Observation of the "Head-Tail" effect in low-energy nuclear recoils with a low-pressure CF_4 TPC

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BU-MIT-Brandeis Collaboration

Outline:

- Physics goals
- Detector concept and prototype
- Measurement of "Head-Tail" with low-energy neutrons
- Summary and Outlook

CYGNUS 2007

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Our goal

Develop a novel detector for direct detection of Dark Matter with the following characteristics:

- Directionality capability
  - No need to explain why here!
- Spin-dependent interactions
  - Enhanced in models in which LSP has substantial Higgsino contribution
- Low cost/unit volume
  - Directionality requires gaseous detectors
- Easy to maintain
  - Very stable, easy to operate underground
- Scalability
  - Modular structure

The BU-MIT-Brandeis Collaboration

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- * indicates undergraduate students
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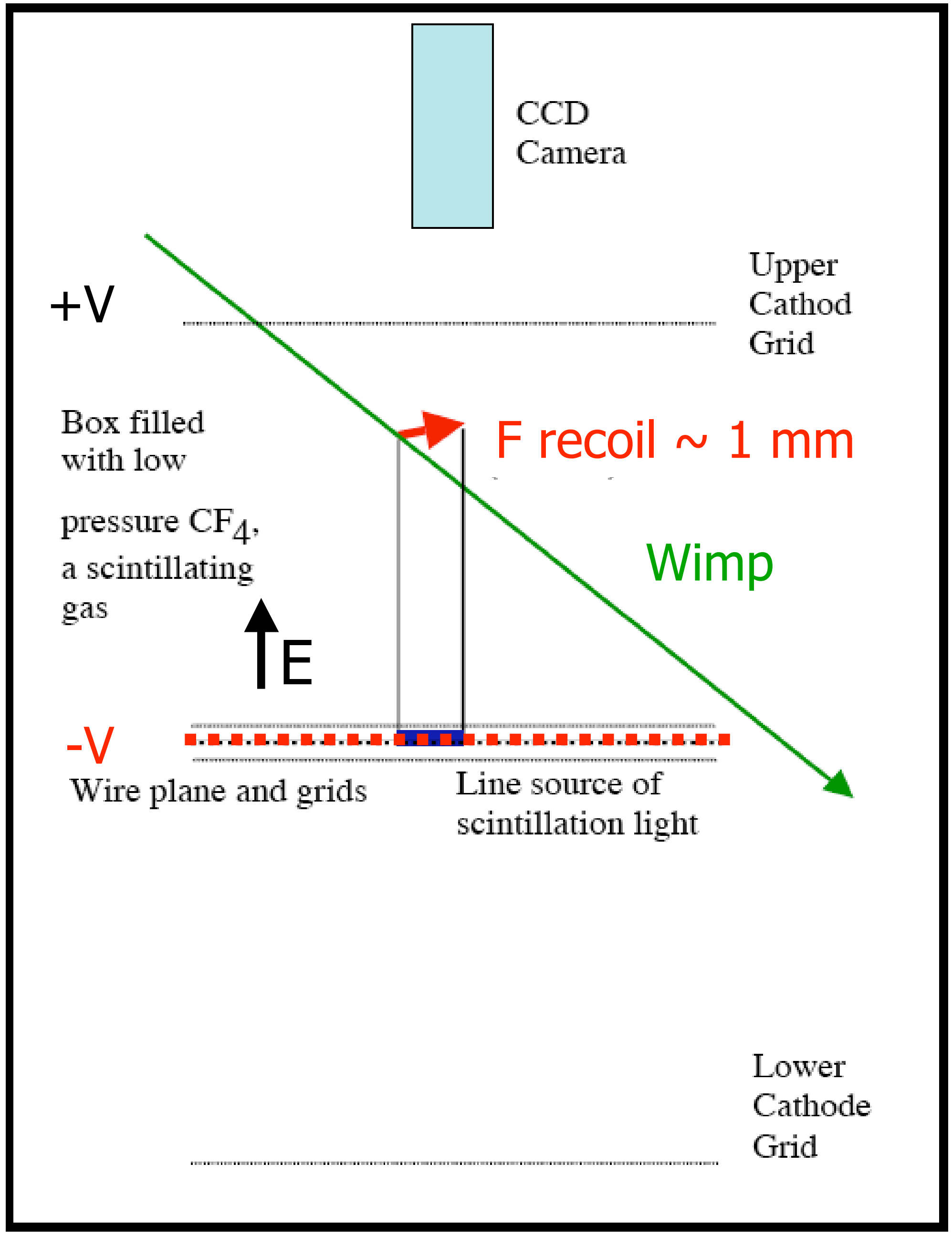
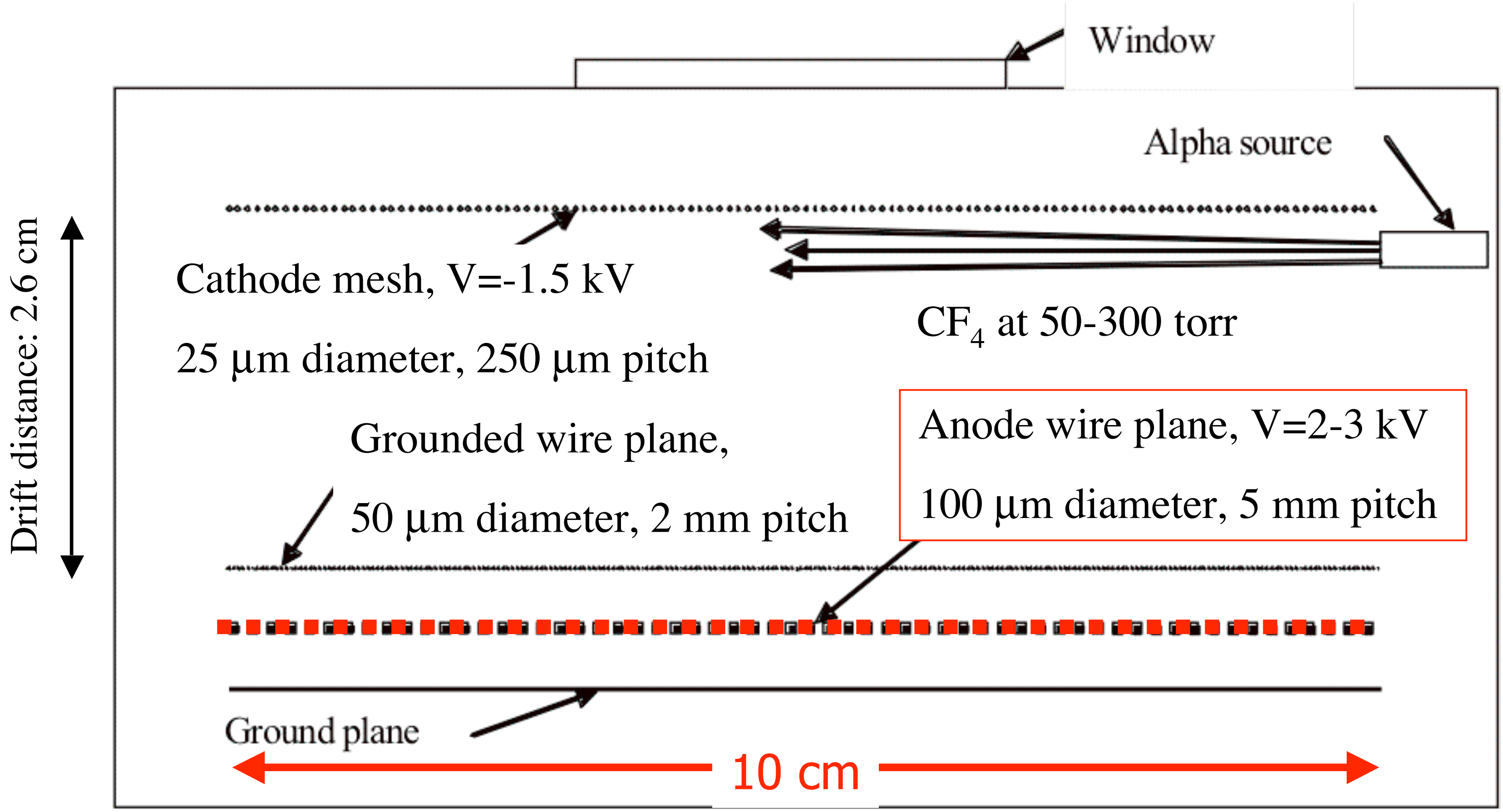
Detector concept

- Low-pressure CF_4 TPC
  - 50-100 torr→recoil ~ 1-2 mm
- CCD readout
  - Image scintillation photons produced in avalanche
    - $\#\gamma_{\text{scintillation}} \propto \#e_{\text{ionization}}$
  - Low-cost, proven technology
- CF_4 is ideal gas
  - Low transverse diffusion
  - Non flammable, non toxic
  - Good scintillation efficiency
  - F: spin-dependent interactions

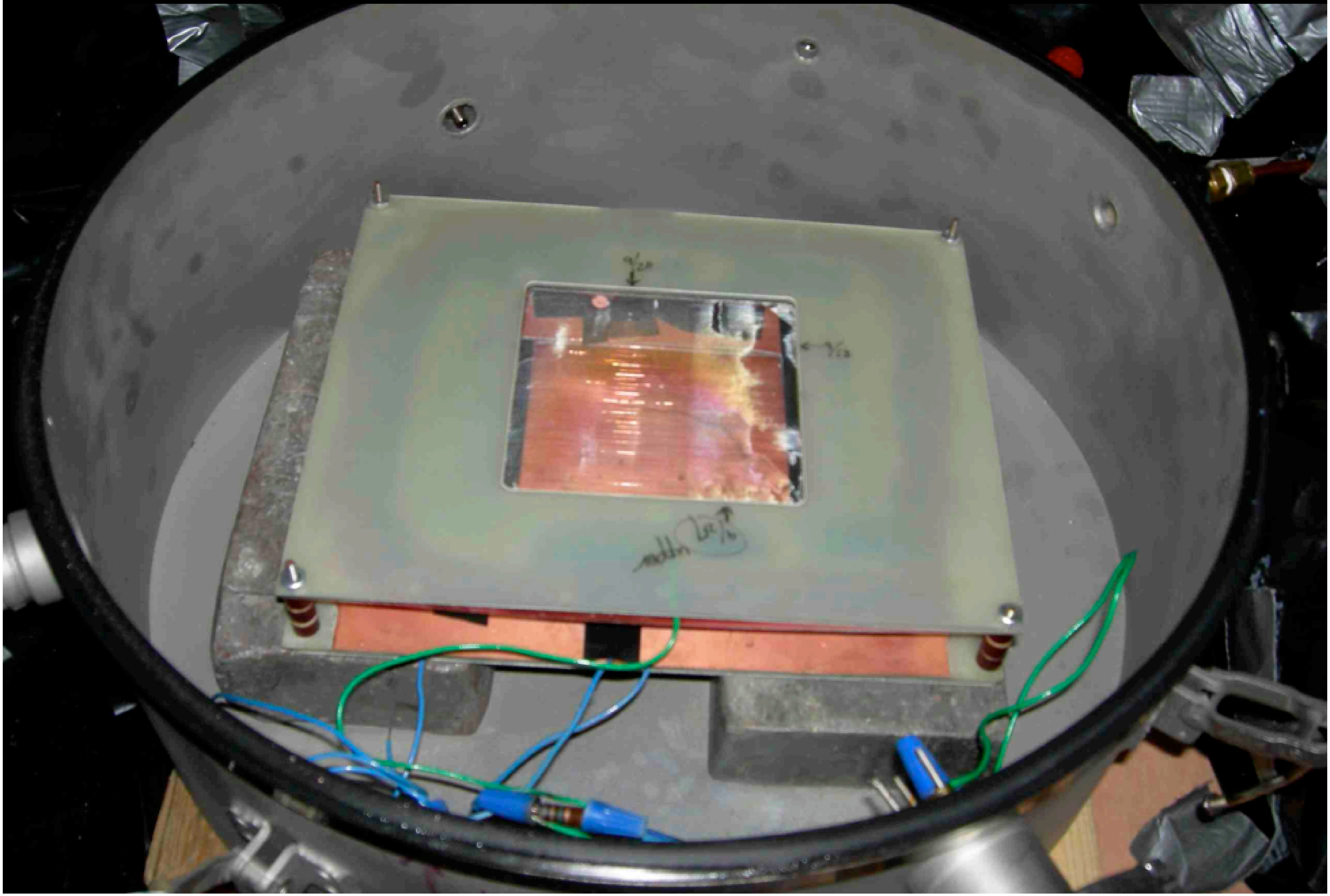


E_{drift}~580 V/cm

Current prototype: the chamber



Current prototype at MIT



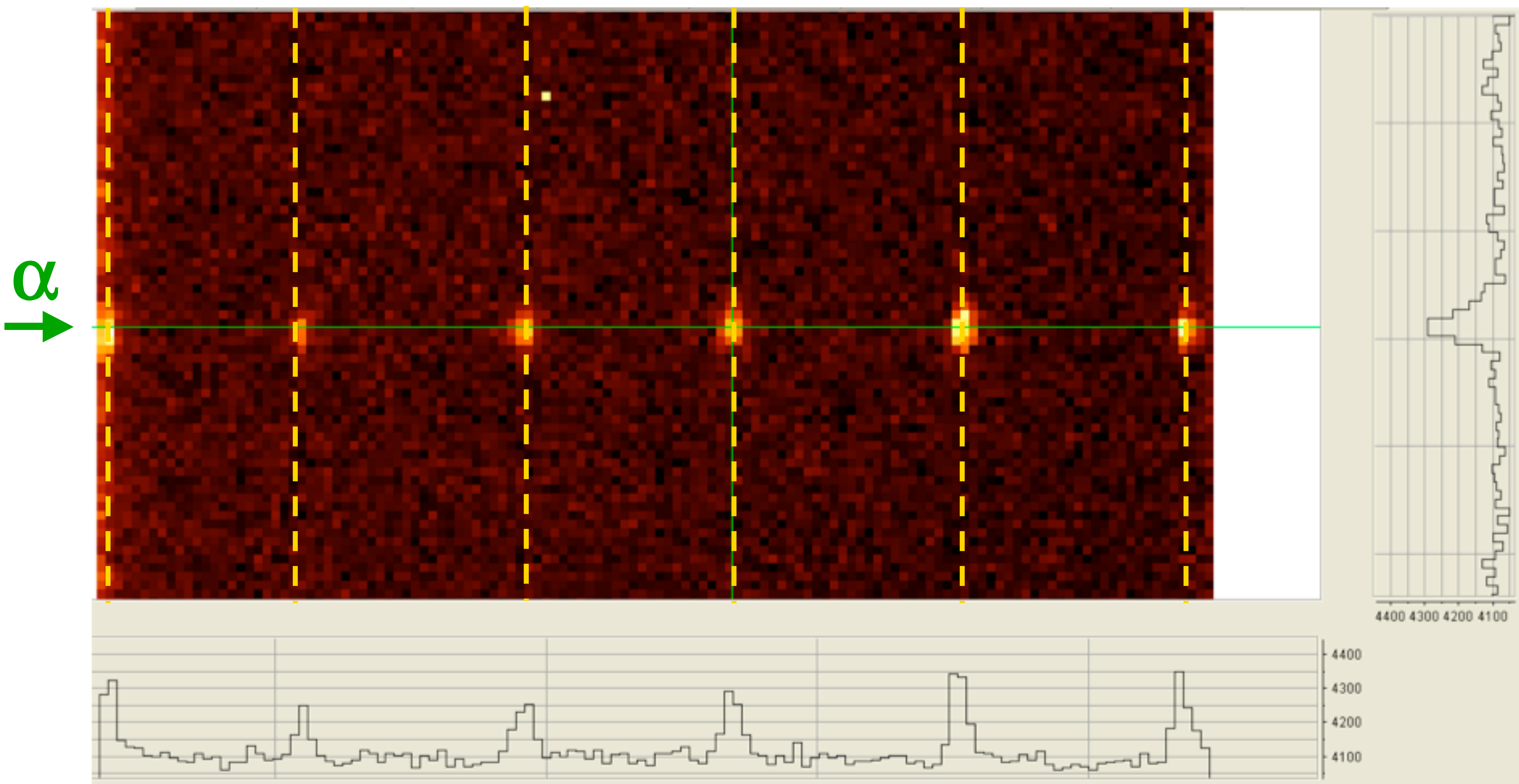
Current prototype: CCD camera

Simple and inexpensive (~$2K)

- Finger Lakes Instrumentation
- Kodak KAF-0401 chip
- # Pixels: 768x512
- Pixel size: 9x9μm^2
- Cooled (-20C)
- Photographic lens (55mm)

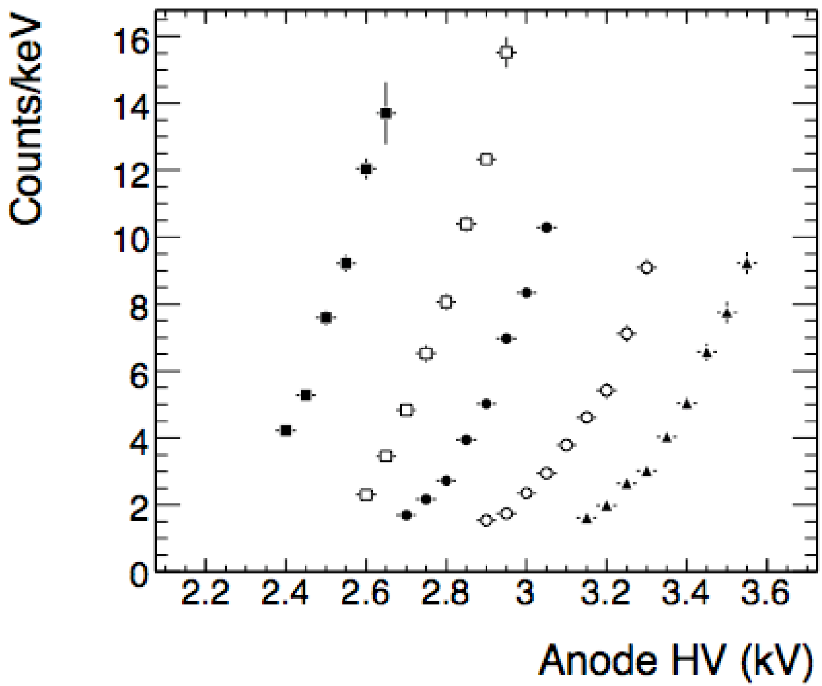
5.5 MeV alphas from ^{241}Am source

Alpha track traveling perpendicular to anode wires (vertical)



Gas Gain and photon yield calibration

- Stable operation for Gas Gain ~ 10^4 -->10^5
  - Large wire by wire dependence (non-uniform spacing between wires)
  - Quality control was poor when we built the chamber
- Photon yield/keV vs V_{anode}

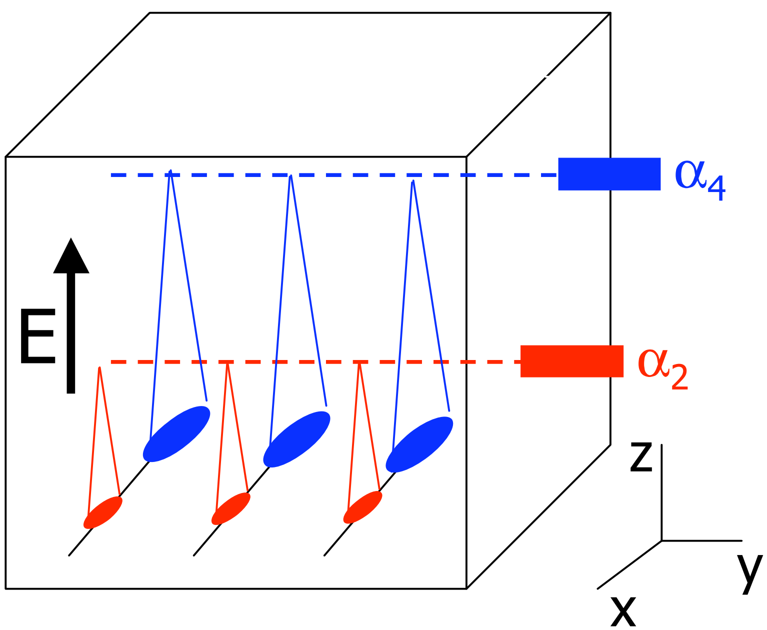


Needs improvements:
- pressure calibration
- non-uniform wire gain
- stability with time

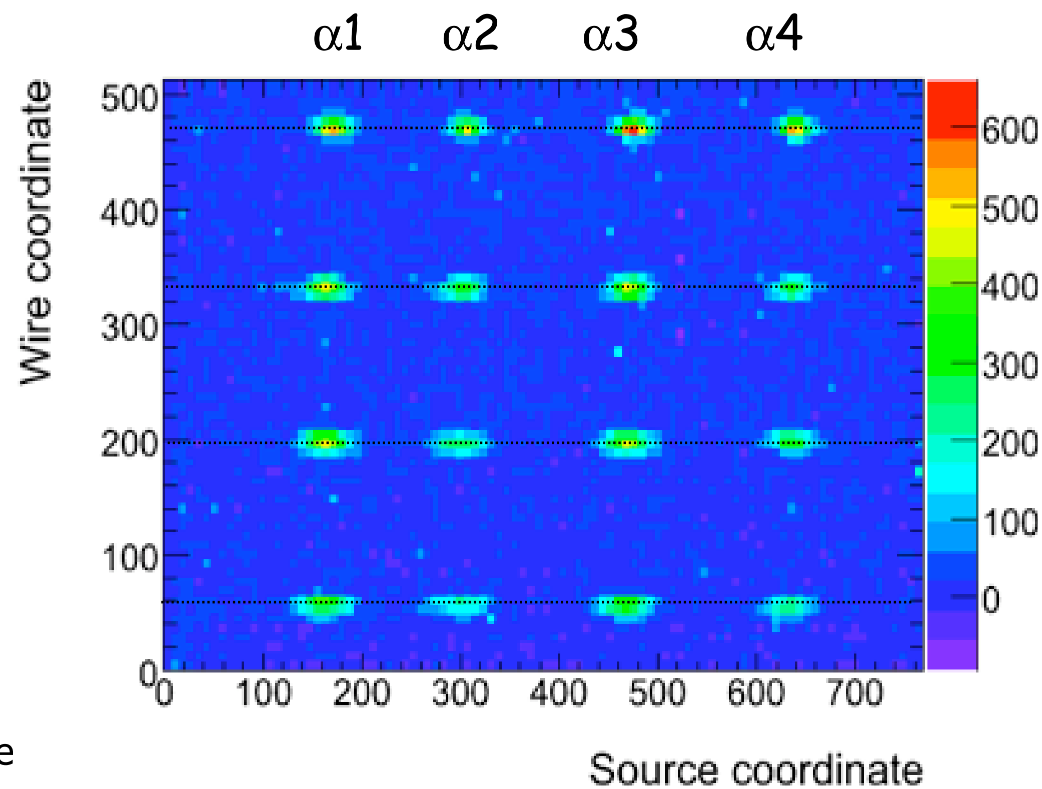
P=150/200/250/300/350 torr

Effect of diffusion on resolution

- Dark Matter recoils ~ 1-2mm
  - Resolution<< 1mm and diffusion must be contained
- Resolution vs drift distance measured with 4 α sources



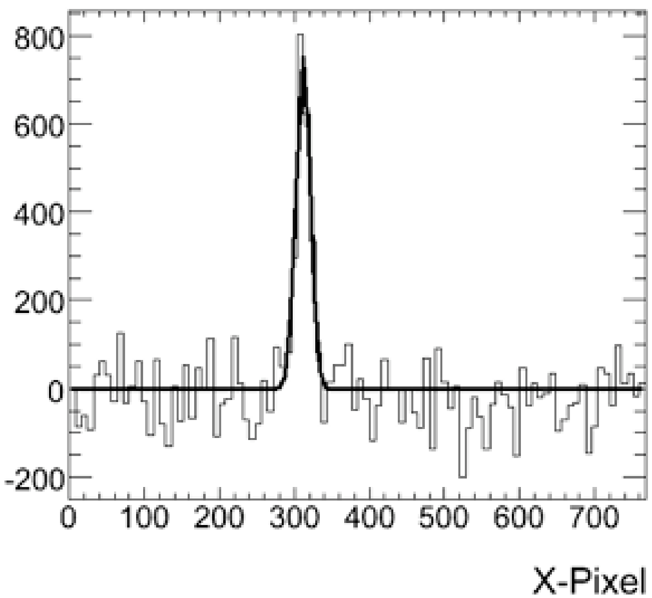
Accumulated image of 250 tracks

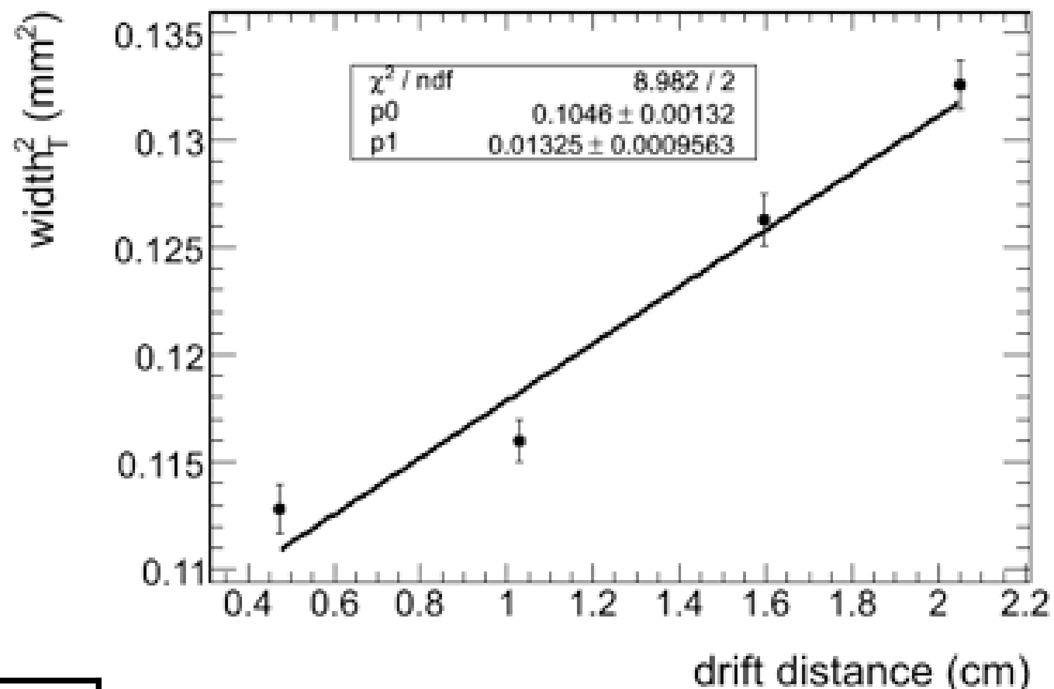


Gabriella Sciolla – MIT

Head-Tail effe

Effect of diffusion on resolution

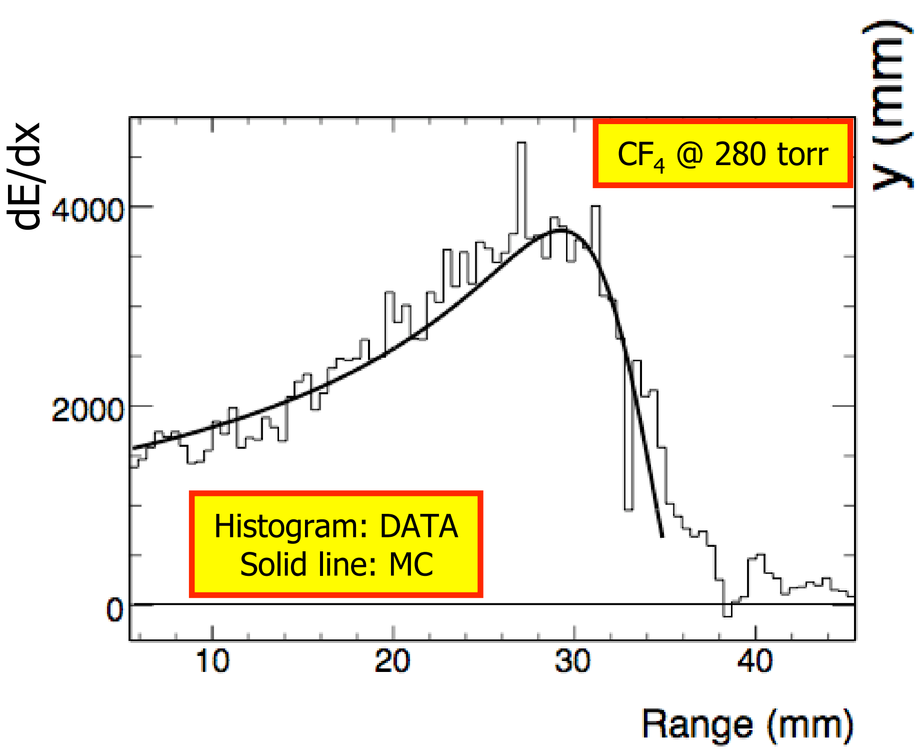


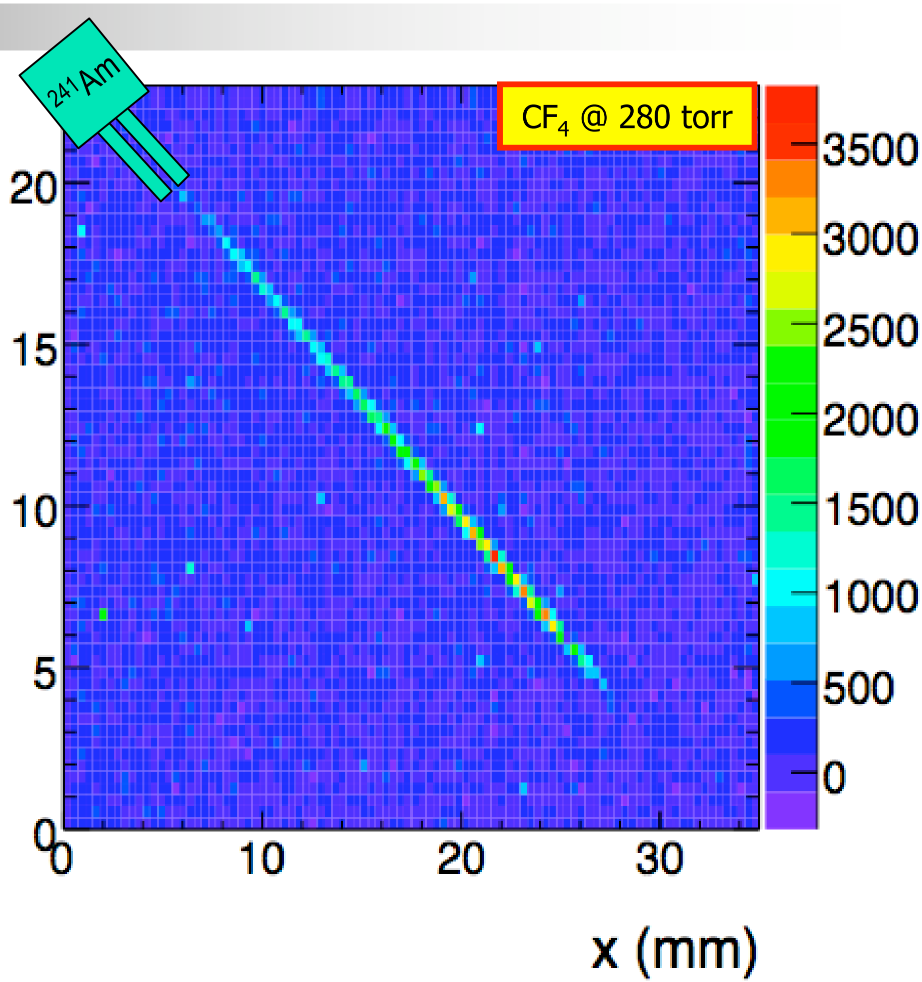


Drift distance	Resolution
1 cm	340 μm
25 cm	670 μm

$$\sigma[\mu m] = 324 \oplus 36\sqrt{\Delta z}$$

Bragg curve for 5.5 MeV alphas

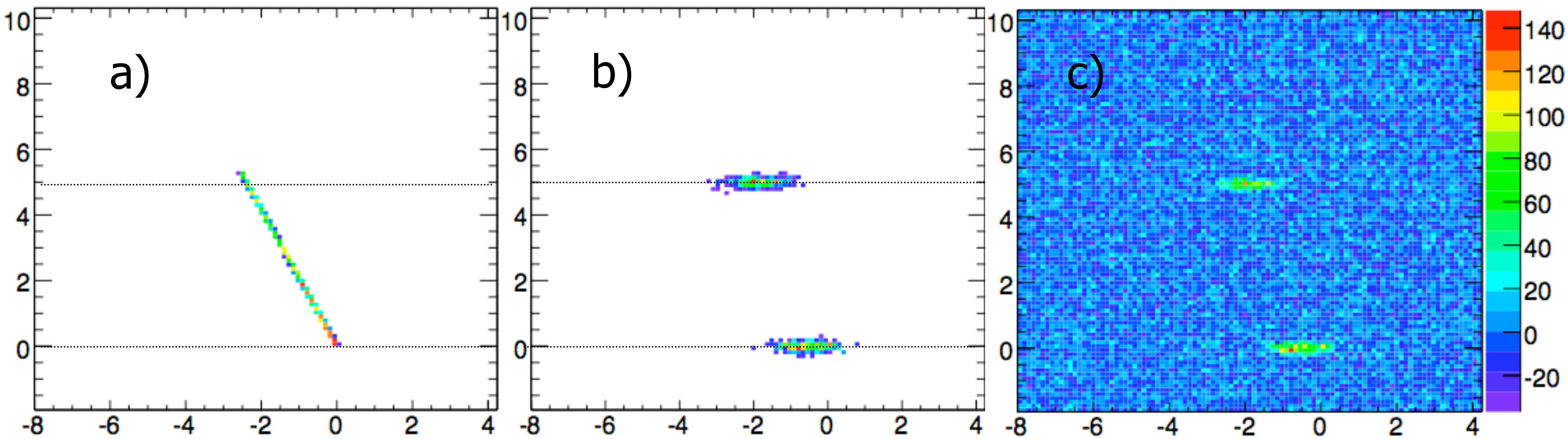




- Alphas emitted parallel to anode wires
  - Wire plane oriented at 45 degrees
- Compare measured dE/dx vs range of the track with SRIM simulation
  - Excellent DATA-MC agreement!

The simulation

- Recoil energy vs scattering angle from kinematics
- Energy loss of recoiling nuclei by SRIM (include straggling)
- Light yield, resolution, diffusion as measured in the prototype
- CCD noise included

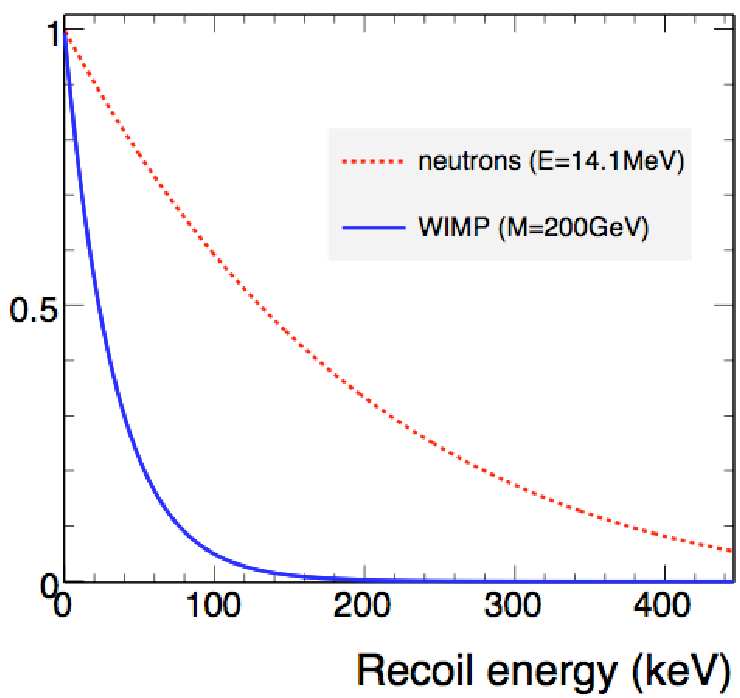


Simulation of a 500 keV F recoil: a) track propagation, b) Signal seen on the wires including diffusion, avalanche, QE, etc c) add CCD noise

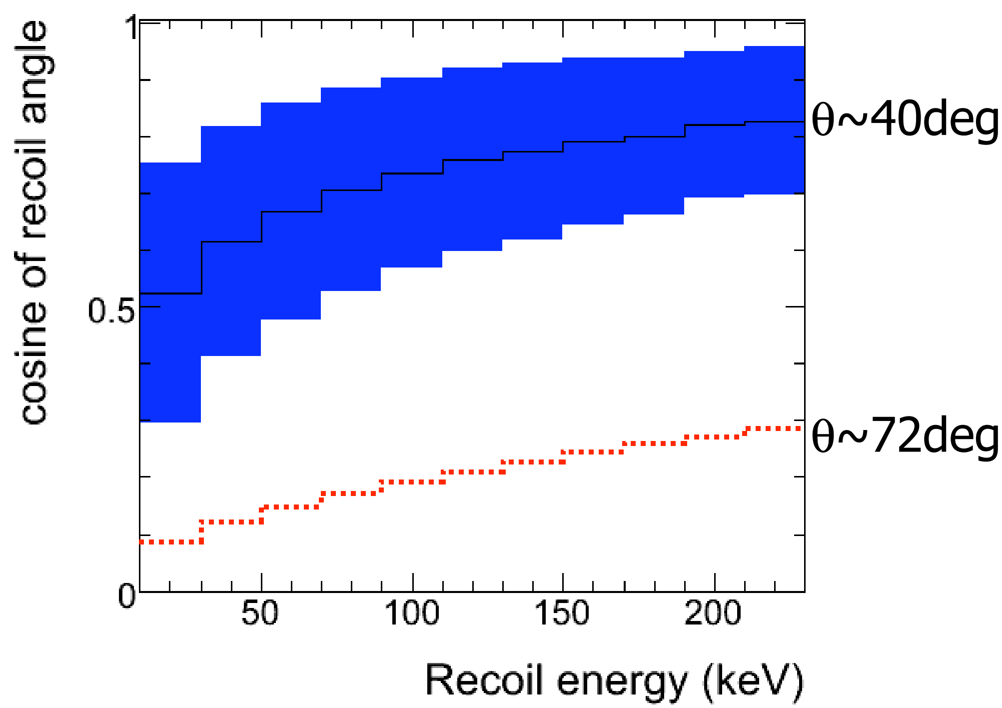
Recoils from low-energy neutrons

- Nuclear recoils by low-energy neutrons mimic Dark Matter
  - DM: F has lower energy but is better aligned with WIMP direction
- Neutron source: 14 MeV neutrons from D-T tube

Fluorine recoil energy



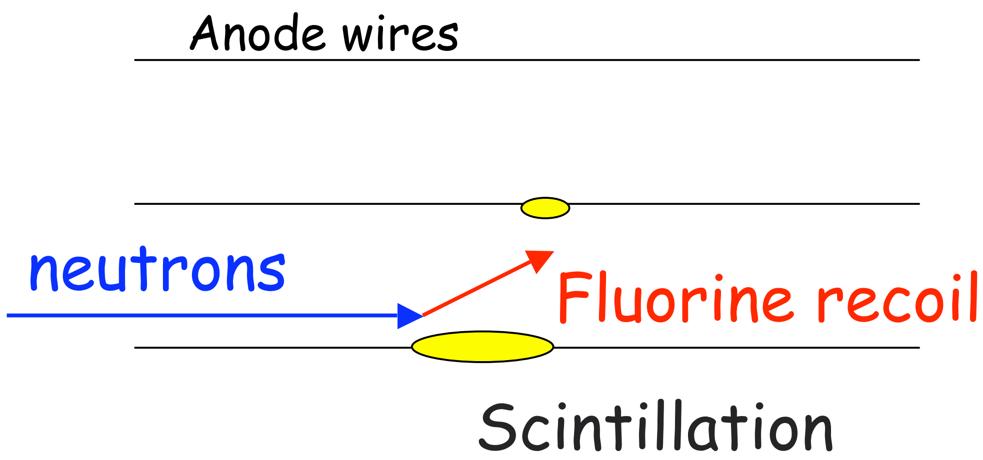
Fluorine recoil angle wrt wires



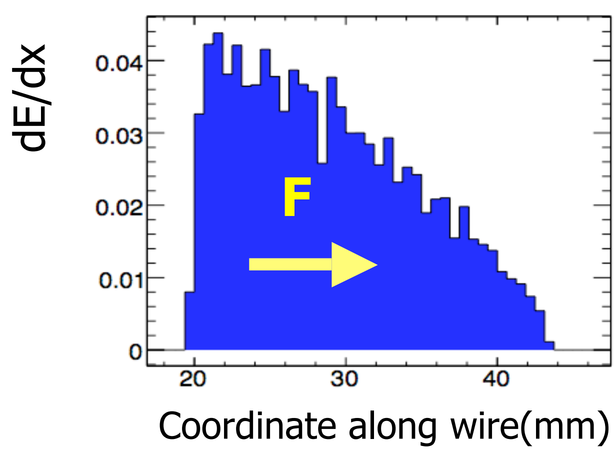
Blue band = spread in WIMP direction

Experimental setup

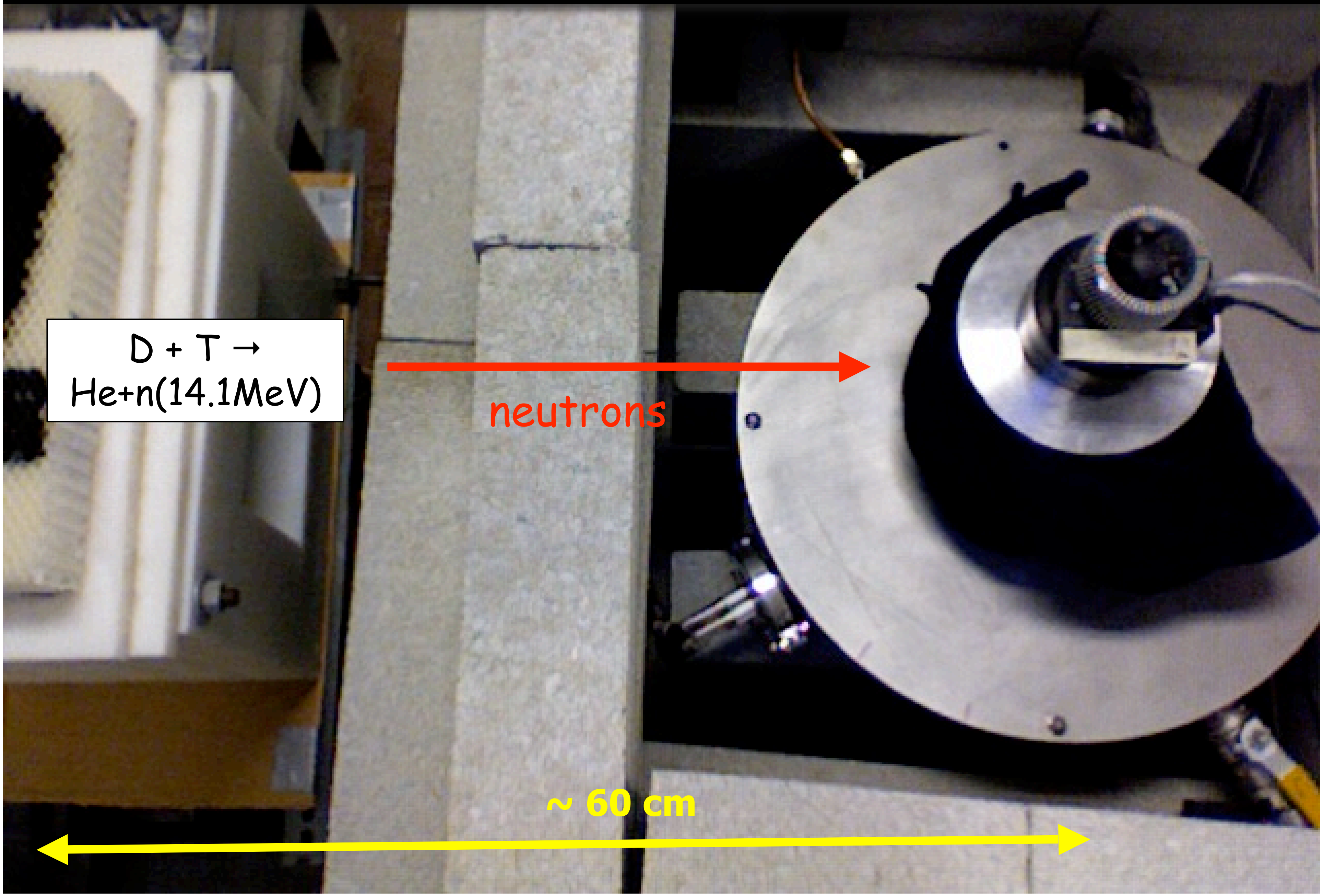
- F recoils produced by 14 MeV neutrons in CF_4 at 180 torr
  - E ~ hundred keV
  - Length ~ 2-3 mm
  - L_x ~1-2 mm



- Anode wires // neutrons
  --> image projection of recoil along wires
- Well below Bragg peak: dE/dx of recoils decreasing along n direction:



Neutron Beam Setup

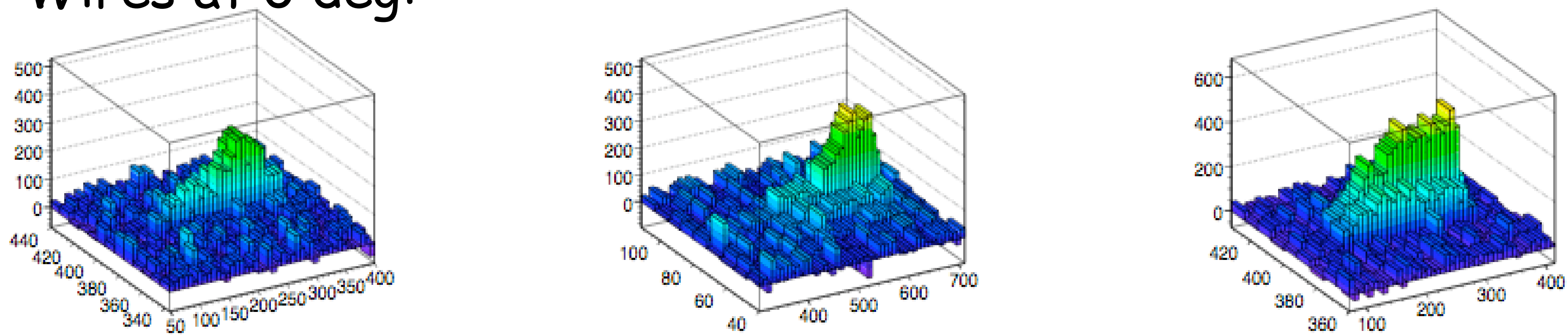


Analysis procedure

- Exposures of 1 second continuously with random trigger
- Selection criteria:
  - Reject empty images (70%)
  - Reject events with more than 1 segment/wire
  - Reject events on boundaries of view field (calibration problems)
  - Reject too short (<5 pixel) and too long tracks
- Selected 7% of events: measured rate 0.07/s
  - Cfr: expected rate ~ O(0.1 Hz) assuming n flux = 5×10^7/s, 1 m distance, (1.2x0.8x2.6) cm^3 active region

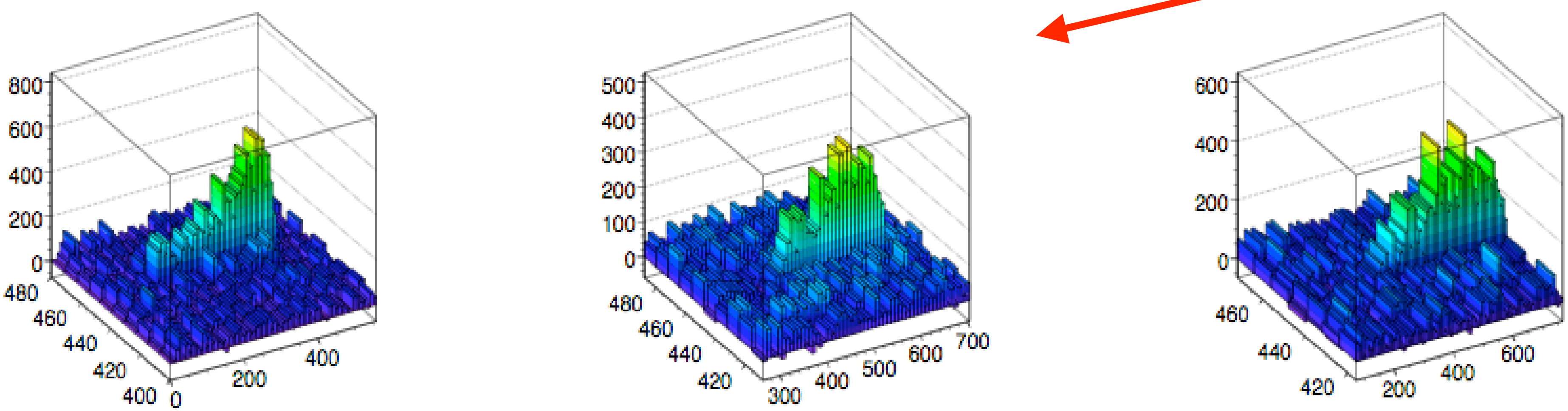
Observation of "head-tail" in recoils

Wires at 0 deg:



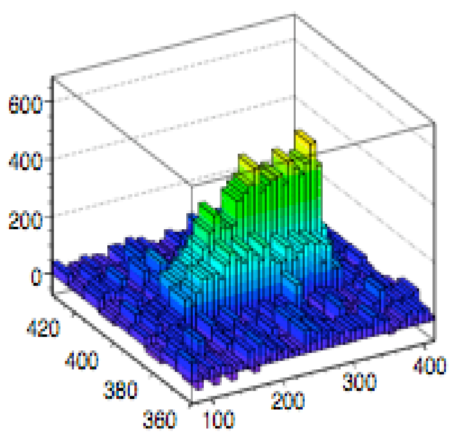
Wires at 180 deg:

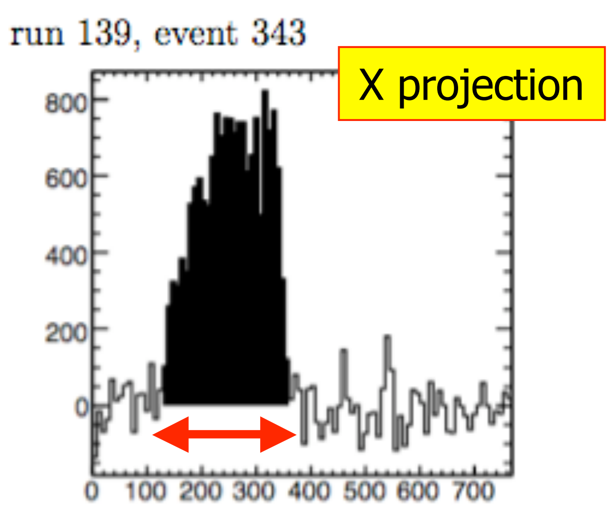
Direction of neutrons

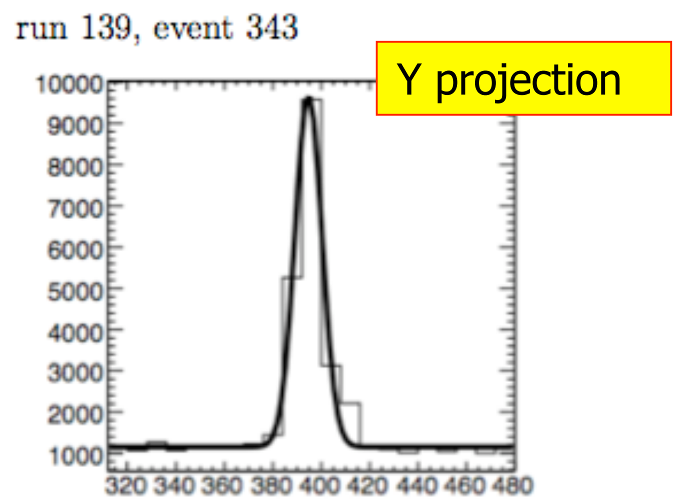


Measured quantities

- Range: # pixels above threshold
  - Measured in x direction // anode wires
  - Cut in y +/- 3 pixels around wire
- Energy: integral of light yield on the wire
  - Measured in the y direction, perpendicular to anode wires
  - In +/- 5 pixels around wire, gaussian fit above flat background

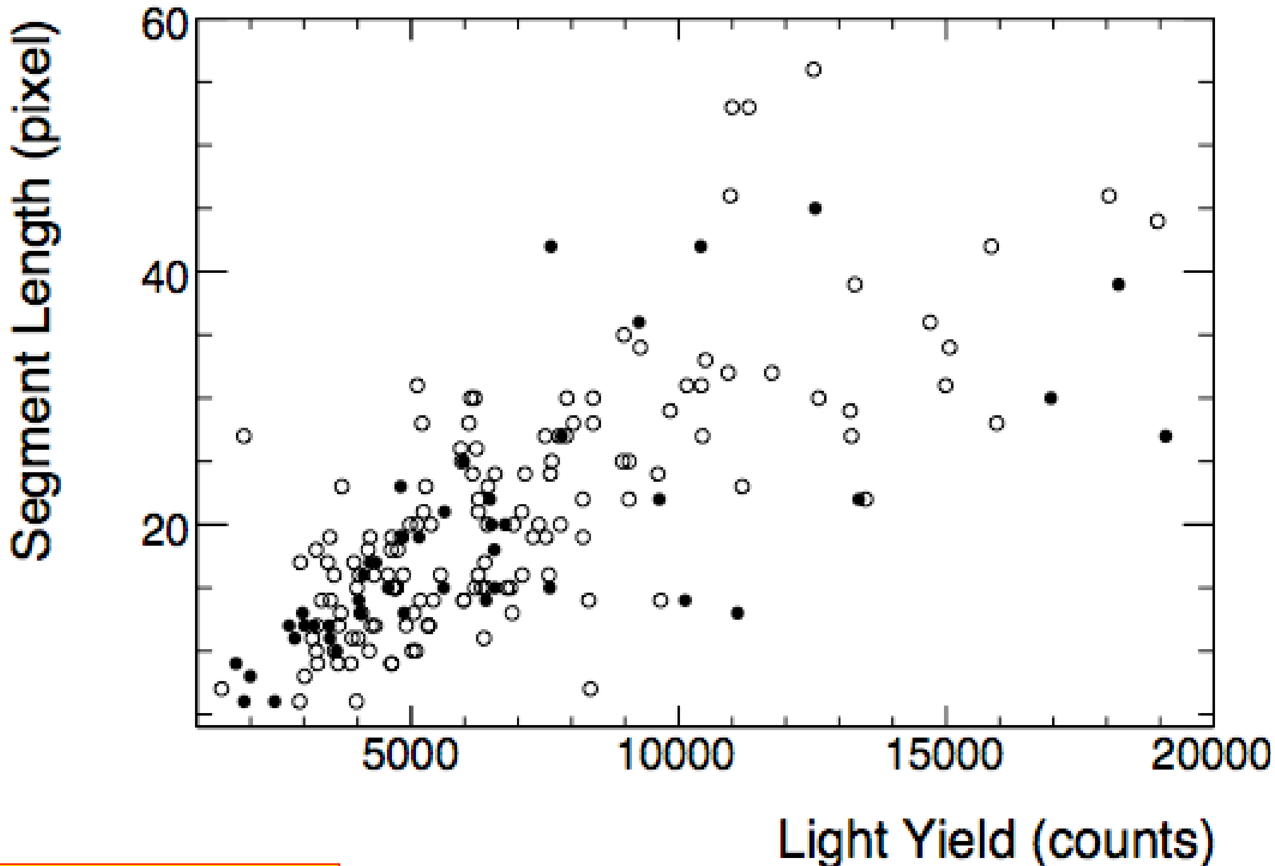






Range vs Energy: DATA

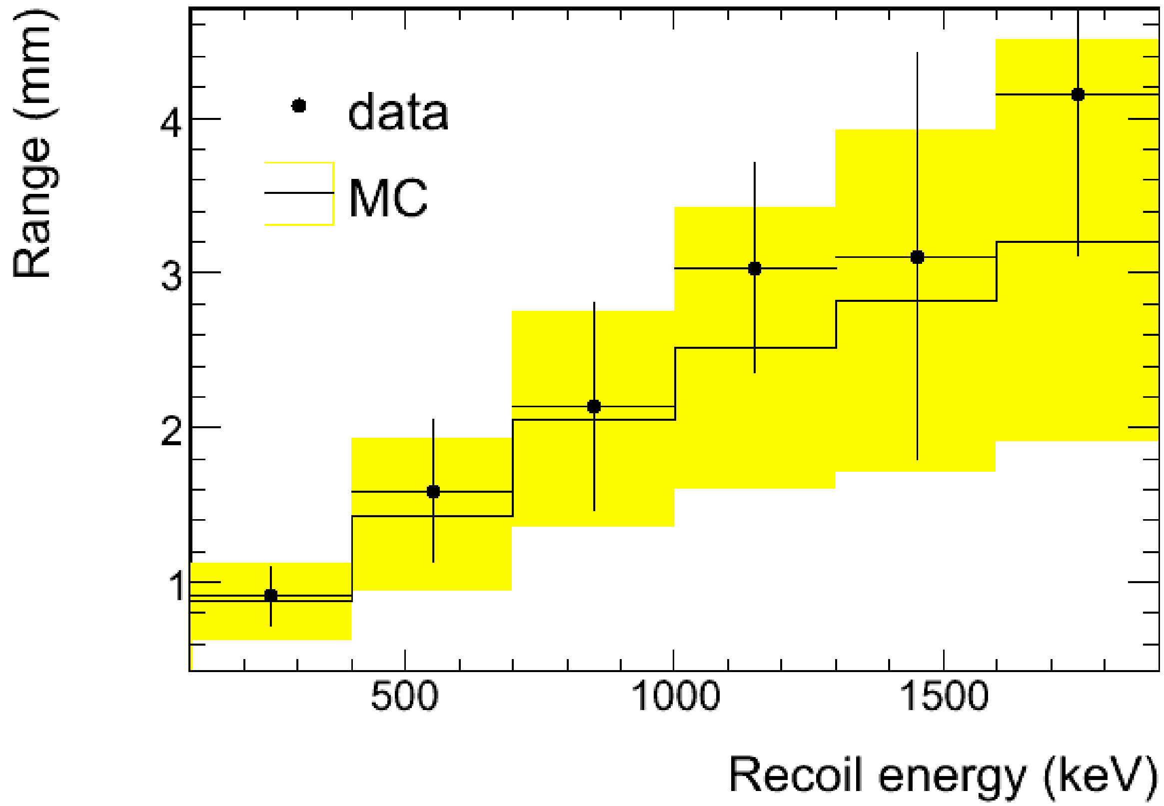
Clear correlation between Range and Energy of the recoil



Black dots: wires @ 0 deg
Open circles: wires @180 deg

Head-Tail effect in low-energy neutrons

Range vs Energy: DATA vs MC

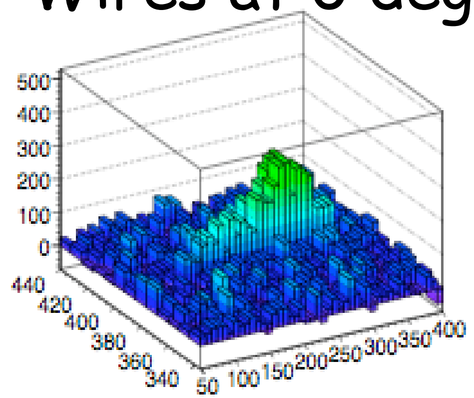


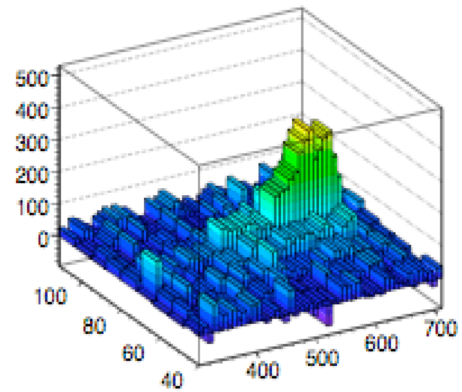
8counts/100keV
8.25bins/mm
P~220Torr

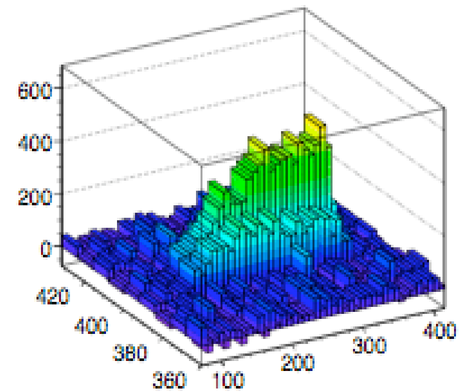
- Error bars (yellow area) indicate <u>spread</u> in DATA (MC)
- Precision on range ~ 15%
- Precision on energy ~ 50% (pressure, wire gain)

Observation of “head-tail” in recoils

Wires at 0 deg:

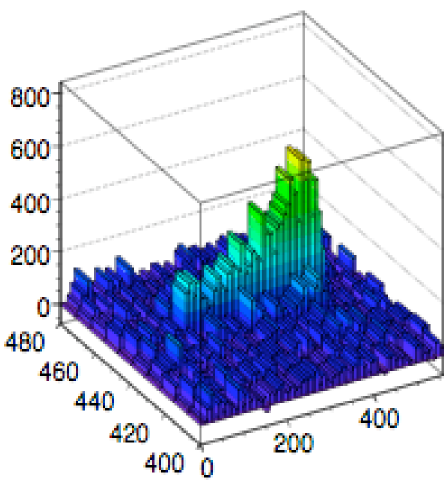


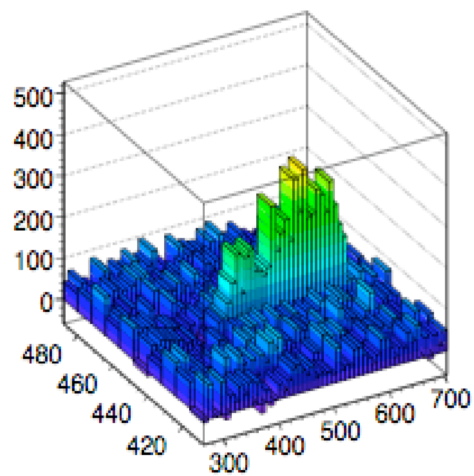


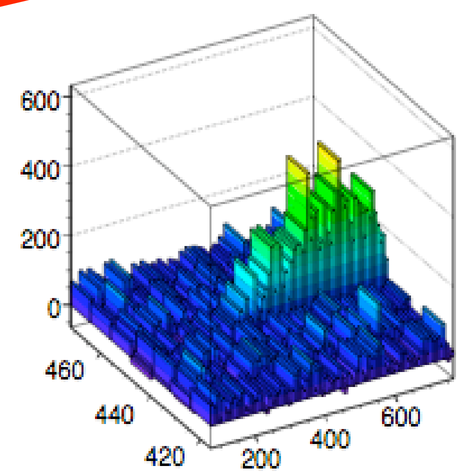


Wires at 180 deg:

Direction of neutrons





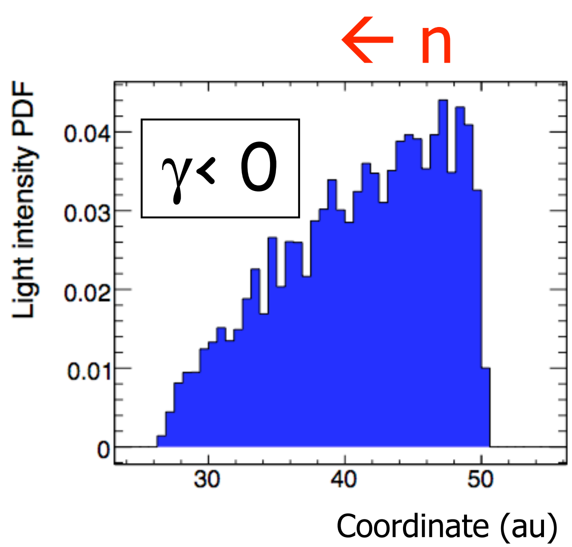


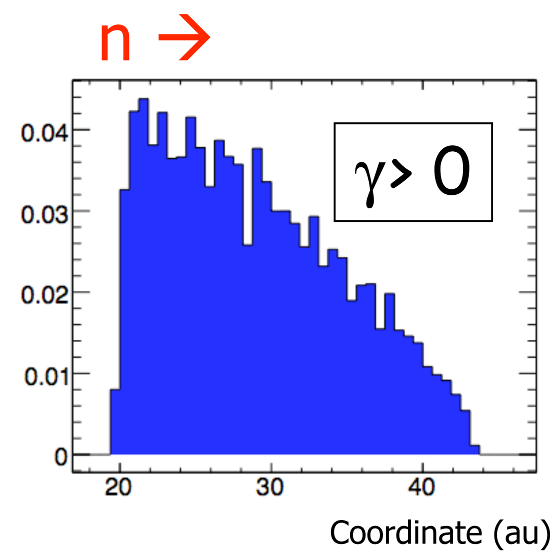
Definition of skewness γ

We measure the skewness of light yield along the wire

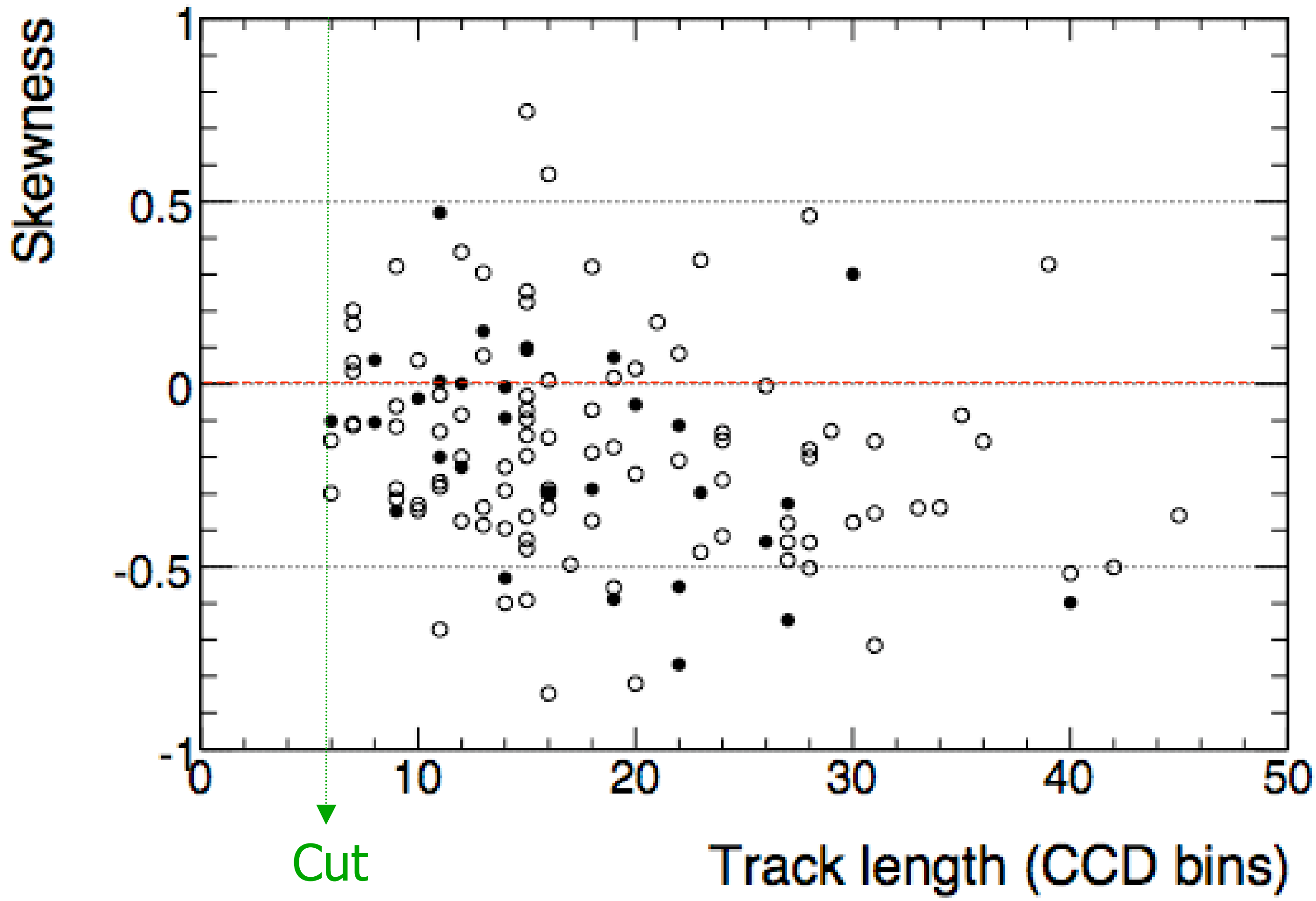
$$\gamma(x) = \frac{\mu_3}{\mu_2^{3/2}} = \frac{\langle (x - \langle x \rangle)^3 \rangle}{\langle (x - \langle x \rangle)^2 \rangle^{3/2}}$$

- Positive sign: neutron travels L to R
- Negative sign: neutron travels R to L





Observation of Head-Tail effect: Skewness for neutrons Right to Left



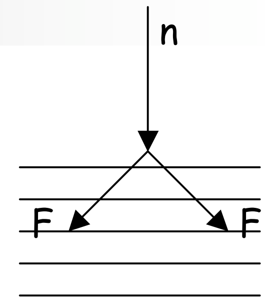
L to R
(24±3)%

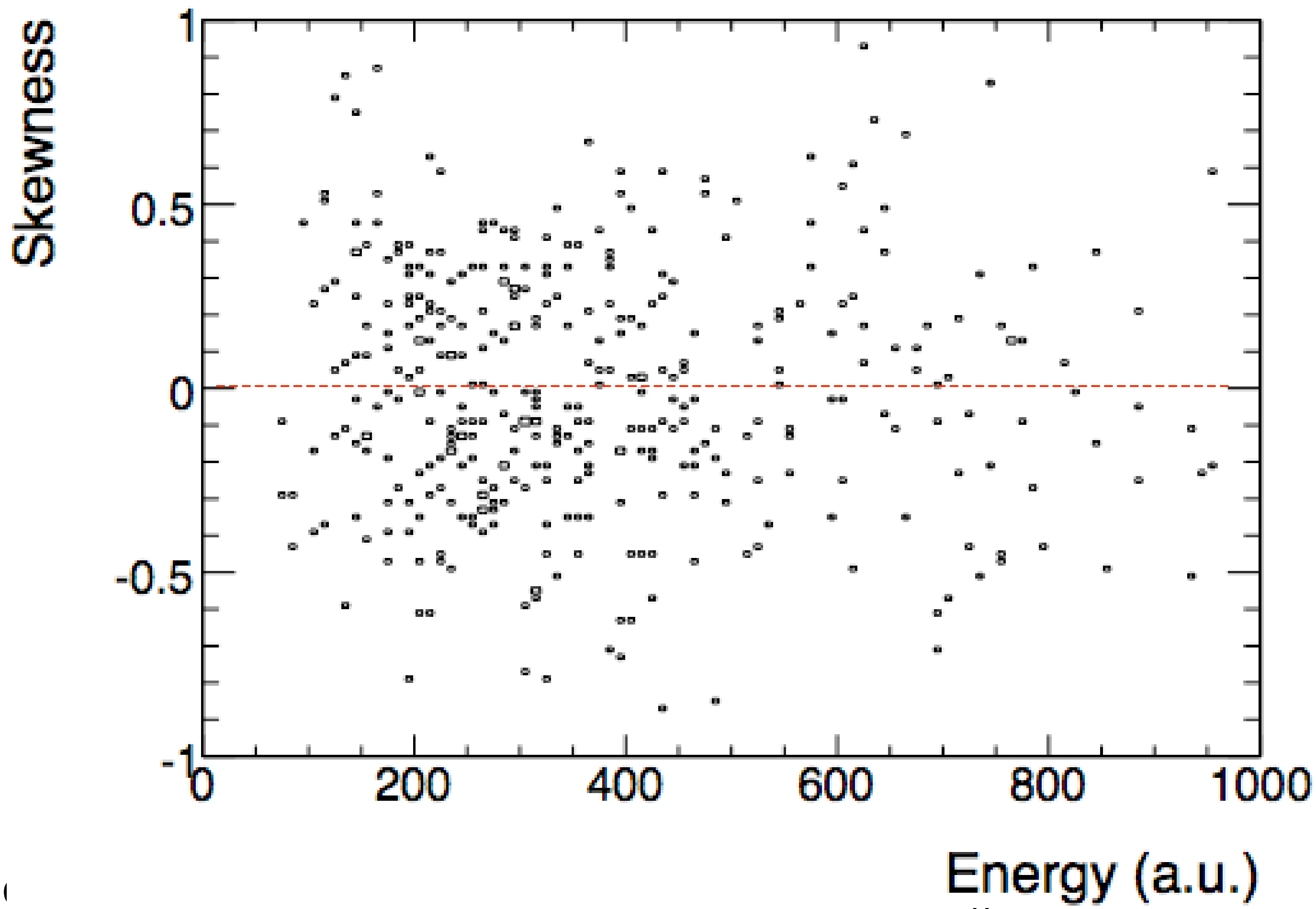
R to L
(76±3)%

Black dots: wires @ 0 deg
Open circles: wires @180 deg

Cross check #1: n ⊥ Wires

Null test with neutrons @ 90deg to wires
Same # of recoils to left, right

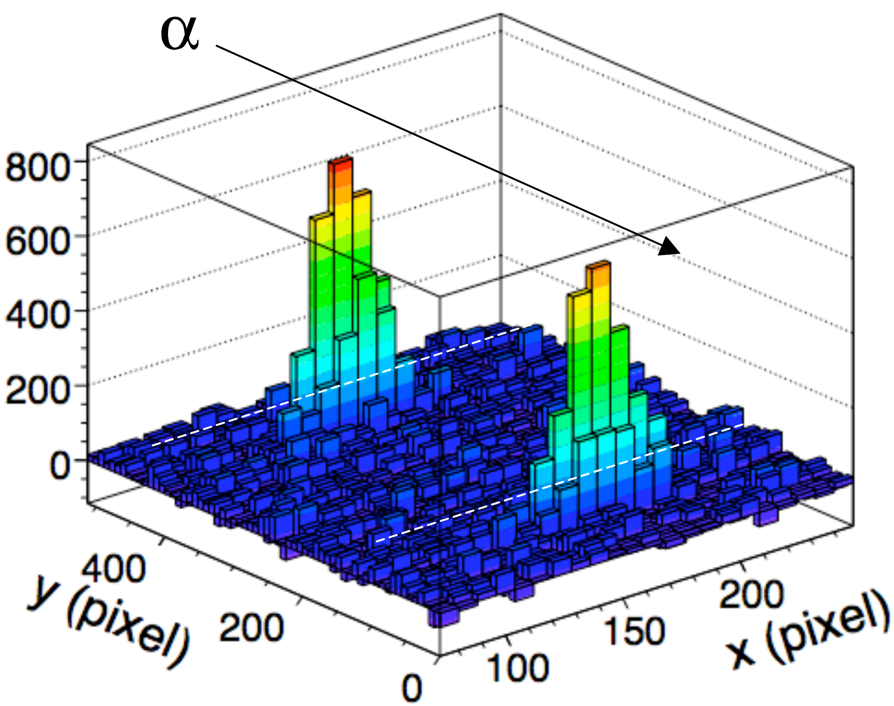


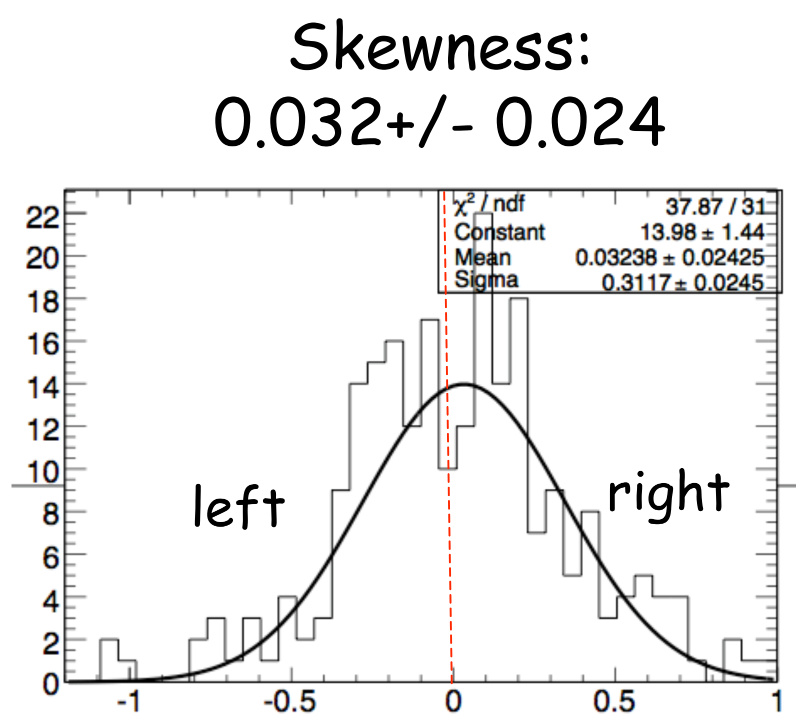


L to Right
(47.3±2.5)%

R to Left
(52.7±2.5)%

Cross check #2: $\alpha \perp$ Wires





Cross check #3: α contamination

- Are we sure we are looking at F recoils and not alphas created by neutron's inelastic scattering in CF_4?
    - $^{19}F + n \dashrightarrow {}^{15}N + \alpha + n$ instead of $^{19}F + n \dashrightarrow {}^{19}F + n$
  - Compare cross sections

$$\frac{\sigma_F}{\sigma_\alpha} = \frac{0.9b}{\sim 0.3b} \sim 3$$

  - Compare fractions of events with energy between 100 and 800 keV (range our detector is most sensitive to with present settings)

$$\frac{F_F}{F_\alpha} = \frac{46\%}{7\%} \sim 6.4$$

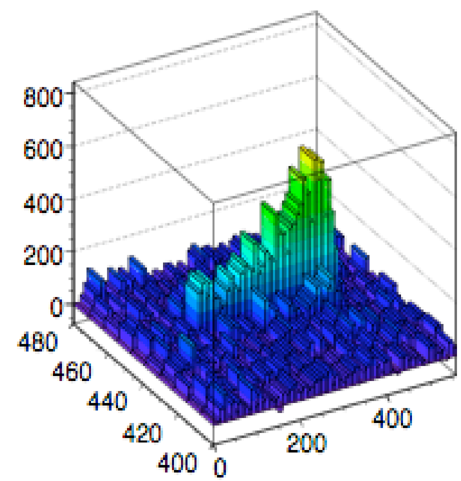
- P (F recoil) : P(α) = 19 : 1

Our sample is dominated by elastic recoils of F

Conclusion

- First prototype of low pressure CF_4 TPC with CCD readout is up and running at MIT
  - Chamber calibrated with alpha sources
  - Satisfactory Data-MC agreement

- First results on measurement of Head-Tail effect for low energy neutrons
  - Preliminary results look very promising
  - Analysis is being finalized



- Proof of principle: detector concept works!
  - Time to move to the next phase…

Outlook

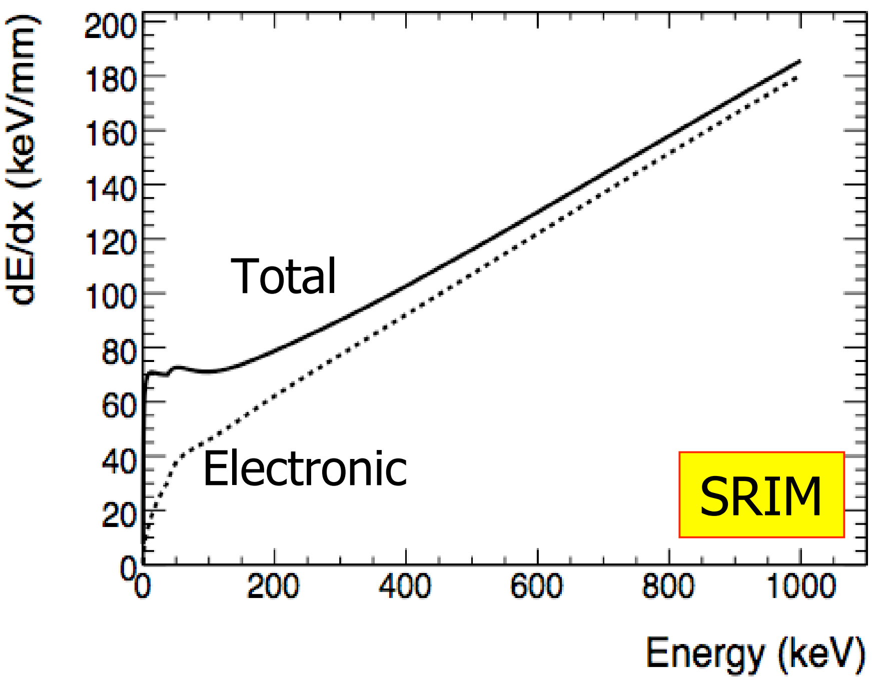
- Limitations of present prototype
  - Small chamber, cheap camera, designed and built on a budget

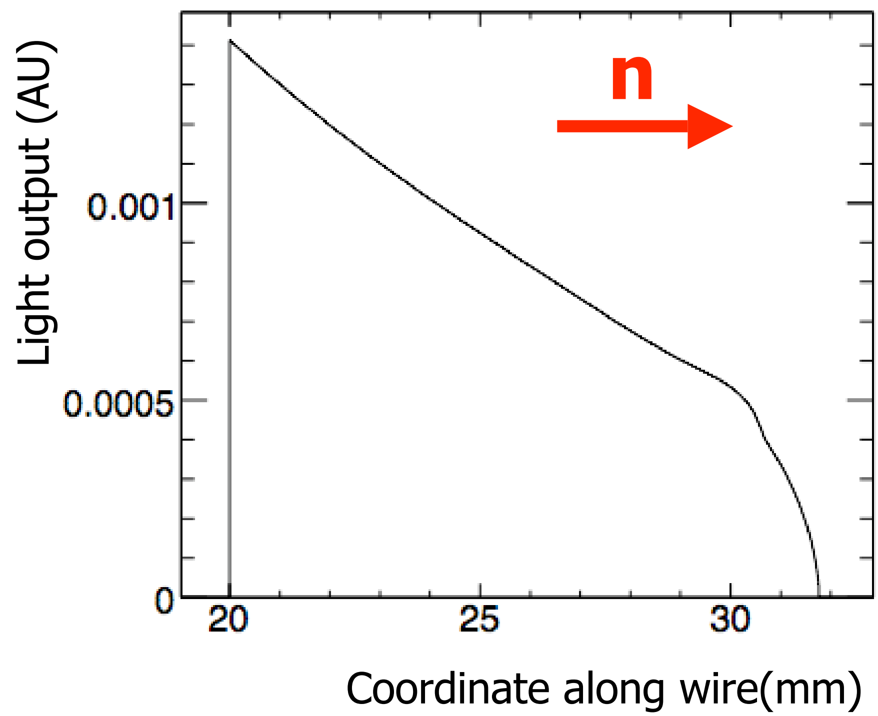
- Next generation prototype being designed
  - A few hundred liters chamber: >~50x50x50 cm^3
  - Optimized design based on MC and experience with prototype 1
  - Much better CCD camera
  - Gas system to purify and re-circulate CF_4
  - Possible improvements: L1 Trigger, Δz measurement, …

- Once new prototype is ready…
  - One year of data taking in underground lab
  - Analyze data, set limit on spin-dependent
  - Likely will hit some background --> improve detector --> repeat iteration…

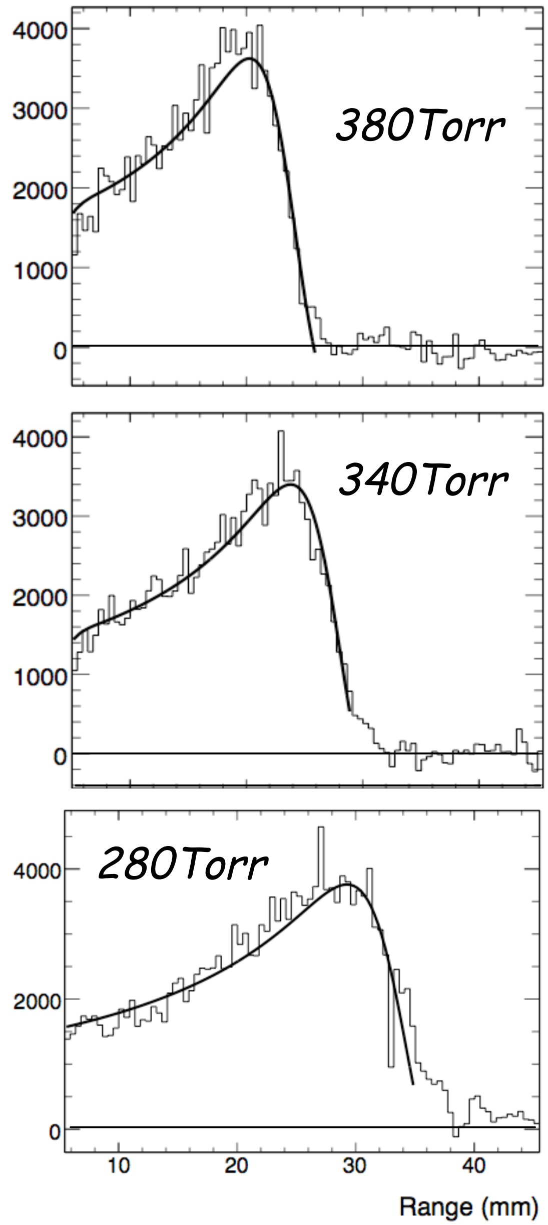
Bragg curve for low-energy neutrons

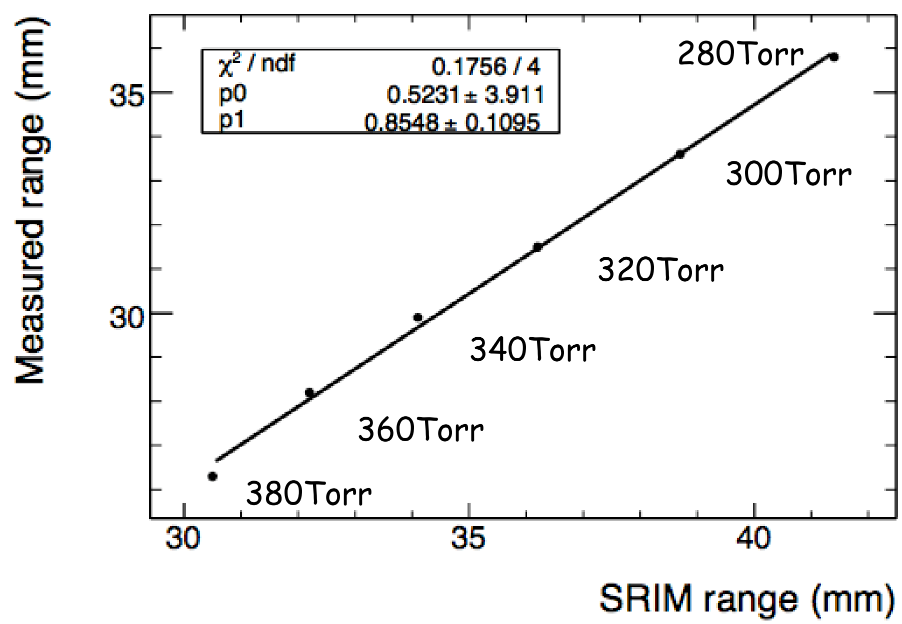
- Much lower energy than 5 MeV alphas
  - 12 MeV n produce F recoils of a few hundred keV: well below Bragg peak!
- Very different dE/dx profile expected
  - dE/dx decreases along the path of the recoil





Scintillation Profile of a Track





ead-Tail effect in low-energy neutrons

Detection Principle