Development of a Negative Ion Gas TPC to Observe the Migdal Effect

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CPAD WORKSHOP NOV 29-DEC 2 2022

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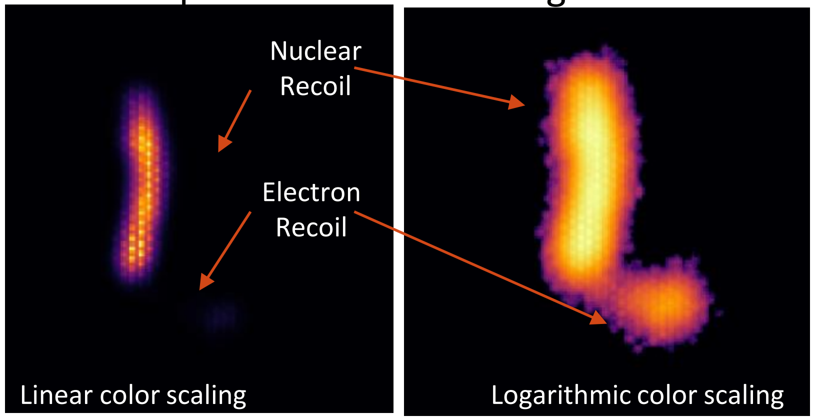
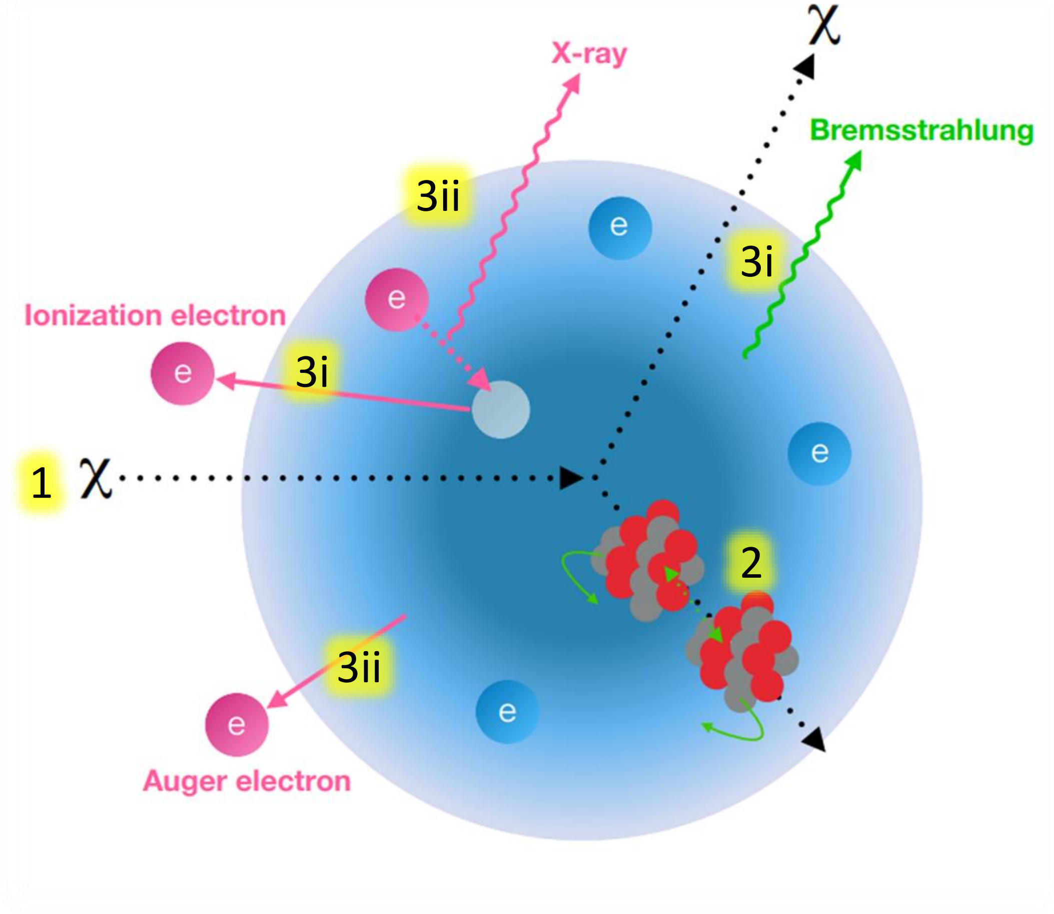
The Migdal Effect

1. Neutral particle impacts atomic nucleus
2. Nucleus recoils, and electron cloud lags behind
3. As the electron cloud “catches up”, there’s a low probability for
   i. The ionization of electrons or Bremsstrahlung emission
   ii. Emission of X-ray or Auger electron

Example of a Simulated Migdal Event





Developing a Detector

Challenges for a *direct* Migdal search

1. Dynamic Range in ionization density between nuclear recoils and Migdal electrons
2. Very low energies (100's keV for NR and 1-10 keV for e-)
3. Track Characterization, particle identification and Background Rejection
4. Migdal Effect is incredibly rare

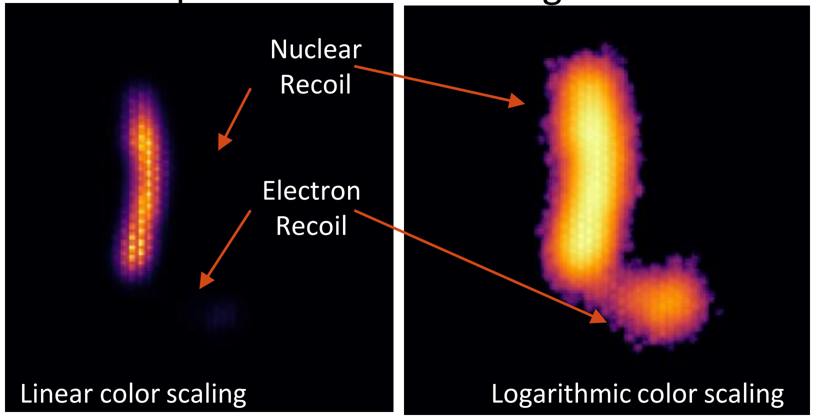
Essentials in a *direct* Migdal search

Capability to resolve and distinguish between low energy tracks

Ability to reconstruct tracks in 3D

High intensity source of neutral particles

Example of a Simulated Migdal Event



Our Detector for a *direct* Migdal search

Low Pressure Gas

Time Projection Chamber

D-D or D-T Generator

Different Detector Technologies

	Optical	Charge Readout
Advantages	1. High resolution detector readouts are commercially available (i.e. scientific grade CCD or CMOS camera)	1. Dynamic range presents less of a problem since high gas gains required in OTPCs aren't necessary 2. We can maximize target gases of interest (in this case, noble gases) while maintaining stable operation at sufficient gas gains 3. Negative Ion doping can be employed to improve resolution in all 4 dimensions
Disadvantages	1. Extremely high gas gains are required to produce enough light to resolve low energy tracks which becomes a problem when a high dynamic range is required (as in the Migdal search) 2. Negative Ion doping significantly suppresses light yield	1. To achieve similar spatial resolution to the optical detector, many channels are needed, which is expensive and challenging to implement

Negative Ion Drift Gases

NI Drift was first used in the DRIFT directional dark matter experiment, which used a Multi-Wire Proportional Chamber

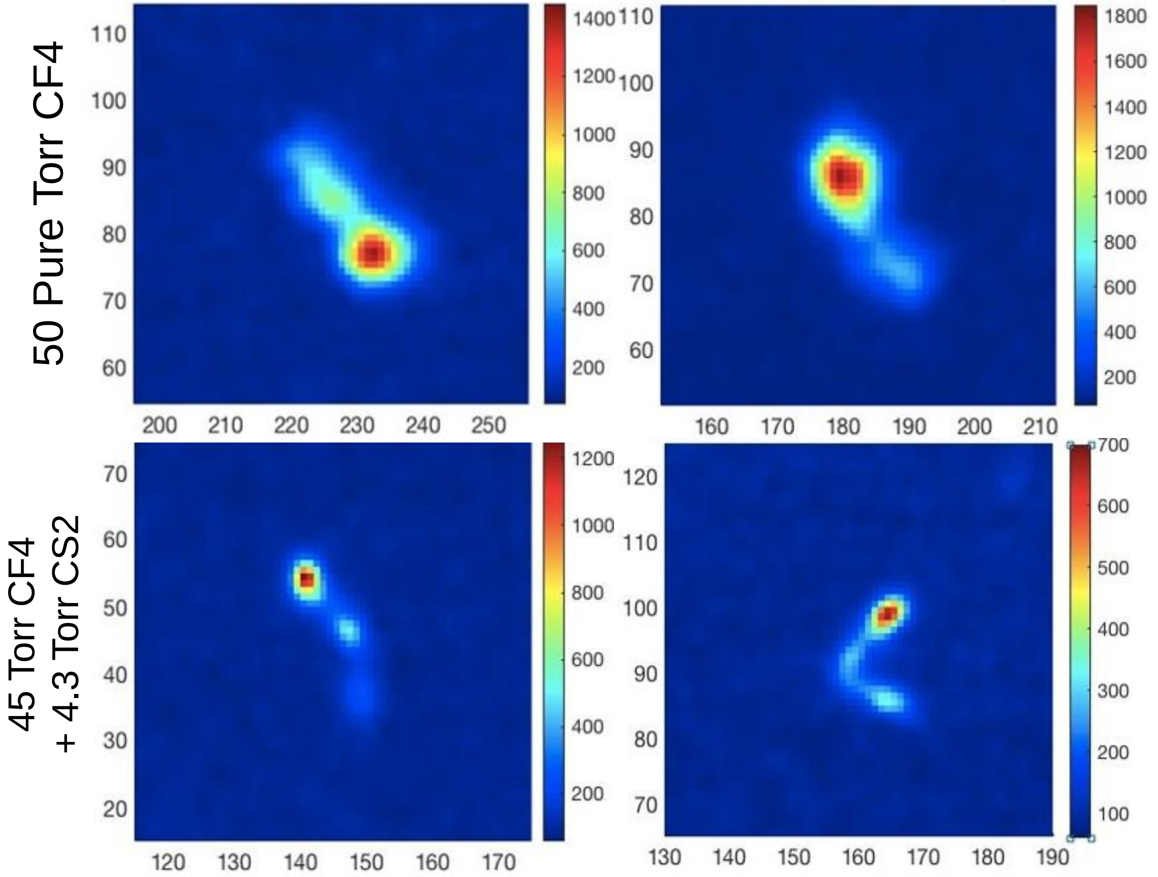
Advantages:

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

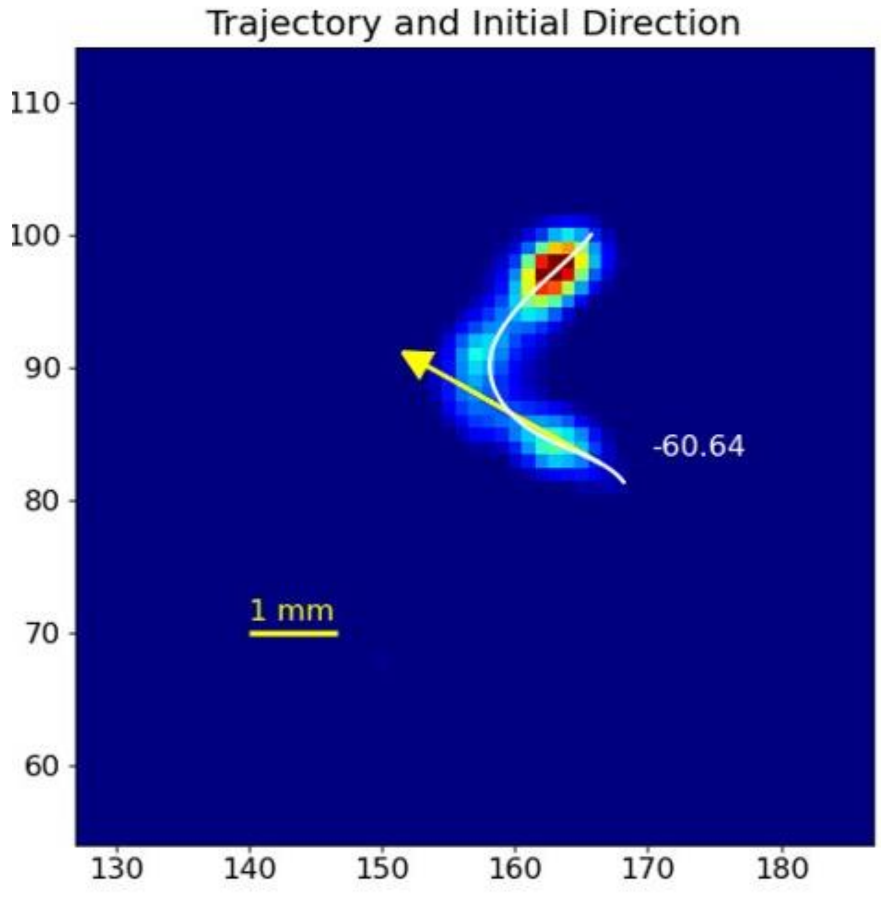
Disadvantages:

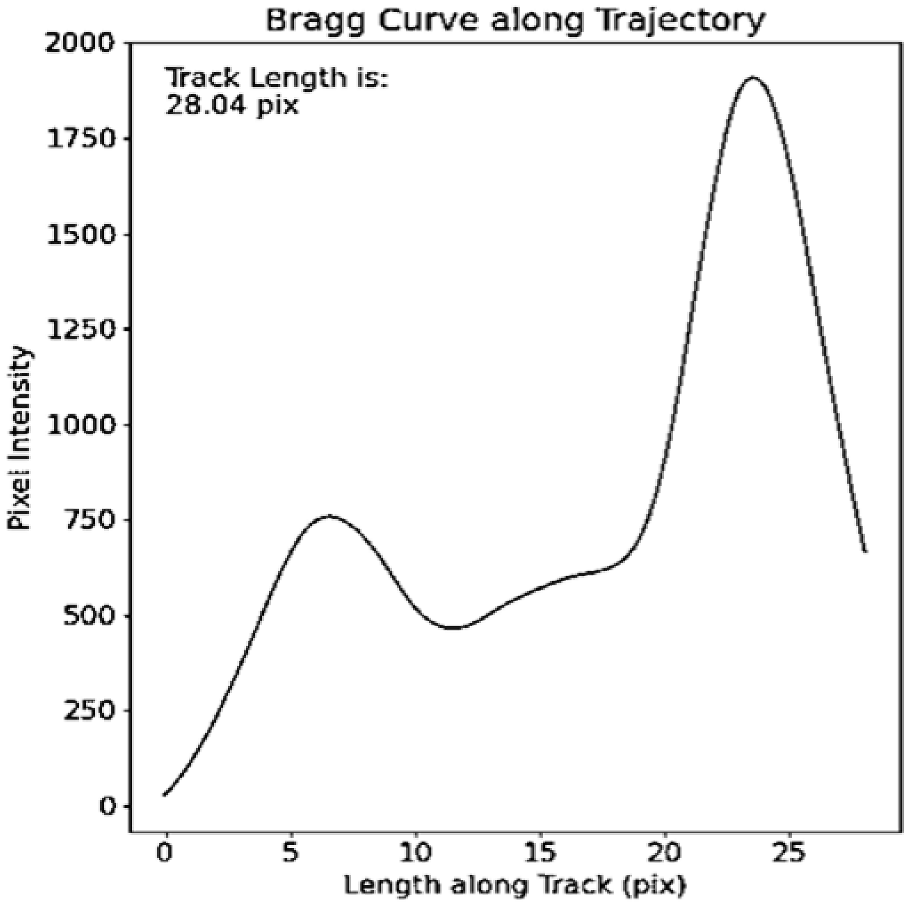
1. Light yield can drop up to 80% with as little as 3% NI gas

5.9 keV e- Tracks from ^{55}Fe

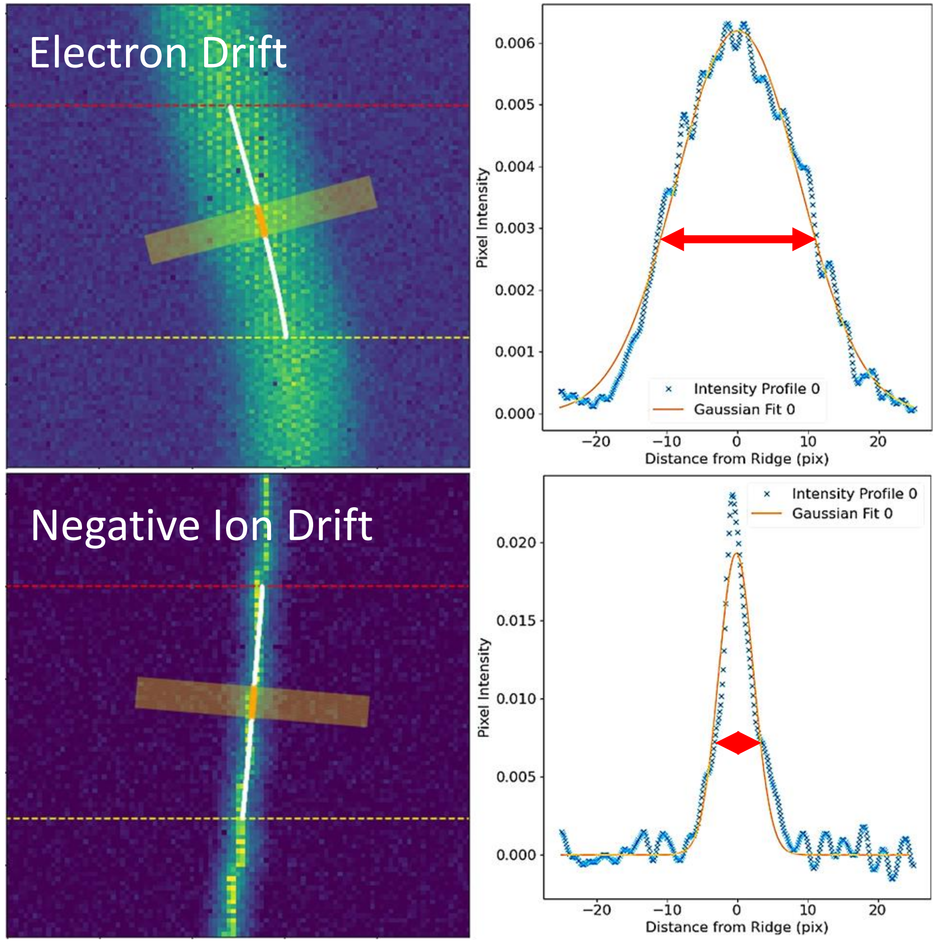


Negative Ion Drift Gases





Negative Ion Drift Gases



Preliminary Diffusion Measurements	
150 Torr CF_4 (normal electron drift) + X torr CS_2 (negative ion drift)	
CS_2 (Torr)	σ(μm)
0	~400
2.9	133.53
4.2	126.10
5.4	125.09

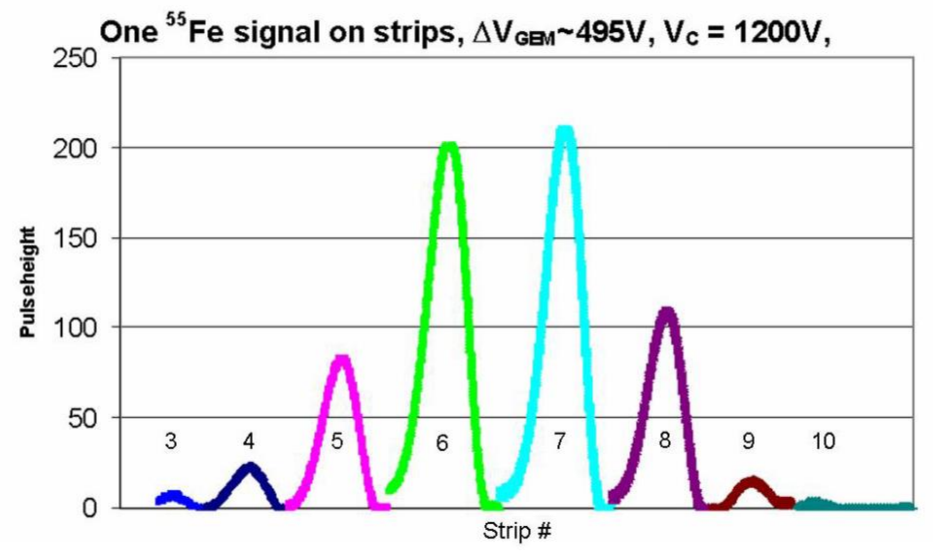
Previous Work from our group

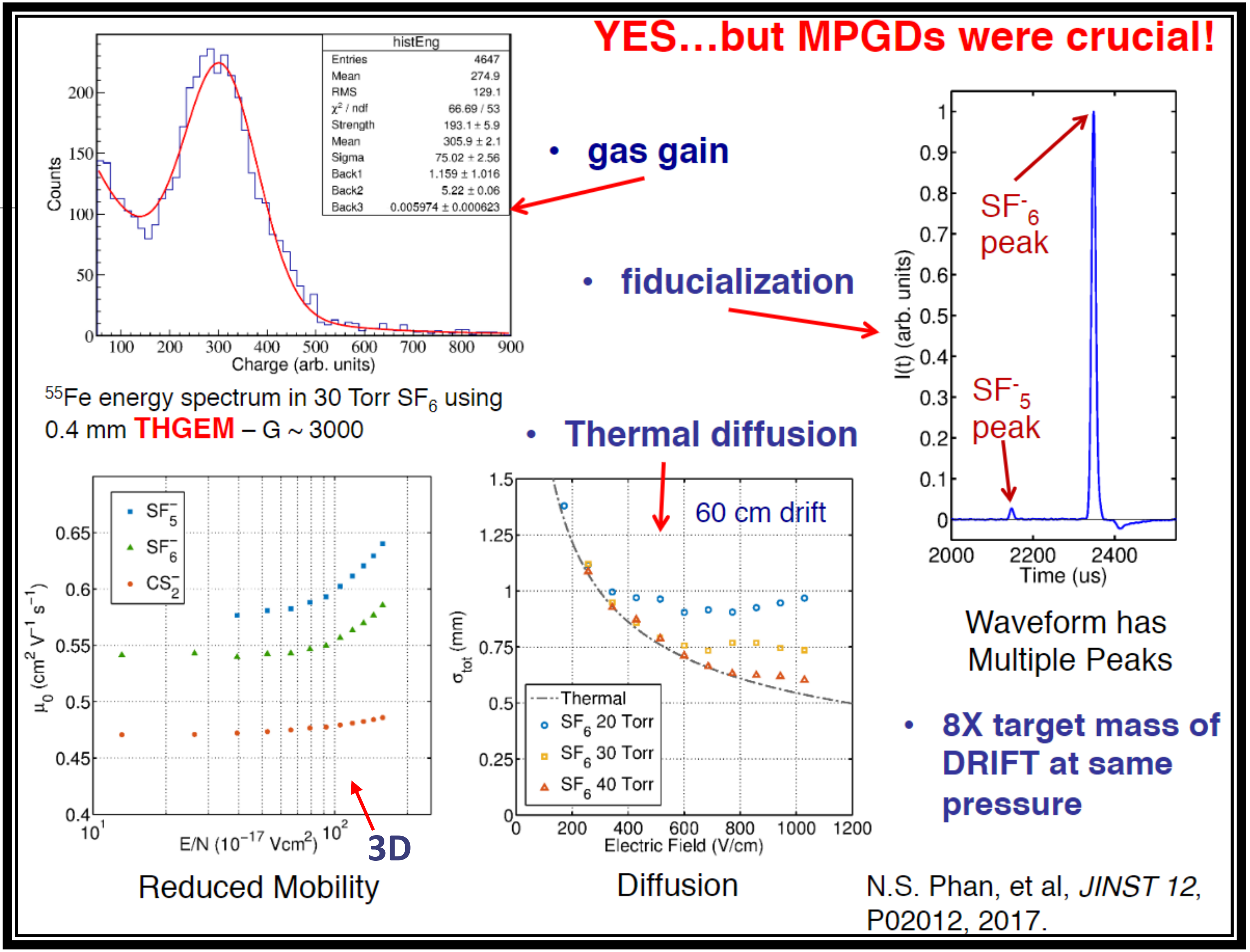
Our group has already begun working on these tests to characterize pure NI gases:

Christina Hagemann, PhD Thesis, UNM (2009)

Nguyen Phan, PhD Thesis, UNM (2016)

Randy Lafler, PhD Thesis, UNM (2019)



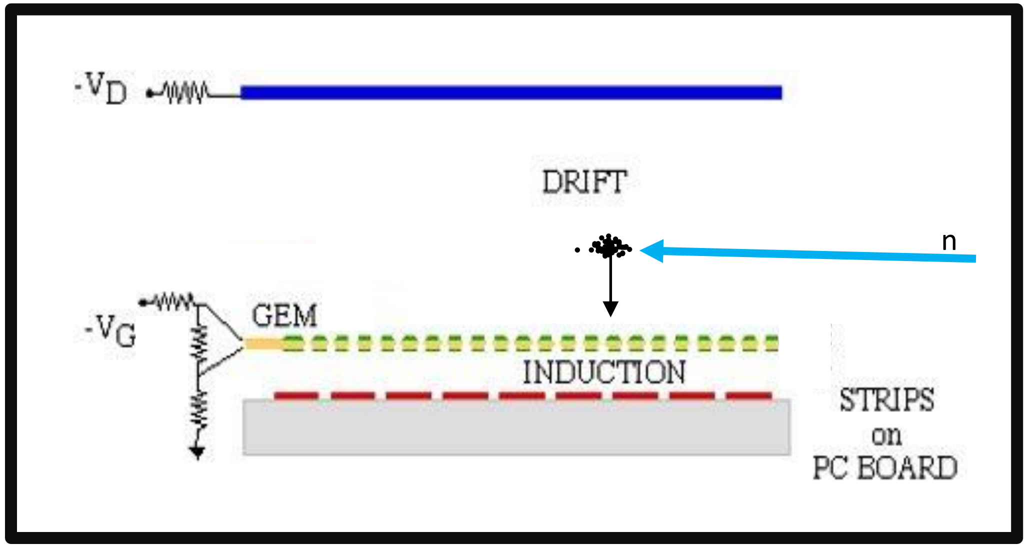


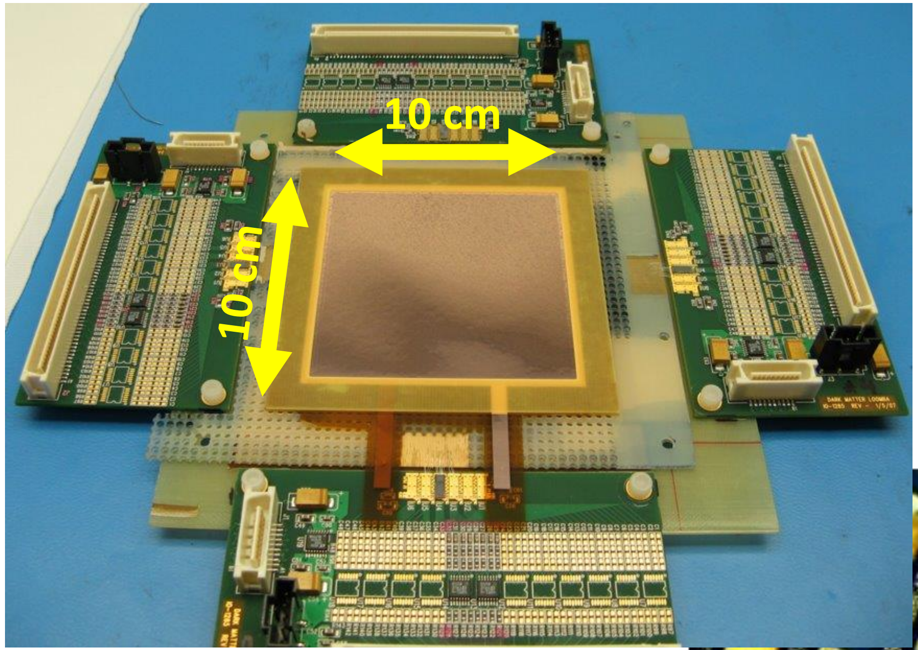
Slide from: D. Loomba, Snowmass MPGD workshop, 2020

General Detector Design

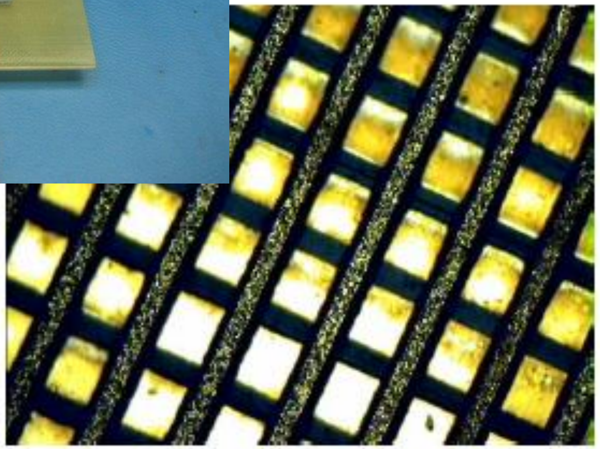
- 10cm x 10cm 2D strips at 200 μm pitch
- Gas Electron Multiplier (GEM) at 140 μm pitch to amplify the signal from the tracks
- Housed inside of a vacuum vessel filled with 50-100 torr of gases of interest
    - CF_4, Xe, Ar, He, etc + CS_2 or SF_6 (NI gases)

Vacuum Vessel

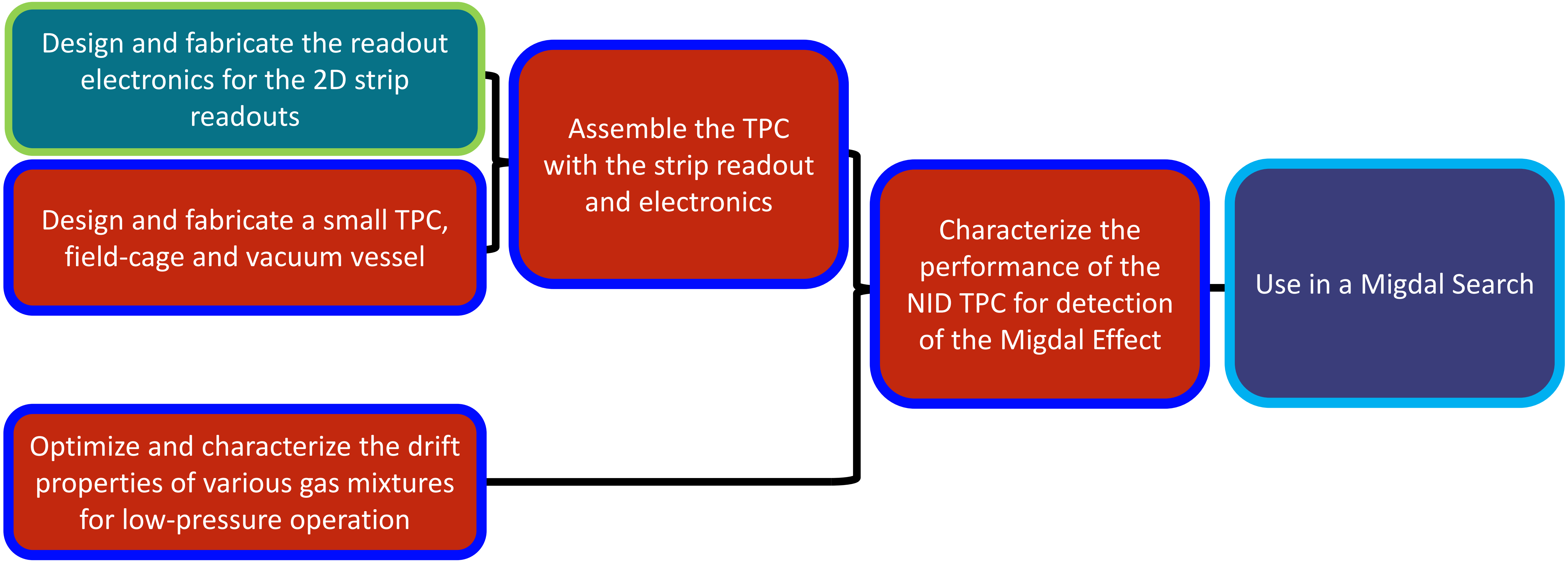




200 μm pitch



Broad Scope of the Project

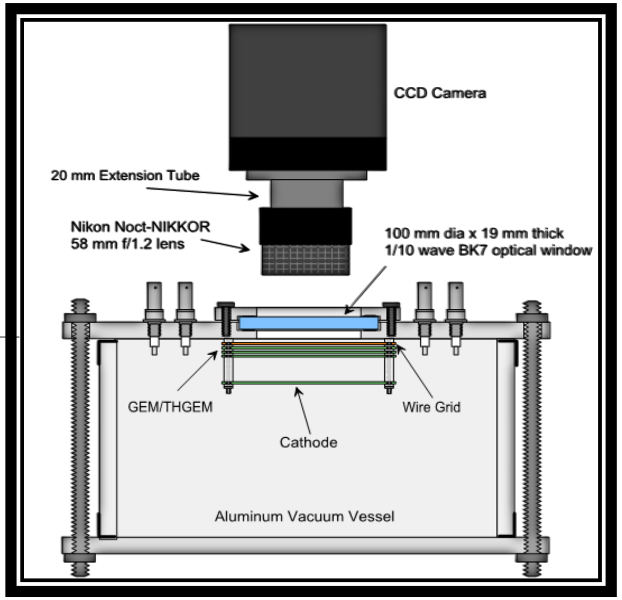


Gas Tests

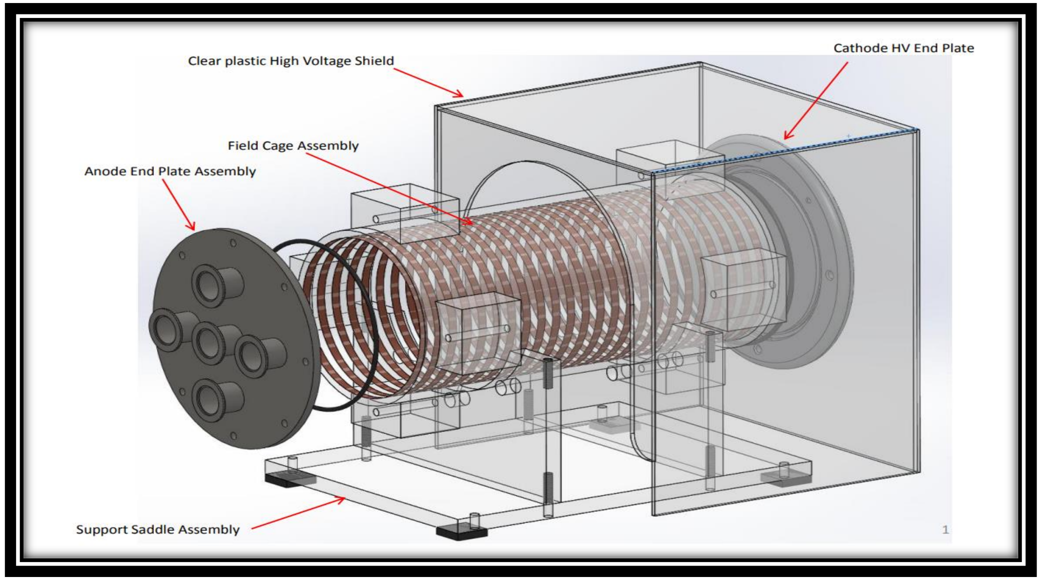
Optimize and characterize the drift properties of various gas mixtures for low-pressure operation

In parallel with developing the strip readout electronics, we intend to study several things about the gases that we'll be using inside of it.

1. What kind of Gas Gains can we achieve in the various gas mixtures?
2. Which gas mixtures can maximize our targets of interest (in this case, noble gases)?
3. Measure diffusion in 3D for NI drift
4. Measure drift velocity with NI drift



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



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

Tentative Timeline

Year 1:

- Design and fabricate the readout electronics for the 2D strip readouts
- Design and fabricate a small TPC, field-cage and vacuum vessel
- Optimize and characterize the drift properties of various gas mixtures for low-pressure operation

Year 2:

- Assemble the TPC with the strip readout and electronics
- Characterize the performance of the NID TPC for detection of the Migdal Effect

Year 3:

- Use in a Migdal Search

Scope Beyond Migdal Searches

Low-pressure gas NI charge readout TPCs with micropattern gas detectors (MPGDs) are ideal for low energy applications of all kinds, such as directional dark matter searches, X-ray polarimetry, rare nuclear decays, etc

Why?

1. Low pressure gases extend track lengths, making low energy particle tracks no longer diffusion limited
2. MPGDs allow high gas amplification with high spatial resolution
3. Charge readout TPCs do not require as high gas gains as in OPTCs to resolve low energy tracks
4. NI gases, with their lower diffusion and slower drift speeds, enhance spatial and temporal resolution leading to ideal reconstruction in all 3 dimensions

Summary

- Charge readout NI low-pressure TPCs show great promise in being able to resolve the full track topology of Migdal events
- To this end, our group intends to design, build and characterize a charge readout NI low-pressure TPC for the purpose of directly observing and characterizing the Migdal effect

Acknowledgements

Dr. Dinesh Loomba (UNM)
Alexandre Mills (UNM)
Steve Elliot (LANL)

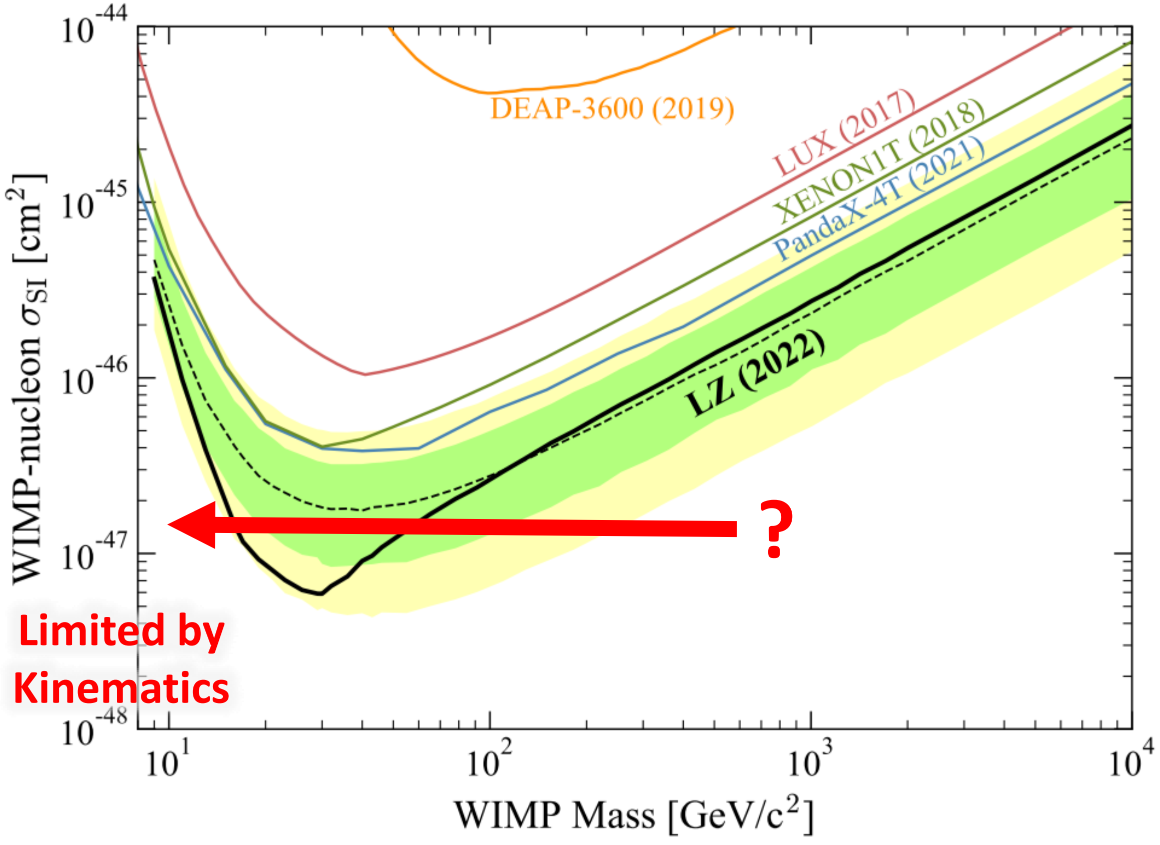
Fermilab/DOE
GIRA Award
Awarded to E.Tilly

MIGDAL

Backup Slides

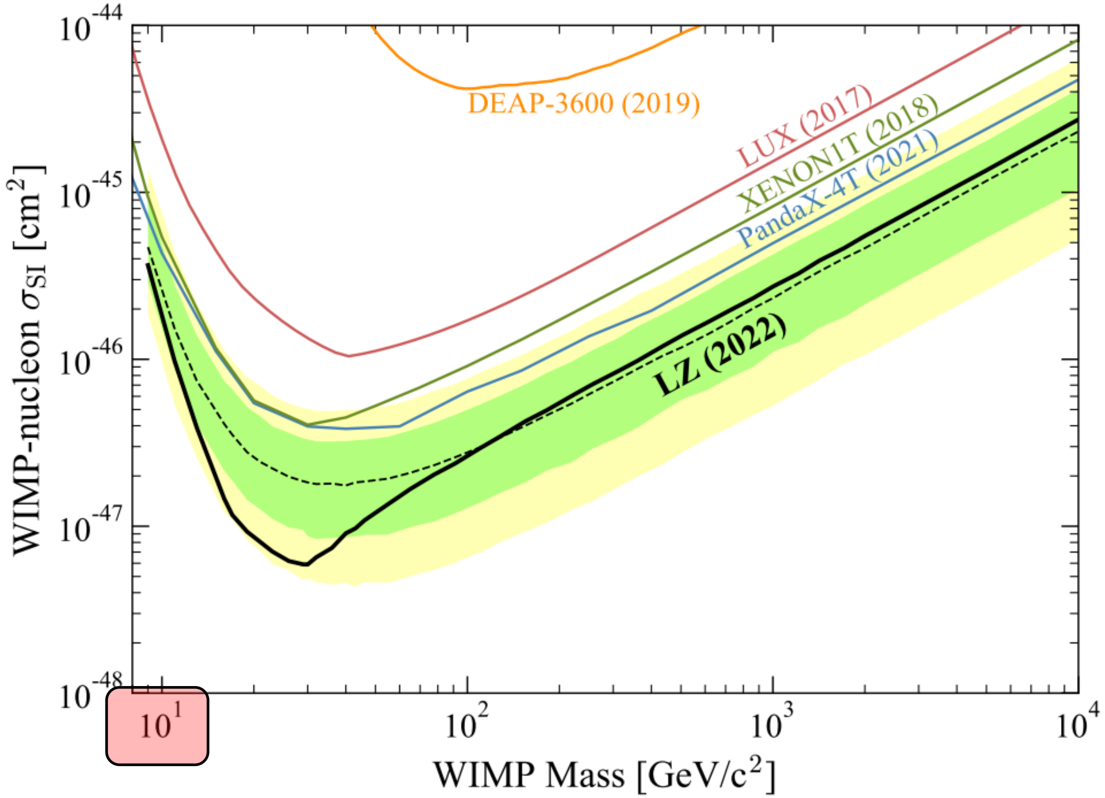
Searching for Dark Matter (DM)

- WIMP mass limits have been set down to ~ 10 GeV/c^2
- Low mass "wall" set by kinematic constraints
  - Most experiments look for energy from nuclear recoils in their detector from DM
- Many recent theories are very interested in the low-mass WIMP regime
- So, how do we probe this space?
  - New experiments with lighter elements
  - The Migdal Effect



https://arxiv.org/pdf/2207.03764.pdf

Extending Low Mass Limits



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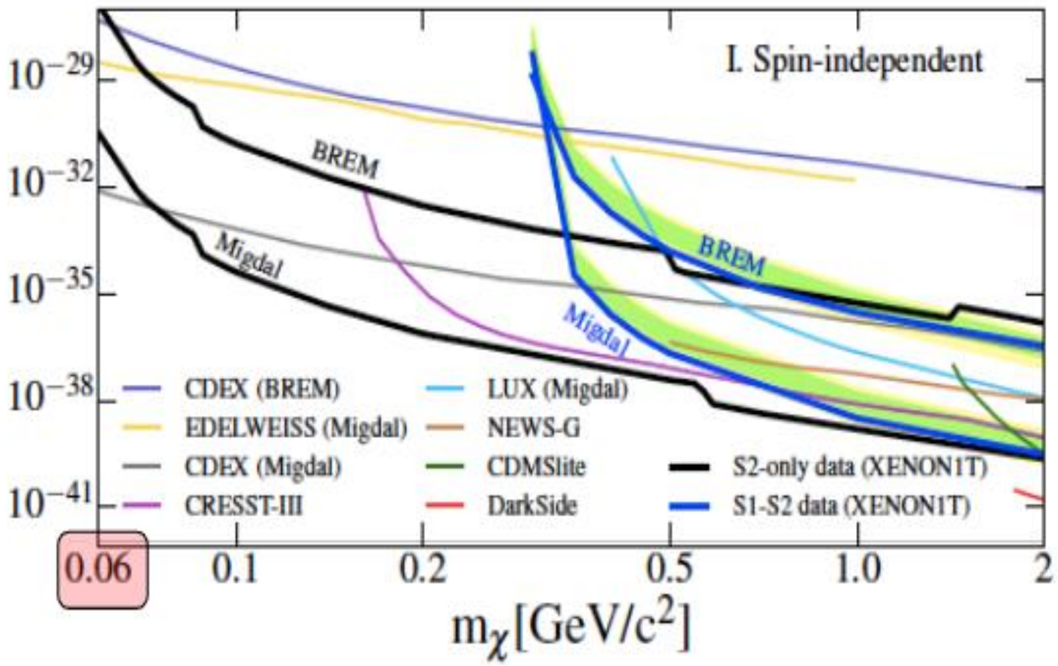
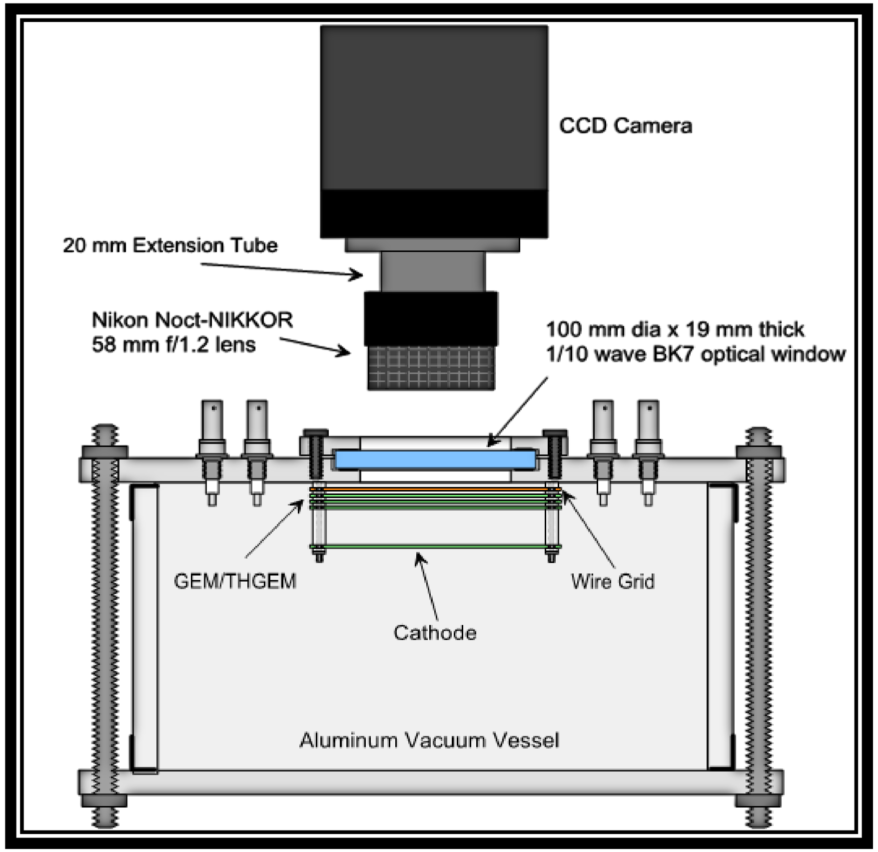


XENON1T collab arXiv:1907.12771

Gas Test Detectors



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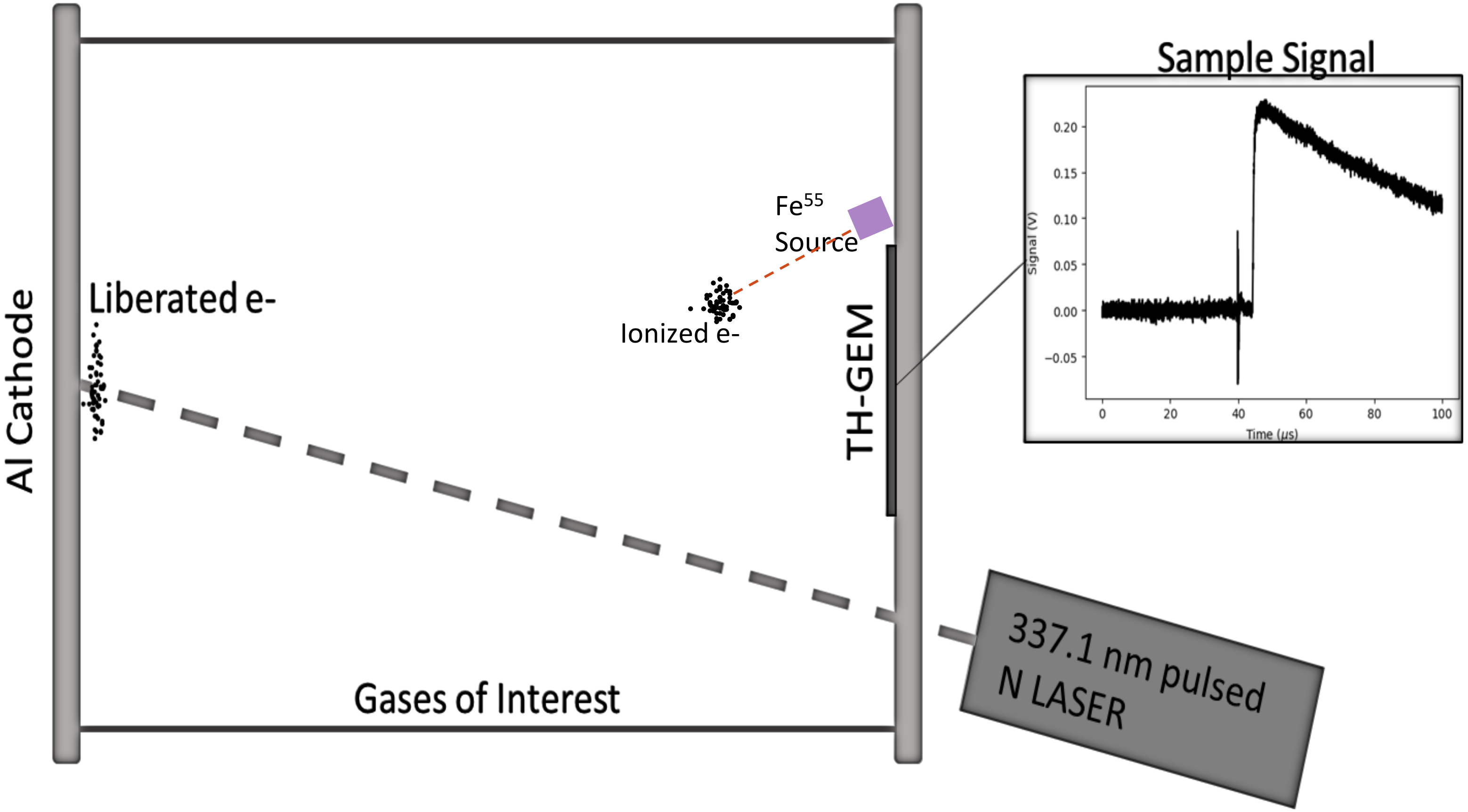
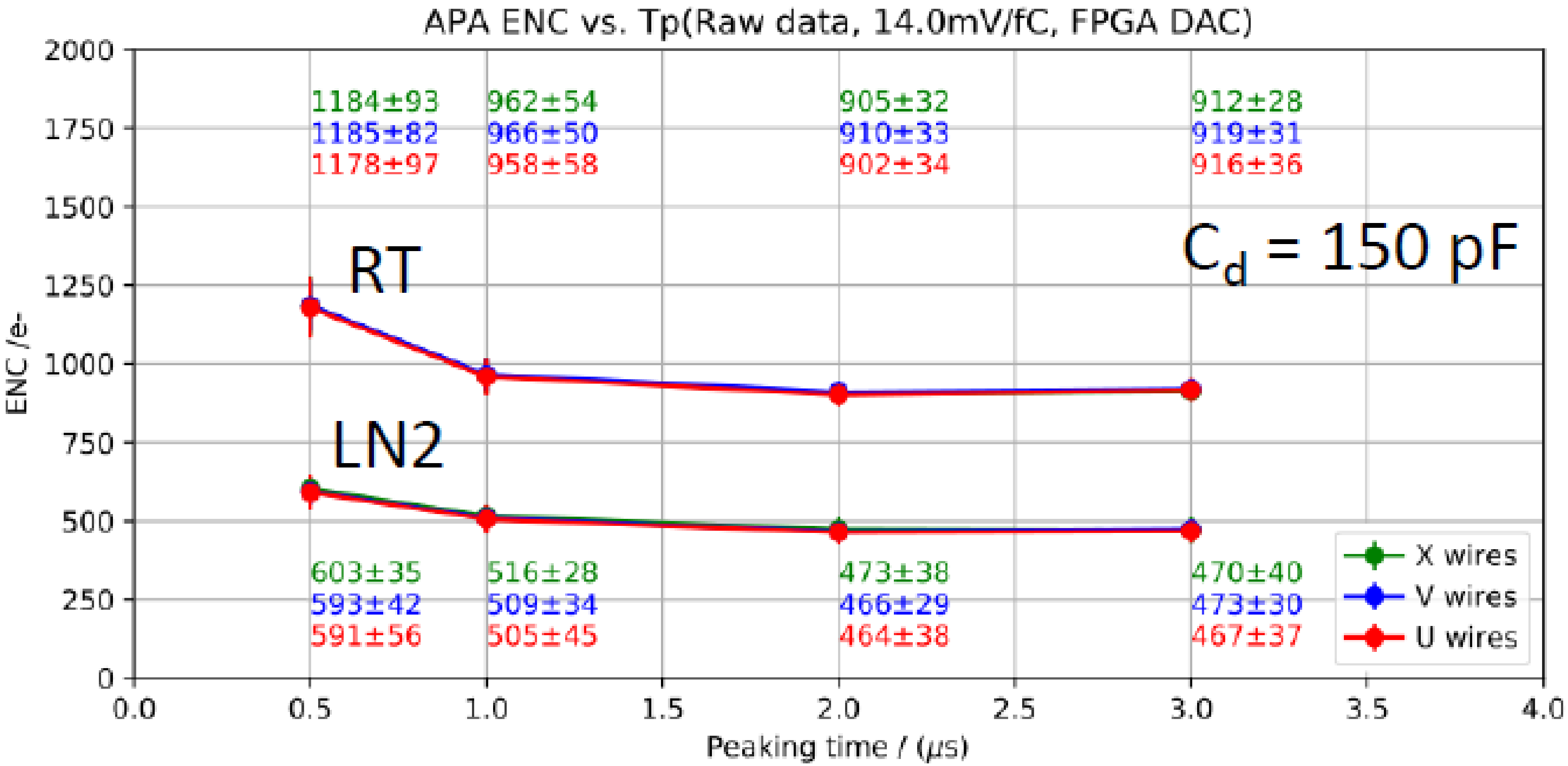


Expected Noise

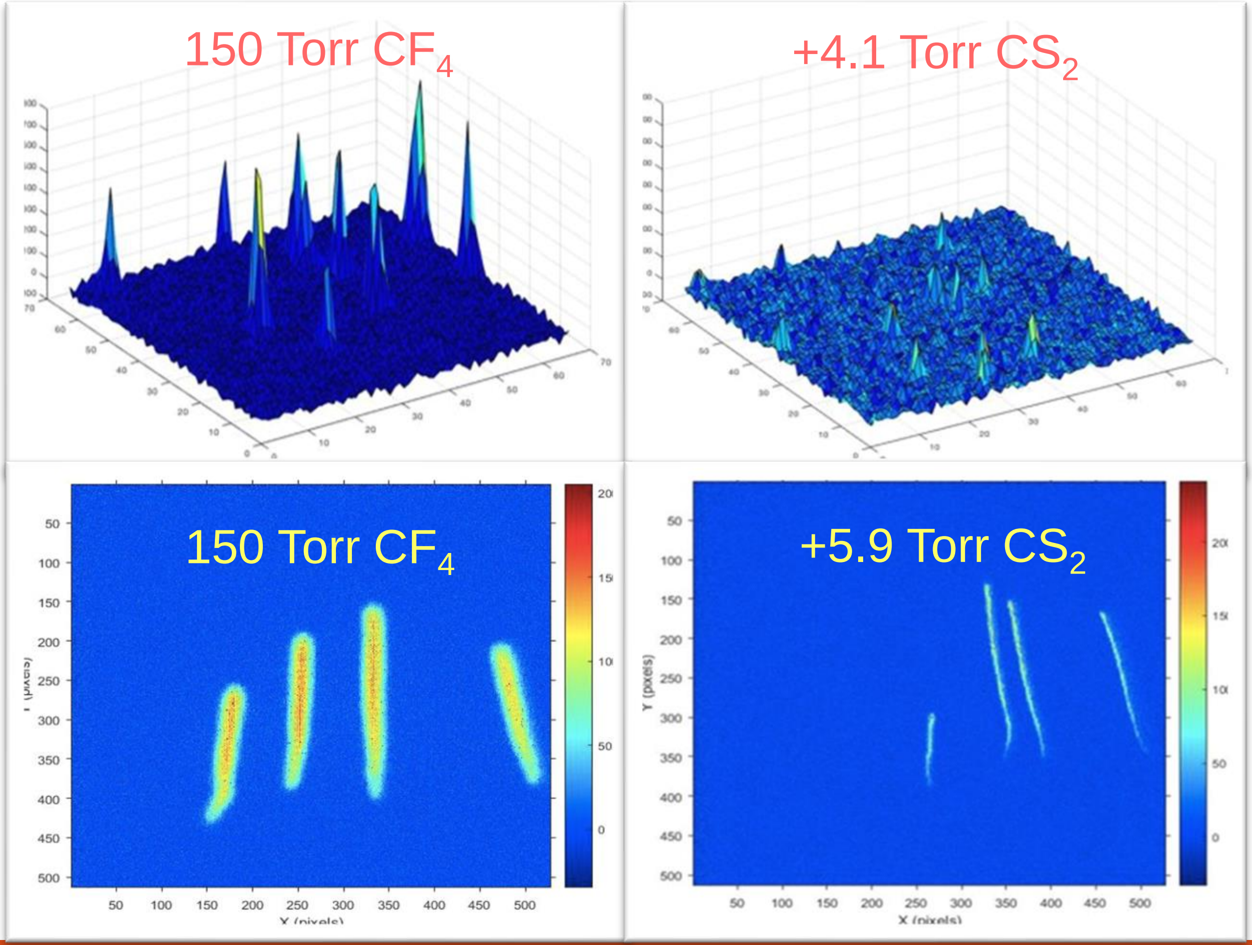


S. Gao - SBND CE R&D - DPF2019

Negative Ion Example

Loss in Light Yield:

Improved transverse diffusion:



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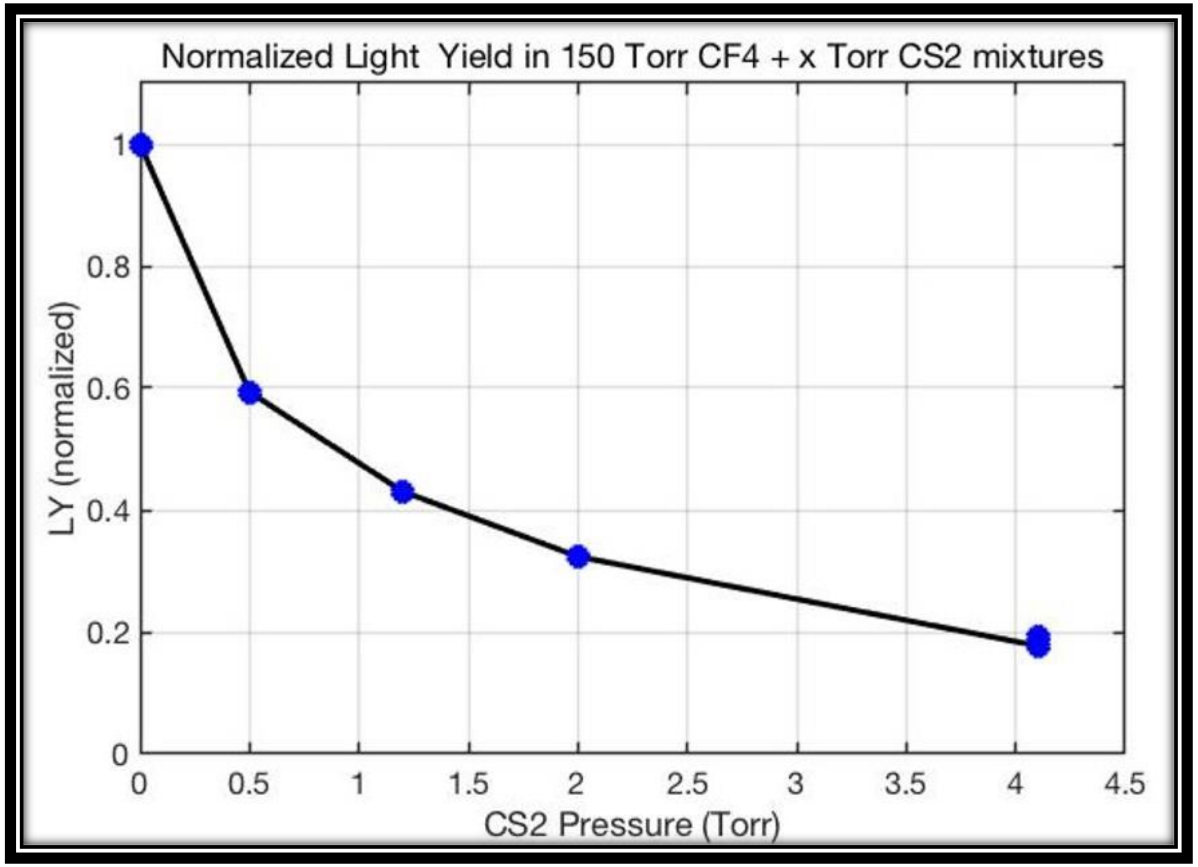
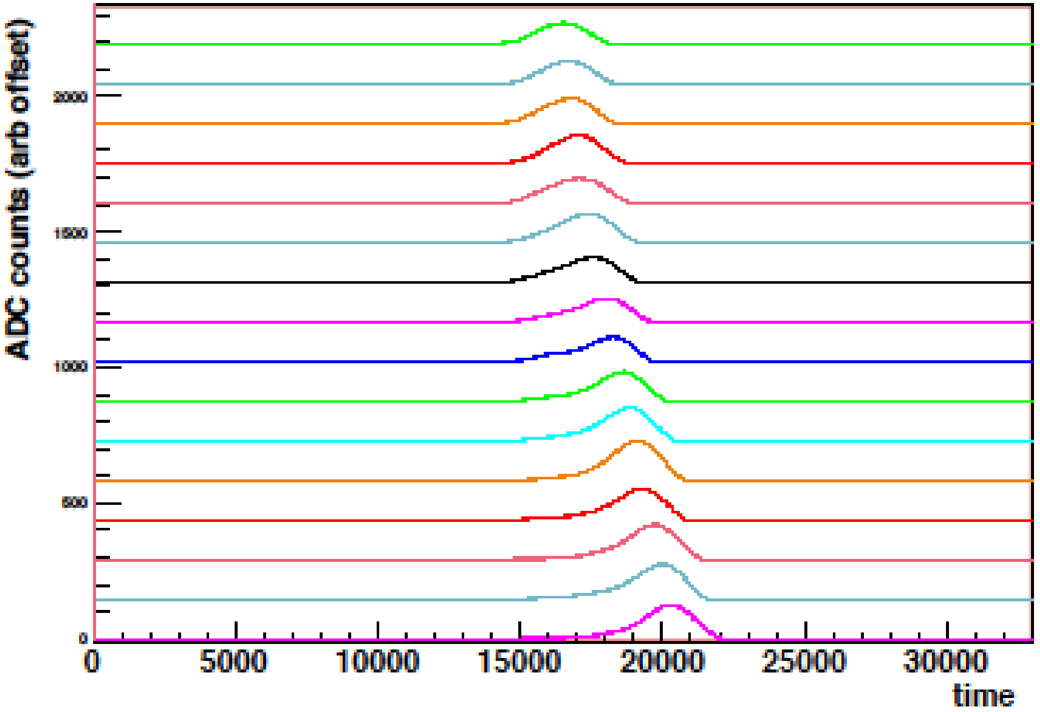
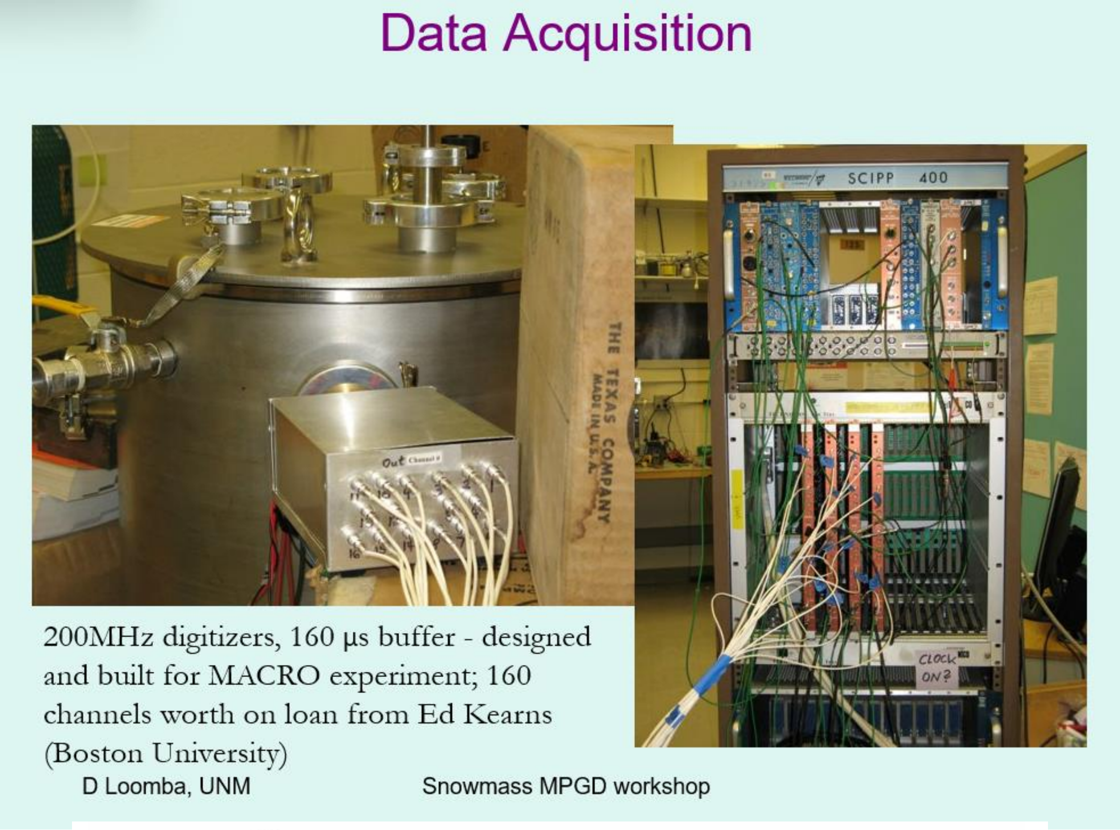
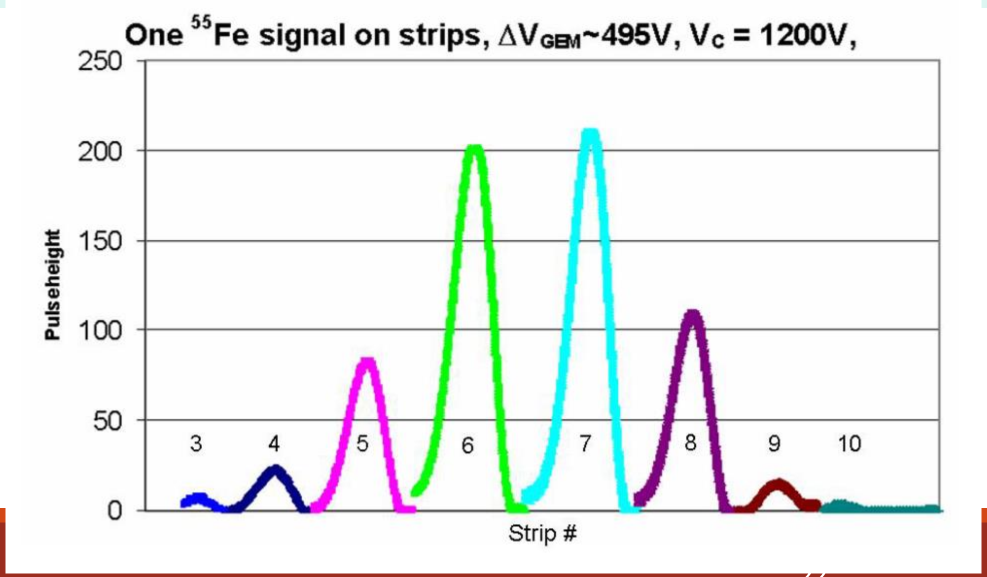


Christina’s Setup (old proof of concept)

A long nuclear recoil track from Cf-252 neutron





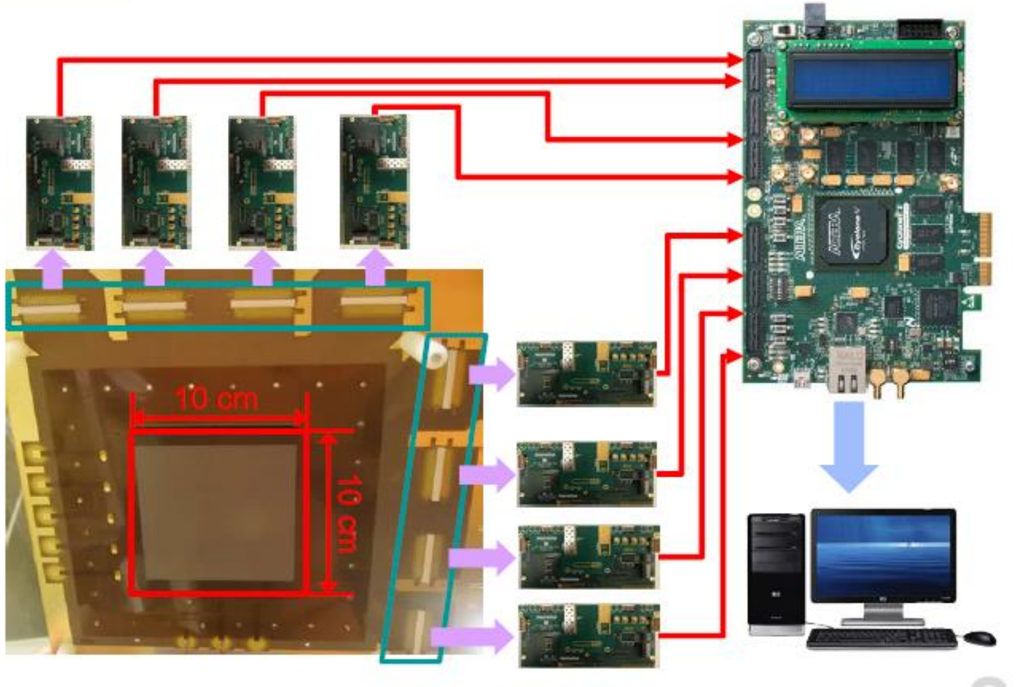


Very Similar Setup to What We Propose

An FPGA-based Data Acquisition System for Directional Dark Matter Detection 10/21/20

Hardware Configuration

- 1,000 channels, with 500 placed horizontally, 500 vertically;
- Strip pitch 200 μm;
- Divided into 8 groups with 125 channels in each group;
- 8 Front-end Board with Cyclone IV FPGA;
- 1 Back-end Board with Cyclone V FPGA;
- Back-end Board connect to PC via Ethernet Port.



Hardware Configuration
(Source: Catherine Nicoloff, Battat Lab, Wellesley College)

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Slide from: Yang, et. al., APS Meeting, Apr 2017

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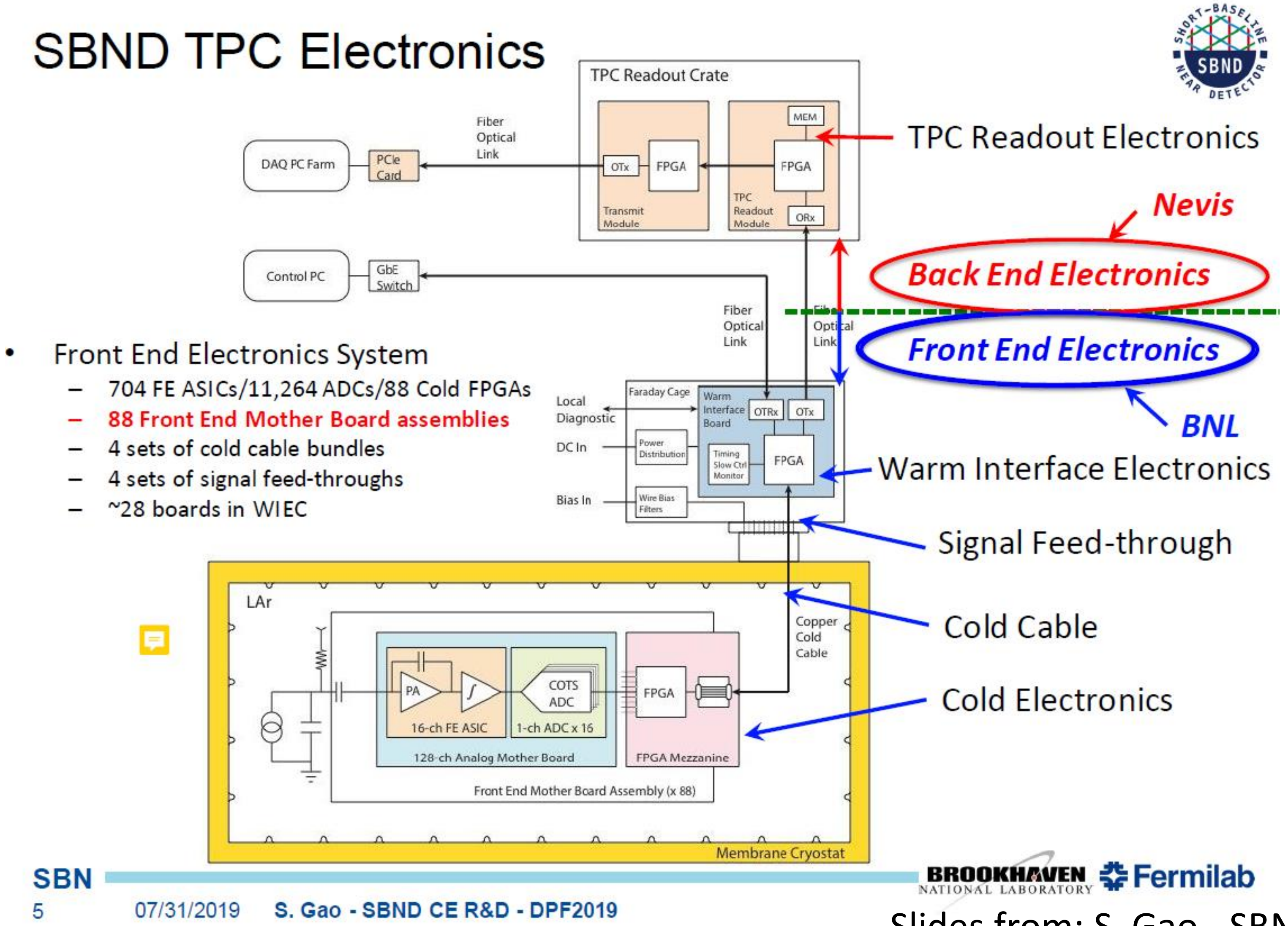

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