First Light from MIGDAL

Migdal In Galactic Dark mAtter expLoration

Results from Commissioning Data Using Fast Neutrons

ELIZABETH TILLY* ON BEHALF OF THE MIGDAL COLLABORATION

CPAD WORKSHOP NOVEMBER 9, 2023

THE UNIVERSITY OF NEW MEXICO

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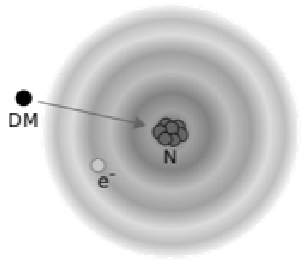
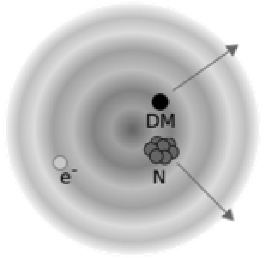
University of Birmingham · UAM · GDD Gas Detectors Development Group · Helsinki Institute of Physics · Imperial College London · King's College London · LIP · The University of New Mexico · University of Oxford · Royal Holloway University of London · Science & Technology Facilities Council Rutherford Appleton Laboratory · The University Of Sheffield

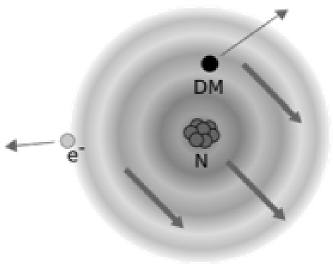
The Migdal Effect



1. Neutral particle impacts atomic nucleus



2. Nucleus recoils, and electron cloud lags behind



3. Small probability of electron ionization as the electron cloud "catches up" with the nucleus

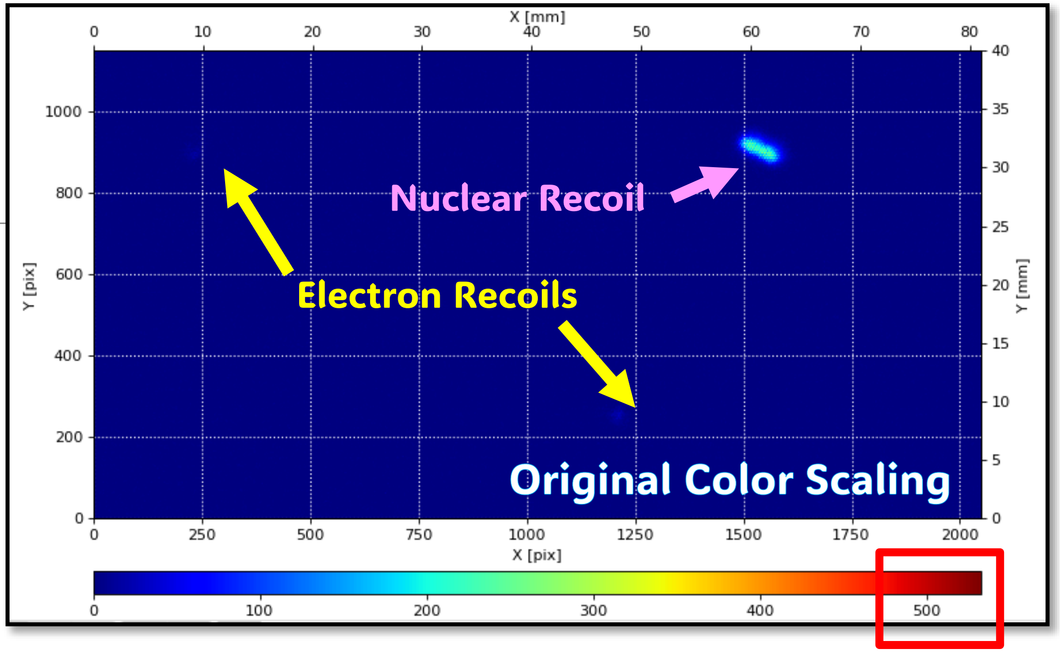
M. Dolan, F. Kahlhoefer, C. McCabe, Phys. Rev. Lett. 121, 101801 (2018), arXiv:1711.09906

- Rare ($O(10^{-5})$) quantum-mechanical process theorized by Russian physicist A. B. Migdal predicting **neutral impact ionization**
- Invoked by WIMP searches to probe low-mass parameter space
  - This resulted in *new limits* ***~2 orders of magnitude lower***
- MIGDAL experiment seeks to make the **first unambiguous direct measurement** of this effect

Building a Detector

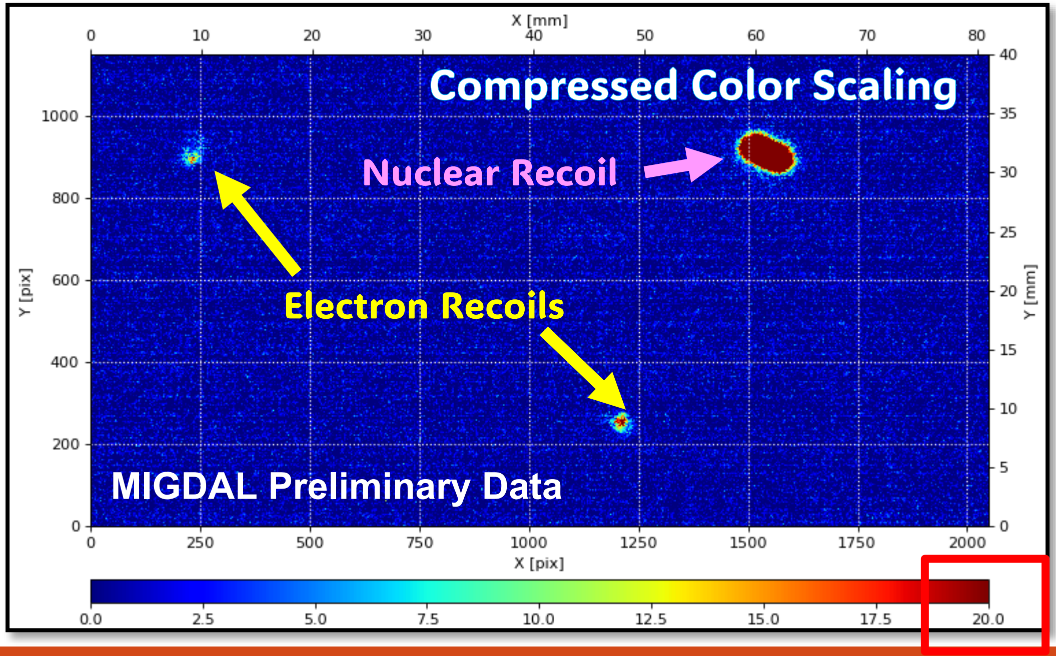
Two biggest challenges in Migdal search:

1. ***Very rare*** (on the order of 1 in ~10^5 NR produce a Migdal e^-)
2. ***Very high dynamic range*** in ***very low energy events*** (O(keV))



We need a detector capable of the following:

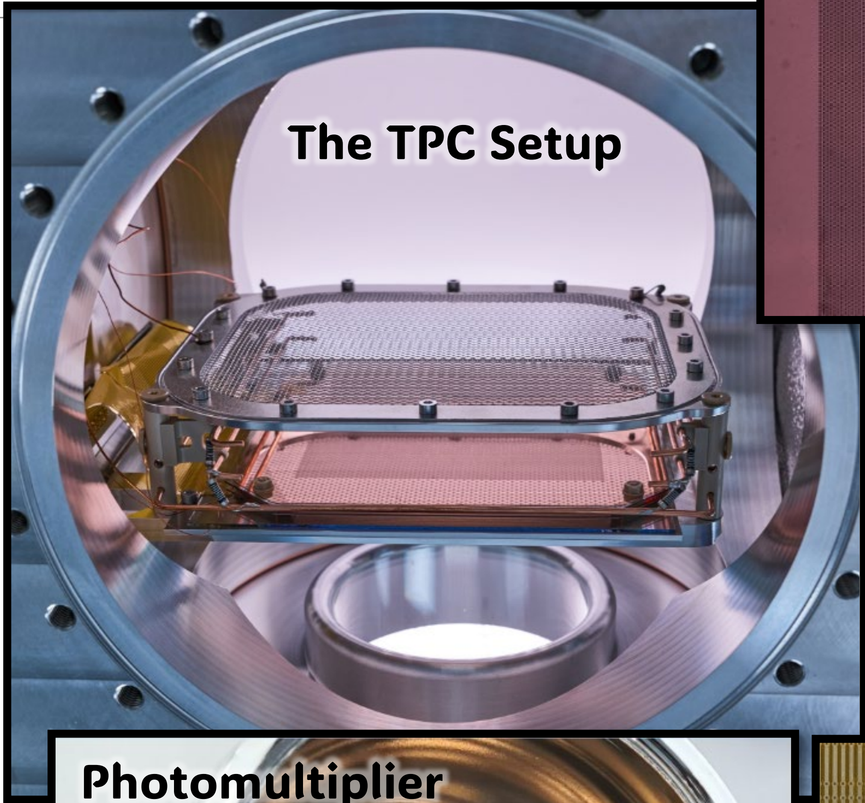
1. *Characterizing* low energy, high dynamic range events
2. High event rate
3. Event discrimination
4. High resolution in 4 dimensions
5. Excellent background rejection

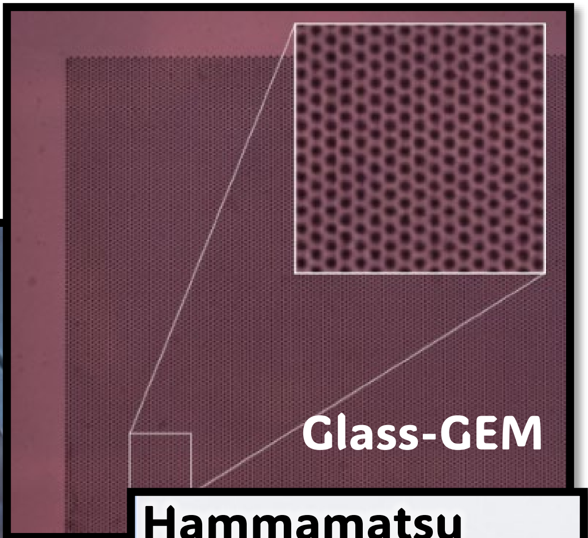


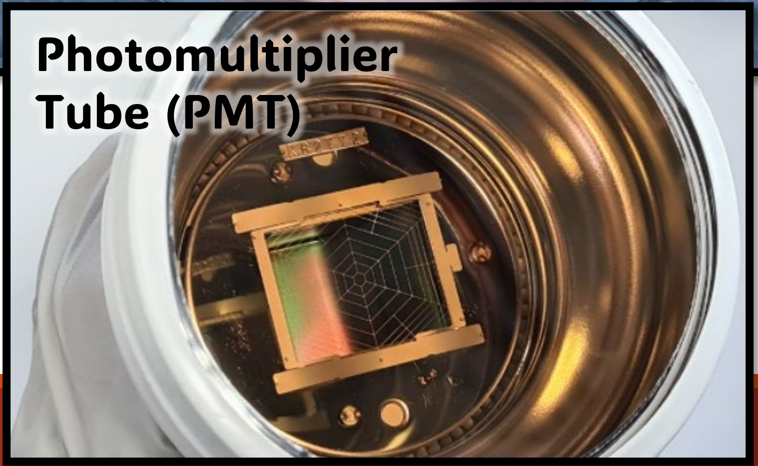
The MIGDAL Detector

An Optical Time Projection Chamber (OTPC)

- Low-pressure gas: 50 Torr of CF_4
  - Extended particle tracks
- 2D Signal amplification with glass-GEMs
  - Very high spatial resolution (280 µm pitch)
- Readouts
  - Optical : Camera + PMT
  - Charge : GEMs + 120 ITO anode strips
- High-yield neutron generator
  - D-D: 2.47 MeV (10^9n/s)
  - Defined beam, “clear” through TPC



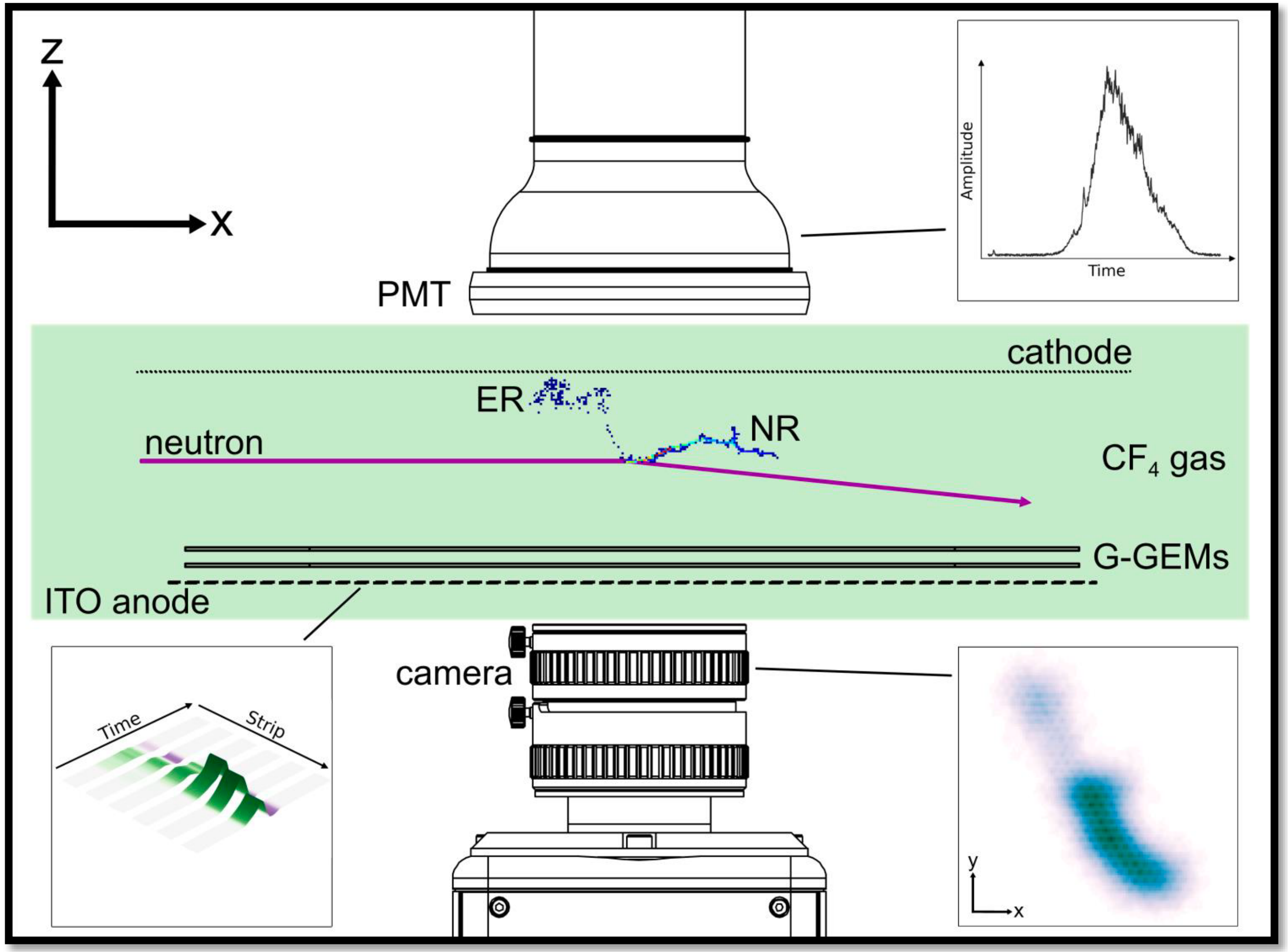




The MIGDAL Detector

3 Primary Components:

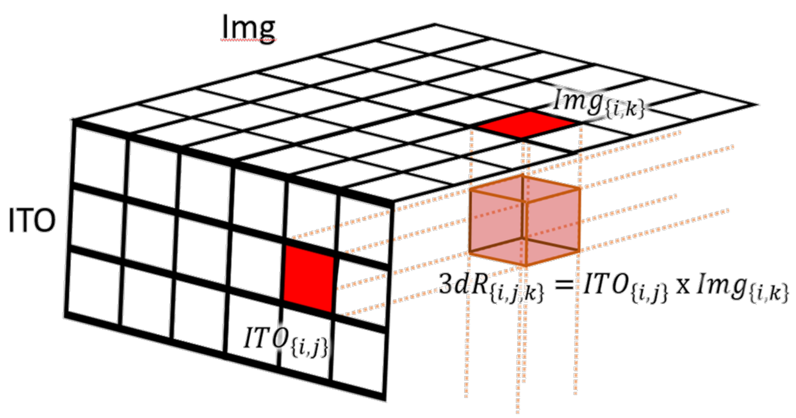
1. qCMOS Camera (Hamamatsu ORCA-QUEST)
   - **Detects GEM scintillation (x,y)**
   - 8 ms exposure time
   - 39 µm resolution
2. Indium Tin Oxide (ITO) anode strips
   - **Measures post-GEM ionization (x,z)**
   - 2ns/sample timing resolution
   - 2µs window events
   - Drift velocity = 130 µm/ns
   - 833 µm pitch (x-resolution)
3. Photomultiplier Tube (PMT)
   - **Detects primary and secondary scintillation (z_{abs})**
   - 2ns/sample timing resolution
   - 2µs window events



H.M. Araújo *et al* 2023 *Astropart. Phys*. **151** 102853 https://doi.org/10.1016/

Analysis: 3D Reconstruction

- Our detector creates 3 measurements:
  1. Camera Image (X,Y)
  2. ITO Strip Readout (X,Z)
  3. PMT (Absolute Z)
- We reconstruct our tracks in two ways:
  1. Voxelize the event
  2. Reconstruct the track path



3D track reconstruction of low-energy electrons in the MIGDAL low pressure optical time projection chamber

E. Tilly[1] and M. Handley[2,3] on behalf of the MIGDAL collaboration

Published 17 July 2023 • © 2023 IOP Publishing Ltd and Sissa Medialab

Journal of Instrumentation, Volume 18, July 2023

Citation E. Tilly *et al* 2023 *JINST* **18** C07013

DOI 10.1088/1748-0221/18/07/C07013 arXiv:2307.10477

IEEE TRANSACTIONS ON PATTERN ANALYSIS AND MACHINE INTELLIGENCE, VOL. 20, NO. 2, FEBRUARY 1998 113

An Unbiased Detector of Curvilinear Structures

Carsten Steger

Abstract—The extraction of curvilinear structures is an important low-level operation in computer vision that has many applications. Most existing operators use a simple model for the line that is to be extracted, i.e., they do not take into account the surroundings of a line. This leads to the undesired consequence that the line will be extracted in the wrong position whenever a line with different lateral contrast is extracted. In contrast, the algorithm proposed in this paper uses an explicit model for lines and their surroundings. By analyzing the scale-space behavior of a model line profile, it is shown how the bias that is induced by asymmetrical lines can be removed. Furthermore, the algorithm not only returns the precise subpixel line position, but also the width of the line for each line point, also with subpixel accuracy.

Index Terms—Feature extraction, curvilinear structures, lines, scale-space, contour linking, low-level processing, aerial images, medical images.

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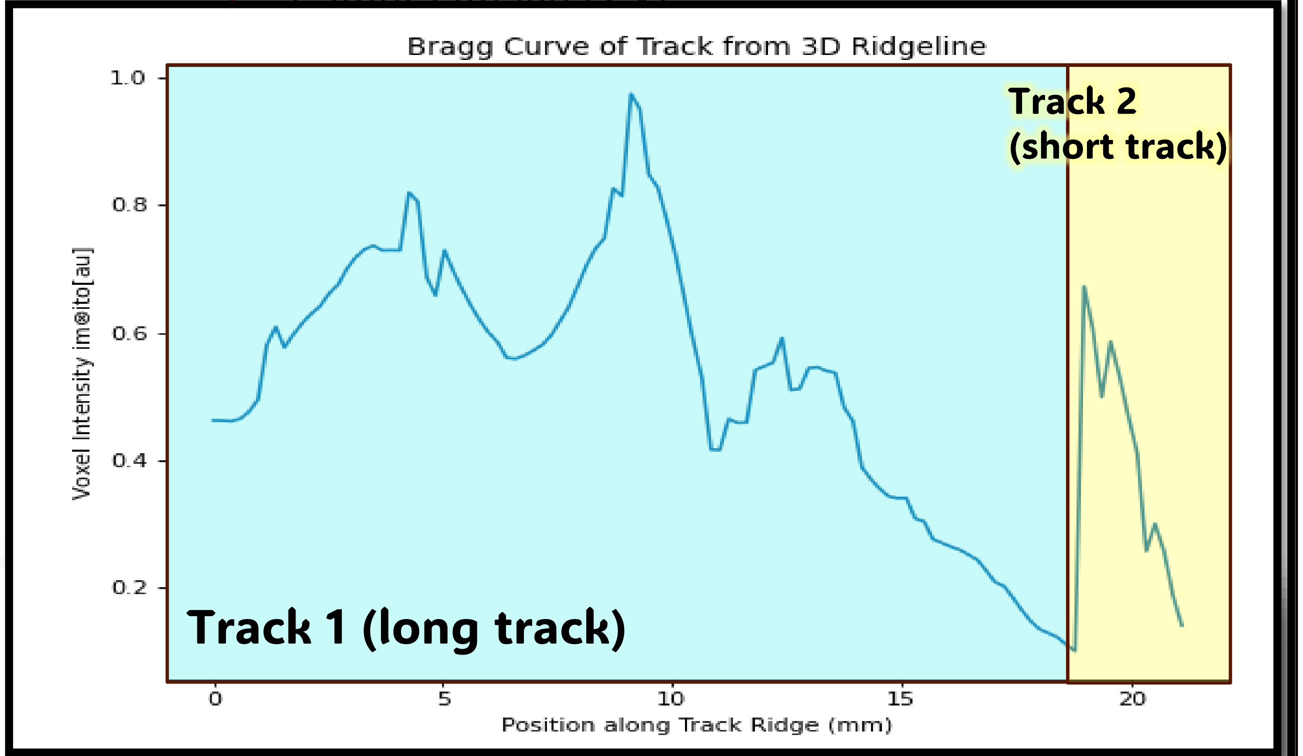
  1. Camera Image (X,Y)



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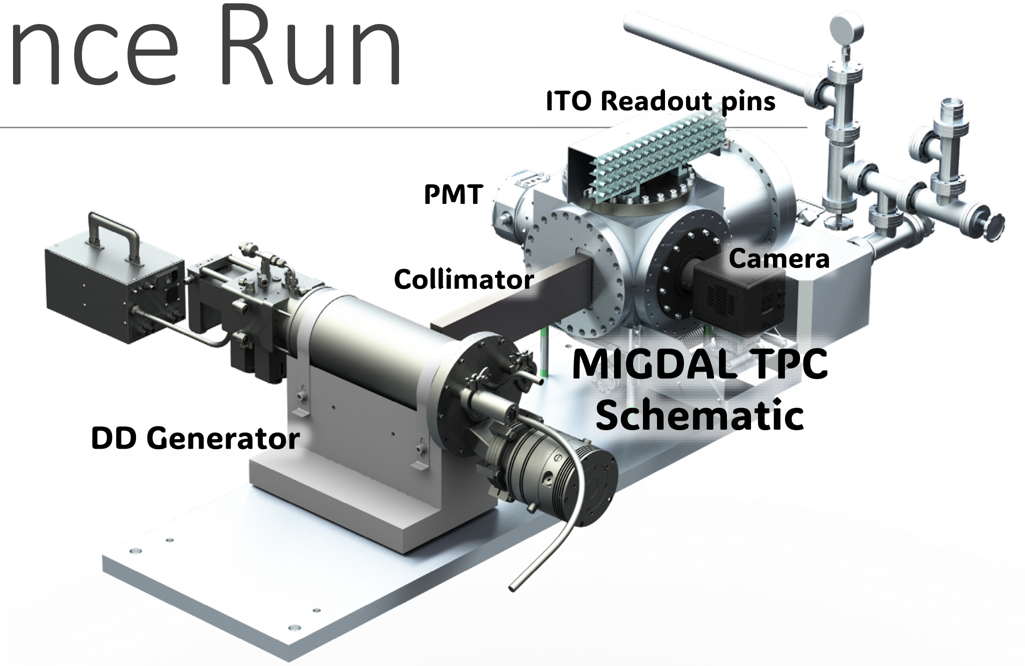
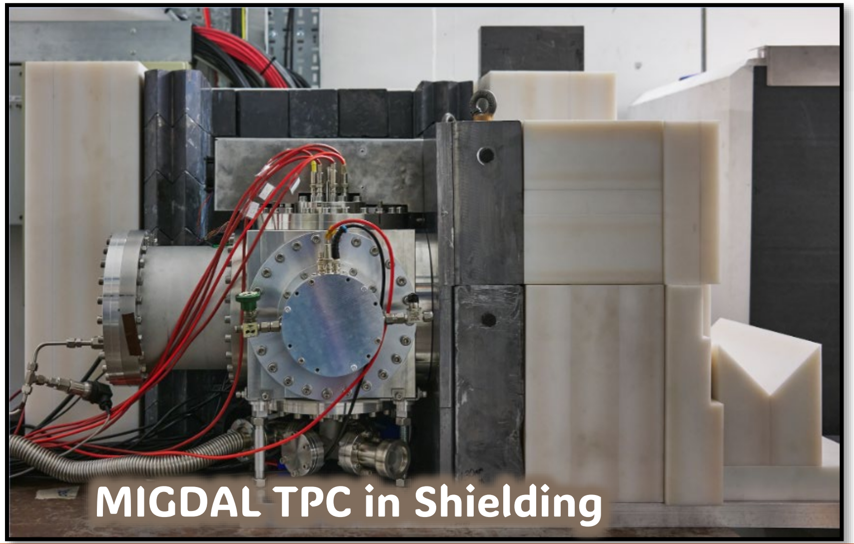
Citation E. Tilly *et al* 2023 *JINST* 18 C07013

DOI 10.1088/1748-0221/18/07/C07013

Results from the First Science Run

- The first science run ran from July 17-August 3, 2023
  - ~10 million unblinded camera frames recorded
- Data monitored in *real time* using a YOLO-based pipeline developed by Jeffrey Schueler
  - Provided live detector health monitoring
  - Discussed in previous talk
- Detector calibrated using 5.9 keV ^{55}Fe source



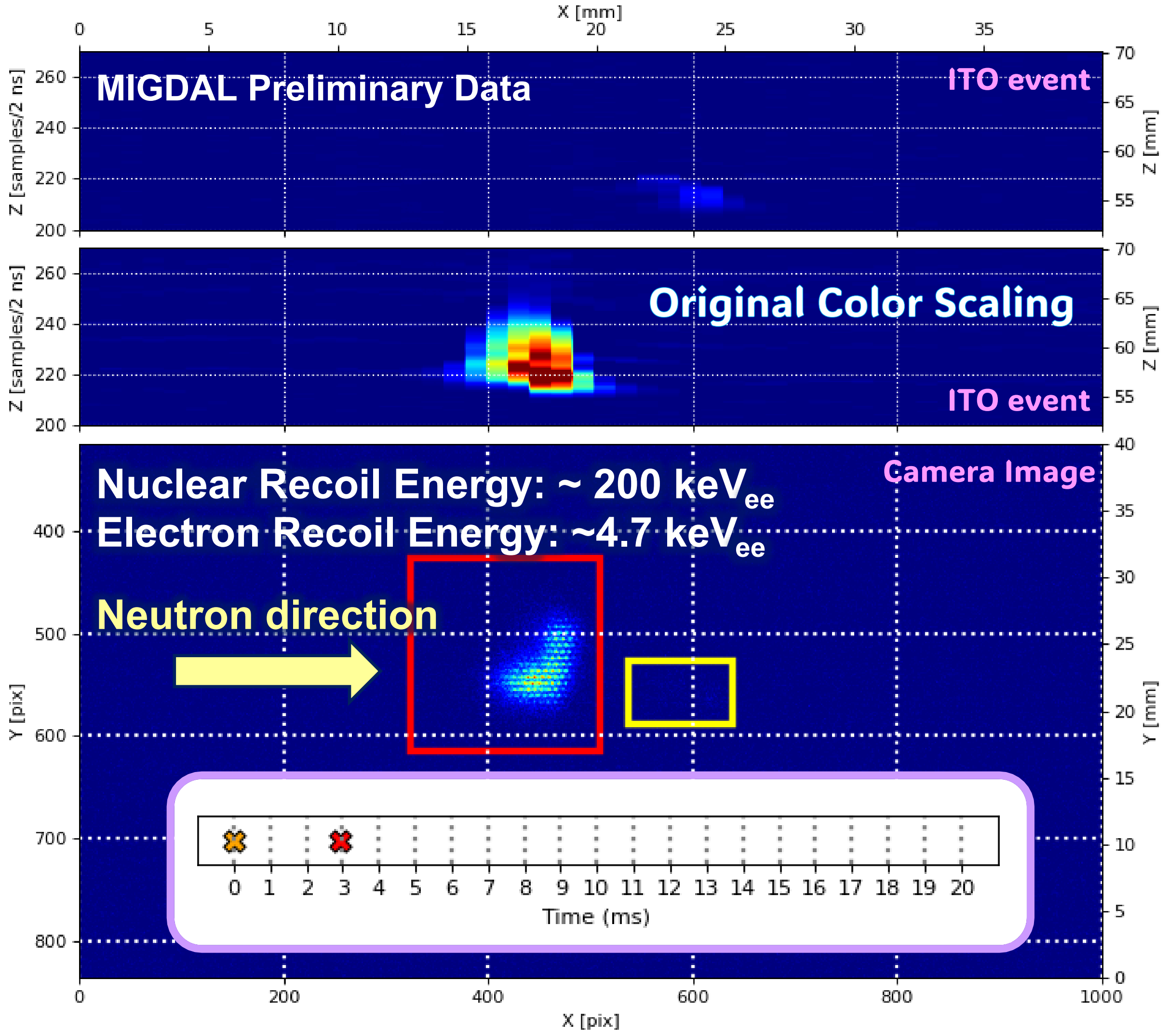


MIGDAL: Our current status

Data analysis is ongoing:
- YOLO pipeline (previous talk) *IDs tracks* and *skims for Migdal candidates* in camera images
- Vet candidates for follow-up using ITO signals
  1. Spatial coincidence? (image = 20 ms, ITOs = 2μs)
  2. A new background?
  3. True Migdal event?

Issues from the first run:
- Software led to longer camera exposure (20ms instead of 8ms)
- A few dead ITO strips
- Lower (~10x) neutron interaction rate from DD generator

Promises from the first run:
- Good coincidence rejection
- **Detector operates as anticipated**
- No new unexpected backgrounds



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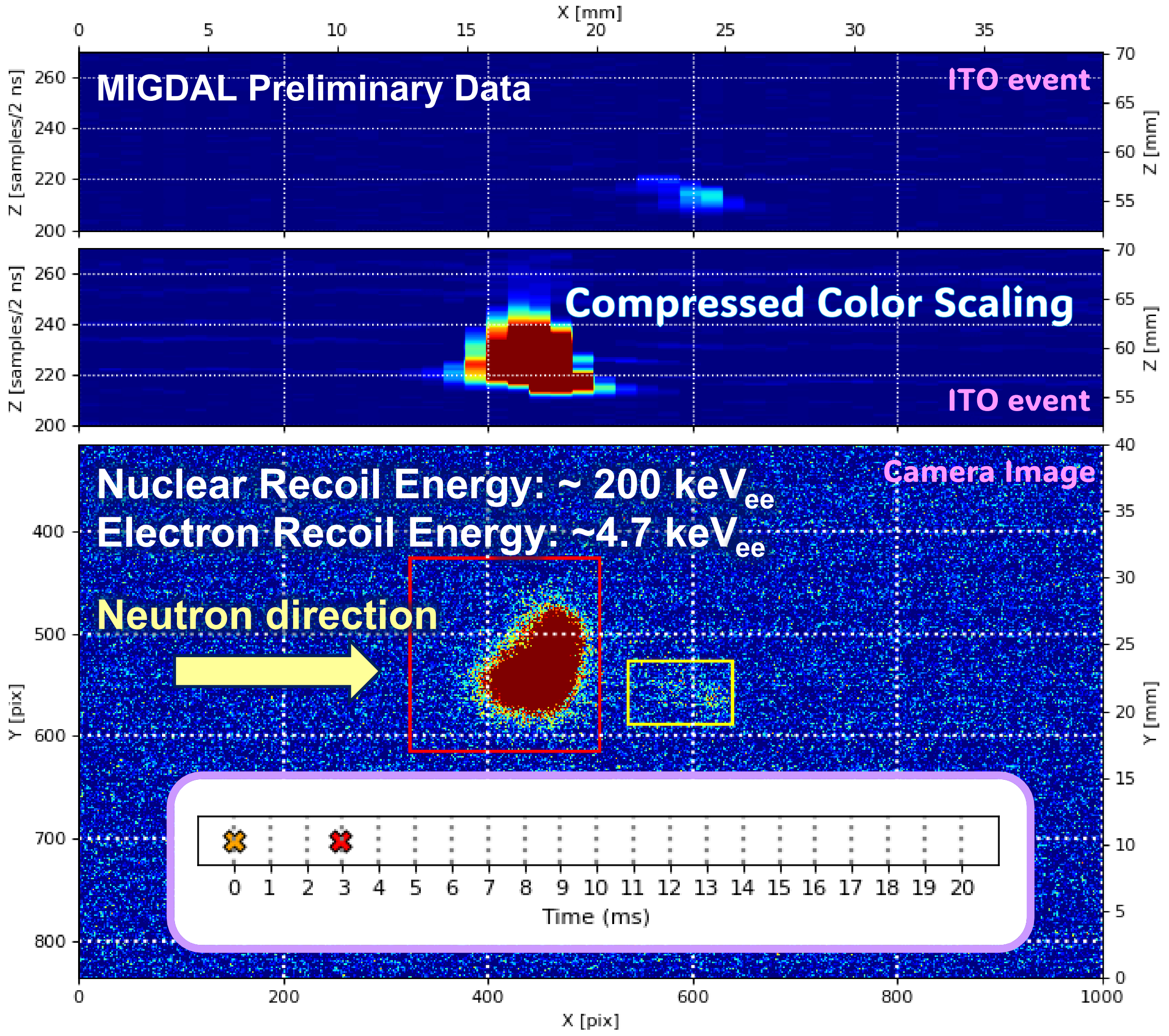

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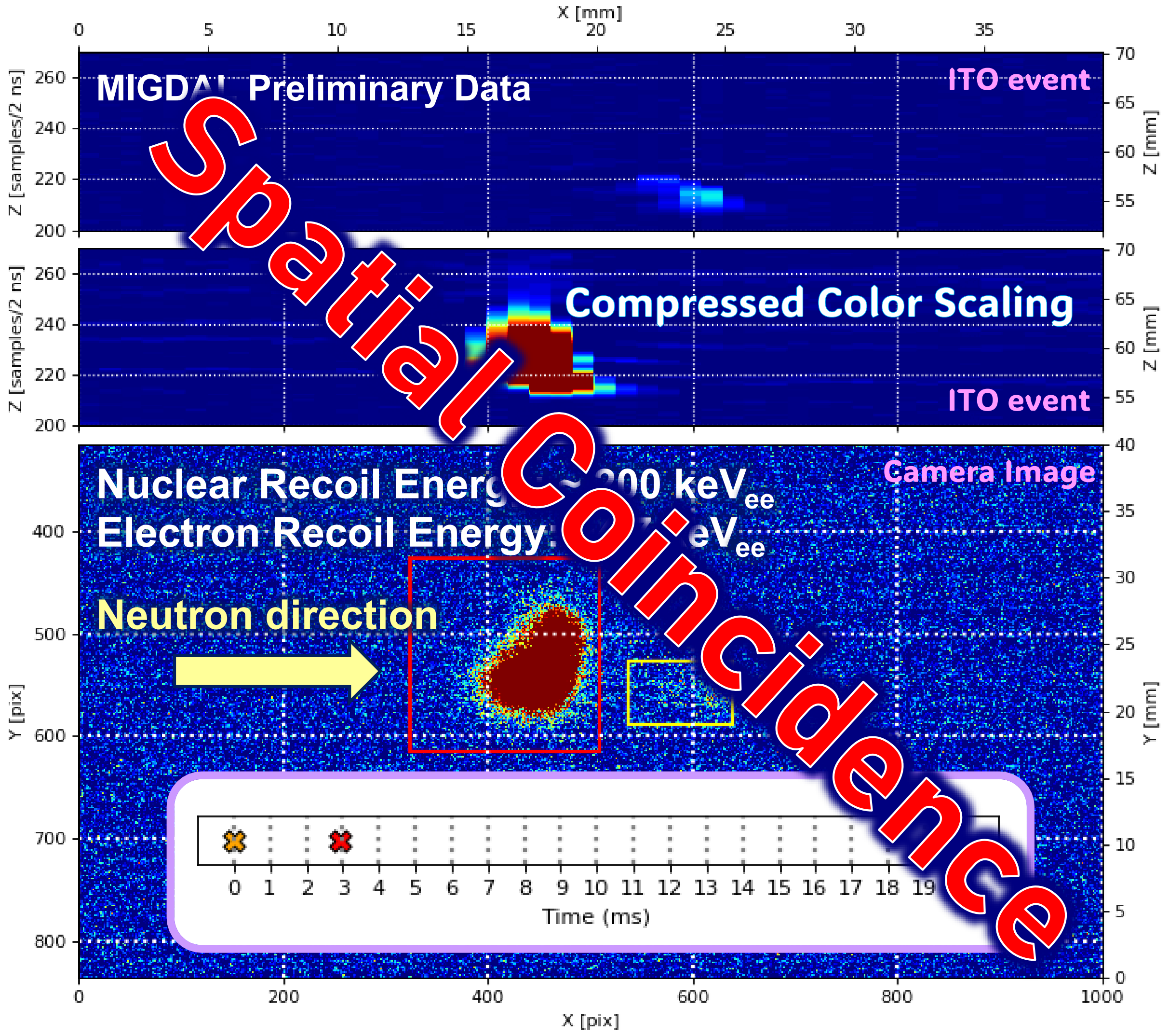
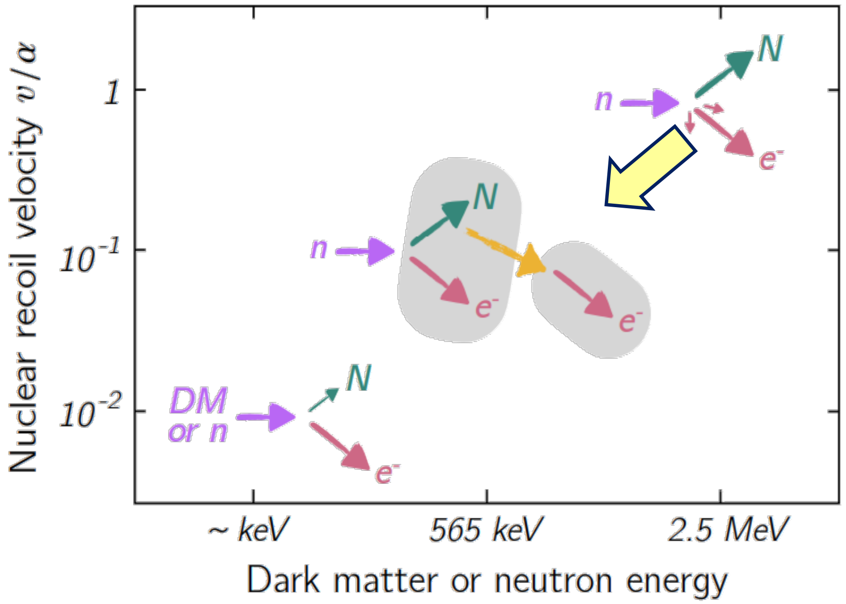


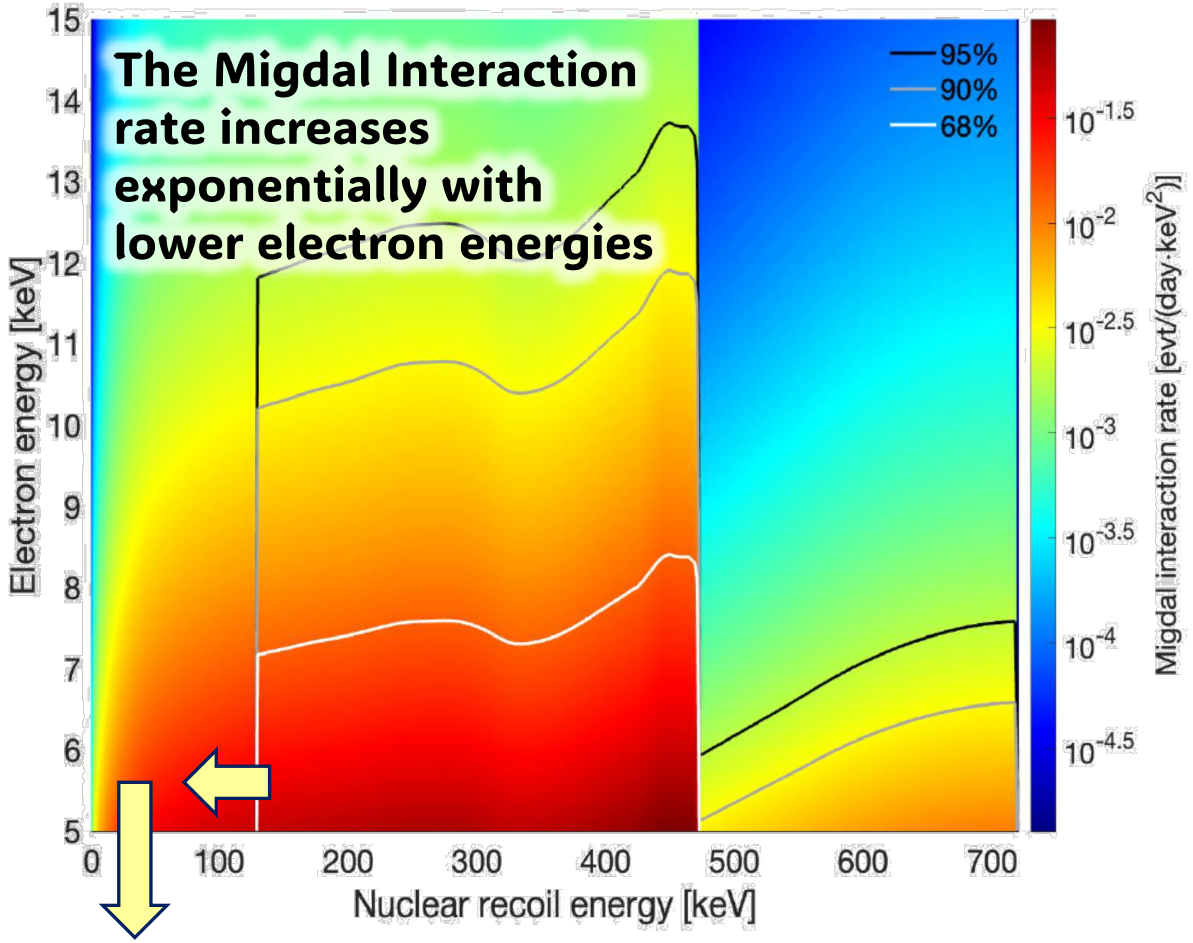
Next Generation Detector

To improve this search, we need to:

- Probe lower energies, closer to the DM search regime
- Attain higher rates (which comes with resolving lower energies)



P. Cox *et al* 2023 *Phys. Rev. D* **107**, 035032
https://doi.org/10.1103/PhysRevD.107.035032

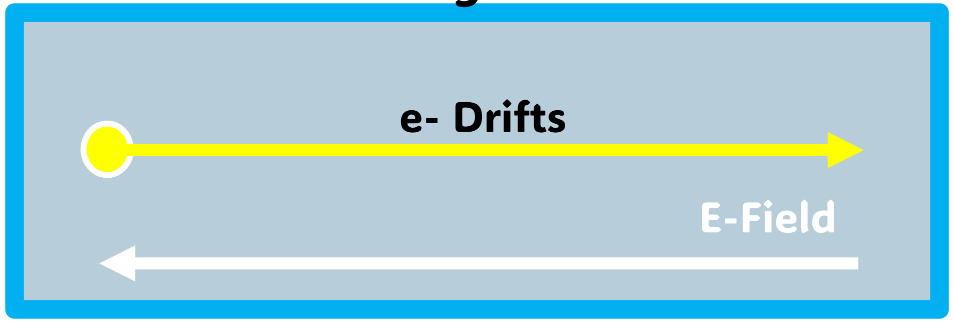


H.M. Araújo *et al* 2023 *Astropart. Phys*. **151** 102853
https://doi.org/10.1016/j.astropartphys.2023.102853

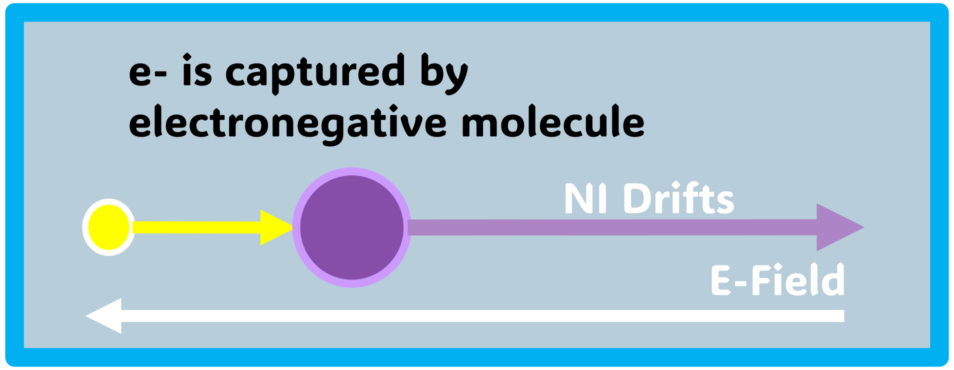
Negative Ion Drift

Mechanism:

Traditional e- drift gases:



NI gases:

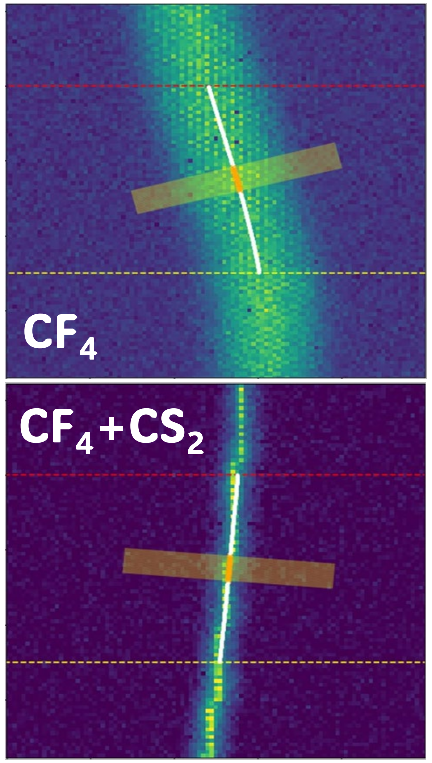


- NI Drift was first used in the DRIFT directional dark matter experiment, using a Multi-Wire Proportional Chamber
- Advantages:
  1. Reduced diffusion leads to ***much higher resolution***
  2. Drift speeds of NI can be ~3 orders of magnitude slower than electron drift leading to ***much finer timing resolution***
- Disadvantages:
  1. Light yield can ***drop up to 80%*** with as little as 3% NI gas

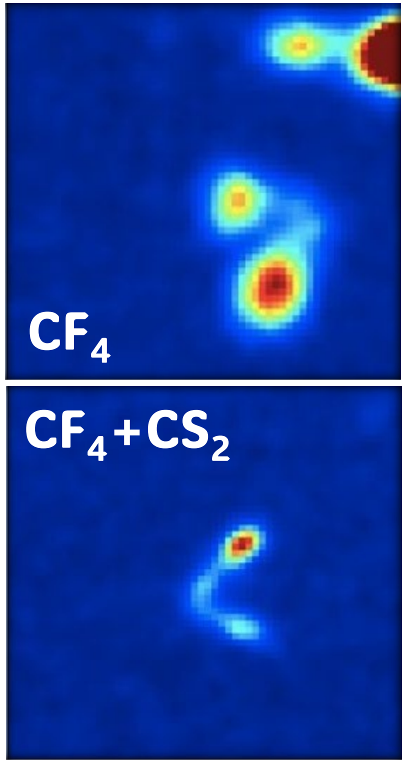
Completed Gas Tests

- We have completed tests on ***transverse diffusion*** and ***light yield***
- Results show great promise for NID in detector enhancement but prove that use in optical detectors will be challenging

Alpha Tracks

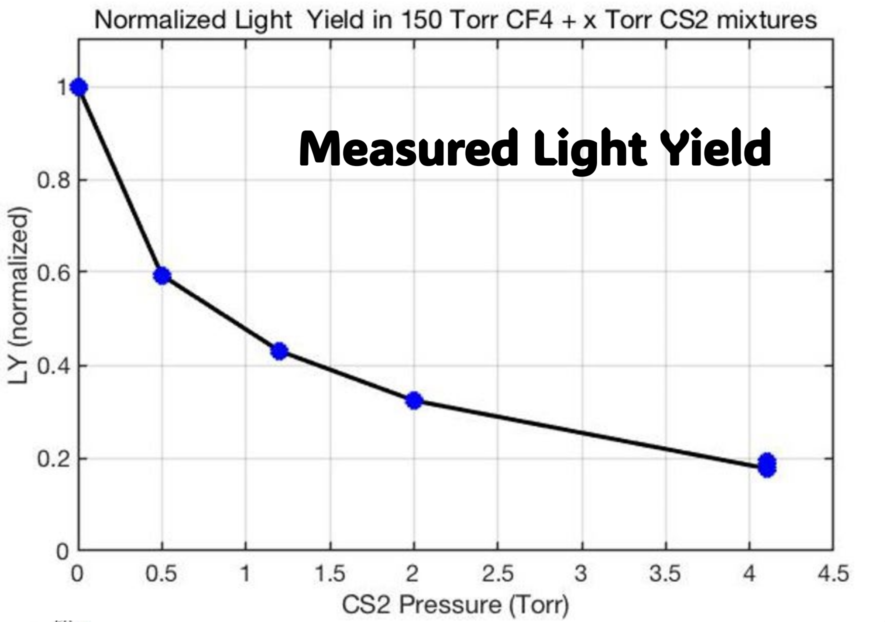


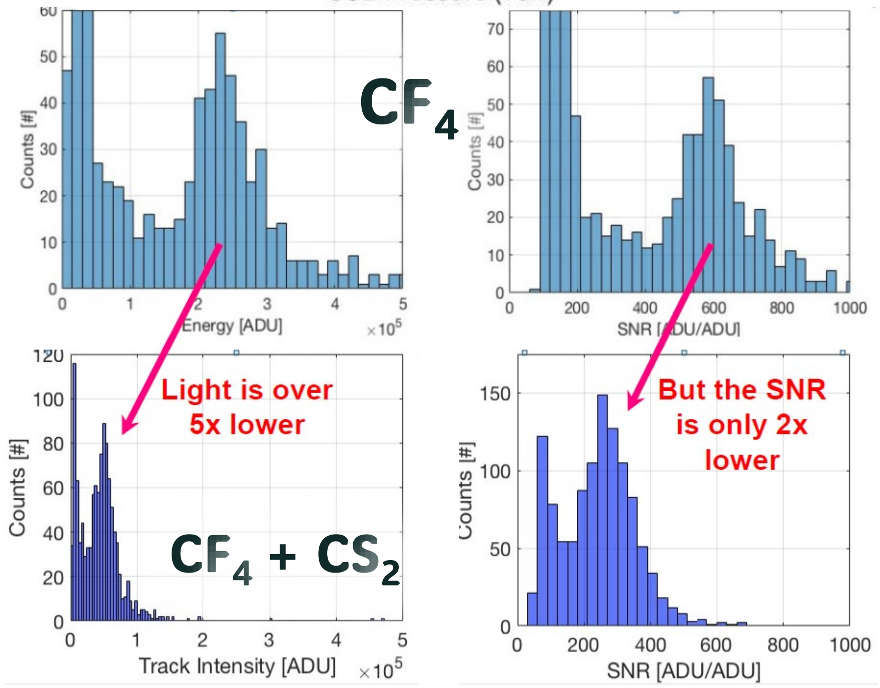
Electron Tracks



Measured Transverse Diffusion

150 Torr CF_4 + X torr CS_2	
CS_2 (Torr)	σ(μm)
0	~400
2.9	133.53
4.2	126.10
5.4	125.09
45 Torr CF_4 + X torr CS_2	
0	~550
4	~150-200





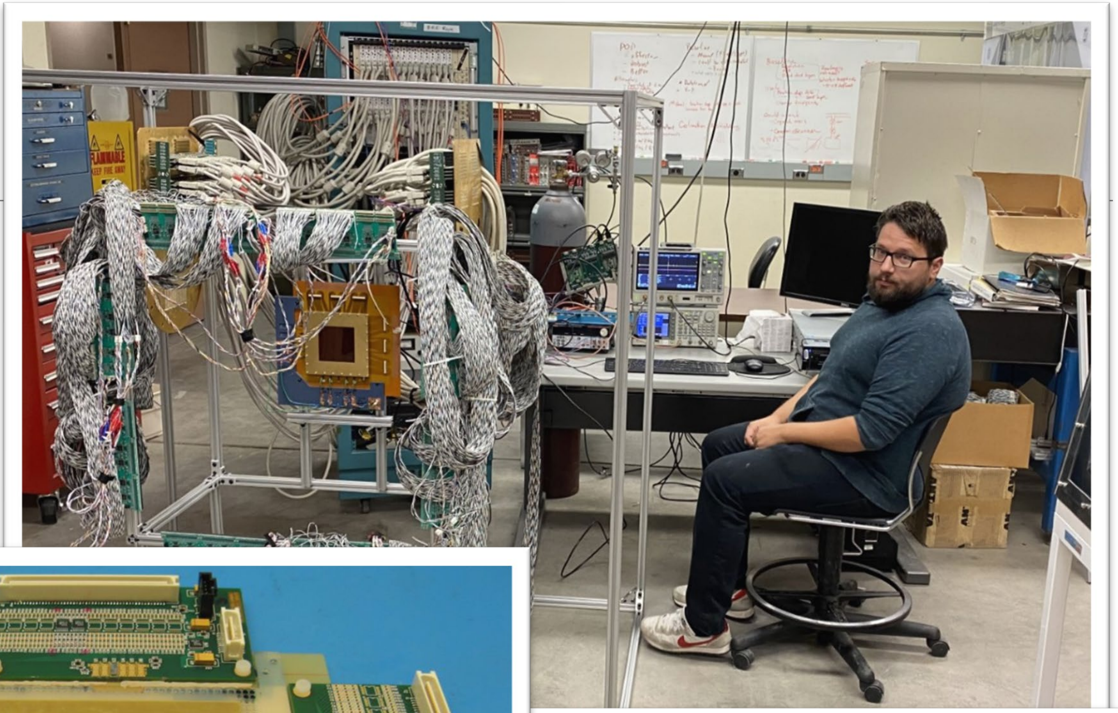
A New Detector

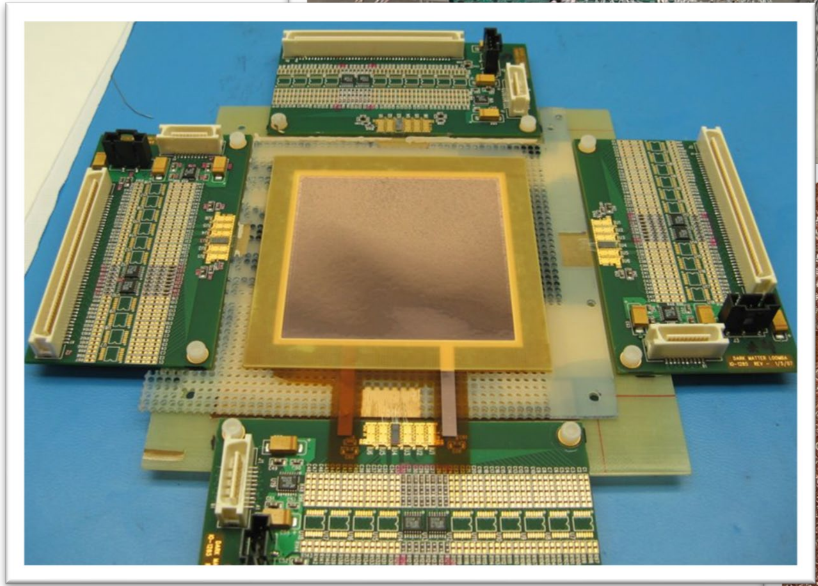
Advantages of a NI charge readout TPC:

- Resolution of high dynamic range in dE/dx does not require as high of gas gains
- NI enables characterization of lower energy events

Work has begun assembling and testing the electronics for this new NID charge readout TPC

- The detector will be built and characterized in the next year or two

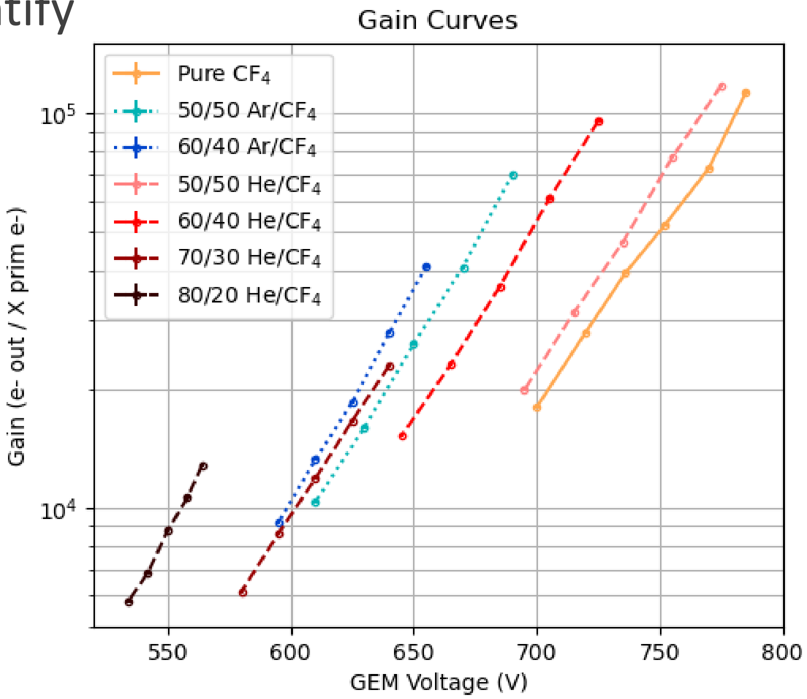


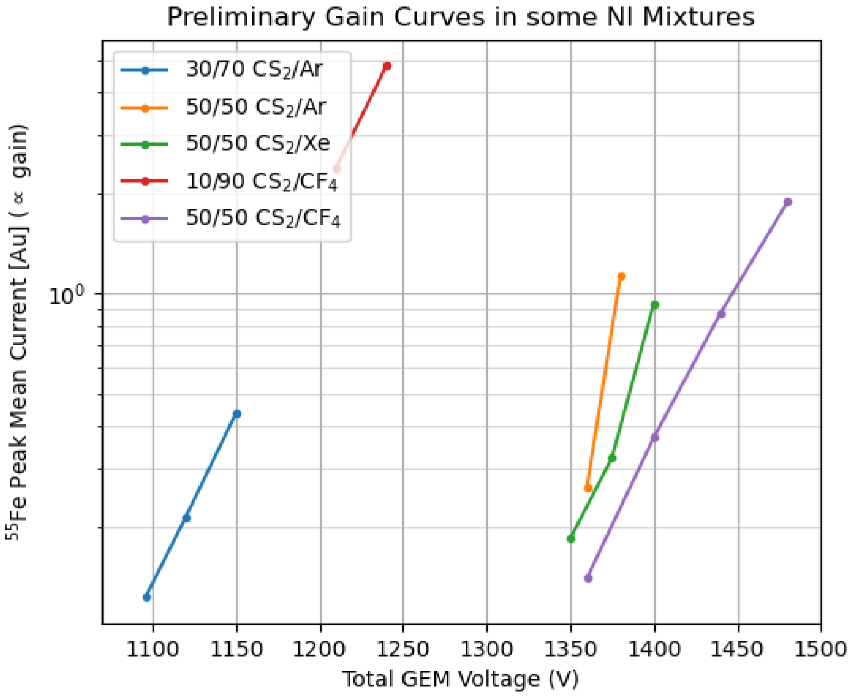


Ongoing Gas Tests

We are working on tests in mixtures of CF_4, CS_2, Ar, He and Xe to quantify

1. Gas gain
2. Longitudinal diffusion
3. Drift velocity/mobility
4. Drifting species
5. Capture efficiency





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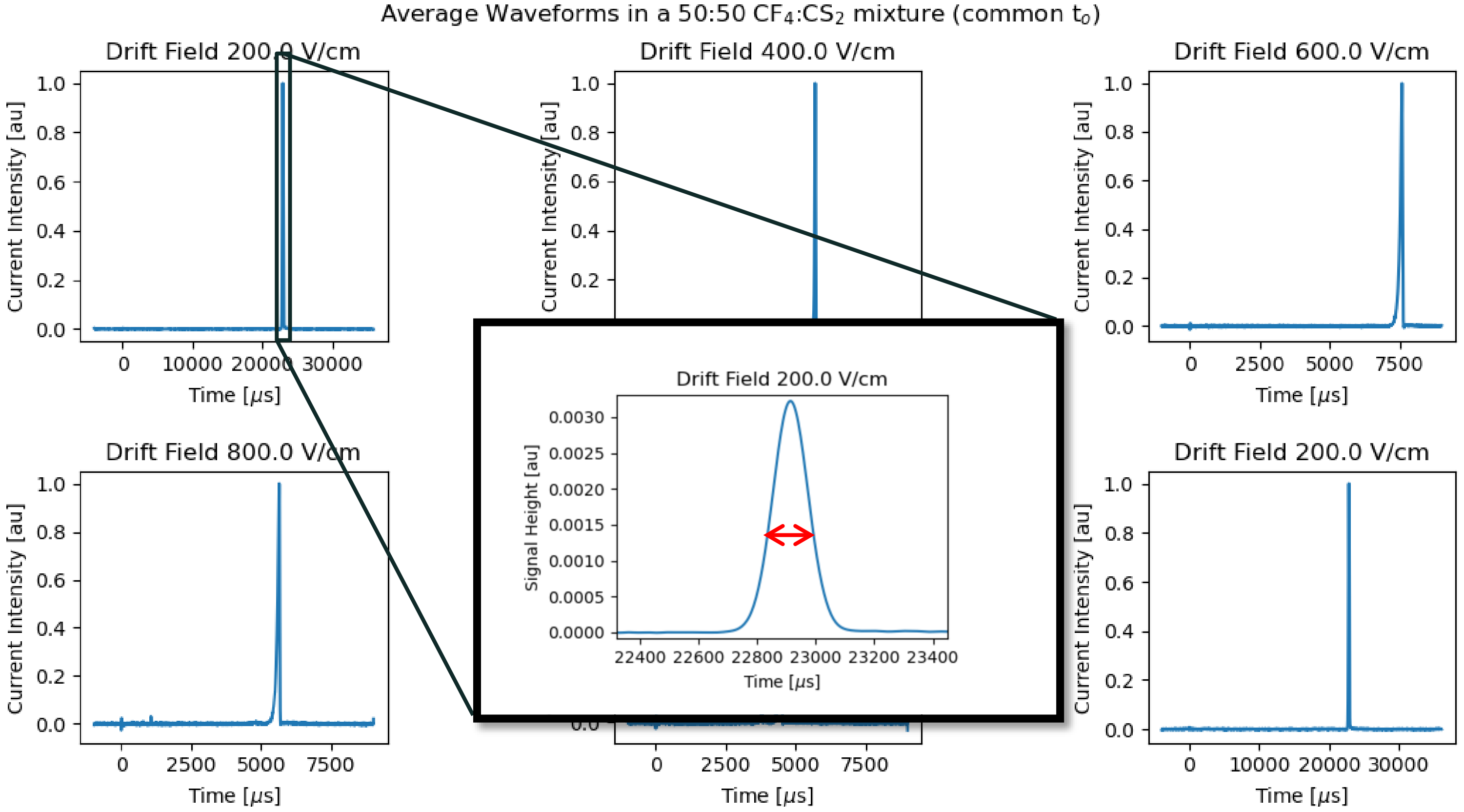

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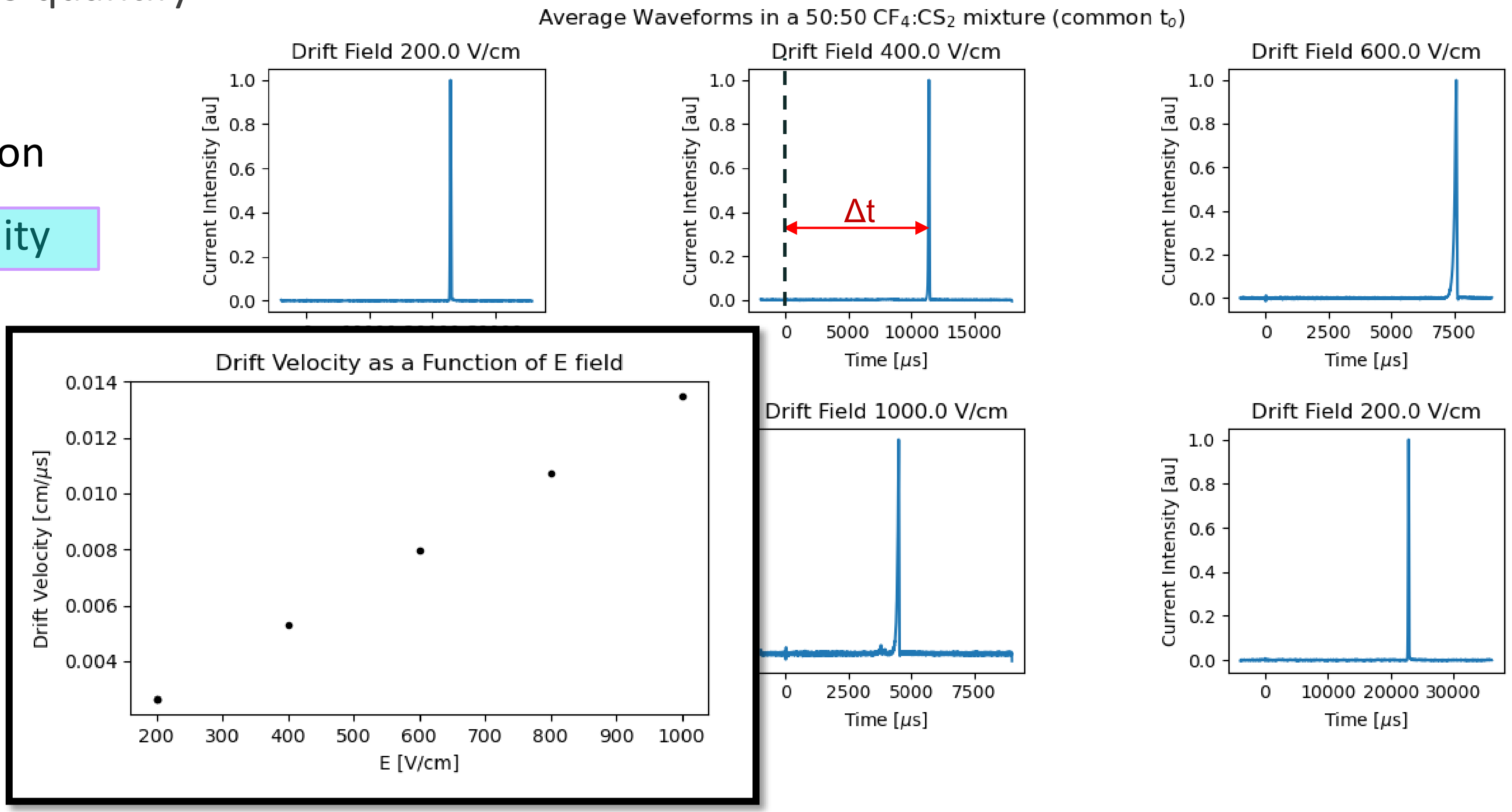

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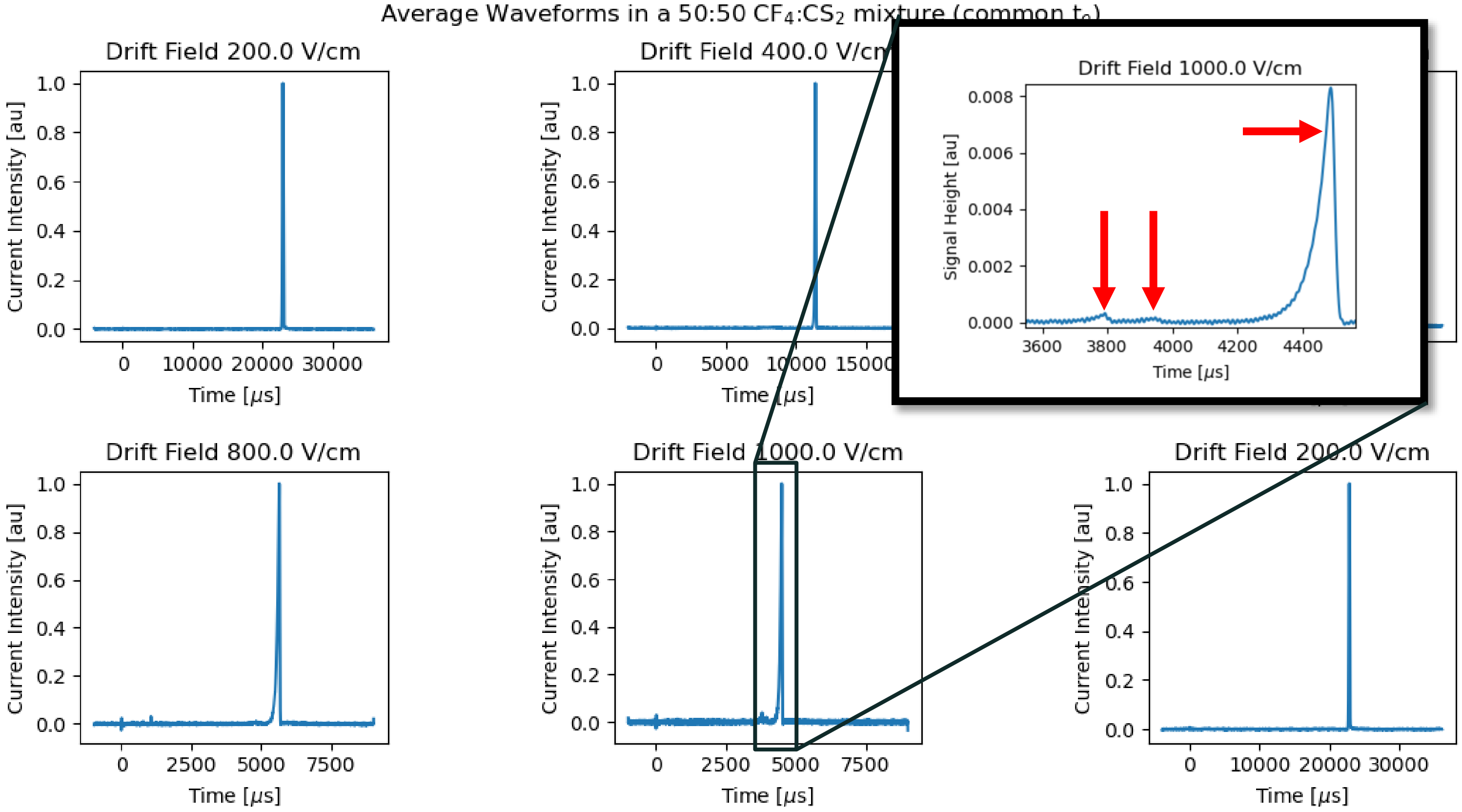

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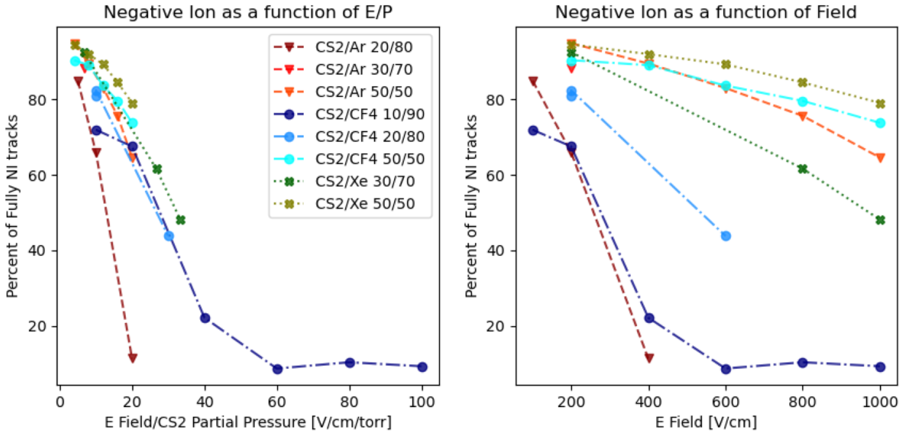
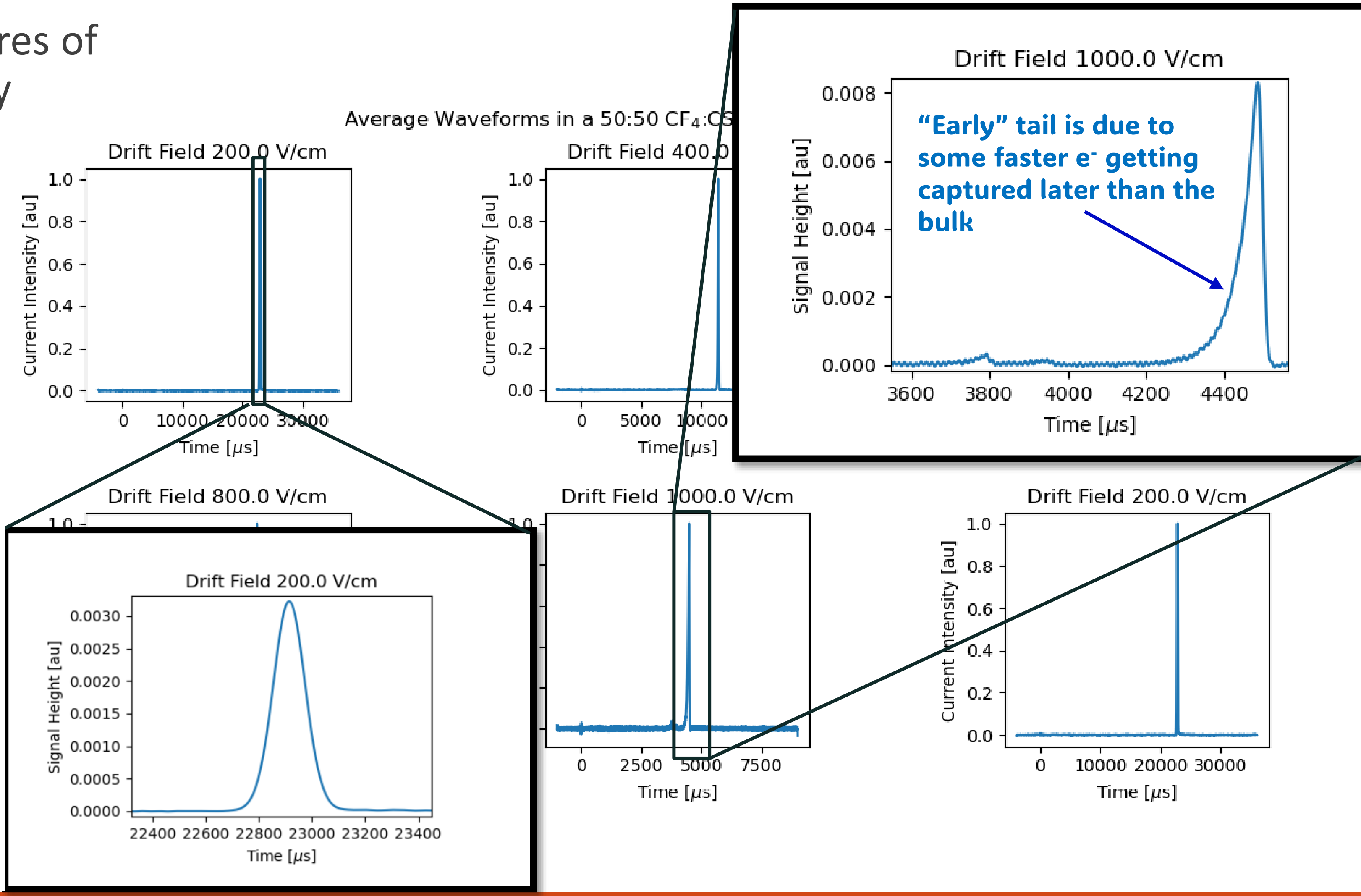




Summary & Acknowledgements

- The MIGDAL experiment hopes to make the first direct & unambiguous measurement of the Migdal effect
  - Analysis from the first science run is ongoing
  - A second science run will begin soon to collect more data
- Work is ongoing to create a next generation NI-TPC to probe lower energy Migdal events

Fermilab/DOE
GIRA Award
Awarded to E.Tilly

MIGDAL

UNIVERSITY OF BIRMINGHAM | UAM | GDD Gas Detectors Development Group | Helsinki Institute of Physics | Imperial College London | King's College London | LIP | The University of New Mexico | University of Oxford | Royal Holloway University | Science & Technology Facilities Council Rutherford Appleton Laboratory | The University Of Sheffield.

Backup Slides

The Search For Dark Matter

Particle Physics

Astrophysics

$$R \propto \frac{\sigma_{DM-nuc}}{M_{DM}} \rho_{DM} v_{DM}$$

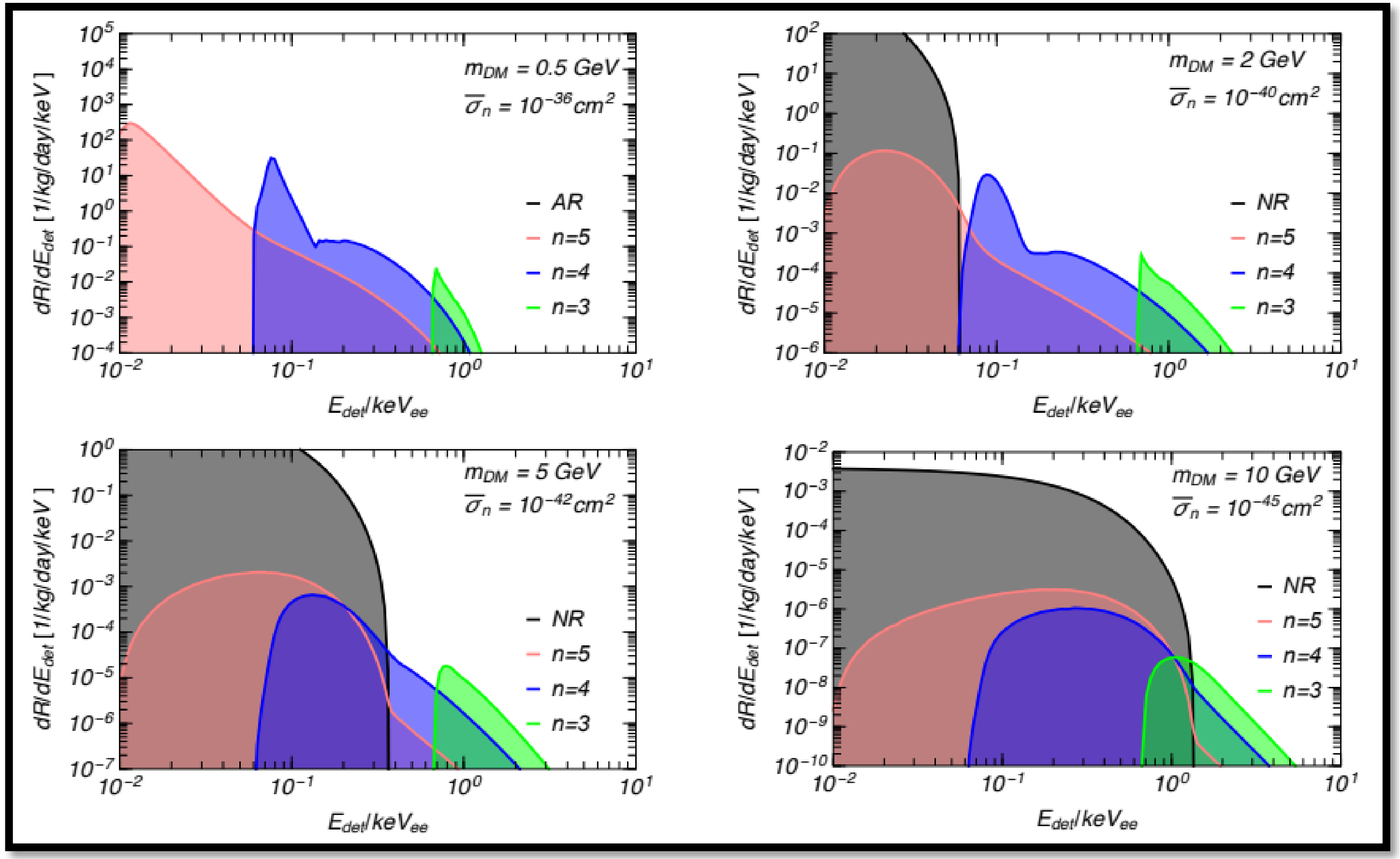
- R: Experimental measurable
- $\frac{\sigma_{DM-nuc}}{M_{DM}}$: Information gained from measuring R
- ρ_{DM}: Local DM density
- v_{DM}: Characteristic velocity of the DM Halo in our rest frame

- Most current large-scale DM experiments look for DM by looking for ***expected nuclear recoils*** from WIMPs colliding with detection media
- As WIMP masses get smaller, so do the recoils, until the nuclear recoil becomes completely undetectable in the detector

The Search For Dark Matter

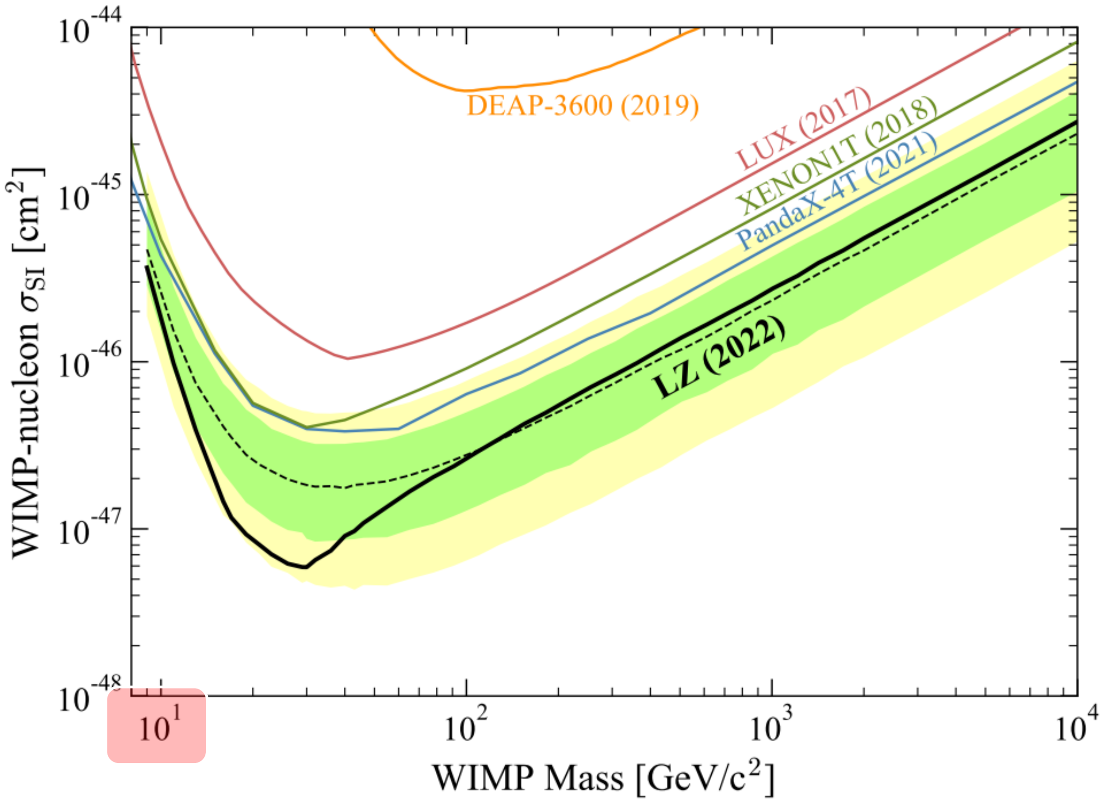
- In the past, experiments primarily looked for deposited energy in nuclear recoils from elastic scatters with DM (gray-shaded regions)

- Now, preexisting data has been re-analysed looking for induced Midgal electrons (G,R,B spectra)

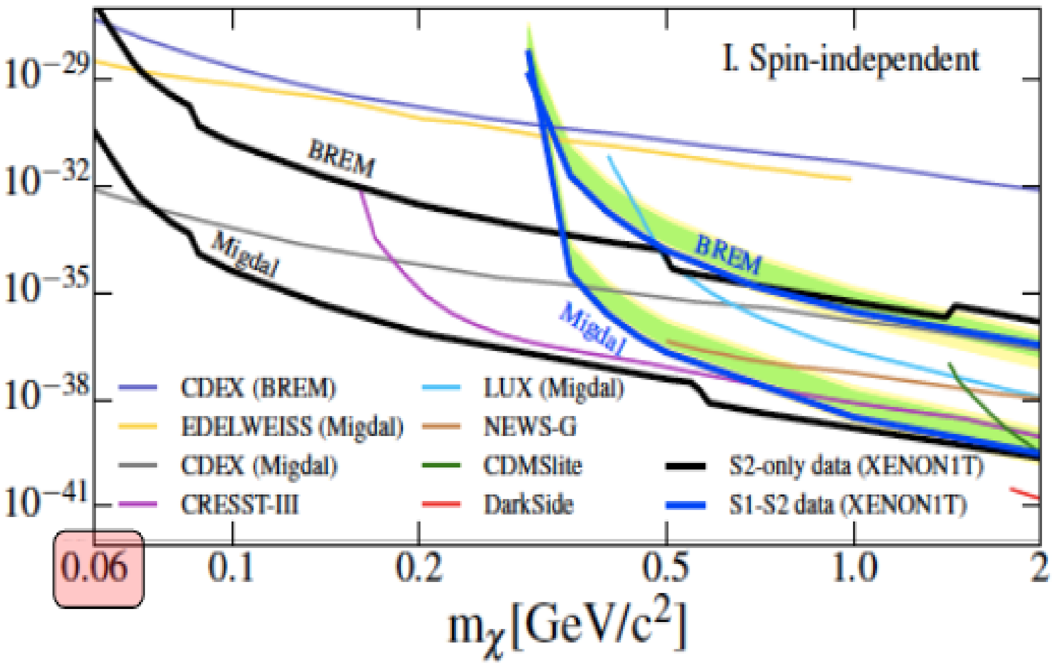


Ibe, M., Nakano, W., Shoji, Y. et al. 2018 *JHEP* **194**(2018)
https://doi.org/10.1007/JHEP03(2018)194

New Low Mass Limits Set



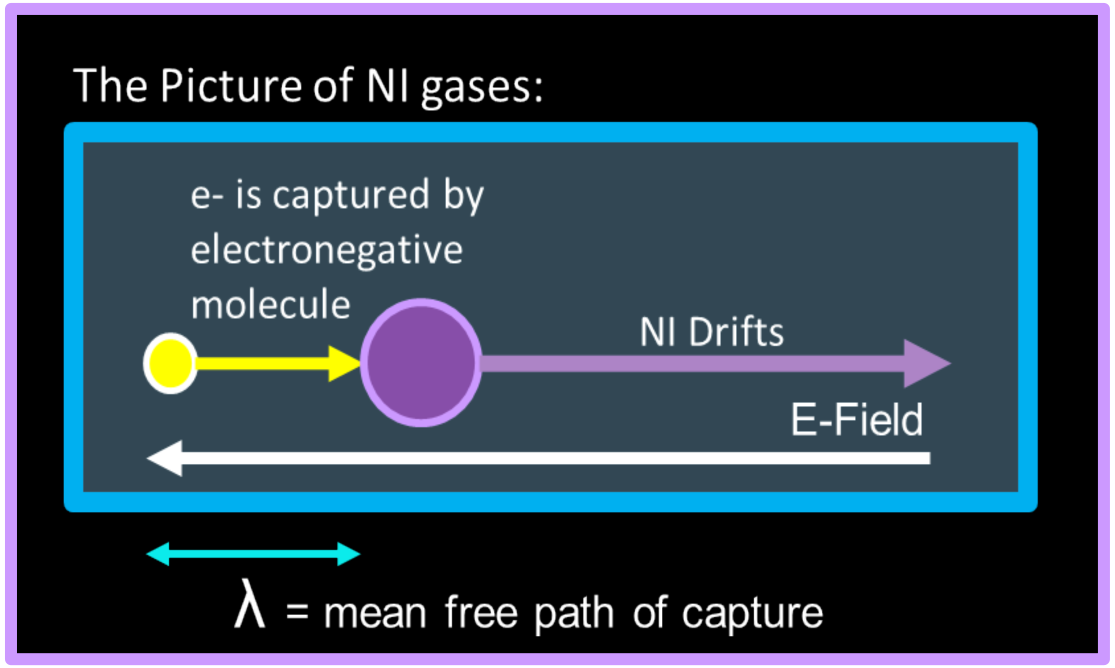
J. Aalbers et al. (LUX-ZEPLIN Collaboration)
Phys. Rev. Lett. 131, 041002

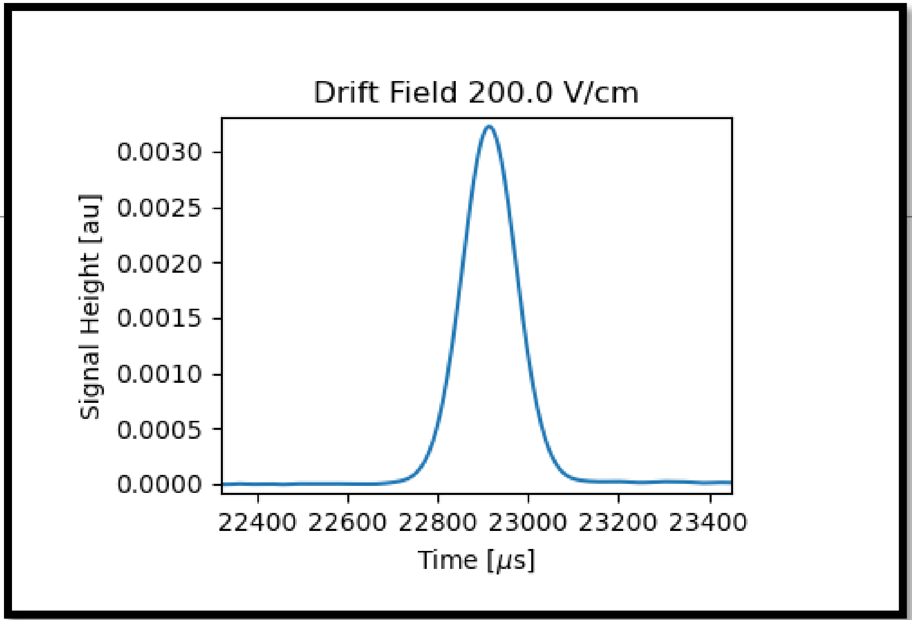


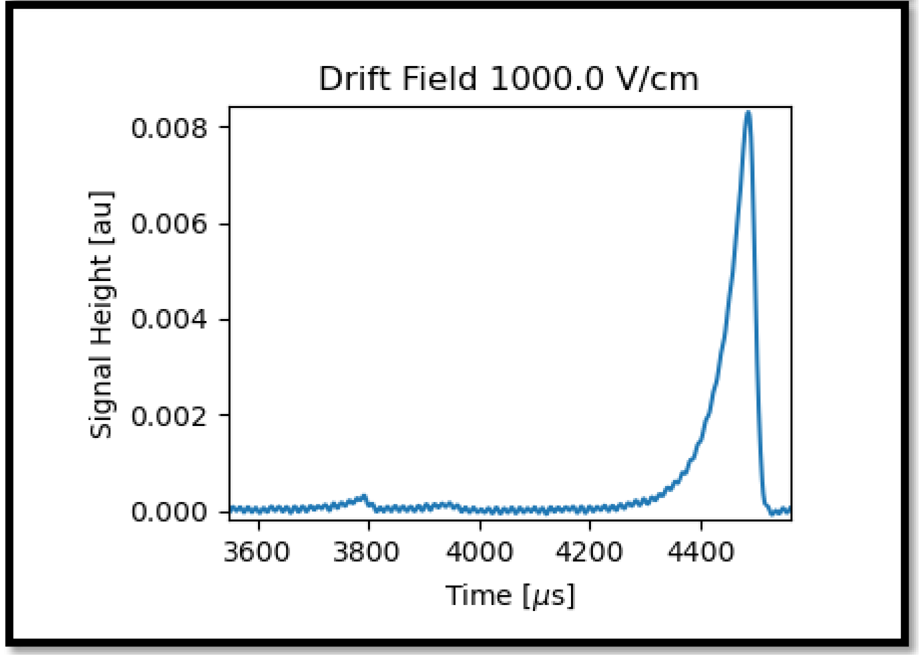
E. Aprile et al. (XENON Collaboration)
Phys. Rev. Lett. 123, 241803

Capture Efficiency

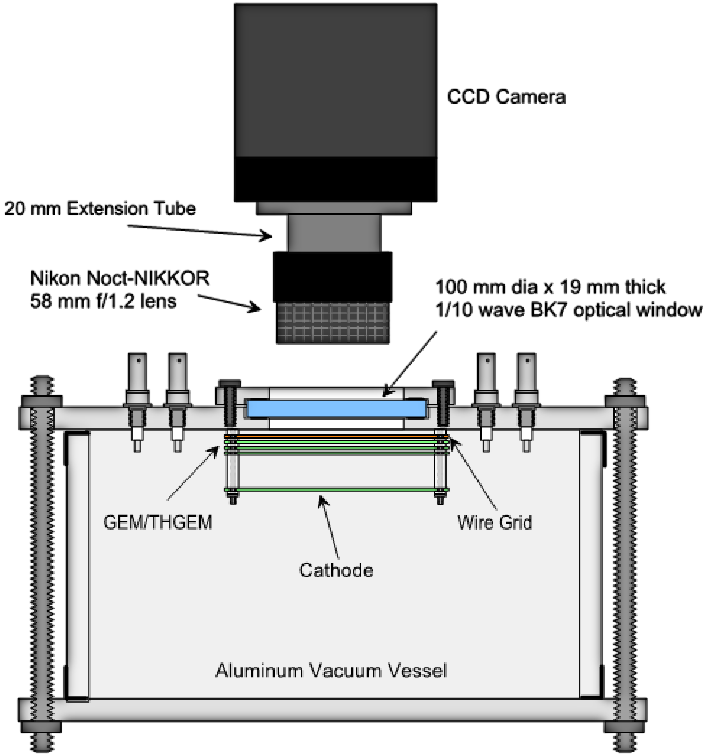
- Probability of attachment goes like $P \propto e^{-\frac{x}{\lambda}}$
- Since e^- have a much higher mobility than NI, this produces a measurable spread in the signal





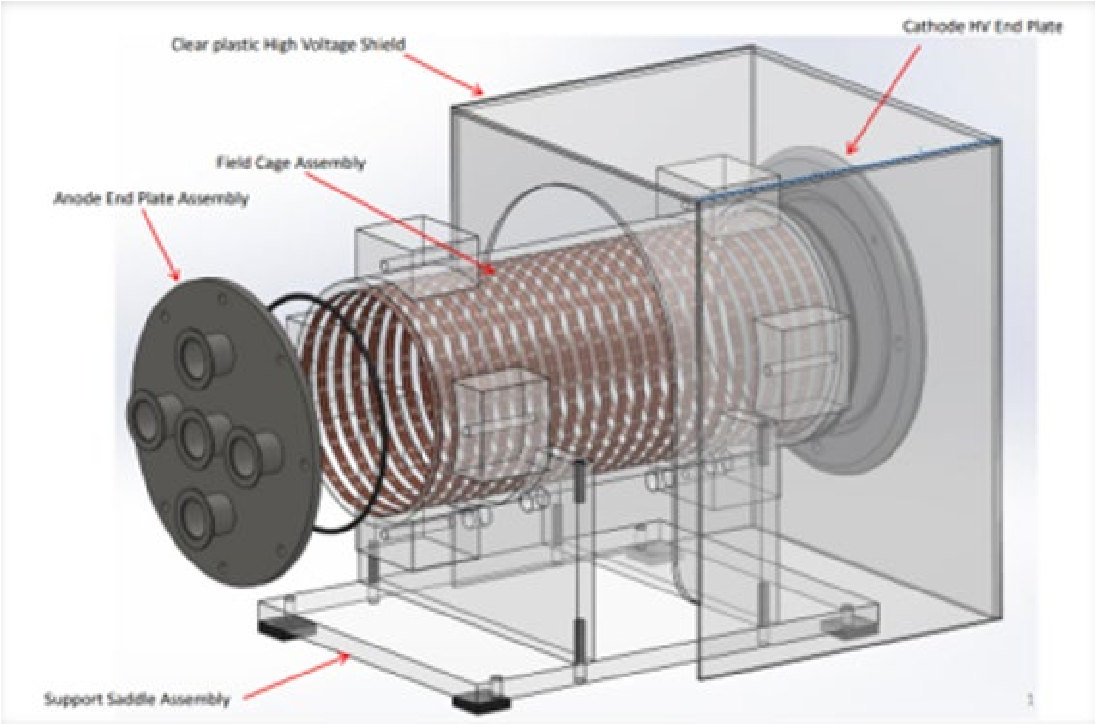


Two Detectors



D. Loomba RD51 Collab. Meeting 6/14/22

1. Transverse Diffusion
2. Light Yield



https://arxiv.org/pdf/1609.05249.pdf

1. Longitudinal Diffusion
2. Drift Velocity/Mobility
3. Gas Gain
4. Ion Species
5. Capture Efficiency