R&D with Implications for a Directional Low Mass Dark Matter Search

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For the DRIFT collaboration
CYGNUS 2013 Toyama
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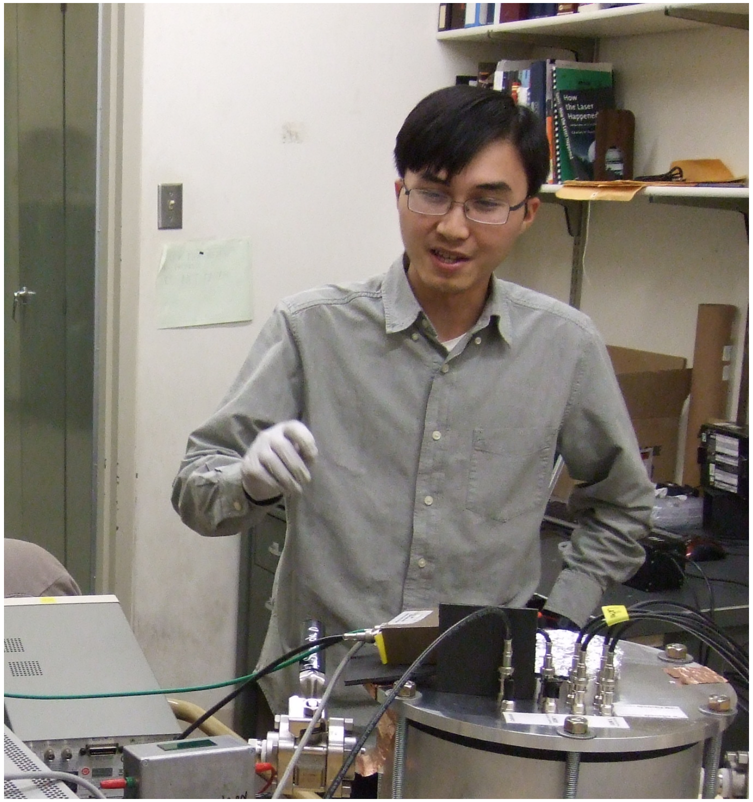
OUTLINE

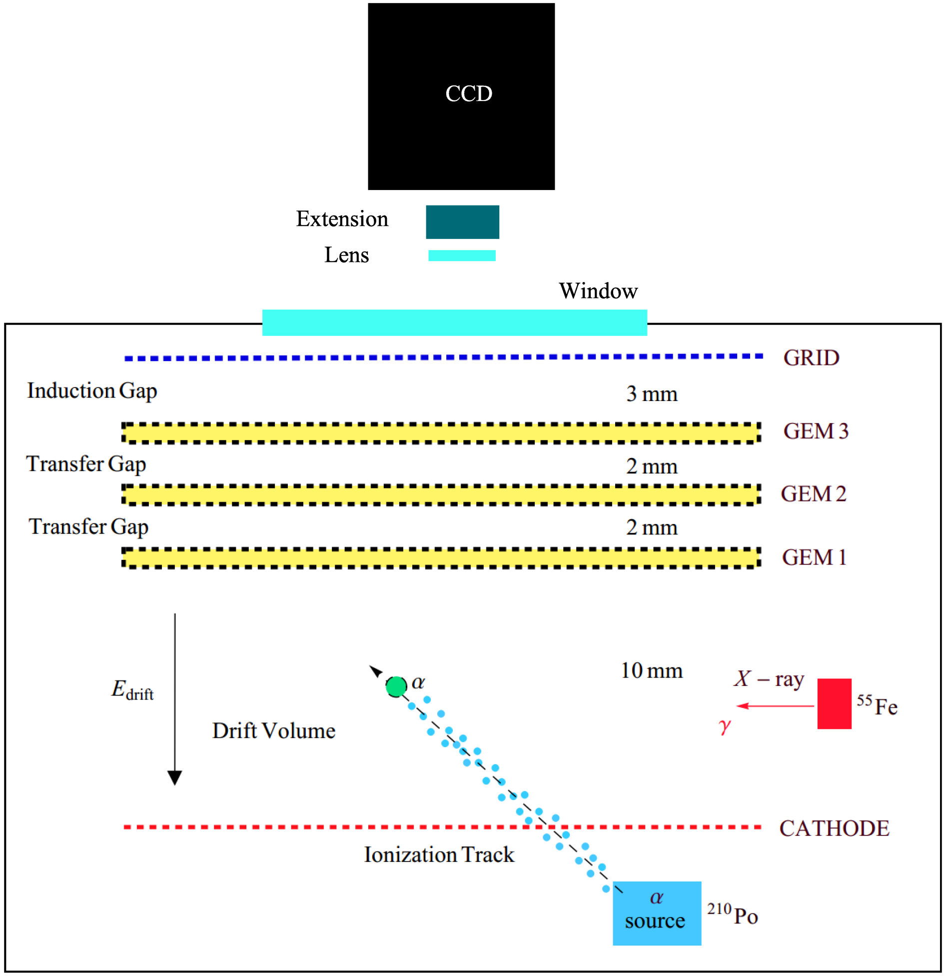
I. Measurements of electronic and nuclear recoils with a high signal-to-noise and high spatial resolution detector

II. Implications for a directional low mass WIMP search

R&D using a CCD-GEM based detector

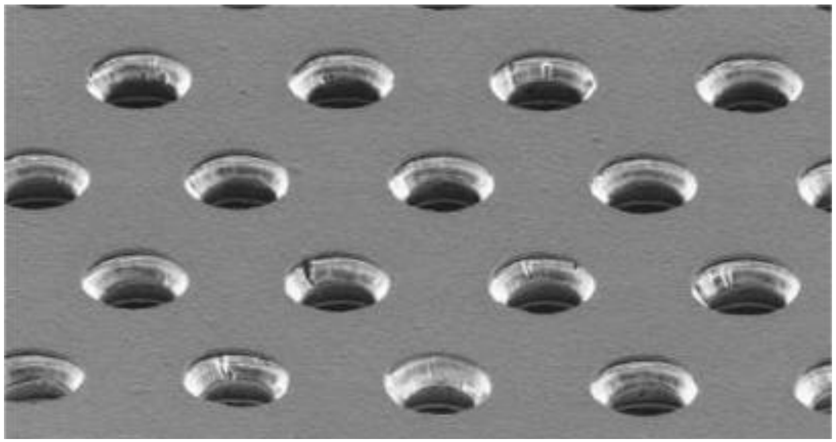


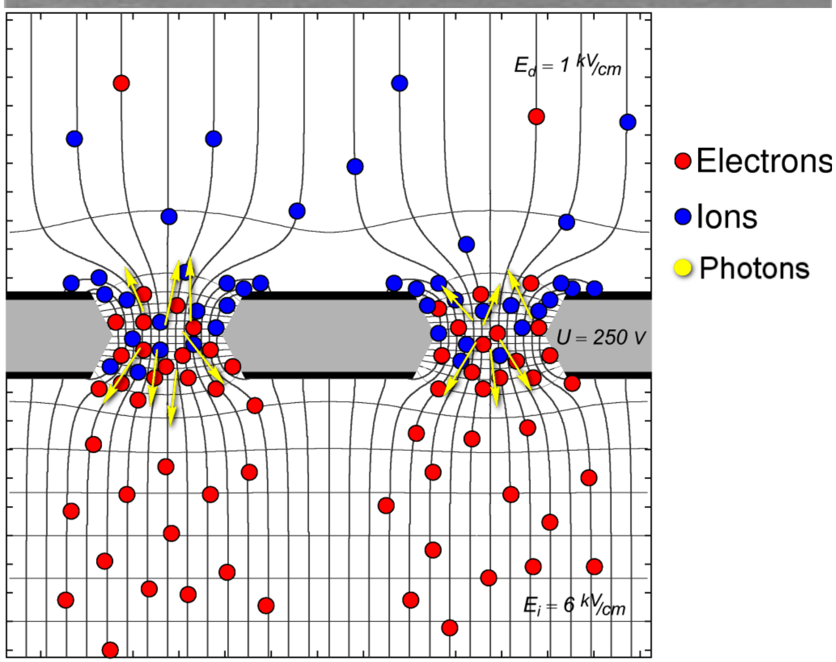
Nguyen Phan (PhD student, UNM)



high S/N, high spatial resolution

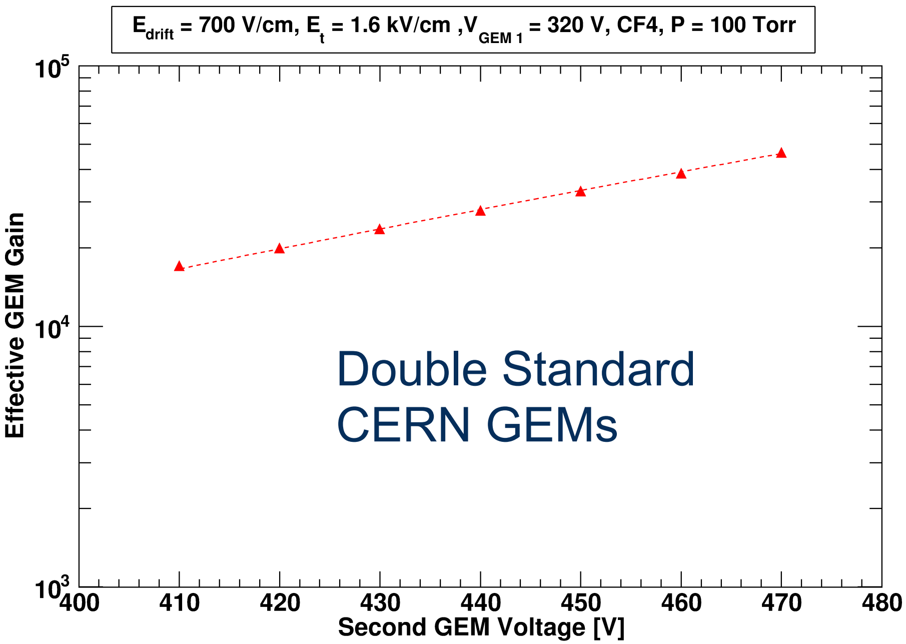
GEMs (Gas Electron Multipliers)



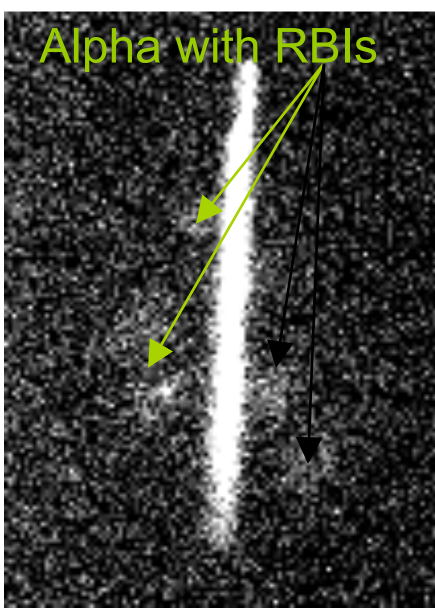


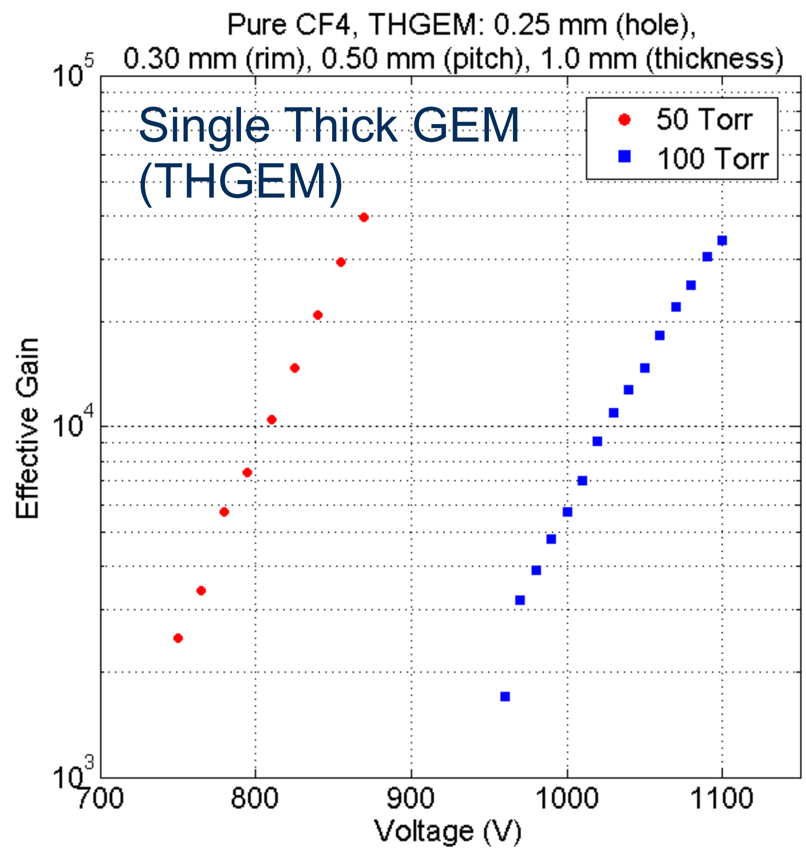
- ~ 50 um thick, 140 um hole pitch.
- Typical dimensions: 10 cm x 10 cm.
- ΔV = 300 – 500 V → electric fields inside holes (10's kV/cm).
- Electrons drift into holes and undergo collisional avalanche → release of secondary electrons and scintillation light.
- Charge gains of 10^7 possible with multiple GEMs cascaded, but ***strongly*** dependent on both the type of gas & pressure.
- THGEMs: ~ 10x in dim., robust, low pressure, high gains.

GEM Gas Gain in CF_4

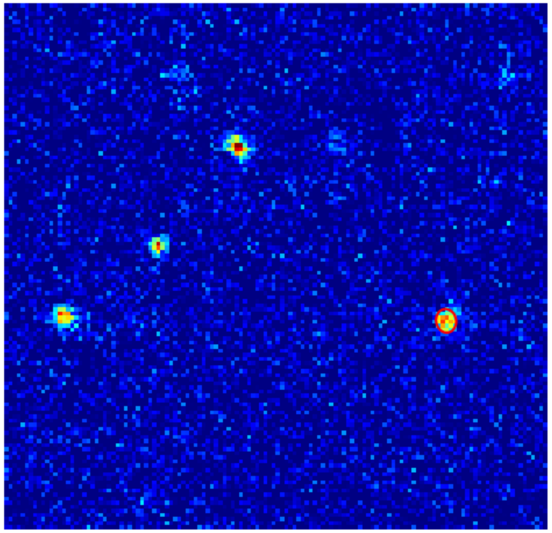


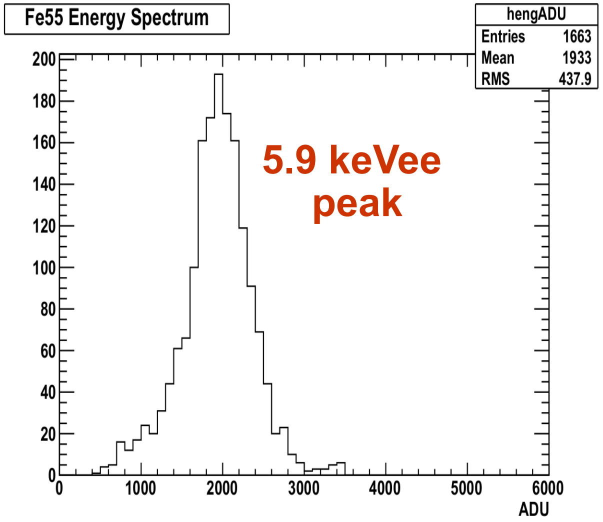
- Max. stable effective gain (α's):
  - 100 Torr CF_4
    - » 2 GEMs: 40,000
    - » 3 GEMs: 200,000
  - 75 Torr CF_4
    - » 2 GEMs: 20,000
    - » 3 GEMs: 40,000



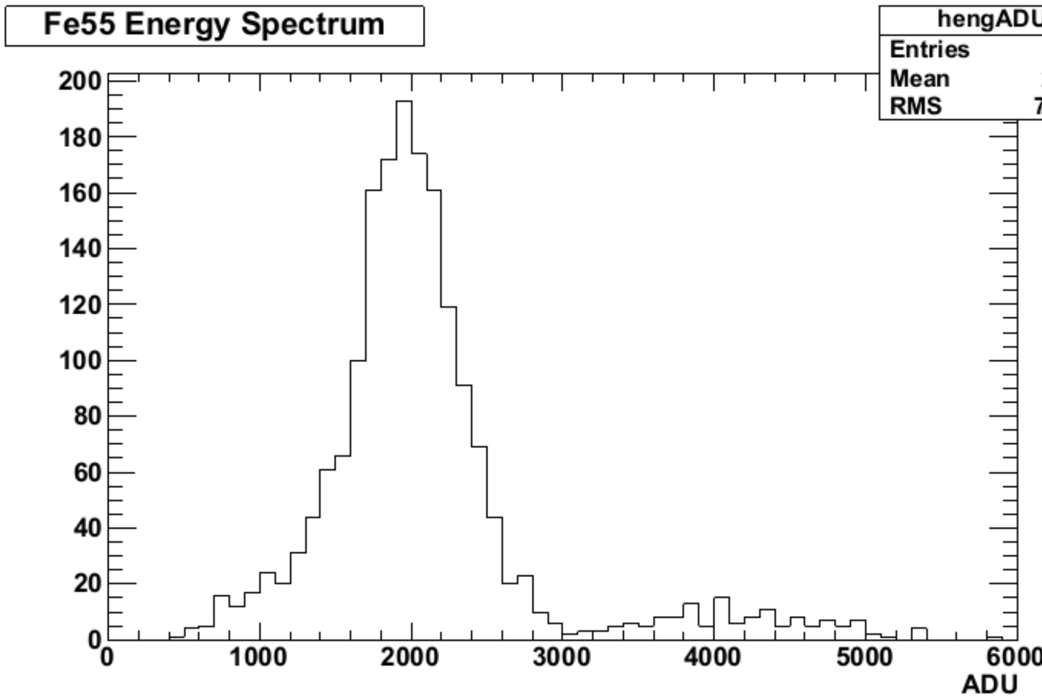


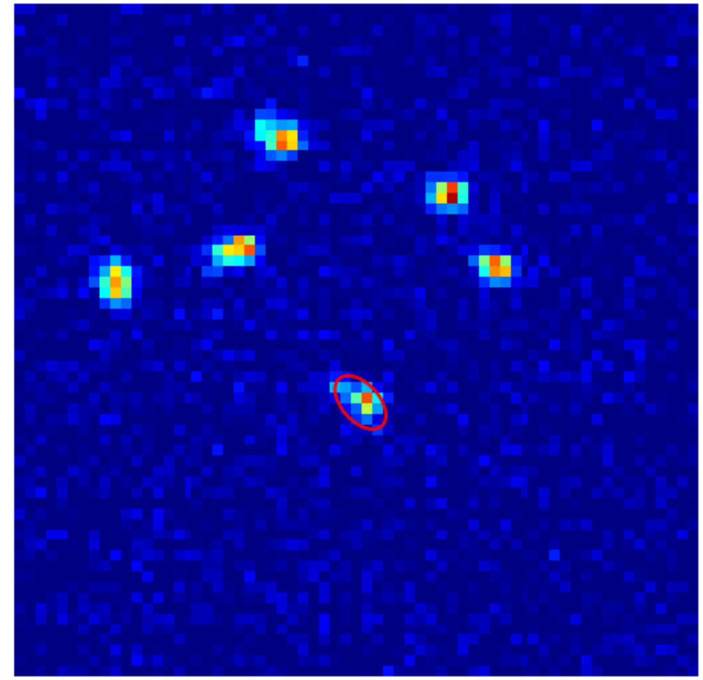
Energy Calibration with Fe-55



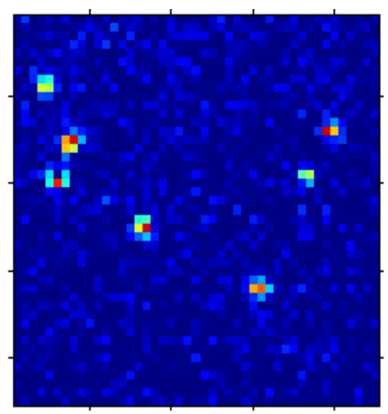


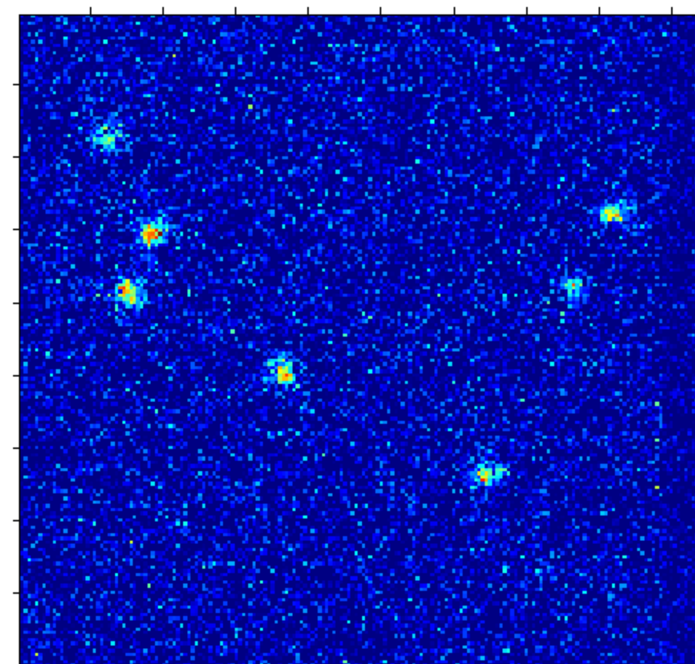
We calibrate using both the electron and light signal **- To our knowledge, this is the first optical Fe55 spectrum obtained in low pressure CF4.**





Energy spectrum of 16x16 binned Fe55 tracks.

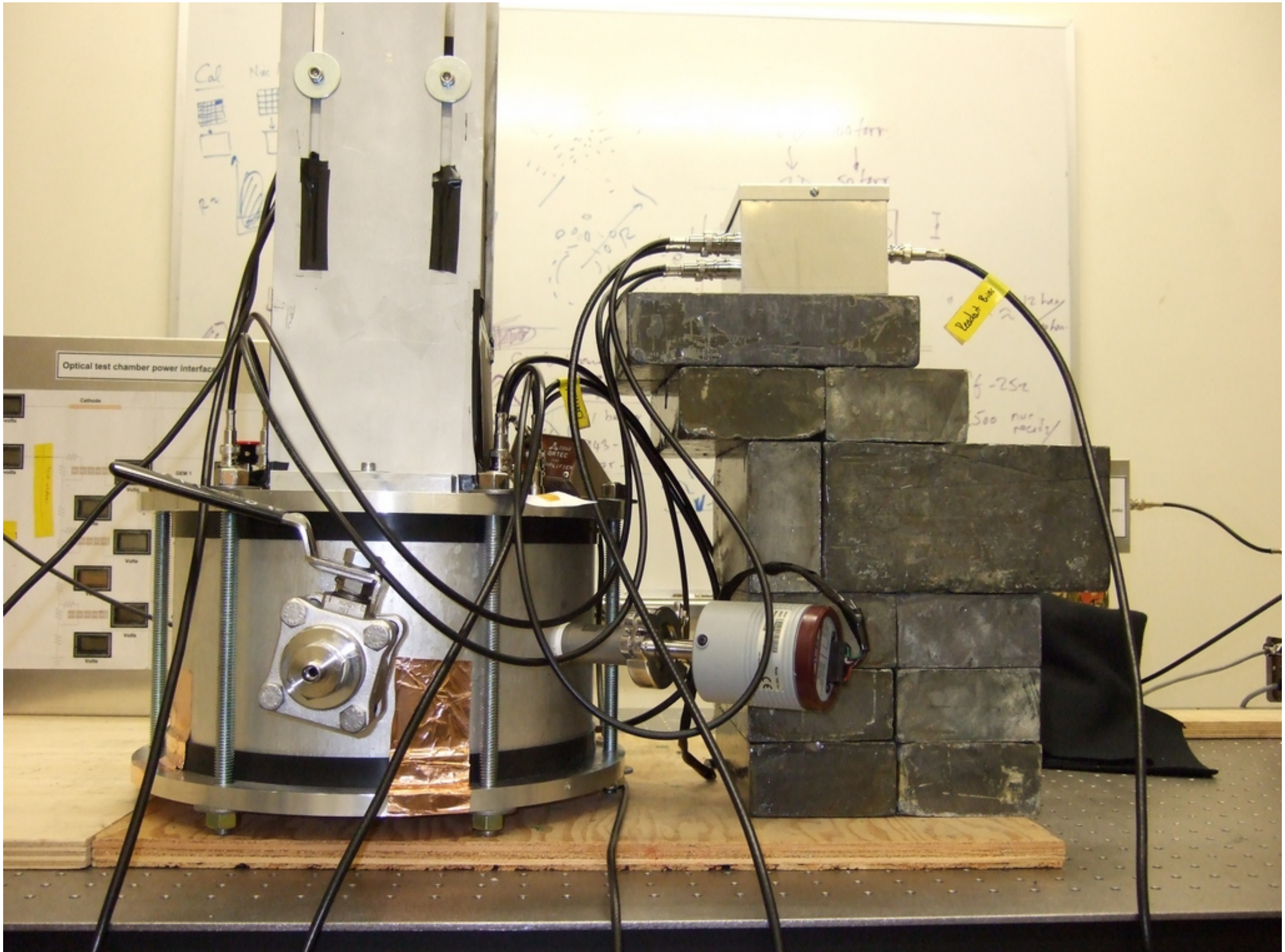




Top Right: Fe55 tracks at 16x16 binning (on-chip) and 380,000 effective gain.

Bottom Right: Fe55 tracks at 6x6 binning (on-chip) . Smaller image is binned 4x4 in software. Gain of 200,000 (same for gamma and neutron runs).

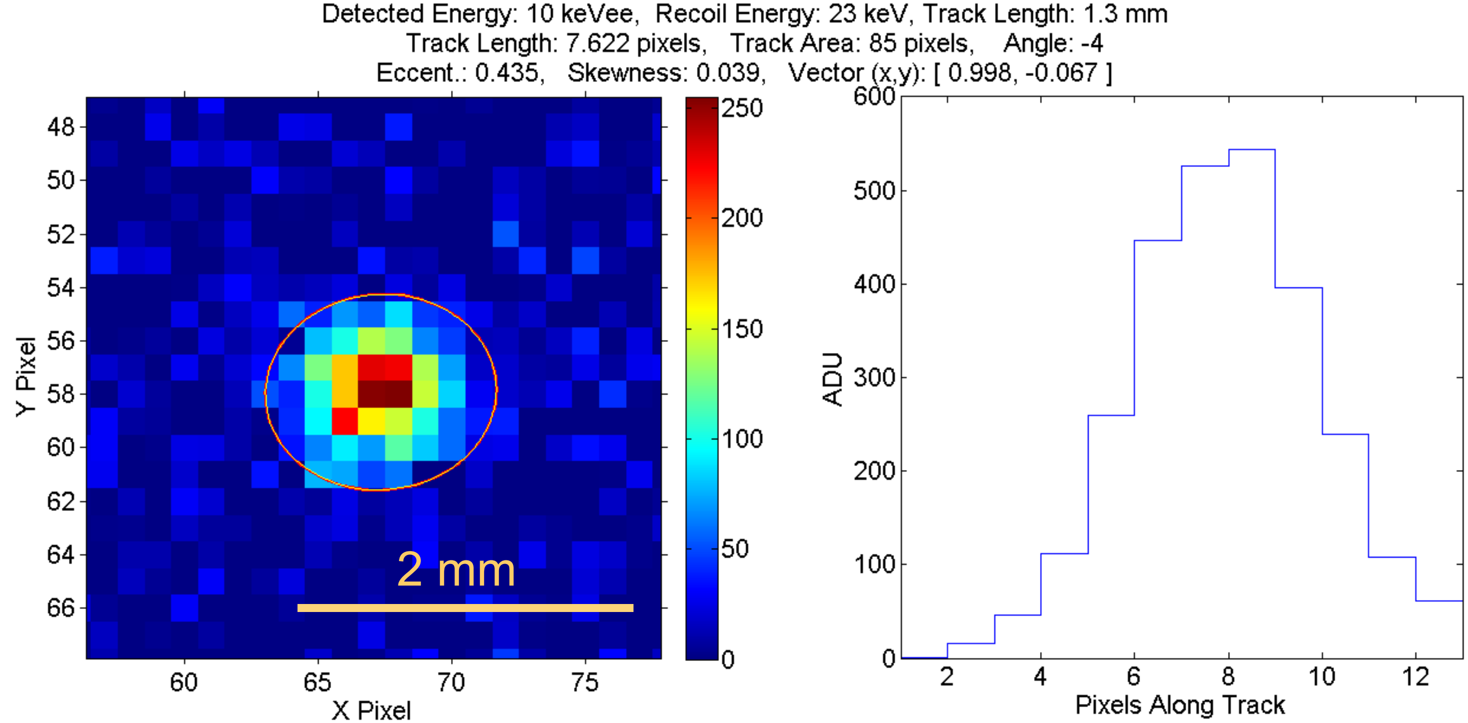
Neutron (Cf-252) & Gamma (Co-60) Runs

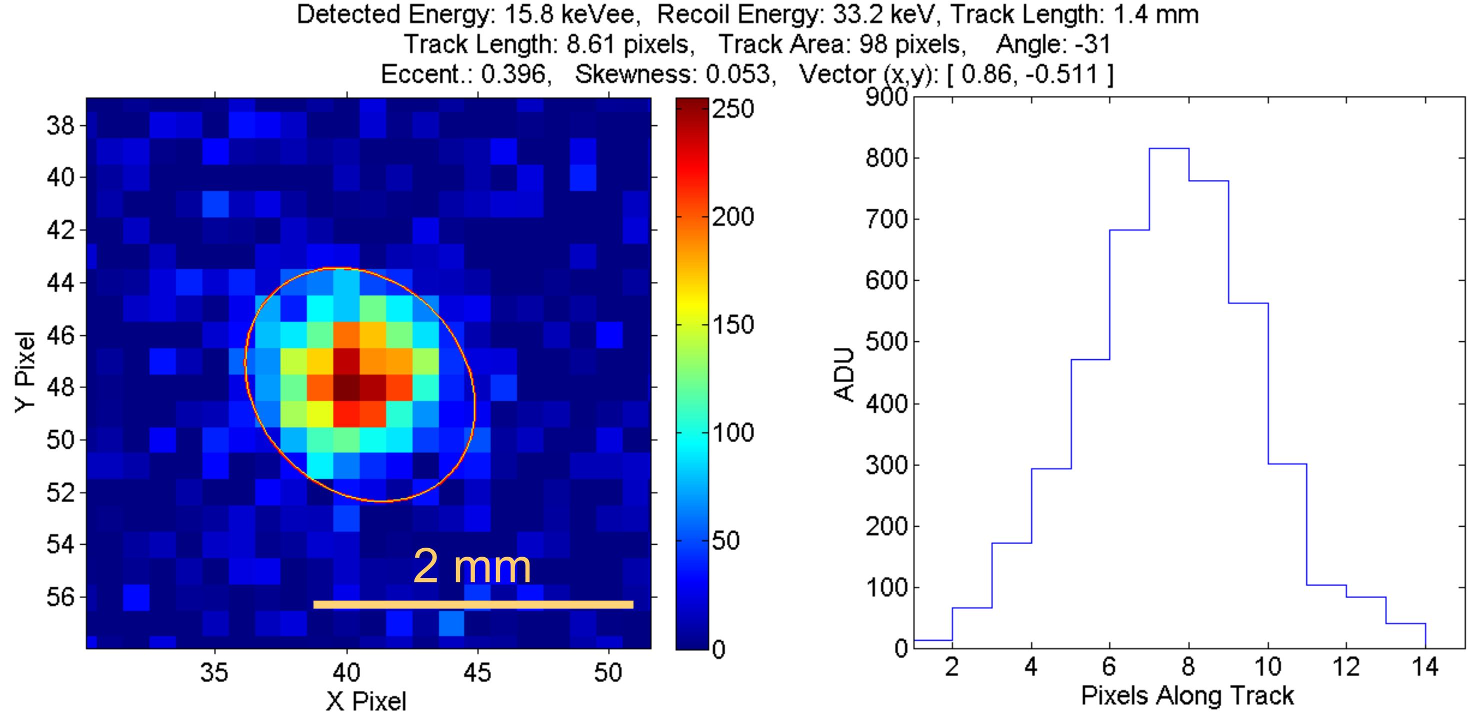


Experimental Parameters

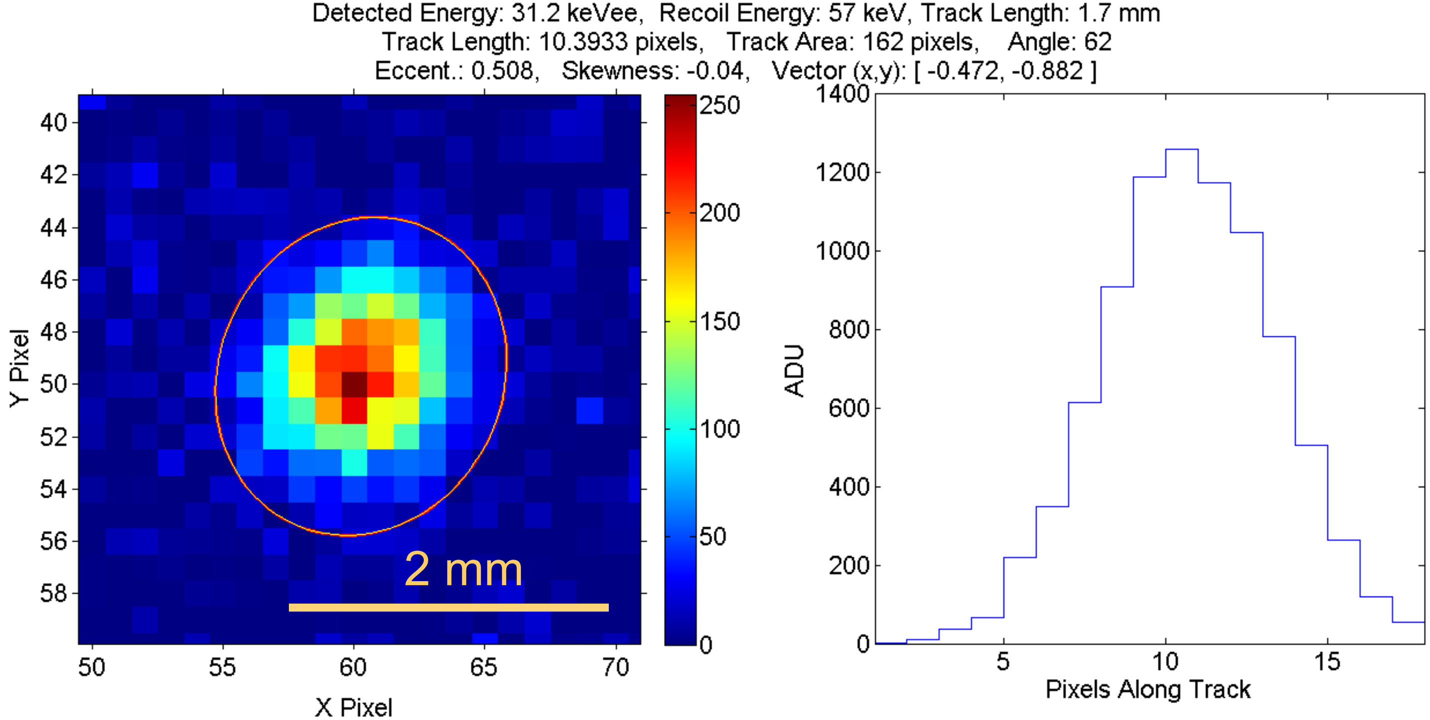
- 3 standard copper CERN GEMs (7 cm x 7 cm).
- Pressure: 100 Torr pure CF_4
- Effective gain: ~200,000
- Diffusion: σ=350 um
- FLI back-illuminated CCD (peak QE ~ 93%, read-noise 10 e- rms)
- 6 x 6 on-chip binning, 5 sec. sequential exposures.
- Energy resolution: 35% (FWHM) at 5.9 keVee

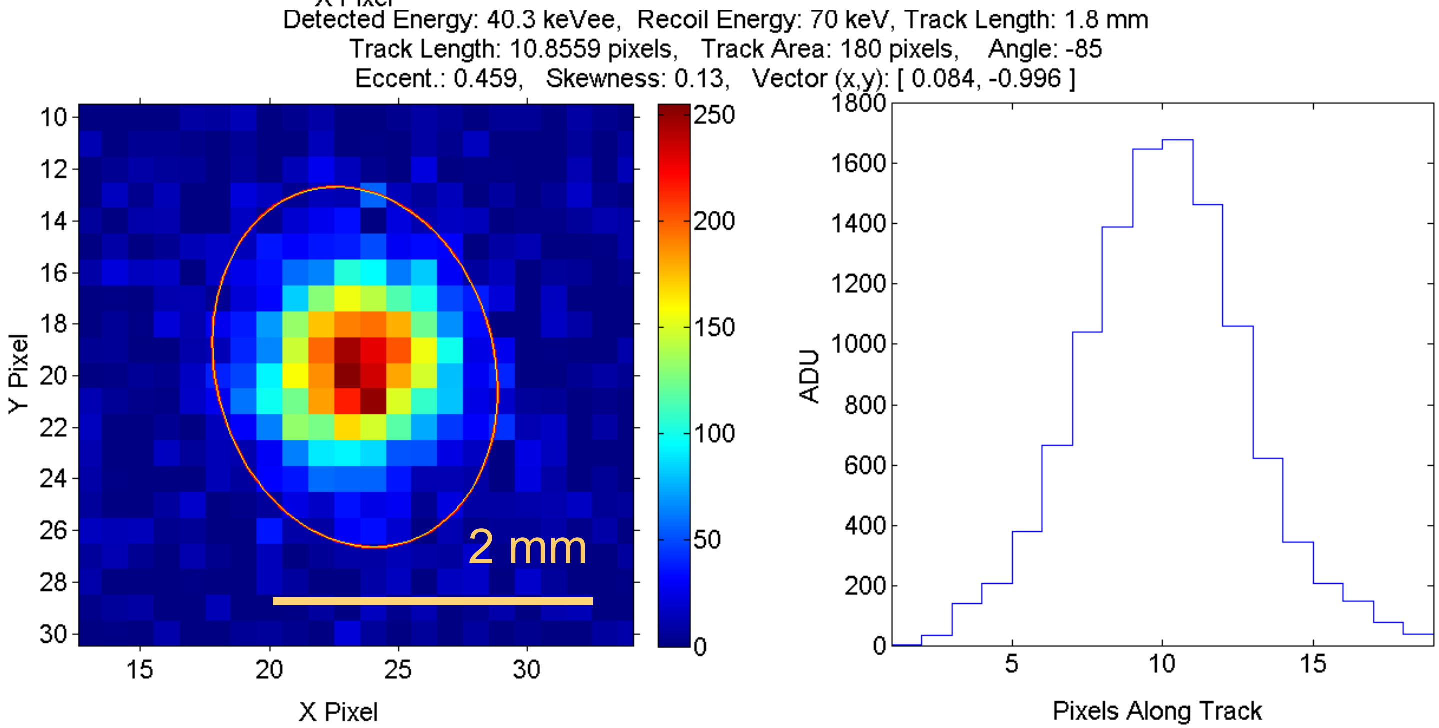
Nuclear Recoils



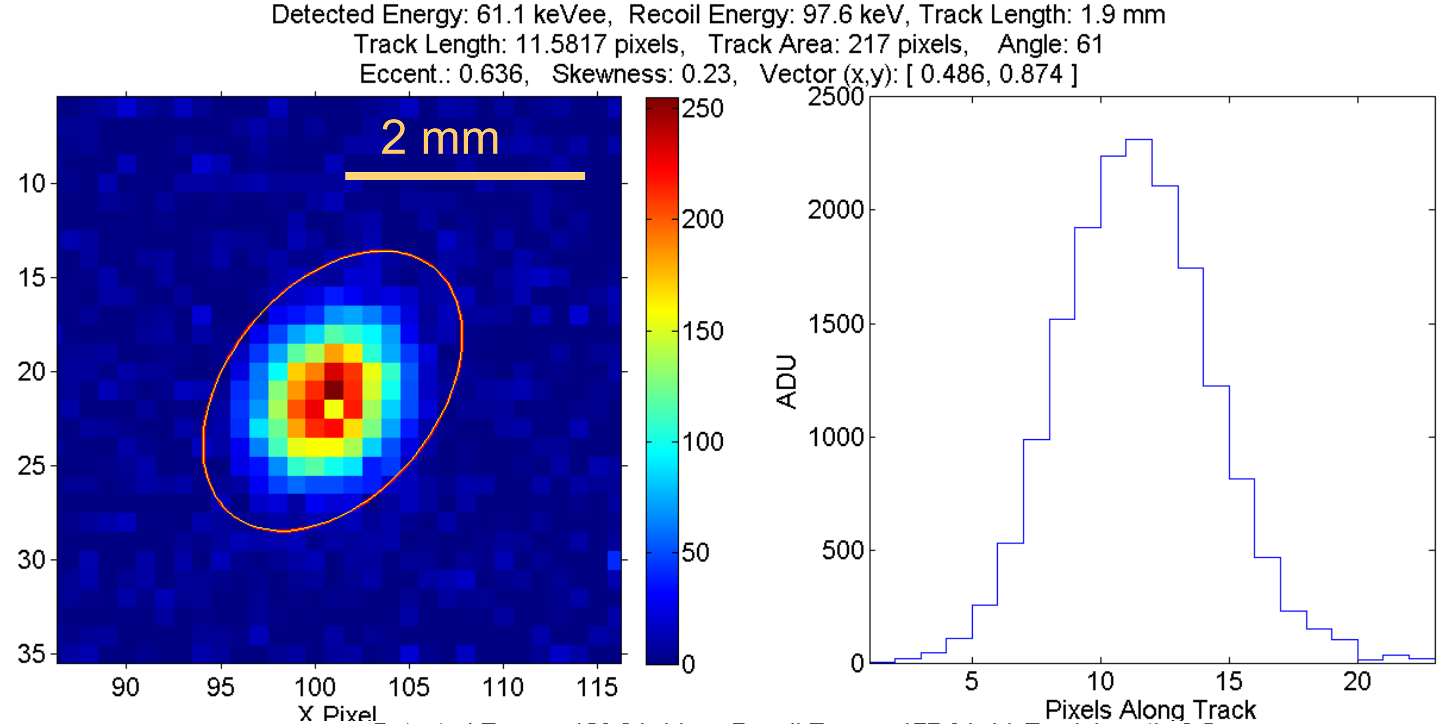


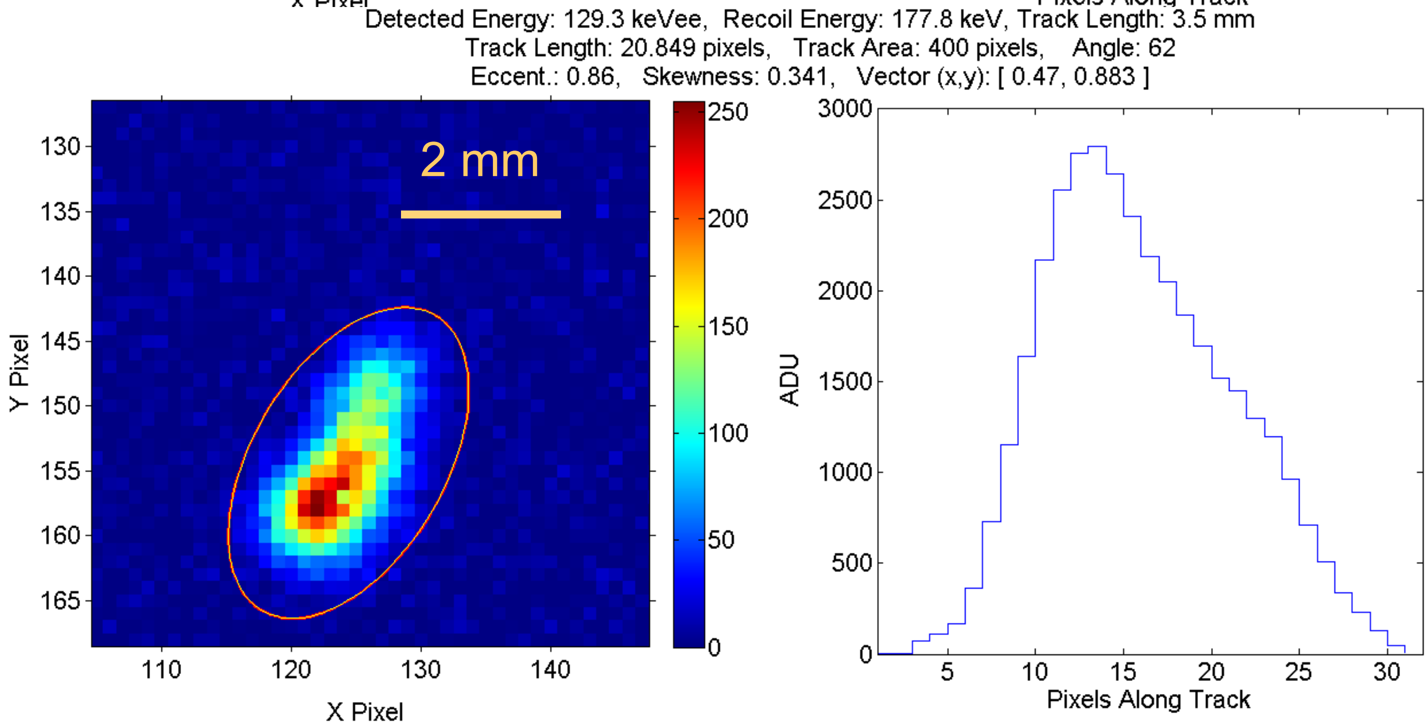
Nuclear Recoils



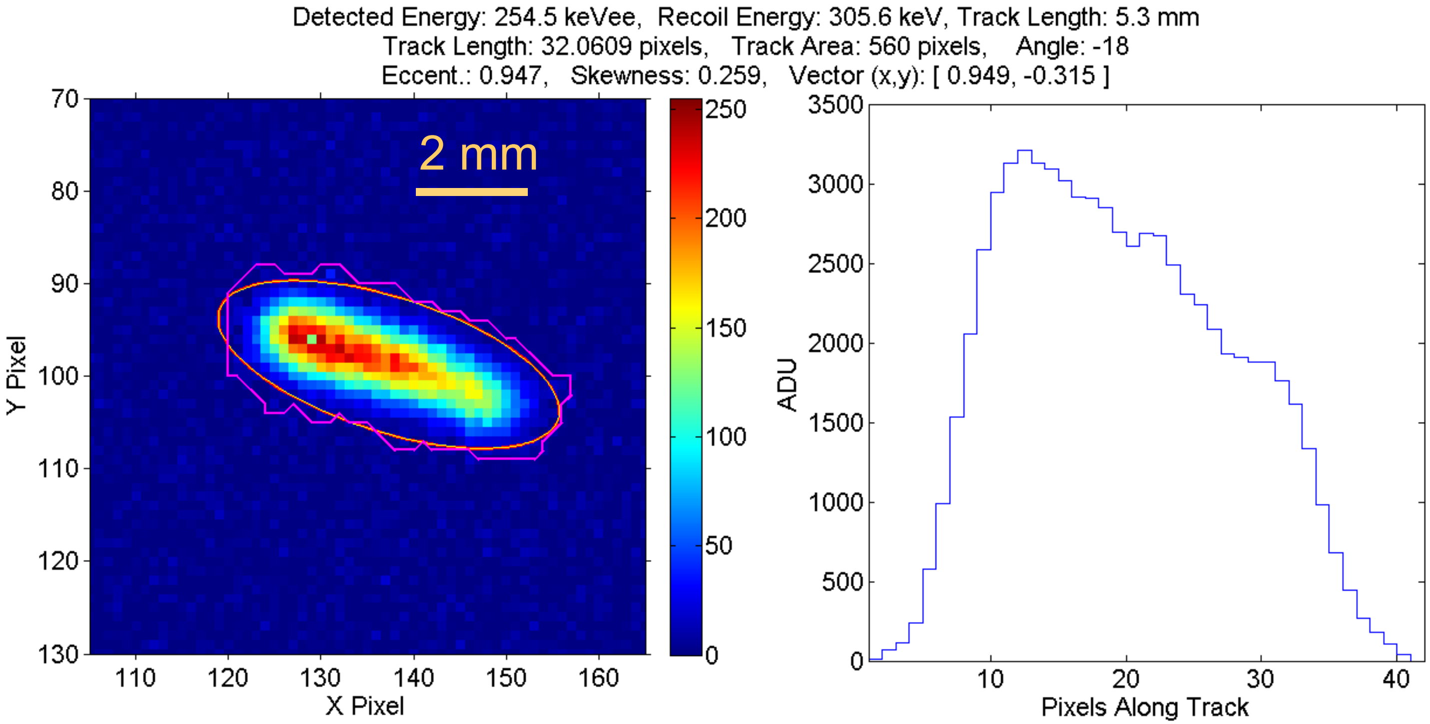


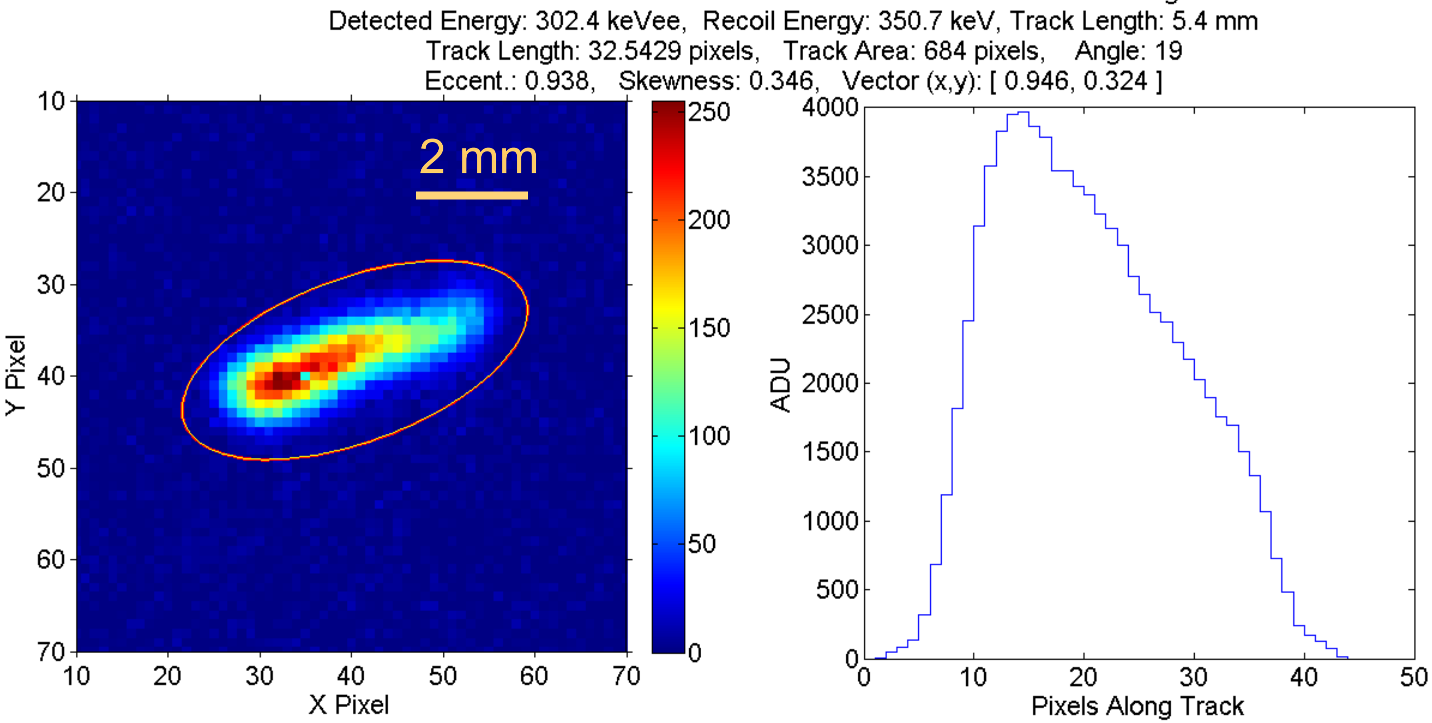
Nuclear Recoils



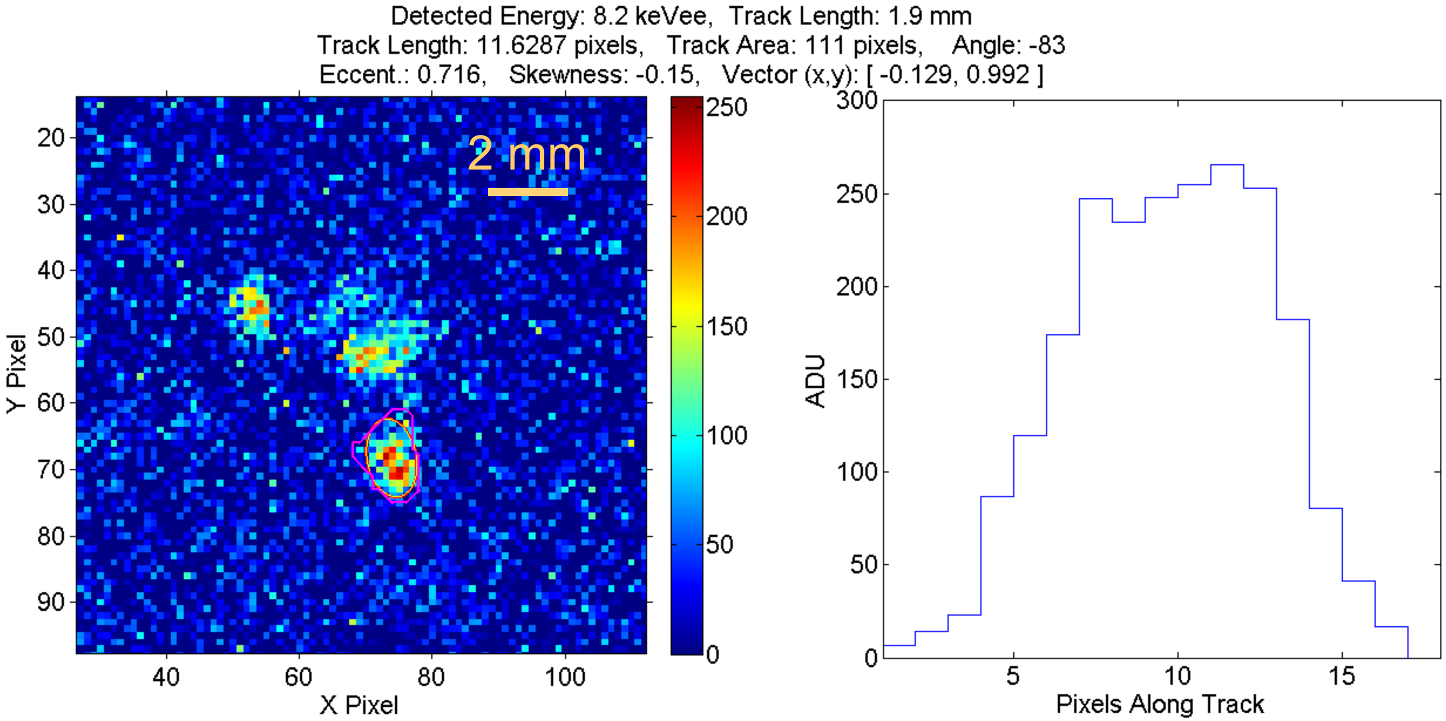


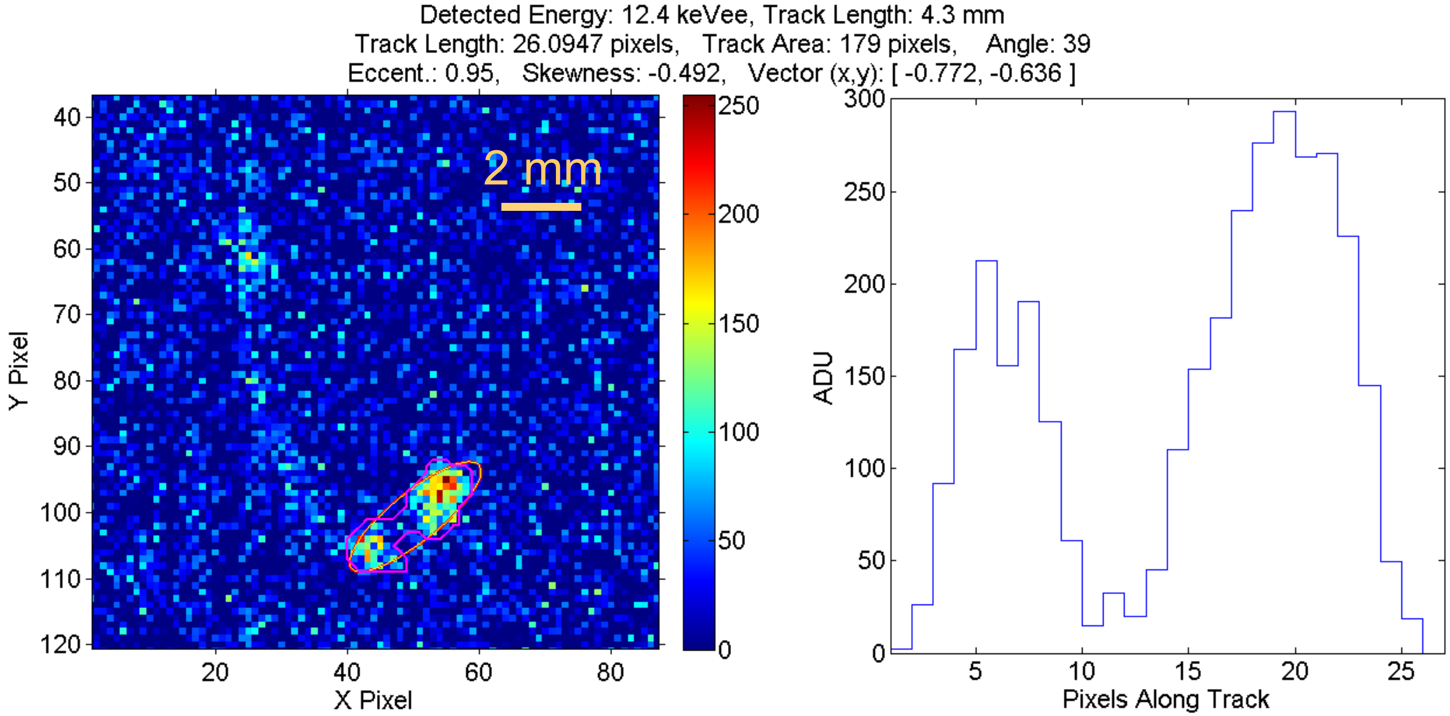
Nuclear Recoils



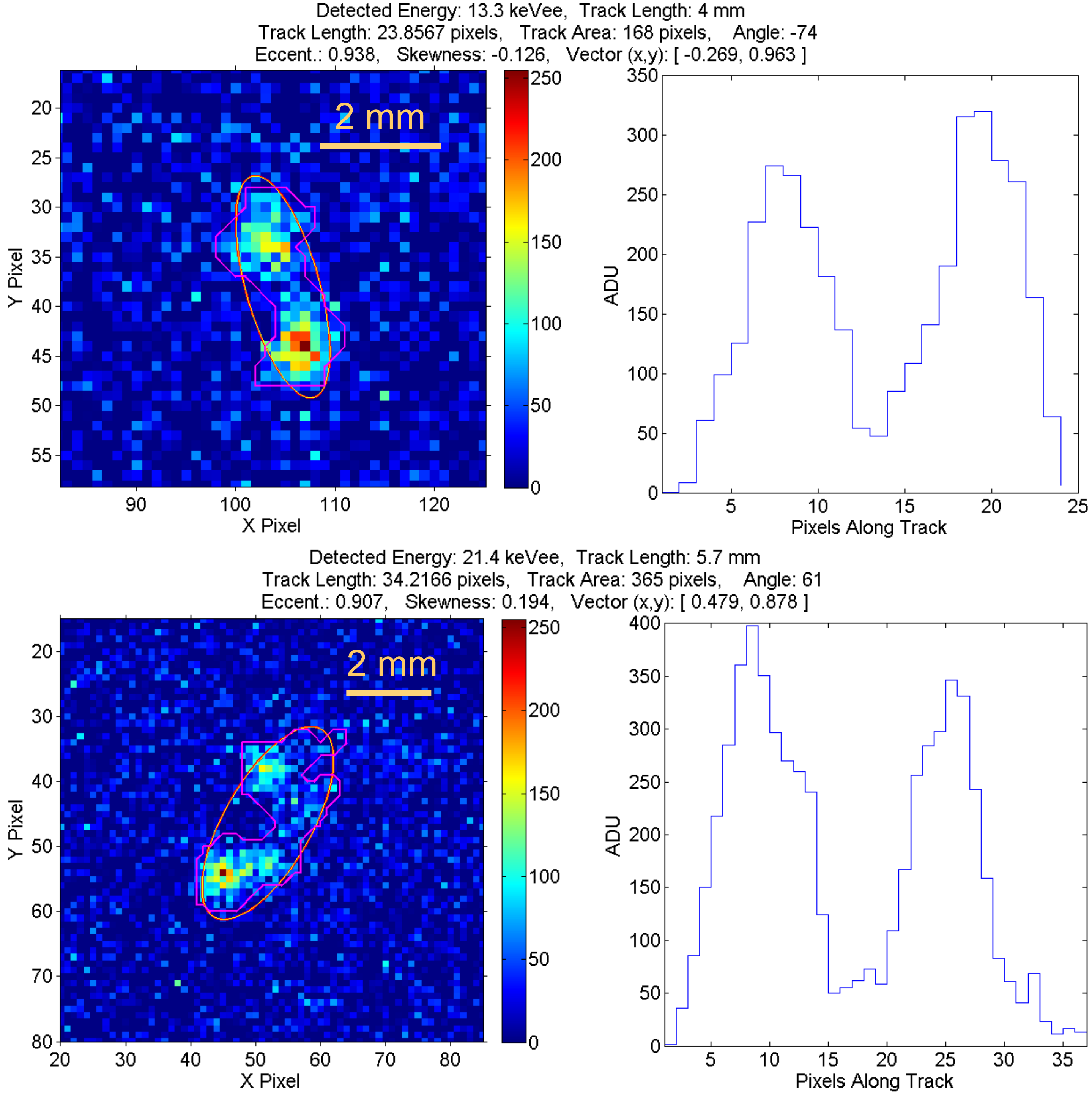


Electronic Recoils

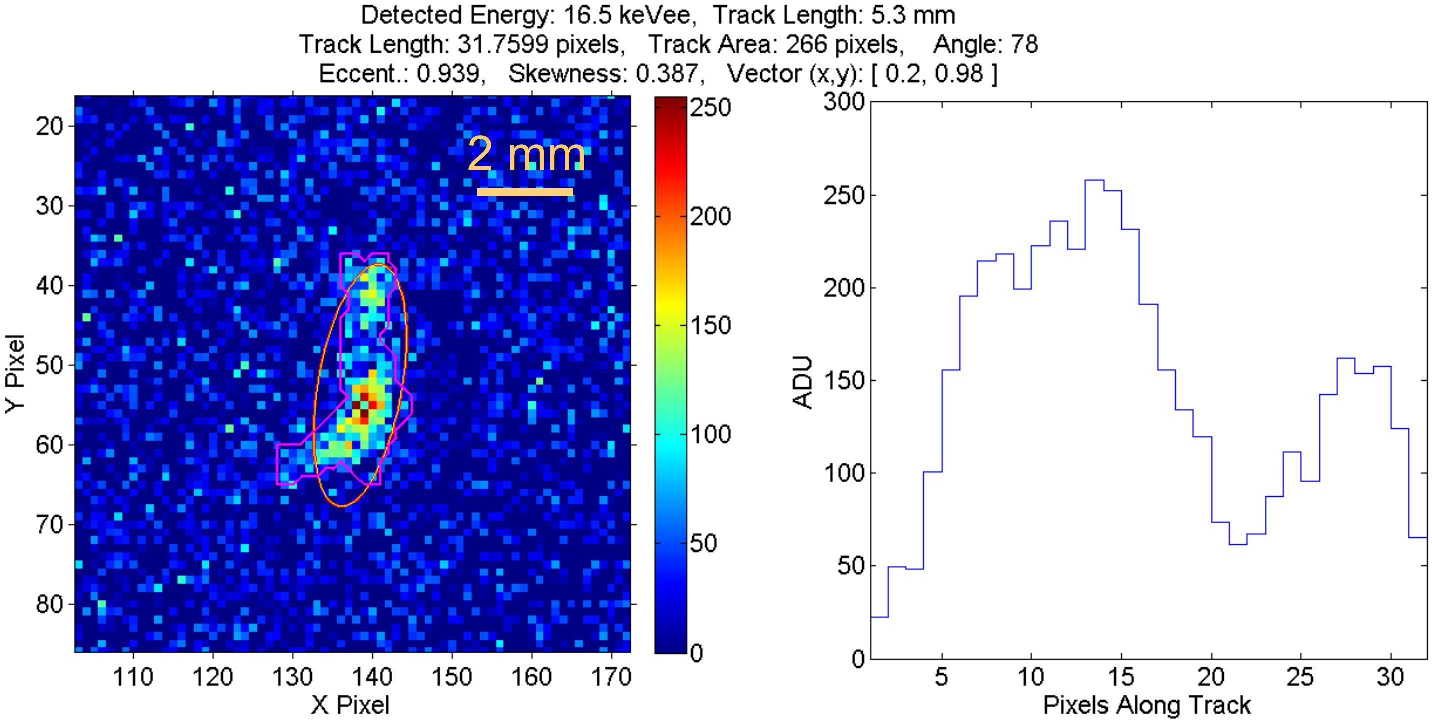


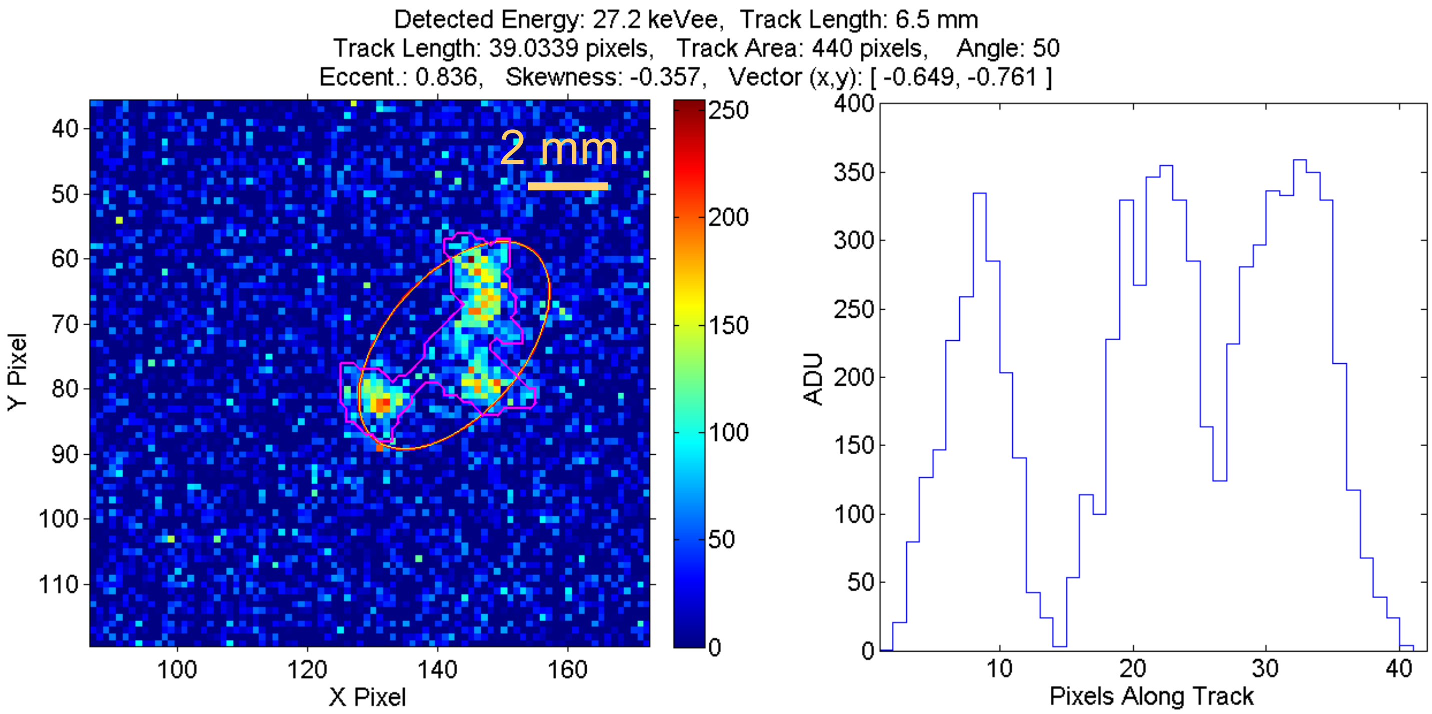


Electronic Recoils

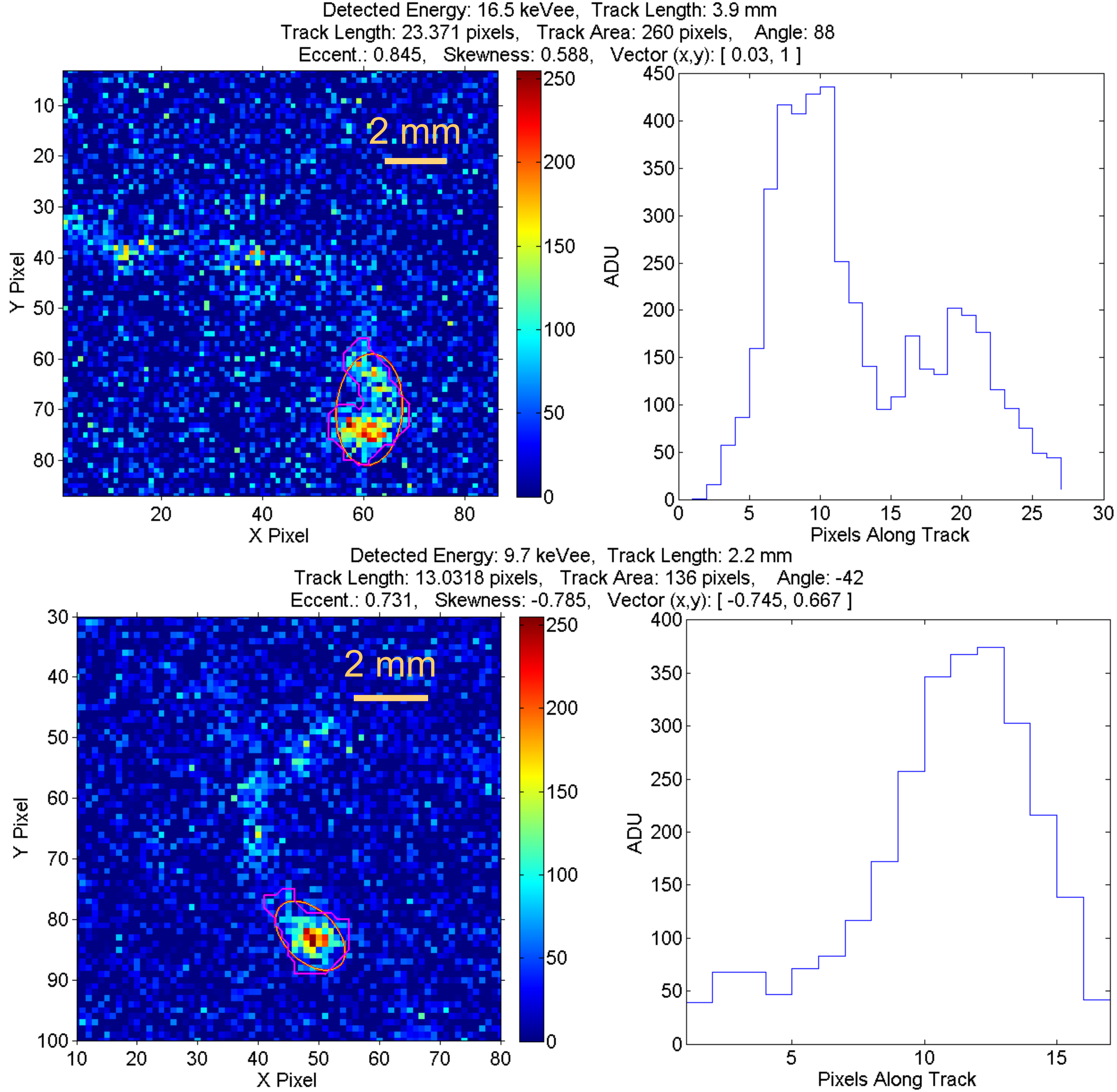


Electronic Recoils





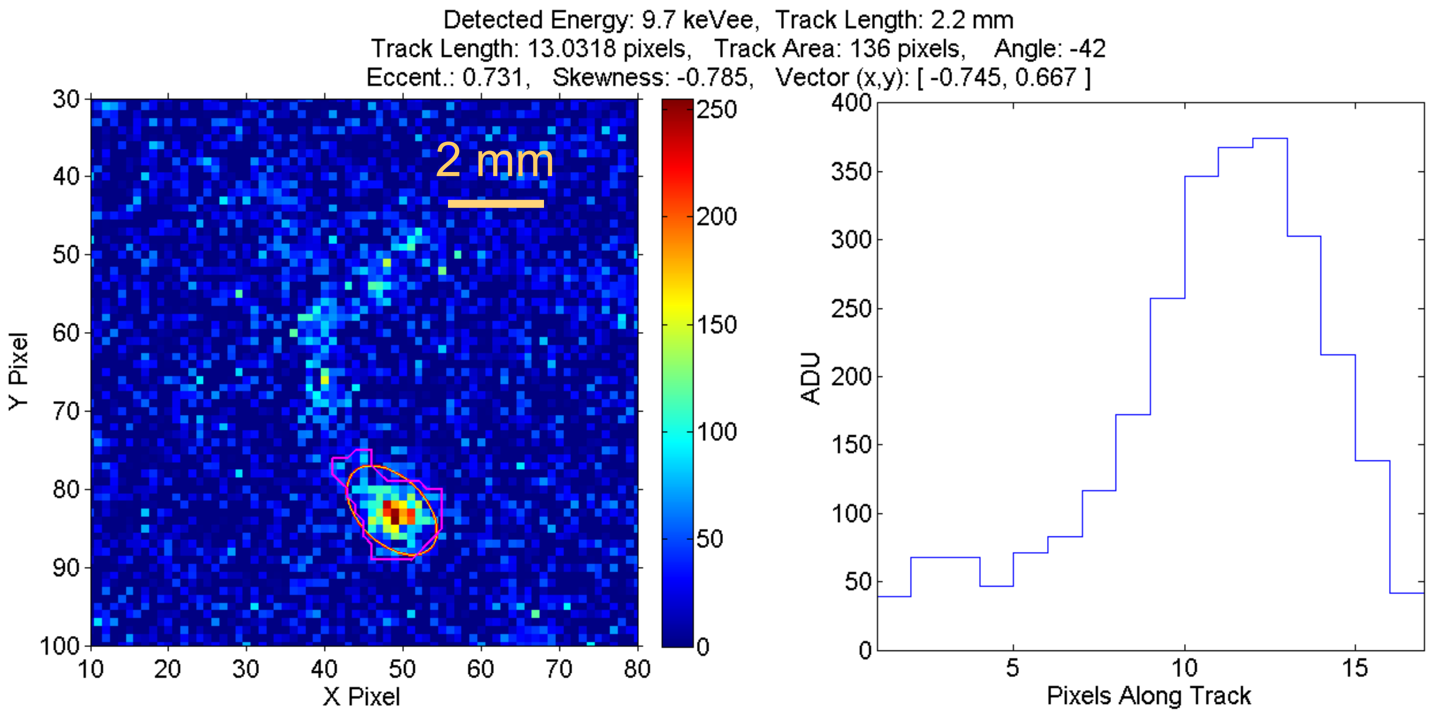
Electronic Recoils



Discrimination and Directionality

Discrimination

- Electronic recoils have small dE/dx with large fluctuations → low S/N leads to confusion with nuclear recoils



A ~10 keVee electron or a ~25 keVr F recoil??

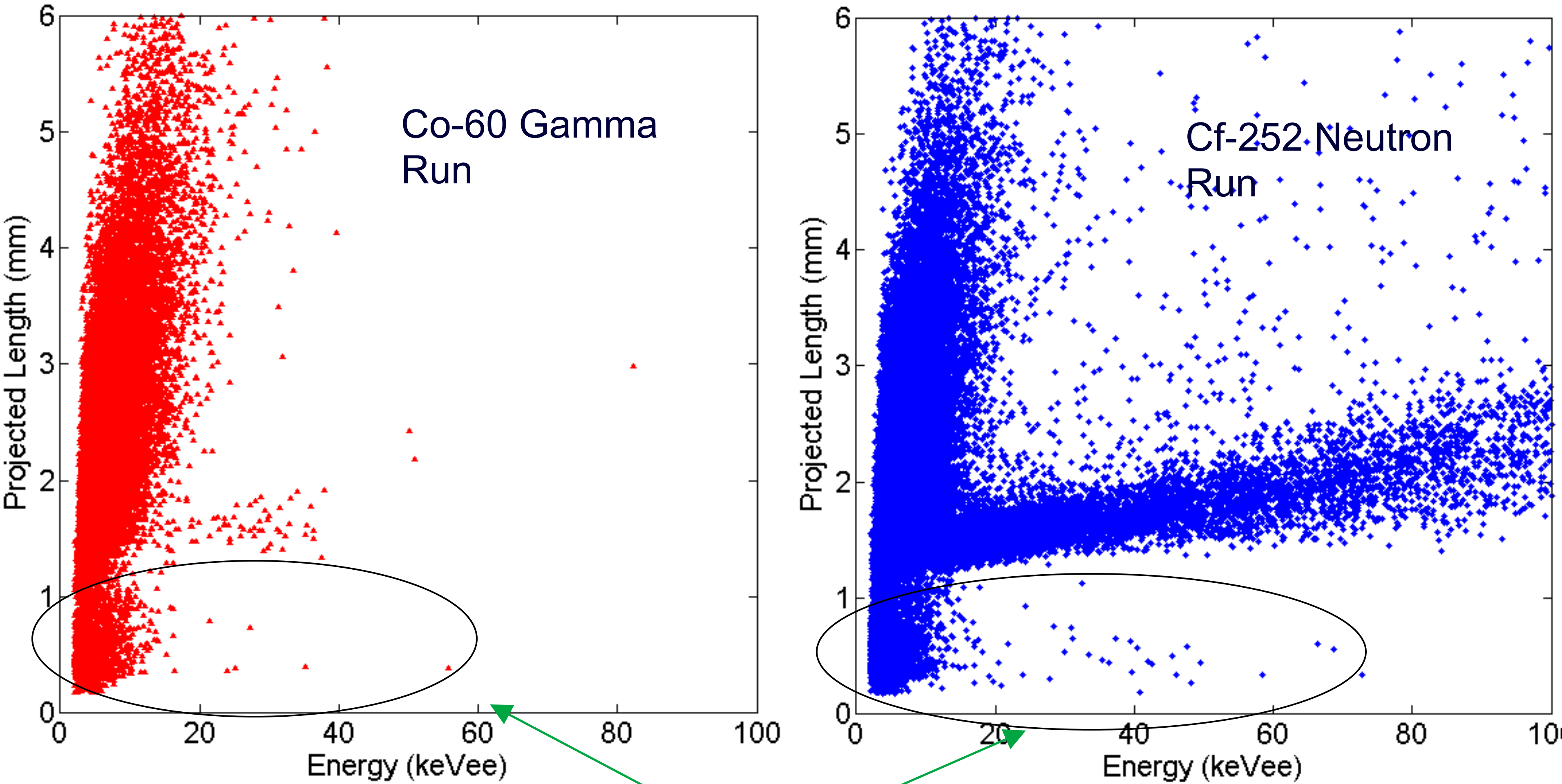
Good Discrimination requires high S/N

- For discriminating between electronic and nuclear recoils down to the lowest possible energies, high S/N is critical. 3D tracks would also help.

- Lower diffusion and pressures would also help, but these are more critical for finding directionality in nuclear recoils.

- Here's the data…

Raw Data: Before any analysis cuts are applied:

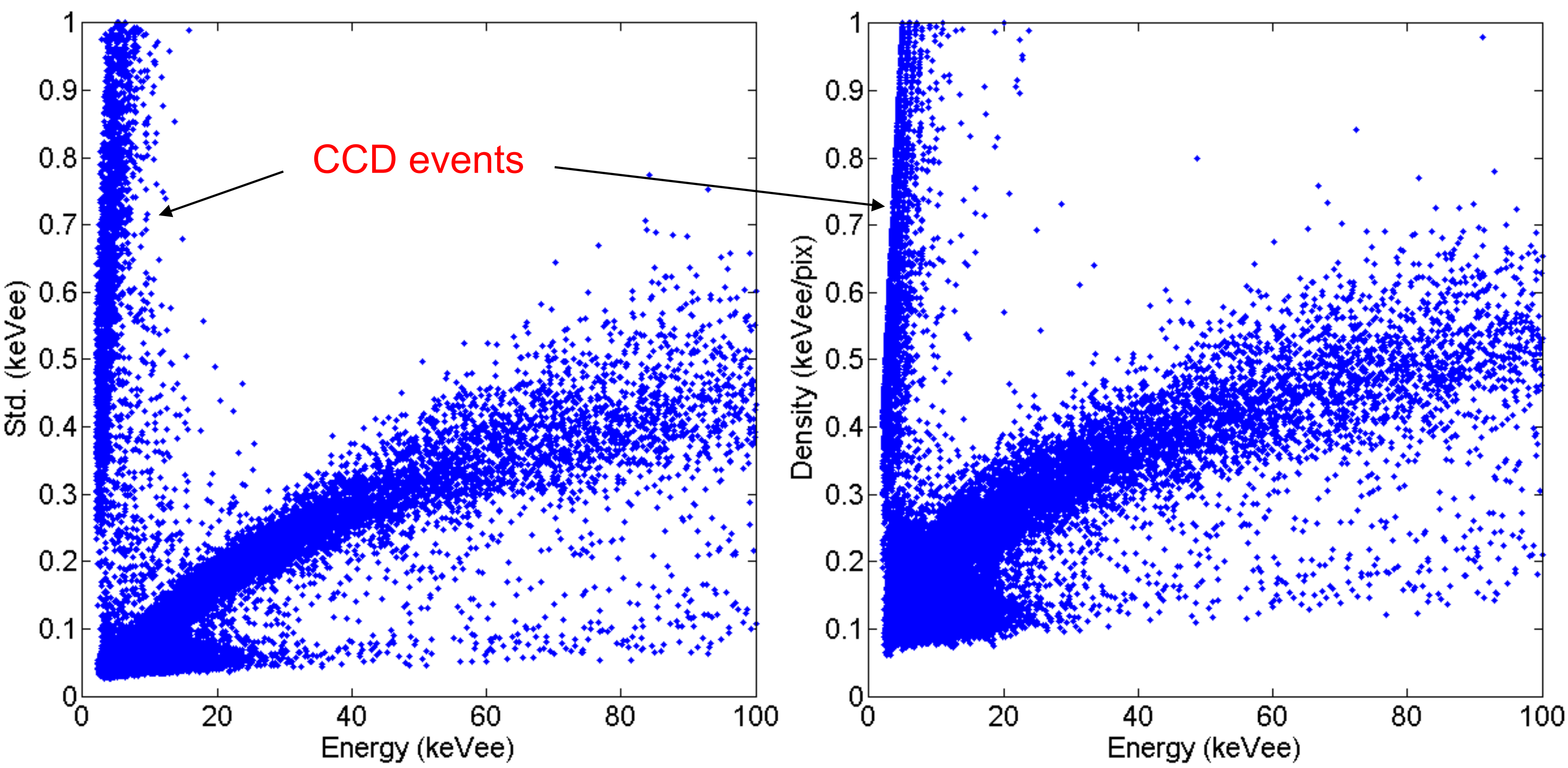


Direct interaction of high energy photons, cosmic rays, neutrons, etc, in the CCD sensor.

CCD Event Cuts

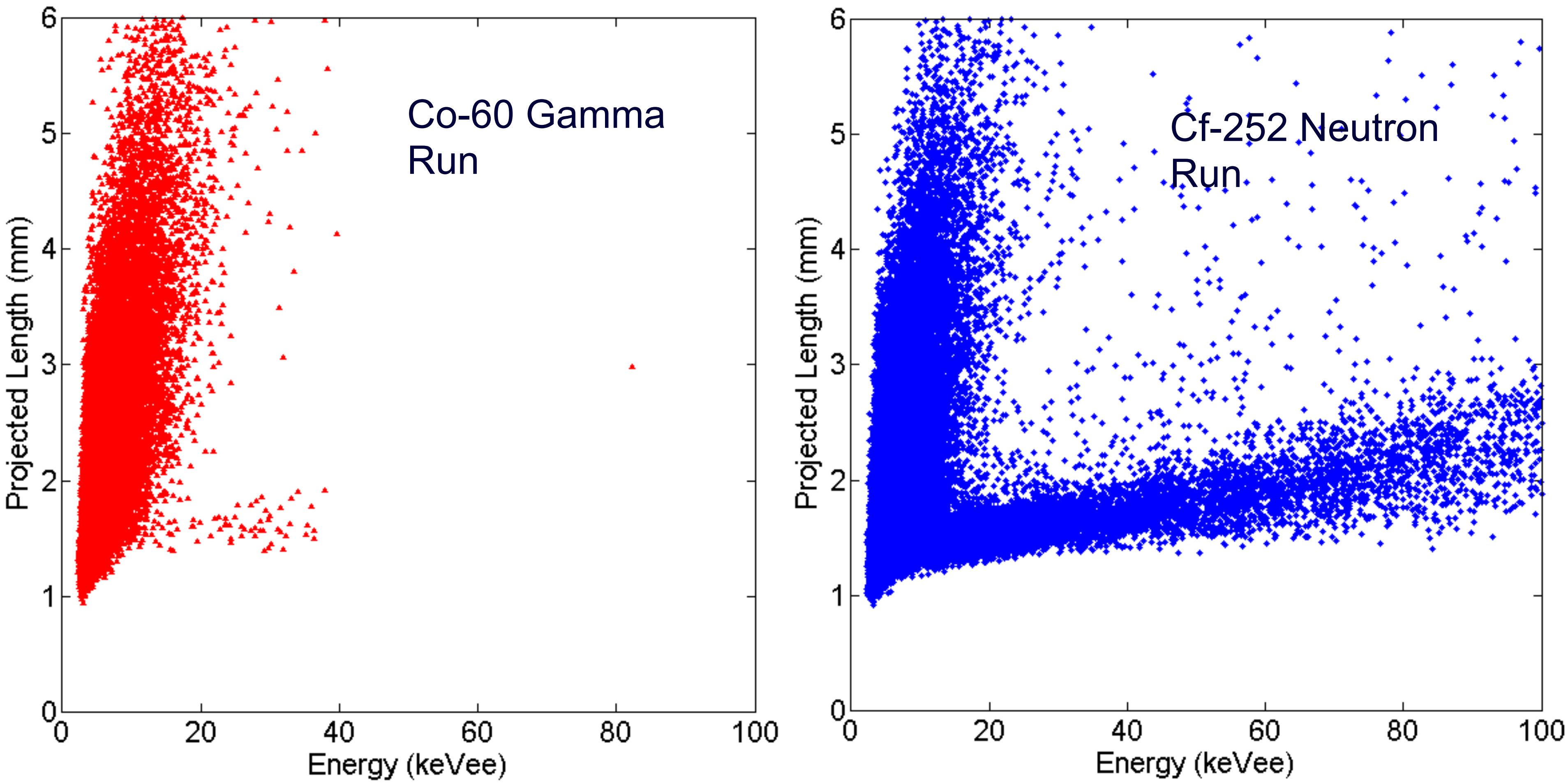
Standard deviation of pixels in a given track.

Ratio of total energy (keVee) to the total number of pixels.



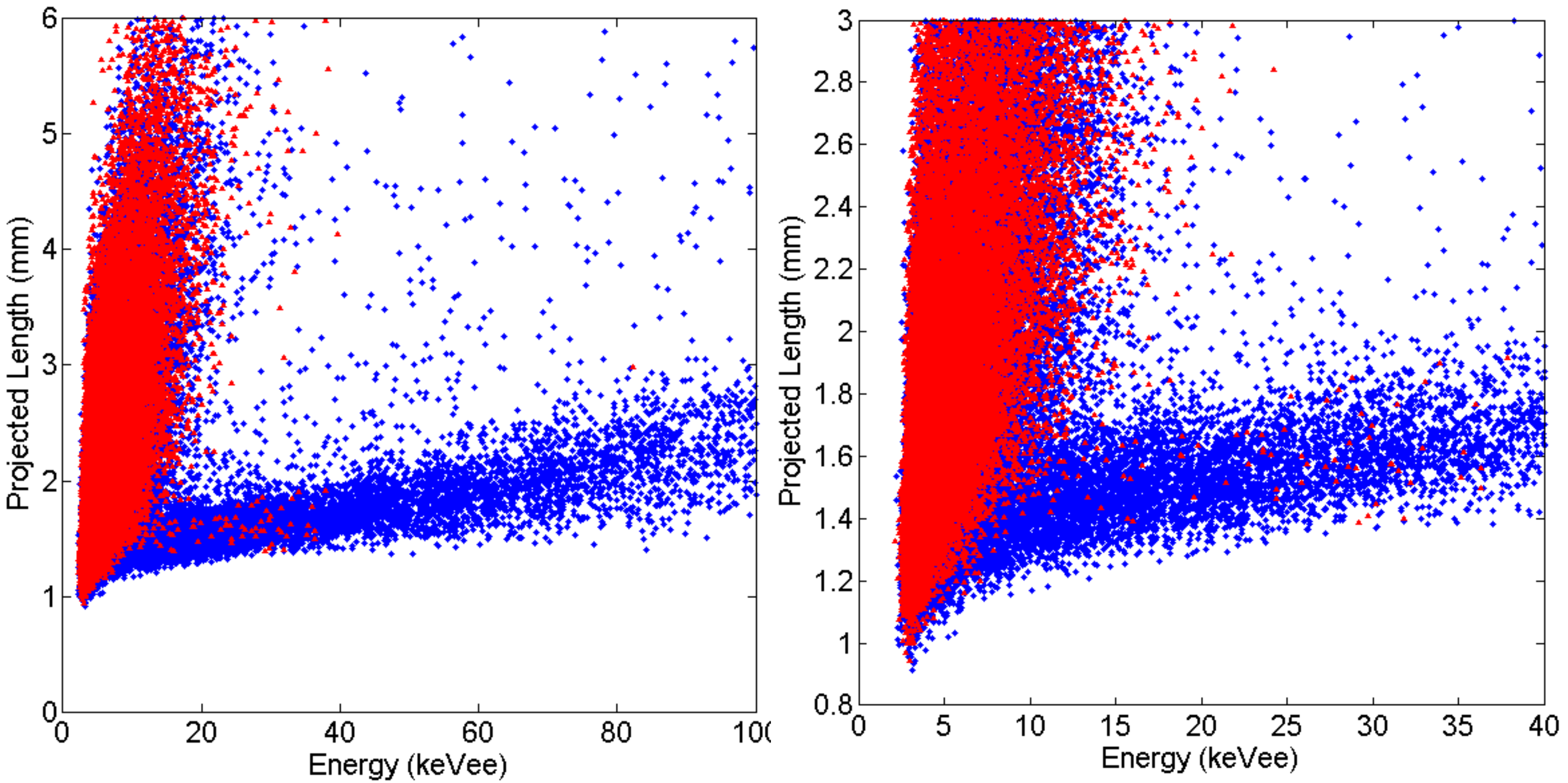
Neutron Run Data

After cuts to remove CCD events

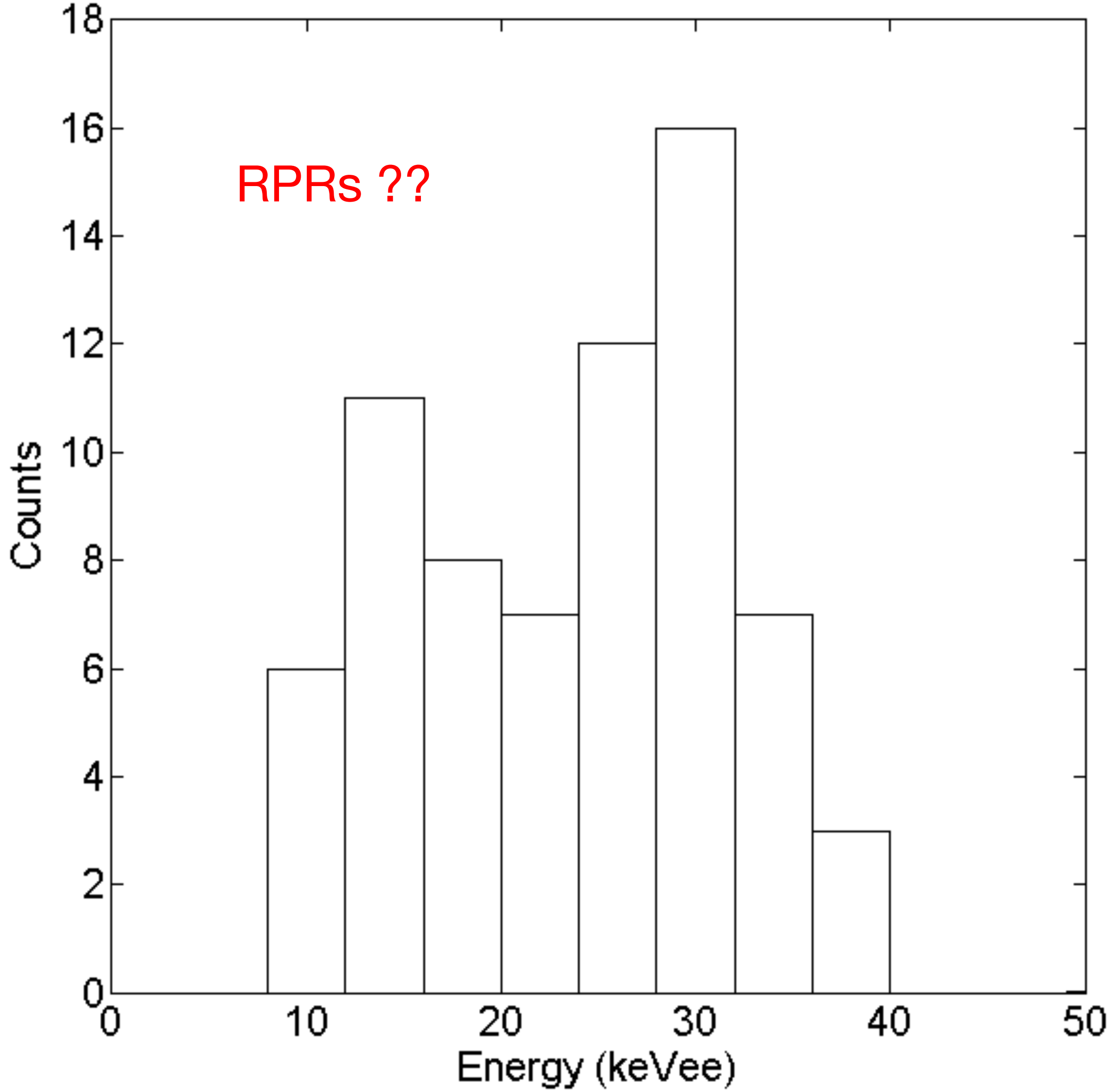


The minimum track length agrees with the expected length for a point-like track with ~ 350 um diffusion (sigma) (810 um FWHM).

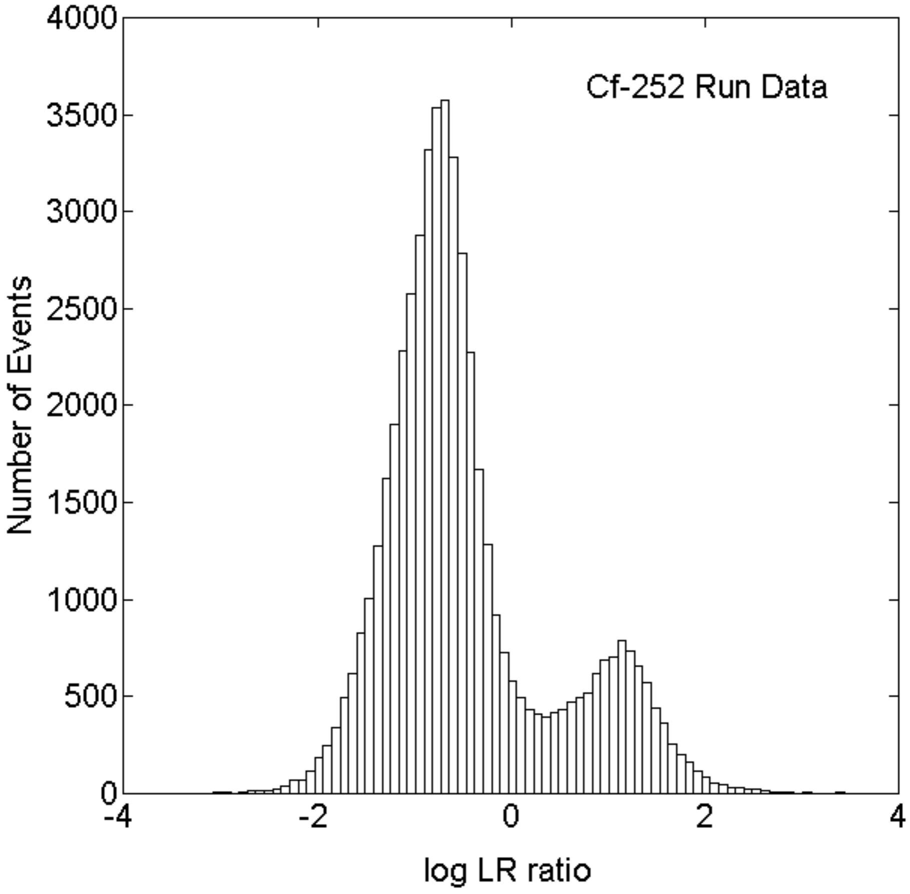
Overlay of neutron run data with gamma run data.

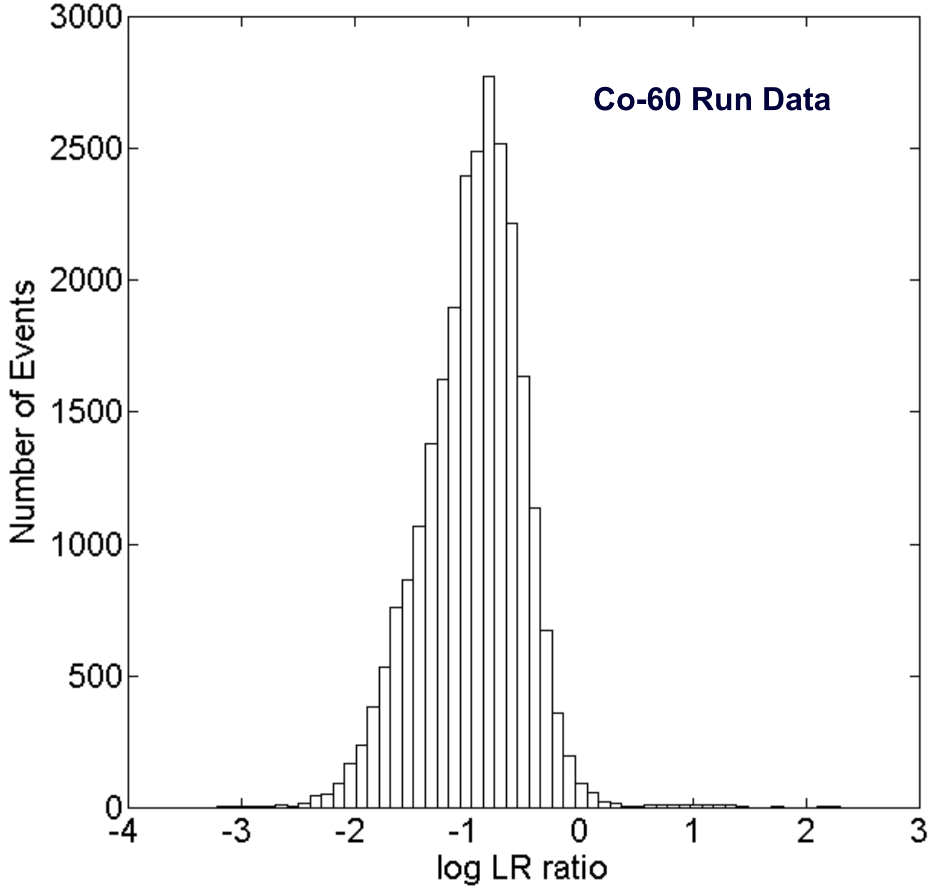


Events from gamma run passing the electronic recoil cuts

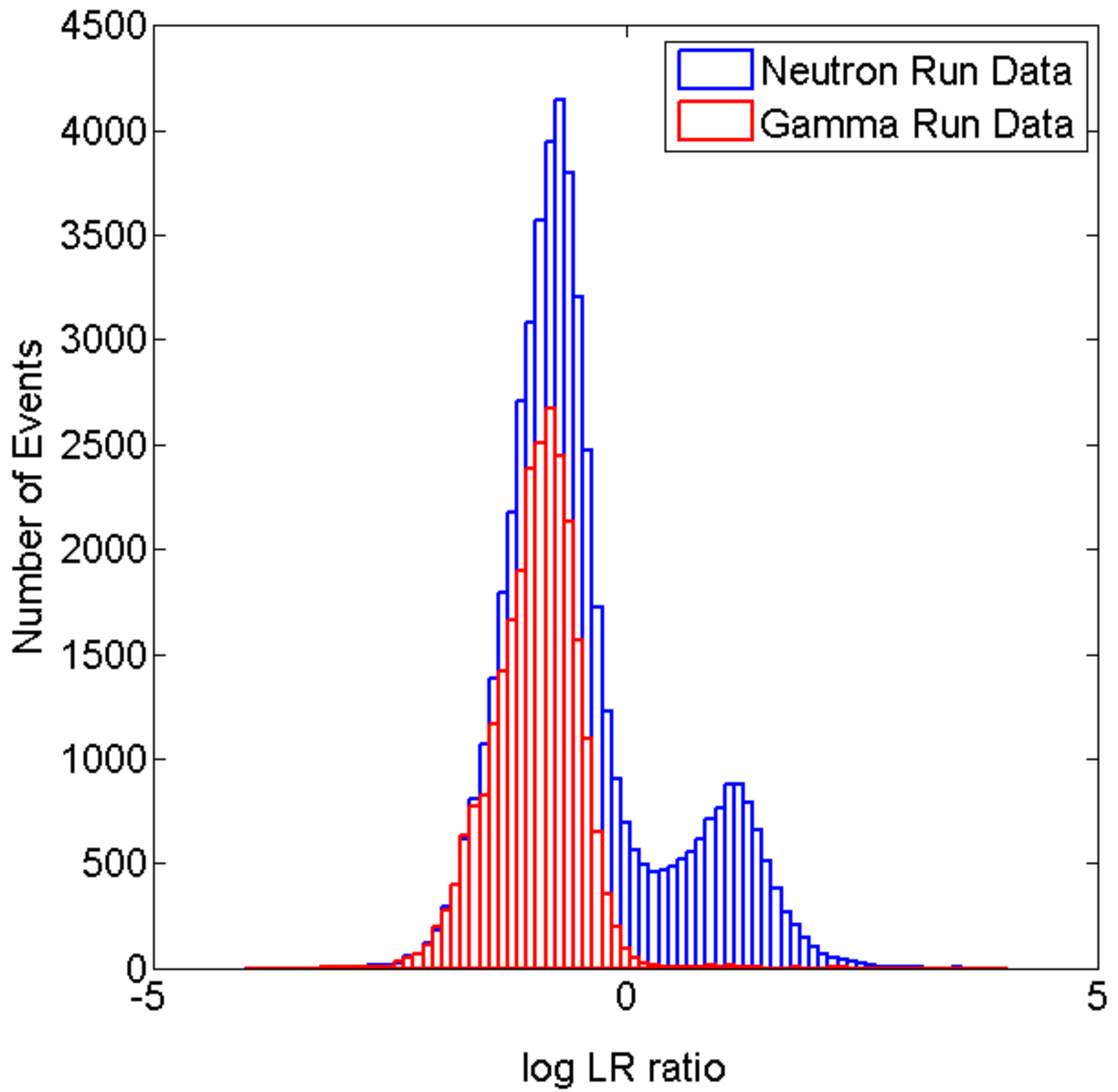


Electronic Recoil Cuts

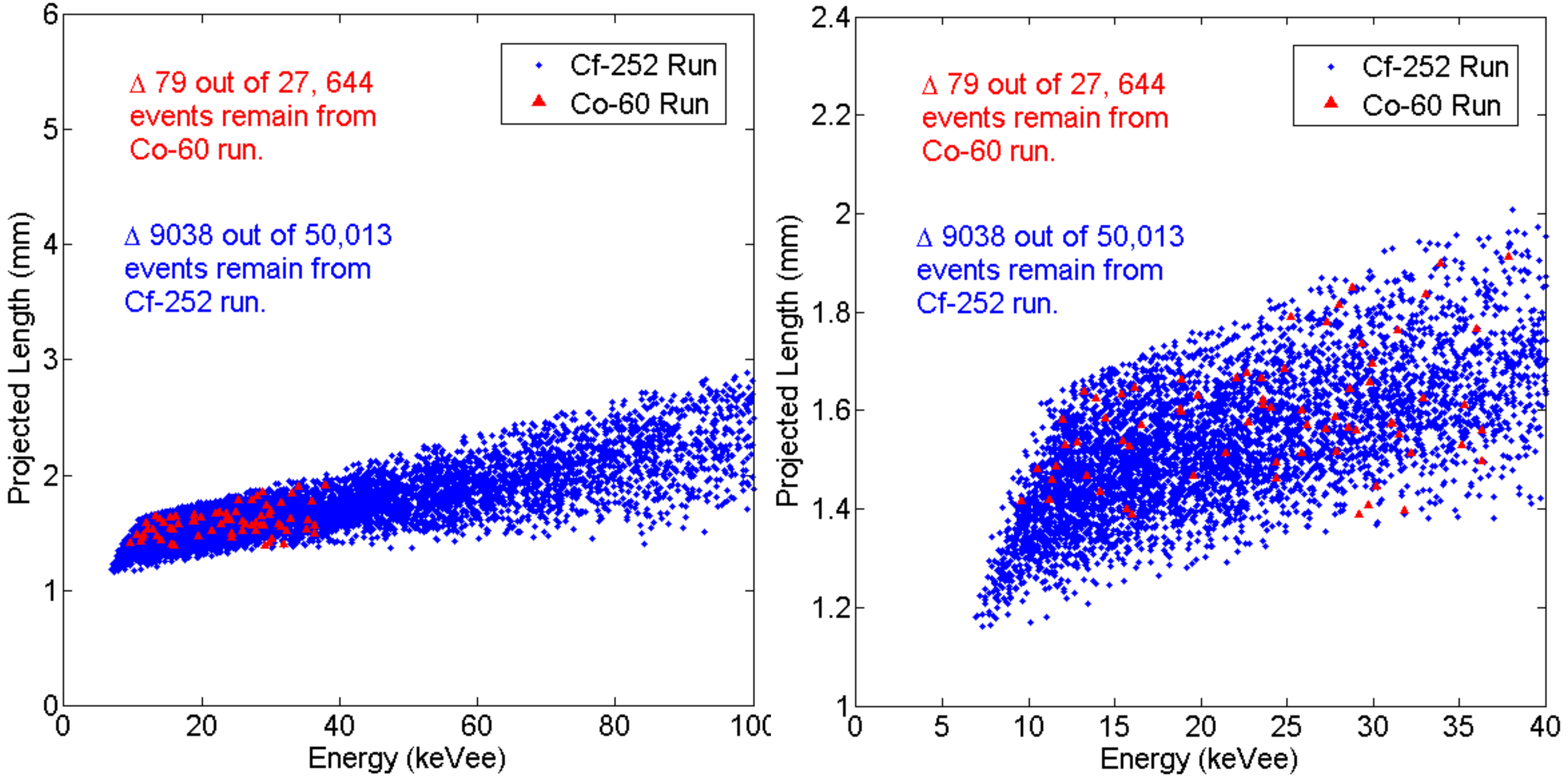




LR: Peak charge to track length ratio



Neutron Run Data
Gamma Run Data
Number of Events
log LR ratio
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-5
0
5



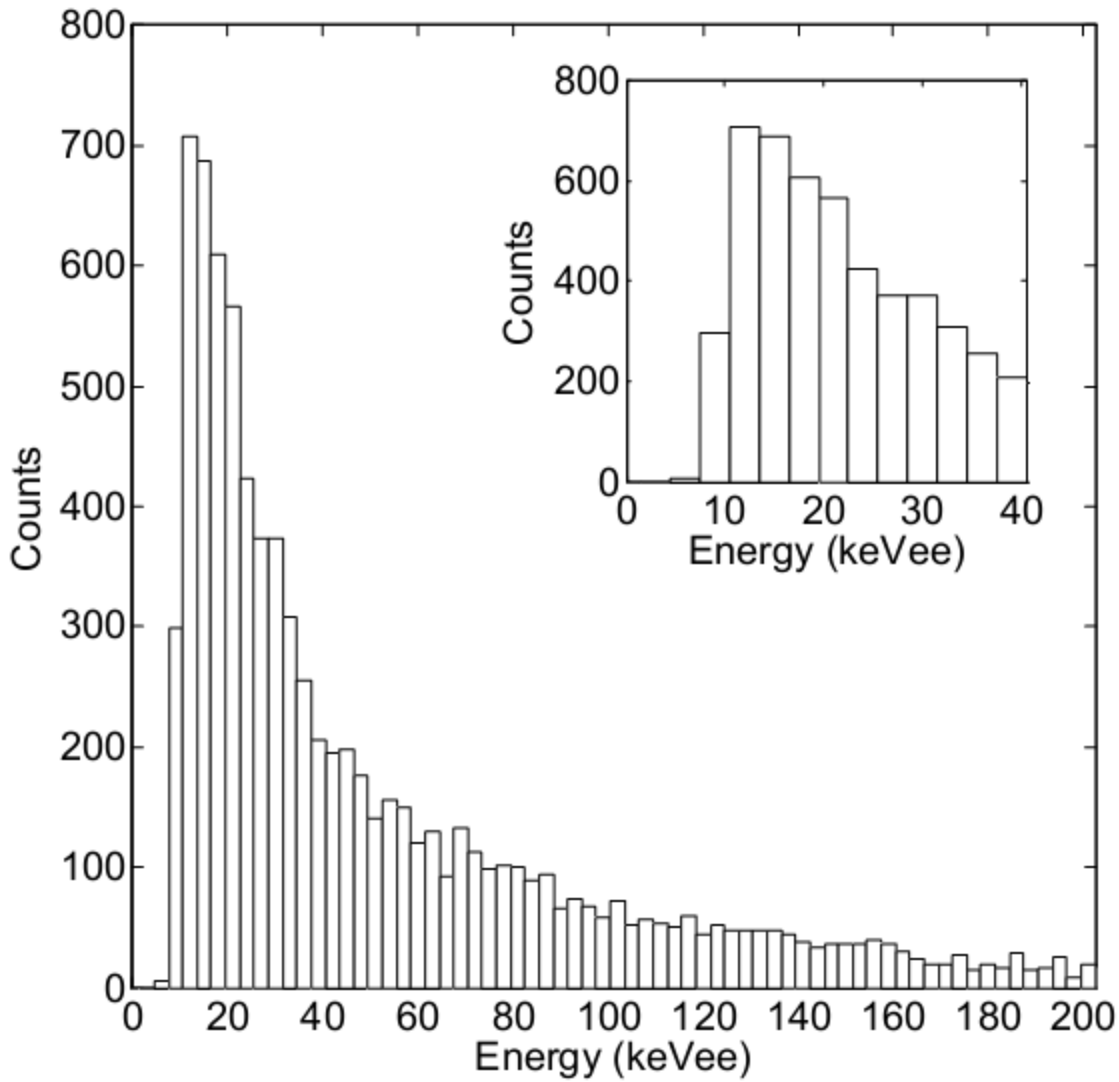
<u>Gamma Run Events:</u>

27,644 (no cuts)
25,763 (CCD events cut)
79 (all cuts)

<u>Neutron Run Events:</u>

55,013 (no cuts)
51,137 (CCD events cut)
9,024 (all cuts)

Energy spectrum of nuclear recoils post analysis cuts



Discrimination threshold: ~10 keVee (~25 keVr, Hitachi).

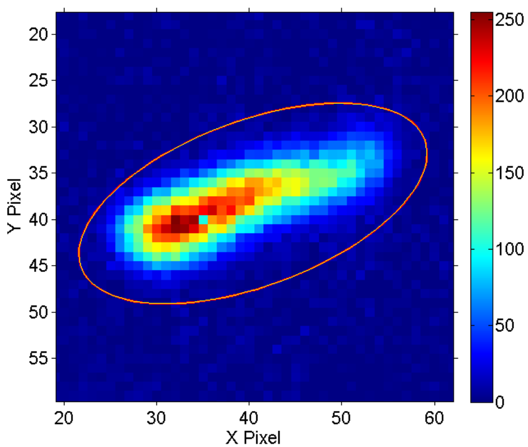
Directionality

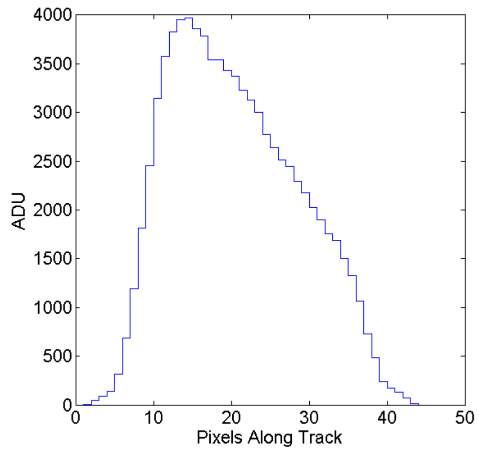
Our analysis takes all events that are classified as neutrons (above our threshold of 25 keVr) and determines their directionality. This involves:

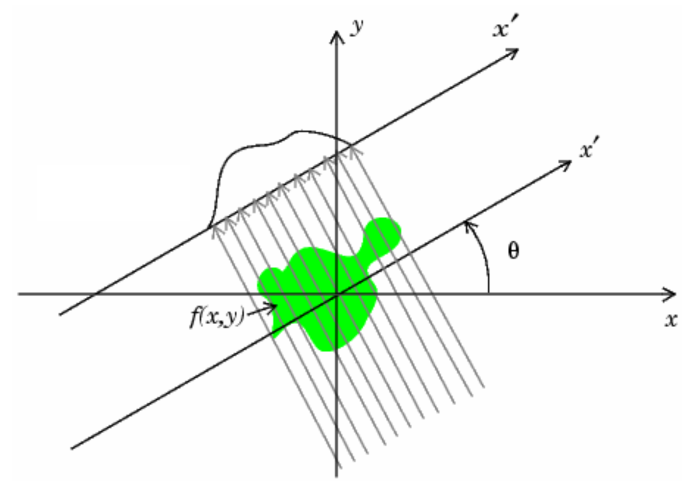
1. Determining the minor and major axes (their length and orientation)
2. Projecting the pixels in the track along the major axis and determining its skewness (head-tail)

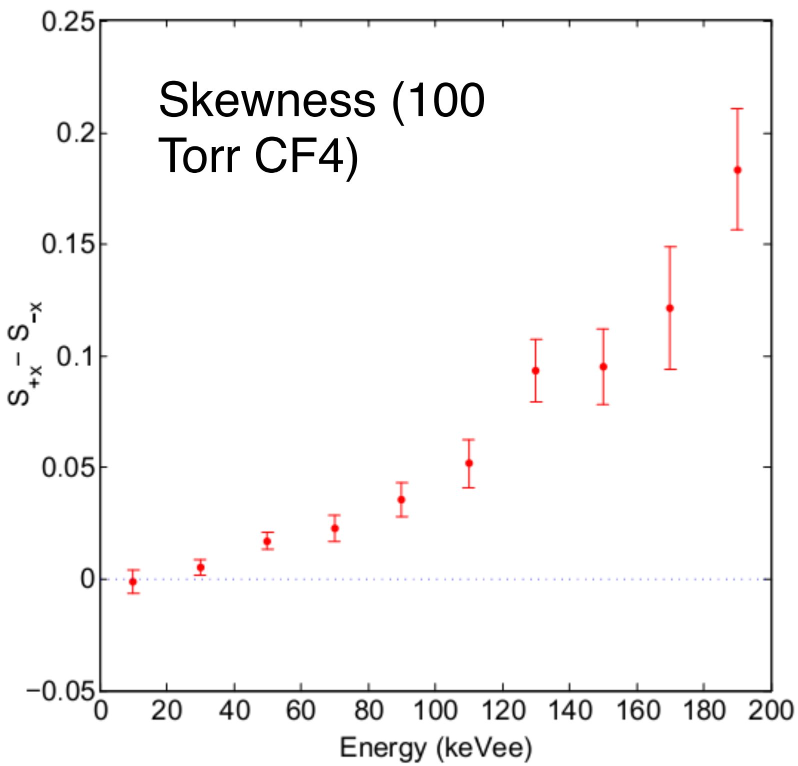
For minor/major Axis length Ratio AR~1, directionality, as determined in this way, is lost. In fact, correct skewness may still exist in the diffused blob, but other algorithms should be used to quantify it.

Head-tail









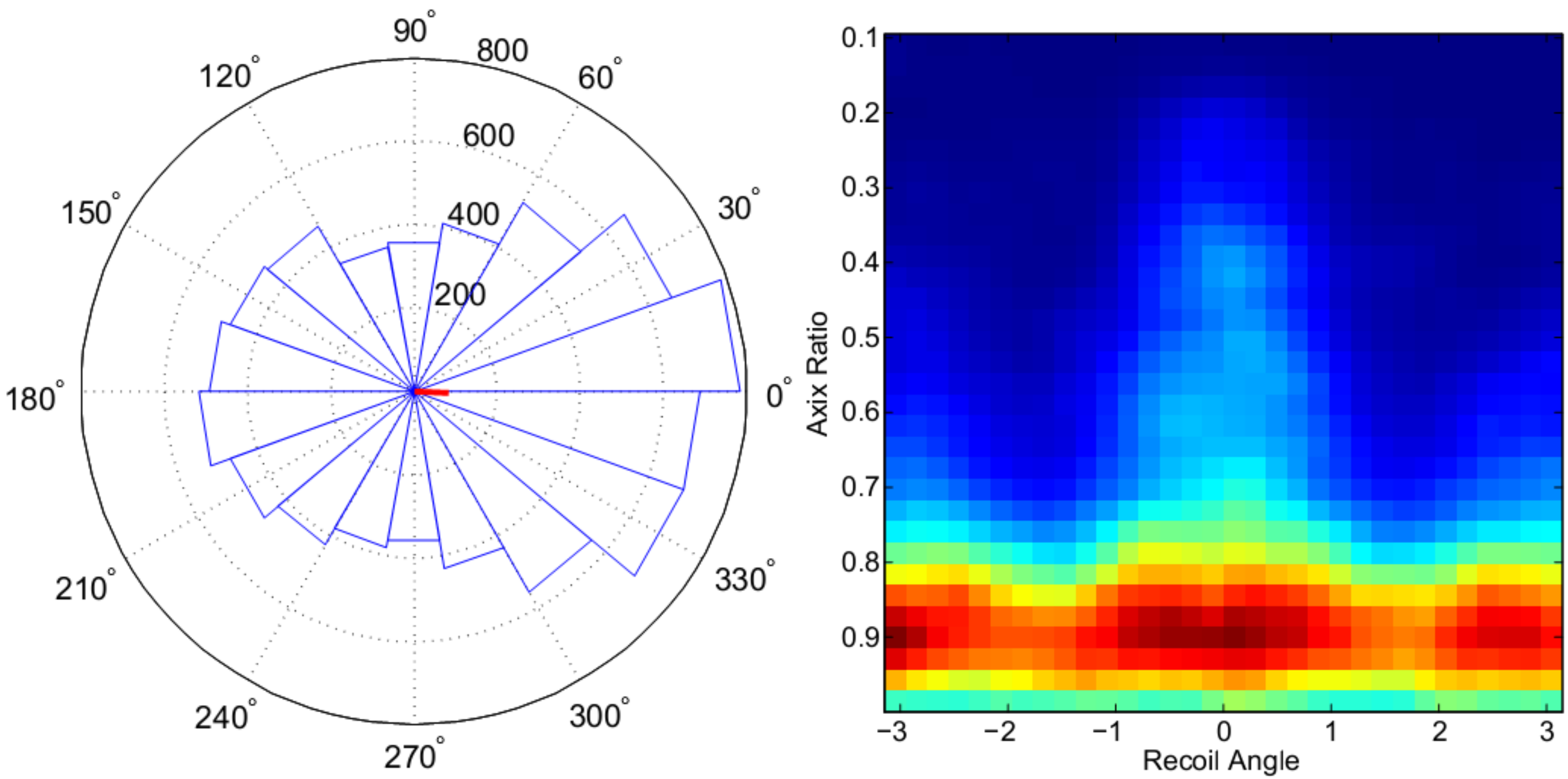
$$s = \frac{\mu_3}{\mu_2^{3/2}}$$

μ_2 and μ_3 are the 2nd and 3rd central moments of the light distribution.

Head-tail measured down to ~55-60 keVr. It is even better because ~30% of our data consists of scattered neutrons.

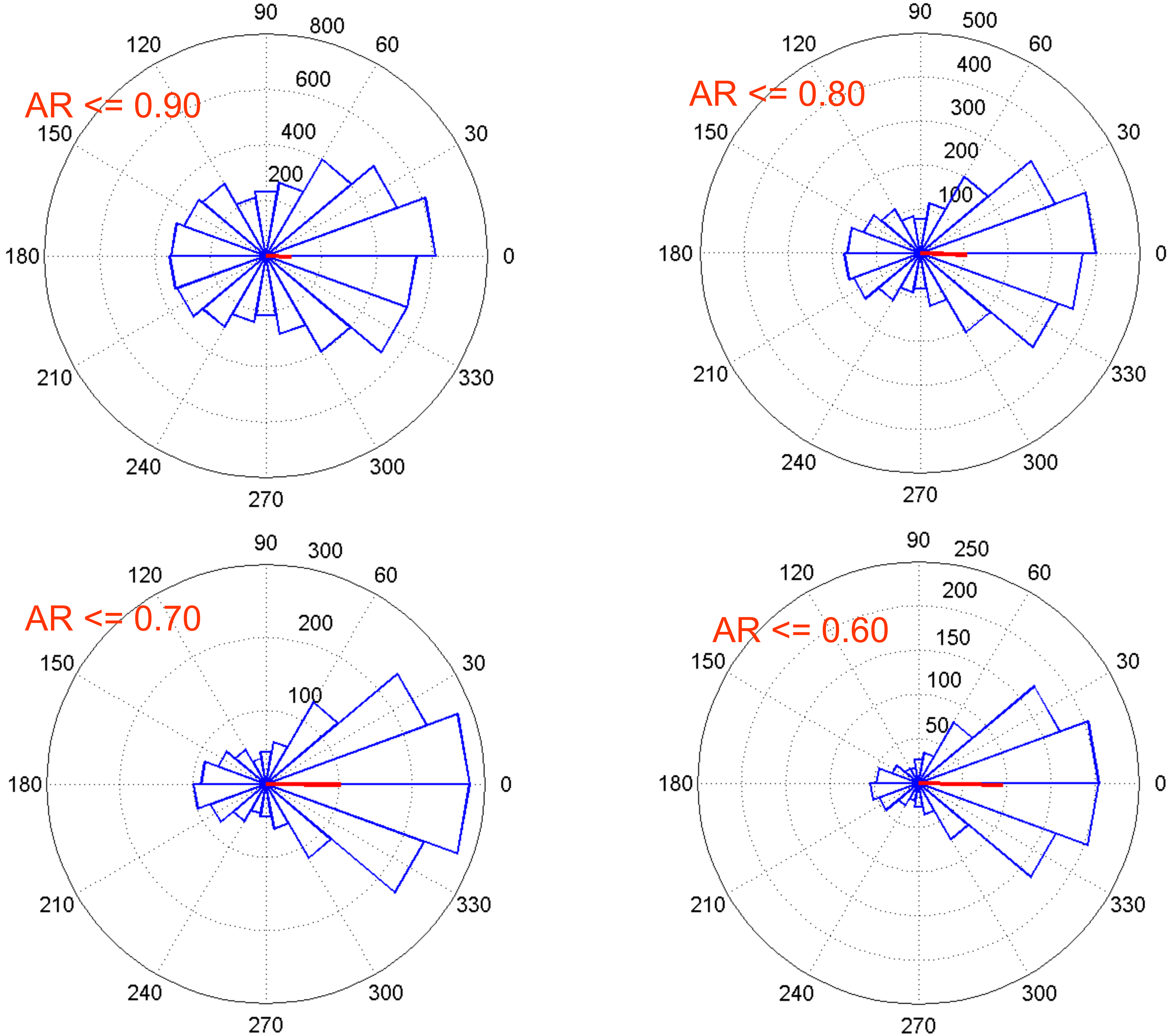
Note that no assumption is made of neutron direction in this analysis.

2D Vector Directionality



Circular histogram of <u>all events</u> classified as nuclear recoils (>25 keVr):

- Red line segment represents the magnitude and direction of the mean resultant vector.
- Antipodal peak due to incorrect assignment of skewness.
- Uniform component due to ambiguity in major axis of very round tracks and scattered neutrons (when AR is close to 1)

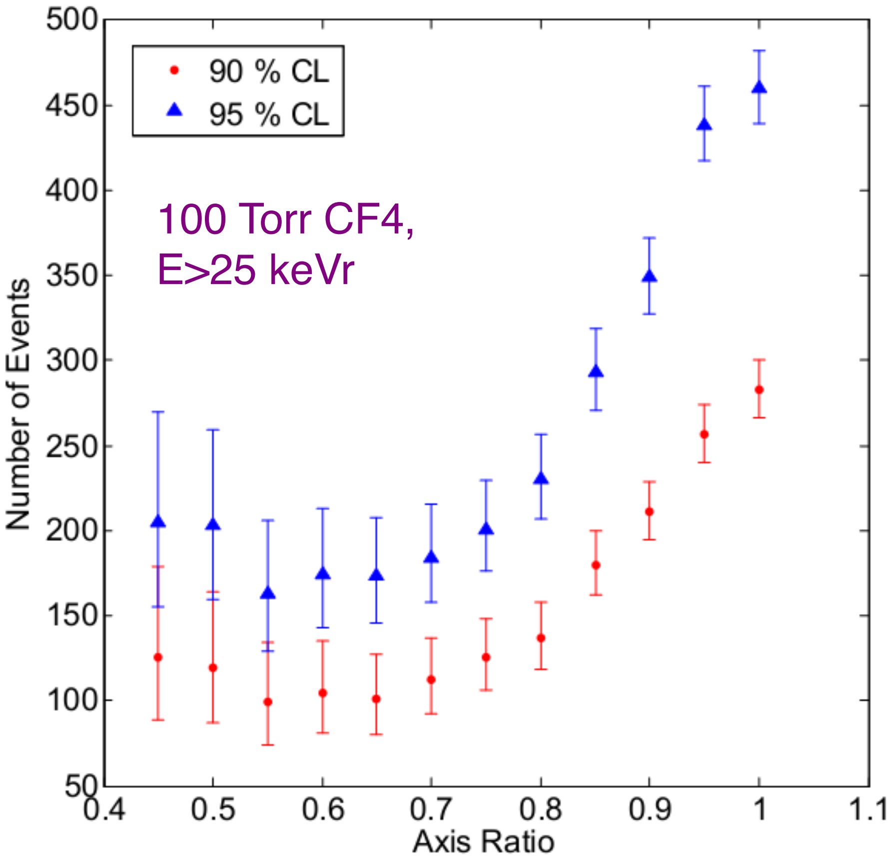


AR <= 0.90
AR <= 0.80
AR <= 0.70
AR <= 0.60

Number of Events for Rejection of Isotropy

- Number of events, N, found using Monte Carlo and modified Rayleigh test.

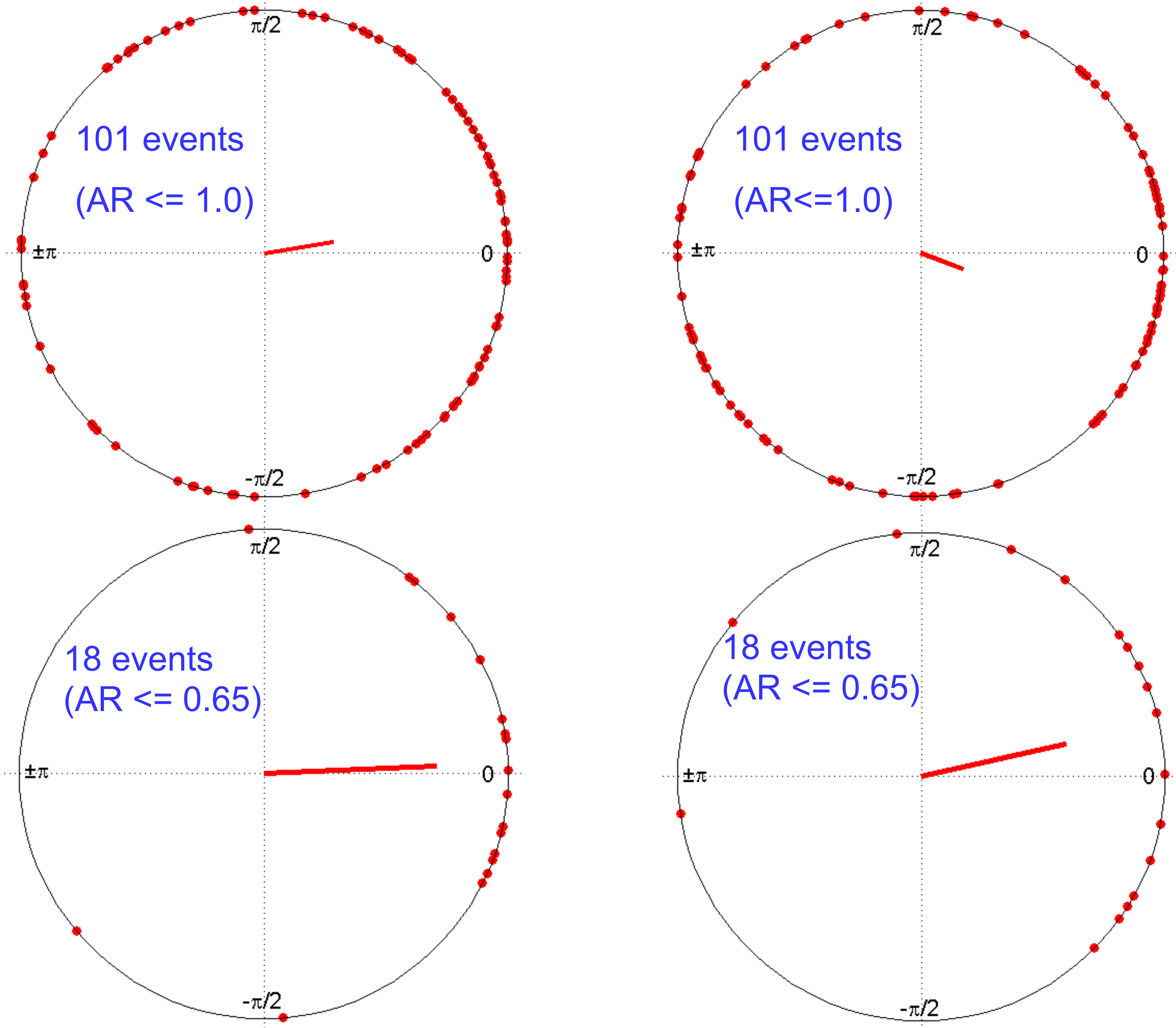
$$V = R\cos(\phi_N - \phi_0)$$



Axis Ratio	90% CL	95% CL
1.00	283	460
0.95	234	400
0.90	150	248
0.85	92	150
0.80	50	84
0.75	35	56
0.70	25	41
0.65	18	31
0.60	15	25
0.55	11	18
0.50	10	17
0.45	8	13

Table 1: The number of events, N_{tot}, needed to reject uniformity at 90% and 95% confidence levels for different cuts on the axis ratio prior to making that cut. The last column gives the number of events in the data set that have an axis ratio equal to or less than the value in the corresponding row.

Axis Ratio	90% CL	95% CL
1.00	283	460
0.95	257	439
0.90	211	349
0.85	180	293
0.80	137	230
0.75	126	201
0.70	113	185
0.65	101	174
0.60	105	174
0.55	100	163
0.50	120	203
0.45	126	205



101 events
(AR <= 1.0)
101 events
(AR<=1.0)
18 events
(AR <= 0.65)
18 events
(AR <= 0.65)
π/2
±π
0
-π/2

II. Implications for a directional low mass WIMP search

Ms. CYGNUS-Lite??

II. Implications for a directional low mass WIMP search

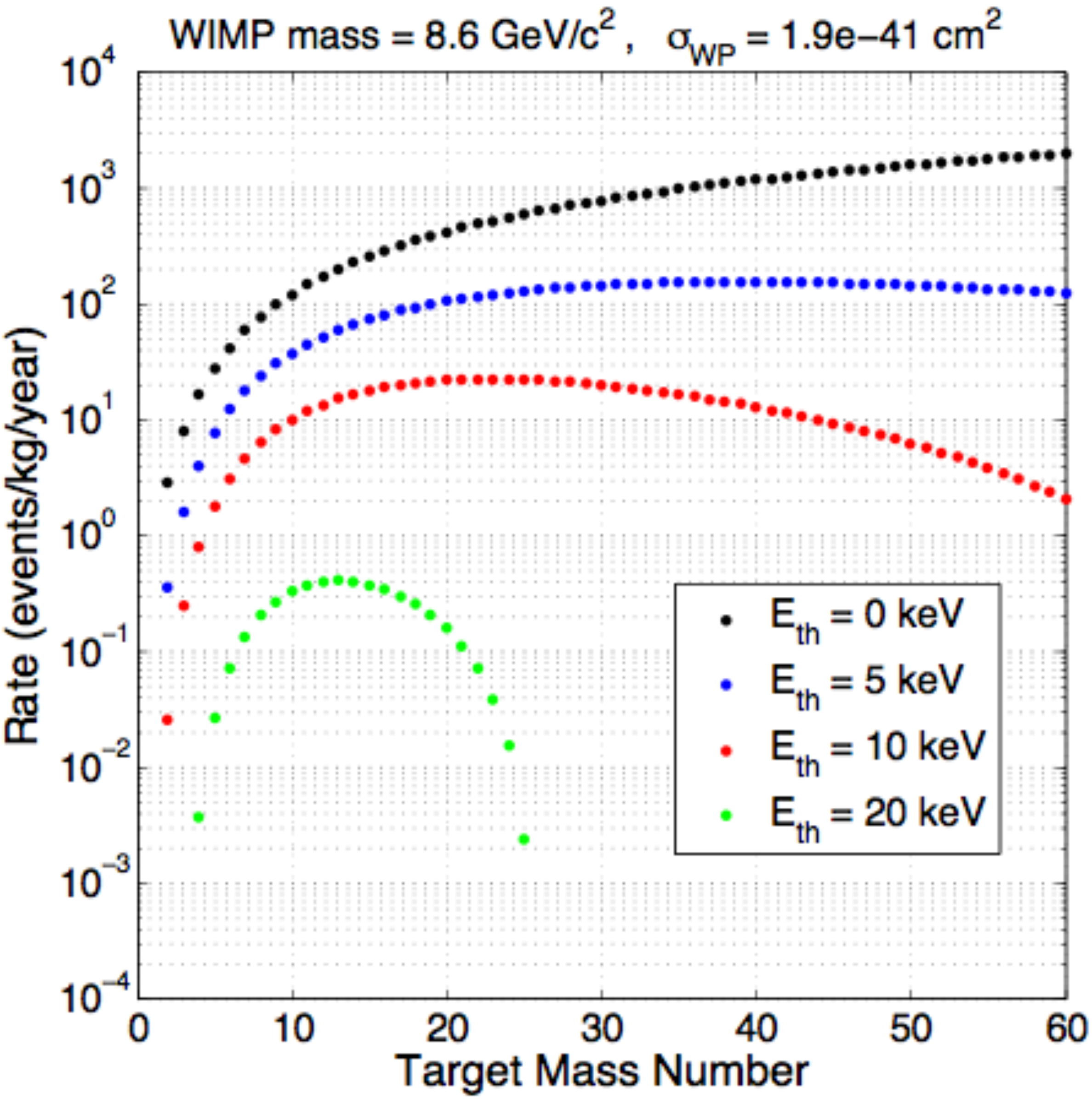
Can we use the results from this work to make a case study for directional low mass WIMP searches?

The experimental parameters critical to our results in 100 Torr CF4 are:

1. high S/N
2. Low diffusion (~0.4mm)
3. High spatial resolution

The first enabled excellent discrimination down to 10 keVee, the second enabled directionality at ~55 keVr. *In 100 Torr CF4 the latter corresponds to F tracks with R~0.6mm. We'll use this in the following.*

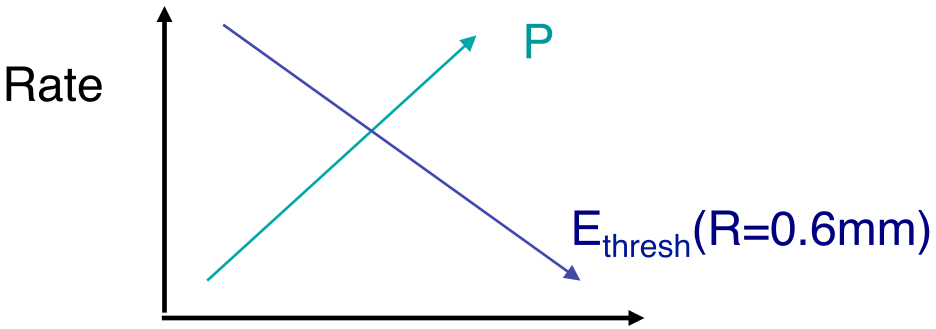
The CDMS Low Mass WIMP *

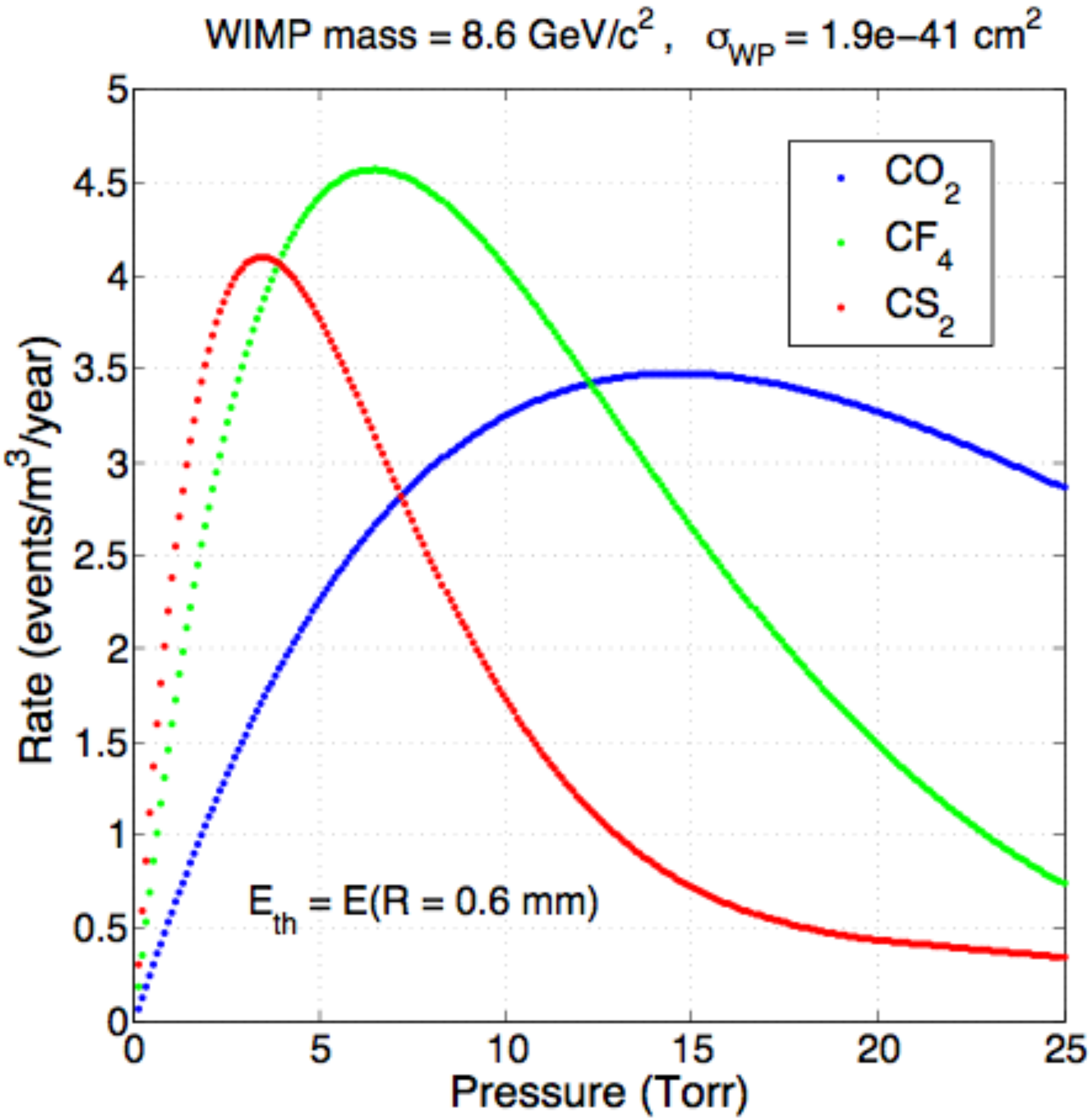


* We will assume a SI LMW

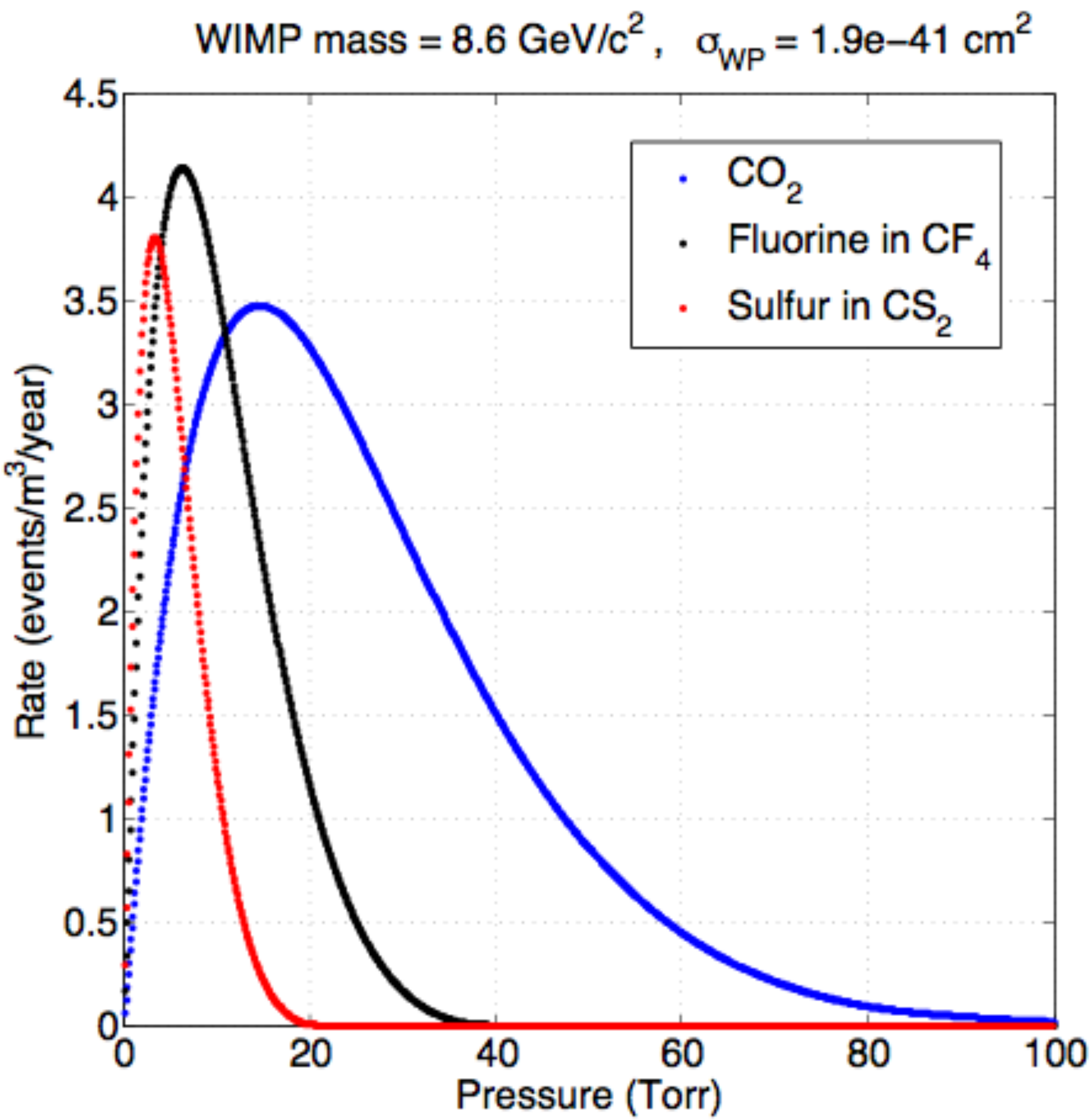
-> The A^2 gain is offset by a steepening spectrum when $E_{threshold}$ is imposed.
-> Requiring directionality further exasperates this.

For this study lets require that the $E_{threshold}$ is where directionality “turns on”. In our work this corresponds to a R = 0.6mm (with σ_{diff}~0.4mm).
In the plot on the next page we maximize the interaction rate above $E_{threshold}$ in a m^3 volume by varying the pressure for each target gas

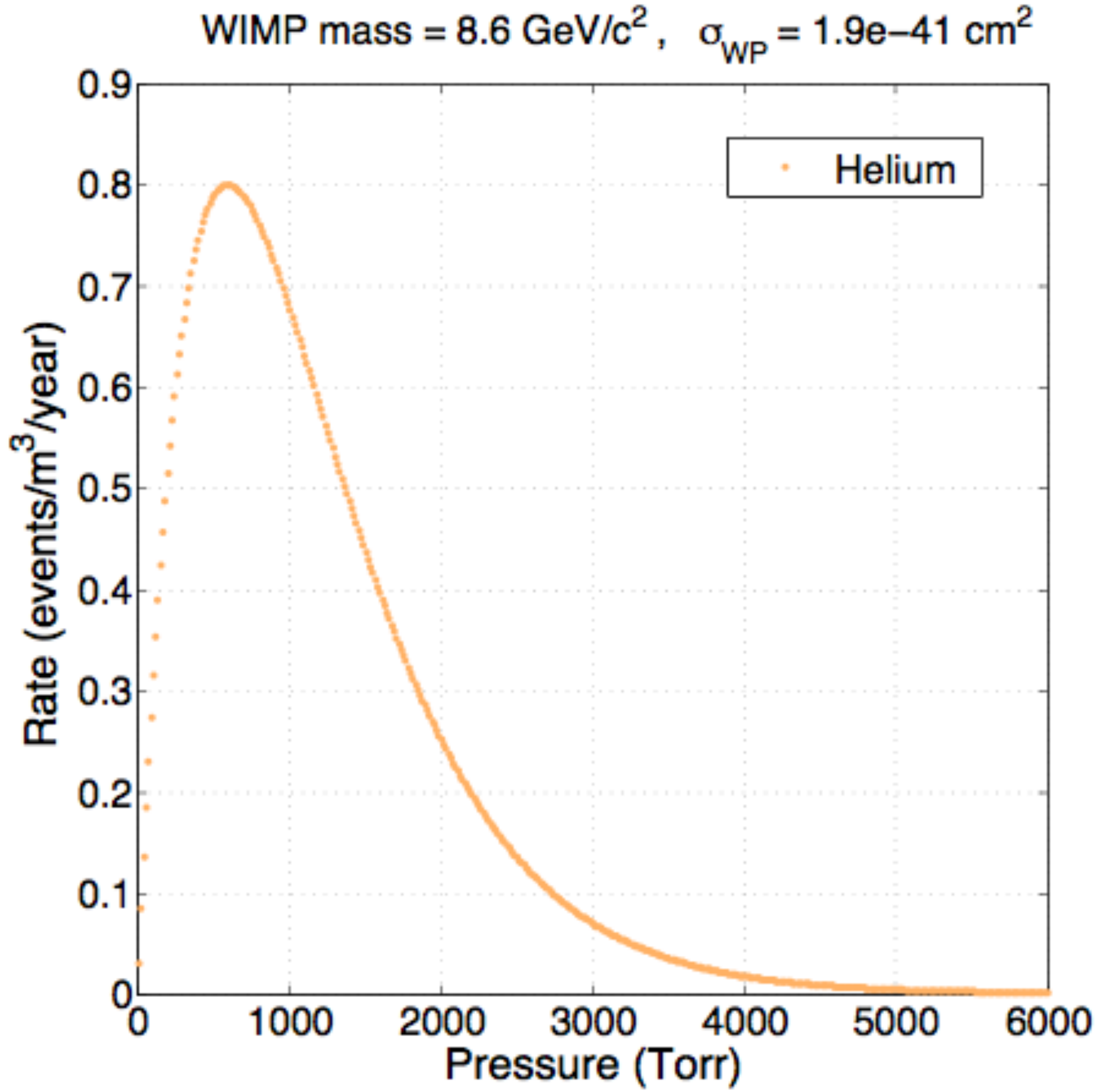




WIMP mass = 8.6 GeV/c^2 , σ_{WP} = 1.9e−41 cm^2
Rate (events/m^3/year)
Pressure (Torr)
CO_2
CF_4
CS_2
E_{th} = E(R = 0.6 mm)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
5
10
15
20
25

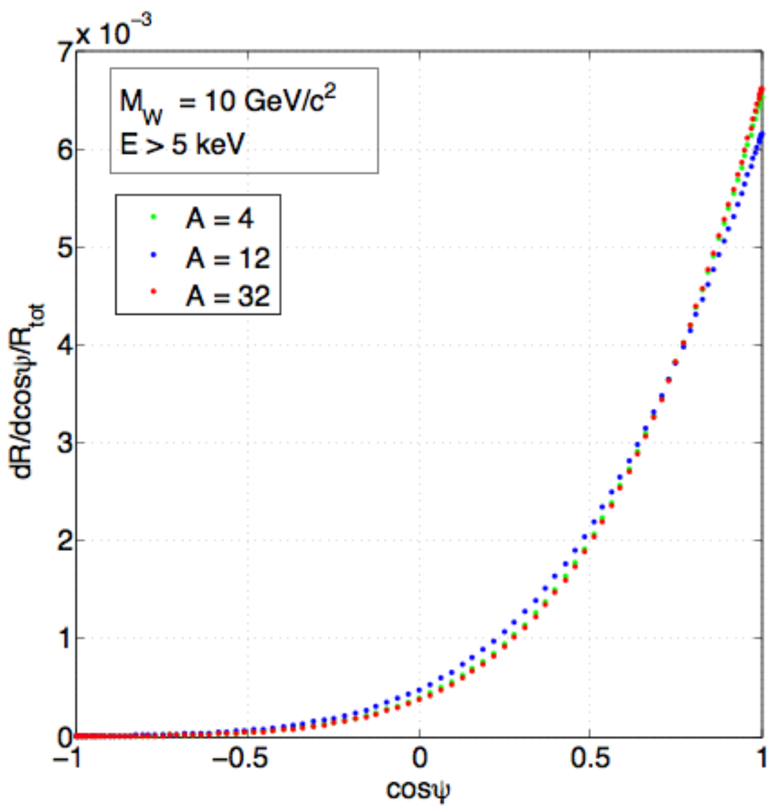


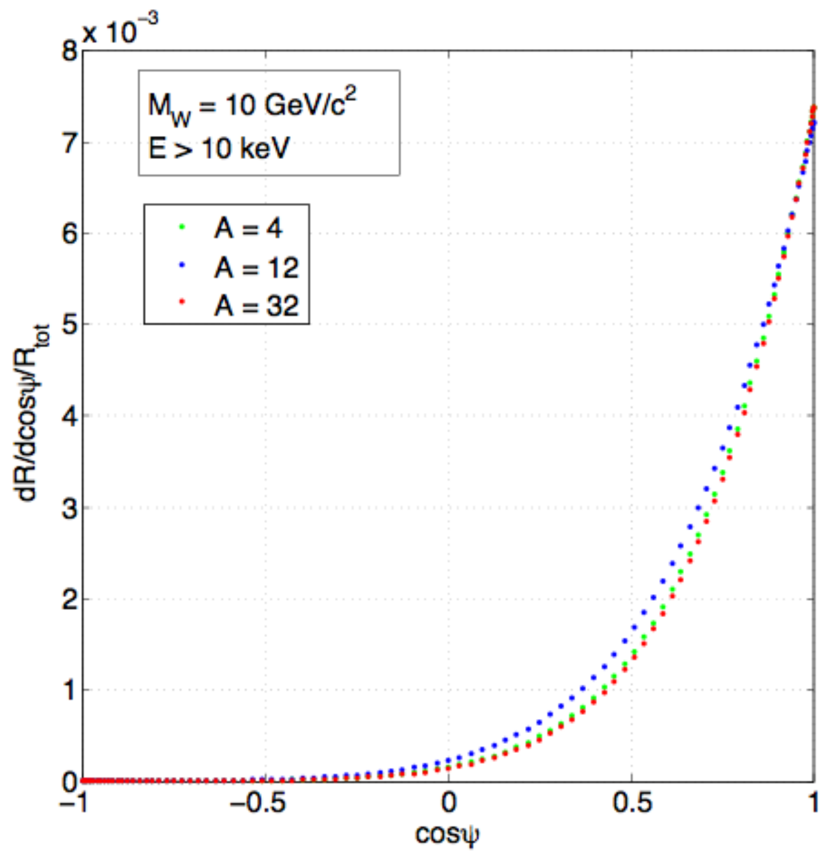
WIMP mass = 8.6 GeV/c^2, σ_{WP} = 1.9e−41 cm^2
CO_2
Fluorine in CF_4
Sulfur in CS_2
Rate (events/m^3/year)
Pressure (Torr)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
0
20
40
60
80
100



WIMP mass = 8.6 GeV/c2 , σWP = 1.9e−41 cm2
Helium
Rate (events/m3/year)
Pressure (Torr)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
1000
2000
3000
4000
5000
6000

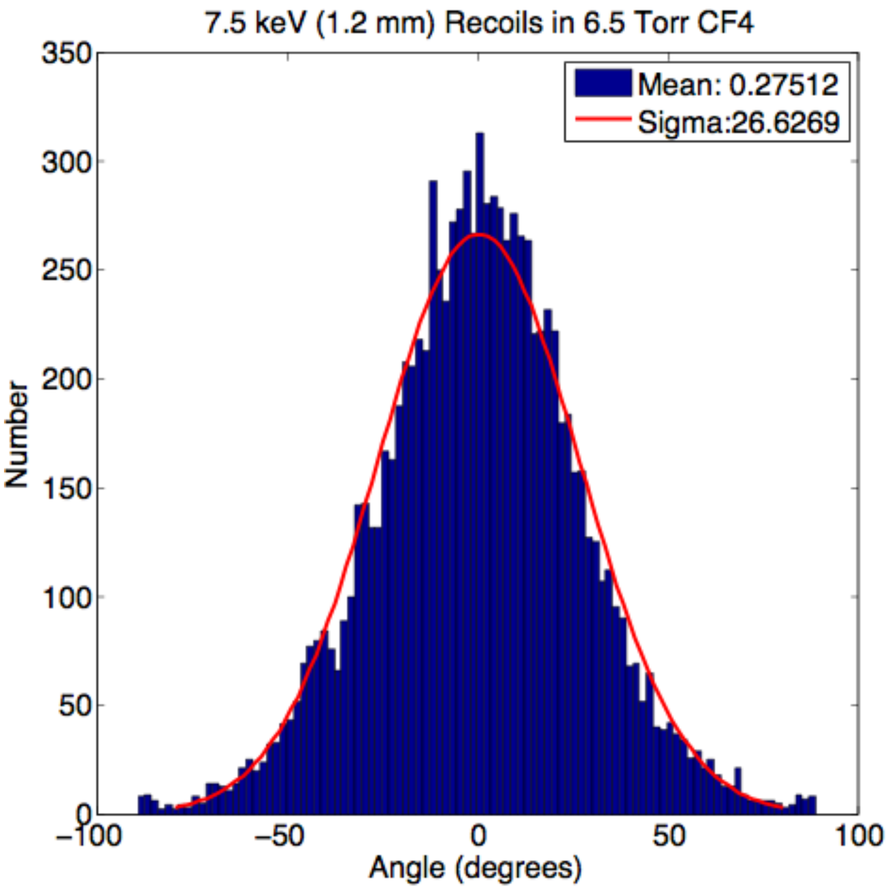
What about the angular spectra?

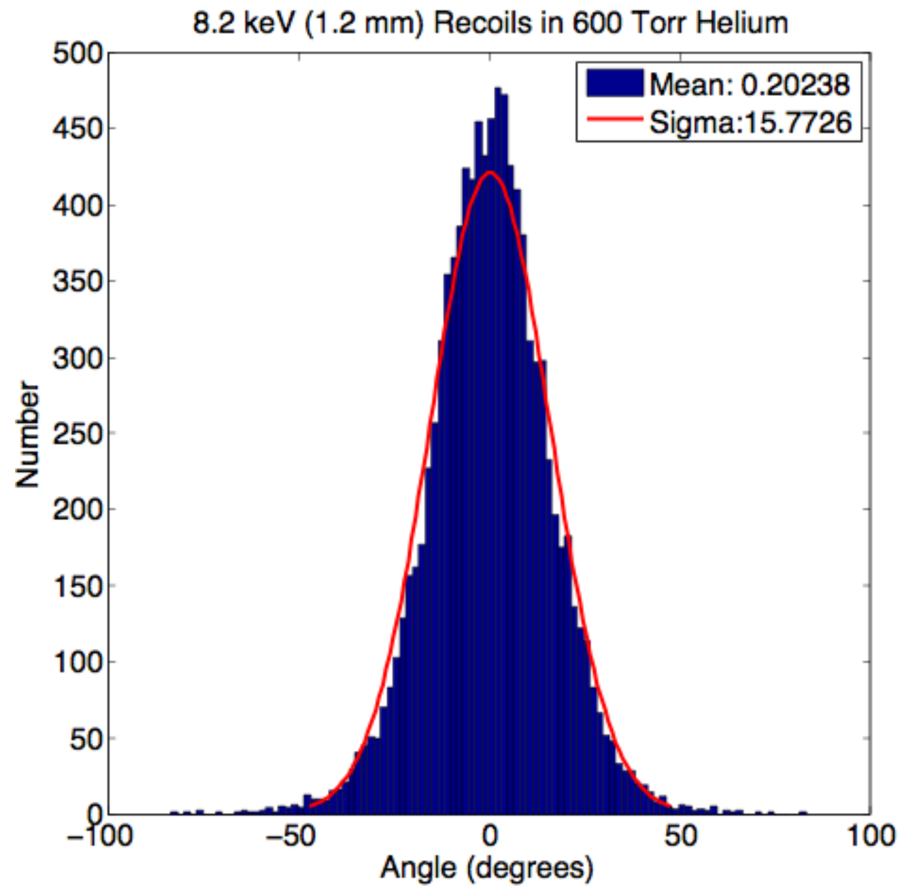




Agrees with Billard et al. PLB 691 (2010)

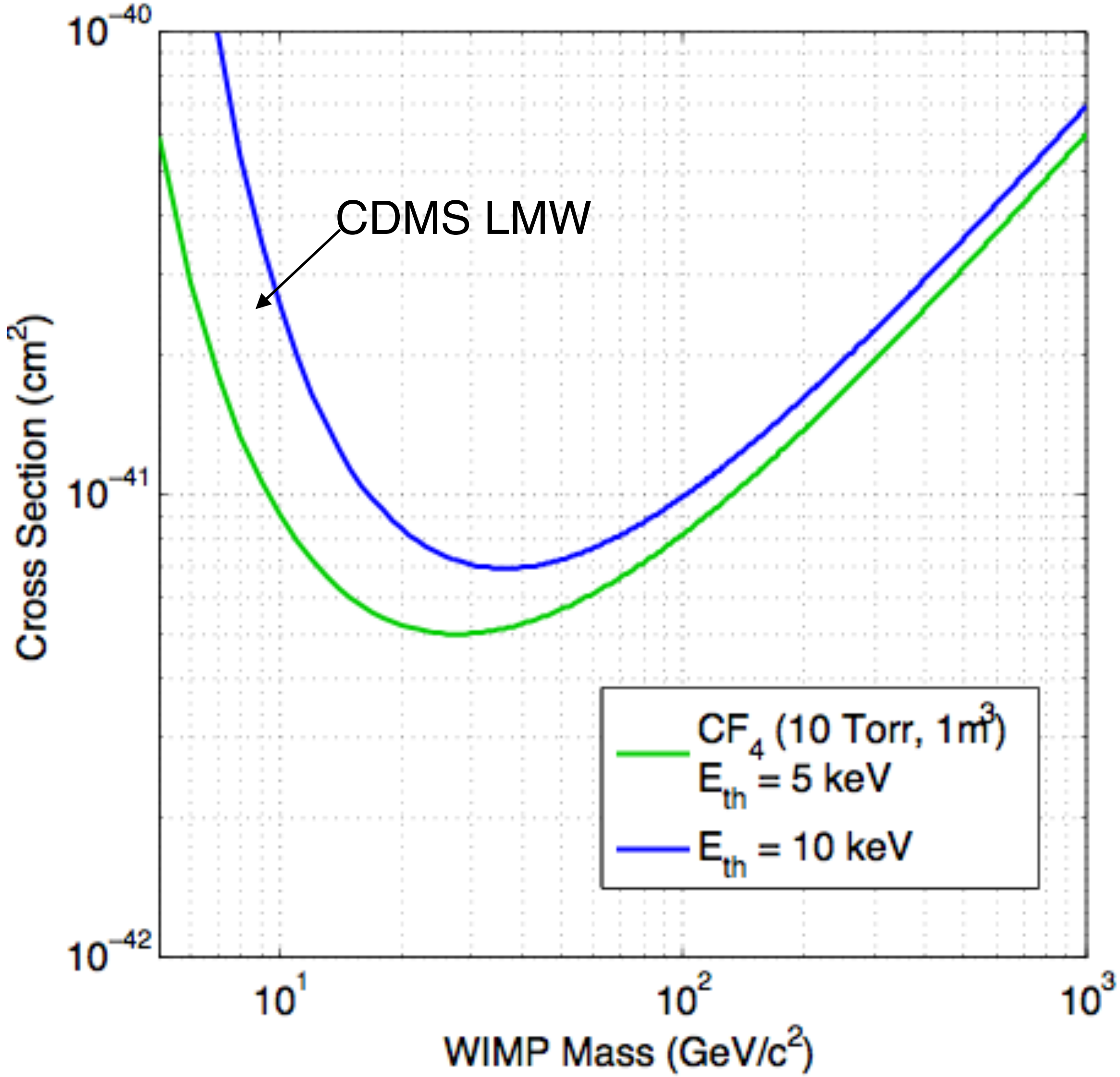
…and Straggling? *





* Here we used SRIM to generate 1.2 mm directional recoils of F and He, which were then diffused (σ=0.4mm) and run through our analysis. S/N was set high.

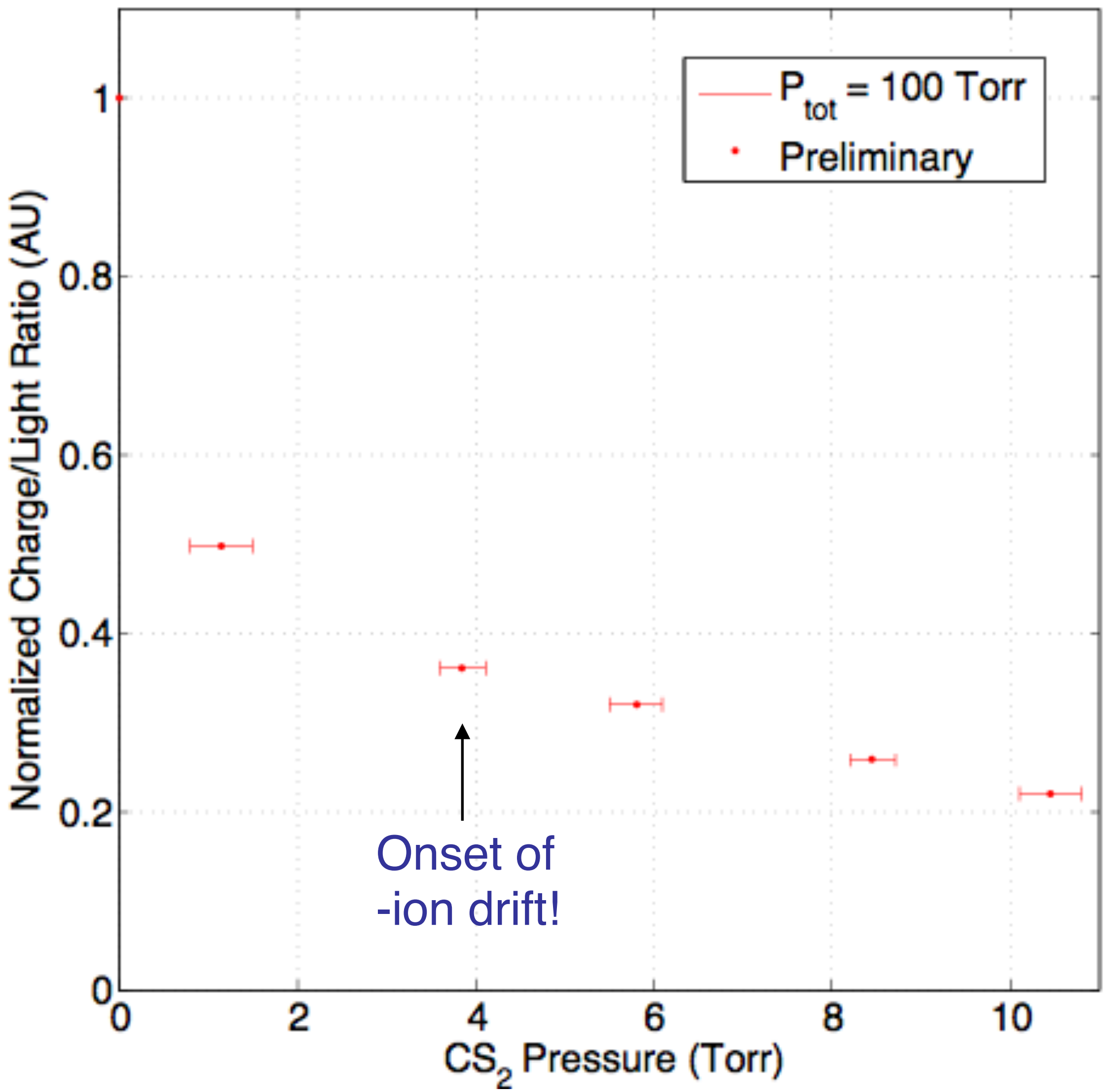
Limits in 1 yr for 1 m^3



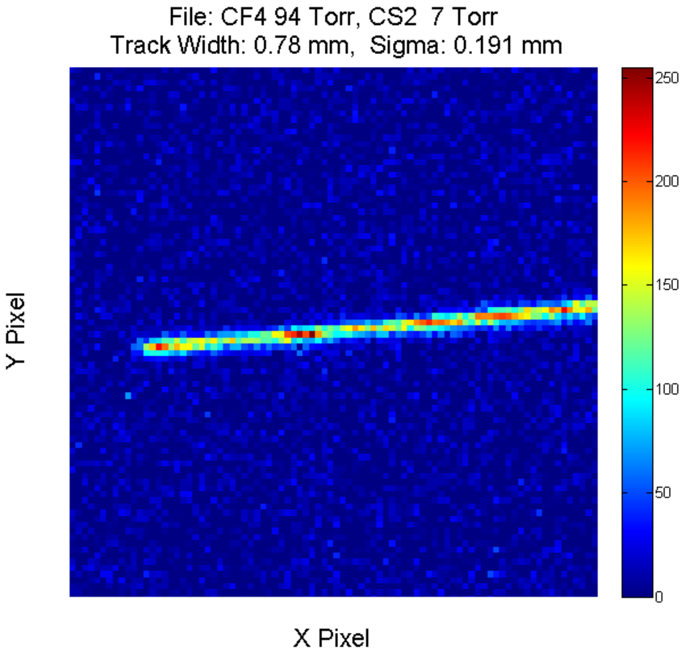
Summary

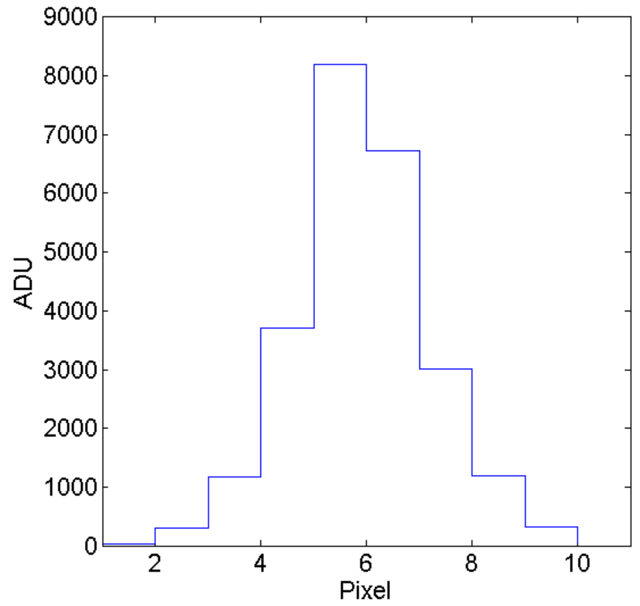
- As a community we need to start thinking about a directional low mass WIMP search
- The experiment will necessarily involve large volume detectors. A few events/yr/m^3 means many m^3 for directionality! (see Neil's talk tomorrow)
- To achieve the goals of discrimination and directionality in this regime we need high S/N, low diffusion and high spatial resolution
- Some of the questions/challenges:
  - Directionality: Is there head-tail directionality down at 5-10 keVr? How many events are needed at the optimal P's for a 5 and 10 keVr, respectively?
  - Discrimination: The very low (a few keVee) energy thresholds requires much better discrimination and control of materials than we have needed thus far. Just how good and can we achieve it? (see Neil's talk tomorrow)
  - Target gases: What are optimal target gases for low pressure stable operation with the highest gas gains?
  - Low diffusion. This is critical in all our assumptions. Can we avoid negative ion drift (*)? We need higher E fields to take better advantage of this. The ability to z-fiducialize will improve this further!
  - Detectors: How many D's do we need?
  - Others

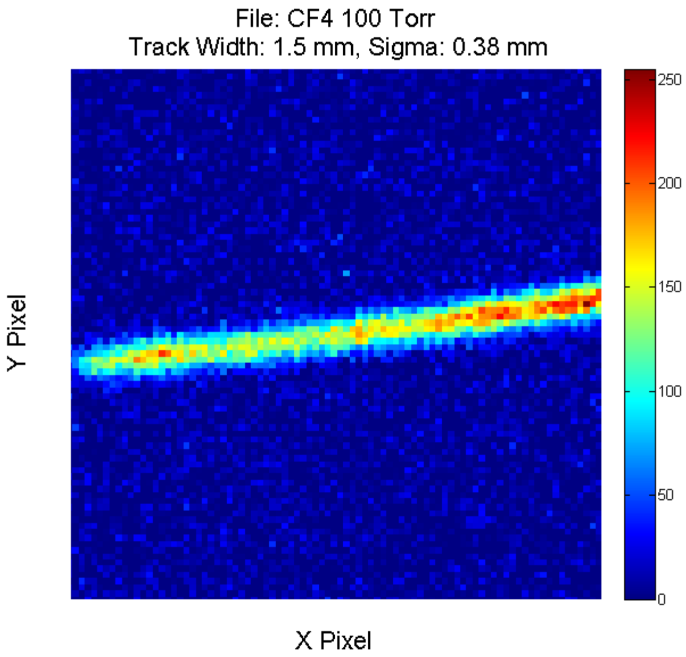
The Magic of CS2 in CF4!

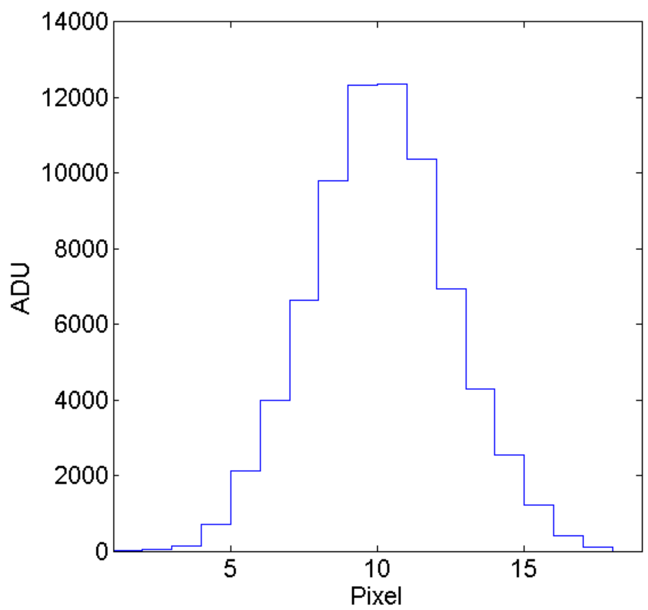


The Magic of CS2!



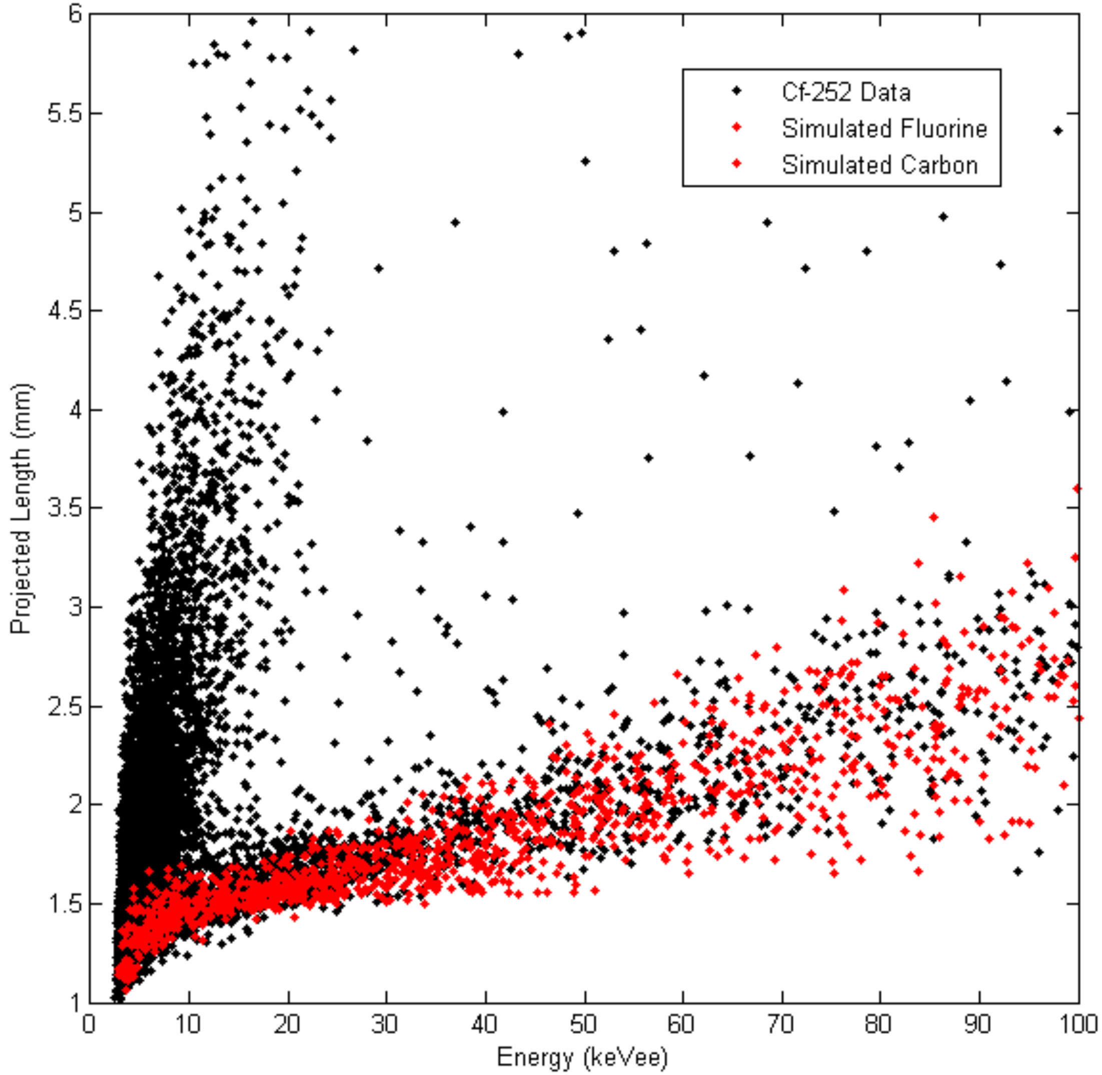






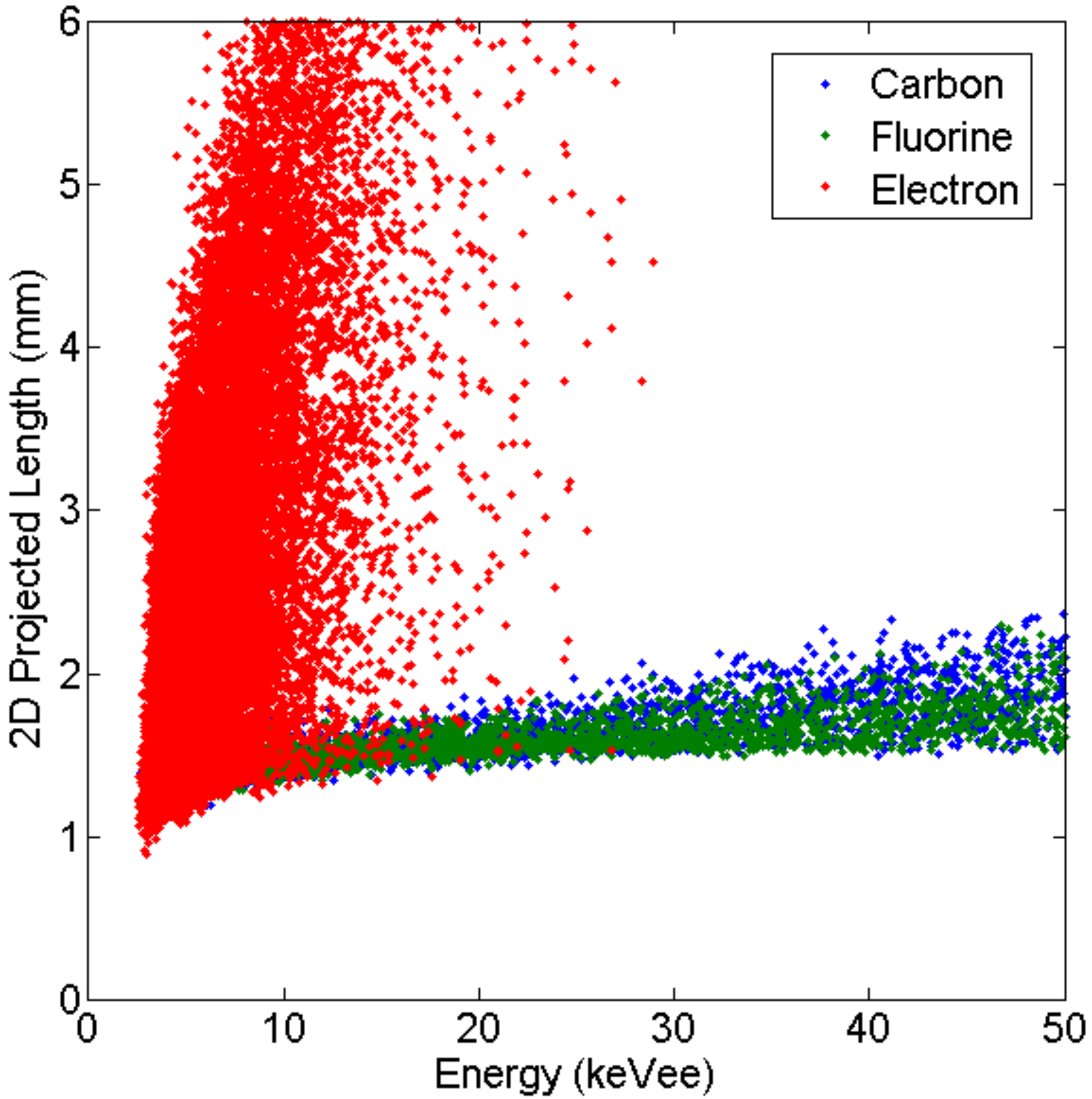

Tyvek
XDS 10

Extra Slides

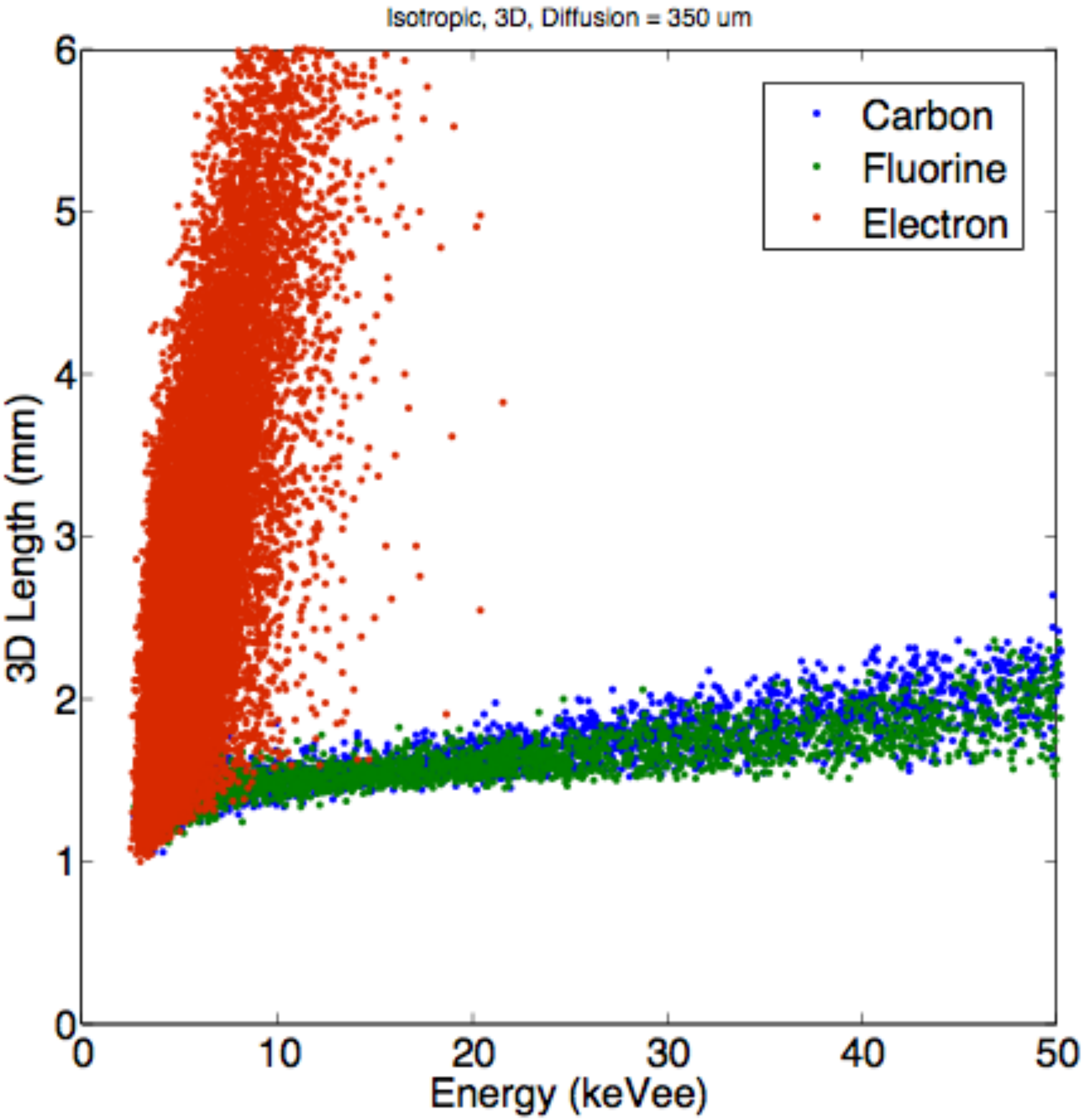


Cf-252 Data
Simulated Fluorine
Simulated Carbon
Projected Length (mm)
Energy (keVee)
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0
10
20
30
40
50
60
70
80
90
100

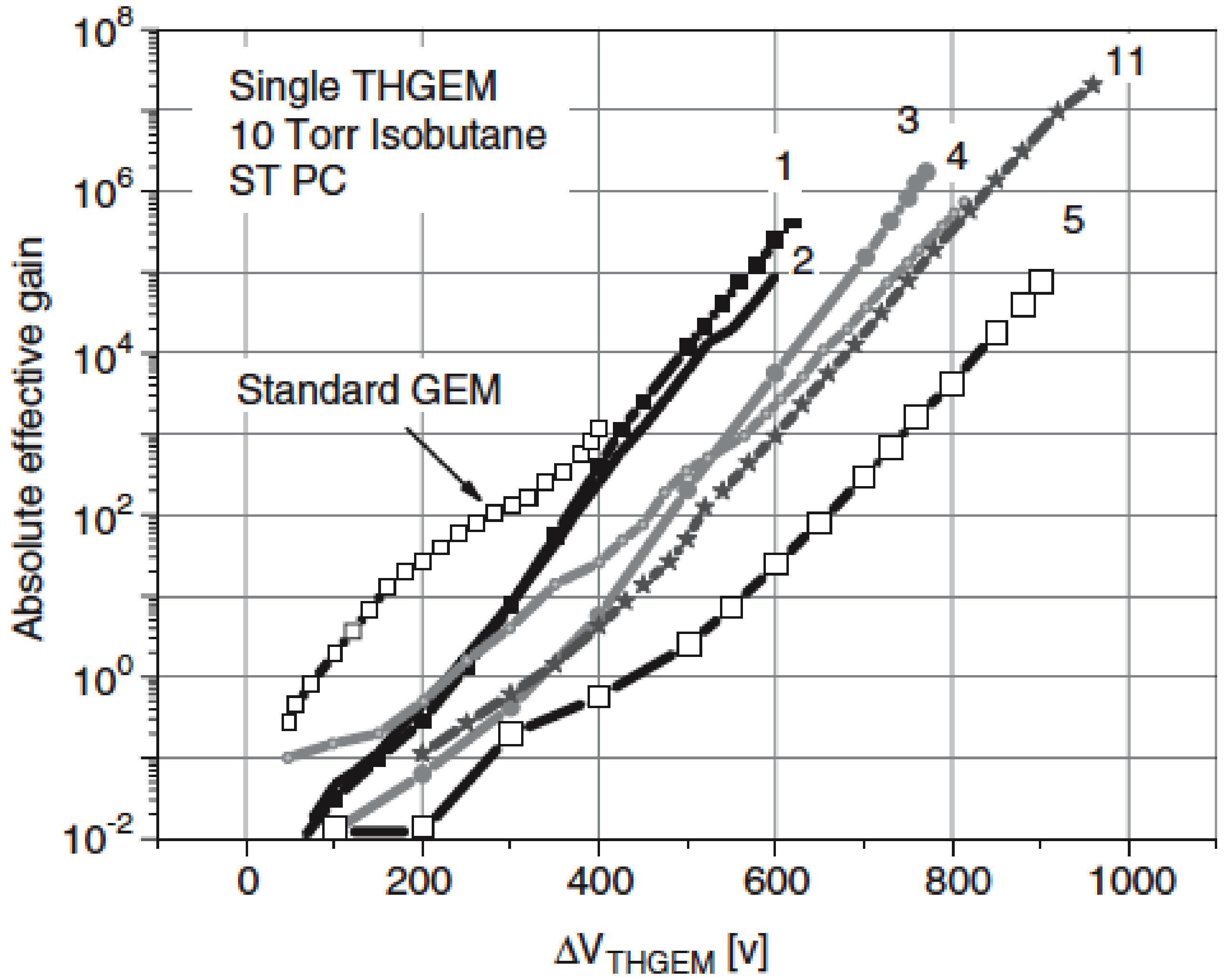
2D Simulation



3D Simulation



THGEMs at low pressure - High Gains!



Shalem, et al NIMA 558 (2006)