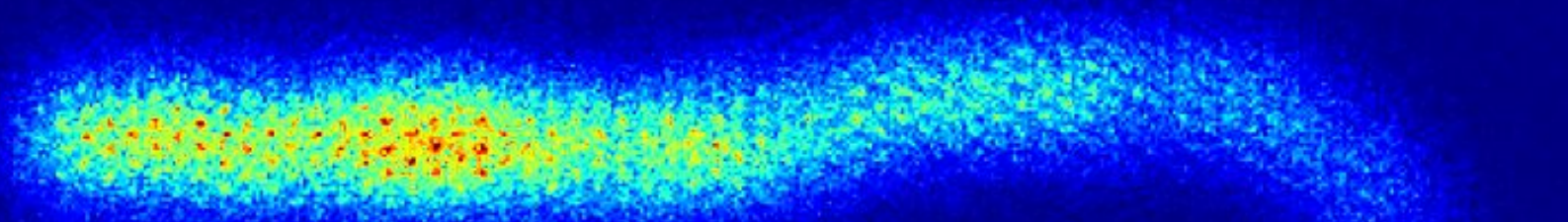


Investigations of the Migdal effect in elements relevant to dark matter searches using the MIGDAL experiment at the NILE/ISIS facility at RAL



Paweł Majewski (RAL/PPD) &
Henrique Araújo (Imperial College London)



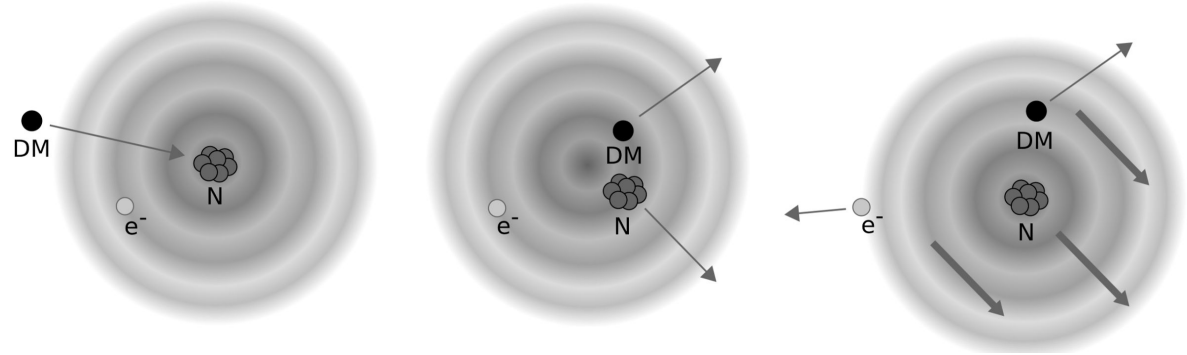
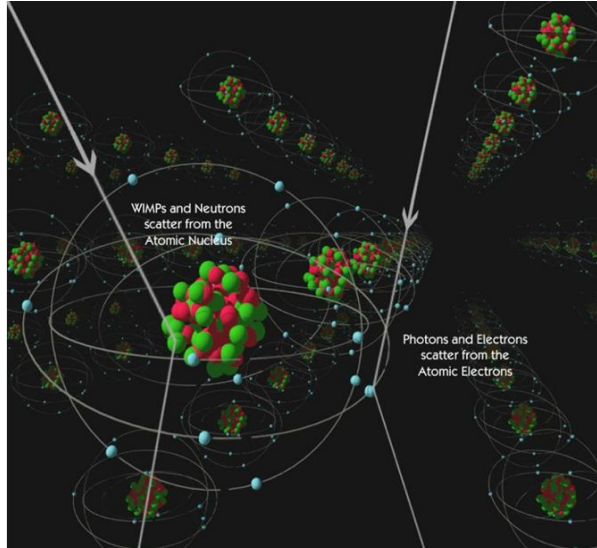
The Dark Matter Problem

- The dark matter problem is the longest outstanding problem in modern physics.
- What we observe in the universe, starting from here, our planet Earth, the galaxies are made of matter.
- However, there's more to the universe than the matter we can see - an elusive substance, which neither emits nor absorbs the light and yet affects us by shaping our universe.
- Scientists around the world are trying to figure out what it is.
- The MIGDAL project is to help them out in their endeavour.



Credit : [link](#)

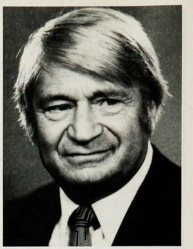
What the Migdal effect is and why it matters in DM searches ?



Migdal Effect - nucleus moves relative to the electron cloud. Individual electron might be ejected leading to ionisation.

- DM searches use signal from nuclear recoils as a signature of the DM interaction with the detector medium
- Targets with heavy elements such as **Xenon and Argon** are immune to light WIMPs unless Migdal effect is experimentally confirmed

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 исследовался эффект ионизации при деинтеграции, сопровождающей передачей большой энергии.

При ядерных столкновениях или деинтеграциях, сопровождающихся передачей большой энергии, всегда происходит ионизация атомных оболочек. При малых скоростях ядра отдачи передача энергии электронам, и ионизация не происходит вообще, при очень больших скоростях ядро вылетает из оболочки, не ударив ее в своей. При промежуточных величинах энергии отдачи ионизация происходит только в наружных, слабо связанных оболочках.

При столкновении ядра с нейтронами такой же энергии является единственно, приводящим к заметной ионизации (вспомогательно, что ионизация, обусловленная магнитным и спиновым ядерным взаимодействием нейтрона с электронами, крайне мала — соответствует величине в первом порядке порядка 10^{-20} см², во втором — порядка 10^{-26} см²).

Вероятность такой ионизации может быть очень мала при резонансе. Так интересна случай большой энергии отдачи, в частности, большие скорости плавающей частицы, то время соударения с ядром много меньше времени периода. Следовательно, величина скорости ядра пропорциональна не квадратично, так что Ψ — функция атомной — не может измениться во время столкновения.

Натуро, кроме того, имеет, что расстояние, на которое смещается ядро за время столкновения, имеет порядок $\frac{v}{V}$, где M_1 — масса таковой ядра, M_2 — масса ядра R — радиус ядра. Так как при заметной доле энергии R много меньше размеров атомных оболочек, то ядро можно считать не смещающимся за время удара.

Для получения вероятности возбуждения или ионизации ядро необходимо иметь функцию отдачи равную по собственным функциям движущегося ядра. Этого можно добиться, только собственными функциями ядра Ψ и Ψ^* — функции волнового ядра. Начальная функция Ψ при этом преобразуется в выражение:

$$\Psi^{(n)} = \int \Psi_n(\mathbf{r}_1, \mathbf{r}_2, \dots, \mathbf{r}_n) \dots$$

Действительно, множитель $e^{i\mathbf{p}\cdot\mathbf{r}}$ представляет собой Ψ -функцию центра ионизирующей оболочки, который в старой системе координат неподвижен, а в новой движется со скоростью V равной по величине и противоположной по направлению скорости ядра.

Пусть কোনো состояние ядра в рассматриваемой системе координат дается функцией $\Phi_n(\mathbf{r}_1, \mathbf{r}_2, \dots, \mathbf{r}_n)$. Так как ядро за время удара не смещается, то координаты электронов в Ψ отнесены от той же точки, что и в Φ_n . Вероятность перехода в конечном состоянии дается выражением:

$$W = \left| \int \Phi_n^* \Psi_n d\mathbf{r}_1 \dots d\mathbf{r}_n \right|^2 \quad (1)$$

QUALITATIVE METHODS IN QUANTUM THEORY

CRC Press

A. B. MIGDAL

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.

I. Ionization accompanying β -decay

1. The probability of ionization of an atom as a result of the β -decay can be not so difficultly 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 in the case of a K -electron, because $(Ze^2/hc)^2 = (V/c)^2$. Therefore, the direct interaction is to be considered as a relativistic correction. The condition (2) is approximately valid even for K -electrons of uranium.

$$\left(\frac{Ze^2}{hc} \right)^2 \ll 1. \quad (2)$$

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 $^6\text{He}^+$ Ions*, PRL 108, 243201 (2012)

[6] X. Fabian et al., *Electron Shakeoff following the β^+ decay of Trapped $^{19}\text{Ne}^+$ and $^{35}\text{Ar}^+$ trapped ions*, PRA, 97, 023402 (2018)

Migdal effect and Dark Matter

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



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PHYSICAL REVIEW D **107**, 035032 (2023)

Migdal effect in dark matter direct detection experiments

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Precise predictions and new insights for atomic ionization from the Migdal effect

Peter Cox^{1,*}, Matthew J. Dolan,^{1,†} Christopher McCabe^{2,‡} and Harry M. Quiney^{3,§}

¹*ARC Centre of Excellence for Dark Matter Particle Physics, School of Physics,
The University of Melbourne, Parkville, Victoria 3010, Australia*

²*Theoretical Particle Physics and Cosmology Group, Department of Physics,
King's College London, London WC2R 2LS, United Kingdom*

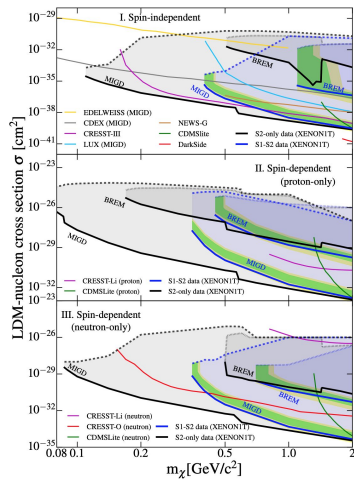
³*School of Physics, The University of Melbourne, Parkville, Victoria 3010, Australia*

 (Received 18 September 2022; accepted 12 January 2023; published 27 February 2023)

Extended model of the Migdal effect
calculated by C. McCabe.

Dark Matter searches and Migdal Effect

- sensitivity extension to low mass region -



LUX (Xenon)

”Results of a Search for Sub-GeV Dark Matter Using 2013 LUX Data”

<https://arxiv.org/pdf/1811.11241.pdf>

XENON1T (Xenon)

”A Search for Light Dark Matter Interactions Enhanced by the Migdal effect or Bremsstrahlung in XENON1T”

<https://arxiv.org/pdf/1907.12771.pdf>

EDELWEISS (Germanium)

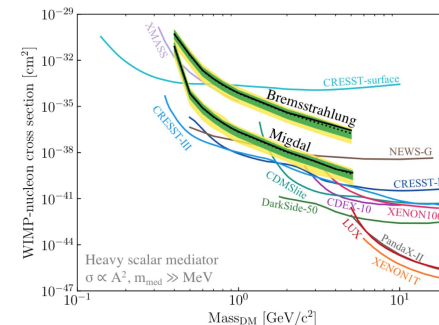
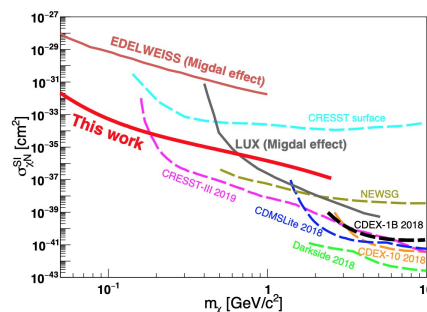
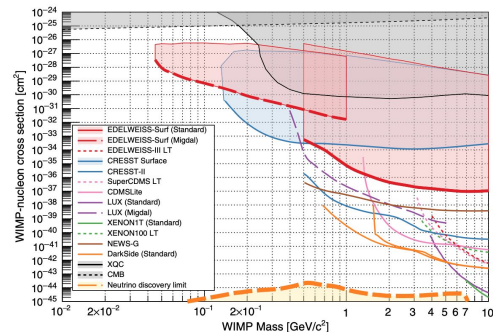
”Searching for low-mass dark matter particles with a massive Ge bolometer operated above-ground”

<https://arxiv.org/abs/1901.03588>

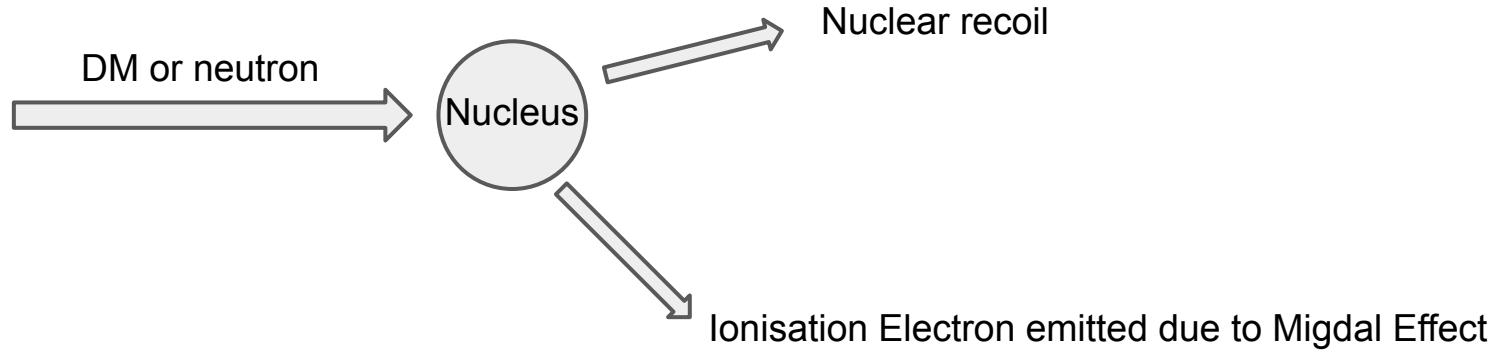
CDEX-1B (Germanium)

”Constraints on Spin-Independent Nucleus Scattering with sub-GeV Weakly Interacting Massive Particle Dark Matter from the CDEX-1B Experiment at the China Jin-Ping Laboratory”

<https://arxiv.org/pdf/1905.00354.pdf>



Migdal In Galactic Dark mAtter expLoration experiment

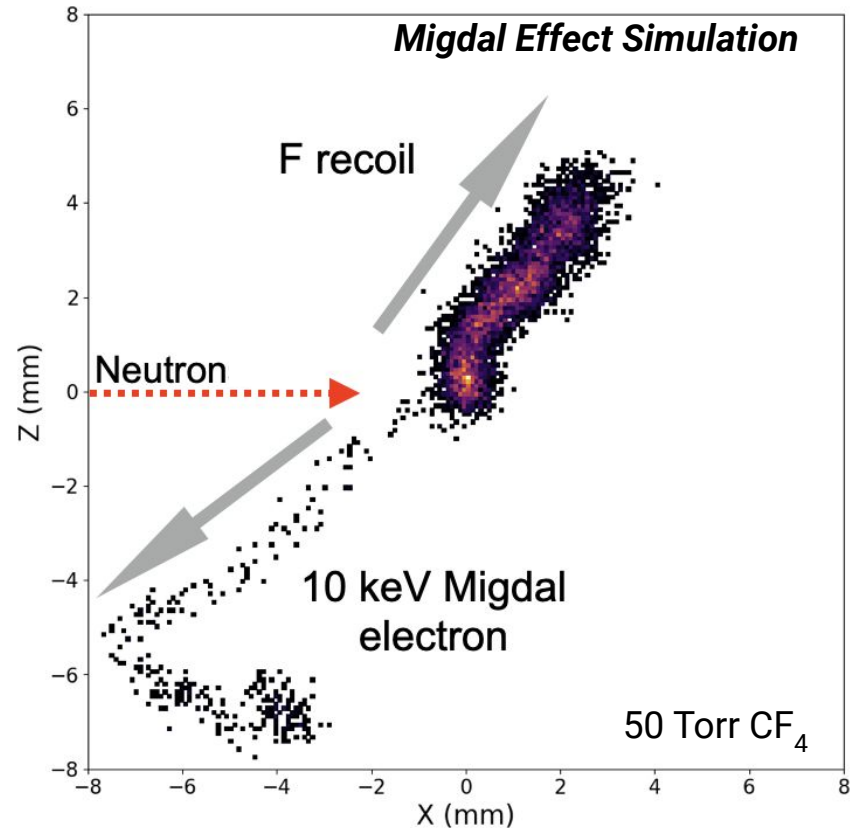


- Extremely challenging experiment : Looking for a rare (10^{-5}) atomic phenomenon never before observed in the nuclear scattering using high flux neutron generators $10^{10} / 10^9$ n/s with D-T/ D-D
- Aim of the MIGDAL experiment - unambiguous observation and measurement of the Migdal effect using a low pressure Optical TPC

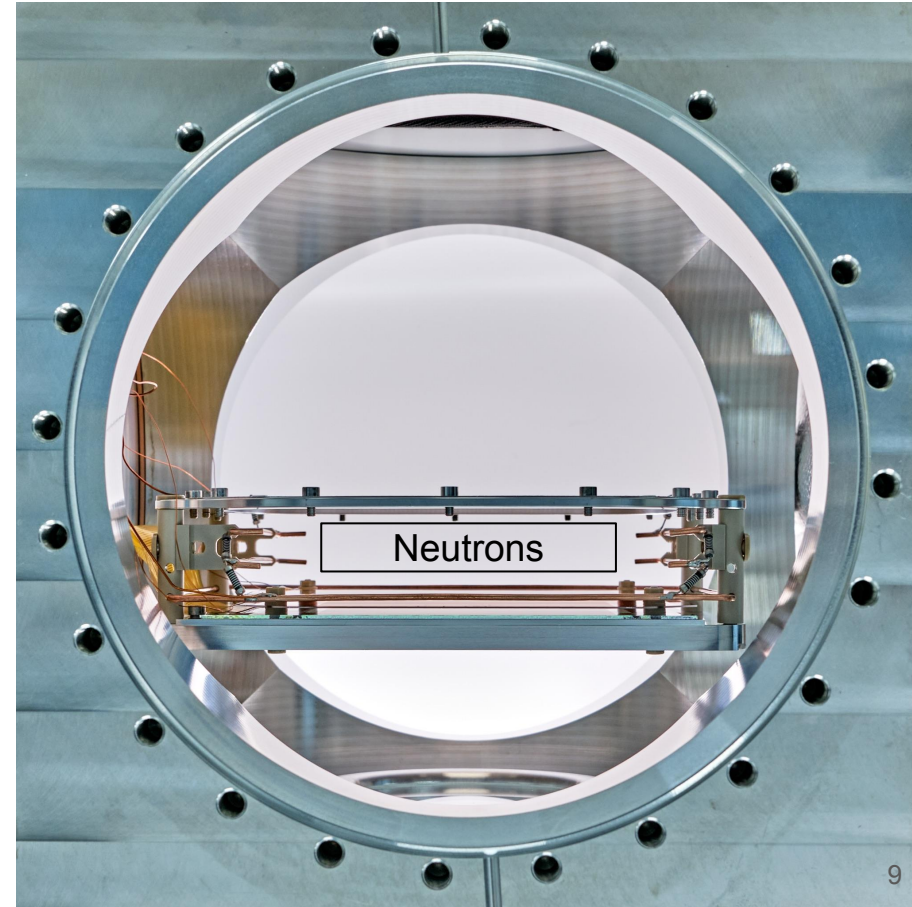
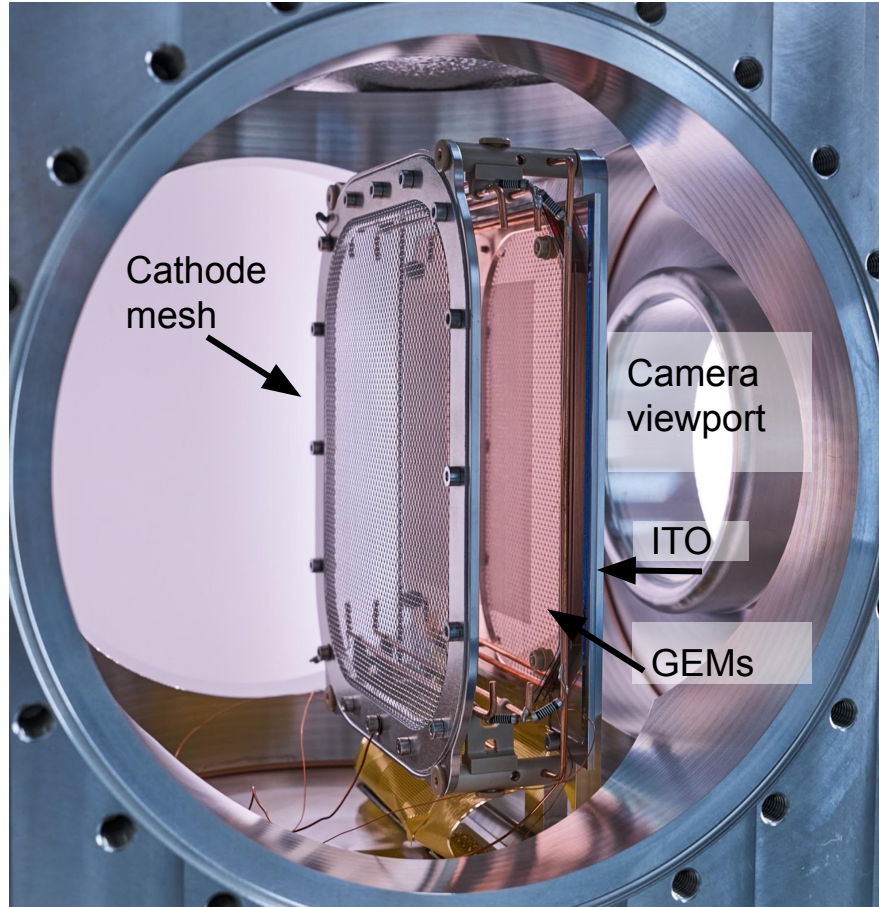
Experimental Goal

- Observation of two tracks - a nuclear recoil and an electron - sharing the same vertex
- Aim to make the first unambiguous observation and measurement by capturing both electron and nuclear recoil

The MIGDAL Experiment has a discovery potential!

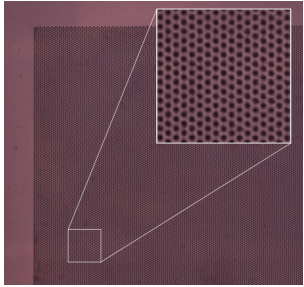


The MIGDAL Optical Time Projection Chamber



The MIGDAL Optical Time Projection Chamber

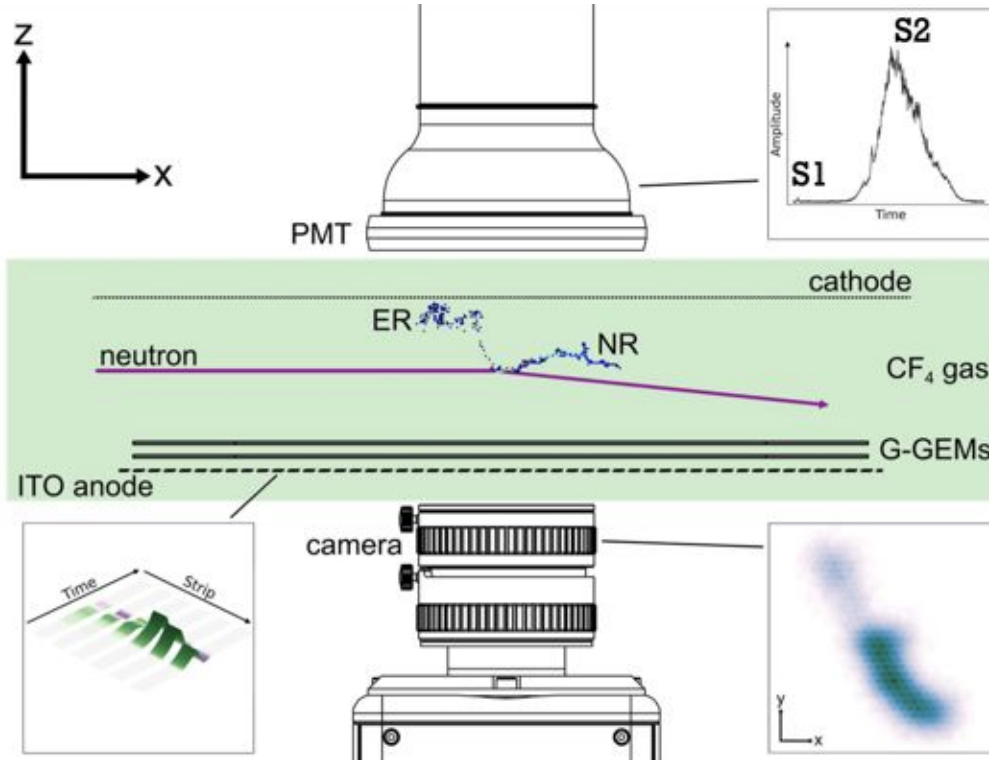
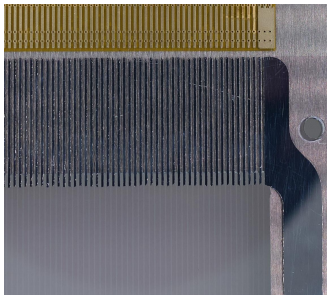
GEMs



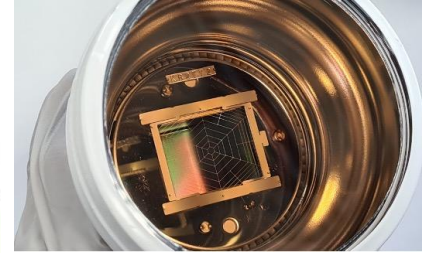
Neutrons

2.45 MeV neutrons from a DD generator at the NILE facility

ITO Anode



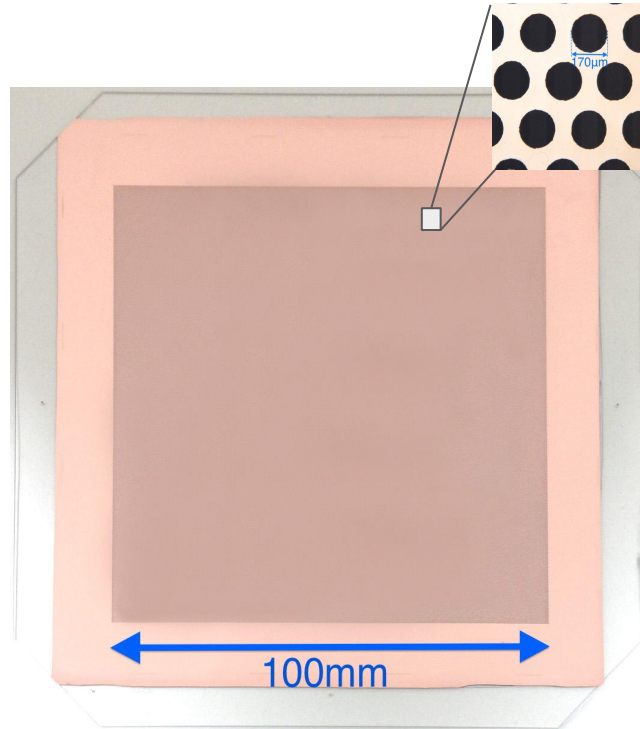
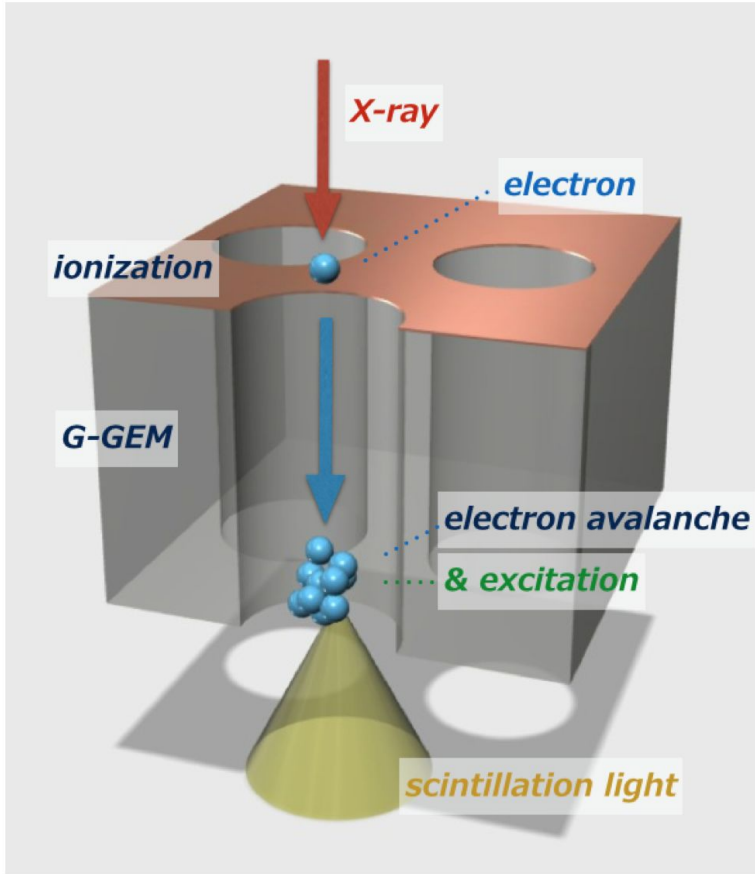
PMT



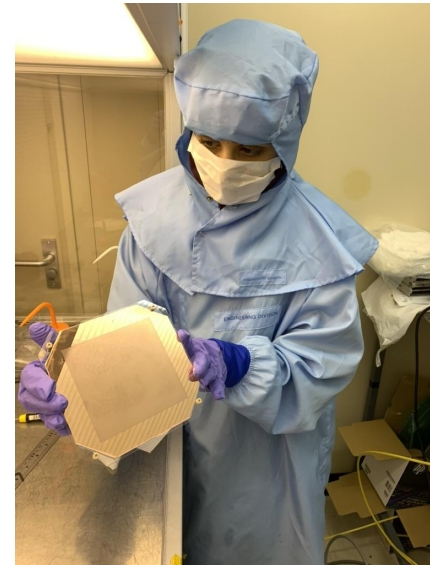
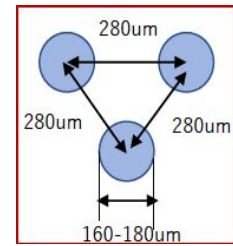
CMOS Camera



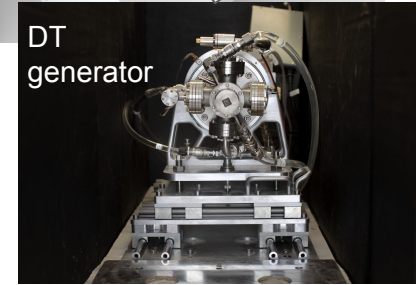
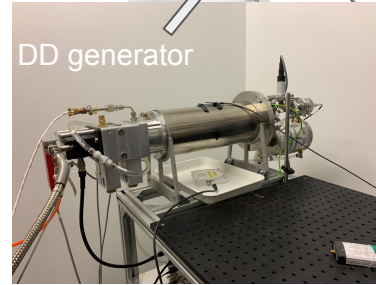
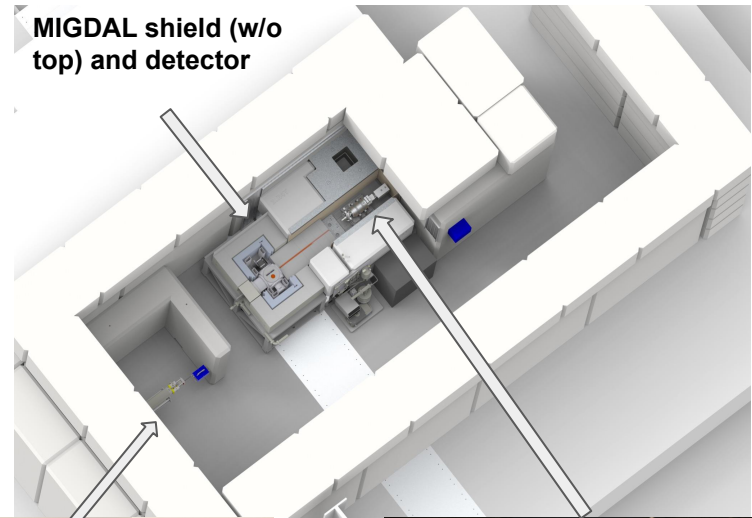
Glass-GEMs



Glass thickness : 570 um



NILE facility and neutron generators



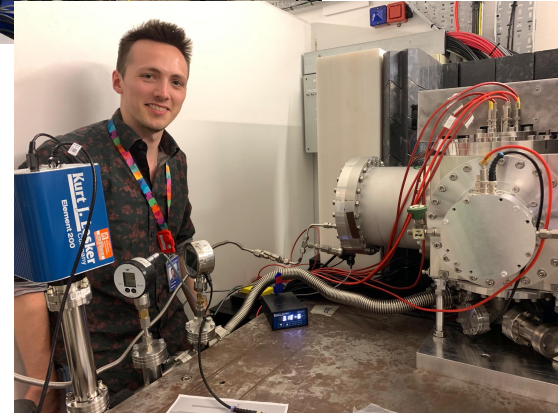
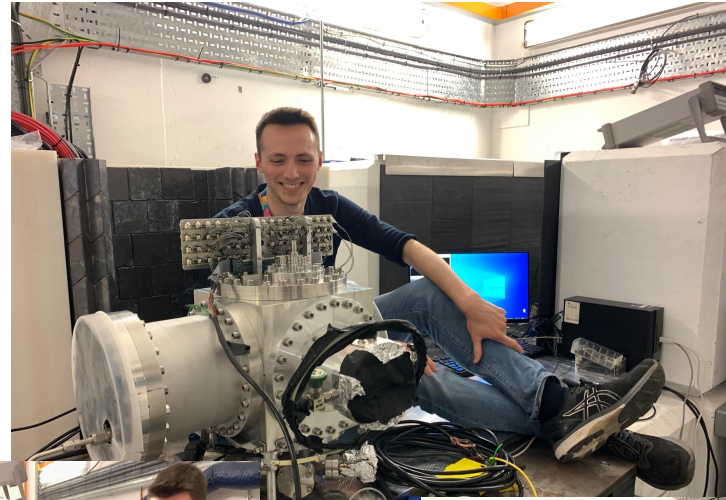
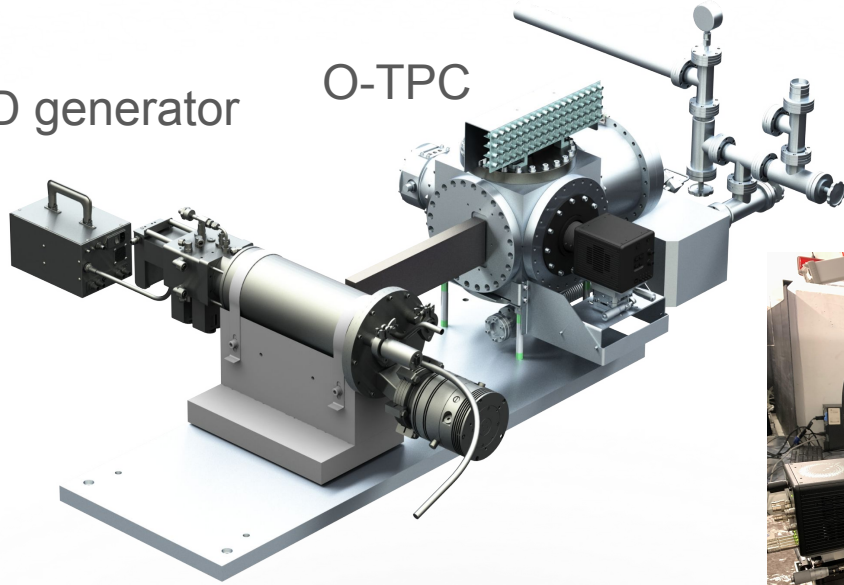
- Commissioning of DD and the MIGDAL experiment - Summer 2023
- First and Second Science Runs (3 weeks each) have accumulated tens of millions of images.

MIGDAL assembly at NILE

To Gas System

DD generator

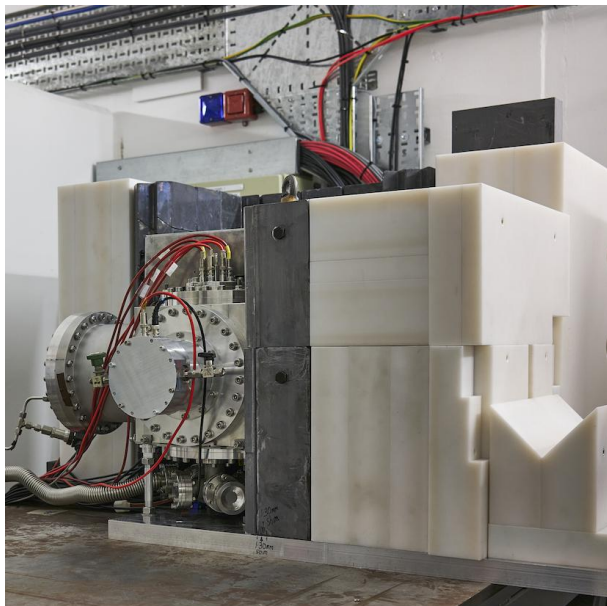
O-TPC



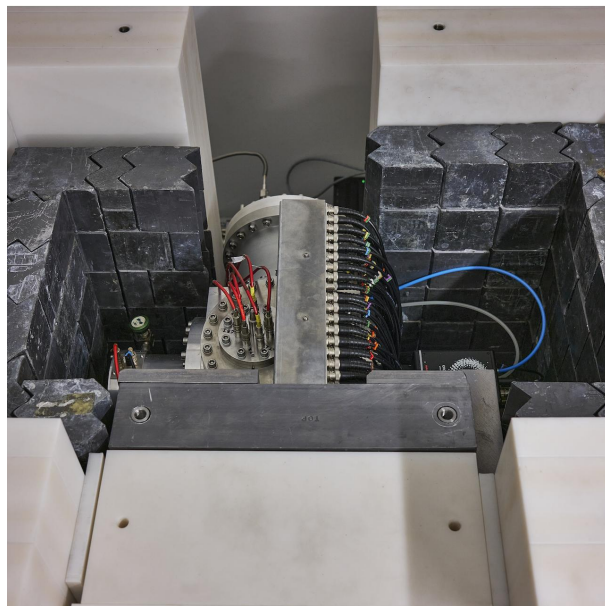
MIGDAL assembly at NILE



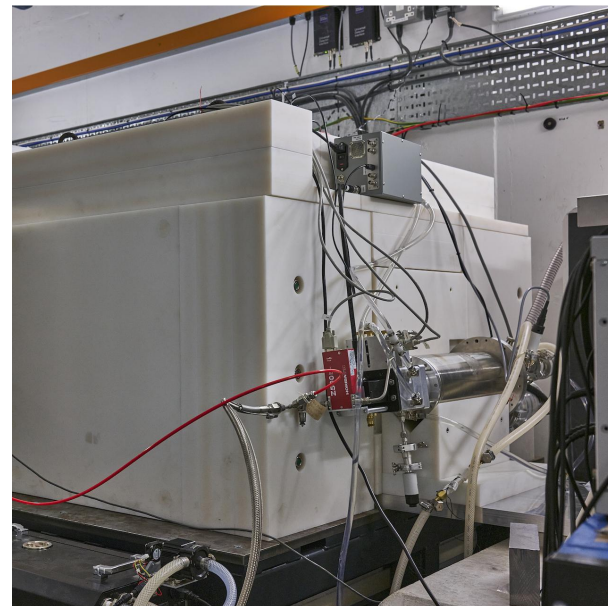
The MIGDAL Experiment at NILE



MIGDAL experiment shielded by borated high density polyethylene (moderates and stops neutrons).

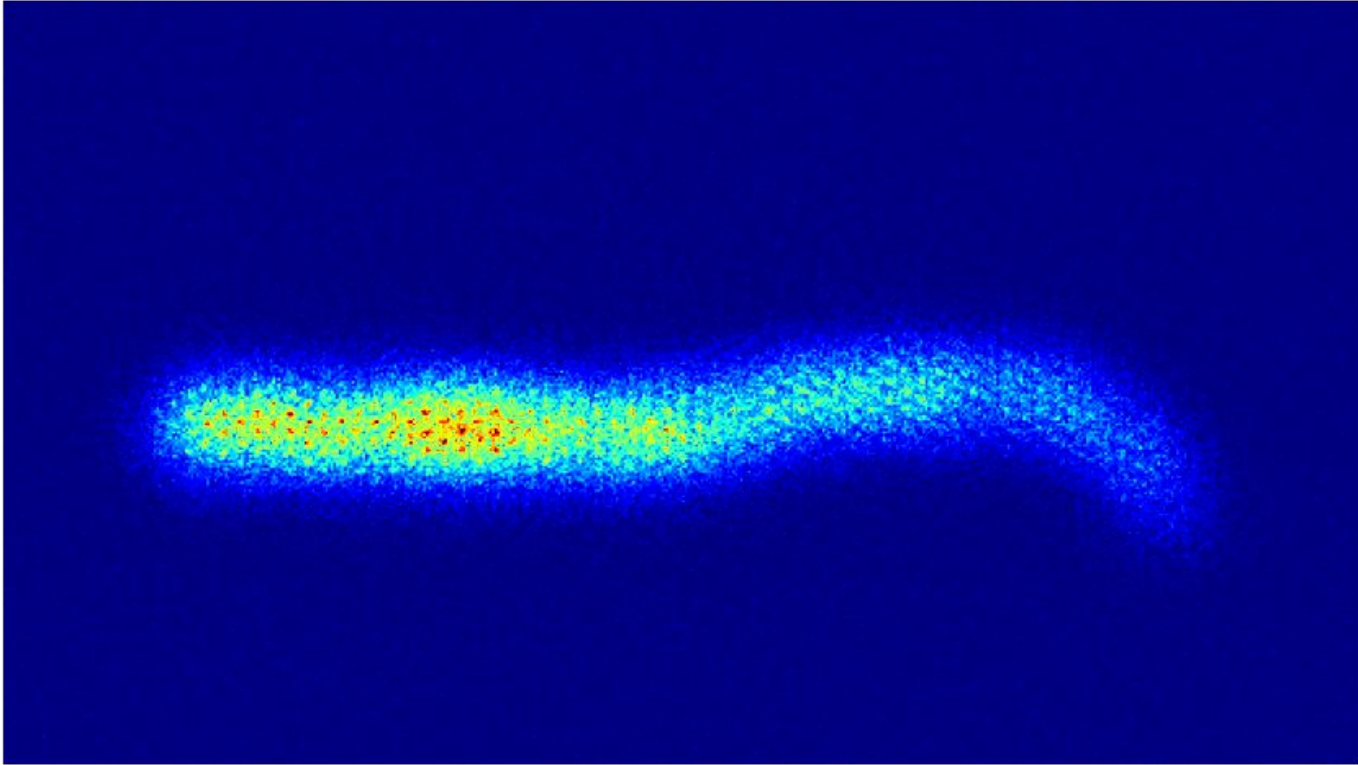


Lead shielding surrounds MIGDAL detector (captures gammas from inelastics and radiative capture).



Fully integrated experimental setup with DD generator at entrance of collimator.

The MIGDAL Experiment at NILE

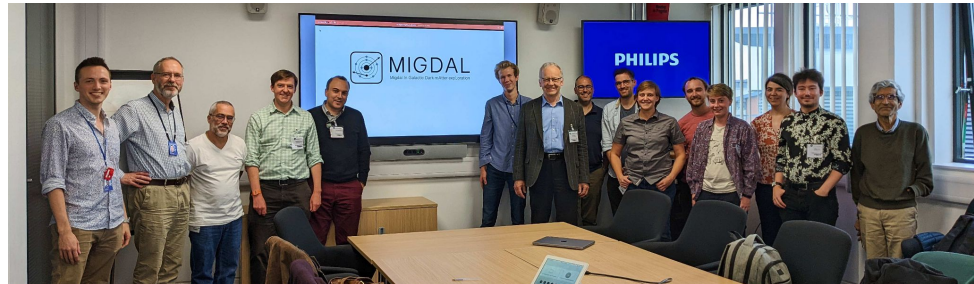


One of the first nuclear recoils captured by the MIGDAL experiment.

The MIGDAL Collaboration



- Over 35 physicists and engineers from 15 institutions across 8 countries led by PPD/RAL and Imperial College
- Supported by RD51, GDD/CERN and ISIS/NILE



If you are thinking about :

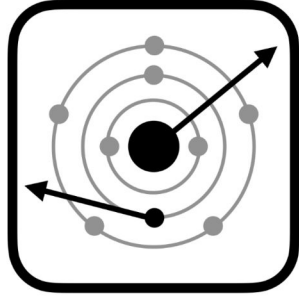
- *Joining an exciting project with a discovery potential impacting globally the dark matter searches*
- *Working with a cutting edge detector technology and detector R&D in the National Laboratory at RAL*
- *Working in a friendly environment with a medium scale international collaboration*
- *Analysing data using extensively machine learning with object detection*
- *Having your experiment “next door” and accessing the data as soon as it is recorded*
- *Presenting results at international conferences*
- *Being recognised by the dark matter community*



This young explorer can be YOU

The MIGDAL project is for you !

More information about MIGDAL: <https://migdal.pp.rl.ac.uk>



MIGDAL

Migdal In Galactic Dark mAtter expLoration

Welcome to the MIGDAL Collaboration's webpage. Funded as part of the STFC's Xenon Futures project, we are working to design and build an experiment capable of observing and measuring the Migdal effect.

ABOUT US AND
PRESS RELEASES

COLLABORATION

PRESENTATIONS