Direction-Sensitive Dark Matter Detection with the DMTPC Experiment

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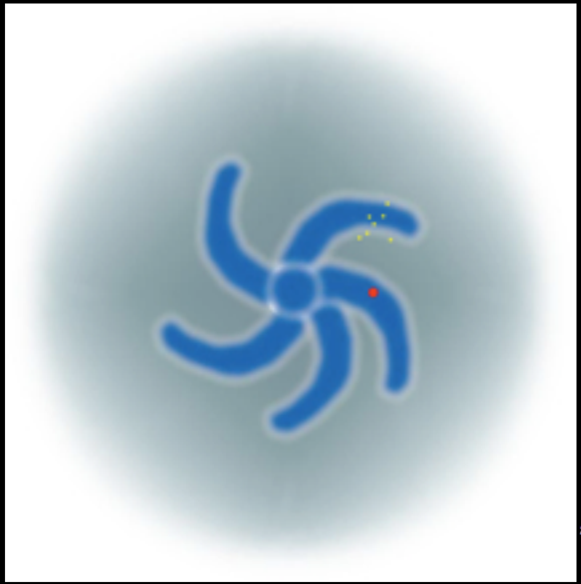
Outline

Experimental Considerations

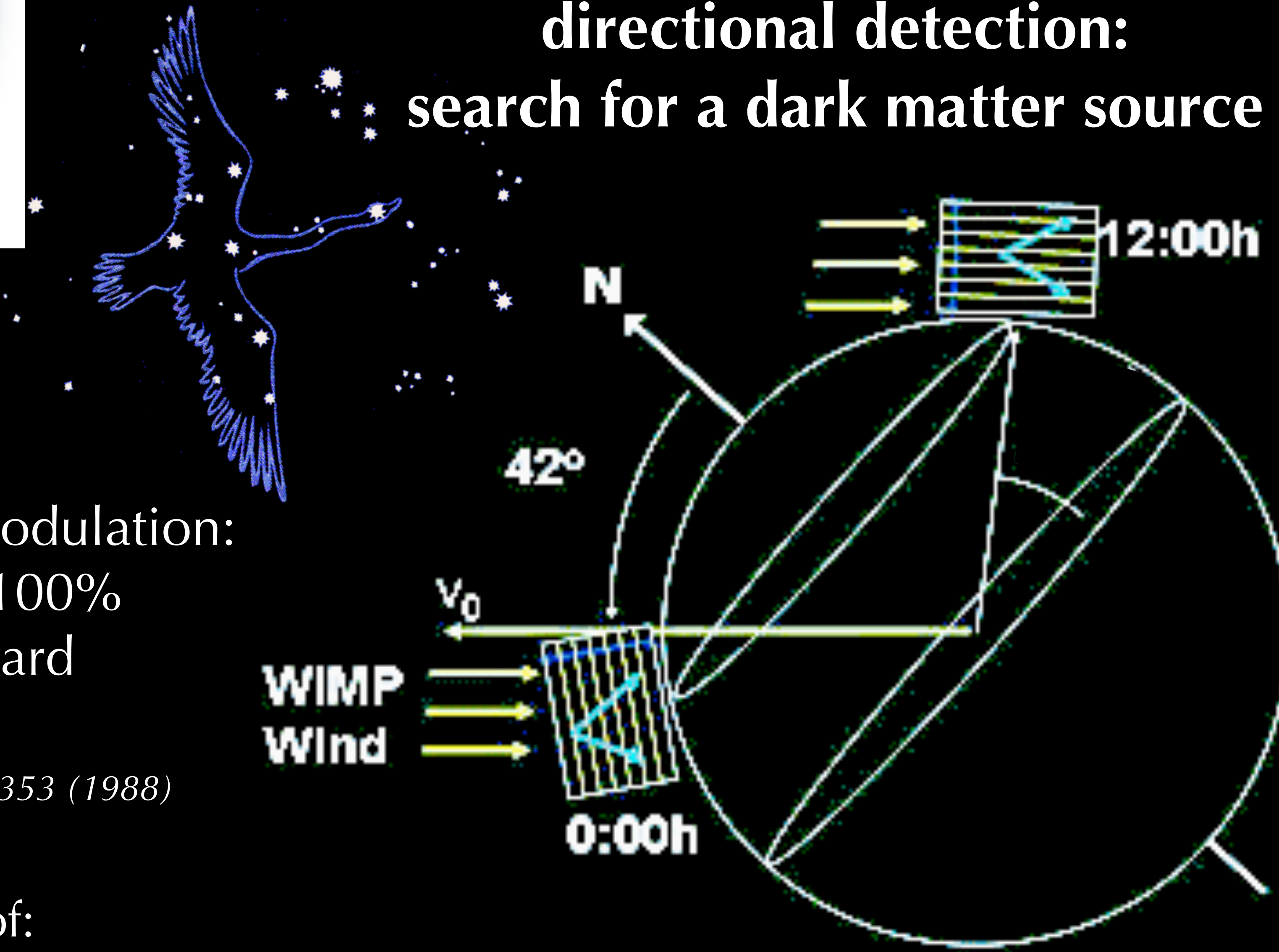
Recent Progress from DMTPC

Directional Detection and the Neutrino Bound



The Dark Matter Wind apparently "blows" from Cygnus

directional detection: search for a dark matter source

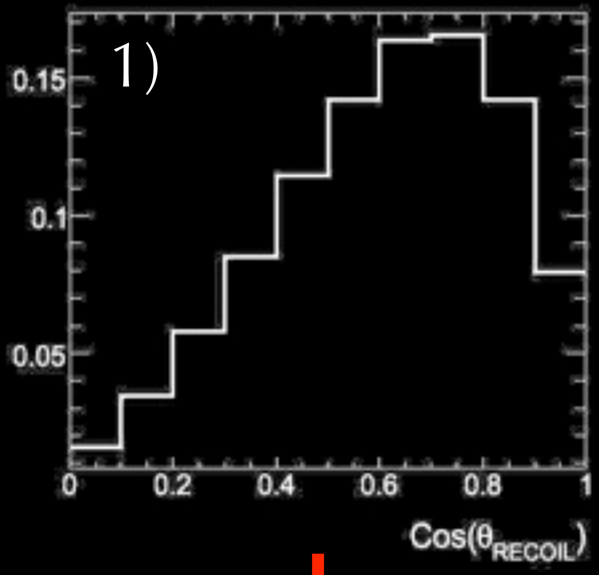


Daily direction modulation:
asymmetry ~ 20-100%
in forward-backward
event rate.

Spergel, Phys. Rev. D36:1353 (1988)

Unambiguous proof:
Correlation of WIMP-induced nuclear recoil signal with galactic motion

Signals in Directional Detectors



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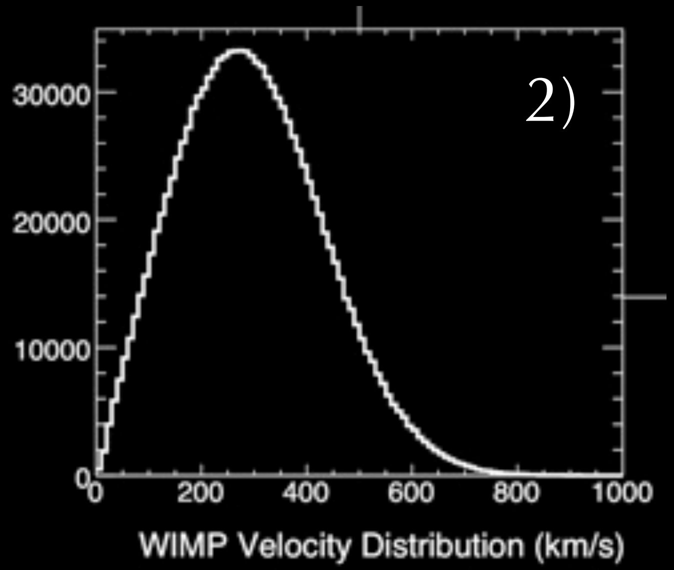
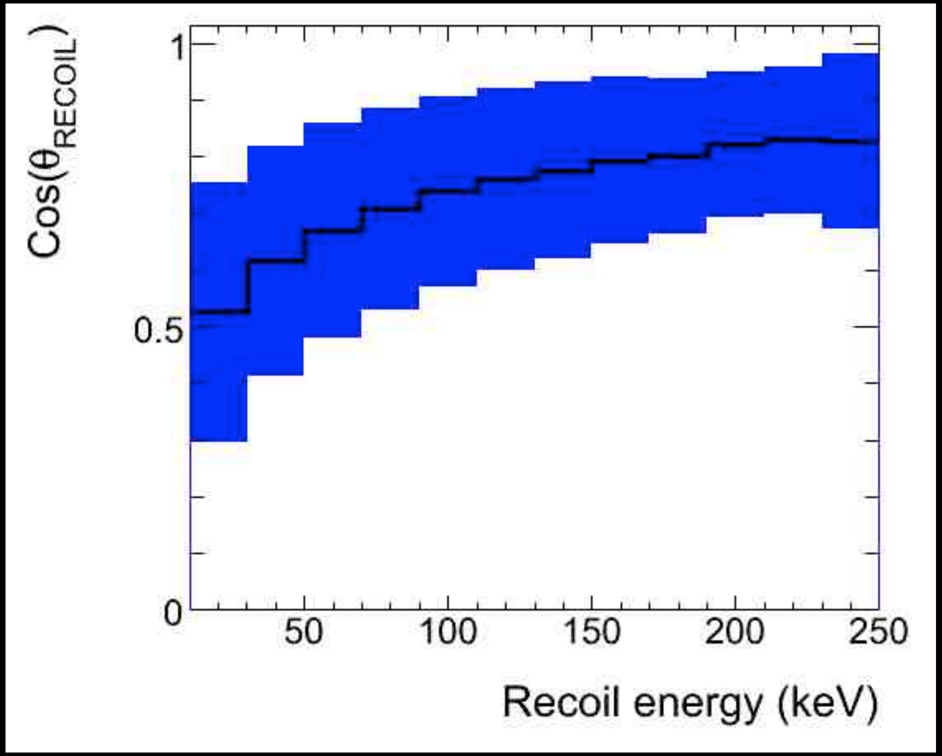


distribution of signal events determined by:

1. angular resolution of elastic scattering
2. dark matter velocity dispersion

=



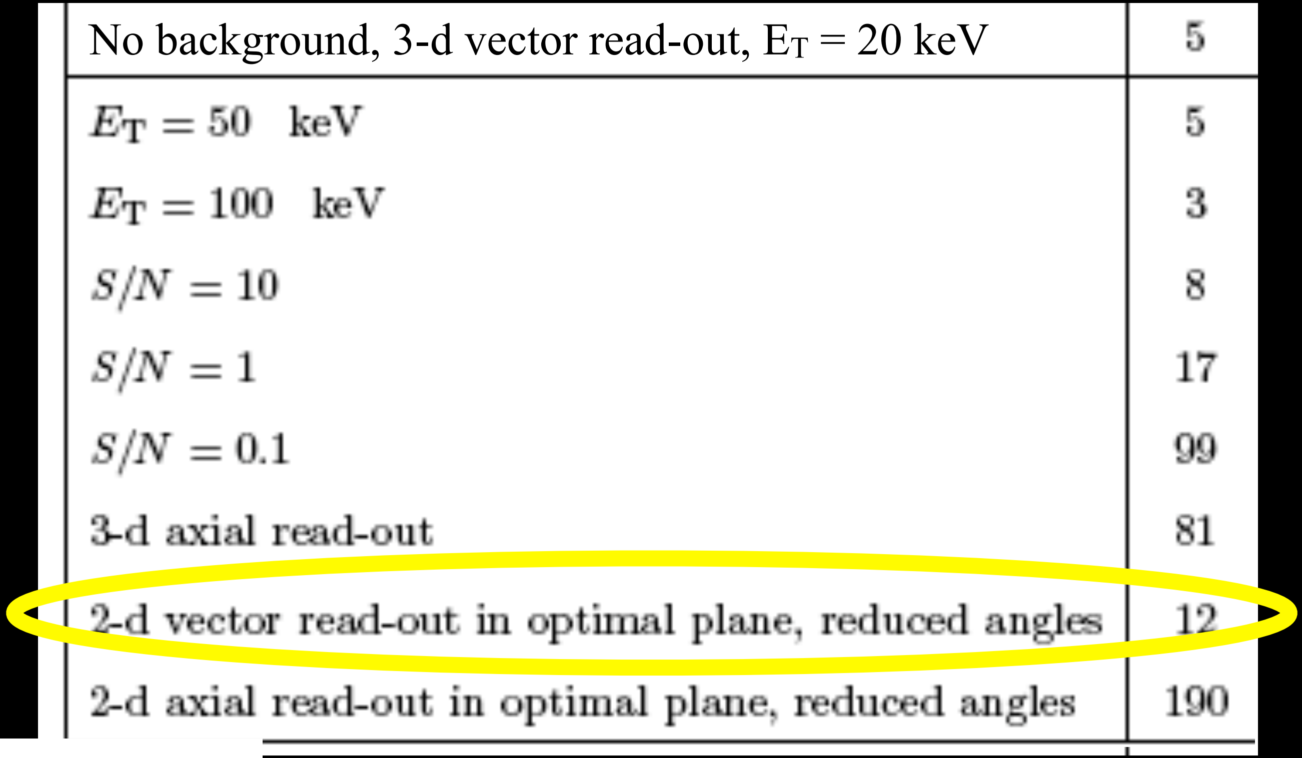
need ~50 keV threshold for directional detectors, for 100 GeV WIMPs

Optimization

how many events to detect the dark matter wind?

<u>Detector Properties:</u>

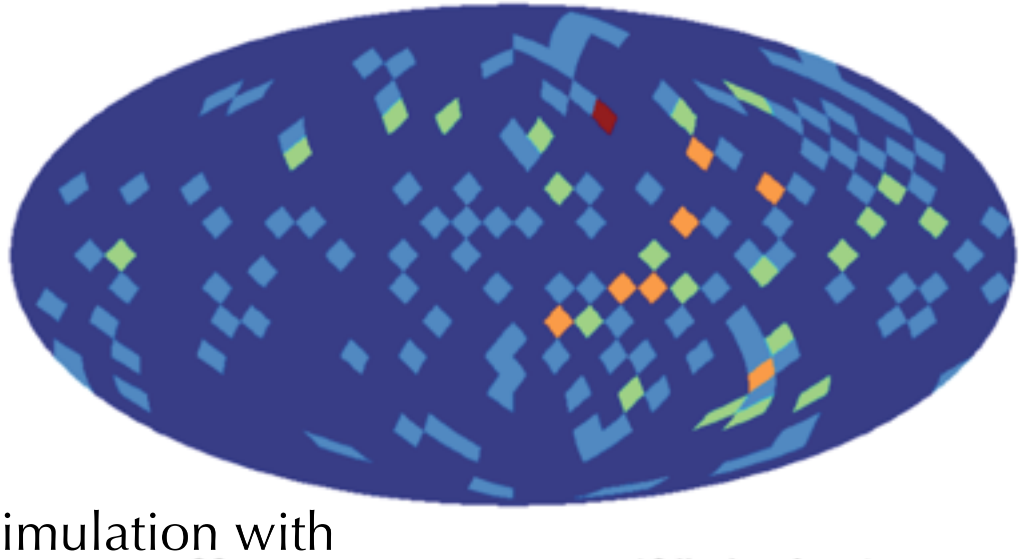
detector resolution
energy threshold
background
reconstruction
(2D vs. 3D)
vector ↗ or axial ⤡
reconstruction



No background, 3-d vector read-out, $E_T = 20$ keV	5
$E_T = 50$ keV	5
$E_T = 100$ keV	3
$S/N = 10$	8
$S/N = 1$	17
$S/N = 0.1$	99
3-d axial read-out	81
2-d vector read-out in optimal plane, reduced angles	12
2-d axial read-out in optimal plane, reduced angles	190

A. M. Green, B. Morgan,
Astropart.Phys.27:142-149,2007

J. Billard, F. Mayet, D. Santos,
PoS IDM2010 (2011) 071, arXiv:1009.5568



simulation with
100 signal, 100 background

Billard et al. 2010

do not need "zero background" for directional detectors

Outline

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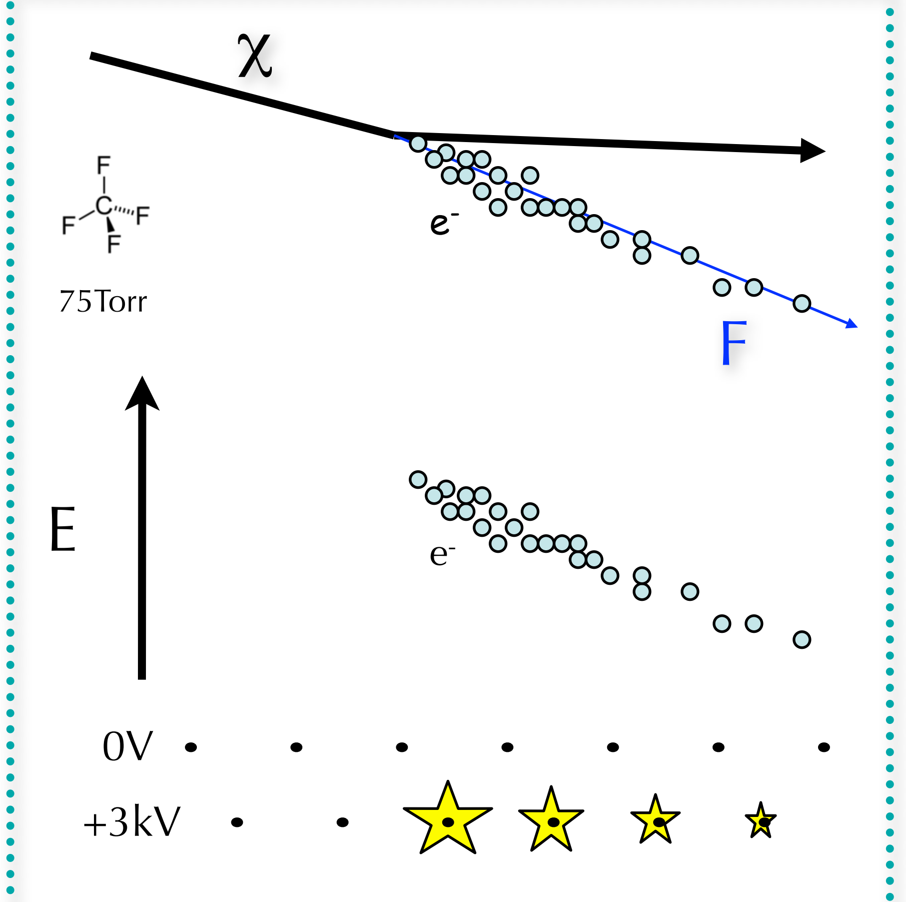
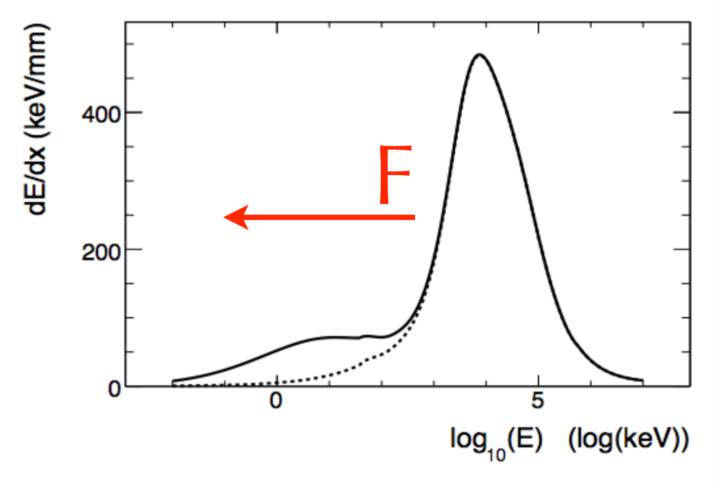
Dark Matter Time Projection Chamber (DMTPC) Principle



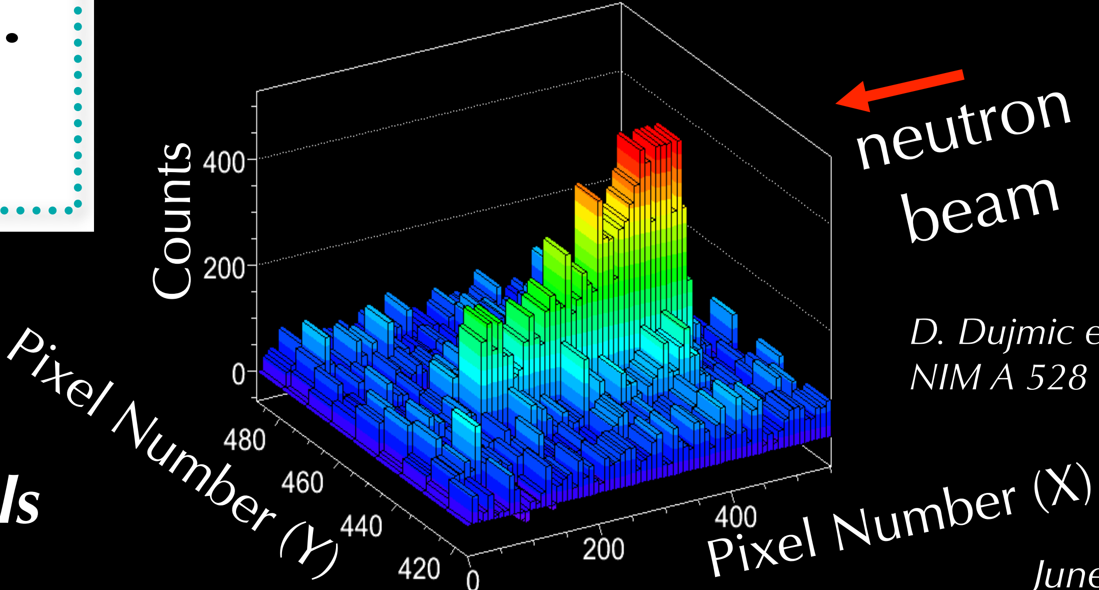
minimum wetted materials

1. primary ionization encodes track direction via dE/dx profile



2. drifting electrons preserve dE/dx profile if diffusion is small

3. multiplication in amplification region produces e- + scintillation



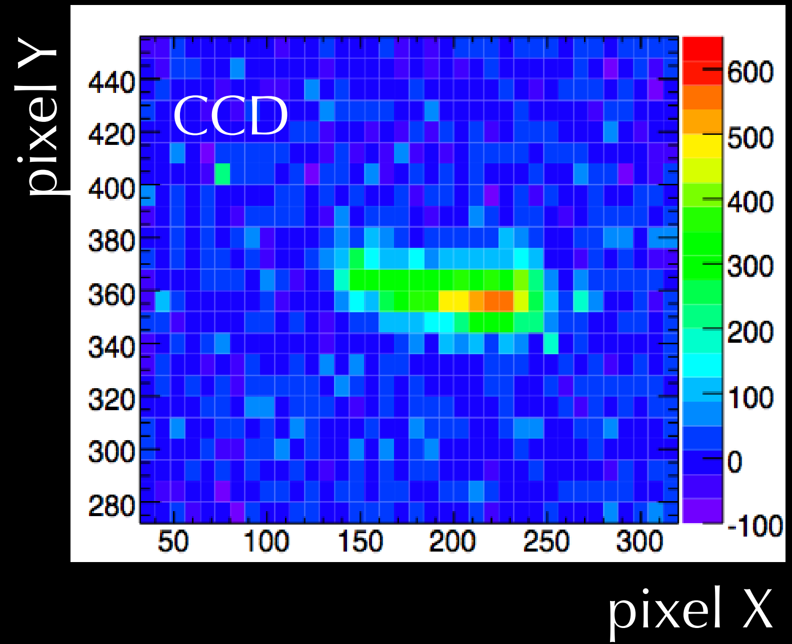
D. Dujmic et al., NIM A 528 (2008) 327

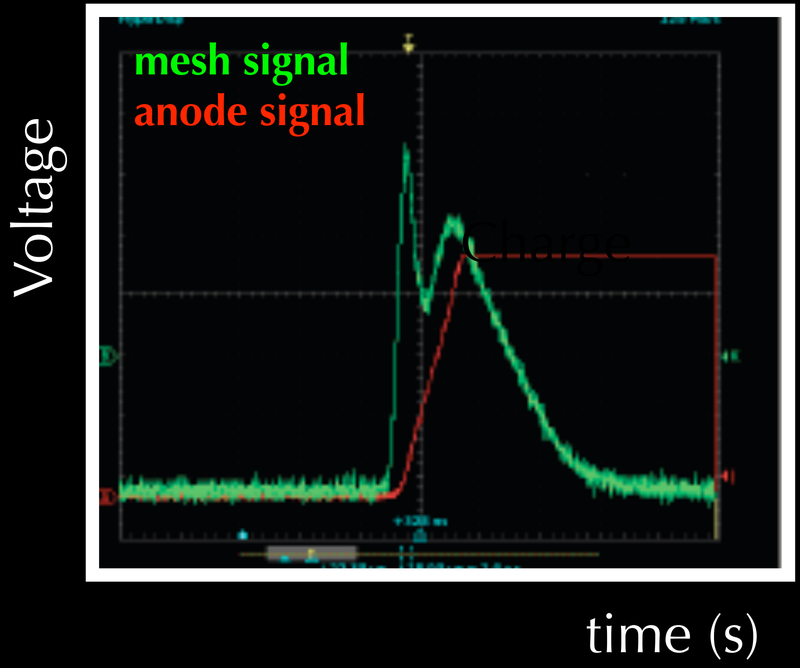
TPC Readout

Light readout

Charge readout

Light readout

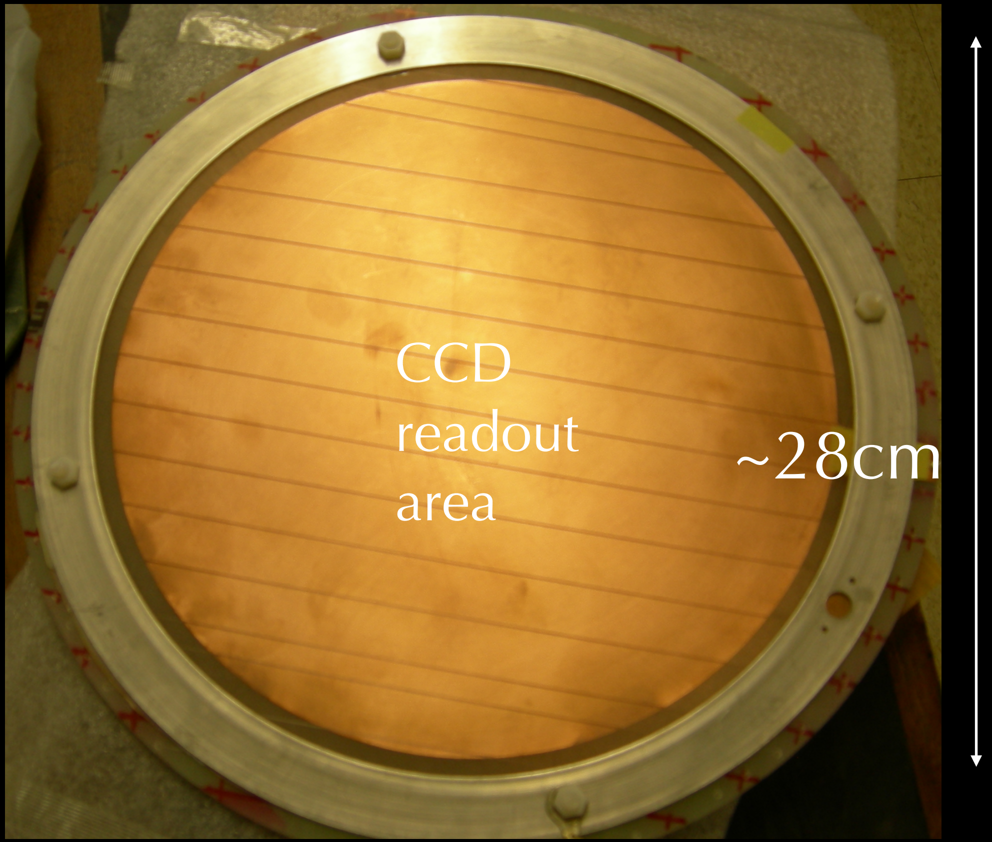




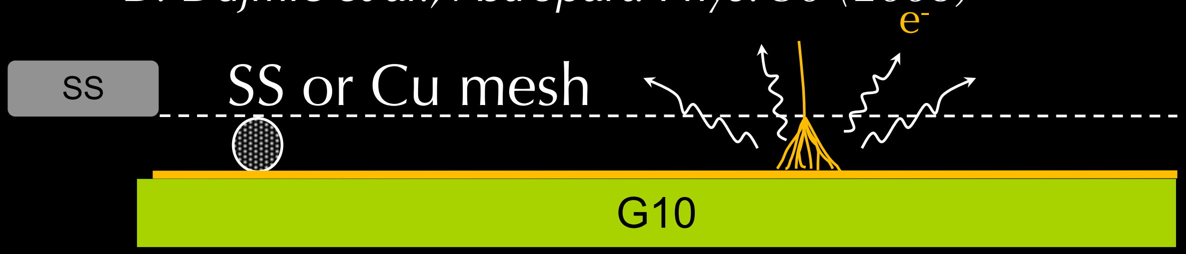
goal: charge and light = 2D -> 3D tracking & reject backgrounds

Amplification Plane

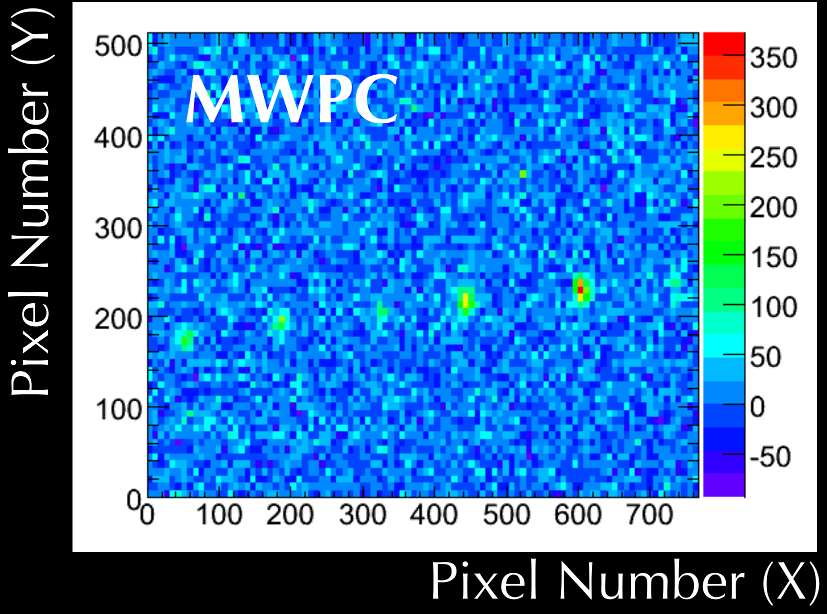
Copper Mesh, 256 um pitch

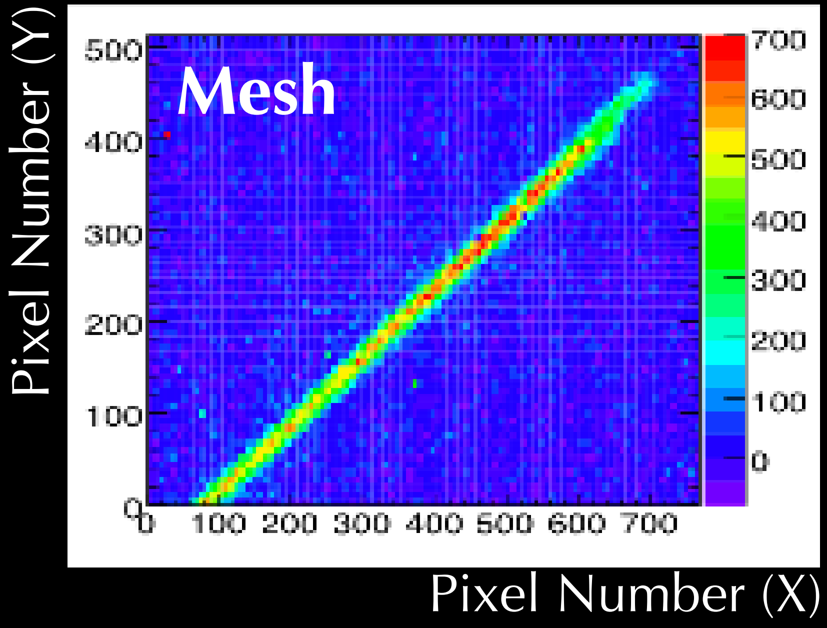


D. Dujmic et al., Astropart. Phys. 30 (2008)



Resistive separators, dia=0.5mm, every 2.5cm

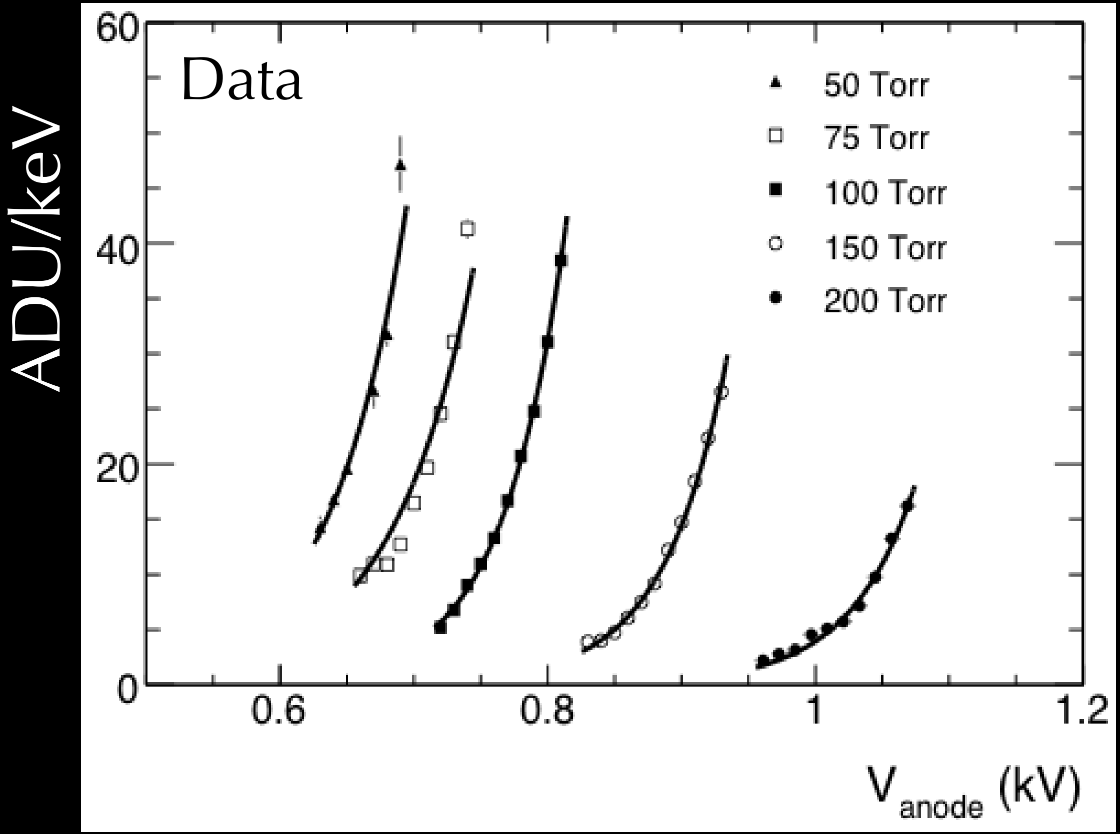




20x smaller pitch,
10x larger gain, 1->2D

CCD Readout

Total light output:



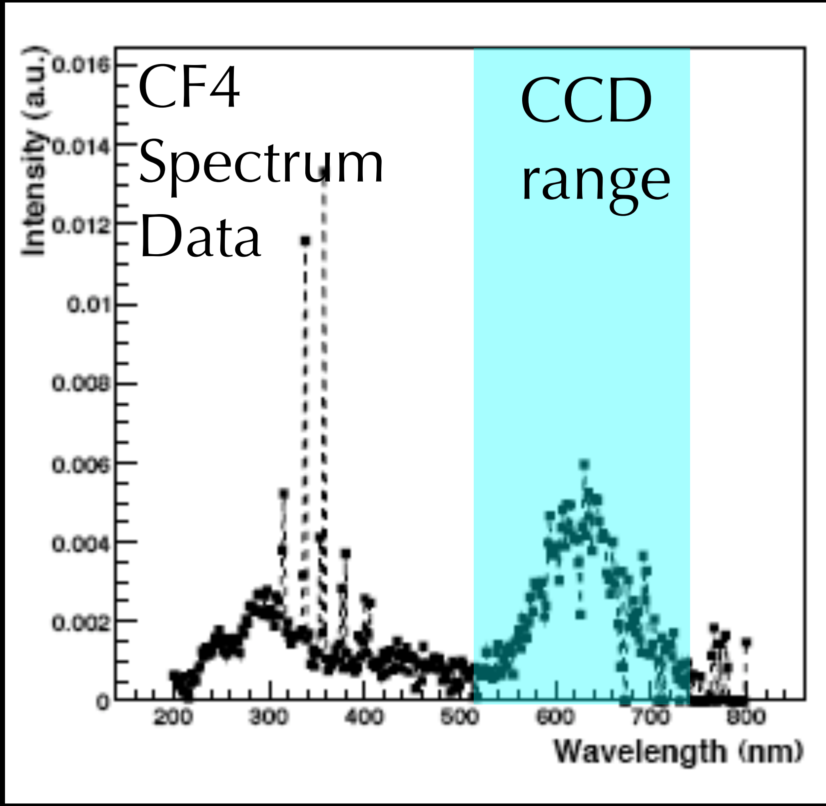
Increasing gain + track length with lower pressure, but decreasing mass!

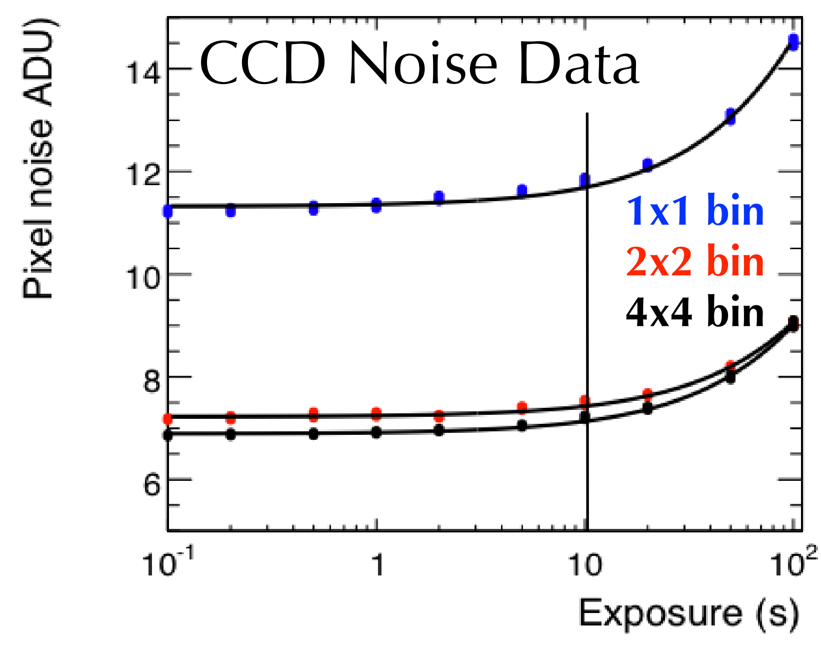
CF4 scintillation: $\gamma/e^- = 0.38 \pm 0.04$

A. Kaboth, et al., NIM A 592:63-72 (2008)

Key: S:N per pixel, @50 keVr S:N~10-20

$$\left(\frac{signal}{noise}\right)/pixel \simeq \frac{[(ADU/keV)\times E_r \times q(E_r)]/[Range/pixel\ size]}{\sqrt{N_{shot}^2+N_{read}^2+N_{dark}^2}}$$

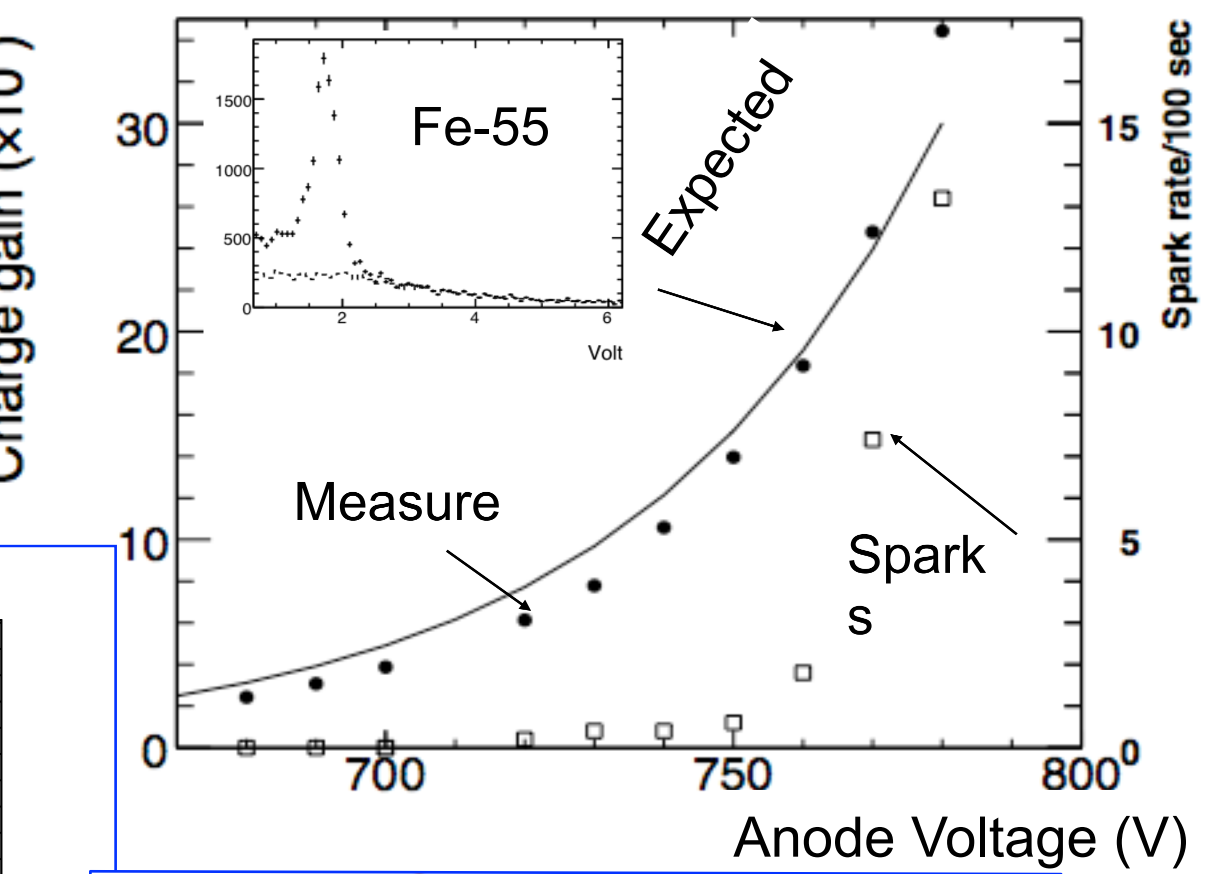


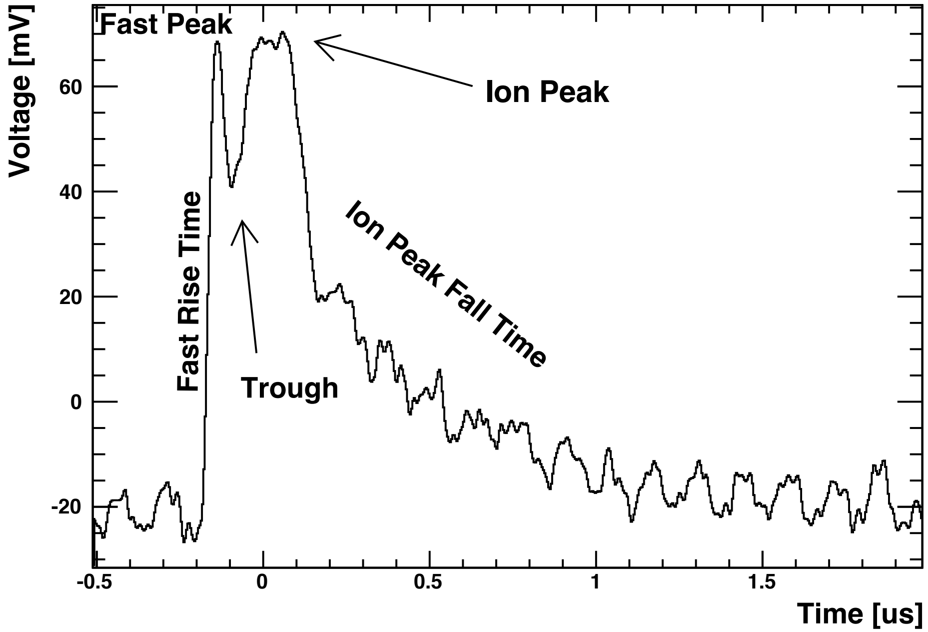


Charge Readout

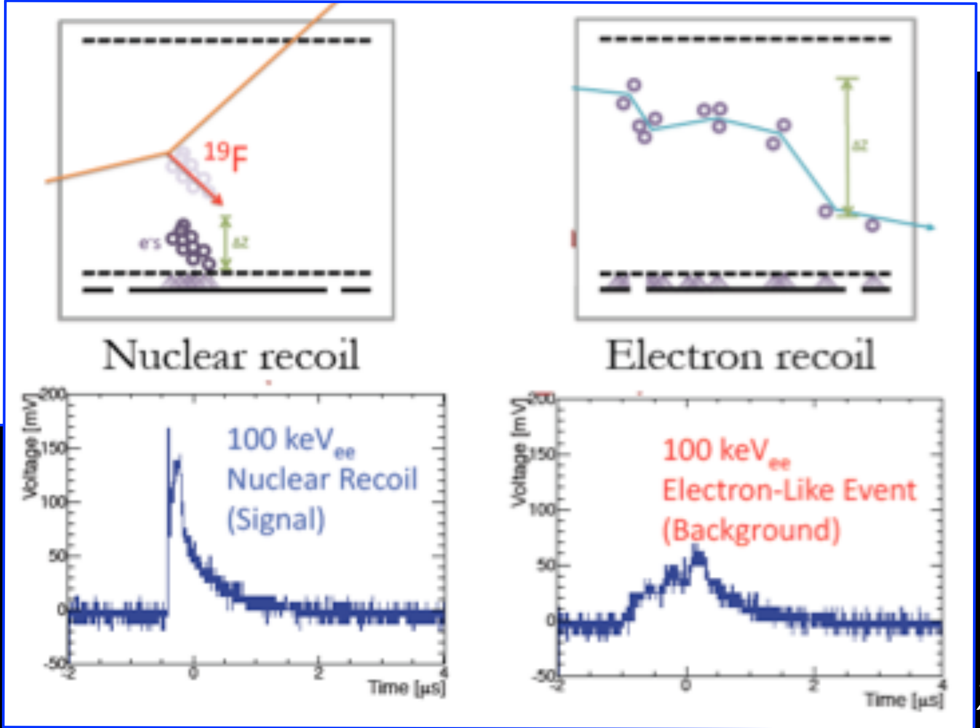
Multiplication calibrated with Fe-55, anode signal amplitude

$M \sim (V_{out} x 1.4pC/V) / (5.9keV/W)$
$W = 33.8 \pm 0.4$ eV *(I. Wolfe thesis)*

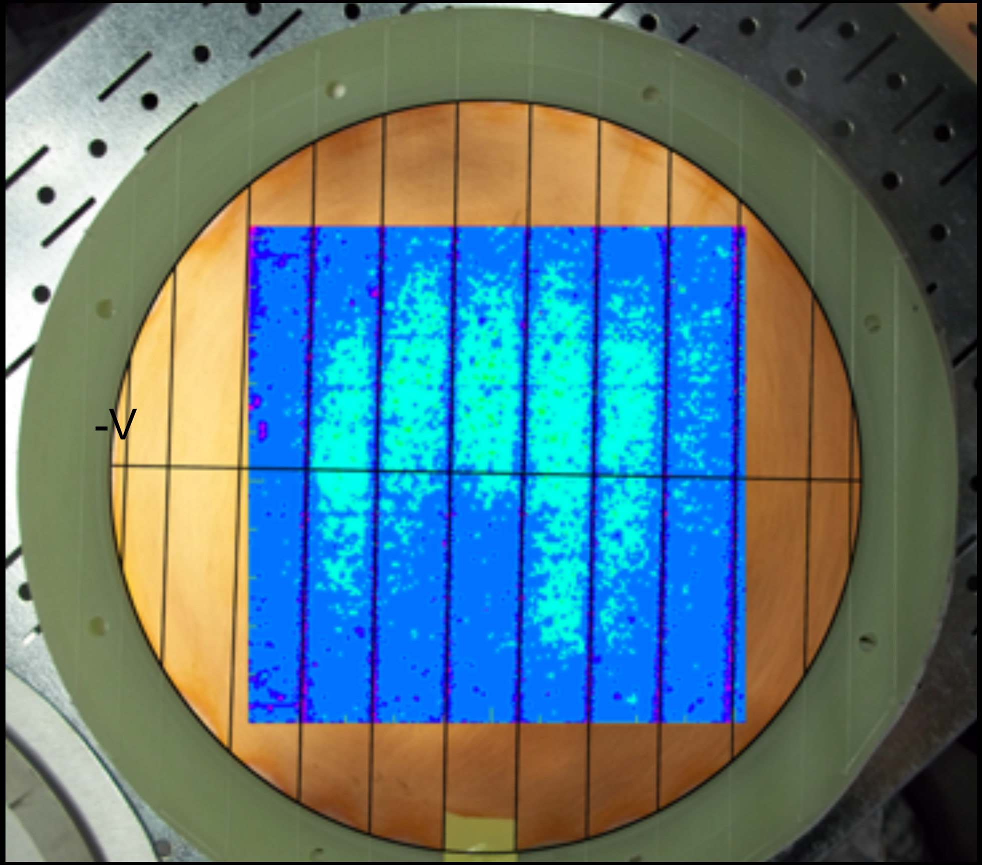




Mesh signal readout with ns-risetime amplifier, to measure Δz and for PID

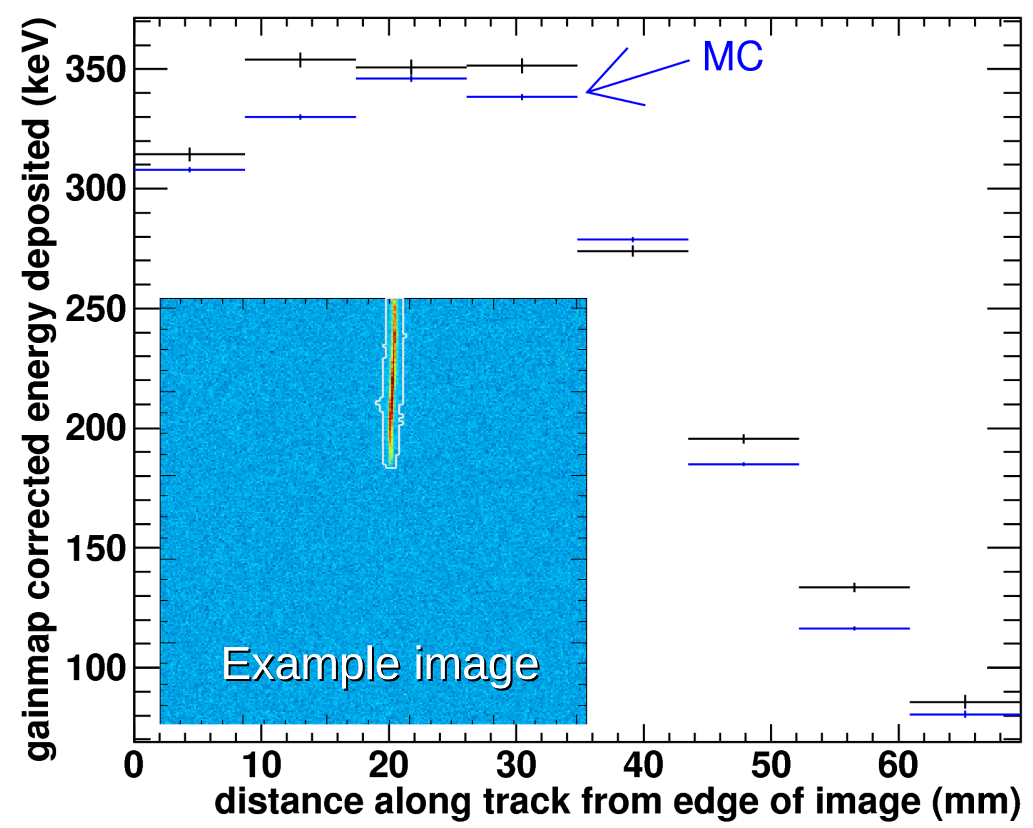


CCD Length and Energy Calibration



illuminate with Co-57 (122,137 keV) and Cs-137 (662 keV) for length calibration

measure optical plate scale by comparing spacer positions in gamma data with photo typically ~140-170 um/pixel



α sources for energy calibration (4.4 MeV)

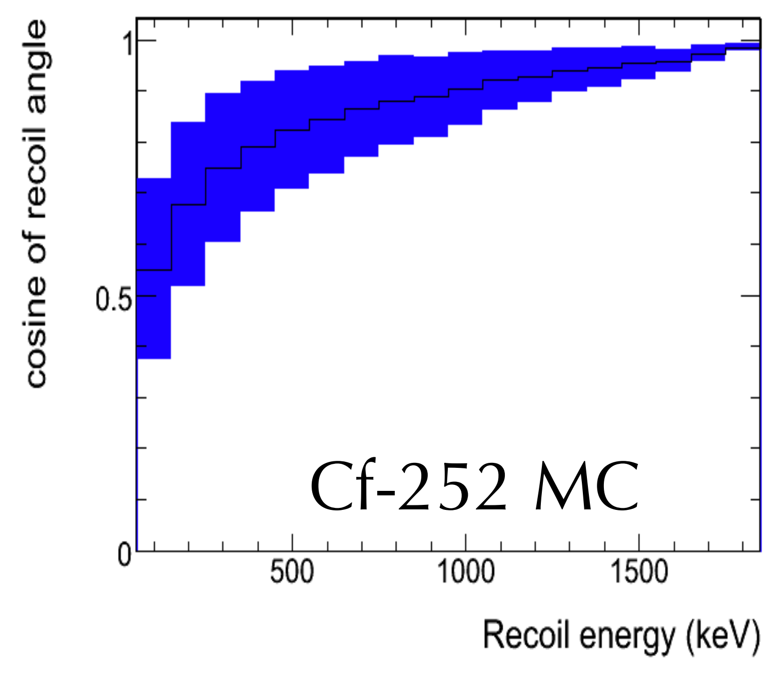
measure gain (ADU/keVee) by comparing **α** energy measured in external solid state detector with energy in CCD, at track end: typical gain ~ 20-40 ADU/keV

“WIMP” Calibration

Neutron elastic scattering mimics dark matter recoils, and most neutrons below ~4 MeV (n,alpha) production threshold

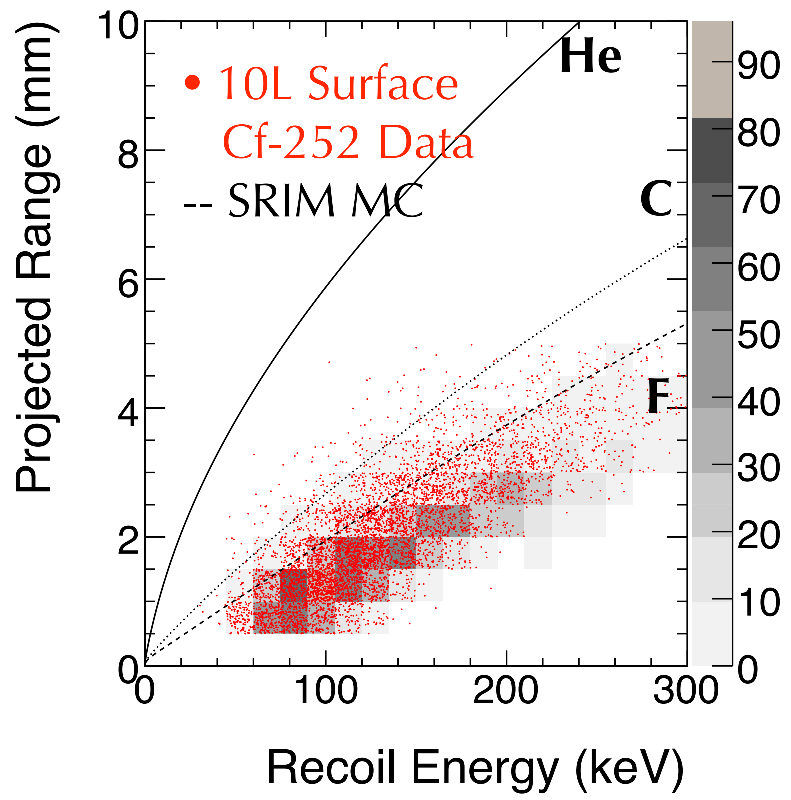
Cf-252 (~mCi) and d-t sources at surface, AmBe (8.9 uCi) source underground

100keV recoil angle	
Source	**Recoil angle**
14.1 MeV neutrons	80deg
Neutrons from AmBe	~68 deg (avg)
Neutrons from Cf252	~57deg (avg)
200GeV WIMP	~43deg (avg)



minimum recoil energy detected: 30-50 keV

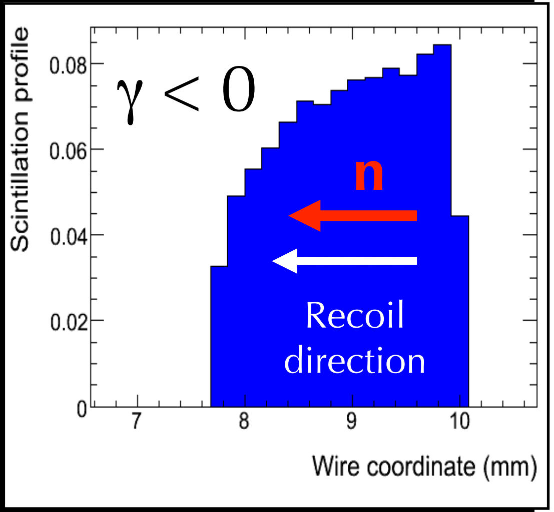
(Hitachi quenching model)

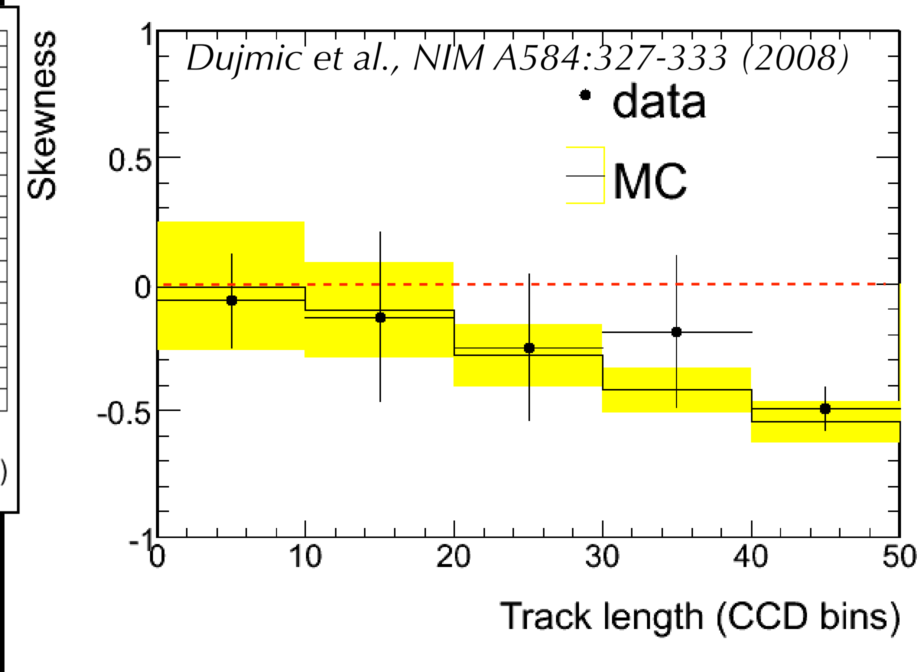


Energy and recoil angle distributions similar to dark matter induced recoils

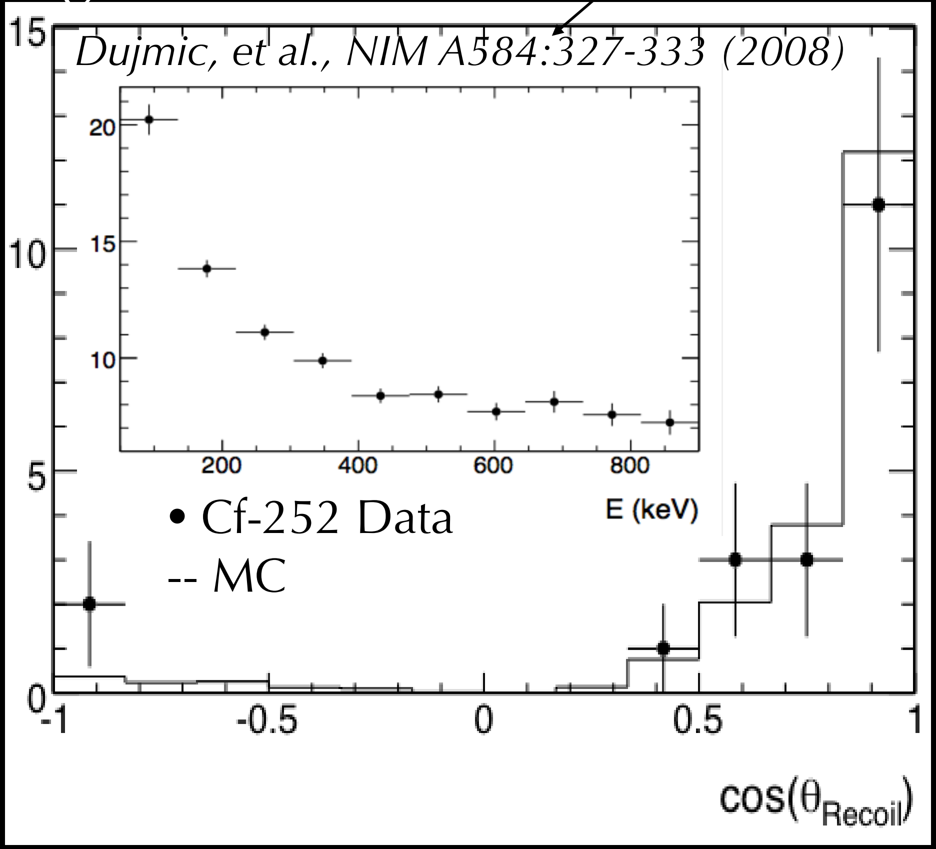
Directionality I

2D angle + head-tail from light asymmetry (measure skewness)



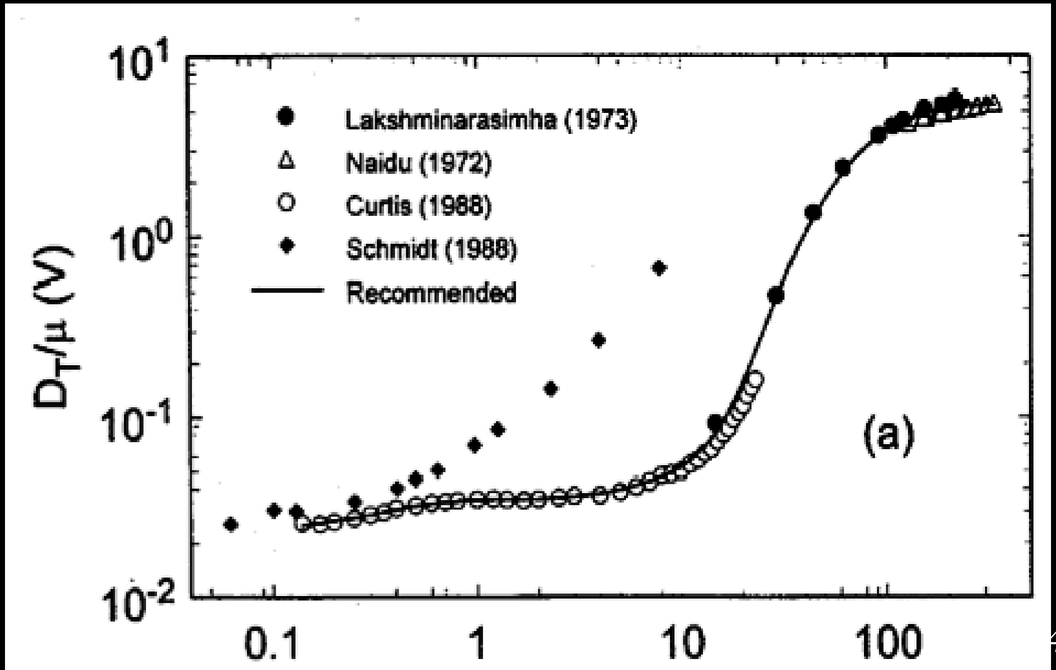

Dujmic et al., NIM A584:327-333 (2008)

Signed cosine (E>200 keV), 5 cm drift


Dujmic, et al., NIM A584:327-333 (2008)

challenge to scaling up: diffusion!

$$\sigma^2 = (D/\mu)\ 2\ z_{DRIFT} / E$$



Diffusion Measurement

Measure track width from alpha source at known heights in detector,

- fit for two terms:

$$\sigma_T^2(z_{DRIFT}) = \sigma_{T,0}^2 + 2\left(\frac{D_T}{\mu}\right)\left(\frac{z_{DRIFT}}{E}\right)$$

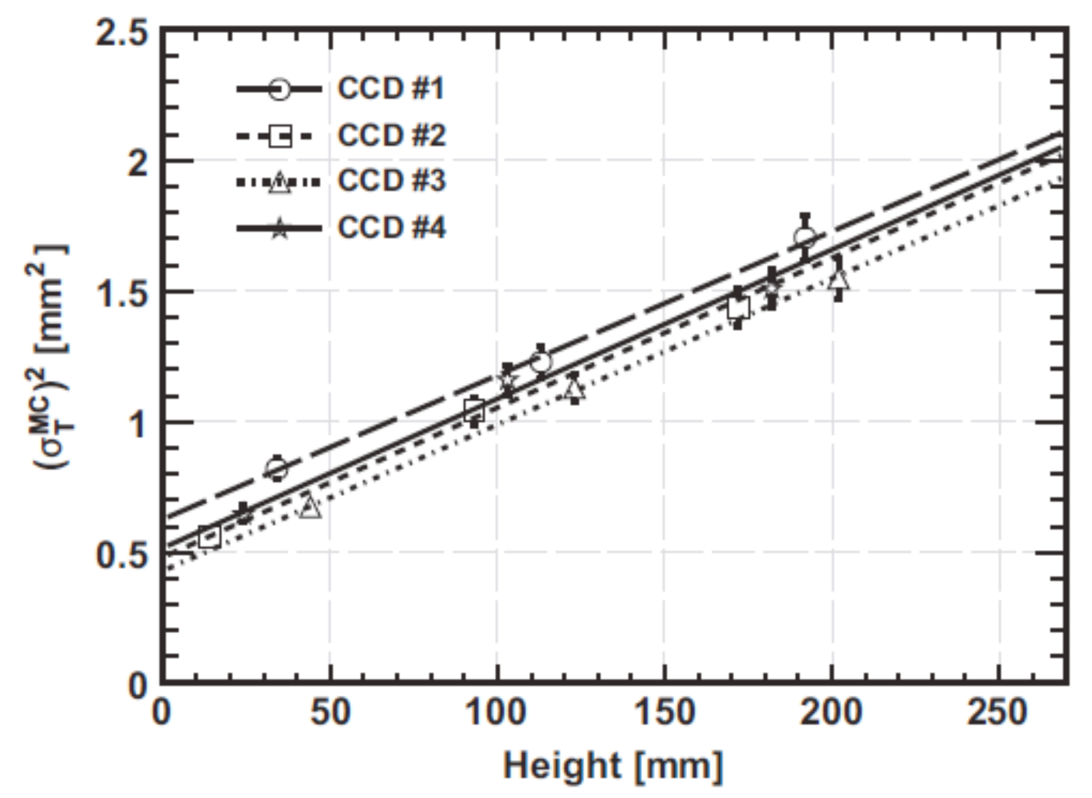
- find z-dependent term consistent with literature recommended value

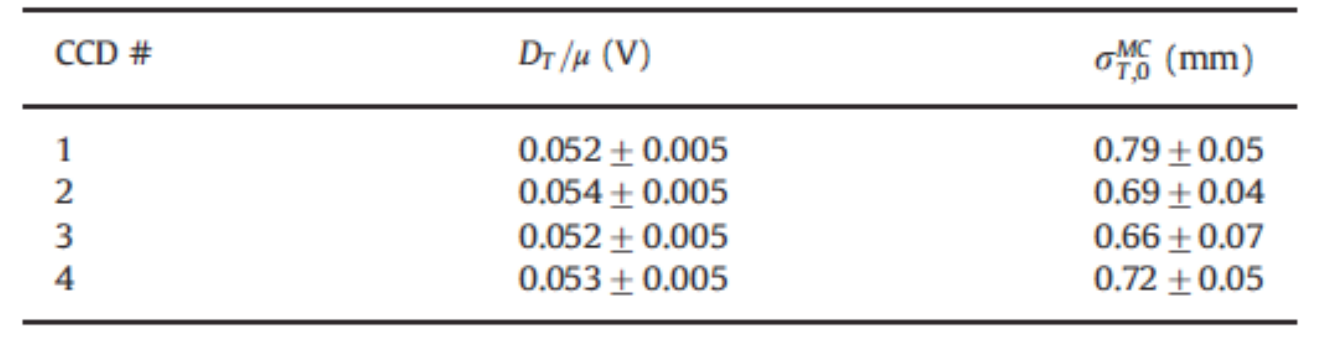
  L. G. Christophorou, et al, Journal of Physical and Chemical Reference Data 25 (1996) 1341

- find constant term dominates until z~20cm, and z=25 cm for σ^2_T<1mm

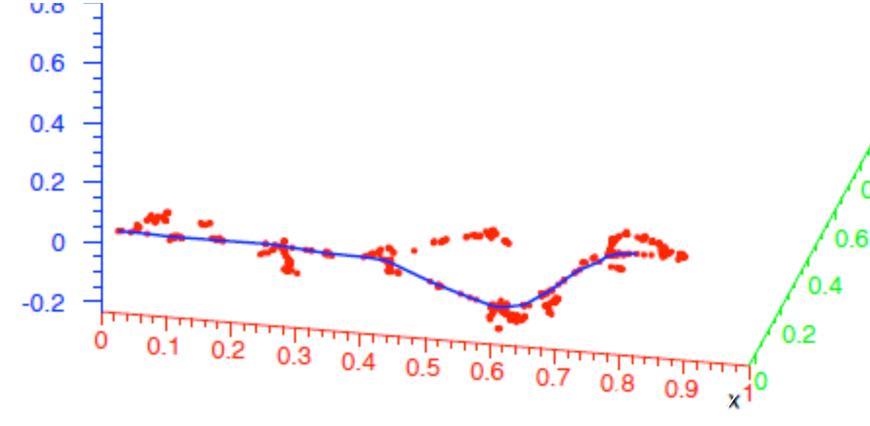
  J. Battat et al., NIMA 755 (2014)

- from simulation, constant term mainly comes from straggling of the primary ion



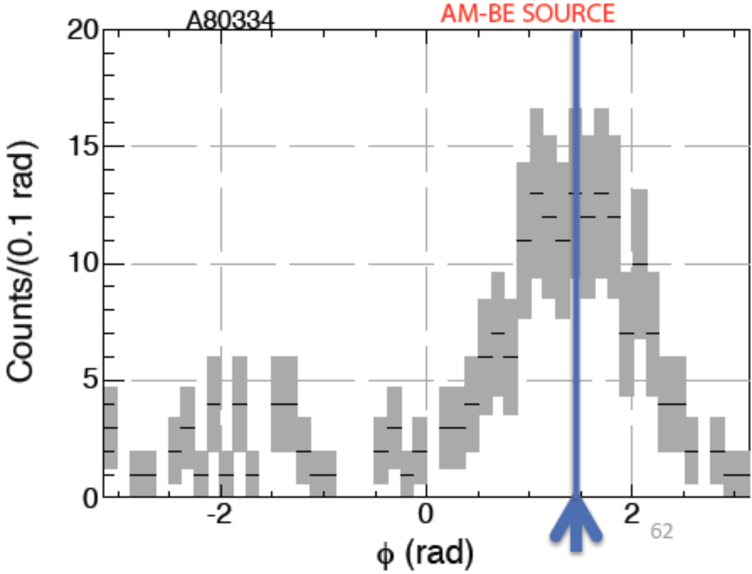


CCD #	D_T/μ (V)	$\sigma_{T,0}^{MC}$ (mm)
1	0.052 ± 0.005	0.79 ± 0.05
2	0.054 ± 0.005	0.69 ± 0.04
3	0.052 ± 0.005	0.66 ± 0.07
4	0.053 ± 0.005	0.72 ± 0.05

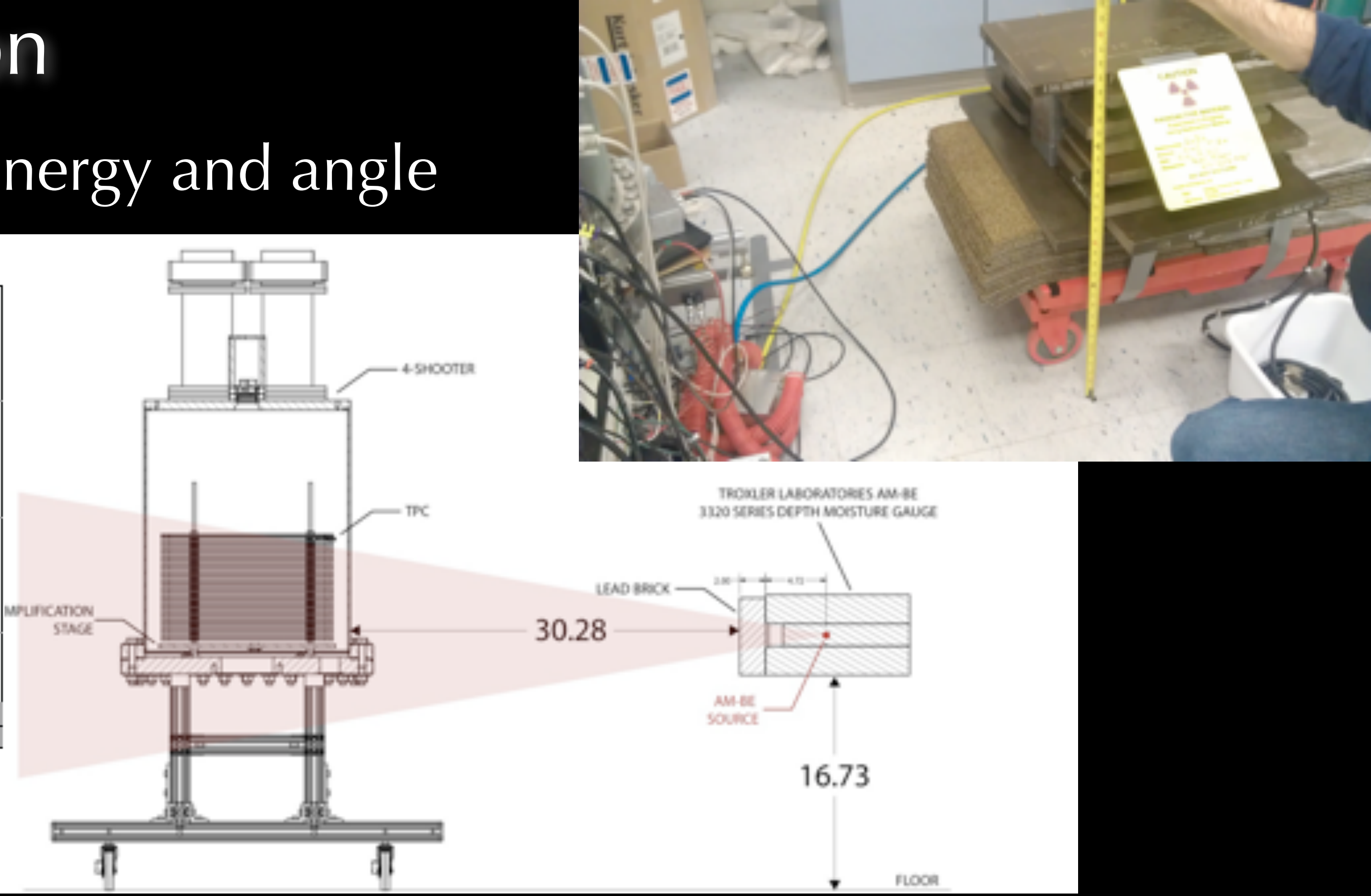


Direction Calibration

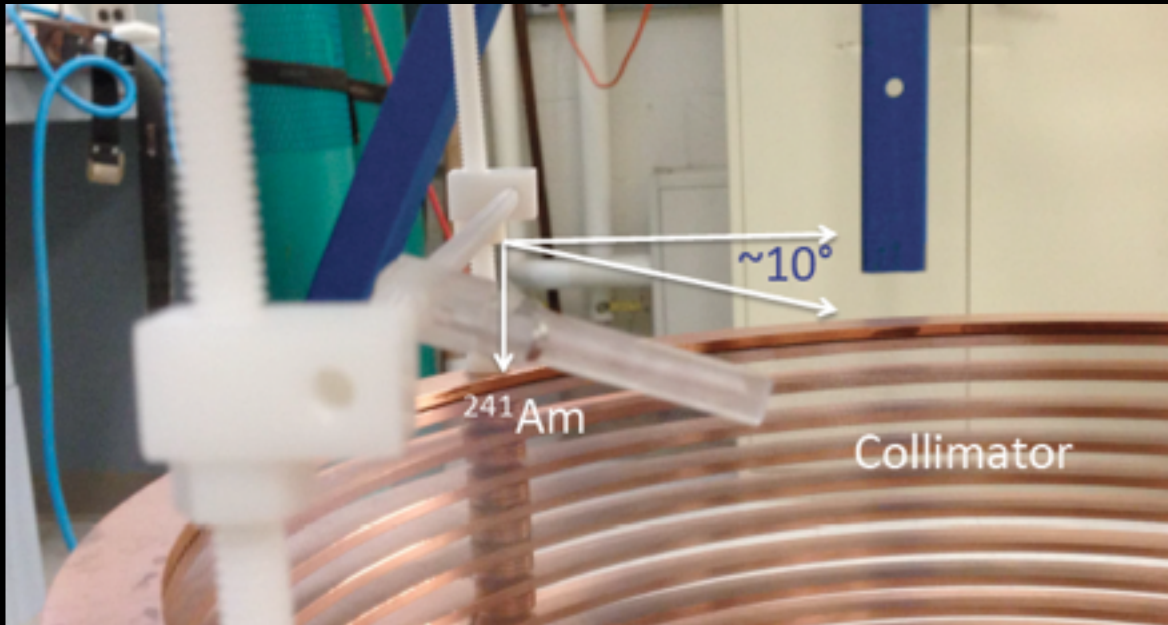
Need a source of known energy and angle



S. Henderson, PhD thesis



But, neutron scattering kinematics produce wide range of angles, and neutrons are hard to collimate.



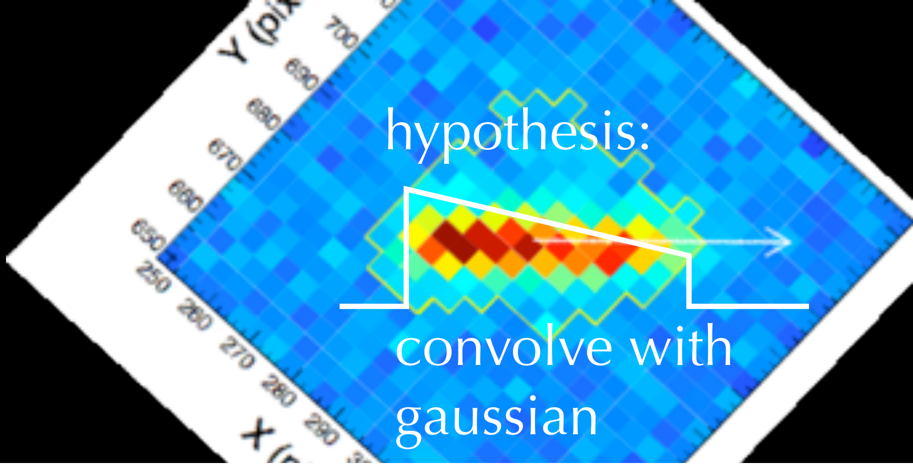
Angled alpha calibration:

- only track ends in active region, can tune energy ~100 keVee
- tune angle by rotating collimator

Track Reconstruction

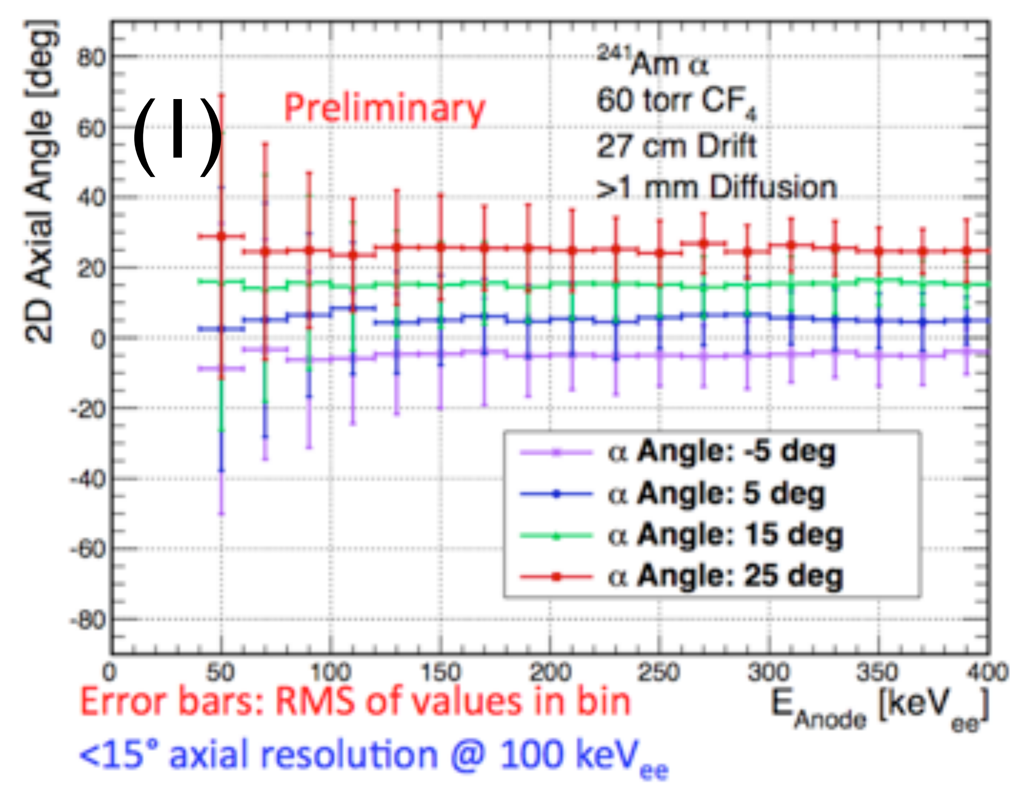
Measure energy from track intensity integral

Make use of the known profile of nuclear recoils from the Bragg curve to
(1) fit for the track parameters
(range, angle)
(2) fit for the head-tail (H-T)
(3) assign confidence in H-T
determination with likelihood
ratio of two possible senses,
cut on confidence



hypothesis:

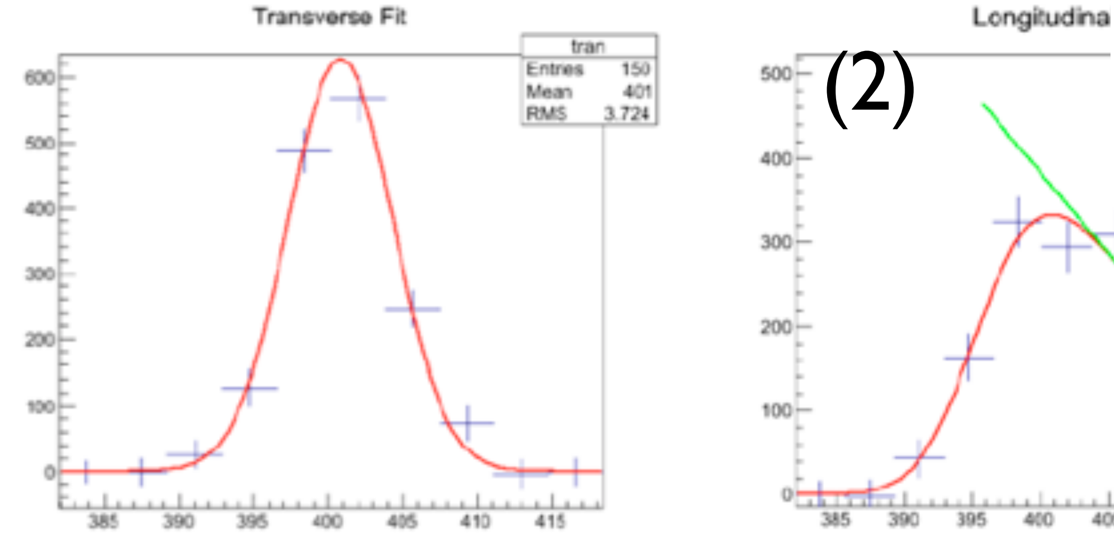
convolve with
gaussian



Error bars: RMS of values in bin

<15° axial resolution @ 100 keV$_{ee}$

S. Henderson, PhD thesis



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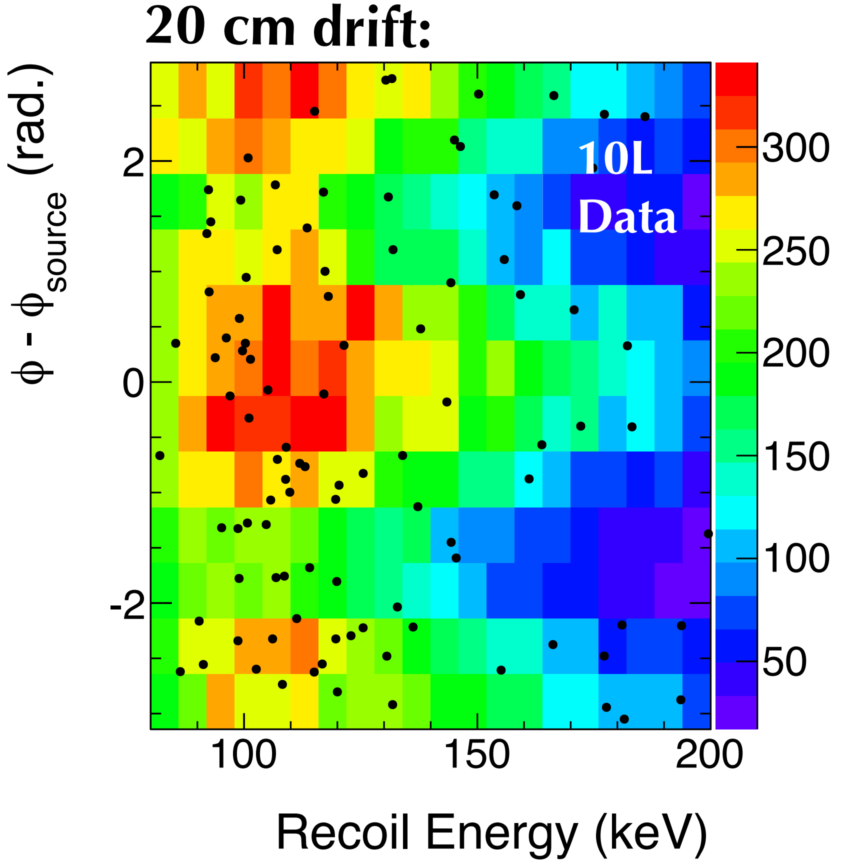
Directionality II

diffusion has a big impact!

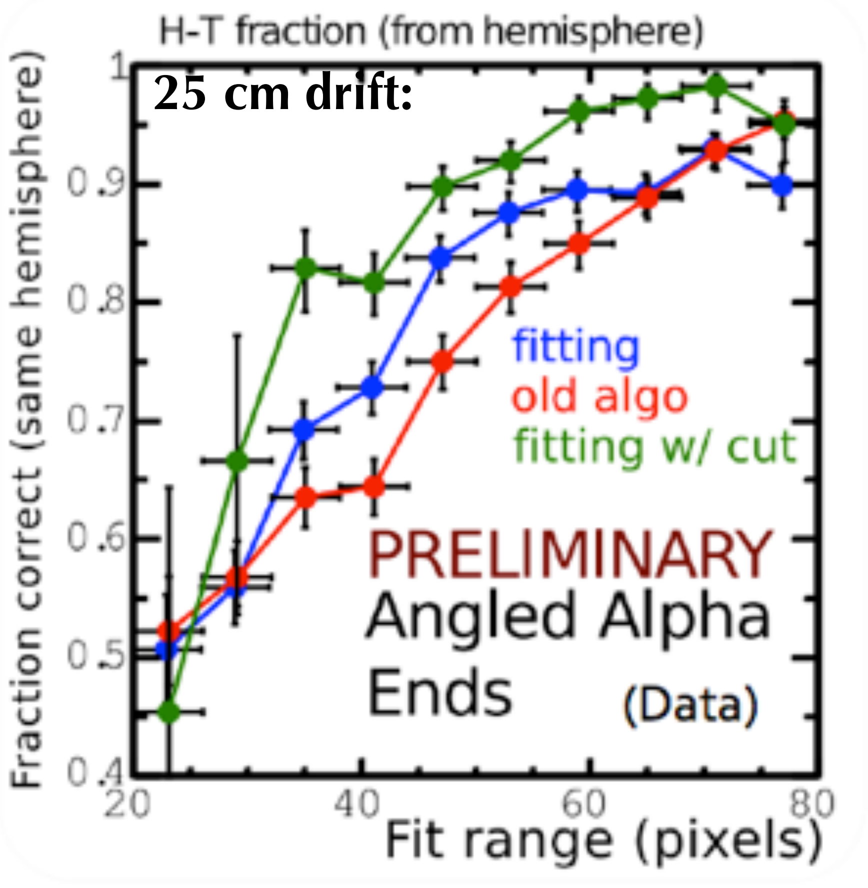
- measure with 20, 25 cm drift
- find direction reconstruction depends most on track length, range/width>3 for head-tail ID,
- working to lower pressure



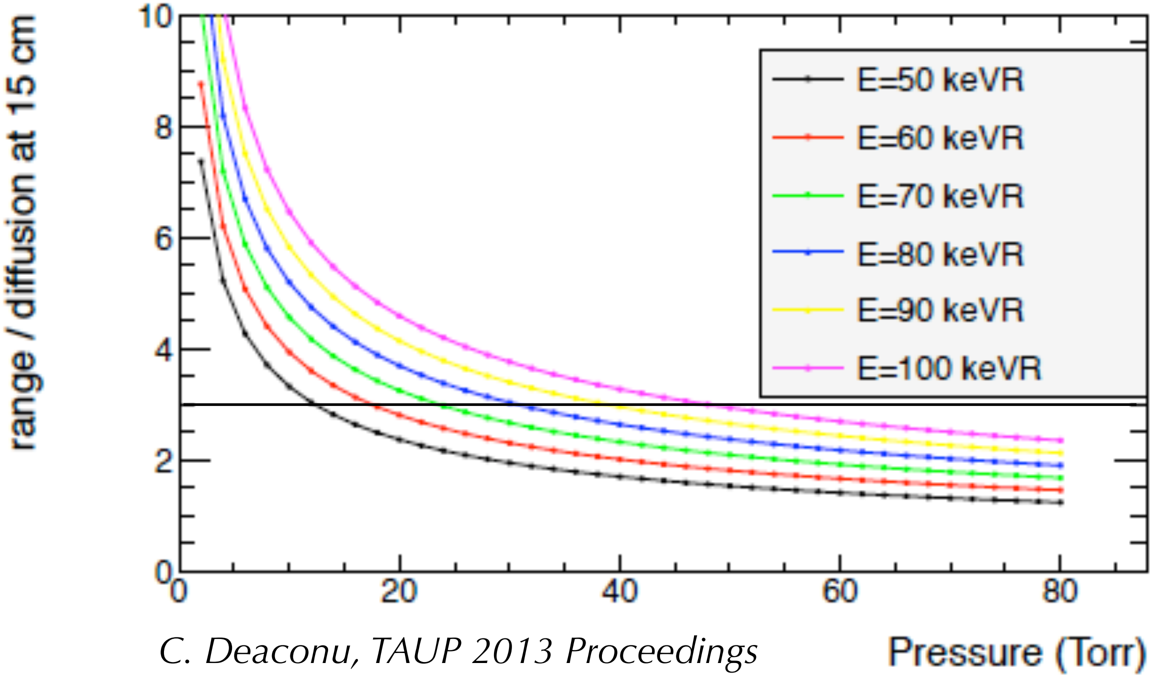
1D "sky map" for ^{252}Cf, and "WIMP " data (80-200 keV)

MC: 40° resolution at 80 keVr

A. Kaboth PhD, S. Ahlen et al., Phys. Lett. B 695 (2011)



Energy range equivalent ~50-200 keV

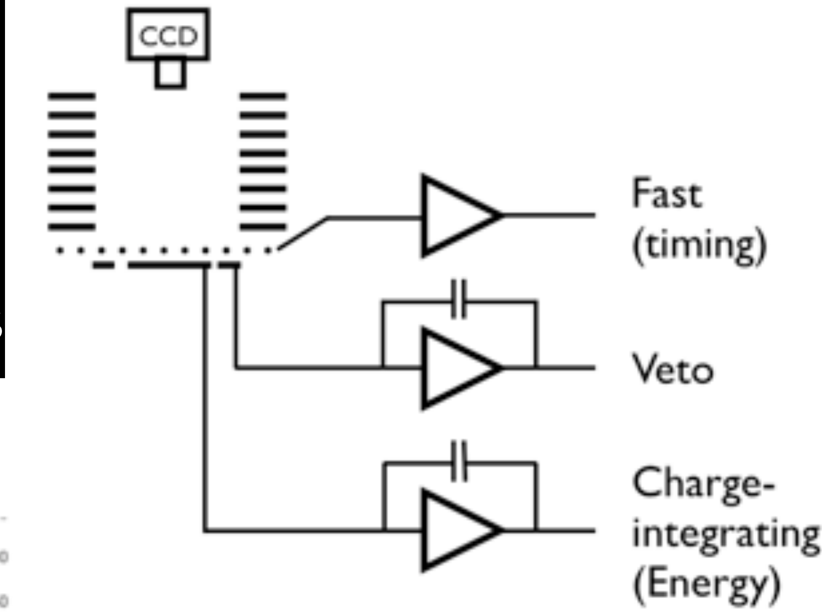


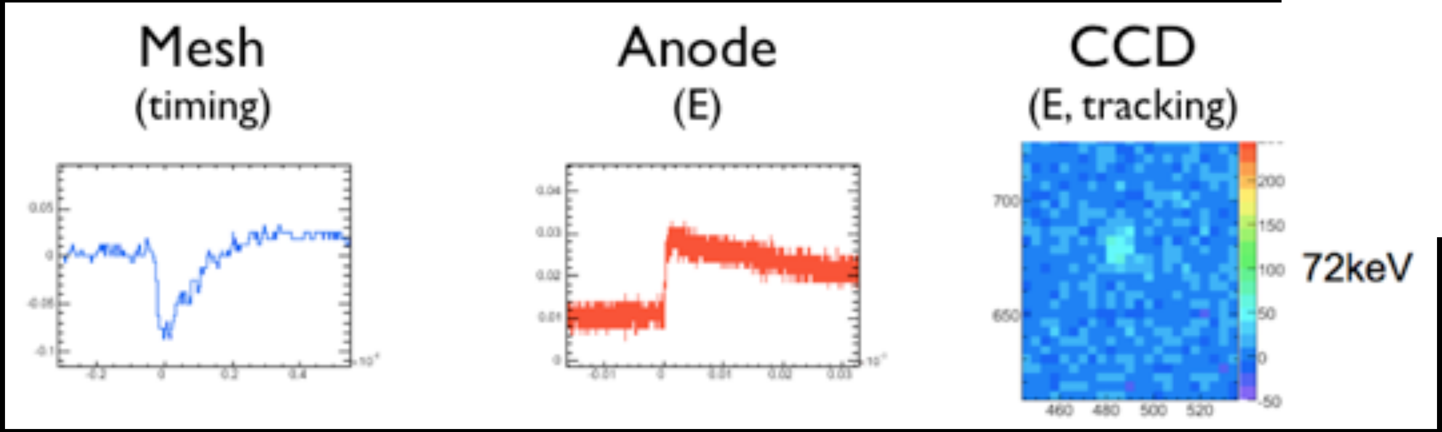
C. Deaconu, TAUP 2013 Proceedings

Background Rejection

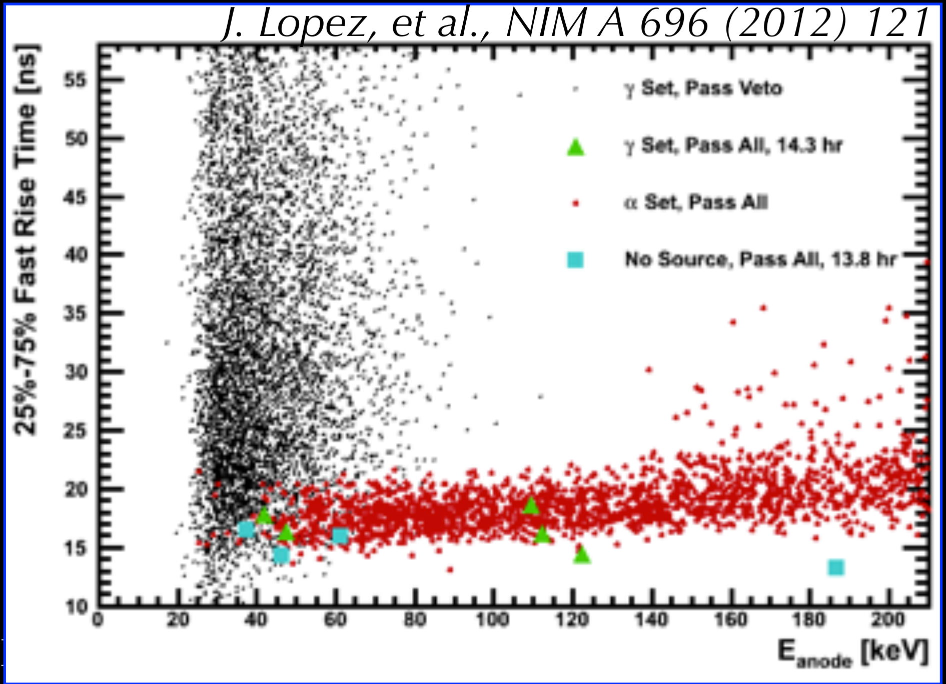
optical readout is used to reject wrong R vs. E in surface limit *S. Ahlen et al., Phys. Lett. B 695 (2011)*

now charge readout rejects gammas, CCD artifacts

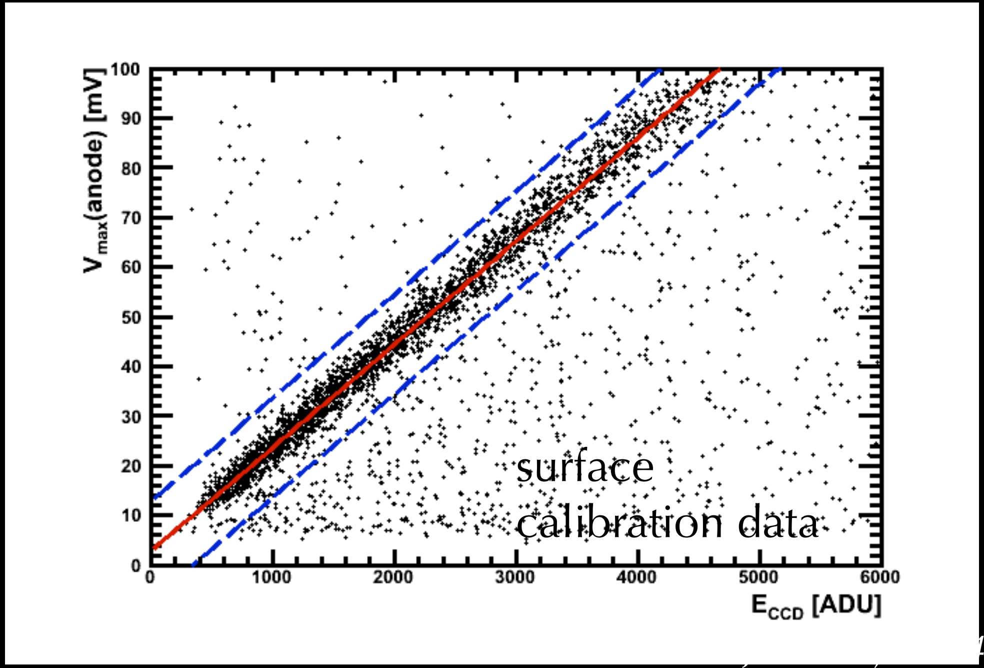




>1.1E-5 (90% CL) γ rejection from rise time vs. E:


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

~10^2 rejection from E_{charge} vs. E_{CCD}:



surface calibration data

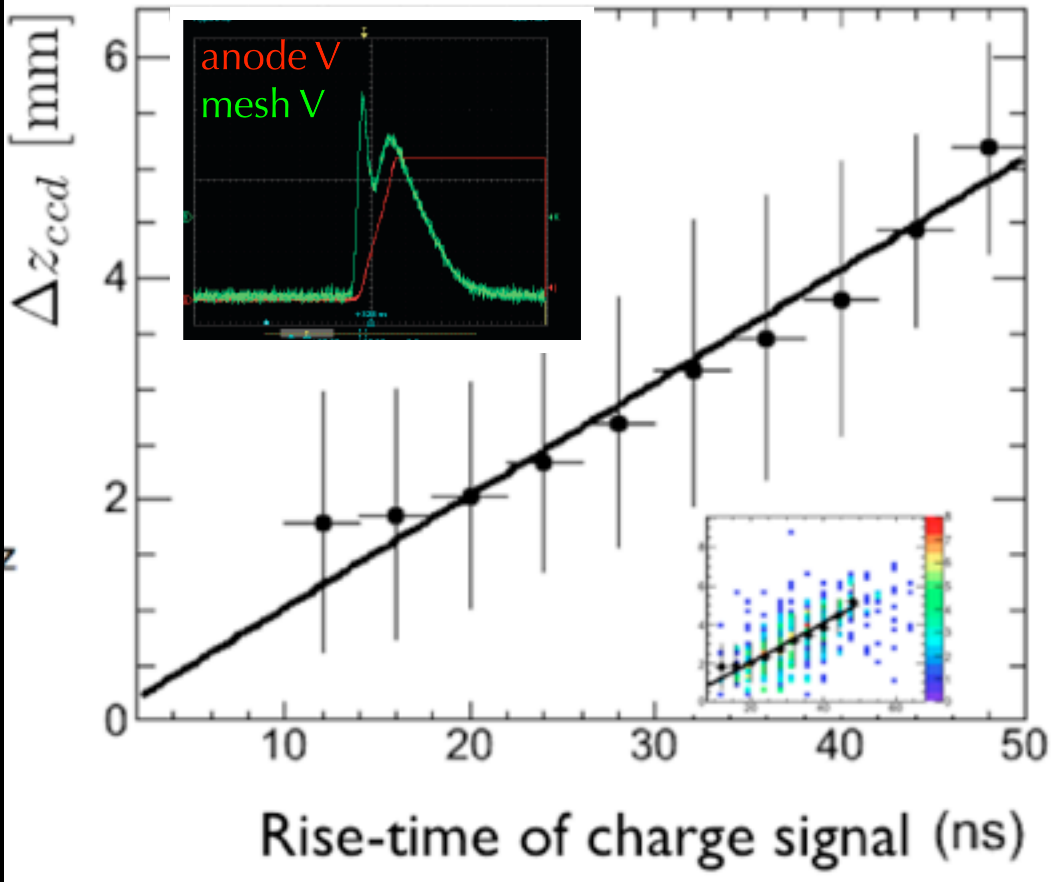
3D R&D

tracking in z (drift direction):

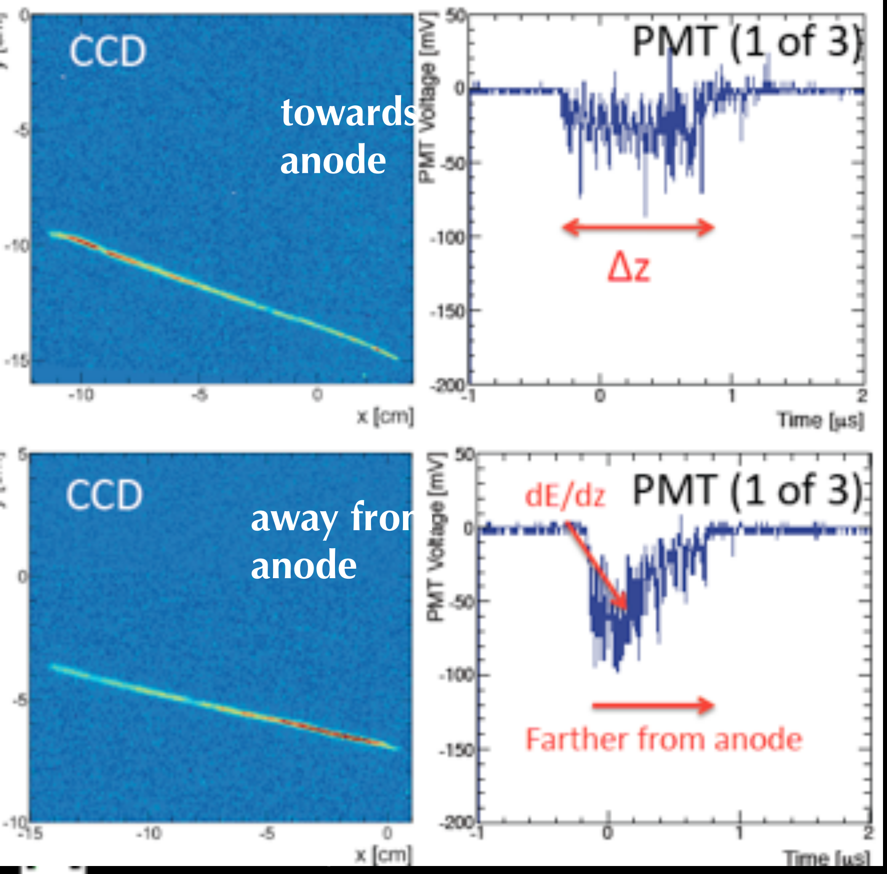
- angled alpha calibration source produces tracks of known Δz

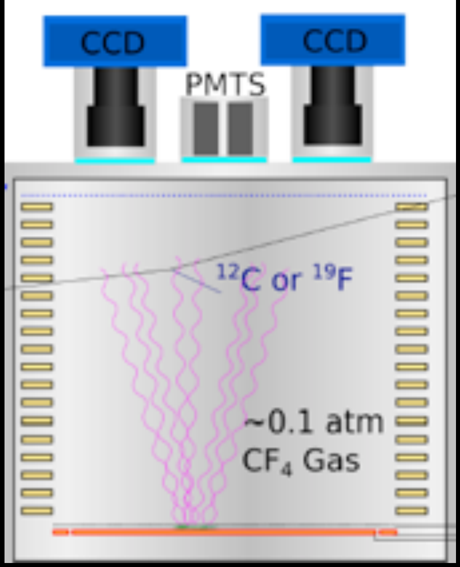
charge:

- measure mesh signal rise time
- find similar tracking resolution in Δz (from charge) as in x-y (from CCD)



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





light:

- measure PMT signal pulse width
- pulse width varies with Δz, shape varies with +/-Δz

R&D on cathode readout for absolute z measurement

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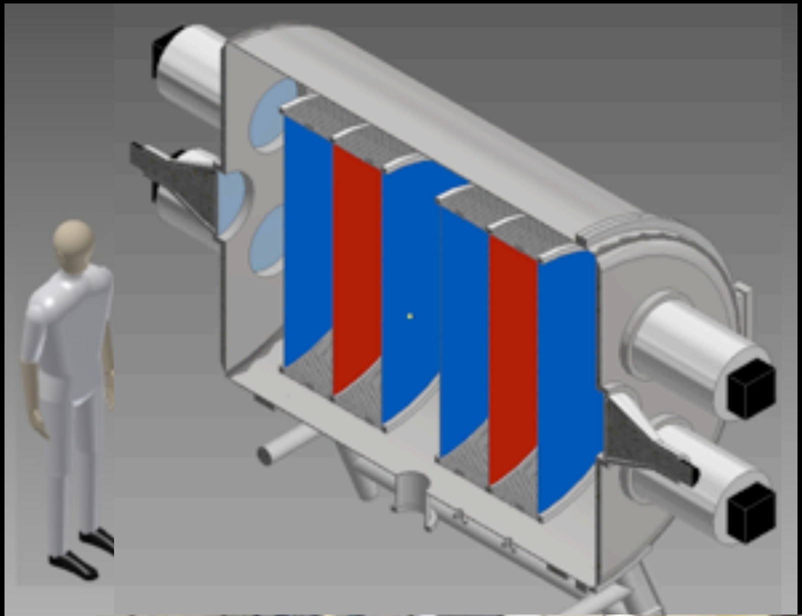
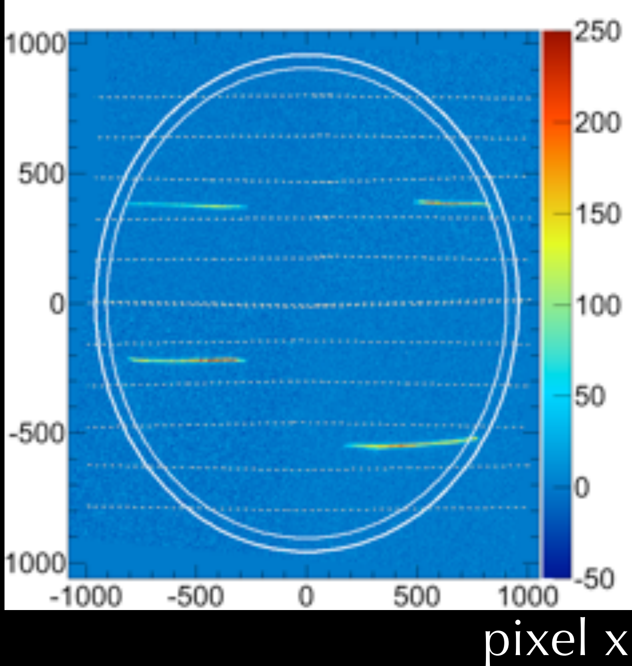
DMTPCino: 1m^3 Detector Module

prototype for very large detector: build many 1m^3 modules, because of diffusion limit



goal: achieve similar or better S:N per pixel, for 35° resolution at 50 keVr in 1m^3 module, ideally: 1 camera+lens/side (~0.005$/channel now)

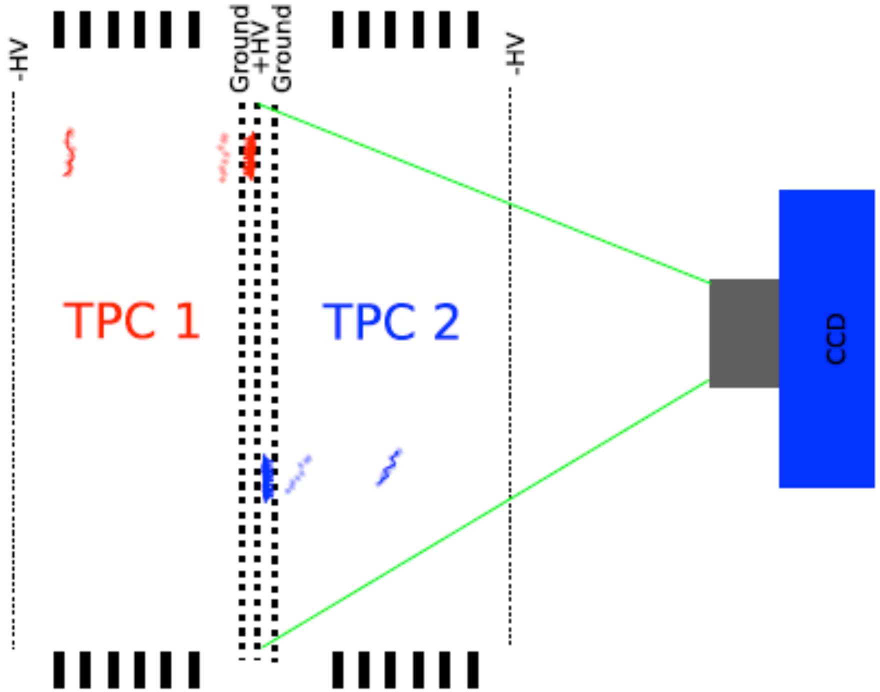


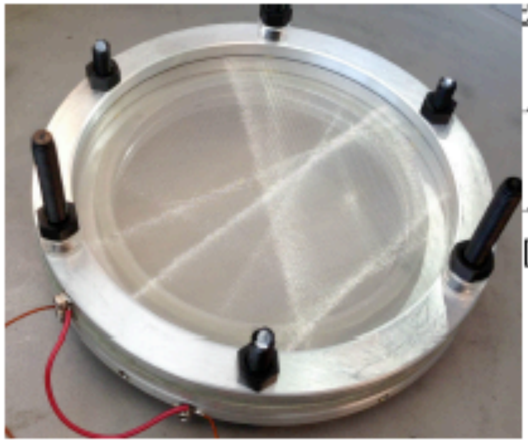
4-shooter 20L prototype has demonstrated
- (i) multi-camera readout
- (ii) low-background materials
- (iii) event discrimination with charge

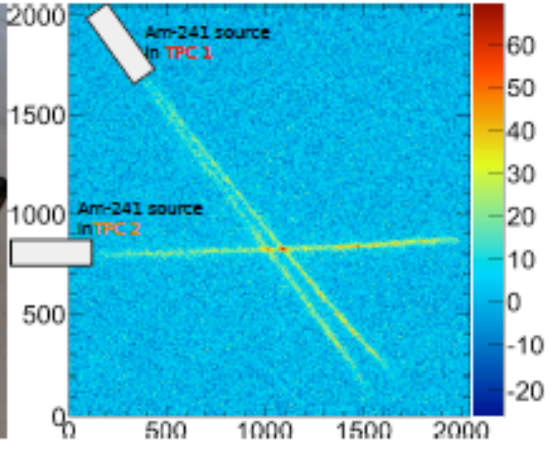
DMTPCino under construction now, commissioning Fall 2014

DMTPCino TPC

new amplification region scheme uses triple mesh: one camera images 2x 25 cm drift regions

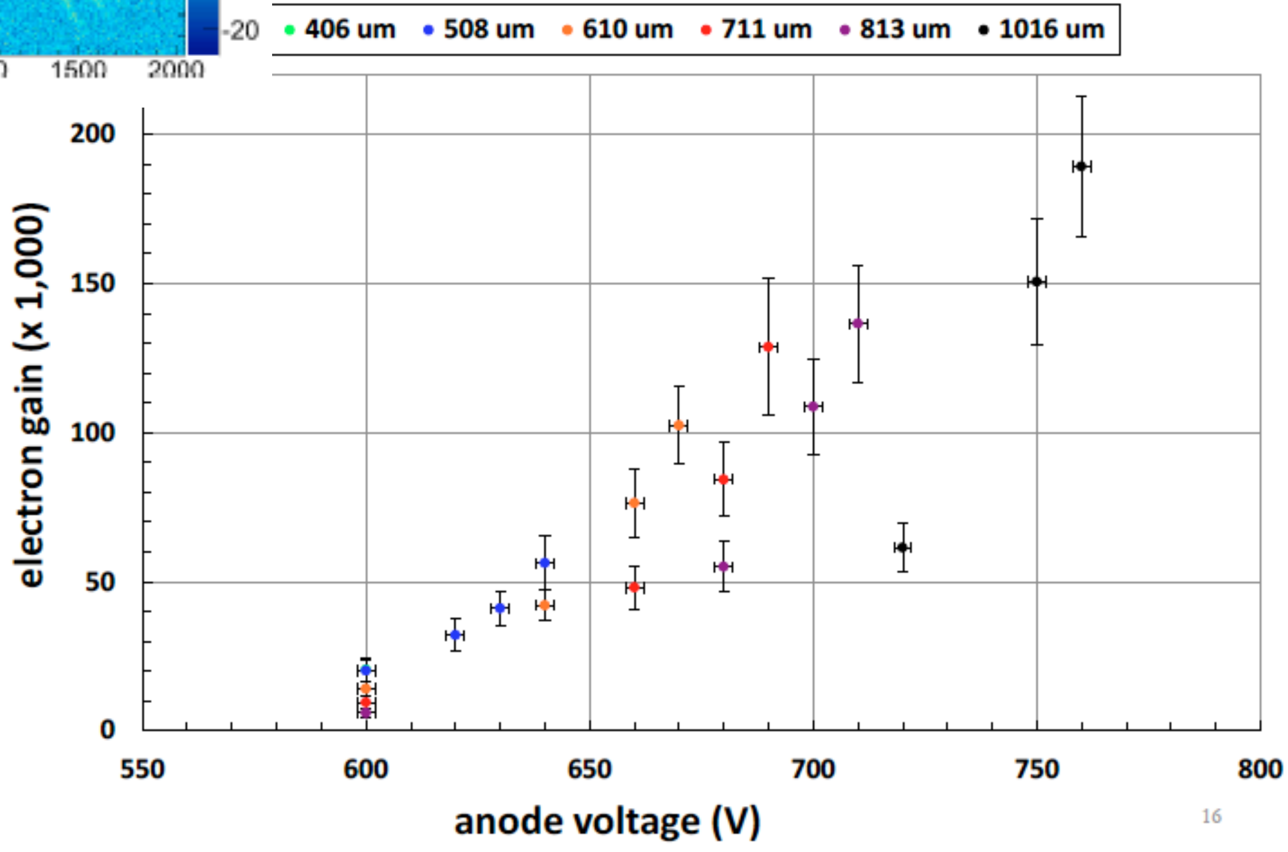






demonstrated high gain in small prototypes, 50-200k

D. Dujmic et al., Astropart. Phys. 30 (2008), C. Deaconu, UCLA DM'14



optimizing gap size, pitch to maximize pixel signal:noise,

•10x gain with 2x gap size

price: 25% amplification region diffusion tails increase

H. Tomita, PhD thesis, J. Battat, Cygnus'13

Outline

Experimental Considerations

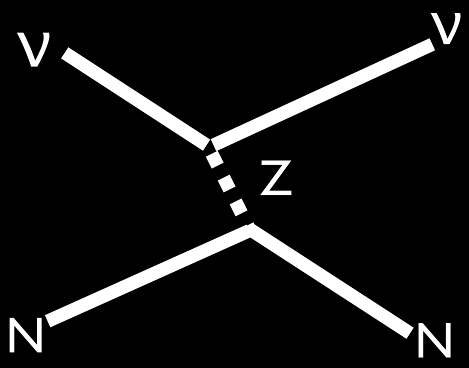
Recent Progress from DMTPC

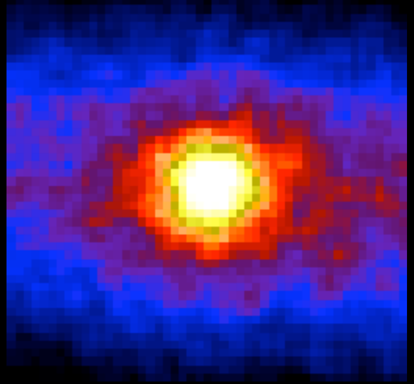
Directional Detection and the Neutrino Bound

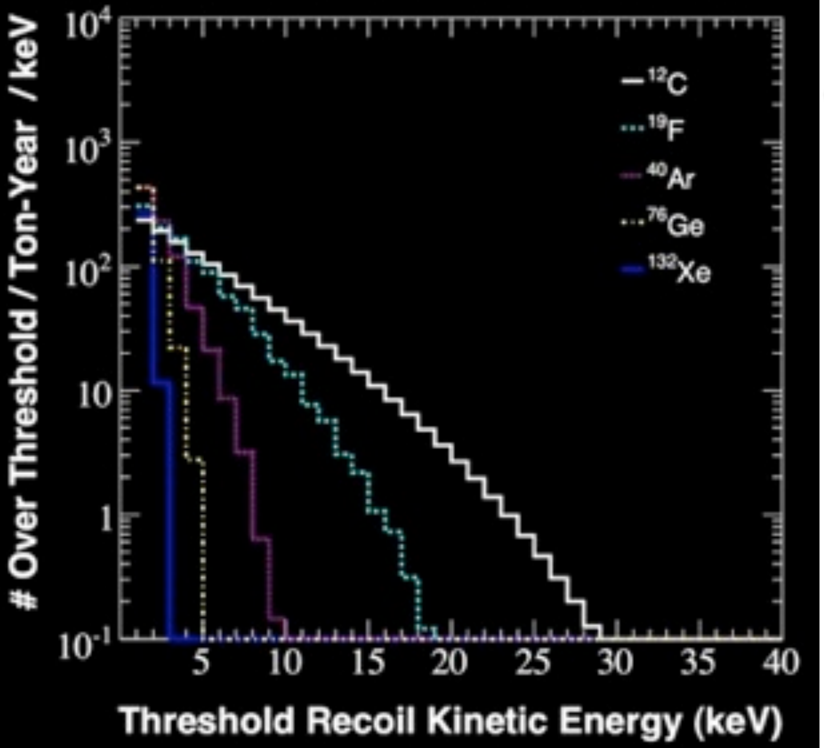
Reminder: The Neutrino Bound

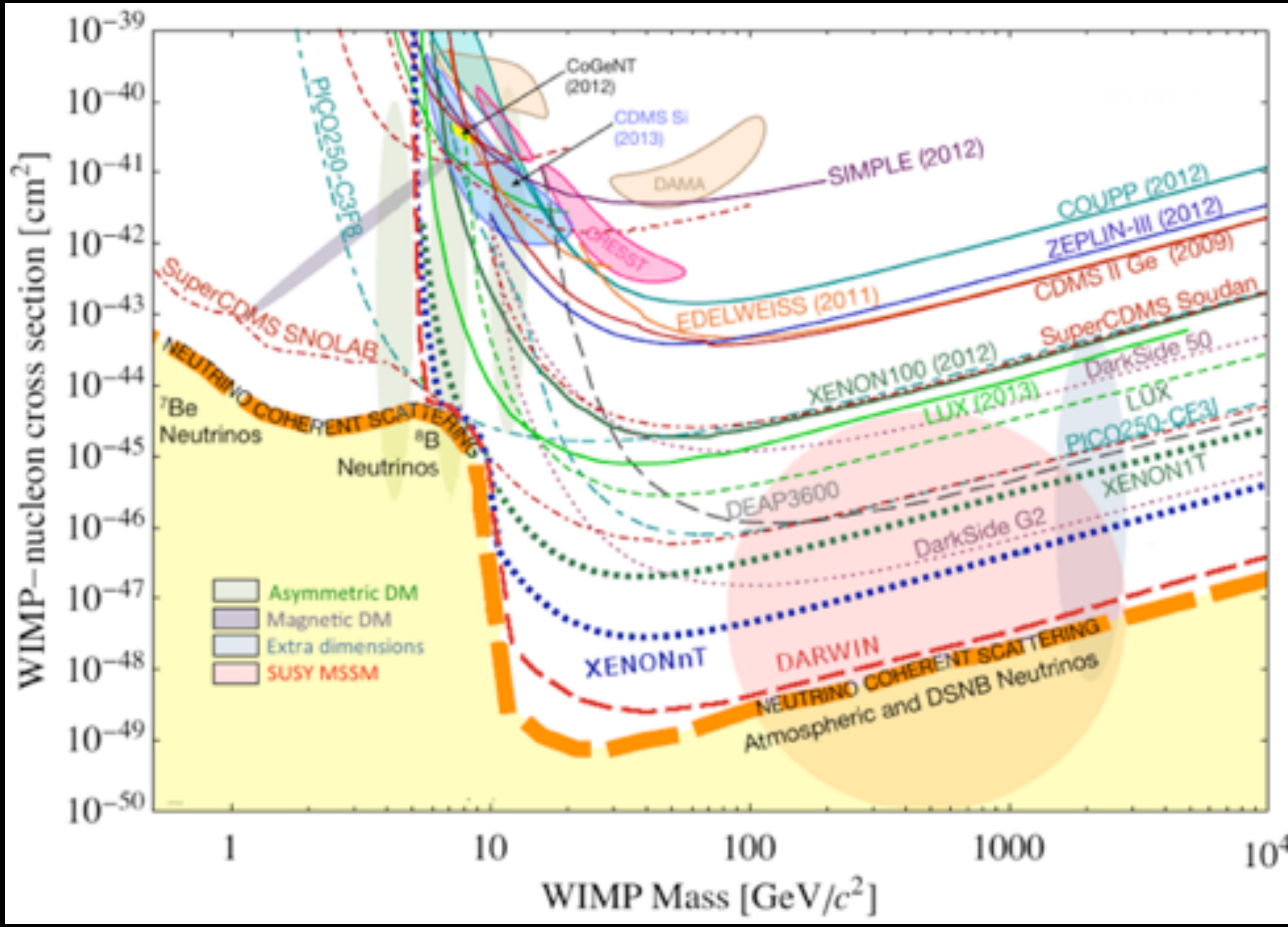
impossible to shield a detector from coherent neutrino scattering!

nuclear recoil final state
1 event/ton-year = 10^{-46}-10^{-48} cm^2 limit
JM, P. Fisher, PRD76:033007 (2007)







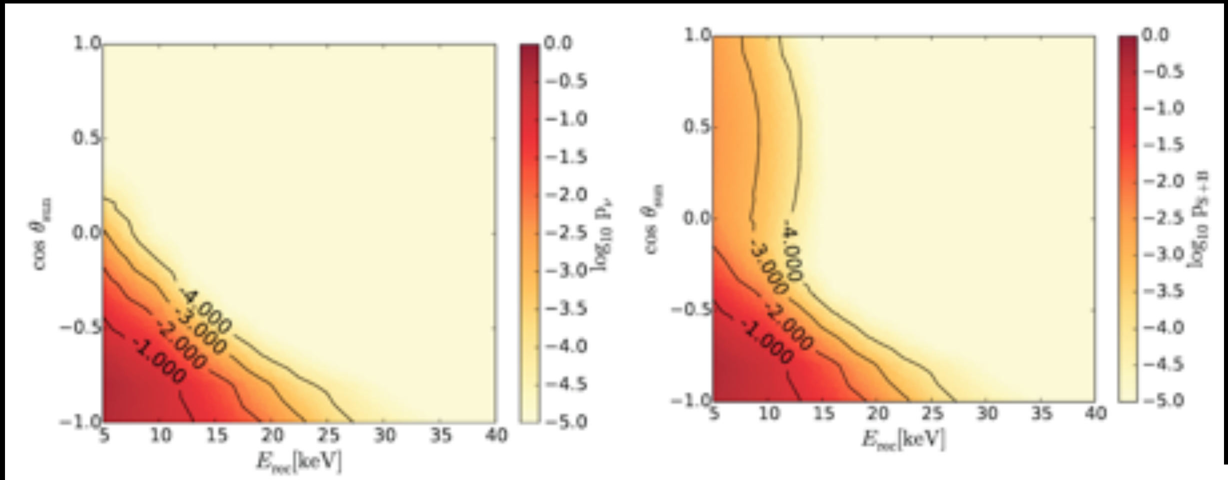


irreducible background, unless you measure the direction!

Beyond the Neutrino Bound

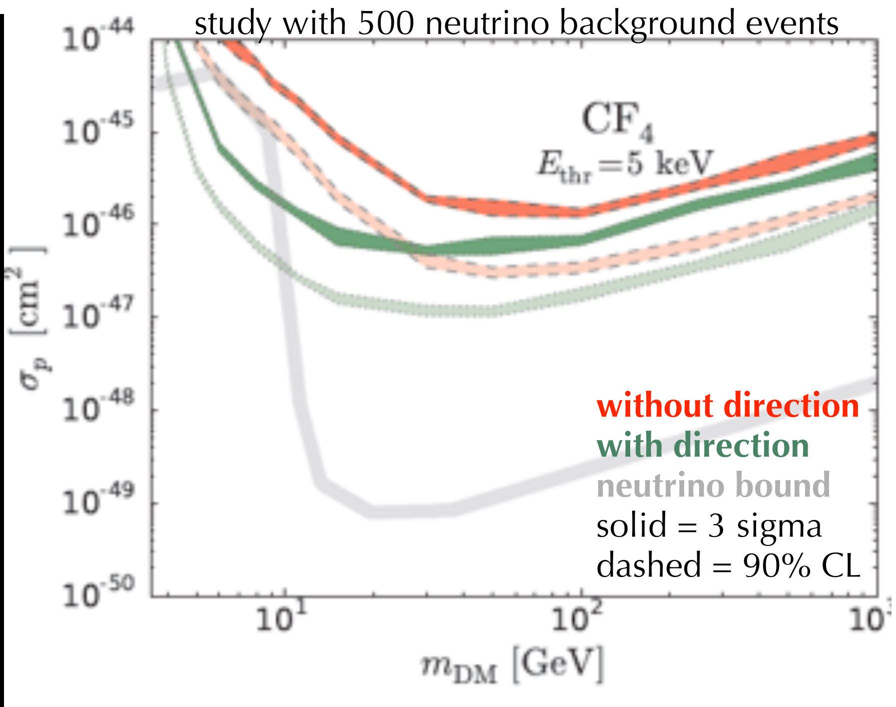
Grothaus, Fairbairn, JM
arXiv:1406.5047

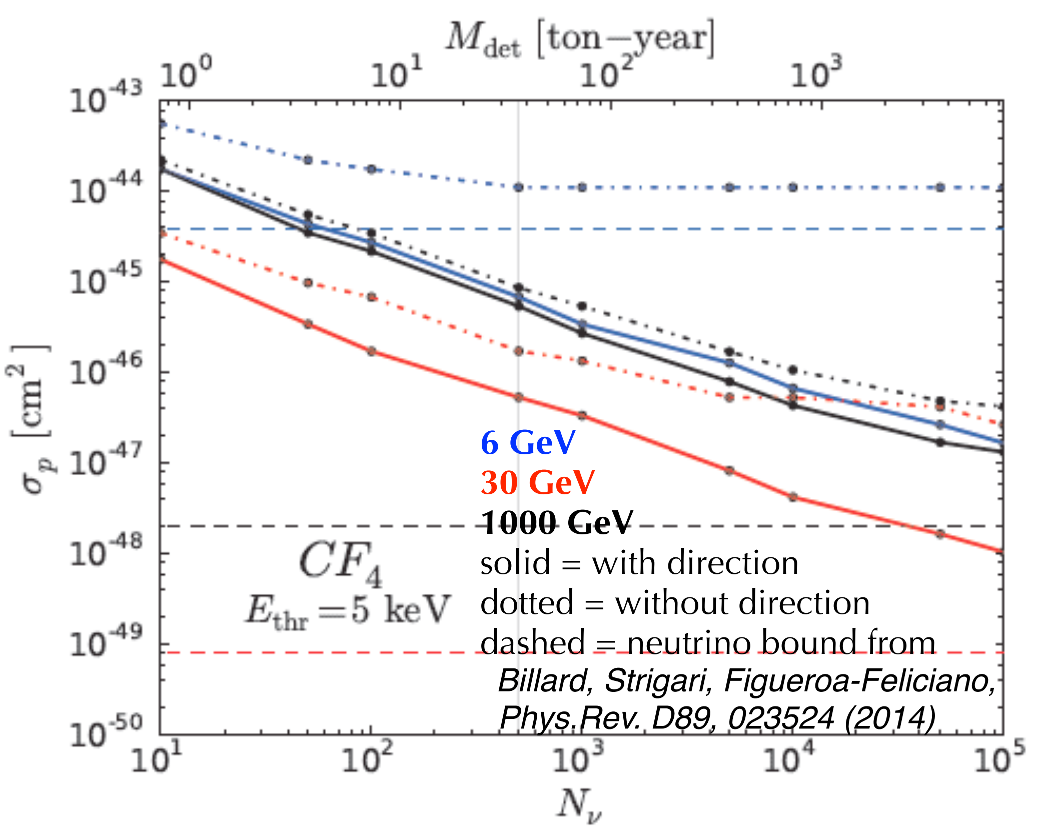
PDFs in (energy, angle, time) of event for coherent solar nu background vs. background+signal show significant differences, including 35° resolution:



statistical test (CLs) shows

- directionality gains 10x in sensitivity with background
- no neutrino bound for directional detectors!


study with 500 neutrino background events



Conclusions and Outlook

Backgrounds make directional detection very attractive. Large low-energy, low-background tracking detectors have potential for *confirmation* of the astrophysical origin of a candidate direct detection dark matter signal.

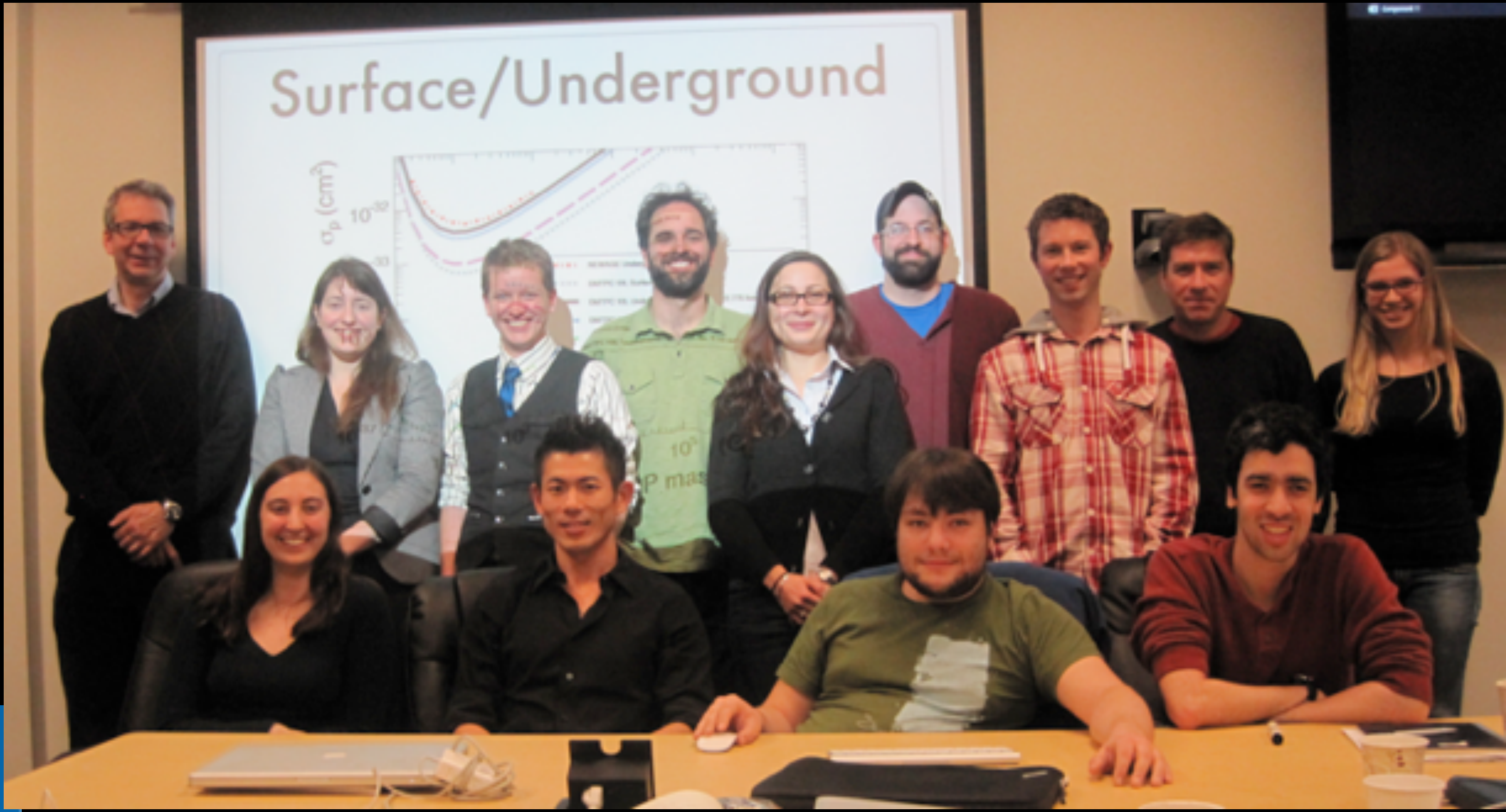
Since last IDM, DMTPC has
- demonstrated $<35^{\circ}$ angular resolution with 25 cm diffusion,
- improved head-tail determination with 2x pixel signal:noise, and new reconstruction developments,
- published background rejection from optical+charge readout,
- demonstrated triple mesh TPC, which halves readout channels,
- design, now construction of 1 m^3 module, unit for large detector.
- (and also lowered energy threshold to 30 keV, and studying internal detector backgrounds an underground laboratory at WIPP)
- *main challenge*: achieve resolution + head-tail, at energy threshold

Directional dark matter telescope:
no neutrino bound!

DMTPC Collaboration

BOSTON
UNIVERSITY

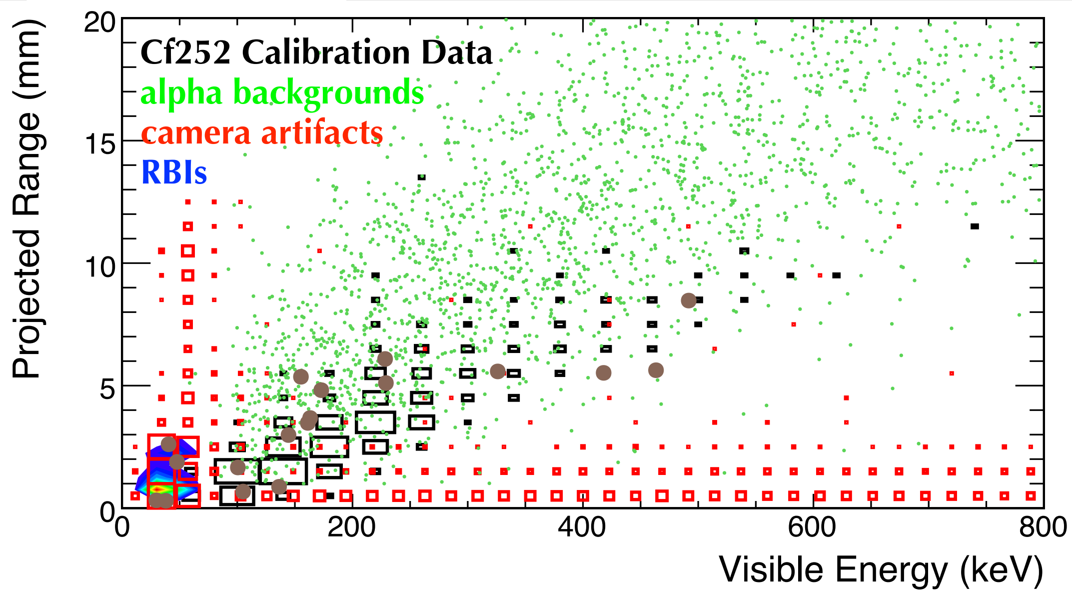
Royal Holloway
University of London



Thank you!

Backup Slides

DMTPC Surface Limit



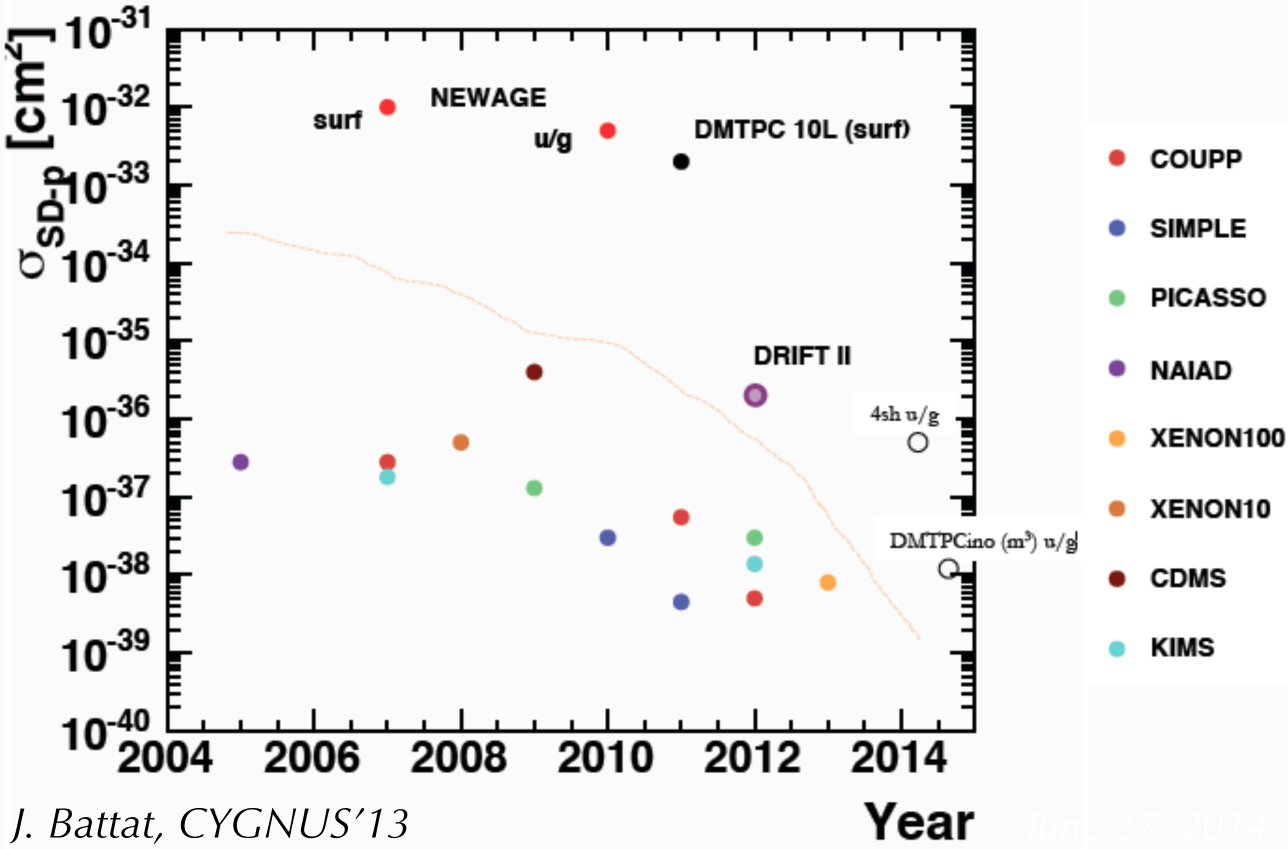
DMTPC limit at surface (2011) with 10L prototype, exposure: 38 gm-day CF_4, 80 keVr Eth

background rejection used range vs. energy from CCD only

S. Ahlen et al., Phys. Lett. B 695 (2011)

substantial improvements in background rejection since with charge readout

projected sensitivity of 1m^3 detector (DMTPCino) approaches competitive sensitivity with current non-directional searches



J. Battat, CYGNUS'13

Directional Detection Future

Eventually: large detector, 10^{-46} cm^2 sensitivity,
how big is it?

MiniBooNE:
$6 \times 6 \times 6$ m^3

detector size for 10^{-44} cm^2 SI sensitivity

DMTPC Observatory
$16 \times 16 \times 16$ m^3

1 ton of CF_4
@50Torr

MINOS:
$15 \times 13 \times 30$ m^3

SNO:
$21 \times 21 \times 34$ m^3

SuperK:
$40 \times 40 \times 40$ m^3