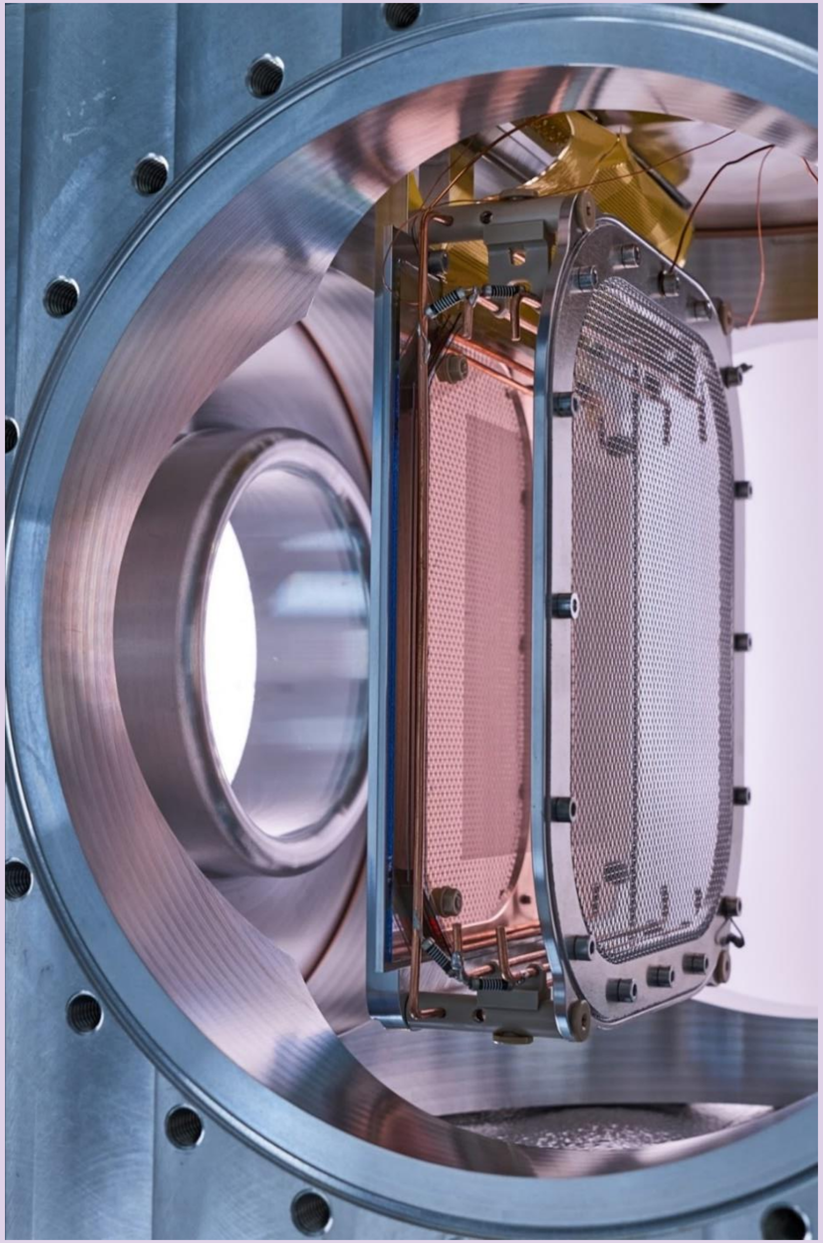


The MIGDAL experiment

Towards observation of the Migdal effect in nuclear scattering

arXiv: 2207.08284 *new*

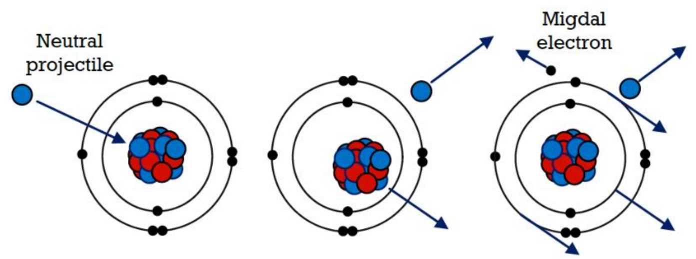
Henrique Araújo, Imperial College London

On behalf of the MIGDAL collaboration

19 July, 2022

14th International Conference on the Identification of Dark Matter – 18-22 July 2022 – Vienna, Austria

The elusive Migdal effect



Migdal event topology involves a nuclear recoil and electron recoil originating from the same vertex.

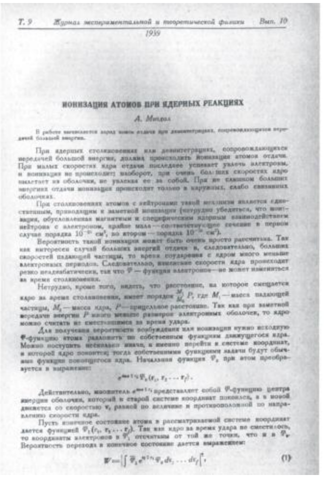
- Direct DM experiments invoke the Migdal effect to search for nuclear recoils below threshold
- Rare atomic effect predicted in the late 1930s and observed since in radioactive decays – but never recorded in nuclear scattering

MIGDAL
Migdal In Galactic Dark mAtter expLoration

Aim: The *unambiguous* observation of the Migdal effect using an optical TPC with low-pressure CF_4 and other gases

Measurements will probe recoil energies well above those indirectly searched for in most DM searches, but will allow a systematic study in various atoms and molecules

>>> See talk by Chris McCabe for new Migdal calculations

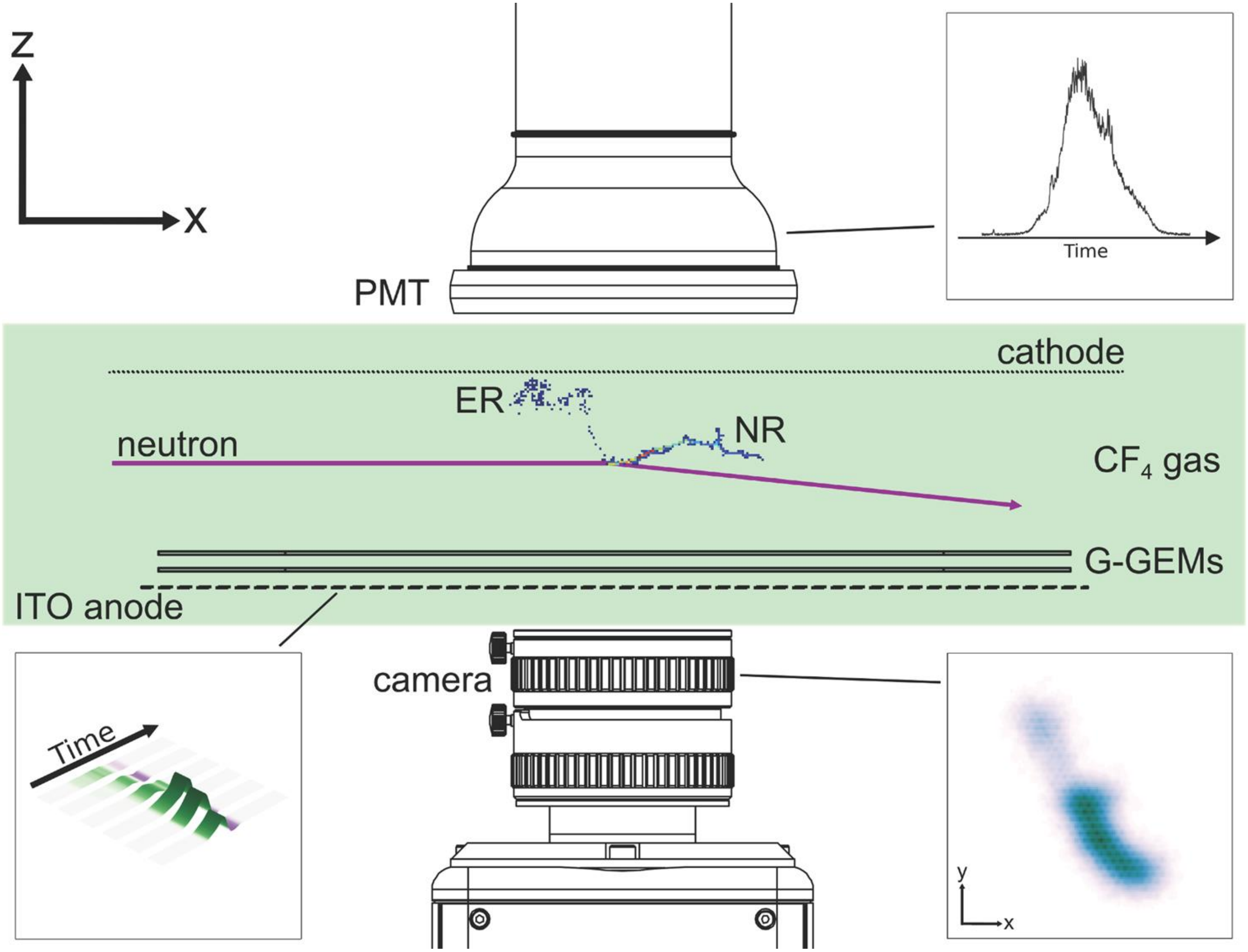

ИОНИЗАЦИЯ АТОМОВ ПРИ ЯДЕРНЫХ РЕАКЦИЯХ

А. Мигдал

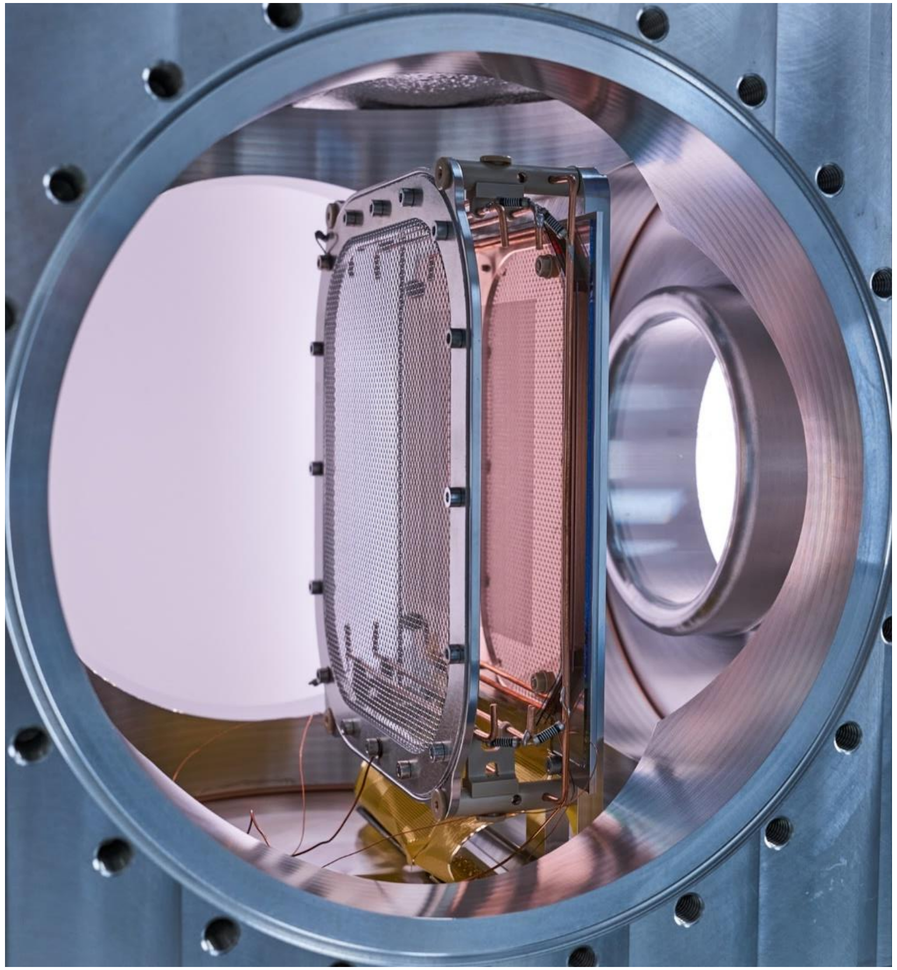
[1] A. Migdal *Ionizatsiya atomov pri yadernykh reaktsiyakh, ZhETF, 9, 1163-1165 (1939)*
[2] A. Migdal *Ionizatsiya atomov pri α- i β- raspade, ZhETF, 11, 207-212 (1941)*
[3] M.S. Rapaport, F. Asaro and I. Pearlman *K-shell electron shake-off accompanying alpha decay, PRC **11**, 1740-1745 (1975)*
[4] 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)*

The MIGDAL experiment

- Low-pressure gas: 50 Torr of CF_4
  - Extended particle tracks
  - Avoid photon interactions
- Optical TPC
  - Imaging: 2x glass-GEMs + camera
  - Ionisation: 120 ITO anode strips
  - Scintillation: photomultiplier tube
- High-yield neutron generators
  - D-D: 2.47 MeV (10^9 n/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 (Fe-55 calibration)

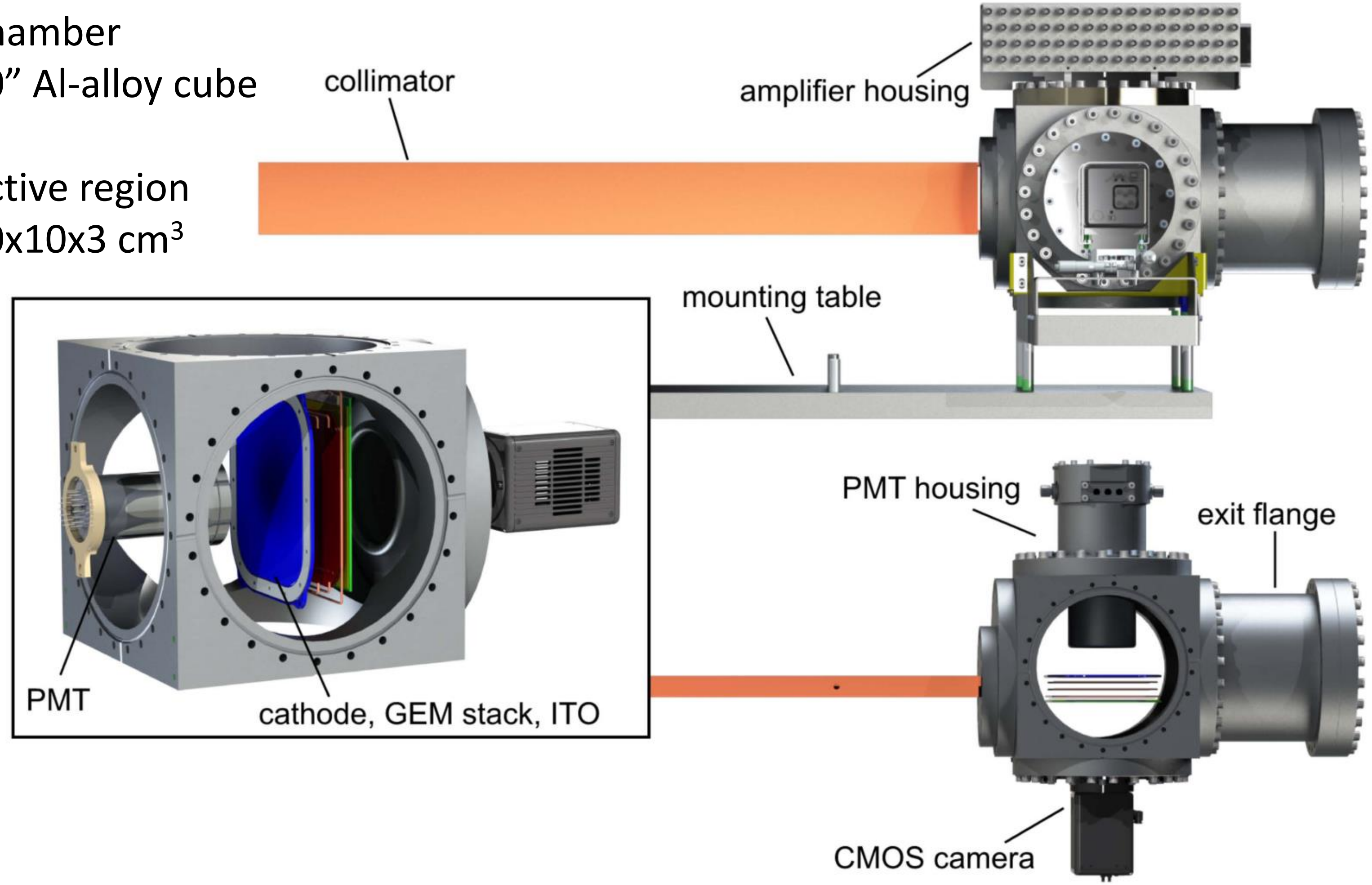


The MIGDAL experiment



Chamber
10” Al-alloy cube

Active region
10x10x3 cm^3



Optical-TPC

Cathode

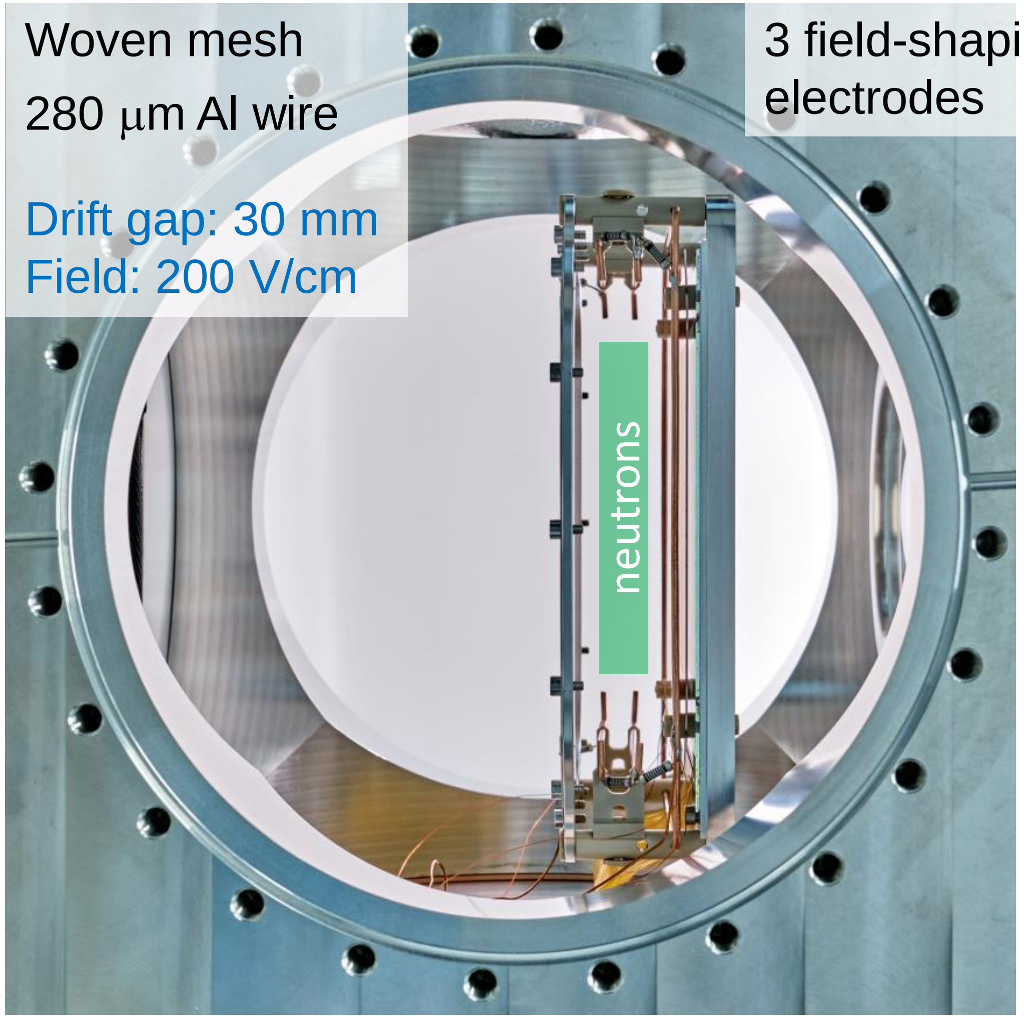
Woven mesh

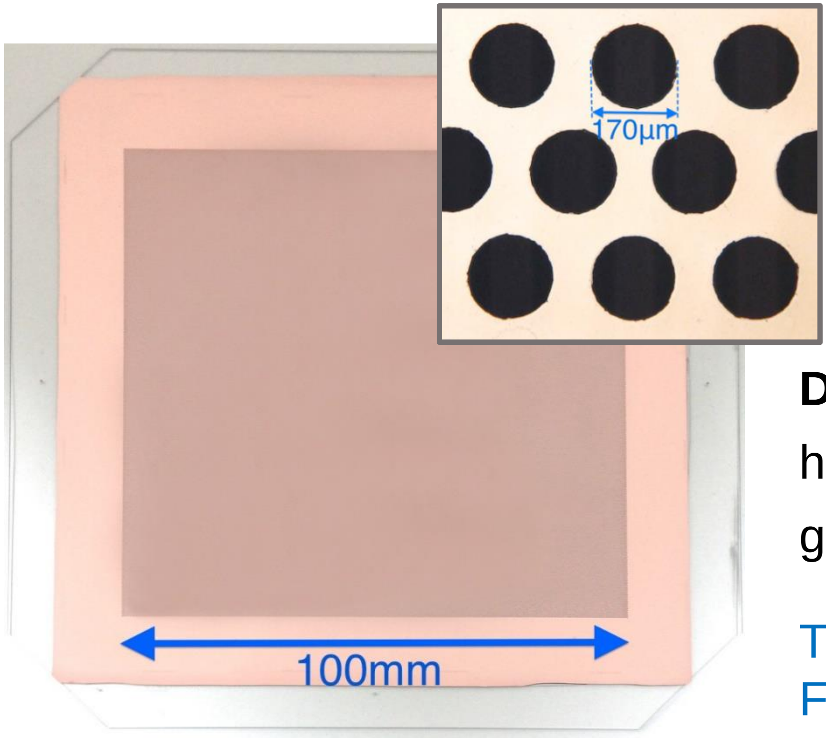
280 μm Al wire

Drift gap: 30 mm
Field: 200 V/cm

Fieldcage

3 field-shaping electrodes



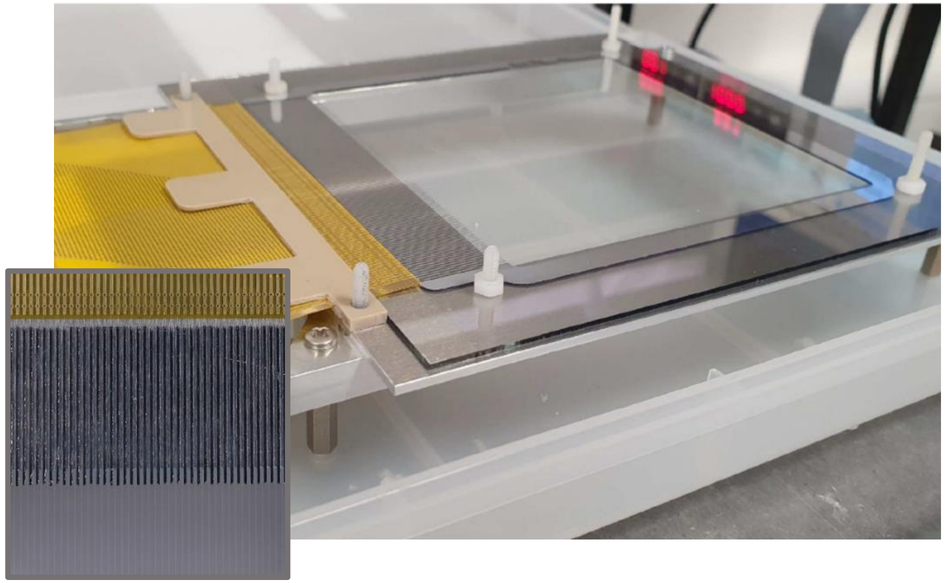


Double glass-GEMs

hole/pitch: 170/280 μm

gain: ~10^5

Transfer gap: 2 mm
Field: 600 V/cm

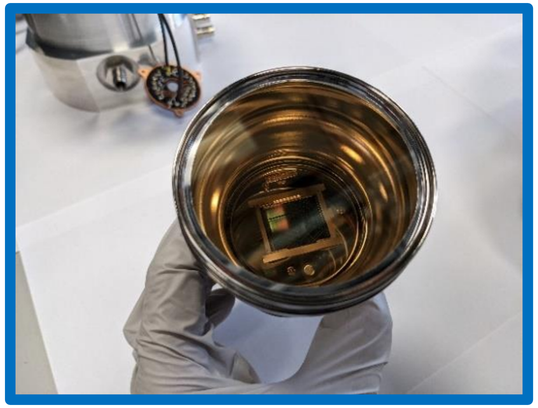


ITO anode

120 strips
wire-bonded to
Kapton flex-cable
strip pitch: 830 μm

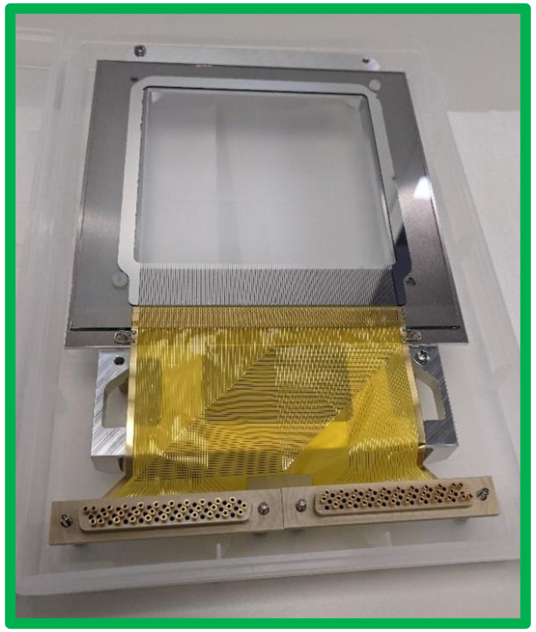
Induction gap: 2 mm
Field: 400 V/cm

Detector readout

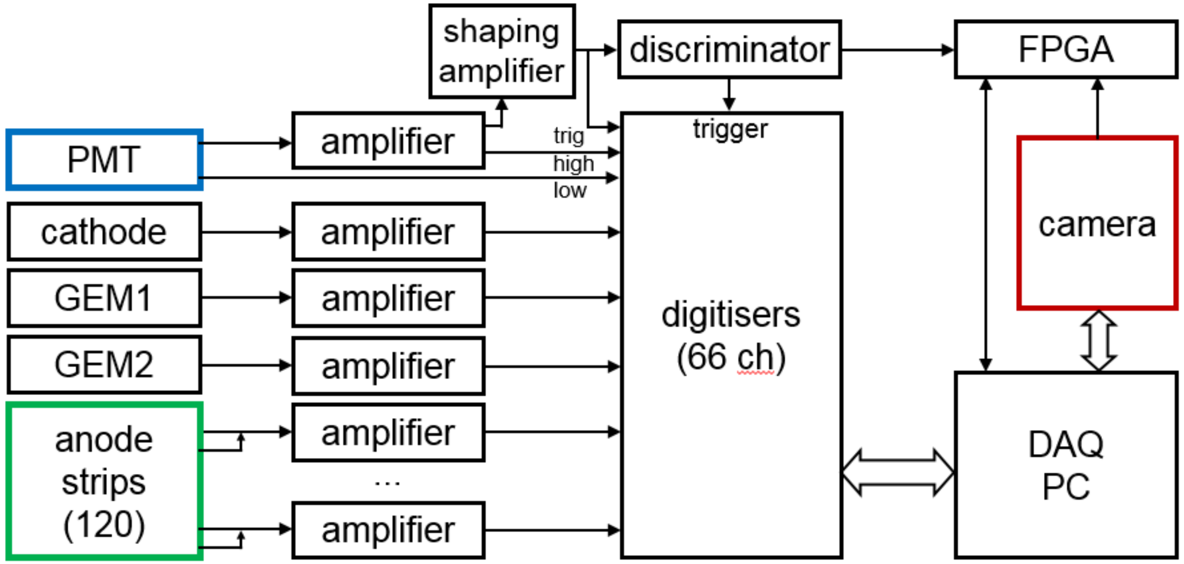


VUV PMT (Hamamatsu R11410)
Detects primary and secondary (GEM) scintillation
Absolute depth (z) coordinate
Digitised at 2 ns/sample
[Trigger]

sCMOS camera (Hamamatsu ORCA-Fusion)
Detects GEM scintillation through glass viewport behind ITO anode
Readout of (x,y) plane
Exposure: 11.2 ms/frame (continuous)

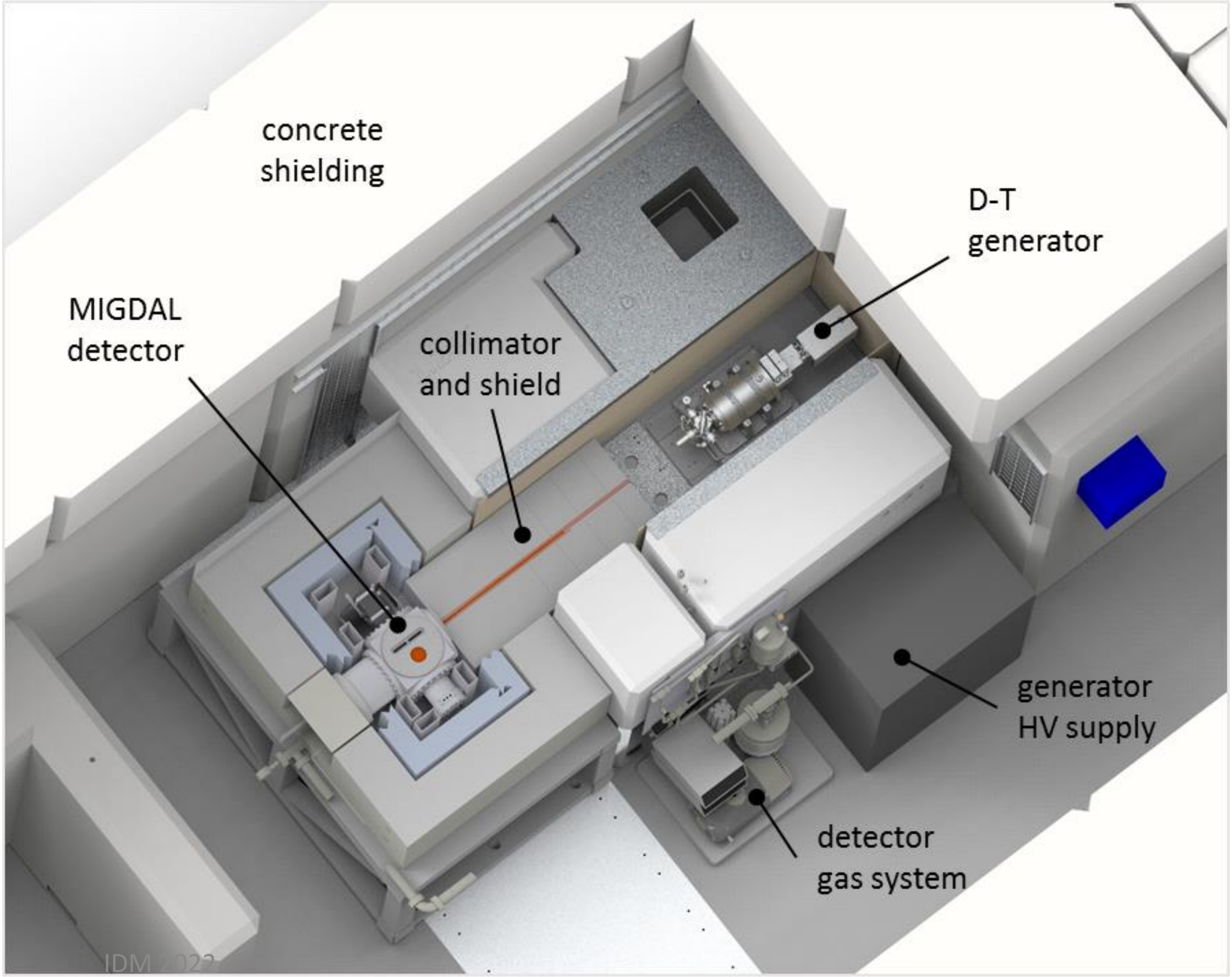


ITO anode strips
Post-GEM ionisation
Readout of (x,z) plane
Digitised at 2 ns/sample



NILE Facility at Rutherford Appleton Laboratory, UK

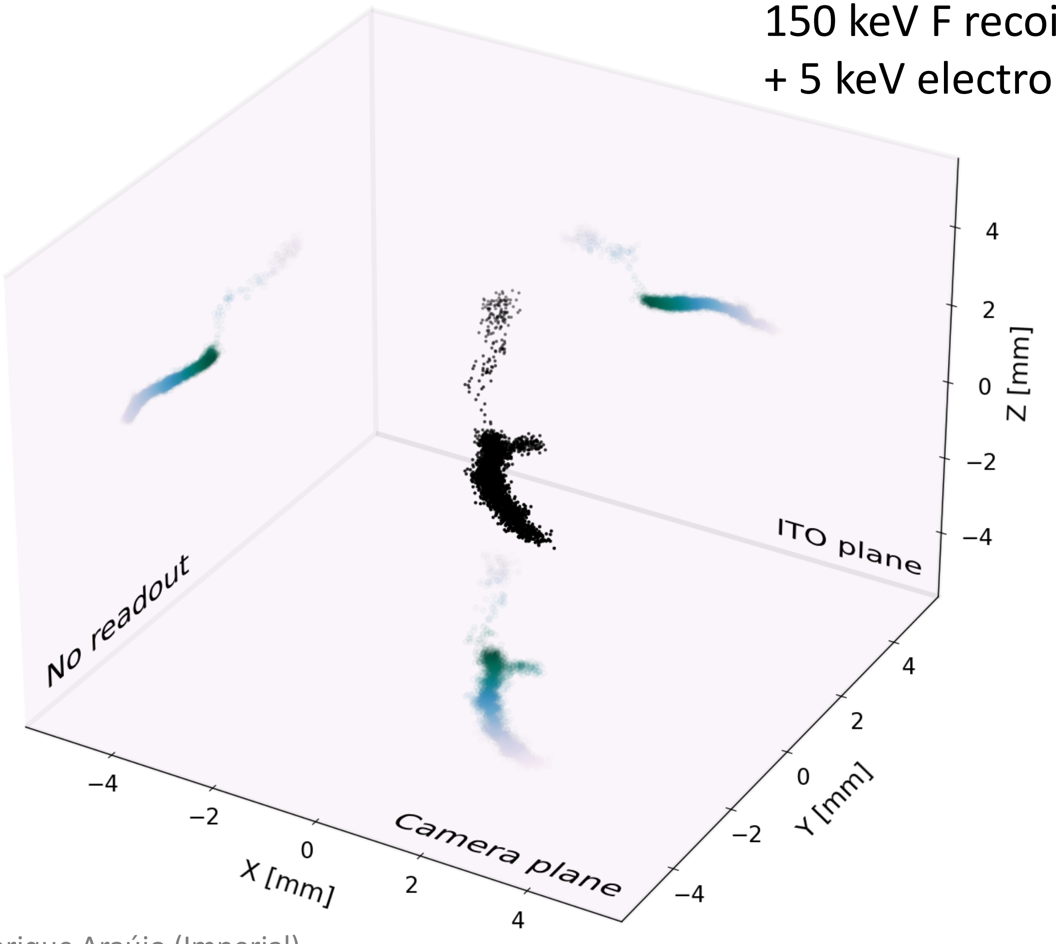
- D-D and D-T fusion generators installed in “shielding bunker”
- Collimators & additional shielding provide clean beam through OTPC
- D-T collimator ~1 m, D-D ~0.5 m



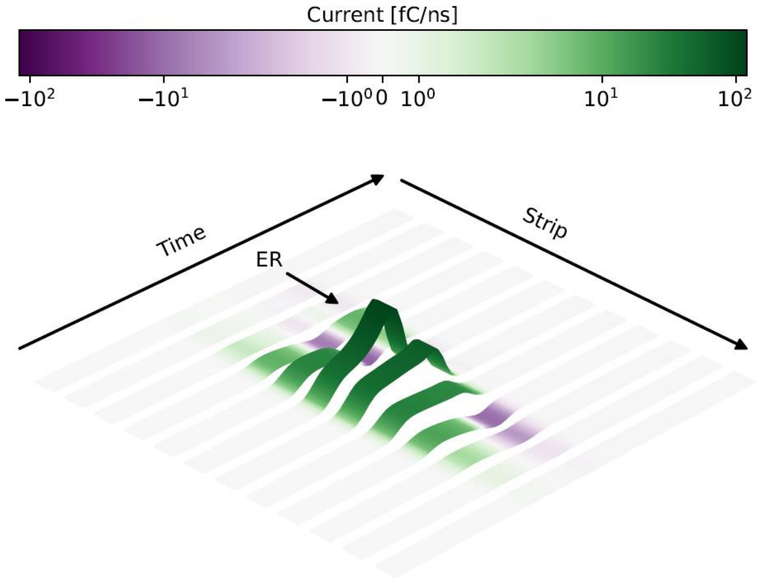
Simulation stack

Degrad • SRIM/TRIM • Garfield++ • Magboltz • Gmsh/Elmer & ANSYS

Migdal event
150 keV F recoil
+ 5 keV electron



Anode strip readout
Induction/collection
(electronics deconvolved)



Camera readout
Drift+diffusion+GEMs+image

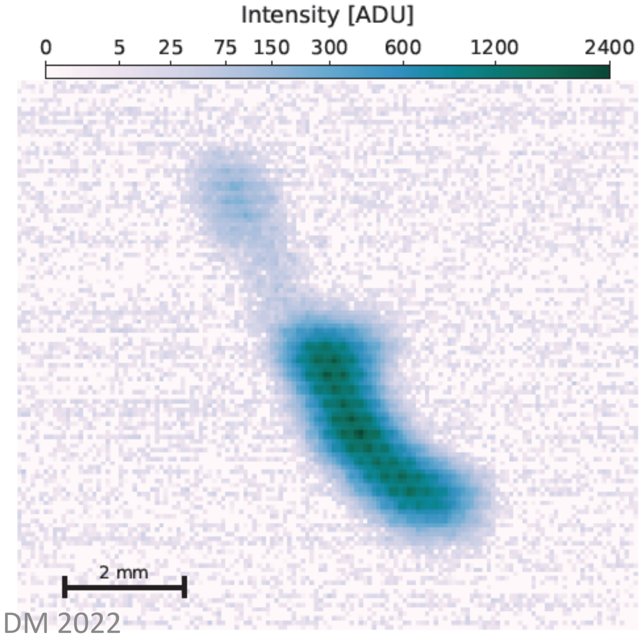
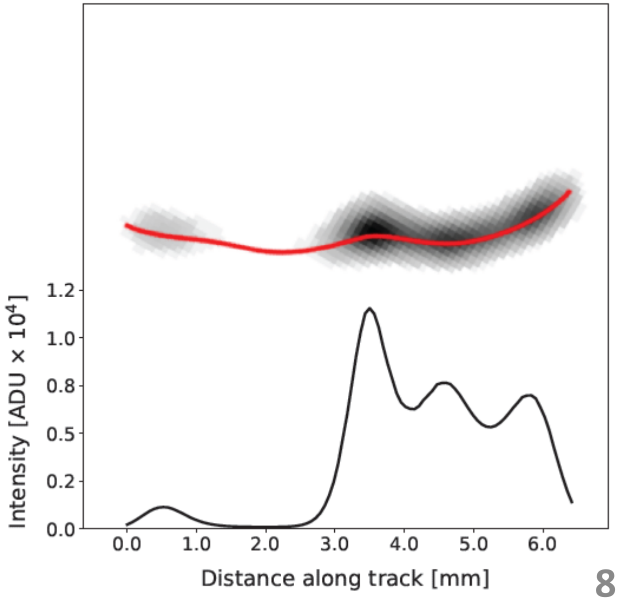


Image analysis
Deconvolution+RidgeFinder

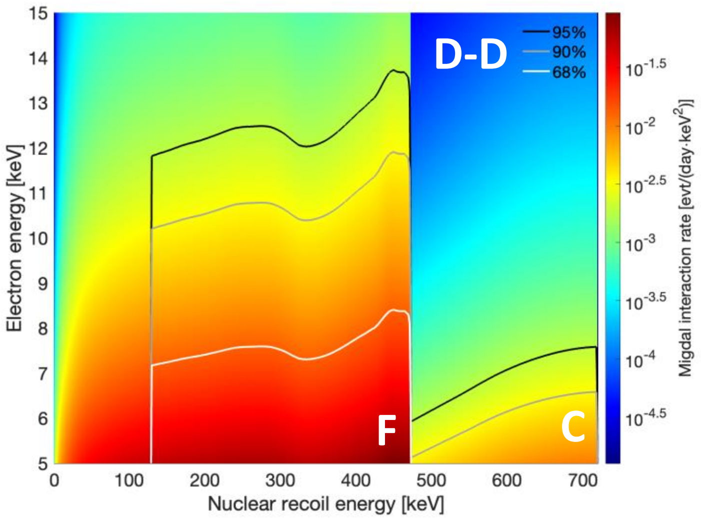


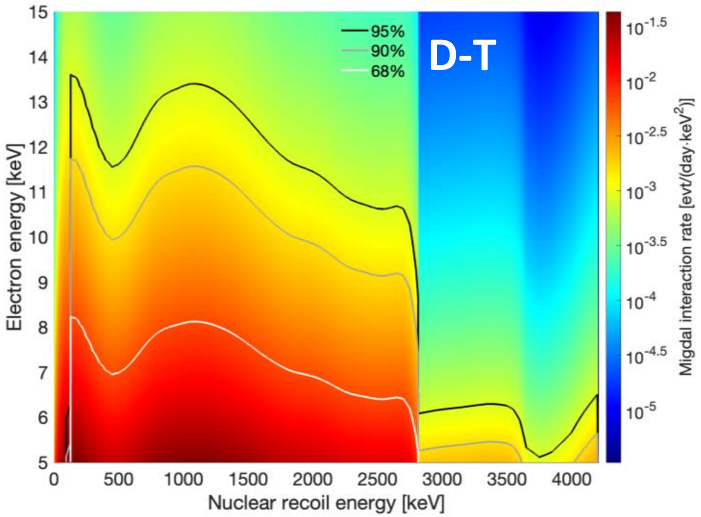
Signal rate calculations

- Folding Migdal double-differential XS (C. McCabe's talk) with C & F recoil spectra + track selection

Migdal search ROI

ER and NR tracks longer than 4 mm: 5-15 keV electron, >130/170 keV F/C recoils





- Apply duty cycle, efficiencies, single-event frames, …
  - D-D source: 8.9 Migdal events/day (3.9M events/day)
  - D-T source: 29.3 Migdal events/day (4.9M events/day)

Table 1: Nominal neutron beam parameters and estimated event rates from the D-D and D-T generators in CF_4 gas at 50 Torr. Beam widths are indicated at FWHM and for 99% of flux ('halo'). Interaction rates are given for all NR tracks originating in the active region and also for those fully contained within an 8×8 cm^2 fiducial region and track length greater than 4 mm. Migdal interaction rates (no efficiencies considered) are given for tracks contained in the fiducial region, at track thresholds of 3 mm, 4 mm and 5 mm. The baseline scenario (4 mm, in bold) integrates the NR spectrum from 130 keV for carbon and 170 keV for fluorine, and electron energies in the range 5–15 keV; rates are indicated also for a low electron energy threshold (0.5 keV).

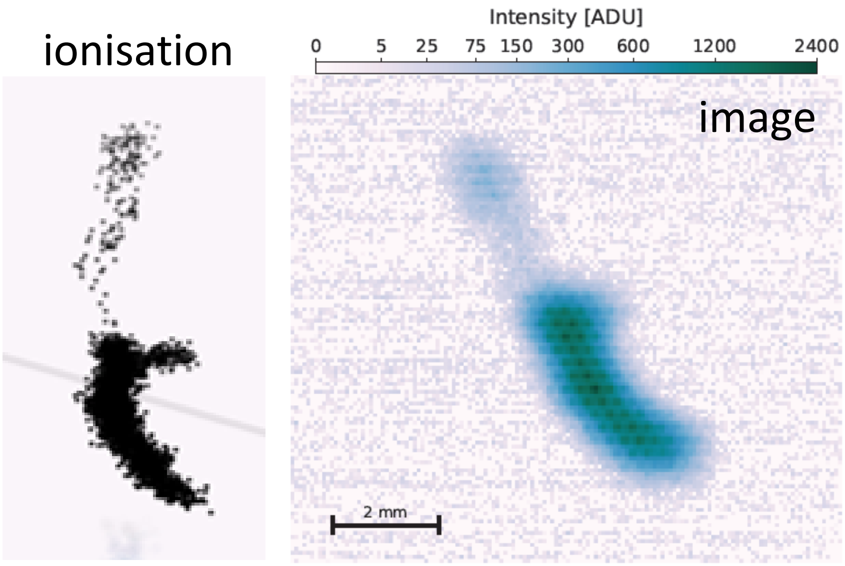
Generator	D-D	D-T
Nominal neutron energy (MeV)	2.47	14.7
Neutron intensity (n/s)		
Emitted (4π)	1×10^9	1×10^{10}
Active region	2.6×10^5	4.7×10^5
Beam width/halo (cm)		
Vertical	9.0/9.0	9.2/9.2
Horizontal	1.4/1.8	1.3/1.5
Recoil spectrum (MeV)		
^{12}C mean/end-point	0.37/0.71	0.97/4.2
^{19}F mean/end-point	0.17/0.47	0.52/2.8
Interaction rates (evt/s)		
Total	53	68
Signal-inducing	53	48
Elastic	40	37
Contained tracks† (evt/s)		
Total	15	22
Signal-inducing	15	18
Elastic	11	14
Migdal rates† (interactions/day)		
NR track $\geq$ 4 mm, ER>0.5 keV	7,250	26,430
Tracks $\geq$ 3 mm (ER $\in$ 4–15 keV)	89	255
Tracks $\geq$ 4 mm (ER $\in$ 5–15 keV)	**43**	**131**
Tracks $\geq$ 5 mm (ER $\in$ 6–15 keV)	22	74

† In 8×8 cm^2 fiducial region, NR track $\geq$ 4 mm unless indicated.

Background

- Many sources considered, mostly insignificant (esp. since C and F K-shells ≪5 keV)
- Most challenging: secondary nuclear recoils + finite discrimination (analysis dependent)

Q: When does this little "stub" look like a 5 keV electron?
A: Less than 1 per 10^6 primary NR



Background events (ER+NR topology) per million NR tracks

Table 3: Number of background and signal events *per million* neutron-induced recoil tracks for D-D (2.47 MeV) and D-T (14.7 MeV) neutrons incident on CF_4 gas at 50 Torr. Data are given for ∼100 keV nuclear recoil threshold and >0.5 keV and 5–15 keV electron energies, with the electron vertex located up to 3 mm from the NR track origin. An entry of "0" indicates that the process cannot occur in the ROI, while "≈0" denotes a negligible rate of ≪0.01 events per million recoils. Individual background components and topologies are discussed in the text. Signal rates are those from Table 1 for contained tracks above threshold, normalised per million signal-inducing events.

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	–	0.5	–	0.5
Total background	Sum of the above components		0.98		0.75
Migdal signal	Migdal electron from NR track origin		32.6		84.2

MIGDAL
Migdal In Galactic Dark mAtter expLoration

Background

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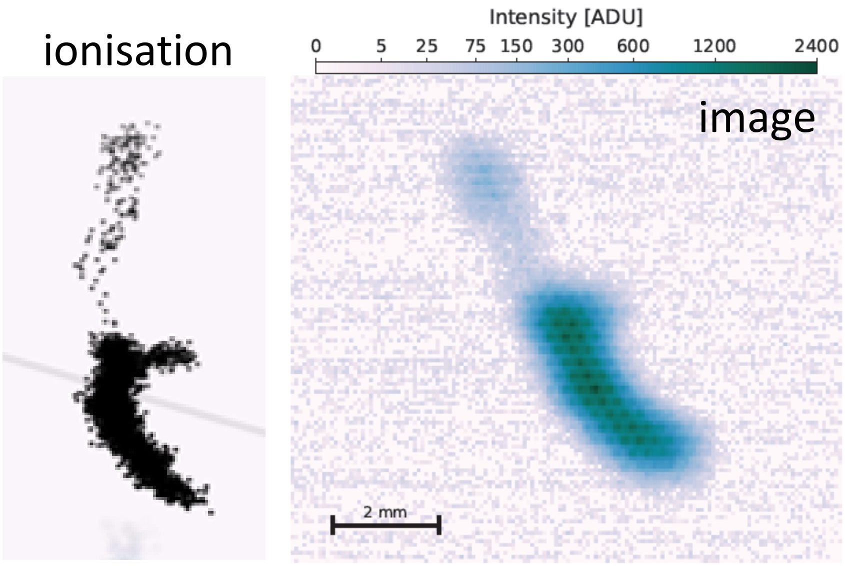

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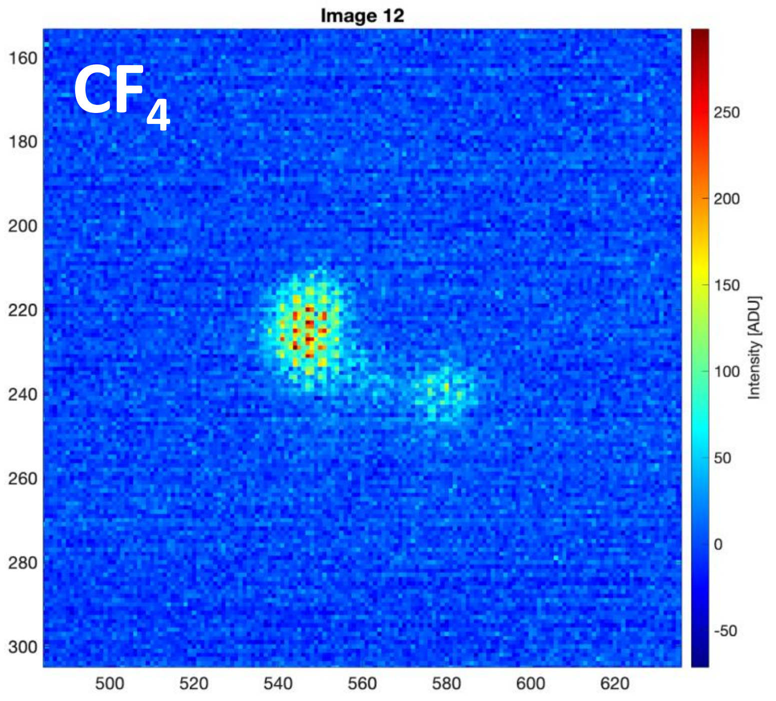
Quasi-Free Electron B					
Secondary Electron B					
Atomic Br. (AB)					
Nuclear Br. (NB)					
Photon interactions					
Neutron inelastic γ-ra					
Random track coincidence					
Gas radioactivity					
Trace contaminants					
Neutron activation					
Secondary nuclear recoil fe					
Total background					
Migdal signal					

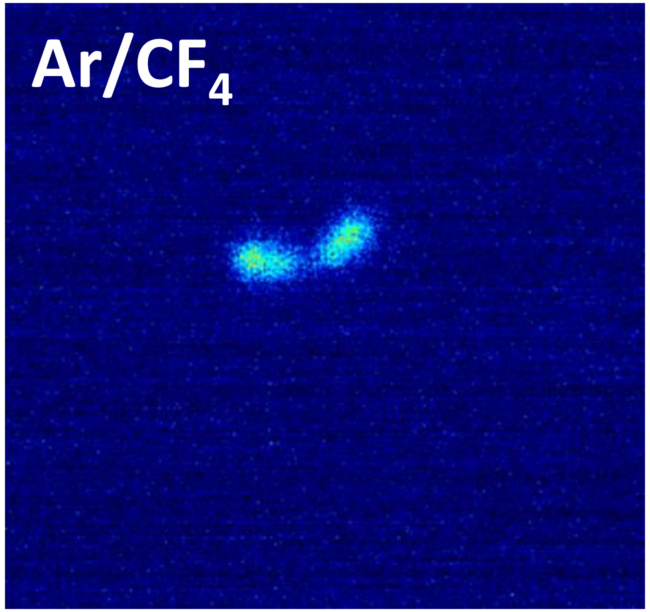
	D-D >0.5	D-D 5–15 keV	D-T >0.5	D-T 5–15 keV
rigin	0.2	0.01	0.03	≈0
rigin	0	0	≈0	≈0
	–	0.5	–	0.5
		0.98		0.75
n		32.6		84.2

Status

- Main items built, testing/optimising in the lab now
  - PMT, GEMs, camera working; ITO anode next, + DAQ integration
- Commissioning at the neutron facility coming soon
  - Collimators and shielding designed and built
  - Awaiting final commissioning of generators
- Ramping up data analysis

- A taster: Fe-55 (5.9 keV) X-ray interactions (50 Torr): very preliminary data, first GEM testing
  - Demonstration that we can identify electrons at the 5-keV threshold Energy measurement improving, head-tail ID very clear
  - Soon adding depth coordinate with ITO + PMT
  - Coming up, dynamic range testing with Cf-252 fission fragments





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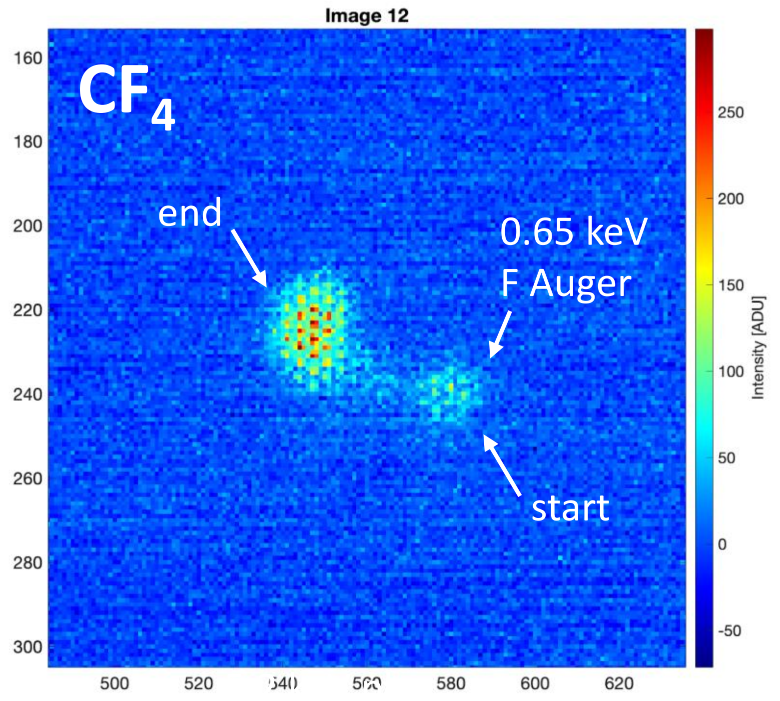
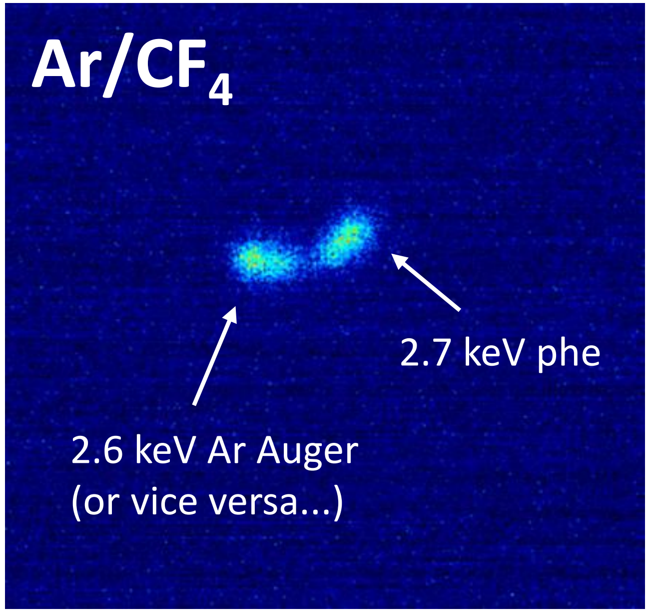




Conclusions

- The MIGDAL experiment aims to make a conclusive detection of the Migdal effect, followed by a systematic study: first in pure CF_4, then in other gases and mixtures
- Design/sensitivity study completed (2207.08284), suggesting 5σ discovery with 1 day
- Optical-TPC has been built, now being commissioned/optimised: 5 keV threshold met
- The neutron facility is ready, awaiting final generator commissioning

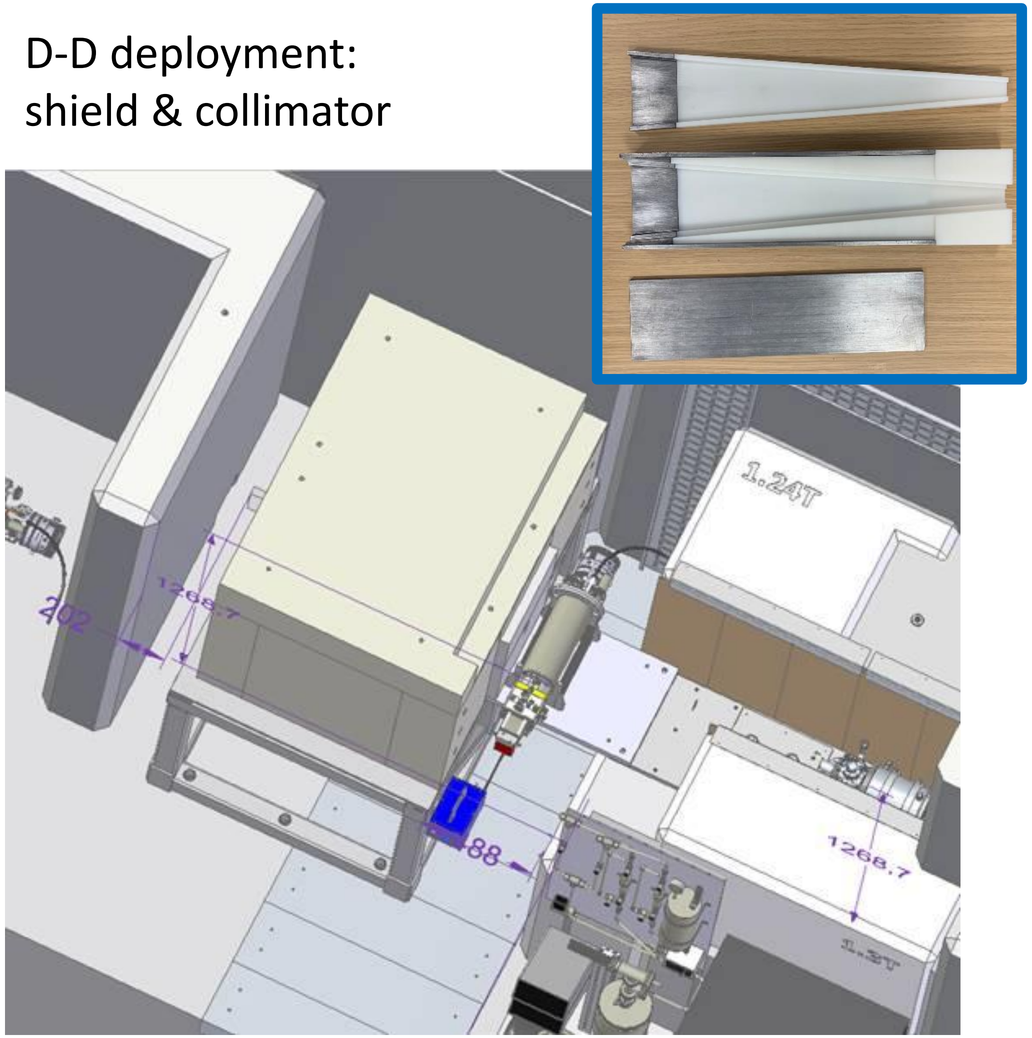
Funding: Science and Technology Facilities Council; U.S. Department of Energy; FCT Fundação para a Ciência e a Tecnologia, Ministério da Educação e Ciência; Horizon 2020 European Union Funding for Research & Innovation

MIGDAL collaboration: U. Autónoma 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/)

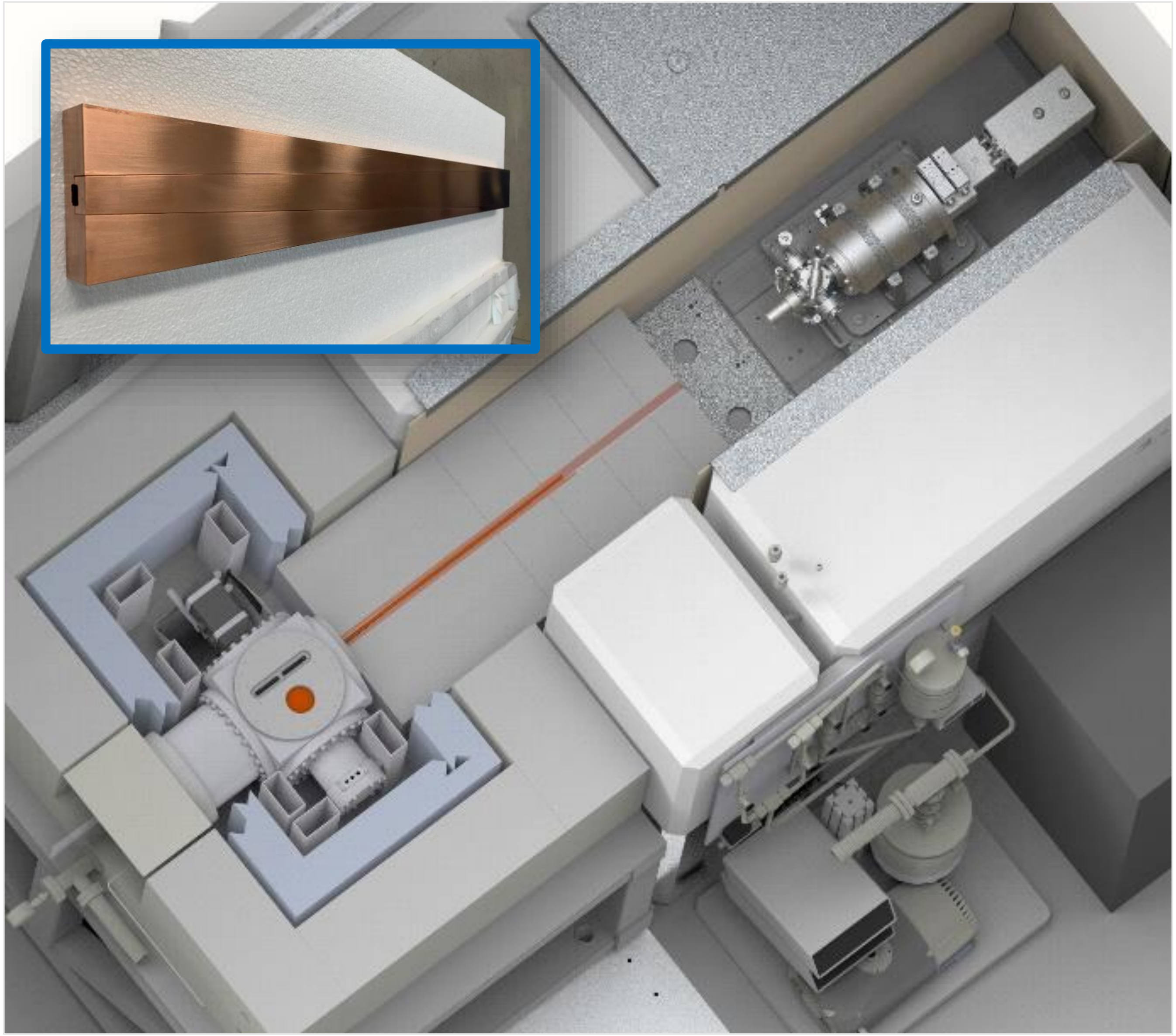
Reserve slides

Collimators & shielding

D-D deployment:
shield & collimator



D-T deployment: shield & collimator



ER and NR tracks in 50 Torr CF_4

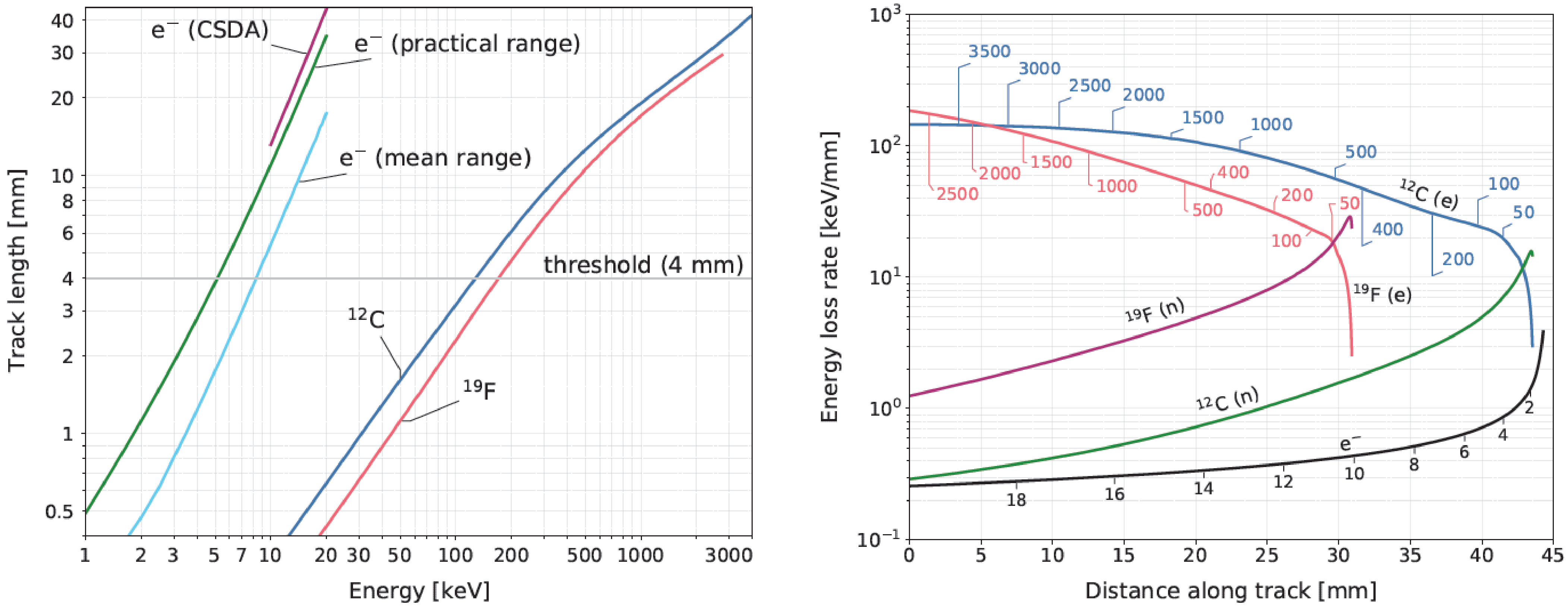


Figure 2: Left – Track length in CF_4 at 50 Torr for electrons (mean projected range calculated with Degrad [46], CSDA range with ESTAR [49], and the practical range formula from Ref. [50]), and mean projected range for carbon and fluorine ions from SRIM [47]). Right – Electronic and nuclear energy loss 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

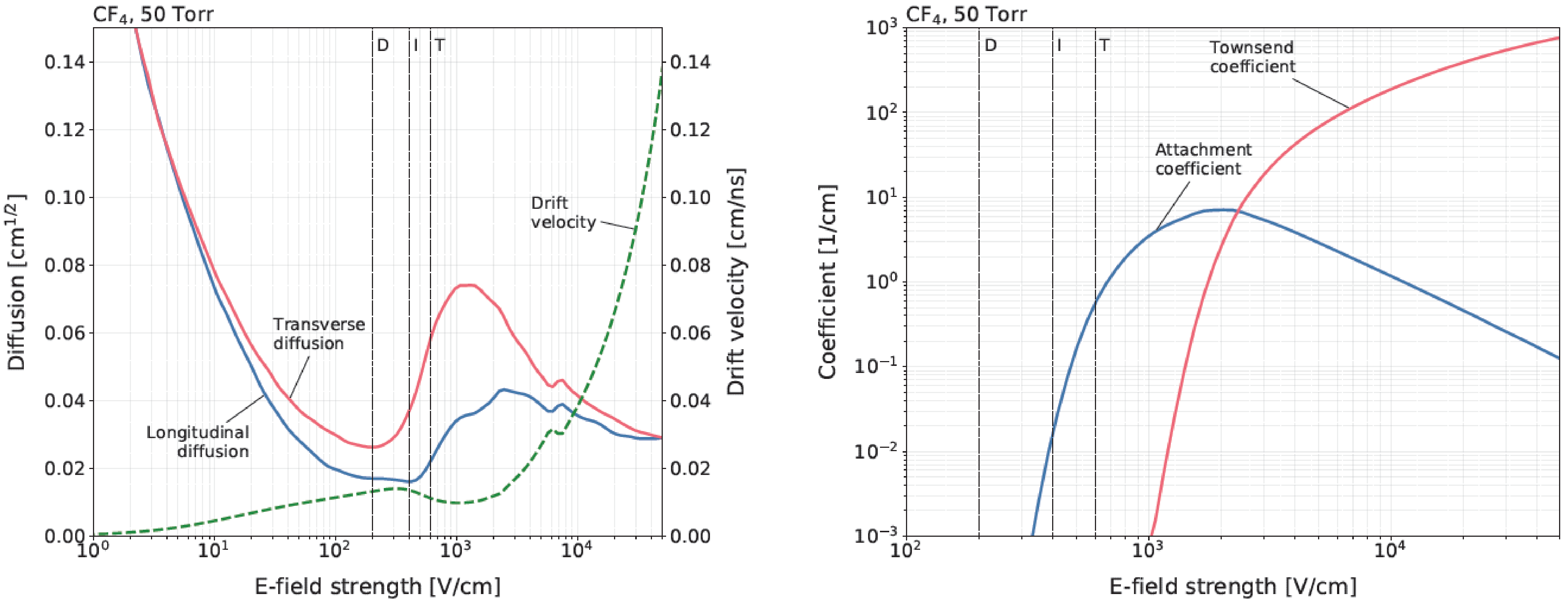


Figure 17: Electron transport properties of CF_4 at 50 Torr. Left – Drift velocity and diffusion. Right – Attachment and Townsend coefficients. Nominal fields in the drift (D), transfer (T) and induction (I) regions are indicated.

Secondary nuclear recoils

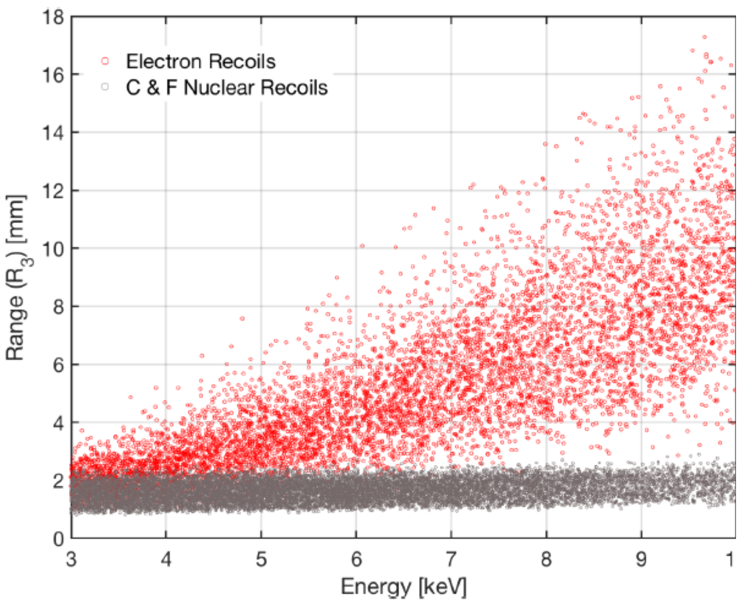
Secondary recoils per million primary ions (TRIM) created within 1 mm from the vertex in 50 Torr CF_4, when the “visible” energy of the secondary is 5–15 keV_{ee}

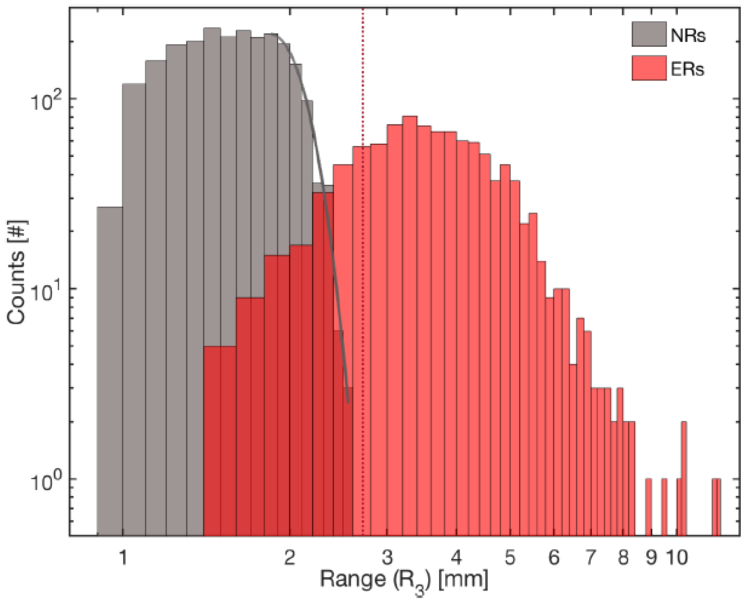
Primary ion	Secondary ion	
Fluorine	**Fluorine**	**Carbon**
500 keV	22,310	4,800
400	26,840	5,930
300	36,640	7,640
200	56,130	1,263
170	67,040	1,418
Carbon	**Fluorine**	**Carbon**
500 keV	6,250	1,210
400	7,950	1,610
300	11,380	2,310
200	17,310	3,700
130	26,120	5,770

~70,000 per million (worst case)

How many of these look like 5-15 keV electrons? Simulate several thousand more tracks using full chain, analyse image and recover track lengths (R_3)

Can cut down to ~0.5 per 70,000 secondaries, retaining 85% electron detection efficiency (i.e. ~0.5 per million primary recoils)





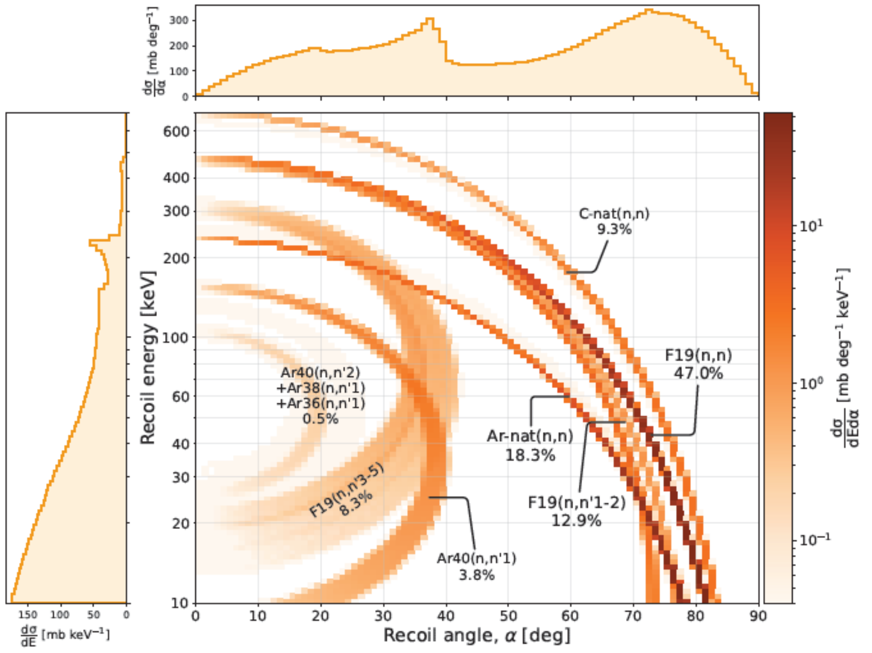
Migdal in other elements

Migdal probabilities in other elements of interest for DM searches which we aim to explore, mostly in mixtures with CF_4

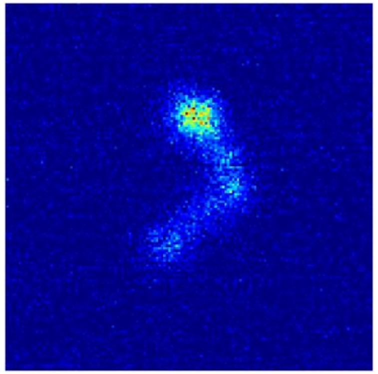
These probabilities are not too dissimilar (except for He)

Neutron scattering cross sections – total (σ_0) and bare-recoil processes (σ_s) plus Migdal probabilities for full neutron-induced NR spectrum, integrated down to zero NR threshold for electron thresholds of 0.5 keV and 5 keV (see C. McCabe's talk)

	2.47 MeV (D-D)				14.7 MeV (D-T)			
	σ_0, mb	σ_s, mb	P(>0.5 keV)	P(>5 keV)	σ_0, mb	σ_s, mb	P(>0.5 keV)	P(>5 keV)
^{4}He	3,239	3,239	2.98×10^{-3}	4.29×10^{-7}	1,017	1,017	9.01×10^{-2}	2.48×10^{-6}
^{12}C	1,613	1,613	6.01×10^{-3}	1.45×10^{-5}	1,379	1,321	2.15×10^{-2}	4.09×10^{-5}
^{19}F	3,038	3,038	2.81×10^{-3}	2.01×10^{-5}	1,786	1,272	9.95×10^{-3}	6.50×10^{-5}
^{nat}Ne	2,474	2,465	2.62×10^{-3}	2.32×10^{-5}	1,677	1,055	8.50×10^{-3}	6.89×10^{-5}
^{nat}Si	3,111	3,111	2.39×10^{-3}	2.87×10^{-5}	1,725	1,150	1.10×10^{-2}	1.25×10^{-4}
^{40}Ar	5,050	5,050	2.18×10^{-3}	2.92×10^{-5}	2,818	2,754	6.85×10^{-3}	8.94×10^{-5}
^{nat}Ge	3,401	3,401	1.64×10^{-3}	2.46×10^{-5}	3,227	3,130	5.47×10^{-3}	8.12×10^{-5}
^{nat}Kr	3,825	3,825	1.56×10^{-3}	2.37×10^{-5}	3,741	3,717	4.65×10^{-3}	7.03×10^{-5}
^{nat}Xe	5,760	5,760	7.31×10^{-4}	1.55×10^{-5}	4,871	4,861	2.80×10^{-3}	5.95×10^{-5}



Energy-angle relations for D-D neutron scattering in 50% Ar/CF_4.



Blessing or curse?
Auger emission in addition to Migdal electron