Direction-Sensitive Dark Matter Detection with the DMTPC Experiment

Jocelyn Monroe,
Royal Holloway University of London

CYGNUS-TPC, Frascati, IT
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J. Balewski, R. Corliss, C. Deaconu*, S. Henderson*, A. Kaboth*,
P. Fisher, J. Lopez*, M. Vargas

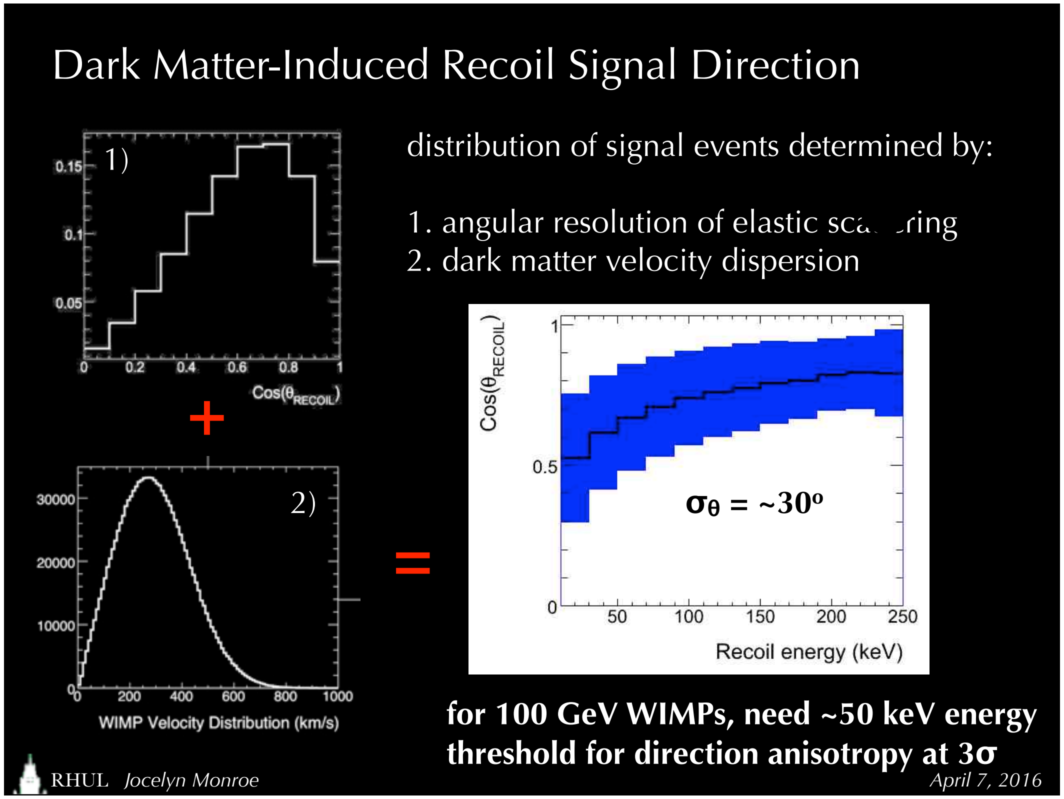
G. Druitt, R. Eggleston*, R. Elsom, M. Geary, M. Leyton, J. Monroe

Outline

Experimental Considerations

DMTPC Detector Design

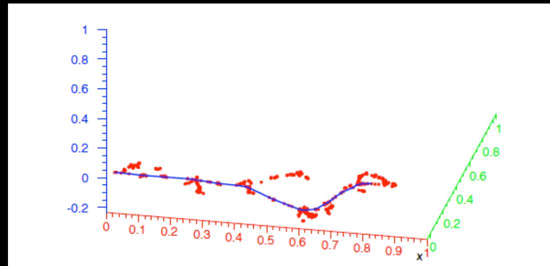
Recent Progress from DMTPC

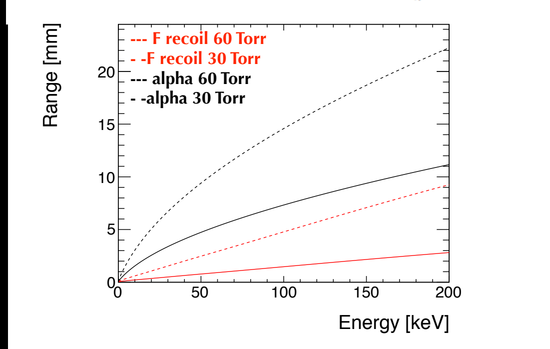


get elastic scattering angular distribution without velocity distribution? For just the mean velocity?

comment about applicability of M-B velocity distribution
comment on intrisic resolution of angular scattering

Readout Requirements: Segmentation





At 50 keV, F recoil track length is 1 mm (@ 60 Torr CF4), 2.5 mm (@ 30 Torr CF4).

As the F travels, it loses energy to the medium, which has significant fluctuations (straggling)

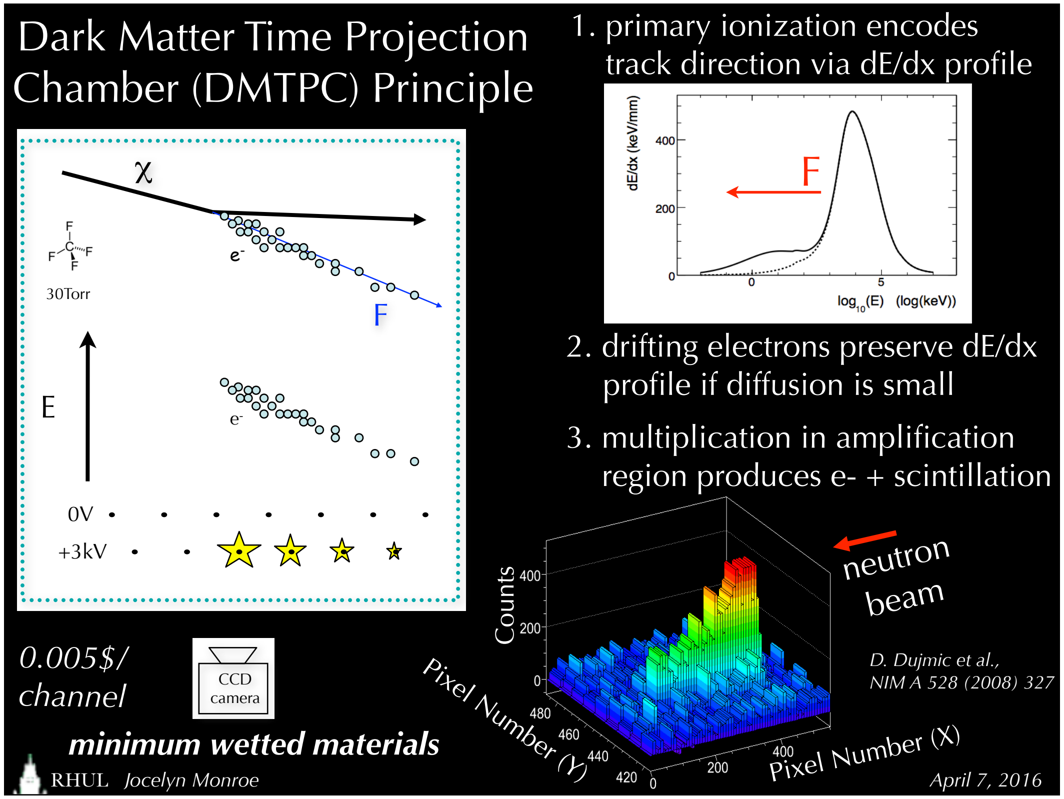
To determine the track angle requires > 2 measurements along the track, and in the presence of straggling, readout noise, etc. require more.

need >500 um resolution, for direction measurement at 50 keV recoil energy.

(and the higher the pressure, the more resolution required)

get elastic scattering angular distribution without velocity distribution? For just the mean velocity?

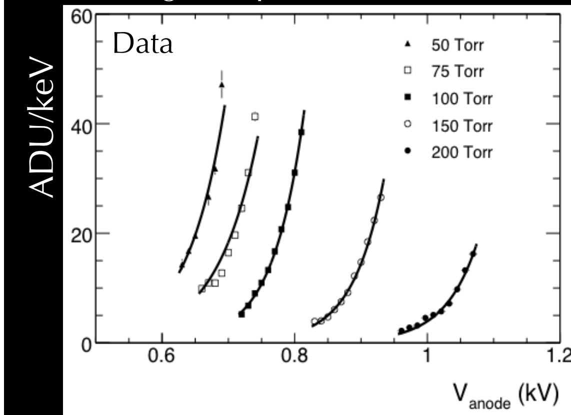
comment about applicability of M-B velocity distribution
comment on intrisic resolution of angular scattering



need the ?? explain that we will use alphas and neutrons, point them out on the Bragg curve

CCD Readout

Total light output:

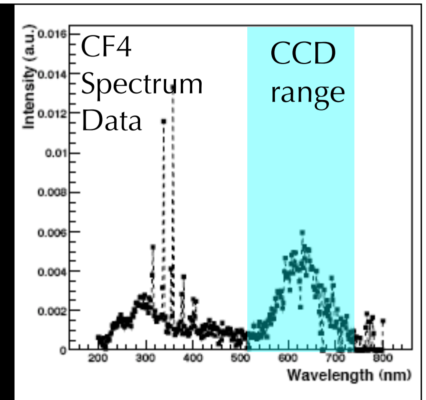


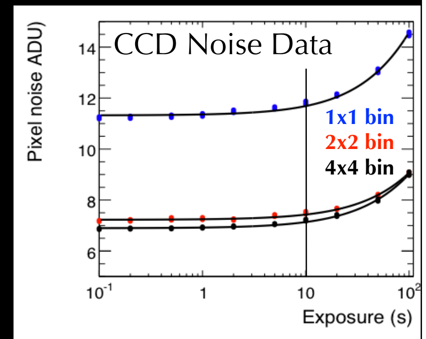
Increasing gain + track length with lower pressure, but decreasing mass!

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

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

Key to identifying low energy tracks is S:N per pixel, @50 keVr S:N~10-20



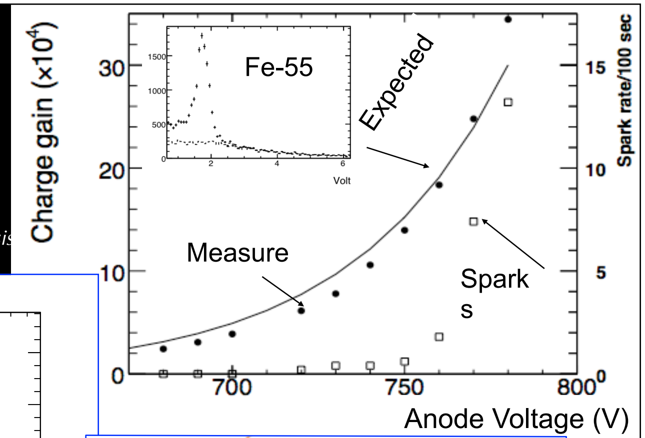


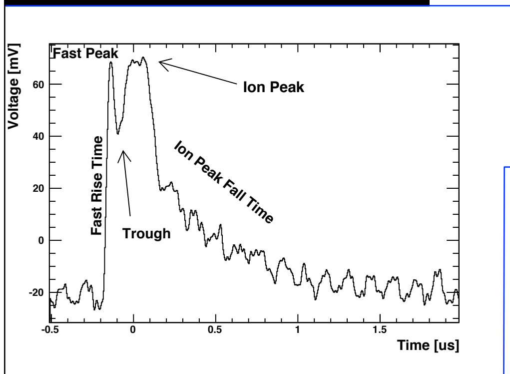
energy threshold for finding tracks depends strongly on CCD signal to noise

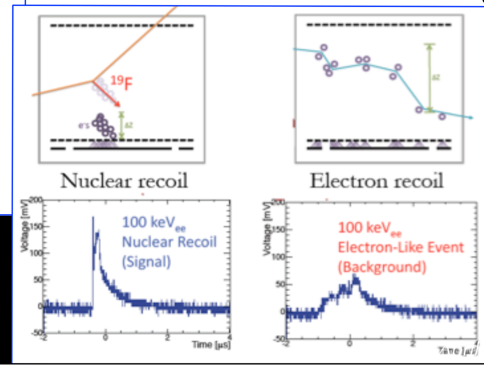
Charge Readout

Multiplication calibrated with Fe-55, anode signal amplitude

M ~ (V_{out}x1.4pC/V) / (5.9keV/W)
W = 33.8 +/- 0.4 eV *(I. Wolfe S.B.thesis*







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

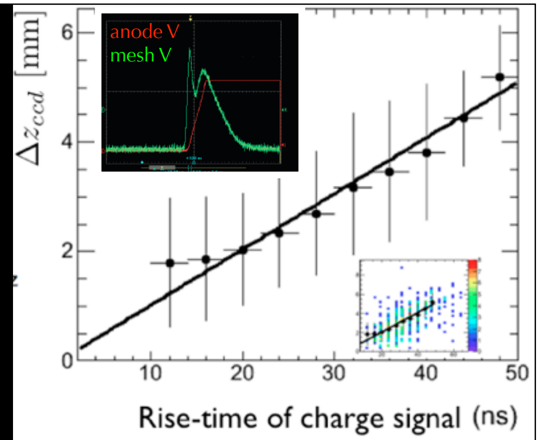
3D R&D

tracking in z (drift direction):

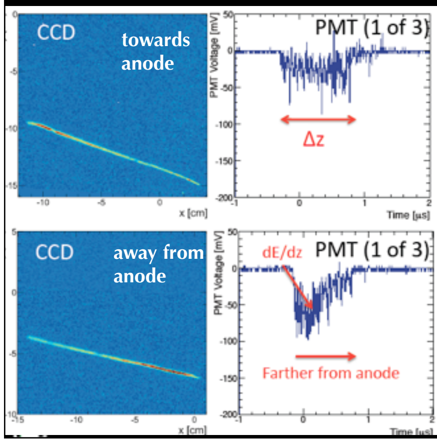
- angled alpha calibration source produces tracks of known Δz

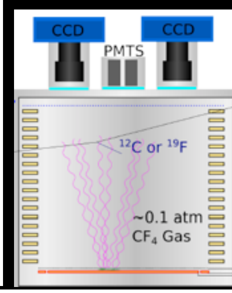
charge:

- 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)





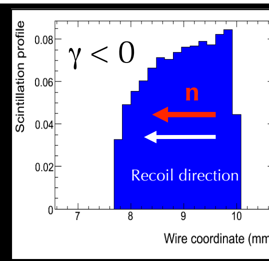
light:

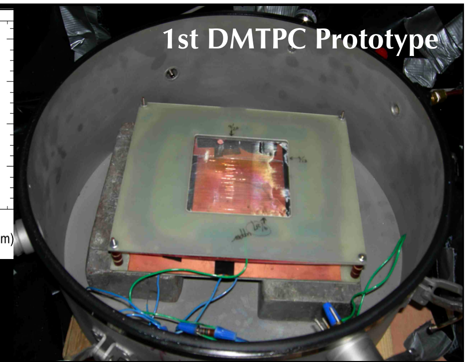
- measure PMT signal pulse width
- pulse width varies with Δz, shape varies with +/-Δz

R&D on identifying events fro
cathode using PMT readout

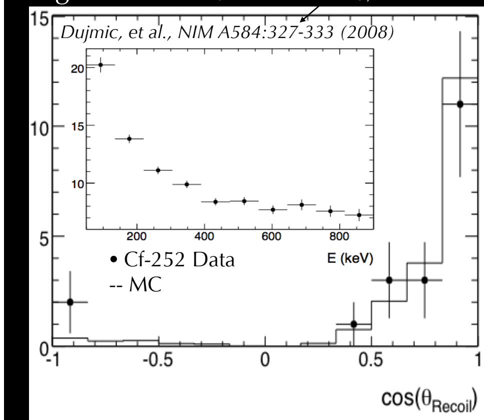
Directionality I

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



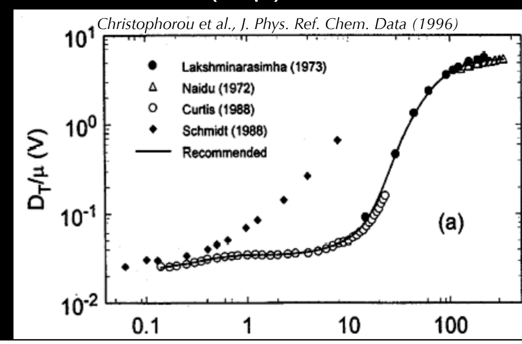


Signed cosine (E>200 keV), 5 cm drift



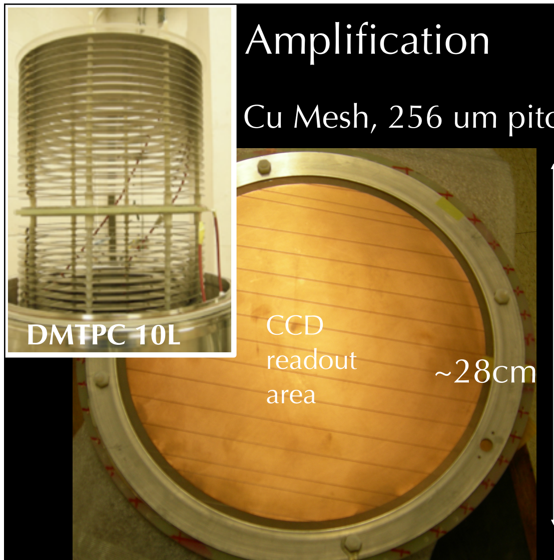
challenge to scaling up: diffusion!

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

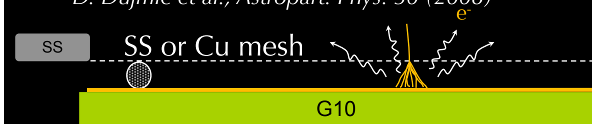


Amplification

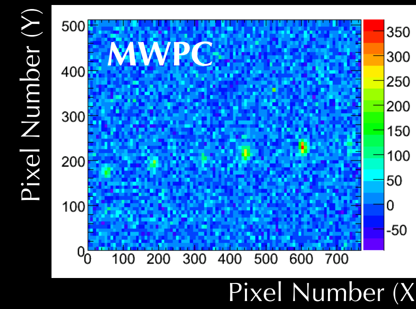
Cu Mesh, 256 um pitch

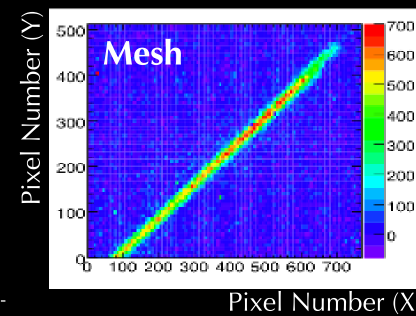


D. Dujmic et al., Astropart. Phys. 30 (2008)



Resistive separators, dia=0.5mm, every 2.5cm

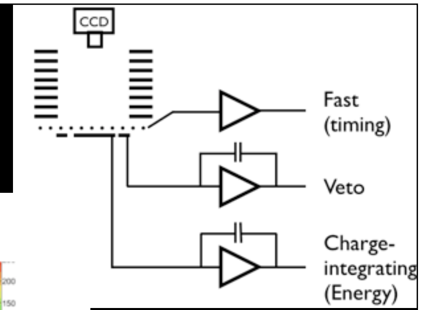


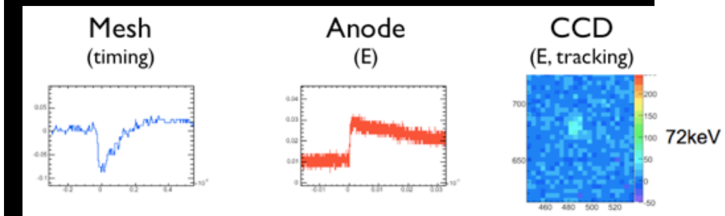


20x smaller pitch,
10x larger gain, 1->2D

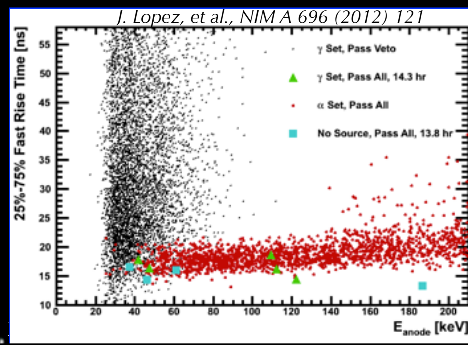
Background Rejection with Charge

optical AND charge readout rejects
CCD artifact AND gamma backgrounds
J. Lopez, et al., NIM A 696 (2012) 121

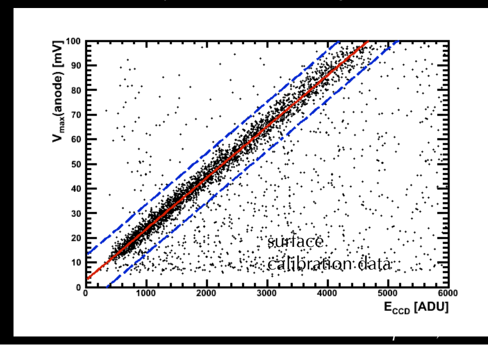




>1.1E-5 (90% CL) γ rejection from rise time vs. E:

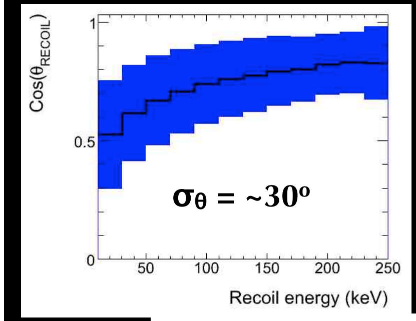


~10^2 rejection from E_{charge} vs. E_{CCD}:

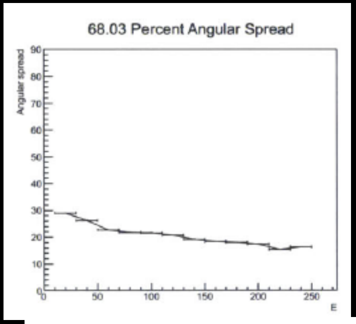


Impact of Detector Physics on Signal Directionality

recoil kinematics:

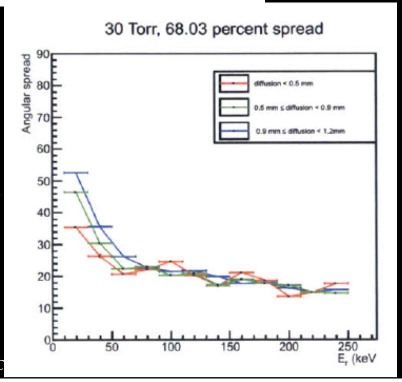


+ straggling:

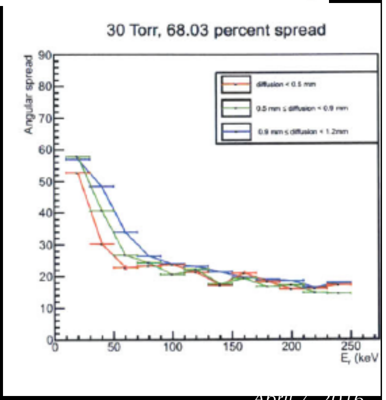


σ_θ of recoil direction, relative to initial track direction
~25° @ 50 keV

2) + diffusion:
σ_θ ~30° @ 50 keV

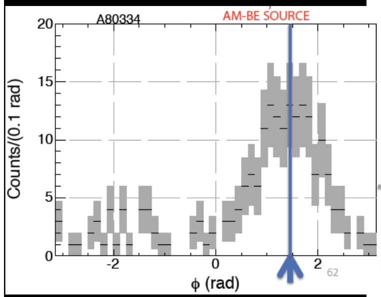


3) + TPC gain and 500 um readout pitch
σ_θ ~35° @ 50 keV

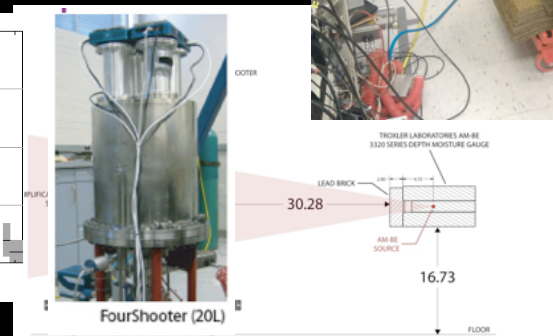


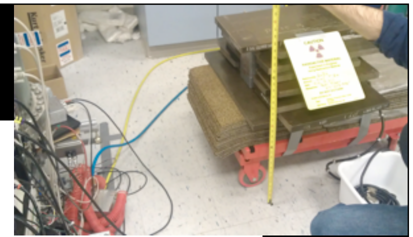
Direction Calibration

Need a source of known energy and angle



S. Henderson, PhD thesis (2013)

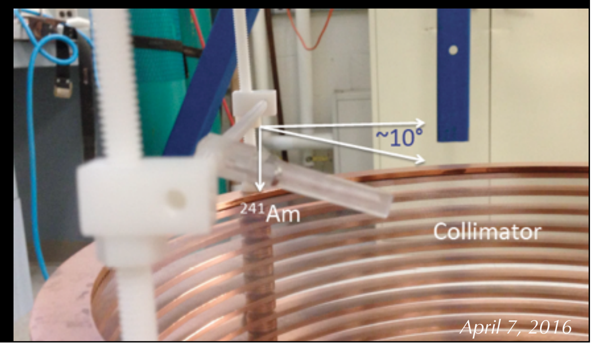




But, neutron scattering kinematics produce wide range of angles, and neutrons are hard to collimate.

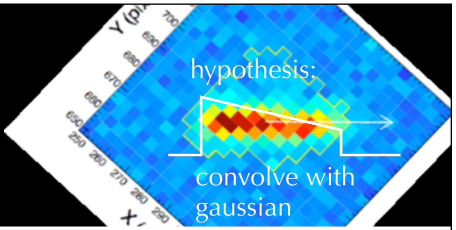
Angled alpha calibration:

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



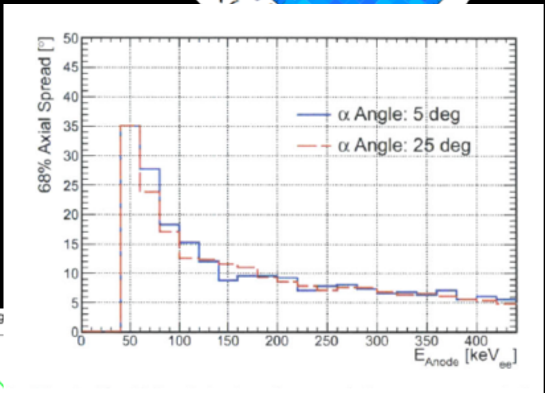
add AmBe column to this table

Track Reconstruction



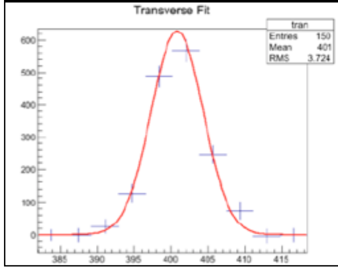
Measure energy from track intensity integral

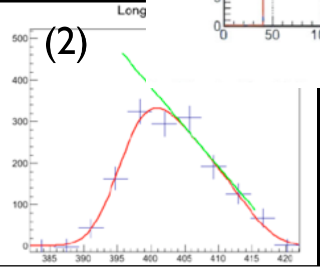
Make use of the known profile of nuclear recoils from the Bragg curve to
(1) fit for the track parameters
(range, angle)
(2) fit for the head-tail (H-T)
(3) assign confidence in H-T determination with likelihood ratio of two possible senses, cut on confidence



J. Lopez, PhD thesis (2014)

C, Deaconu, PhD thesis (2015)



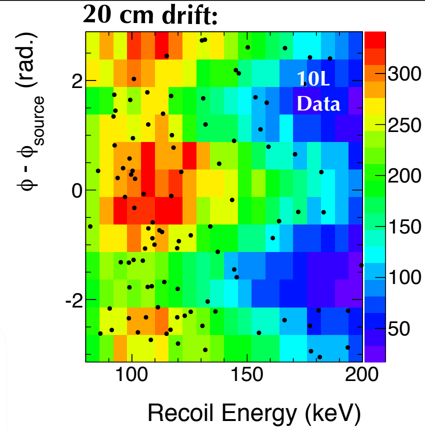


Directionality II

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,

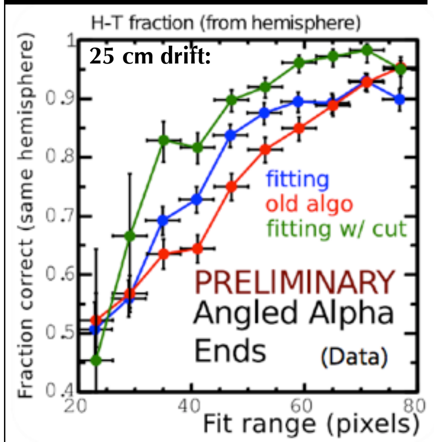
C. Deaconu, PhD (2015), Phys. Procedia 261 (2015) 39



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

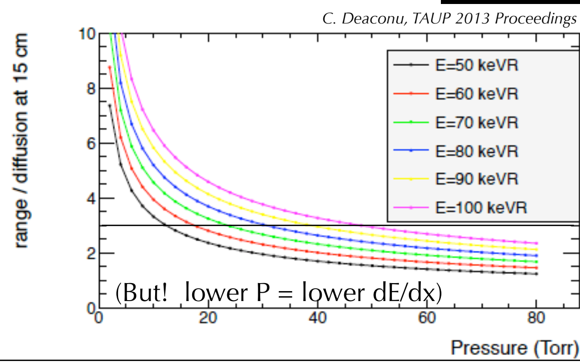
MC: 40^{o} resolution at 80 keVr

A. Kaboth PhD thesis (2012)



Energy range equivalent ~50-200 keV

C. Deaconu, TAUP 2013 Proceedings



Signal:Noise

Lower P gives longer range (good), higher gain (good), but lower dE/dx at fixed E (bad)

Signal size:

$$S = \frac{(\frac{E \times q}{w}) \times G \times (\gamma/e^-) \times \rho \times QE \times \eta}{N_{pixels/track}} \tag{11}$$

Where:

- E = 50 keV the target nuclear recoil energy threshold at which DMTPC wants to be able to reconstruct the direction of tracks well
- q = 0.6 is the gas quenching and is defined as the fraction of energy released by a recoil in a medium through ionization compared with its total kinetic energy [14]
- w = 34 eV represents the mean energy required to produce an ion/e^- pair in CF_4, work function of the gas [7]
- G = 10^5 is the gas gain
- γ/e^- = 0.3, is the number of photo-electron pairs created as a result of the scintillation light produced
- ρ is the geometric acceptance of the lens
- η = 0.64 is the combined anode (0.8), cathode (0.9) and detector window (0.9) transparency

Noise size:

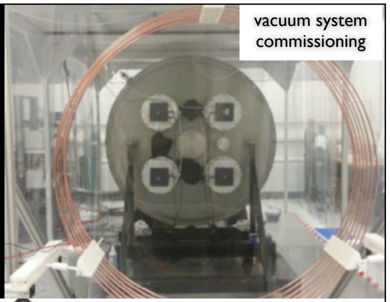
$$N_{total} = \sqrt{N_{Shot}^2 + N_{readout}^2 + N_{Dark}^2}$$

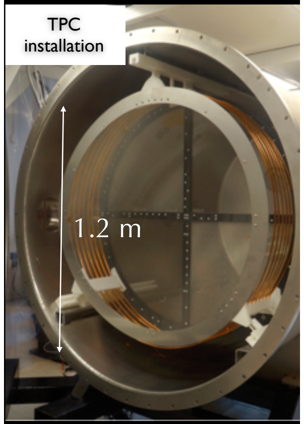
To increase S:N: 1) increase geometric acceptance, 2) increase gas gain, 3) reduce N

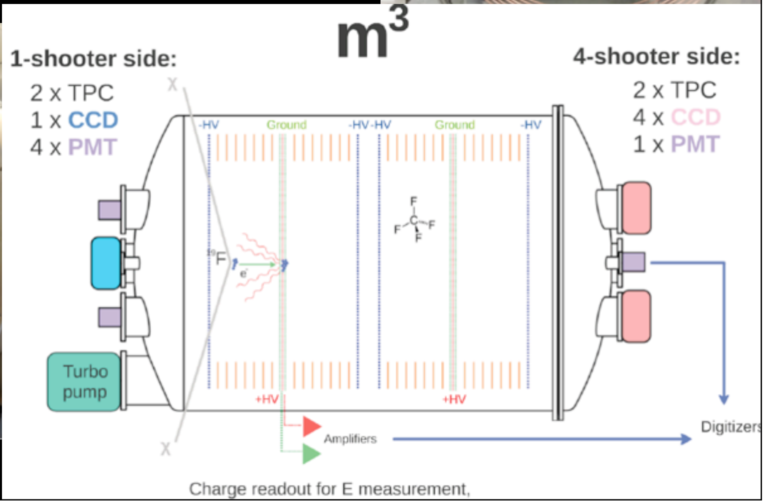
DMTPCino: m3 Module

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^o resolution at 50 keVr in 1m^3 module, and
R&D: 1 camera+lens/side (~0.005$/channel now)







Optical System R&D: Large Area Optical Readout

comparison of 4shooter prototype vs. DMTPCino optical systems S:N

prototype: 4x Alta CCD + Canon f/1.2lens

DMTPCino: 4-CCD side: Proline9000 CCD (0.01 e/pix/s dark rate) + Nikon f/0.95 lens
1-CCD side: Fairchild 486 CCD (0.0001 e/pix/s dark rate) with quad readout + large angle-of-view Canon f/0.95 lens

calculation inputs:

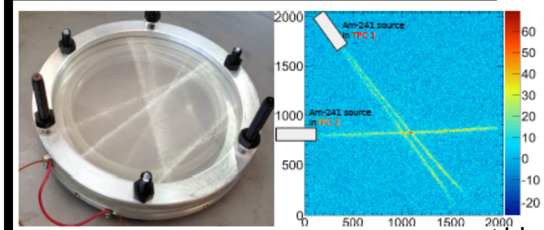
- 30 Torr pressure: 2.5 mm long track, 1 mm wide @ 50 keVr to estimate S/pixel
- gas gain = 100,000k for DMTPCino, vs. 65,000 gain for prototype
- dark current rate and read noise from camera specs
- measured scintillation spectrum, Y/e-, lens transmittance vs. wavelength, lens vignetting

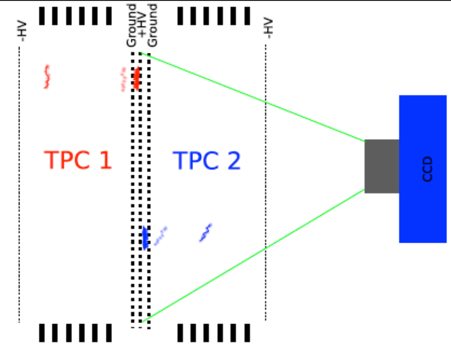
Lens/Camera	F(cm) / f#	pixel (um)	sensor diag. (cm)	FoV (cm)	m	acceptance (rho)	read noise (e-)	vixel size (um) (map to 1 pixel)	S/N (e-/e-)
1-CCD side	5/0.95	15	6.14	$(113)^2$	18	2E-04	7	276	189/16 = 12
4-CCD side	5/1.2	12	3.66	$(57)^2$	16	2E-04	10	243	95/14 = 6.8
prototype	8.5/1.2	24	2.45	$(16)^2$	6.7	5E-04	10	160	87/13 = 6.3

empirically: S:N>15 results in ~20 keVr track-finding threshold -> bin 2x2 before readout
nb. big potential gain in acceptance, using astronomy solutions beyond lenses
(fiber plate, Q focussing optics,++)

Gas Gain R&D

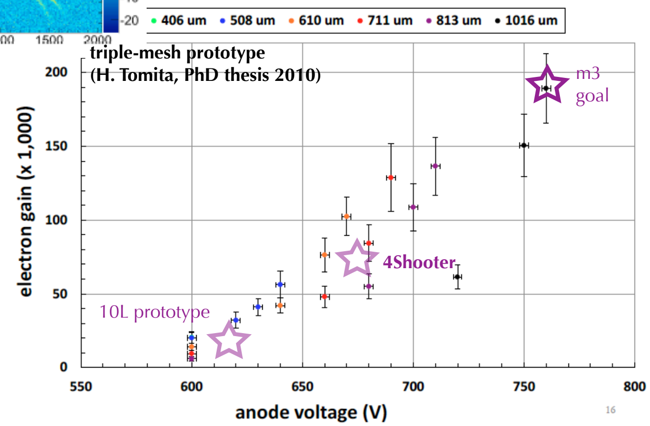
triple mesh amplification: one camera images 2x 25 cm drift regions





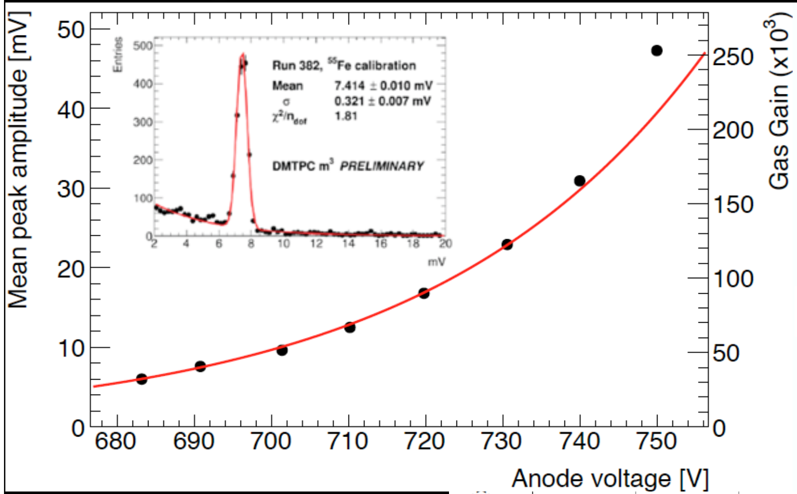
demonstrated high gain in small prototypes, 50-200k

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 (2010)

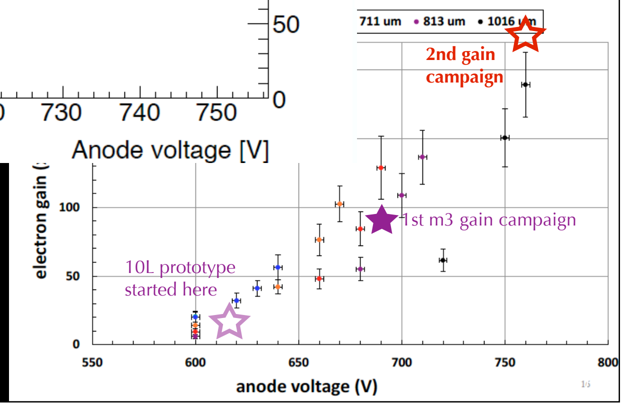


Recent Progress: Gas Gain Calibration

higher gain = lower energy threshold.



Fe-55 source (5.9 keV) deployed to measure absolute gas gain vs. anode voltage, at 30 Torr operating pressure.

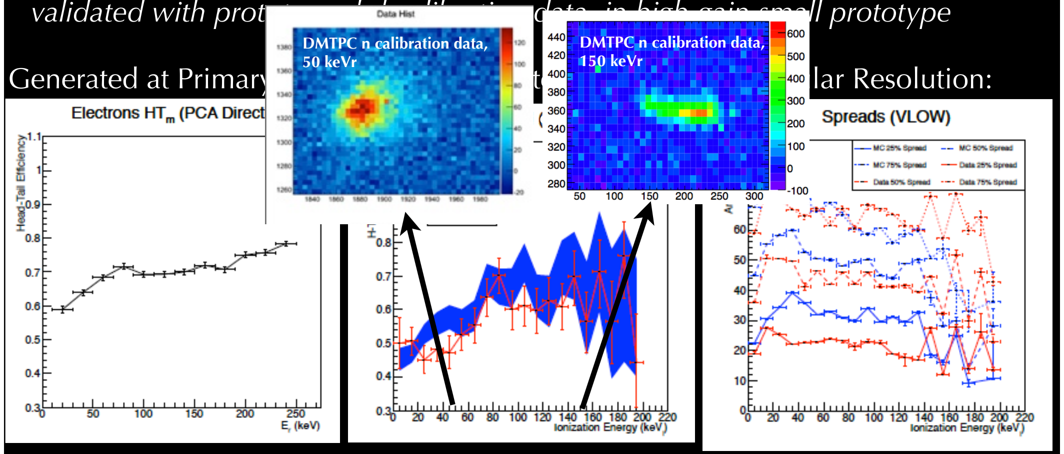


result: gain>250,000 can be achieved = factor of 4x higher than previous operating point of 65,000 (in 4shooter prototype), 25x 10L prototype operating point.

Full Microphysics Simulation

validated with prot[...] data, in high gain small prototype

Generated at Primary [...] lar Resolution:



C. Deaconu, PhD thesis (2015)

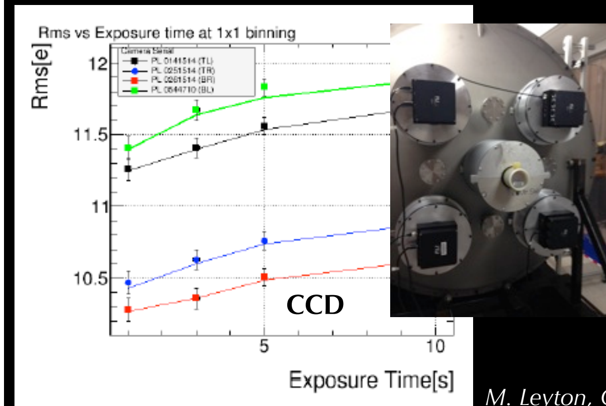
Bottom lines:

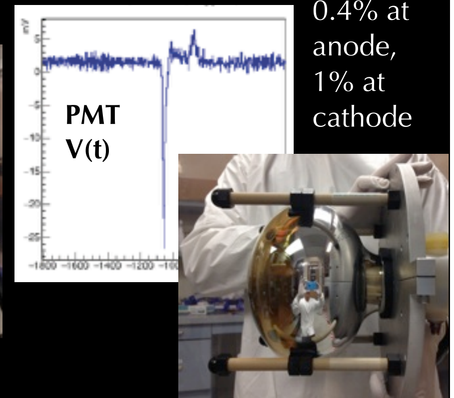
- we are reconstructing direction (including head-tail) at ~physics limit from straggling of primary F ion. Need to reduce ion straggling! He?
- axial resolution is ~40 degrees (FWHM) at 50 keVr
- TRIM MC predicts ~50% larger spread in angle than we observe

Recent Progress: Integration of all Readout Channels

Optical: CCD + PMT

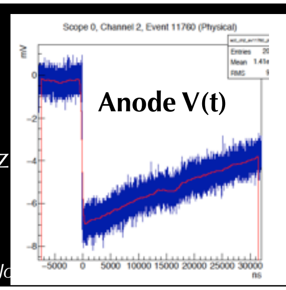
PMT dΩ 0.4% at anode, 1% at cathode

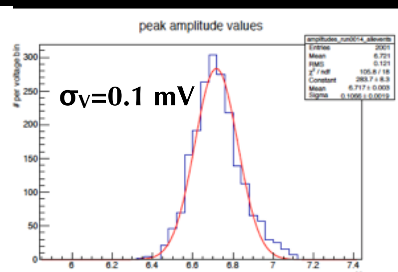


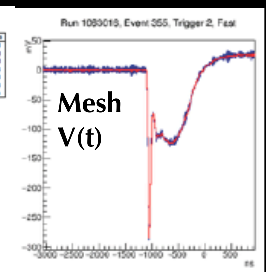


M. Leyton, G. Druitt, N. Guerrero

Charge: Anode + Mesh @ 500 MHz readout





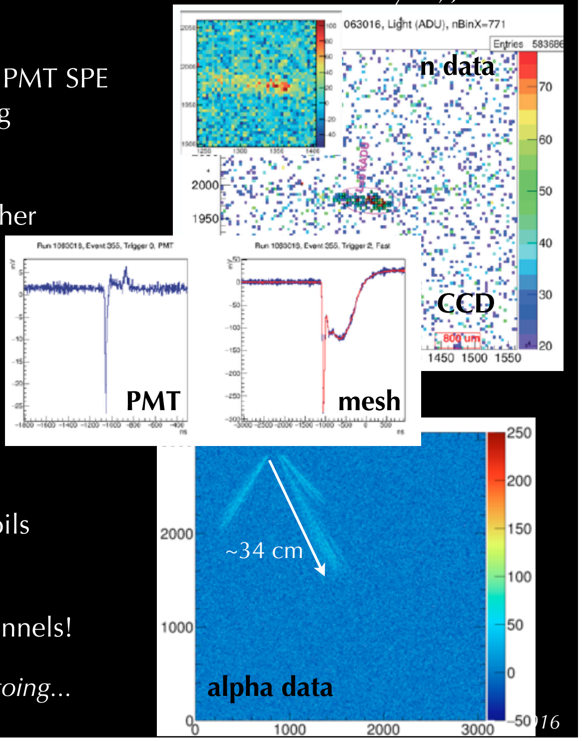


Recent Progress: DMTPCino Calibration

M. Leyton, J. Balewski

- in-situ CCD and charge noise, ex-situ PMT SPE
  - -per-pixel threshold for cluster-finding
- absolute gas gain (Fe-55)
  - -stable operation at 150k, can go higher
  - -gain stability vs. time at few % level
- gain uniformity (Fe-55,Cs-137)
  - -continuous operation over 4 weeks, detector stability to <1 ADU
- system absolute gain calibration
  - -3-4.5 MeV alphas, lower energies produced with same source, mylar foils
- direction calibration (external AmBe)
  - -coincident signals in all readout channels!

ongoing...



Conclusions and Outlook

- DMTPC has demonstrated <35º angular resolution with 25 cm diffusion

- In the process of moving from small prototypes to ‘physics-scale’ detector module. Commissioning of DMTPCino underway…
  - demonstrated 4x increase in gas gain
  - coincident readout of charge (fast, slow), light (fast, slow) signals powerful for background rejection.
    - Next: incorporate fast signals into direction reconstruction.

- *main challenge*: achieve resolution + head-tail, at lower energy threshold

- Exploring applications to neutrino scattering physics

counting

Diffusion Measurement

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

- fit for two terms: $\sigma_T^2(z_{DRIFT}) = \sigma_{T,0}^2 + 2\left(\frac{D_T}{\mu}\right)\left(\frac{z_{DRIFT}}{E}\right)$

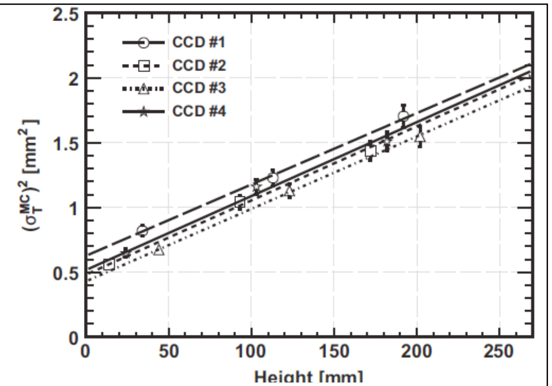
- find z-dependent term consistent with literature recommended value

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

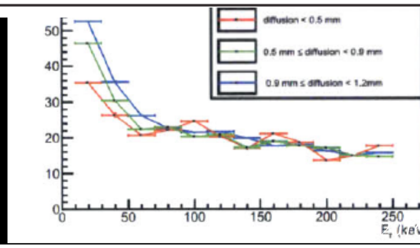
- constant (straggling) term dominates until z~20cm, and z=25 cm for σ^2_T<1mm

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

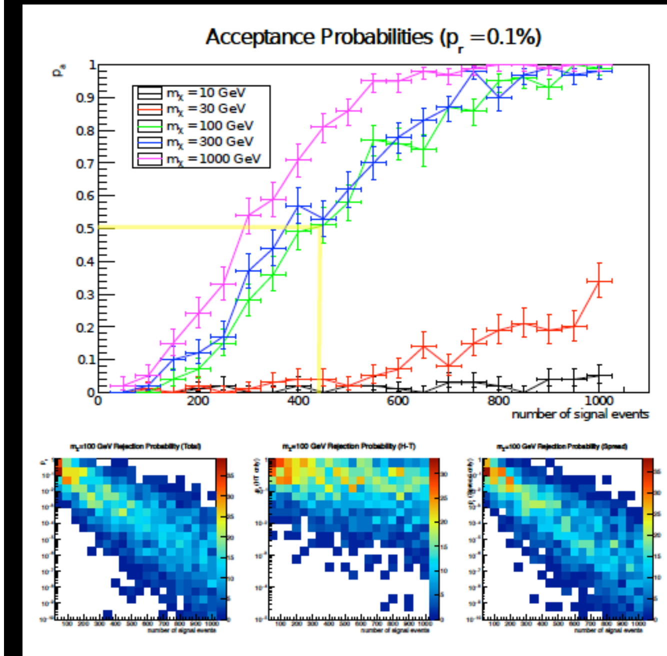
- sets a maximum drift length per TPC to be ~25 cm to preserve track direction



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



DMTPCino Sensitivity Projection



<u>Analysis assumptions</u>

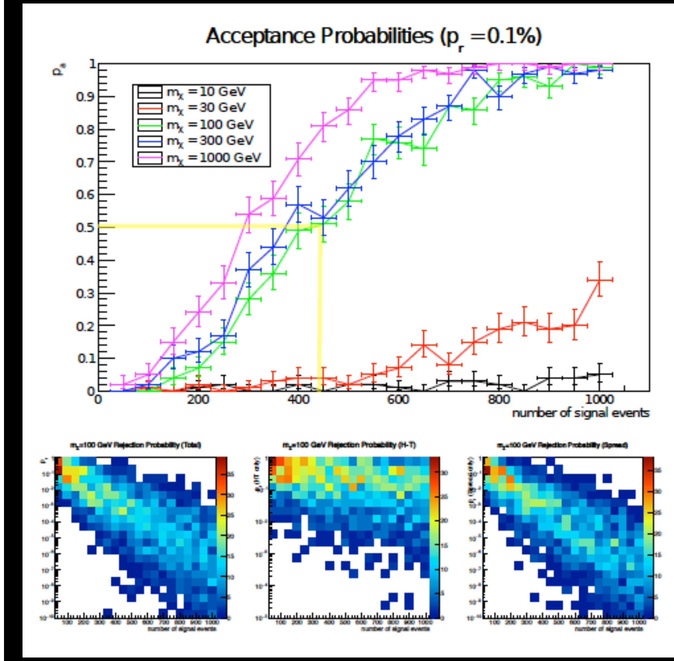
- Use physics model tuned on data, assume 100k gain

- simulate *n* experiments, compute forward fraction and axial spread per bin

- calculate *p* of obtaining these values from isotropic distribution, and combine bins using Fisher's method

- Result: need 450 events to measure anisotropy at 3σ in >50% of experiments.

DMTPCino Sensitivity Projection

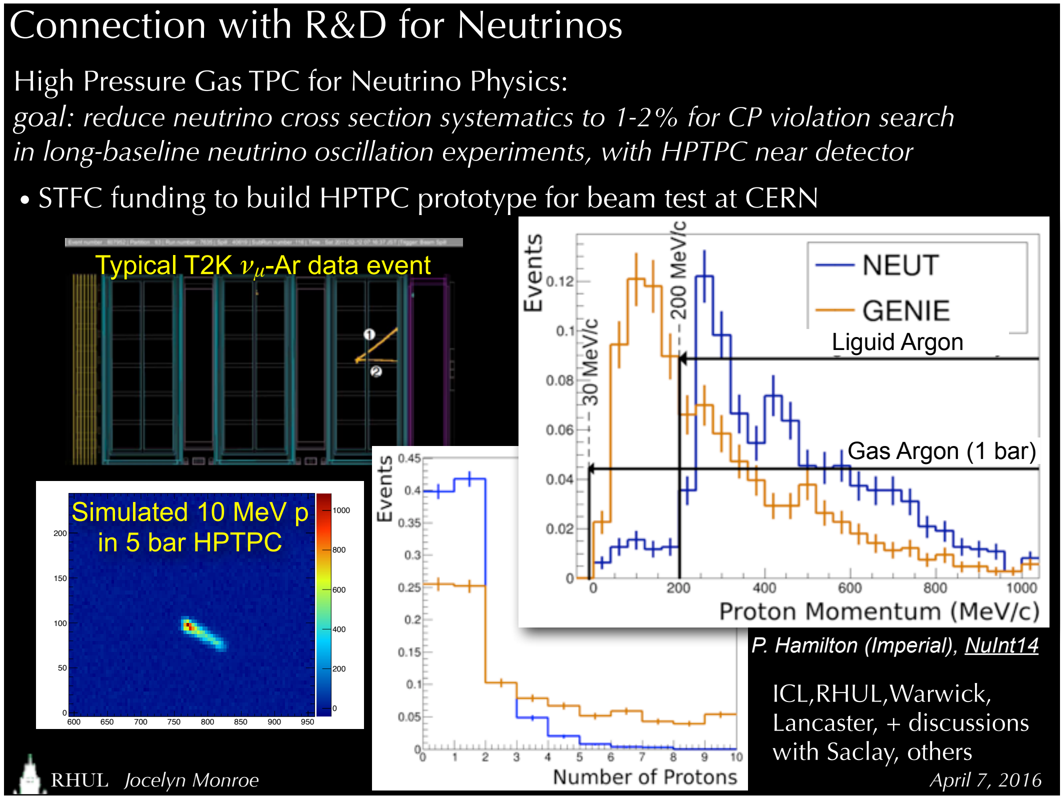


<u>Analysis assumptions</u>

e.g. DEAP veto: 200 m^3

- Result: need 450 events to measure anisotropy at 3σ in >50% of experiments.

(= 500 [300] m3-years for 100 (1000) GeV/c^2 DM at 1 fb SD xsec on F)
(=25 kg-years)



Development of large mass detectors for low-energy neutrinos and dark matter may allow supernova detection via neutrino-nucleus elastic scattering. An elastic-scattering detector could observe a few, or more, events per ton for a galactic supernova at 10 kpc (3.1 °—10$_{20}$ m). This large yield, a factor of at least 20 greater than that for existing light-water detectors, arises because of the very large coherent cross section and the sensitivity to all flavors of neutrinos and antineutrinos. An elastic scattering detector can provide important information on the flux and spectrum of
$_{\mu}$ and

from supernovae. We consider many detectors and a range of target materials from ^{4}He to ^{208}Pb. Monte Carlo simulations of low-energy backgrounds are presented for the liquid-neon-based Cryogenic Low Energy Astrophysics with Noble gases (CLEAN) detector. The simulated background is much smaller than the expected signal from a galactic supernova.

Event Rates of Solar and Geoneutrino ν-N Coherent Scattering

TABLE I: Ambient sources of neutrinos. Fluxes are given in number per cm^2 per second.

Source	Predicted flux
[41] Solar ν pp	5.99×10^{10}
[41] Solar ν CNO	5.46×10^{8}
[41] Solar ν ^{7}Be	4.84×10^{9}
[41] Solar ν ^{8}B	5.69×10^{6}
[41] Solar ν h.e.p.	7.93×10^{3}
[45] Atmospheric $\nu+\bar{\nu}$	$O(1/E(GeV)^{2.7})$
[44] Diffuse Supernovae	$T_\nu \approx 8$ MeV

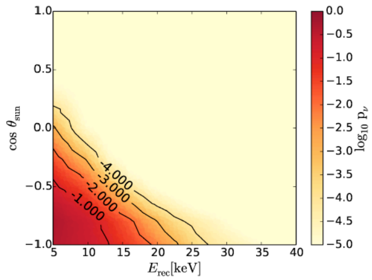
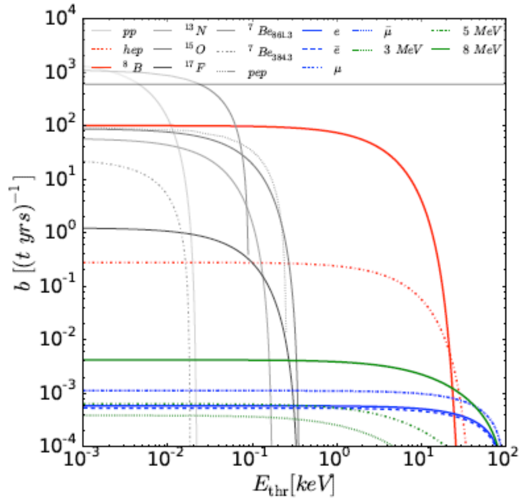


FIG. 5: The two dimensional probability distribution ρ of recoil energy and event angle of neutrinos in a CF_4 detector with 5 keV threshold.



Grothaus, Fairbairn, Monroe (2014)

FIG. 4: Neutrino event rate in a CF_4 detector. For this plot a perfect energy efficiency and an upper threshold of 100 keV

Event Rates of Solar and Geoneutrino ν-e Elastic Scattering

TABLE II: Predicted and measured (unoscillated) solar ν_e flux in units of $cm^{-2}\ \mu s^{-1}$, from [16] and [23–25], respectively.

Source	Predicted Φ	Measured Φ
pp	5.99×10^4	$(6.6 \pm 0.7) \times 10^4$
^{7}Be	4.84×10^3	$4.75^{+0.26}_{-0.22} \times 10^3$
CNO	5.40×10^2	$< 7.7 \times 10^2$
pep	1.42×10^2	$(1.6 \pm 0.3) \times 10^2$
^{17}F	5.84	–
^{8}B	5.69	$5.02^{+0.17}_{-0.19}$
hep	7.93×10^{-3}	–

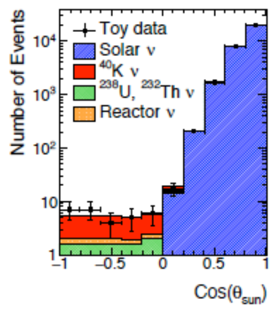
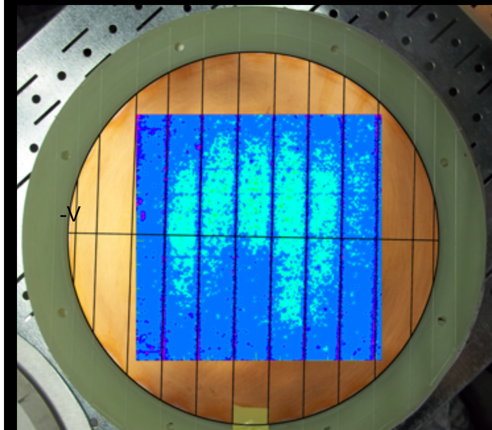


TABLE III: Predicted number of solar ν, reactor $\overline{\nu}$ and geo-$\overline{\nu}$ events per metric-ton-year exposure vs. electron energy, assuming a CF_4 target and 55% probability of oscillation into ν_μ or ν_τ. Geo-$\overline{\nu}_e$ rates are calculated using the normalization at Gran Sasso from Table I.

Source	Total	> 150 keV	> 300 keV	> 500 keV
solar *pp*	435.3	63.3	0.00	0.00
solar ^{7}Be	161.8	119.7	82.3	35.8
solar CNO	18.3	13.7	9.71	5.56
solar *pep*	9.21	7.98	6.74	5.22
solar ^{8}B	1.99	1.93	1.88	1.82
solar ^{17}F	2.47×10^{-1}	1.96×10^{-1}	1.50×10^{-1}	9.87×10^{-2}
solar hep	4.01×10^{-3}	3.92×10^{-3}	3.88×10^{-3}	3.79×10^{-3}
solar ν total	626.8	206.9	100.8	48.5
reactor $\overline{\nu}$	2.23×10^{-2}	1.84×10^{-2}	1.45×10^{-2}	1.16×10^{-2}
^{238}U	7.18×10^{-2}	4.69×10^{-2}	3.13×10^{-2}	1.89×10^{-2}
^{235}U	2.56×10^{-3}	1.48×10^{-3}	8.83×10^{-4}	4.19×10^{-4}
^{232}Th	5.00×10^{-2}	3.08×10^{-2}	2.05×10^{-2}	1.22×10^{-3}
^{40}K	3.67×10^{-1}	2.04×10^{-1}	1.09×10^{-1}	4.36×10^{-2}
geo $\overline{\nu}$ total	4.92×10^{-1}	2.83×10^{-1}	1.61×10^{-1}	7.51×10^{-2}

Leyton, Dye, Monroe (in preparation)

CCD Length and Energy Calibration

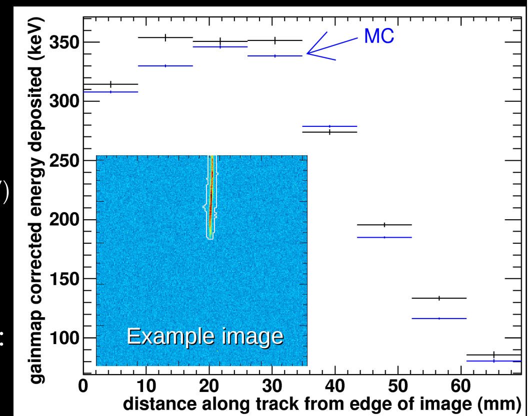


illuminate with Co-57 (122,137 keV) and Cs-137 (662 keV) for length calibration

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

α sources for energy calibration (4.4 MeV)

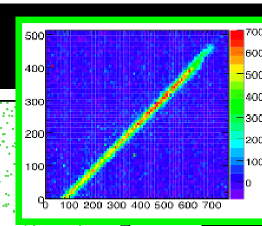
measure gain (ADU/keVee) by comparing **α** energy measured in external solid state detector with energy in CCD, at track end:
typical gain ~ 20-40 ADU/keV

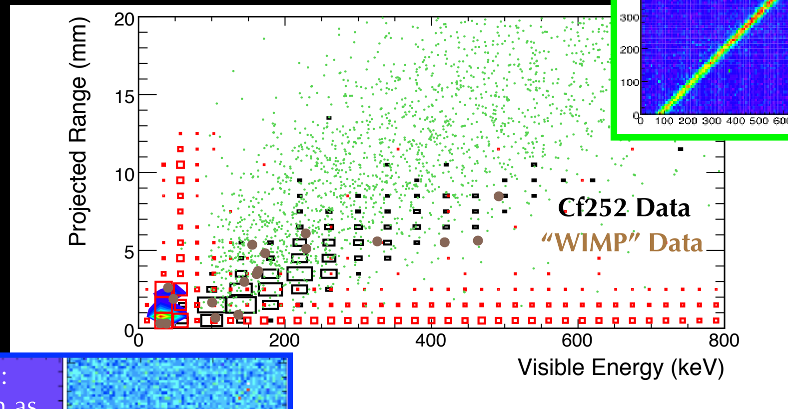


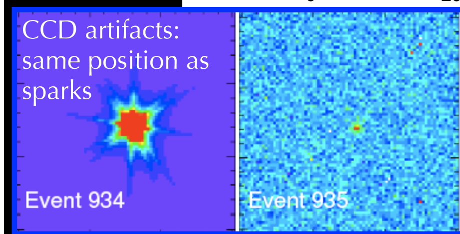
Energy resolution

Backgrounds, CCD Readout

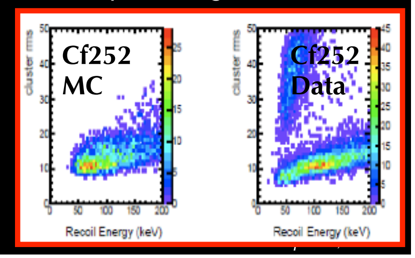
Alphas:
edge crossing







"Cosmics": one hot pixel, large cluster rms



10^4 rejection of backgrounds from range vs. energy

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