Surface Commissioning of the DMTPC 4-Shooter Directional Dark Matter Detector

Shawn Henderson

on behalf of the
DMTPC Collaboration

March 7, 2013

LEPP Journal Club

Surface Commissioning of the DMTPC 4-Shooter Directional Dark Matter Detector

Outline

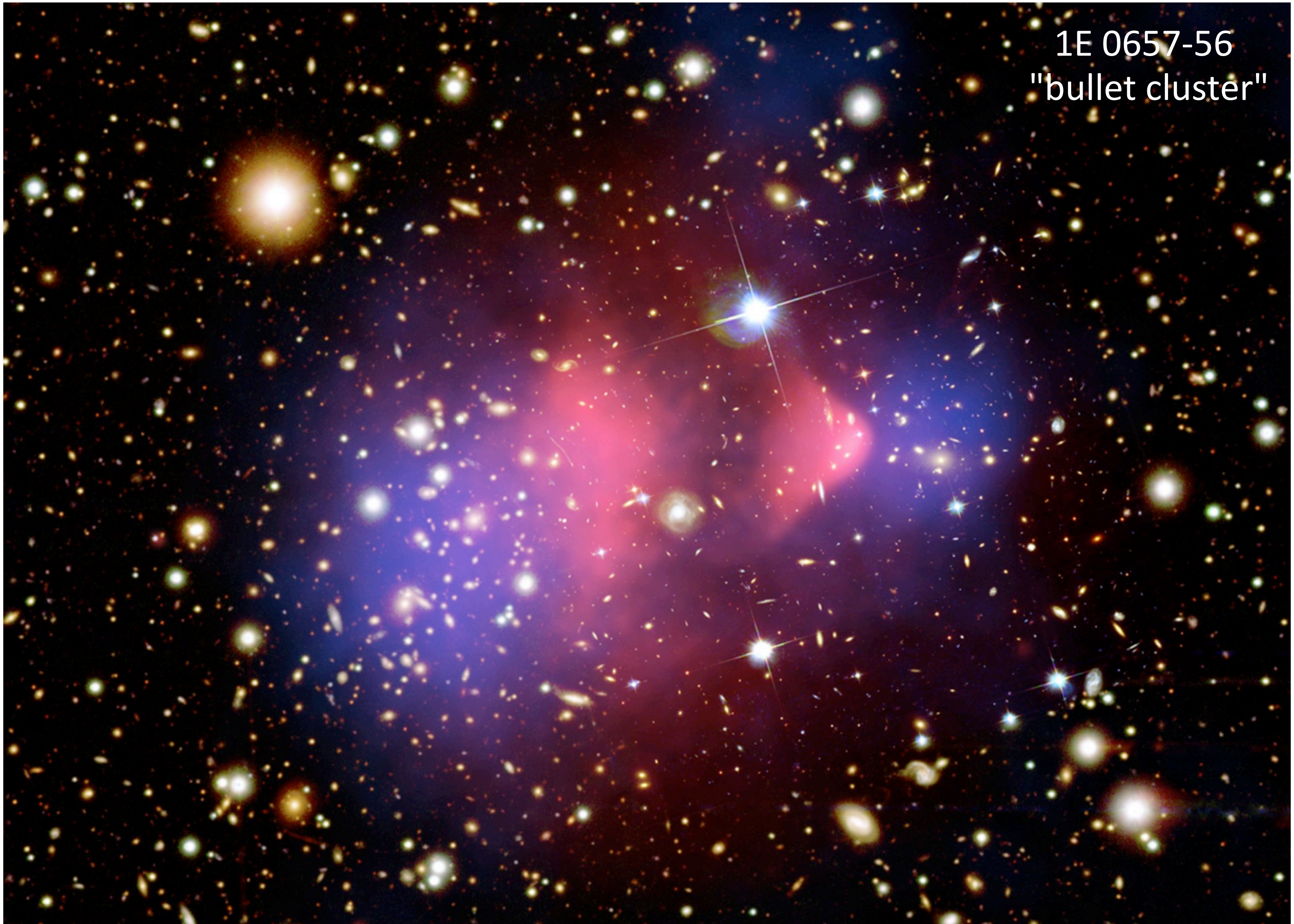
- Introduction
- Directional Sensitivity Measurements
- Future plans

Surface Commissioning of the DMTPC 4-Shooter Directional Dark Matter Detector

Outline

- Introduction
  - Direct detection
  - Directional direct detection
  - The DMTPC collaboration
  - The 4-shooter detector
- Directional Sensitivity Measurements
- Future plans

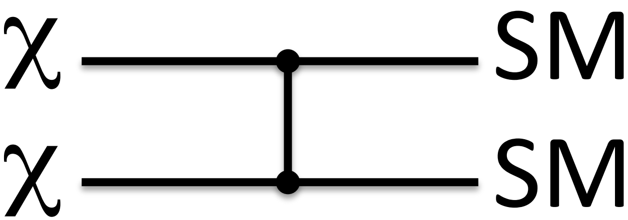
Dark matter



X-ray: NASA/CXC/CfA/ M.Markevitch et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/ U.Arizona/ D.Clowe et al. Optical: NASA/STScI; Magellan/U.Arizona/ D.Clowe et al.

Weakly Interacting Massive Particles

- If $M_\chi \approx 100$ GeV and $\sigma_A \approx 1$ pb

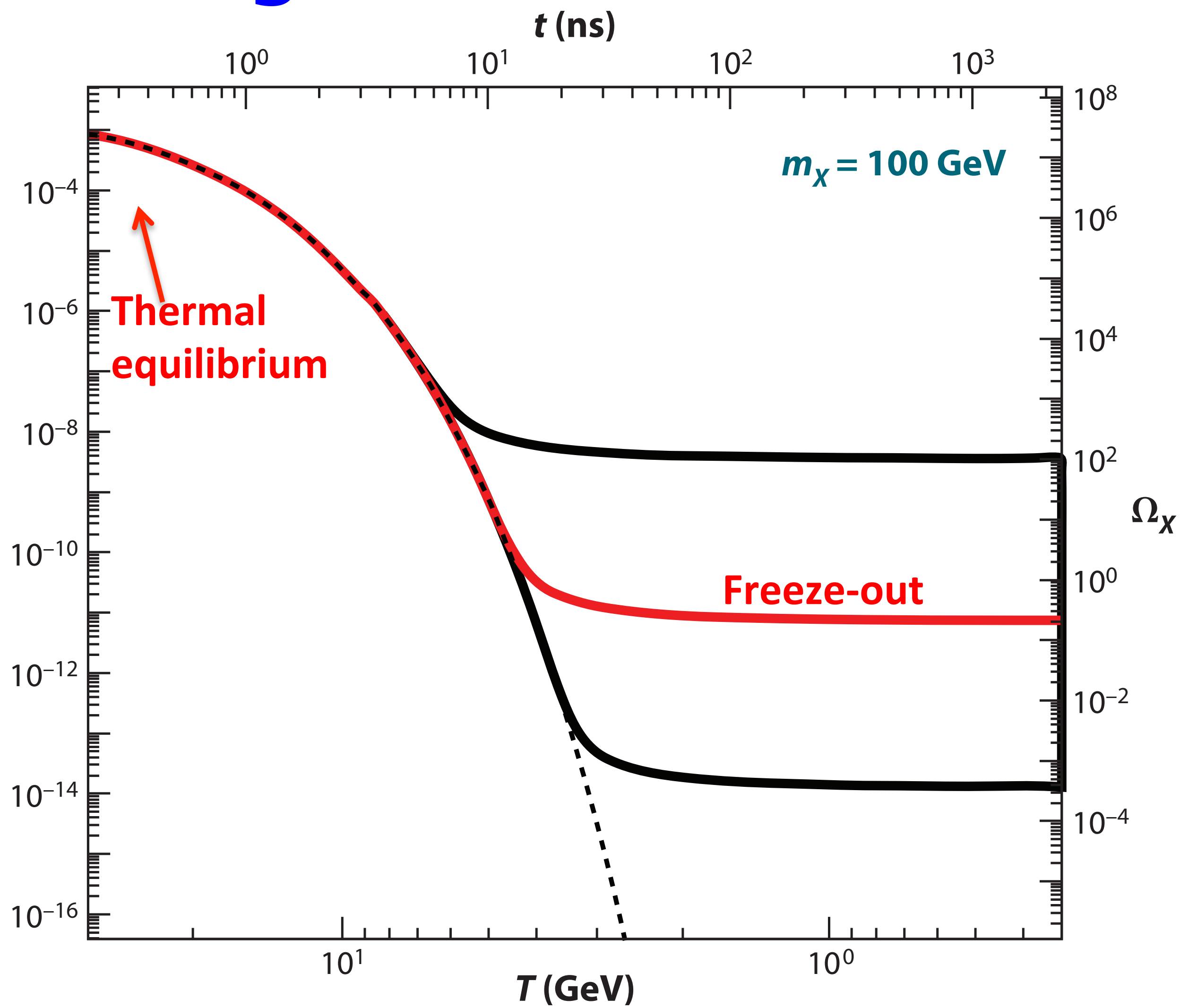


then $\Omega_\chi \approx 0.1$

- $\Omega_\chi = 0.228 \pm 0.07$

WMAP Seven-year Mean
E. Komatsu et al. 2011 ApJS 192 18

- $M_H \approx 125$ GeV and Higgs σ's are around 1 pb

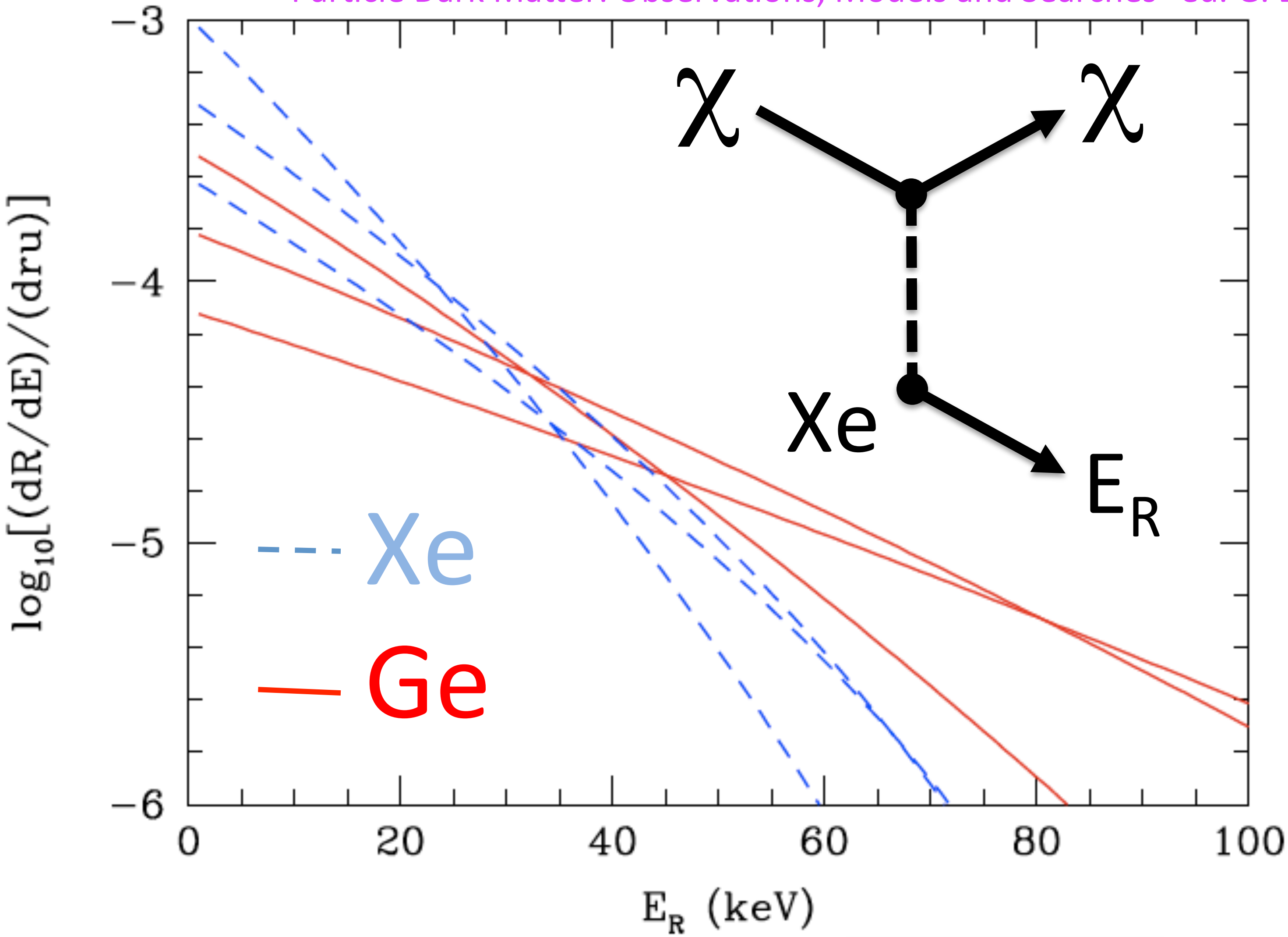


Annu. Rev. Astron. Astrophys. 2010. 48:495–545

The "WIMP Miracle"

Experimental signature : Recoiling Nuclei

"Particle Dark Matter: Observations, Models and Searches" ed. G. Bertone, 2010

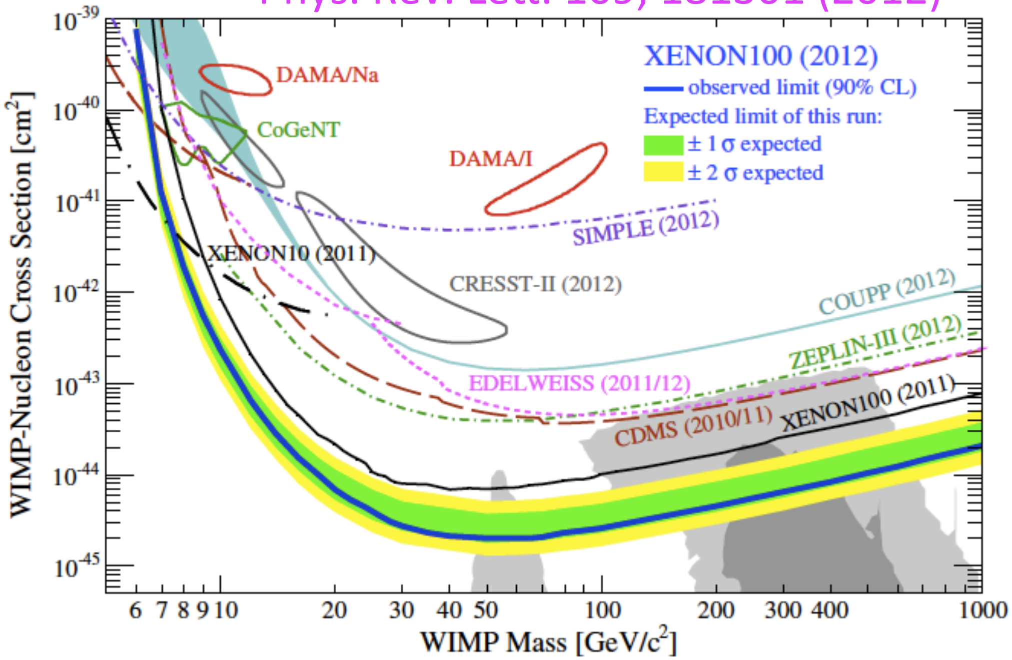


$$\frac{dR}{dE_R} \approx \left(\frac{dR}{dE_R}\right)_0 F^2(E_R) \exp\left(-\frac{E_R}{E_c}\right)$$

OR

Spin-independent WIMP-matter interactions

Phys. Rev. Lett. 109, 181301 (2012)



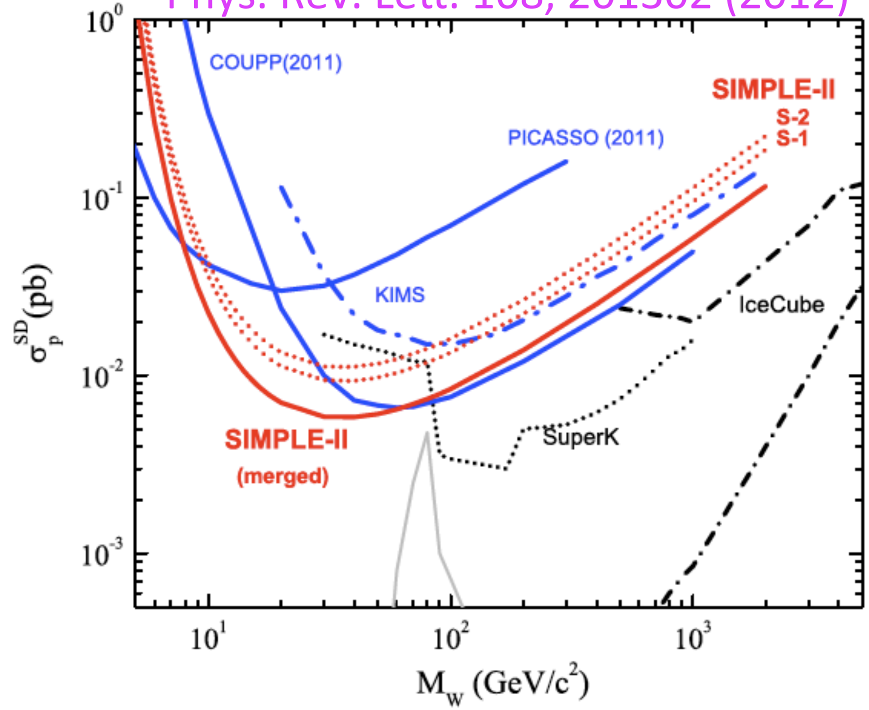
Best so far – XENON100

2 events in **8.4** ton-days

(expected 1±0.2)

Spin-dependent WIMP-matter interactions

Phys. Rev. Lett. 108, 201302 (2012)



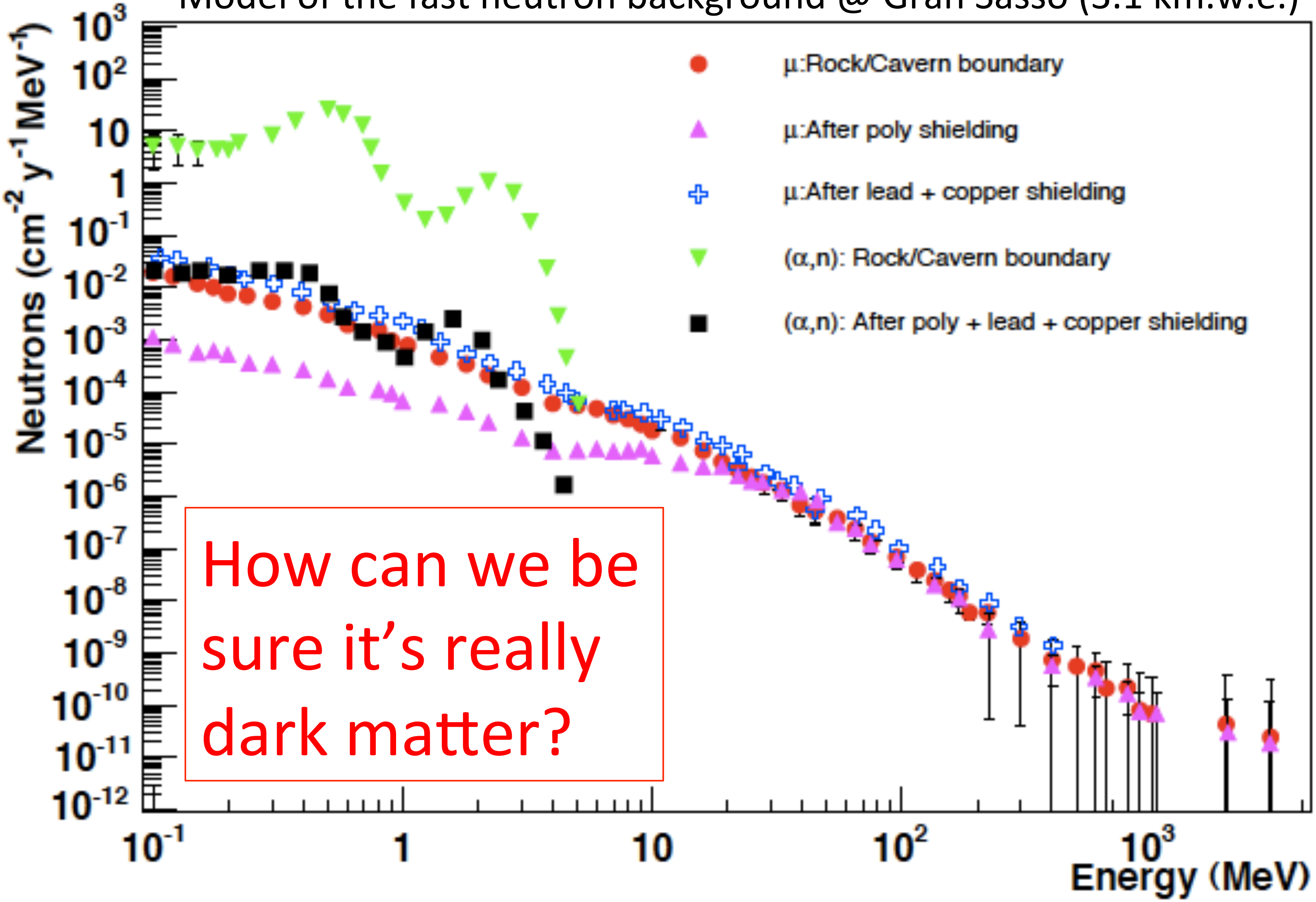
Best so far – SIMPLE-II

11 events in **0.022** ton-days

(expected 15±2)

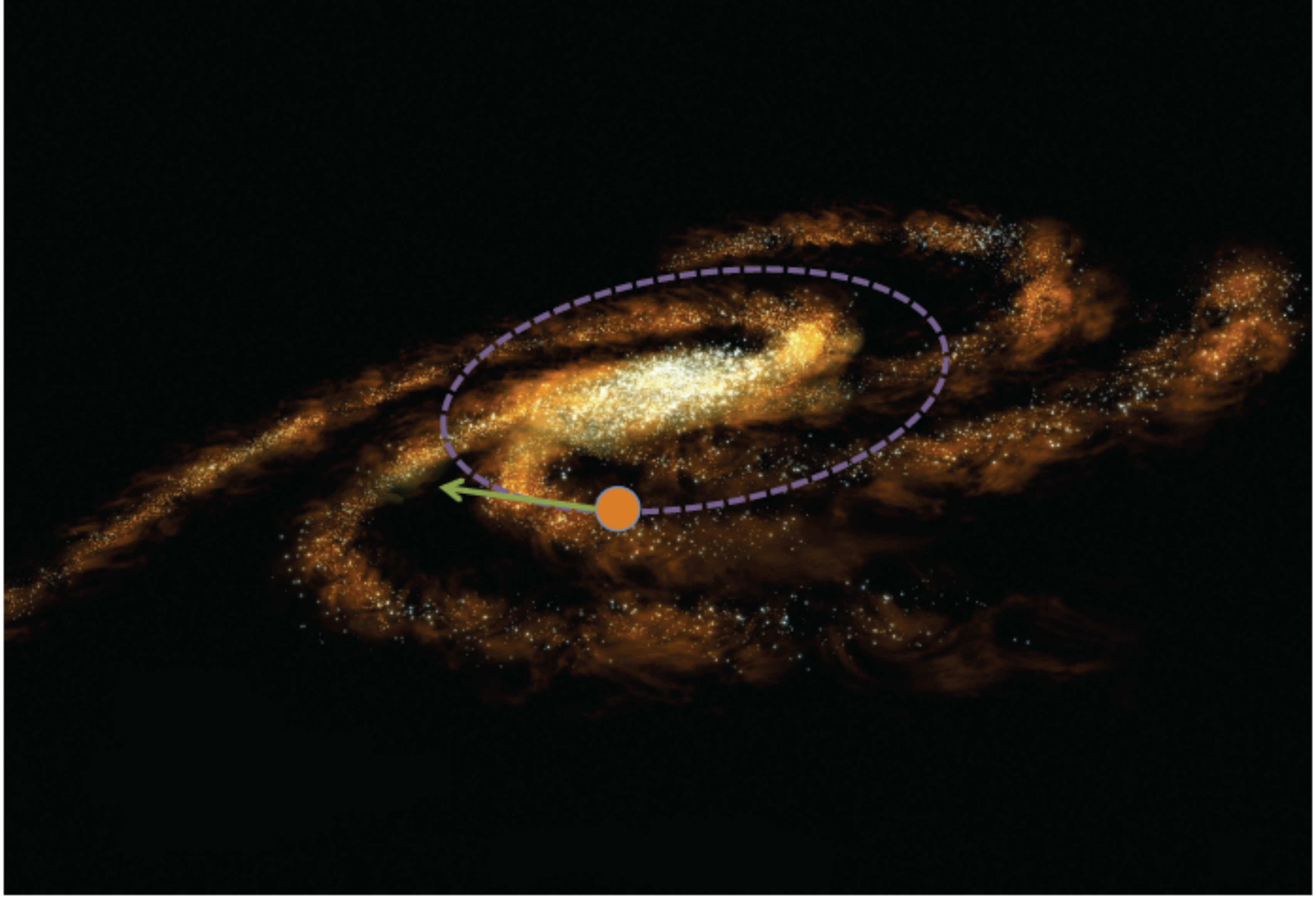
Background energy spectra identical to signal

Model of the fast neutron background @ Gran Sasso (3.1 km.w.e.)



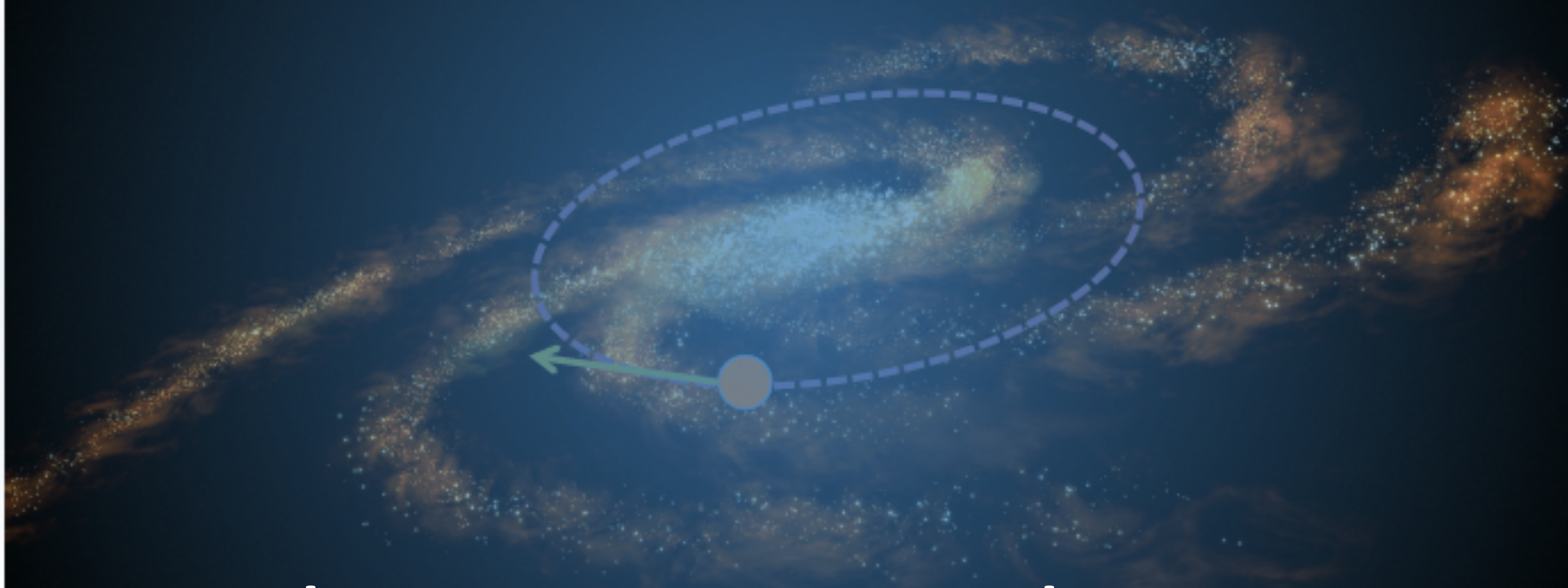
D.-M. Mei and A. Hime, Phys Rev D73 053004,2006

Directional direct detection



The WIMP wind

Motion of the Earth and the detection of weakly interacting massive particles
D. Spergel, Phys. Rev. D 37, 1353–1355 (1988)

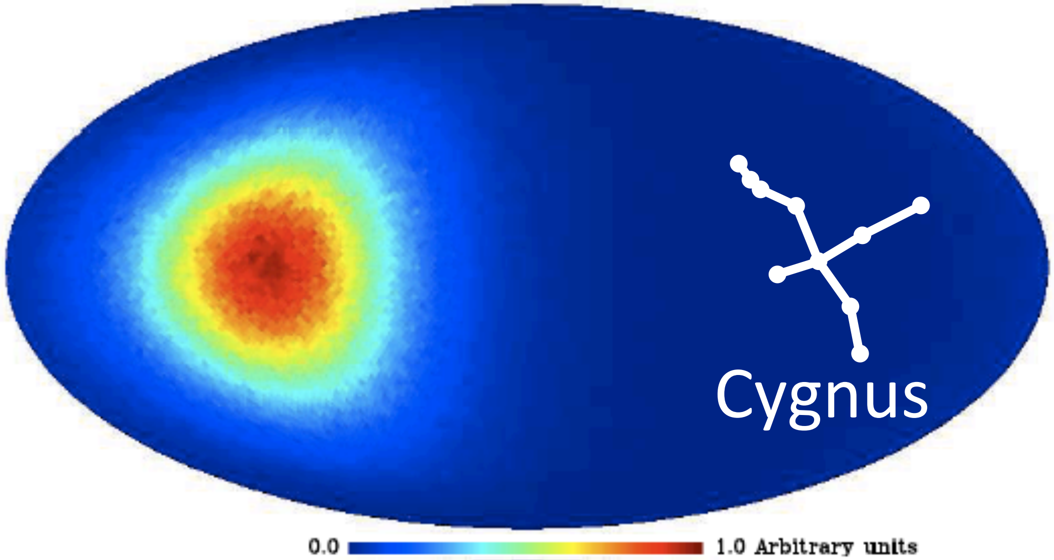


Solar motion results in an apparent dark matter wind

WIMP direction is imprinted on nuclear recoil direction

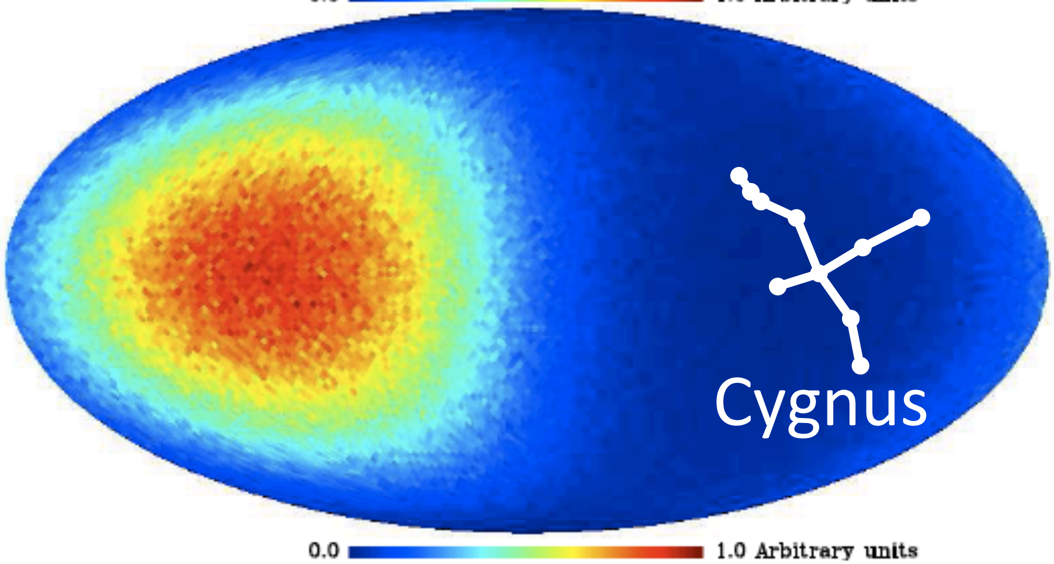
Billard, J. *et al.*, 2010, Phys. Lett. B, 691, 156-162

WIMP flux in the case of an isothermal spherical halo



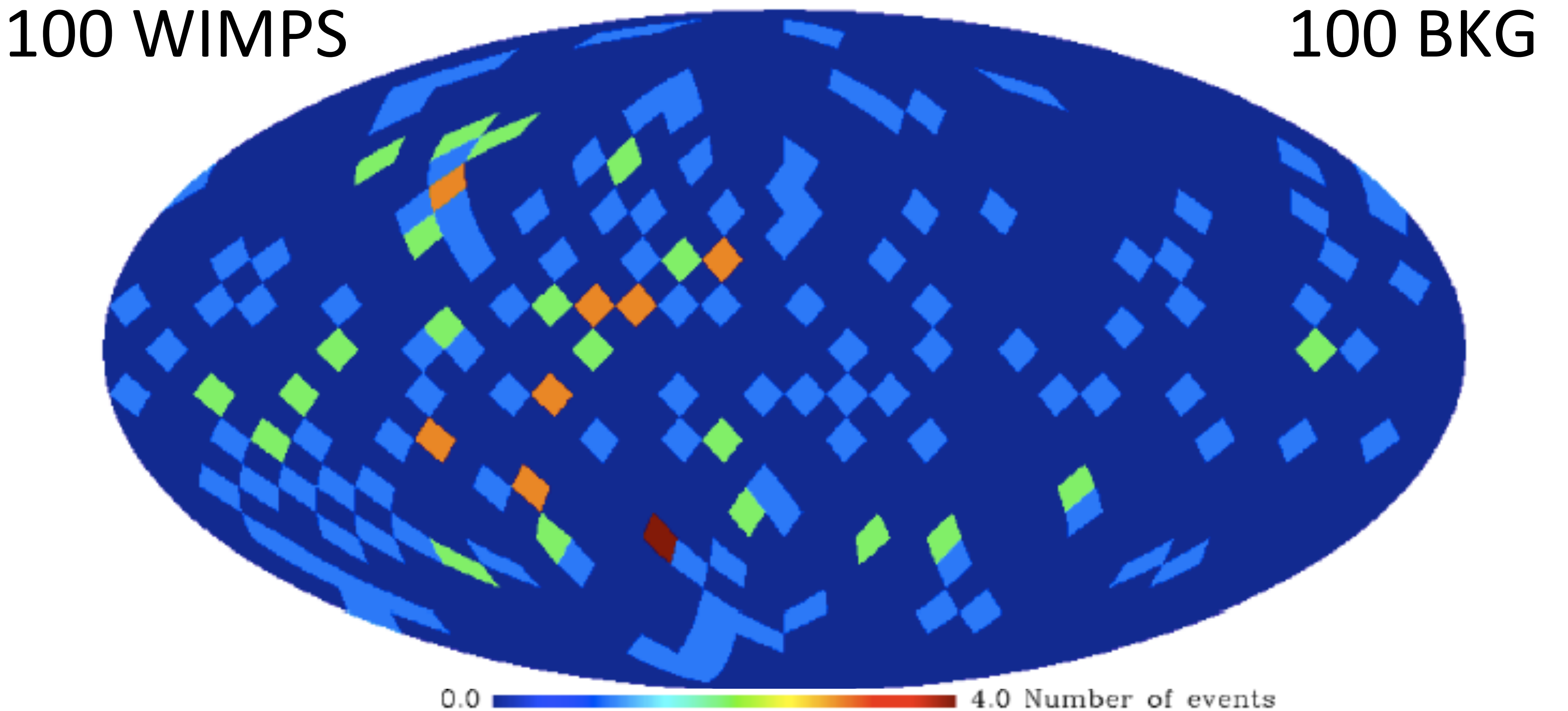
WIMP-induced recoil distribution

- ^{19}F target
- 100 GeV/c^2 WIMP
- 5 keV<E_R<50 keV



The Case for a Dark Matter Detector and the Status of Current Experimental Efforts, Ahlen, S. et al., Int. J. Mod. Phys. A. 25, 1, 2010

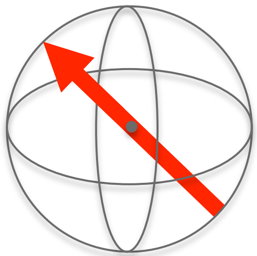
Detection possible even in the presence of sizeable backgrounds



7-σ detection of WIMP content even with $N_{BKG} = N_{WIMP}$ (SNR = 0.5)

Billard, J. *et al.*, 2010, Phys. Lett. B, 691, 156-162

Hierarchy of directional sensitivity

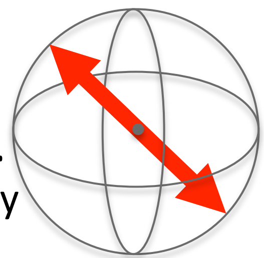


stretch goal

full 3D vector

Numbers assume a 100 GeV mass WIMP and a 20 keVr nuclear recoil detection threshold.
A. Green and B. Morgan,
Astropart. Phys. 27: 142-149, 2007

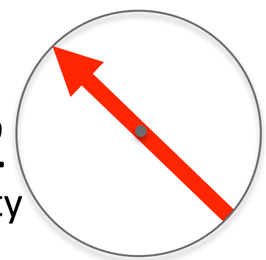
1/12
sensitivity



axial 3D vector

Goal: do this as well as we can

1/2
sensitivity

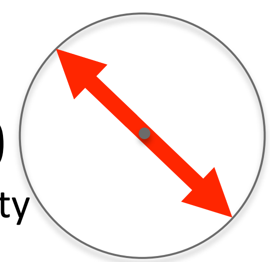


full 2D vector
"Head-Tail"

Keep in mind

Low pressure (0.1 atm) gas detectors have 10^3-10^4 x **less** mass/volume than solid-phase detectors.

1/30
sensitivity



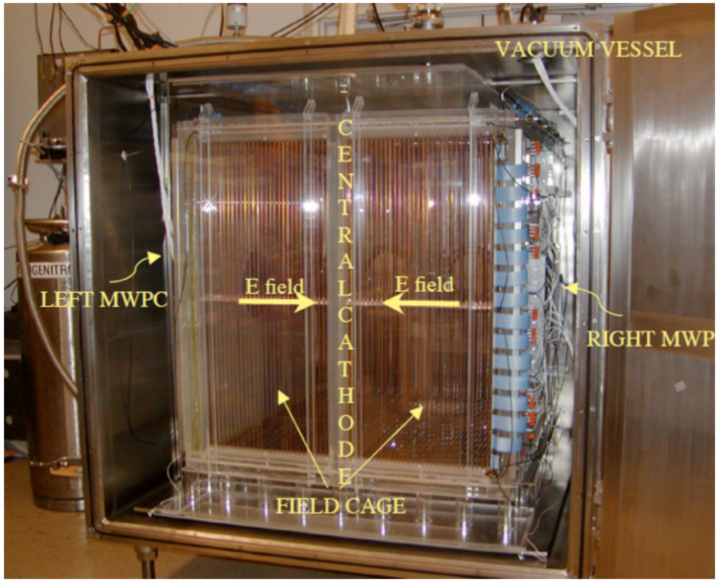
axial 2D vector

Billard, J. *et al.*, 2010, Phys. Lett. B, 691, 156-162

Directional Efforts

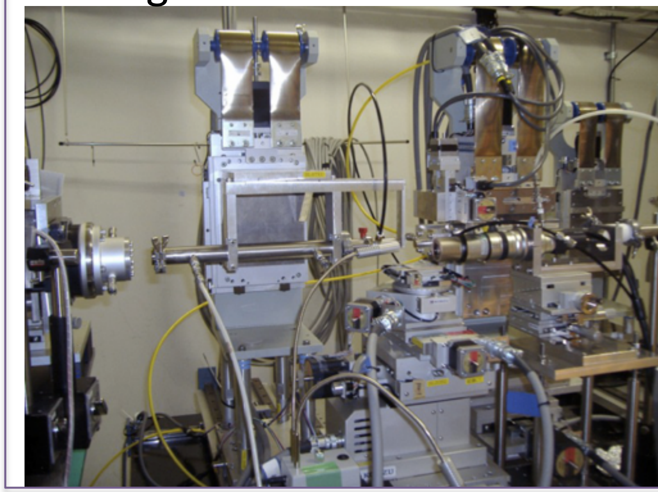
DRIFT-IId Boulby England

Negative ion TPC with MWPC readout



Emulsions Japan and LNGS, Italy

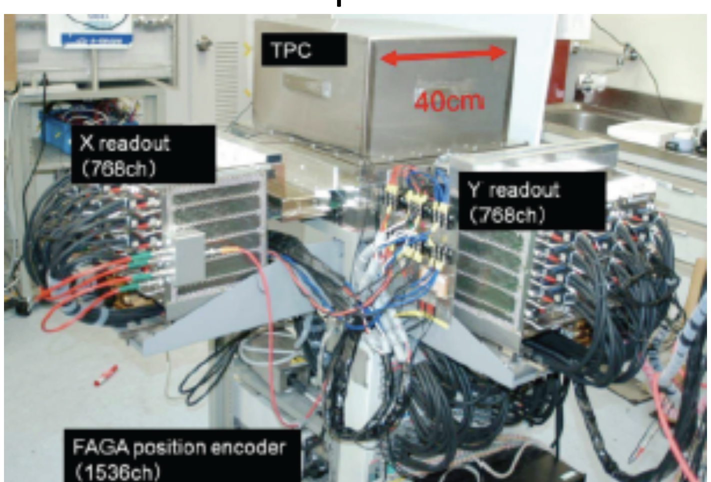
Fine grained nuclear emulsion



DMTPC MIT WIPP

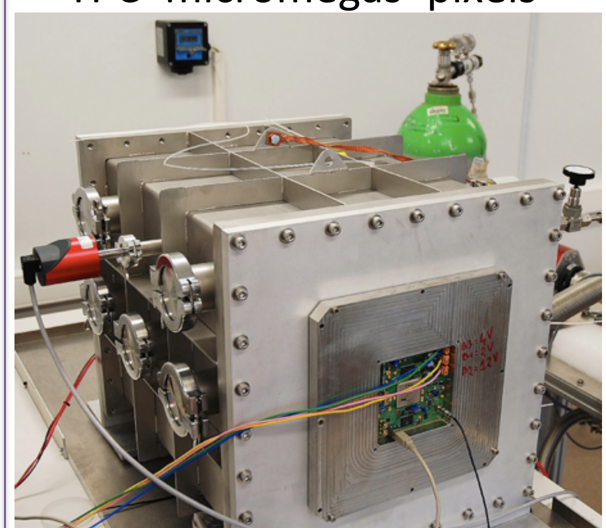
NEWAGE Kamioka Japan

TPC with GEM + µPIC readout



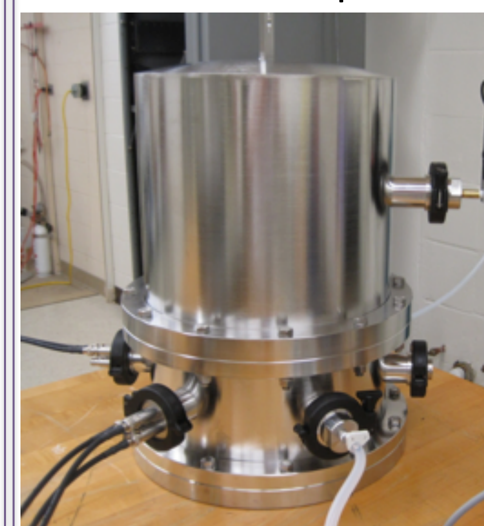
MIMAC Modane France

TPC+micromegas+pixels



D^3 U. Hawaii

TPC+GEMs+pixels



The DMTPC Collaboration

http://dmtpc.mit.edu

H. Choi, C. Deaconu, P. Fisher **(PI)**, S. Henderson, W. Koch, J.P. Lopez, H. Tomita
Massachusetts Institute of Technology

A. Dushkin, H. Wellenstein **(PI)**
A. Brandeis University

R. Eggleston, P. Giampa, J. Monroe **(PI)**, G. Muraru
University of London Royal Holloway

I. Jaegle, S. Ross, S. Vahsen **(PI)**
University of Hawaii

J. Battat **(PI)**, V. Gregoric, K. Hartung, K. Recine, E. de Souza
Bryn Mawr College

Papers:

Dujmic *et al.* NIMA 584 (2007)

Kaboth *et al.* NIMA 592 (2008)

Dujmic *et al.* Astropart.Phys.30:58-64 (2008)

Caldwell *et al.* arXiv:0905.2549 (2008)

Roccaro *et al.* NIMA 608 (2009)

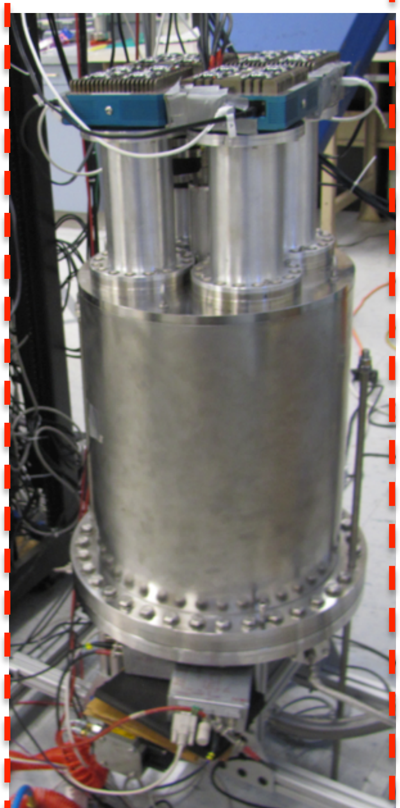
Ahlen *et al.* IEEE Trans. Nucl. Sci. (2009)

Ahlen *et al.*, Phys.Lett. B695 (2011)

J. Lopez *et al.* NIM A 696 (2012)

undergraduate   graduate student   post-doc   professor

The "4-Shooter"
18L TPC
4x CCD
Sea-level @ MIT
taking initial suite of calibration data



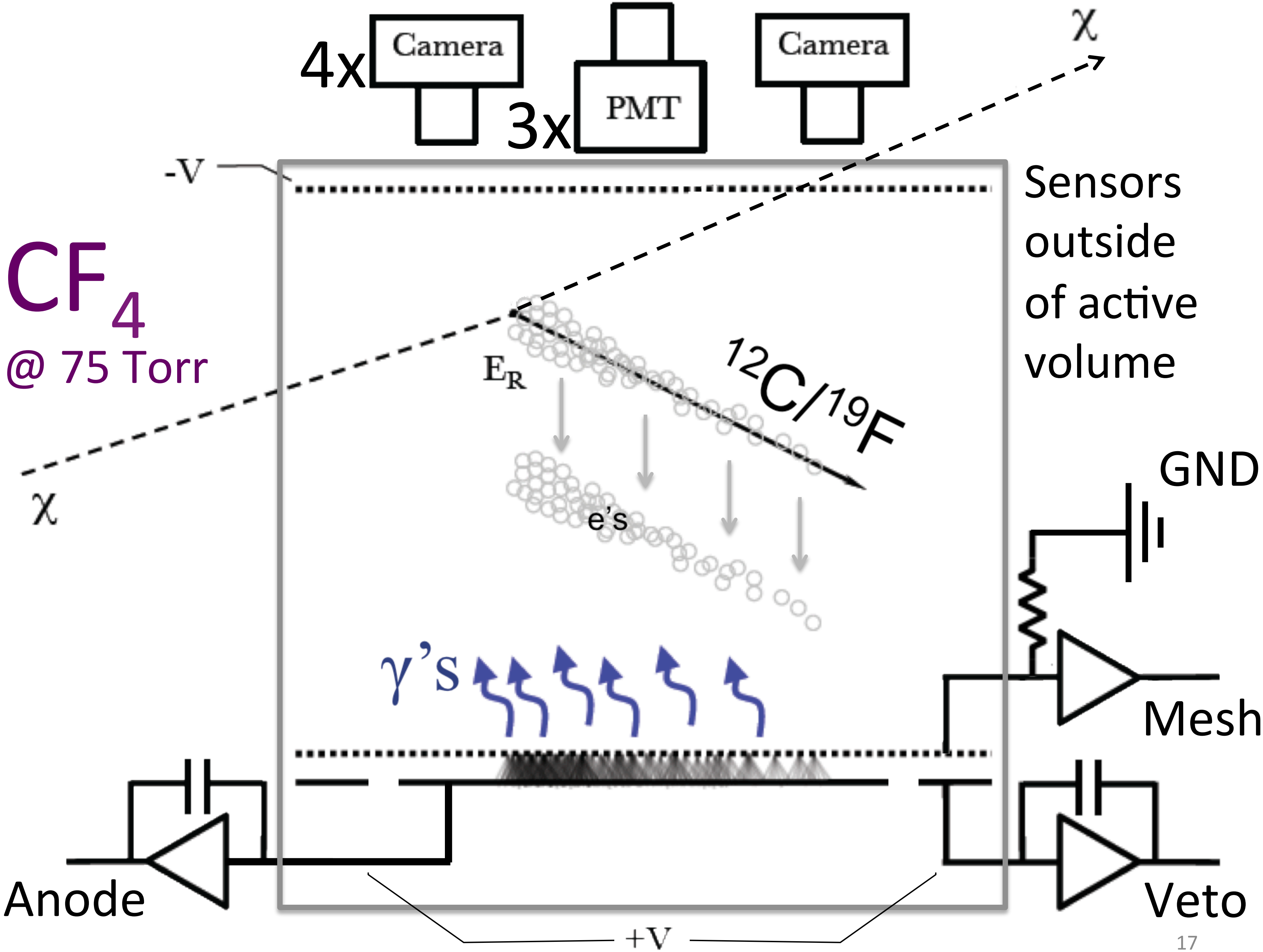
The "10L"
2x 5L TPCs, CF4
Underground @ WIPP taking data
S. Ahlen *et al.*, Phys. Lett. B695 (2011) 124-129

arXiv:1108.4894

R&D Vessel/DCTPC
6L TPC, He+CF_4 mix
@ Double Chooz measuring cosmogenic neutrons

Raytheon
50L TPC, pure CF_4 and He+CF_4 mix @ MIT; focused on neutron detection
50 cm drift length

DMTPC
Dark **M**atter **T**ime **P**rojection **C**hamber


4x
Camera
3x
PMT
Camera
χ
-V
Sensors
outside
of active
volume
CF4
@ 75 Torr
E_R
12C/19F
χ
GND
e's
γ's
Mesh
Anode
Veto
+V

The "4-Shooter"

45-75 Torr CF_4

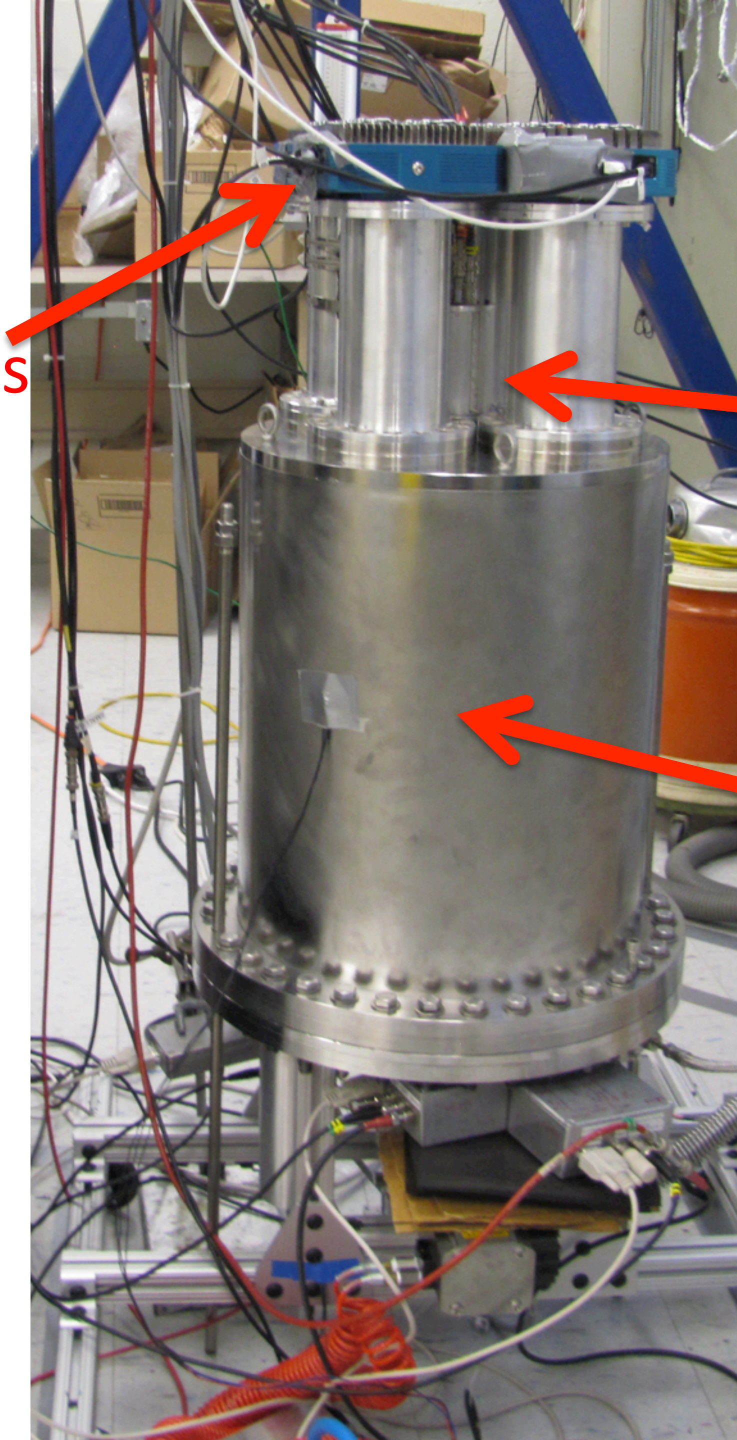
18L, 6.6 gm

-5 kV drift

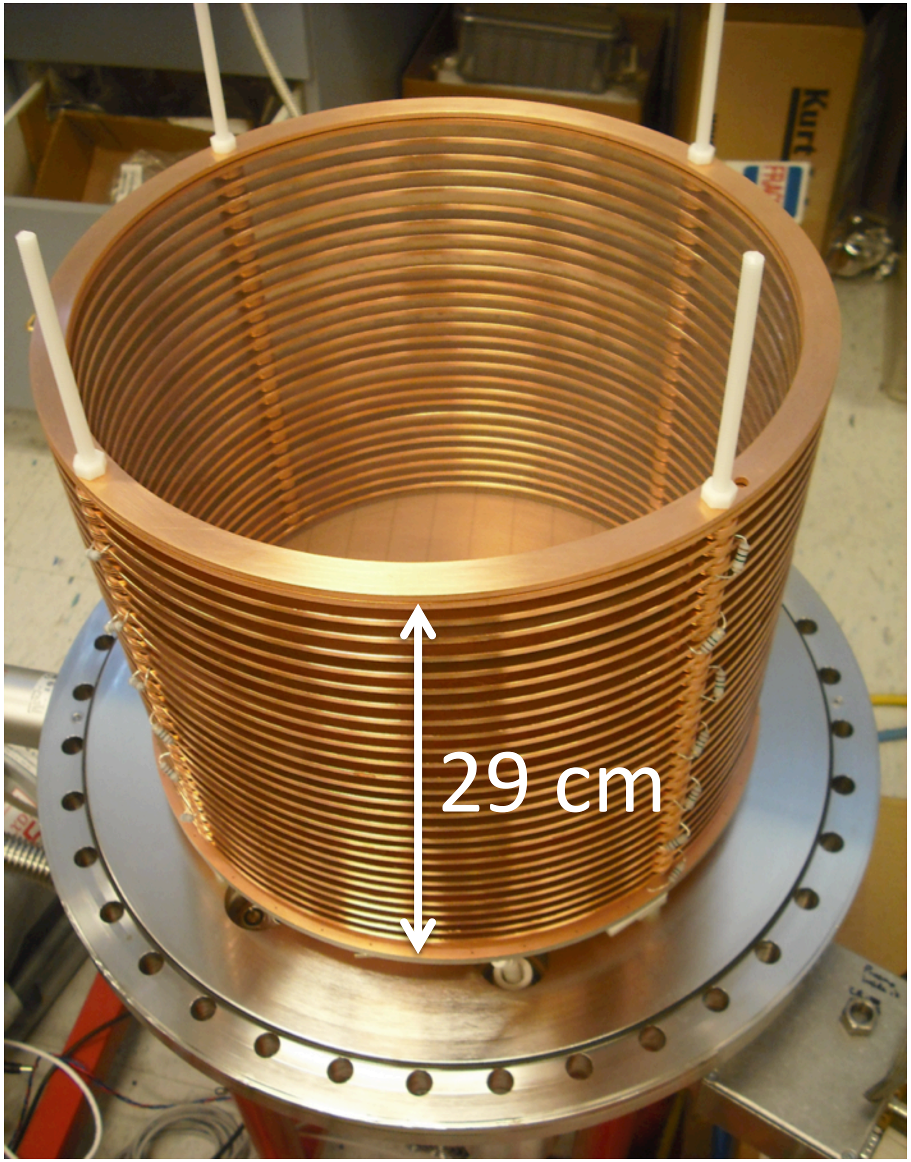
650V-720V anode

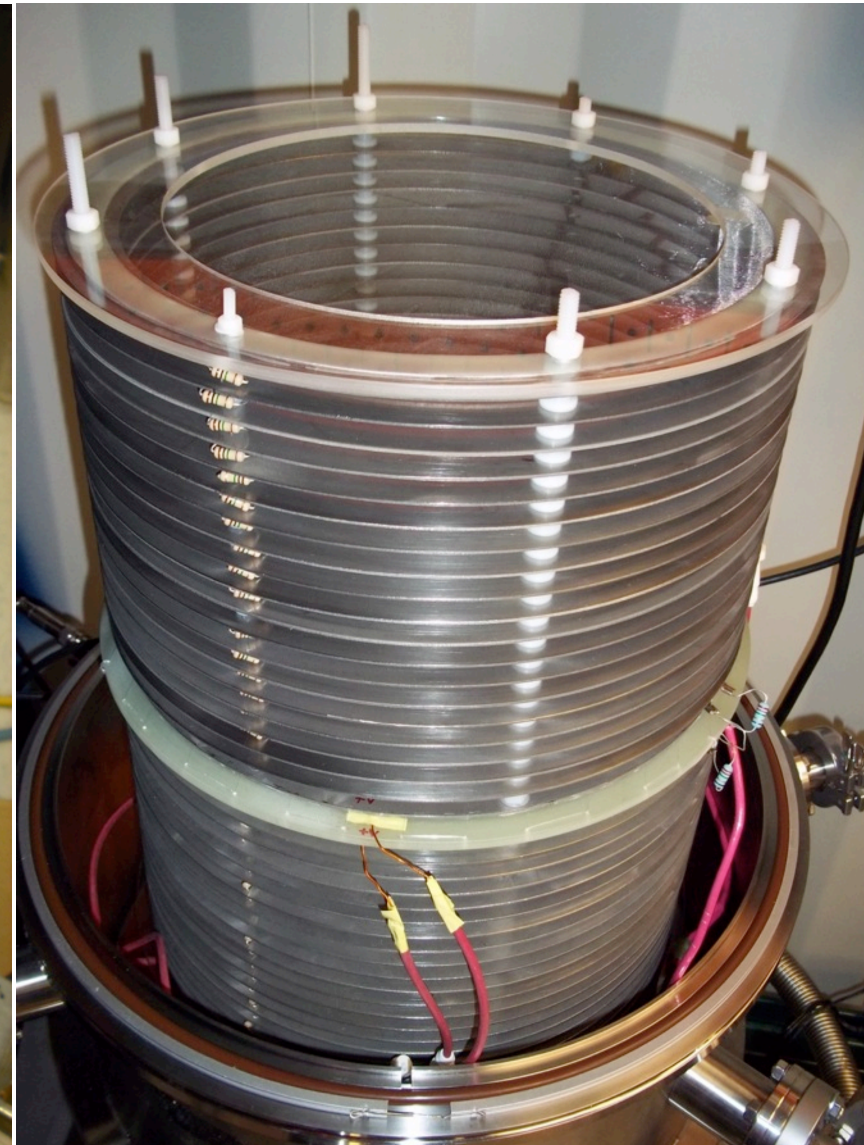
Spin-dependent WIMP Search on ^{19}F

large spin-dependent-p coupling



Careful cleaning and materials selection



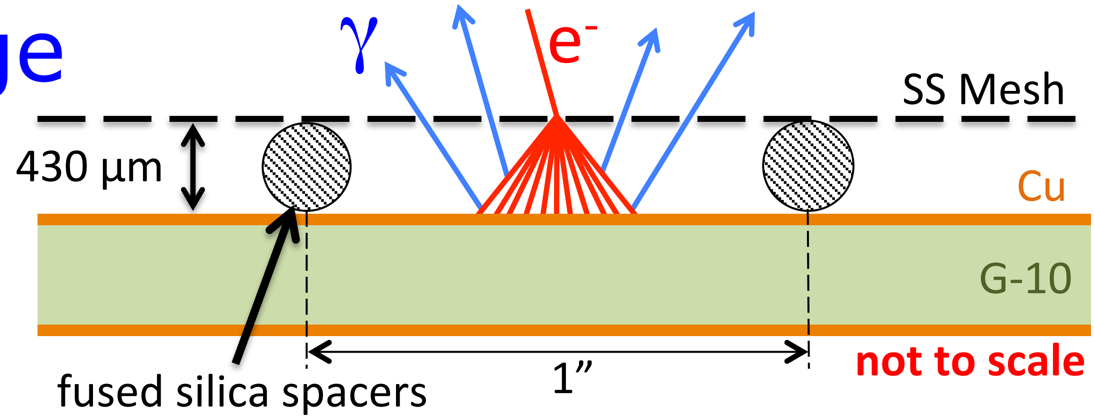


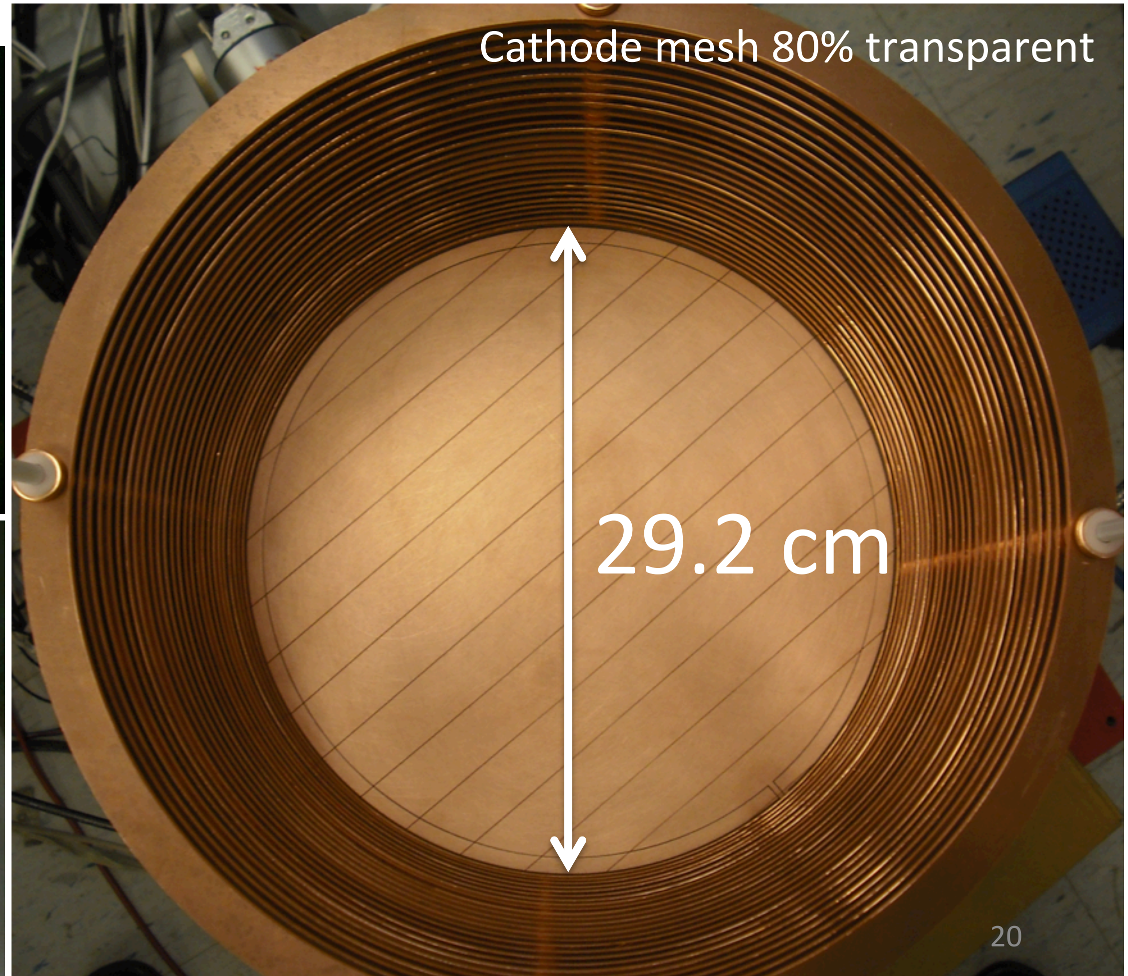
Minimal materials – much lower backgrounds

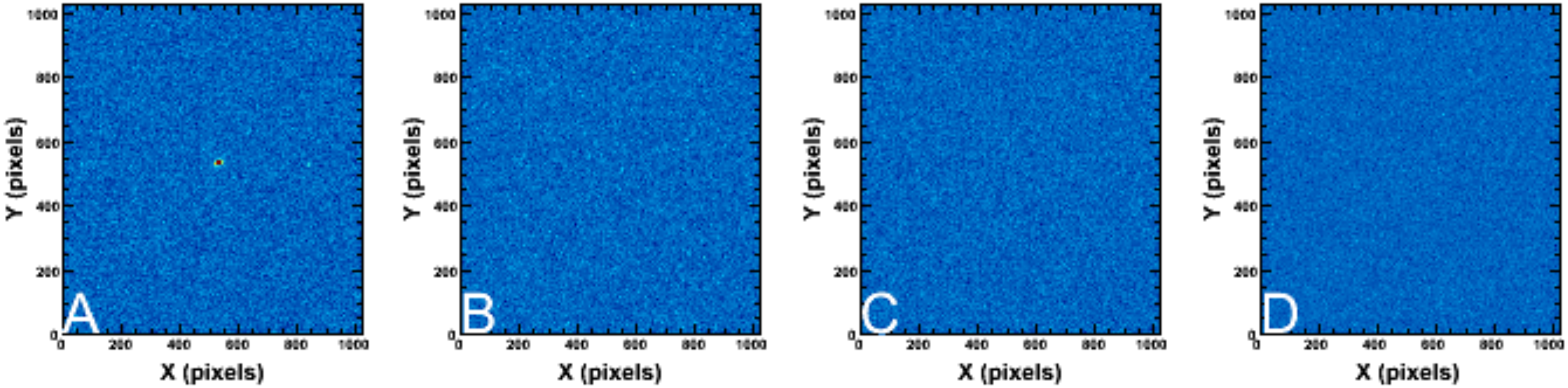
Environmental α rate 19x smaller

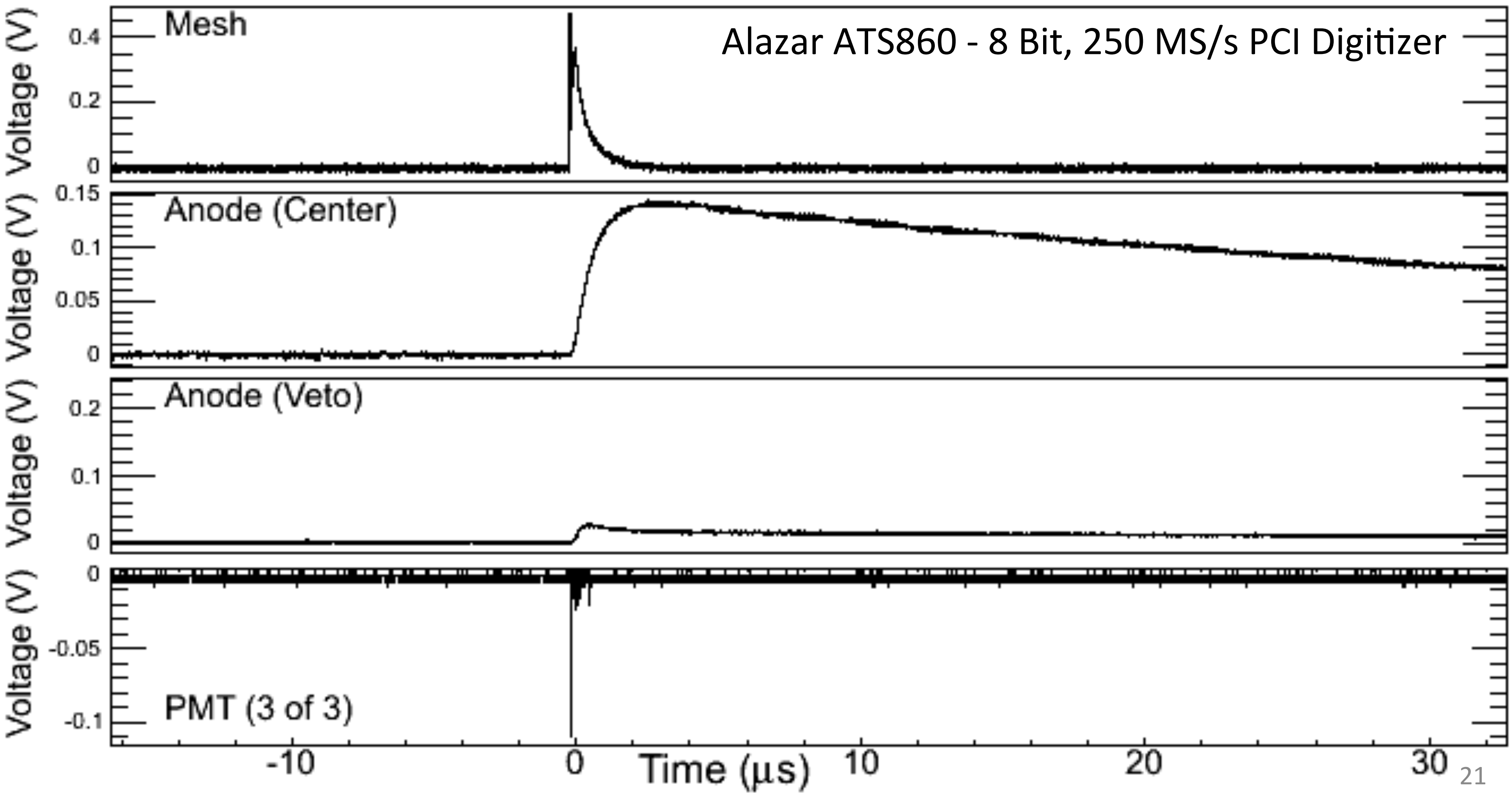
Amplification Stage

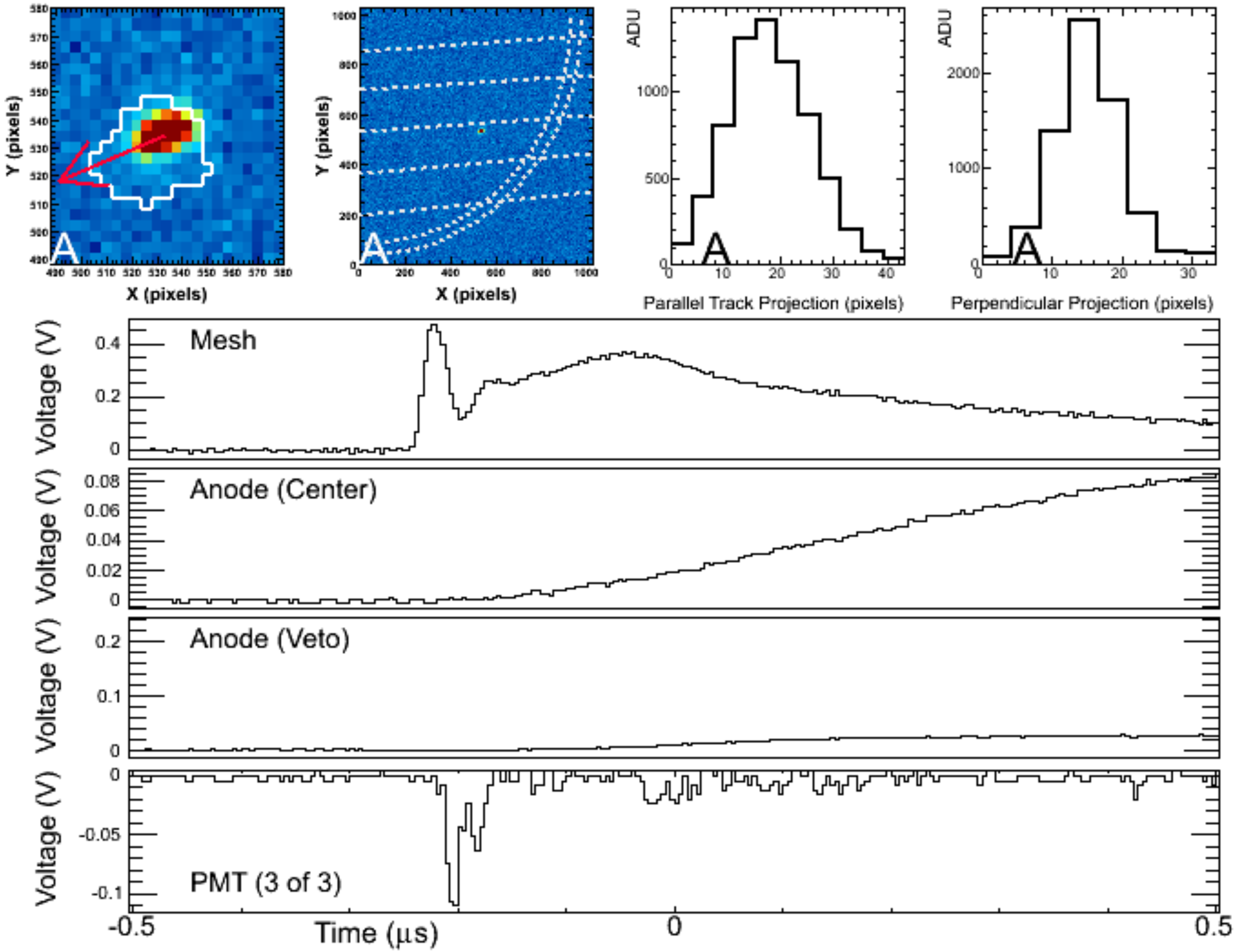
Home-brew
Small # of materials
Assembled in cleanroom



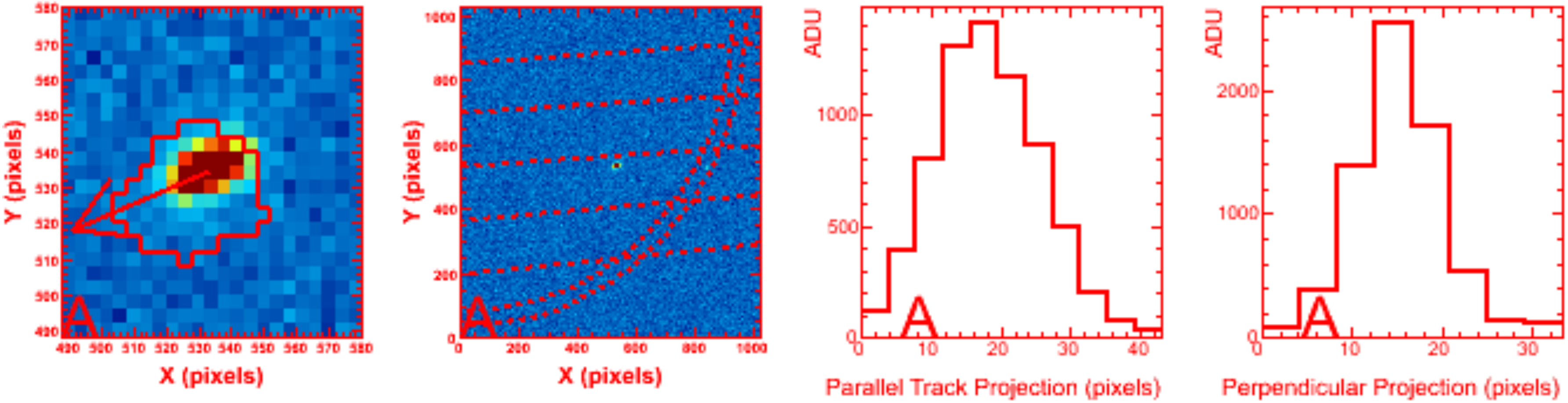


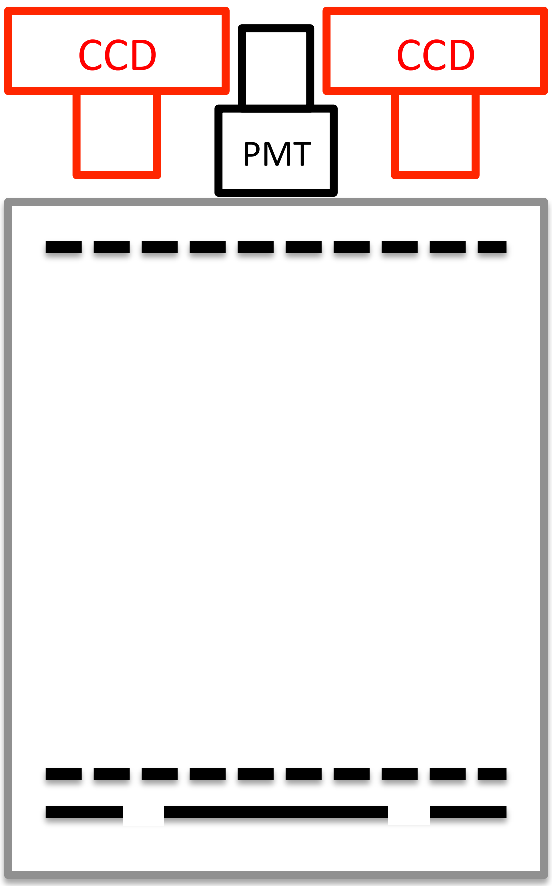

A
B
C
D
Y (pixels)
X (pixels)
0
200
400
600
800
1000

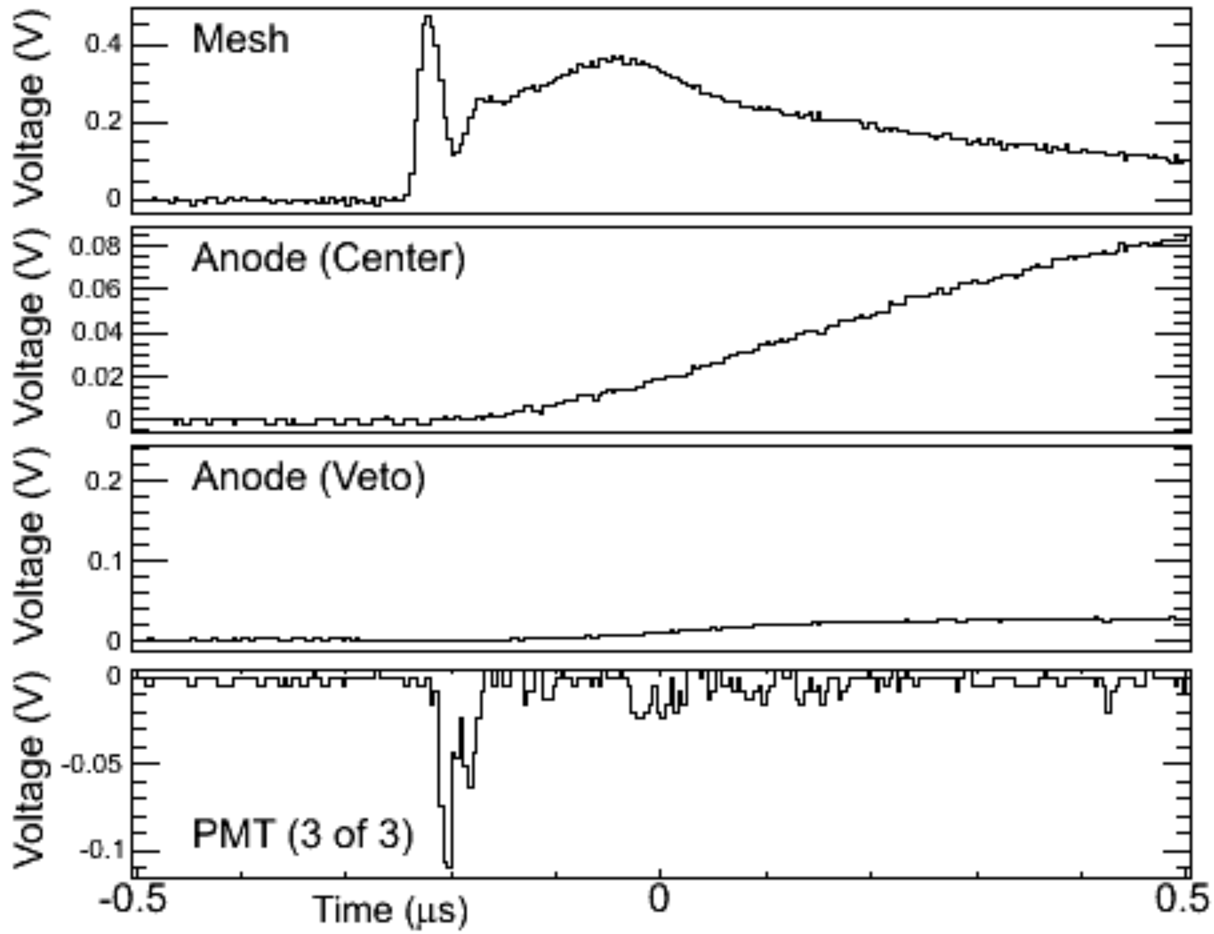

Alazar ATS860 - 8 Bit, 250 MS/s PCI Digitizer
Mesh
Anode (Center)
Anode (Veto)
PMT (3 of 3)
Voltage (V)
Time (μs)
-10
0
10
20
30
0.4
0.2
0.15
0.1
0.05
-0.05
-0.1



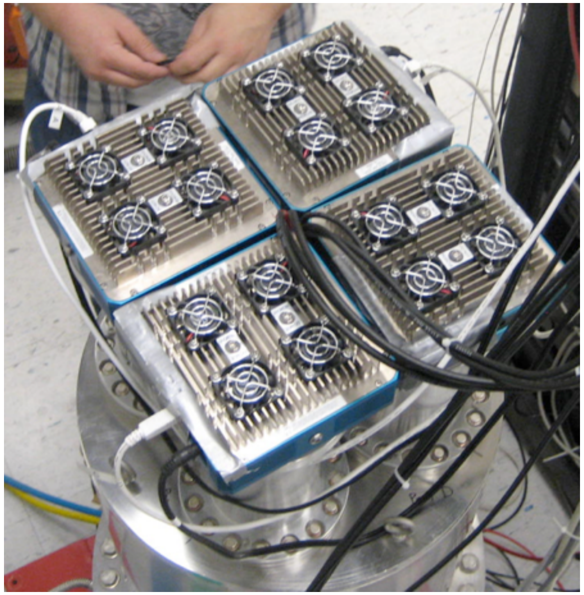
A
Y (pixels)
X (pixels)
ADU
Parallel Track Projection (pixels)
Perpendicular Projection (pixels)
Mesh
Anode (Center)
Anode (Veto)
PMT (3 of 3)
Voltage (V)
Time (μs)

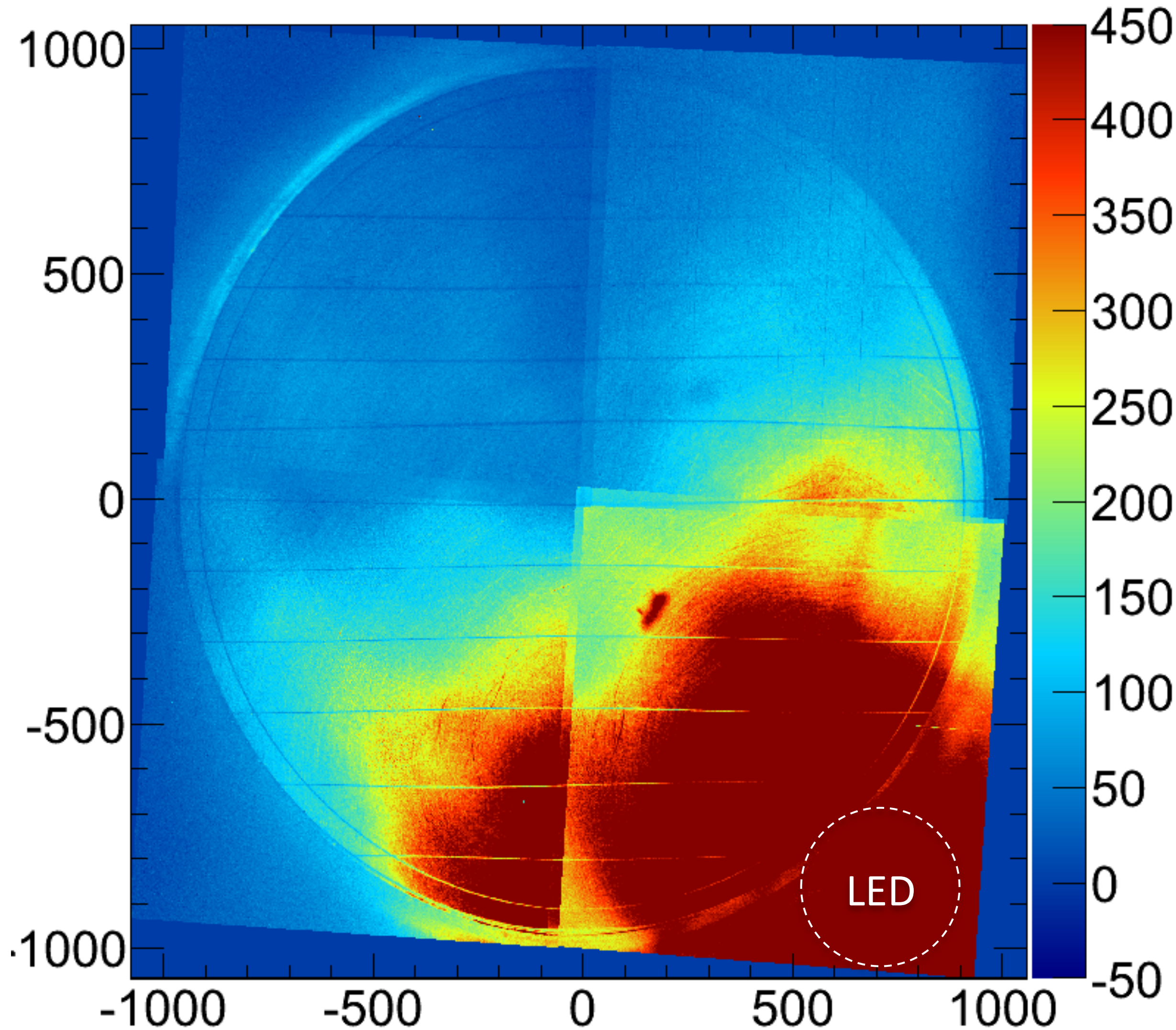

Y (pixels)
X (pixels)
A
Y (pixels)
X (pixels)
A
ADU
Parallel Track Projection (pixels)
A
ADU
Perpendicular Projection (pixels)
A


CCD
CCD
PMT


Mesh
Anode (Center)
Anode (Veto)
PMT (3 of 3)
Voltage (V)
Time (μs)

CCD Readout





Alta U6 CCDs

1024x1024, 24µm pixels

1"x1", 1.05 Mpixel chip

Binned 4x4 in hardware

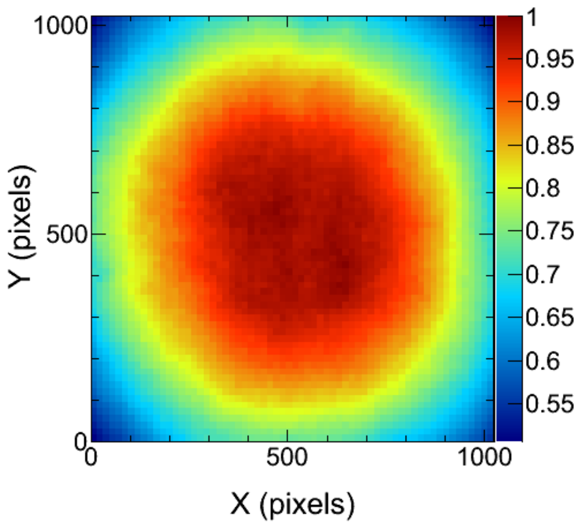
Shutter-less operation

Canon telephoto lenses

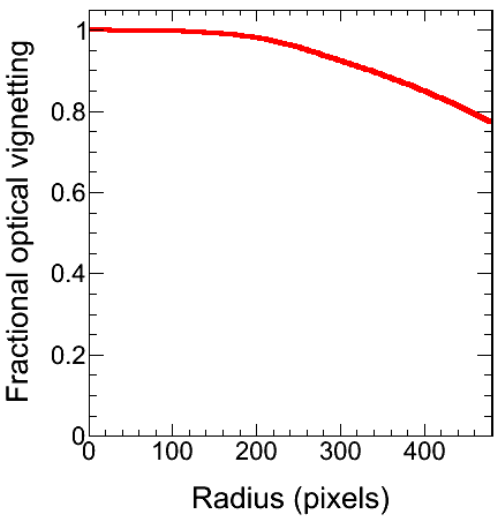
FD 85mm f/1.2

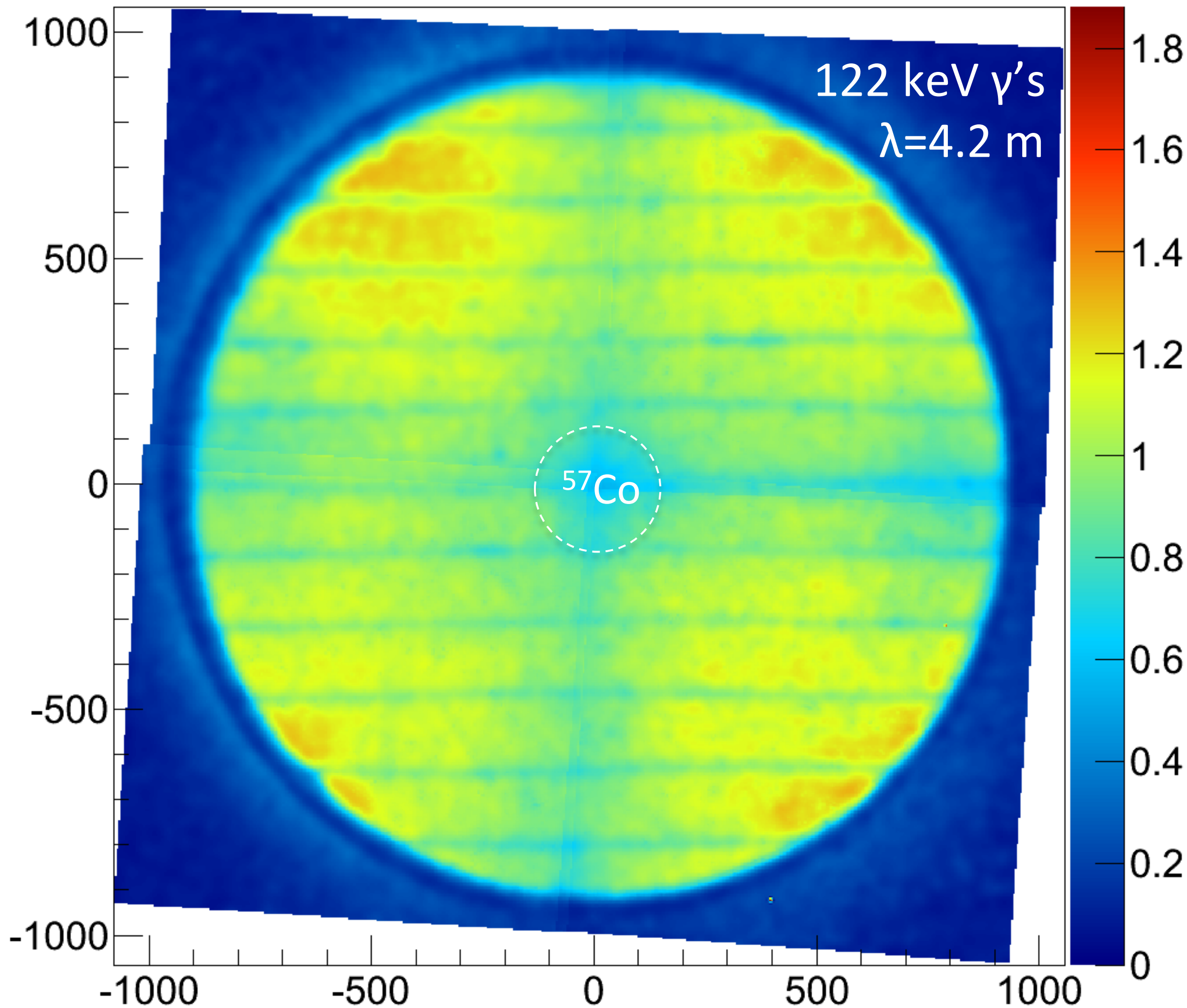
Must stitch 4 camera images into 1 composite image

CCD Spatial Gain Correction



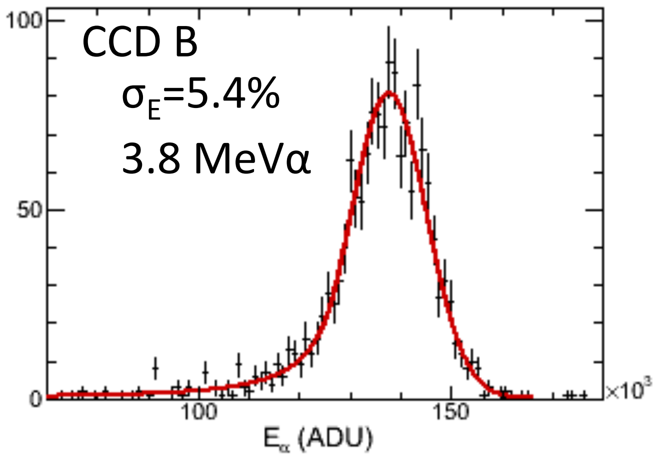
CCD optical flat field showing radial fall-off



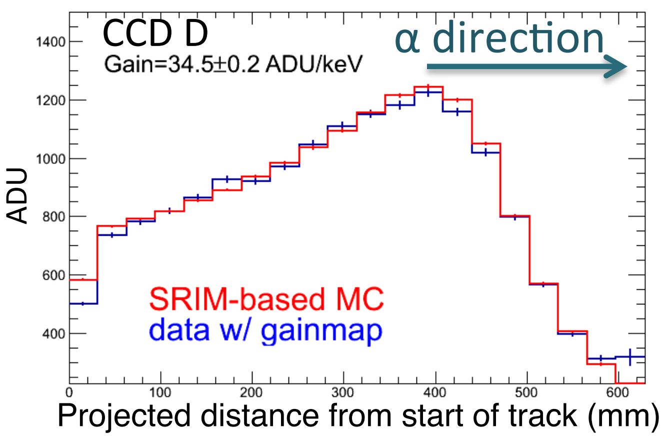


CCD gain(X,Y) measured using a ^{57}Co γ source to generate spatially uniform signal

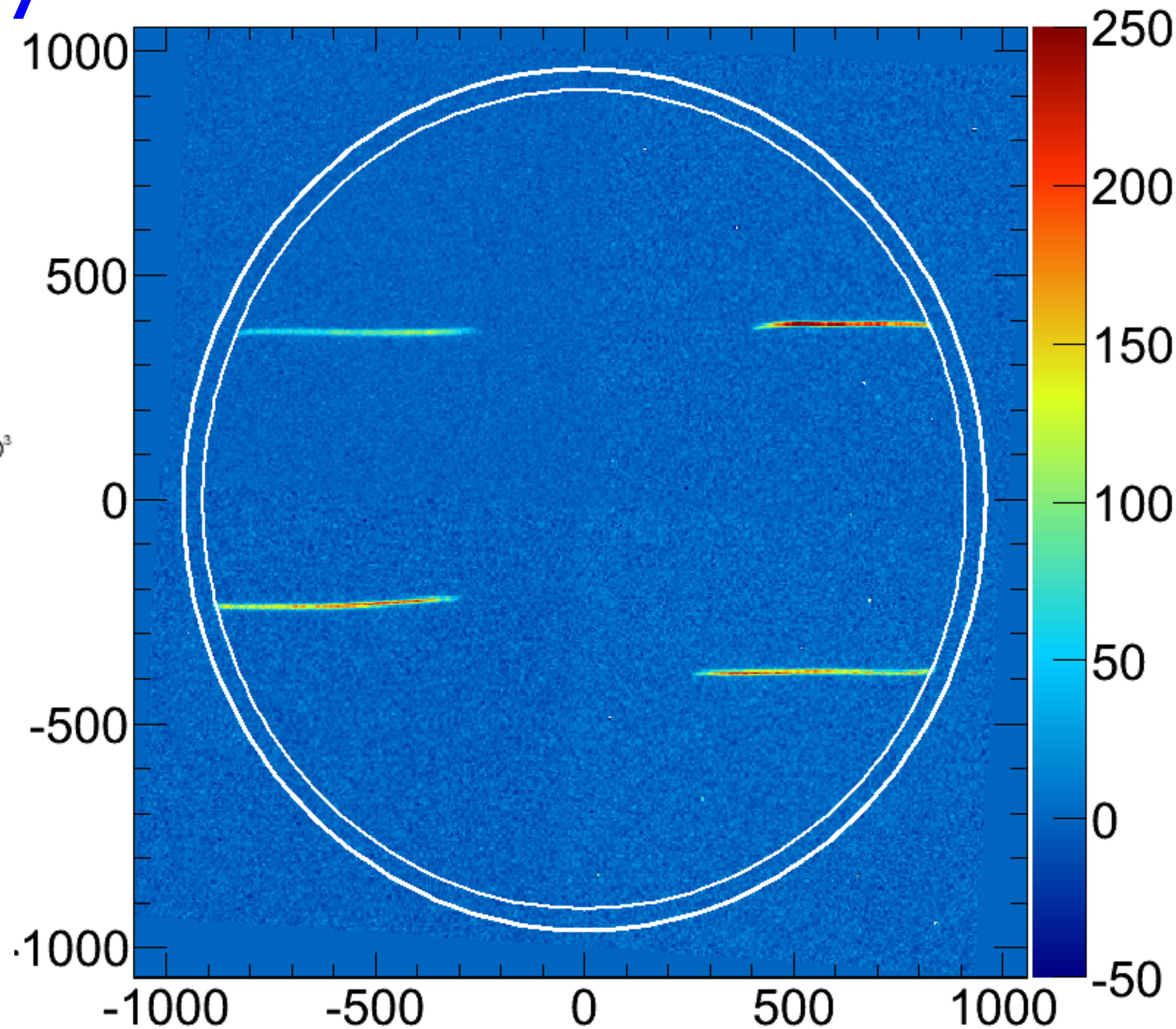
CCD Energy Calibration



Crystal ball fit to 1 CCD's ^{241}Am α energy spectrum



^{241}Am α energy vs range data-MC agreement



^{241}Am α source calibration; α's in all 4 cameras

The benefits of material selection

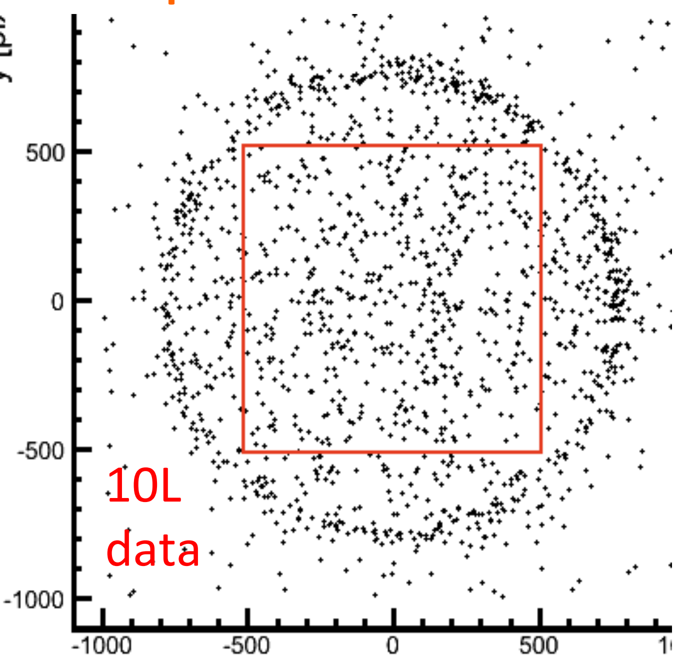
Mostly;

OFHC Cu, Acetal,
SS and G-10

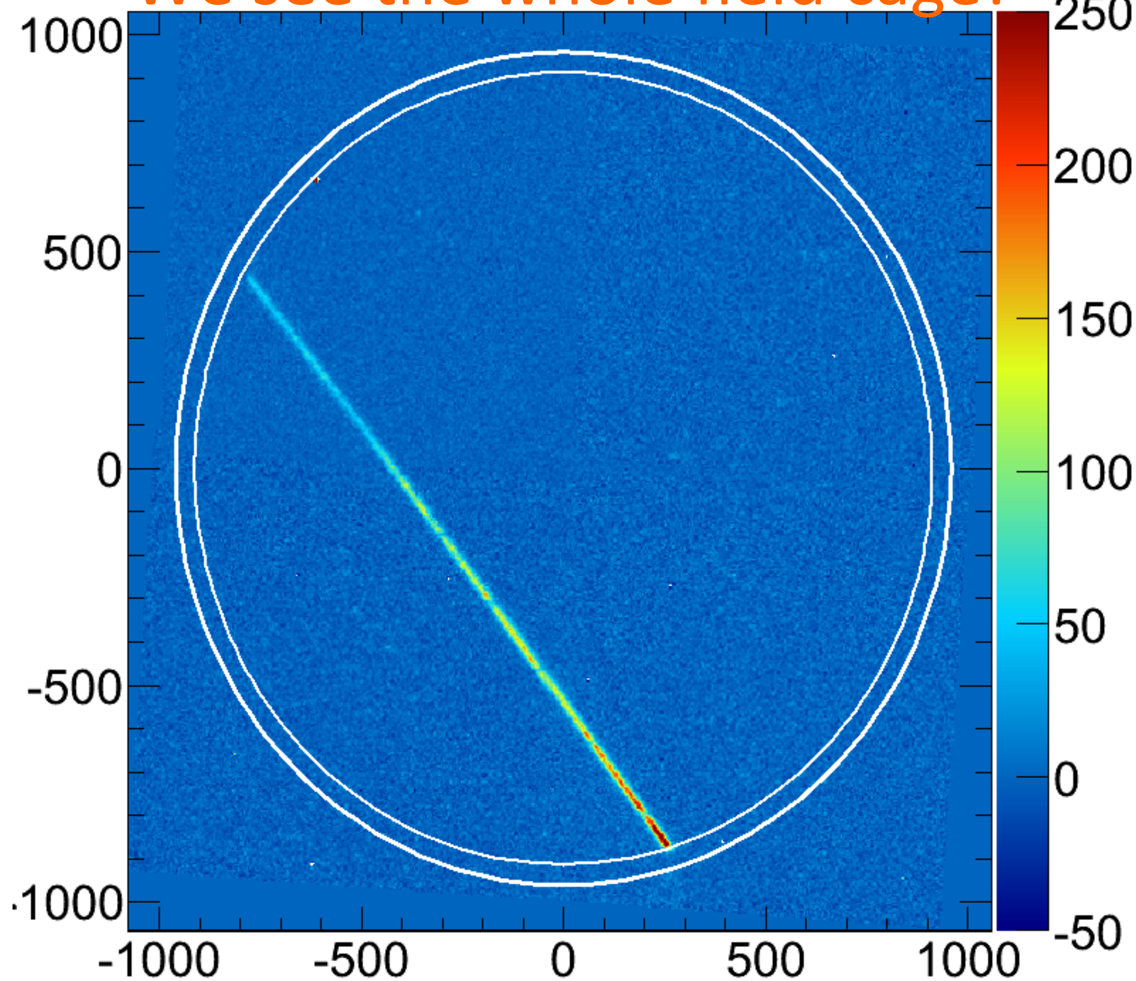
Some;

DP460EG epoxy, kodial glass,
fused silica, kapton, resistors

Careful cleaning of all parts

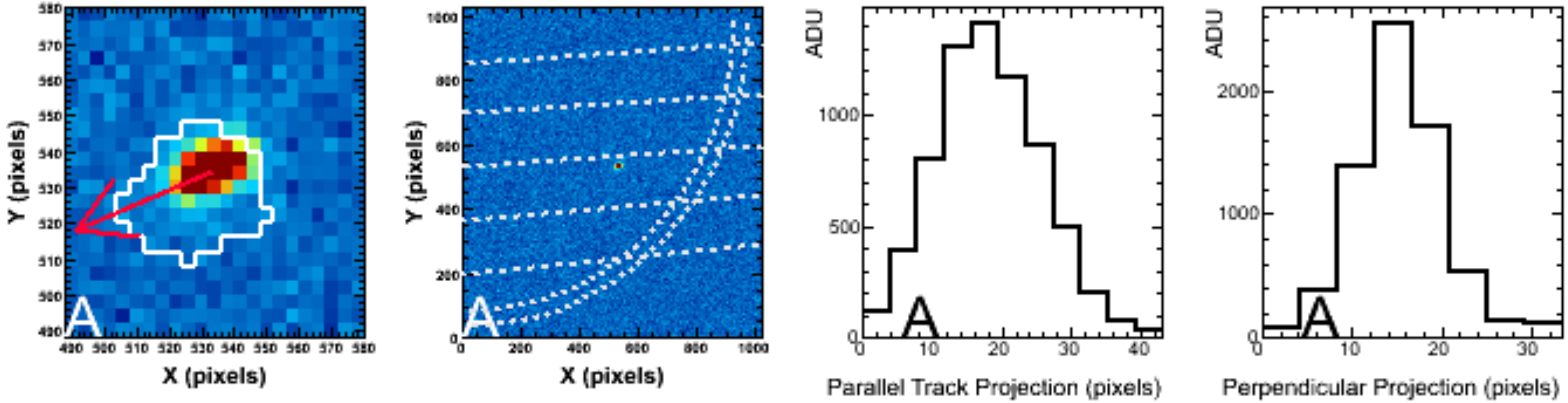


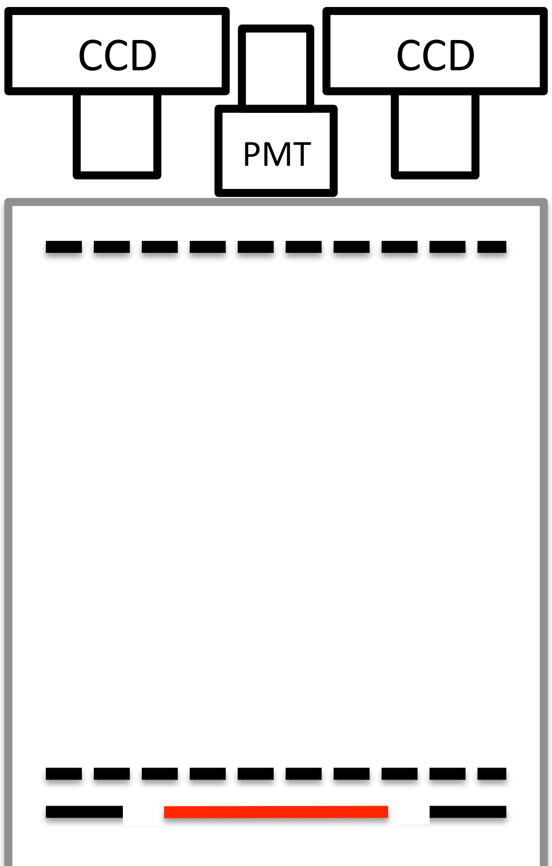
We see the whole field cage!

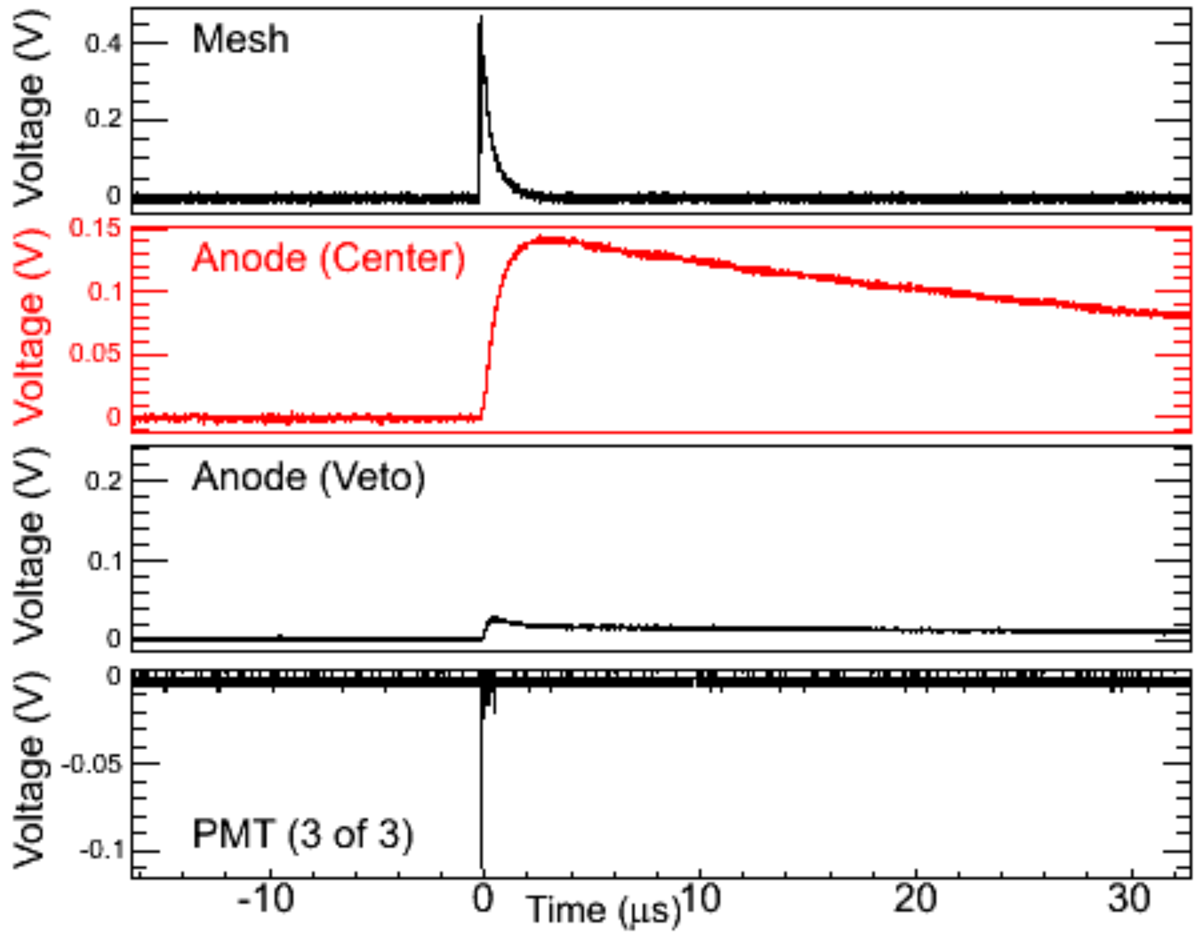


4sh α rate 11 mHz
10L α rate 210 mHz

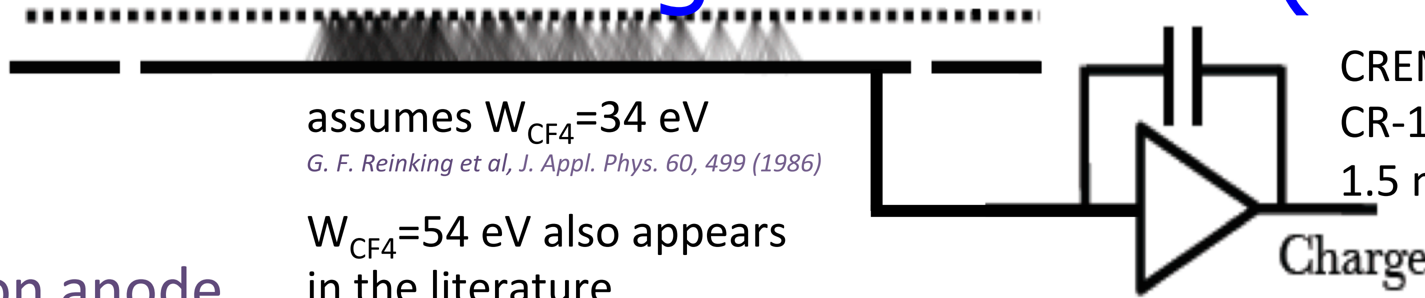
19x improvement


Y (pixels)
X (pixels)
A
ADU
Parallel Track Projection (pixels)
Perpendicular Projection (pixels)


CCD
PMT
CCD


Mesh
Anode (Center)
Anode (Veto)
PMT (3 of 3)
Voltage (V)
Time (µs)

Anode charge readout (Gain)

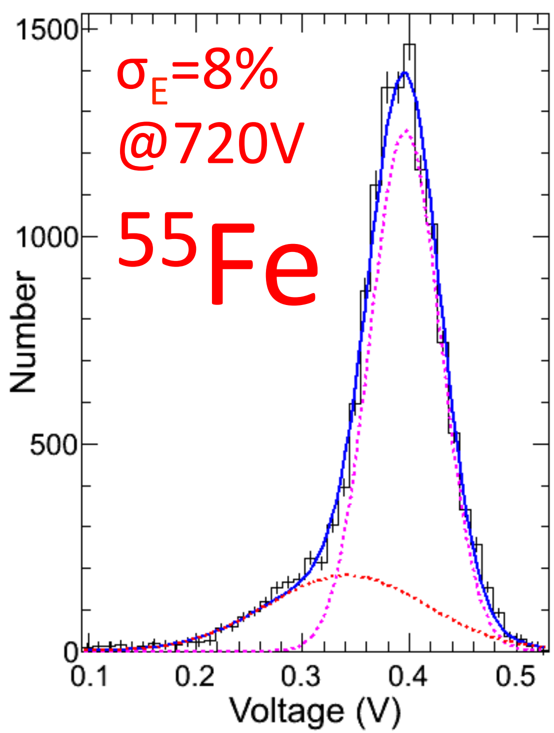


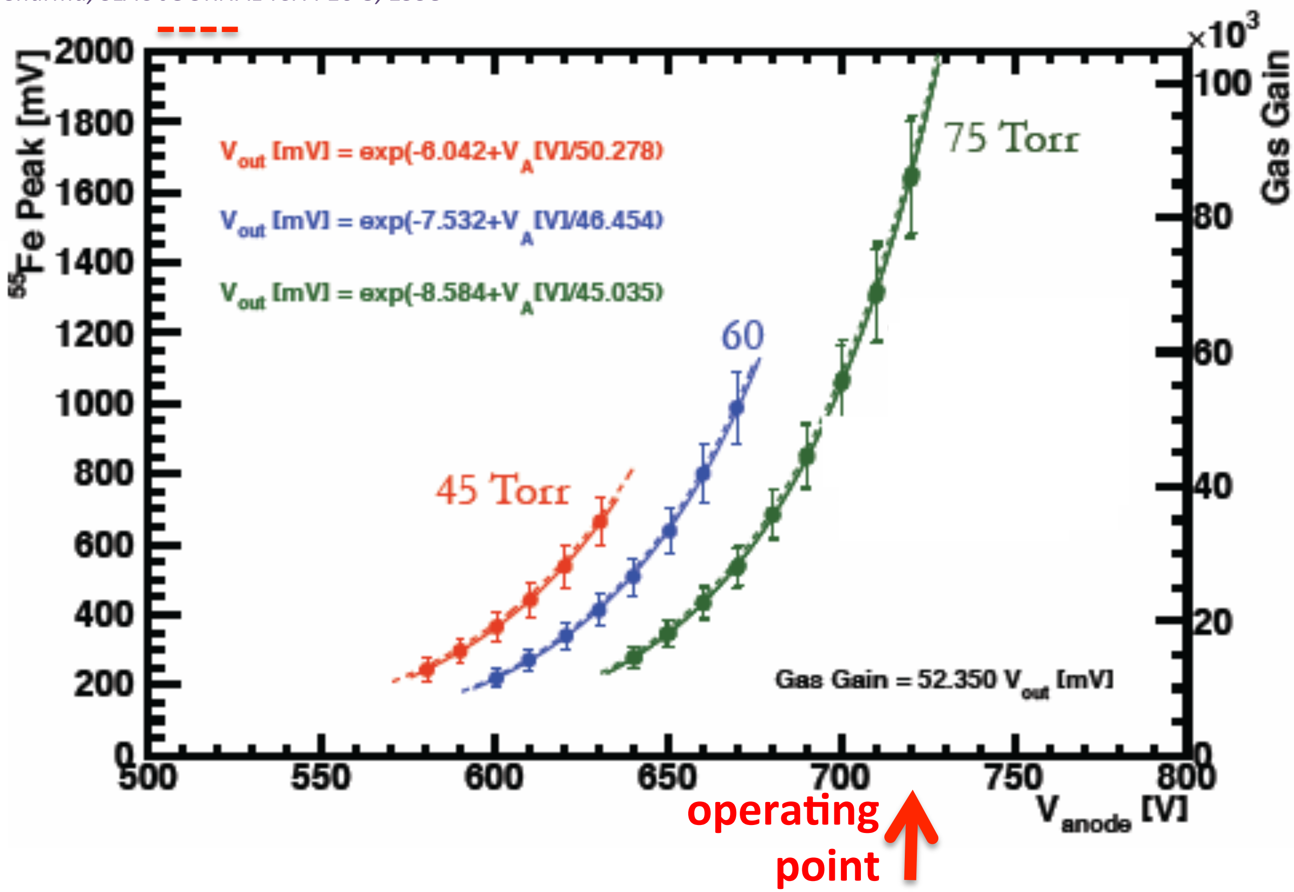
CREMAT
CR-113
1.5 mV/pC

assumes W_{CF4}=34 eV
G. F. Reinking et al, J. Appl. Phys. 60, 499 (1986)

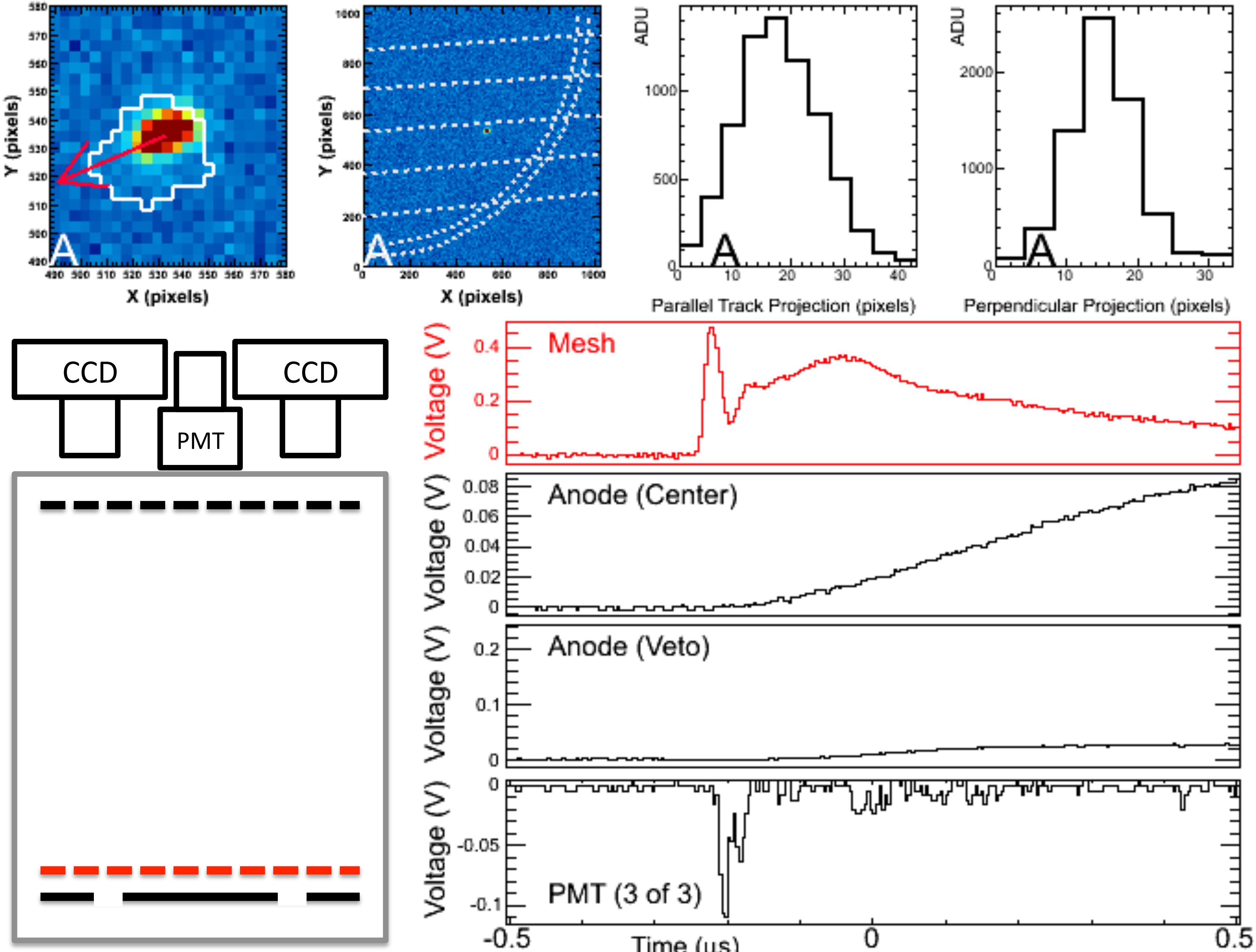
W_{CF4}=54 eV also appears in the literature
A. Sharma, SLAC-JOURNAL-ICFA-16-3, 1998

Charge on anode using ^{55}Fe source and spectroscopy amplifier



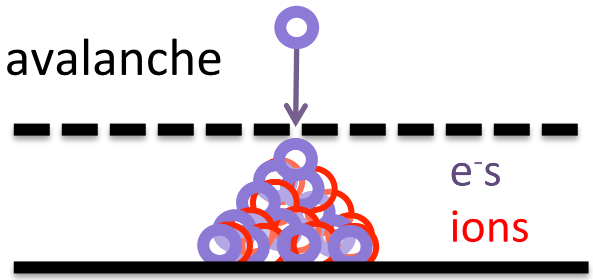


Gas gain is 71,200 ± 1100

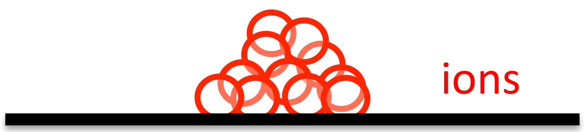


Y (pixels)
X (pixels)
A
Y (pixels)
X (pixels)
A
ADU
Parallel Track Projection (pixels)
A
ADU
Perpendicular Projection (pixels)
A
CCD
PMT
CCD
Mesh
Voltage (V)
Anode (Center)
Voltage (V)
Anode (Veto)
Voltage (V)
PMT (3 of 3)
Voltage (V)
Time (μs)

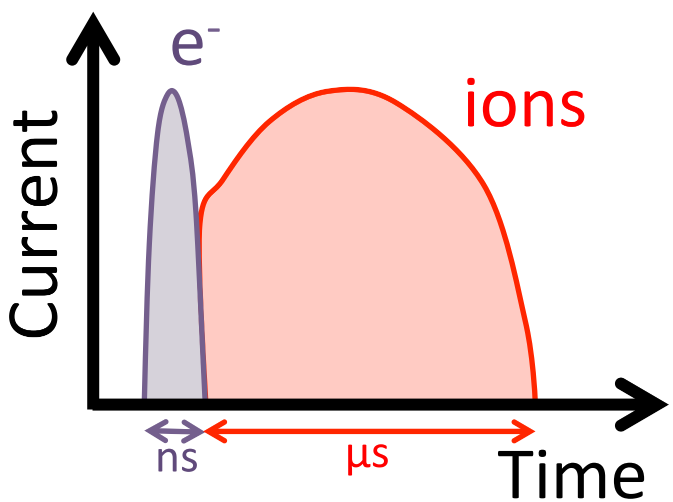
Mesh Fast Readout

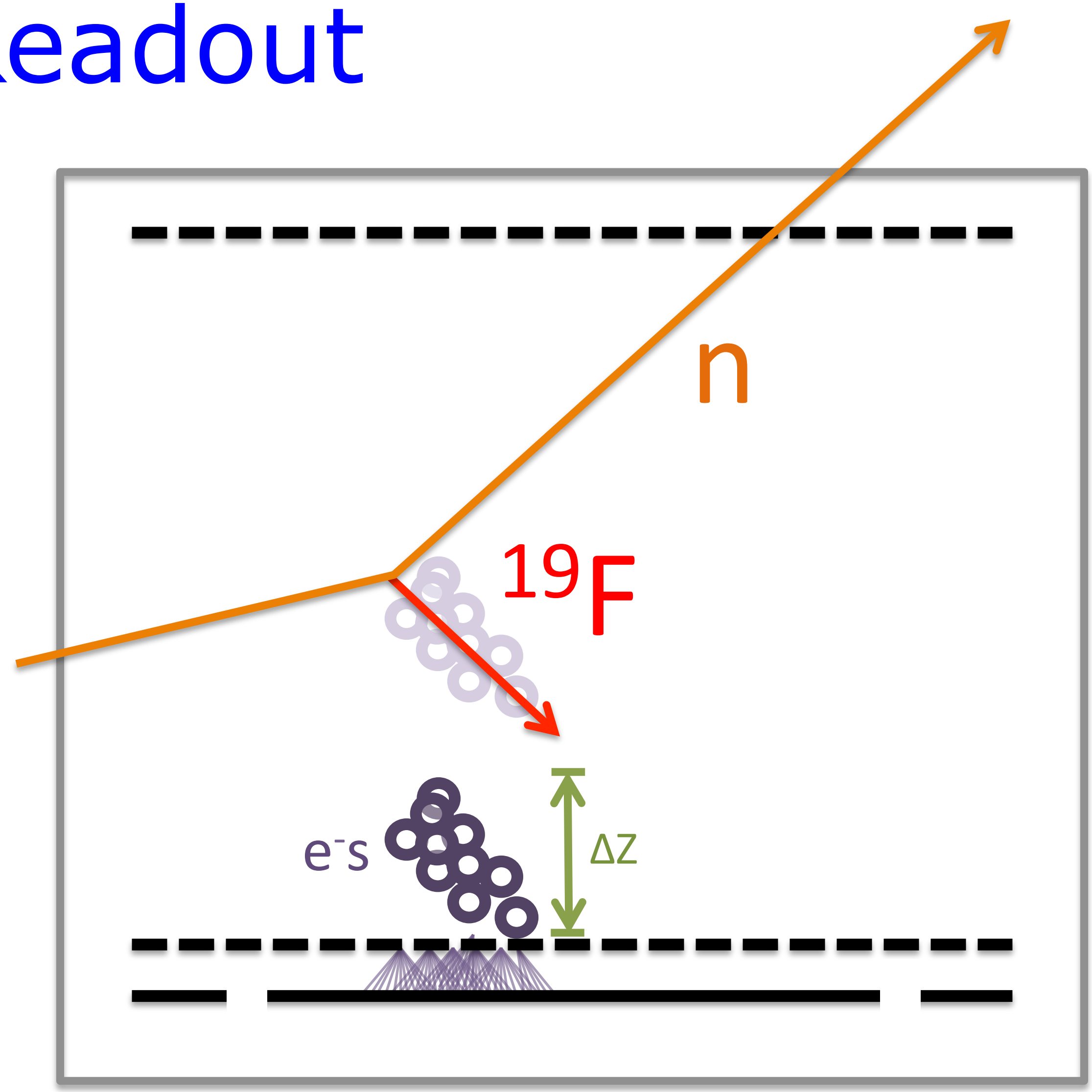


electrons collected quickly (ns)



avalanche ions take longer (μs) because of CF_4 ion mobility



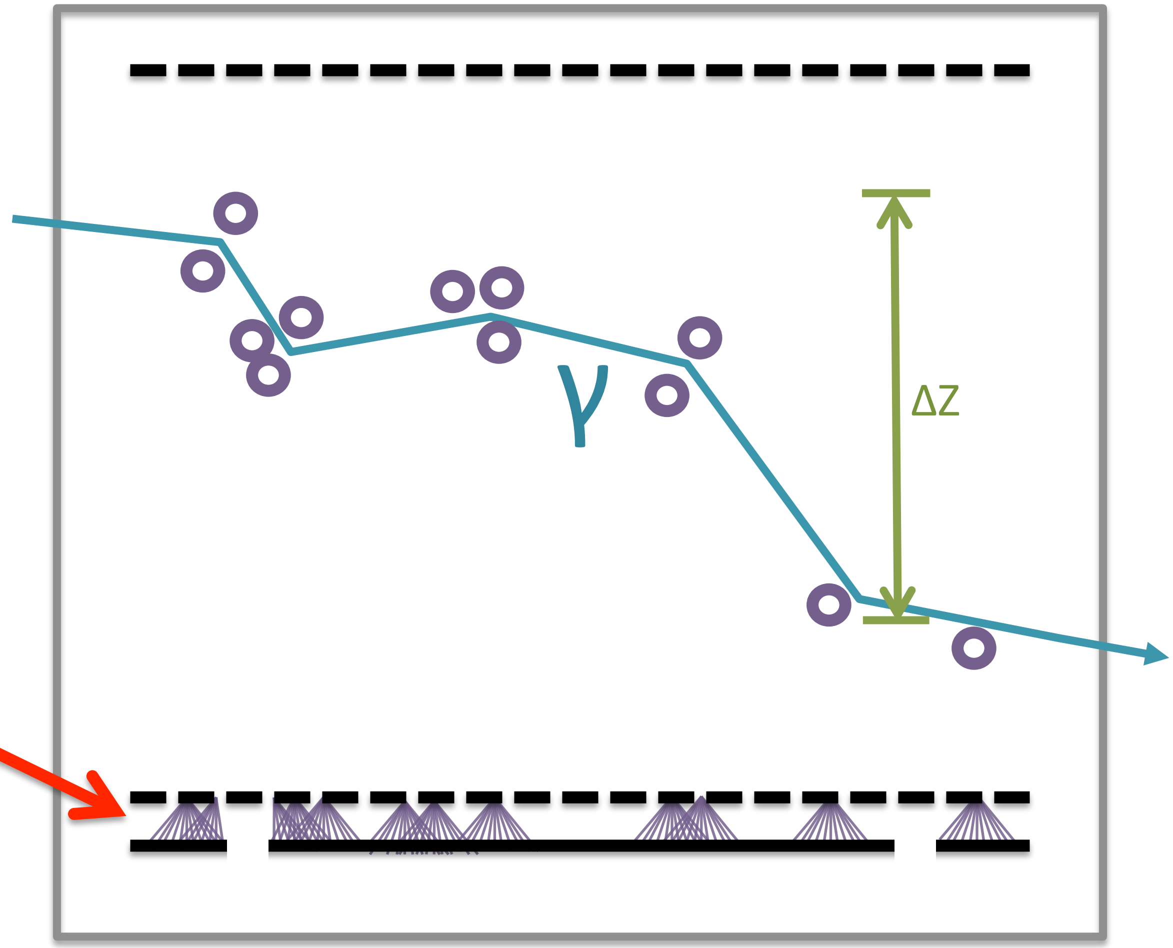


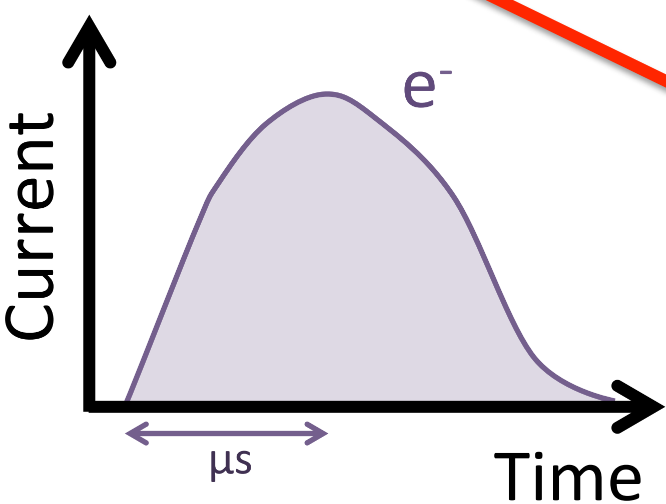
Rise time of e^- current pulse depends on track ΔZ

Mesh Fast Readout

γ energy deposition much less spatially localized

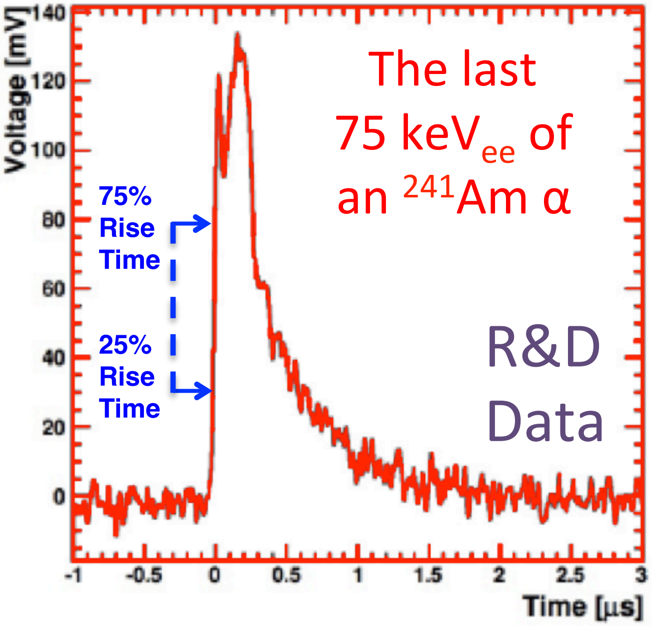
More likely to deposit energy in veto

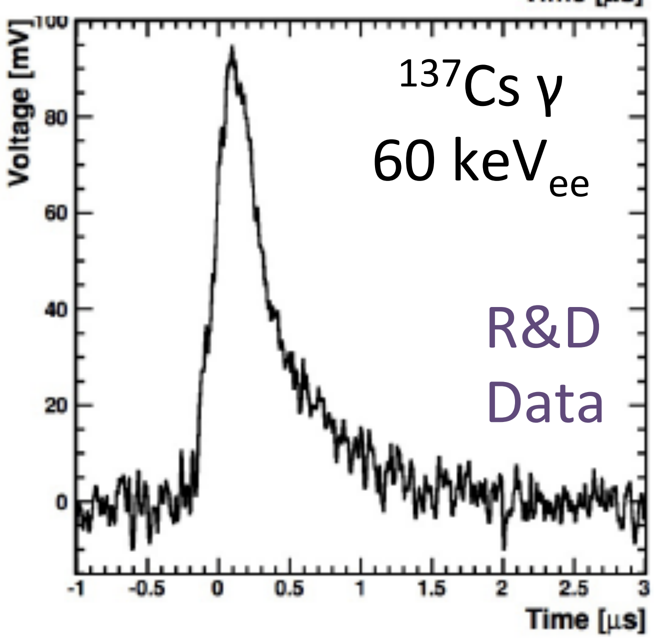


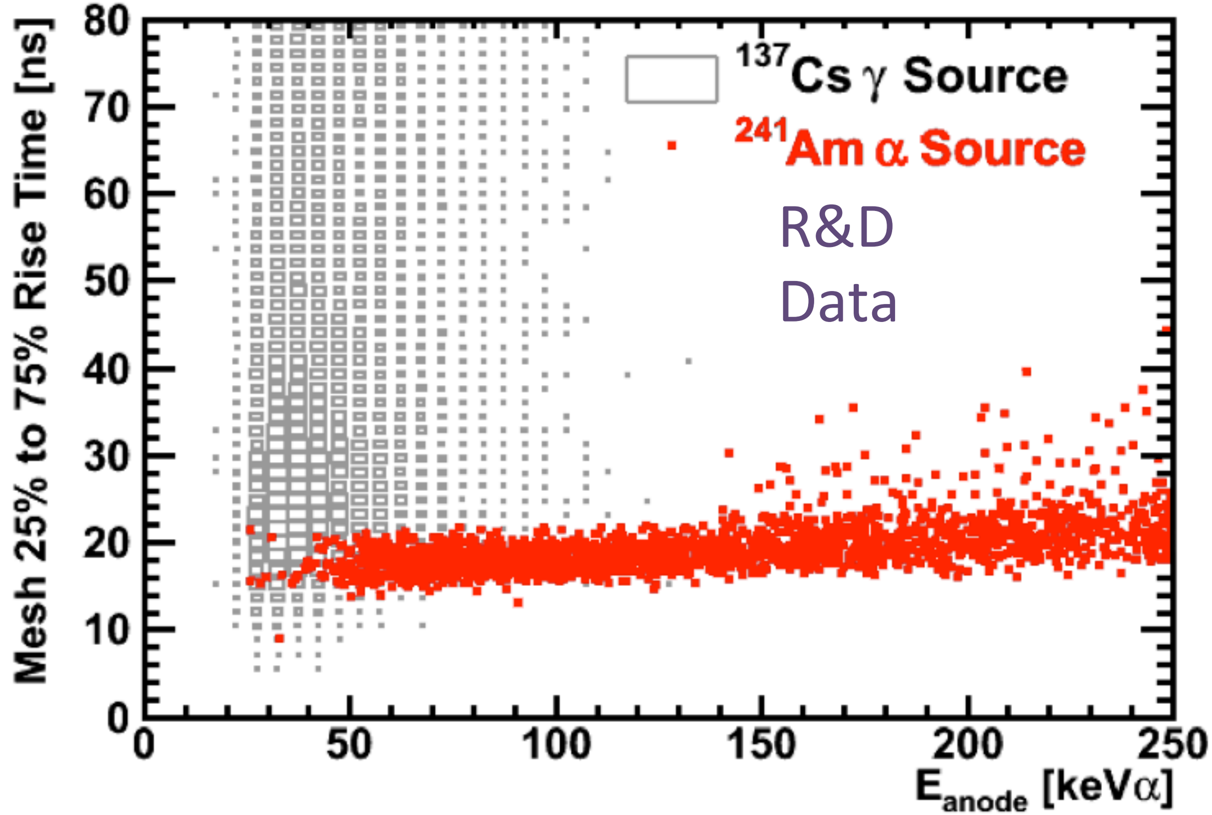


Rise time of e⁻ current pulse much wider in time for γ's

PID with Mesh Readout



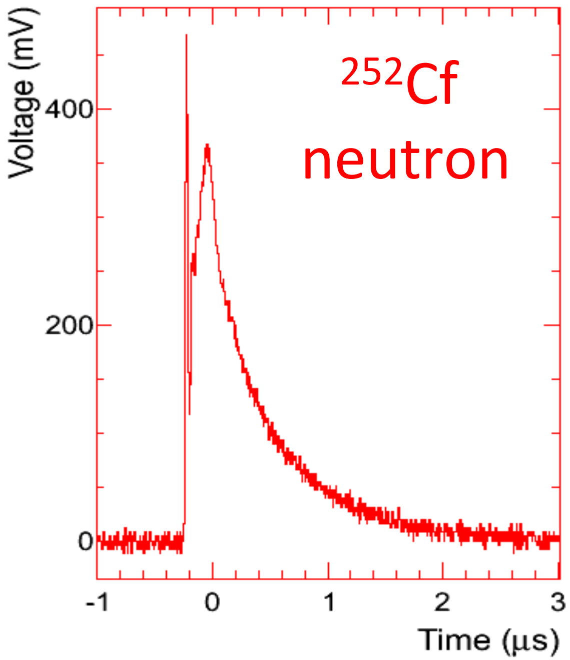


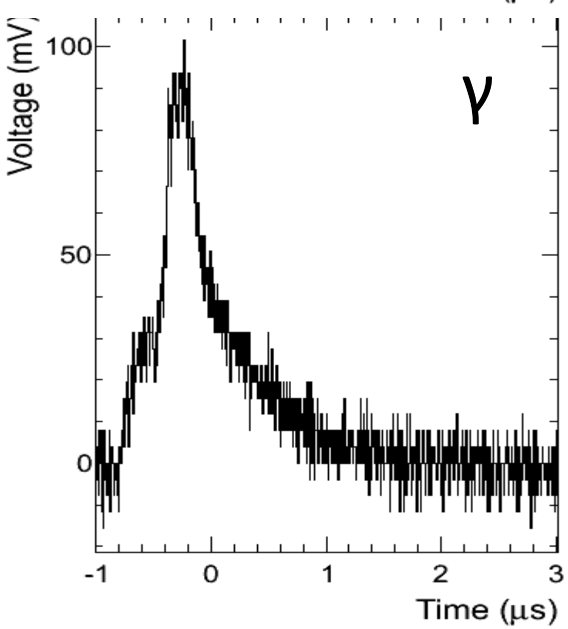


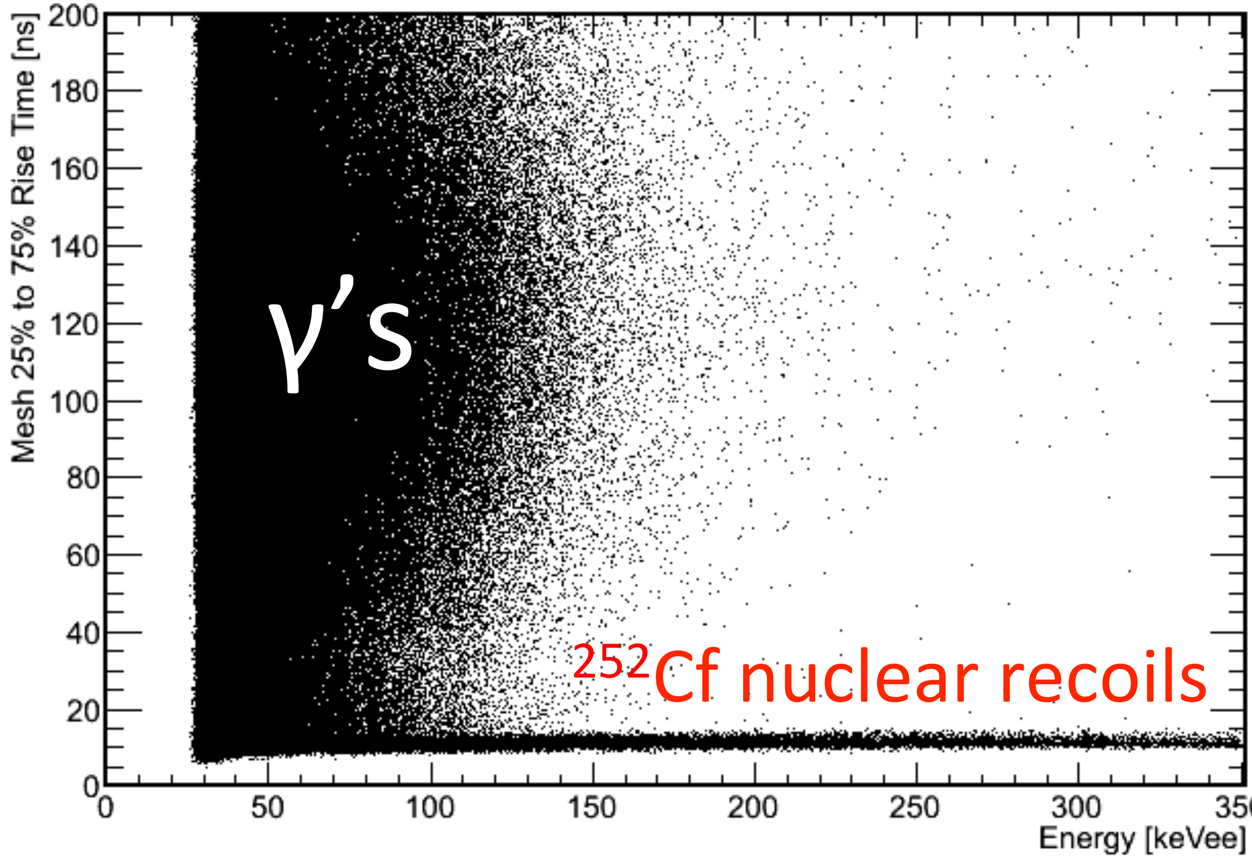
Demonstrated rejection of Cs-137 γ's between 40 keV$_{ee}$ < E < 200 keV$_{ee}$ of 10^5 (90% CL upper-limit) using CCD+veto+mesh

J. Lopez *et al.* NIM A 696, 121-128 (2012)

PID in the 4-shooter







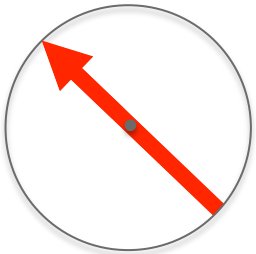
We hope to demonstrate even greater γ-NR rejection power in the 4-shooter

Surface Commissioning of the DMTPC 4-Shooter Directional Dark Matter Detector

Outline

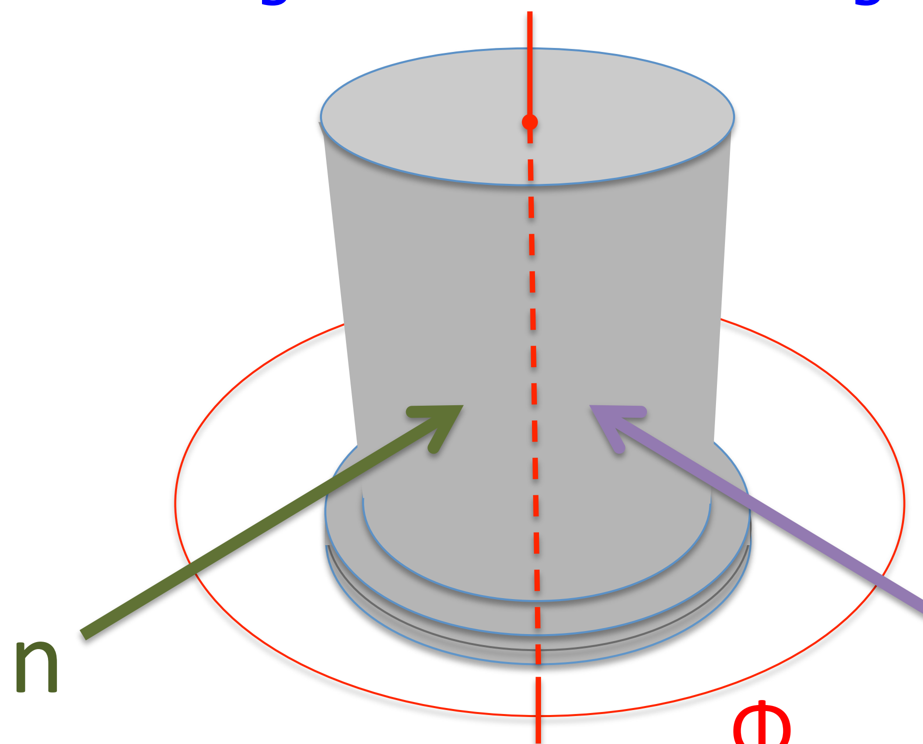
- ❑ Introduction
- ❑ Directional Sensitivity Measurements
  - ❑ High gain ^{252}Cf neutron study
  - ❑ Low gain & pressure AmBe neutron study
  - ❑ Directionality with alpha tails
- ❑ Future plans

How well can we measure Head-Tail?



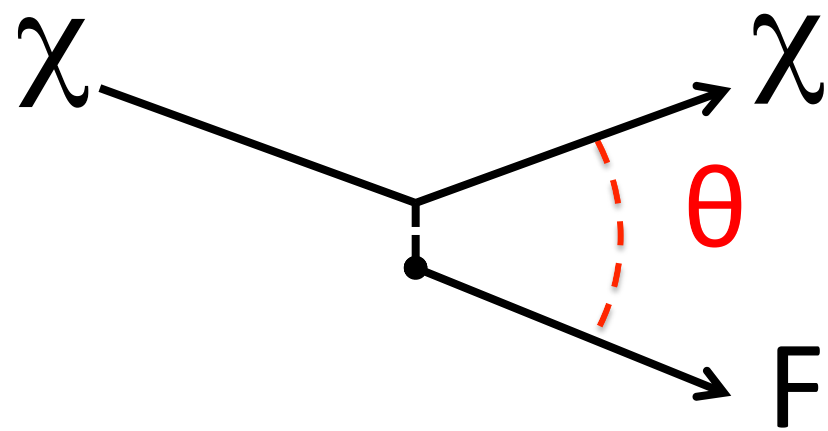
… for low energy nuclear recoils like those expected to be generated in WIMP scatters?

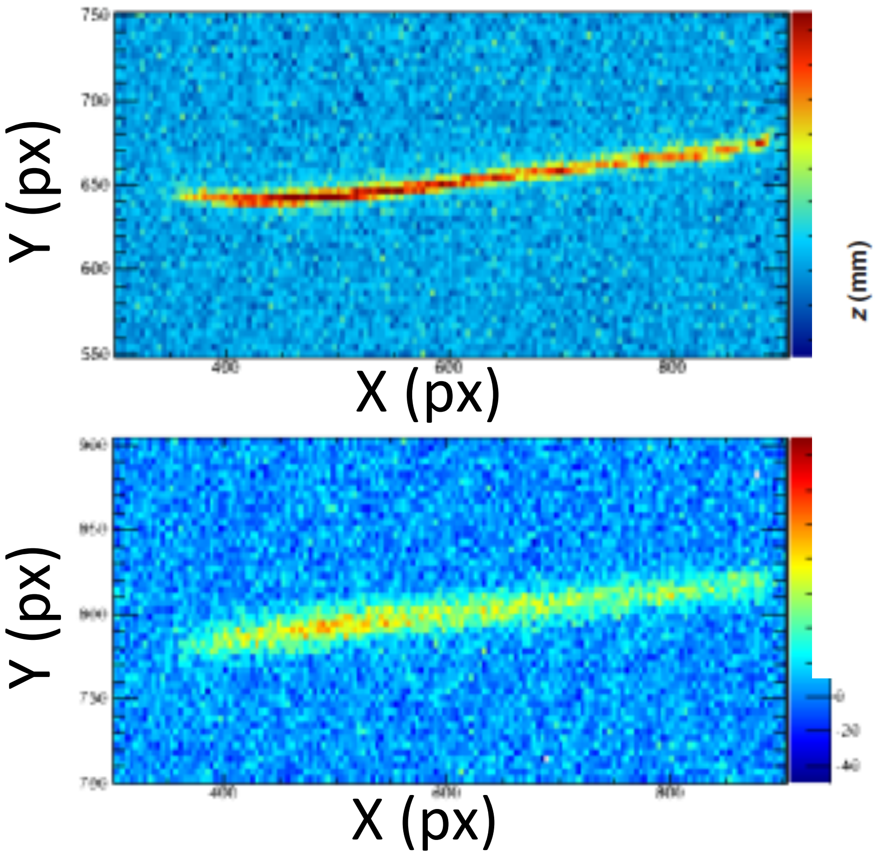
Strategy: place neutron source at 2 positions in lab and quantify ability to measure Head-Tail at energies low enough to be interesting for a dark matter search.

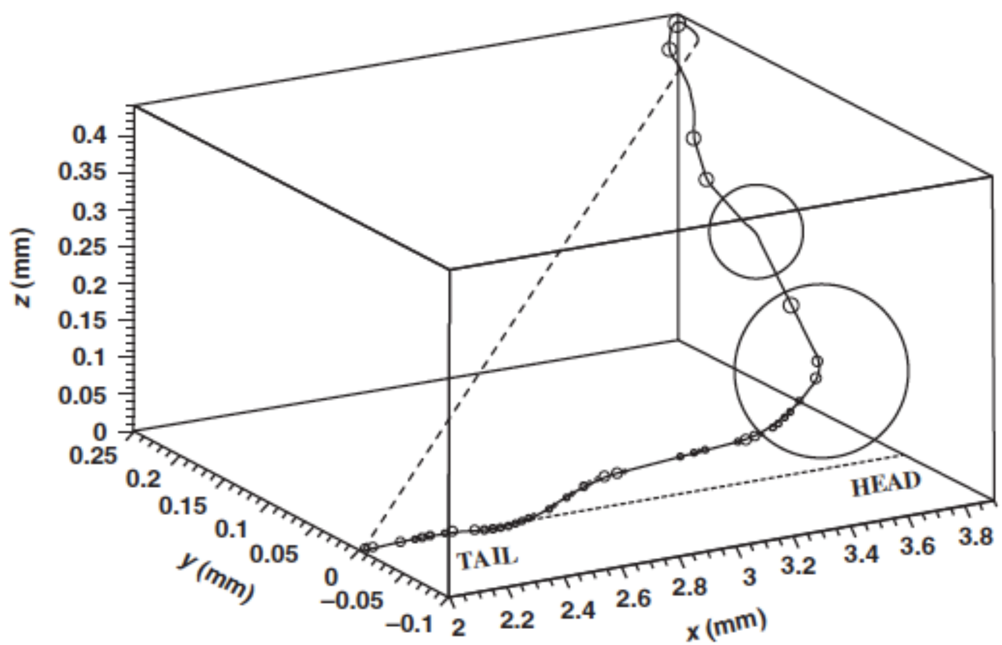


Experimental challenges

- The nuclear recoil is not perfectly correlated with the WIMP direction (kinematics)
- Ion straggling
- Diffusion







100 keVr S recoil in 40 Torr CS_2

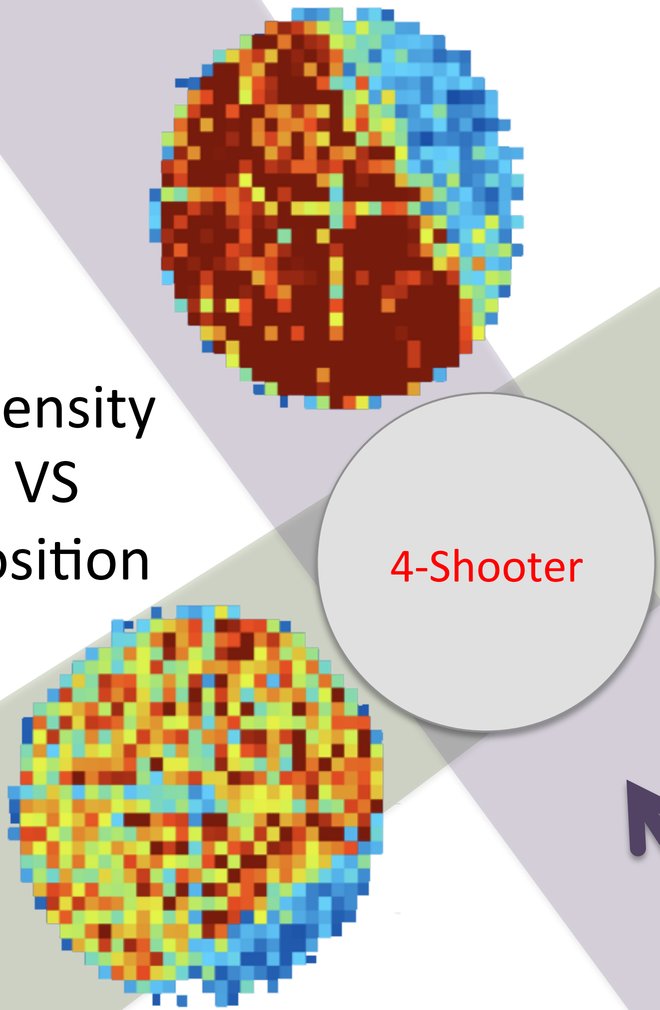
N. Spooner *et al.* Phys.Rept. 405:279-390,2005

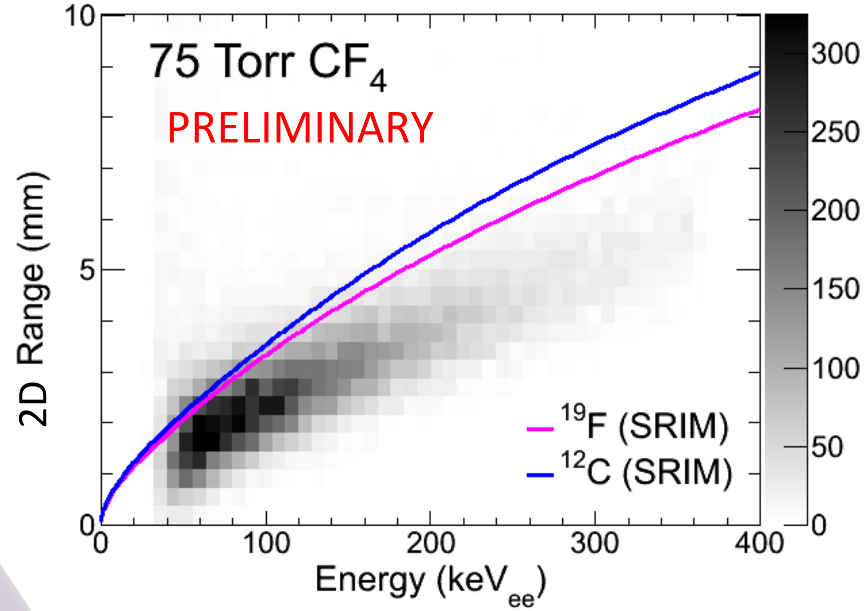
^{252}Cf calibration

^{252}Cf source position #1

Beam profile evident in found track positions

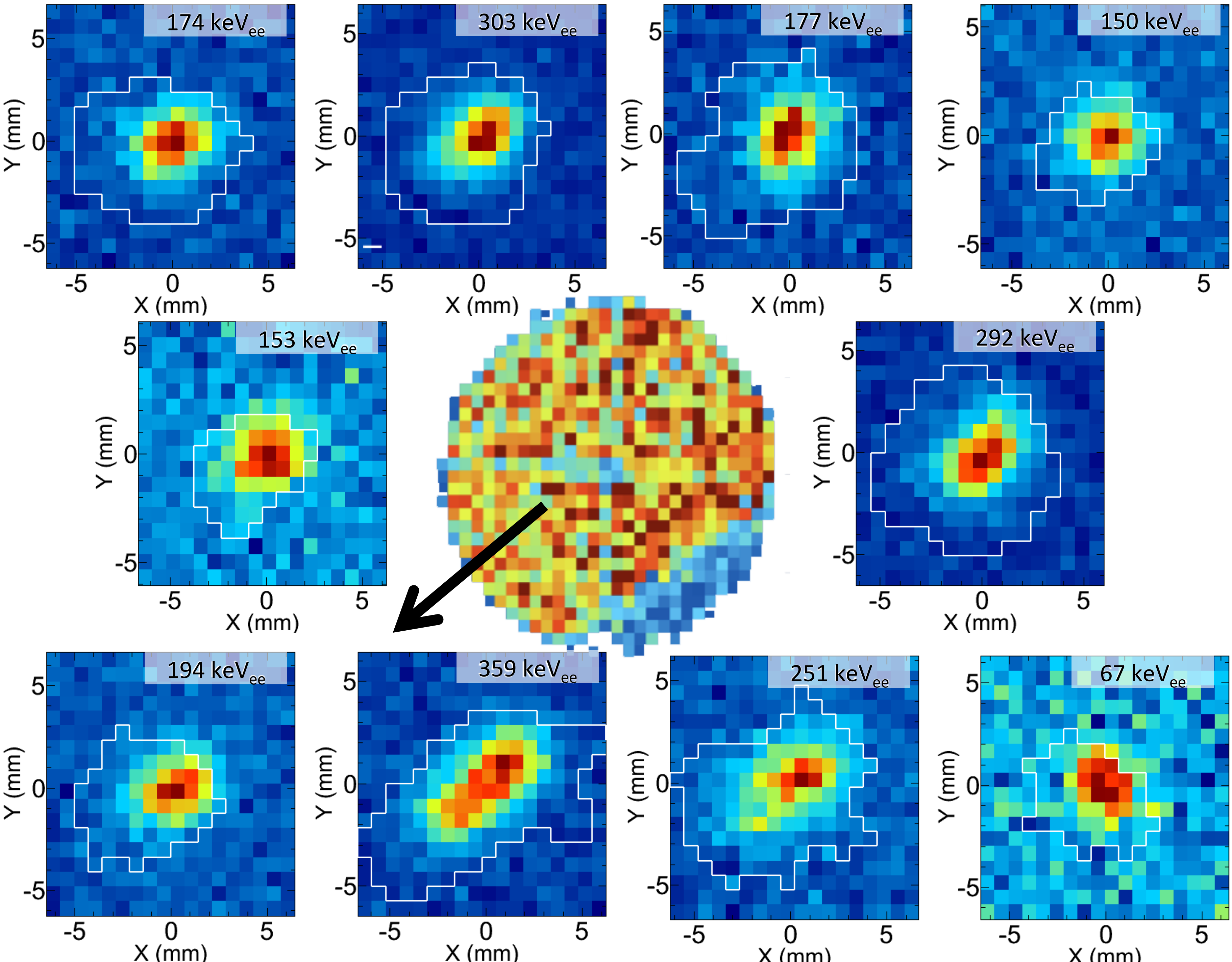
intensity VS position





^{252}Cf source position #2

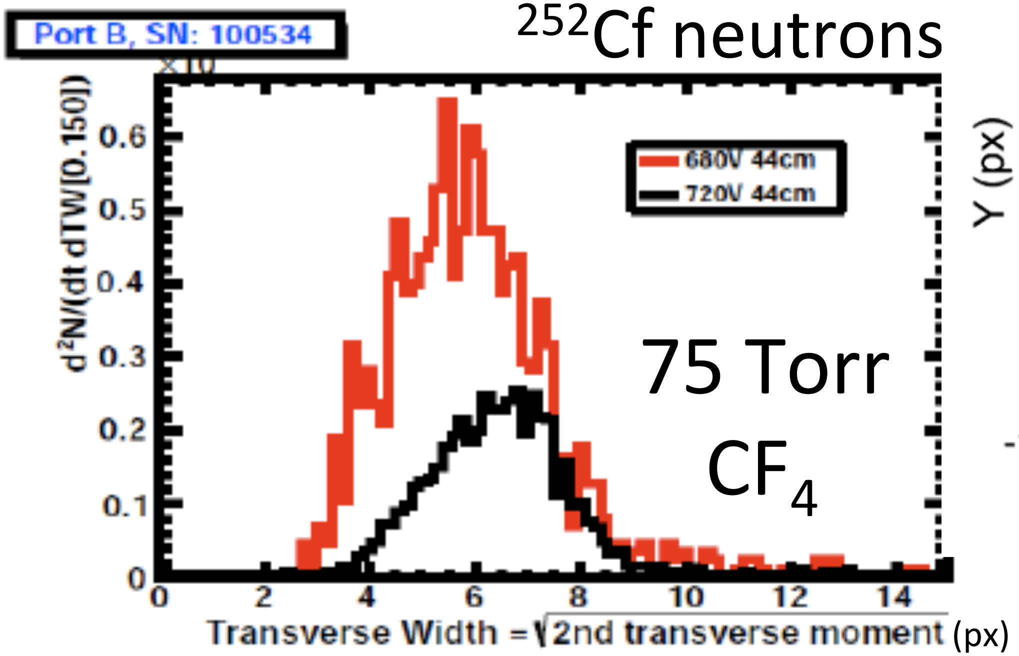
Good range vs. energy Agreement with SRIM


174 keV$_{ee}$
303 keV$_{ee}$
177 keV$_{ee}$
150 keV$_{ee}$
153 keV$_{ee}$
292 keV$_{ee}$
194 keV$_{ee}$
359 keV$_{ee}$
251 keV$_{ee}$
67 keV$_{ee}$
X (mm)
Y (mm)

The Raether Limit

sparking induced by low z-tracks

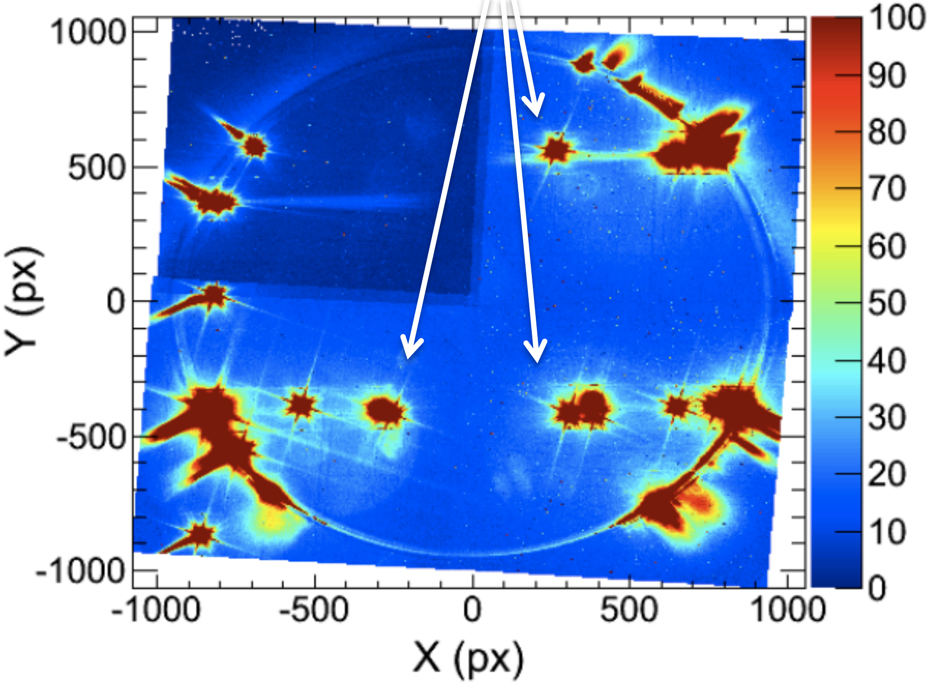
^{252}Cf neutrons

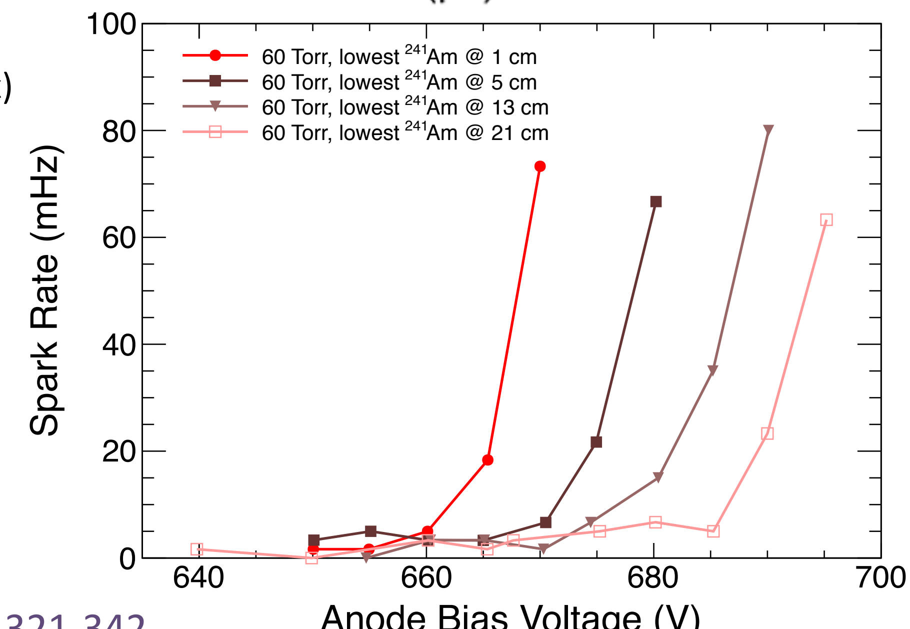


- At very high gain, all tracks have large transverse widths.
- **The Raether Limit** avalanches containing ~10^7 electron-ion pairs leads to a discharge

A. Bressan *et al.*, NIMA 424 (1999) 321-342

^{241}Am Bragg peaks





AmBe neutron study

Lower activity than The ^{252}Cf source

-5 kV drift

670V anode

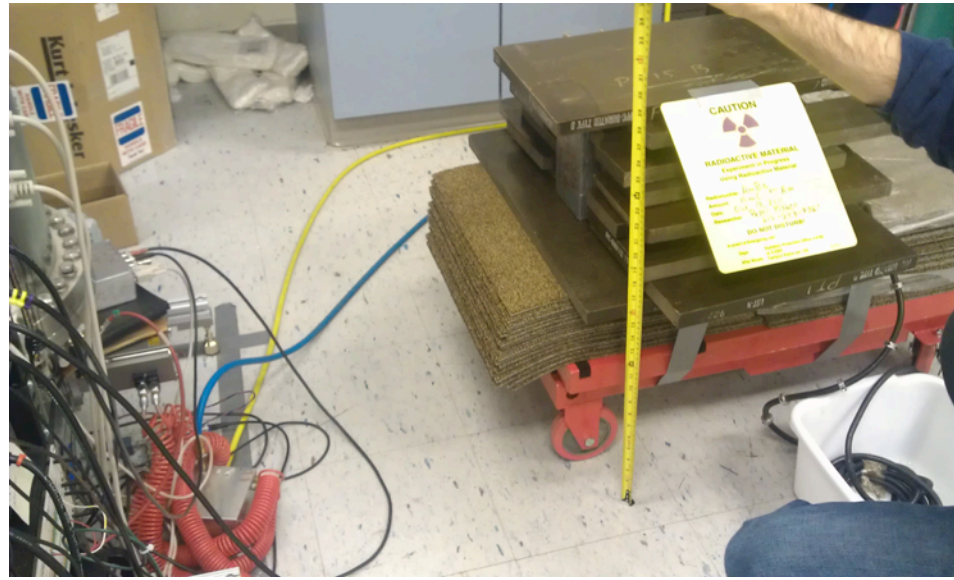
lower gas gain

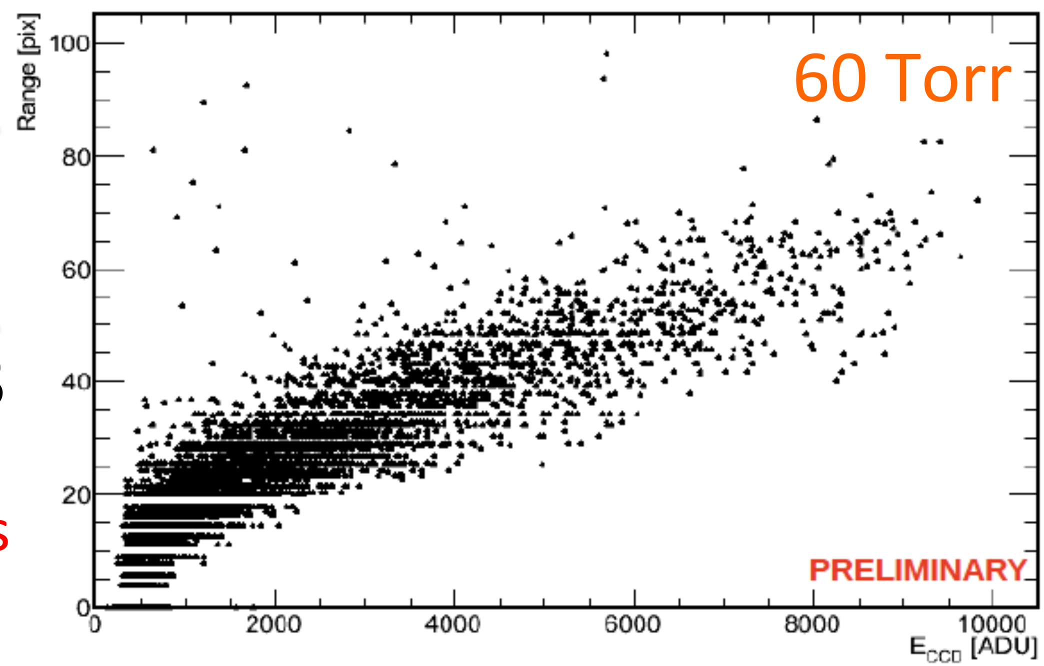
1,864,000 images

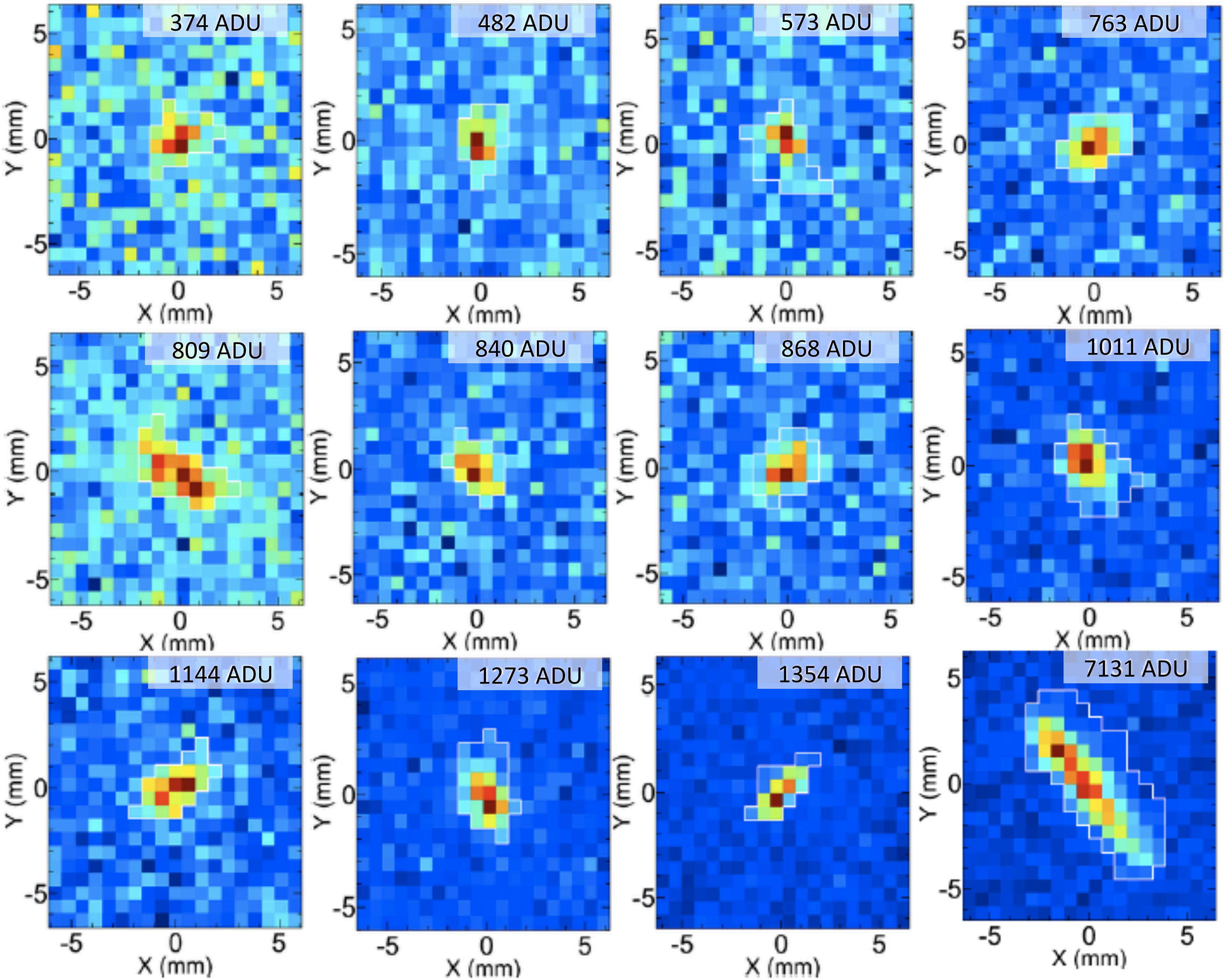
3,363,398 charge triggers

8,591 NR candidates

Assessment of Head-Tail sensitivity for low energy recoils in progress



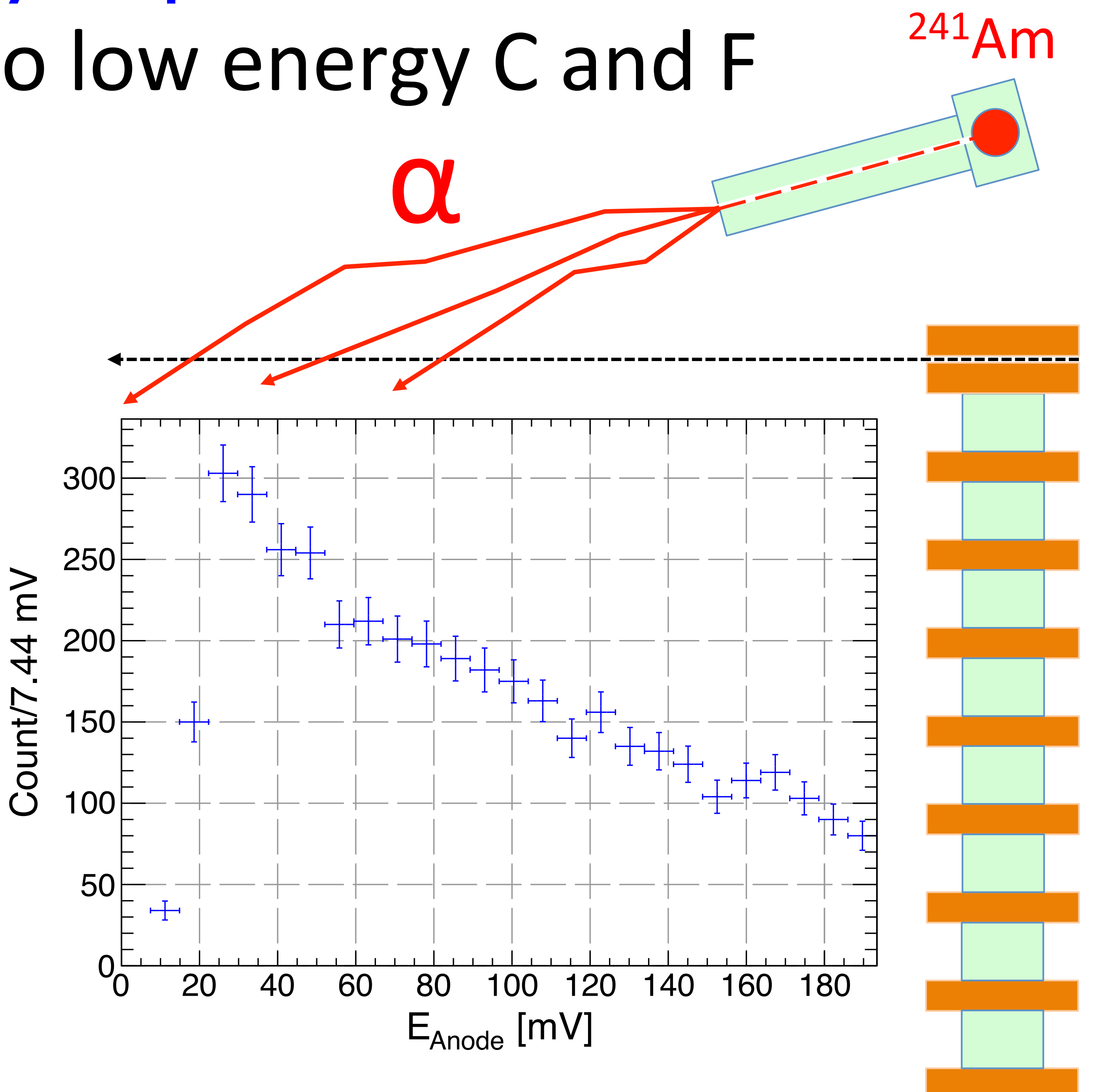




374 ADU
482 ADU
573 ADU
763 ADU
809 ADU
840 ADU
868 ADU
1011 ADU
1144 ADU
1273 ADU
1354 ADU
7131 ADU
X (mm)
Y (mm)

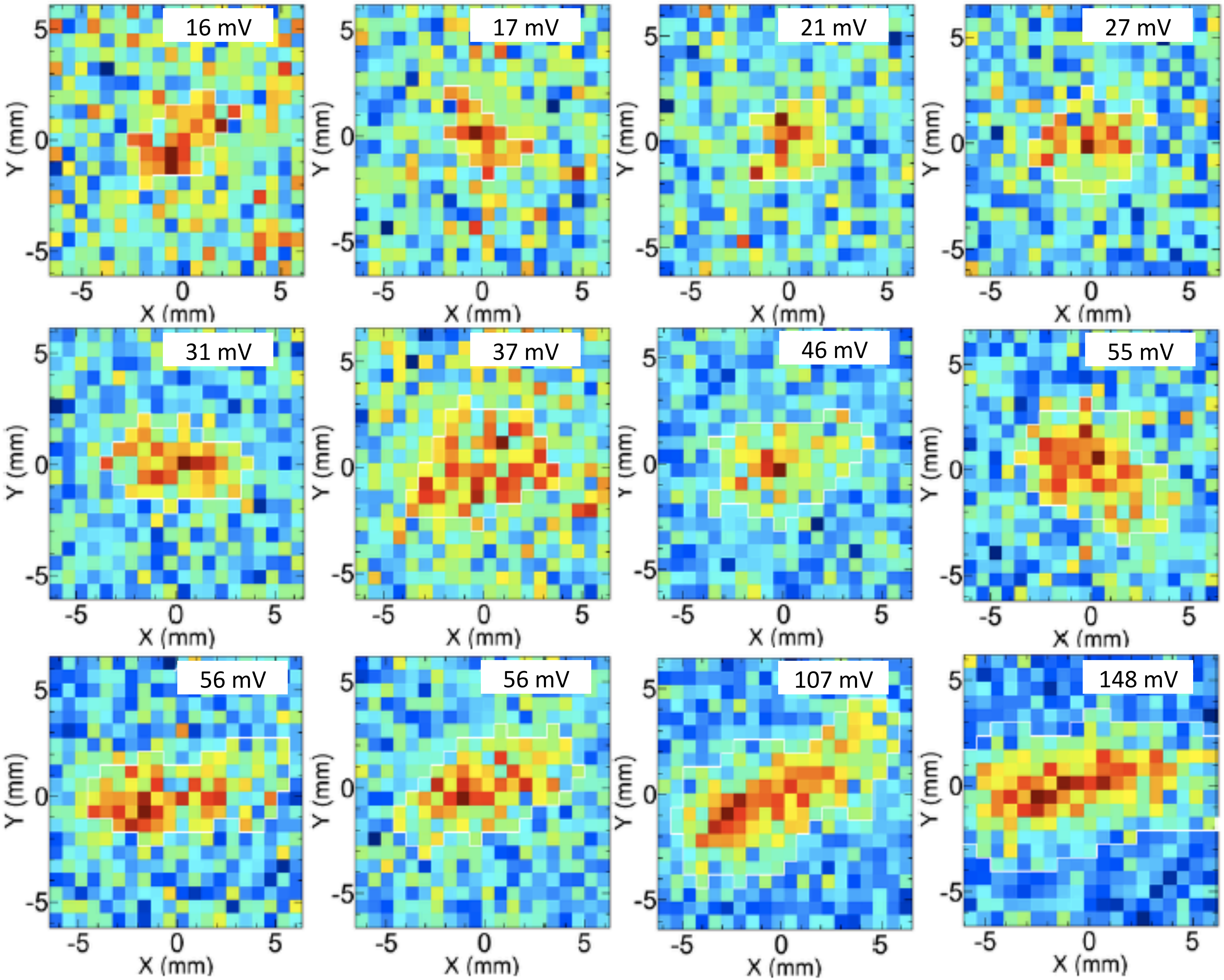
Low energy alpha-ends

Very similar to low energy C and F recoils

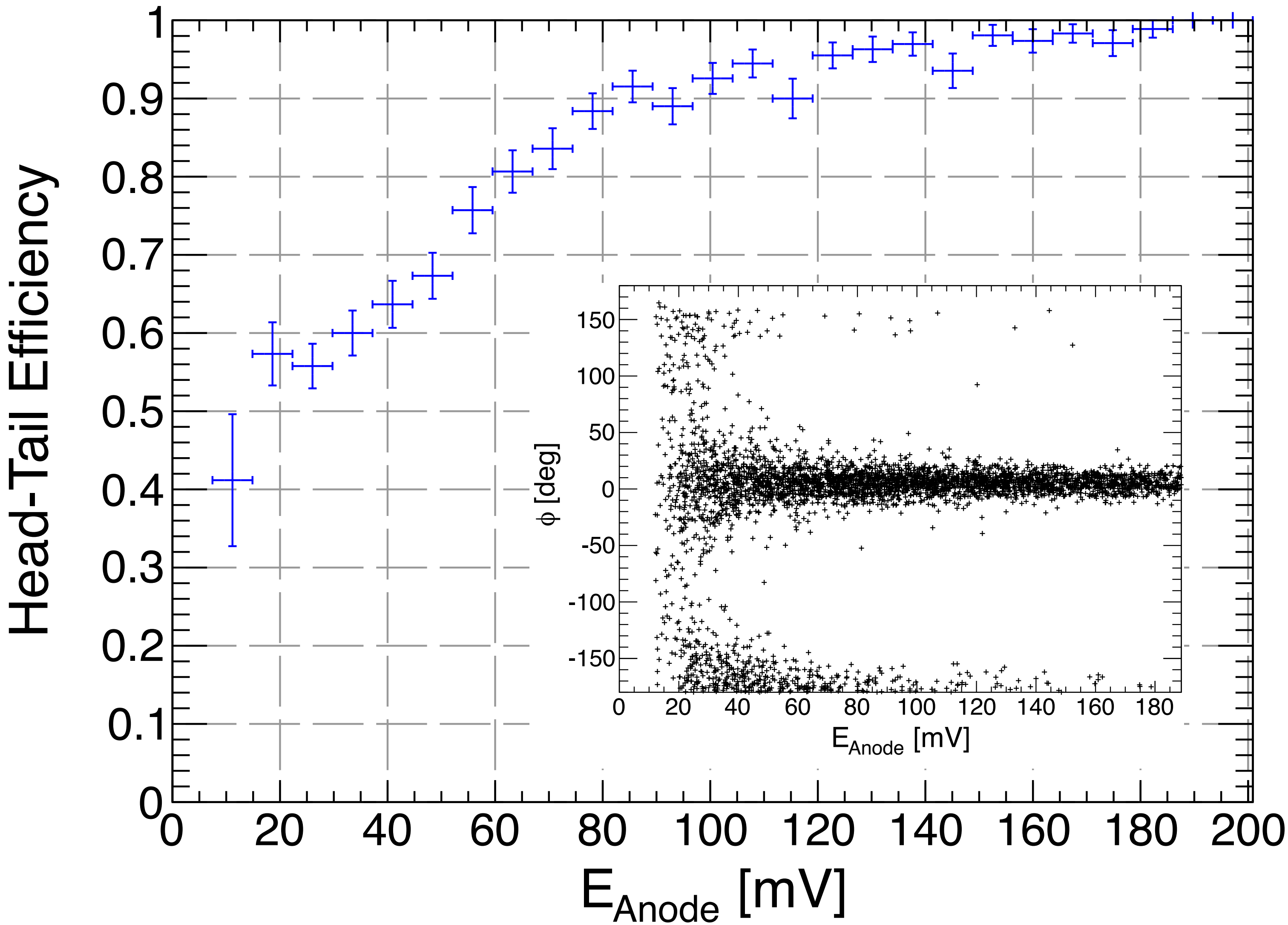


Keep in mind:

- These tracks experience maximum diffusion.
- He ions have a systematically longer range than C or F ions.


16 mV
17 mV
21 mV
27 mV
31 mV
37 mV
46 mV
55 mV
56 mV
56 mV
107 mV
148 mV
X (mm)
Y (mm)

Low energy alpha-end head-tail



60% correct at 35 mV. 10° axial angular resolution above 28 mV.

Surface Commissioning of the DMTPC 4-Shooter Directional Dark Matter Detector

Outline

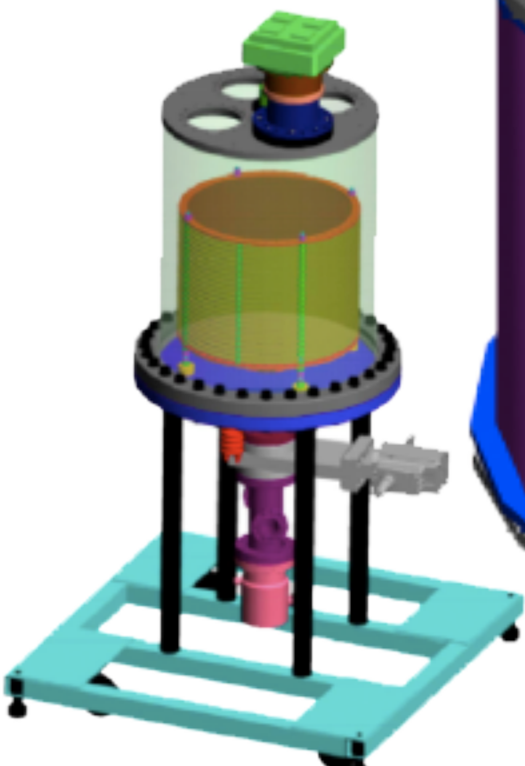
- ❑ Introduction
- ❑ Directional Sensitivity Measurements
- ❑ Future plans
    - ❑ WIPP deployment

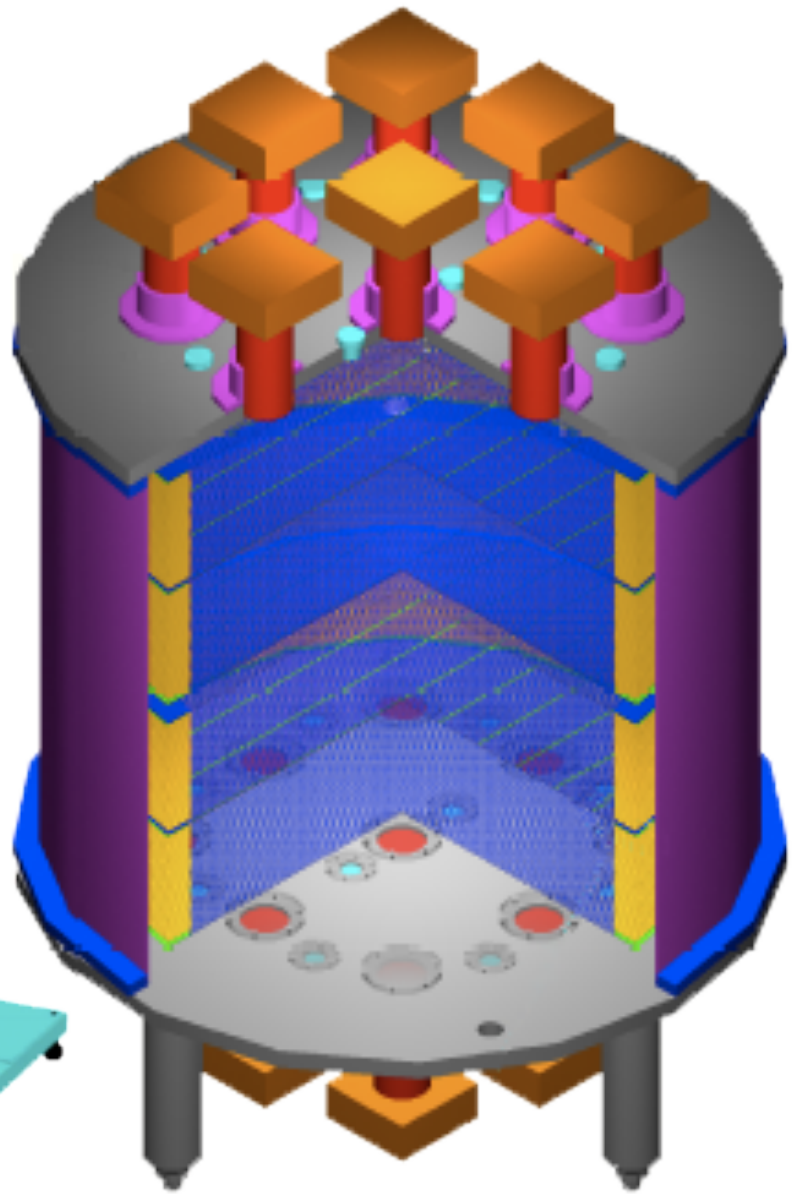
WIPP

Waste **I**solation **P**ilot **P**lant
Carlsbad, NM

1.6 km.w.e.

Funded by NSF & DoE to build a m^3 detector





WIPP

Waste **I**solation **P**ilot **P**lant
Carlsbad, NM