Low Mass WIMP Directional Detection

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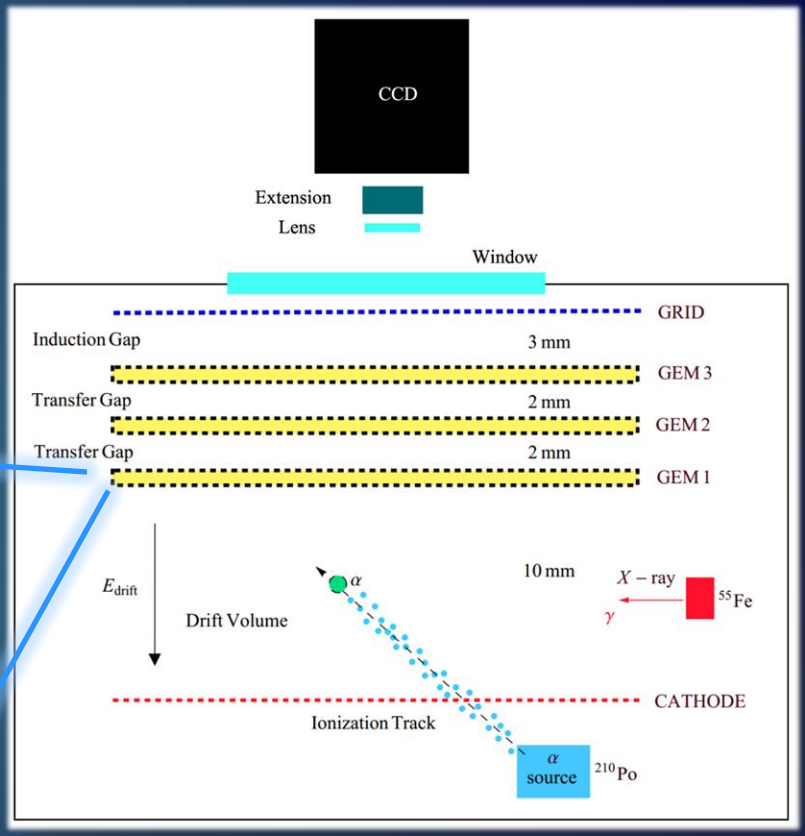
Motivation & Outline

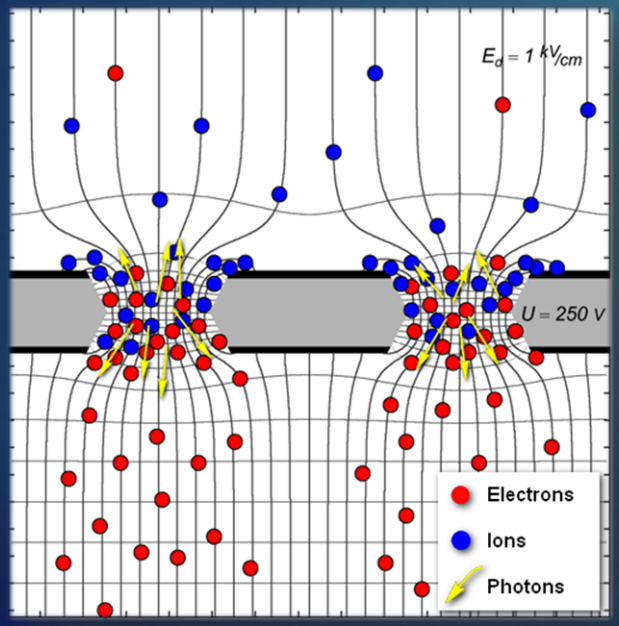
- Motivation: To study directionality in low energy nuclear recoils with a high resolution and high signal – to –noise detector (optimal, but realistic).
  - How low in energy does the directional signature exists?
  - How well can it be measured?

- Brief description of R&D detector (1 slide)
- 100 Torr CF_4 data
  - Discrimination an directional thresholds
  - Number of events needed to reject isotropy
- Extrapolation for low mass WIMPs
- Preliminary data at low pressure

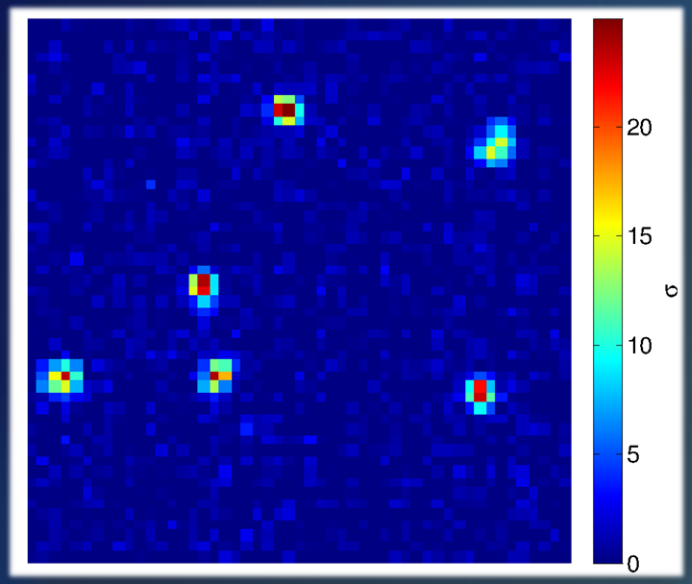
R&D Detector

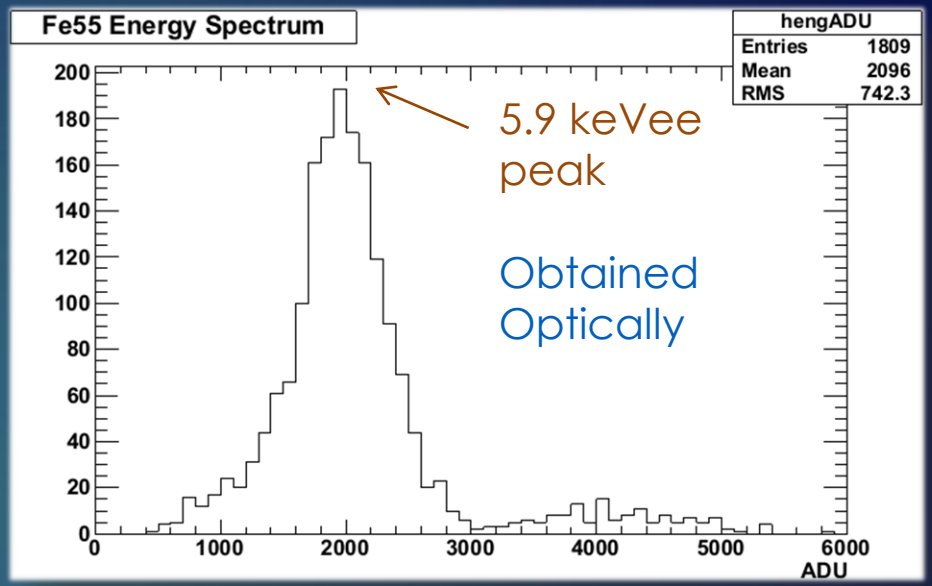
- Triple GEM (gas electron multiplier) low pressure TPC with optical readout.
  - Three 7 cm x 7 cm CERN GEMs (140 μm pitch, 50-70 μm hole dia., ~ 50 μm thick)
  - FLI Back-illuminated CCD (13 μm pix., 1024 x 1024) + 58 mm F 1.2 Nikon lens.
  - 1 cm conversion gap, 3 cm x 3 cm imaging area.
  - 100 Torr CF_4 gas.



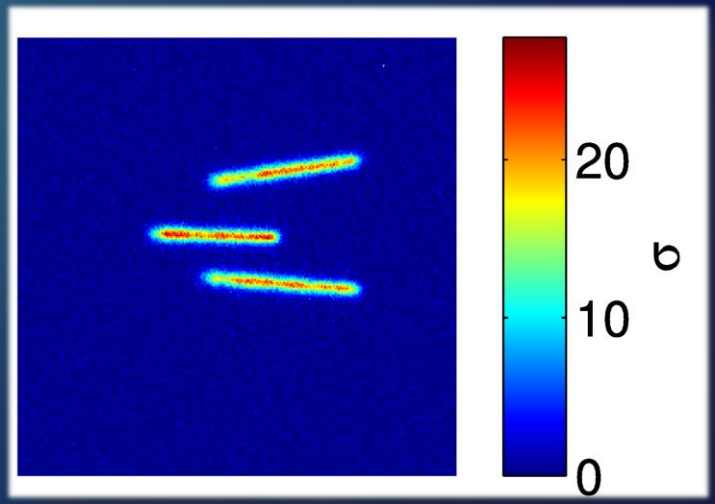


^{55}Fe and ^{210}Po Calibrations



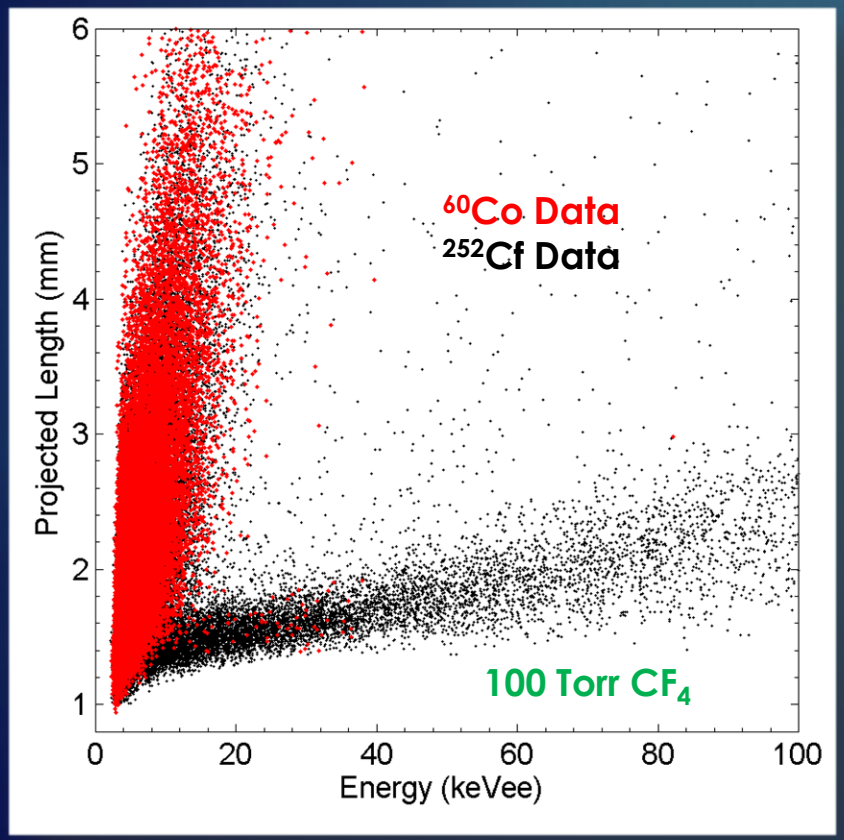


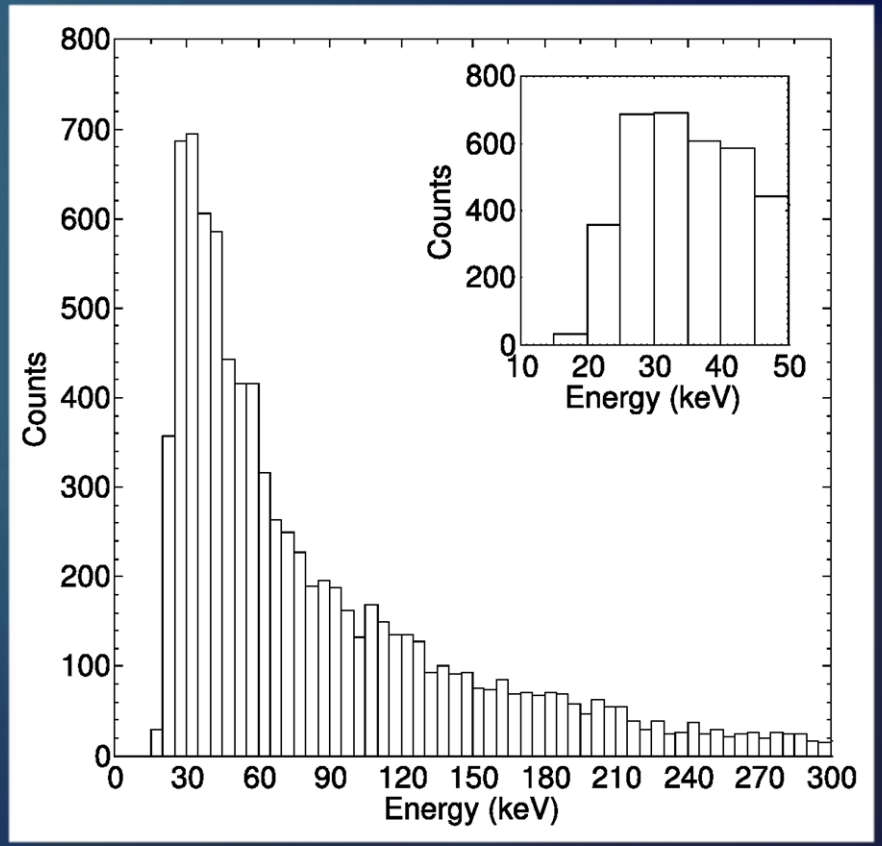
- ^{55}Fe energy spectrum (obtained optically via CCD) and image of tracks at 16x16 pixel binning .
- Alpha track segments (right) at 6x6 binning and max stable gain (~ 10^5).
  - Excellent signal-to-noise (SNR), Peak SNR > $25\sigma_{im}$
- Energy Resolution: 35 % (FWHM) at 5.9 keVee.
- Diffusion: σ ~ 350 μm, mostly from GEM stages.



^{252}Cf and ^{60}Co Data

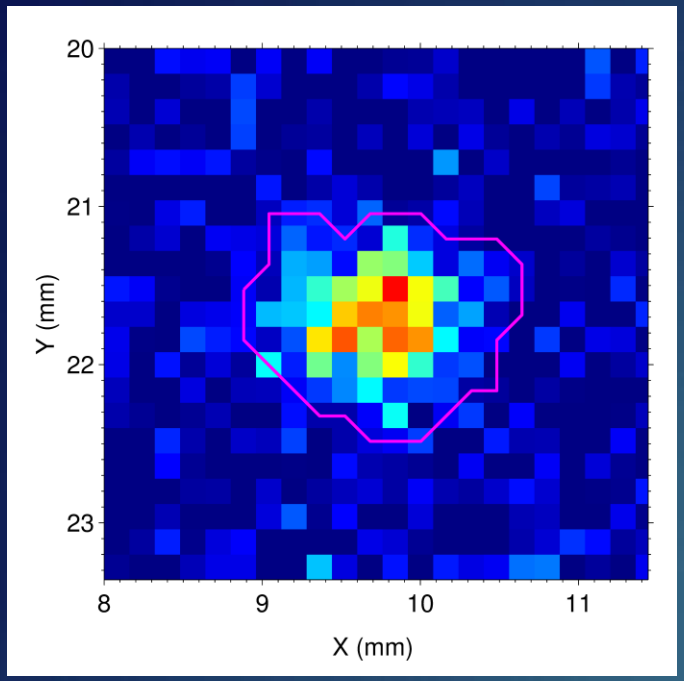
- Discrimination down to ~ 10 keVee (~ 25 keV). Recoil energy assumes fluorine and Hitachi quenching factors (Hitachi, Rad. Phys. & Chem. 77 (2008)).
- Electronic recoils have small dE/dx but large fluctuations → low S/N could lead to confusion with nuclear recoils.



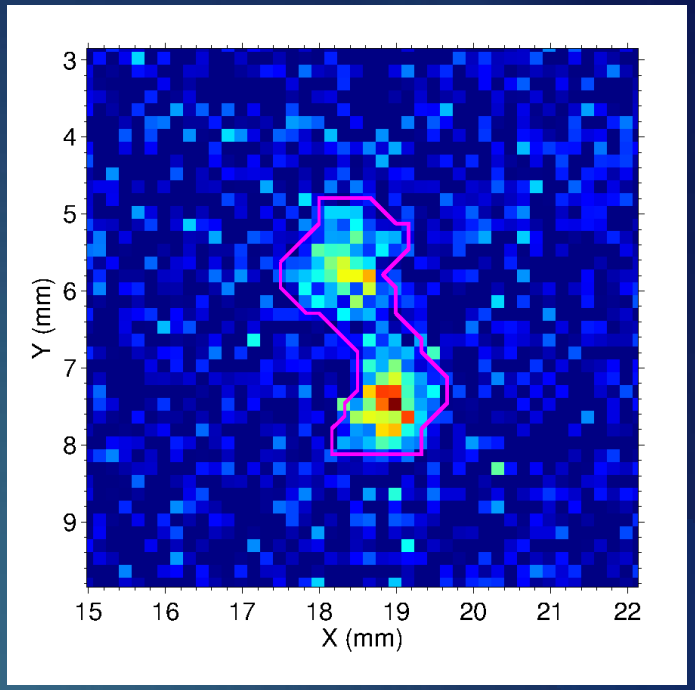


Electronic Recoils

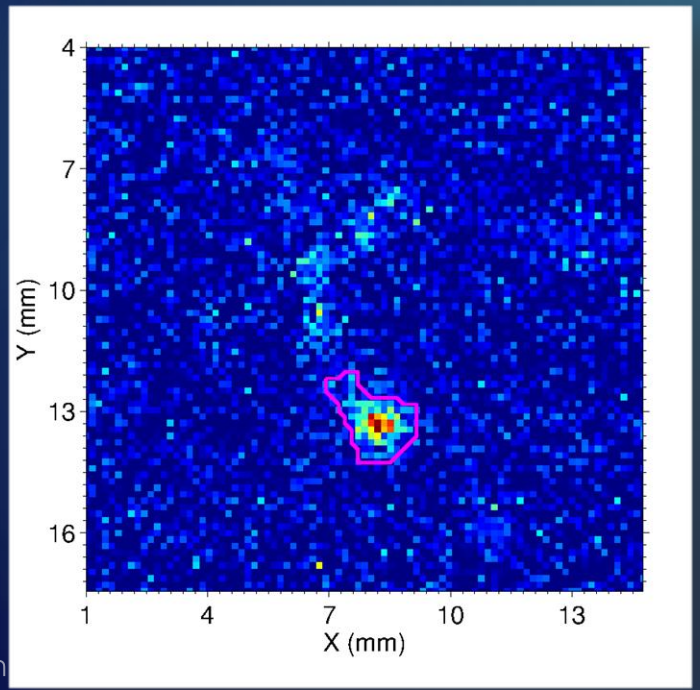
9 keV



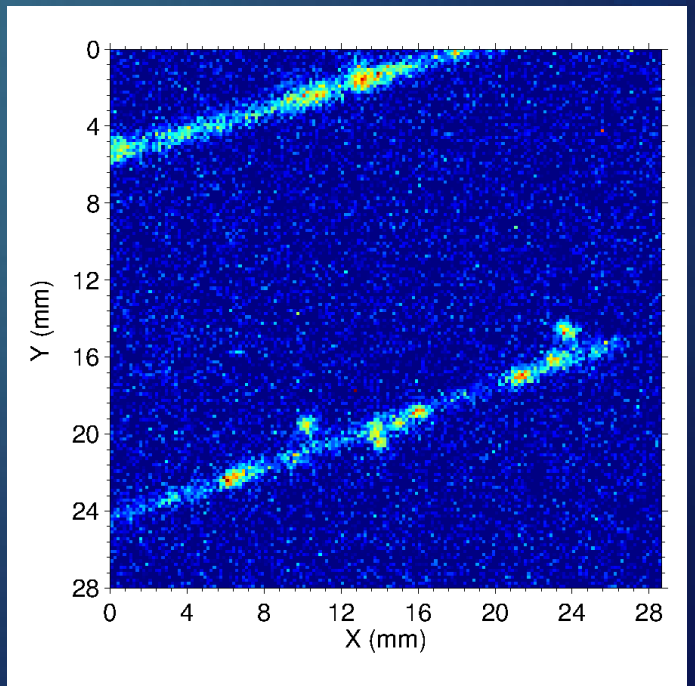
13 keV



> 13 keV

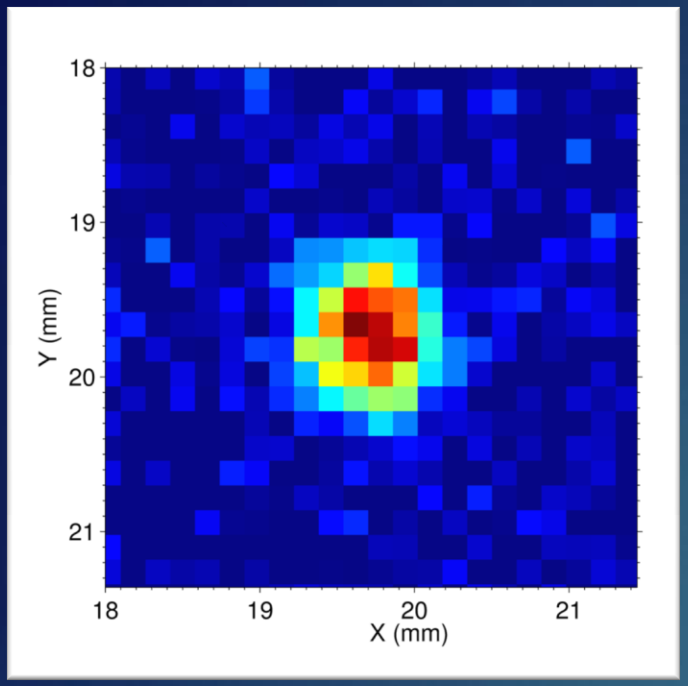


> 30 keV

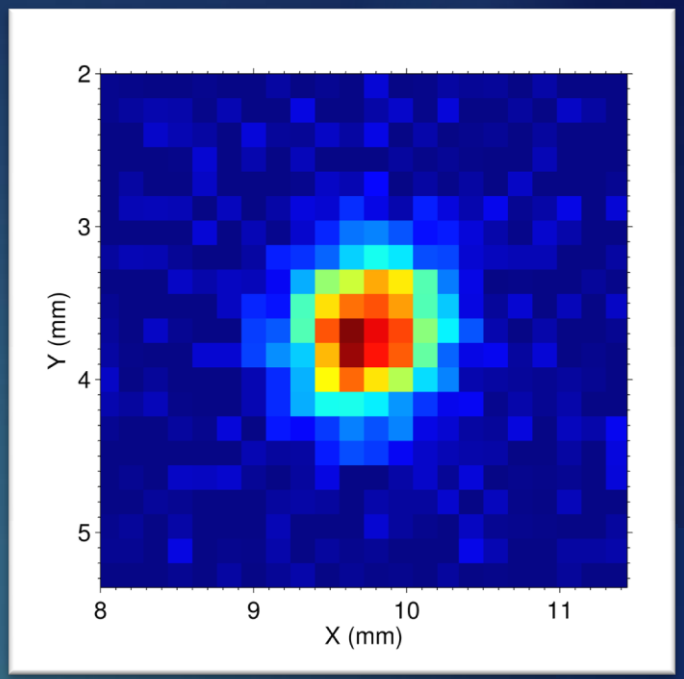


Nuclear Recoils

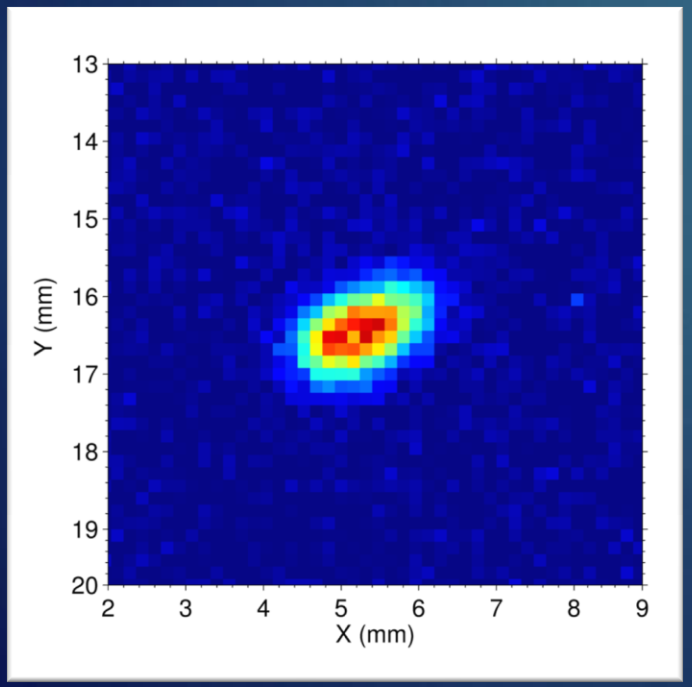
28 keV



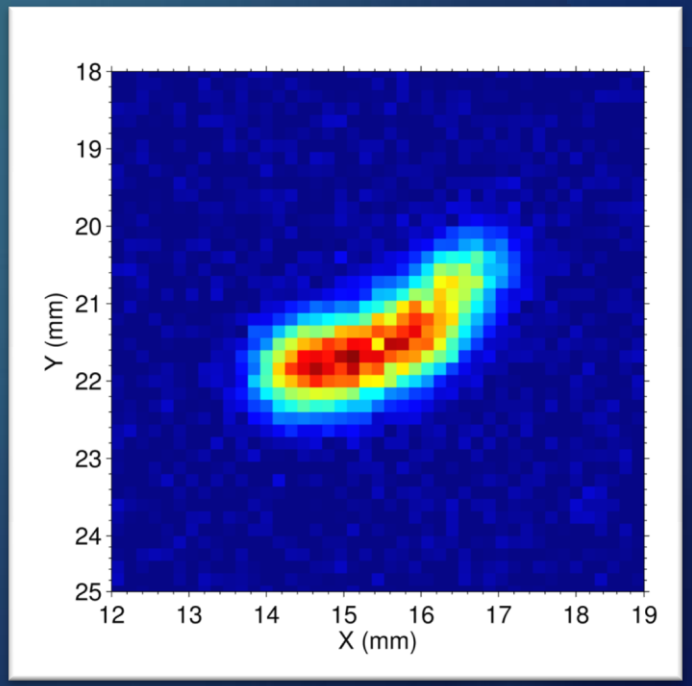
53 keV



104 keV



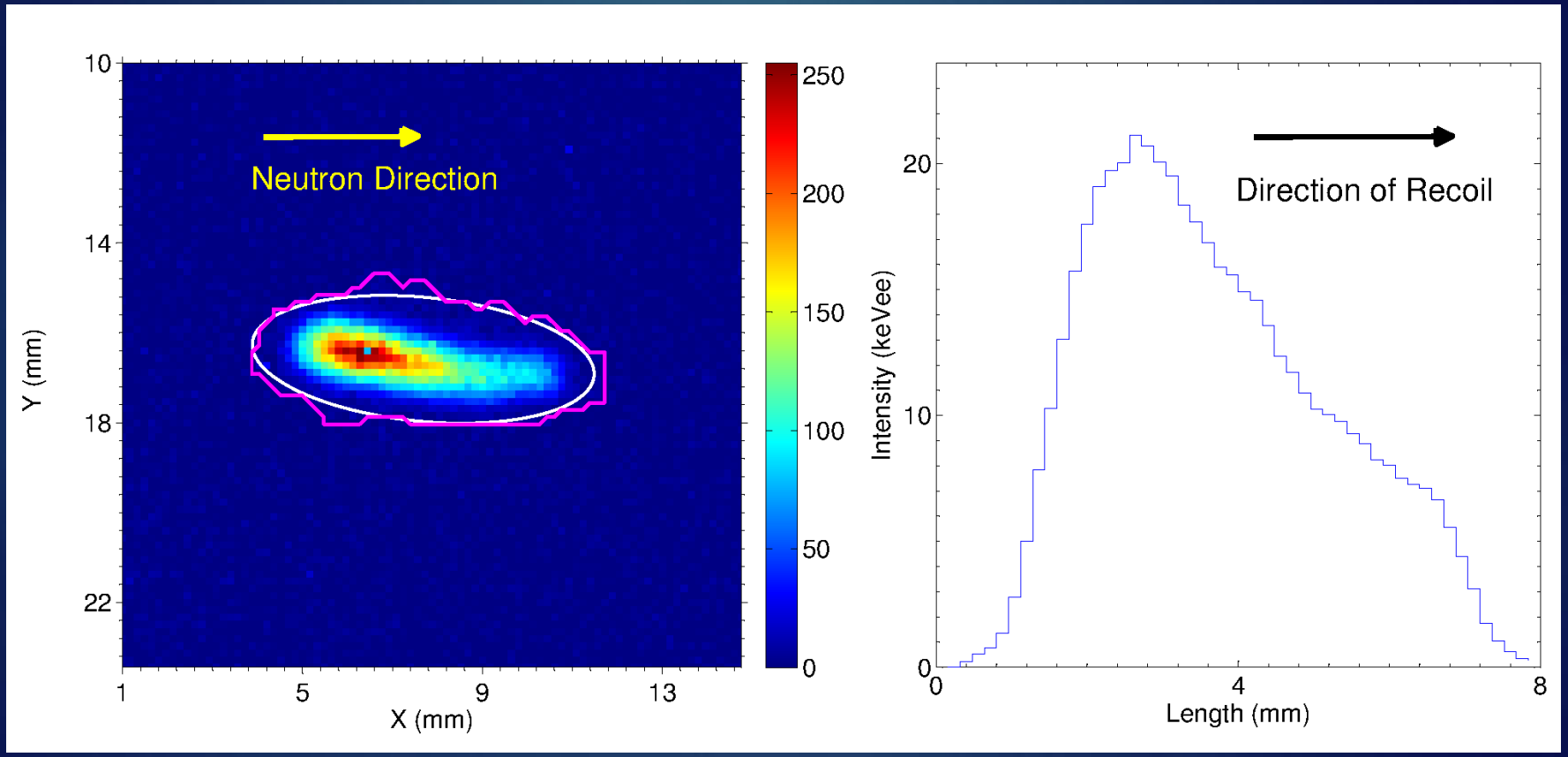
214 keV



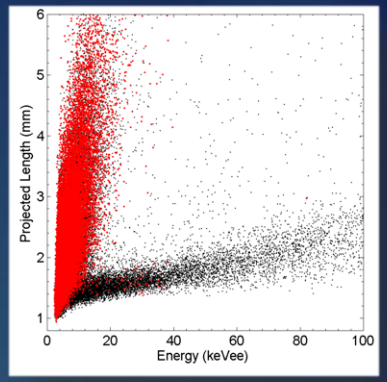
Directionality

$$\text{Skew: } S = \frac{\mu_3}{\mu_2^{3/2}}$$

$$\text{Orientation Angle: } \alpha$$

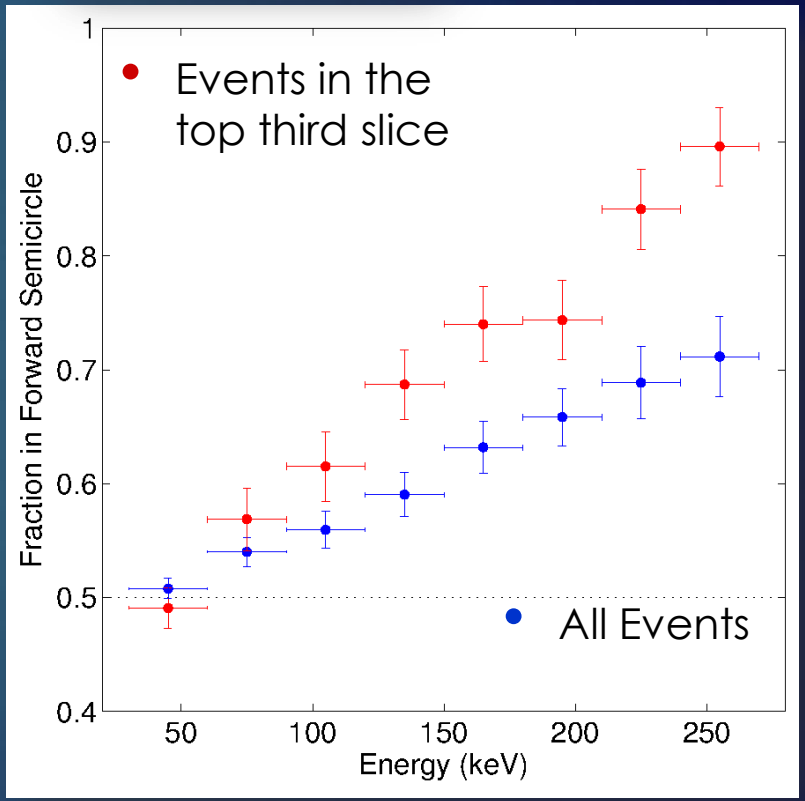


Head-Tail (Sense)



- Head-tail sensitivity down to 60 keV.
- Multiple scatterers not taken into account.

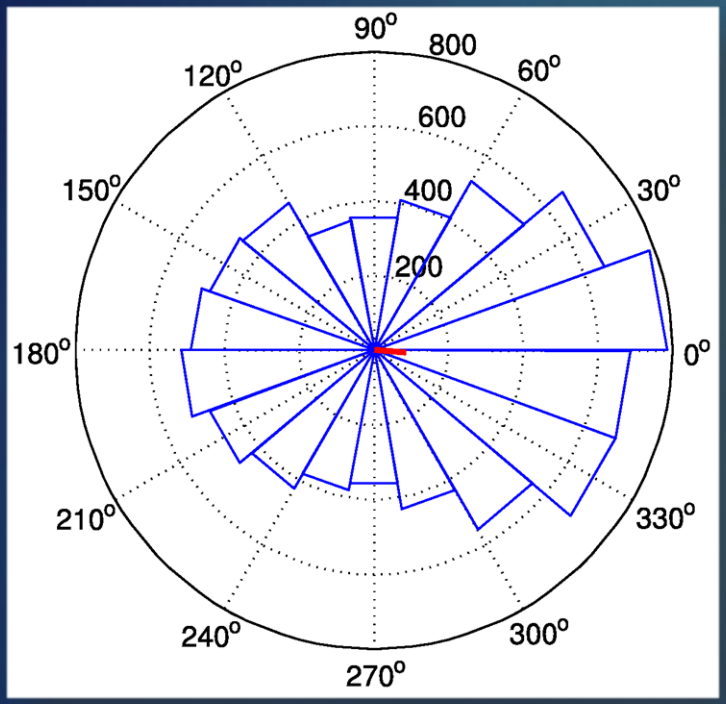
- How do we improve it?
  - Straggling –- Target choice. Less straggling for lighter targets (e.g. He) vs. heavier ones (e.g. F).
  - Projection Effect --- 2D vs. 3D
  - Pressure --- Lower pressure to increase track lengths.
  - Resolution/Diffusion



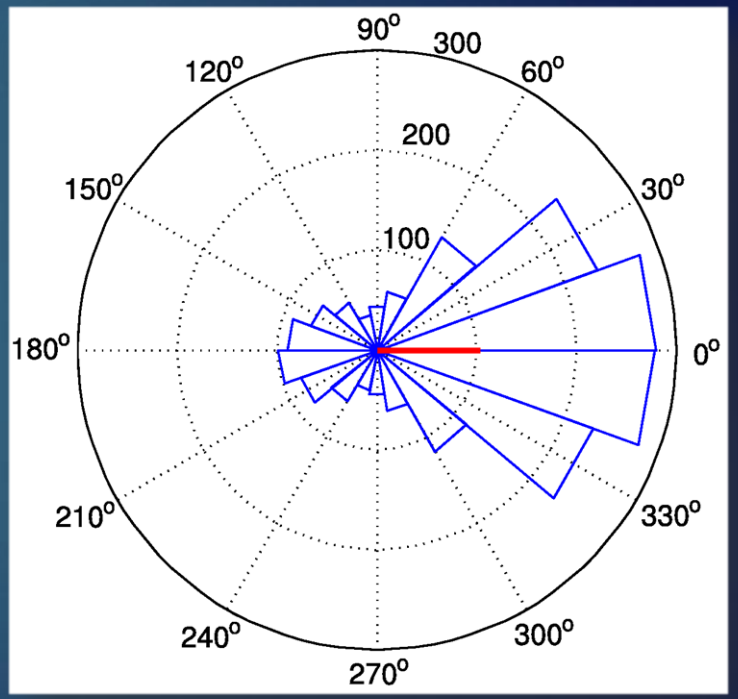
The fraction of nuclear recoil events in the forward half-circle from the ^{252}Cf data run.

- Combine orientation angle with skew to create vectors.
- For minor/major axis length ratio AR~1, directionality, as determined in this way, is lost. But correct head-tail may still exist in the diffused blob, but other algorithms should be used to quantify it.

Left: Circular histogram of all nuclear recoils (E > 25 keV).



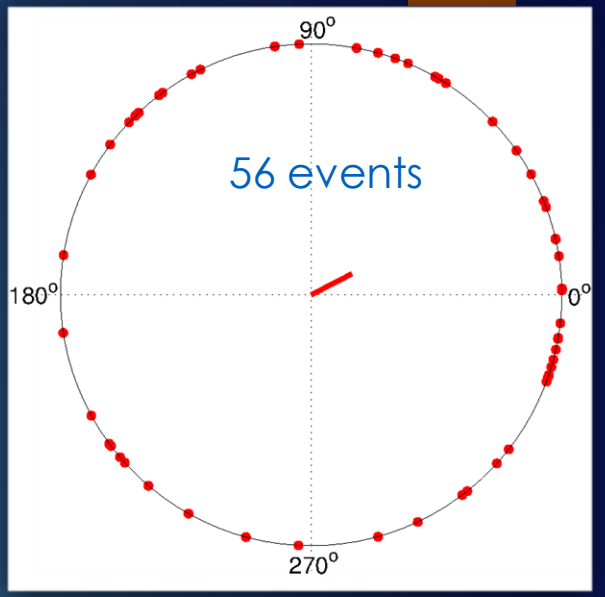
Right: Circular histogram of nuclear recoils with axis ratio (minor axis/major axis) <= 0.7

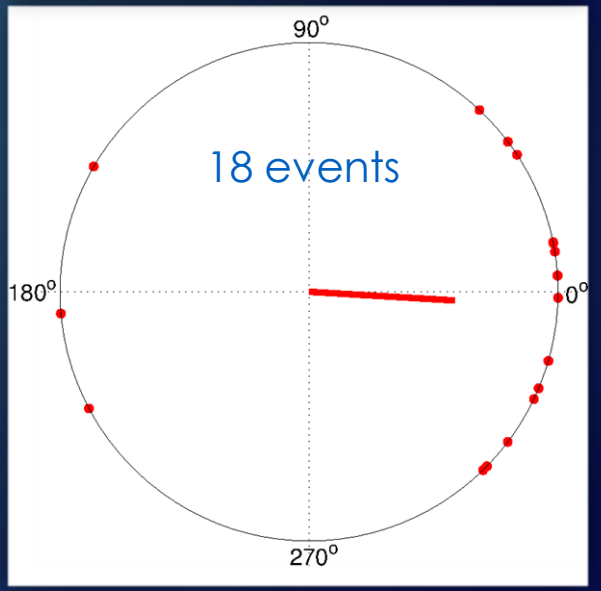


- ❖ Red line segment represents the magnitude and direction of the mean resultant vector.
- ❖ Antipodal peak due to incorrect assignment of head-tail and multiple scatterers.

^{252}Cf Isotropy Rejection

- 101 events to rule out isotropy at 90 % C.L. with 60 keV threshold (Modified Rayleigh Test).
- Weighting the events reduces number to 56. ~ 2x reduction.
  - **Axis Ratio Cut:**
    - Making cut on the axis ratio (0.7) reduces the number to 18.
    - But 41 events above 60 keV were needed to get quality 18 events.
  - **Slice Cut:**
    - Divide R2 vs energy recoil band into slices and only select events in the top slices → reduces the number to 20.
    - But 45 events above 60 keV were needed to get quality 20 events.

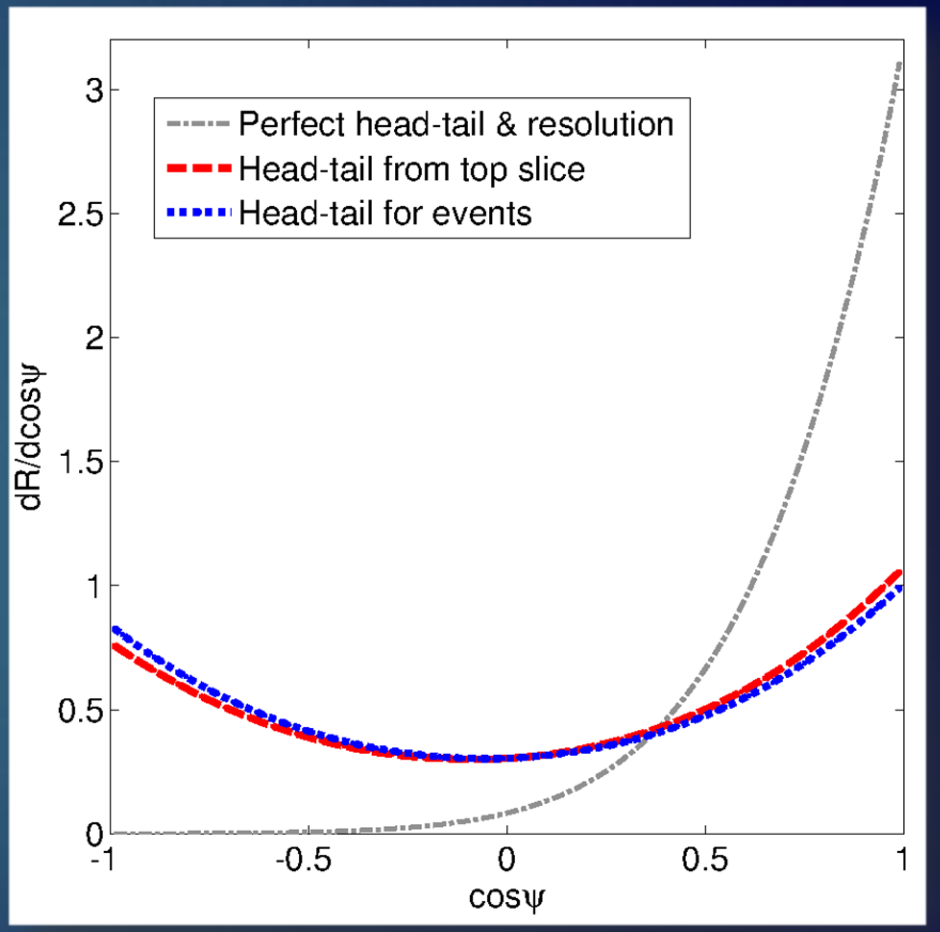




$^{252}Cf \rightarrow$ WIMPs

WIMP Angular Spectrum

- Consider 100 GeV WIMP with a 60 keV threshold in standard halo model.
  - Use measured angular resolution and head-tail percentage from 252Cf data to simulate angular distribution seen in a 3D detector.
- Intrinsic Asymmetry in WIMP induced recoil directions (no detection uncertainties):
  - 98/2 % --- Forward/Backward
- Asymmetry with detector uncertainties (measured angular resolution & head-tail):
  - 56/44 % --- Forward/Backward (top)
  - 54/46 % --- Forward/Backward (all)
- Simulated data is essentially axial because of small head-tail effect.



Normalized angular spectra for a100 GeV WIMP on fluorine target with E = 60 keV for three different cases.

WIMP Isotropy Rejection

- Table: The number of events and exposure needed to reject isotropy at 90% C.L. for a fluorine target with a 60 keV threshold.
- High level head-tail is required to provide significant improvement over axial data.
- Vector directional tests (e.g. Rayleigh, Cosine) are not suitable because data are ~ axial.
  - > 1000 events .

	Axial Cosine	Likelihood Ratio	Vector Cosine (Perfect Detector)	Exposure
100 GeV	54	46	~ 5	70 kg-yr*(10^{-42} cm^2/σ_{xp})

Exposure is for fluorine target and 46 events (spin-independent).

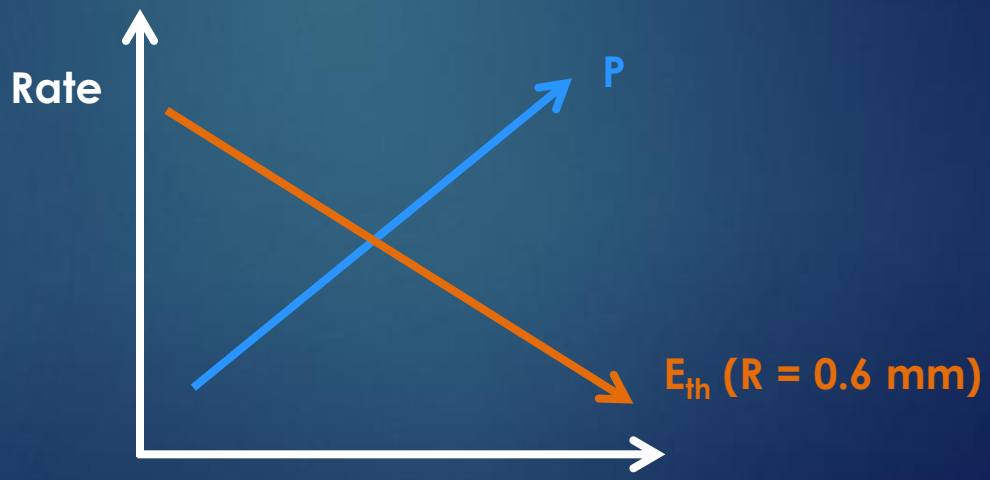
See papers by A. Green & B. Morgan, J. Billard

Extrapolation for Low Mass WIMPs

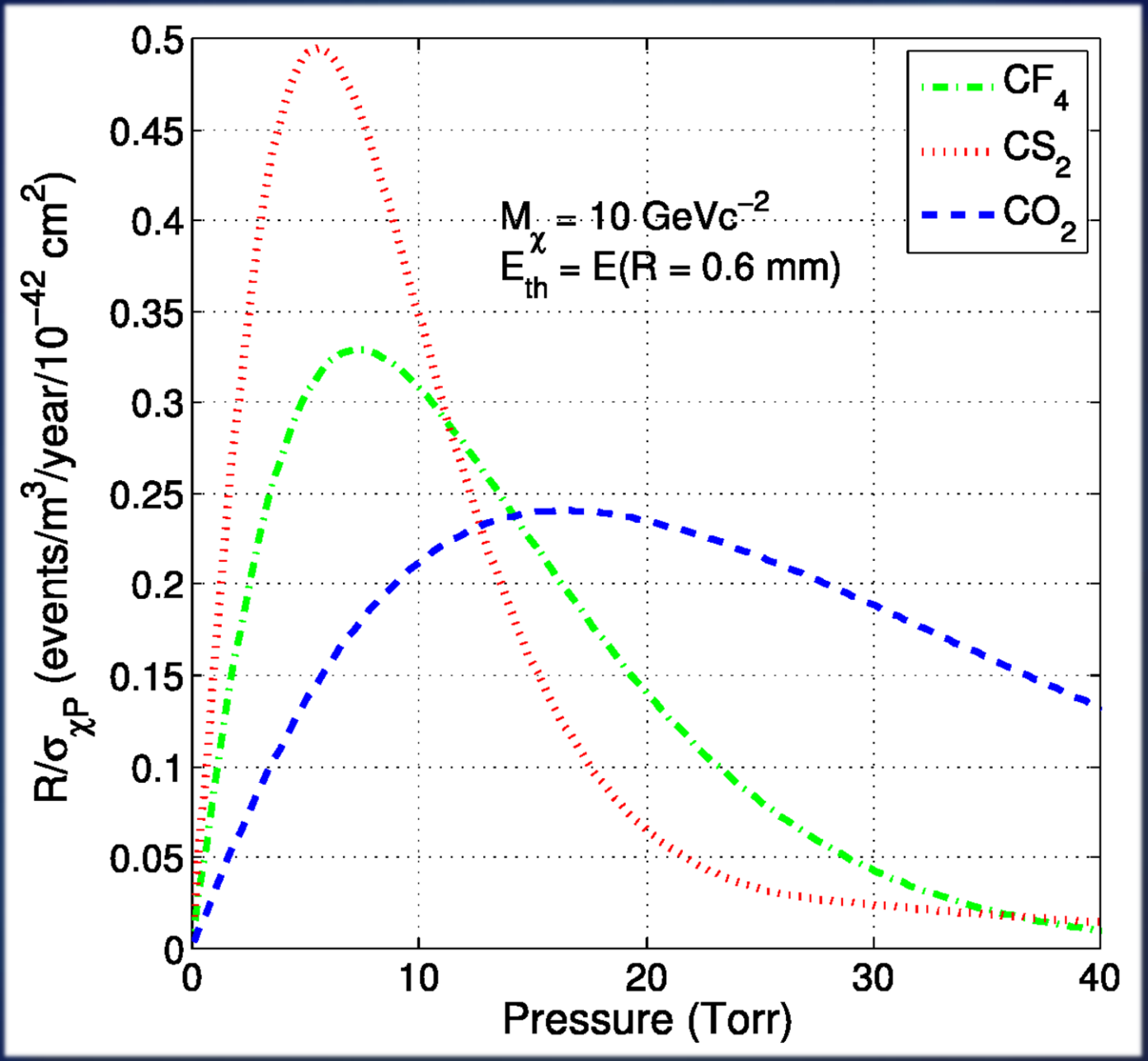
- We use the results from this work to make a case study for directional low mass WIMP searches.
- The experimental parameters critical to our results in 100 Torr CF4 are:
  - 1. high S/N
  - 2. Low diffusion (~0.35 mm)
  - 3. High spatial resolution
- These enabled discrimination down to 25 keV and directionality at ~60 keV. *In 100 Torr CF4 the latter corresponds to F tracks with R~0.6mm.*

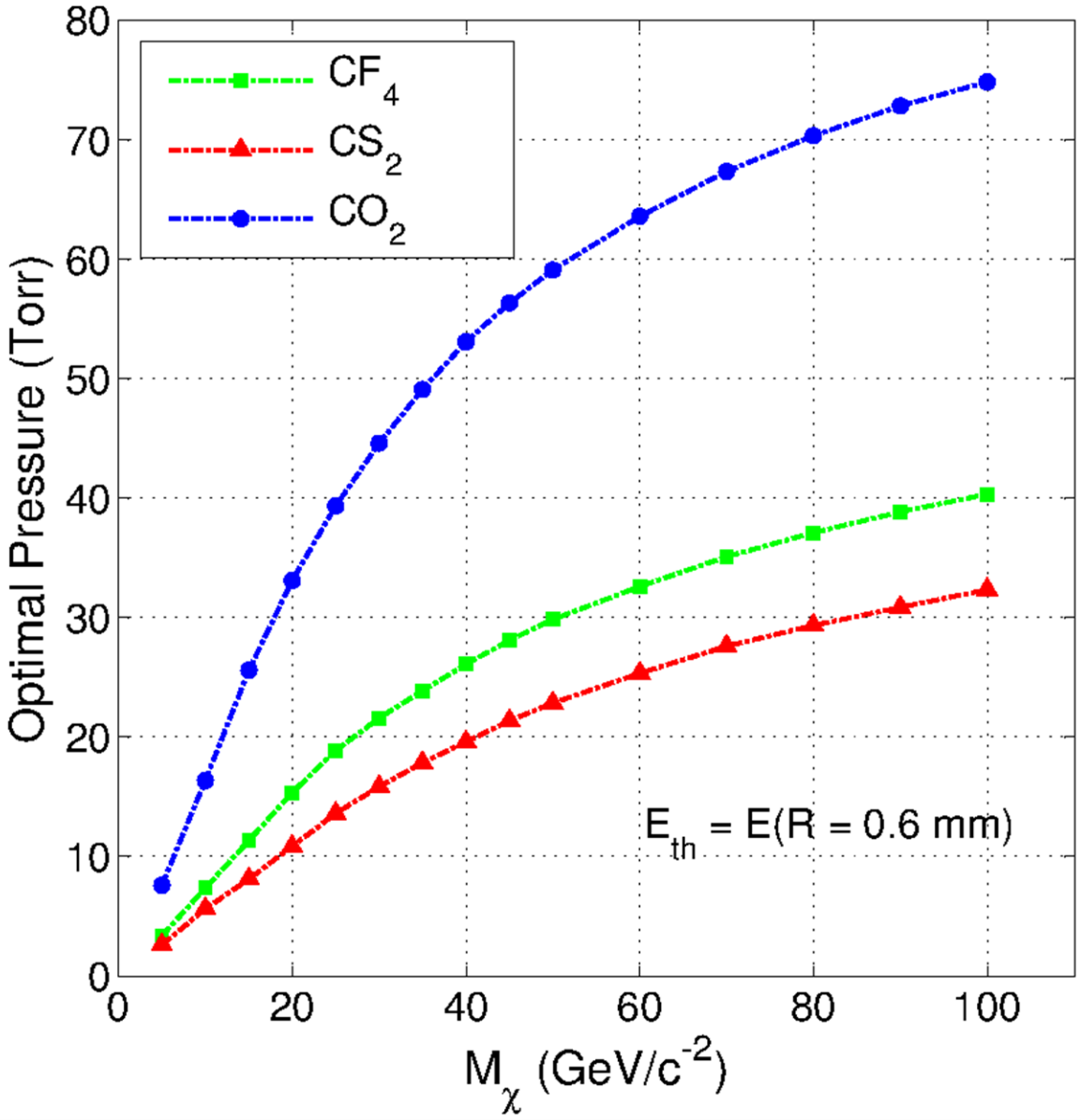
Extrapolation for Low Mass WIMP

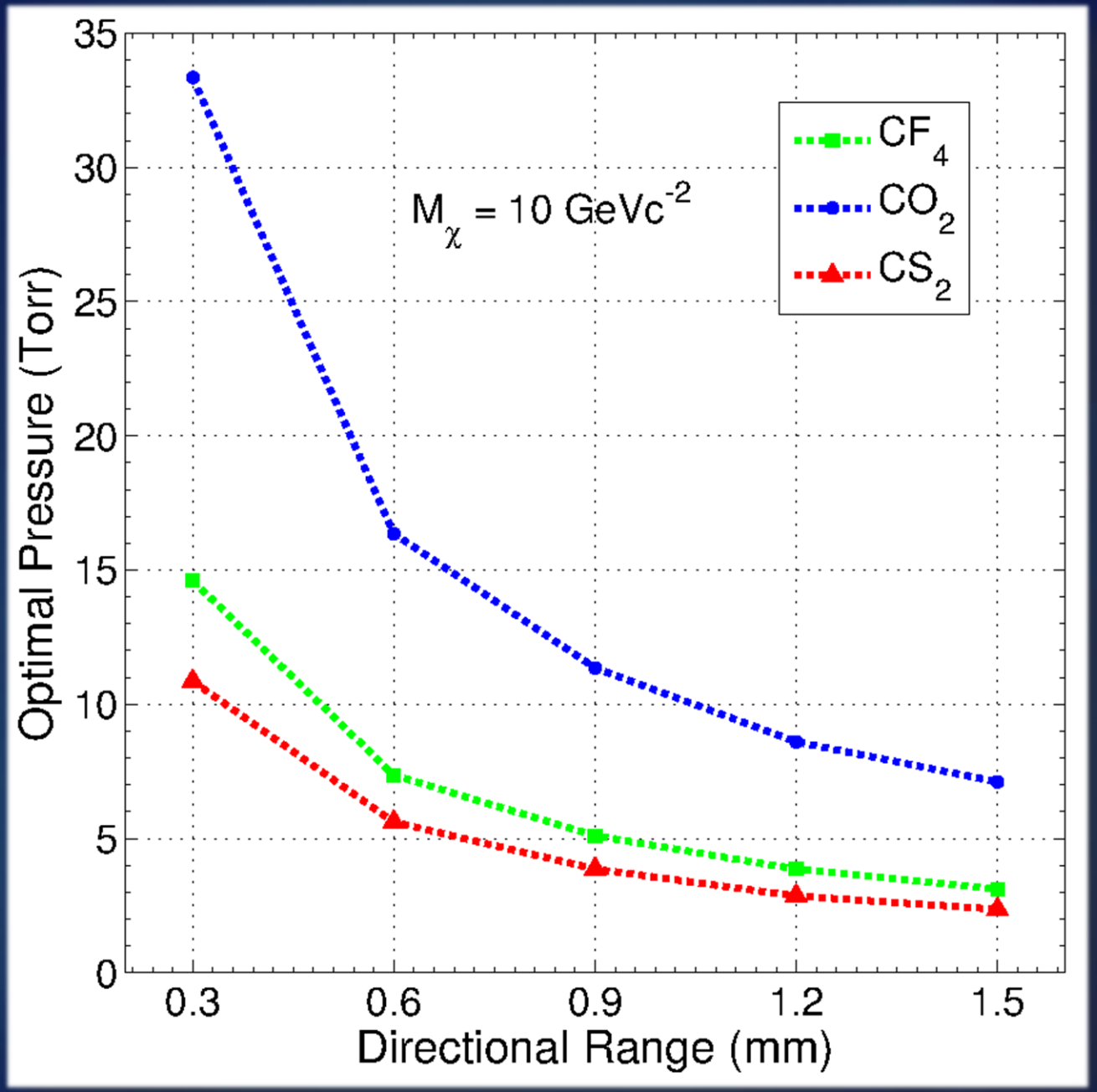
- For this study, we take the energy threshold to be the energy at which there is directionality (60 keV ←→ 0.6 mm).
- The directional interaction rate is maximized by varying the pressure for each target gas in a 1 m^3 volume.
  - At each pressure, E_{th} = E(R = 0.6 mm) → Directional Range.
- Simplistic because the strength of the directional signature is not constant over the threshold.



For a different method, see Tatarowicz & Martoff, Astroparticle Physics 35 (2011).


0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
10
20
30
40
Pressure (Torr)
R/σχP (events/m3/year/10−42 cm2)
CF4
CS2
CO2
Mχ = 10 GeVc−2
Eth = E(R = 0.6 mm)

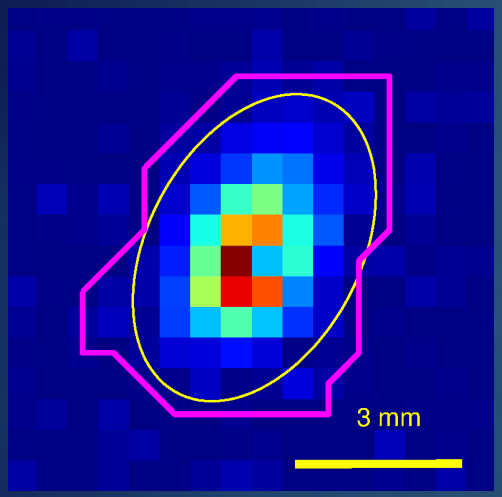

CF4
CS2
CO2
Optimal Pressure (Torr)
Mχ (GeV/c-2)
Eth = E(R = 0.6 mm)
0
10
20
30
40
50
60
70
80
0
20
40
60
80
100


Optimal Pressure (Torr)
Directional Range (mm)
M_χ = 10 GeVc^{-2}
CF_4
CO_2
CS_2
0
5
10
15
20
25
30
35
0.3
0.6
0.9
1.2
1.5

Low Pressure Results (Preliminary)

35 Torr CF_4

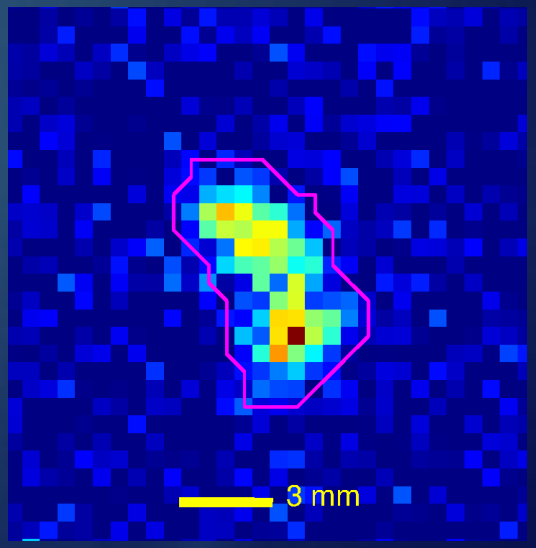
50 keV recoil in 35 Torr CF_4



25 Torr CF_4

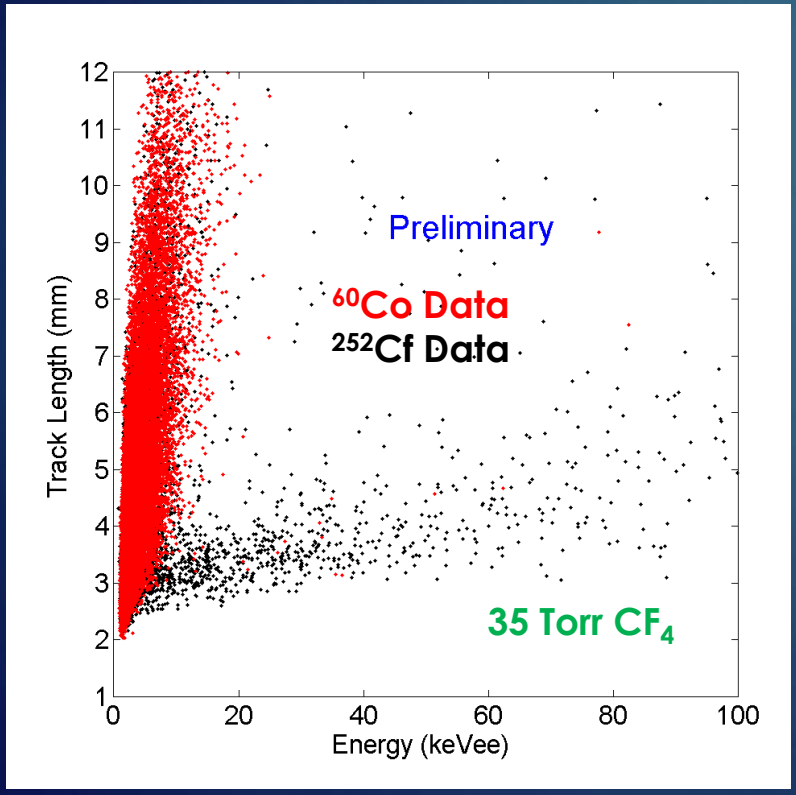
13 Torr CS_2

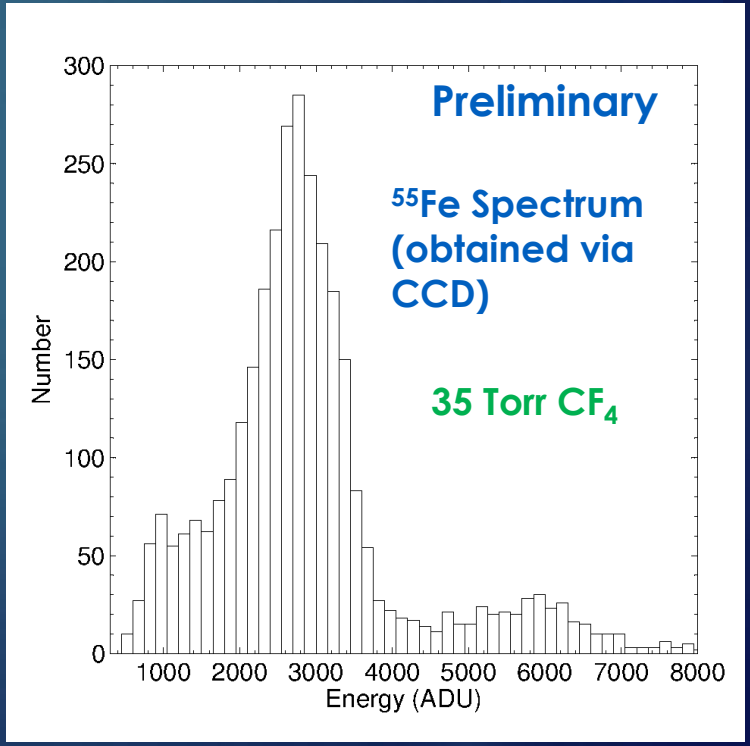
^{55}Fe track in 25 Torr CF_4



35 Torr CF_4

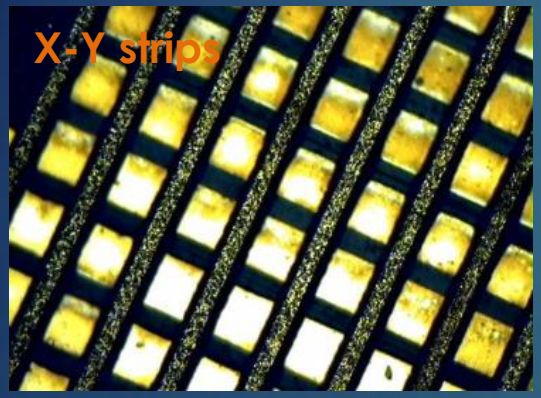
- Double THGEM (thick GEMs)
  - 500 um pitch. 400 um thickness
  - Single photoelectron sensitivity (charge readout)
  - Gain > 10^6 (Shalem et al. NIMA 558 (2006)).



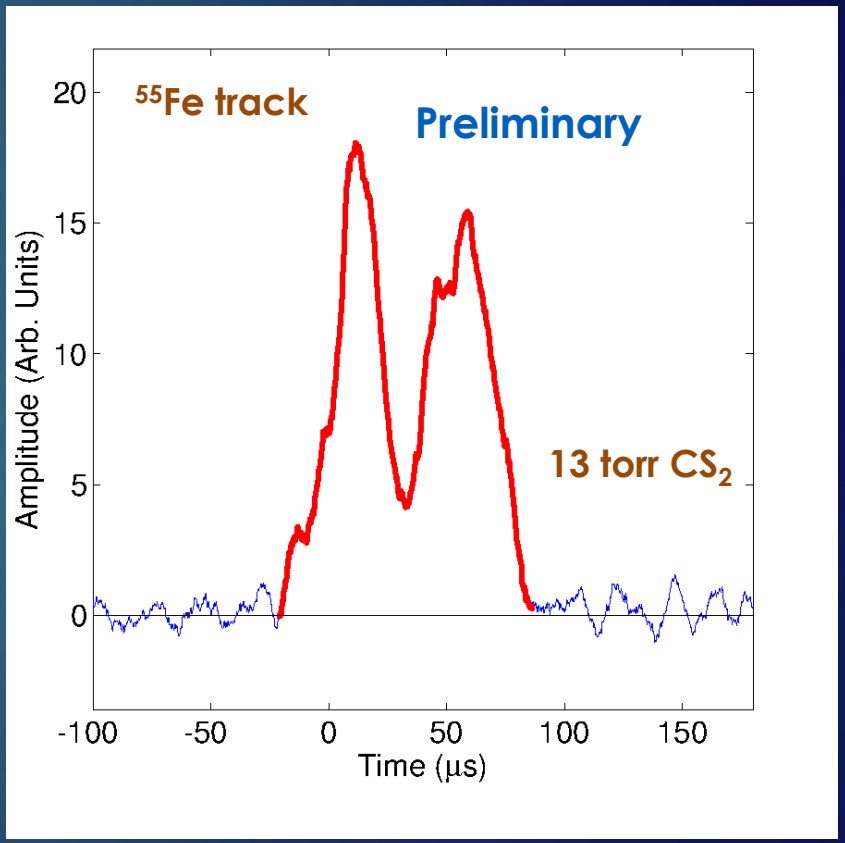


CS_2 13 Torr

- Charge Readout in Negative Ion Gas
  - 3D readout with X-Y strip detector (200 um pitch).
  - Don't need gain as high as optical readout.



  - Questions
    - Max. attainable gain?
    - Lowest pressure?
    - Diffusion?
    - Electron attachment? Field Strength? Gas Mixtures.
    - Saturation effects on head-tail?

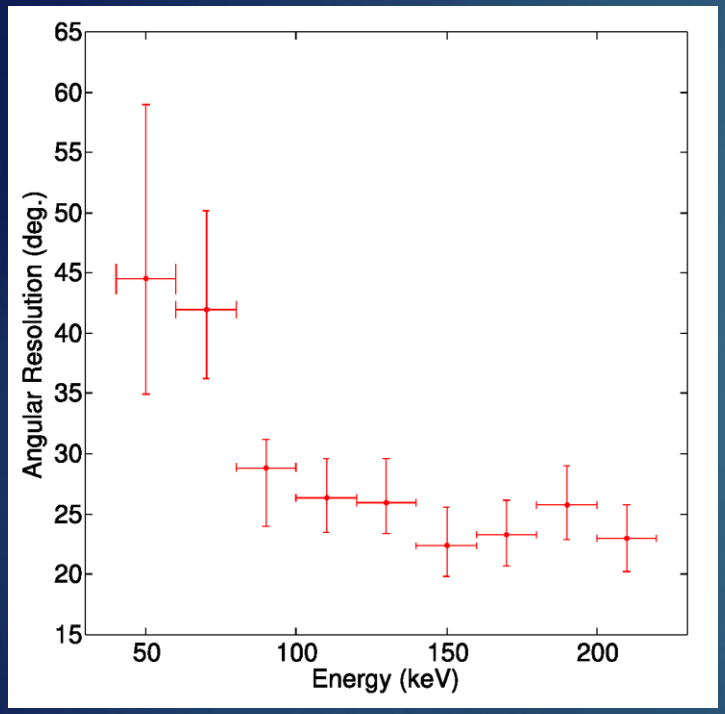


Z profile of ^{55}Fe track (5.9 keV) in 13 Torr CS2 using single THGEM.

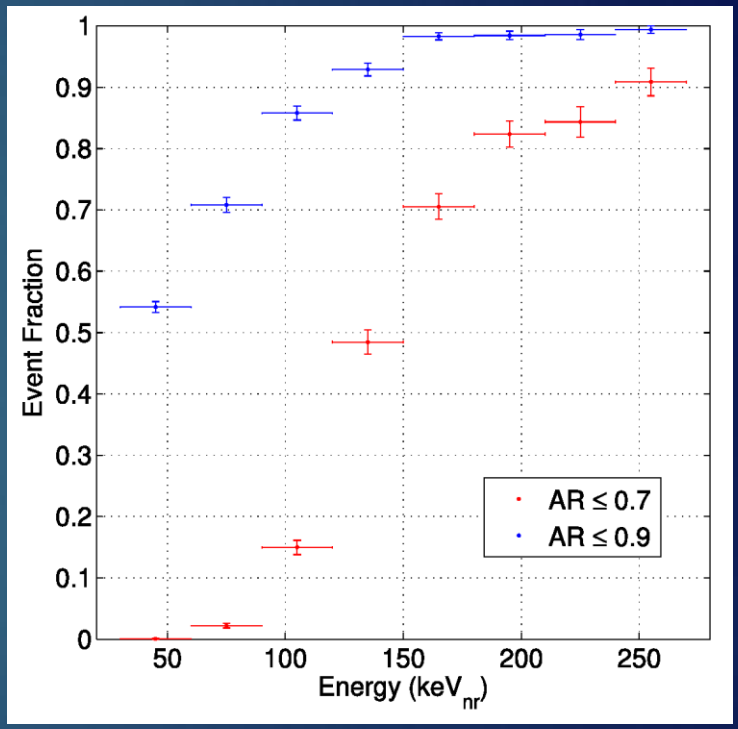
Summary

- High resolution and signal-to-noise detector
  - Obtained an ^{55}Fe optical spectrum.
  - Showed the importance of signal-to-noise for electron recoil discrimination down to ~ 25 keV.
  - Directionality down to 60 keV
  - ~ 45 events to reject isotropy for ^{252}Cf and WIMP spectrum
- Extrapolation for low mass
  - Large detection volume is needed.
  - Low pressure operation at ~ 10 Torr for CF_4 & CS_2
- Preliminary data at low pressure
  - 35 Torr CF_4 with CCD readout --- currently analyzing the data
  - 13 Torr CS_2 with charge readout via strips
    - Able to resolve ^{55}Fe tracks (5.9 keV).
    - Many open questions remain.

Back Up Slides



- Angular resolution (2D), but assuming recoils are parallel to imaging plane. Multiple scatterers not accounted for.



- The fraction of events with axis ratio greater than 0.7 and 0.9 as a function of energy.

Back Up Slides

Axis Ratio <= (60 keV)	Fraction of Events
1.0	1
0.9	0.871
0.8	0.634
0.7	0.419
0.6	0.270
0.5	0.158

Slices (60 keV)	Fraction of Events
1 (events in top 1/10th)	0.059
2	0.159
3	0.296
4	0.449
5	0.620
6	0.764
7	0.877
8	0.944
9	0.980
10 (all events)	1.000