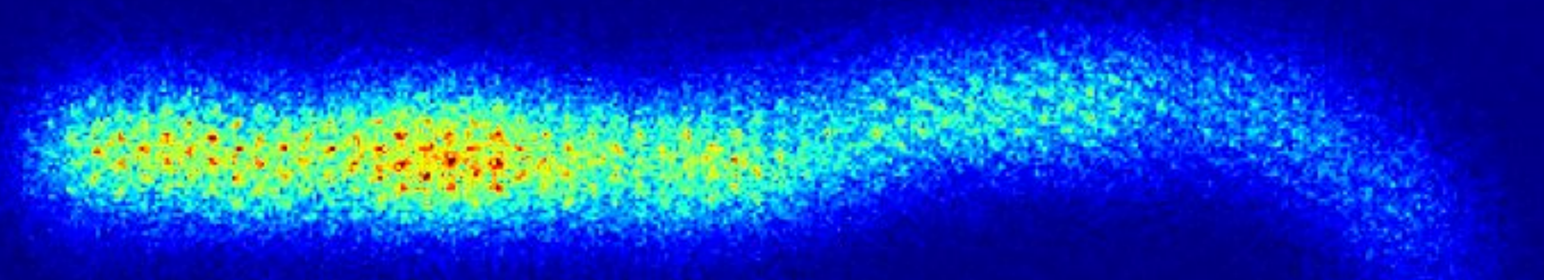
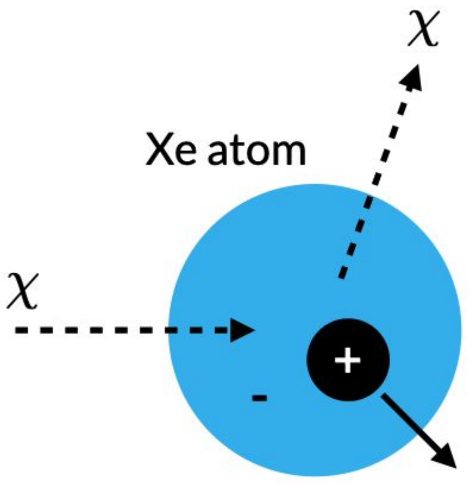
The Migdal effect for low-mass WIMP search

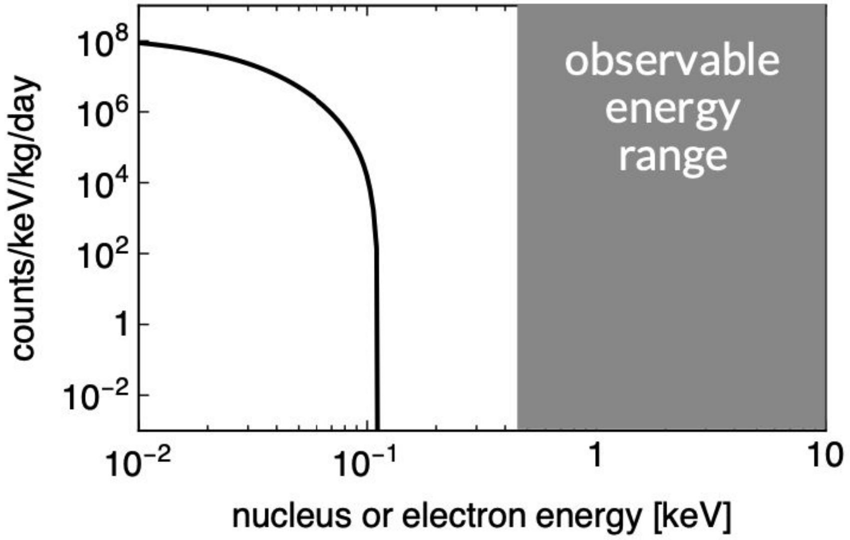


Pawel Majewski
STFC/Rutherford Appleton Laboratory
on behalf of the MIGDAL collaboration

11th Symposium on Large TPCs for low-energy rare event detection, 11-13 Dec 2023, Paris

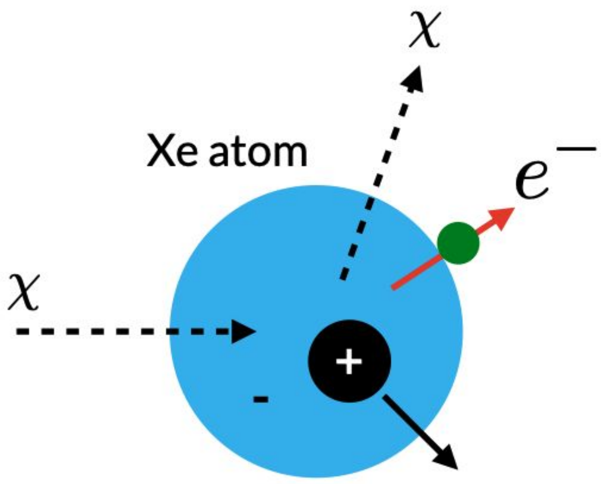


m_{DM} = 1 GeV
'Normal' nuclear scattering



Sudden displacement of a nucleus with respect to electrons.

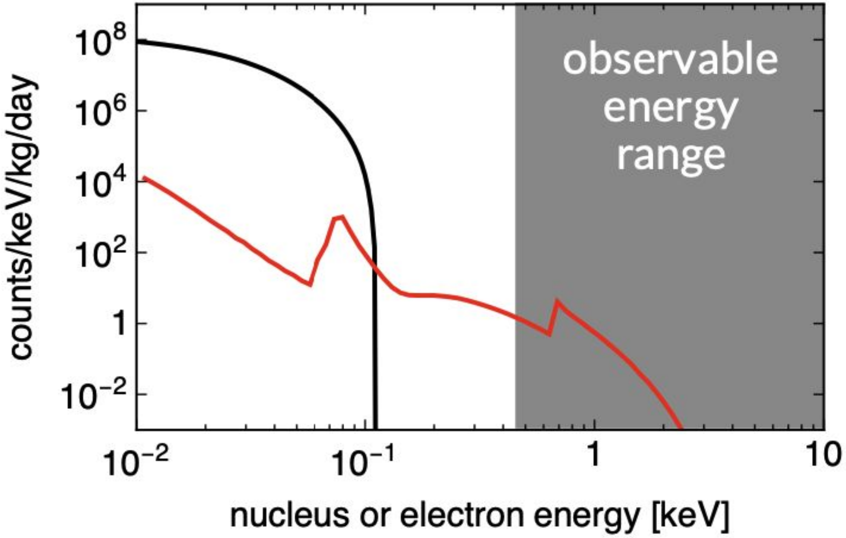
C. McCabe [PADUA talk]



m_{DM} = 1 GeV

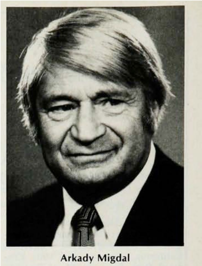
'Normal' nuclear scattering

+ Migdal effect (ionisation of 1 electron)

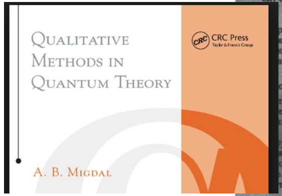


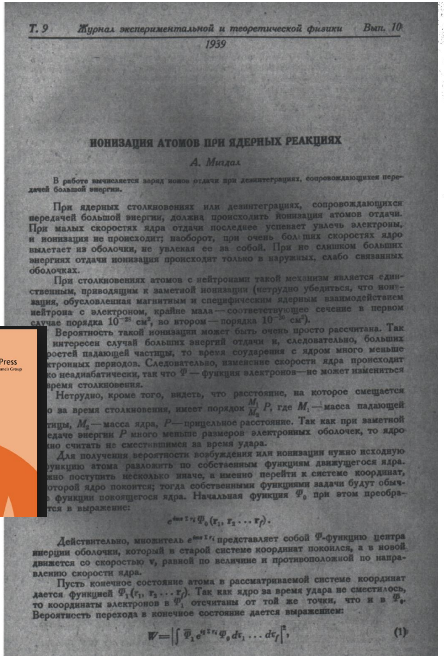
C. McCabe PADUA talk

What do we already know about the Migdal effect ?



Arkady Migdal





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

ИОНИЗАЦИЯ АТОМОВ ПРИ ЯДЕРНЫХ РЕАКЦИЯХ

А. Мигдал

В работе вычисляется заряд ионов отдачи при дезинтеграциях, сопровождающихся передачей большой энергии.

При ядерных столкновениях или дезинтеграциях, сопровождающихся передачей большой энергии, должна происходить ионизация атомов отдачи. При малых скоростях ядра отдачи последнее успевает увлечь электроны, и ионизация не происходит; наоборот, при очень больших скоростях ядро вылетает из оболочки, не увлекая ее за собой. При не слишком больших энергиях отдачи ионизация происходит только в наружных, слабо связанных оболочках.

При столкновениях атомов с нейтронами такой механизм является единственным, приводящим к заметной ионизации (нетрудно убедиться, что ионизация, обусловленная магнитным и специфическим ядерным взаимодействием нейтрона с электроном, крайне мала — соответствующее сечение в первом случае порядка 10^{-28} см^2, во втором — порядка 10^{-30} см^2).

Вероятность такой ионизации может быть очень просто рассчитана. Так
интересен случай больших энергий отдачи и, следовательно, больших
ростей падающей частицы, то время соударения с ядром много меньше
ктронных периодов. Следовательно, изменение скорости ядра происходит
ко неадиабатически, так что Φ — функция электронов — не может измениться
время столкновения.

Нетрудно, кроме того, видеть, что расстояние, на которое смещается
о за время столкновения, имеет порядок $\frac{M_1}{M_2}P$, где M_1 — масса падающей
тицы, M_2 — масса ядра, P — прицельное расстояние. Так как при заметной
едаче энергии P много меньше размеров электронных оболочек, то ядро
жно считать не сместившимся за время удара.

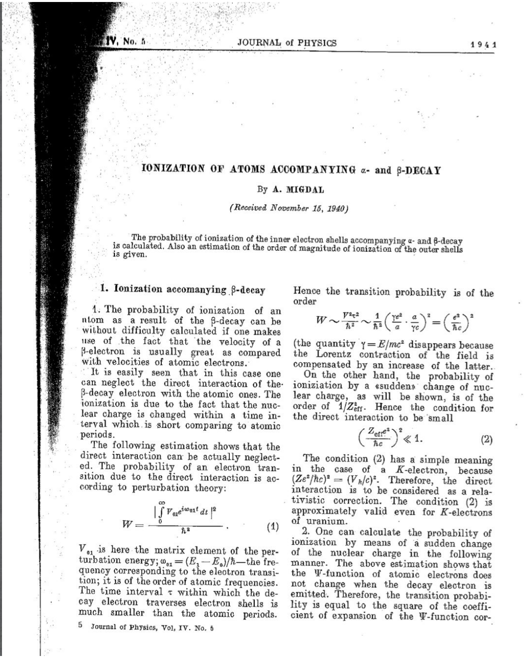
Для получения вероятности возбуждения или ионизации нужно исходную
ункцию атома разложить по собственным функциям движущегося ядра.
жно поступить несколько иначе, а именно перейти к системе координат,
оторой ядро покоится; тогда собственными функциями задачи будут обыч-
функции покоящегося ядра. Начальная функция Φ_0 при этом преобра-
тся в выражение:

$$e^{imv\Sigma r_i}\Phi_0(\mathbf{r}_1, \mathbf{r}_2 \dots \mathbf{r}_f).$$

Действительно, множитель $e^{imv\Sigma r_i}$ представляет собой Φ-функцию центра инерции оболочки, который в старой системе координат покоился, а в новой движется со скоростью $\mathbf{v}$, равной по величине и противоположной по направлению скорости ядра.

Пусть конечное состояние атома в рассматриваемой системе координат дается функцией $\Phi_1(r_1, \mathbf{r}_2 \dots \mathbf{r}_f)$. Так как ядро за время удара не сместилось, то координаты электронов в Φ_1 отсчитаны от той же точки, что и в Φ_0. Вероятность перехода в конечное состояние дается выражением:

$$W = \left|\int \overline{\Phi}_1 e^{iq\Sigma r_i}\Phi_0\, d\tau_1 \dots d\tau_f\right|^2, \tag{1}$$



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 accomanying 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-decay 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:

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

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

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

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-

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

A. Migdal publications:

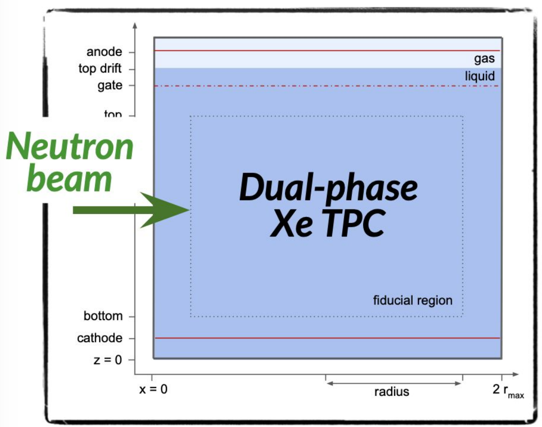
- Ionisation in nuclear reactions [1]
- Ionisation in radioactive decays [2]

First observations of the Migdal effect in :

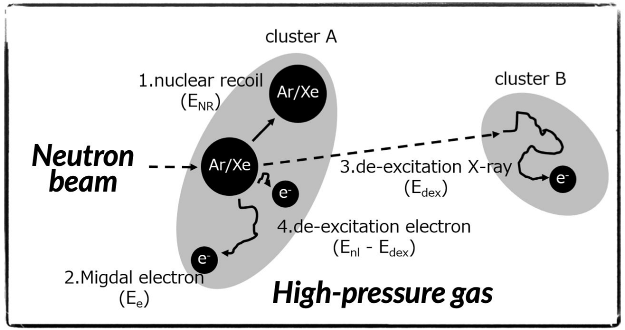
- Alpha decay [3,4]
- Beta decay [5]
- Positron decay [6]
- Nuclear scattering [ ]

[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 ^{6}He$^+$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)*

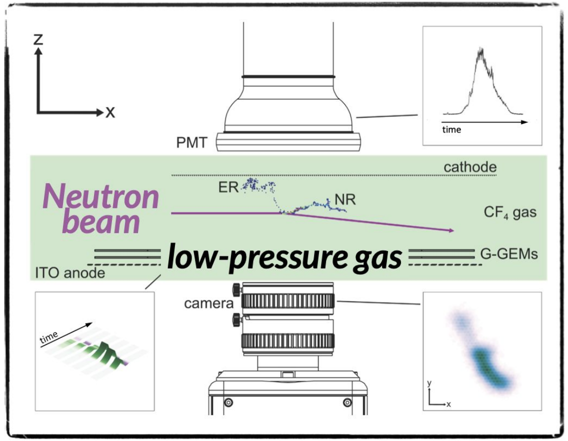
Migdal effect searches in liquid/gases using neutron scattering



1. Dense medium.
2. NR+EL transitions in close proximity.
3. Signal from enhanced S1 and S2 due to X-rays from L and M shells.
4. Experiment at LLNL with fast neutrons from DT generator.
5. LZ experiment at SURF with fast neutrons from DD generator.

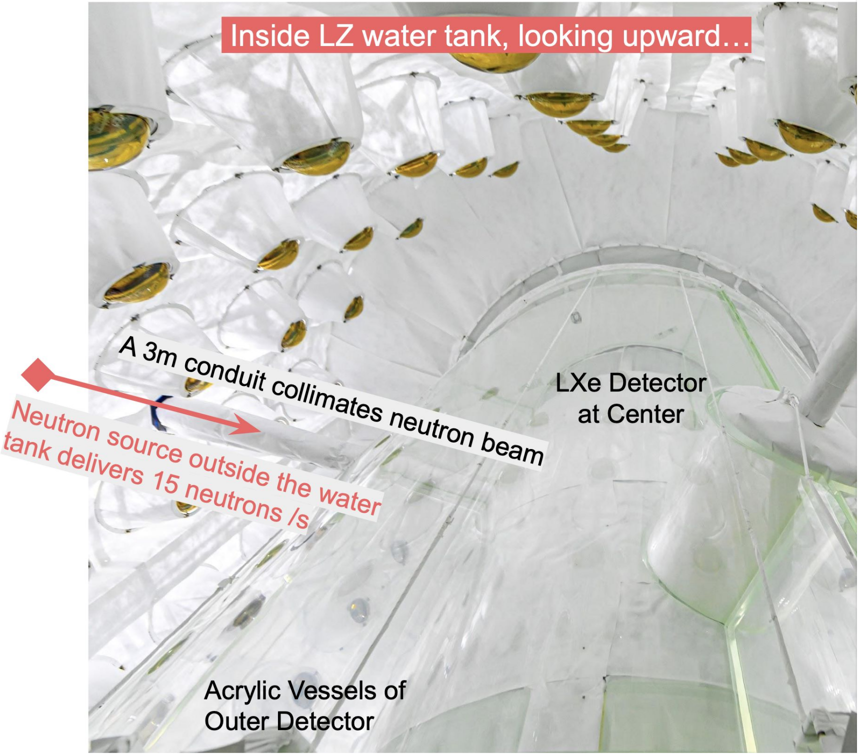


1. High pressure Ar (1 bar) and Xe (5 bar).
2. Looking for two-cluster signals from NR+Migdal electron (cluster A). and characteristic X-ray (cluster B).
3. Experiment at in Tsukuba with 565 keV neutrons from ^{7}Li(p, n)^{7}Be reaction at an irradiation facility at the National Institute of Advanced Industrial Science and Technology (AIST), Japan.



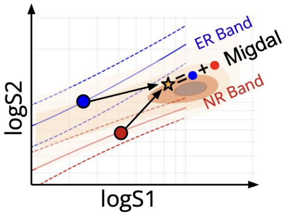
1. Low pressure operation at 66 mbar.
2. Enough mass as a target for fast neutrons from DD/DT neutron generators.
3. NR and electrons tracks with 5 keV threshold long enough for optical detection to provide direction and dE/dx information.
4. Experiment at ISIS/NILE (UK).

Migdal effect searches in liquid/gases using neutron scattering. LZ experiment with DD neutron generator.

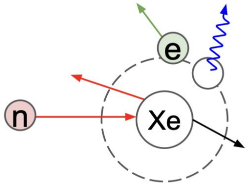


SIGNAL

Migdal : **Signal**



ER component boosts the signal above the NR band.



MFP of e- or x-ray from L or M shell Migdal is <<1 mm close to NR site → single S2 (SS)

Simulations:

1. N shell Migdal is too similar to NR

2. M Shell: Expected 152 events, with +1 keVee 3

L Shell: Expected 6 events, with +5 keVee

4. K shell Migdal is too few

Results:

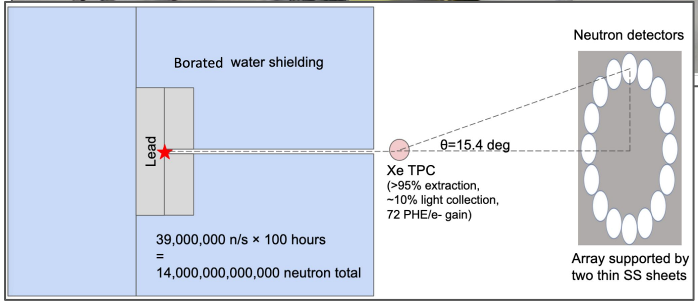
1. Collected 36k single scatter events E>20 keVnr (after cuts)

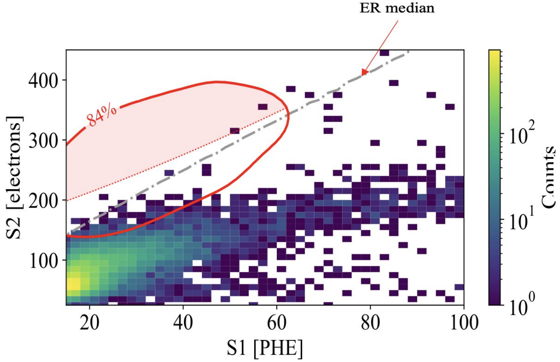
2. Main backgrounds: multiple scatters and inelastic scattering together with compton scattering with unresolved position

3. In preliminary high-S2 region analysis, observing 23 events on a background 9.6±0.5(sys). Observed excess consistent with Migdal signal predicted by Ibe and Cox. Profile Likelihood Ratio (PLR) analysis is being finalised.

J. Bang, A. Vaitkus, C. Ding on behalf of the LZ Collaboration at UCLA Dark Matter 2023 03/31/2023

Migdal effect searches in liquid/gases using neutron scattering. Experiment at ILL with DT neutron generator.



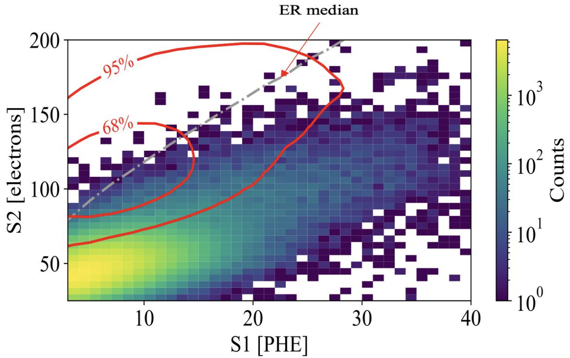


Data set used for the L-shell Migdal interaction (E_{ER}>0.5keV) search

5.7+/-1.2 signals expected

2 events observed

2.1+/0.9 backgrounds expected

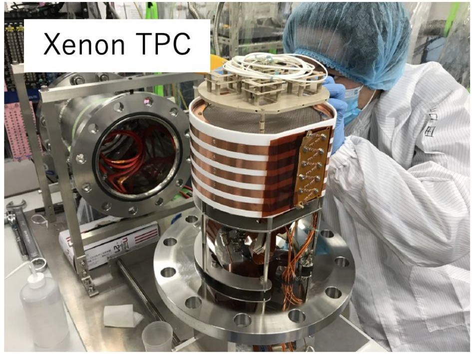


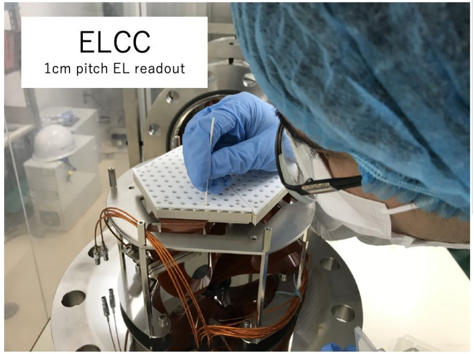
Data set used for the M-shell Migdal interaction (E_{ER}>0.5keV) search

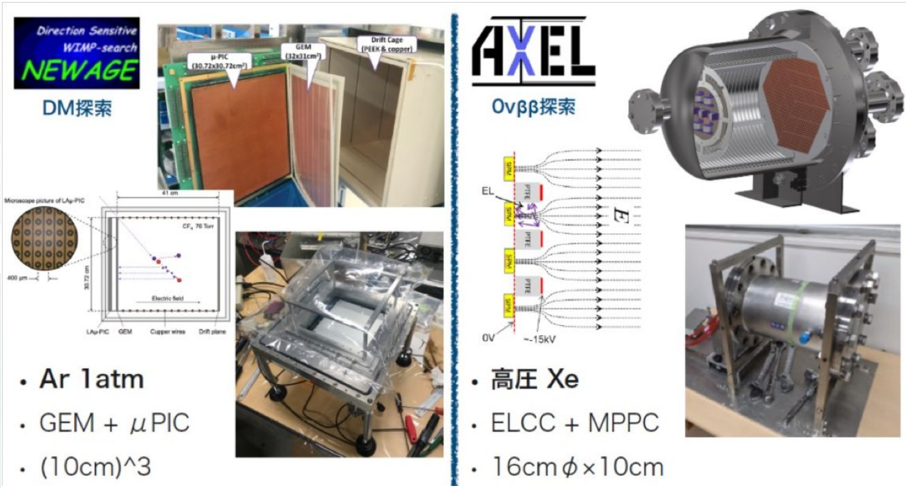
~10 times fewer Migdal events estimated by fit than prediction, statistically consistent with 0 signals

1. Jingke Xu, Experimental result on measuring the Migdal effect with neutron-induced nuclear recoils at the keV level in liquid xenon; UCLA Dark Matter 2023 03/31/2023
2. https://arxiv.org/abs/2307.12952

Migdal effect searches in Ar and Xe using neutron scattering. MIRACLUE experiment with ^{7}Li(p, n)^{7}Be neutron beam.







- **Ar 1atm**
- GEM + μPIC
- (10cm)^3

- **高圧 Xe**
- ELCC + MPPC
- 16cmφ×10cm

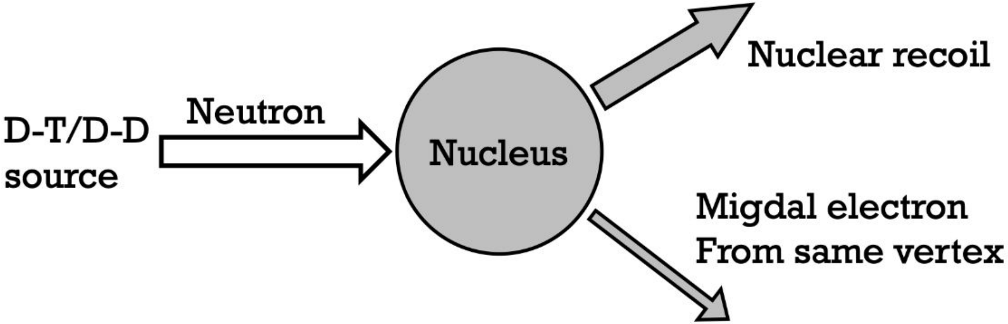
Detector tests:

1. Xenon TPC worked with neutron beam successfully
2. Energy & topology were measured
3. Analysis for Migdal branching is ongoing
4. Argon TPC: planning neutron test for Jan 2024

K. Nakamura et al. Detection capability of the Migdal effect for argon and xenon nuclei with position-sensitive gaseous detectors
Progress of Theoretical and Experimental Physics, Volume 2021, Issue 1, January 2021, 013C01, https://doi.org/10.1093/ptep/ptaa162

The MIGDAL experiment

Create a dedicated experiment for the *unambiguous* observation of the Migdal effect in nuclear scattering:

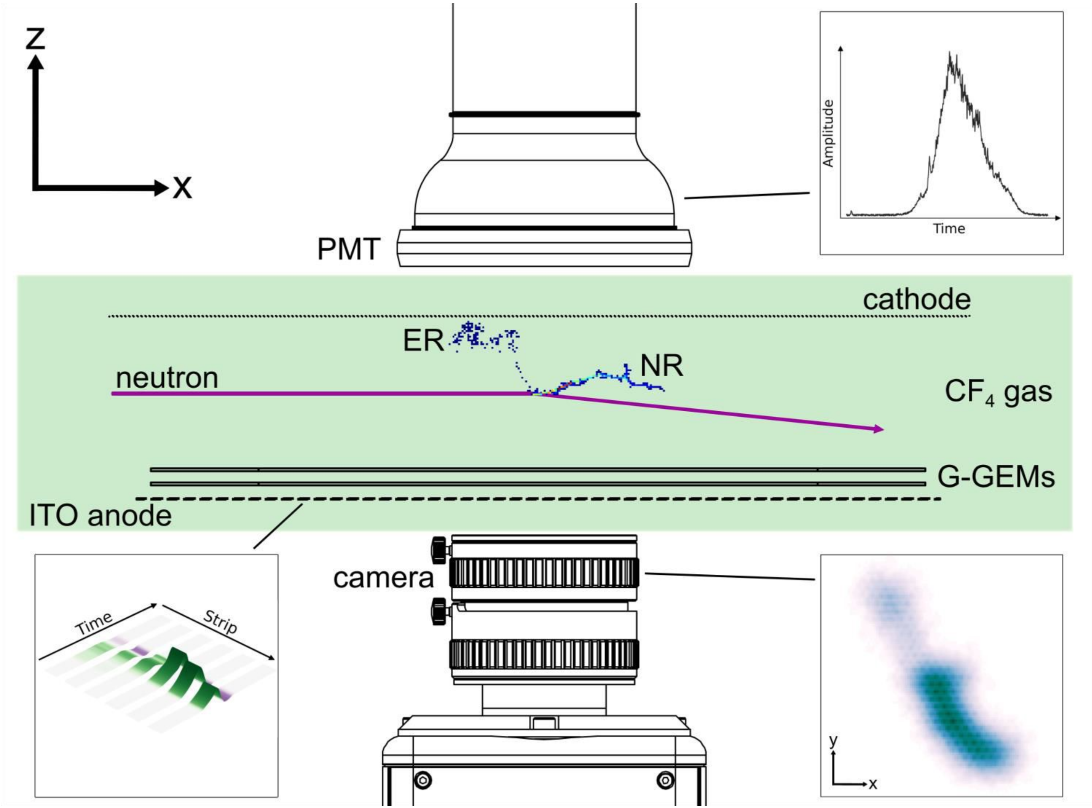


We are the only experiment aiming to observe the nuclear and electron recoils emerging from a common vertex

- Phase 1: Observe the effect in CF4 in high energy recoils
- Phase 2: Observe the Migdal effect in CF4 + noble gases

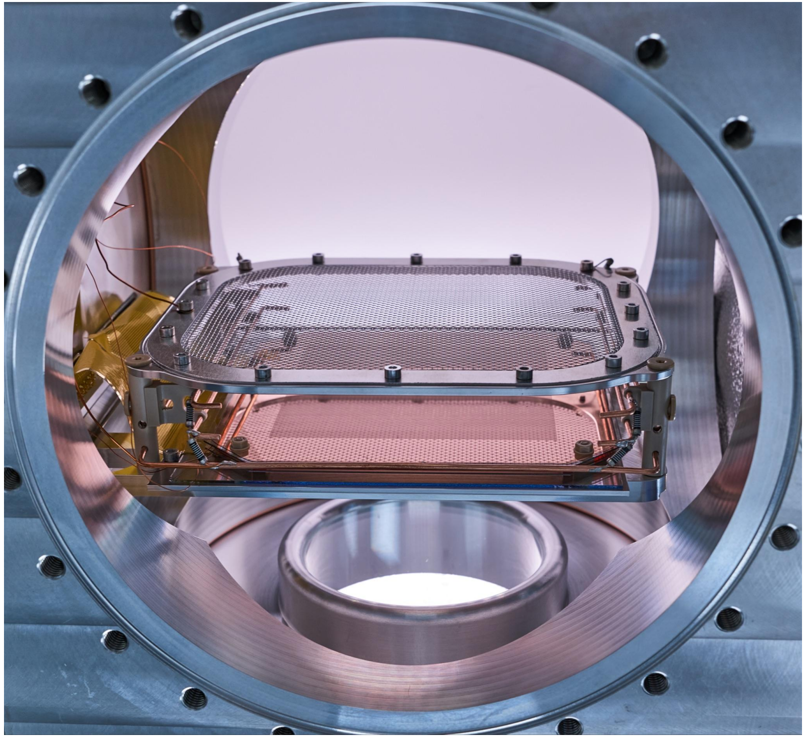
H. Araujo et al.,The MIGDAL experiment: Measuring a rare atomic process to aid the search for dark matter.

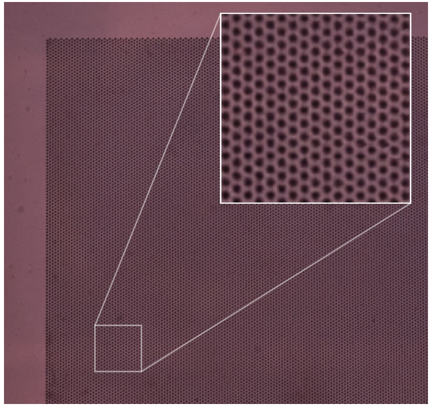
The MIGDAL experiment

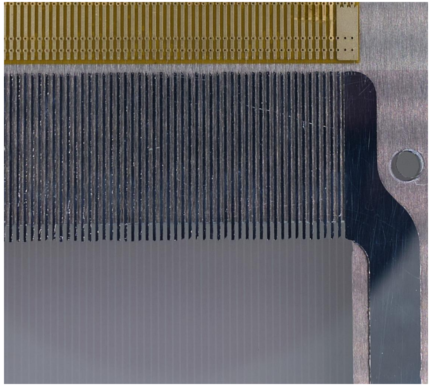


- Low-pressure gas: 50 Torr of CF$_4$
  - Extended particle tracks
  - Avoid gamma interactions
  - Can stably work with fraction of Ar
- TPC Signal amplification
  - 2 x glass-GEMs (Cu + Ni cladded)
- Readout :
  - Optical : Camera + photomultiplier tube
  - Charge: GEMs + 120 ITO anode strips
- High-yield 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.

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

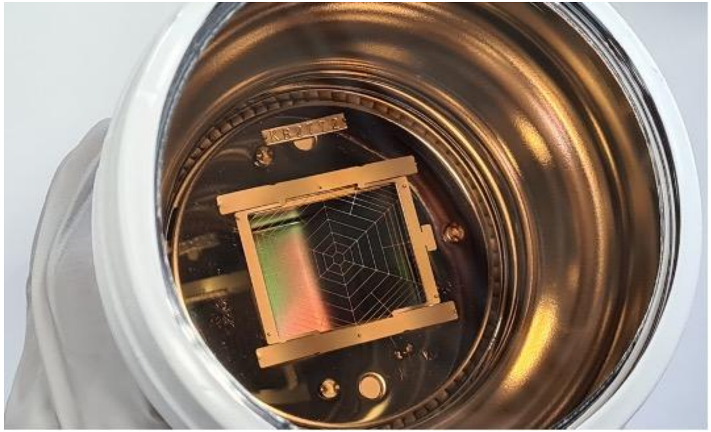
- 120 strips

- 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

Light and charge readout

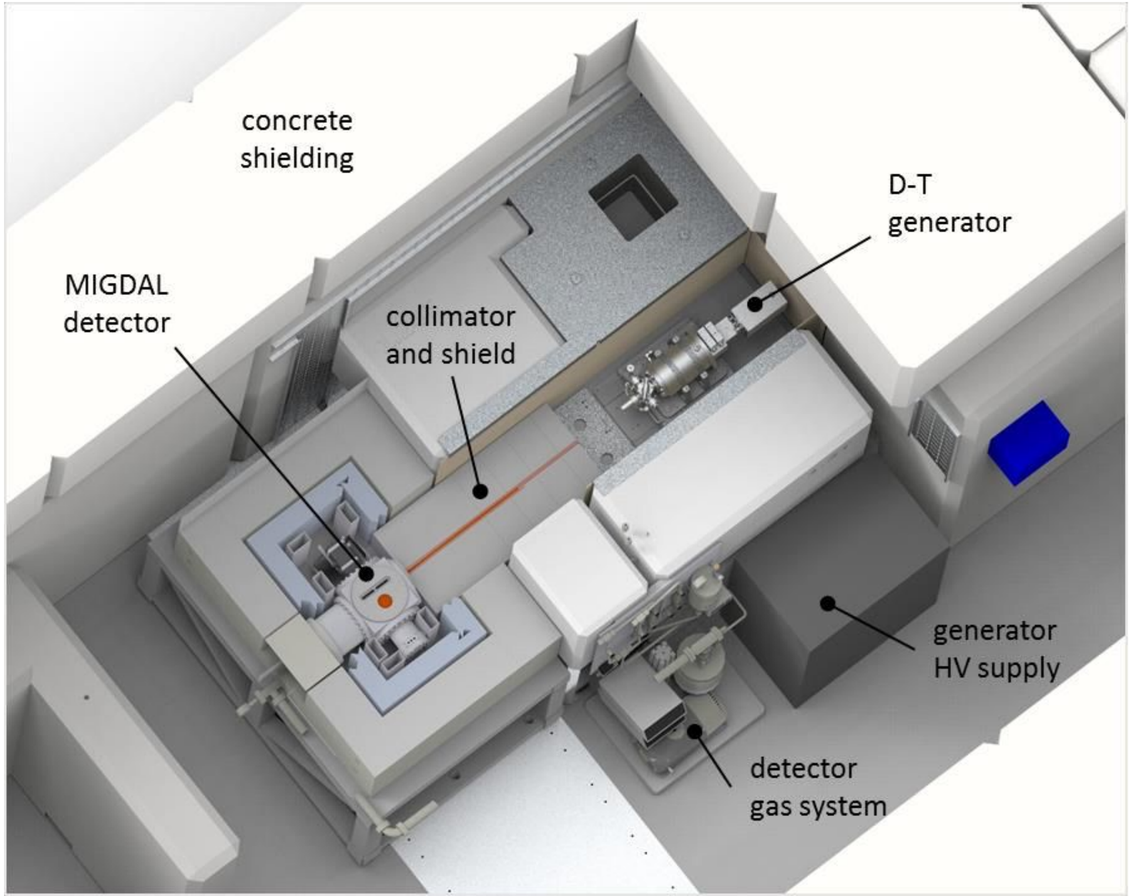


ITO anode strips
Post-GEM ionisation
Readout of (x,z) plane
Pitch: 833 μm
Digitised at 2 ns/sample
(Drift velocity: 130 μm/ns*)*

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]

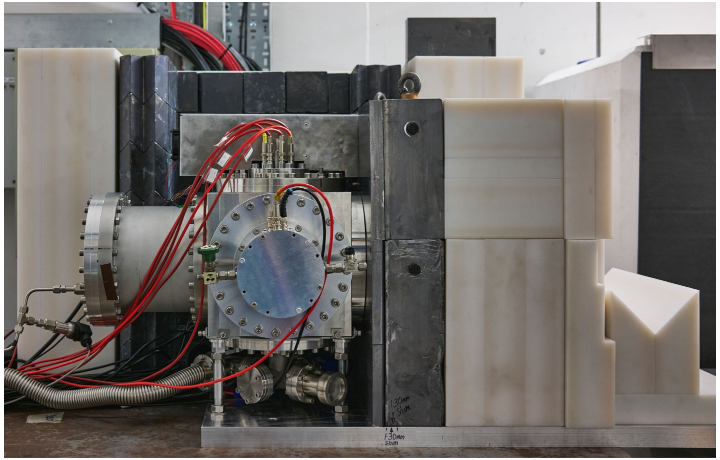
The NILE facility at Rutherford Appleton Laboratory

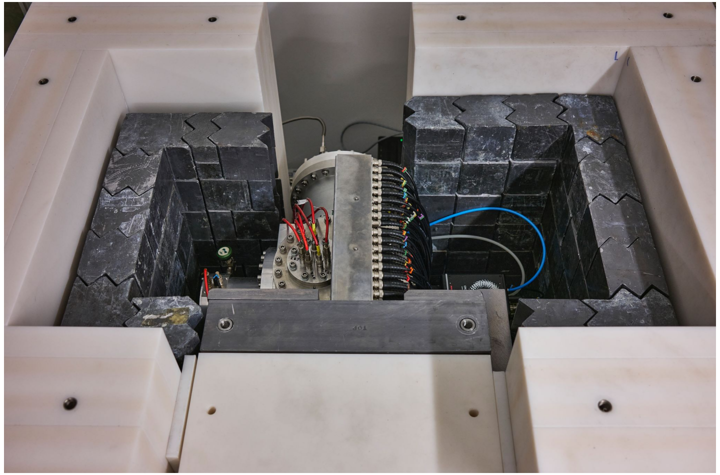


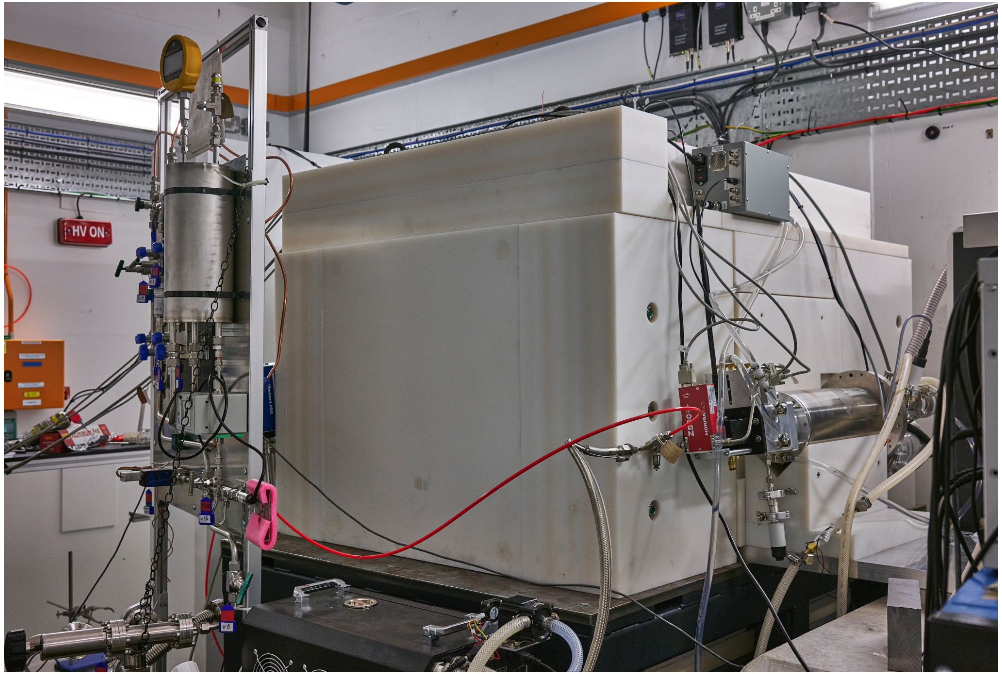
Experiment setup with D-T generator

- D-D and D-T fusion generators installed in “shielding bunker”
- Collimators & additional shielding provide clean beam through OTPC
- D-T collimator 1 m, D-D 30 cm

Experiment installation in the NILE bunker





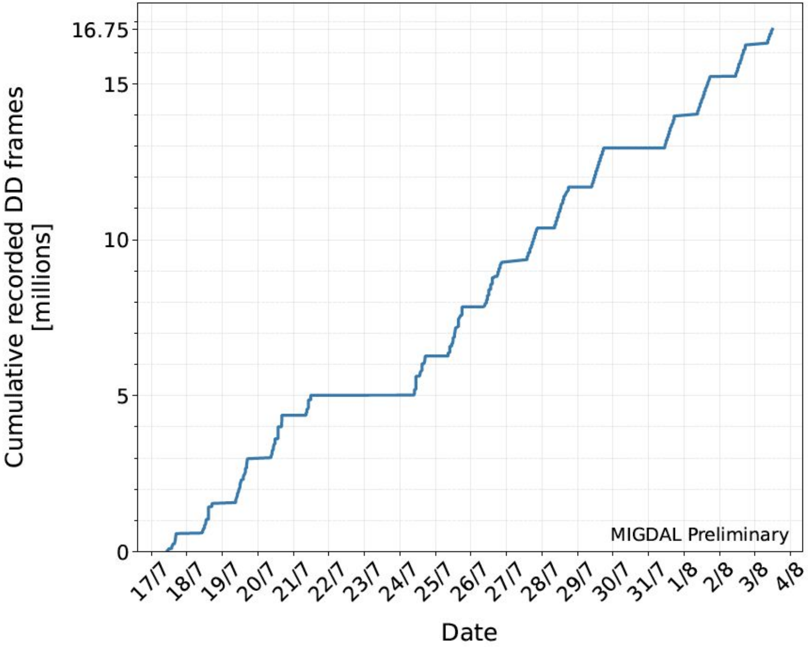


MIGDAL experiment fully assembled at NILE

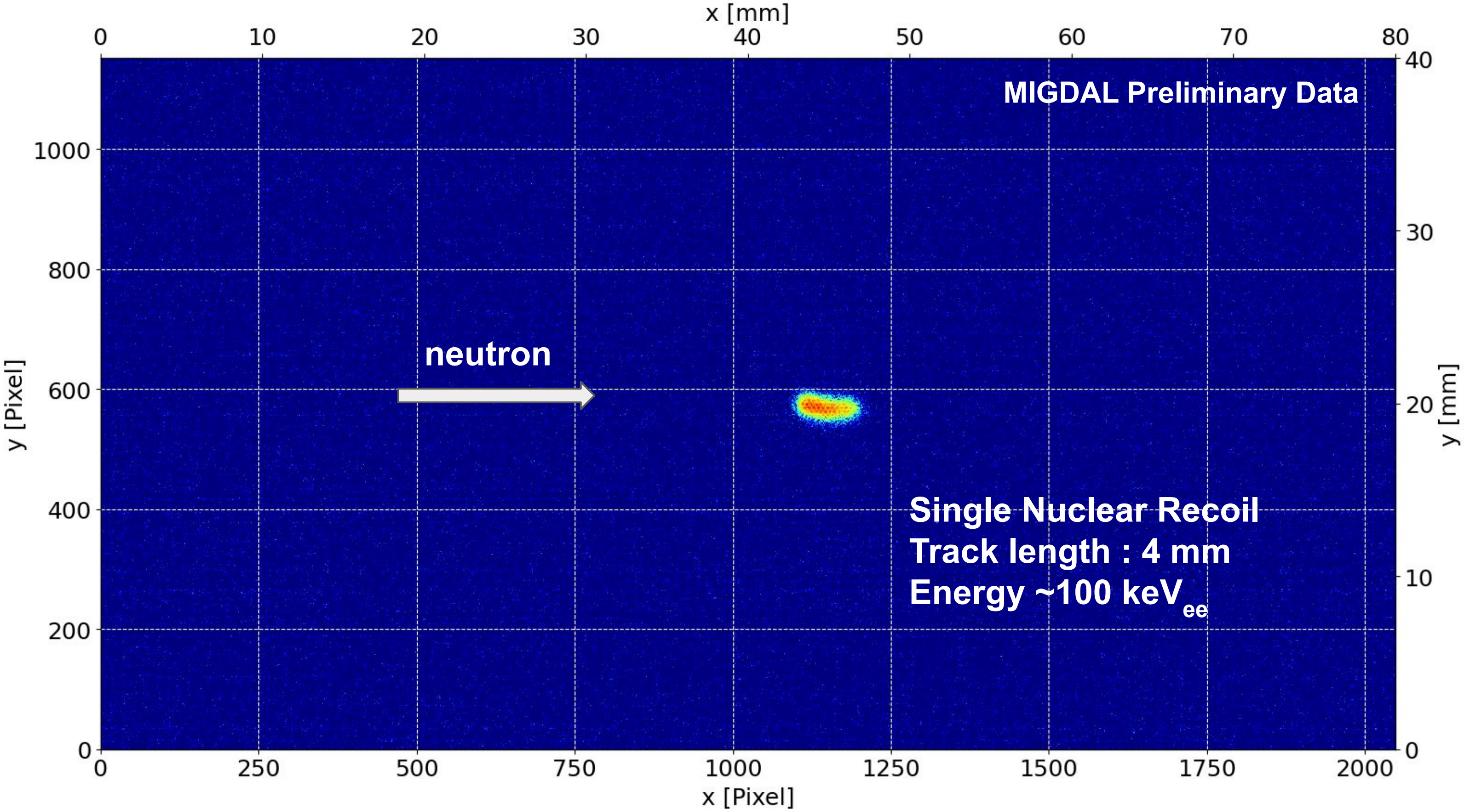
- Lead shield : 10 cm
- Borated HDPE shield : 20 cm
- Collimator HDPE+ lead : 30 cm long

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.

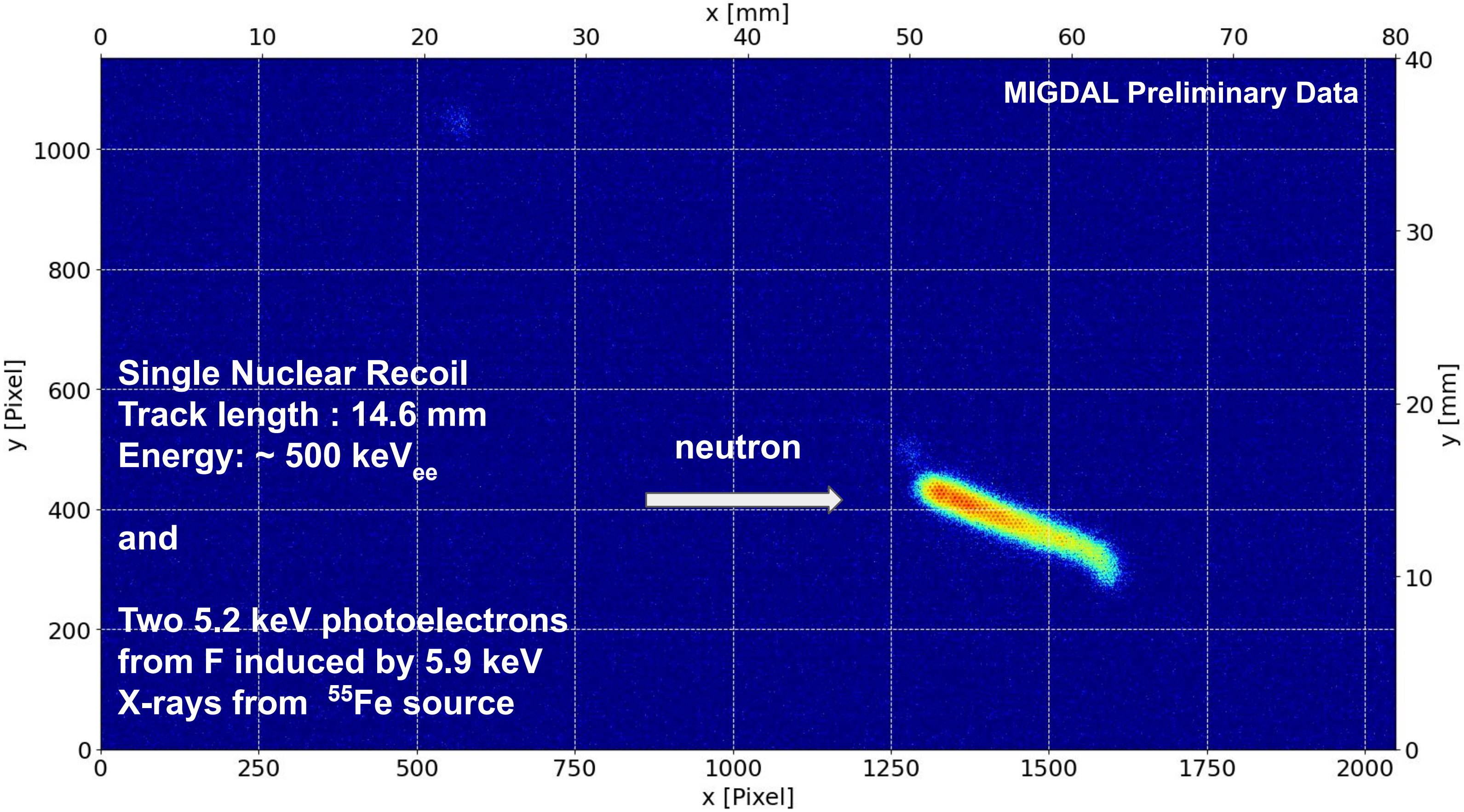


Examples of events (Single Nuclear Recoil)



Single Nuclear Recoil
Track length : 4 mm
Energy ~100 keV_{ee}

Examples of events (Migdal-like event)



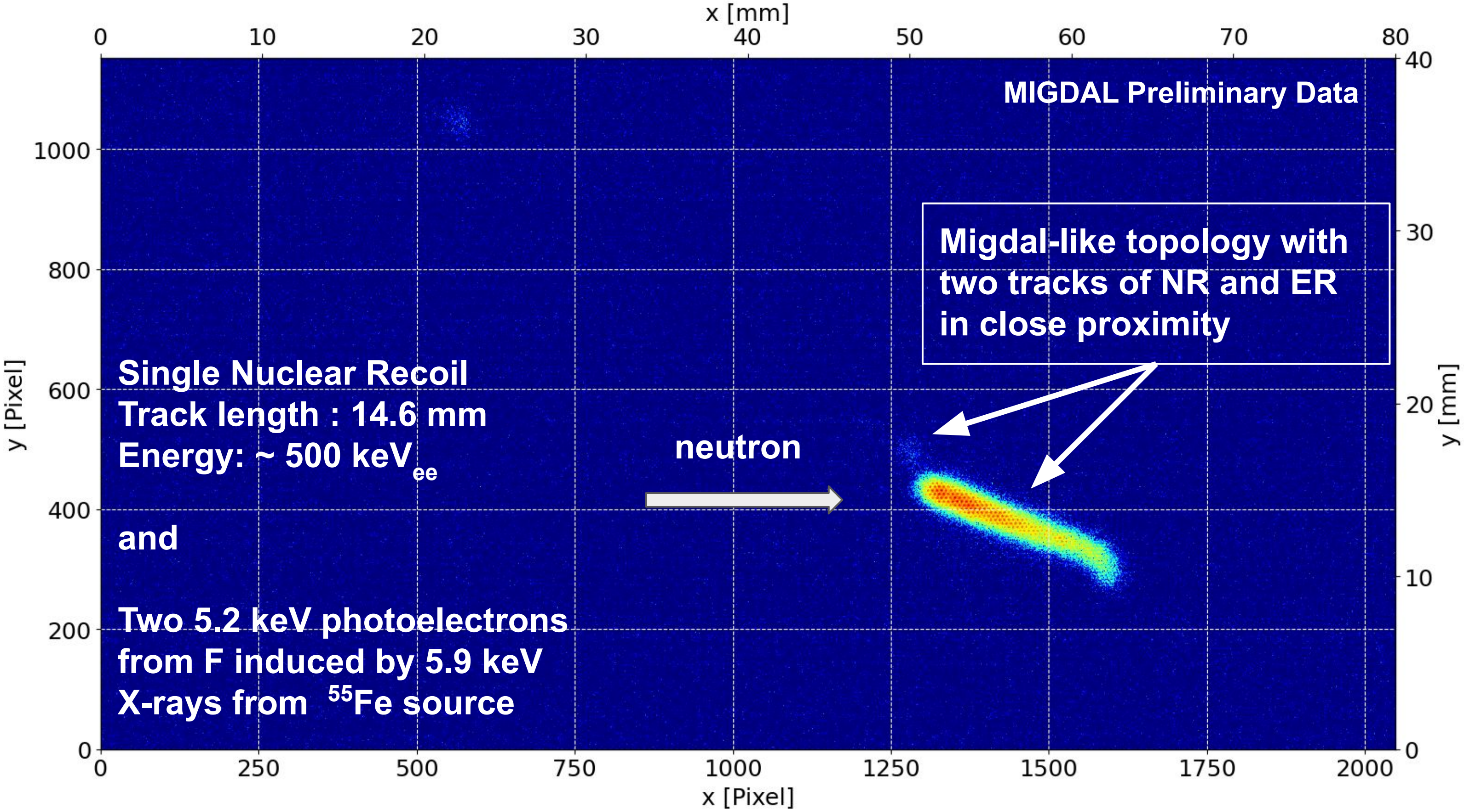
MIGDAL Preliminary Data

Single Nuclear Recoil
Track length : 14.6 mm
Energy: ~ 500 keV_{ee}

and

Two 5.2 keV photoelectrons
from F induced by 5.9 keV
X-rays from ^{55}Fe source

Examples of events (Migdal-like event)



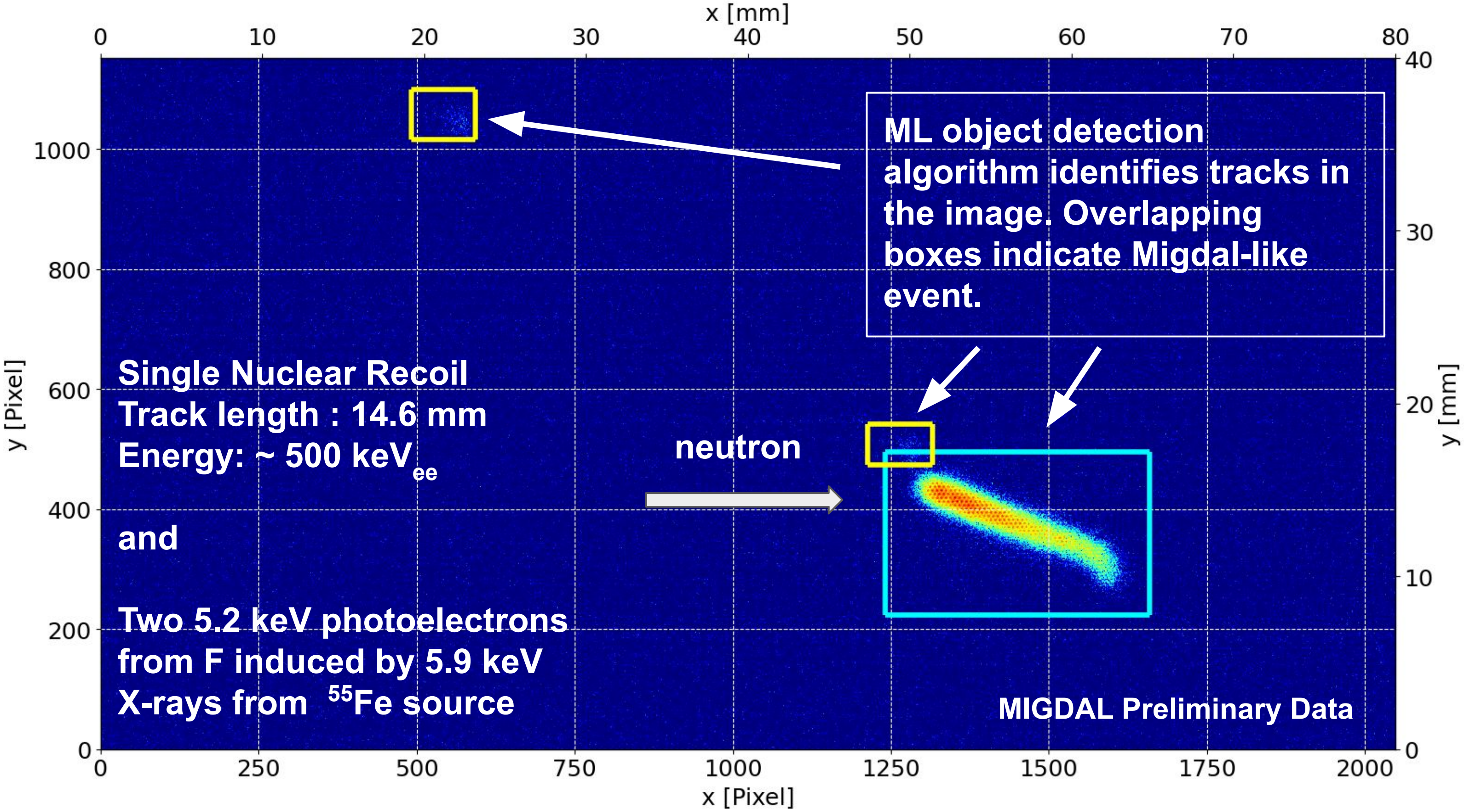
Single Nuclear Recoil
Track length : 14.6 mm
Energy: ~ 500 $\mathrm{keV_{ee}}$

and

Two 5.2 keV photoelectrons
from F induced by 5.9 keV
X-rays from ^{55}Fe source

Migdal-like topology with two tracks of NR and ER in close proximity

Examples of events (Migdal-like event)



ML object detection algorithm identifies tracks in the image. Overlapping boxes indicate Migdal-like event.

Single Nuclear Recoil
Track length : 14.6 mm
Energy: ~ 500 keV_{ee}

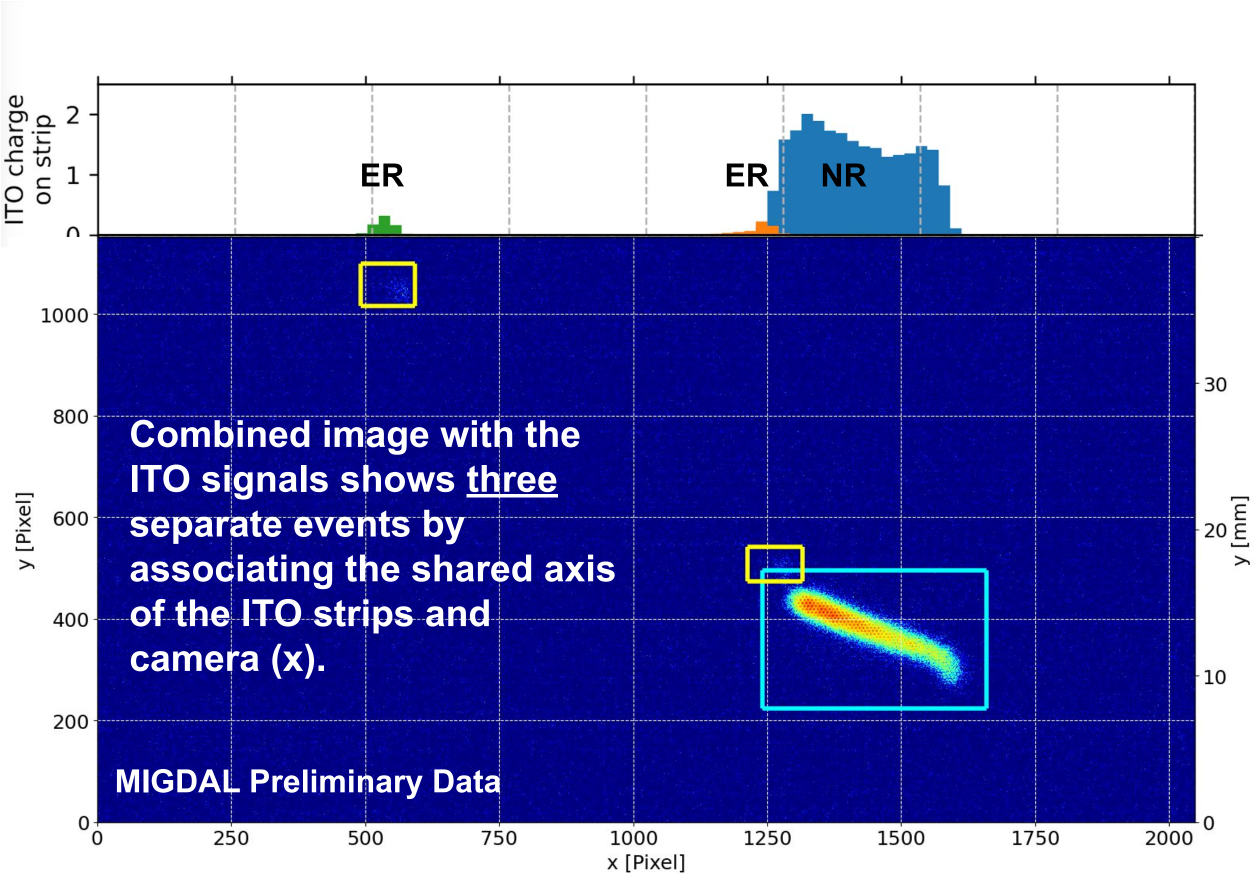
and

Two 5.2 keV photoelectrons from F induced by 5.9 keV X-rays from ^{55}Fe source

MIGDAL Preliminary Data

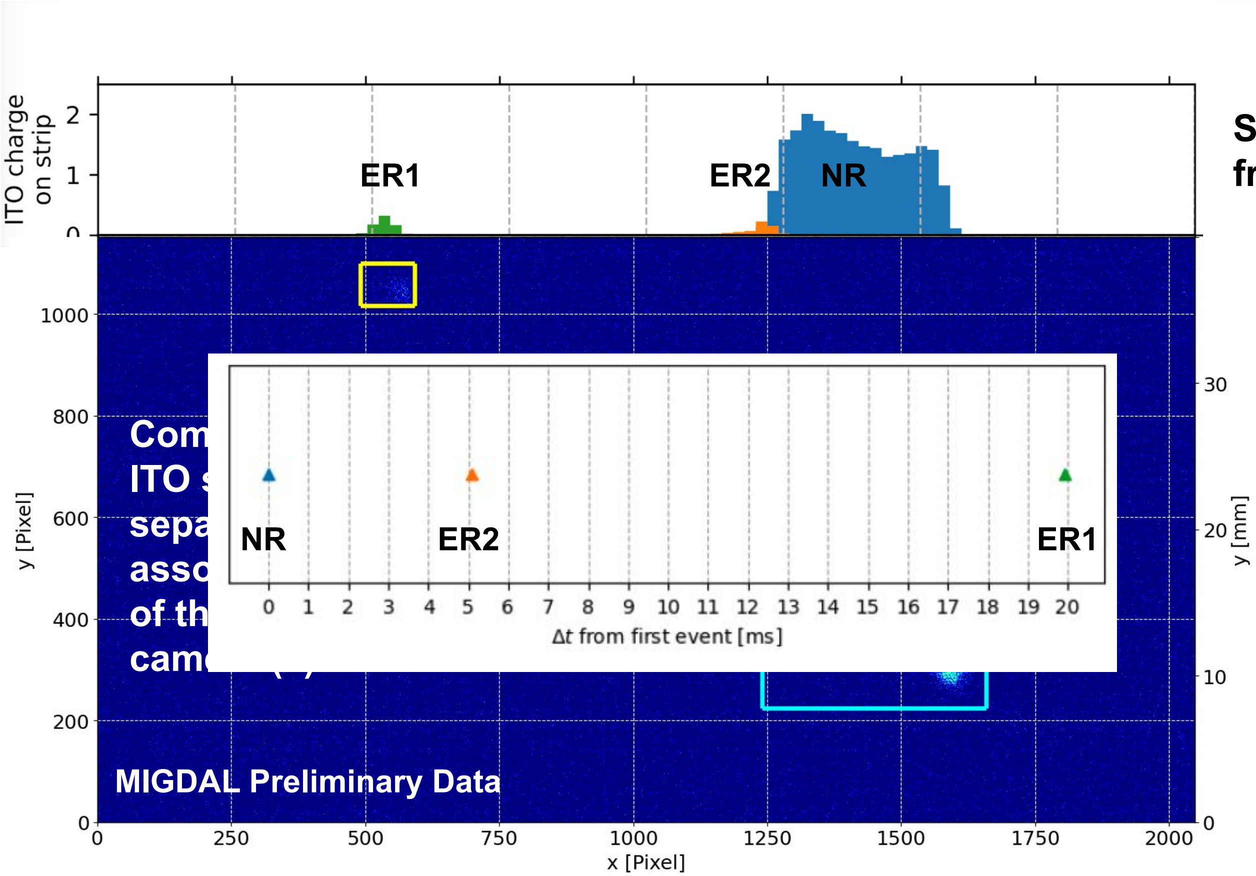
Examples of events (Migdal-like event)

Synchronised signals from ITO strips.



Combined image with the ITO signals shows <u>three</u> separate events by associating the shared axis of the ITO strips and camera (x).

Examples of events (Migdal-like event)

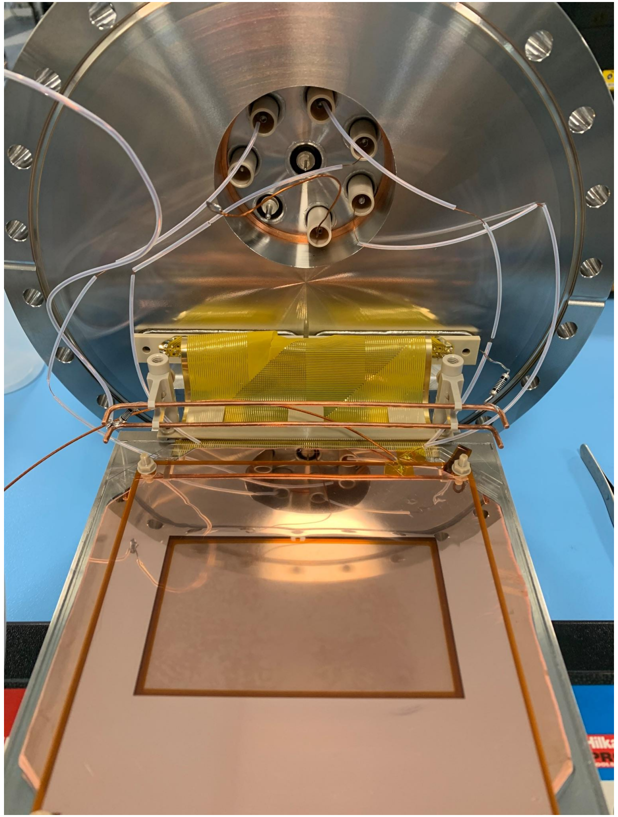


Synchronised signals from ITO strips.

Timing information from ITO strips separates all 3 tracks.

Improvements for the Second Science Run (SSR)

1. Fixed communication between DAQ PC and camera - use CoaXPress instead of UBS decreasing exposure time from 20 ms to 8.3 ms - less chance for coincidence events.
2. Fixed missing bonded connection to central ITO strips.
3. Use FPGA to record timing information of every trigger also within 3 ms of DAQ dead time.
4. New GEMs w/o metallisation around mounting holes
5. Use of mask limiting events detected by the ITO strips without being seen by the camera
6. At the later stage of the SSR - use of a new collimator increasing NR rate x3.



Summary

- Several experiments using different detection techniques search for the Migdal effect.
- Effect is investigated in light atoms like C and F as well as in heavier Ar and Xe.
- We have first results from experiments using LXe (LZ and experiment at LLNL).
- Early next year we should hear results from MIRACLUE using high pressure TPC filled with gaseous Xe at high pressure.
- The MIGDAL experiment’s 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.
- Analysis of recorded data underway with 50% of recorded data kept blinded.
- Second Science Run planned for January.