

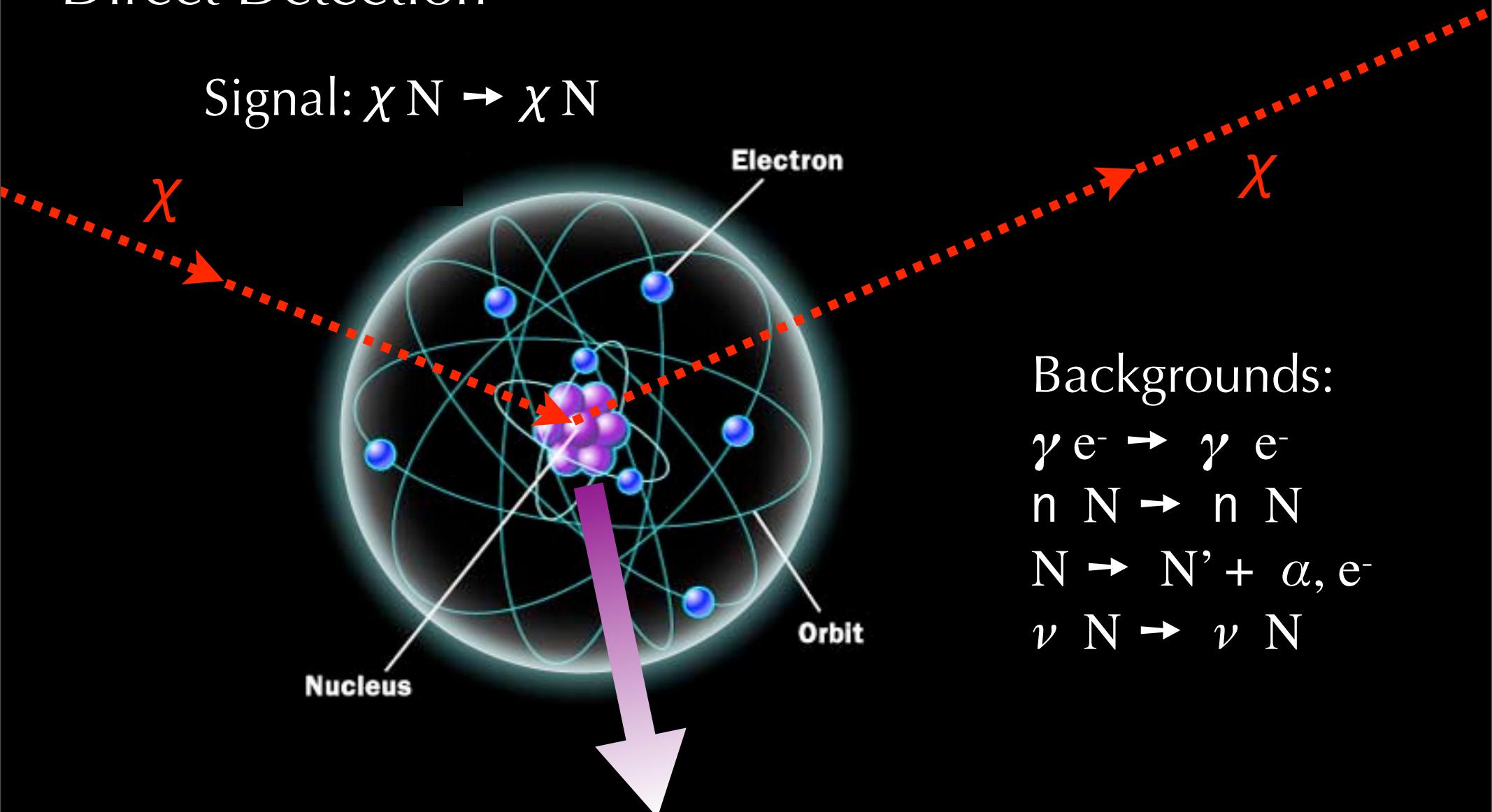
# Neutrino Backgrounds to Dark Matter Searches and Directionality

*Jocelyn Monroe, MIT*

- 
1. Dark Matter Detection and Neutrino Backgrounds
  2. Directionality
  3. **Dark Matter TPC**

# Direct Detection

Signal:  $\chi N \rightarrow \chi N$

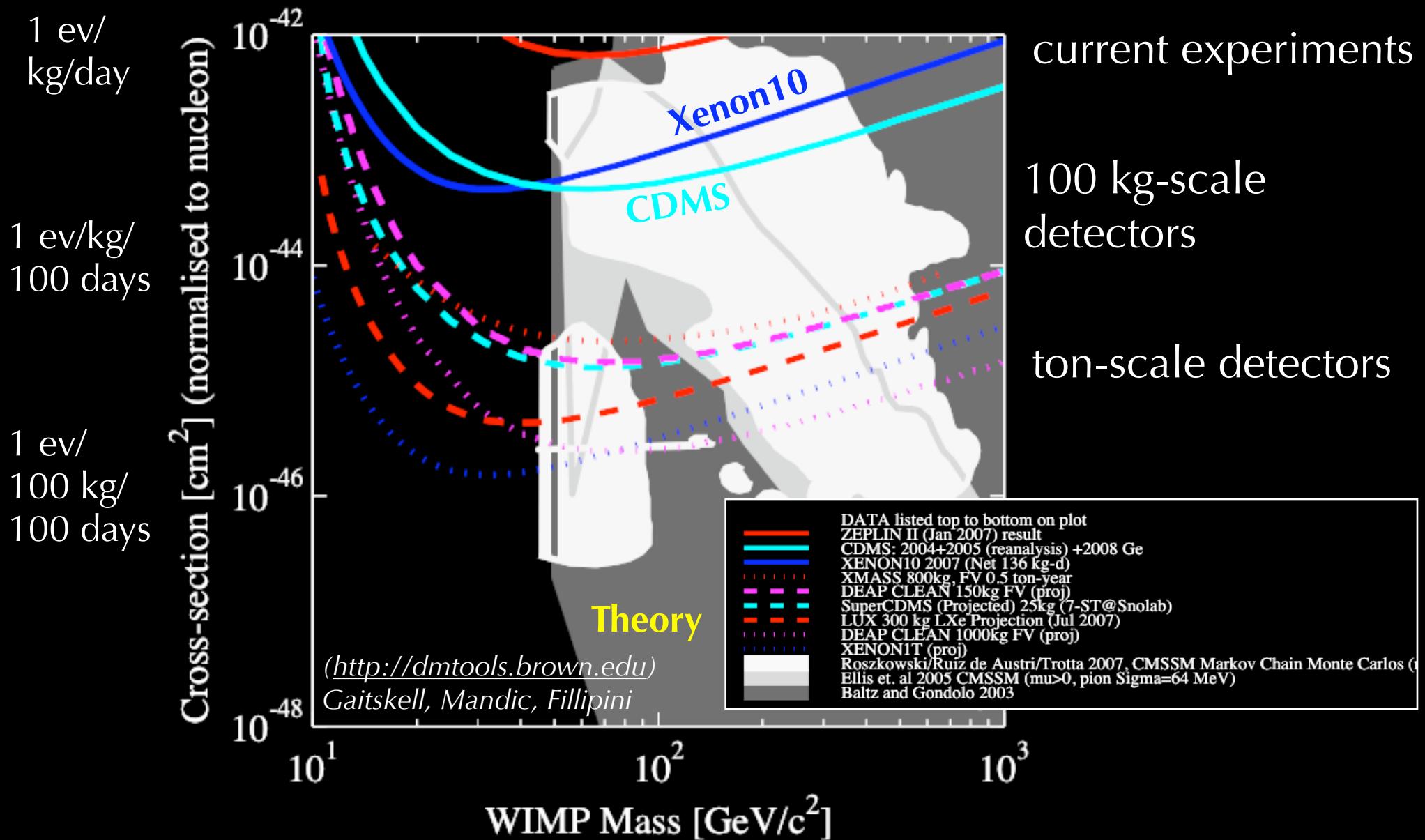


Backgrounds:



*measure nuclear recoil energy*

# Spin-Independent Cross Section Limits



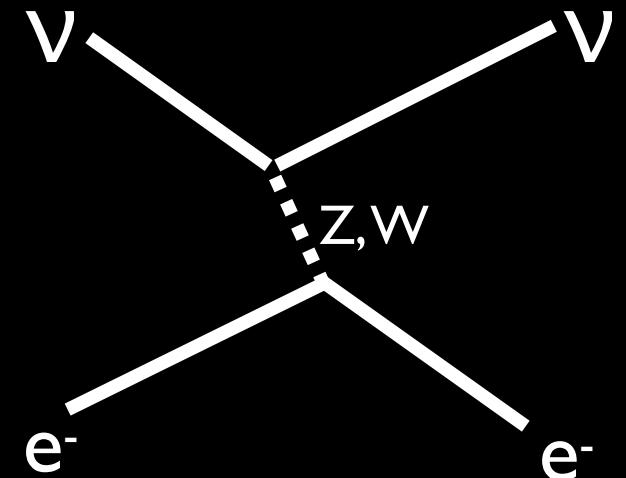
# $\nu$ Cross Sections: $\nu$ -e<sup>-</sup> Elastic Scattering

impossible to shield a detector from neutrino scattering, very large ambient fluxes from solar, geo- $\nu$

proposed detection mechanism for solar pp, <sup>7</sup>Be vs (XMASS, CLEAN, GENIUS,...)

TABLE VIII. Total neutrino-electron scattering cross sections. Radiative corrections were included and  $\sin^2\hat{\theta}_W = 0.2317$  was used. The minimum allowed recoil kinetic energy is zero in all cases considered in this table; the maximum recoil energy is given in column 3. The neutrino energy,  $q$ , and the maximum electron recoil energy,  $T_{\max}$ , are given in MeV; the neutrino cross sections,  $\sigma_{\nu_e-e}$  and  $\sigma_{\nu_\mu-e}$  are given in units of  $10^{-46} \text{ cm}^2$ .

Source	$q$	$T_{\max}$	$\sigma_{\nu_e-e}$	$\sigma_{\nu_\mu-e}$
pp	$\leq 0.420$	0.261	11.6	3.28
<sup>7</sup> Be	0.862	0.665	57.9	12.8
<sup>7</sup> Be	0.384	0.231	19.2	5.08
<sup>8</sup> B	<15.0	14.5	594	106
<sup>13</sup> N	$\leq 1.199$	0.988	45.8	10.4
<sup>15</sup> O	$\leq 1.1732$	1.509	70.8	15.1



C. J. Horowitz, K. J. Coakley,  
D. N. McKinsey, PRD 68, 023005 (2003)

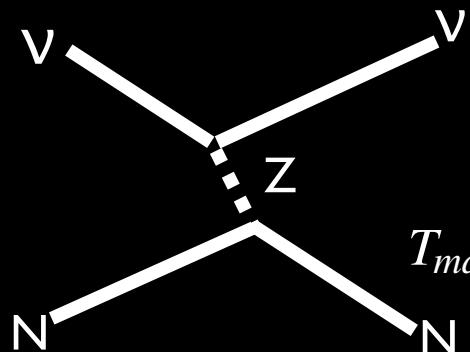
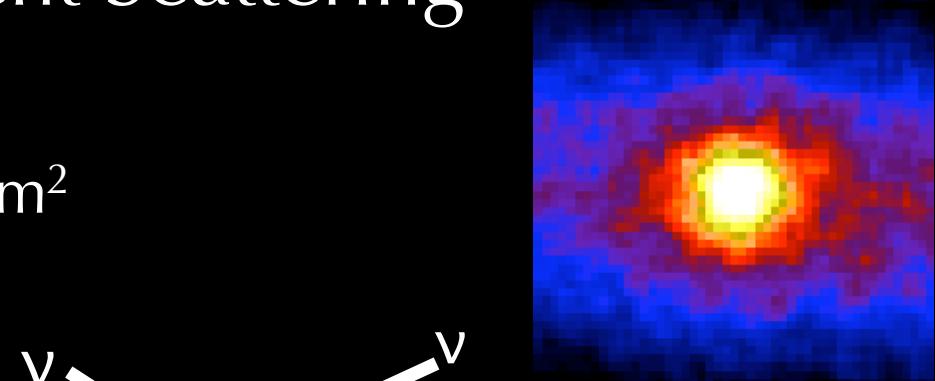
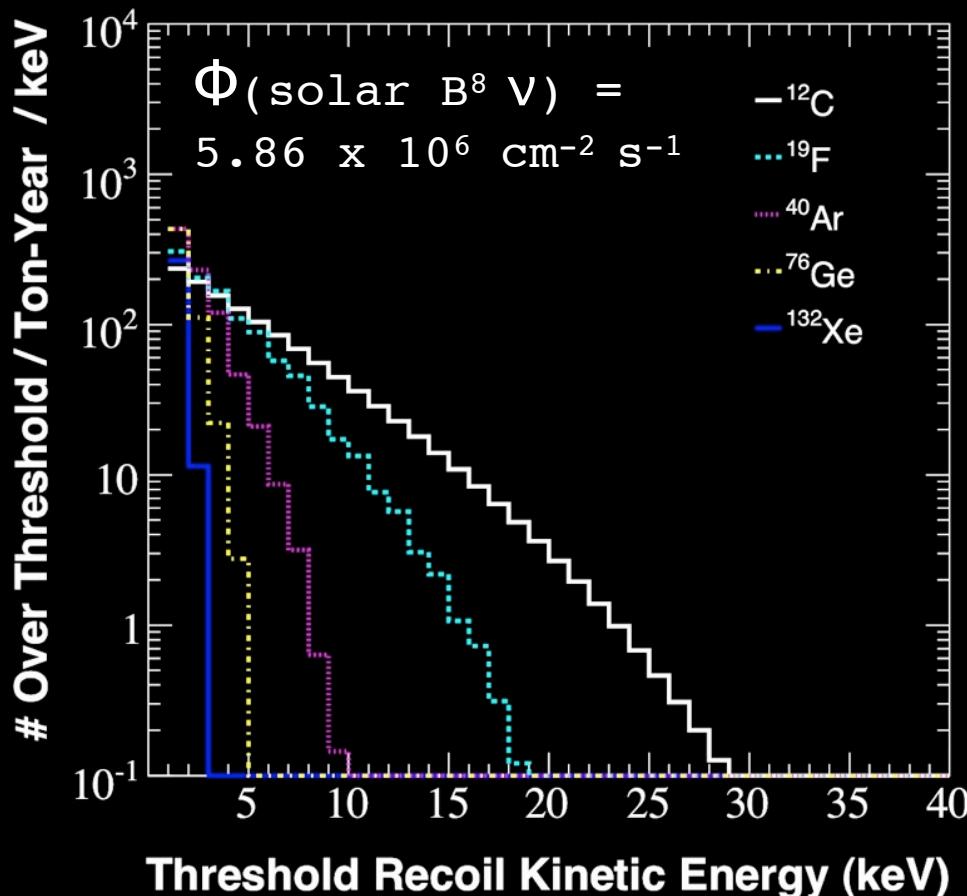
Cross sections are small  
 $\sim (E_\nu/10 \text{ MeV}) \times 10^{-44} \text{ cm}^2$   
 Recoils are  $\mathcal{O}(10^2 \text{ KeV})$

J. Bahcall, M. Kamionkowski, A. Sirlin,  
PRD 51, 6146 (1995)

# $\nu$ Cross Sections: $\nu$ -N Coherent Scattering

Cross sections are coherently enhanced,  $\sim A^2 \times (E_\nu/\text{MeV})^2 \times 10^{-44} \text{ cm}^2$   
recoils are  $O(10 \text{ KeV})$

D. Z. Freedman, Phys. Rev. D9. 1389 (1974)



$$T_{max} = \frac{2E_\nu^2}{m_{nucleus} + 2E_\nu}$$

30 events/ton-year =  
 $\sim 10^{-46} \text{ cm}^2$  limit

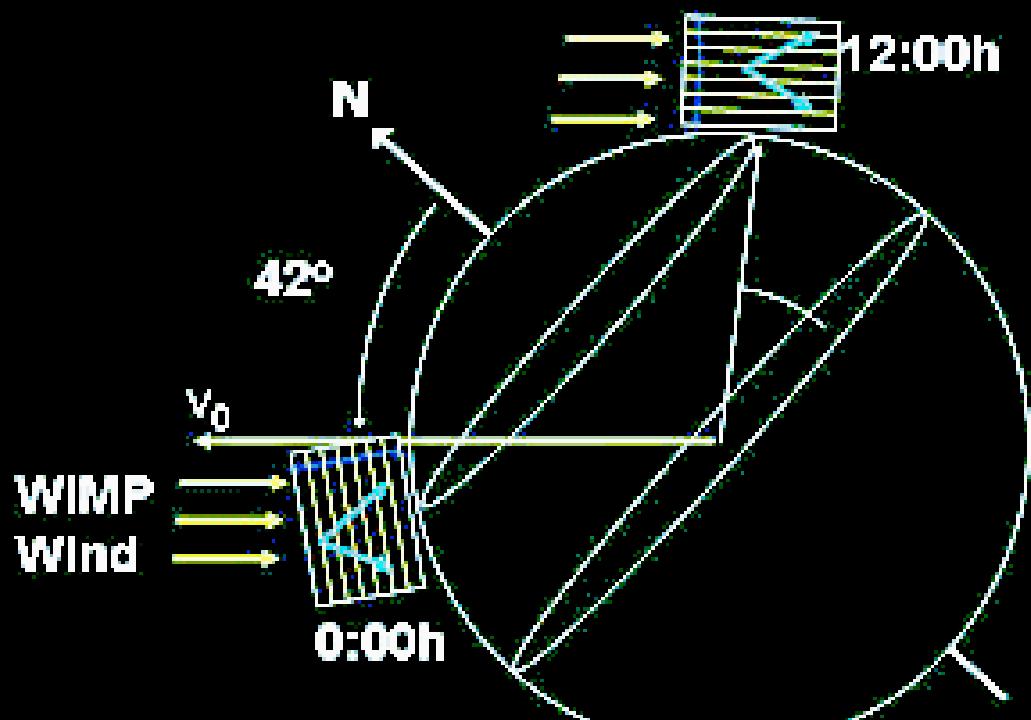
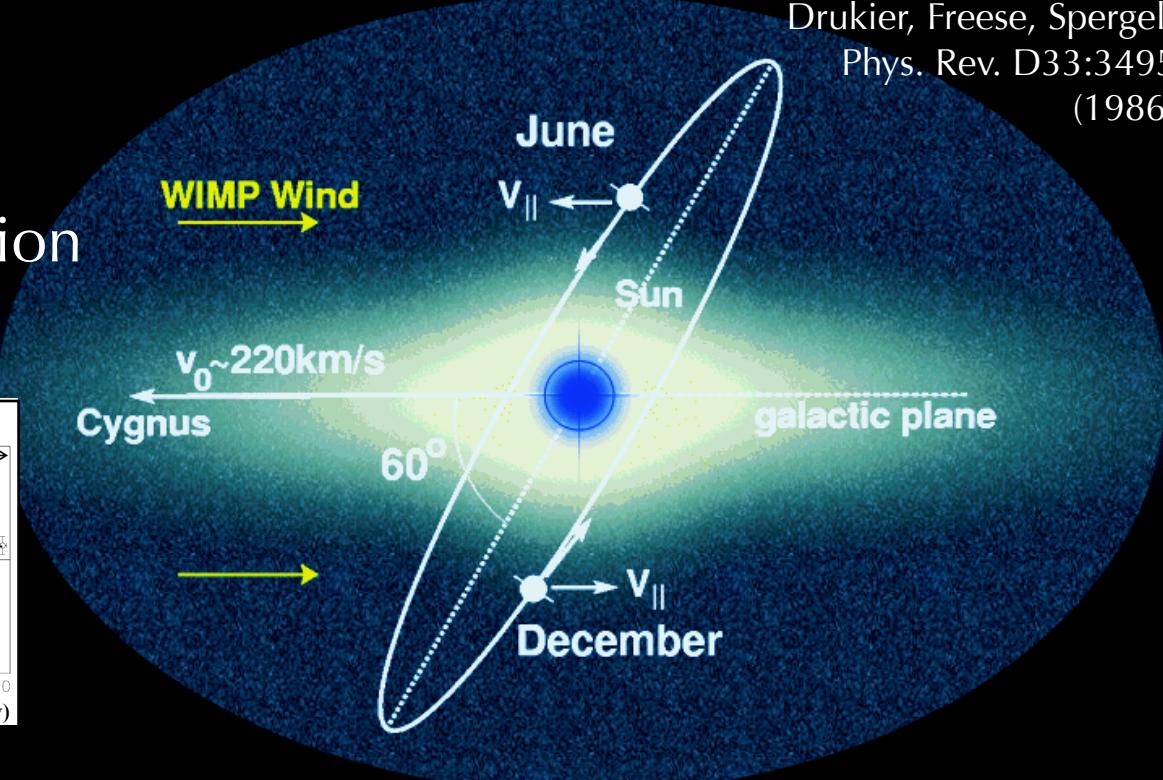
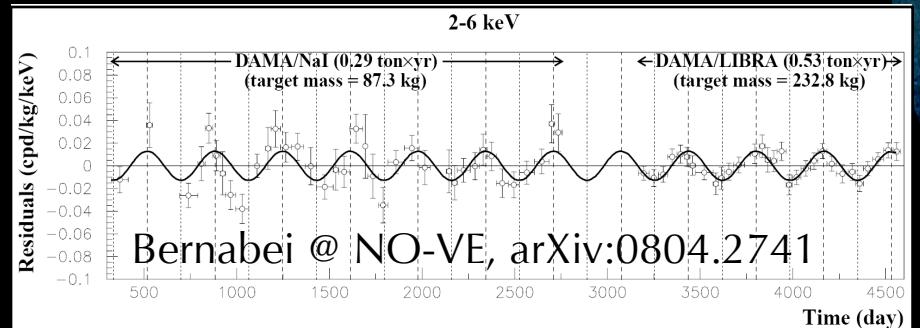
*An irreducible background,  
without direction measurement!*

JM, P. Fisher, Phys. Rev. D 76:033007 (2007)

# Directionality

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

If DAMA/LIBRA annual modulation  
(1-2%) due to WIMP wind...



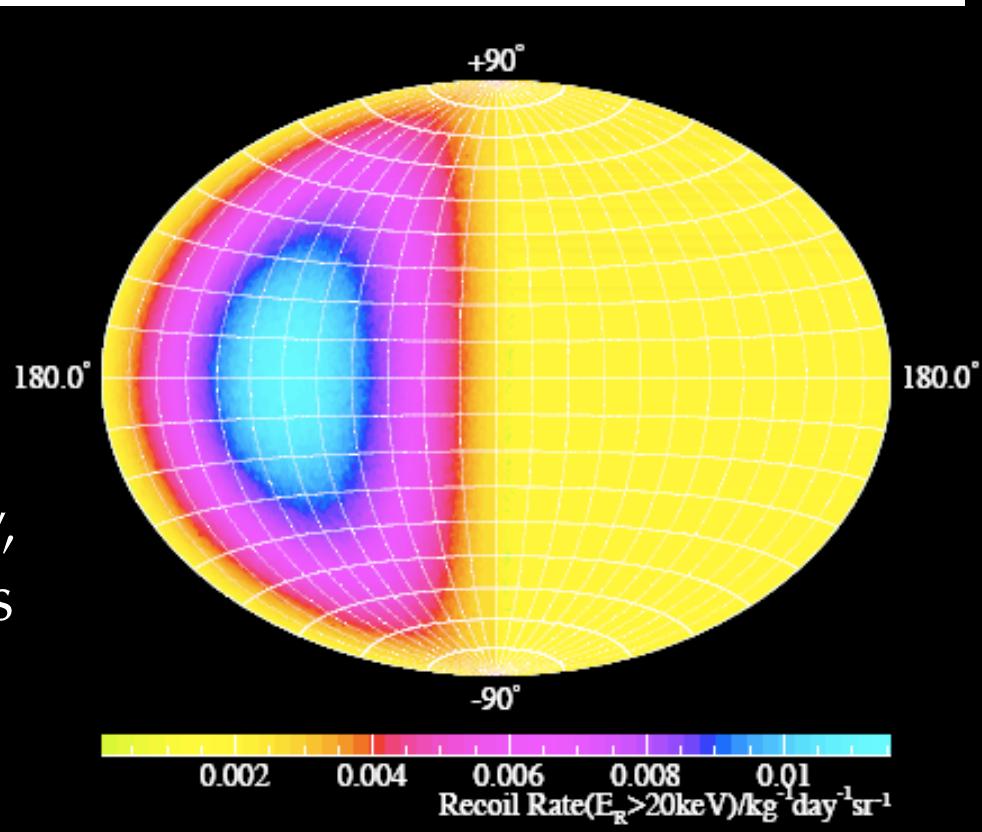
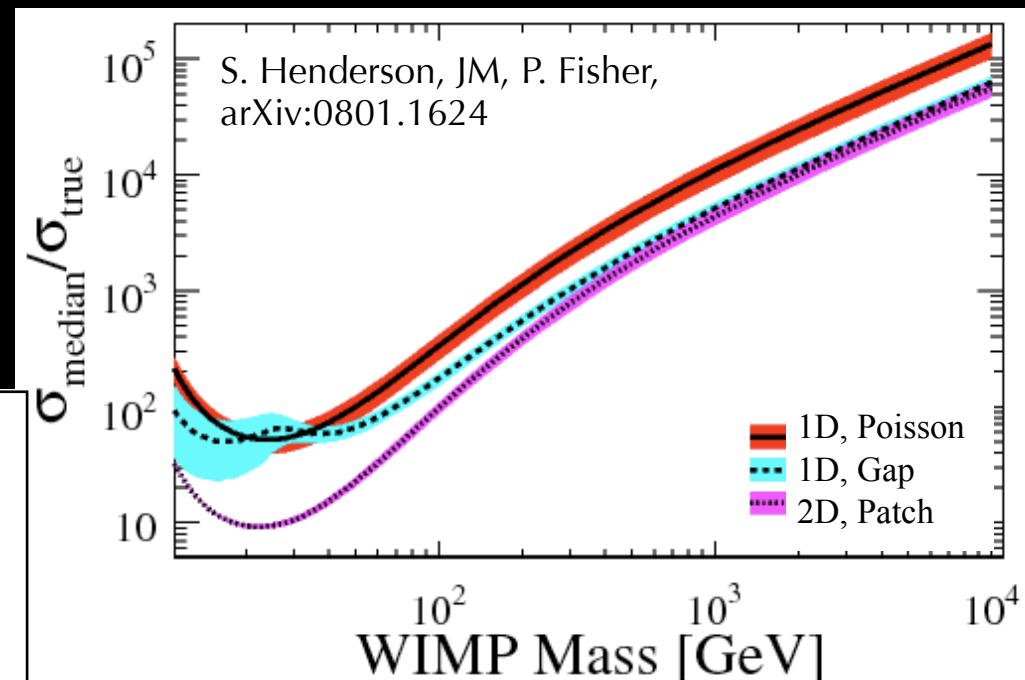
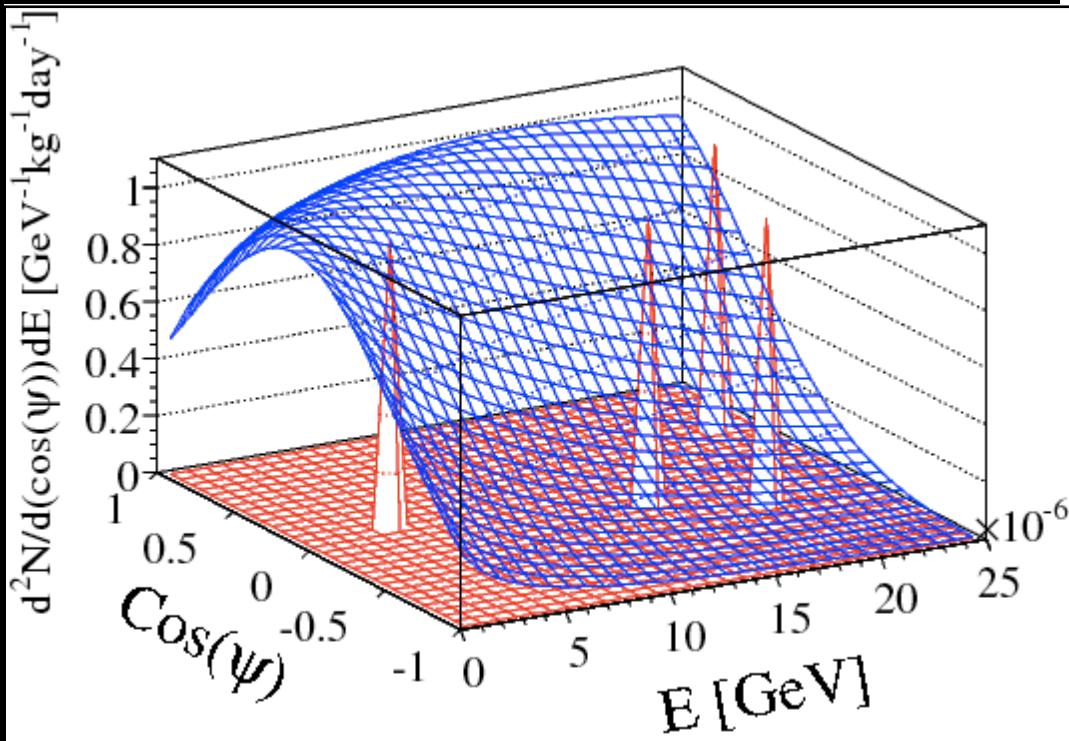
... search for much larger  
(30-100%) diurnal oscillations  
in WIMP **direction**

Spergel, Phys. Rev. D37:1358 (1988)

*need to measure both  
recoil energy and angle*

# Directionality Potential

(i) sensitivity in the presence of backgrounds better for 2D vs. 1D



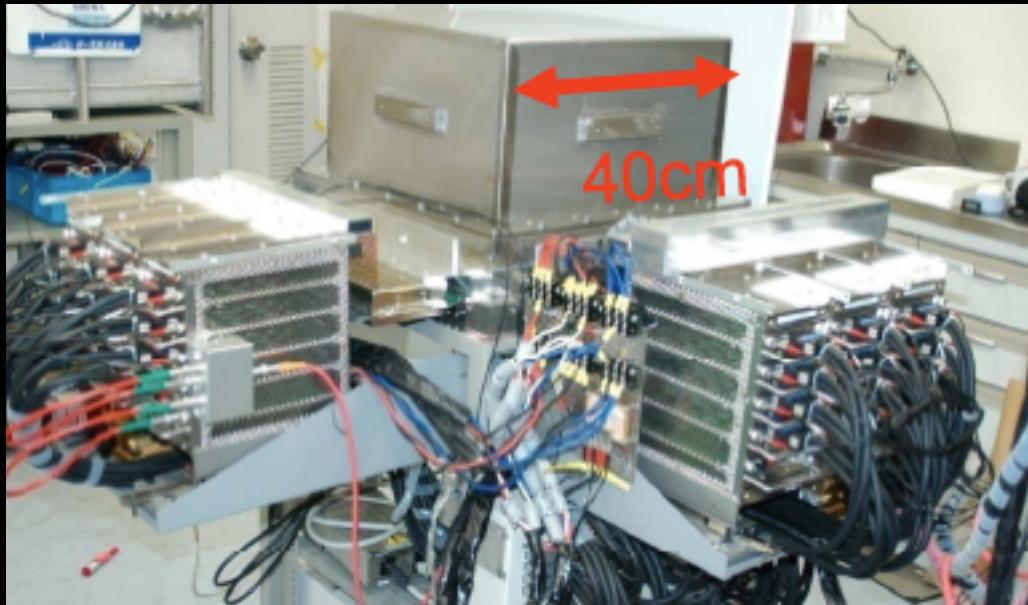
(ii) search for dark matter sky anisotropy,  
90% CL detection requires 5-100 events

A. M. Green, B. Morgan, astro-ph/0609115

# Directionality Around the World

**DRIFT:** in Boulby (UK), wire readout,  $\text{CS}_2$  gas, negative ion drift, 16 kg-day exposure

S. Burgos et al., Astropart. Phys. 28, 409 (2007)

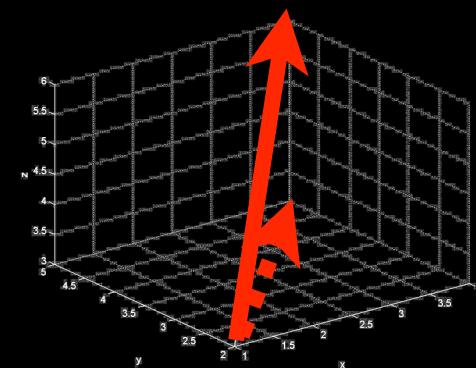


**NEWAGE:** in Kamioka,  $\mu$ -pattern gas detector readout,  $\text{CF}_4$  gas, *first* directional dark matter limit!

K. Miuchi, et al., Phys.Lett.B654:58-64 (2007)

**MiMAC-He3:** (ILL)  
above-ground R&D,  
 $\text{He}_3$  gas, MicroTPC  
readout, A-dependence

D. Santos, et al., J. Phys. Conf. Ser. 65, 021012 (2007)



**DMTPC:** (Boston)  
above-ground R&D,  
 $\text{CF}_4$  gas, CCD readout,  
direction tag

D. Dujmic, et al., NIM A 584:337 (2008)

# Dark Matter TPC Collaboration



## Boston University

S. Ahlen, D. Avery\*, M. Lewandowska,  
K. Otis, A. Roccaro, H. Tomita

## MIT

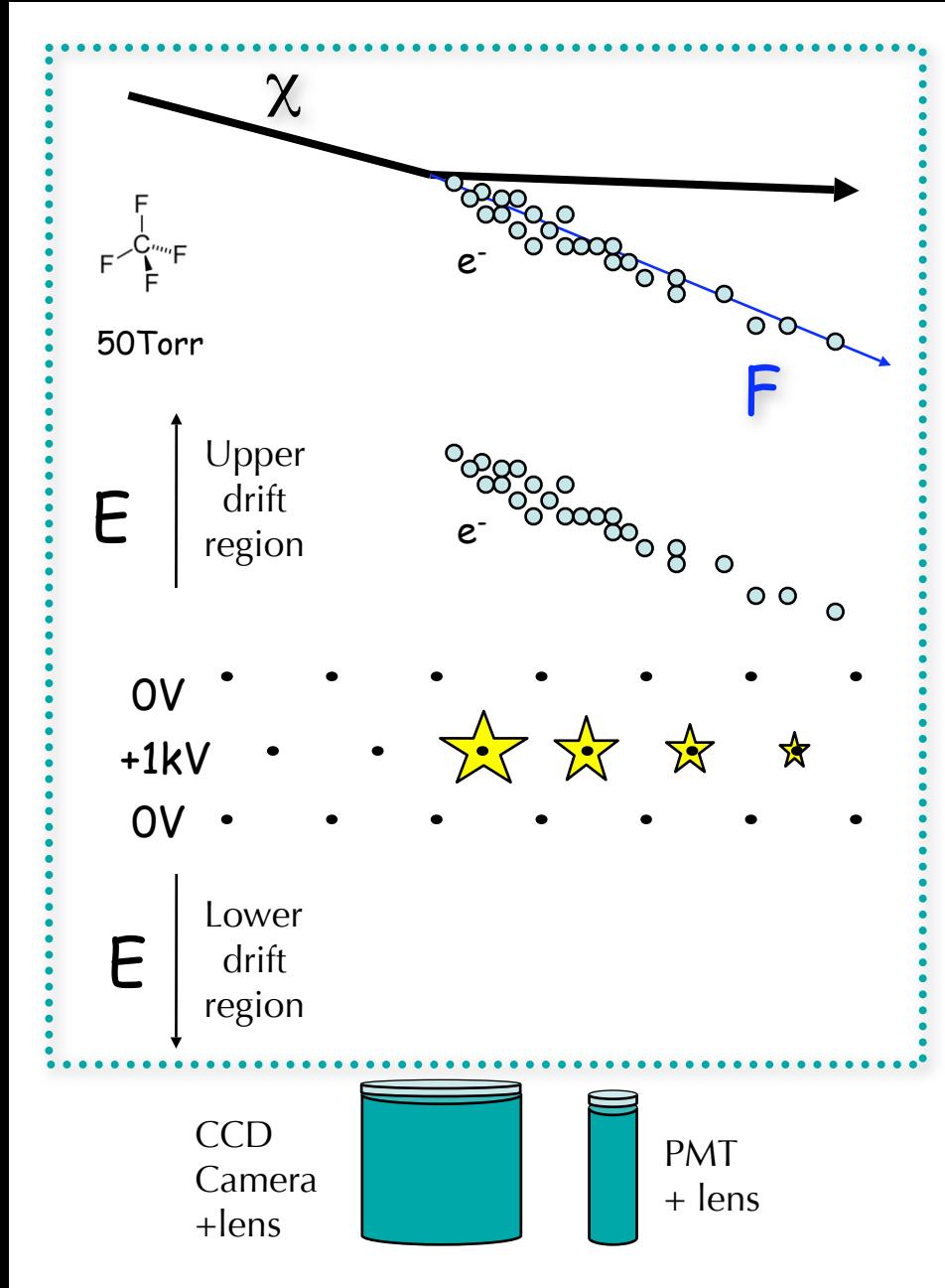
O. Bishop, B. Cornell\*<sup>1)</sup>, D. Dujmic,  
W. Fedus\*, P. Fisher, S. Henderson,  
A. Kaboth, J. Monroe, T. Sahin\*,  
G. Sciolla, R. Vanderspeck,  
R. Yamamoto, H. Yegoryan\*

## Brandeis University

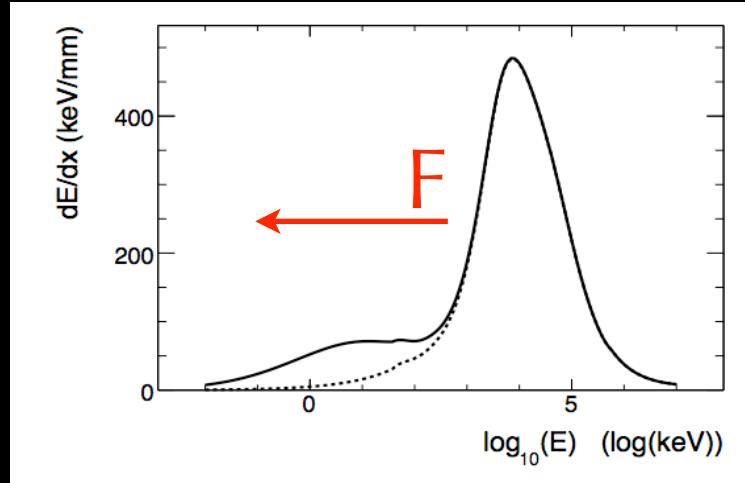
H. Wellenstein, N. Skvorodnev

\*) undergraduate student, 1) Harvard U.

# DMTPC Detector Concept



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



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

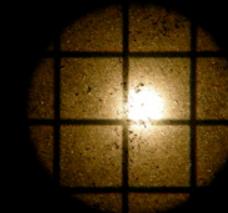
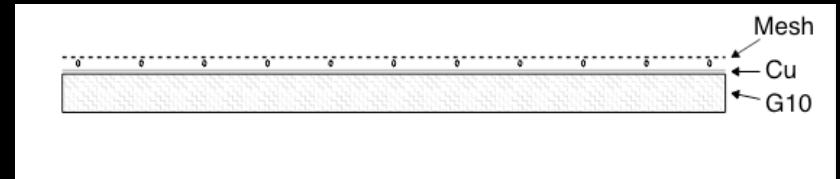
3. avalanche multiplication in amplification region produces gain, scintillation photons

# DM-TPC: 2nd Generation Prototype

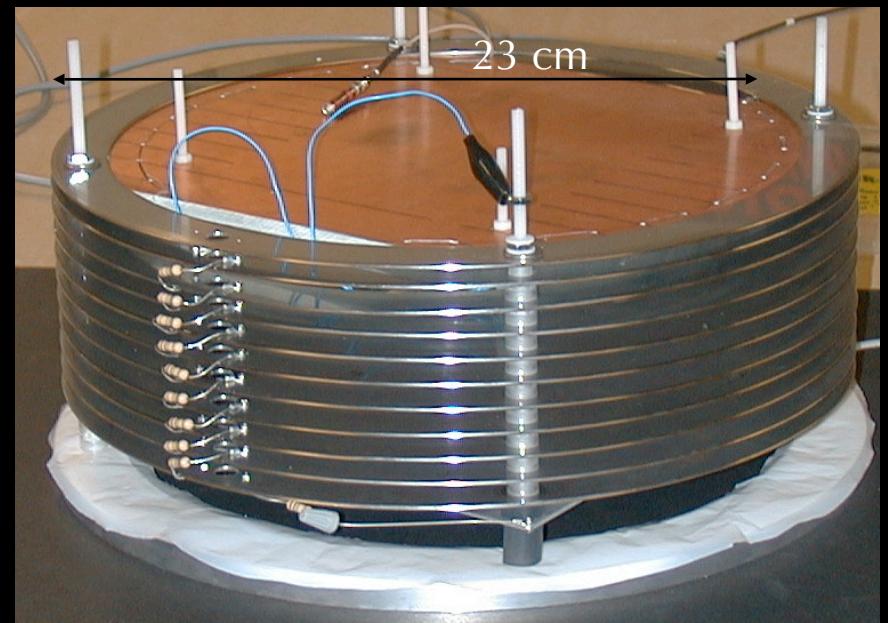


Apogee U2 CCD

Surface operation at BU:



256  $\mu\text{m}$  mesh pitch  
30  $\mu\text{m}$  wire diameter  
79% transparency

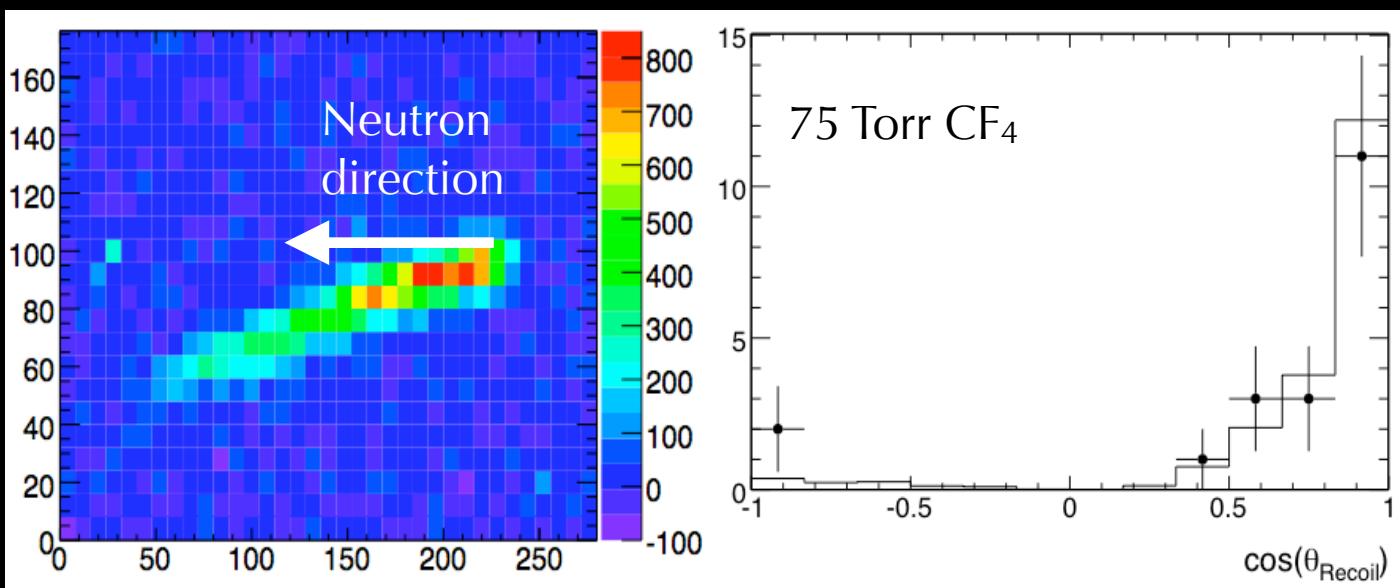
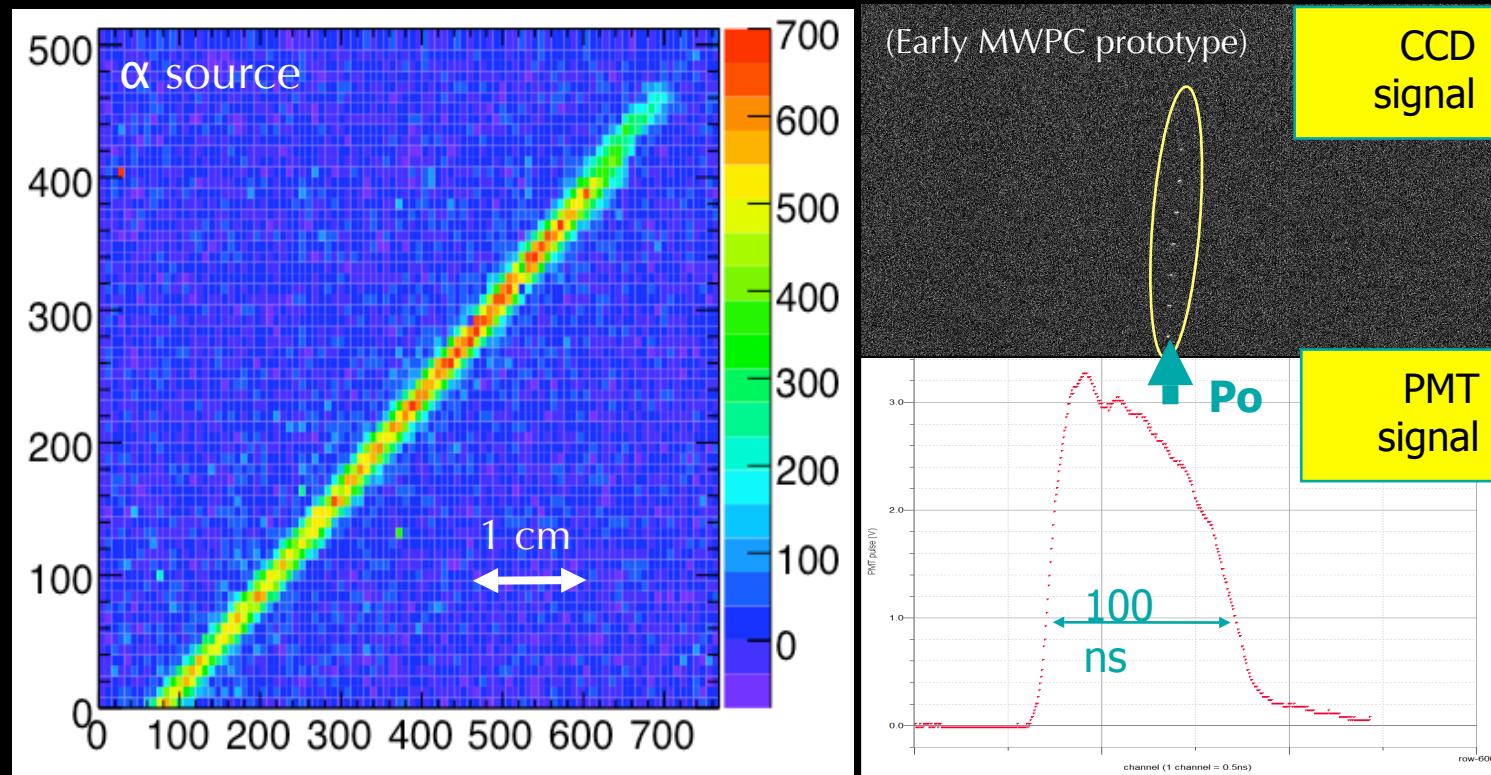


May 30, 2008

# Tracking

X-Y from CCD +  
Z from PMT timing

Alphas: (bgnd)  
Am-214 calibration,  
Po inside detector



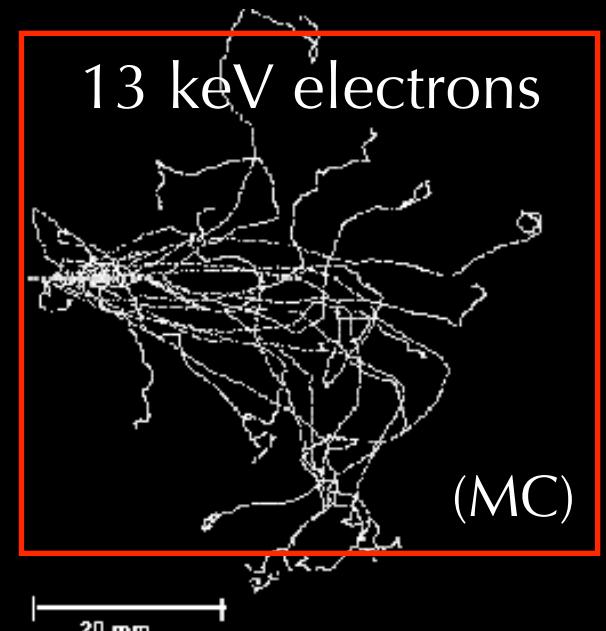
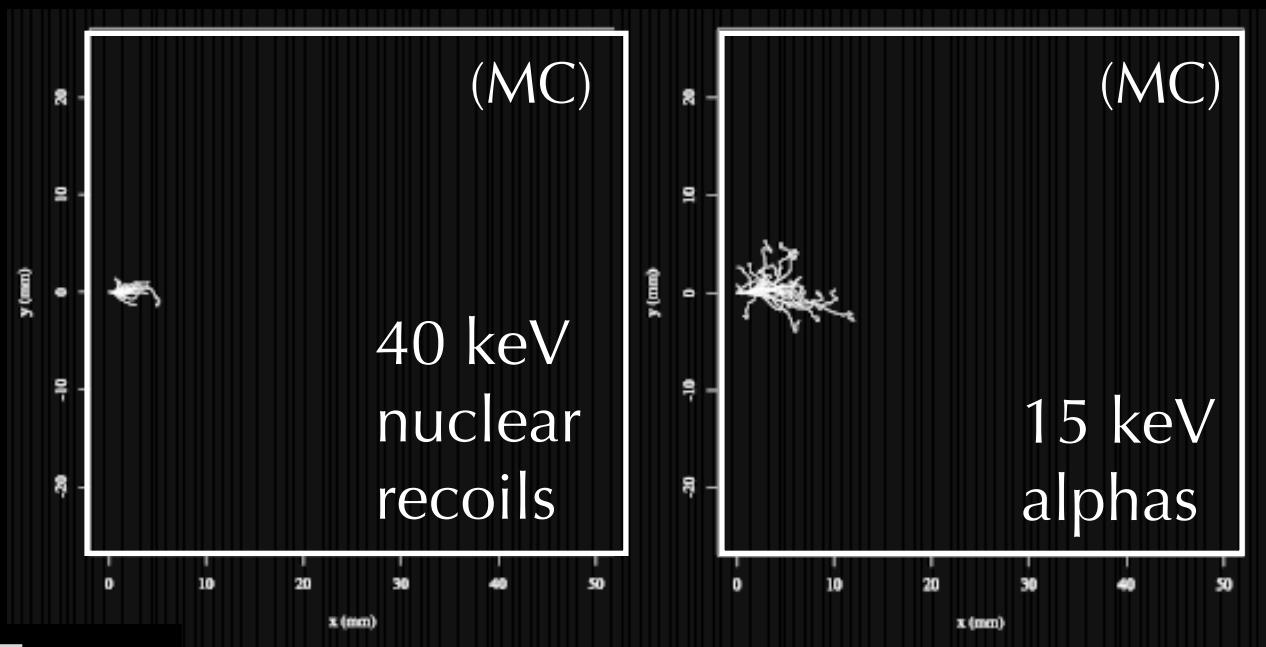
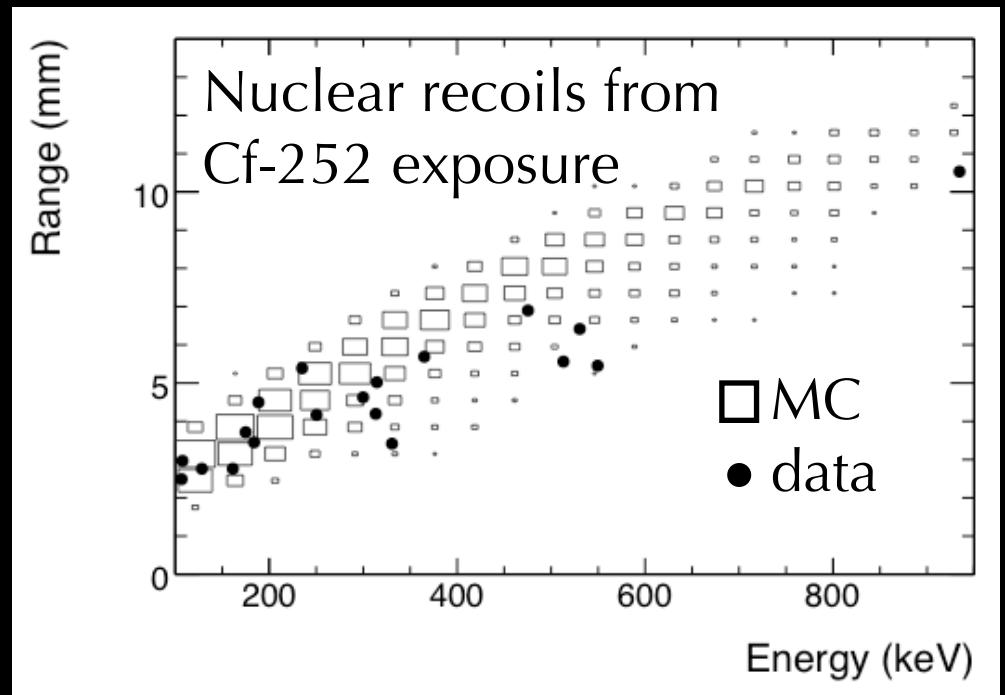
Nuclear recoils: (signal)  
induced by neutrons  
from Cf-252 source

2D angle + head-tail  
from light asymmetry

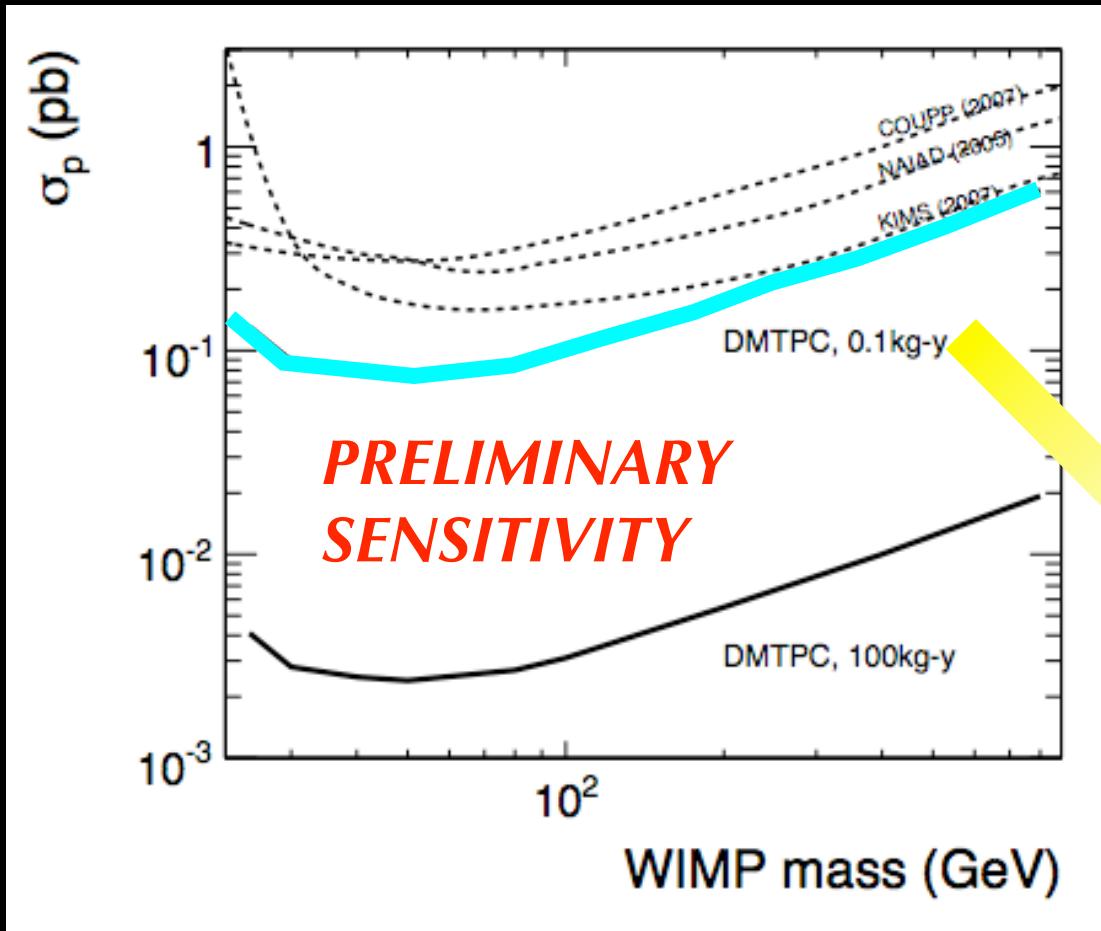
# Particle ID: Range vs. Energy

Range vs. ionization energy  
very different for electrons  
vs. nuclear recoils

$\gamma e^- \rightarrow \gamma e^-$  rejection  
 $>1e6$  from Cs137 calibration



# Spin-Dependent Dark Matter Cross Section Reach

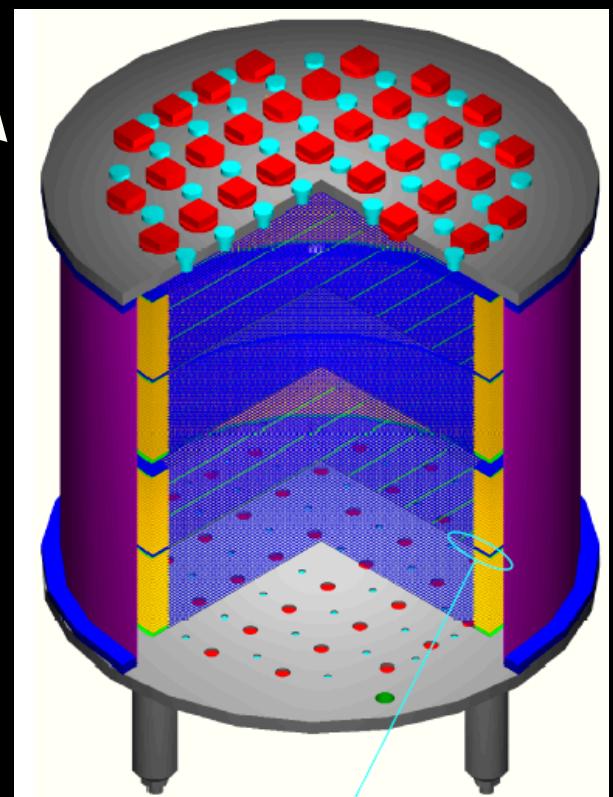


Assumes background of 1 eV/kg/100 days

*next steps:* 1 m<sup>3</sup> detector + low background materials = basic module for large detector, R&D underground

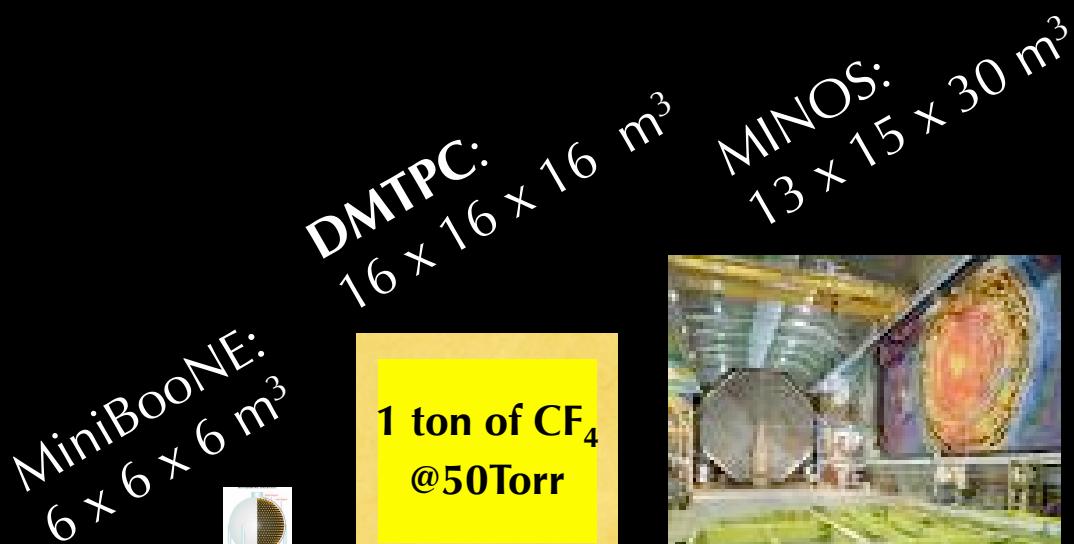
Fluorine spin factor:  
 $\lambda^2 J(J+1) \sim 0.65$

0.1 kg-y improves limits  
100 kg-y tests MSSM



# Directionality Future

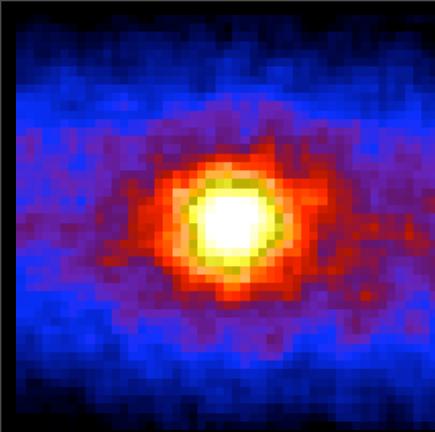
Eventually: large detector,  $10^{-46}$  cm<sup>2</sup> sensitivity,  
sited at DUSEL?



detector size for 100 kg CF<sub>4</sub> @ 50 Torr  
 $10^{-39}$  cm<sup>2</sup> *spin-dependent* sensitivity (tests MSSM)  
 $10^{-44}$  cm<sup>2</sup> spin-independent sensitivity (current SI experiments)



SuperK:  
 $40 \times 40 \times 40 \text{ m}^3$



Directional detection is a powerful new way to search for dark matter.

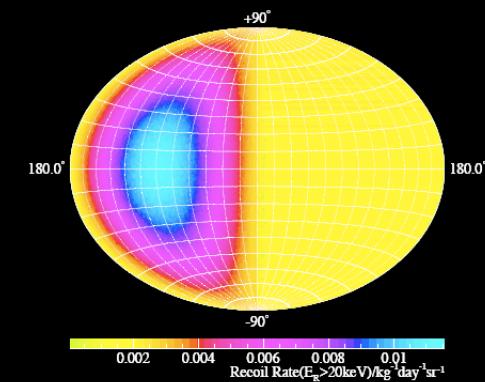
Backgrounds make directional detection very attractive.

Coherent scattering of solar vs is an irreducible background to ton-scale, O(keV) threshold dark matter searches without direction.

Huge progress experimentally in last few years:

*first* directional experiment (DRIFT), *first* directional limit (NEWAGE),  
*first* observation of vector direction in low-energy nuclear recoils (DMTPC)

Dark matter telescope:  
transition from discovery to observatory.



# Backup

# Dark Matter Wind

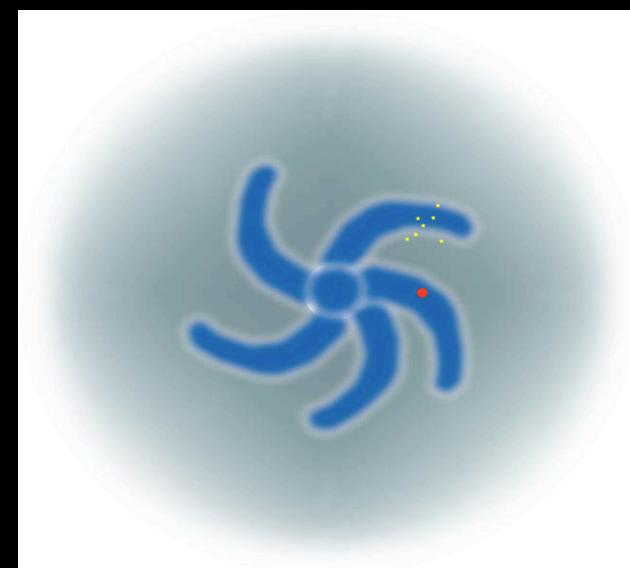
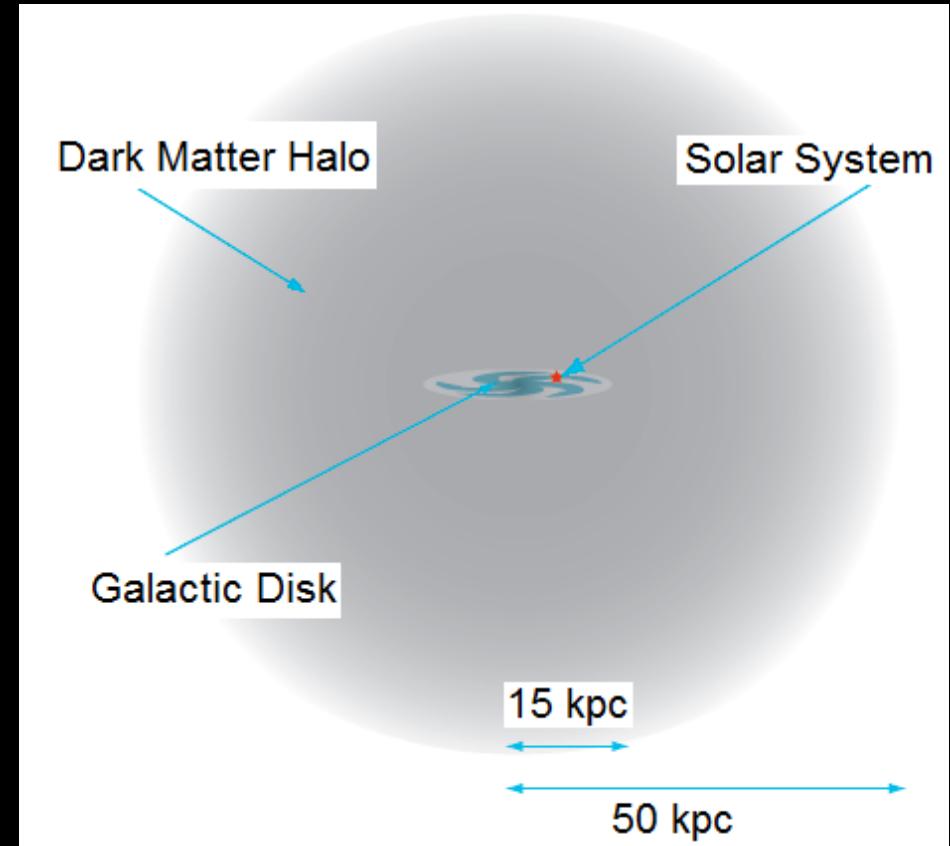
kinetic energy dissipation  
by baryons

+

conservation of  
angular momentum  $L = m(v \times r)$

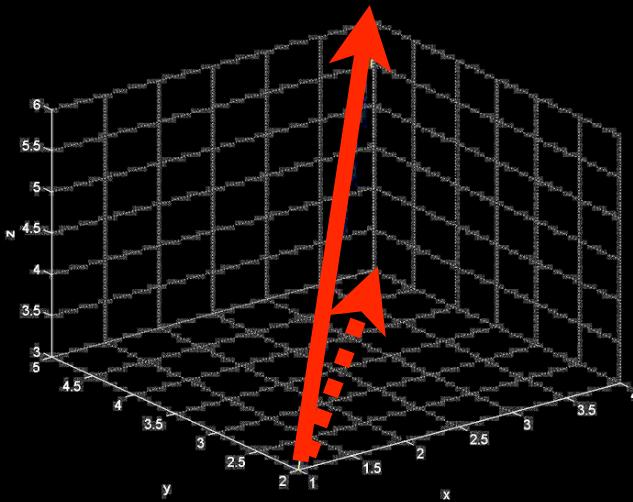


*a difference in velocity between  
baryons and dark matter*



...appears  
to “blow”  
from  
Cygnus

# Optimization



## Detector Properties:

detector resolution  
energy threshold  
background  
reconstruction

(2D vs. 3D)

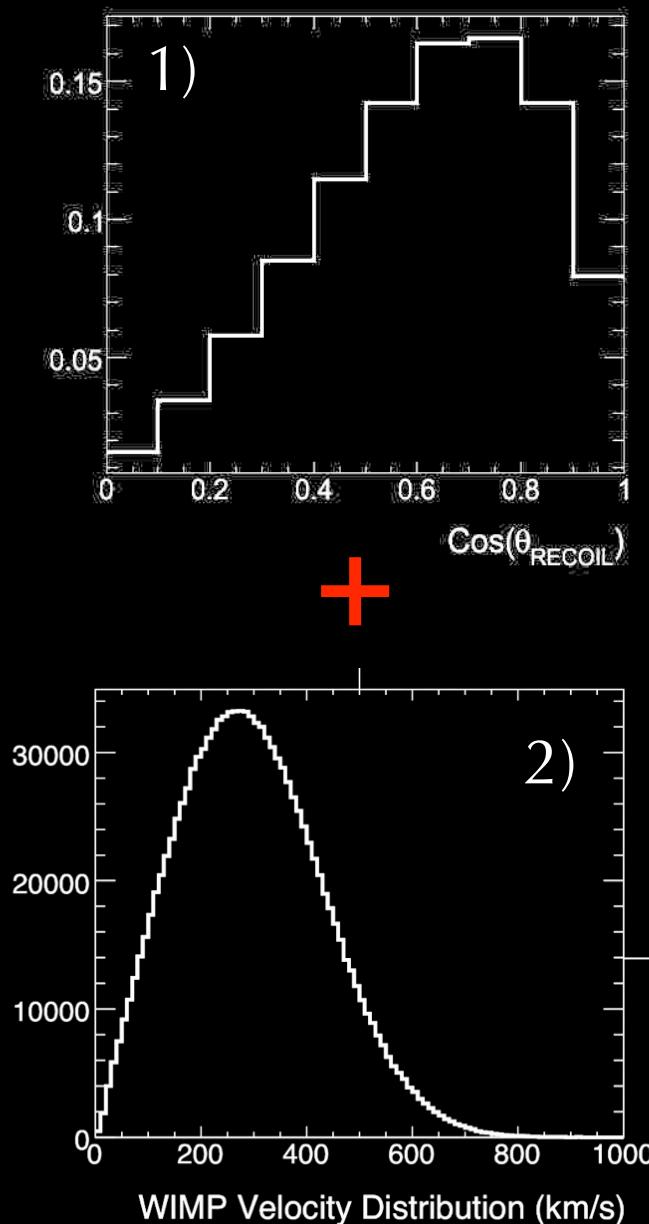
vector or axial reconstruction

*how many events to detect  
the dark matter wind?*

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

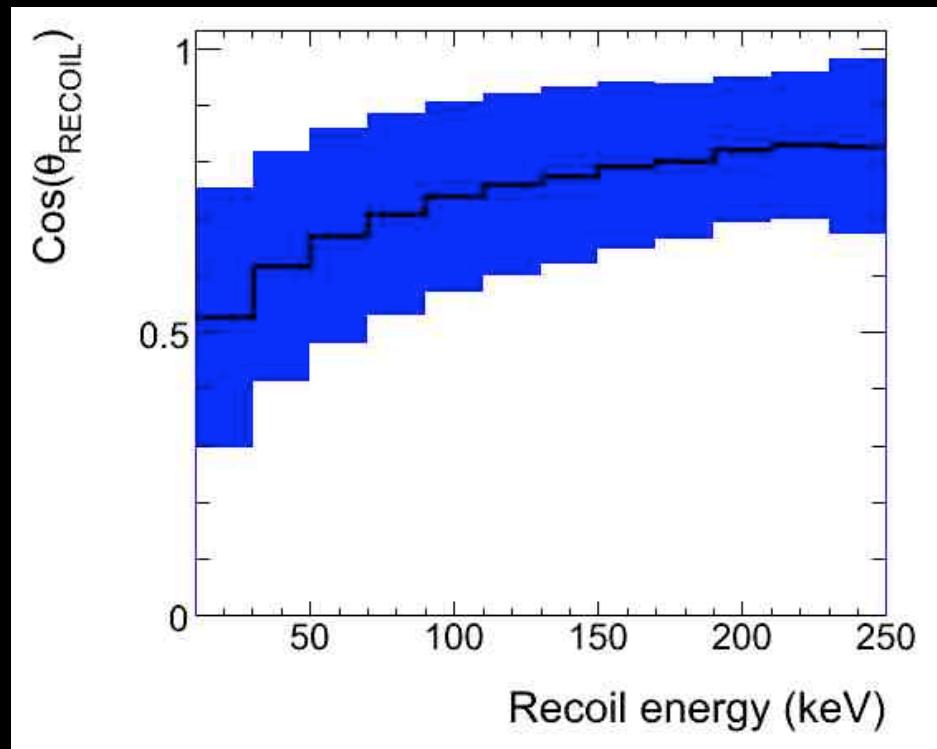
A. M. Green, B. Morgan, astro-ph/0609115

# Signals in Directional Detectors



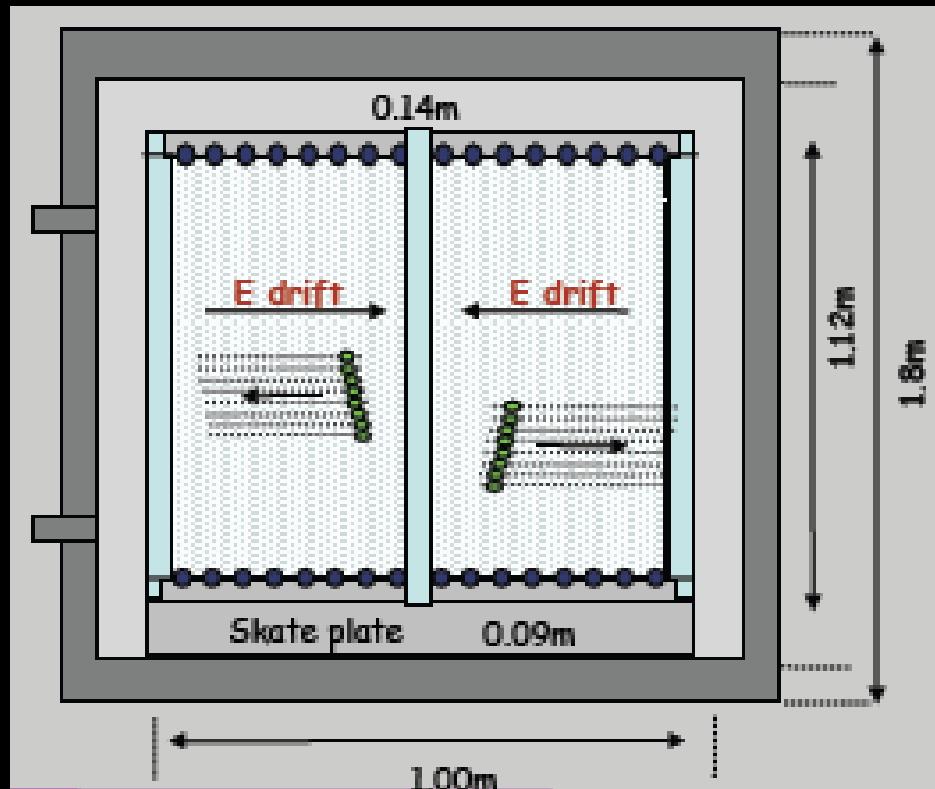
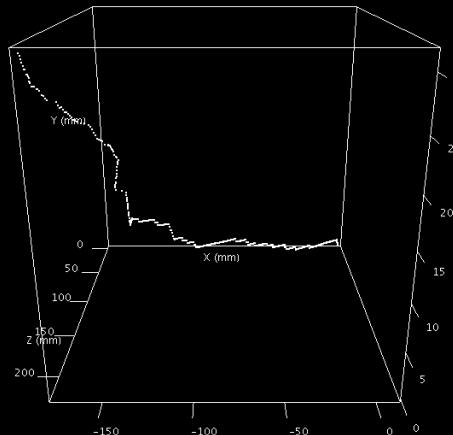
distribution of signal events determined by:

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

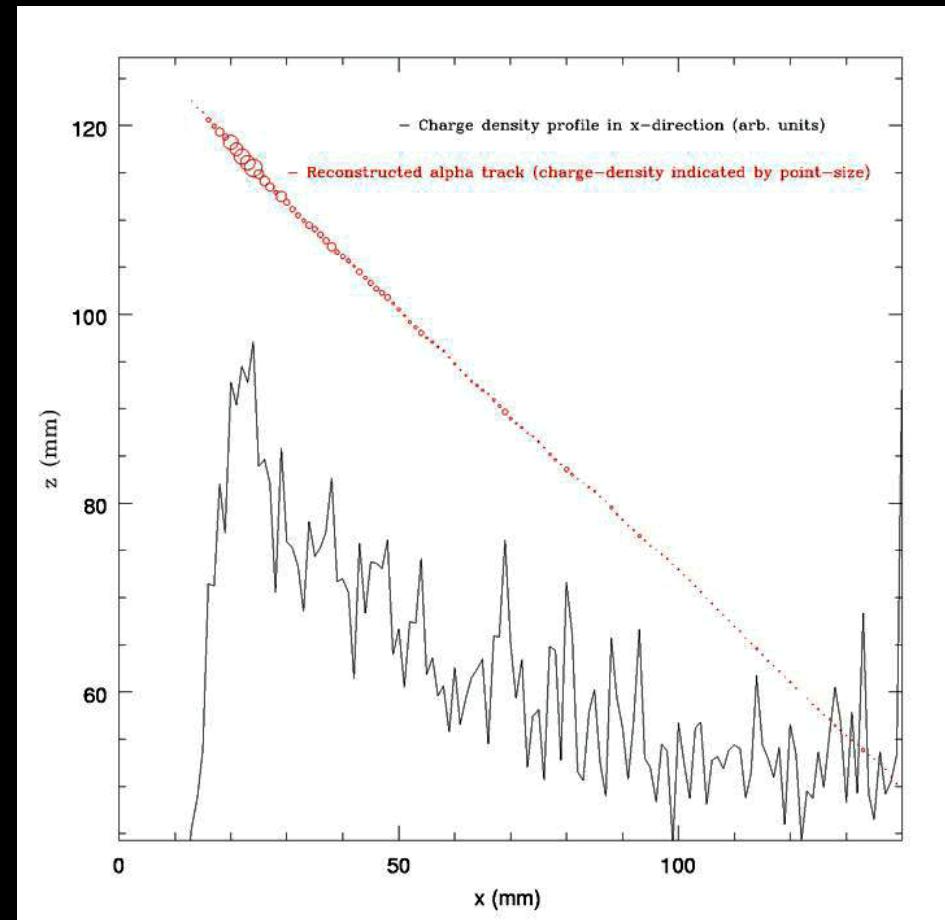


# DRIFT

Operating in Boulby (UK),  
wire readout, 40 torr CS<sub>2</sub> gas,  
negative ion drift,  
16 kg-day exposure



head-tail for ~5 MeV alphas



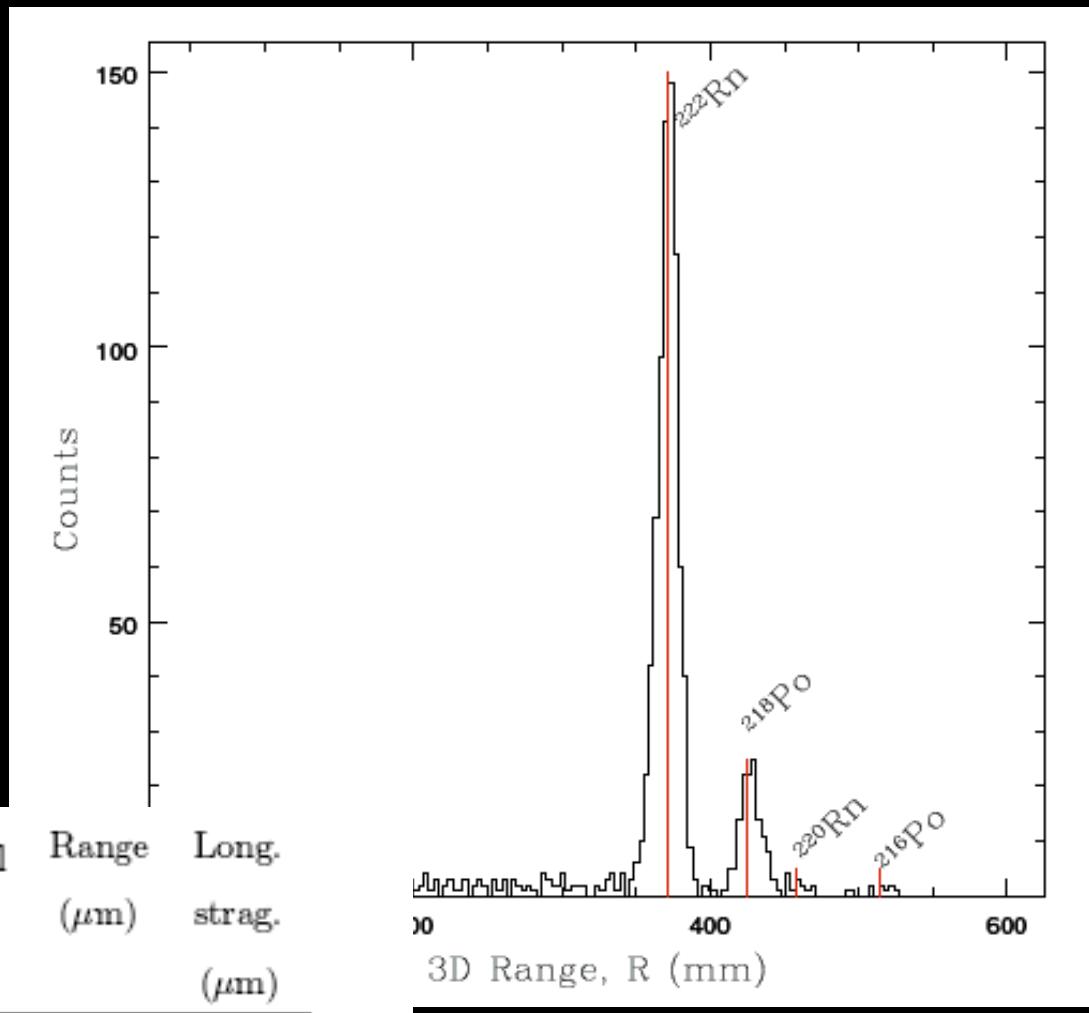
# DRIFT

Currently radon limited  
(~ $10^3$  events/kg/day)

can distinguish different parts of the Rn222 decay chain by range

Drift Collaboration, accepted for publication in AstroPart. Phys.

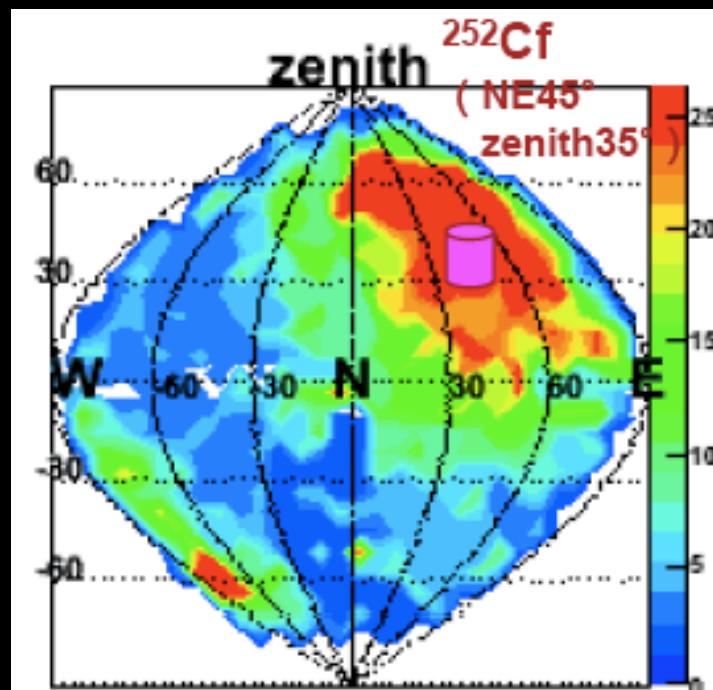
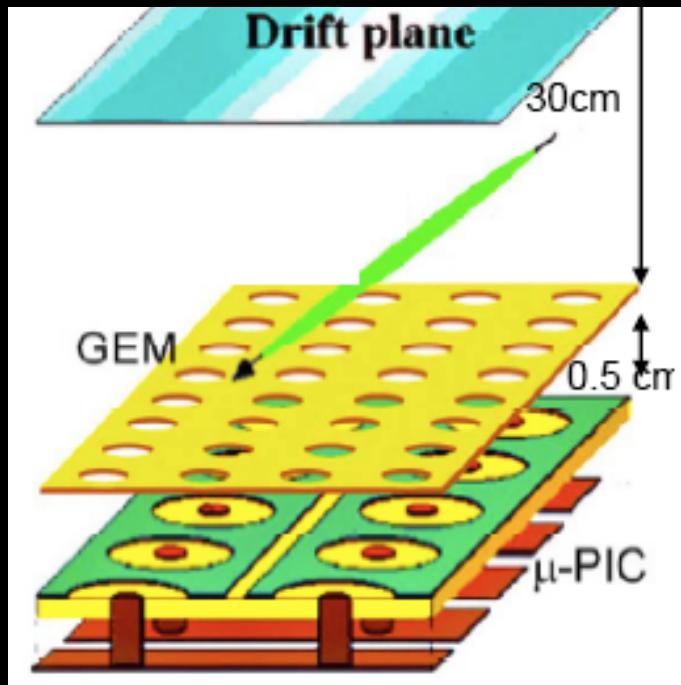
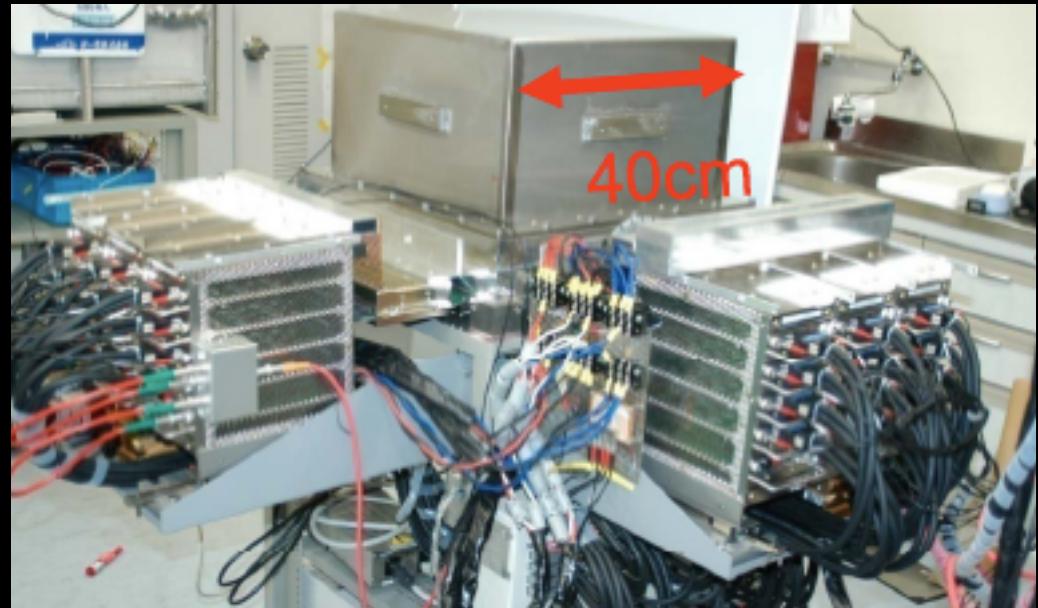
Isotope	$E_\alpha$ (MeV)	Range (mm)	Long. strag. (mm)	Recoil	$E_{\text{recoil}}$ (keV)	Range ( $\mu\text{m}$ )	Long. strag. ( $\mu\text{m}$ )
$^{222}\text{Rn}$	5.48948	334	13.4	$^{218}\text{Po}$	100.82	577.91	119.61
$^{218}\text{Po}$	6.00235	383	15.3	$^{214}\text{Pb}$	112.33	628.54	129.62
$^{214}\text{Po}$	7.68682	567	23.3	$^{210}\text{Pb}$	146.64	745.25	149.99
$^{220}\text{Rn}$	6.288	413	16.3	$^{216}\text{Po}$	116.5	631.99	129.08
$^{216}\text{Po}$	6.778	464	18.1	$^{212}\text{Pb}$	127.9	682.27	139.07
$^{212}\text{Po}$	8.785	701	30.0	$^{208}\text{Pb}$	168.9	818.14	162.45



expected nuclear recoil signal range ~mm

# NEWAGE

Operating in Kamioka (Japan),  
 $\mu$ -pattern gas detector readout,  
100 torr CF<sub>4</sub> gas, e<sup>-</sup> drift,  
e<sup>-</sup> rejection: < 2E-4  
100 keV recoil threshold

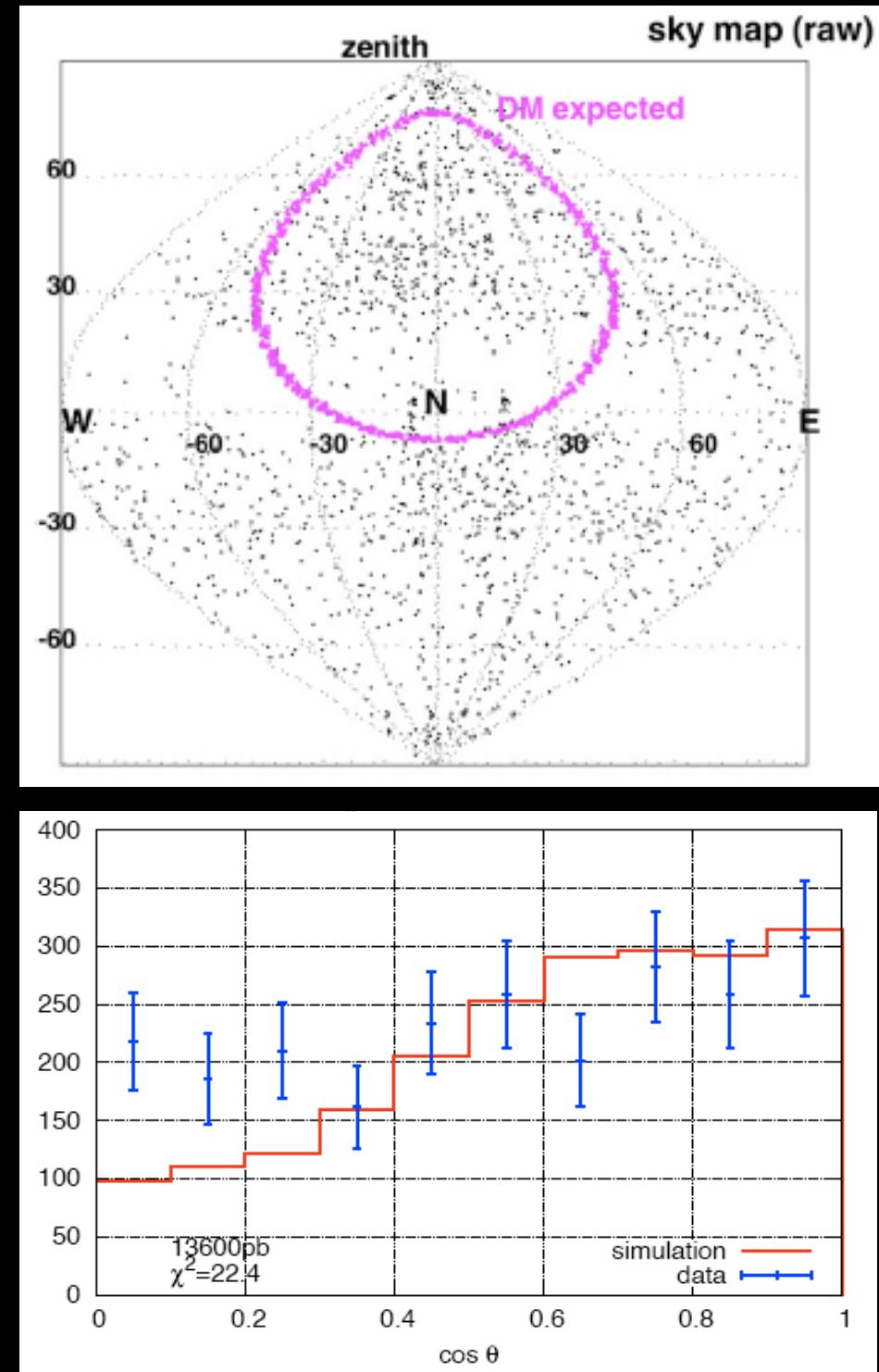
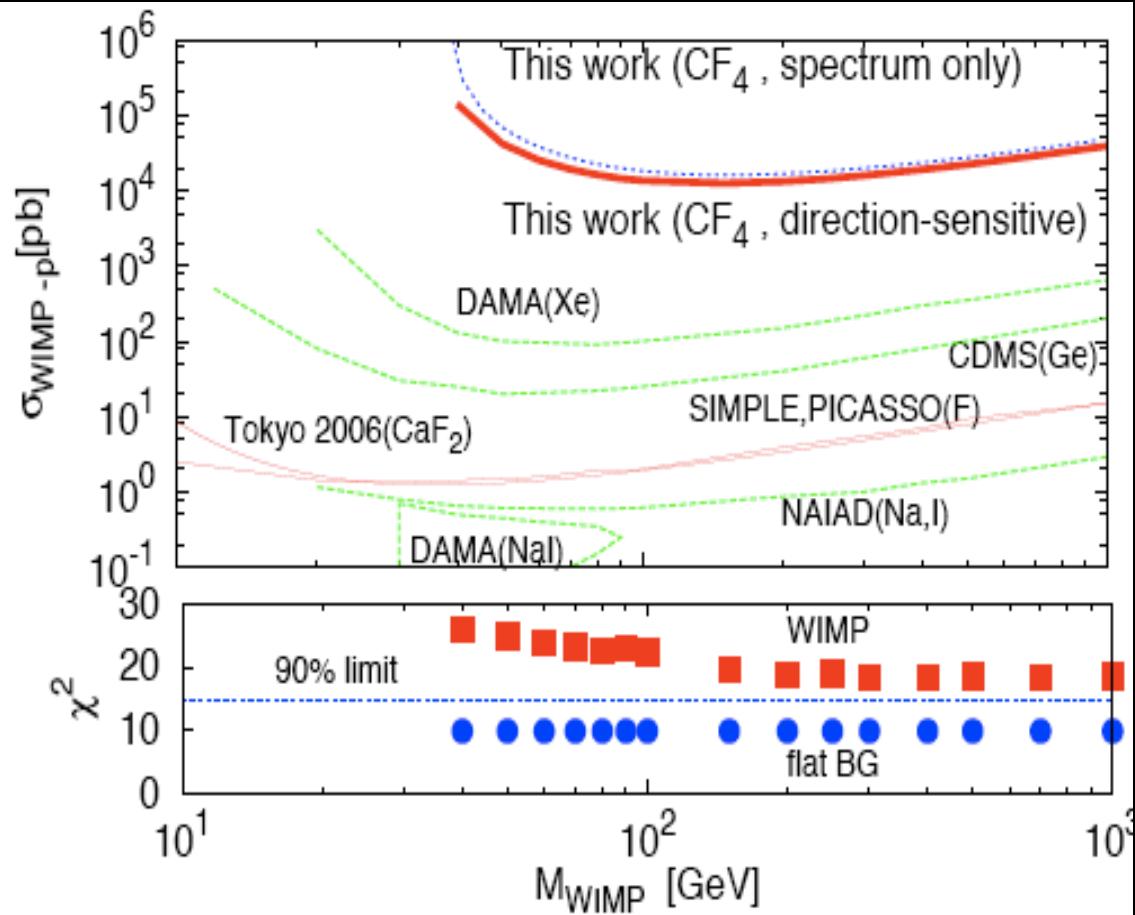


demonstrated  
axial 3D track  
reconstruction  
with <sup>252</sup>Cf source

# NEWAGE

first directional detector limit!  
 surface run, 0.15 kg-day exposure,  
 spin-dependent cross section

K. Miuchi, et al., Phys.Lett.B654:58-64 (2007)



# v Coherent Scattering

$Q^2 = 2mT$ , low  $Q^2$  simplifies nuclear description  
(to 1st order no  $Q^2$  dependence except in form factor)

$$\frac{d\sigma}{dT} = \frac{G_F^2 (\hbar c)^2 m_{nucleus}}{4\pi} \left( N - (1 - 4\sin^2\theta_W)Z \right)^2 \left( 1 - \frac{m_{nucleus} T_{nucleus}}{2E_v^2} \right) F(Q^2)^2$$

$N$  = number of target nucleons

$Z$  = number of protons

$F(Q^2)$  = nuclear form factor

- cross section  $\sim N^2$ , heavier nucleus = more events
- as  $T_{nucleus}$  increases, cross section decreases

D. Z. Freedman, PRD 9, 1389 (1974);

H. T. Wong, et al., J. Phys. Conf. Ser. 39, 266 (2006);

K. Scholberg, PRD 73, 033005 (2006)

# $\nu$ Fluxes ( $\text{cm}^{-2} \text{ s}^{-1}$ )

Source	Predicted	$E_\nu$ Range
Solar Total	$O(1E13)$	<18 MeV
pp	5.99E10	<0.4 MeV
CNO	5.46E8	<2 MeV
7Be	4.84E9	0.3 /0.8 MeV
8B	5.69E6	<12 MeV
hep	7.93E3	<18 MeV
Geo Total	$O(1E7)$	<5 MeV
238U	2.34E6	<5 MeV
232Th	1.99E6	<2.5 MeV
235U	$\sim 4E3$	<2 MeV
40K	$\sim 1E7$	<2 MeV
Atmospheric	$O(1/E(\text{GeV})^{2.7})$	0 to multi-GeV
Reactor	$O(1E20/d^2)$	<10 MeV
Supernova Relic	$O(10)$	<60 MeV

Considered here

# Prediction vs. Measurement

## Predicted

Solar  $\nu$ :  $\Phi(B^8) = 5.86 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$

16% normalization uncertainty

<http://www.sns.ias.edu/~jnb/SNdata/snldata.html>

Geo  $\nu$ :  $\Phi(U^{238}) = 2.34 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$

$\Phi(Th^{232}) = 1.98 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$

<http://www.awa.tohoku.ac.jp/~sanshiro/geoneutrino/spectrum/index.html>

Atm  $\nu$ :  $\Phi(U^{238}) = 9.6 \times 10^{-1} \text{ cm}^{-2} \text{ s}^{-1}$

(geomagnetic cutoff important)

20% normalization uncertainty

## Measured

SNO: 1.09 x predicted (10%)

SK:  $\Phi(B^8)$  uncertainty = 3.5%

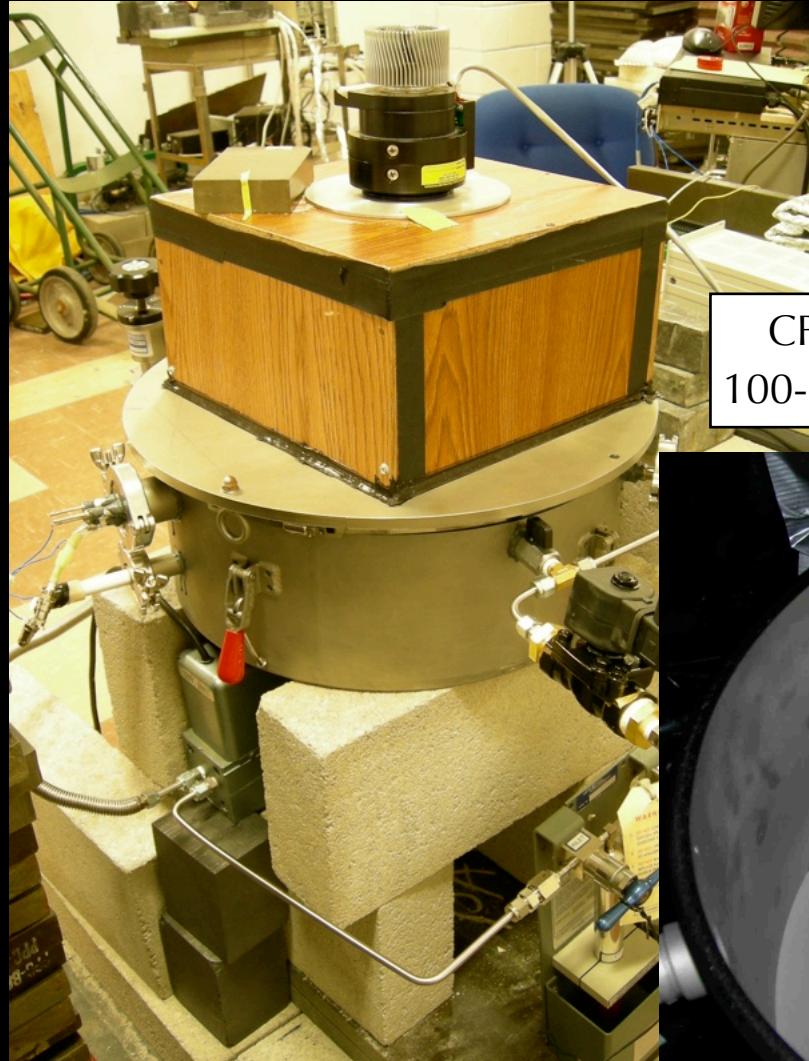
KamLAND: ~4 x predicted,  
76% measurement uncertainty

SuperK: normalization within  
10% of prediction (+ osc.) for  
 $E\nu < 100 \text{ MeV}$

**never measured!**

(historically, surprises at low  $Q^2$ )

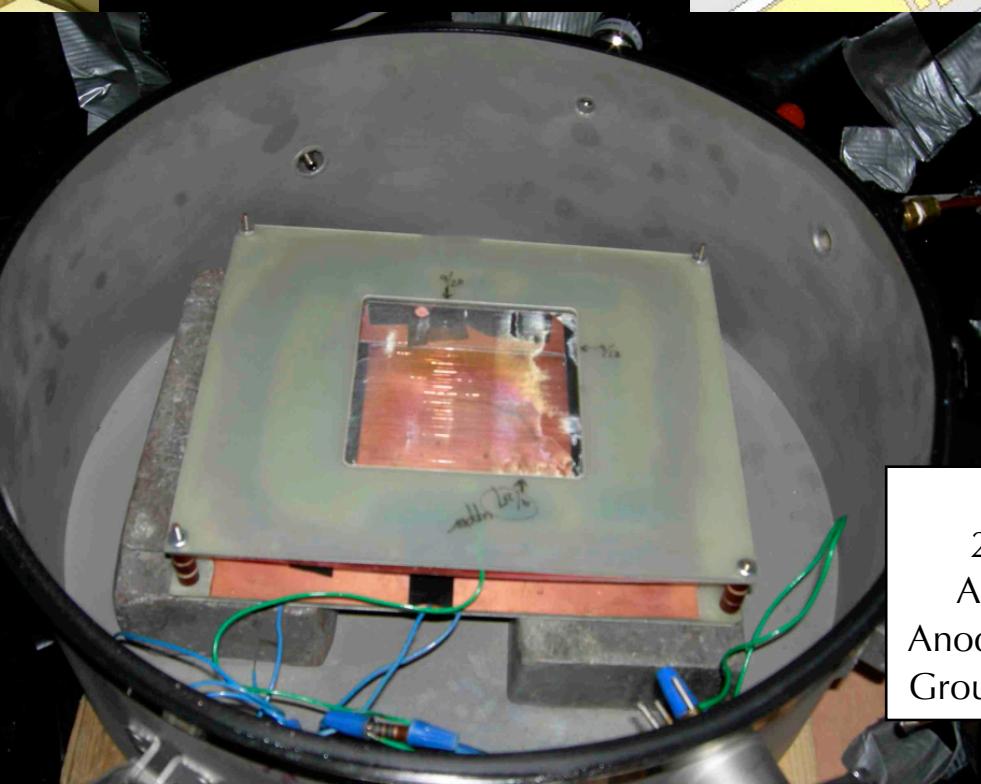
# First Generation Detector Prototype



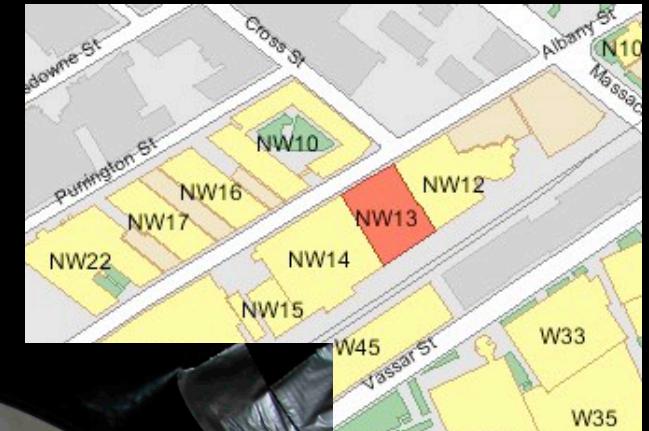
CF<sub>4</sub> gas  
100-380Torr



CCD Camera  
Kodak KAF0401 chip  
768x512 (9x9um)  
Cooled (-20C)  
Photographic lens (55mm)  
Finger Lakes Instrumentation



Drift region:  
2.6cm, E=580V/cm  
Amplification region:  
Anode: 5mm pitch, 100μm  
Ground: 2mm pitch, 50μm



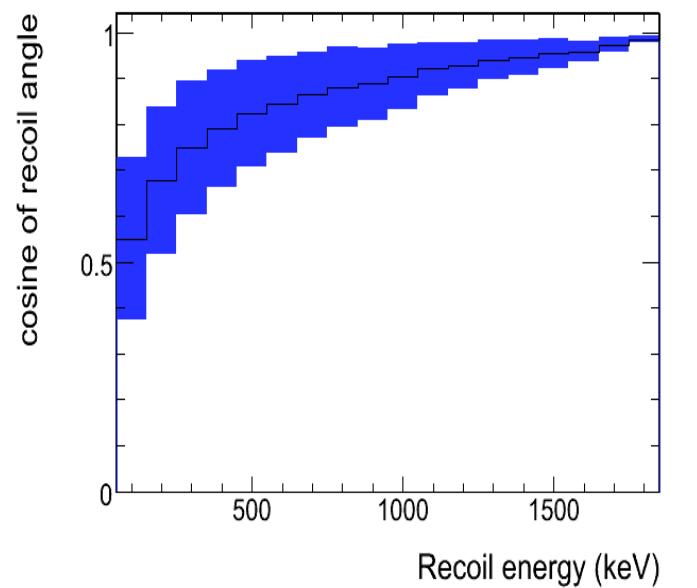
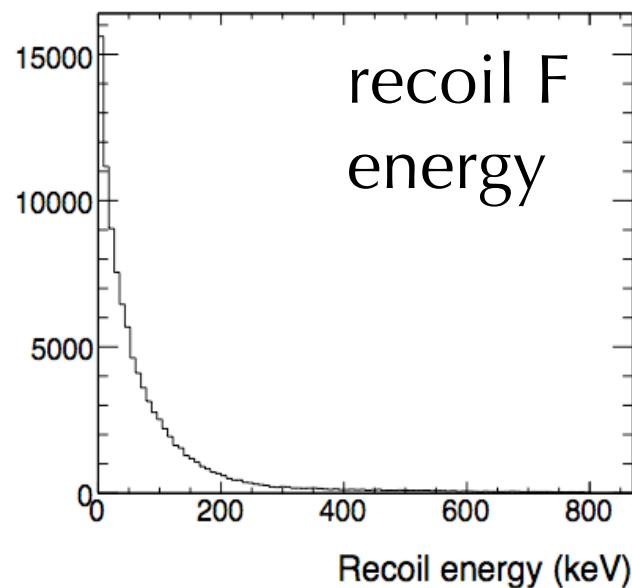
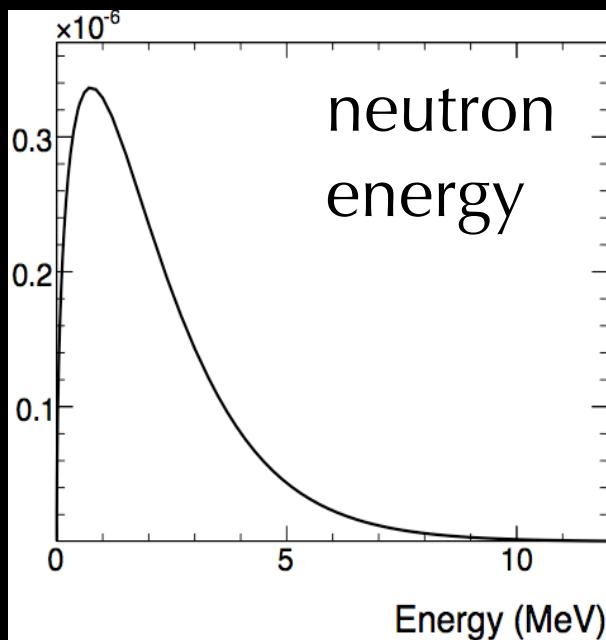
# Cf-252 Calibration

Soft energy spectrum:

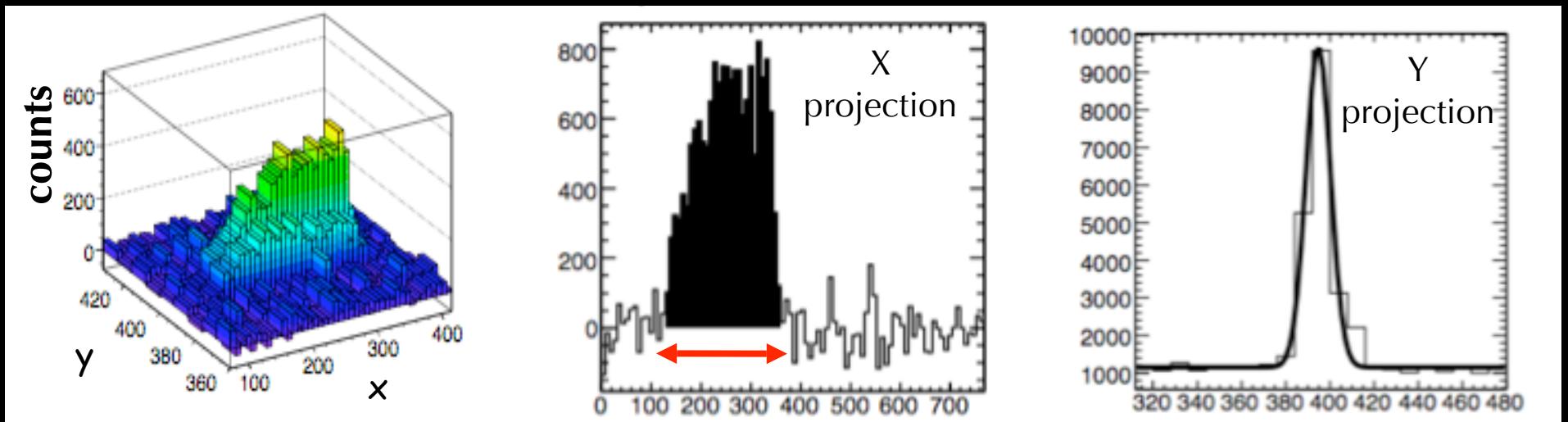
most neutrons below ~4 MeV alpha production threshold

Energy and recoil angle distributions  
similar to dark matter induced recoils

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



# Track Analysis



Range: count # of pixels above threshold

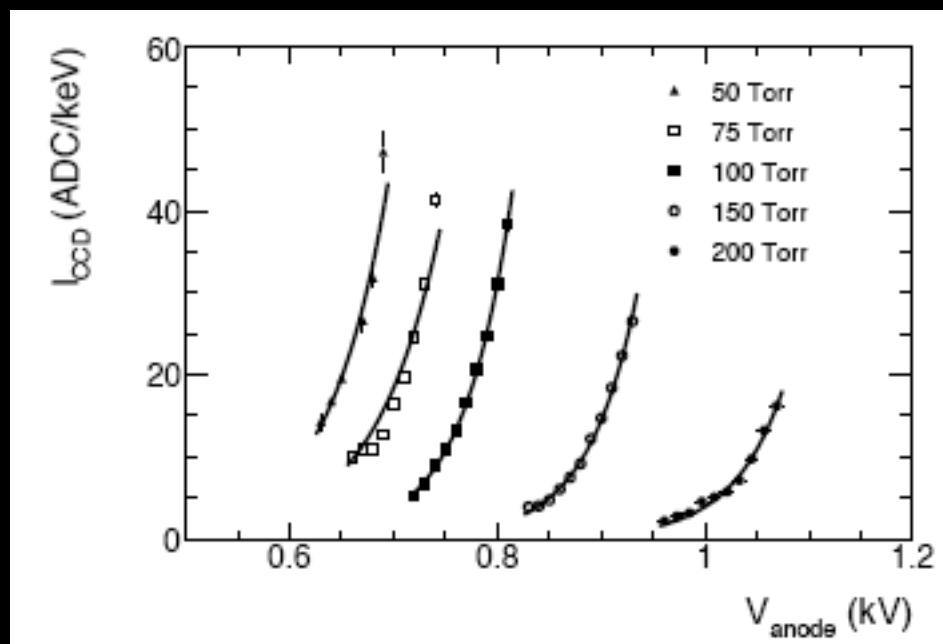
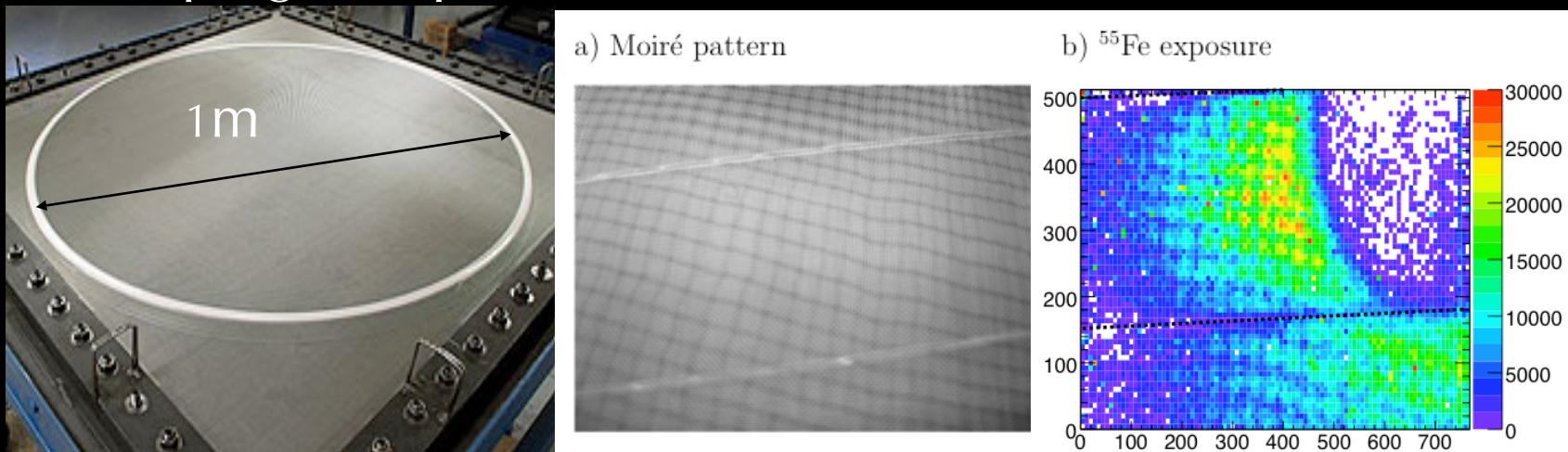
Measured along track direction (+/- 3 pixels around track),  
background estimate from neighboring pixels.

Energy: integral of light yield on the wire

Measured perpendicular to track direction, in +/- 5 pixels  
around segment, Gaussian fit above flat background.

# Amplification and Gain

Mesh amplification planes with copper anode: gain  $1-2 \times 10^4$   
developing transparent electrodes for double-sided readout



Calibrate gain, energy with  
5.5MeV  $\alpha$ 's from Am-241

CCD: ~15-45 counts/keV

$\Delta E/E$ : ~10%

spatial resolution: ~400 um

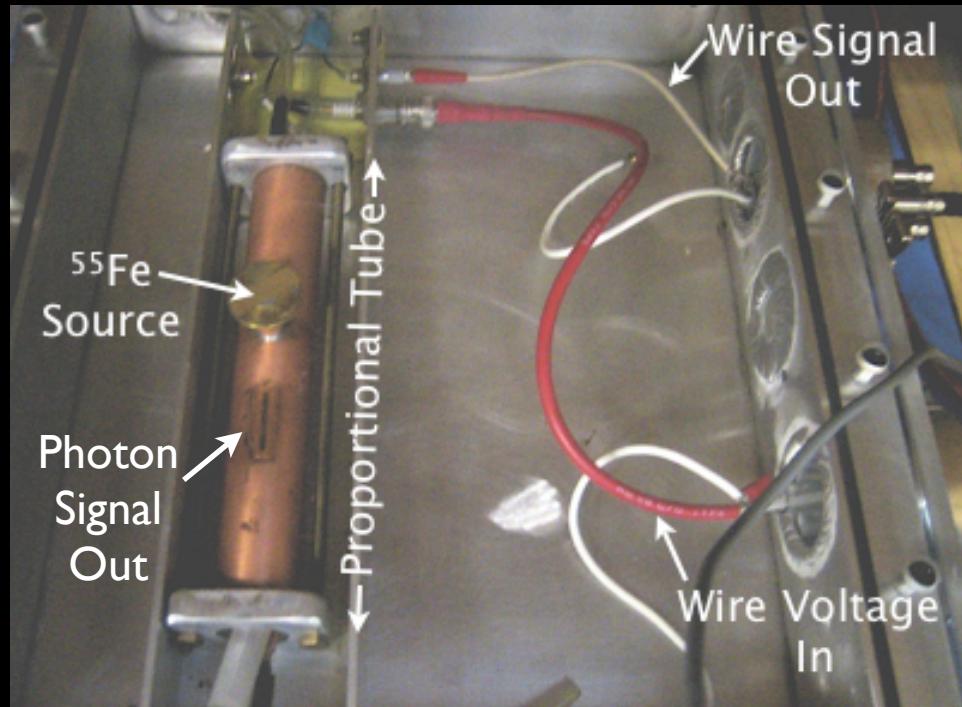
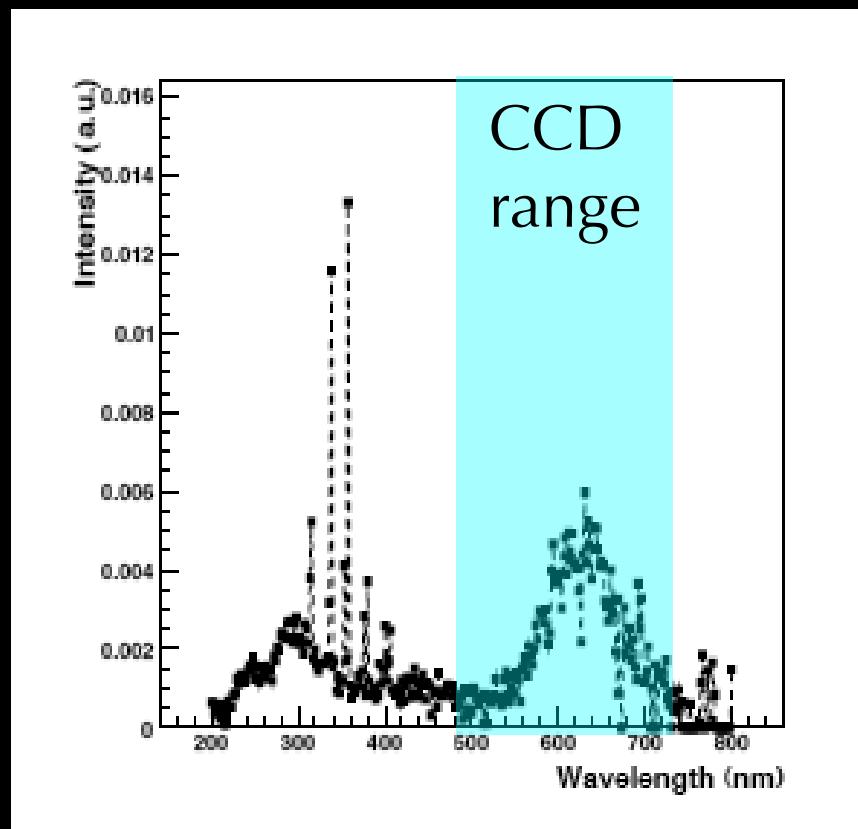
stability: ~1/2 day

(without flowing gas)

# Scintillation Yield

ratio of scintillation to ionization  
determines signal amplification

*result:*  $\gamma/e^- = 0.34 \pm 0.04$   
 $= 6,000 \text{ photons/MeV}$



spectrum of  $\text{CF}_4$  scintillation  
determines CCD signal acceptance

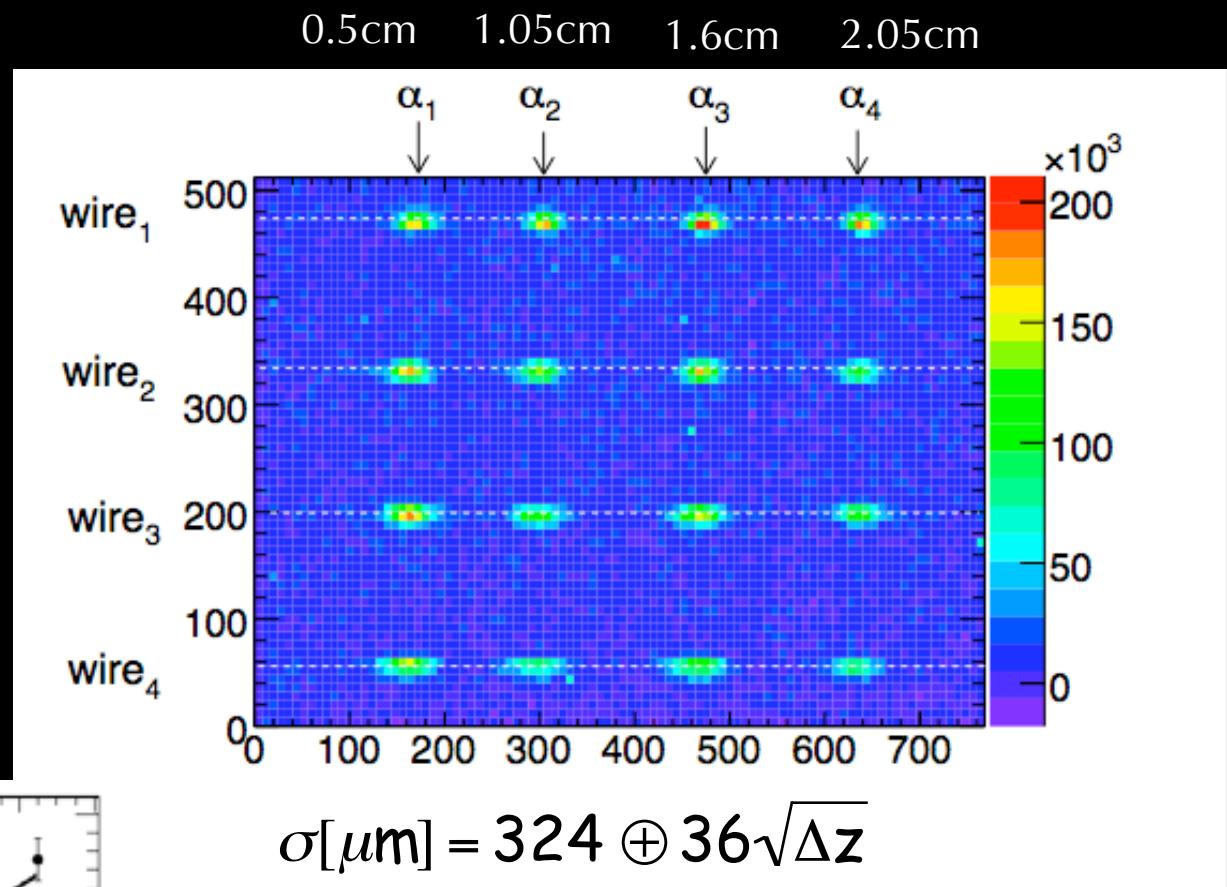
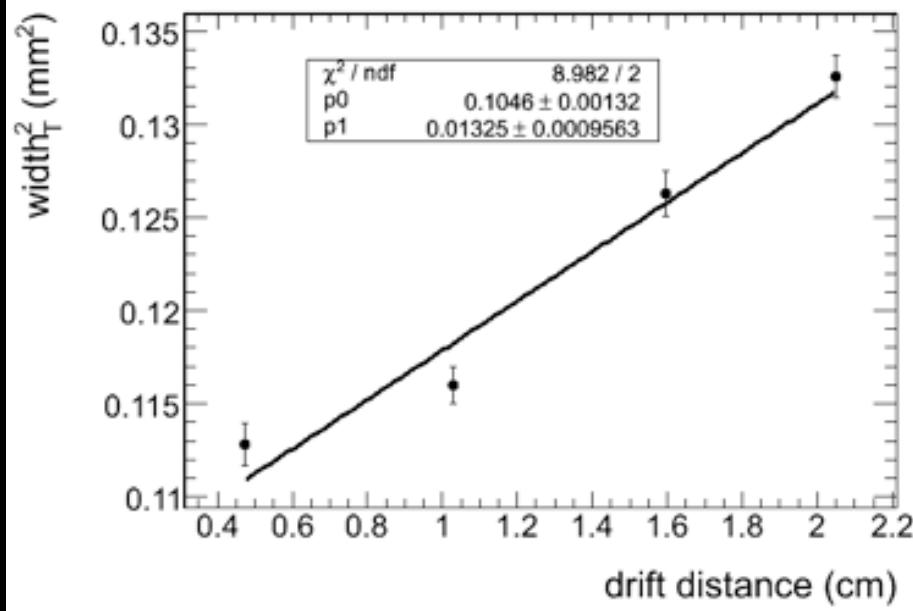
*result:*  $\text{CF}_4$  dark matter target well  
matched to CCD readout

# Diffusion

Critical parameter:  
nuclear recoil range  $\sim$  mm

Measure with alpha sources  
at different heights in drift  
region ( $\Delta z$ )

200Torr



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

D. Dujmic, et al., NIM A 584:337 (2008)

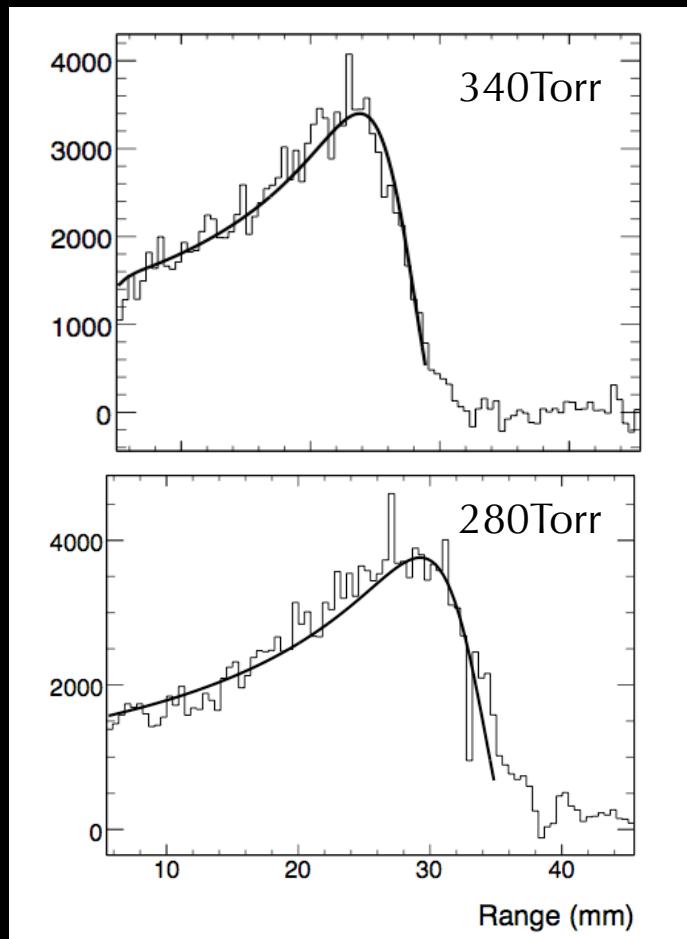
340 $\mu\text{m}$  for  $\Delta z=1\text{cm}$

670 $\mu\text{m}$  for  $\Delta z=25\text{cm}$

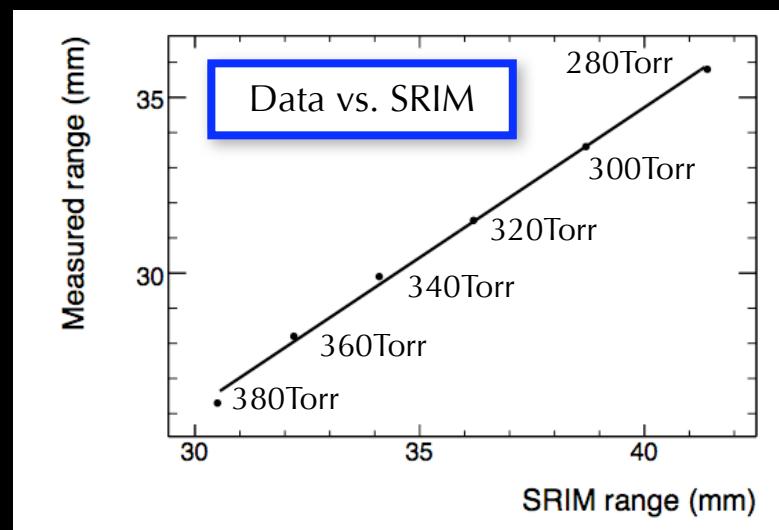
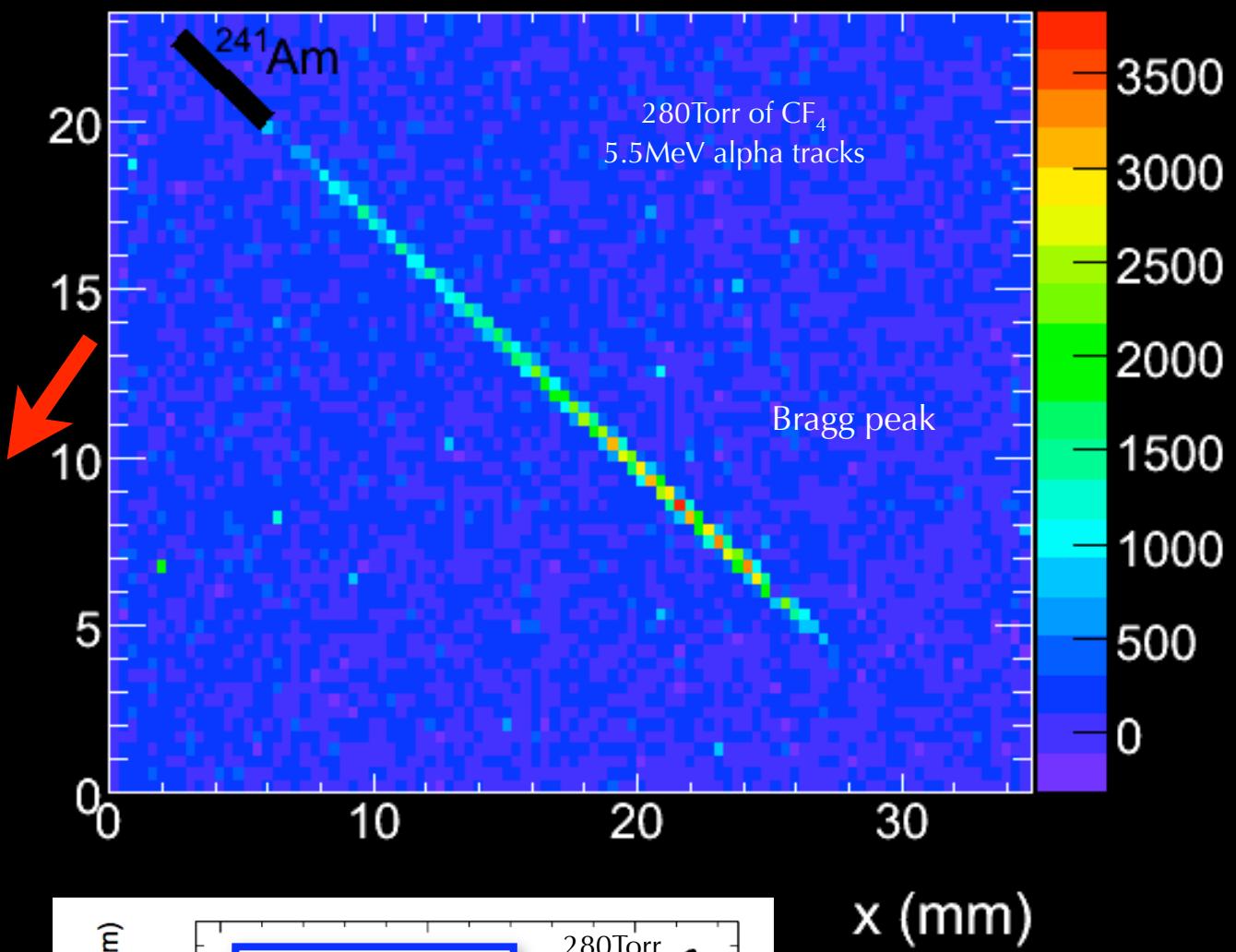
Maximum size of drift region



# Range Calibration



fit for endpoint

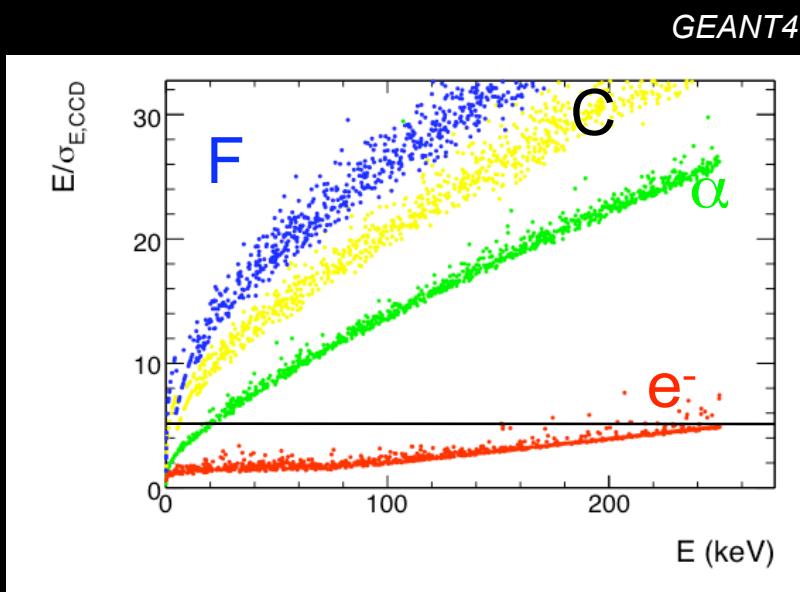


range  
calibration  
relative to SRIM  
simulation

# Threshold

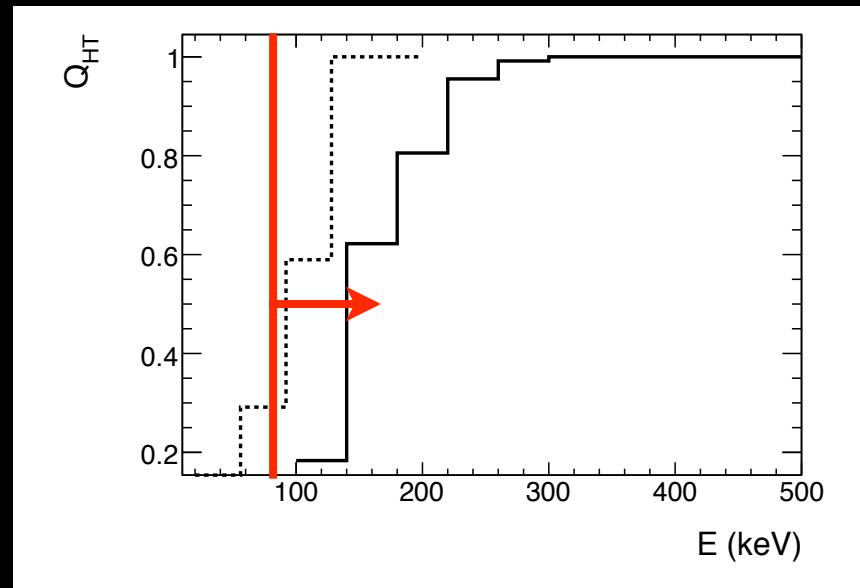
currently head-tail quality factor  
>50% above ~120 keV

with reasonable improvements in  
gain, expect to lower 50% fraction  
to 80 keV



now vs. future:  
75 vs. 50 Torr, 25 vs. 60 ADU/keV,  
3x less CCD noise, 1 vs. 2-drift readout

Now:



Future:

