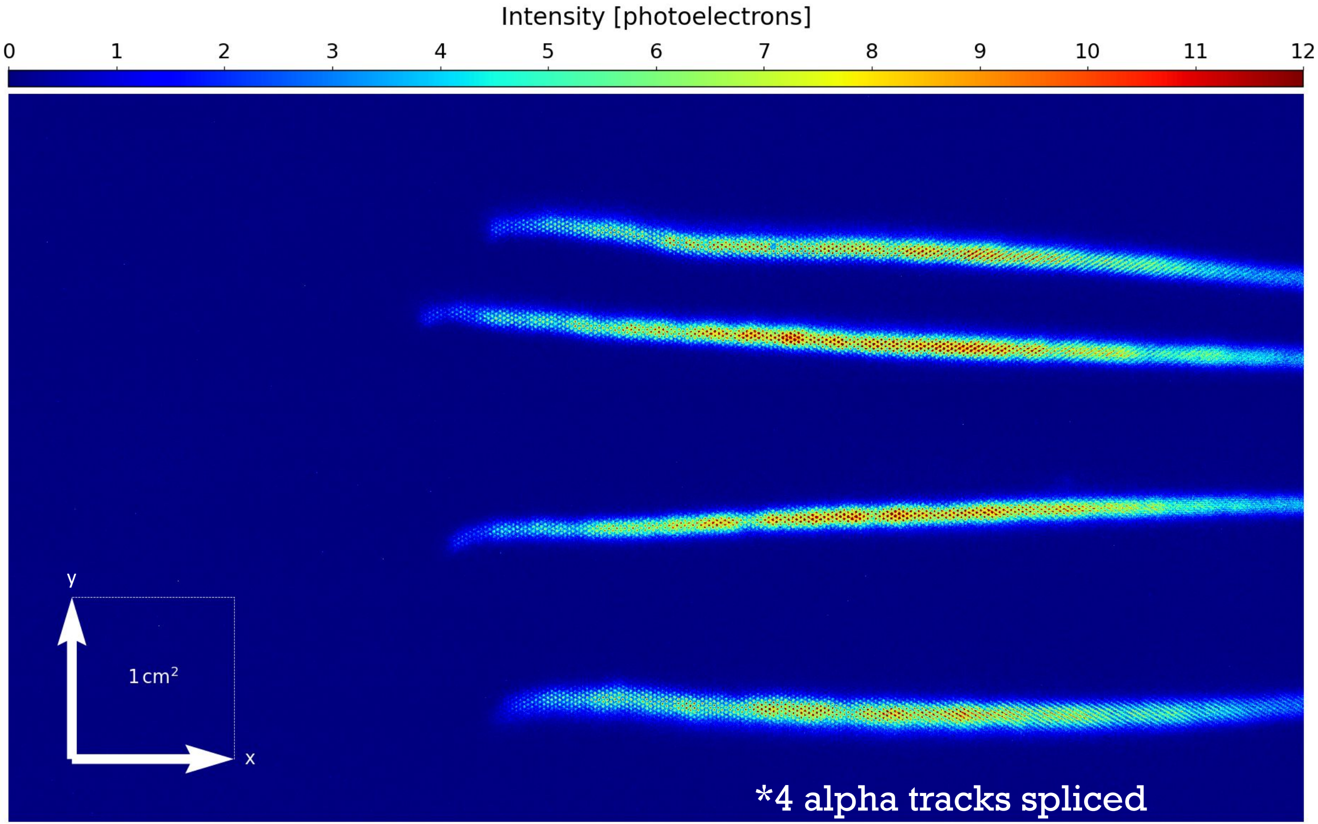
Alphas

- ^{252}Cf source was moved back to ~20 cm from active volume.
- At this distance Bragg peak for α terminates in the active volume.
- dE/dx comparable to nuclear recoil tracks produced by **DD (2.47 MeV)** neutron scattering.
- Can simultaneously observe α and 5 keV phe!



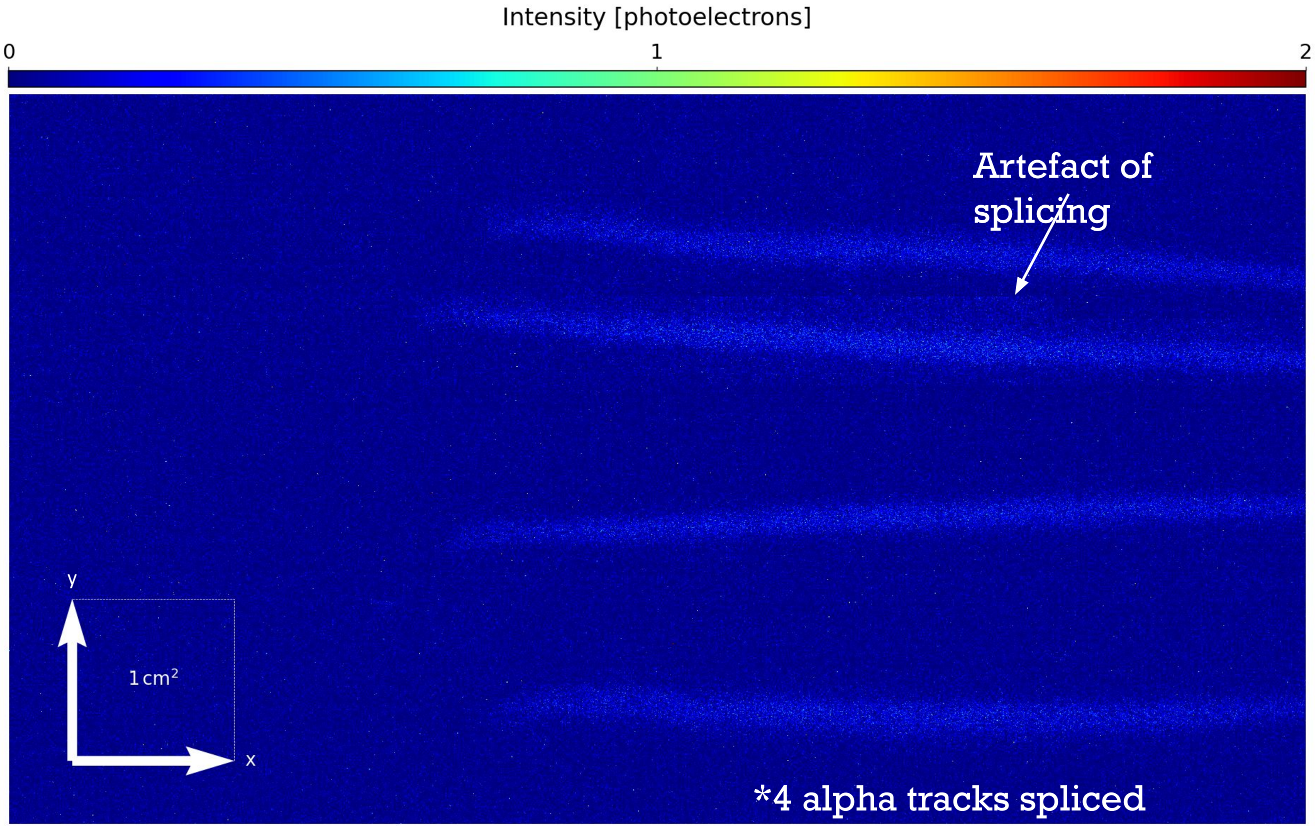
Alphas with ORCA Quest

- 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.



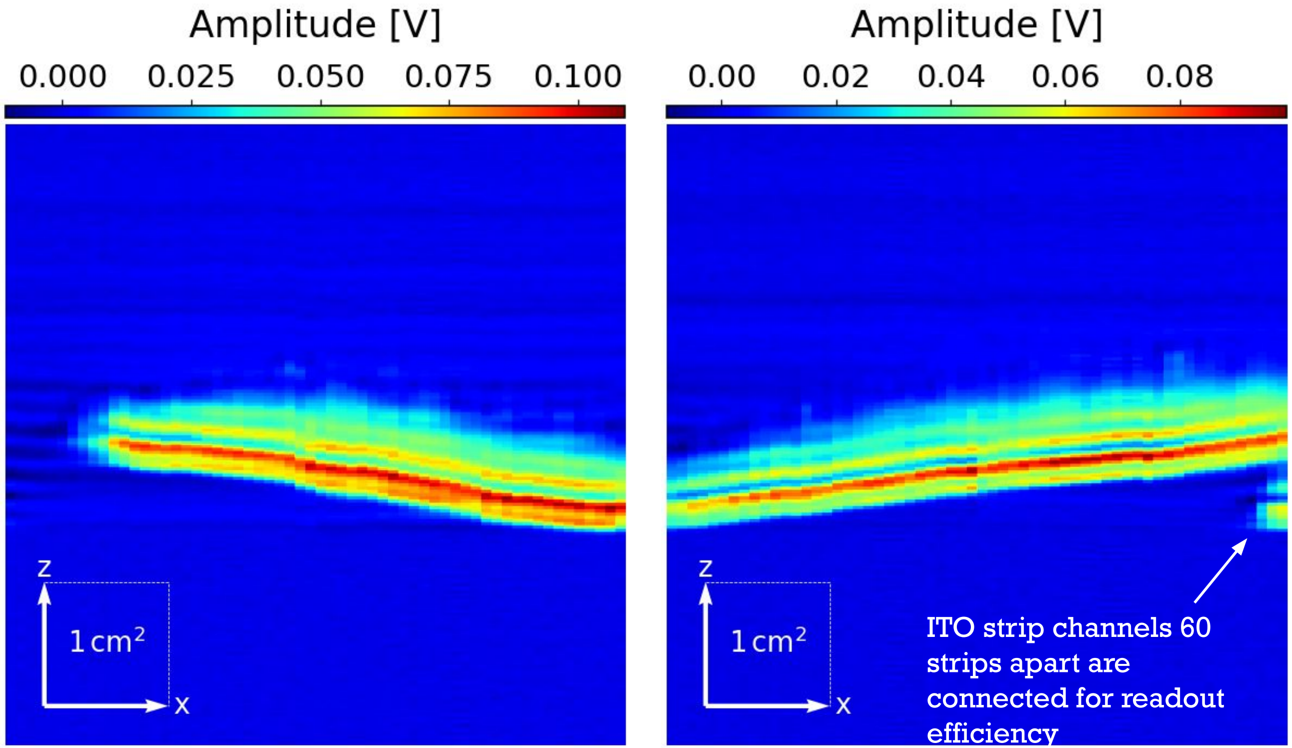
Afterglow with ORCA Quest

- In the following frame of each alpha 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.

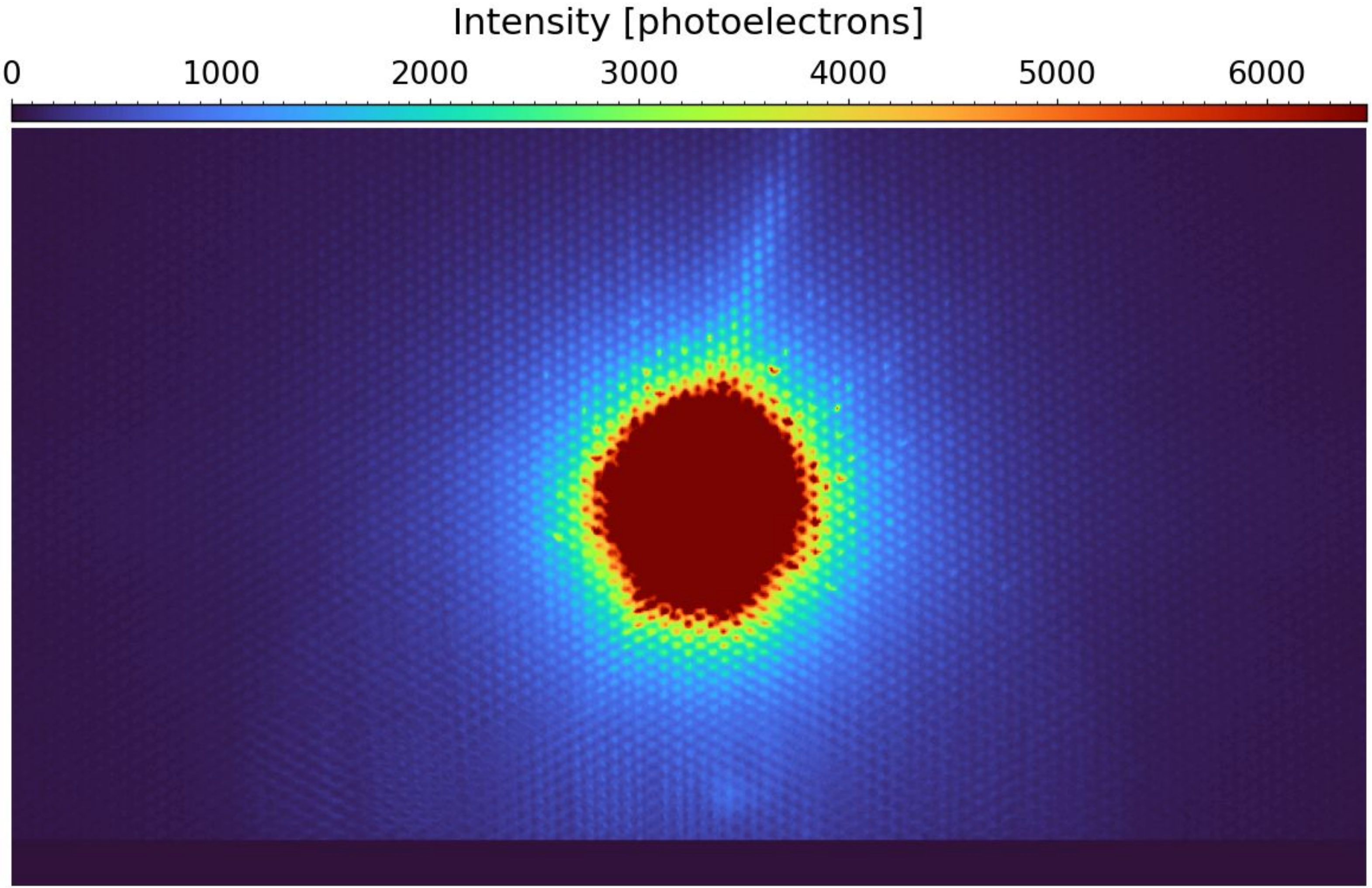


Alphas in the ITO strips

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



Spark



NILE facility

- NILE facility is at TS2, ISIS
- We packed up the chamber and moved it from lab 7 to NILE mid-May.

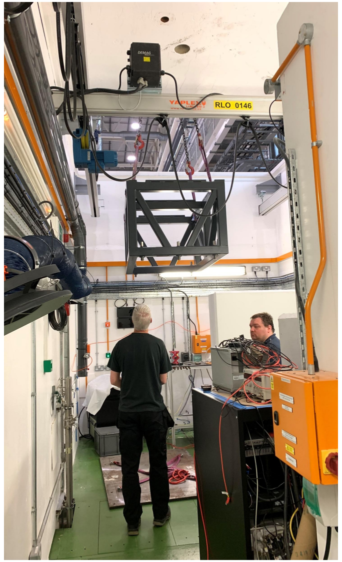
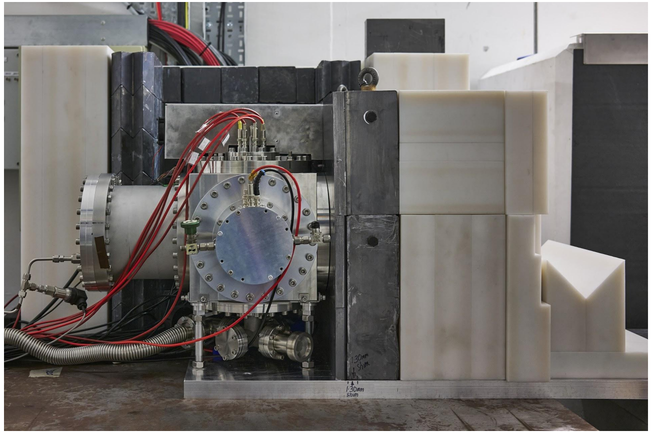
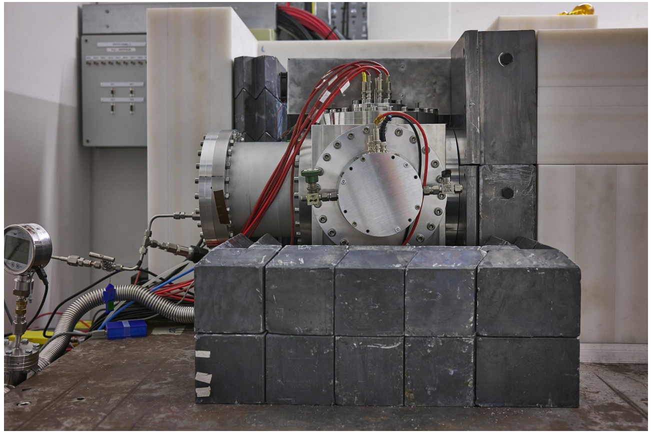


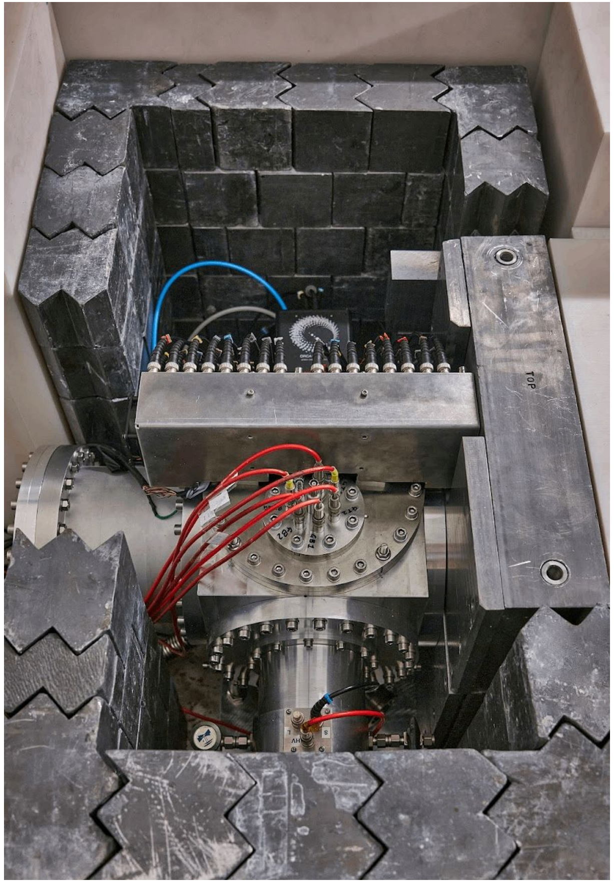

Table installed with lead under-shield

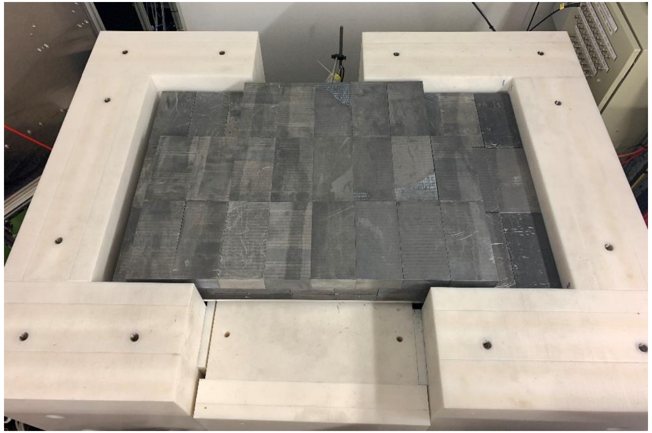

Chamber driven over to NILE

Assembling at NILE

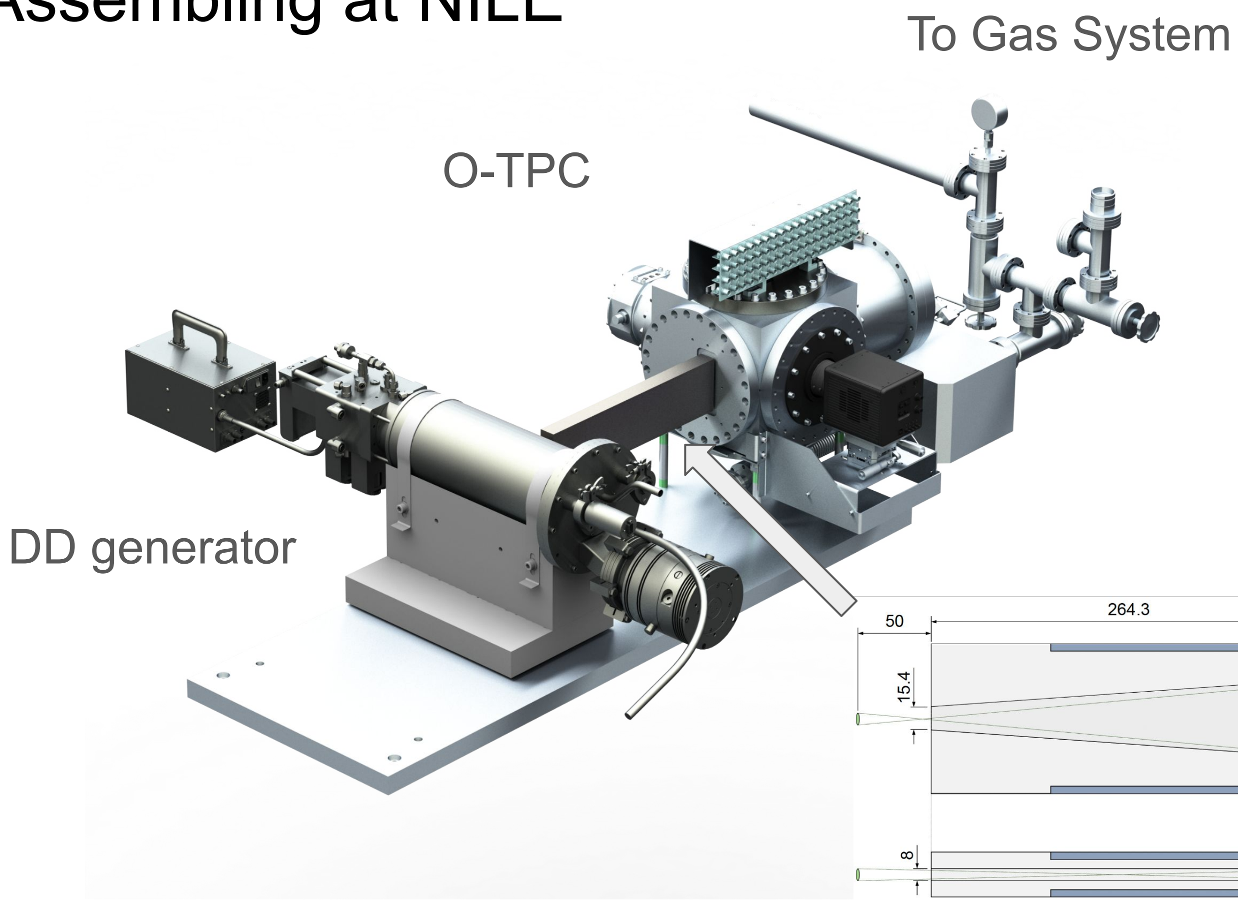


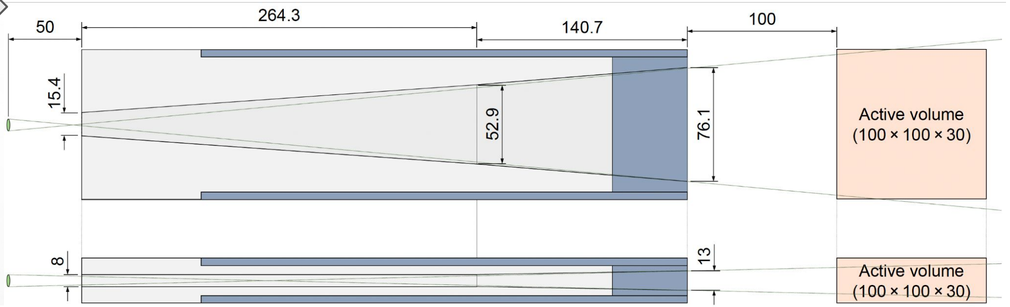






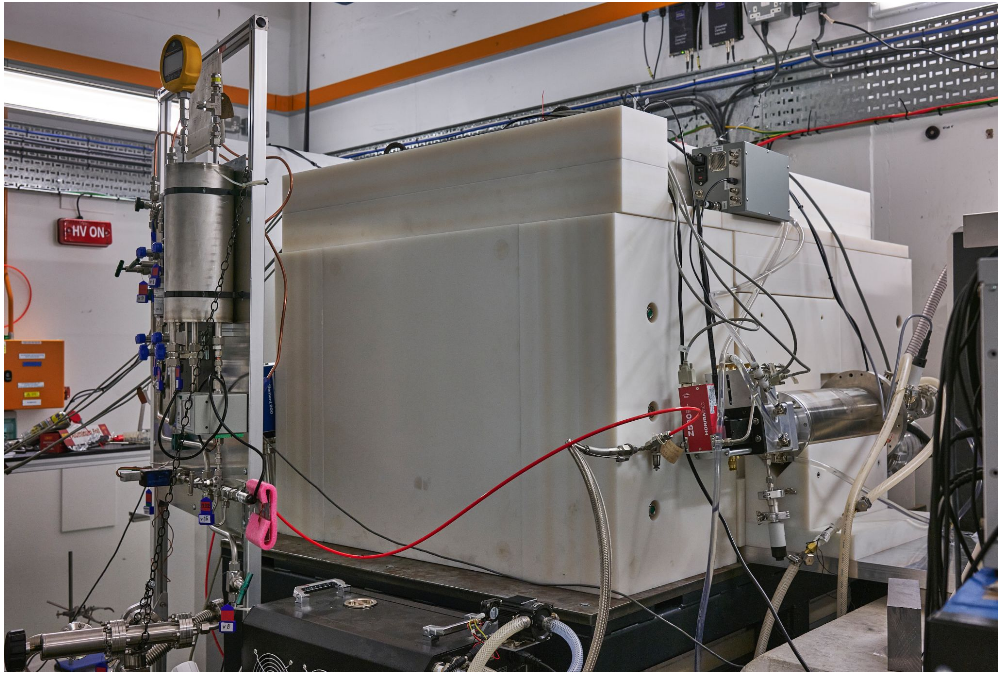
Assembling at NILE





30 cm long collimator

Experiment installation in the NILE bunker

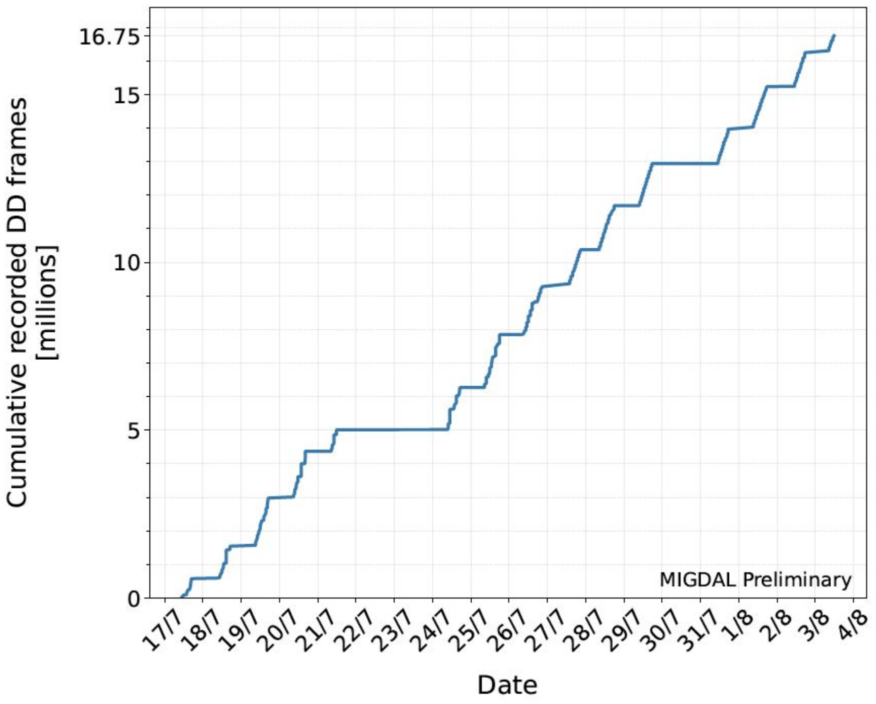


MIGDAL experiment fully assembled at NILE

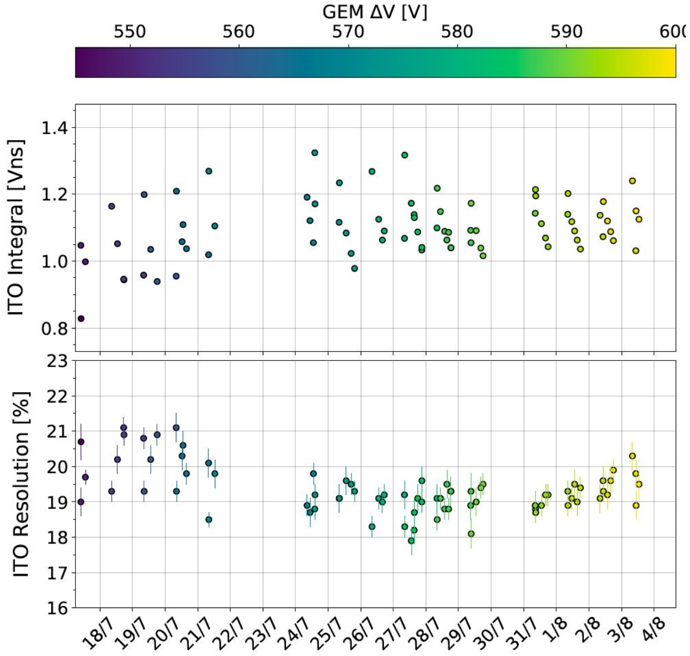
- Lead shield : 10 cm
- Borated HDPE shield : 20 cm
- Collimator HDPE+ lead : 30 cm long

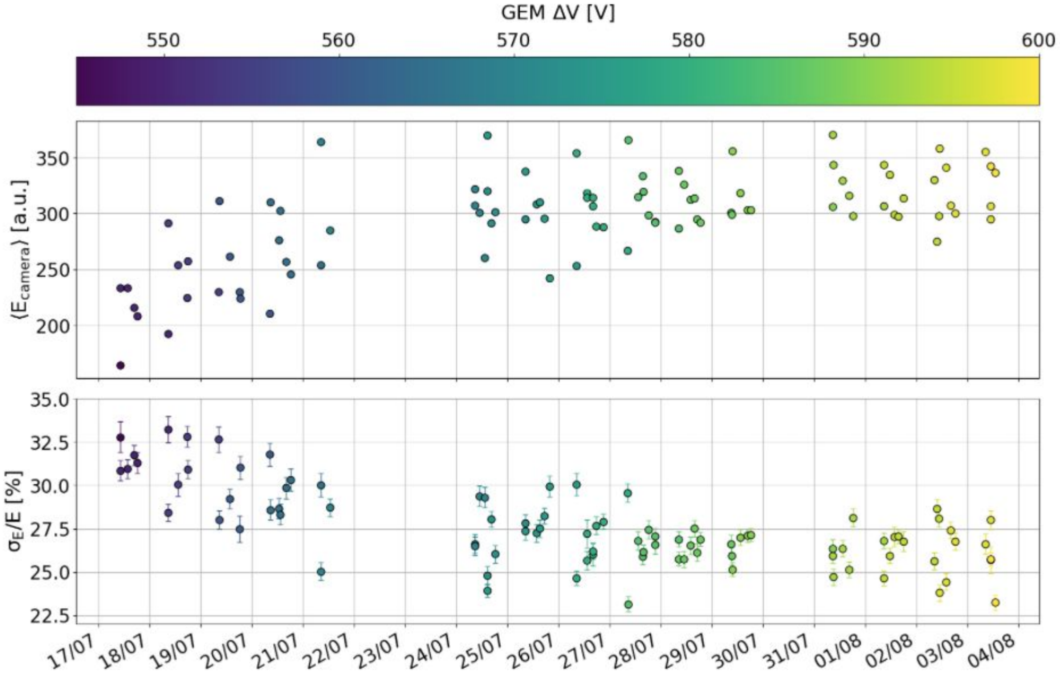
First Science Run (Summary)

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



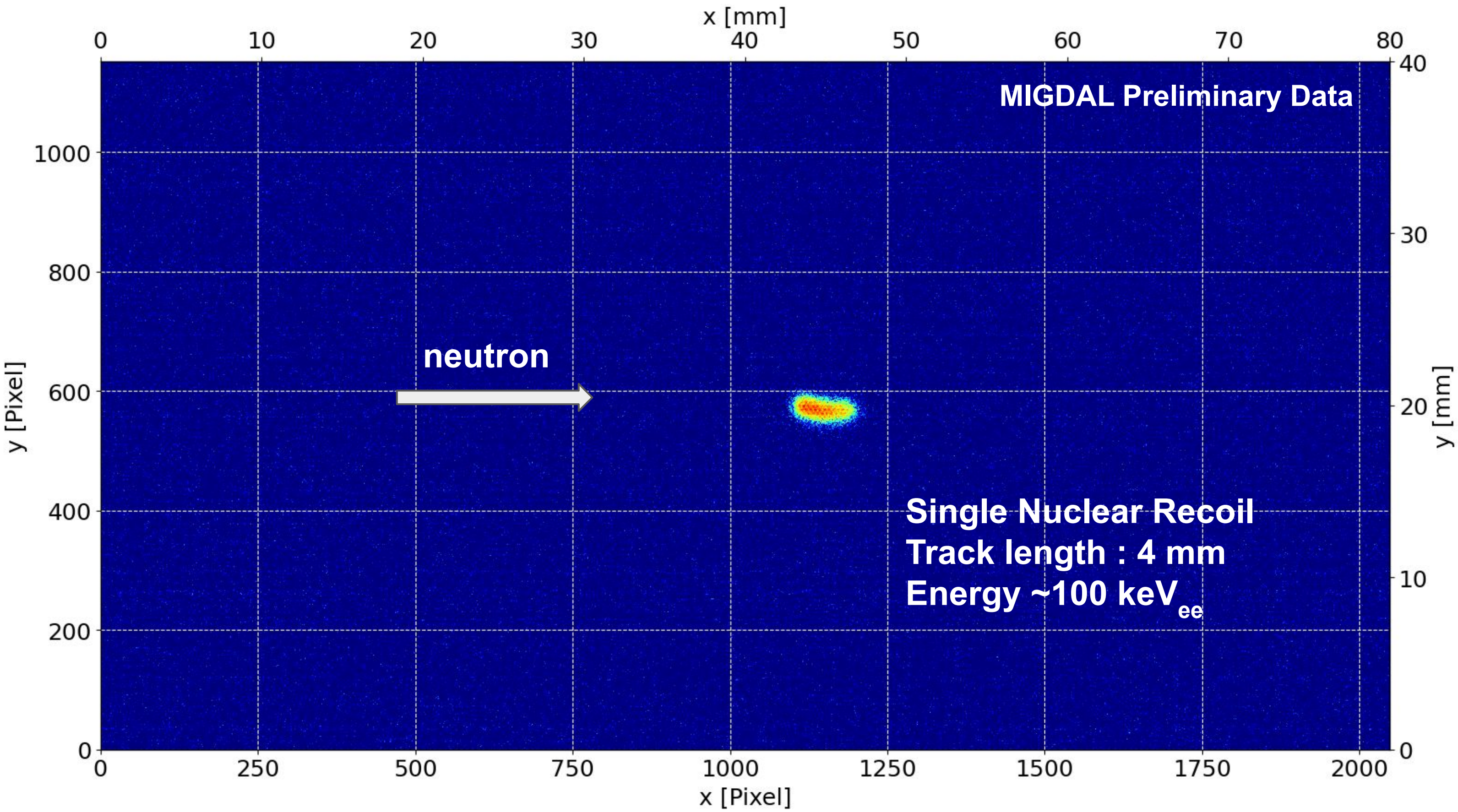
Detector calibration



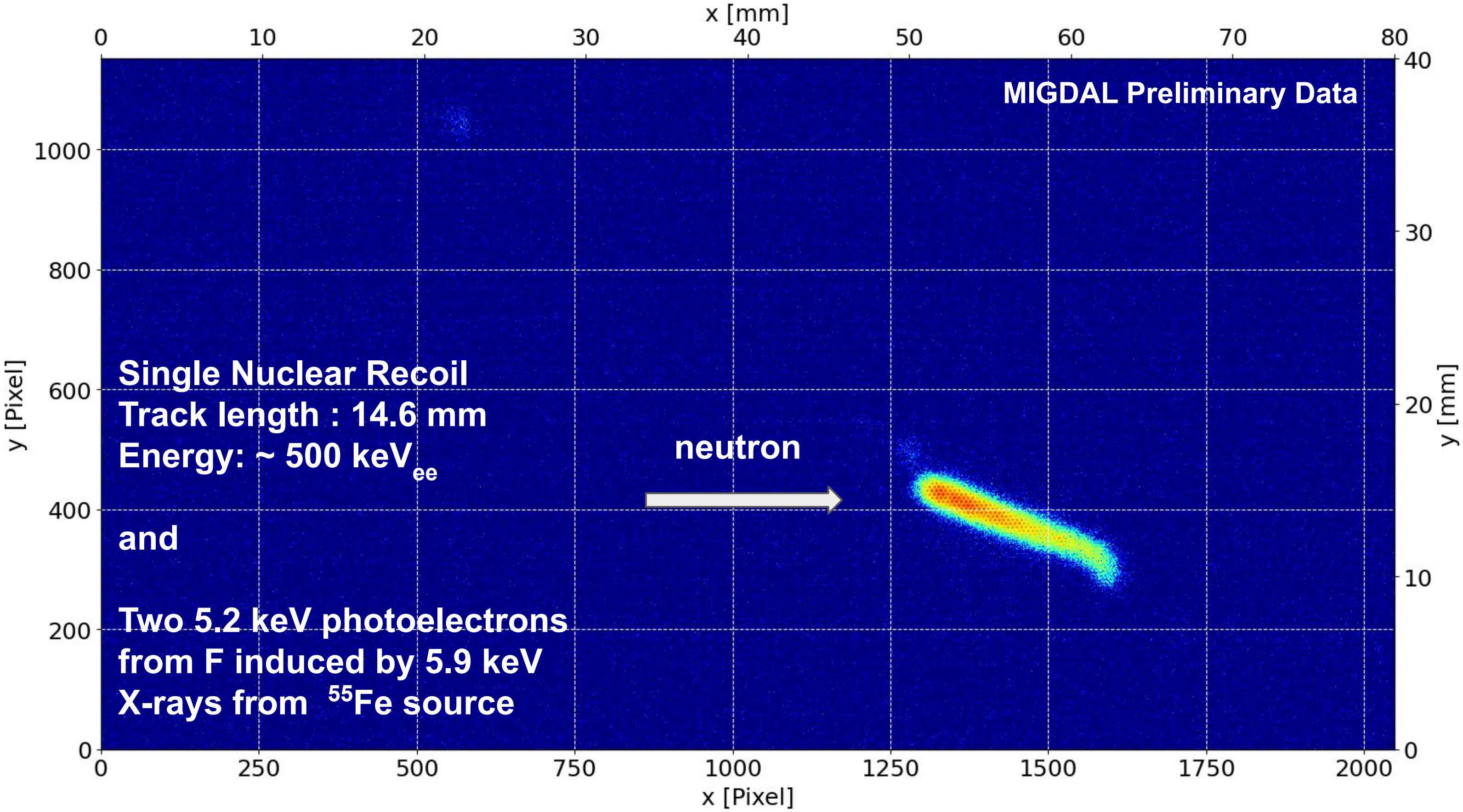


- ^{55}Fe calibration performed several times per day.
- Energy scale is consistent over the course of the science run with ~20% variation.
- Resolution in ITO ~20% and in camera ~ 25 - 32 % camera readout depending on the gain.
- Further improvements are expected with better calibration methods.

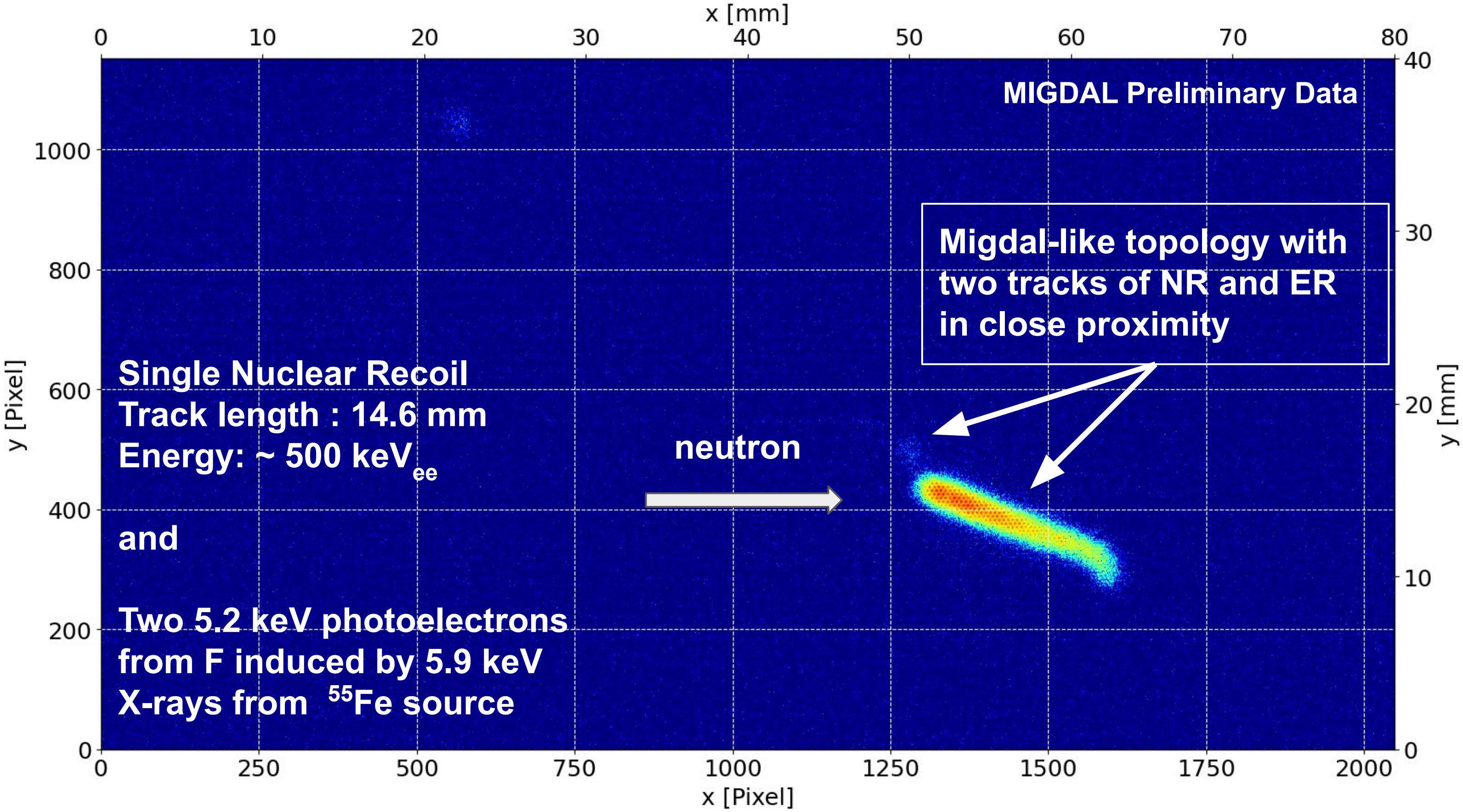
Examples of events (Single Nuclear Recoil)



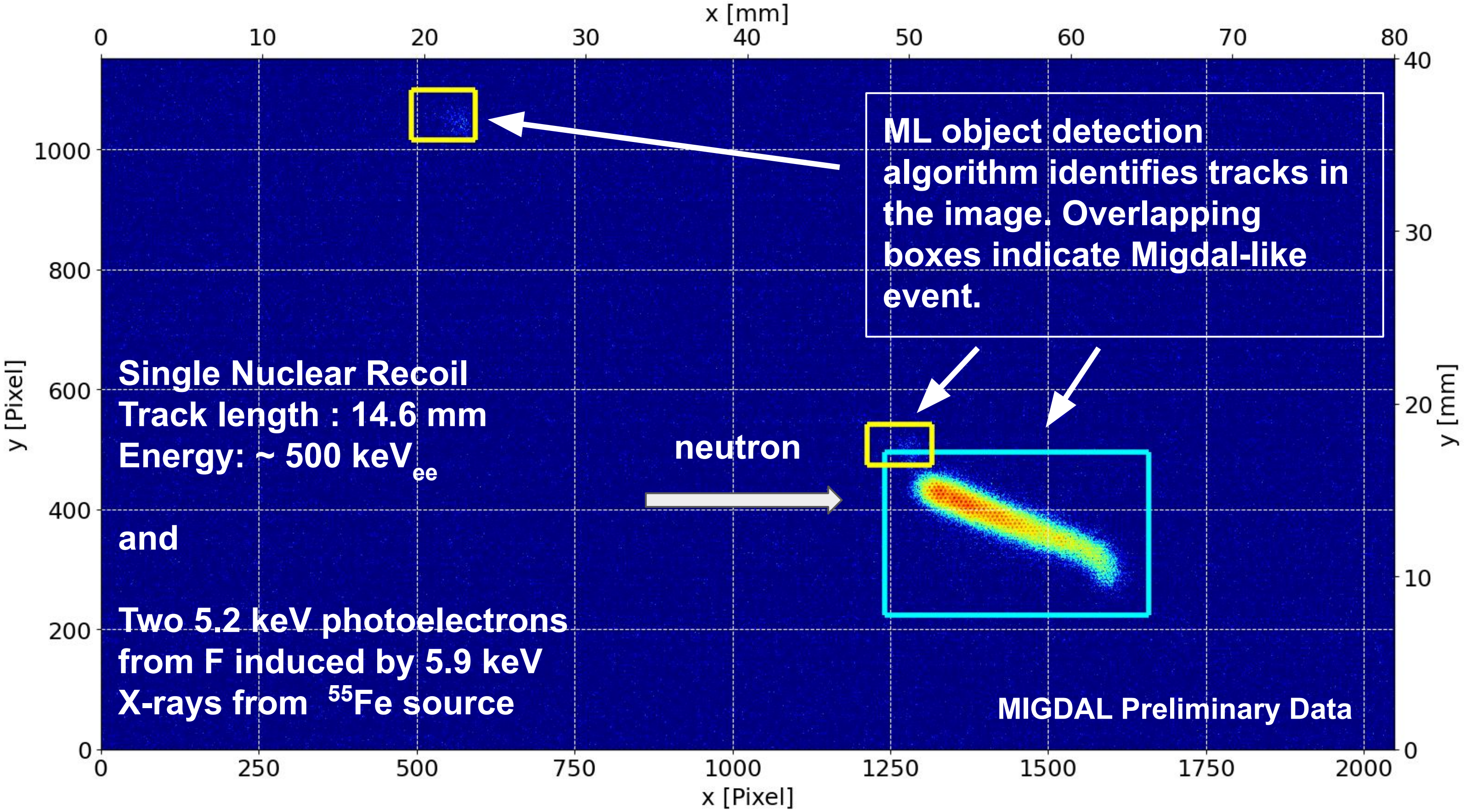
Examples of events (Migdal-like event)



Examples of events (Migdal-like event)

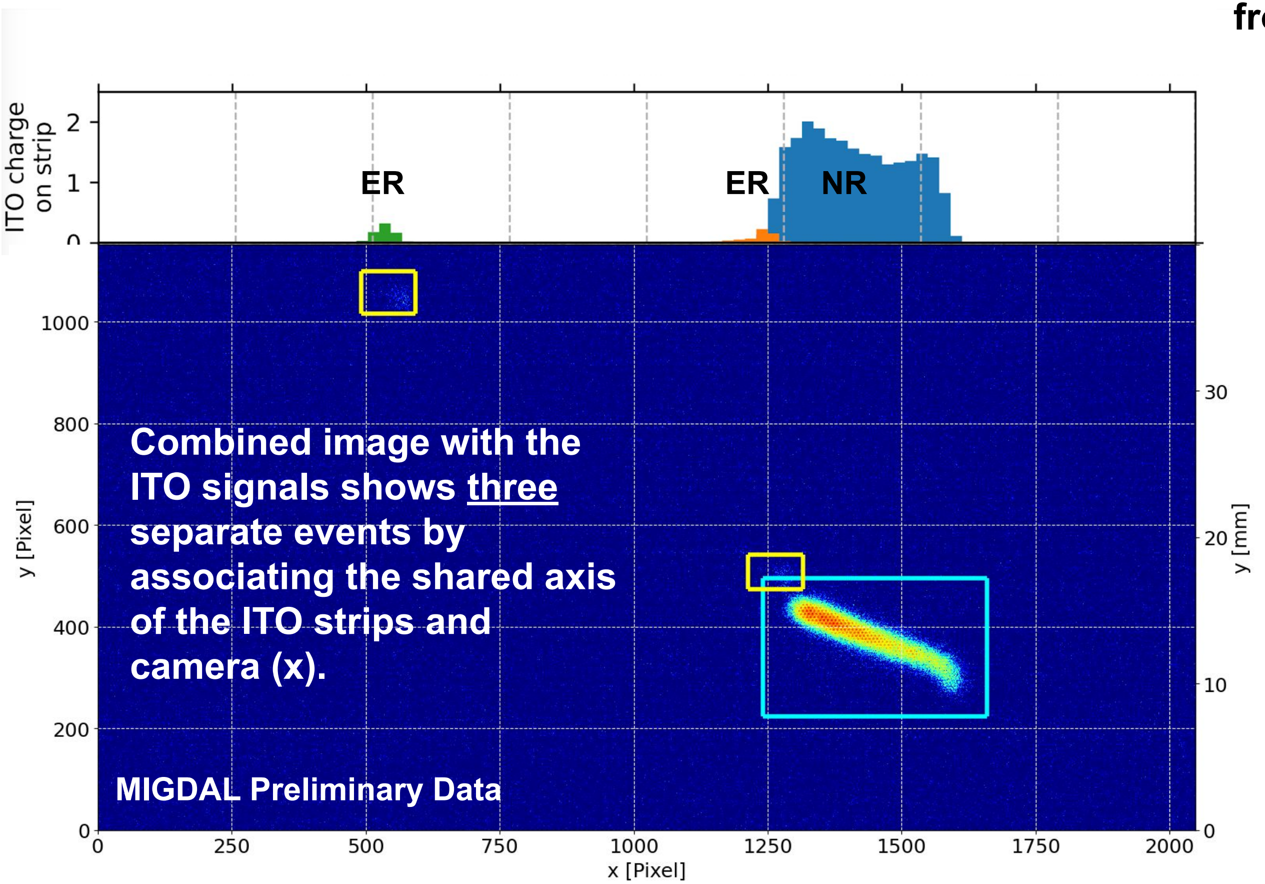


Examples of events (Migdal-like event)

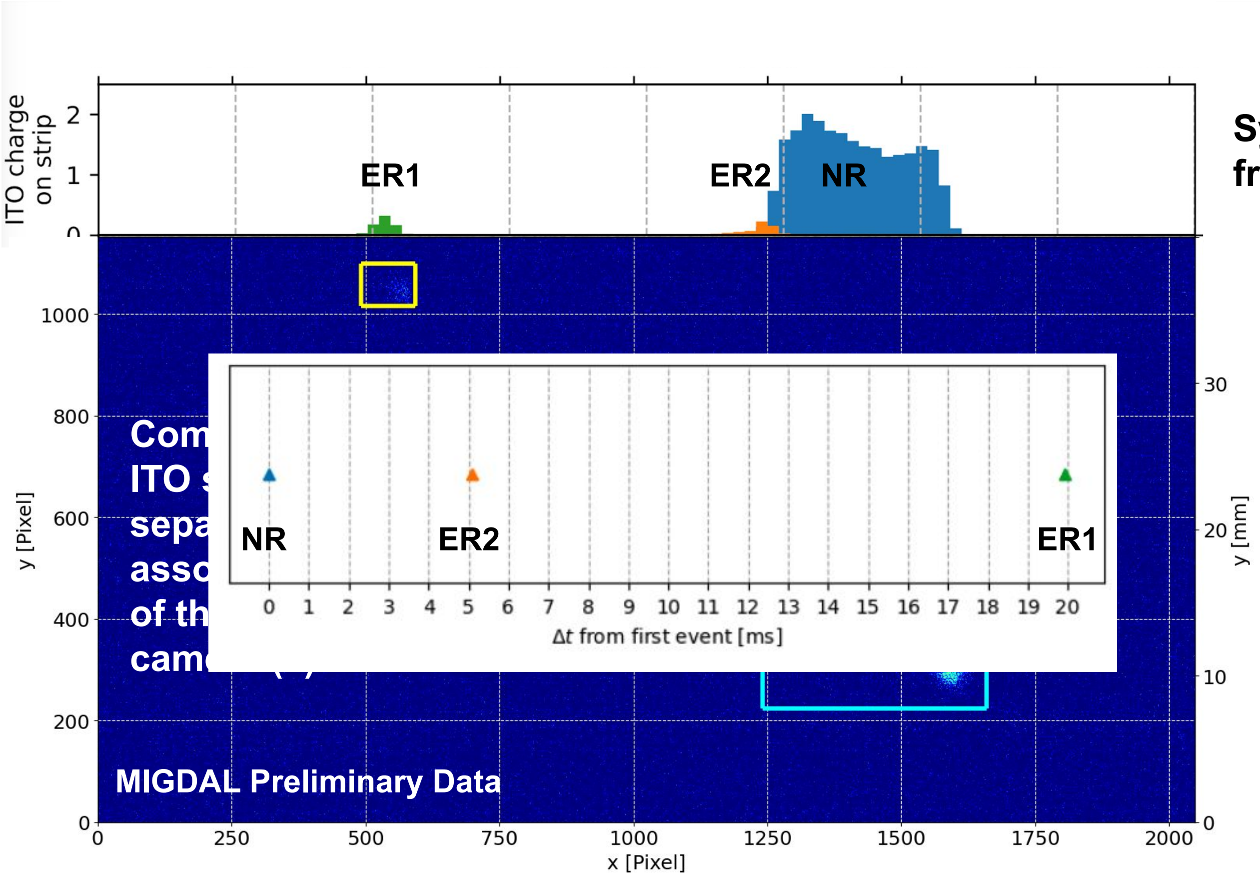


Examples of events (Migdal-like event)

Synchronised signals from ITO strips.



Examples of events (Migdal-like event)

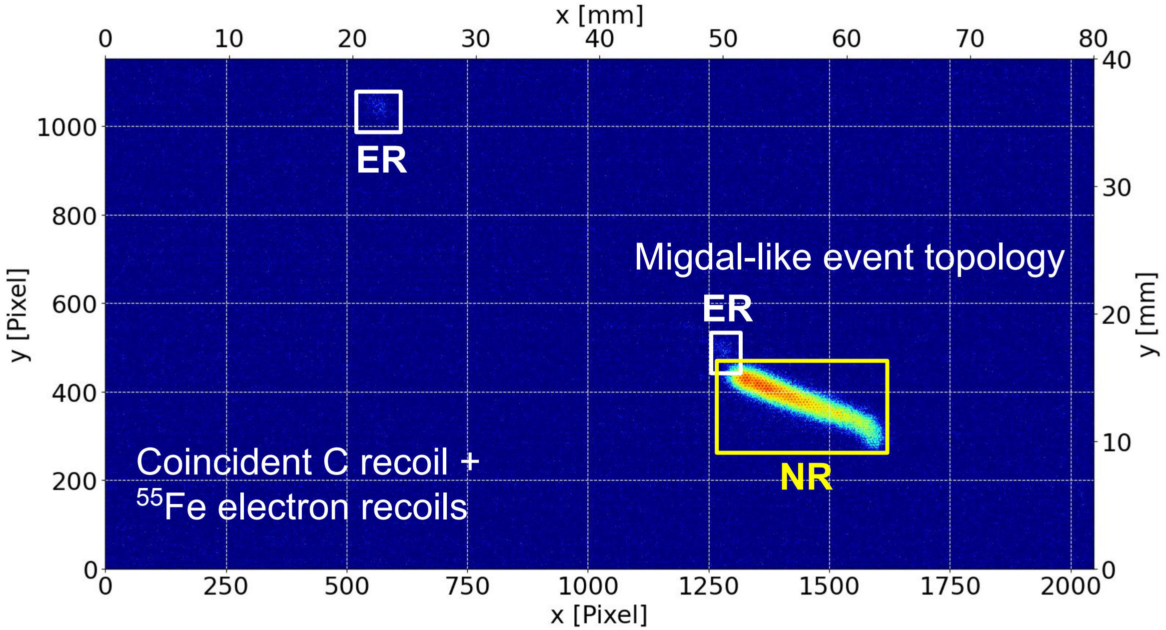


Synchronised signals from ITO strips.

Timing information from ITO strips separates all 3 tracks.

Enter 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



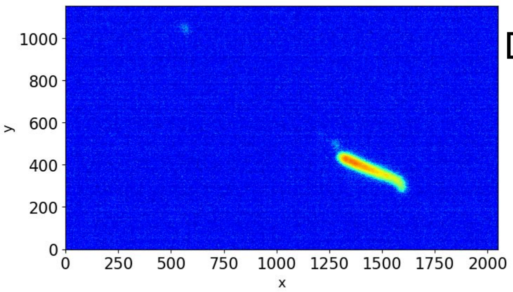
We train YOLOv8 on measured data *to identify ERs, NRs, protons, alphas, sparks, camera afterglow, rolling shutter, etc.*

Benefits:

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

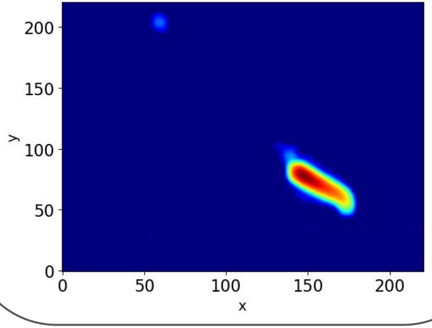
The data processing pipeline

(1) Dark subtracted image



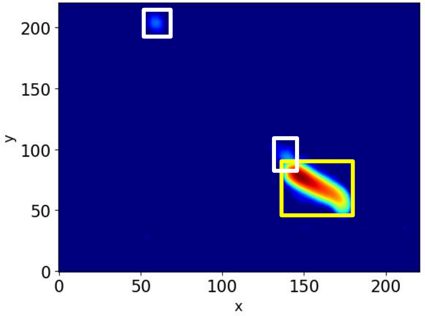
(2) Downsample

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!

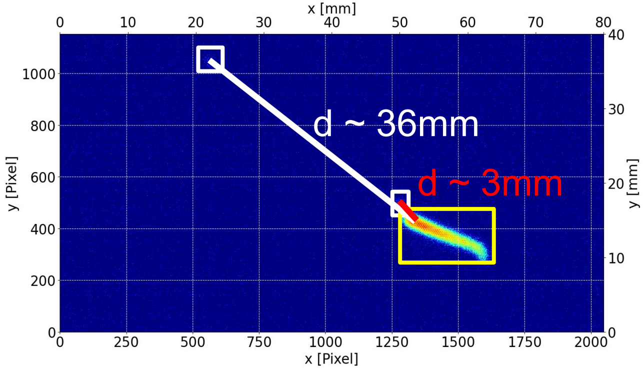
Application to MIGDAL searches

- 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
  - **20ms exposure → We expect coincidences in the camera frames**

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

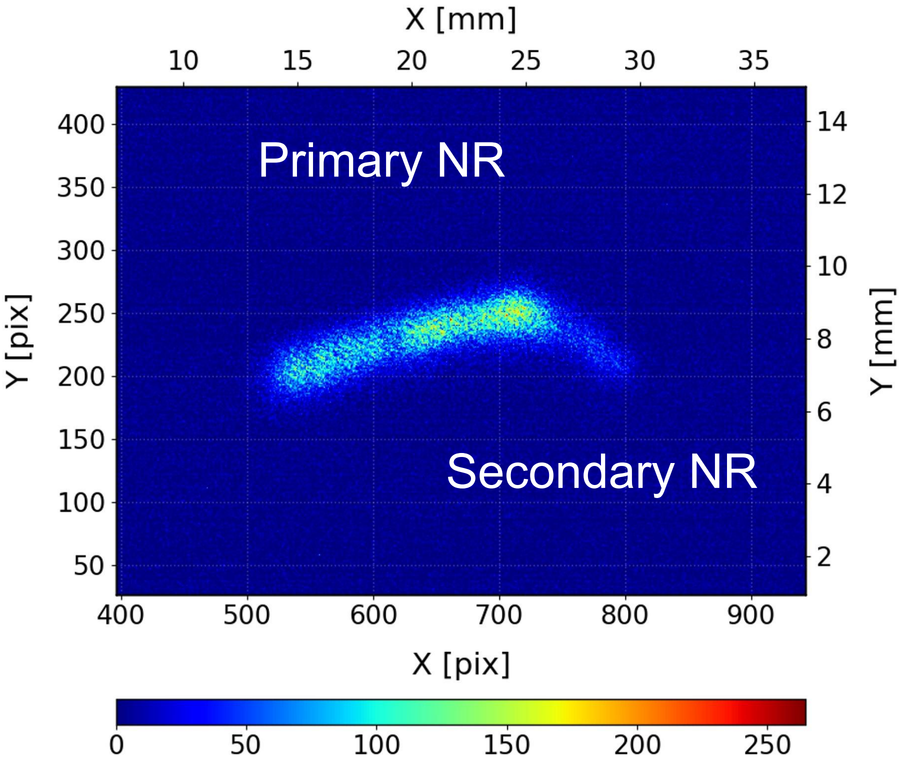
(2) Find frames containing at least 1 ER and 1 NR ***(~25,000 frames)***

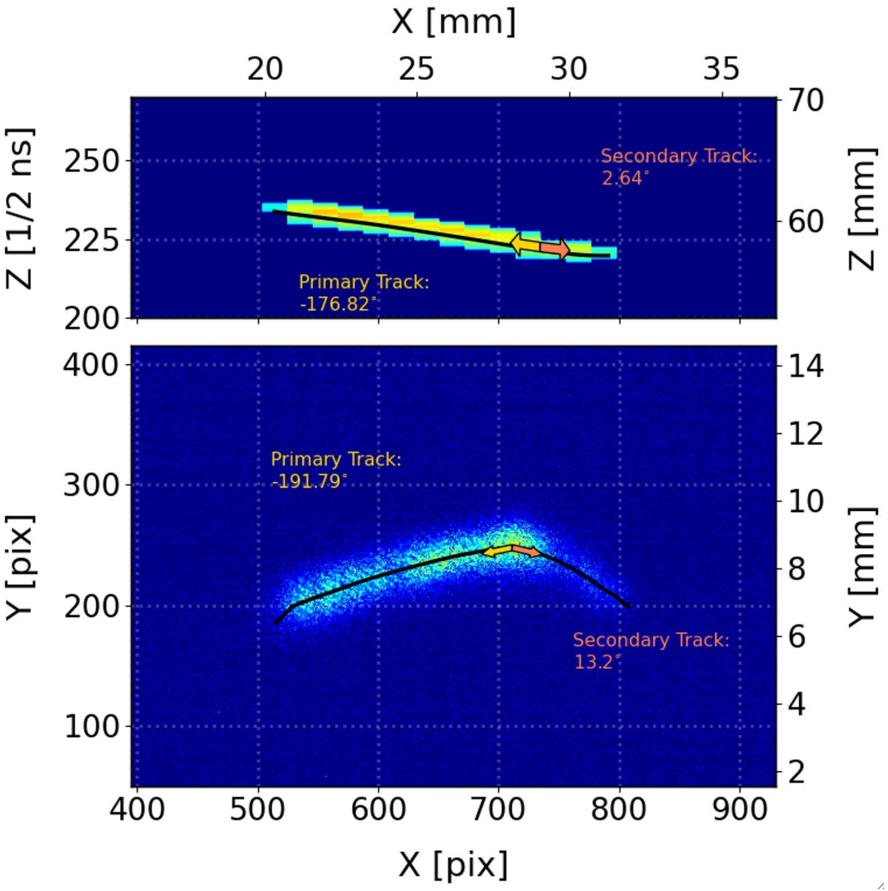
(3) Map bounding boxes to raw image and compute the distances between NR vertices and centers of ER bounding boxes



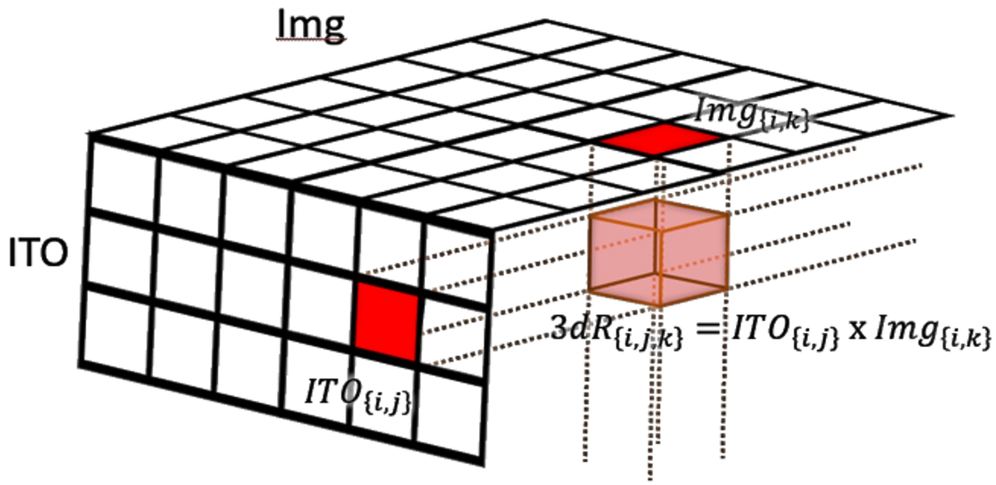
(4) Filter frames based on distance between ER and NR ***(~1,000 frames*** with d < 7.5mm and NR > 100 keV_{ee})

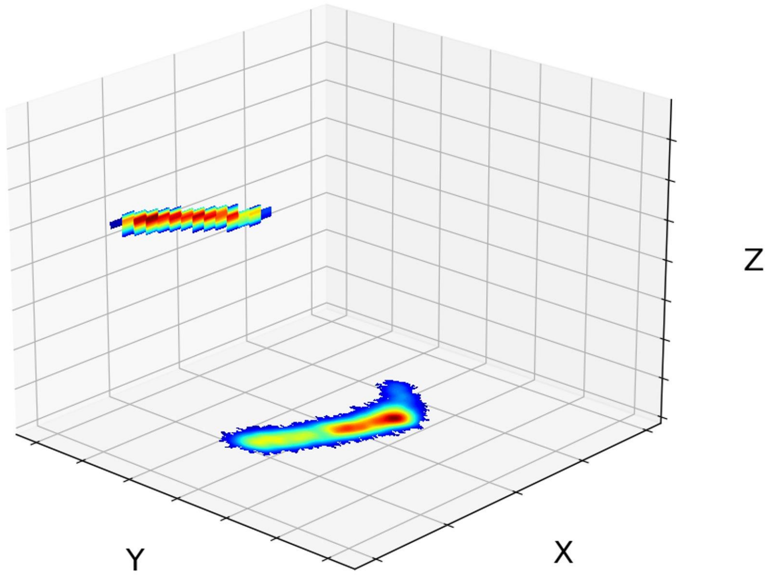
3D track reconstruction





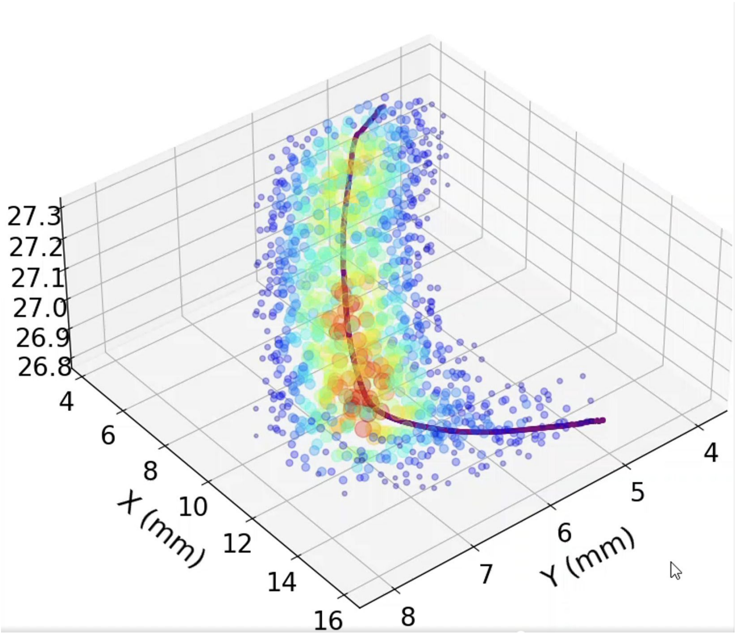
3D track reconstruction

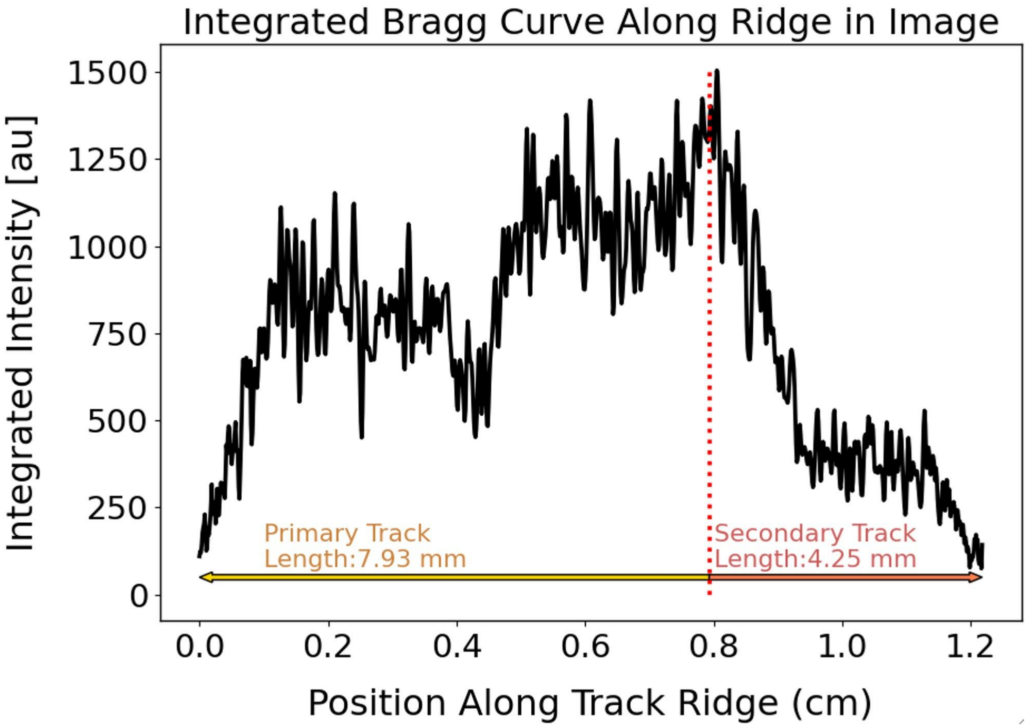




Stitching along common axis

3D track reconstruction





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 ionising NRs.
- More data to be taken later in September. Regular calibration runs performed.
- Analysis of recorded data underway.
- 50% of recorded data are blinded.
- Stay tuned for results !

Funding:

MIGDAL collaboration: U. Autonoma Madrid, U. Birmingham, GDD Group/CERN, U. Helsinki, Imperial College London, King's College London, LIP-Coimbra, U. New-Mexico, U. Oxford, Royal Holloway, Rutherford Appleton Laboratory, U. Sheffield (https://migdal.pp.rl.ac.uk)

Signal / background

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

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