MIGDAL

Migdal In Galactic Dark mAtter expLoration

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

Dr. Tom Neep, on behalf of the MIGDAL collaboration

EPS-HEP, Hamburg

August 24, 2023

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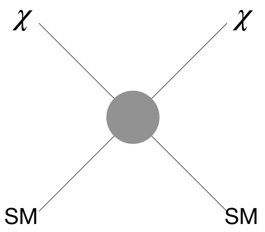
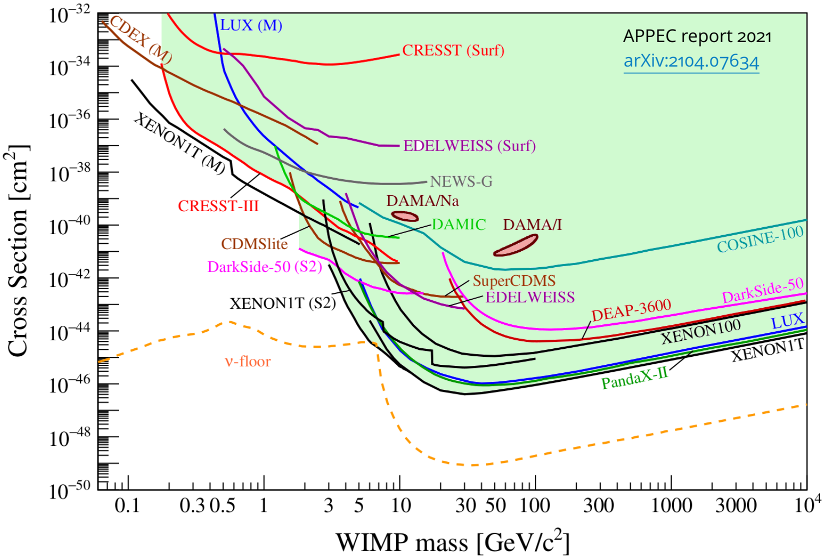
The (WIMP) Dark Matter landscape

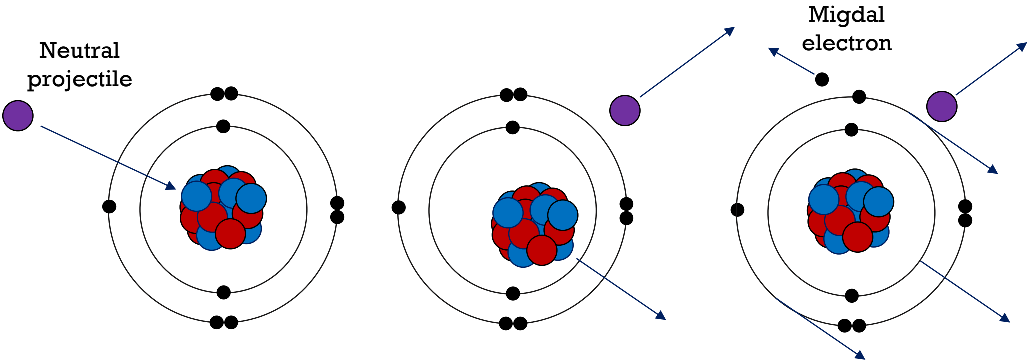


- Direct dark matter searches have made great strides in excluding WIMP-like dark matter
- Increasing interest in pushing towards lower masses, $\mathcal{O}(100\ \mathrm{MeV})$



The Migdal effect

- Typically we assume that the electron cloud in an atom move instantaneously with a nuclear recoil
- In reality the electrons take a short amount if time to catch up with the recoiling nucleus
- This can cause ionisation and excitation of the atoms, emission of one or more **Migdal electrons** (with very low probability)
- Electronic recoil detection increases the sensitivity of our detectors to light WIMPs
- First described by A. Migdal in 1939 A. Migdal, ZhETF, 9, 1163-1165 (1939), ZhETF, 11, 207-212 (1941)



The Migdal effect

- The Migdal effect has been observed in:
  - α decay ✓ Phys. Rev. C 11 (1975), 1740-1745, Phys. Rev. C 11 (1975), 1746-1754
  - β^- decay ✓ Phys. Rev. 93 (1954), 518-523
  - β^+ decay ✓ Phys. Rev. A 97 (2018), 023402
- **However,** it has not yet been observed in nuclear scattering, the key process we want to use it in
- **In fact,** recent attempts to measure the effect in nuclear scattering have returned conflicting results

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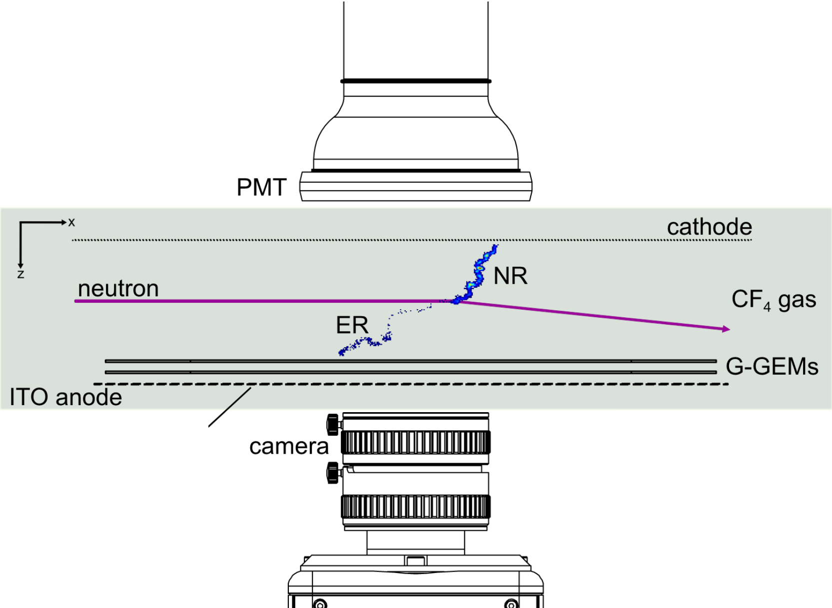
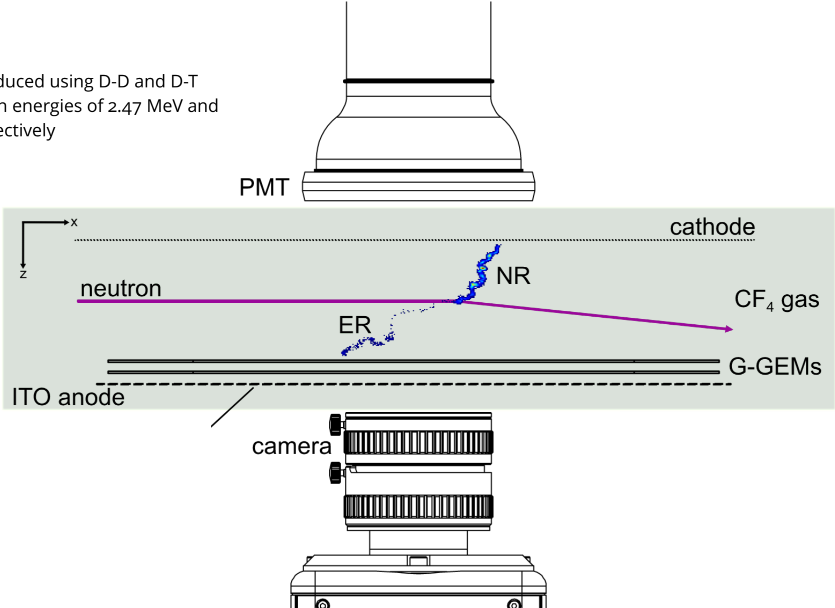
- The **M**igdal **I**n **G**alactic **D**ark M**A**tter Exp**L**oration experiment aims to make an unambiguous observation of the Migdal effect in nuclear scattering using an optical time projection chamber
- **Two phases:**
  1. Measure the Migdal effect in pure **Carbon tetrafluoride** (CF_4)
  2. Observe the Migdal effect in CF_4 + **other gas (Ar, Xe, . . .)** mixtures
- **Searching** for nuclear recoils with accompanying electronic recoils from the same vertex

The MIGDAL detector: An Optical TPC



The MIGDAL detector: An Optical TPC

- **Neutrons** produced using D-D and D-T generators with energies of 2.47 MeV and 14.7 MeV, respectively



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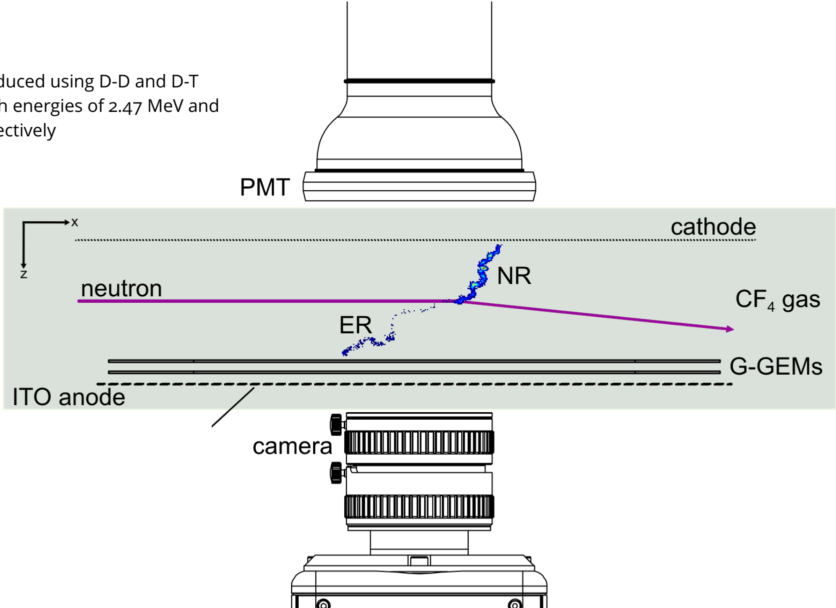

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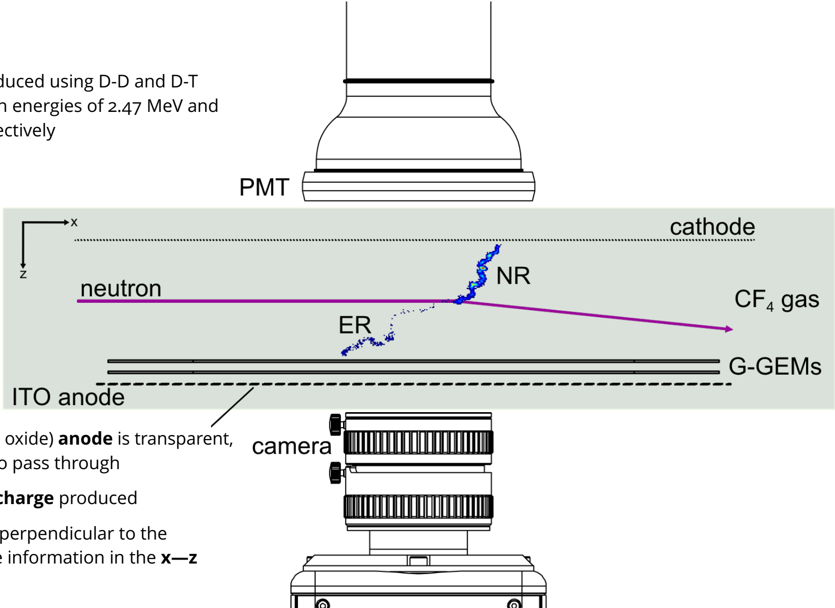

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- **ITO** (Indium tin oxide) **anode** is transparent, allowing light to pass through
- Measures the **charge** produced
- Strips running perpendicular to the x-direction give information in the **x—z plane**

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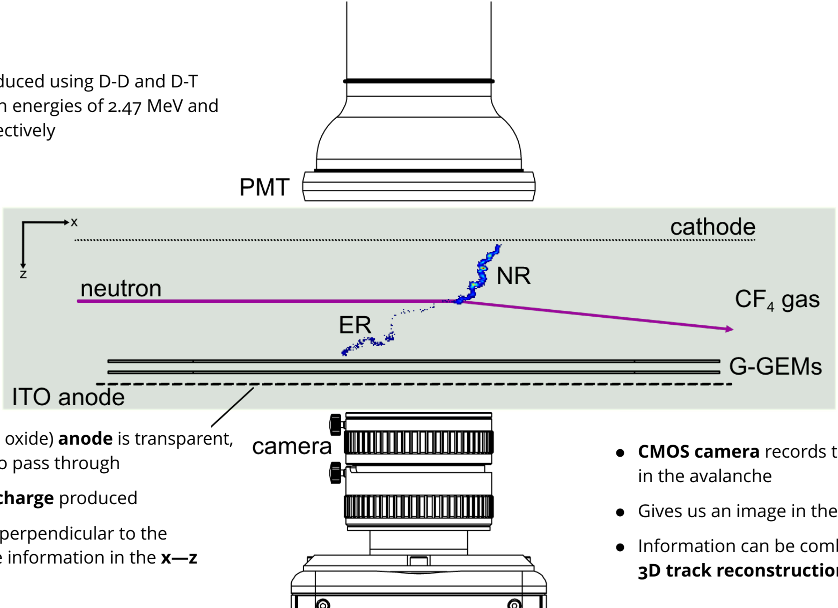

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- Gives us an image in the **x—y plane**
- Information can be combined with ITO for **3D track reconstruction**

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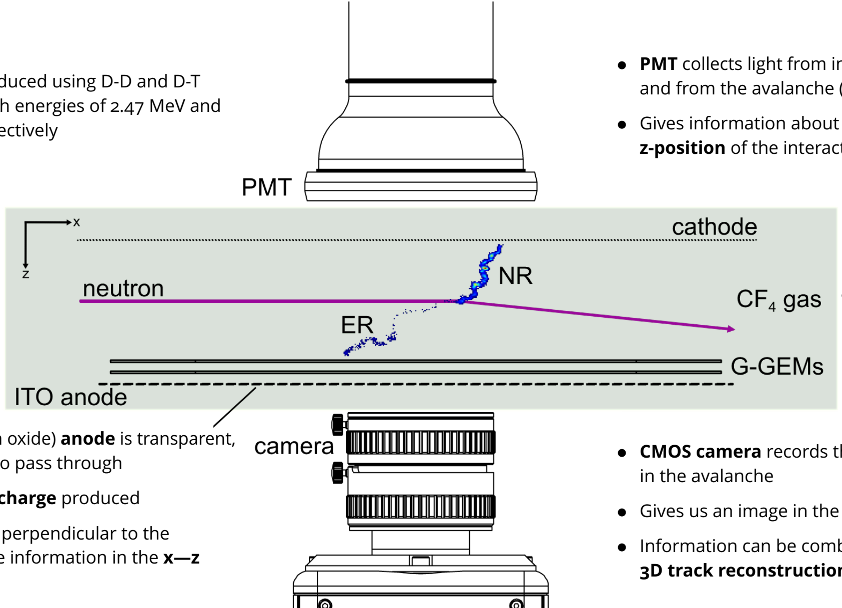

- **PMT** collects light from initial ionisation (**S1**) and from the avalanche (**S2**)
- Gives information about the **absolute z-position** of the interaction

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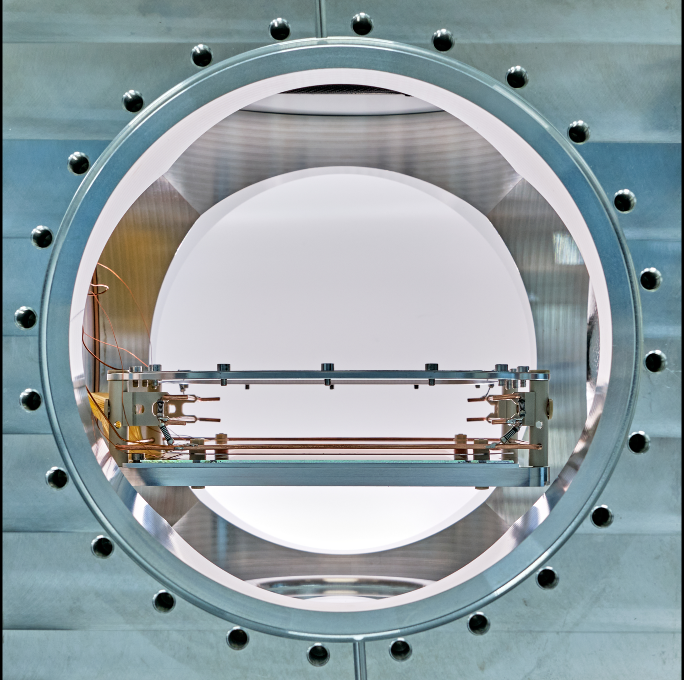
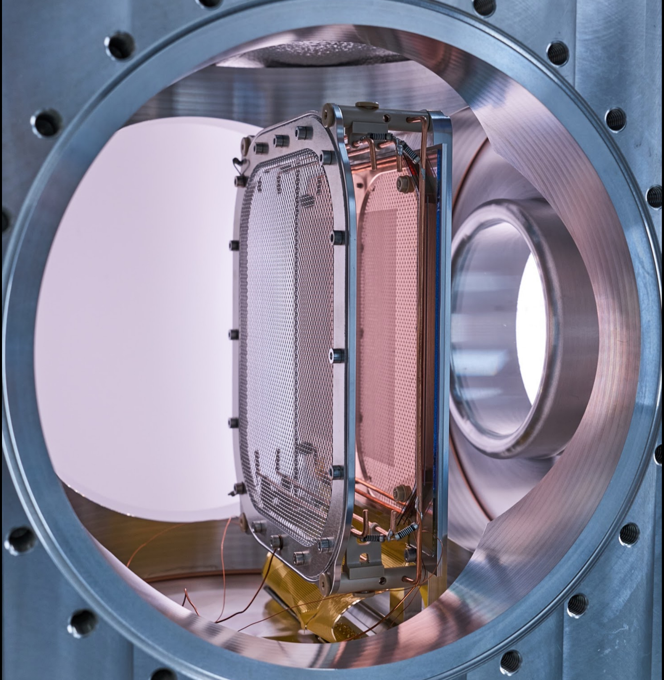
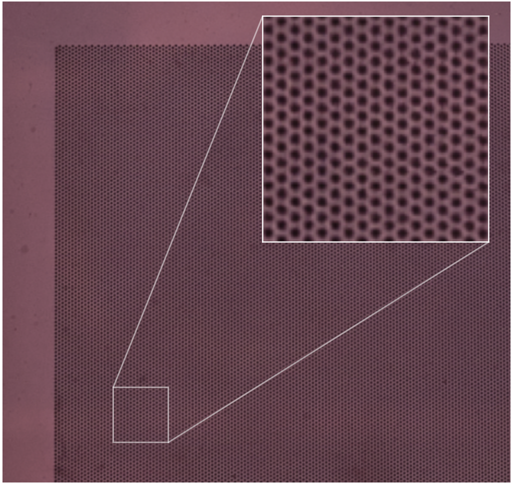




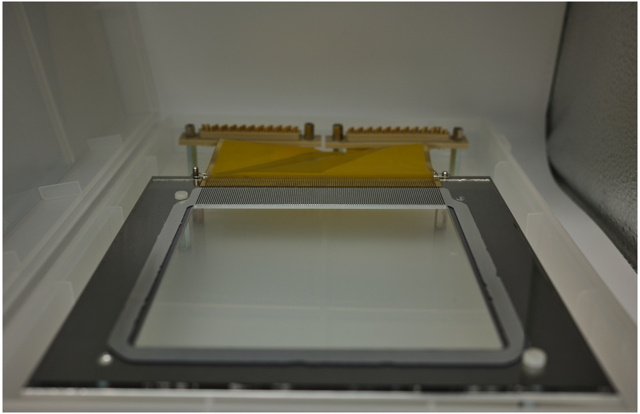
Gas Electron Multipliers



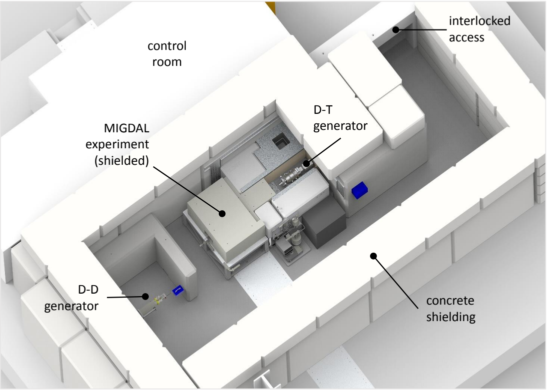
- **Gas Electron Multipliers** are micropattern gas detectors
- Glass sandwiched with copper/nickel (0.57 mm thick glass with 2 μm of metal on either side)
- Many tiny holes, 170μm in diameter, 280μm pitch, 10 cm $\times$ 10 cm active area
- Voltage applied across dielectric, funnels electrons through the holes. Strong electric field inside holes where **Townsend avalanche** occurs
- We use a double GEM system with a 2 mm gap between them

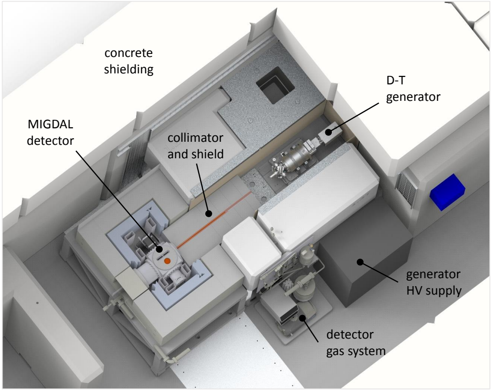
ITO anode

- 120 **Indium tin oxide (ITO)** strips with 60 readout channels allow us to readout the charge produced
- Strips 0.6 mm wide with a 0.8mm pitch, 10 cm $\times$ 10 cm active area
- Digitised with 2 ns sampling rate
- Charge arrival times give us information about the depth of the track in the z-direction
- Crucially, the anode is **transparent** so that light produced in the avalanche can be recorded by the CMOS camera

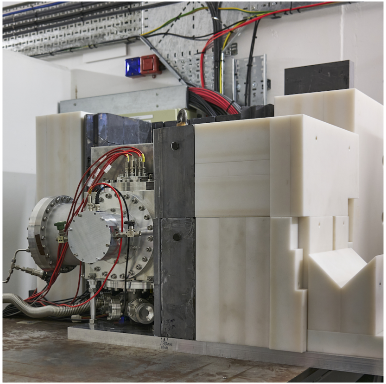
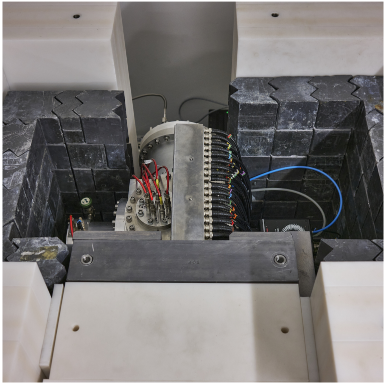
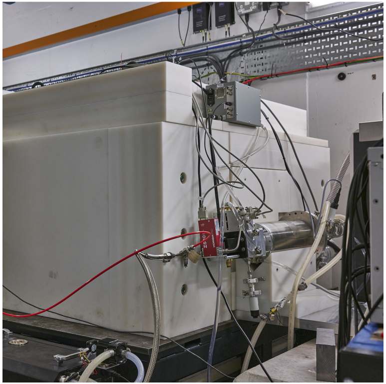


The NILE facility at ISIS, RAL



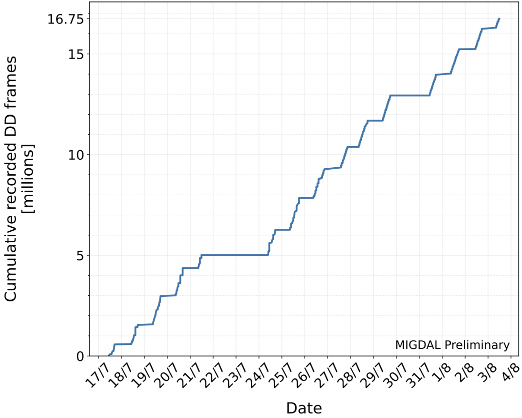


MIGDAL @ NILE

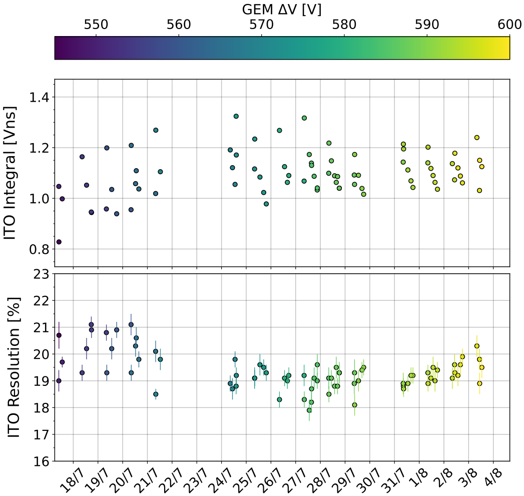




First science run

- The first science run took place $\approx$ 1 month ago, from the 17th of July to the 3rd of August
- Data taken using D-D neutron generator
- Lower neutron rate than design for first commissioning
- Frames taken with 20 ms exposure time. Longer than planned due to problems with camera 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

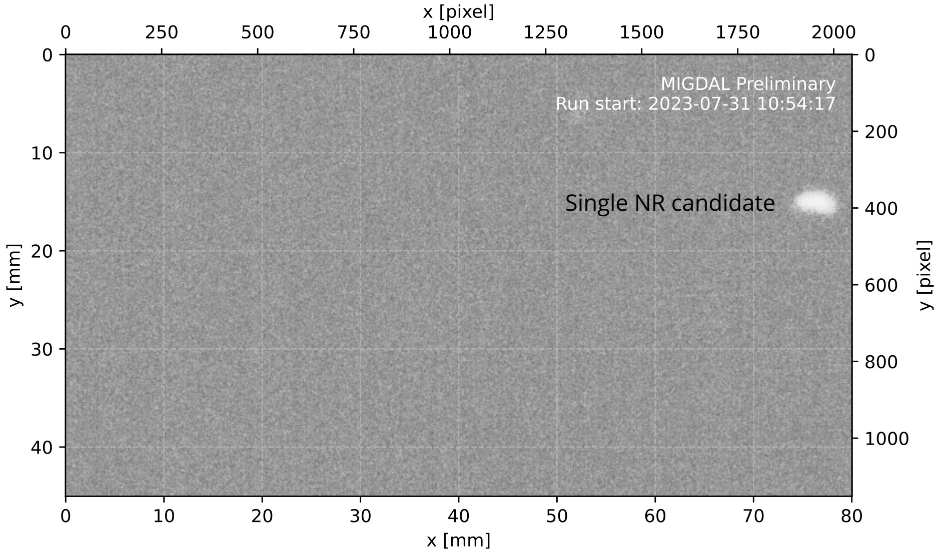


Calibration

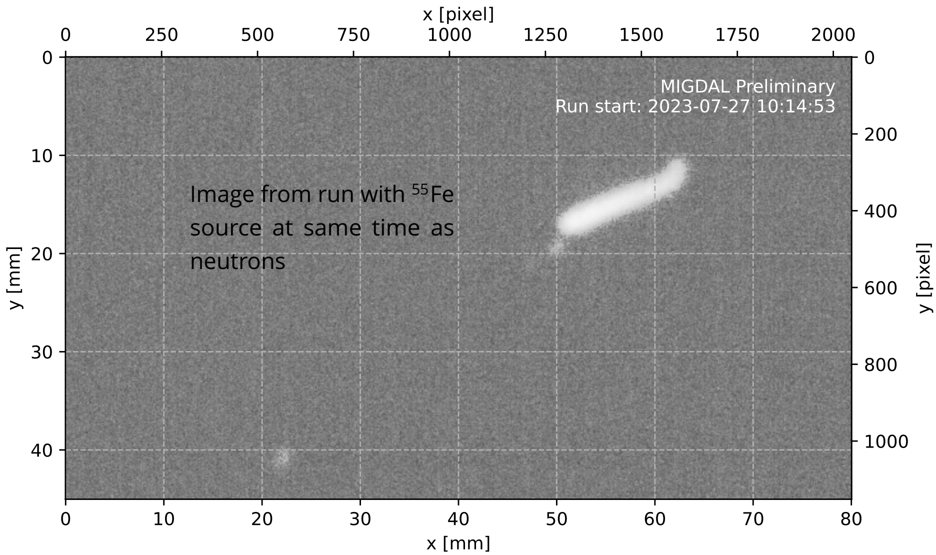


- ^{55}Fe calibration performed **several times per day**
- Energy scale is **consistent** over the course of the science run with $\approx$ 20% variation
- Resolution in ITO $\approx$ 20% and comparable with other readouts (e.g. camera)
- **Further improvements** are expected with better calibration methods

Example events



Migdal-like event



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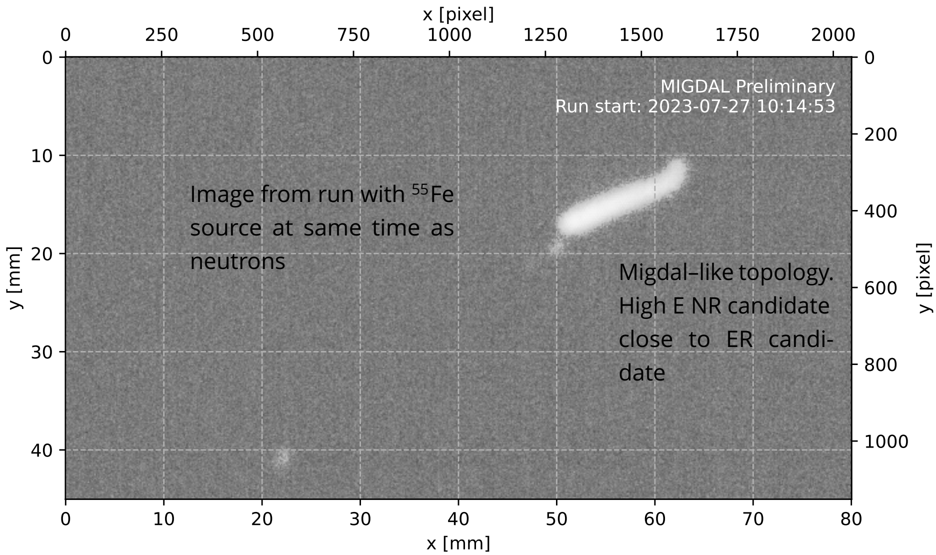

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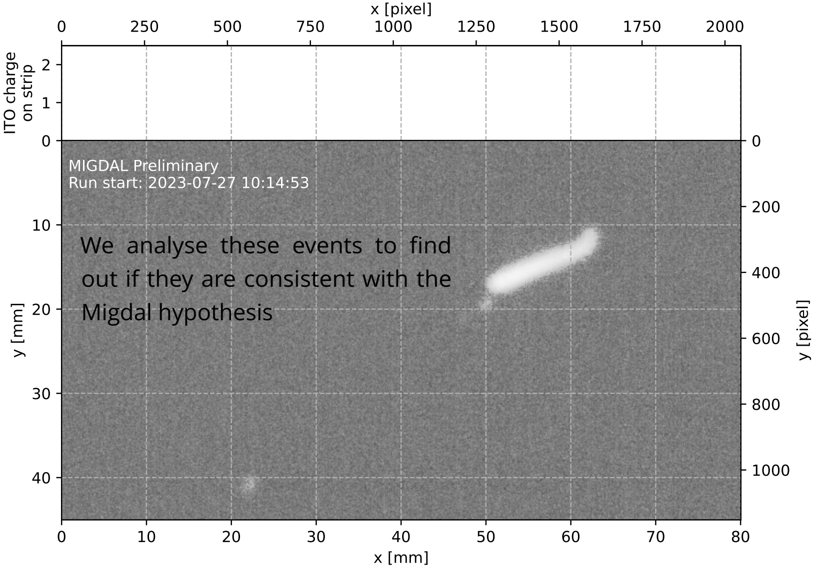
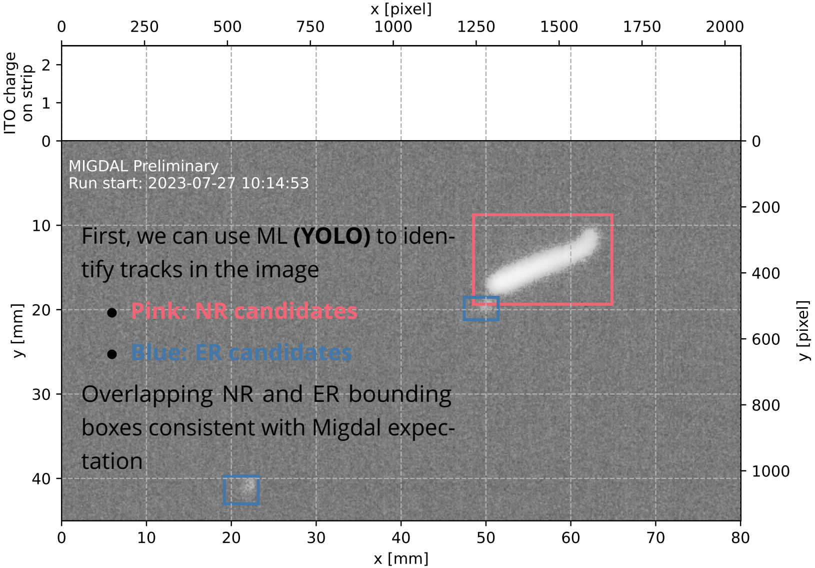


We analyse these events to find out if they are consistent with the Migdal hypothesis

Migdal-like event

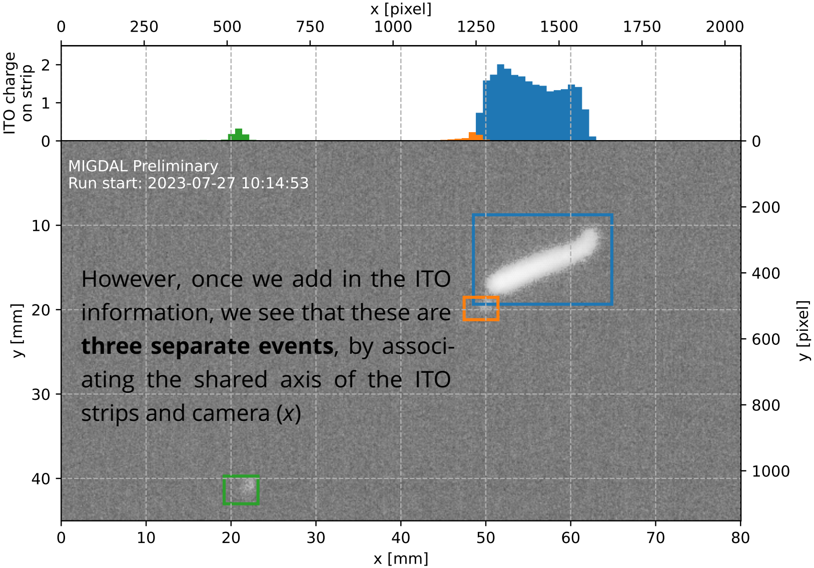


First, we can use ML **(YOLO)** to identify tracks in the image

- Pink: NR candidates
- Blue: ER candidates

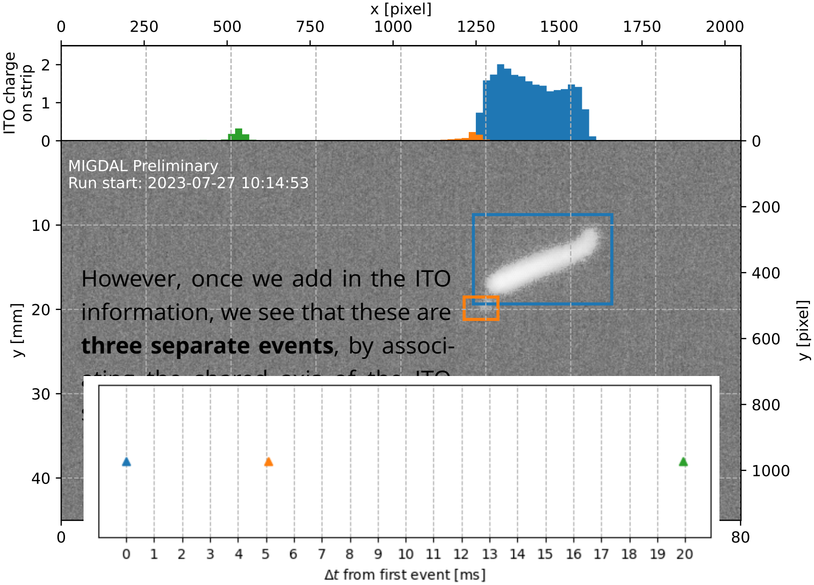
Overlapping NR and ER bounding boxes consistent with Migdal expectation

Migdal-like event



However, once we add in the ITO information, we see that these are **three separate events**, by associating the shared axis of the ITO strips and camera (*x*)

Migdal-like event



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Summary

- The **MIGDAL** experiment aims to perform an unambiguous observation the Migdal effect
- **First science run** took place $\approx$ 1 month ago with DD neutron source
- Regular **calibration** runs performed
- **Analysis** of recorded data underway
- **50% of recorded data is blinded**
- **Stay tuned for results!**
- See experiment paper for more detail: **Astropart.Phys. 151 (2023) 102853**

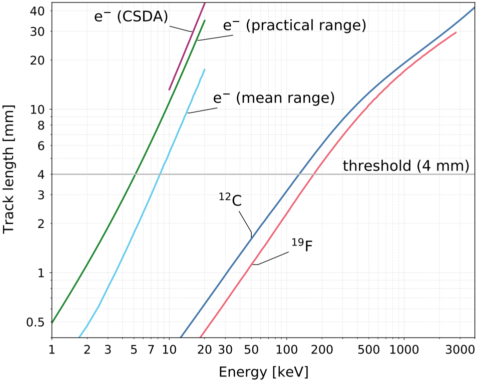
Back-up

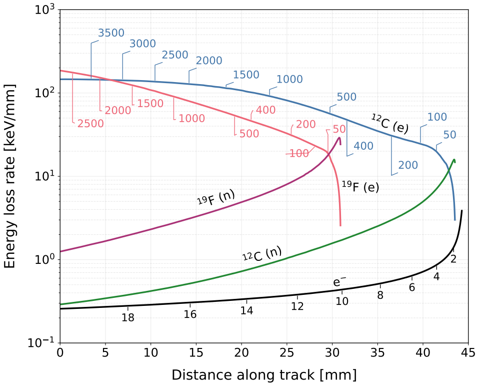
Signal versus background

Component	Topology	D-D neutrons >0.5	D-D neutrons 5–15 keV	D-T neutrons >0.5	D-T neutrons 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
Neutron inelastic γ-rays	Compton electron near NR track origin	1.6	0.47	0.86	0.25
Random track coincidences					
External γ- and X-rays	Photo-/Compton electron near NR track	≈ 0	≈ 0	≈ 0	≈ 0
Trace radioisotopes (gas)	Electron from decay near NR track origin	0.2	0.01	0.03	≈ 0
Neutron activation (gas)	Electron from decay near NR track origin	0	0	≈ 0	≈ 0
Muon-induced δ-rays	Delta electron 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 evaluated at the endpoint of the nuclear recoil spectra.

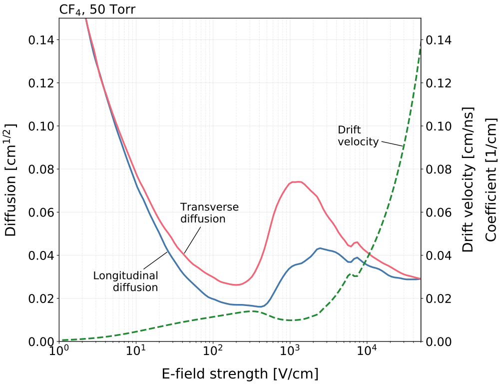
Tracks

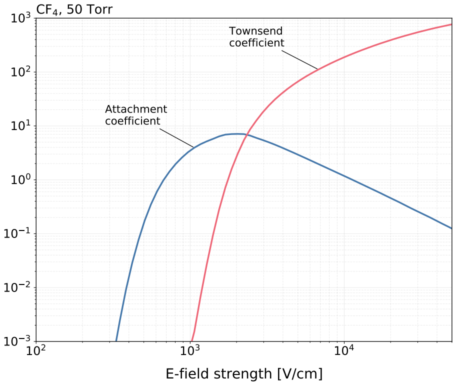




- We can exploit different track lenghts and dE/dx to distinguish nuclear and electronic recoils
- Nuclear recoils deposit more of their energy at the beginning of the track, while electrons deposit more energy at the end of the track

Gas properties

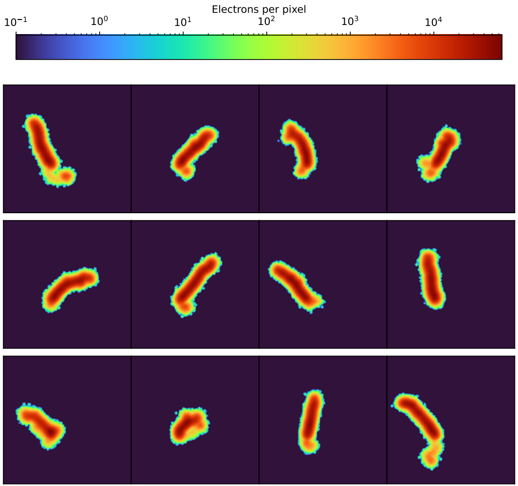




- Gas properties for CF_4 at 50 Torr, calculated with Magboltz
- Electric fields chosen to minimize diffusion and attachment

End-to-end simulation

- We have a full end-to-end simulation combining:
  - DEGRAD
  - SRIM/TRIM
  - Garfield++
  - Magboltz
  - Gmsh/Elmer & ANSYS
- Plots show Migdal-like events with a 250 keV NR and a 5 keV ER
- Studying various methods to identify Migdal events (dE/dx, track lengths, etc)
- Currently estimate ≈ 75% Migdal identification efficiency for the most promising energies



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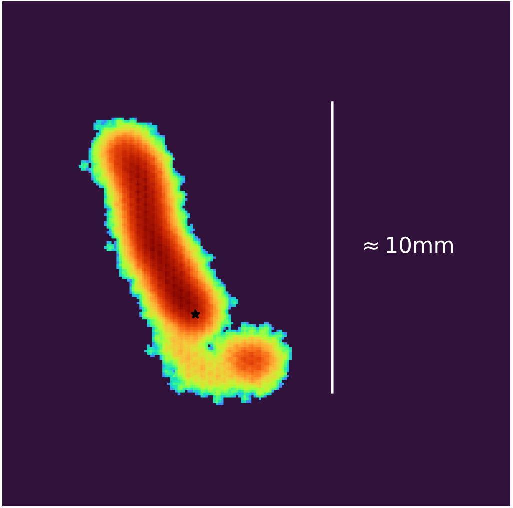
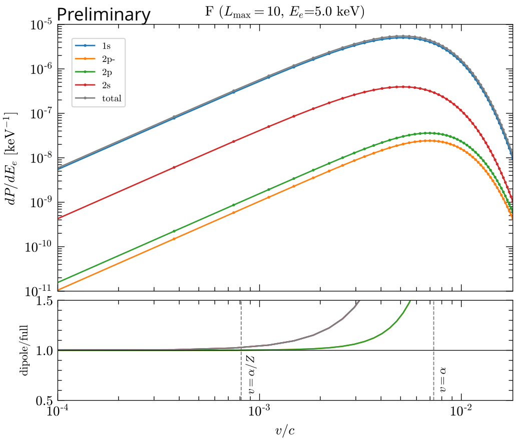


Rates

- **One billion neutrons per second** produced by the D-D generator
- Expect ≈ **60 nuclear recoils per second** in the TPC
- Migdal event rate $\mathcal{O}$(**10 events**) per day
- **Challenging!**



Plot from Chris McCabe