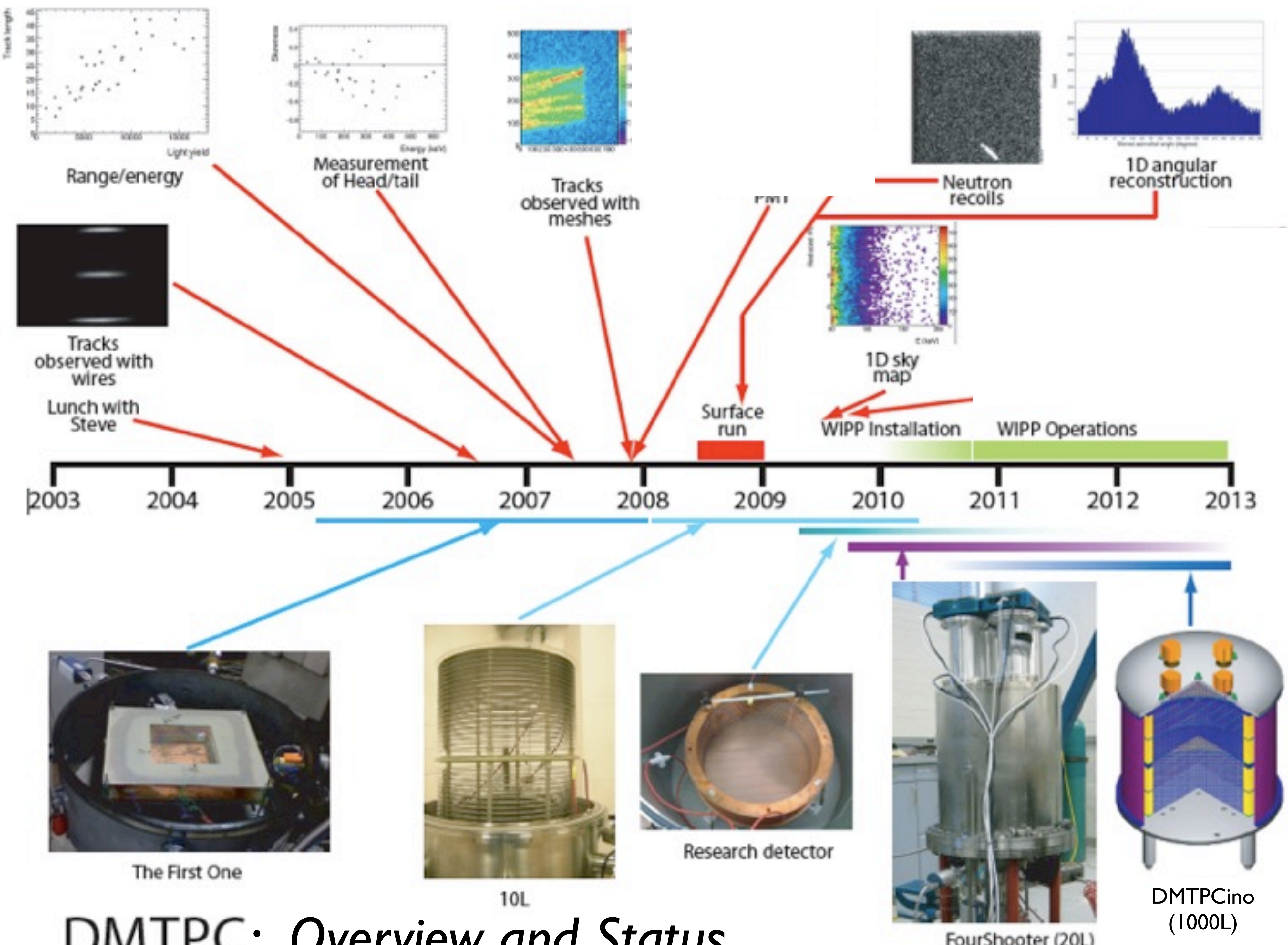
Dark Matter Time Projection Chamber (DMTPC): Overview and Status

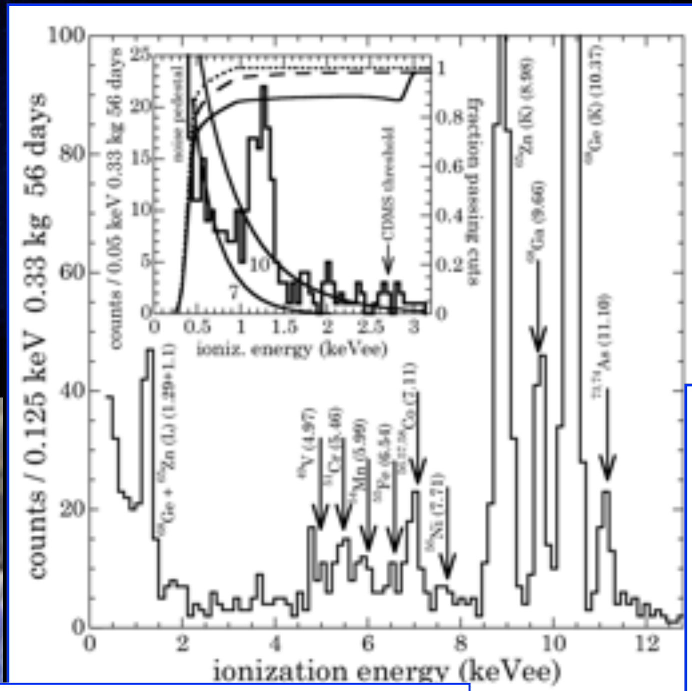
Jocelyn Monroe,
MIT/RHUL

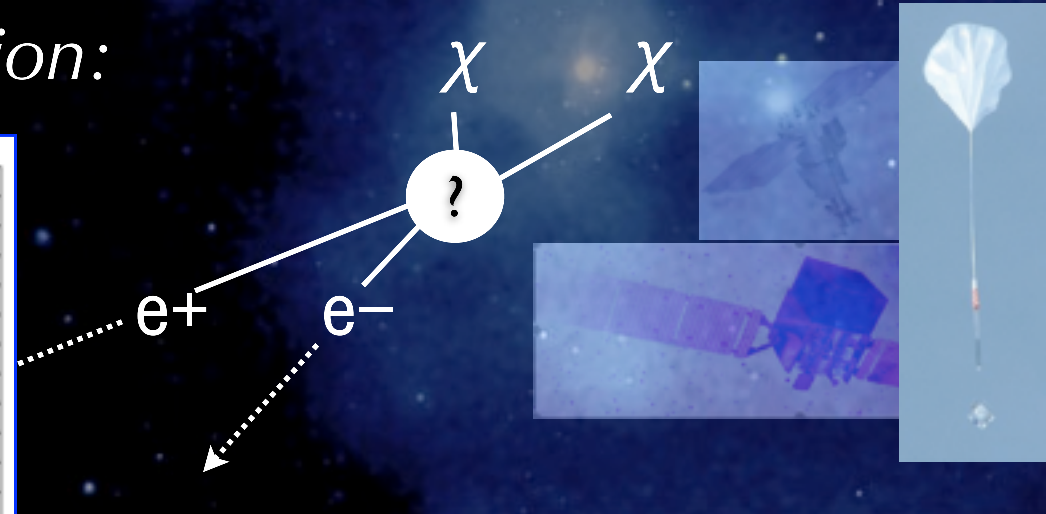
Cygnus Directional Dark Matter Detection Workshop
Aussois, France
June 8, 2011

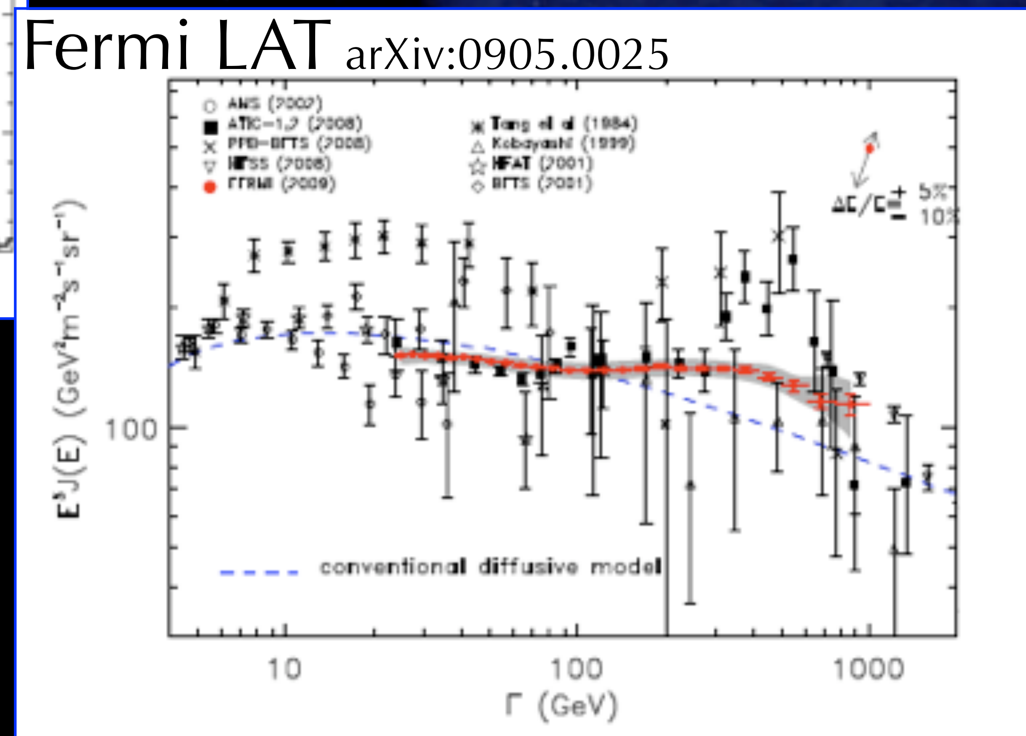


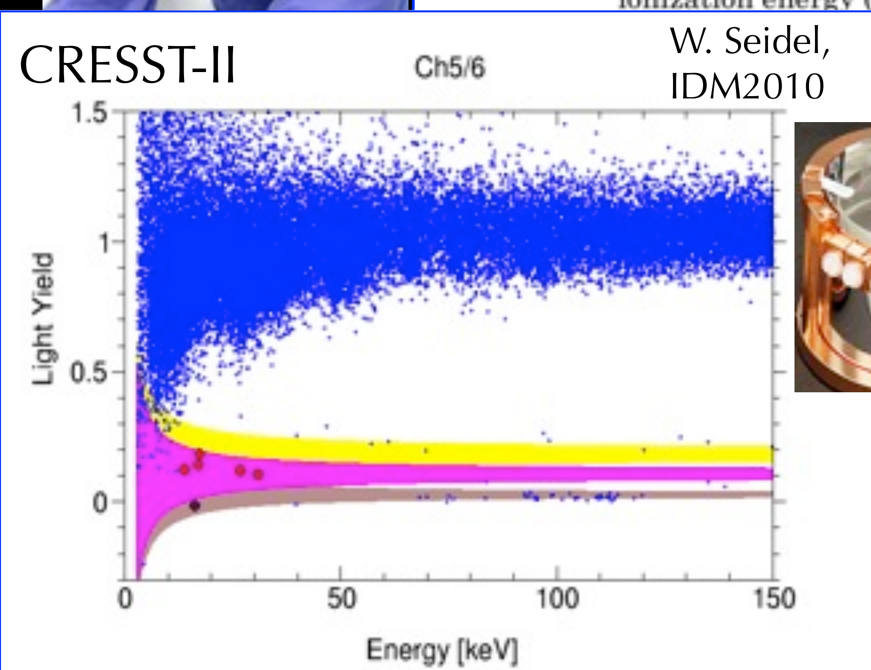
DMTPC: *Overview and Status*

Motivation for Directional Detection:









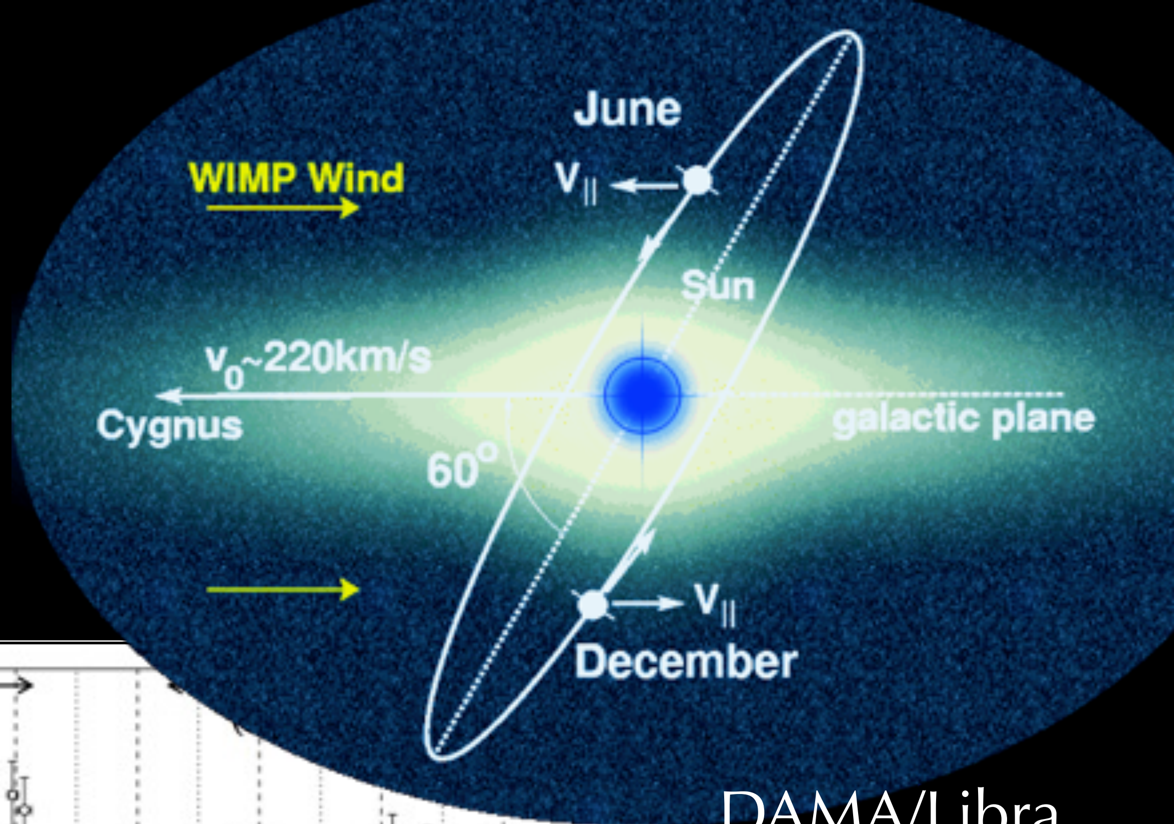
Recent anomalies: local astrophysics?
new backgrounds? dark matter?

a definitive test of the astrophysical origin of a candidate dark matter signal.

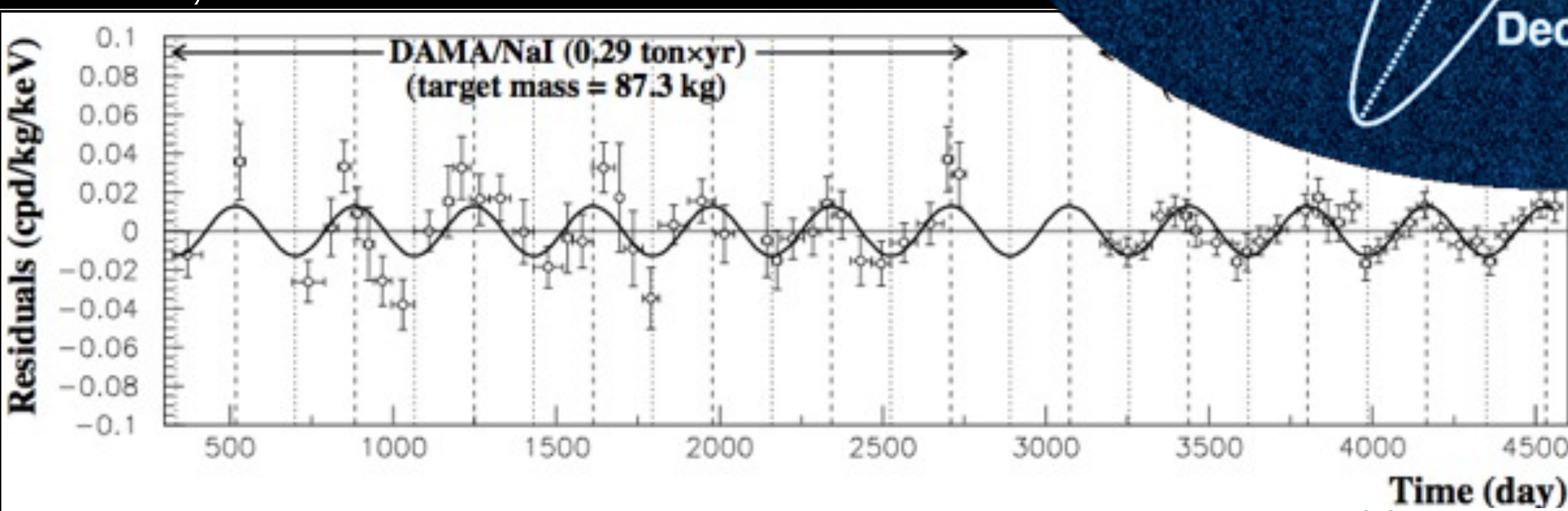
Annual Modulation

June-December event rate asymmetry ~2-10%

Drukier, Freese, Spergel, Phys. Rev. D33:3495 (1986)



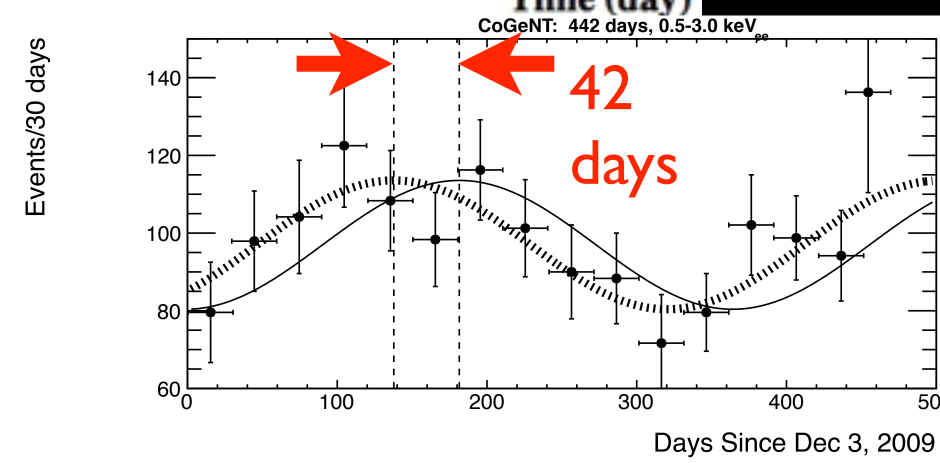
Eur. Phys. J. C56:333-355 (2008)



DAMA/Libra positive result, $>8\sigma$, *inconsistent with many expts*

CoGeNT modulation result, 2.8σ, *consistent with DAMA/Libra*

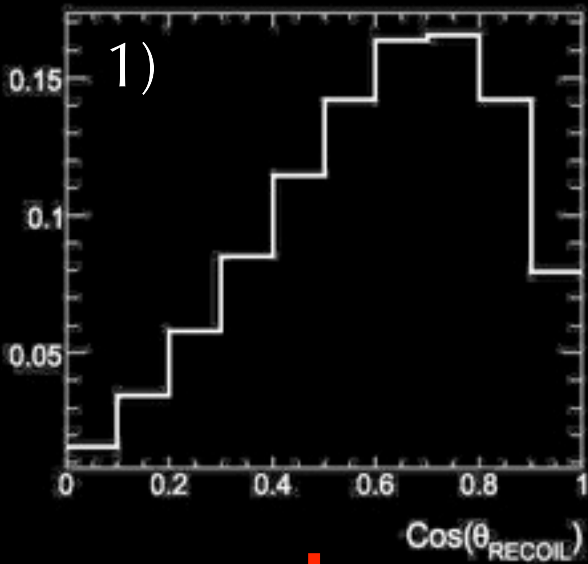
J. Collar, STSI (2011), arXiv:1106.0650v1



CoGeNT (dashed line)

DAMA (solid line)

Signals in Directional Detectors



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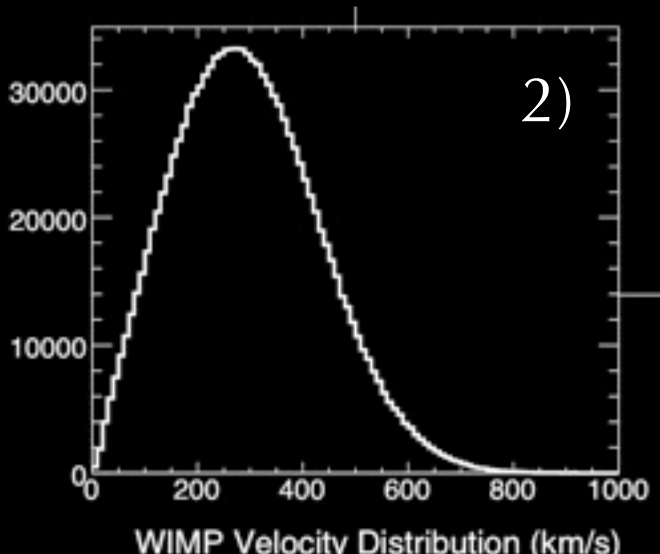
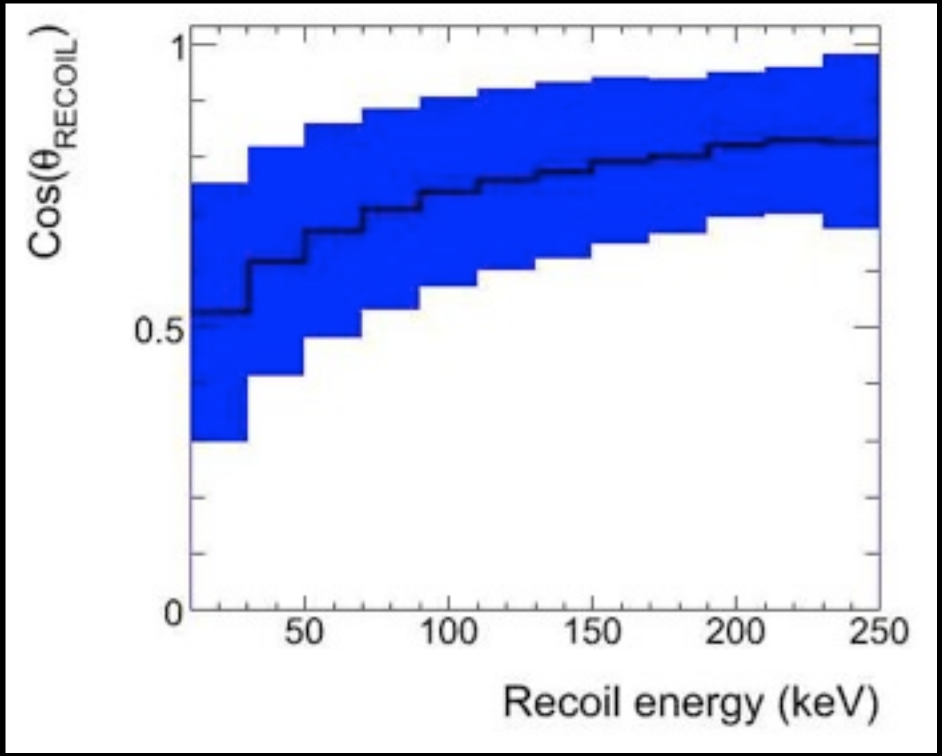


distribution of signal events determined by:

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

=



need ~50 keV threshold for directional detectors

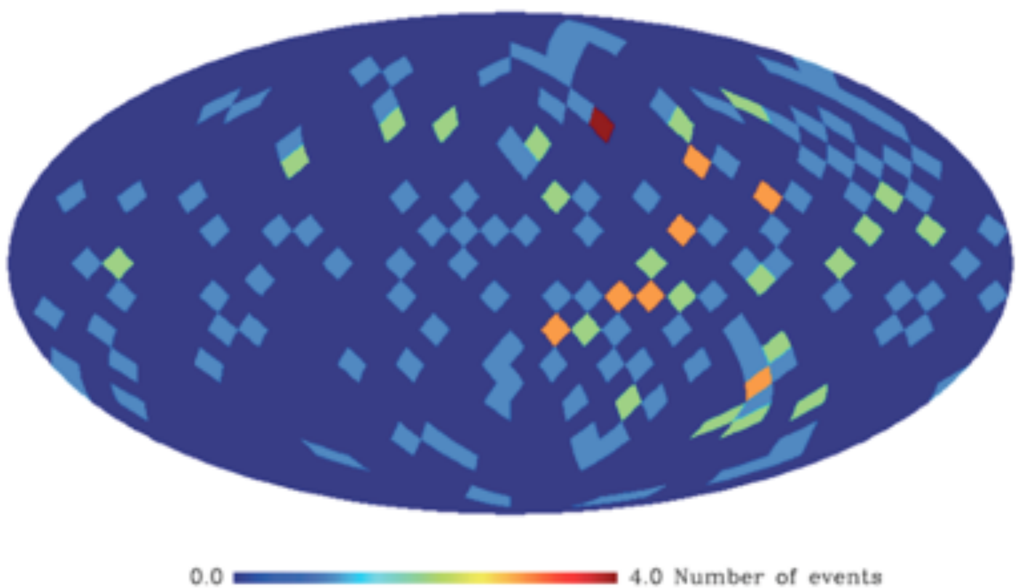
Optimization

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



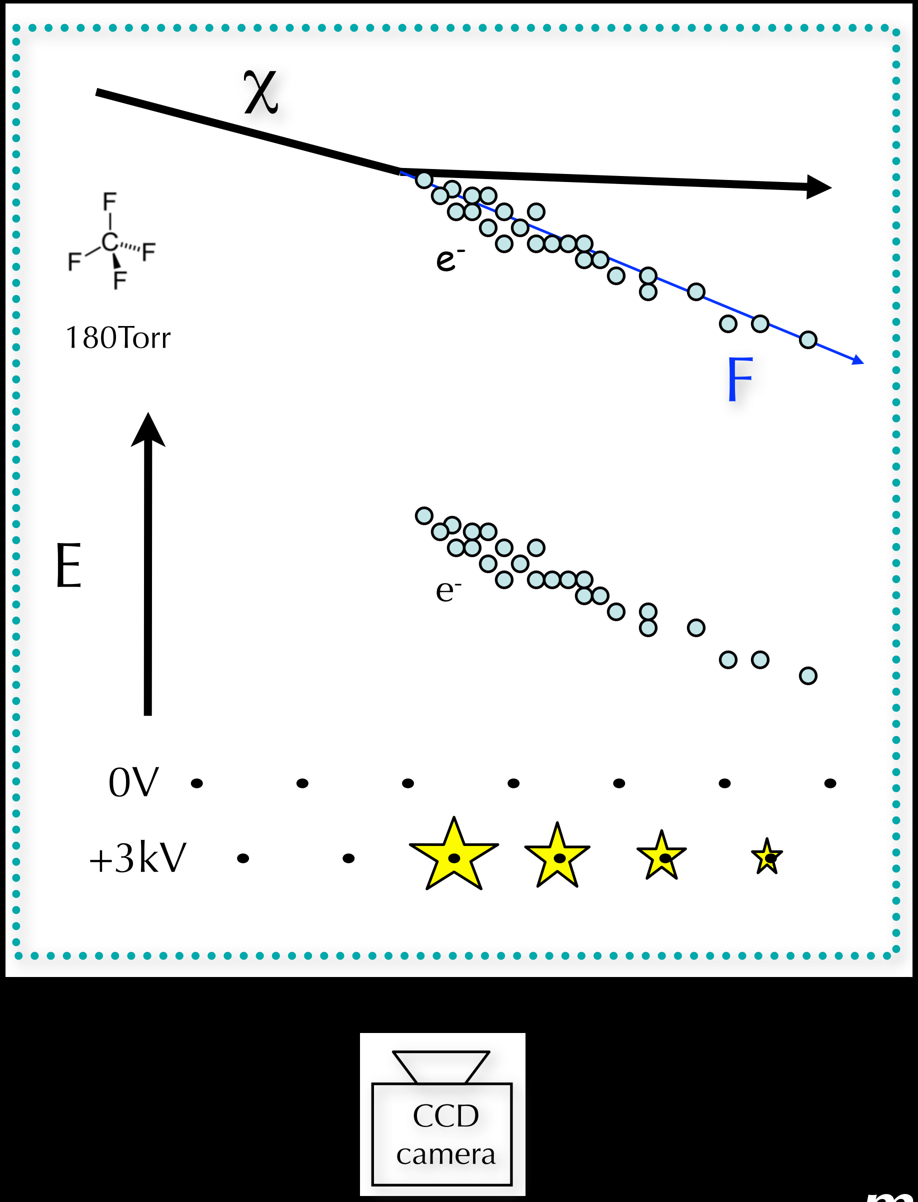
Billard et al. 2010

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

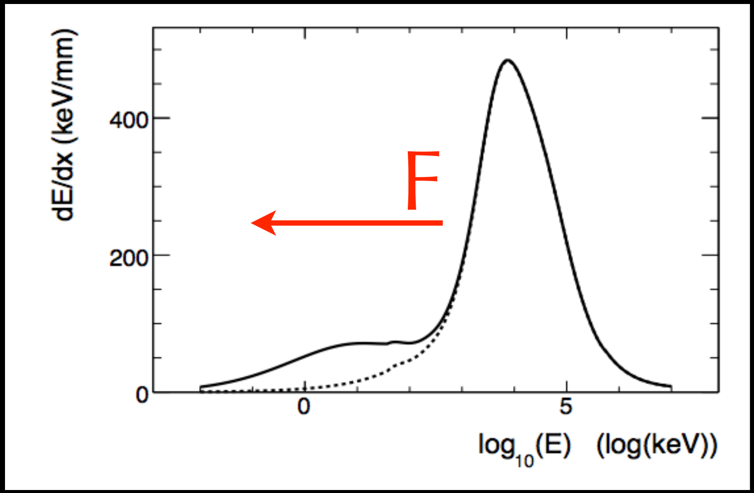
J. Billard, F. Mayet, D. Santos, arXiv:1009.5568

do not need "zero background" for directional detectors

DMTPC Principle



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



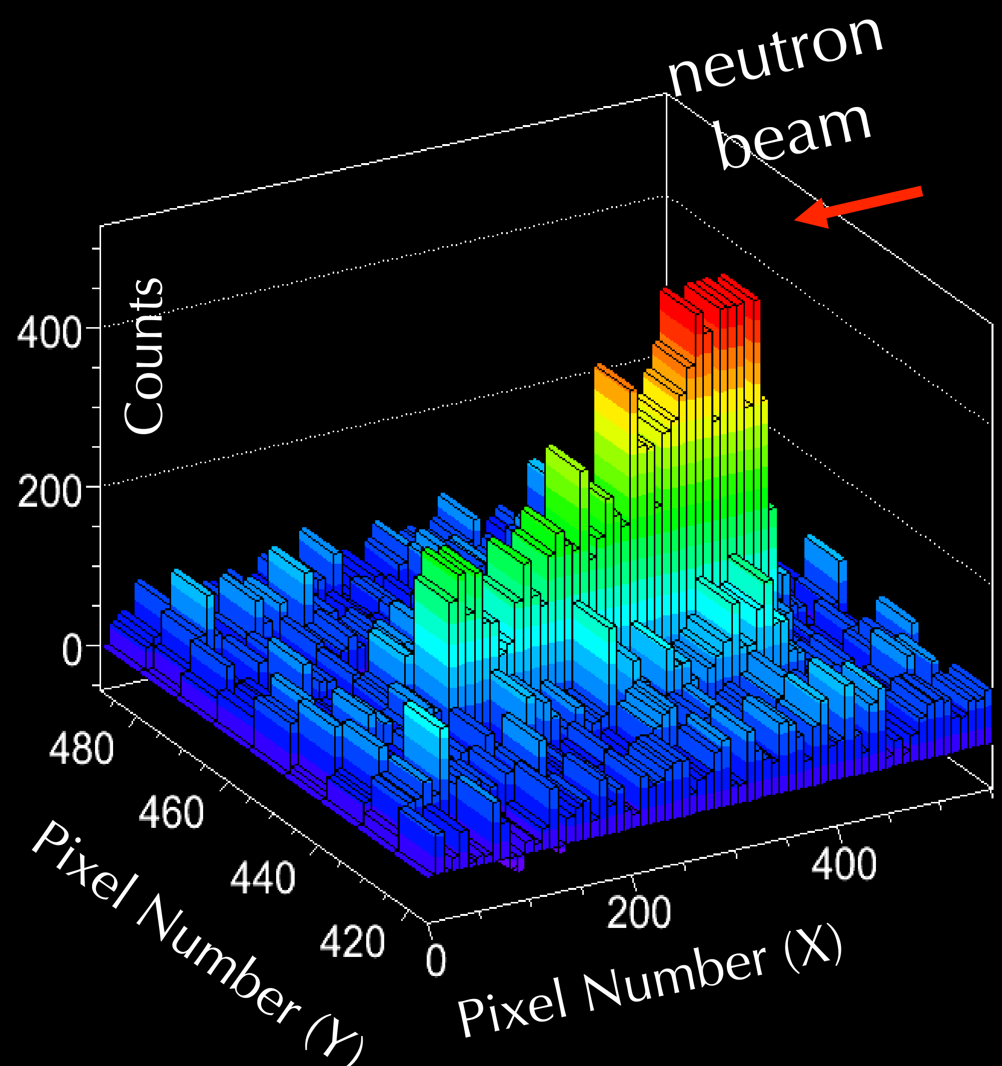
2. drifting electrons preserve dE/dx profile if diffusion is small

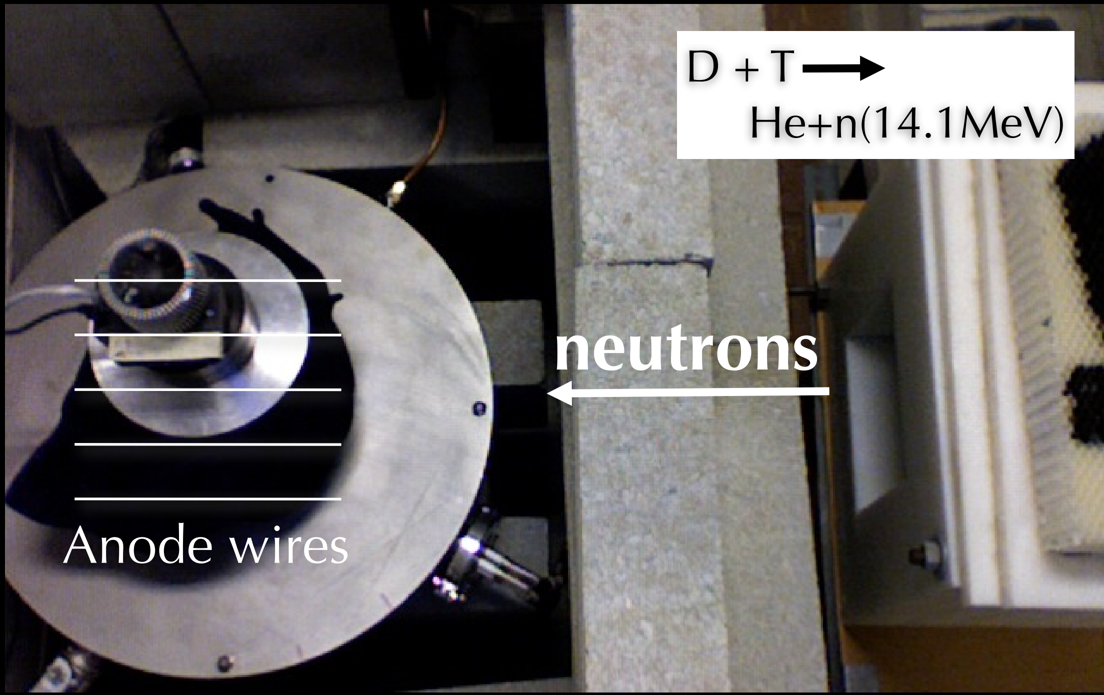
3. avalanche multiplication in amplification region produces gain, scintillation photons

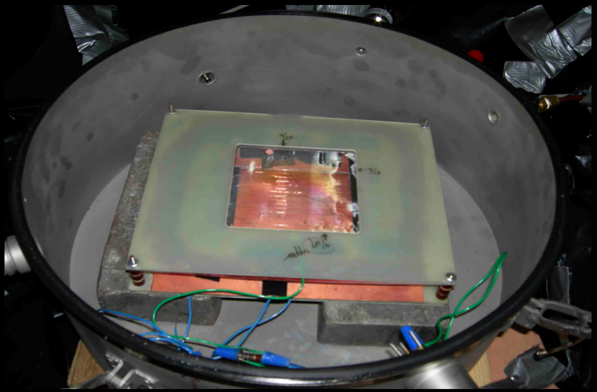
minimum wetted materials

DMTPC Proof-of-Principle

Neutron-fluorine elastic scattering mimics dark matter-induced recoils



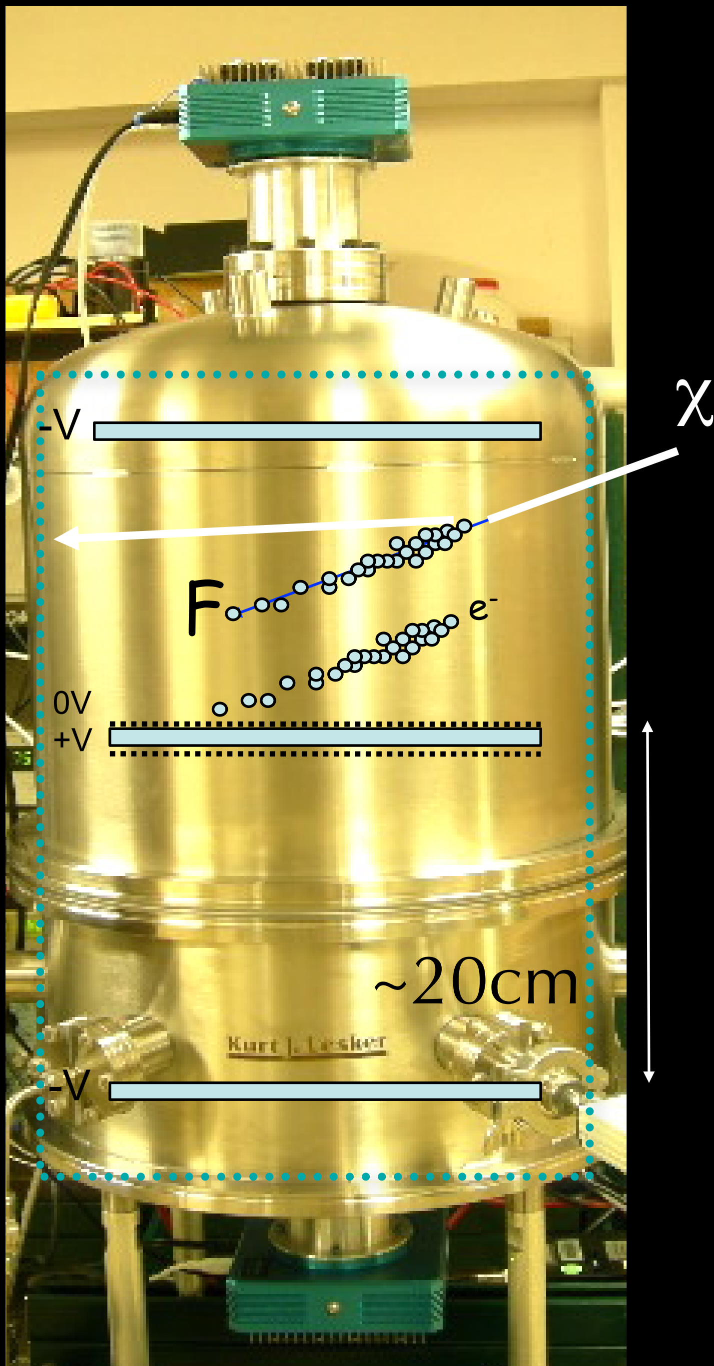




We can reconstruct the direction of ~100 keV fluorine recoil tracks!

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

DMTPC Now



<u>Brandeis University</u>
A. Dushkin, L. Kirsch, *H. Ouyang,* G. Sciolla, H. Wellenstein*

<u>Bryn Mawr</u>
J. B. R. Battat*

<u>Boston University</u>
S. Ahlen*, ***M. Chernikoff,*** A. Inglis, H. Tomita

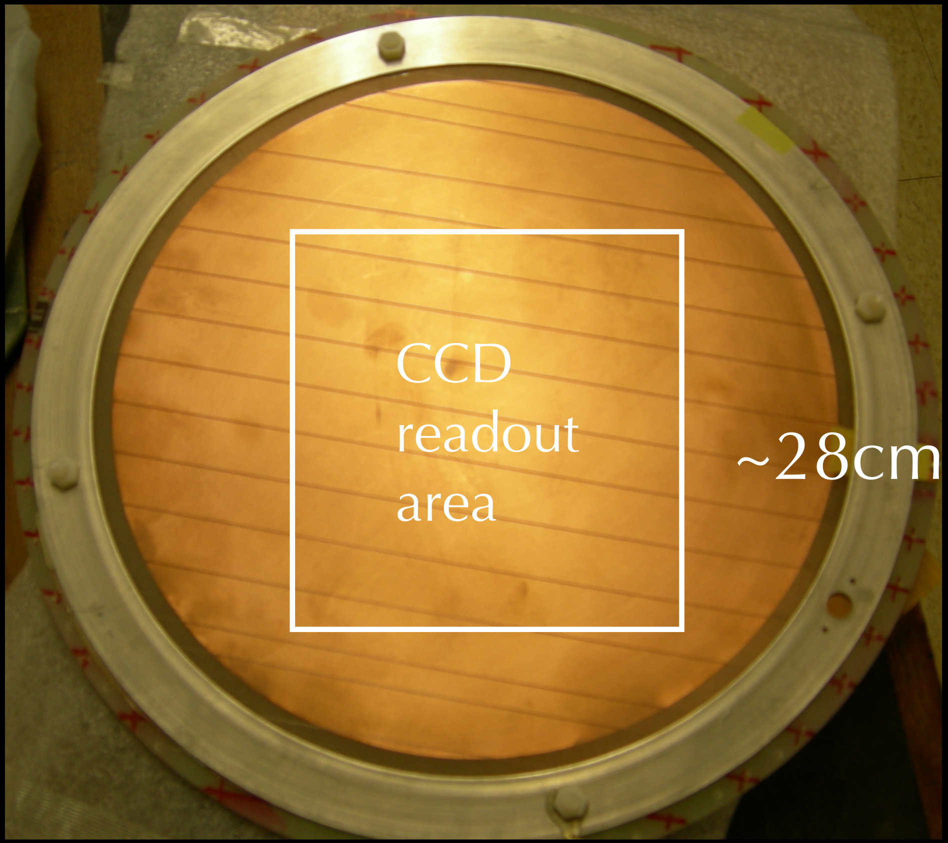
<u>MIT</u>
T. Caldwell, ***C. Deaconu***, D. Dujmic, *W. Fedus*, P. Fisher*, ***S. Henderson, A. Kaboth***, G. Kohse, R. Lanza, *A. Lee,* ***J. Lopez***, *E. Nardoni, T. Sahin*, R. Vanderspek, *I. Wolfe*, R. Yamamoto, *H. Yegoryan*

<u>Royal Holloway University of London</u>
J. Monroe**

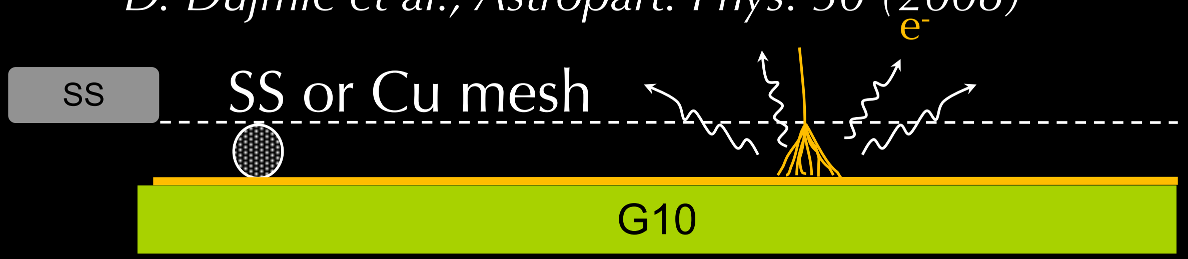
*) PI, **) spokesperson, *student,* ***PhD student***

Amplification Plane

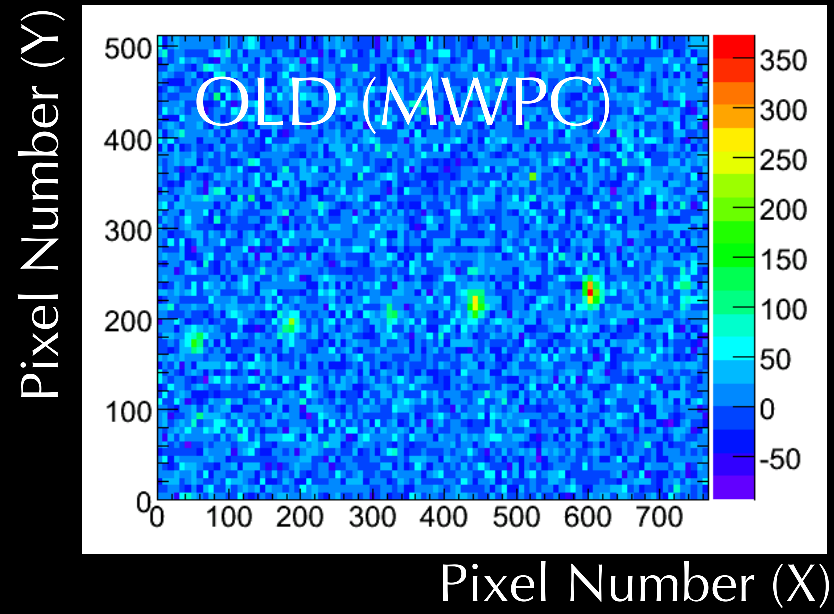
Copper Mesh, 256 um pitch

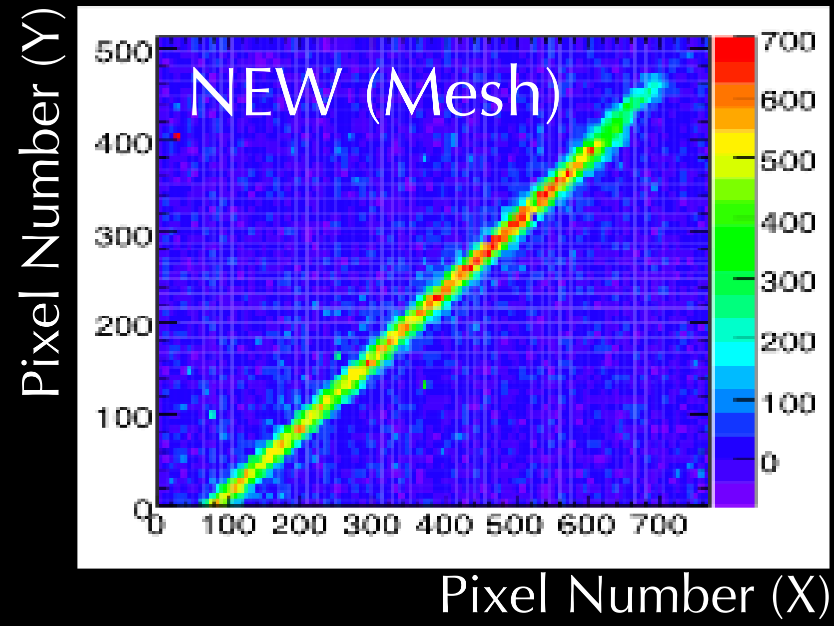


D. Dujmic et al., Astropart. Phys. 30 (2008)



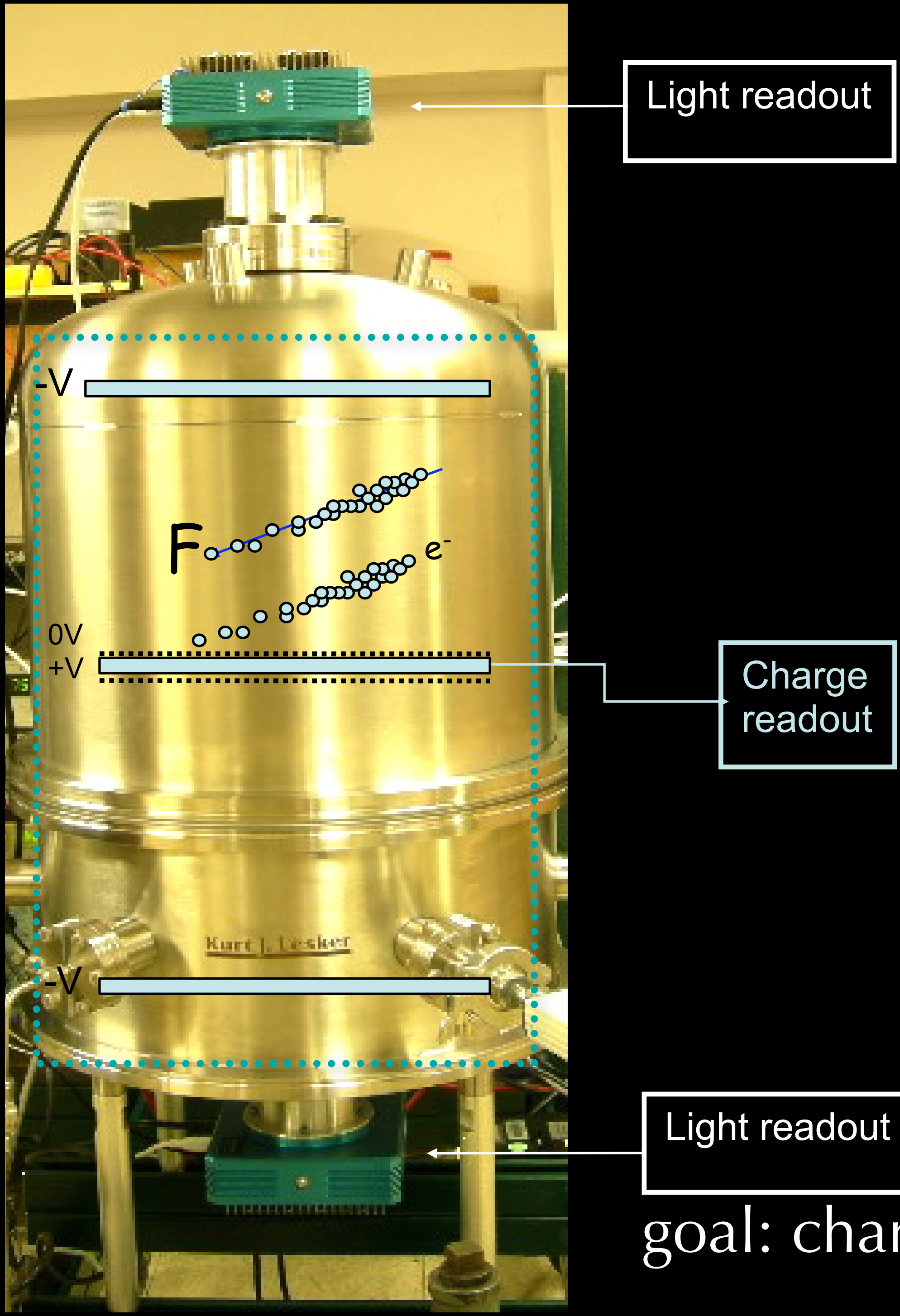
Resistive separators, dia=0.5mm, every 2.5cm

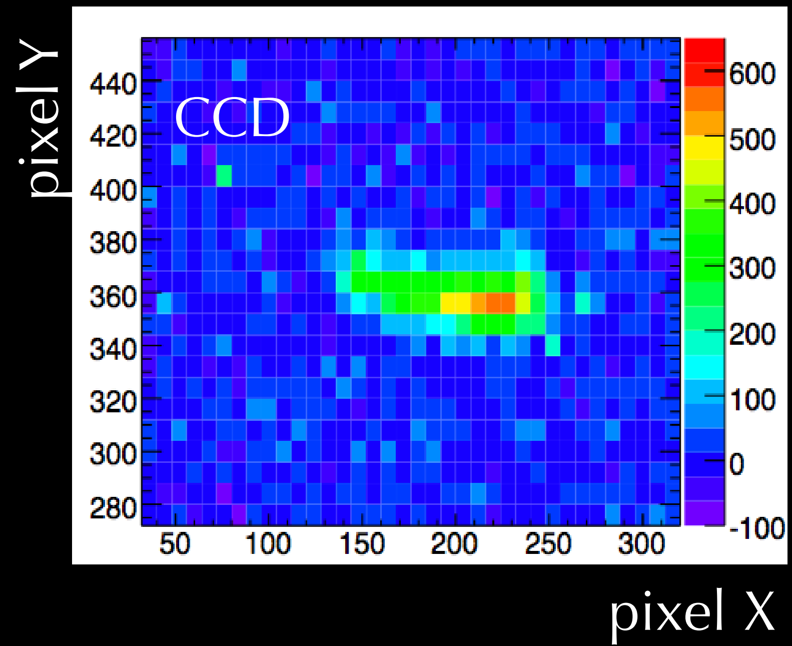


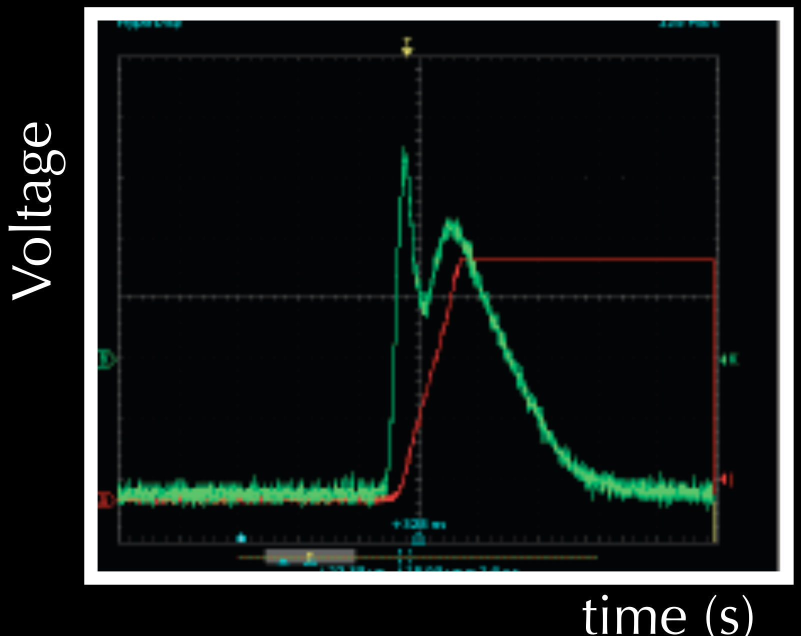


20x smaller pitch,
13x higher gain, 1->2D

TPC Readout

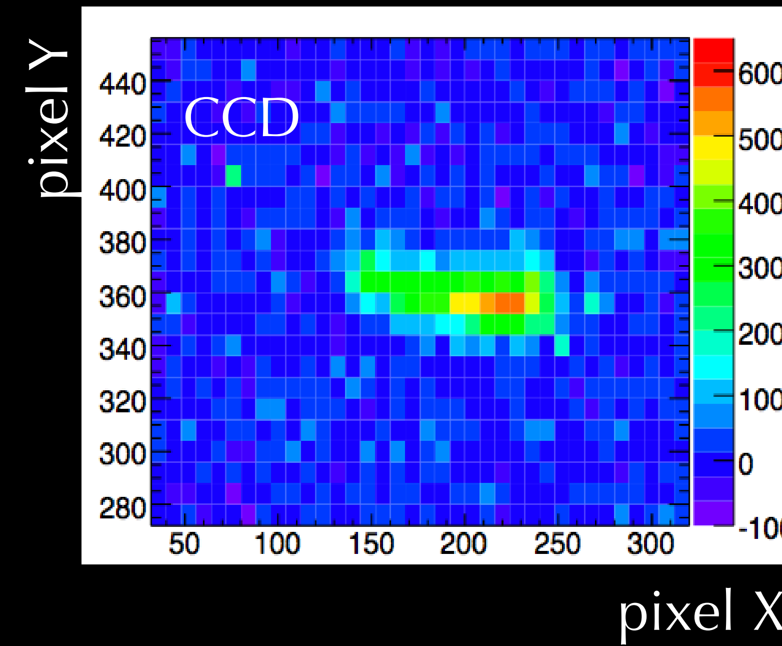


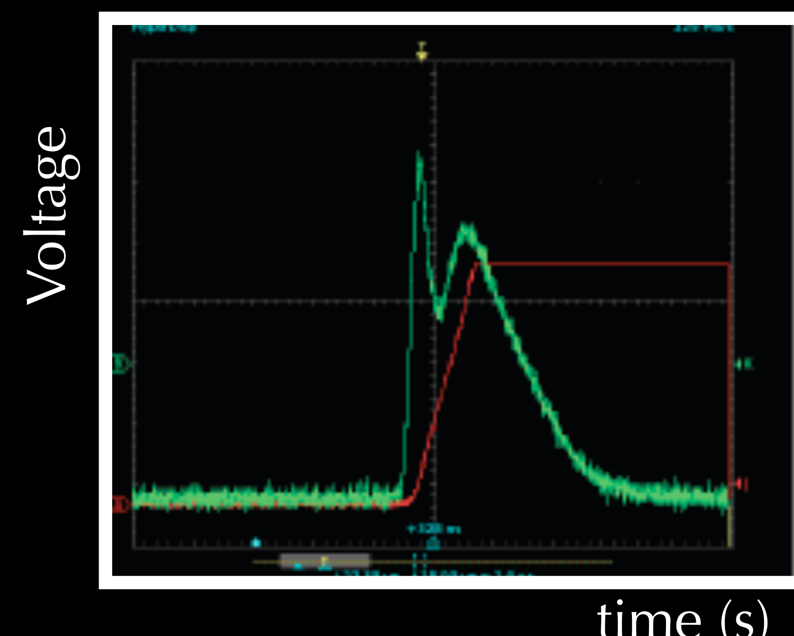




goal: charge and light= 2->3D *(J. Battat)*

TPC Readout





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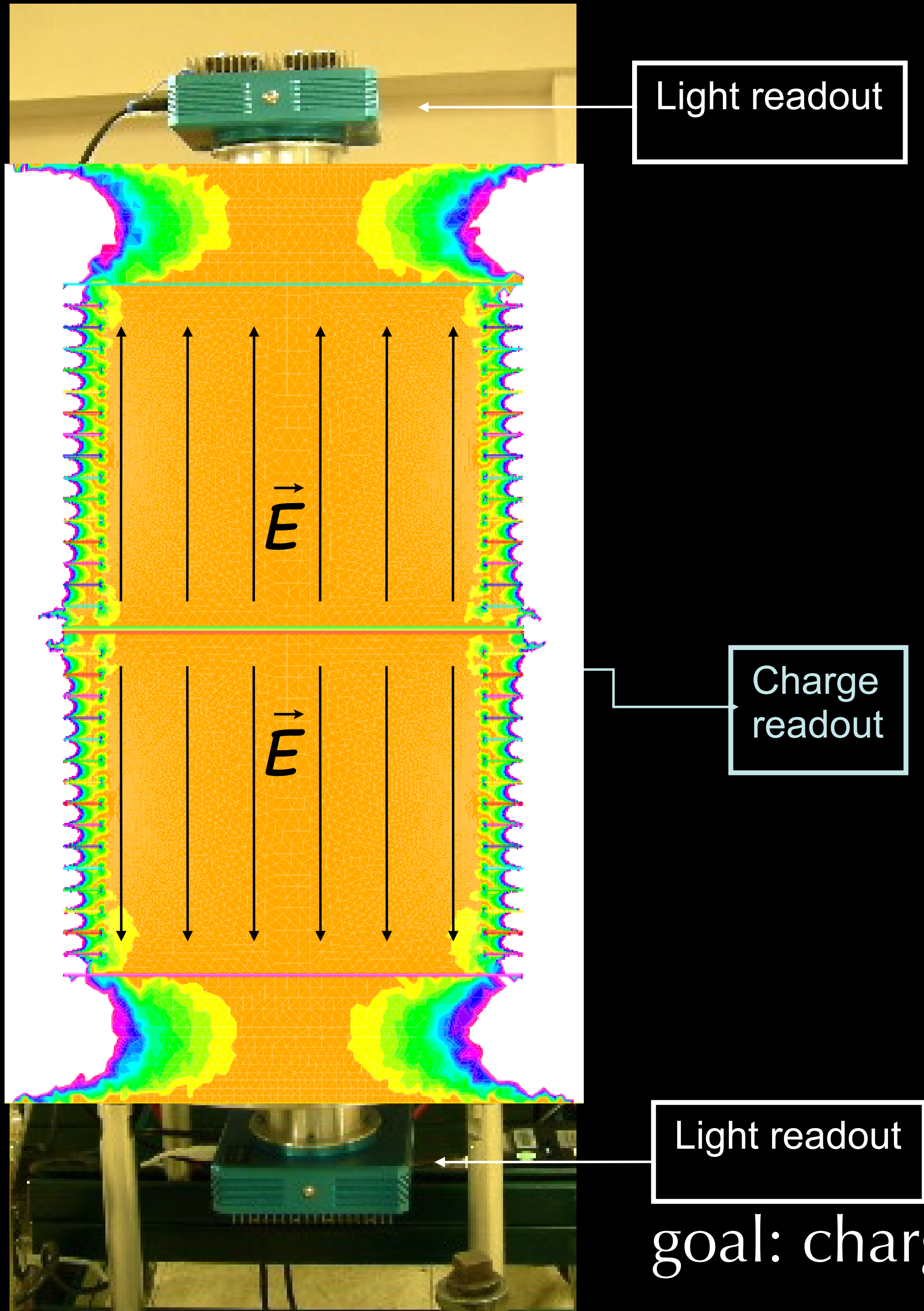
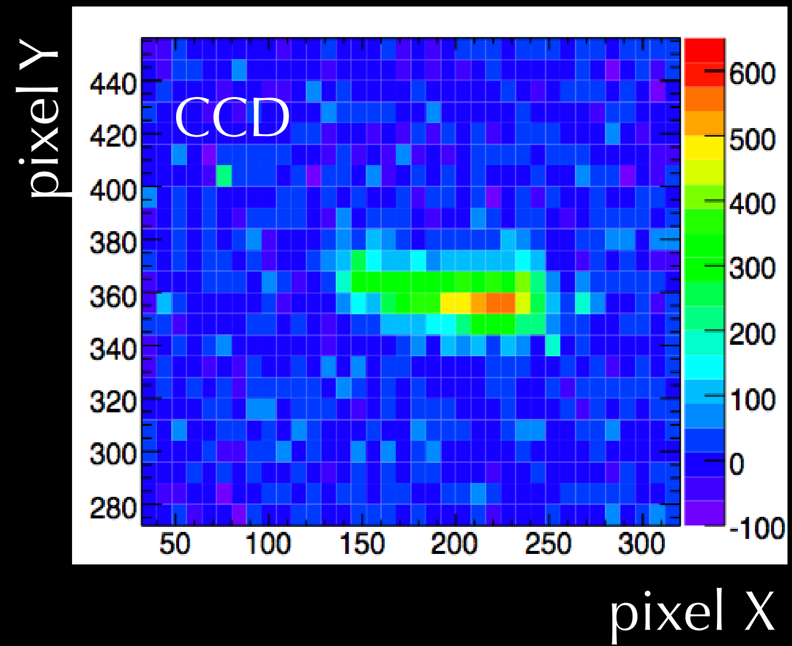
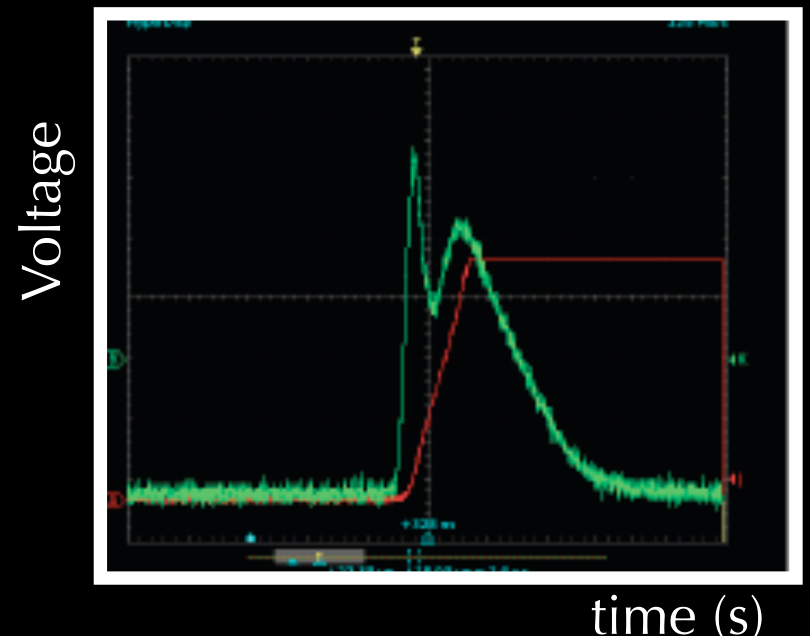
TPC Readout







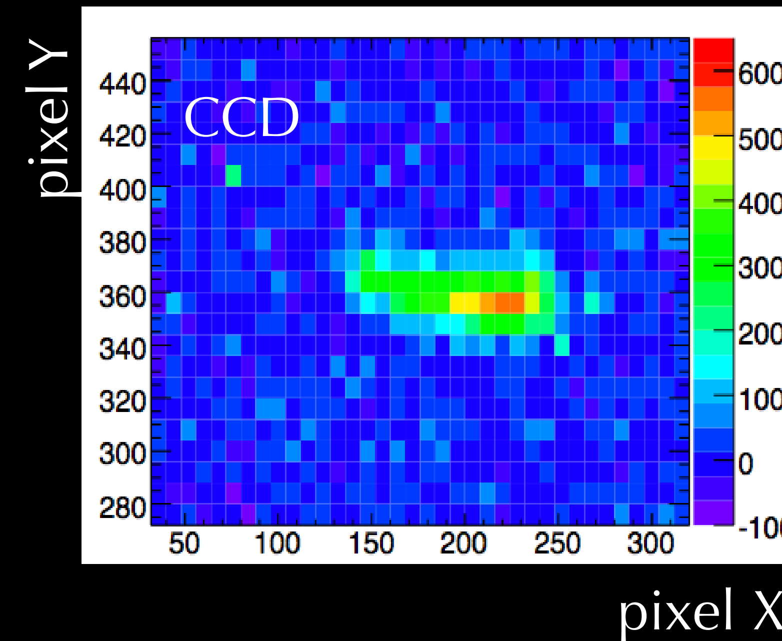
goal: charge and light= 2->3D *(J. Battat)*

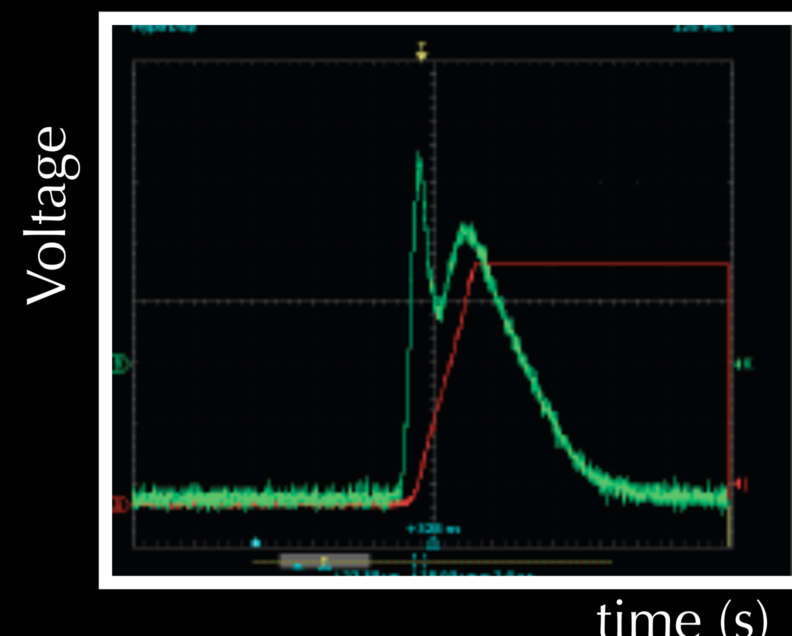
TPC Readout

Light readout

Charge readout

Light readout

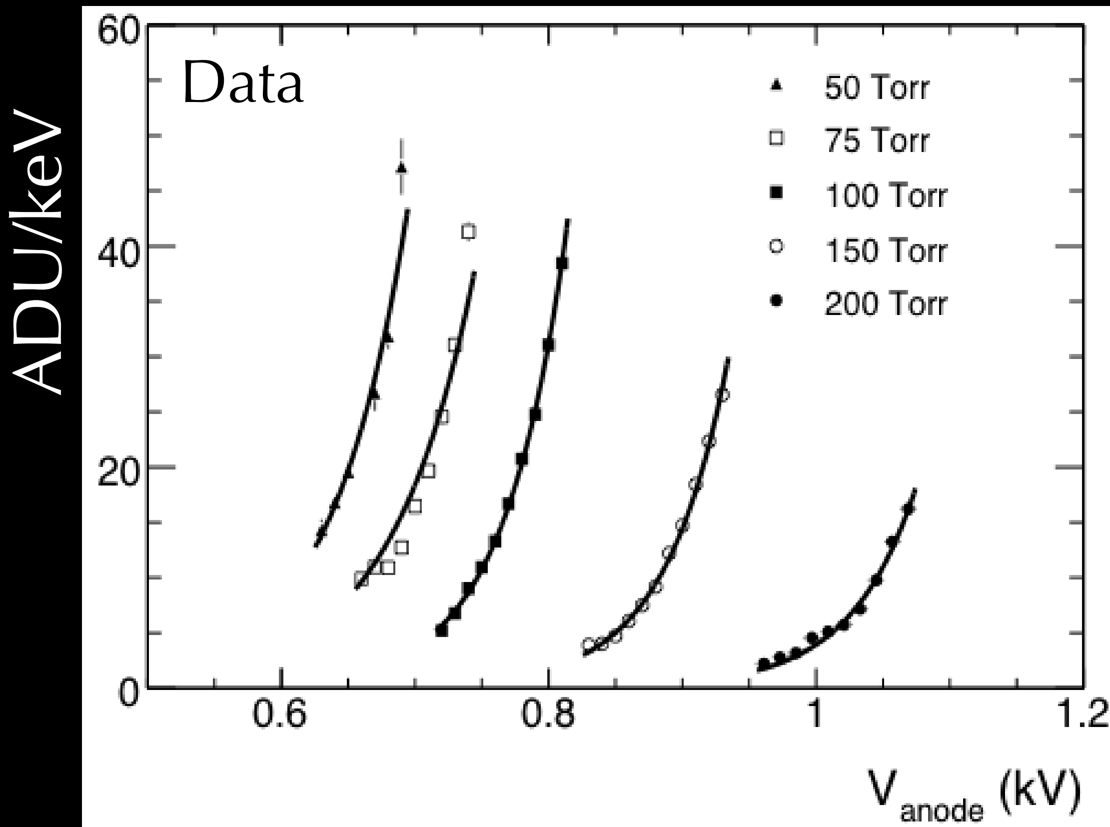


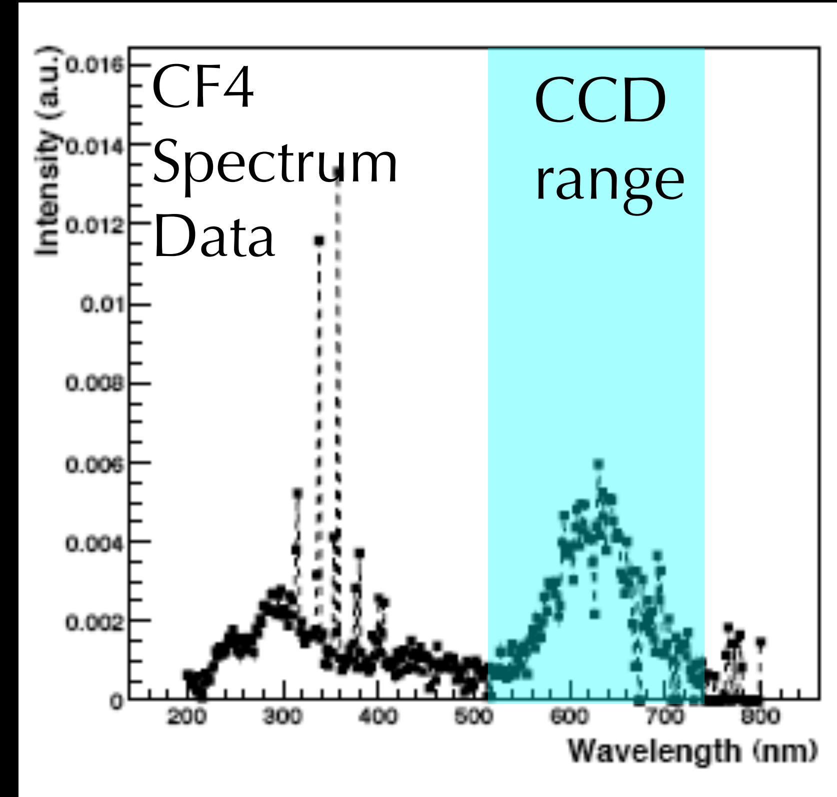


goal: charge and light= 2->3D *(J. Battat)*

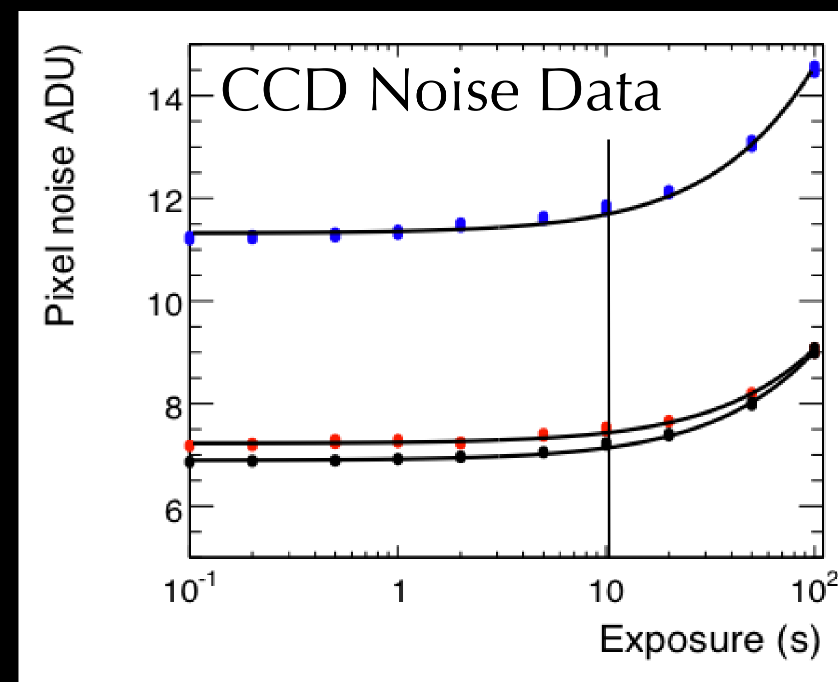
CCD Readout

Total light output:





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



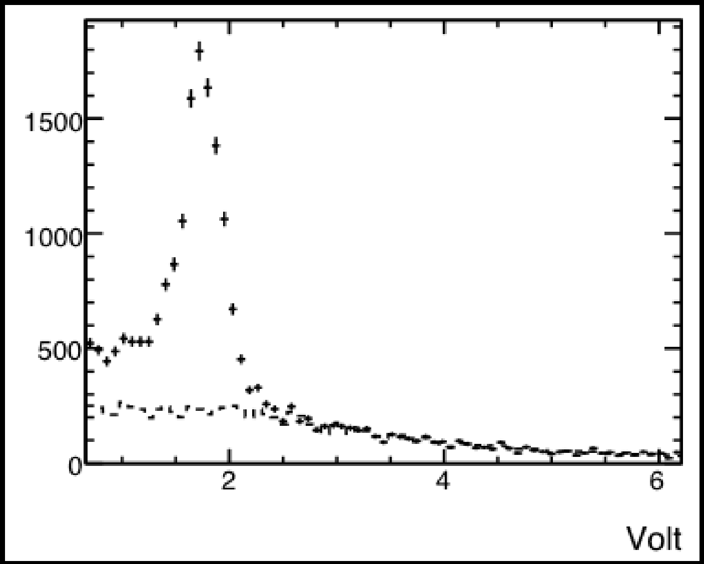
CF4 scintillation: γ/e^{-} = *0.38 +/- 0.04*

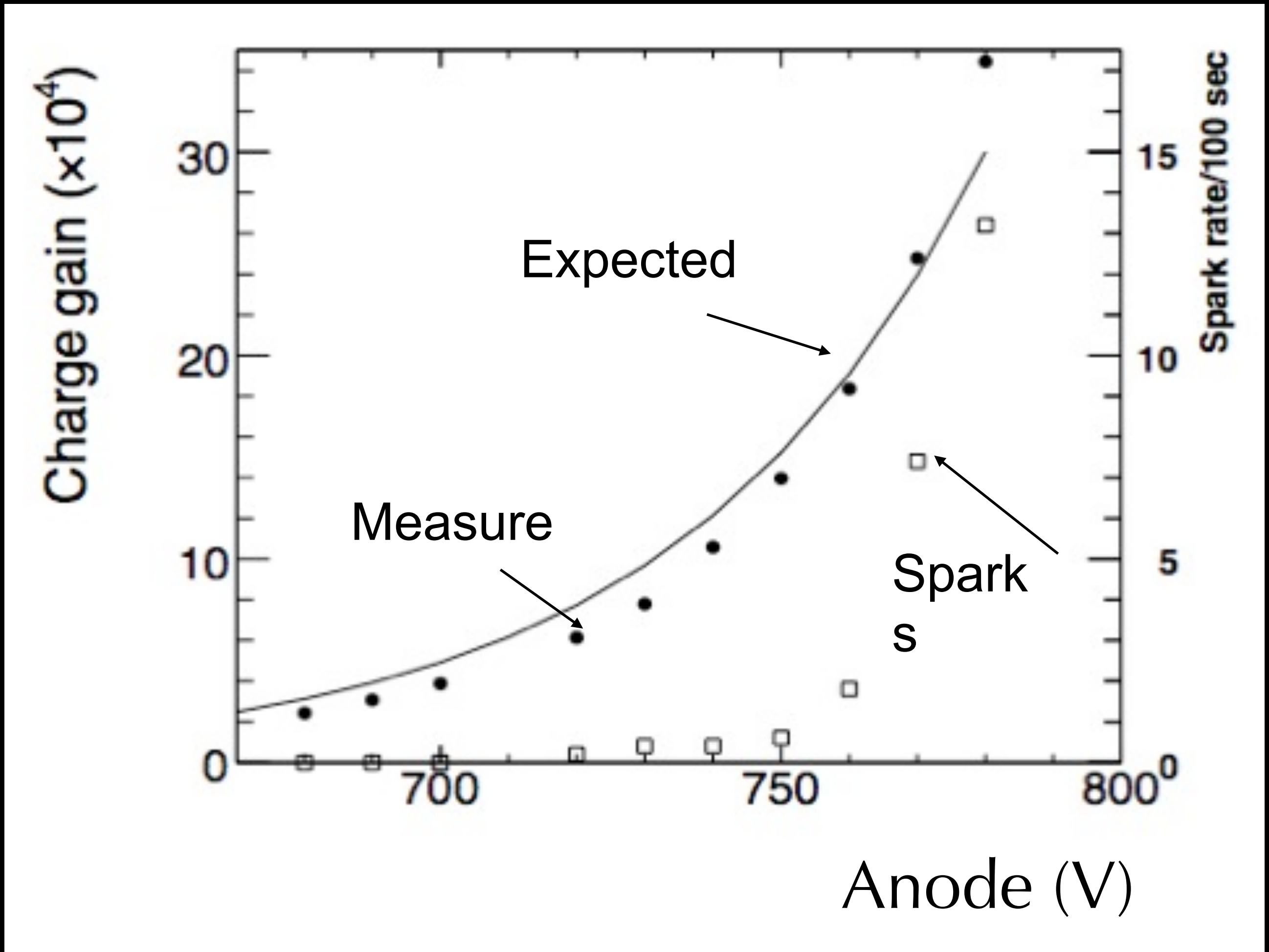
A. Kaboth, et al., NIM A 592:63-72 (2008)

(D. Dujmic, I. Wolfe)

Charge Readout

Calibrate anode charge readout with Fe55 source





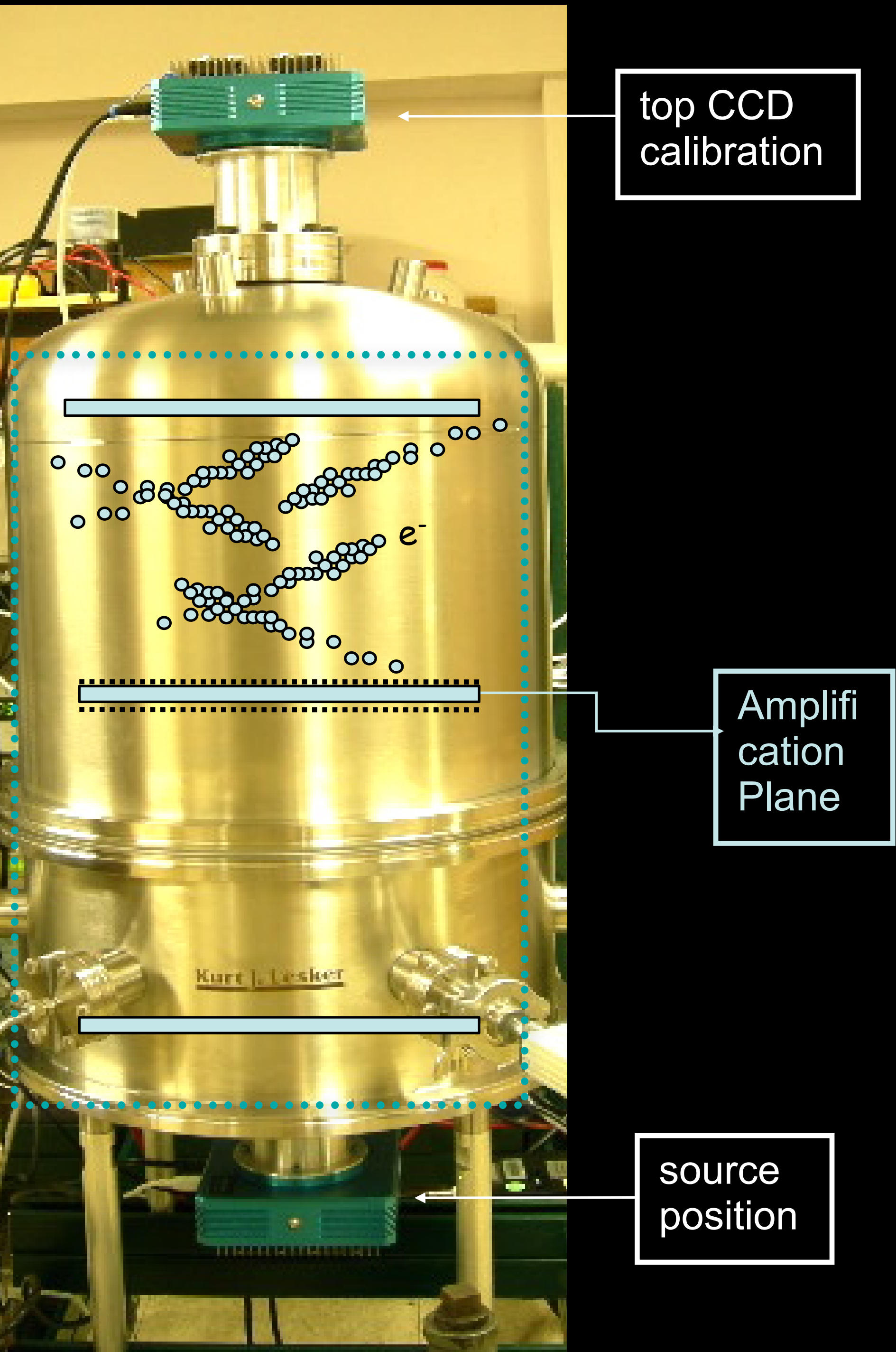
W = 33.8 +/- 0.4 eV (I. Wolfe)

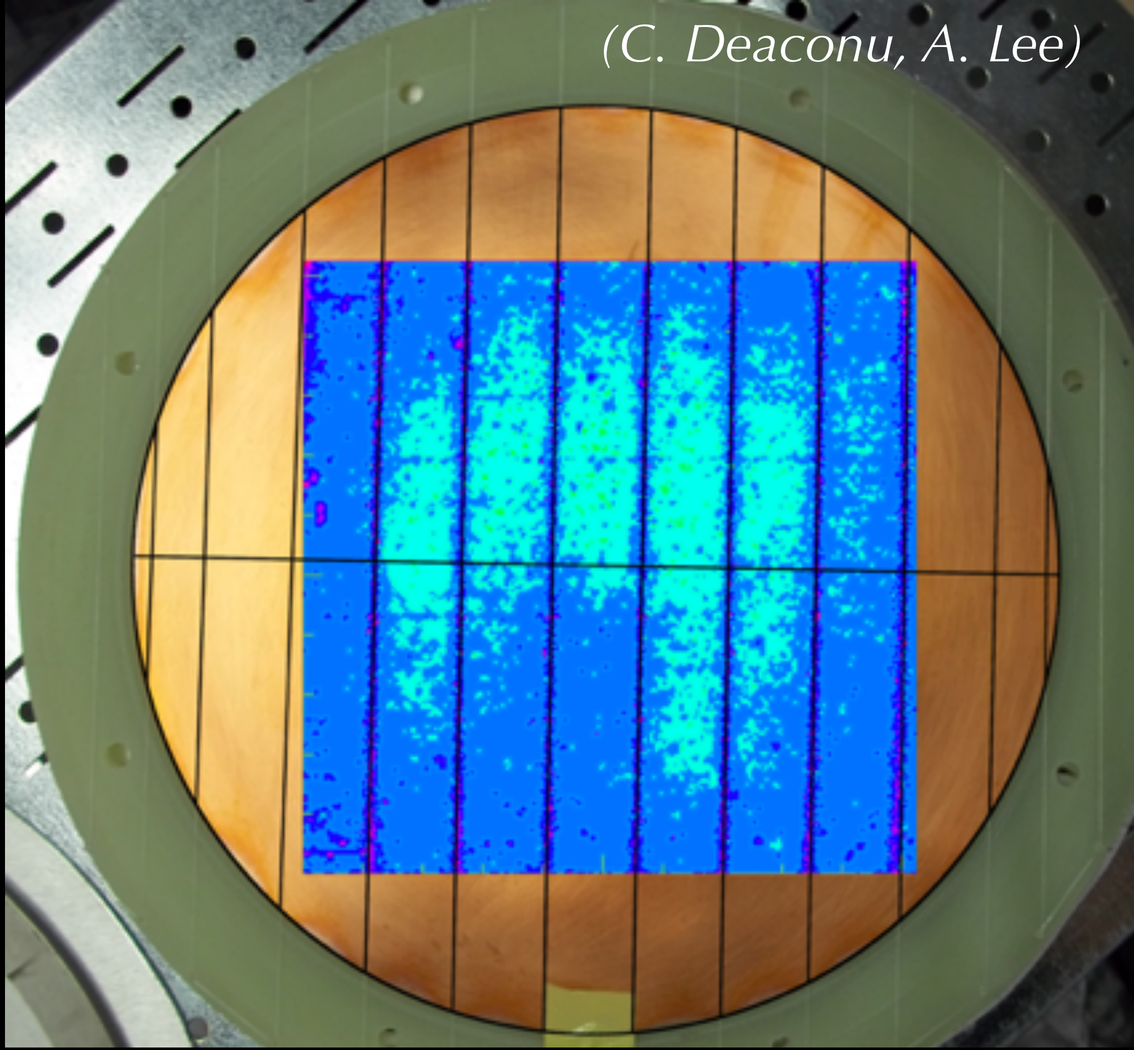
Charge multiplication $M = (V_{out} / 1.4pC/V) / (5.9keV / W)$

$M > 10^4$ at operating pressure (60, 75Torr)

Determine anode operating voltage to maximize M, with <few% sparks

Length Calibration





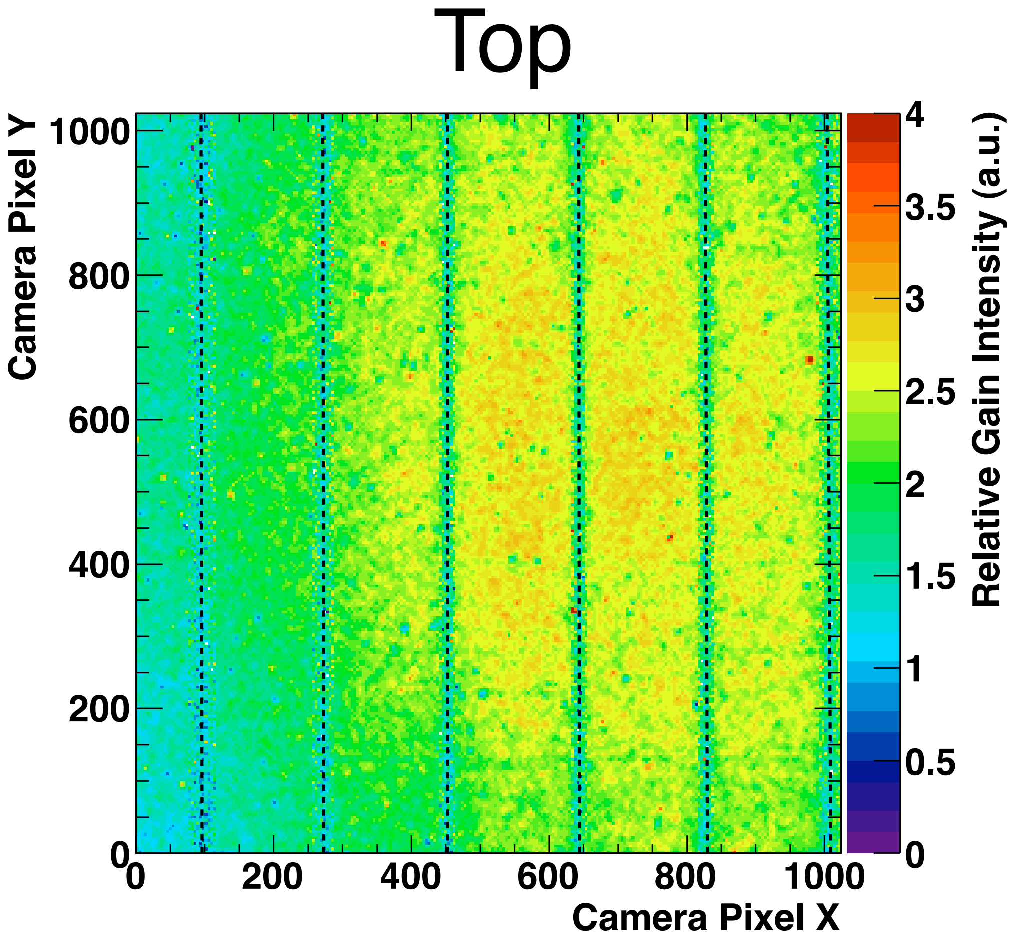
uniformly illuminate each TPC with gamma
from 31 uCi Co-57 (122,137 keV) and
9.5 uCi Cs-137 (662 keV) sources for 0.67 d

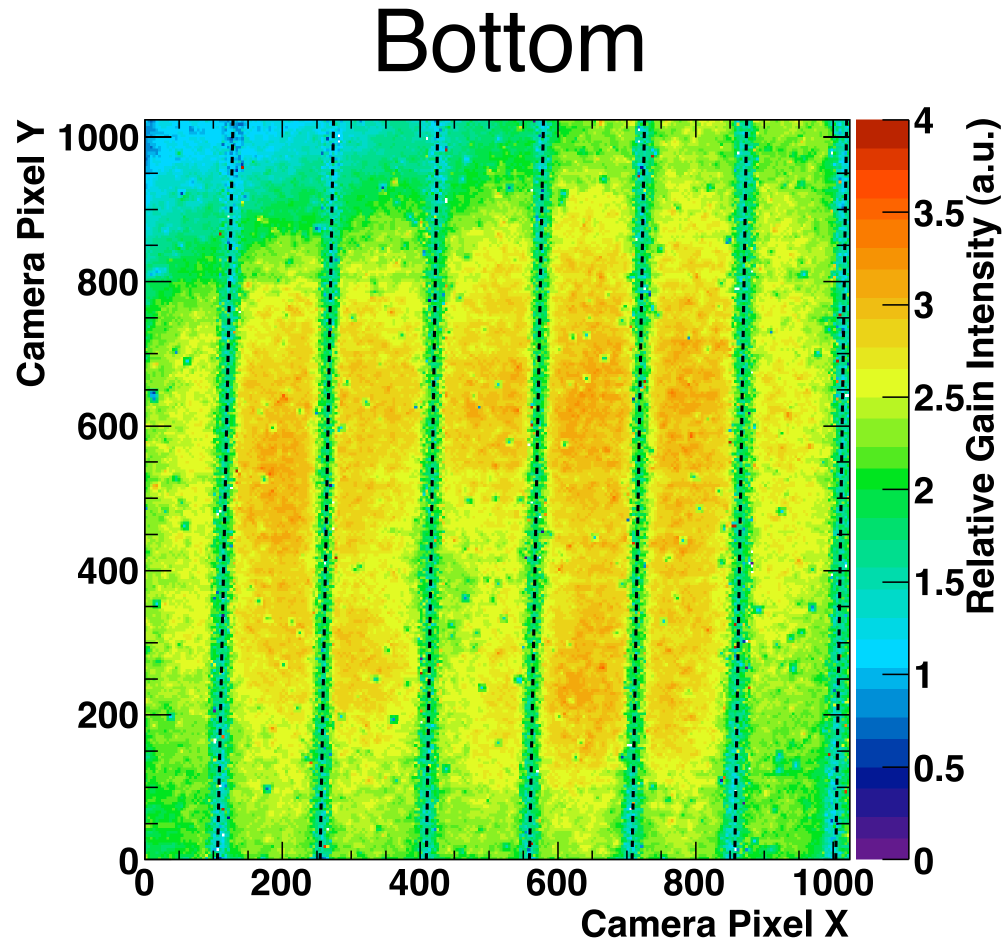
optical plate scale from comparing measure
spacer positions in gamma data with photo
= 136, 168 um/pixel (top,bottom)

Amplification Region Non-Uniformity Calibration

10L Gain Maps

(A. Kaboth)

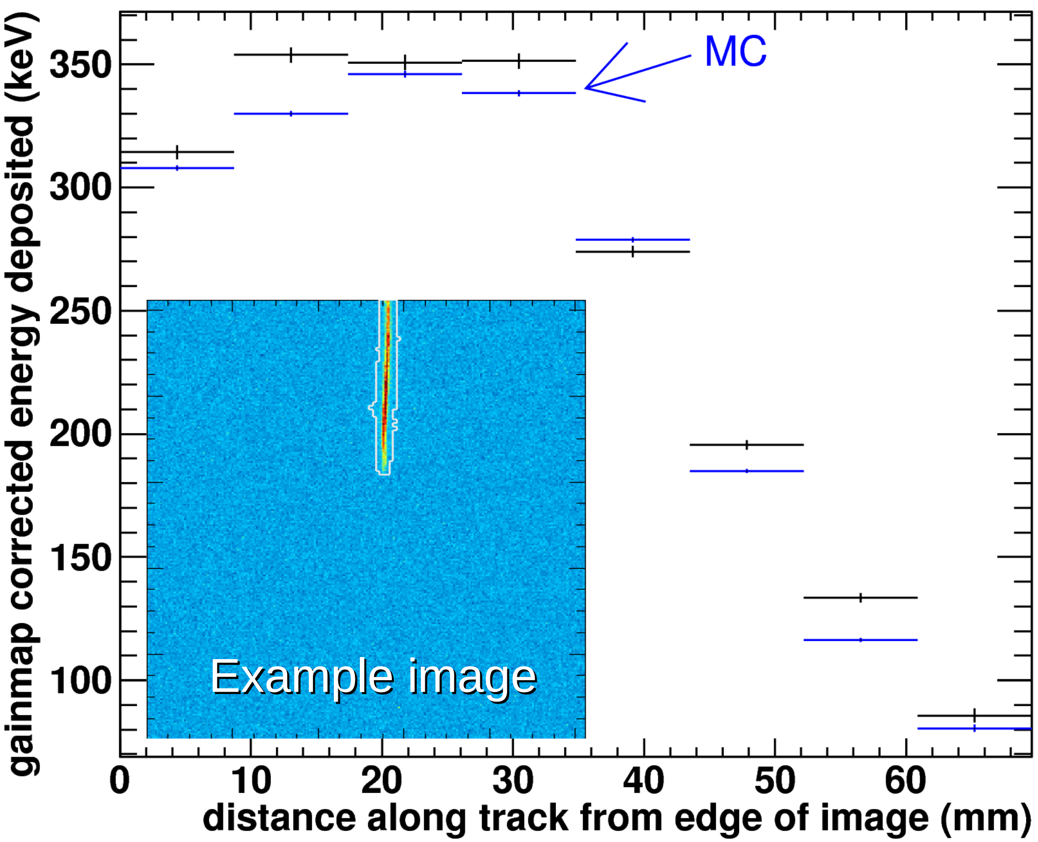




measured non-uniformity samples total system gain, can come from mesh-anode spacing, lens transmission, etc. Correct for this pixel-by-pixel in energy estimate.

CCD Energy Calibration

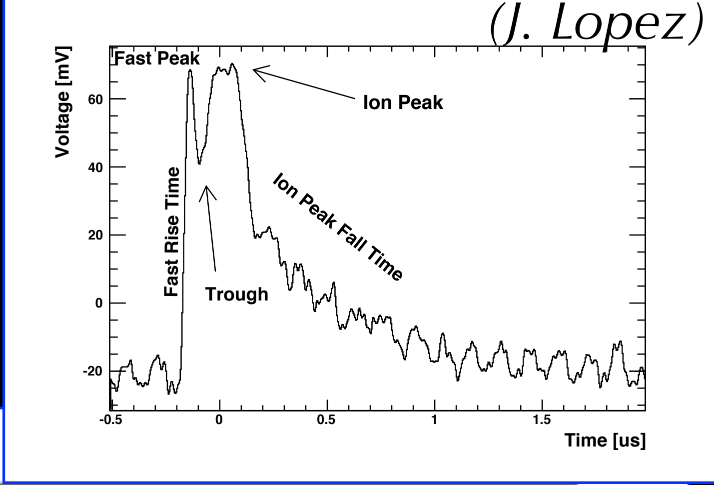
(C. Deaconu)



- Data taken with Am-241 source of known energy pointing towards image region.
- SRIM-based MC generates images with alphas of same energy and position and set gain (adu/keV).
- Reconstruct tracks in both sets of images to avoid any reconstruction bias.
- Project energy deposition along track axes, correct data for gain non-uniformity, and compare data vs. MC energy curves to figure out gain.

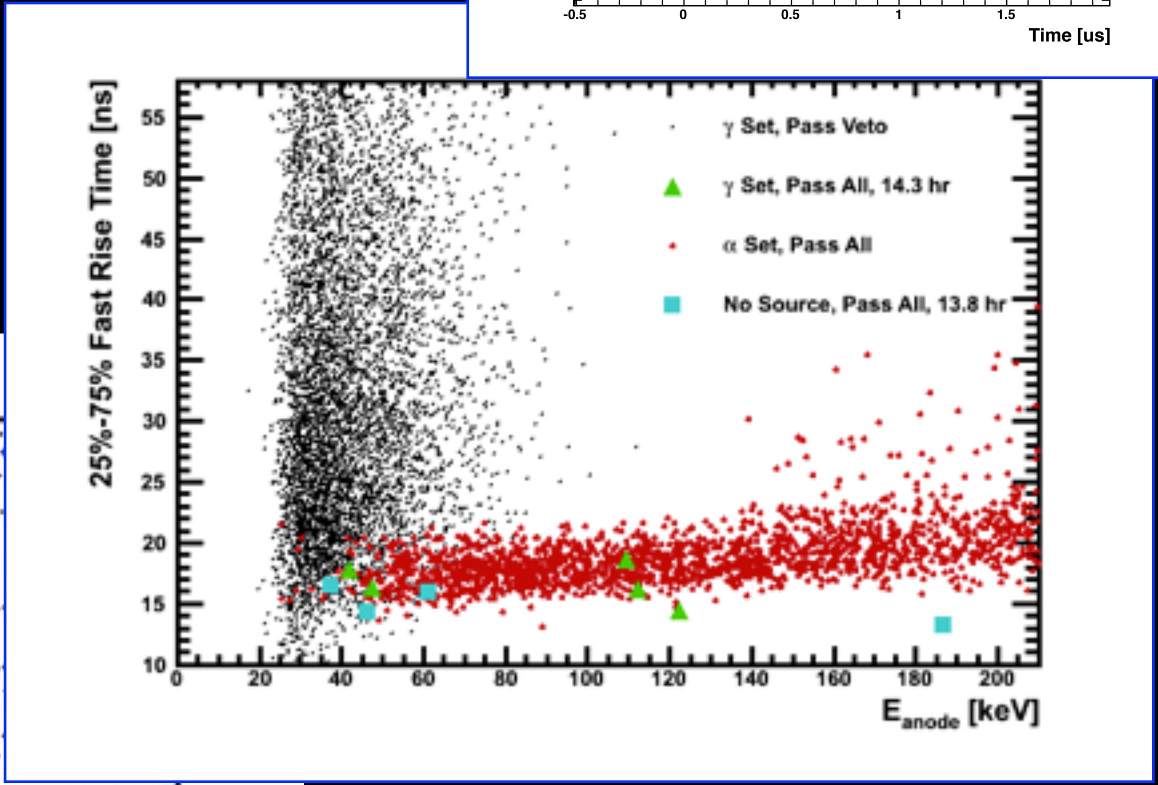
alpha energies measured in external solid sate detector (4.4 meV) compared to measured energy in CCD, at alpha track end: gain = 21,18 ADU/keV (top,bottom)

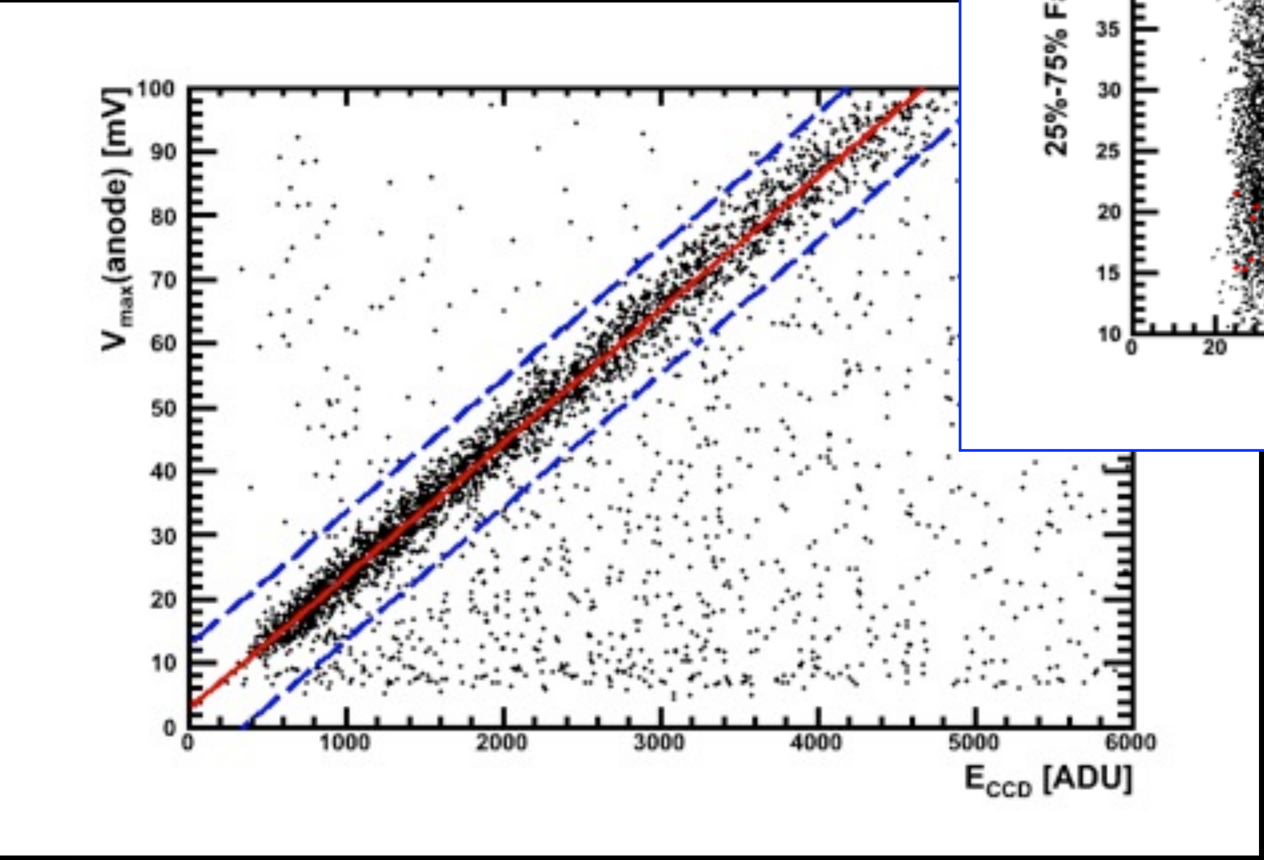
Charge Energy Calibration



Cut on mesh rise time vs. anode amplitude to reject gamma backgrounds in charge readout

Determine anode amplitude proportionality to CCD energy (calibrated with alphas)





$$V_{anode}[mV] = 2.82911 + 0.020814 N_{CCD}[ADU]$$

$$E_{anode}[keV] = 3.89 V_{anode}[mV]$$

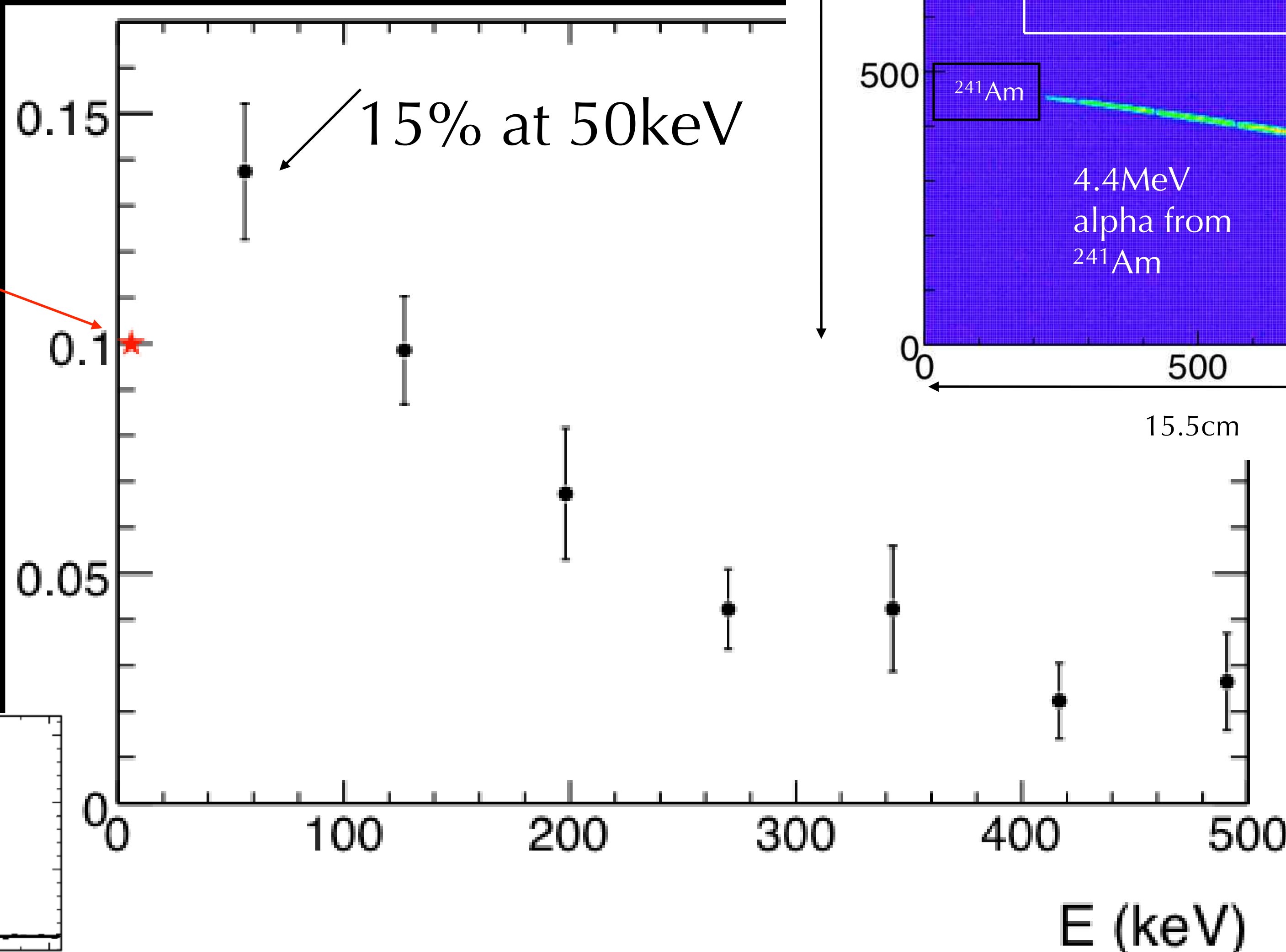
$$E_{CCD}[keV] = 11.0 + 0.08091 N_{CCD}[ADU$$

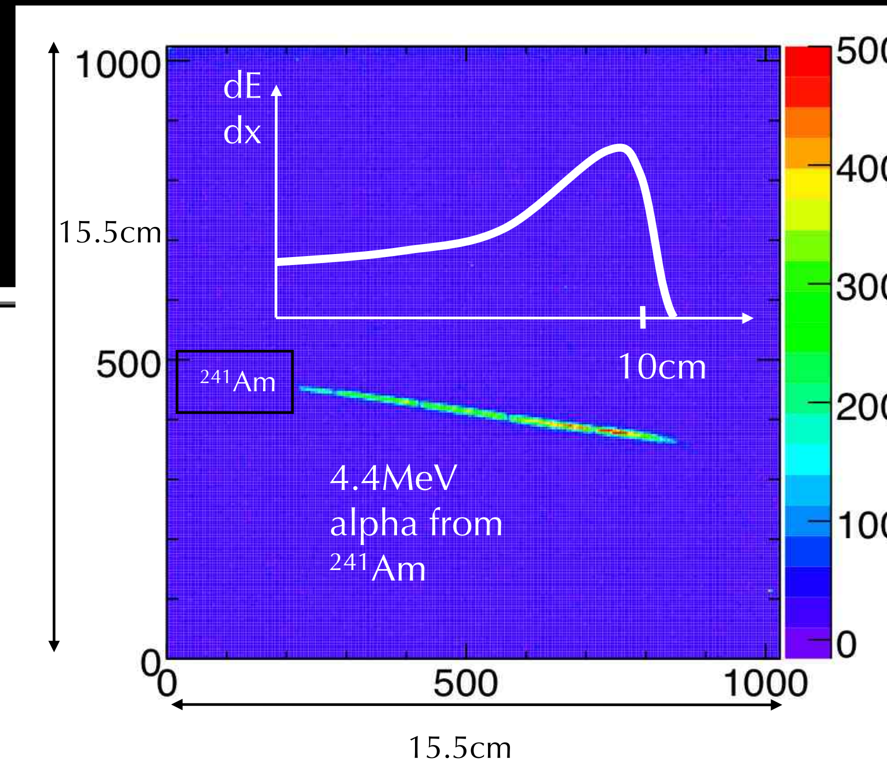
charge trigger threshold ~40 keVr

Energy Resolution

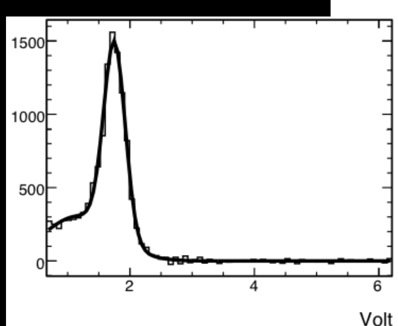
σ_E/E from CCD Readout:

~10% at 5.9keV for charge readout





(D. Dujmic)



Expected fluctuation (avalanche + primary) ~ 10%

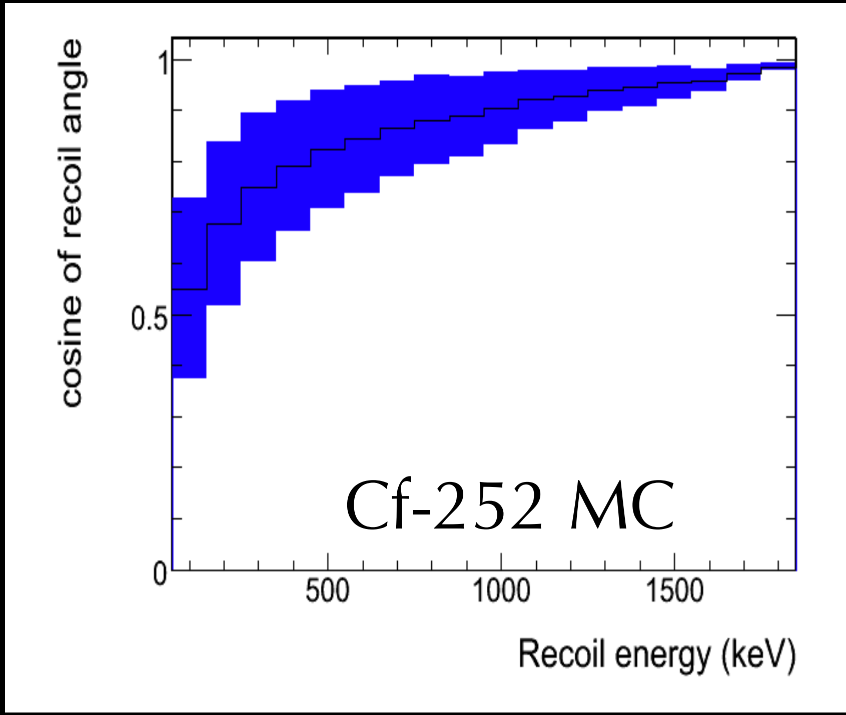
Avalanche=Alkhazov, NIM89 (1970) 155, primary=Poisson

"WIMP" Calibration

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

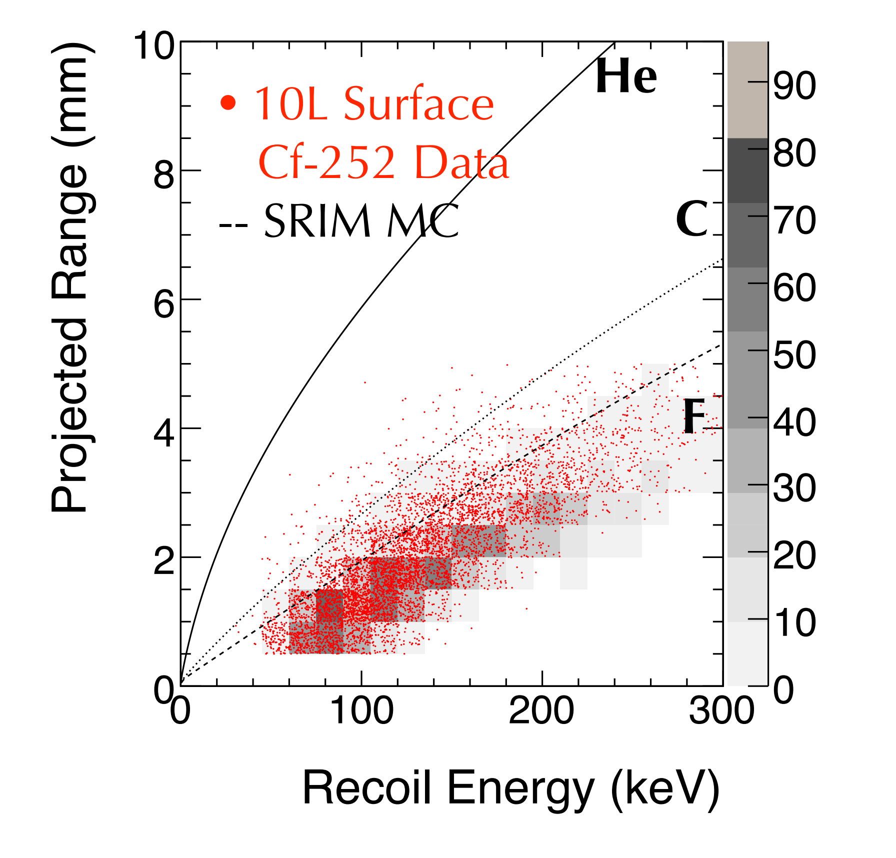
Cf-252 (~mCi) and d-t sources at surface, AmBe (8.9 uCi) source underground

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: ~50 keV

(Hitachi quenching)



Energy and recoil angle distributions similar to dark matter induced recoils

CF_4 Electron Attenuation

(D. Dujmic, T. Caldwell)

Attachment to CF_4:

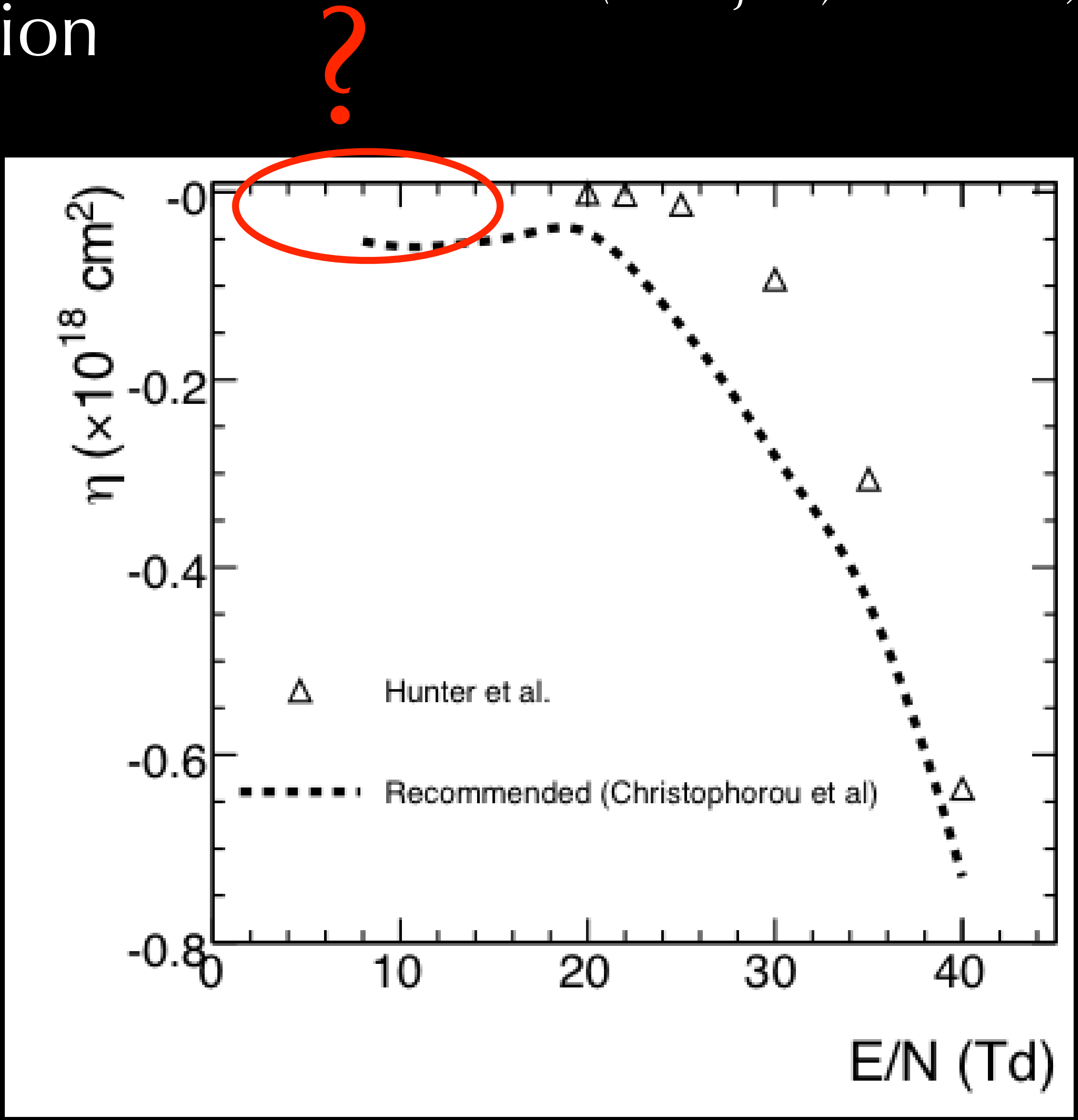
e.g.

$e^- + CF_4 \rightarrow CF_4^- \rightarrow CF_3 + F^-$

$e^- + CF_4 \rightarrow CF_4^- \rightarrow CF_3^- + F$

$e^- + CF_4 \rightarrow CF_4^{*-} \rightarrow F^- + CF_2 + F$

From previous measurements, 0% loss, or 70% loss after 20cm drift length?



(D. Dujmic, T. Caldwell)

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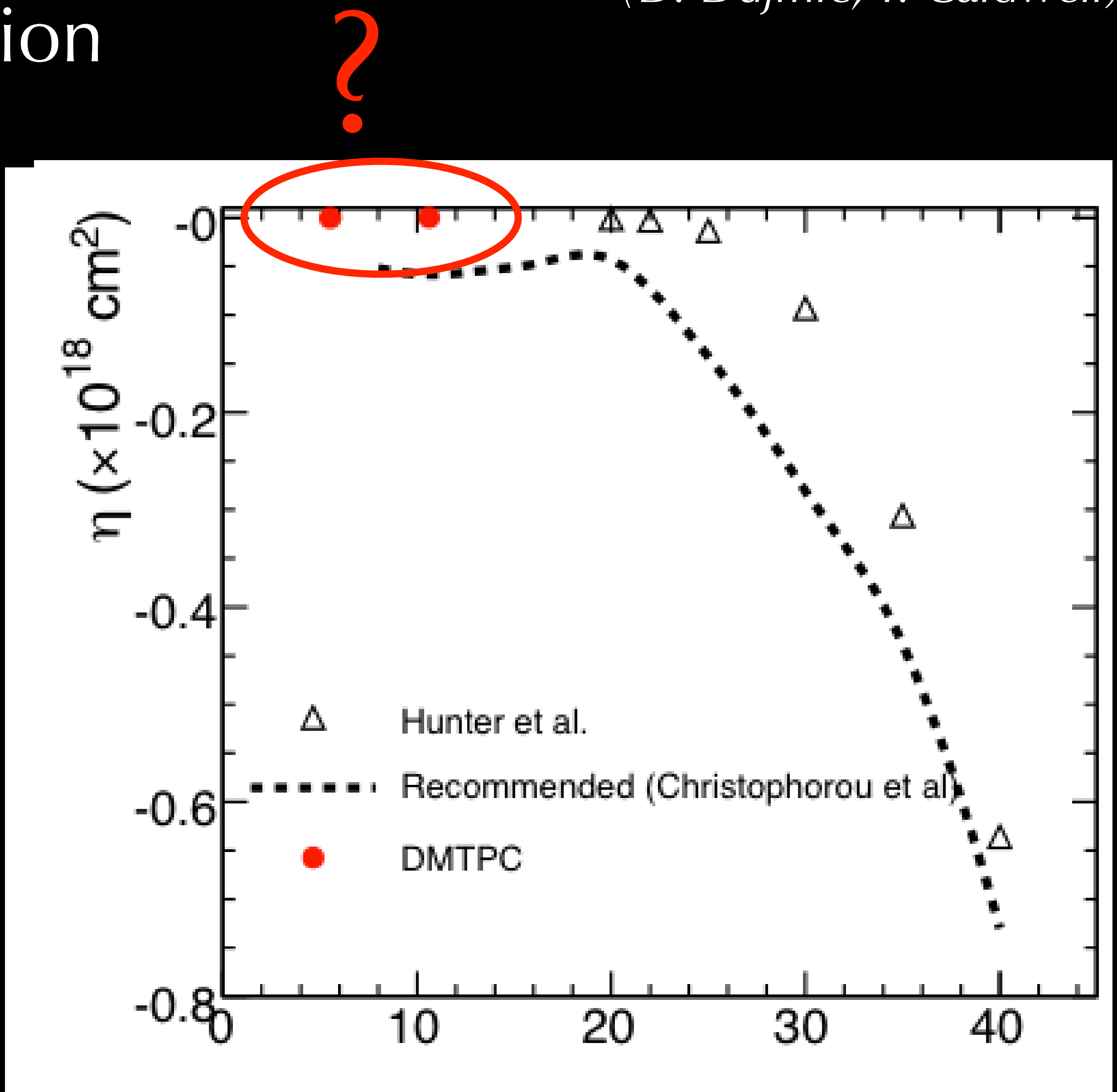


T. Caldwell, et al., arXiv:0905.2549

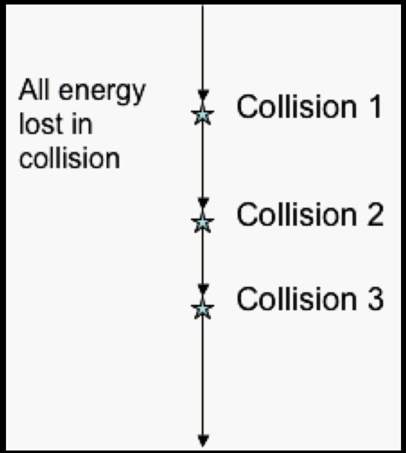
DMTPC measures ~0 charge loss over 20 cm drift length.

(D. Dujmic, T. Caldwell)

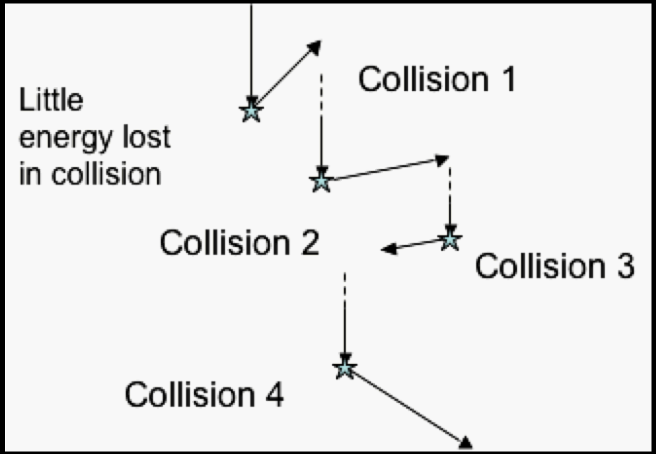
CF_4 Electron Diffusion

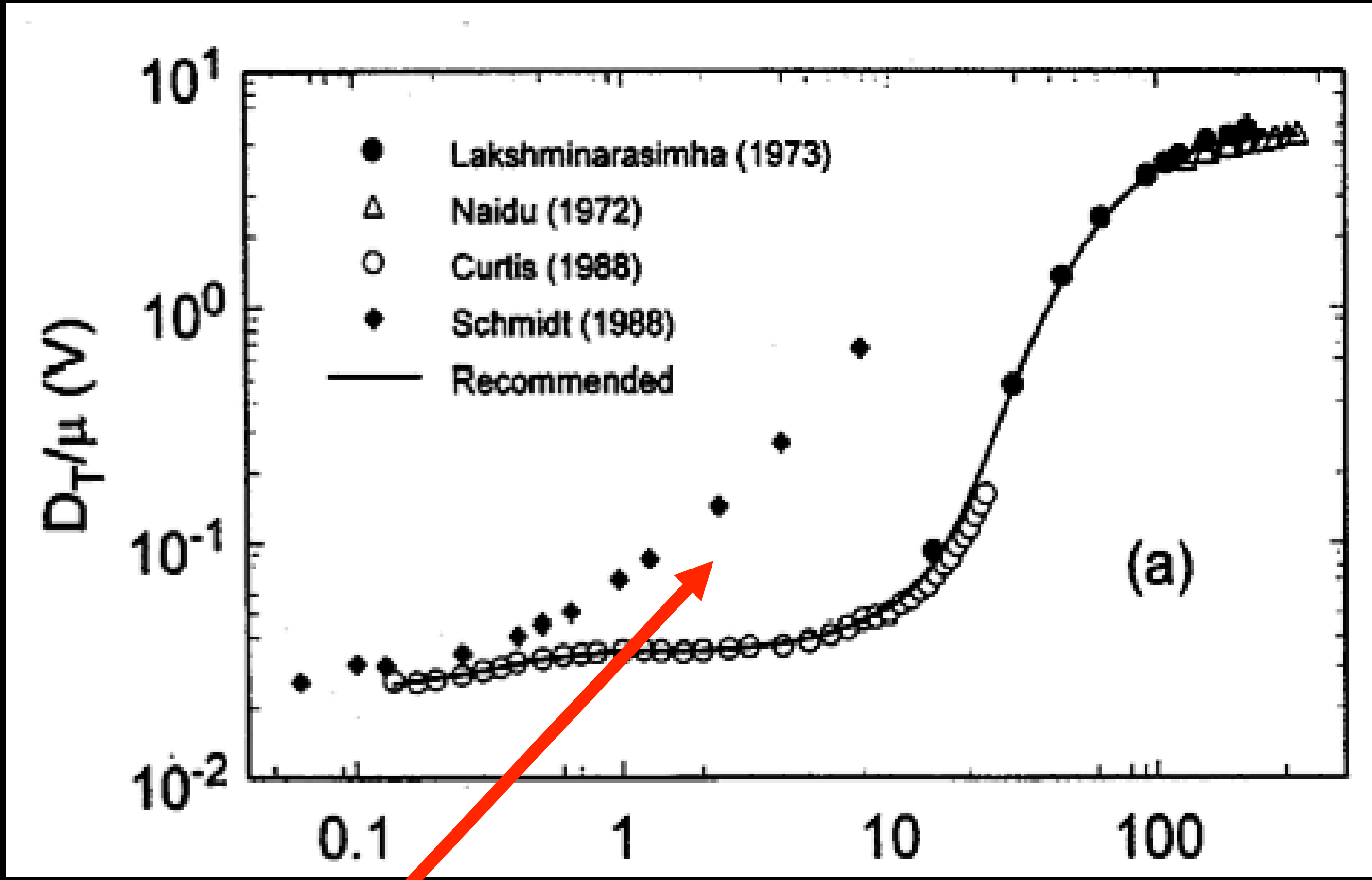
Large impact on spatial resolution:

$$\sigma^2 = (D/\mu)\, 2z/E$$



or?





E/N [Td]

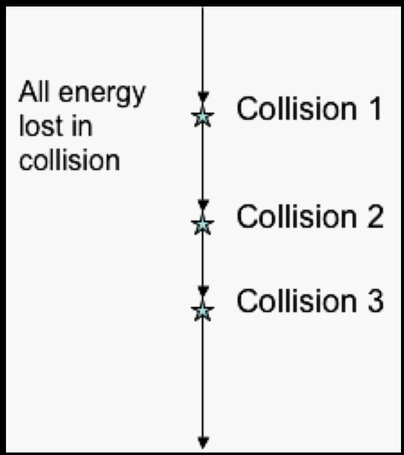
>10x discrepancy in measurements in our range-of-interest

CF_4 Electron Diffusion

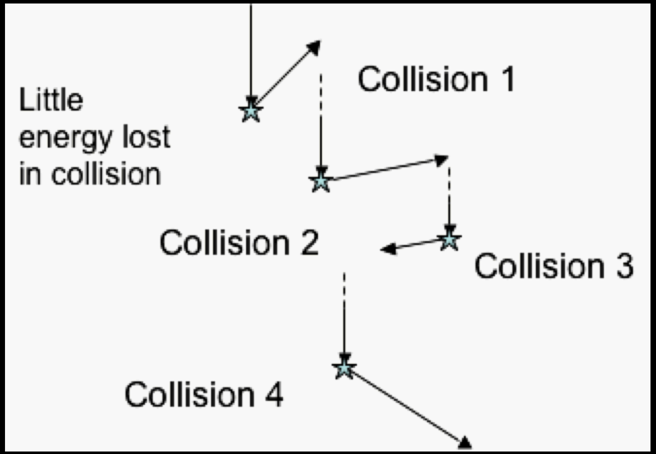
(D. Dujmic, T. Caldwell)

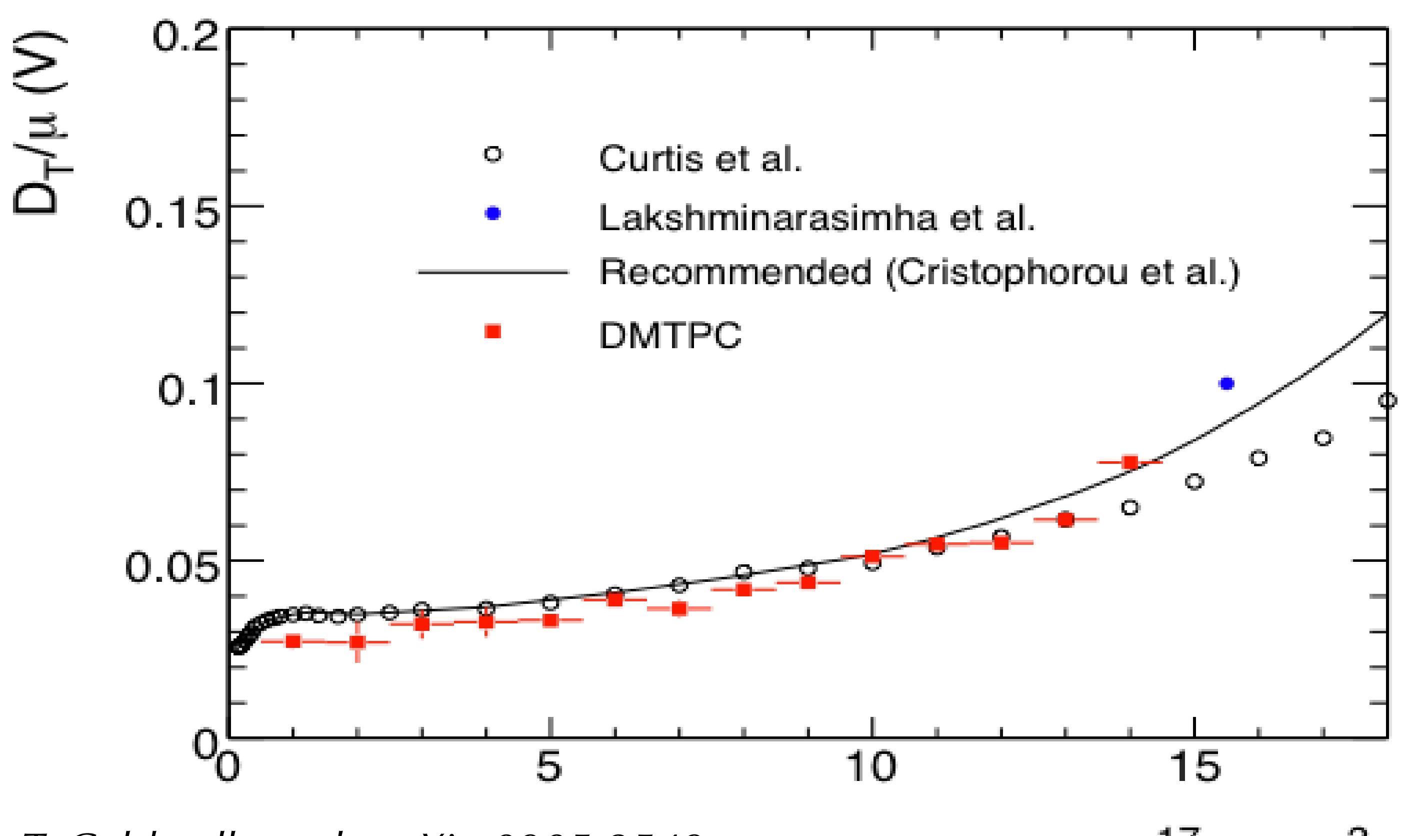
Large impact on spatial resolution:

$$\sigma^2 = (D/\mu)\ 2z/E$$



or?





T. Caldwell, et al., arXiv:0905.2549

E/N [Td]

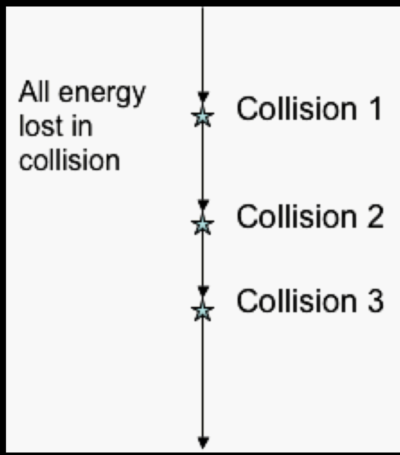
>10x discrepancy in measurements in our range-of-interest

CF_4 Electron Diffusion

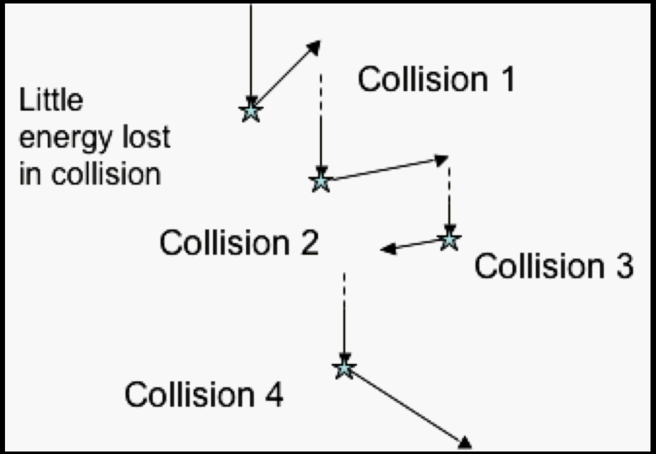
(D. Dujmic, T. Caldwell)

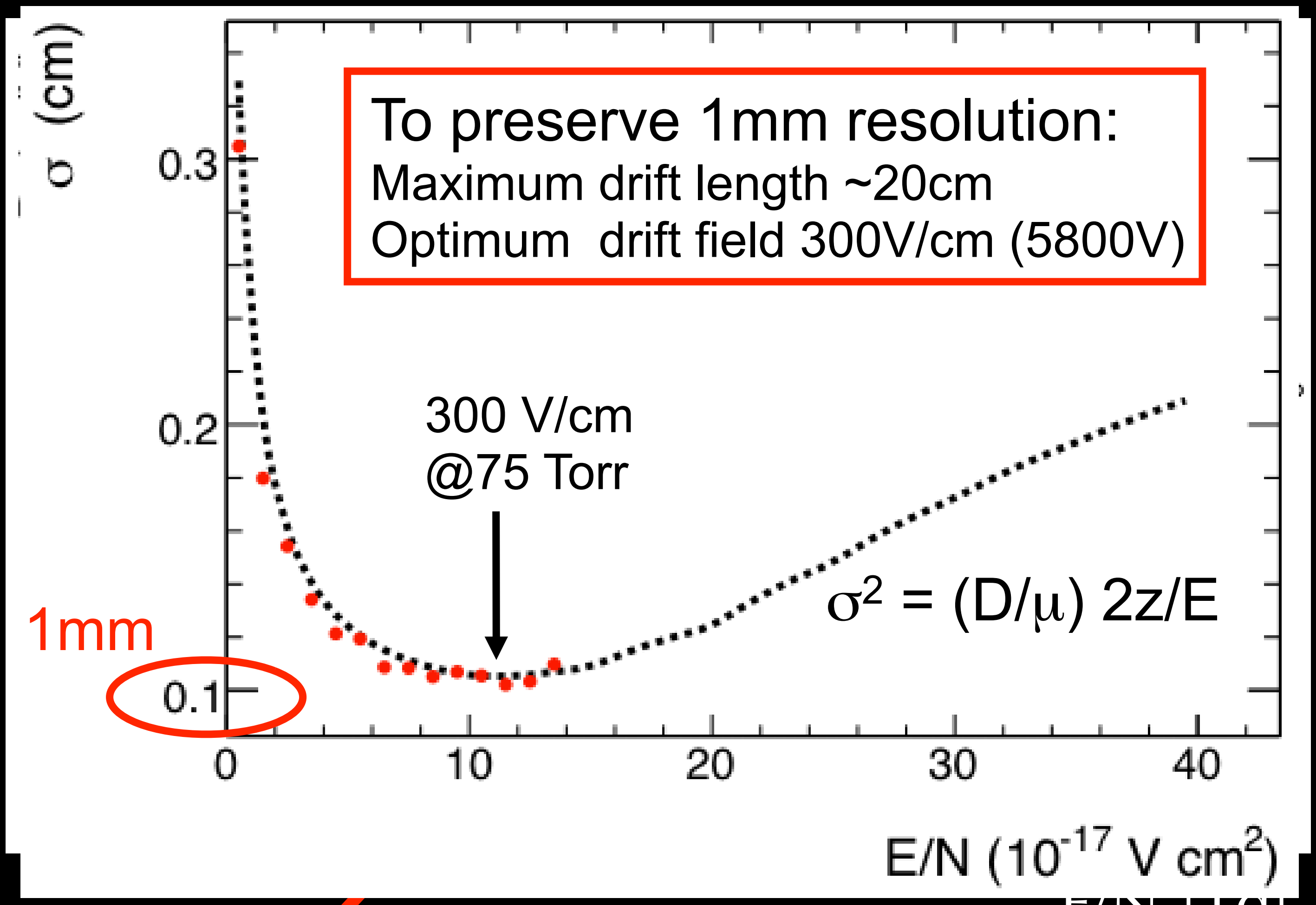
Large impact on spatial resolution:

$\sigma^2 = (D/\mu)\, 2z/E$



or?



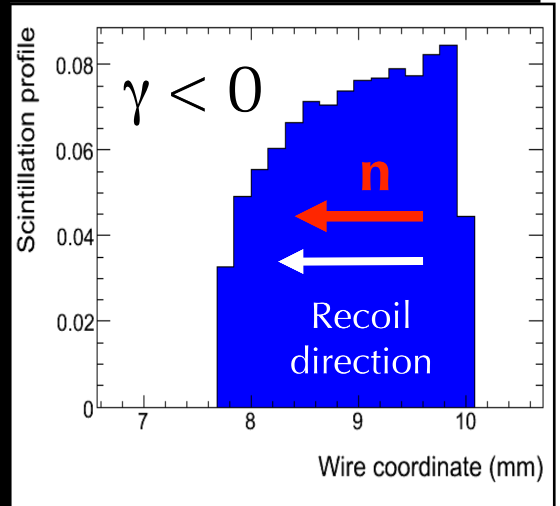


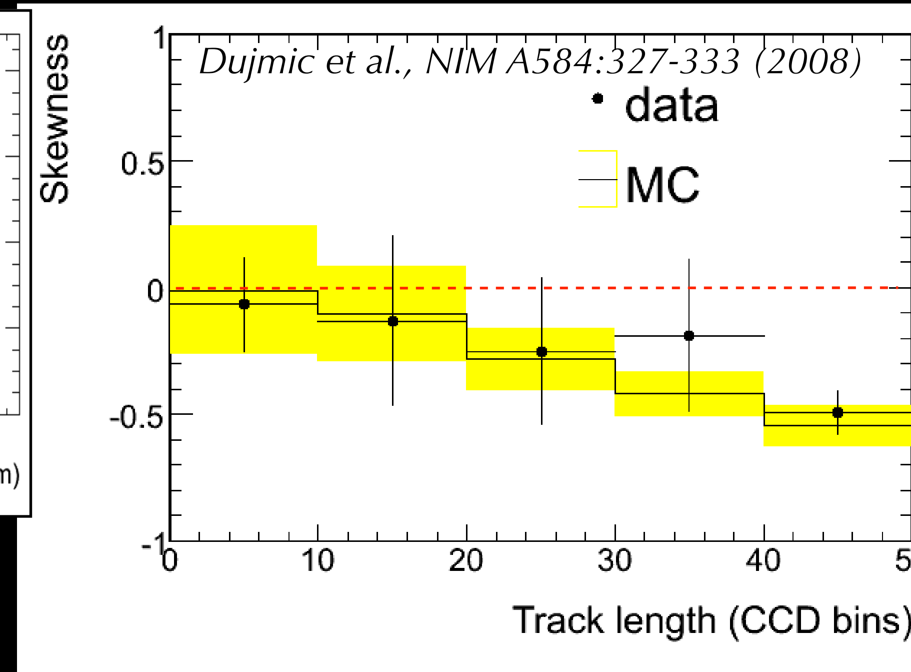
>10x discrepancy in measurements in our range-of-interest

DMTPC maximum drift length for <1 mm diffusion ~20 cm.

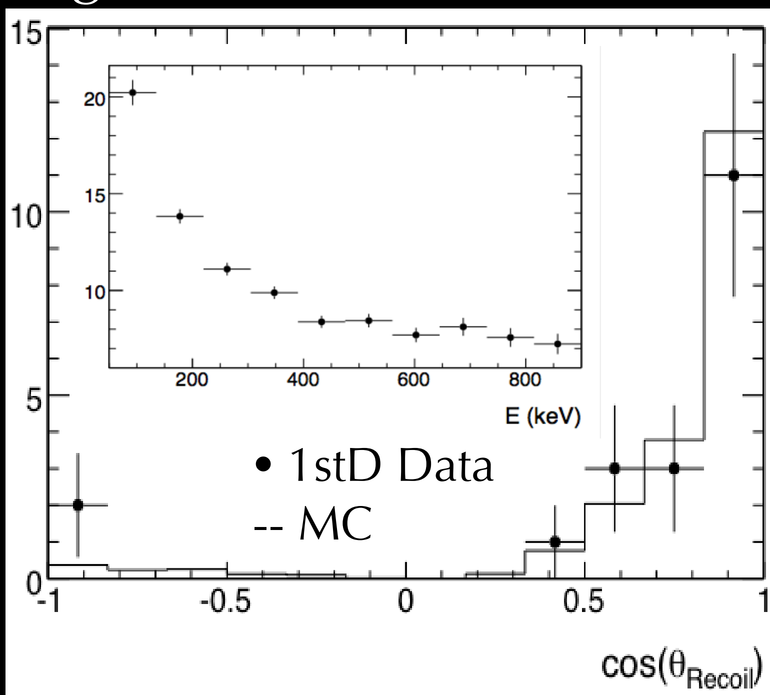
Directionality

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

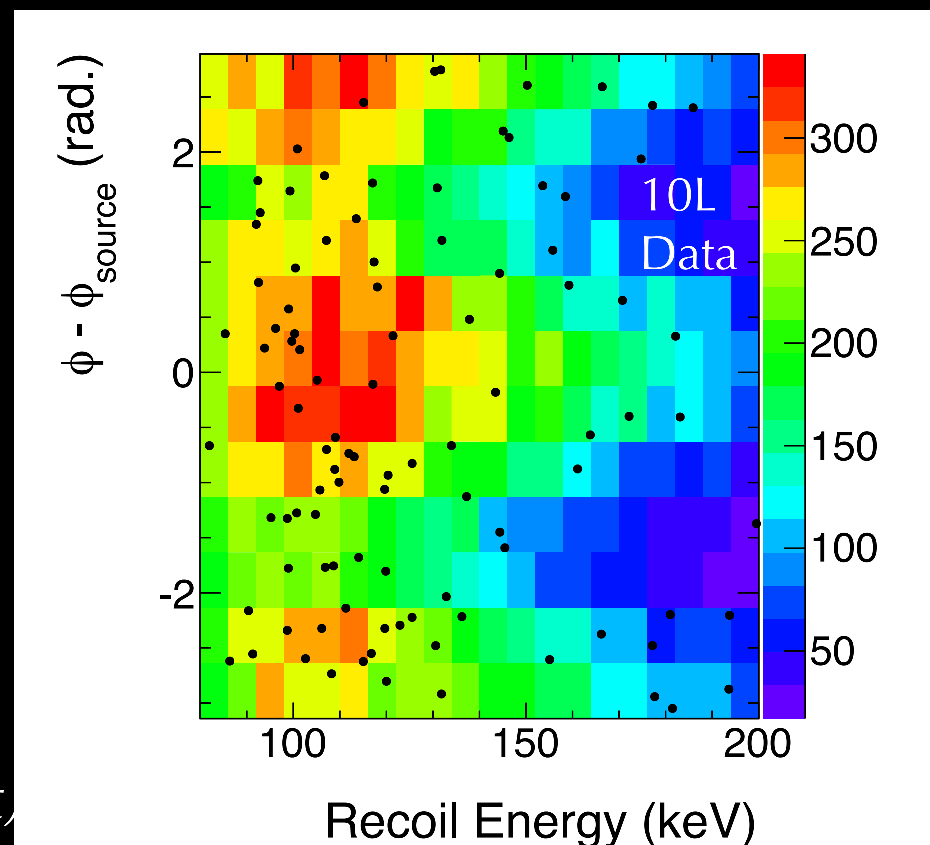




Signed cosine (E>200 keV), 5 cm drift



diffusion has a big impact on head-tail, working on 3D readout for 4-shooter *(J. Battat)*



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

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

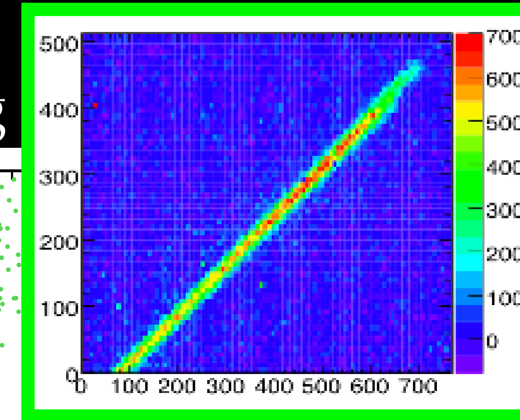
20 cm drift (10L detector)

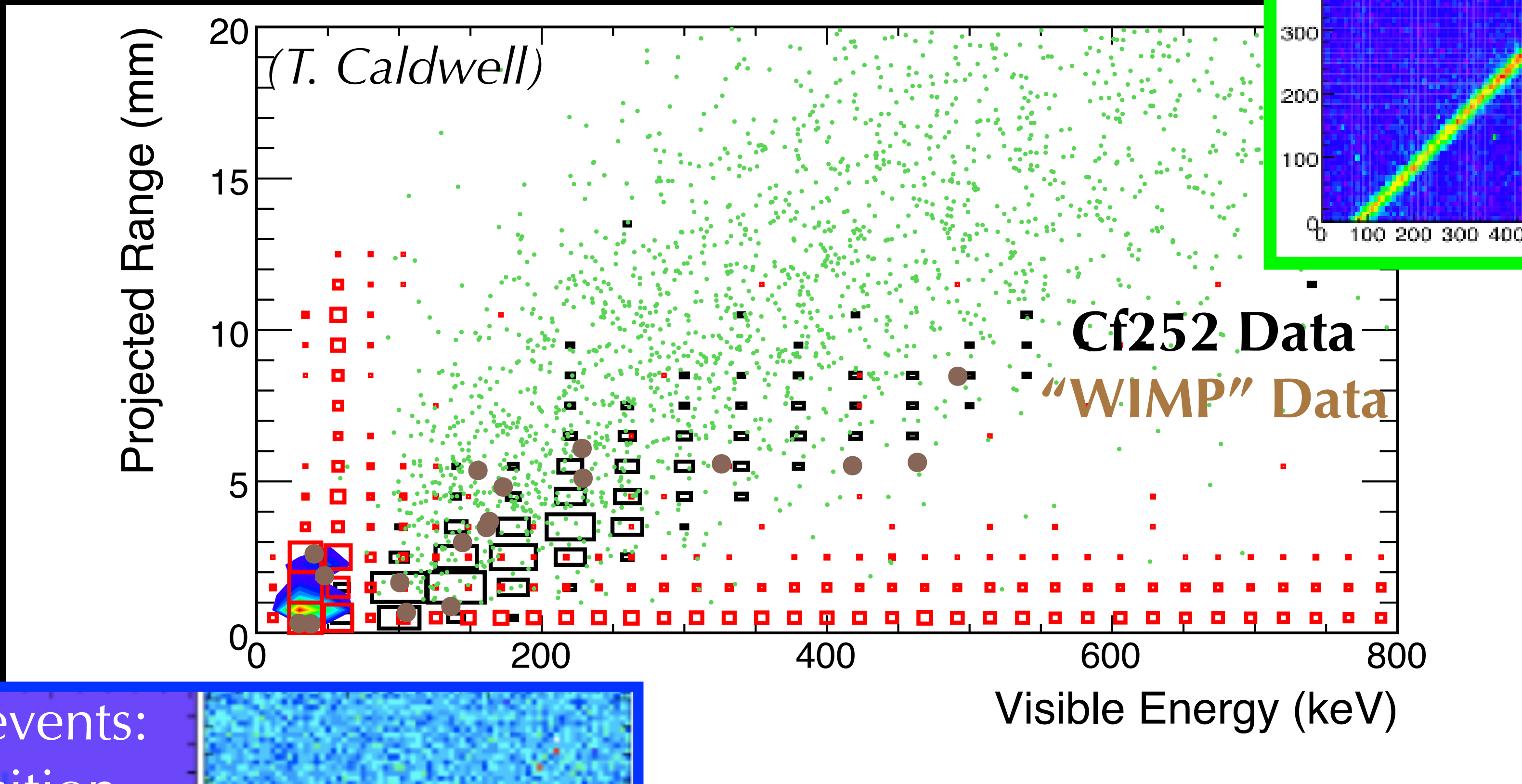
MC: 40^o resolution at 80 keVr

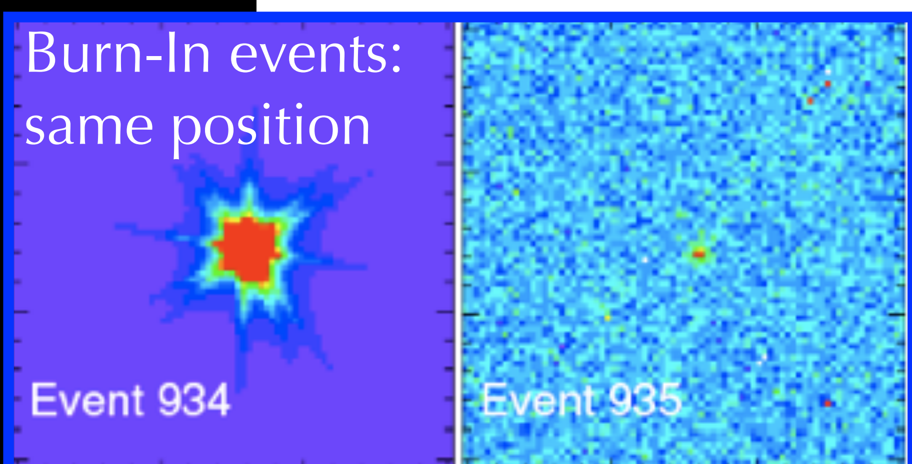
(A. Kaboth)

Surface Backgrounds

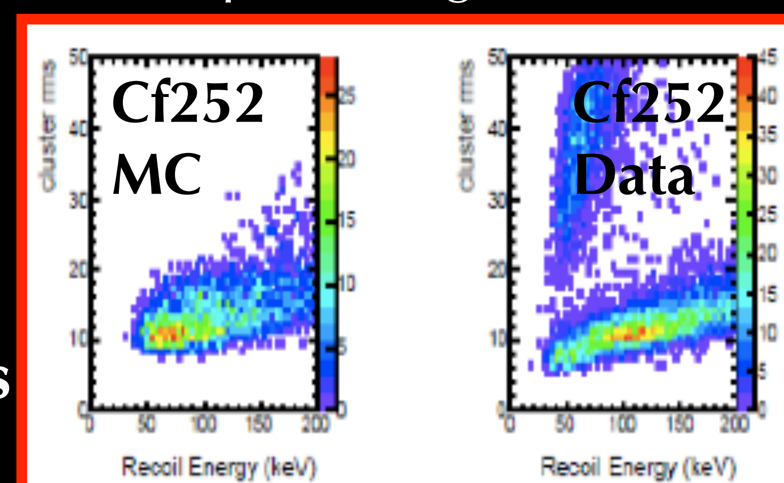
Alphas:
edge crossing







“Worms”: one hot pixel, large cluster rms

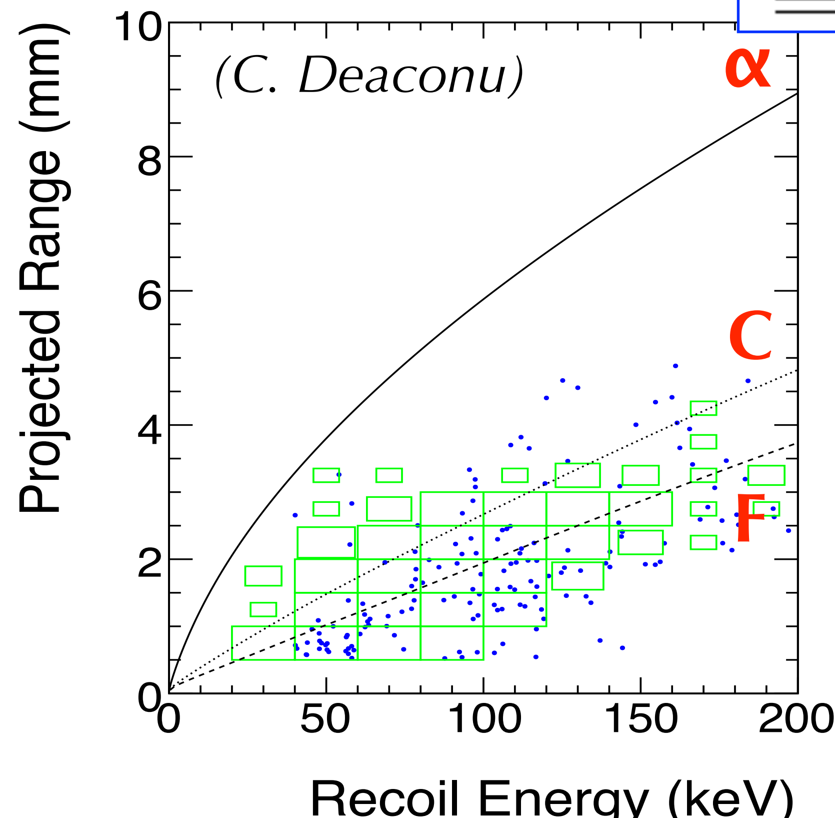


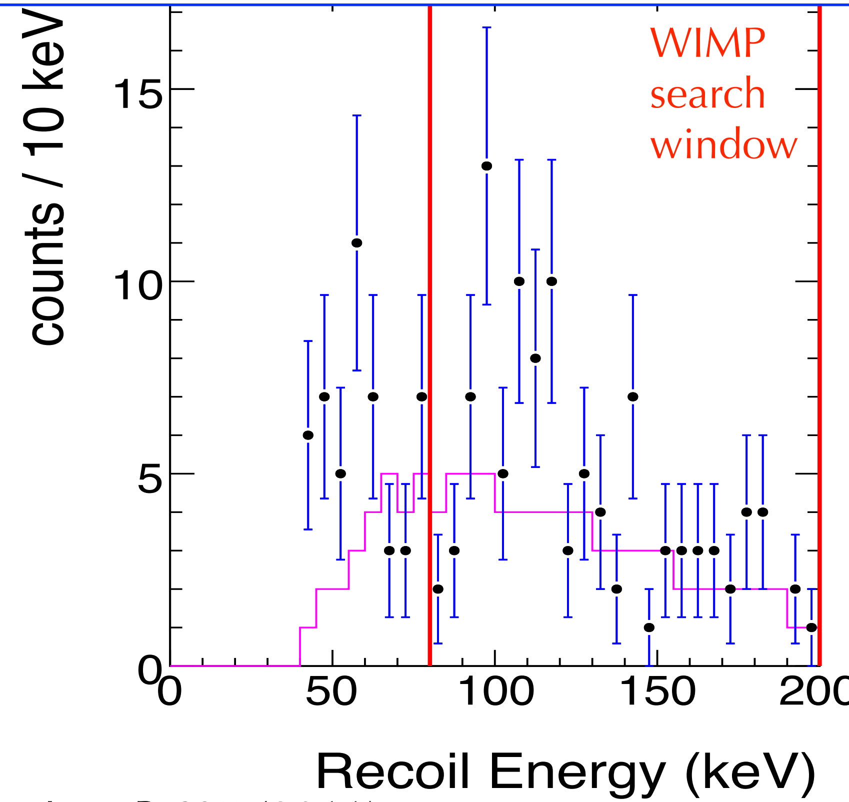
10^4 rejection of backgrounds from range vs. energy strategy, unique to directional detectors

Surface Run Results

nuclear recoil selection cuts set using calibration data

Event Selection Cut	Rate (Hz)
All Tracks	0.43
Residual Bulk Images	0.15
CCD Interactions	4.4×10^{-3}
Alpha Candidates	8.2×10^{-5}
Nuclear Recoil Candidates in $80 < E_R < 200$ keV	5.0×10^{-5}





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

surface neutron flux measurement: T. Nakamura, T. Nunomiya, S. Abe, K. Terunuma, and H. Suzuki, J. of Nucl. Sci. and Tech. 42 No. 10, 843 (2005).

observed 105 events above 80 keV threshold chosen for dark matter search (threshold chosen for max. recoil efficiency), consistent with neutron prediction (74 events)

Surface Run Limit

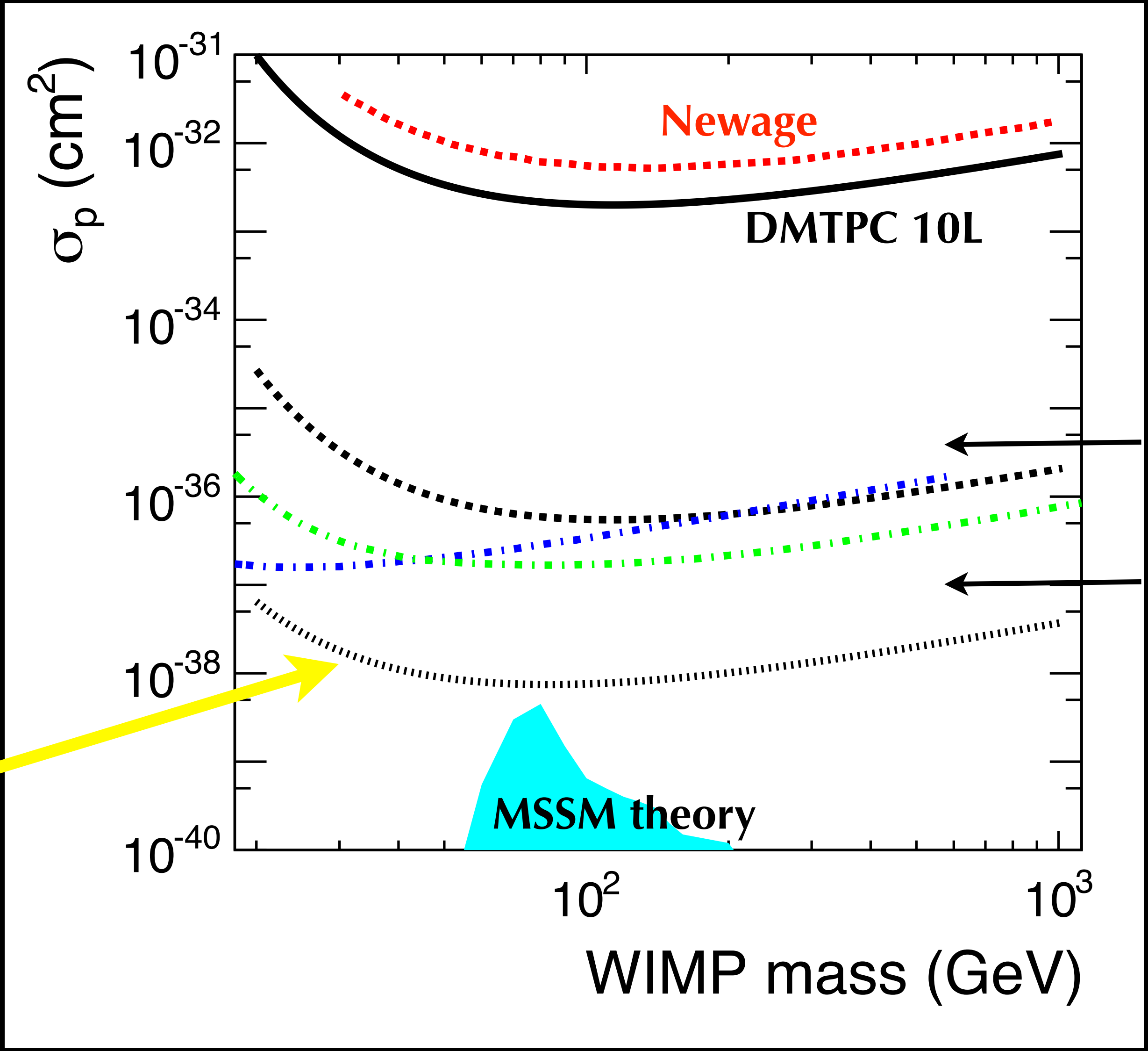
NEWAGE limit (Kamioka)

K. Miuchi et al., Phys.Lett.B686:11-17 (2010)

DMTPC limit (surface, 38 gm-day)

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

1m^3 at WIPP (DMTPCino) projected sensitivity



directional results

DRIFT, *arXiv: 1010.3027*

1D results

COUPP, IDM2010

Next steps for DMTPC: low-background detector R&D, go 2150′ underground at WIPP, DMTPCino at WIPP (1m^3)

2150 feet underground

July 2010

Yamamoto Laboratory at WIPP

October 2010

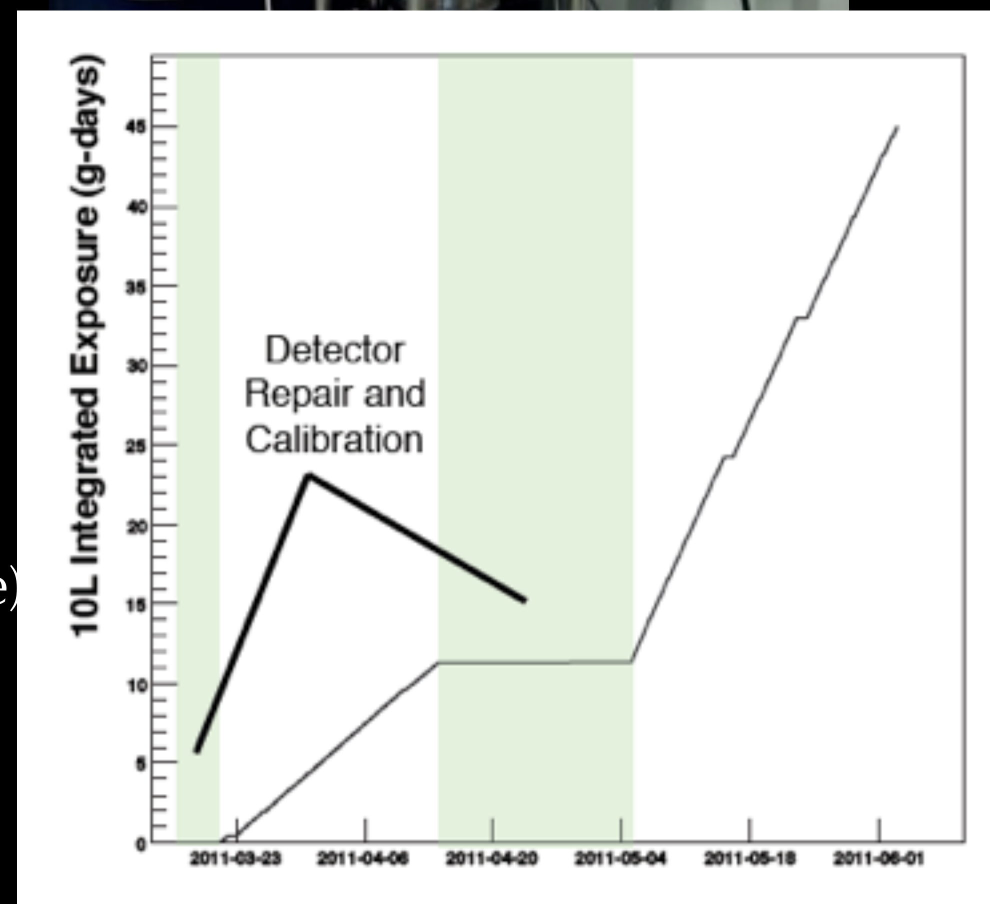
Sept. 2010

major effort at WIPP is to measure the in-situ detector backgrounds

August 2010, certified miner

“WIMP search” run started in March, typically 60-70% livetime (1 second exposure)

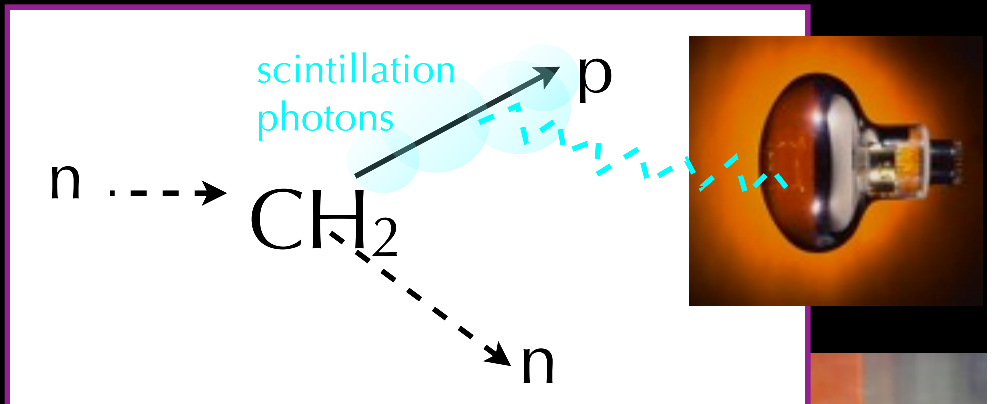
blind analysis, selection cuts defined on AmBe calibration data (Jan.-Mar.)

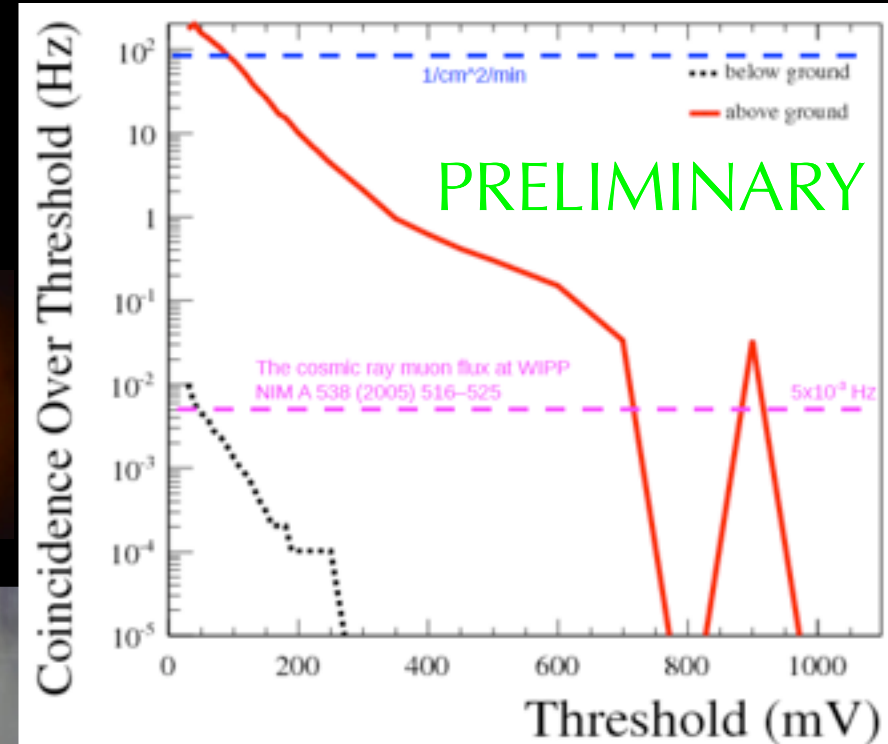


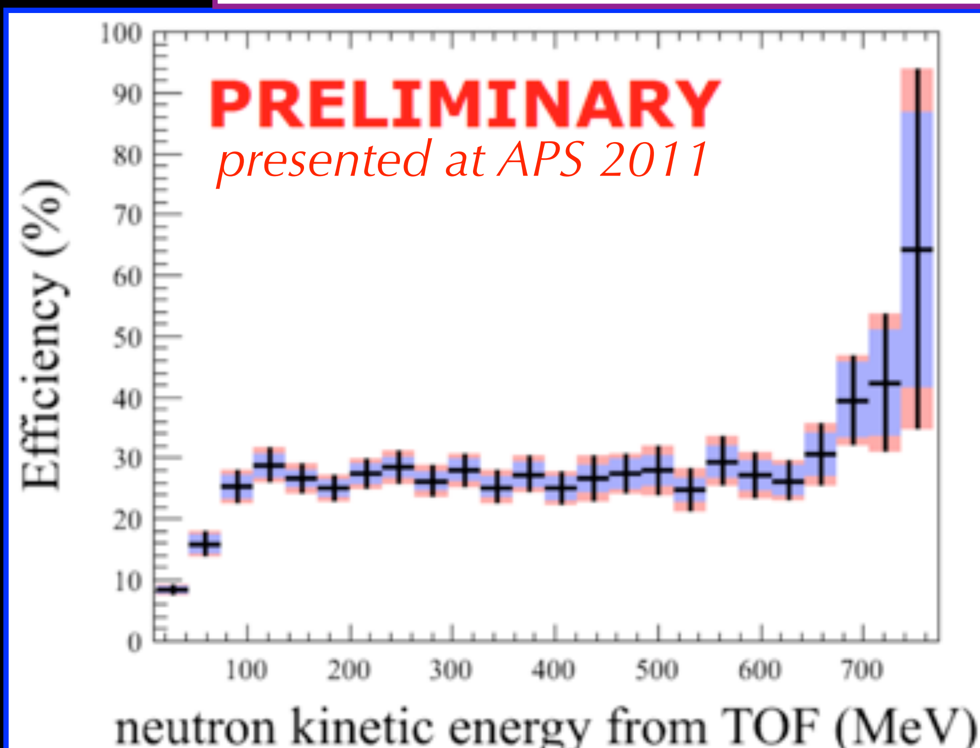
Active Neutron Veto Prototype

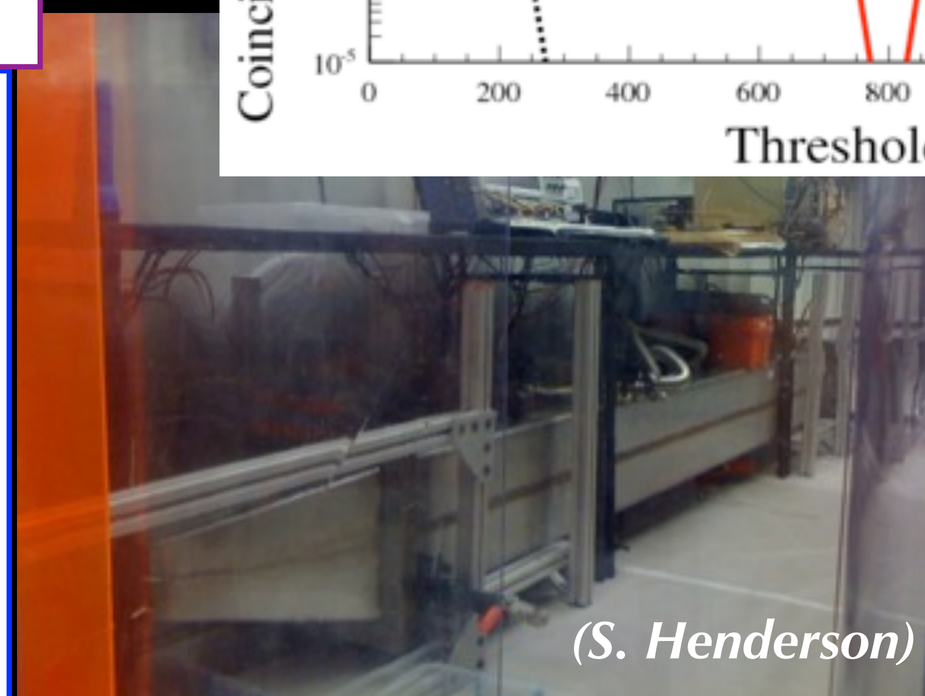
measure proton light, reconstruct neutron E

liquid
scintillator
active
volume









prototype calibrated at LANL WNR beam test, deployed since August 2010

goals: *measure* high energy neutron flux+energy spectrum underground at WIPP

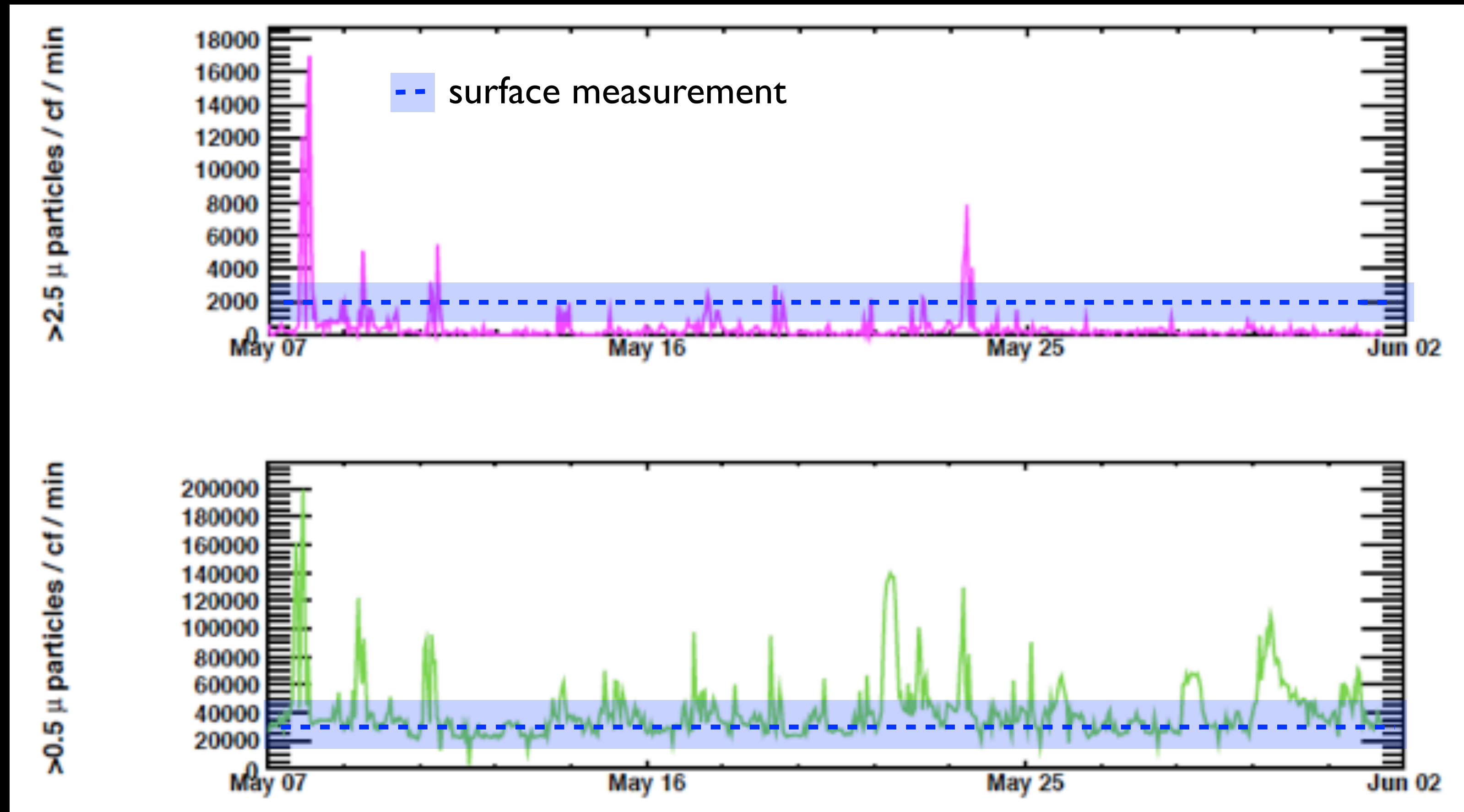
Underground Laboratory Conditions

WIPP measured background rates: *(I. Esch)*

- 21.6x lower gamma rate(25 -1600 keV) than surface
- lower limit of 415x lower neutron flux (predict x10^5)
- upper limit on Rn rate of <7 Bq/m^3
- muon flux reduction of 10^5 (1.6 km.w.e.)

NIM A 538 (2005)

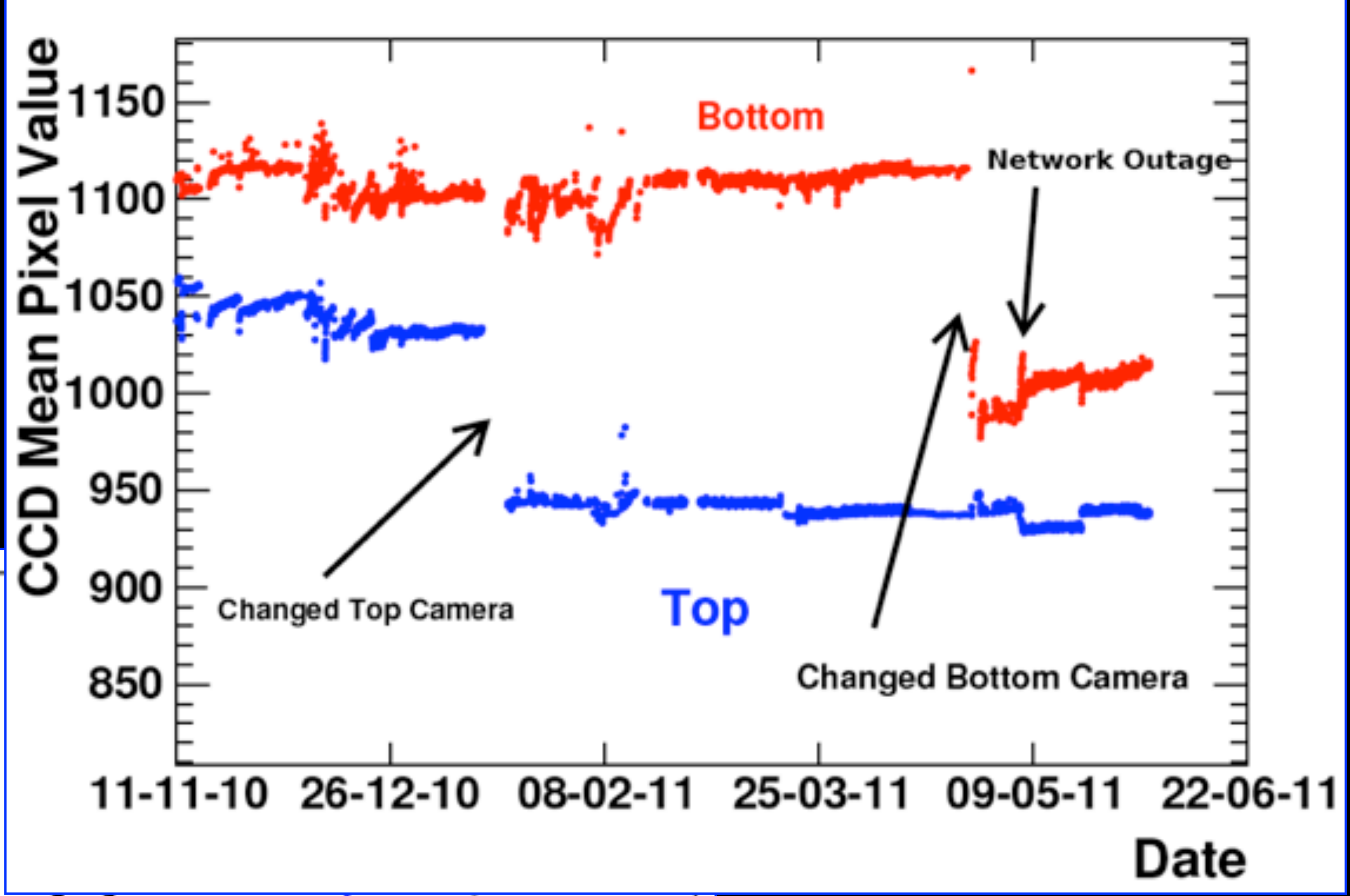
- lab particle count comparable to measured surface rate (at MIT)

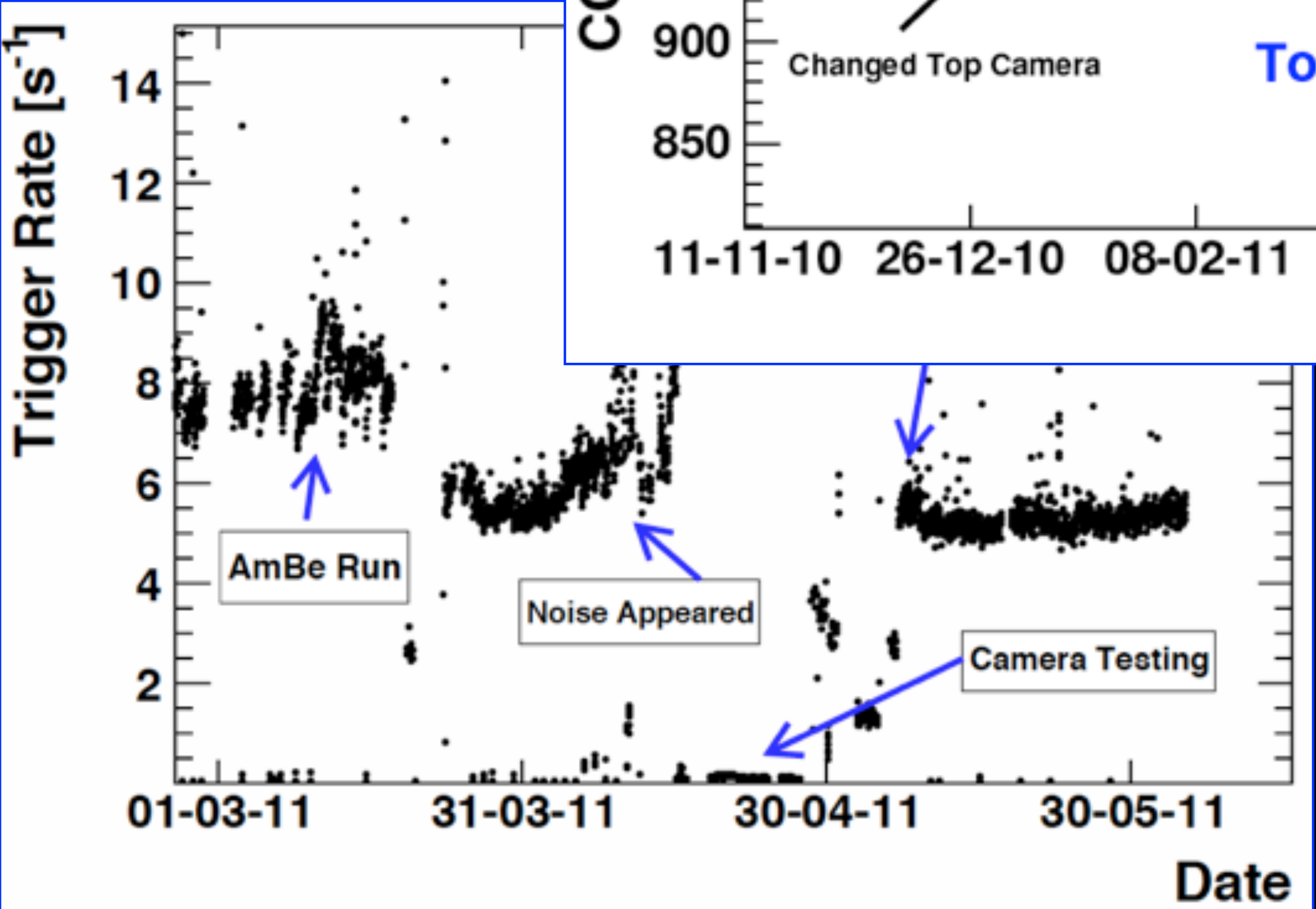


	at the WIPP			Range in Soil			Ratio
Element	Mass Spec. $[\frac{\mu g}{g}]$	Gamma Spec. $[\frac{\mu g}{g}]$	Avg $[\frac{\mu g}{g}]$	low $[\frac{\mu g}{g}]$	high $[\frac{\mu g}{g}]$	typical $[\frac{\mu g}{g}]$	Soil vs. WIPP
Uranium	0.048	<0.37	0.048	0.5	2.5	1.5	30
Thorium	0.08	0.25	0.25	1.2	3.7	2.4	10
Potassium	784	182	480	500	900	700	1.5

Table 4.21: Natural Radioactivity at the WIPP underground [WEB98].

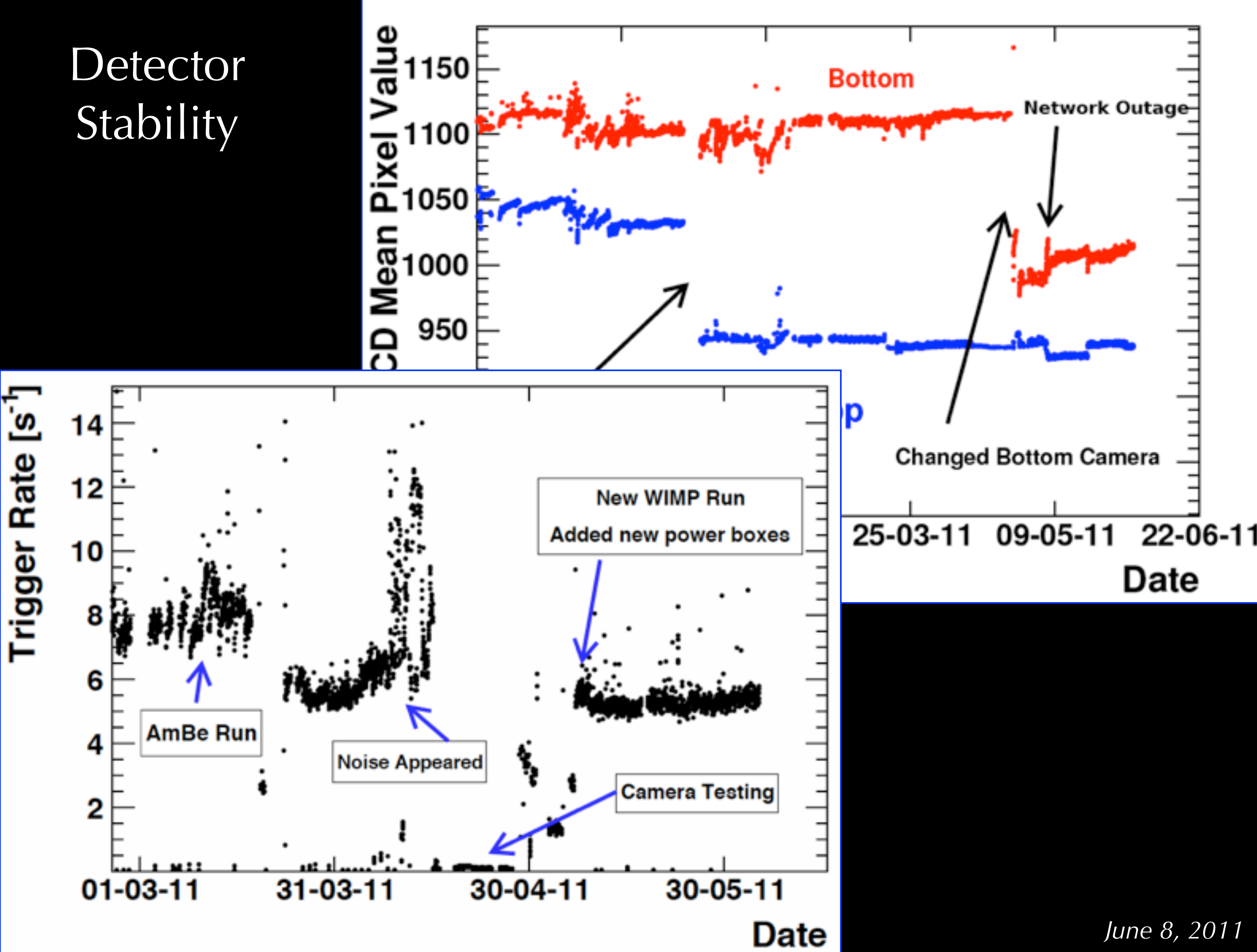
Detector Stability





June 8, 2011

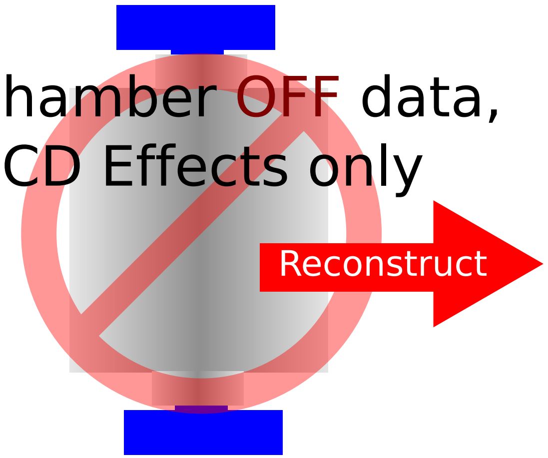
Detector Stability

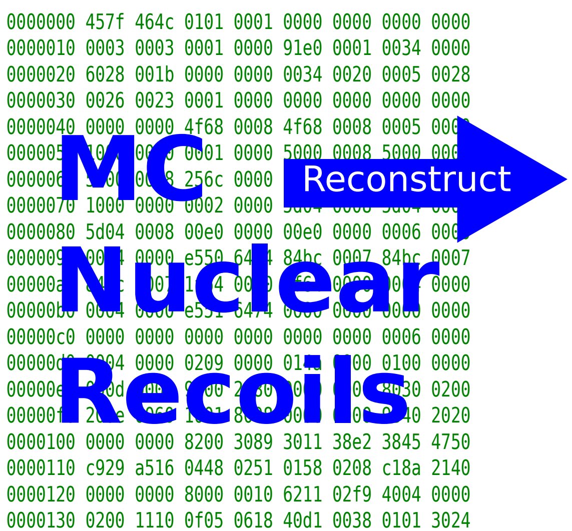


June 8, 2011

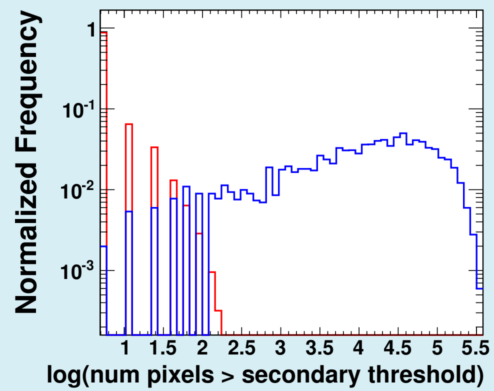
CCD Artifact Rejection Improvements

(C. Deaconu)





Discriminating Variables



projected range

pixel integral

maxpixel

pixel RMS

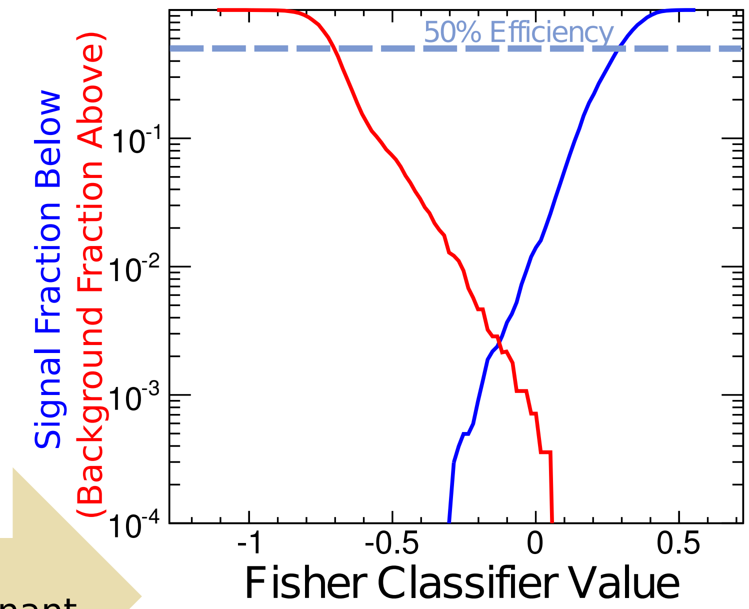
num pixels

num pixels > thresh

num maxpixel neighbors > thresh

Fisher Discriminant

Discriminating Parameter



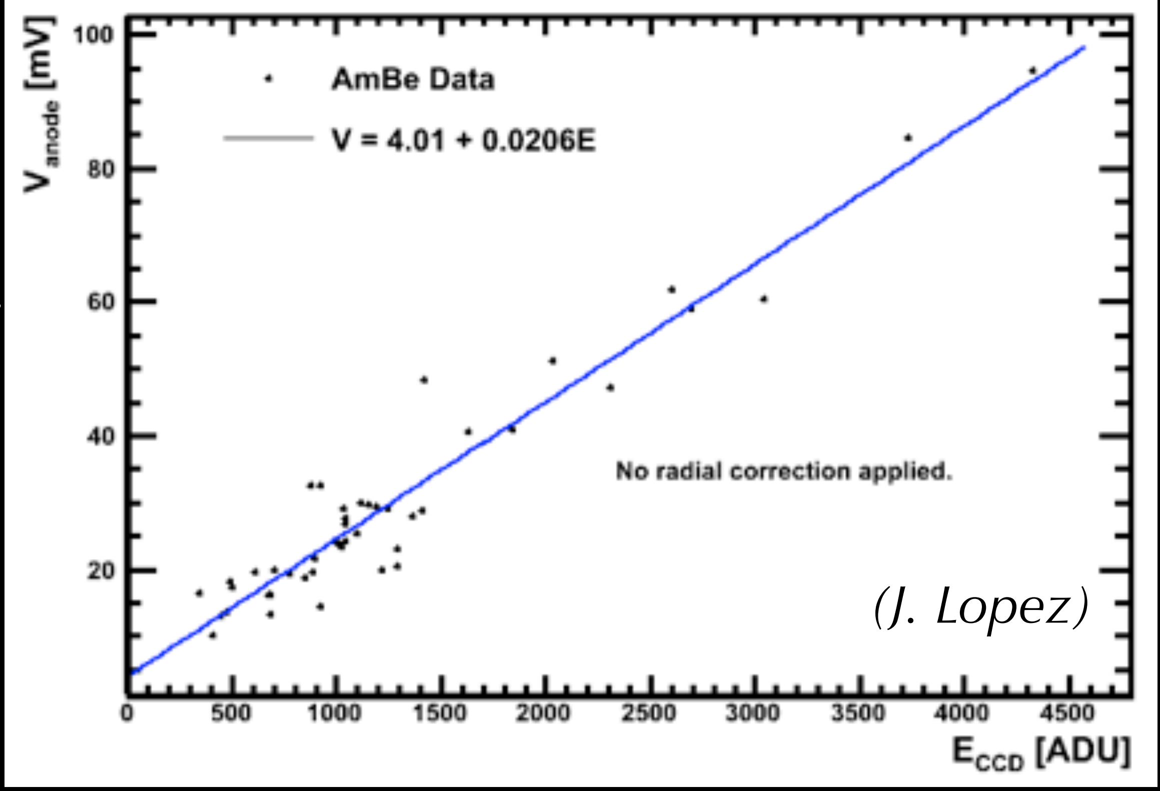
Fisher Discriminant is implemented with the ROOT TMVA framework, so can be easily swapped for a different multivariate algorithm if we find that necessary in the future.

now collect dedicated "cosmic" data set during gas re-fill for background calibration

Redundant Readout for Background Rejection

(+fiducialization and directionality, see J. Battat talk)

10L detector instrumented with charge readout of anode and mesh in December 2010 (WIPP)
(surface run analysis used no charge data)



preliminary bifurcated analysis result:

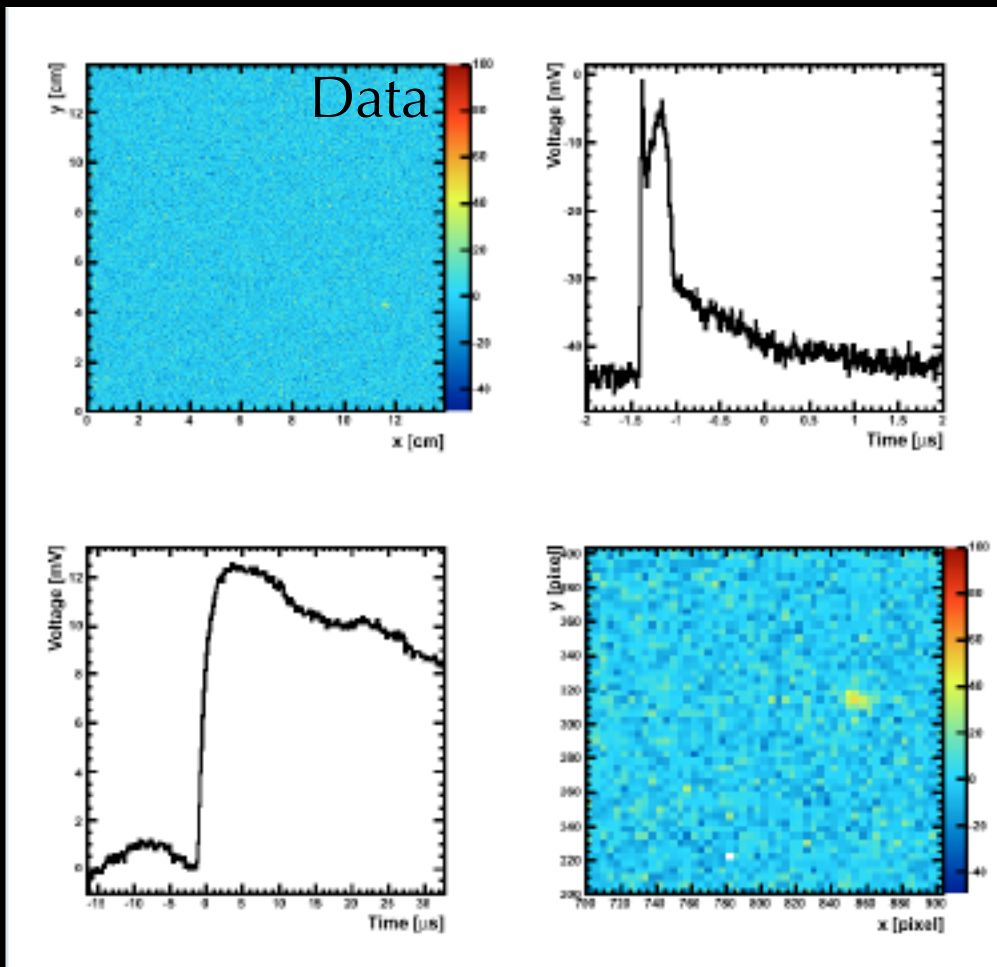
Cut	Pass CCD RBI	Pass CCD RBI & Artifact
Fail NR Charge	400	244
Pass NR Charge	4	2

require charge consistent with nuclear recoil in mesh rise time, and energy match to within 35 mV in anode amplitude, for 80 < E_recoil < 200 keVr

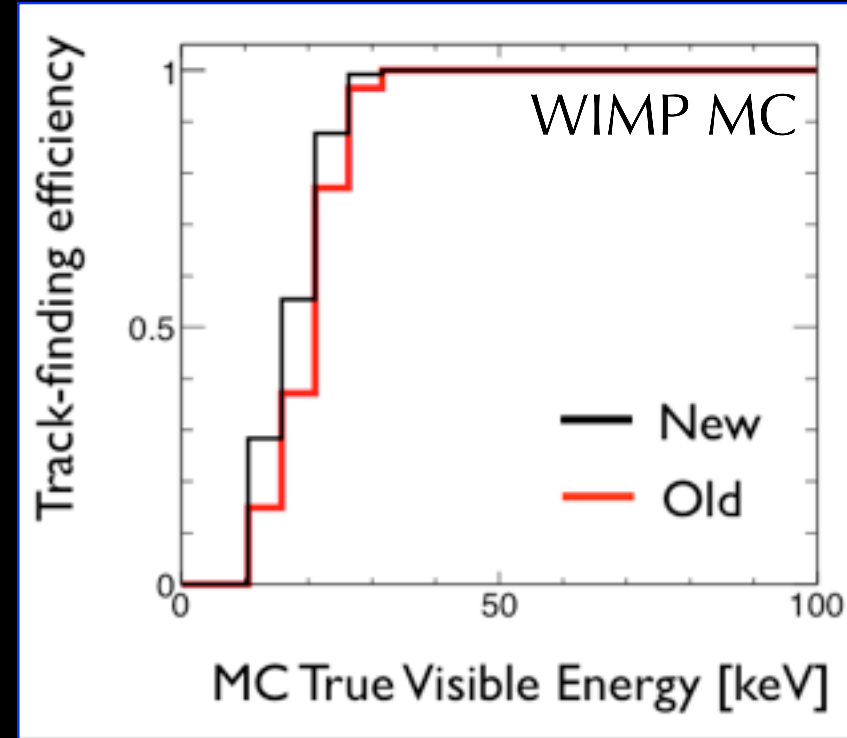
x100 rejection of non-nuclear recoil backgrounds from charge readout

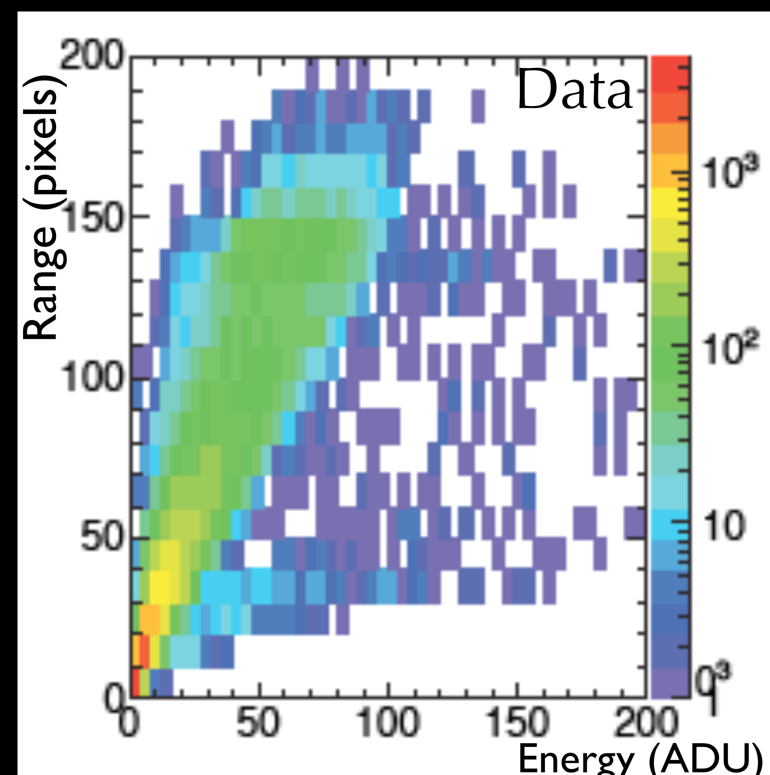
Energy Threshold Improvements

from analysis improvements to cluster-finding algorithm, and running at lower pressure (60 torr cf 75 torr), increased gain (~20 ADU/keV)



candidate **25 keV** nuclear recoil event from AmBe calibration data underground





AmBe calibration data (WIPP)

DMTPC Next Steps: DMTPCino 1m^3 Detector at WIPP

Goal:

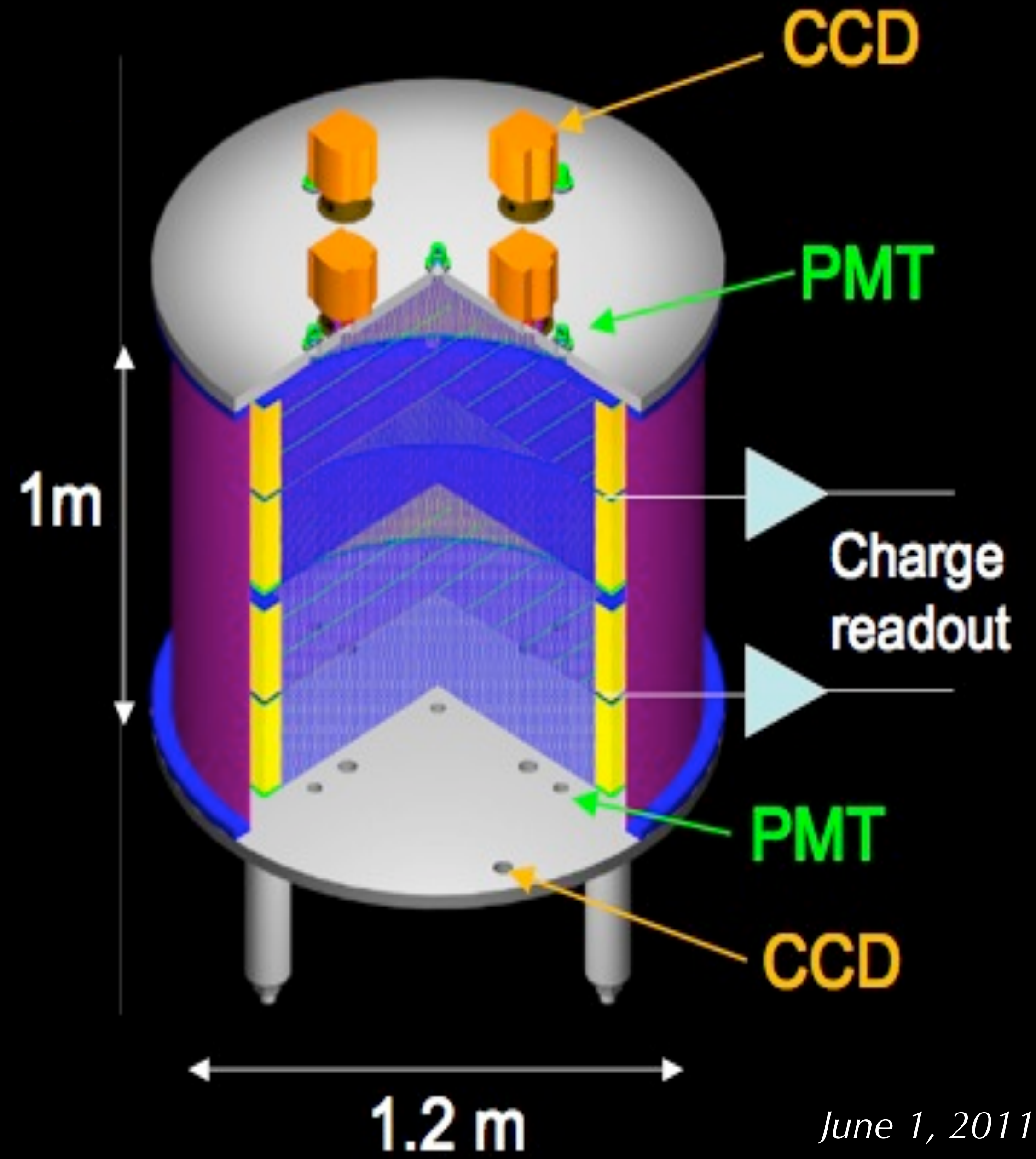
prototype for O(10 kg) fiducial mass detector, with 1 m^3 (0.25 kg) instrumented now

Require significant R&D on

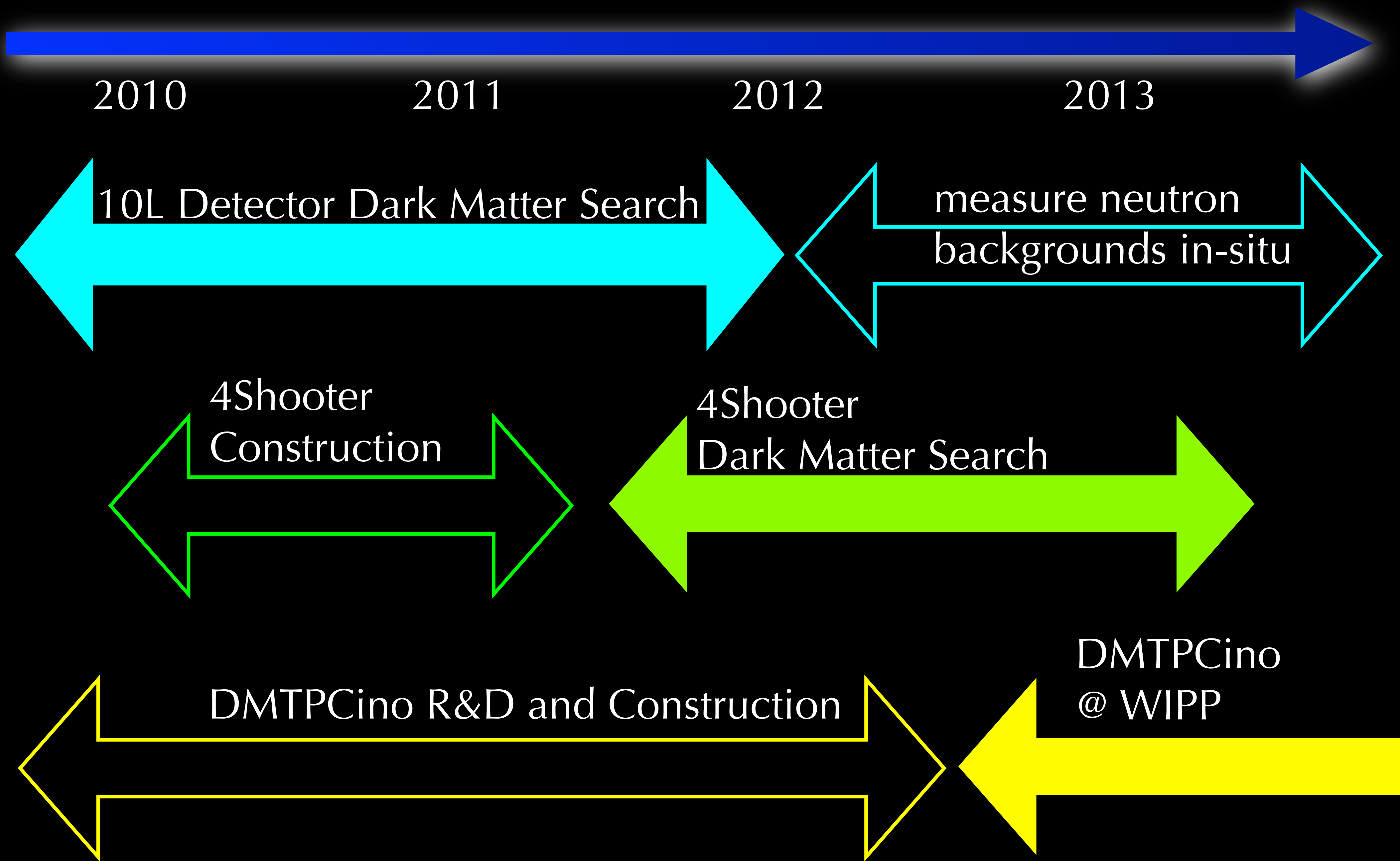
(i) readout
(ii) optical system
(iii) directional
(iv) backgrounds
(v) scalability

Proposal for capital funded by NSF and DOE (2010).

Collaboration has realized we need to grow in order to field detectors at WIPP and build DMTPCino.



Time Line


2010
2011
2012
2013
10L Detector Dark Matter Search
measure neutron backgrounds in-situ
4Shooter Construction
4Shooter Dark Matter Search
DMTPCino R&D and Construction
DMTPCino @ WIPP

Conclusions

Since Cygnus '09:

- DMTPC has gone underground, and we are learning that working underground is tough! 10L dark matter run is underway.
- developed calibration, identified and measured surface backgrounds
- published dark matter limit
- R&D on adding charge and PMT readout (J. Battat talk)

Future:

- deploy next generation detector (4-shooter) with ~3D readout
- build 1m^3 detector, prototype for O(10kg) directional experiment
- measure the neutron background angle and energy distributions underground at WIPP, use in directional dark matter search for signal above well-characterized background

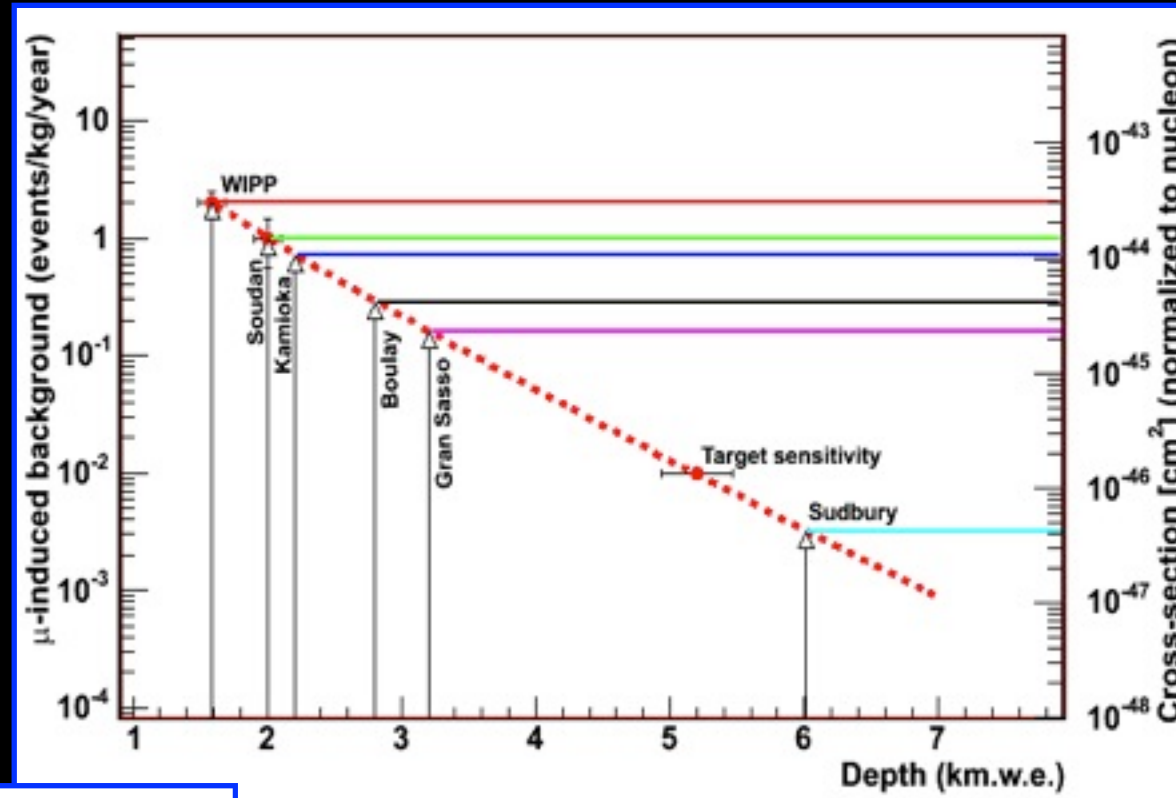
Backup Slides

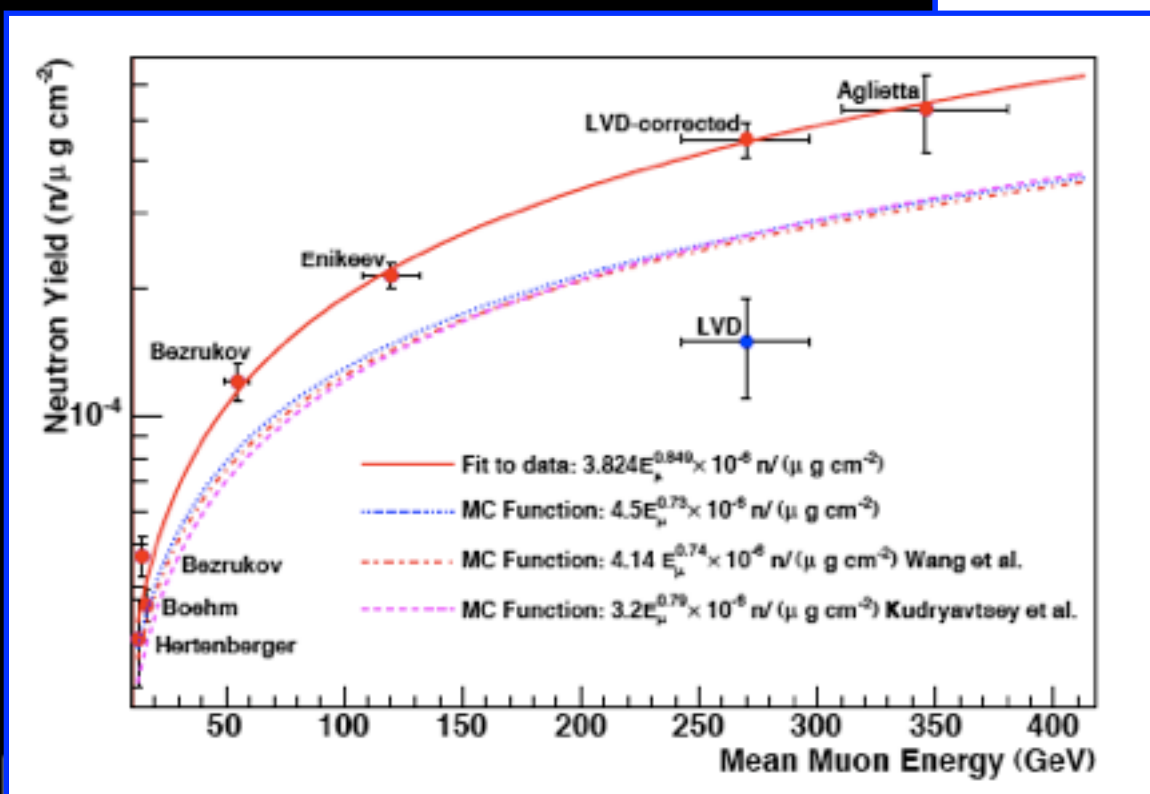
The Neutron Problem

1. can't distinguish neutron from dark matter scattering

2. neutron flux underground is poorly understood

D.-M. Mei, A. Hime, PRD73:053004 (2006)





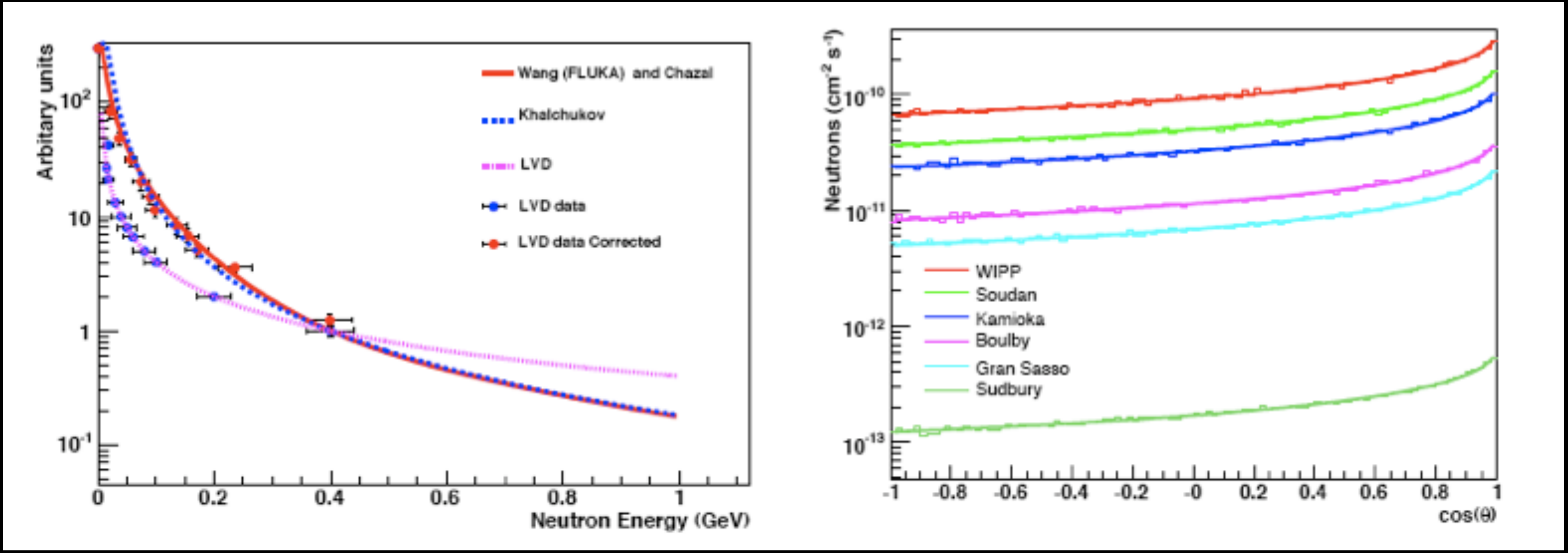
*3. **no** measurements of neutron angular distribution underground*

*4. **one** measurement of neutron energy distribution underground*

Neutron Angular Distribution

fast neutron angular distribution depends weakly on muon flux

D.-M. Mei, A. Hime, PRD73:053004 (2006)



1 year run of neutron veto detector: (2011)
-measure the absolute neutron flux >10 MeV, first high energy spectrum
-run in "active veto mode" adjacent to DMTPC 10L directional detector

1 year run of 10L DMTPC with ^{4}He target (2012)
-measure neutron angular distribution (1st measurement underground)