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

MIGDAL

Migdal In Galactic Dark mAtter expLoration

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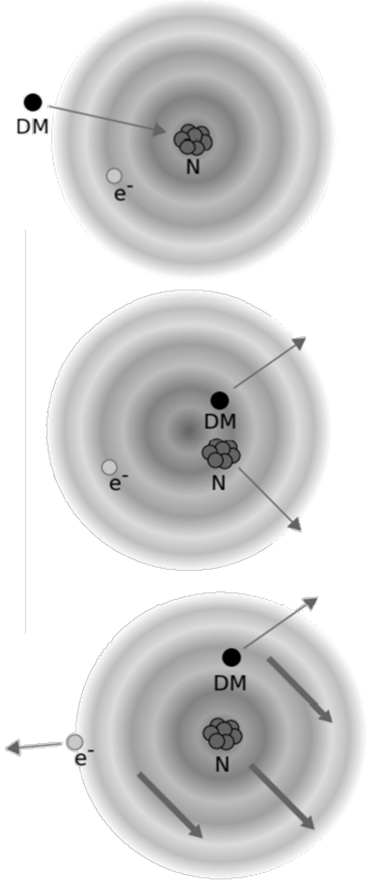
ON BEHALF OF THE MIGDAL COLLABORATION

CONFERENCE ON MICRO PATTERN GAS DETECTORS DECEMBER 2022

The Migdal Effect

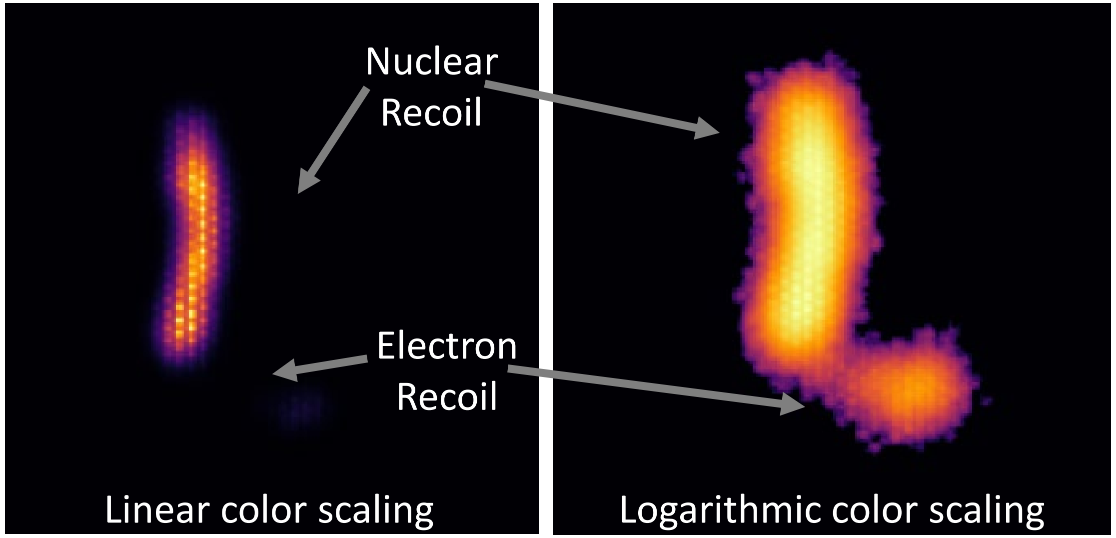


1. Neutral particle impacts atomic nucleus
2. Nucleus recoils, and electron cloud lags behind
3. Small probability of electron ionization as the electron cloud “catches up” with the nucleus

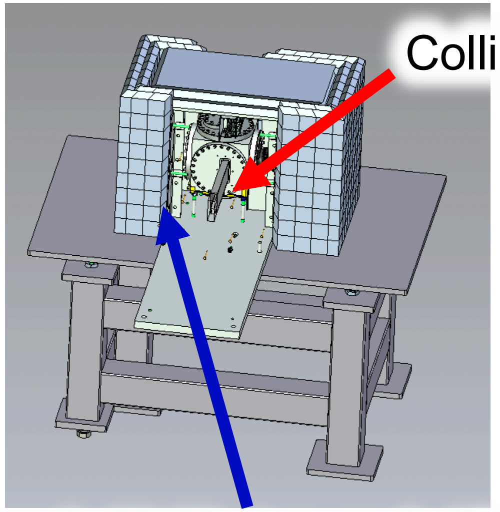
M. Dolan, F. Kahlhoefer, C. McCabe, Phys. Rev. Lett. 121, 101801 (2018), arXiv:1711.09906

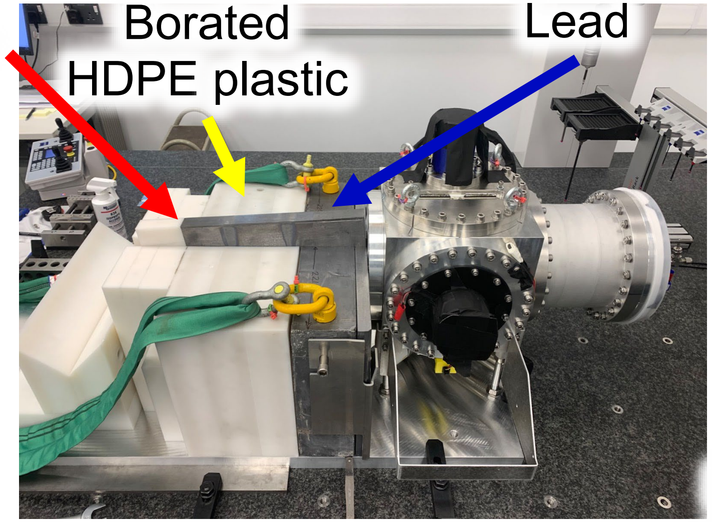
- Recently has been used to extend DM WIMP low mass limits ~2 orders of magnitude
- **<u>Never</u>** *been experimentally observed or characterized in this context (neutral ionization)*

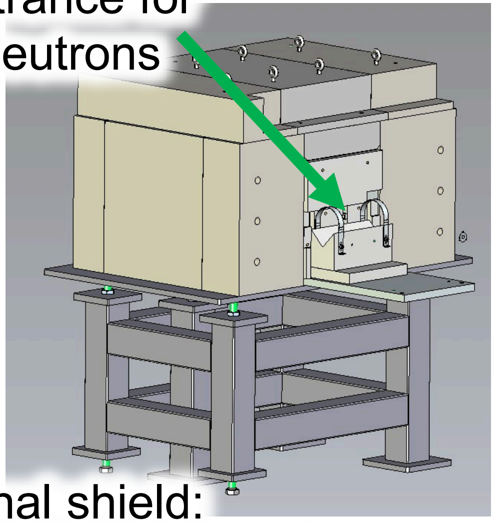
Example of a Simulated Migdal Event in 50 torr CF_4

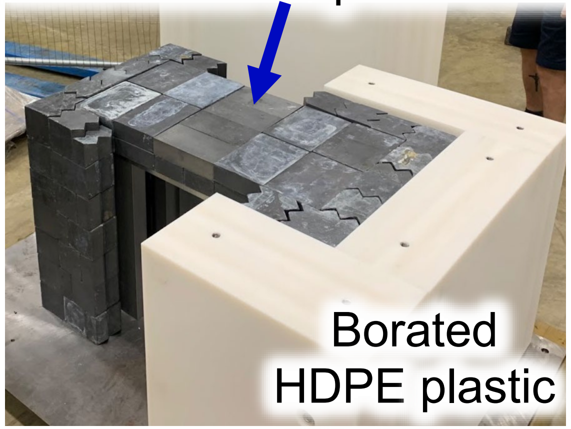


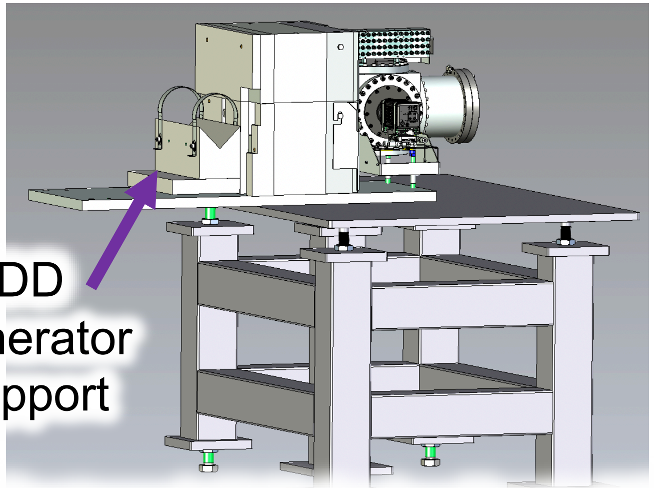
Neutrons Collimation and Shielding Against Backgrounds







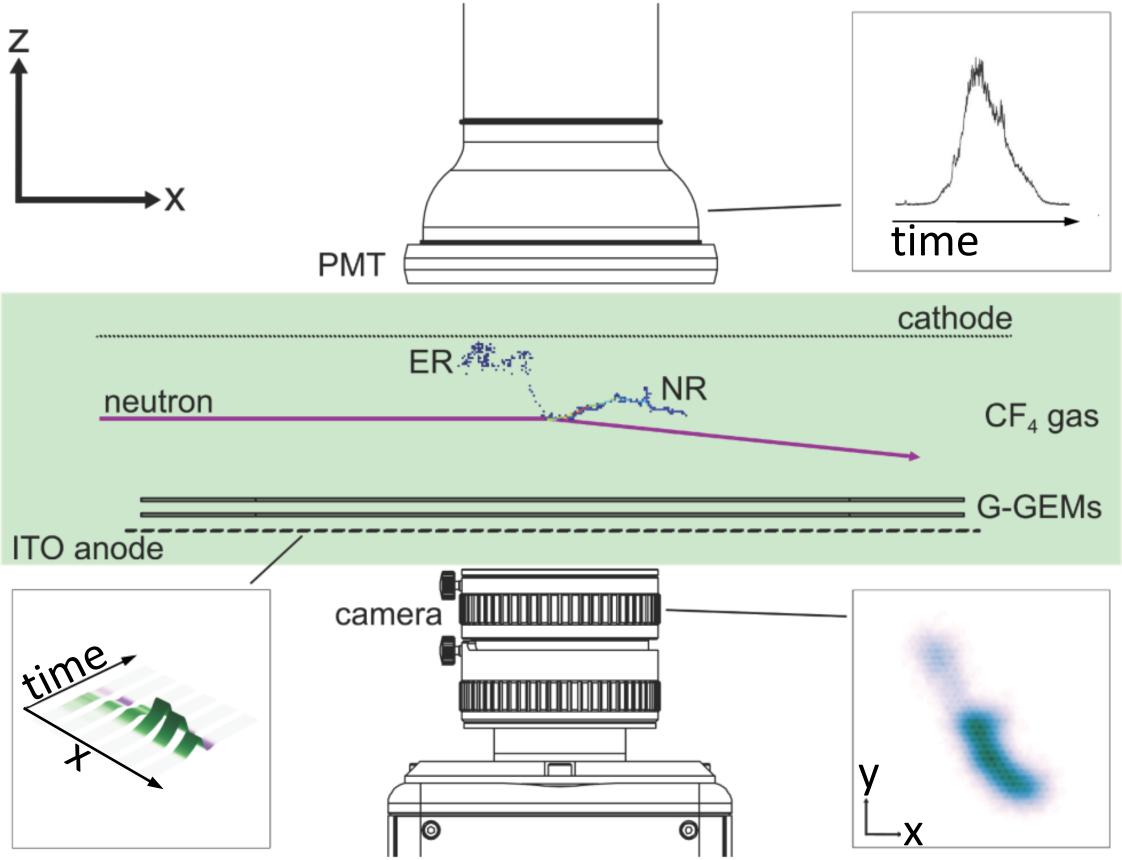




Front collimator and shield : lead and borated HDPE

3 Measurements Tied Together

For more details, refer to Tim Marley's talk from Monday



PMT:
Absolute Z position of full track

ITO strip readout:
Z position relative to X coordinate along full track

Camera:
Absolute X and Y position along full track

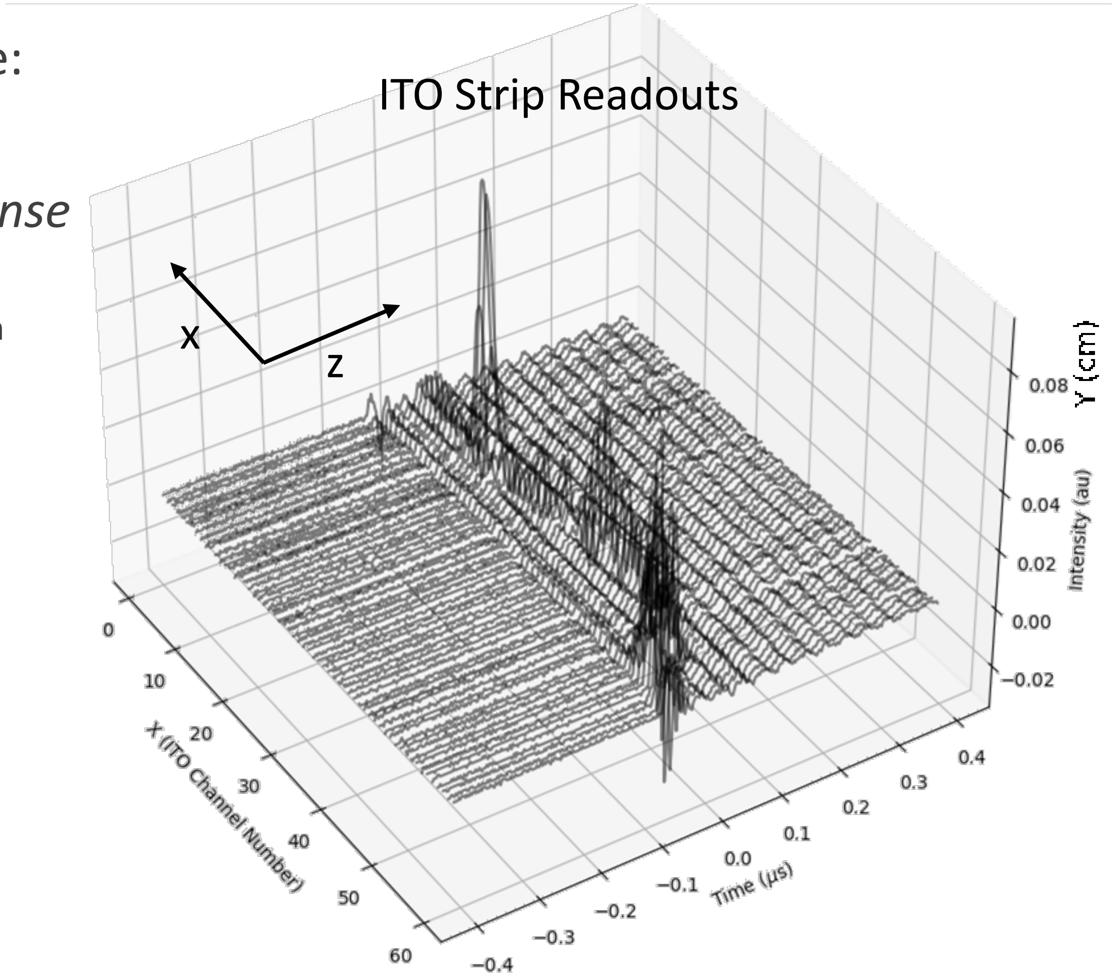
The MIGDAL Experiment: arXiv:2207.08284v2

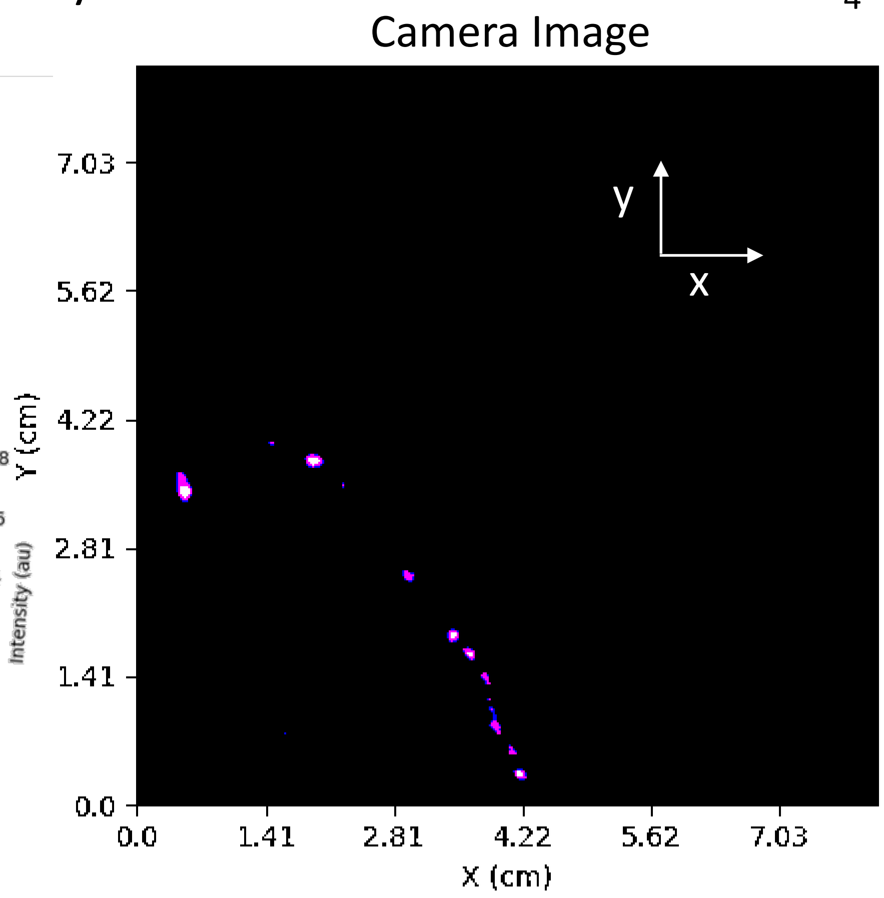
Our Signals

We need to combine:

1. Low granularity *electronic response* information
   - Strip pitch: 833 µm
   - Sample Rate: 2ns
2. High granularity *pixelized optical* information
   - 70.3 µm per pix

β-like event recently recorded by the MIGDAL detector in 50 torr CF_4

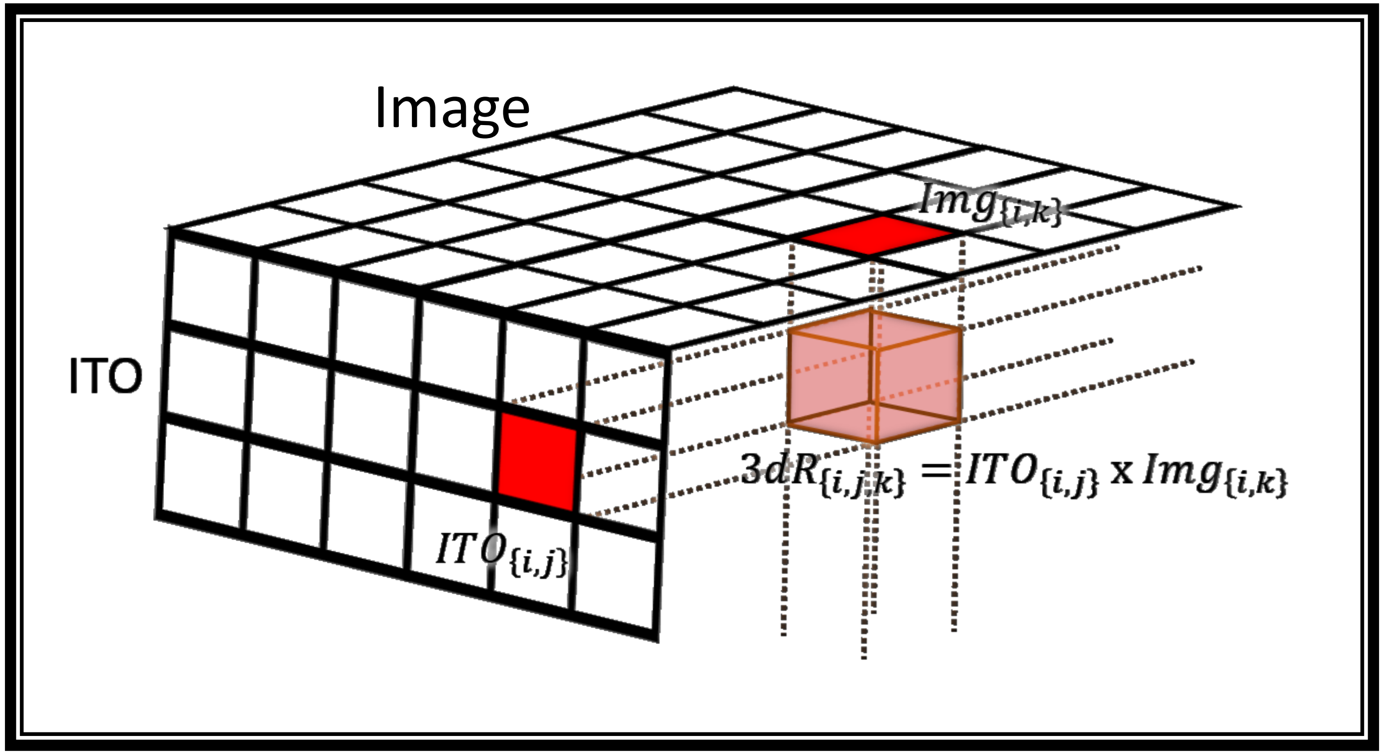




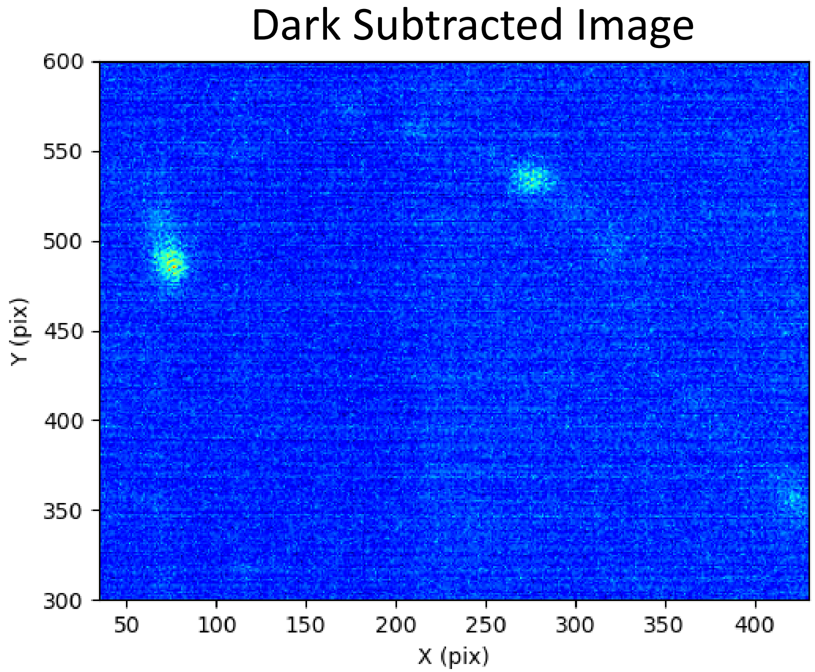
3D Track Reconstruction: Voxels

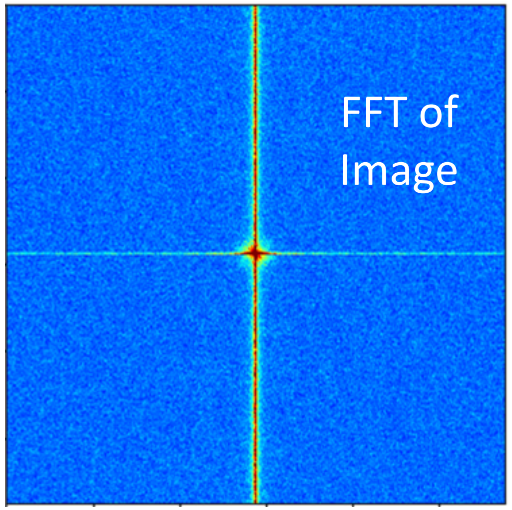
- Camera image is a projection of the event in the x-y plane
- ITO signals are a projection in the x-z (time) plane

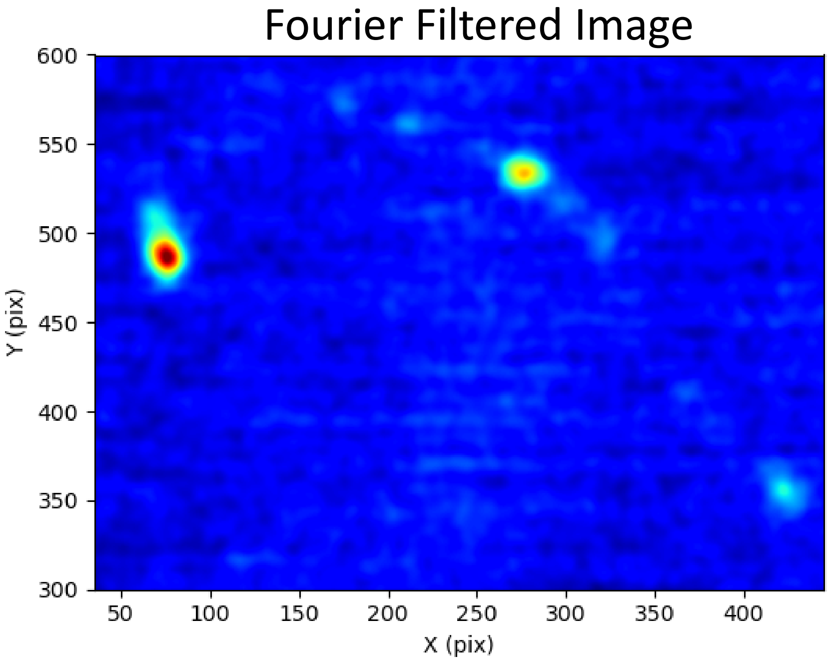
3D track extracted by finding *where these two signals overlap*



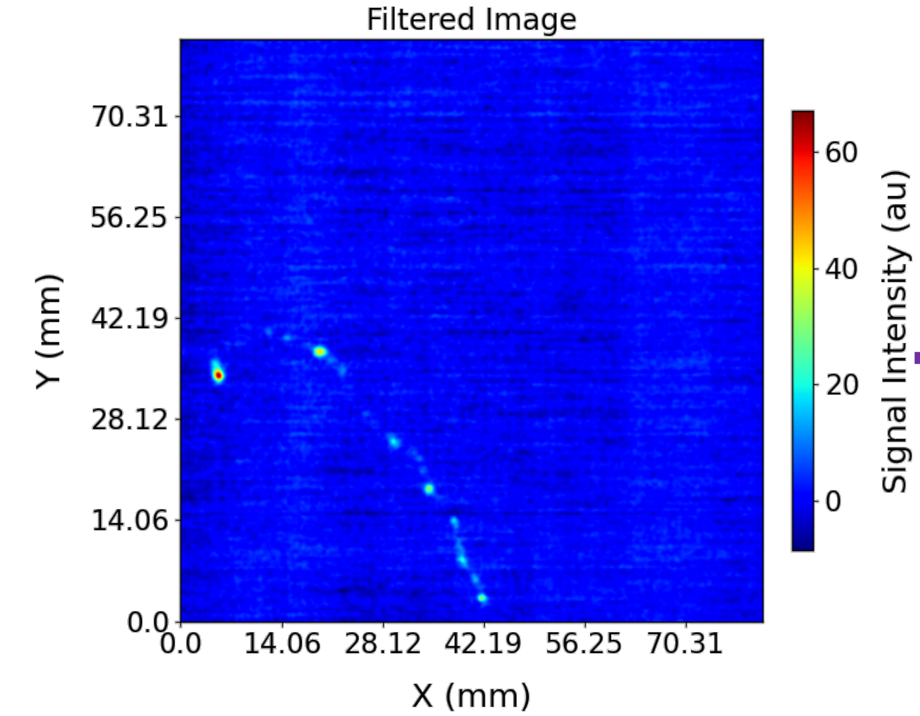
Preprocessing: Filtering

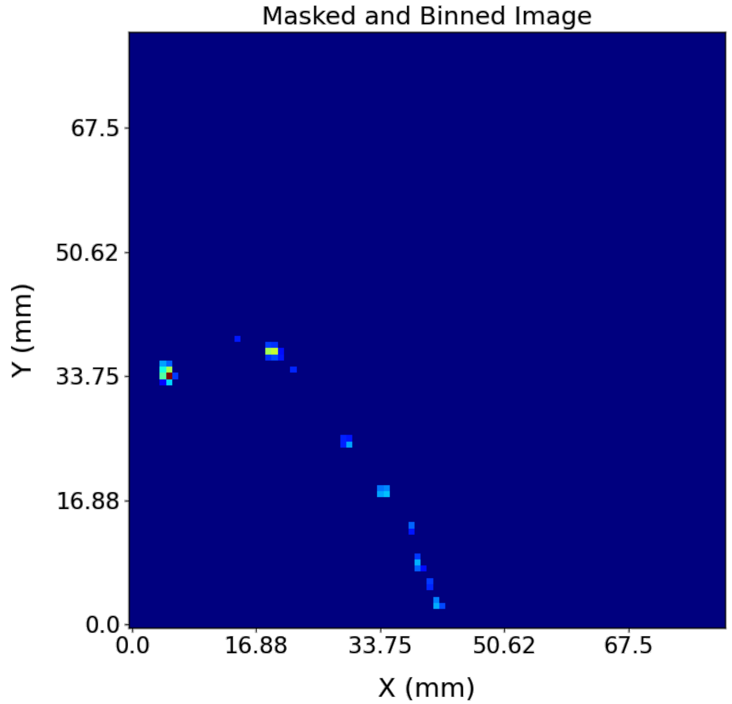


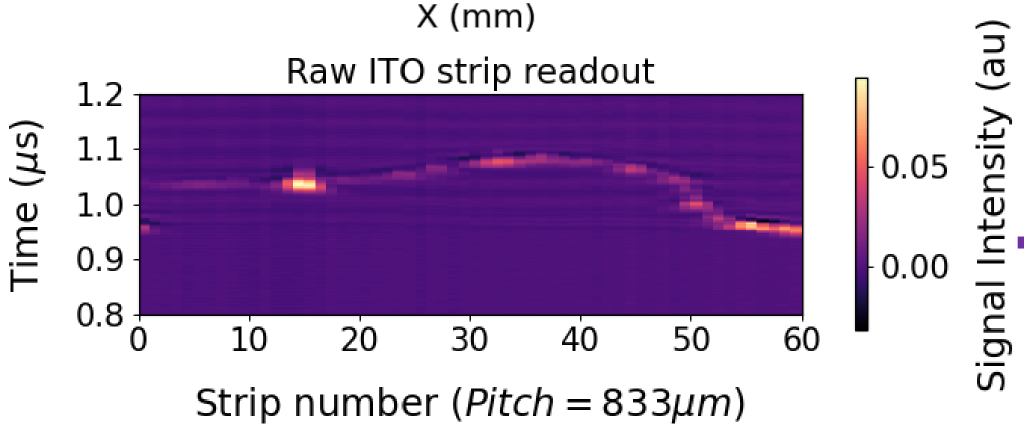


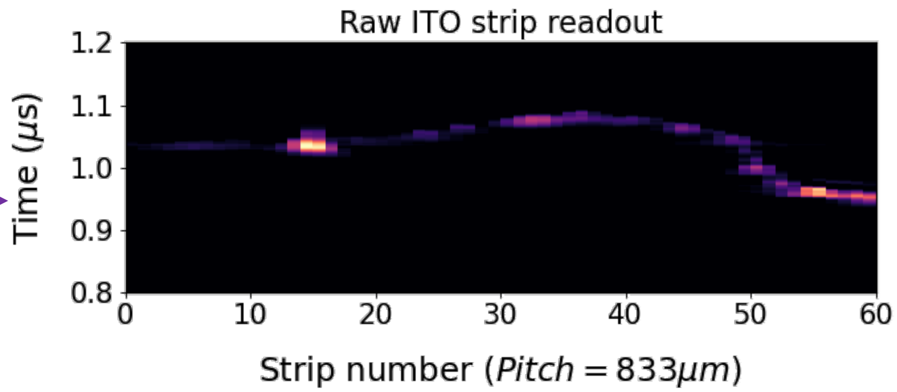


Preprocessing: Masking and Matching Scale

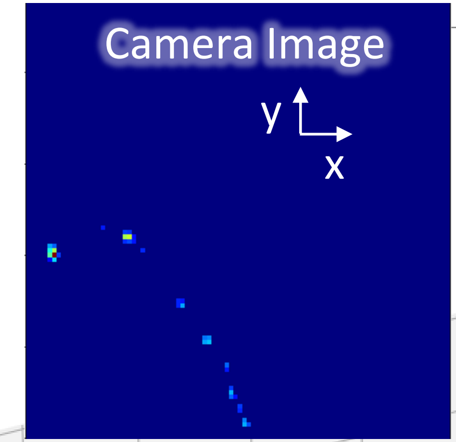








3D Track Reconstruction: Voxels



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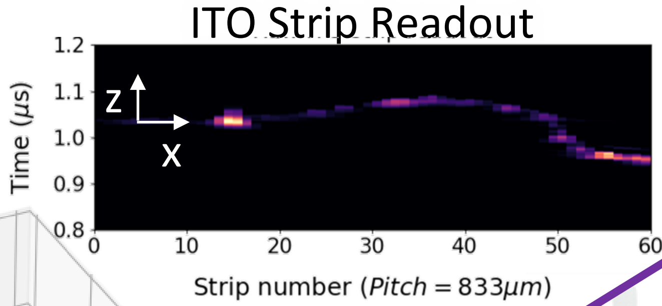
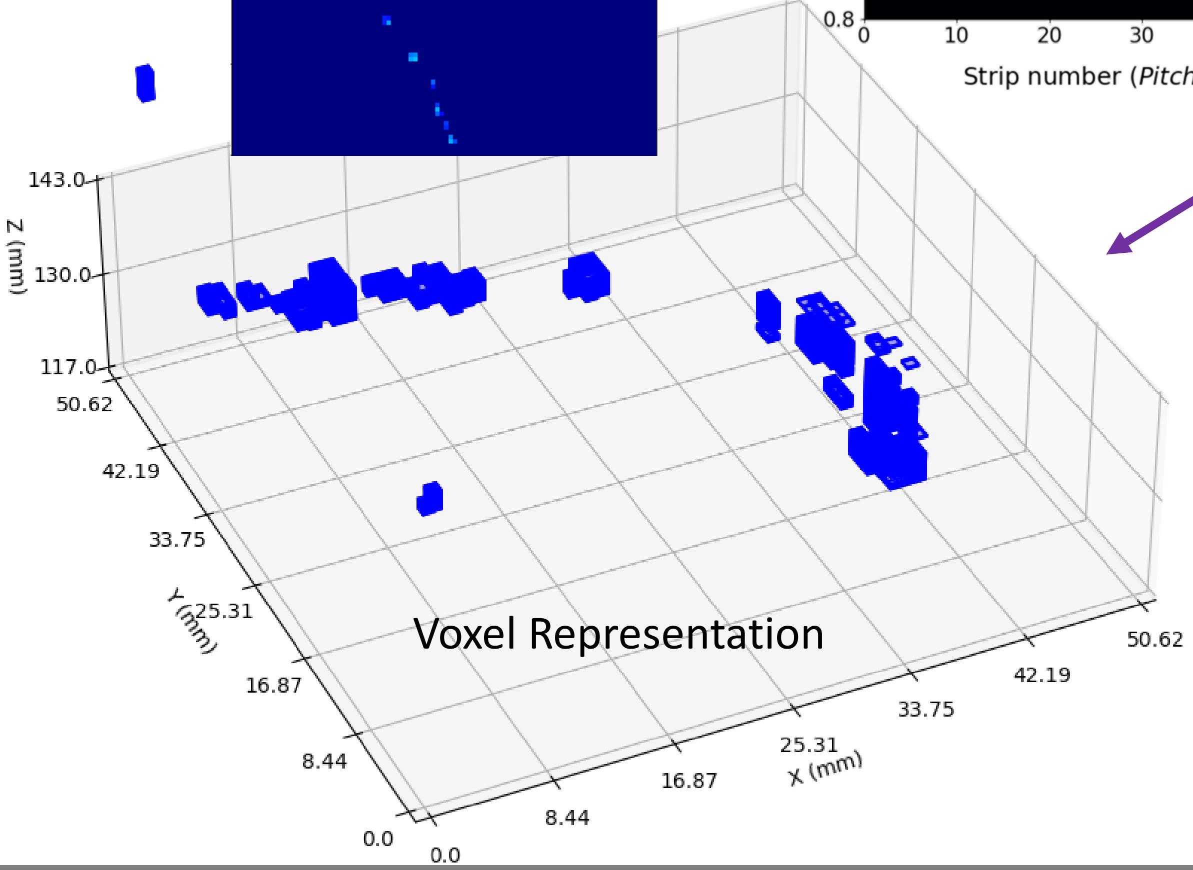
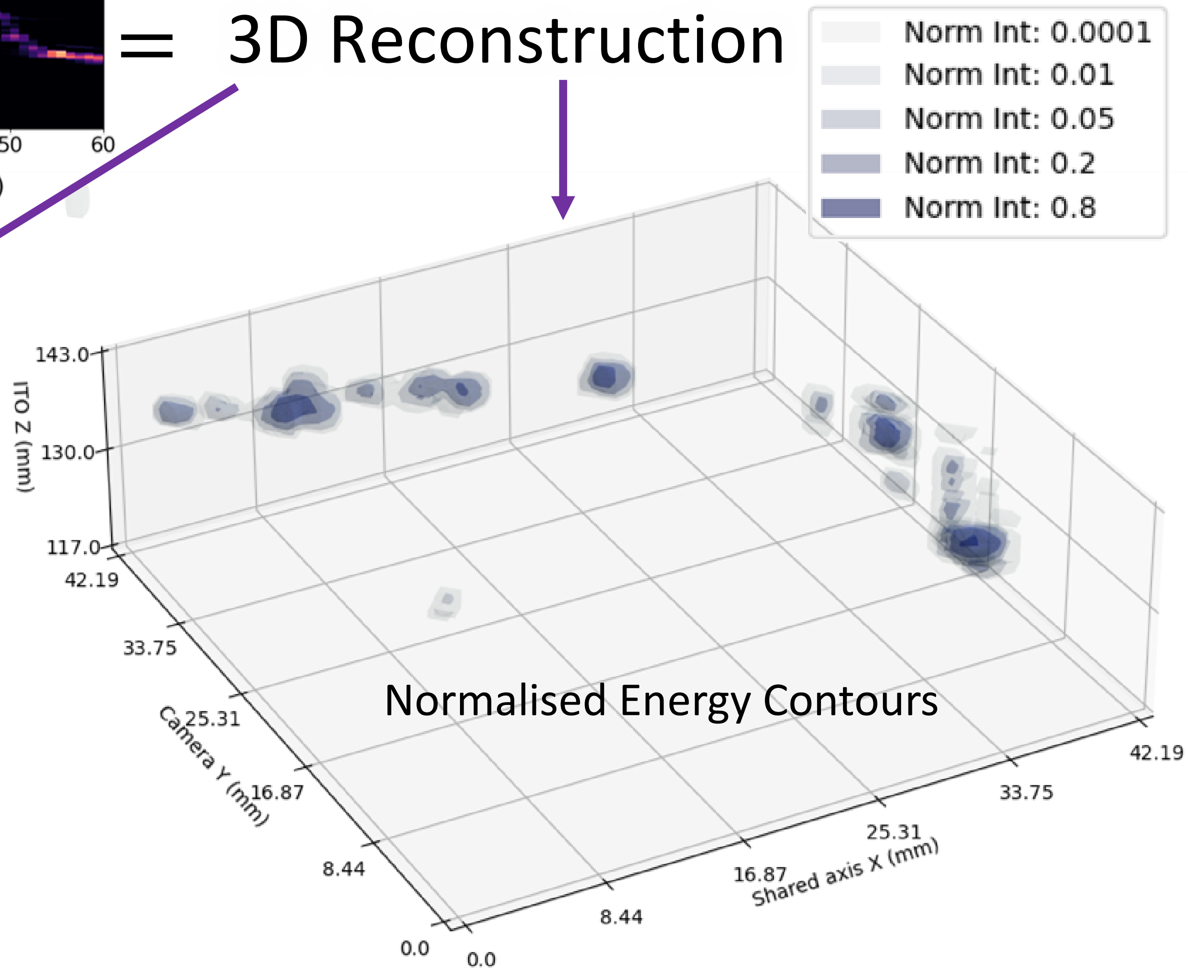


= 3D Reconstruction





3D Track Reconstruction: Ridgeline

Our Aim:

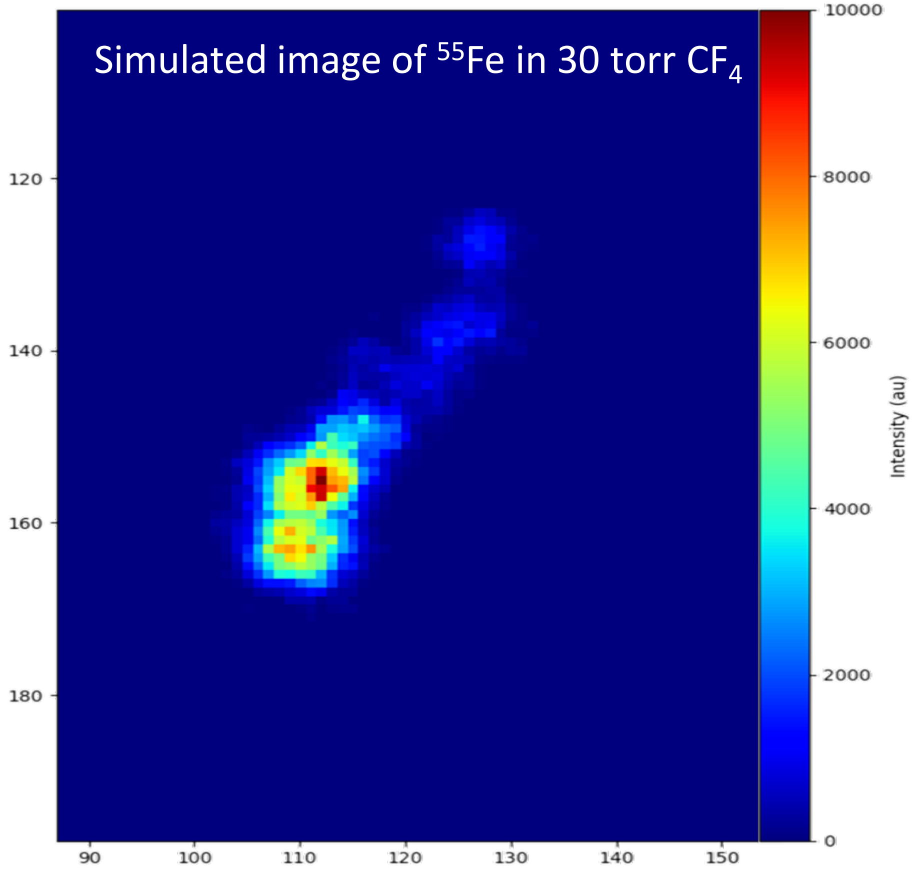
Observe and ***characterize*** the Migdal effect

We need:

- ❑ The track's actual path
- ❑ dE/dx
- ❑ True Track Length

Solution: a Ridge Finding Algorithm

http://fieldcraftguide.com/guide-to-land-navigation-terrain-association-gps-reviews/



3D Track Reconstruction: Ridgeline

Ridge Finding Algorithm (in brief):

1. Calculate the Hessian matrix of each pixel ($\begin{bmatrix} dxx & dxy \\ dxy & dyy \end{bmatrix}$)
2. Find the eigenvalues of these matrices
3. Highest eigenvalues correspond to ridgepoints
4. Connect these points to create ridges

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

An Unbiased Detector of Curvilinear Structures

Carsten Steger

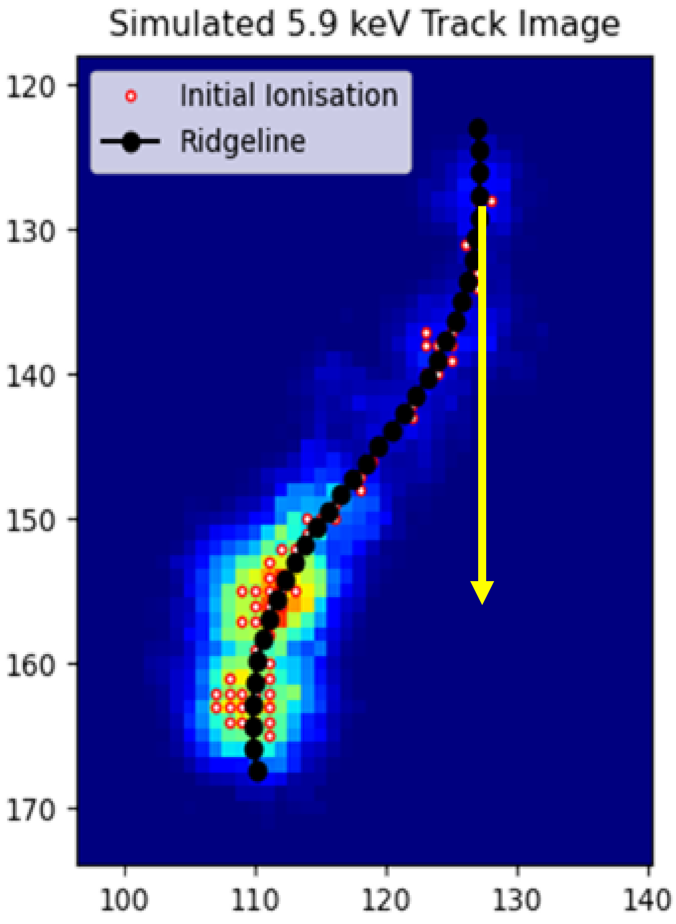
Abstract—The extraction of curvilinear structures is an important low-level operation in computer vision that has many applications. Most existing operators use a simple model for the line that is to be extracted, i.e., they do not take into account the surroundings of a line. This leads to the undesired 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.

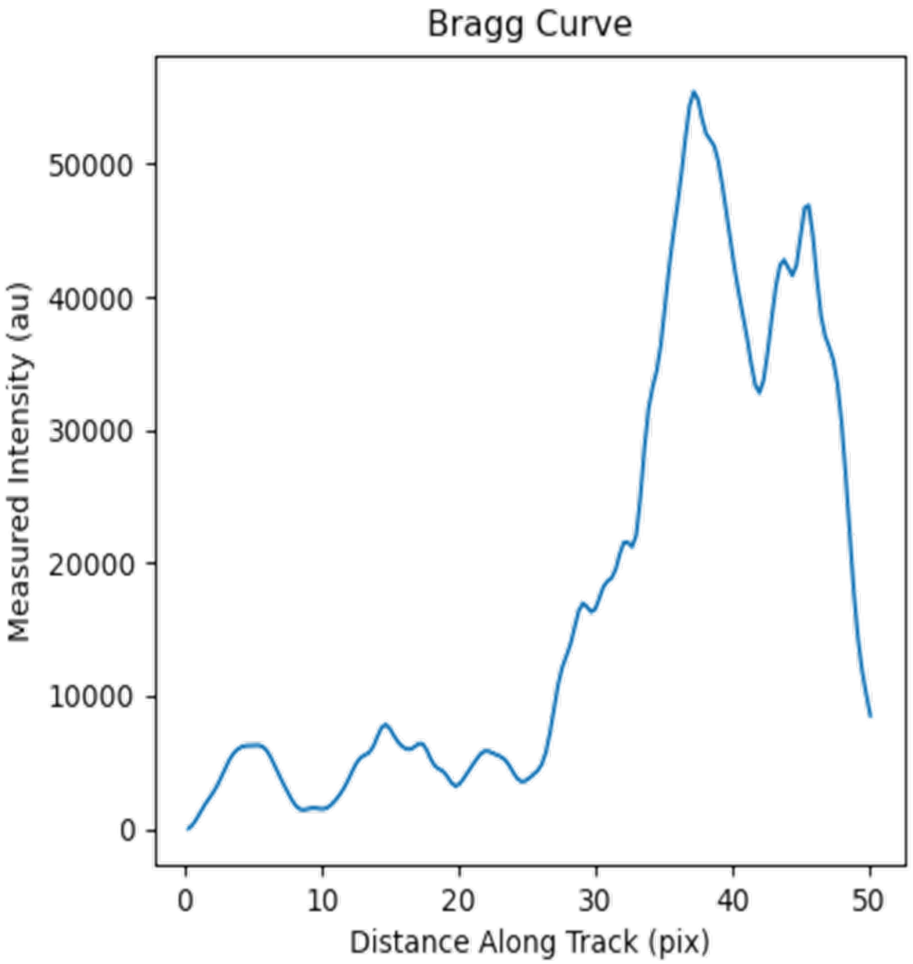
Index Terms—Feature extraction, curvilinear structures, lines, scale-space, contour linking, low-level processing, aerial images, medical images.

3D Track Reconstruction: Ridgeline

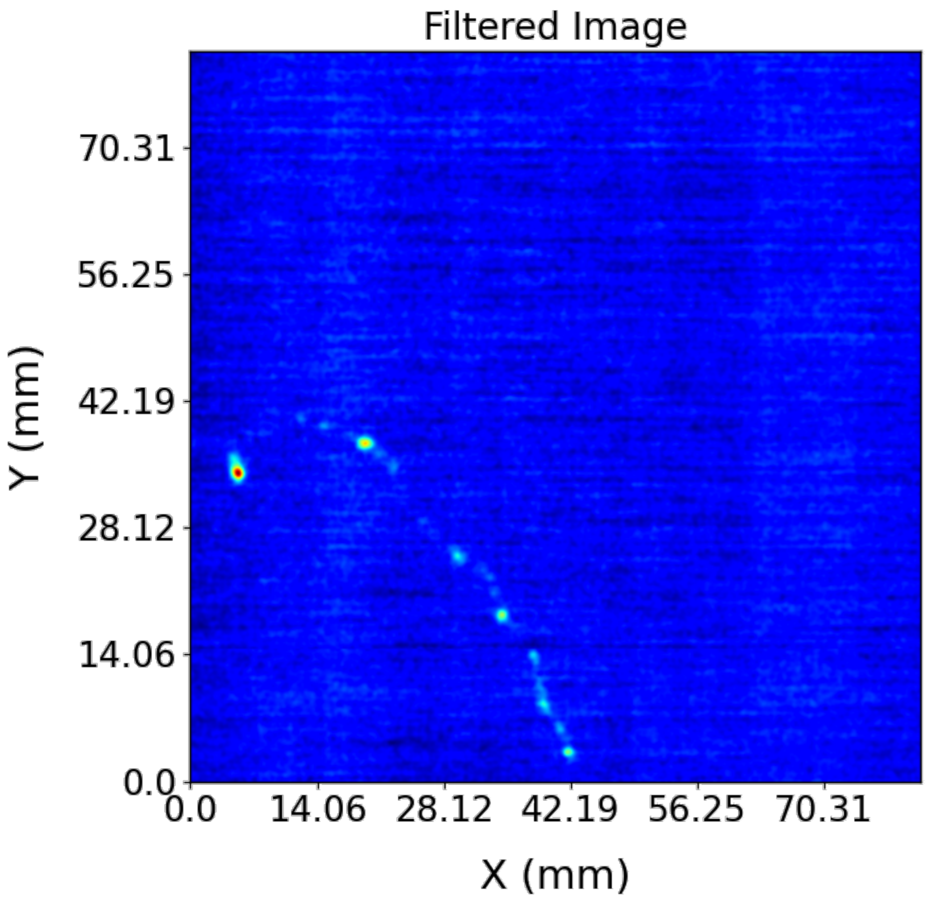
We need:

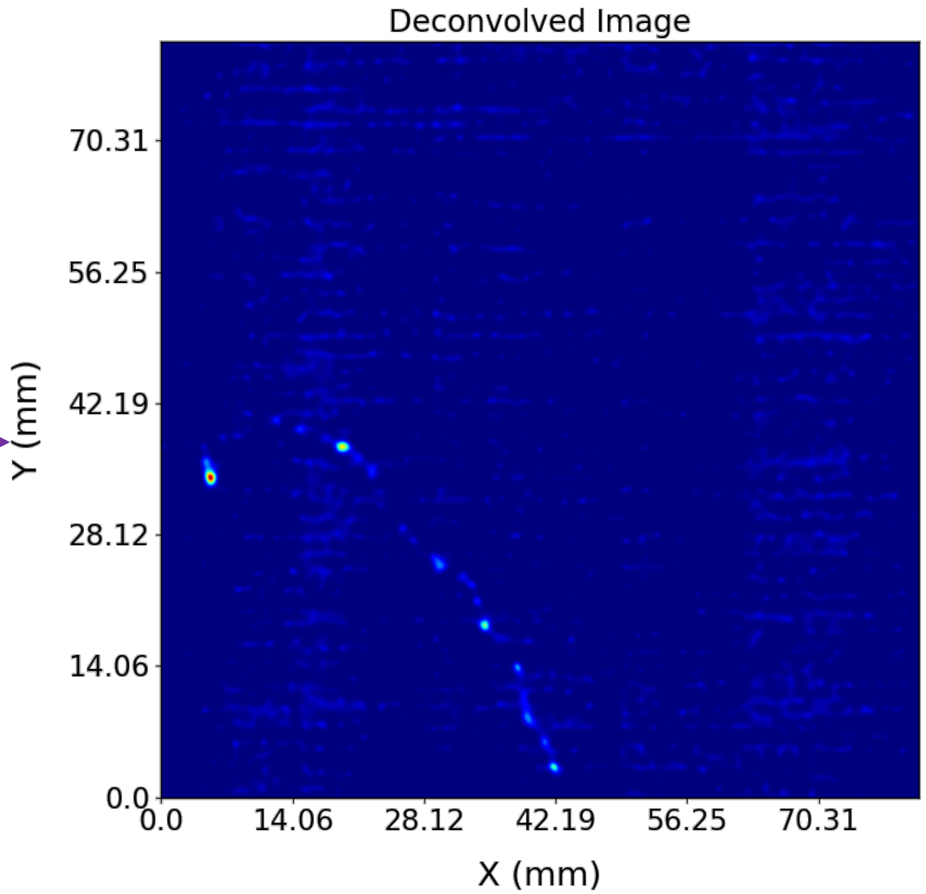
- ✓ The track's actual path
- ✓ dE/dx
- ✓ True Track Length



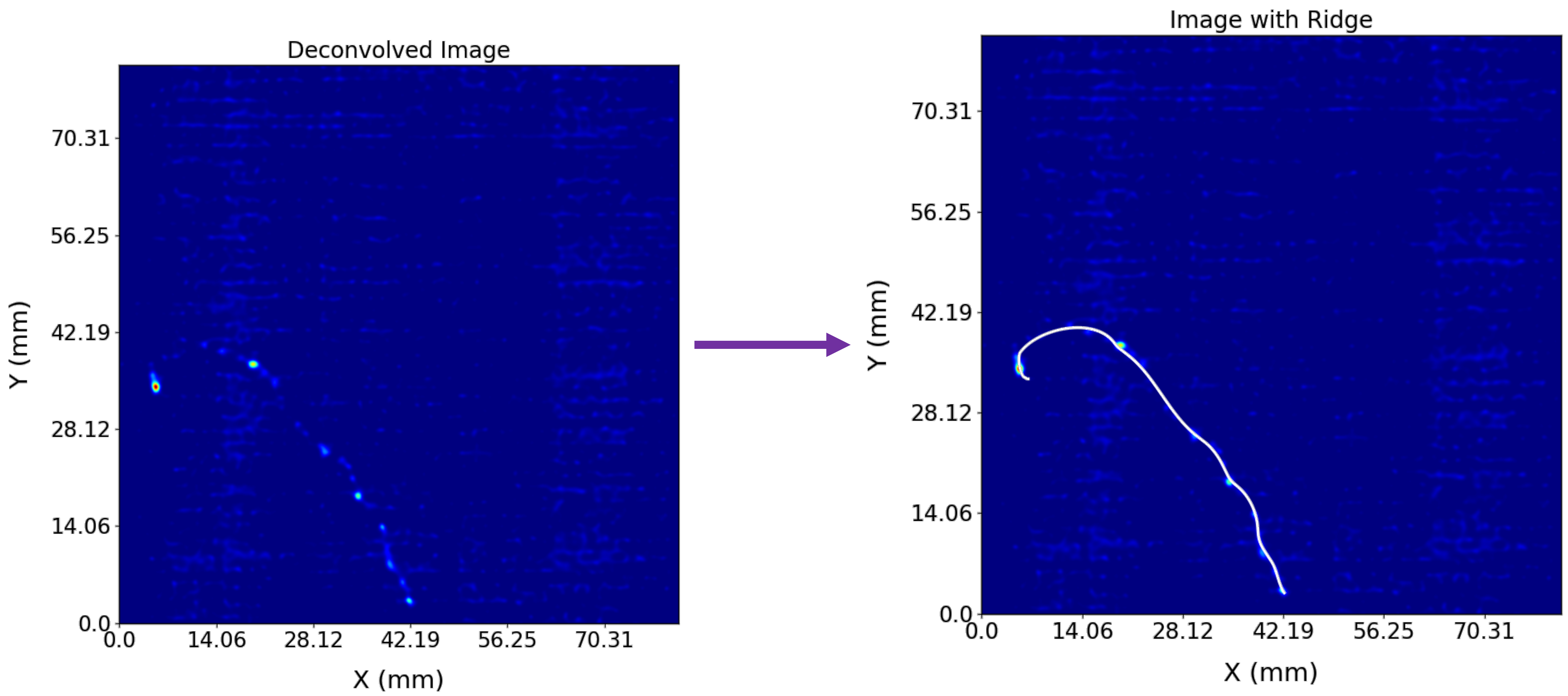


Preprocessing: Lucy-Richardson Deconvolution

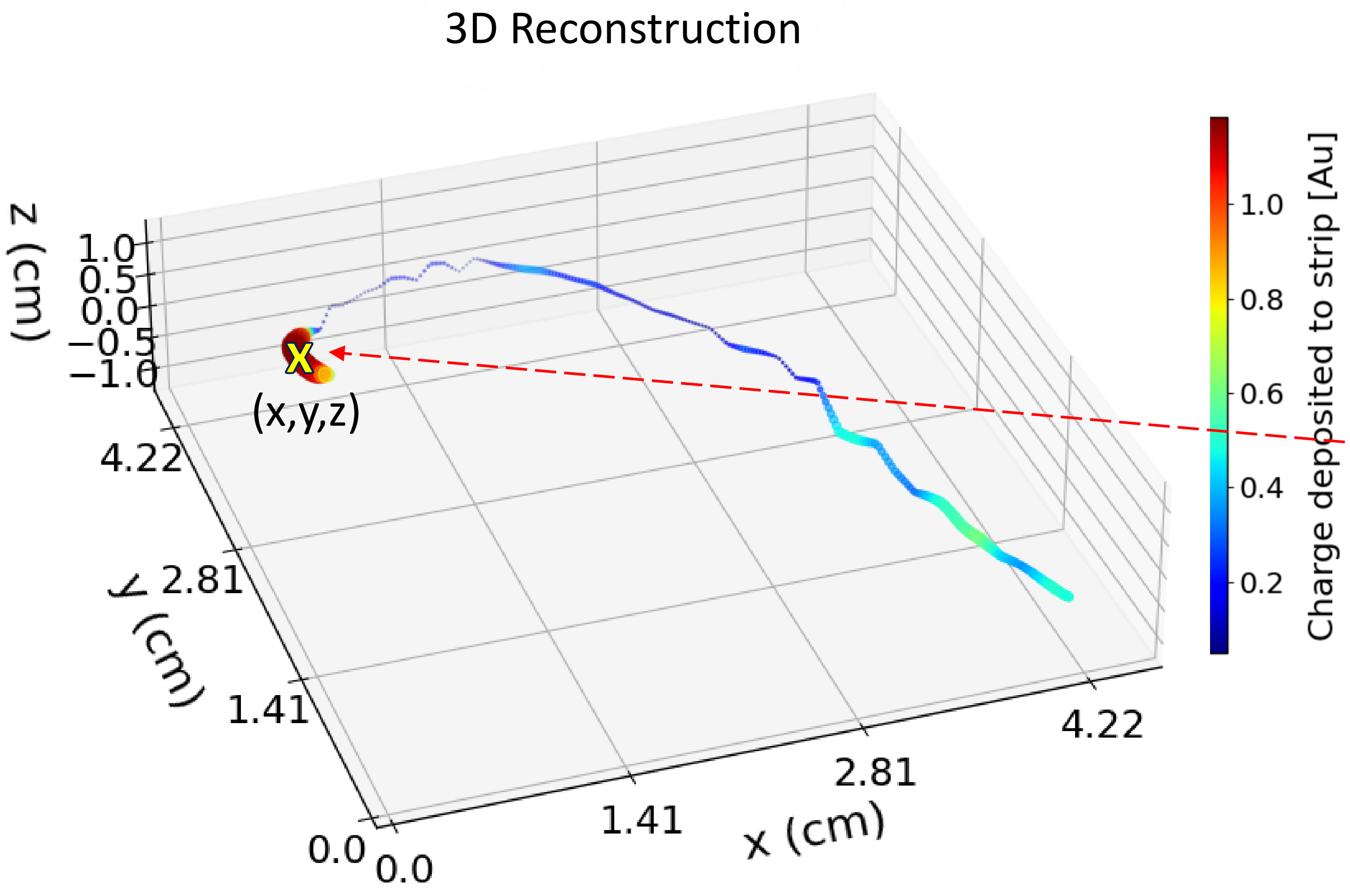


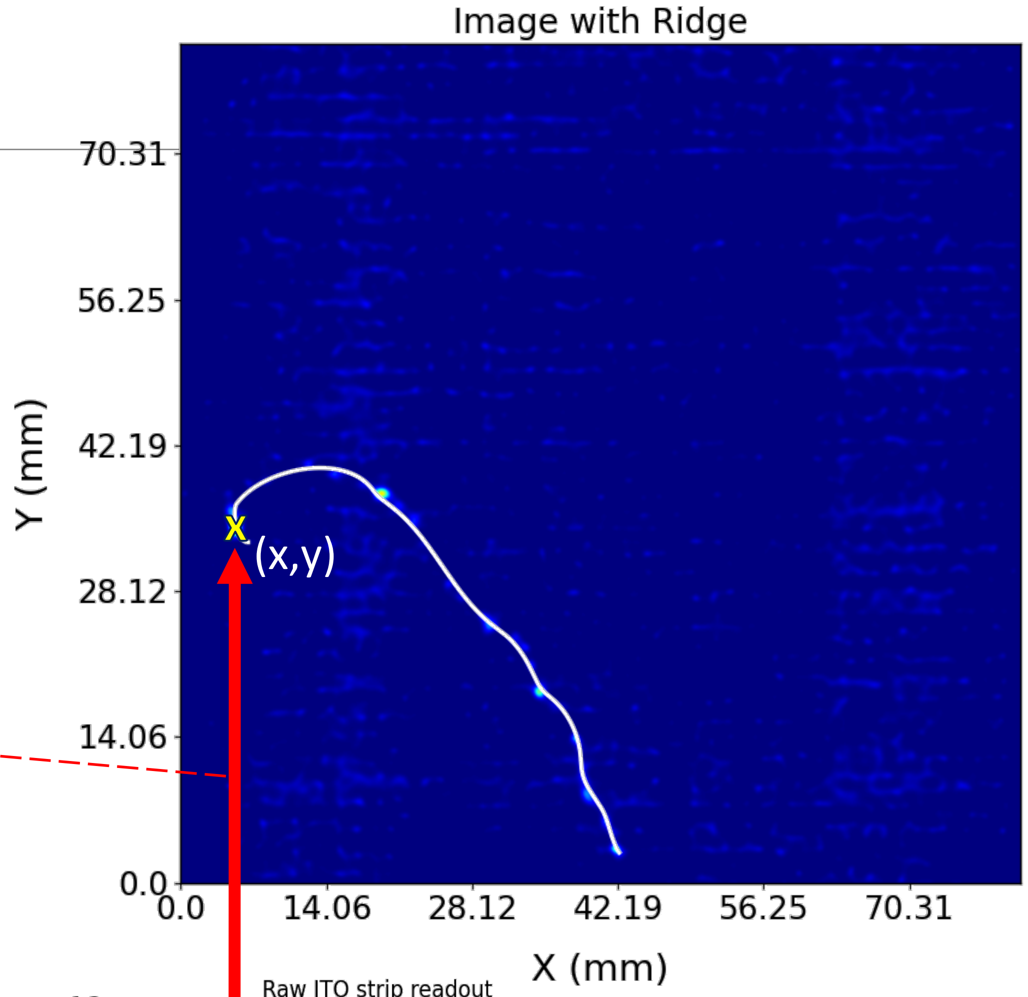


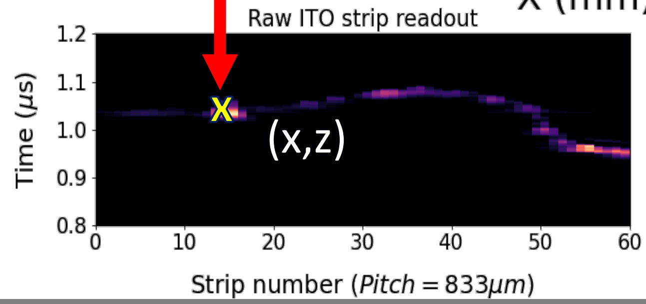
Getting A Ridge



Bringing it to the 3rd Dimension

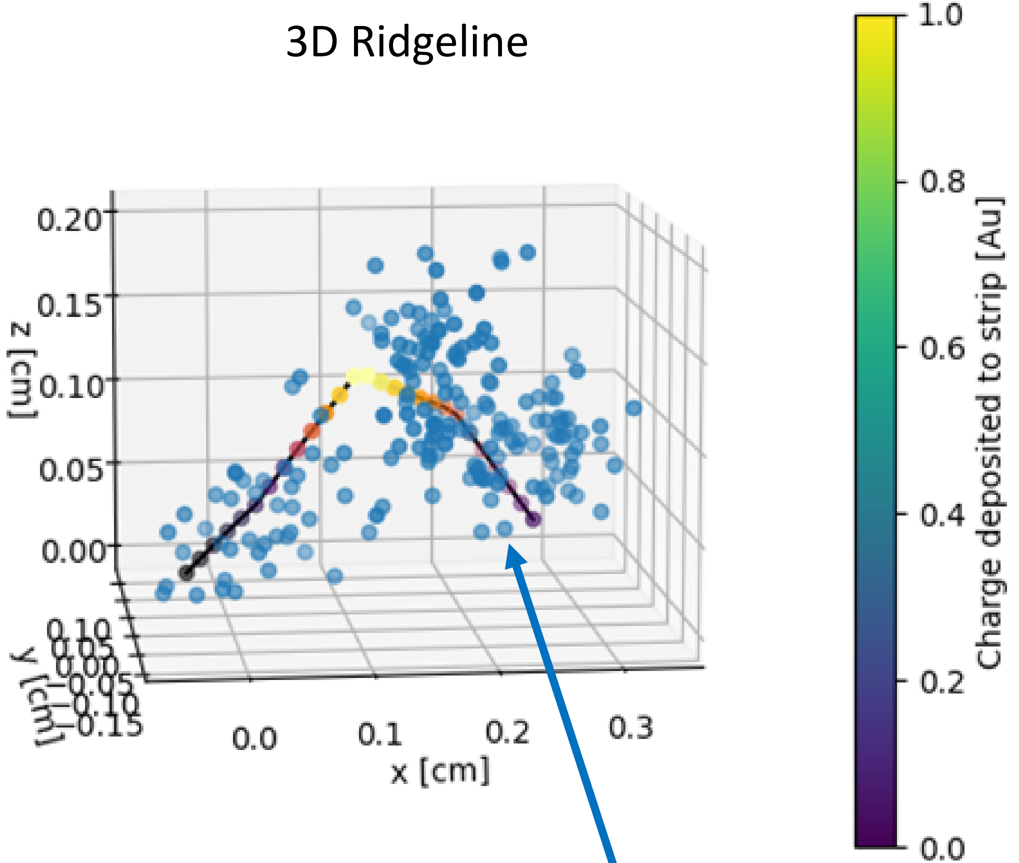


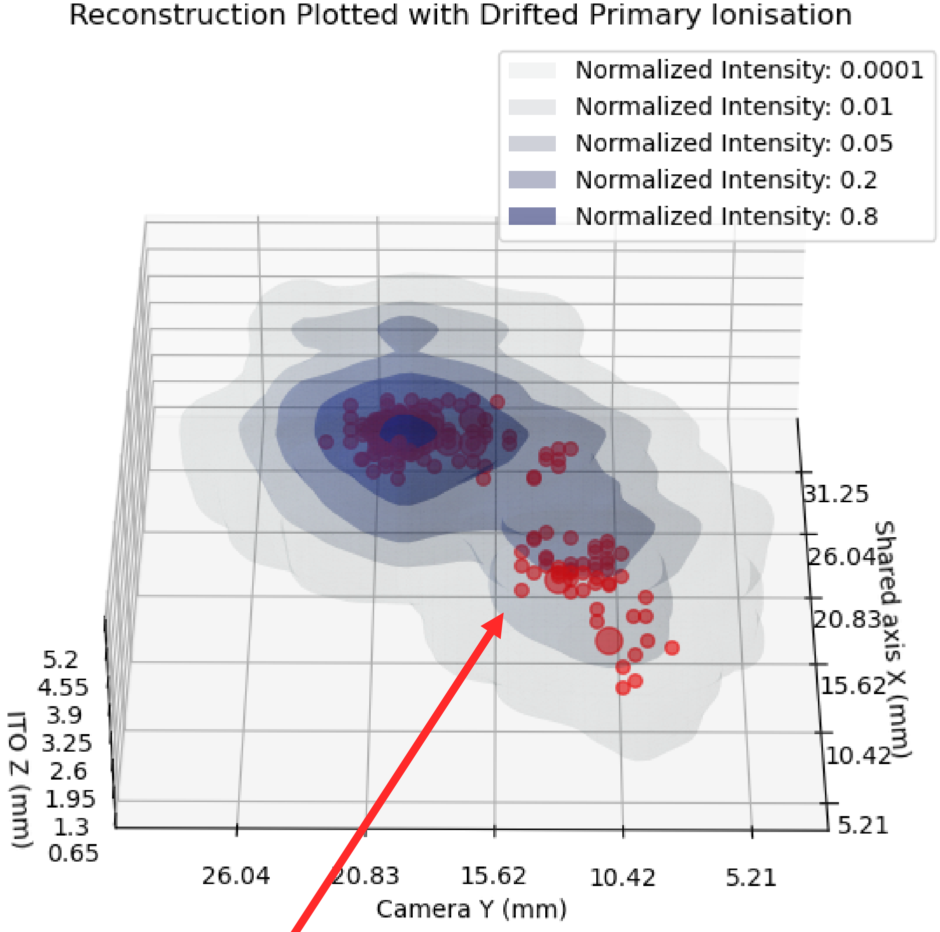




- $t(x)$ from maximum intensity of signal on an ITO strip (x)
- $z(x) = v_{drift}\, t(x)$

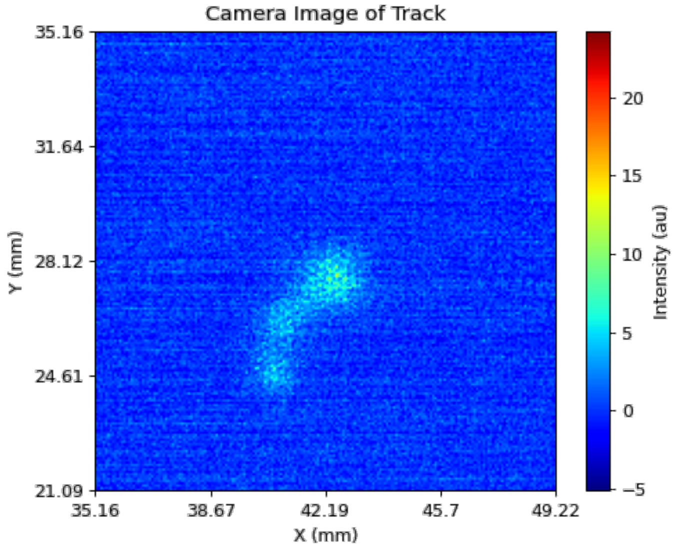
Comparing With Simulations (5.9 keV events in 50 torr CF_4)



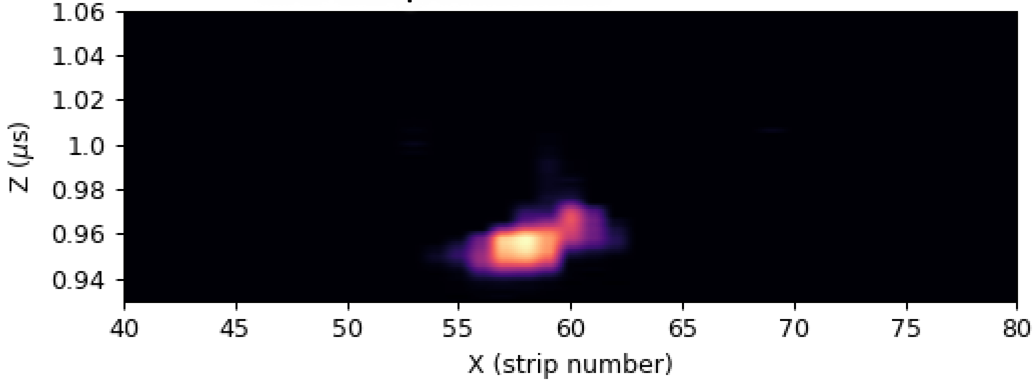


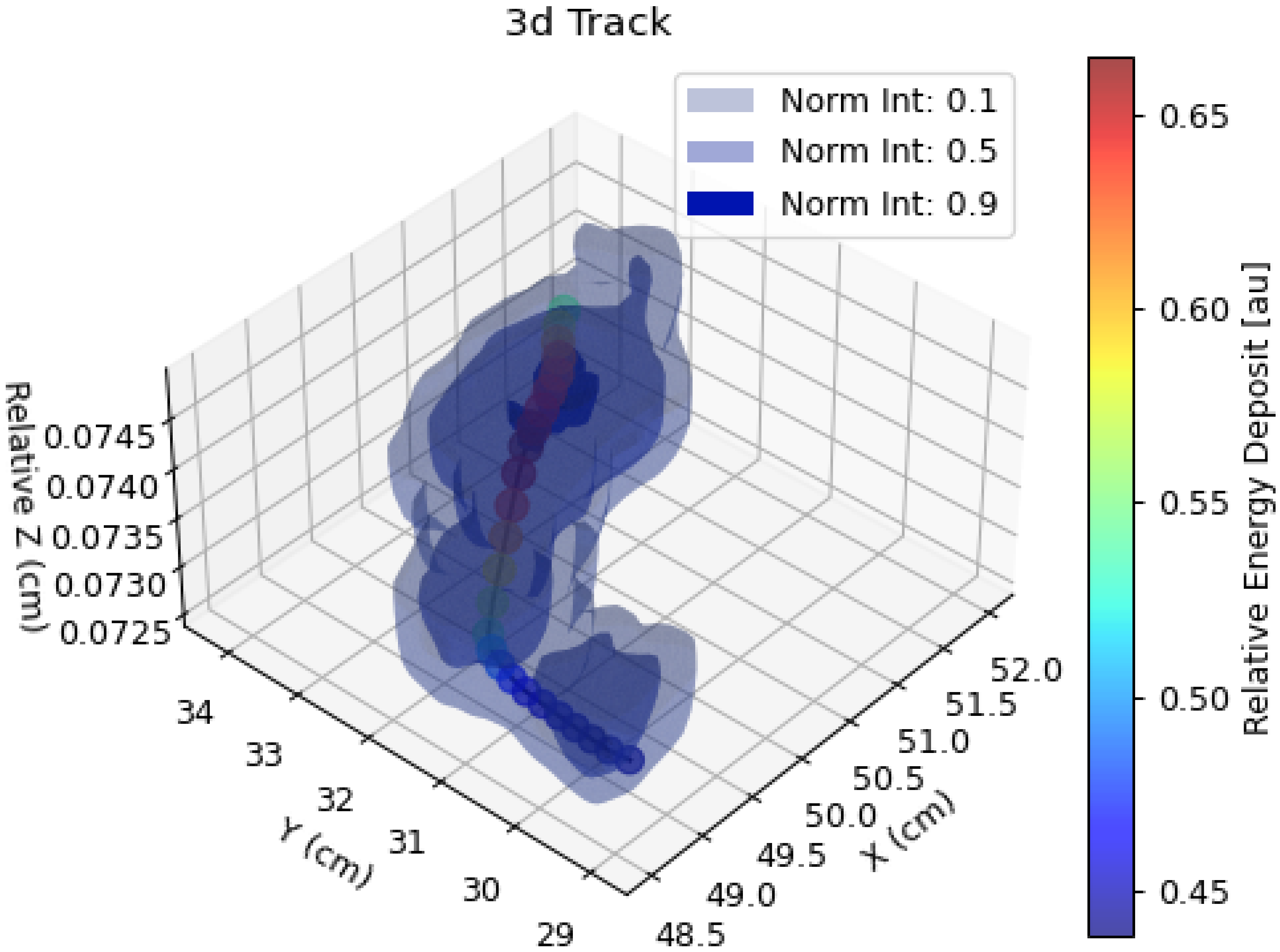
Drifted Primary Ionisation (Pre-GEMs)

3D Reconstruction 5.9 keV e- Event in 50 torr 20:80 Ar:CF_4 (**real data**)

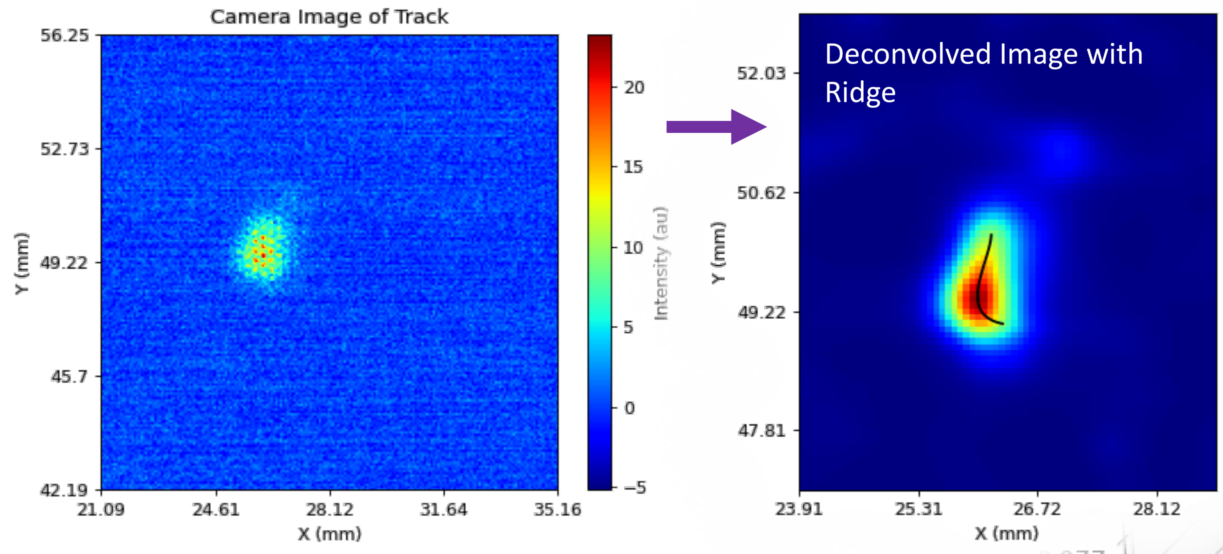


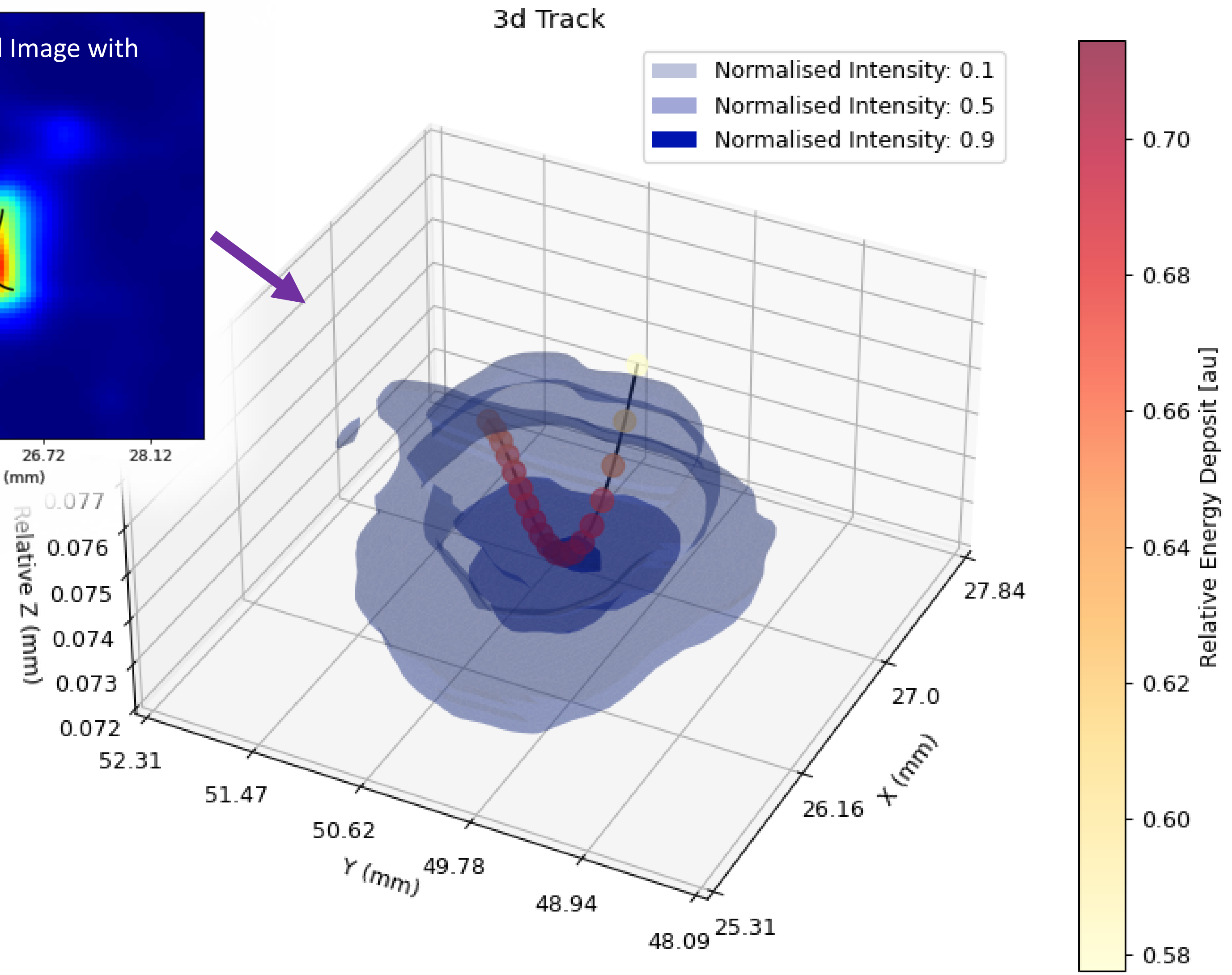
ITO Strip Readout



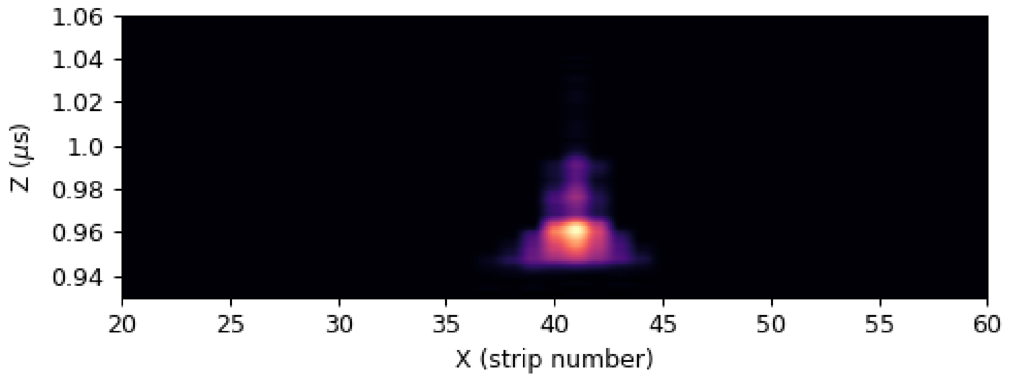


3D Reconstruction 2.9 keV!! e- Event in 50 torr 20:80 Ar:CF_4 (**real data**)



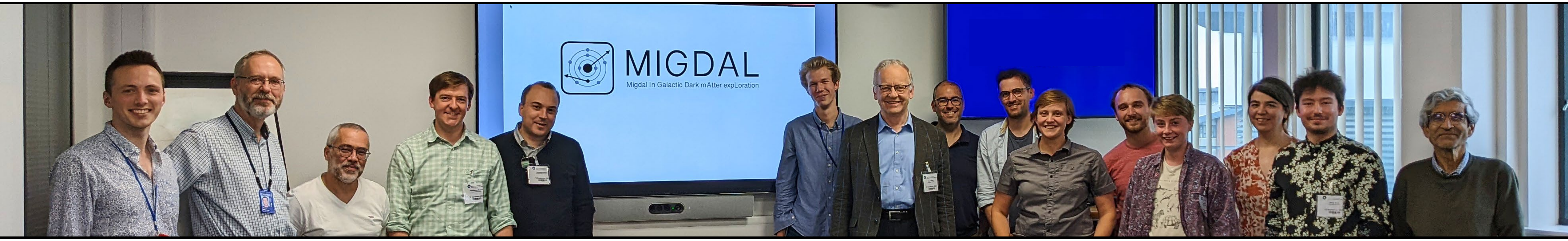


ITO Strip Readout



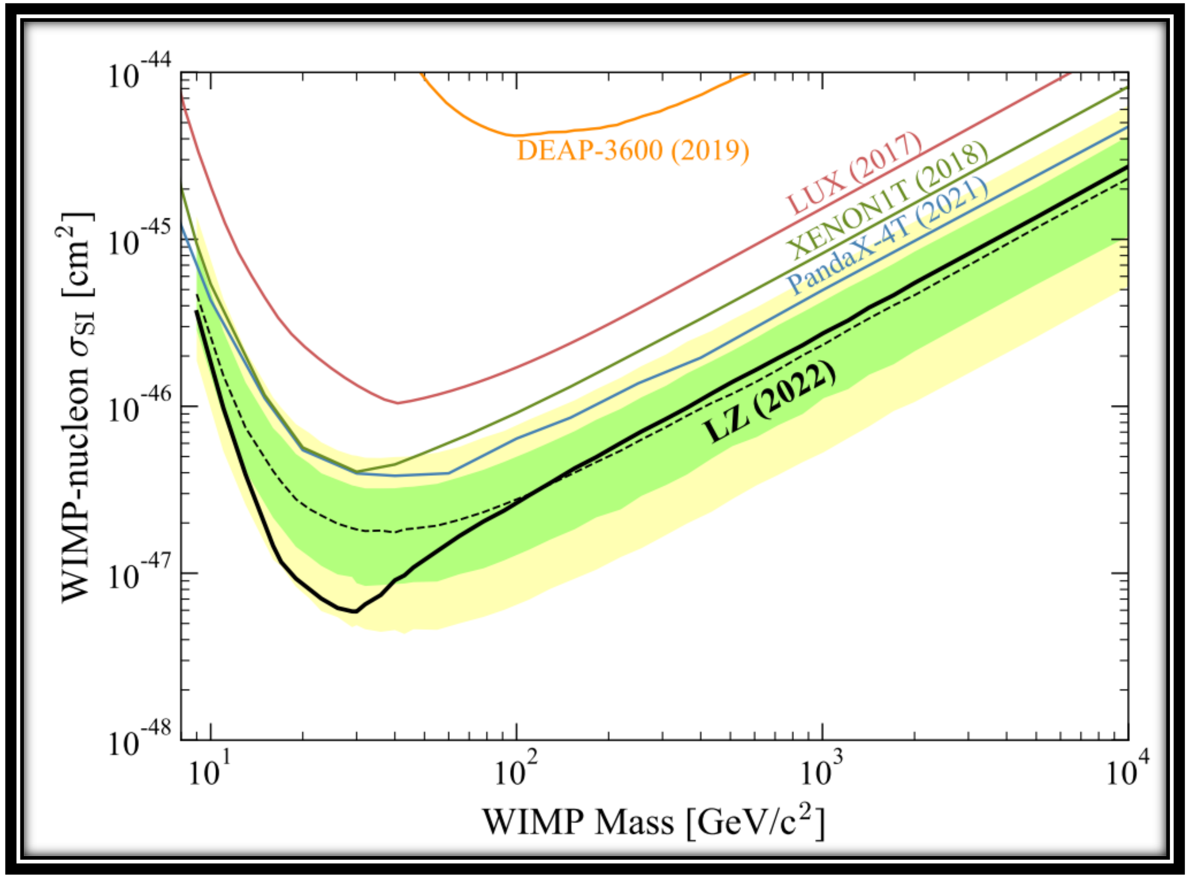
Summary

- The Migdal effect has been used by DM experiments to extend sensitivity to low-mass WIMP parameter space (~2 orders of magnitude lower)
- MIGDAL collaboration goal: observe and characterize the Migdal effect in CF_4 and noble gases
- To characterize this effect, it is essential that we reconstruct these low energy Migdal electrons in 3D
- By combining 2D information from a strip readout and 2D information from a camera image, we have been able to successfully reconstruct electrons as low as 2.7 keV
- For more details on the detector/experiment, refer to Tim Marley's talk from Monday or our paper: arXiv:2207.08284v2

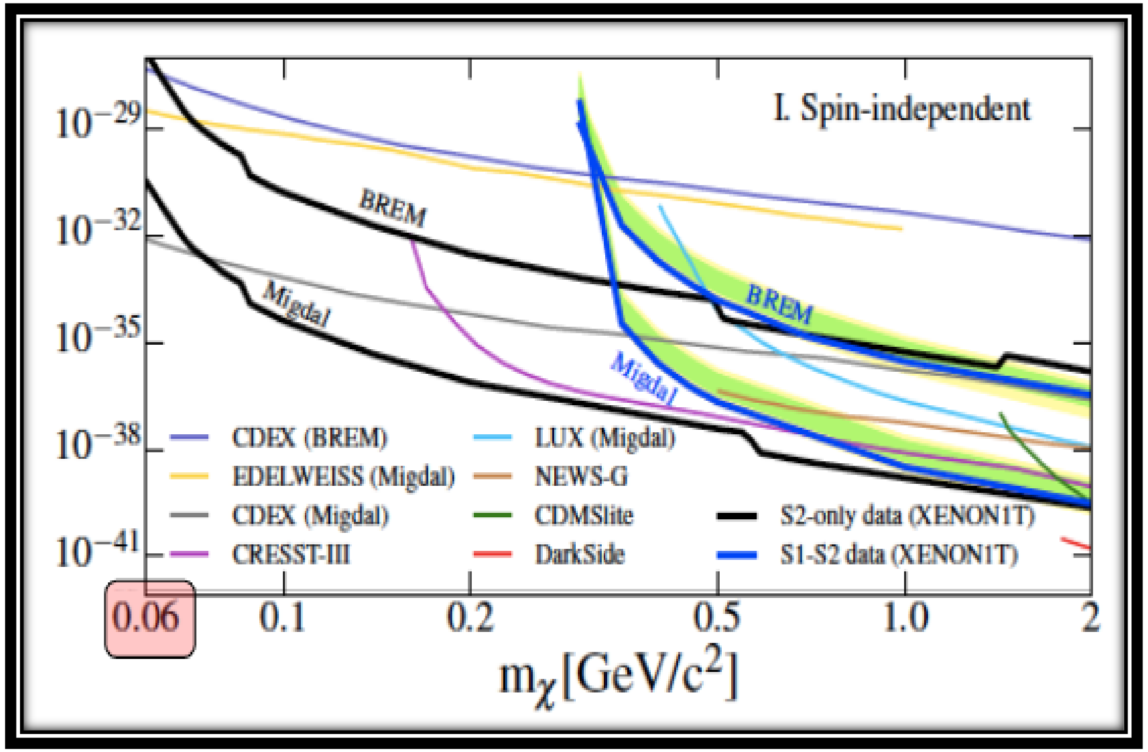


Backup Slides

New WIMP Low Mass Limits

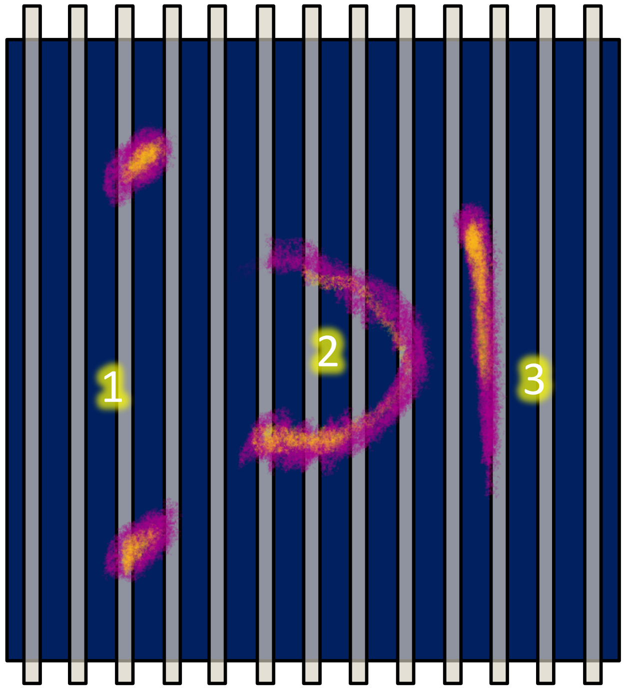


arXiv: 2207.03764

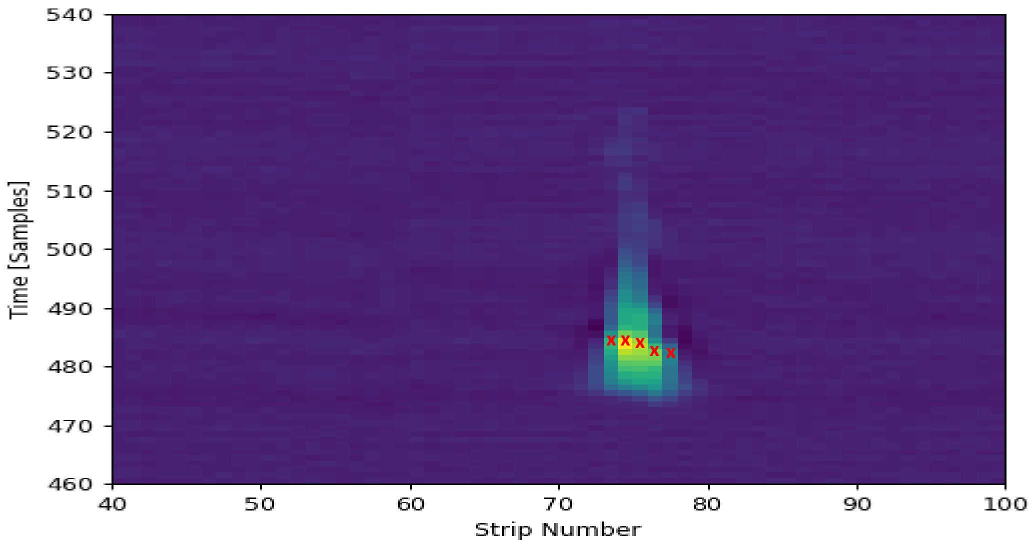


XENON1T collab arXiv:1907.12771

Geometric Challenges with 3D Reconstruction

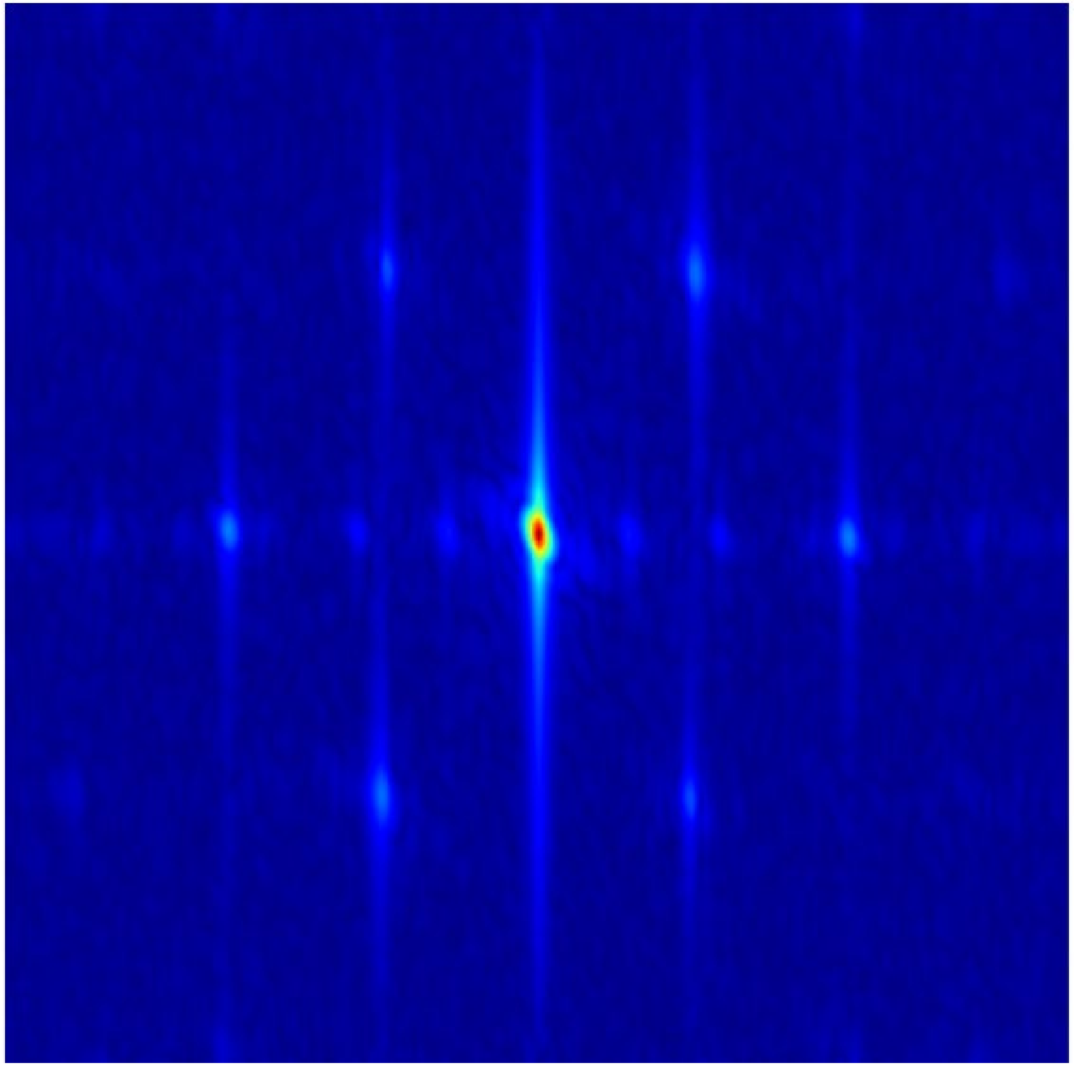


1. Indistinguishable Tracks
2.&3. Indistinguishable Vertices



Current algorithm does not recognize vertical extent in ITO but looks for “peak” locations along each ITO strip

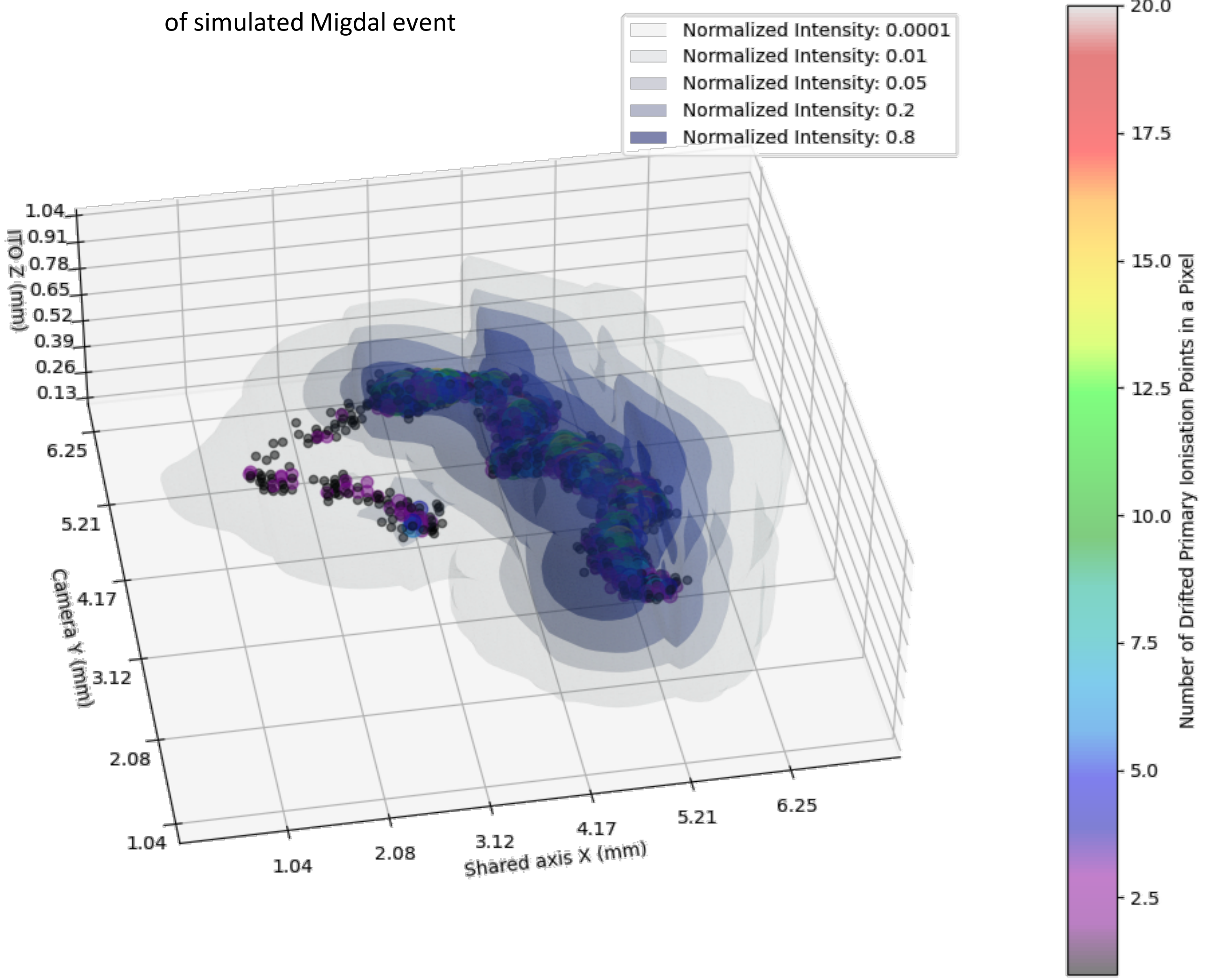
GEM holes in FFT image



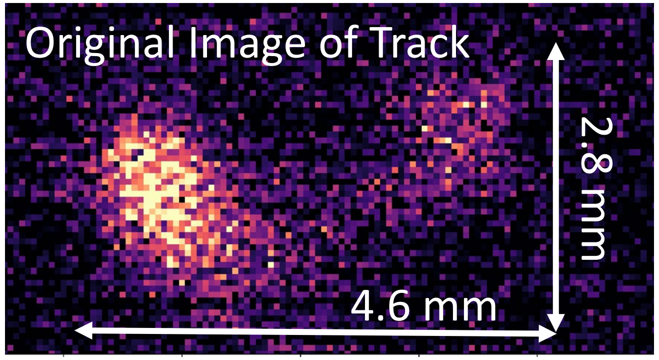
Reconstructing a Migdal Event

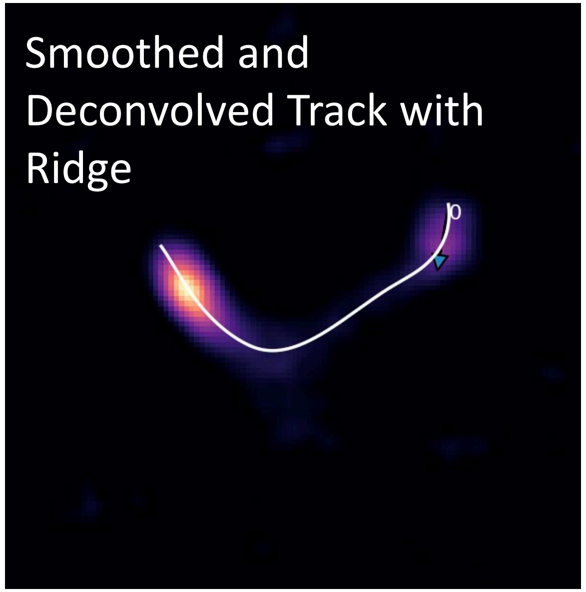
- Reconstructing Migdal events will be more challenging than just reconstructing nuclear recoils (NR) or electron recoils (ER) individually
    - The high energy/ionization density of the NR tends to wash out the signal from the ER
    - Becomes most apparent when trying to fit a ridge to the tracks, but the voxelization does not seem to suffer from this as much

Reconstruction Plotted with Drifted Primary Ionisation of simulated Migdal event



3D Reconstruction 5.2 keV e- Track in 50 torr 20:80 Ar:CF_4 (real data)





3D Reconstructed Track Ridge