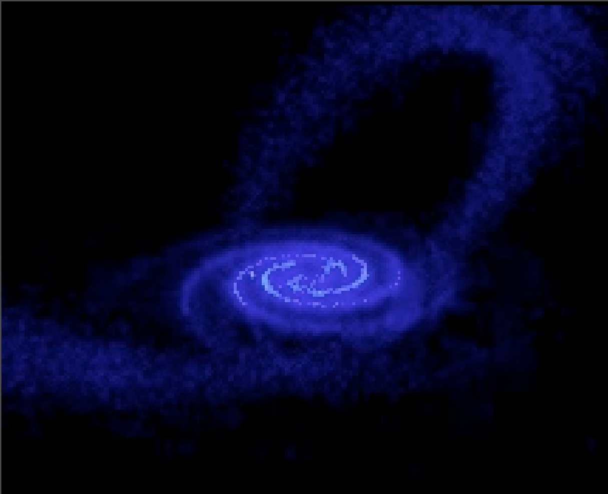


Searching for the Dark Matter Wind: a Novel Approach to Dark Matter Detection

Jocelyn Monroe, MIT

Imperial College HEP Seminar

November 8, 2007

Outline

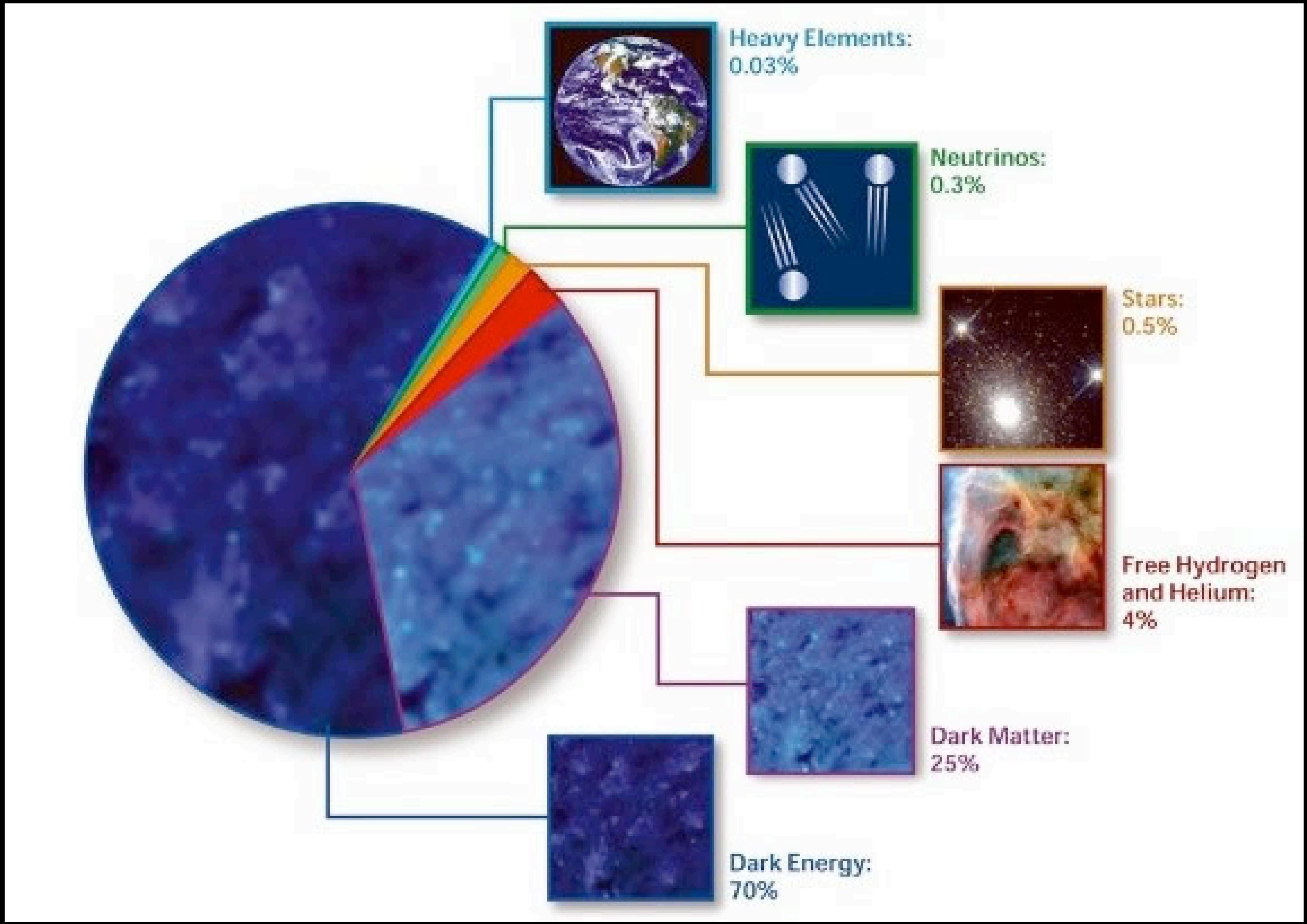
The Dark Matter Wind

Dark Matter Search Strategy

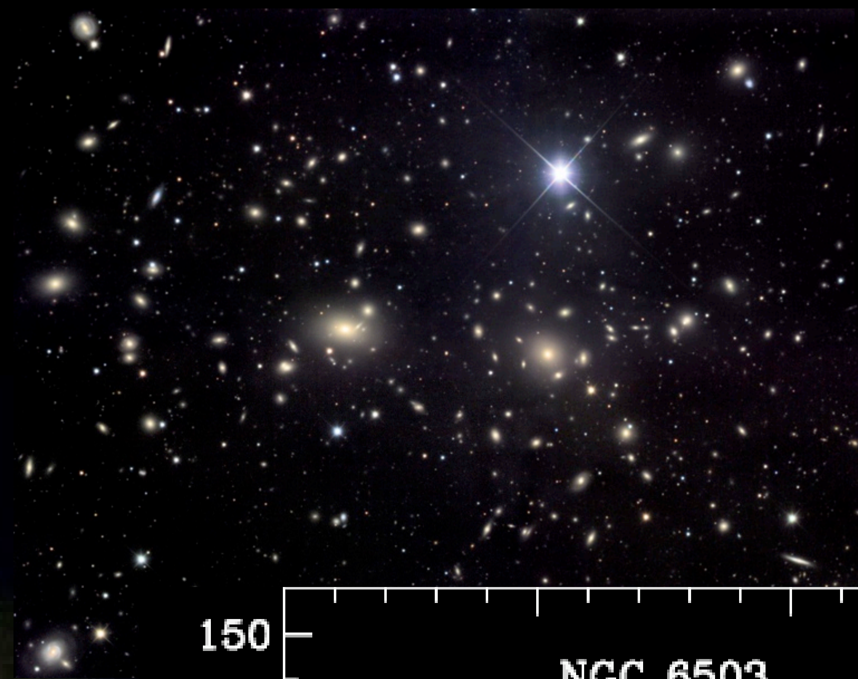
Directionality

Where We Are Now:
DMTPC Detector Development

Dark Matter is ~25% of the energy density of the universe.

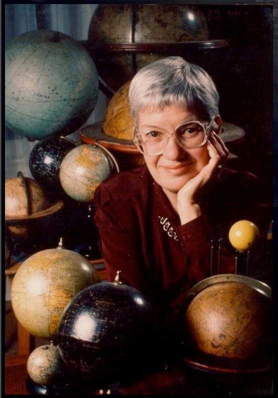


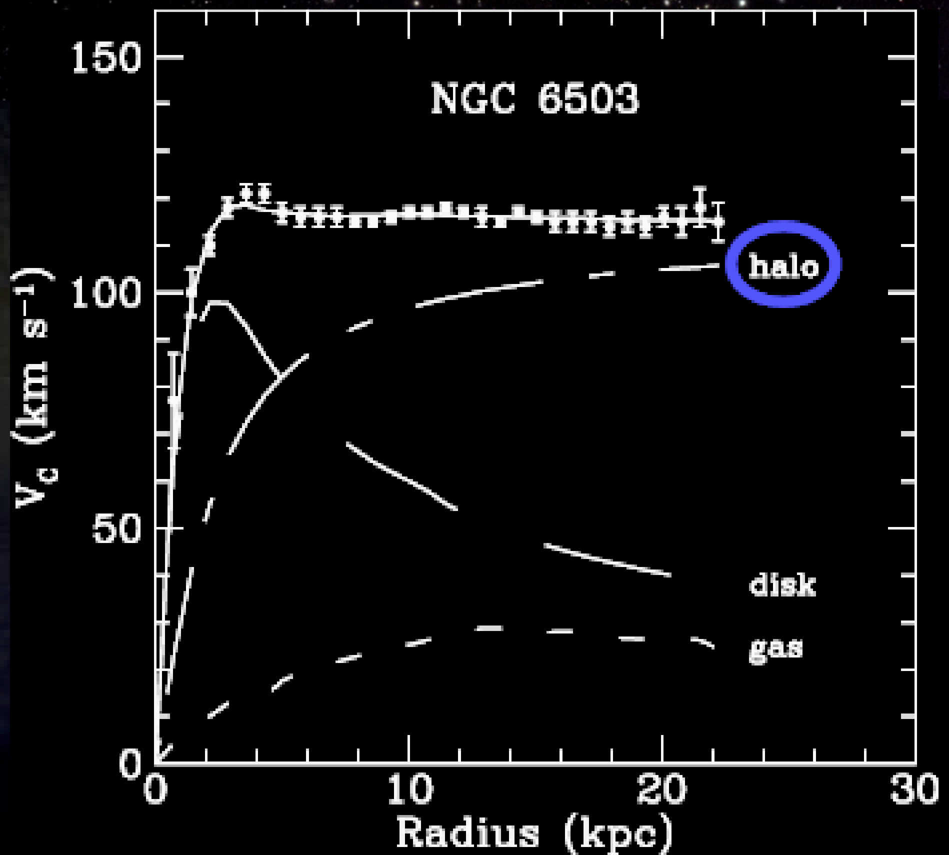
1st Dark Matter Evidence



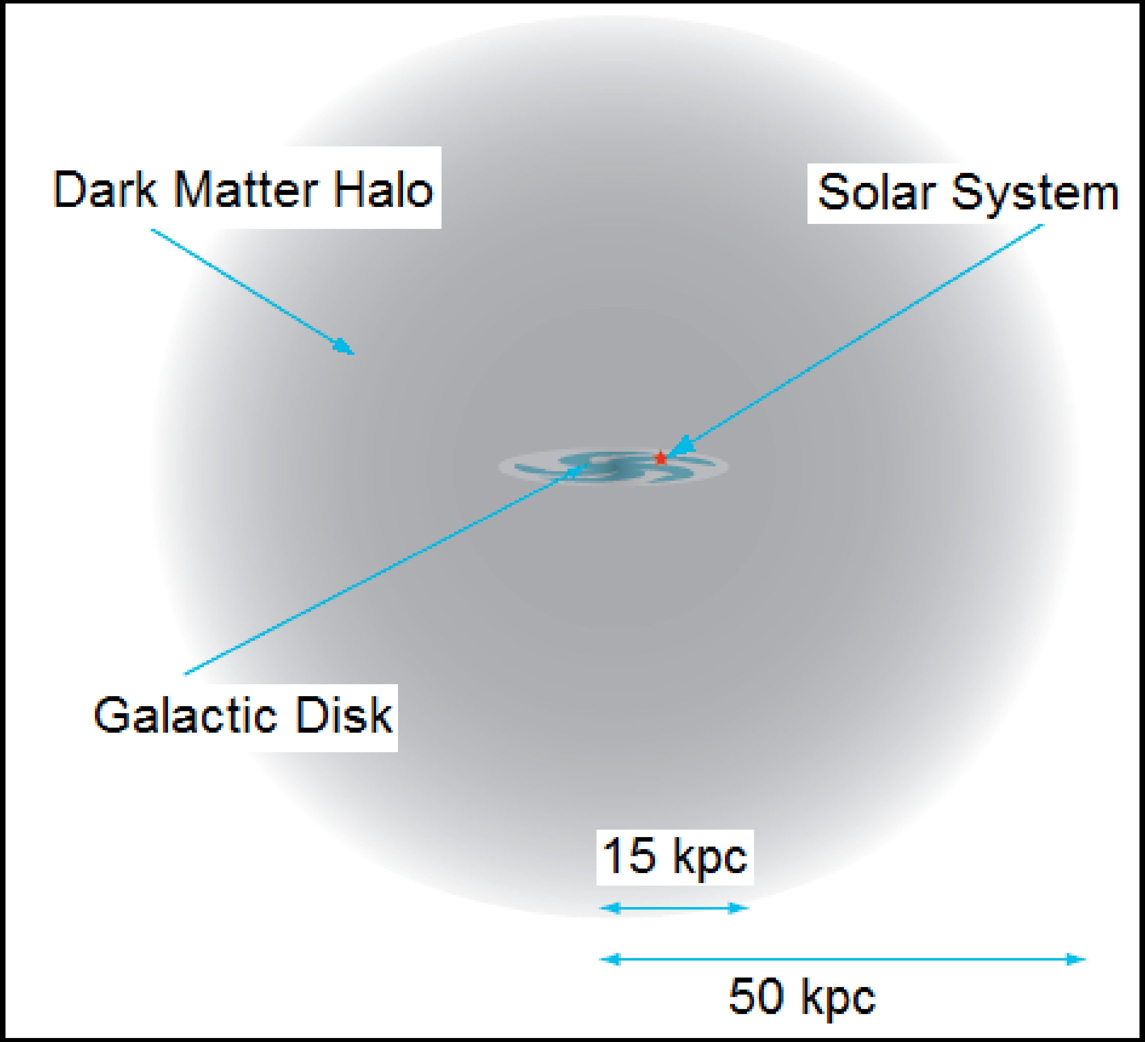
Fritz Zwicky

Vera Rubin





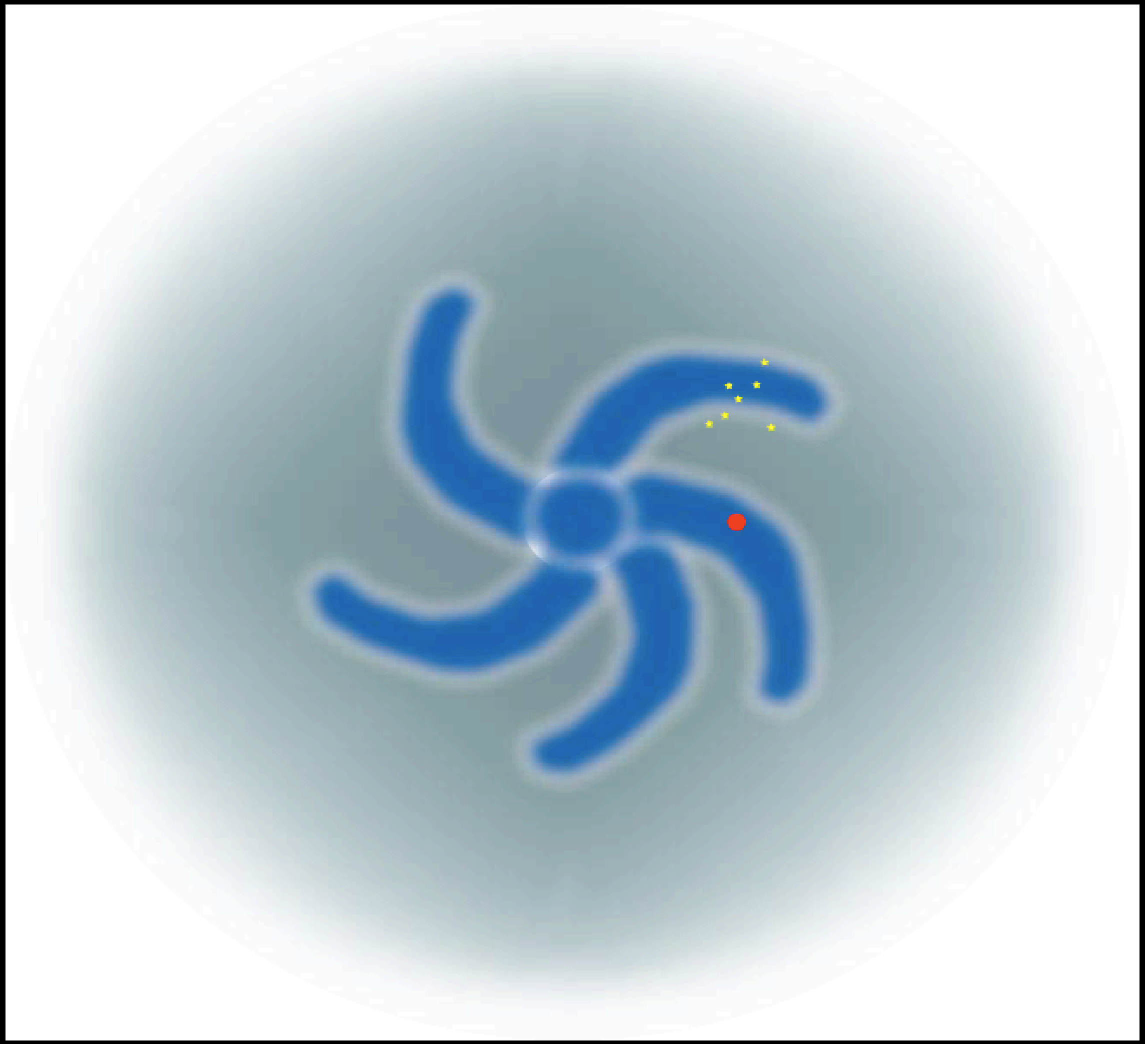
Properties



density ~ 0.3 GeV/cm^3
optically dark
cold
mass: ~unconstrained
interactions: < weak σ
dust-like, collisionless
v_{RMS} ~ 230 km/s

we are rotating relative to the halo: **a dark matter wind**

Properties



density ~ 0.3 GeV/cm^3
optically dark
cold
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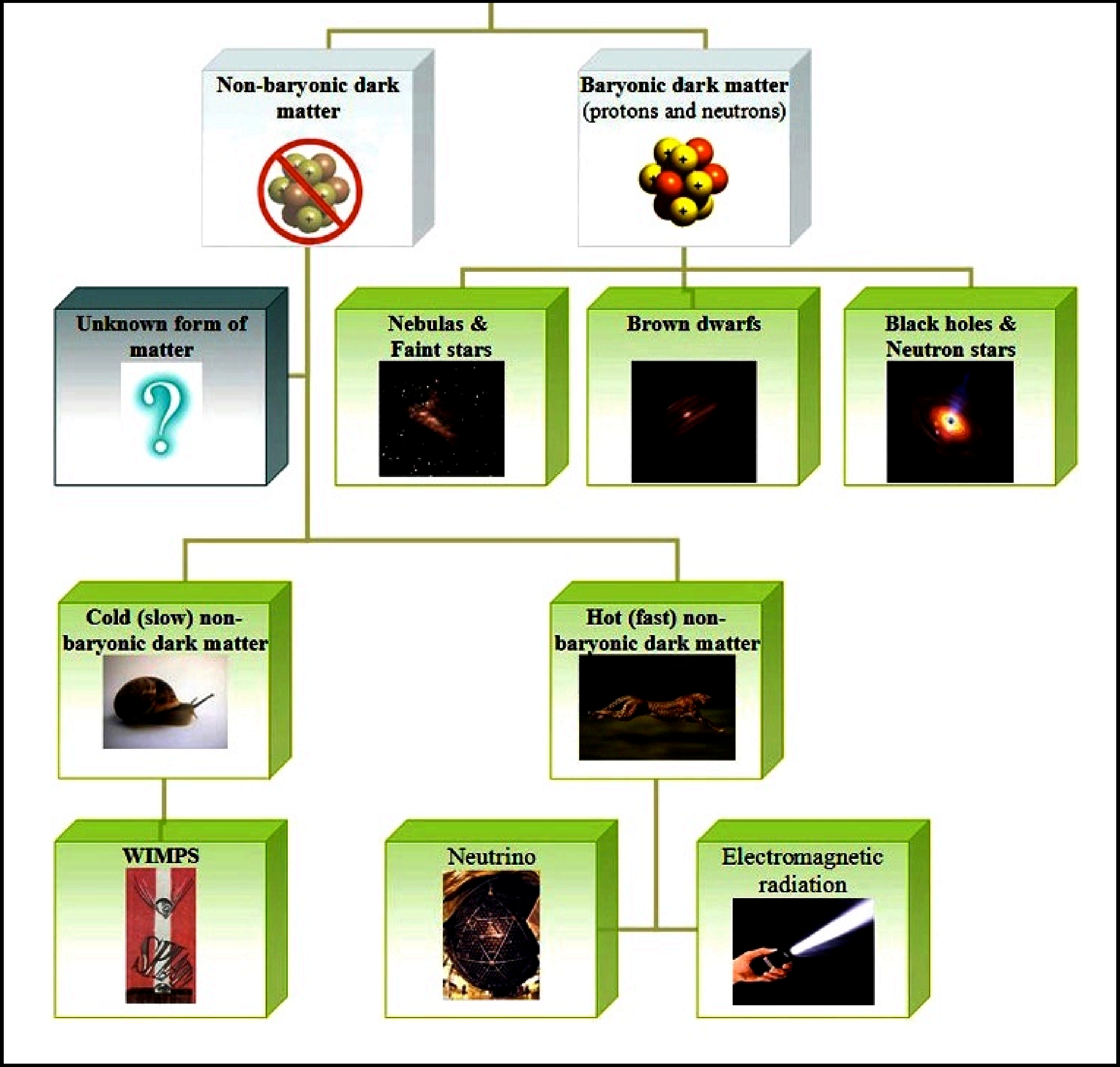
dust-like, collisionless
v_{RMS} ~ 230 km/s

we are rotating relative to the halo: **a dark matter wind**

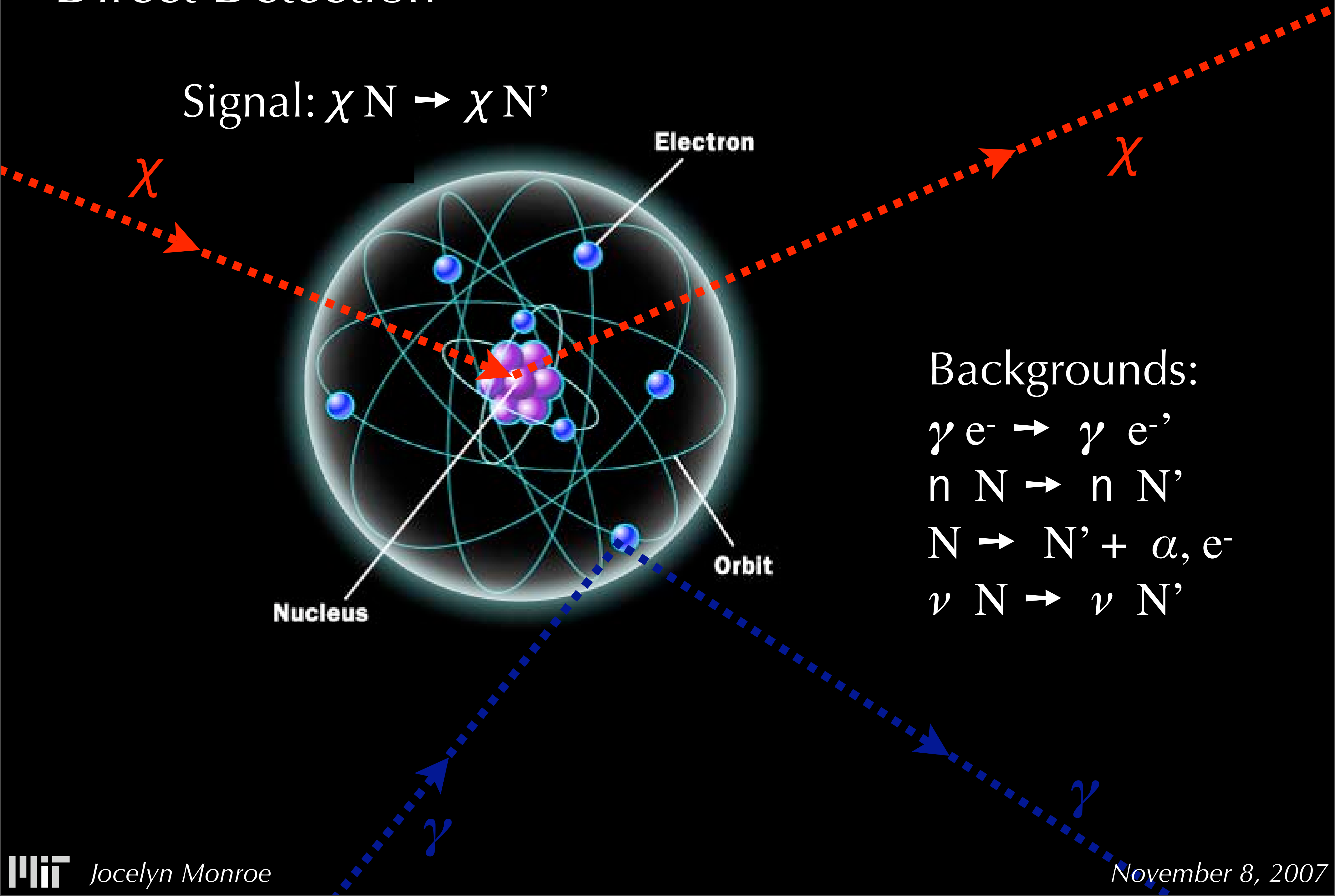
Candidates

SUSY dark matter (neutralinos, gravitinos, sneutrinos, axinos)
axions,
simpzillas,
light scalar dark matter,
little Higgs dark matter,
Kaluza-Klein dark matter,
CHAMPS,
D-matter,
Cryptons,
SWIMPS,
Mirror particles,
Brane world dark matter,
Q-balls,
sterile model neutrinos,
etc.



Direct Detection

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



Backgrounds:

$\gamma e^- \rightarrow \gamma e^{-\prime}$

$n \; N \rightarrow n \; N'$

$N \rightarrow N' + \alpha, e^-$

$\nu \; N \rightarrow \nu \; N'$

WIMP Scattering

kinematics: $\beta_D \sim 8E\text{-}4!$

$$E_D = \frac{1}{2} m_D v^2$$

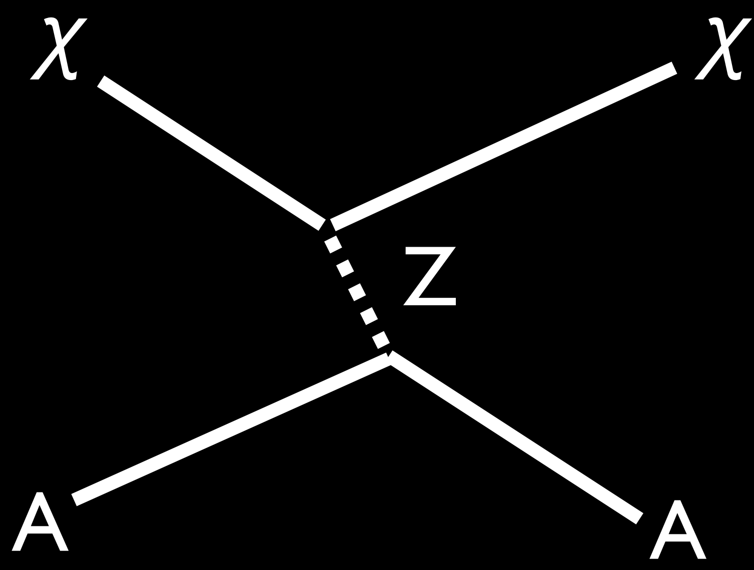
$$E_{recoil} = E_D r \frac{(1-cos\theta)}{2}$$

$$r = \frac{4 m_D m_T}{(m_D + m_T)^2}$$

$$q^2 = 2 m_T E_{recoil}$$

coherent interactions,
very low recoil energies

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

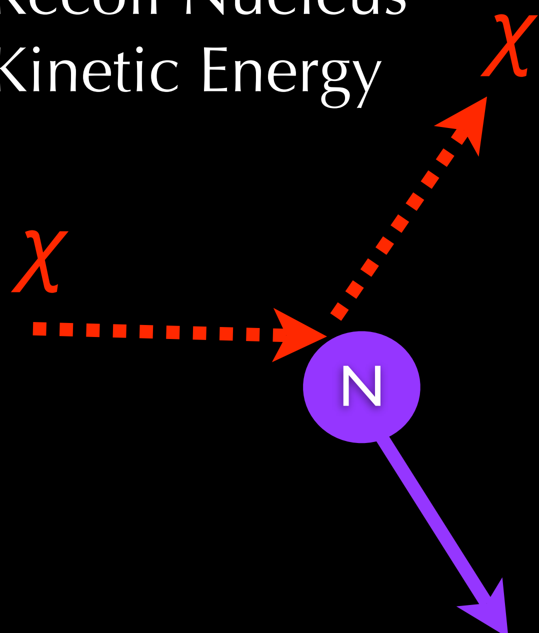


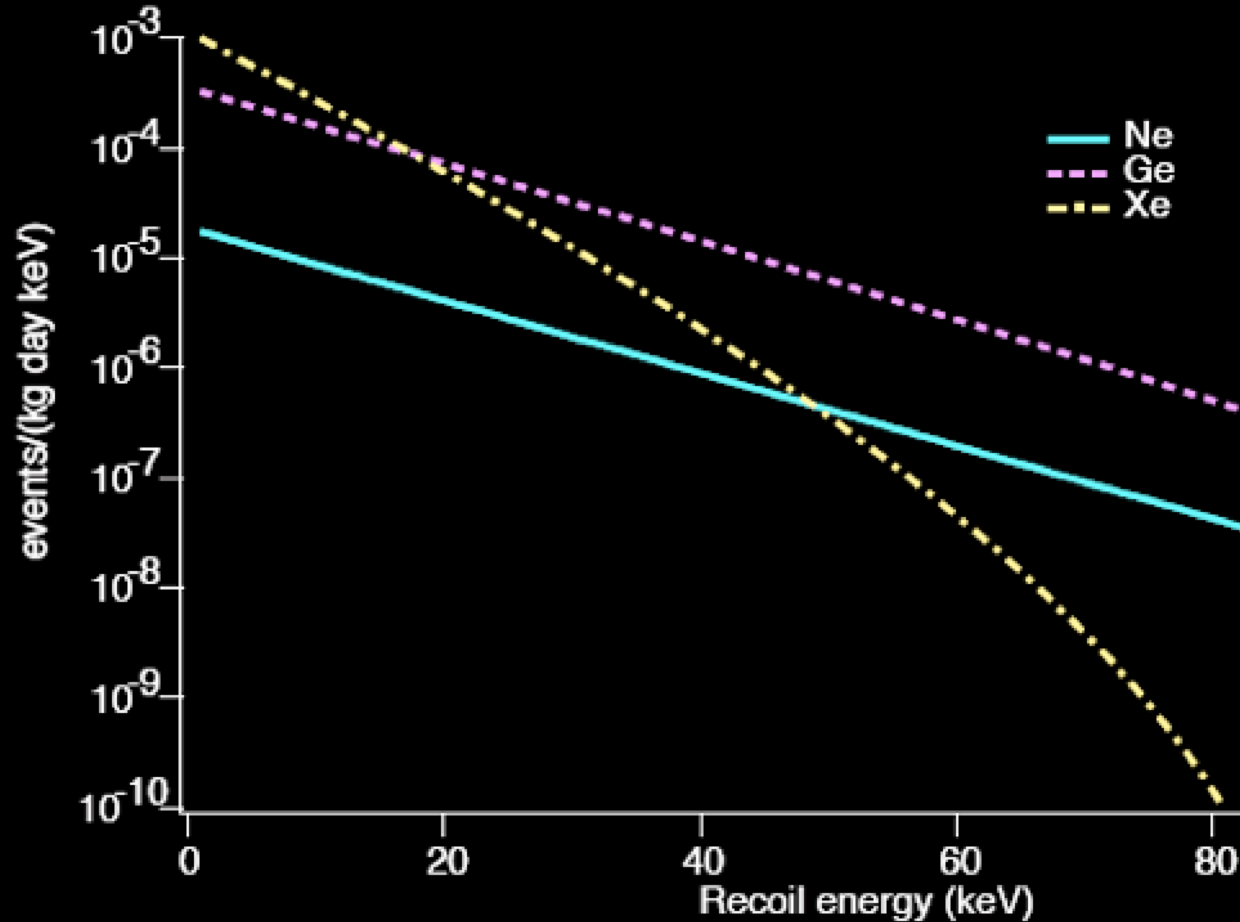
Spin Independent:
χ scatters coherently off of the entire nucleus A: $\sigma \sim A^2$

Spin Dependent:
only unpaired nucleons contribute to scattering amplitude: $\sigma \sim J(J+1)$

Measurement

Recoil Nucleus
Kinetic Energy





Scattering rate

Sun's velocity around the galaxy

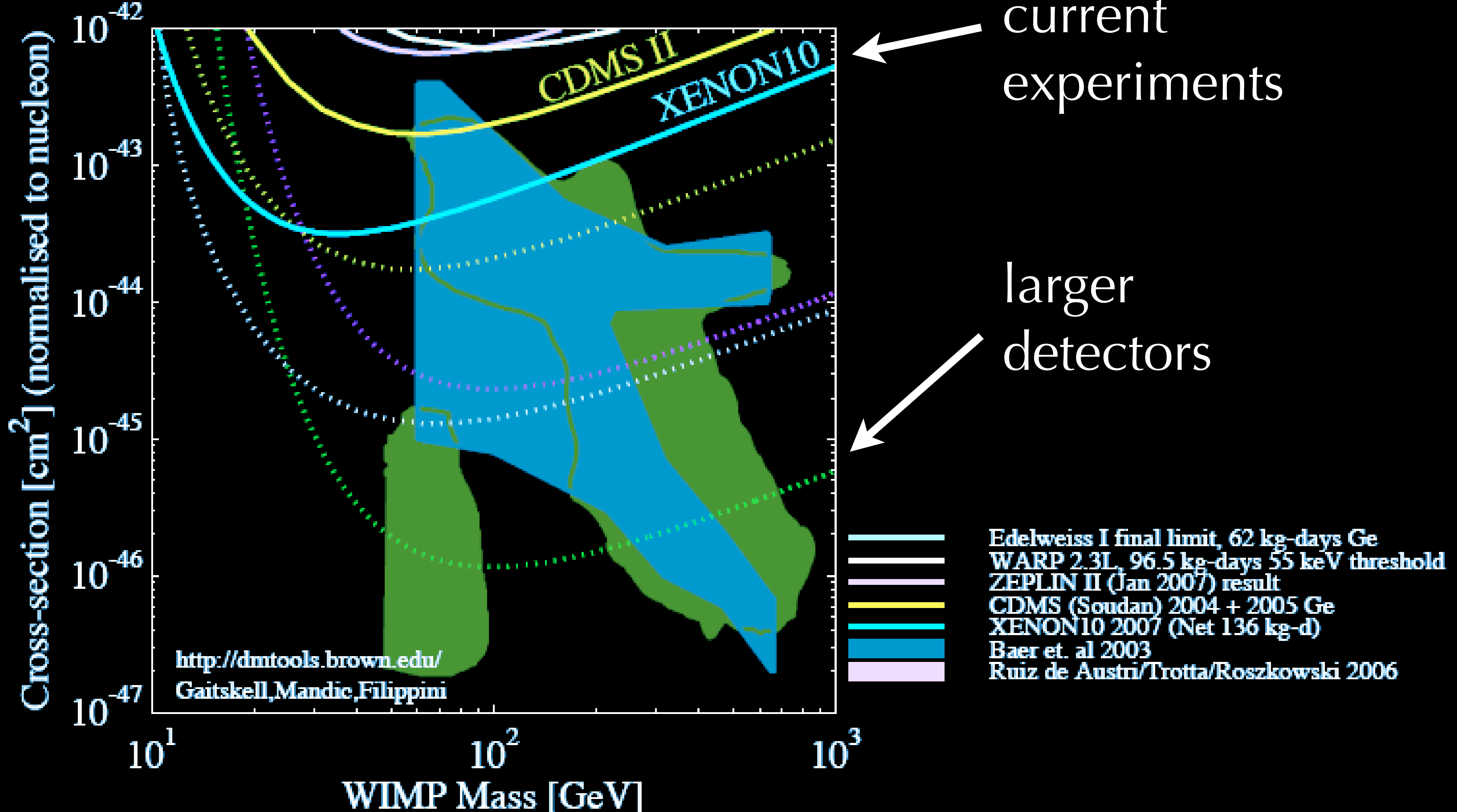
WIMP velocity distribution

$$dR/dQ \sim (\sigma_0 \rho_0 / \sqrt{\pi}\, v_0 m_\chi m_r^2)\, F^2(Q)\, T(Q)$$

WIMP energy density, 0.3 GeV/cm³

Form factor

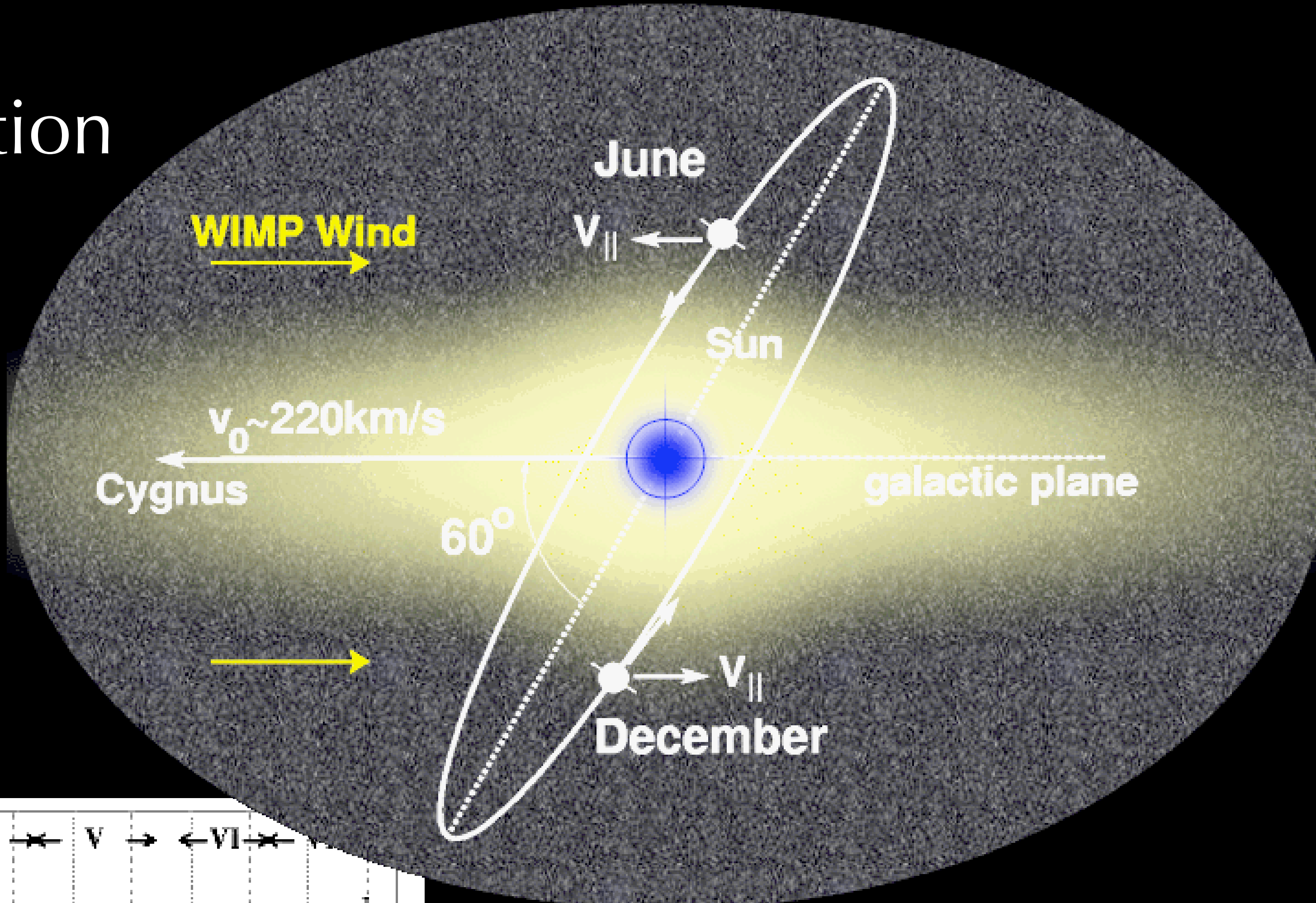
Spin-Independent Cross Section Limits

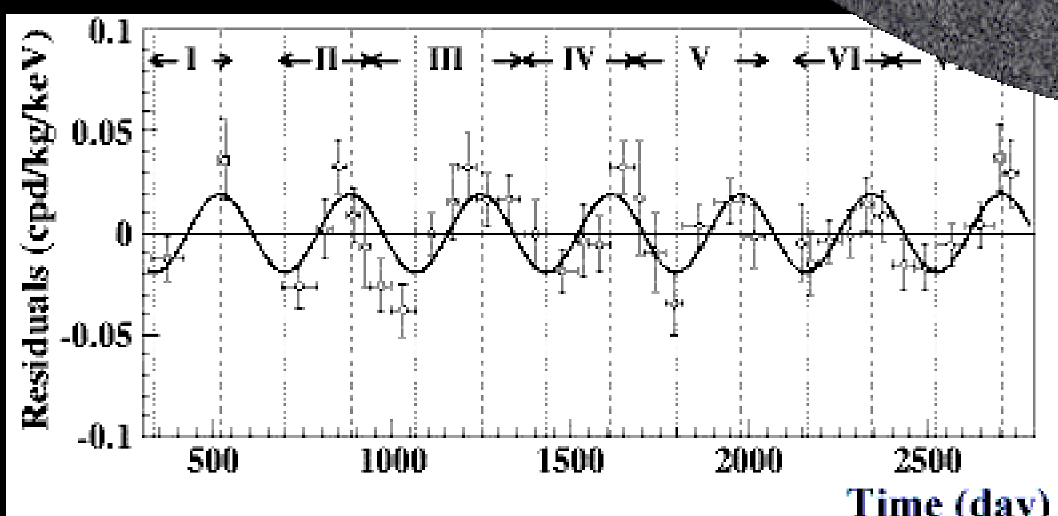


The Wind:
Annual Modulation

June-December event rate asymmetry ~2-10%

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

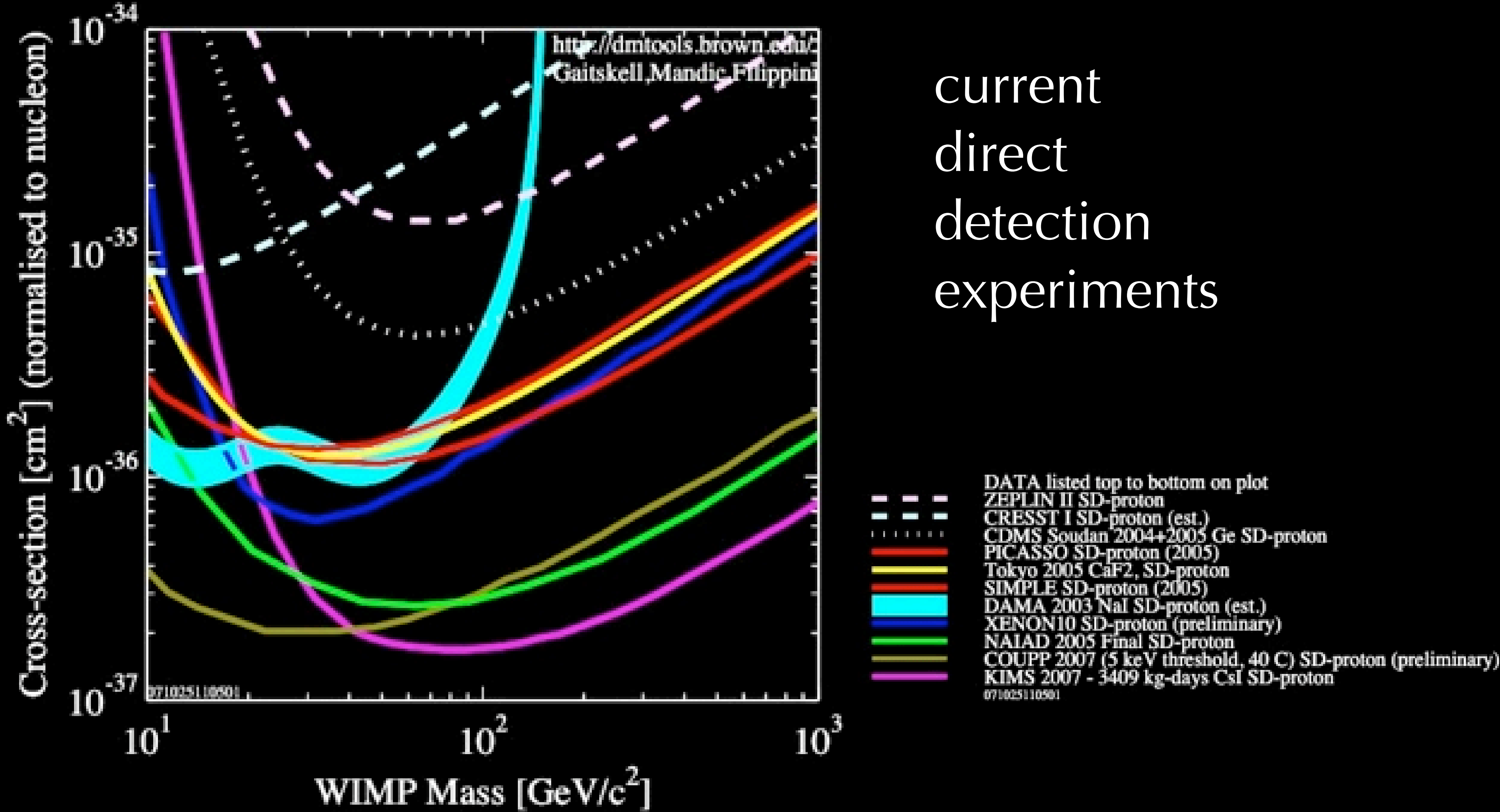




Dama positive result: 6.1σ

excluded by other experiments

Spin-Dependent Cross Section Limits

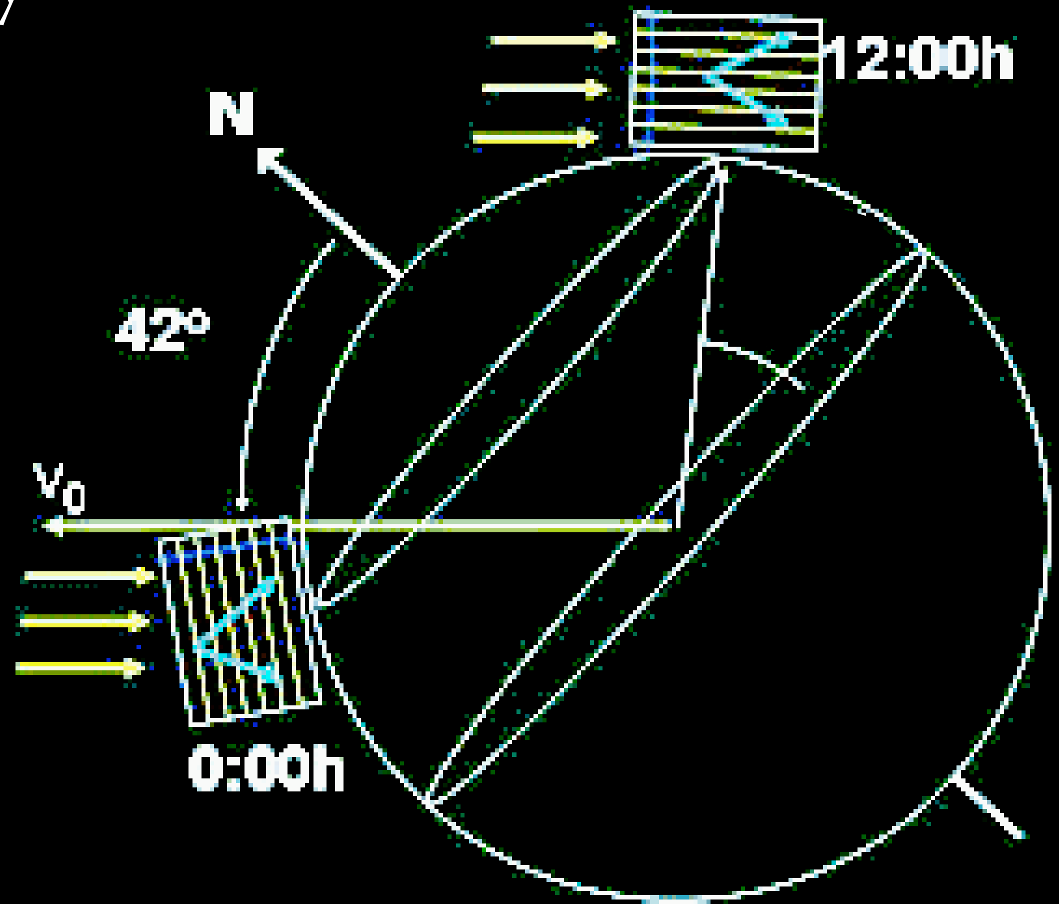


current direct detection experiments

10^7x larger upper limits than SI cross sections

The Wind: Directionality

Cygnus



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

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

a dark matter source!

Dark Matter Search Strategy

Expected WIMP Interaction Cross Section

Backgrounds

The Zero-Background Paradigm

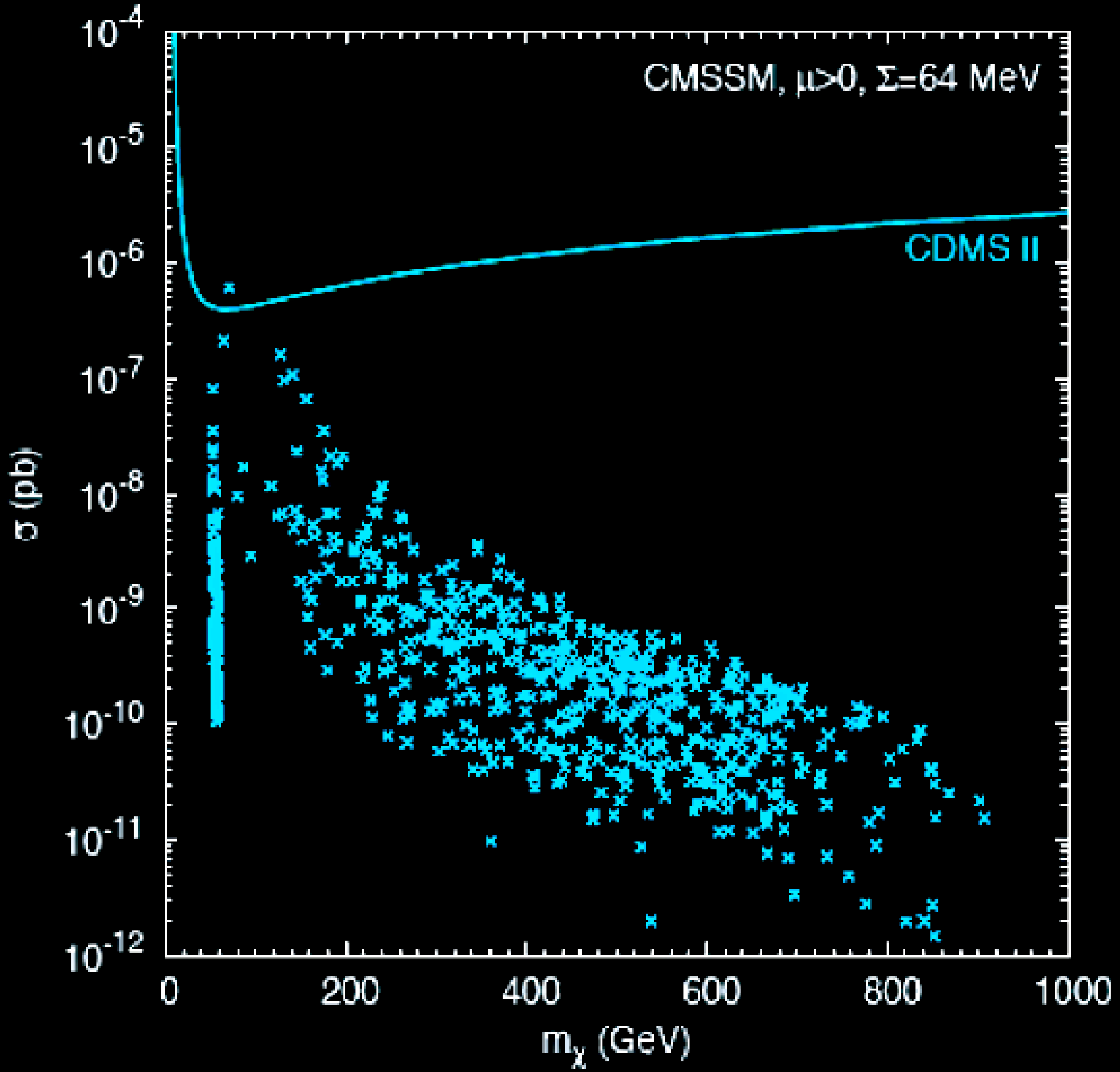
Signal

SUSY+ collider limits: σ(χ A) may be as small as 10^{-48} cm^2

Shrimps, not WIMPS:

```
1 pb = 10^-36 cm^2
σ(weak) ~ 10^-3 pb
σ(DM el) ~ 10^-10 pb
```

~10^4 below current expt'l sensitivity



J. R. Ellis, et al., PRD **71**, 095007 (2005)

10^4 is a lot of σ

Not to Scale

10^{-28} cm^2: σ(total inelastic pp at TeVatron)

10^{-35} cm^2: σ(gg → H) at LHC (Standard Model)

10^{-37} cm^2: σ(gg → H) at TeVatron (Standard Model)

10^{-39} cm^2: σ(single top) at TeVatron

10^{-40} cm^2: σ(ν QE) at MiniBooNE (E_ν = 1 GeV)

10^{-43} cm^2: σ(ν NC Elastic) for geo-ν (E_ν = 2 MeV)

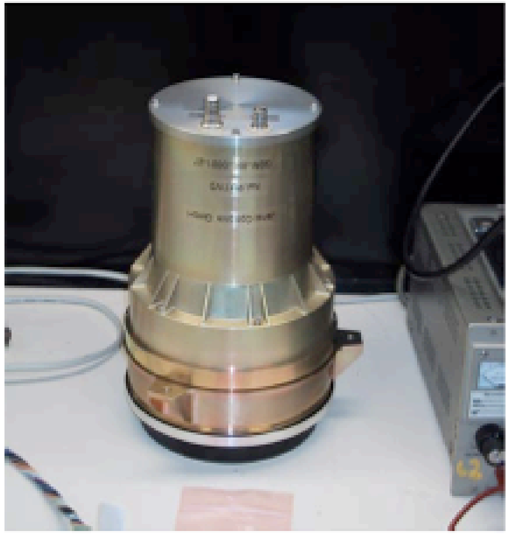
10^{-45} cm^2: σ(ν-e Elastic) for solar ν

σ(DM coherent scattering)? 10^{-48} cm^2

EM Backgrounds

(D. McKinsey)

Geiger counter



Sodium iodide crystal

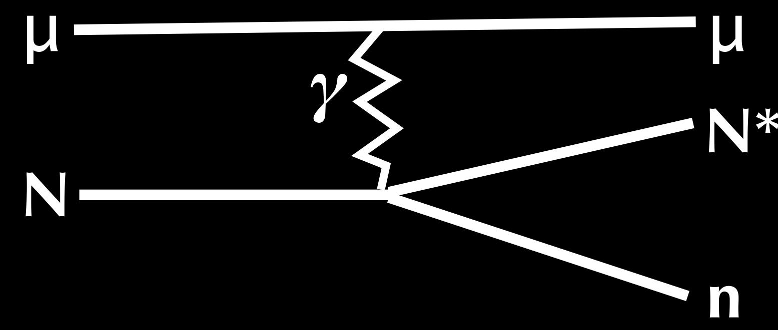
Germanium

Gamma ray interaction rate is proportional to
(# of electrons in detector) x (gamma ray flux)

Typical count rate = 100 events/s/kg = 10,000,000 events/day/kg
in a good lead shield, rate drops to 100 events/day/kg

Best dark matter detectors: sensitive to **0.01 events/day/kg**
(σ~1E-44 cm^2)

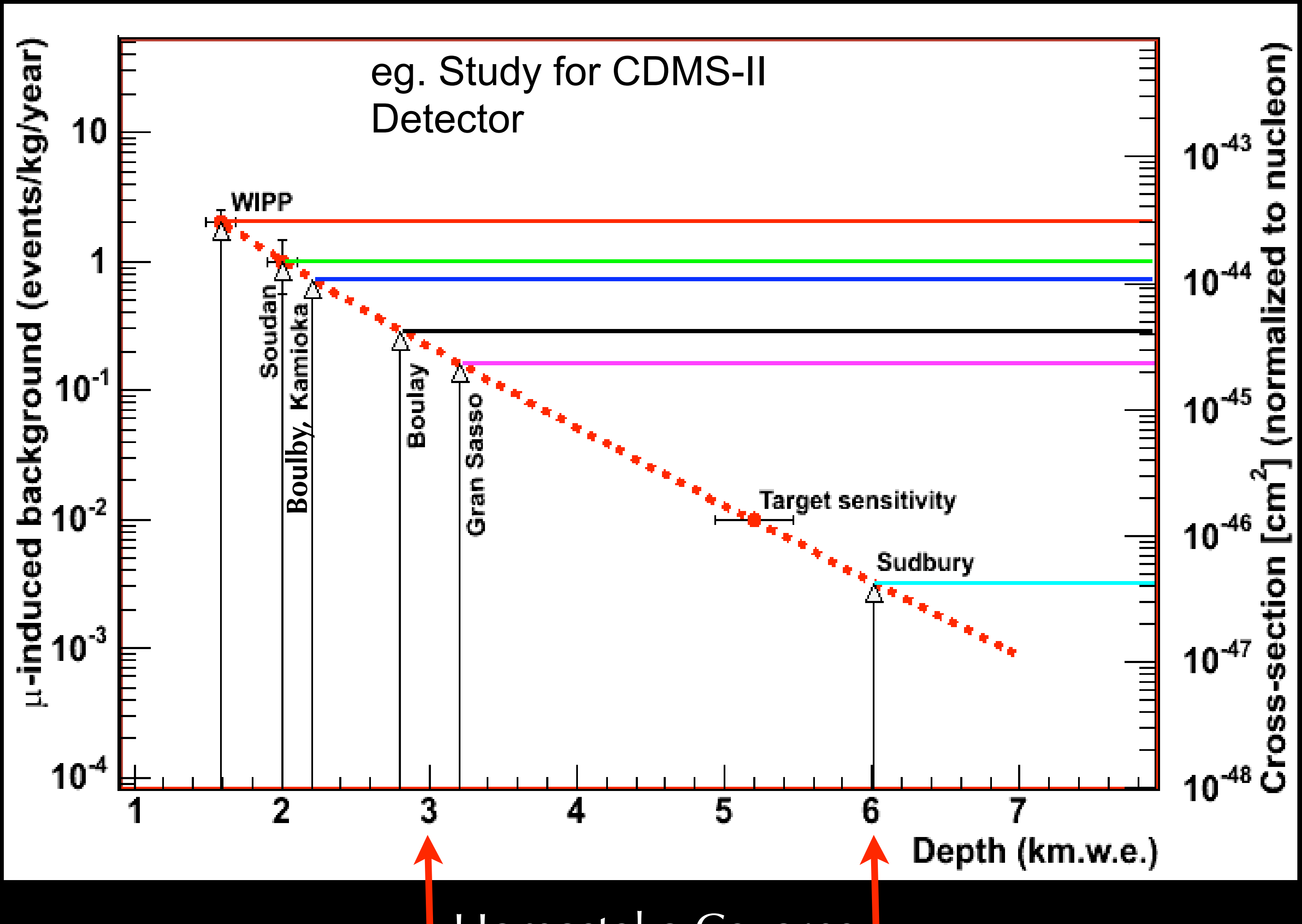
Neutron Backgrounds



(A. Heim/D. M. Mei)

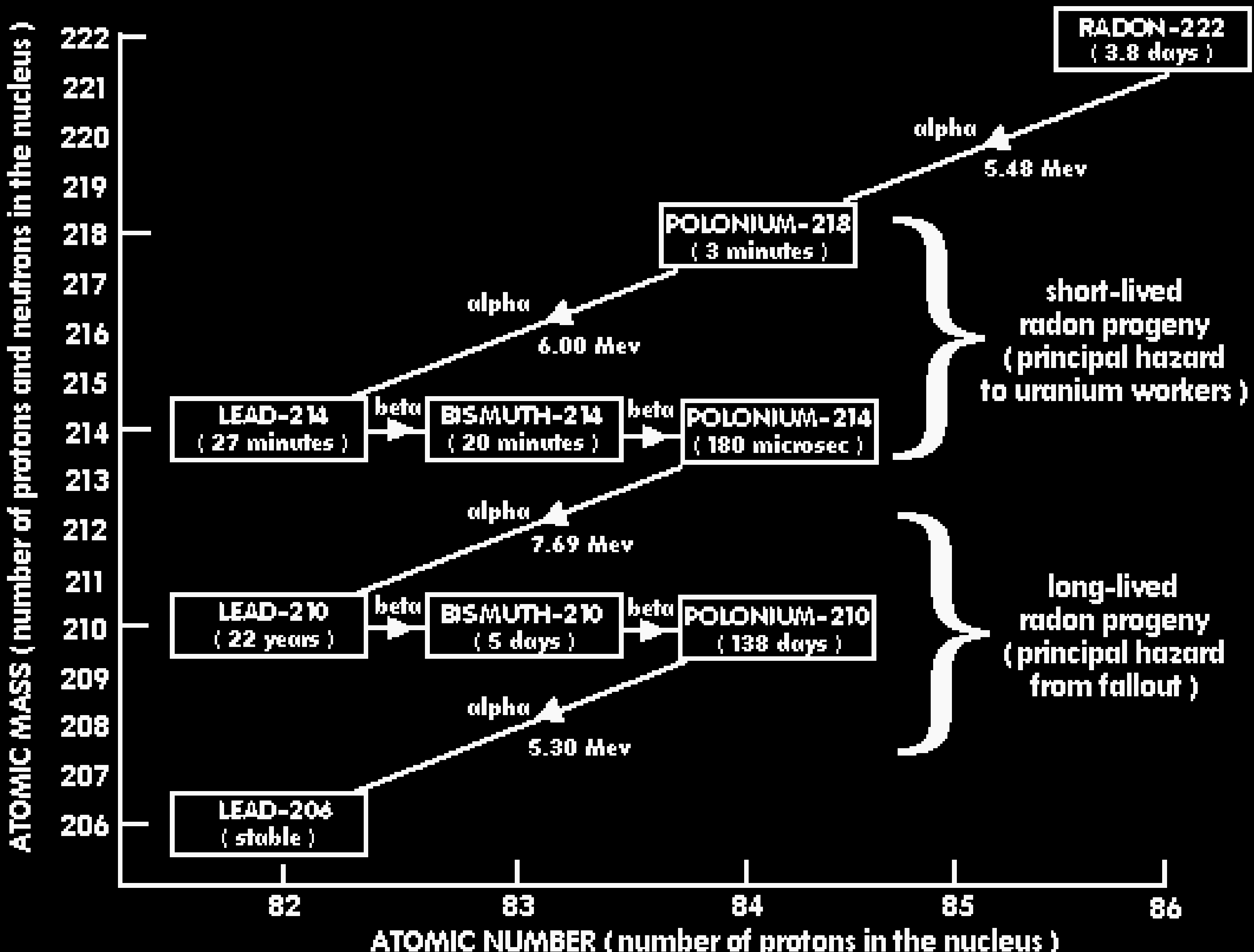
Cosmic muons spall neutrons: ~10^{-4} neutrons/ (100 GeV μ)/ gm/cm^2

neutron flux: 10^{-8} - 10^{-10}/cm^2/s (range for depth)

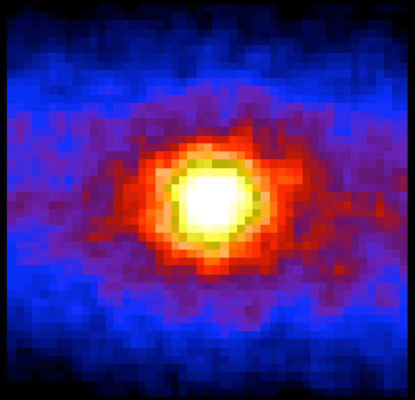


U and Th Decay Backgrounds

can't shield a detector from U and Th inside, recoiling progeny and associated betas can fake nuclear recoils

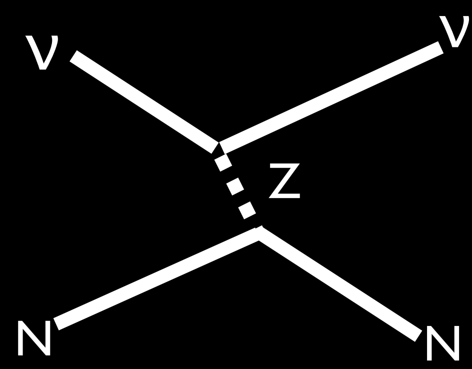


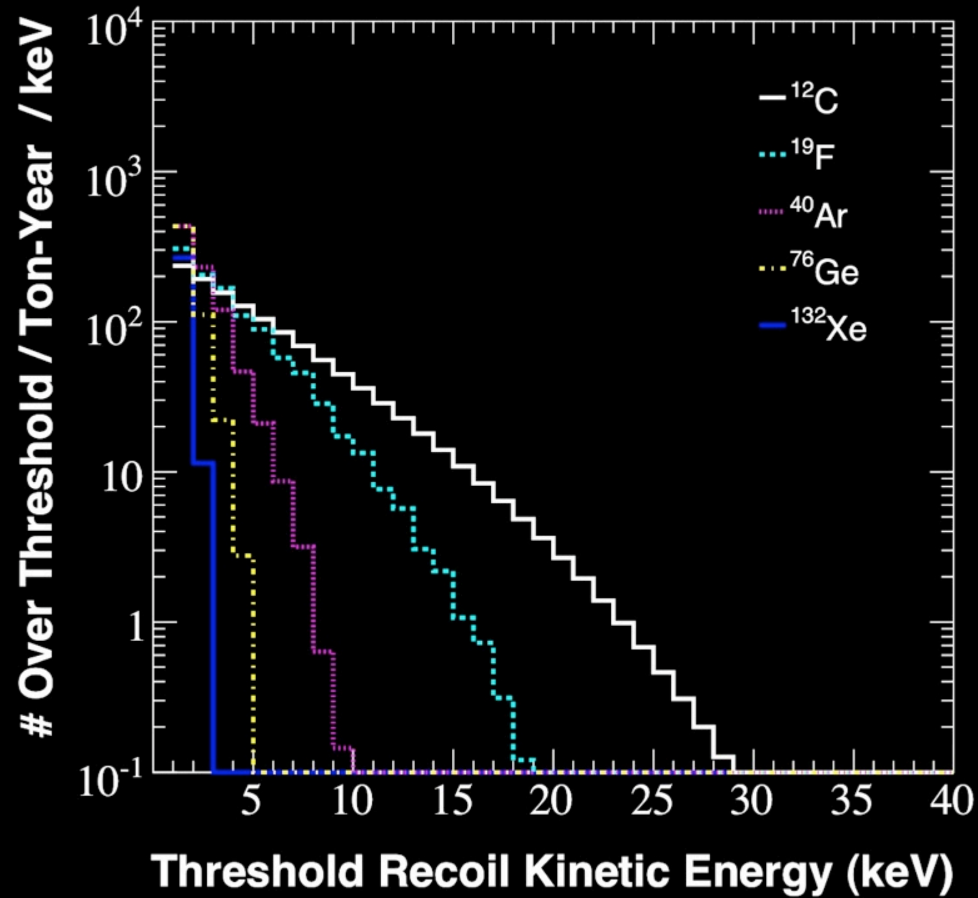
ν Backgrounds



can't shield a detector from coherent elastic scattering of solar neutrinos

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





100 events/ton-year = ~ 10^{-46} cm^2 limit

unless you measure the direction!

JM, P. Fisher, PRD76:033007 (2007)

Setting a Limit

1. The theoretical dark matter interaction rate is:

$$\frac{dR}{dE_R} = \left(\frac{c_1 R_0}{E_0 r}\right) exp\left(\frac{-c_2 E_R}{E_0 r}\right)$$

E_R = nuclear recoil energy,
E_0 = dark matter particle energy

2. Experiments measure:

$$R_0 = \left[\left(\frac{2v_0}{\sqrt{\pi}}\right)\left(\frac{N_0(\rho_D/m_D)}{A}\right)\right]\sigma_0 \times exposure$$

$$\sigma_A = \sigma_0 F^2(E_R,A) I_c\,, \quad F^2(E_R,A) = nuclear\ form\ factor, \quad I_c = A^2$$

3. vary σ_A until (90% of the time) theory predicts observed rate

4. Normalize to σ_{W-N} to compare limits:

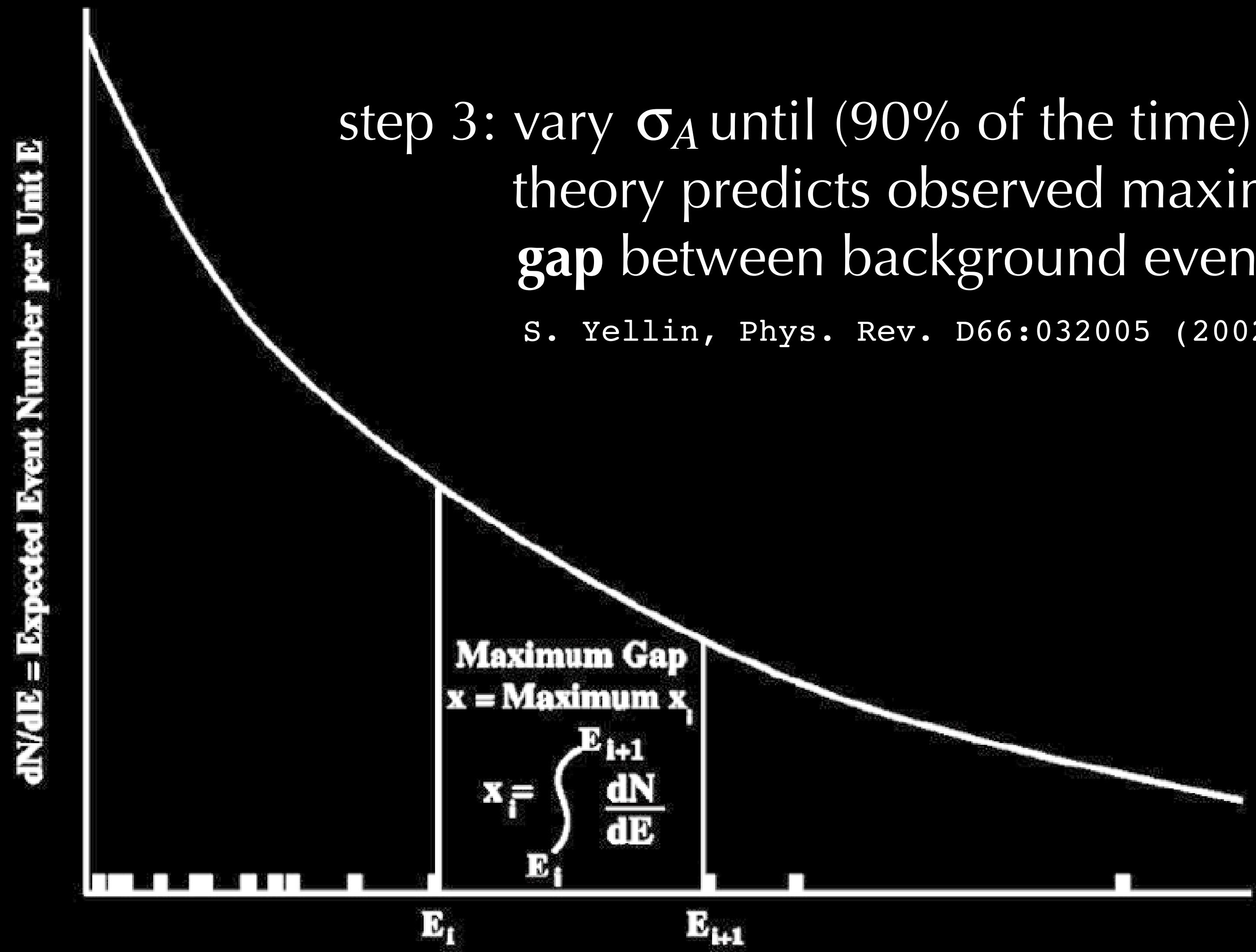
$$\sigma_{W-N} = \left(\frac{\mu_1}{\mu_A}\right)^2\left(\frac{1}{A}\right)^2\sigma_A$$

$$\mu = \frac{m_D\, m_{target}}{(m_D + m_{target})}$$

... in the Presence of Background

step 3: vary σ_A until (90% of the time) theory predicts observed maximum **gap** between background events

S. Yellin, Phys. Rev. D66:032005 (2002)



Yellin gap method: a way to make a “zero-background” measurement over a restricted range of an experiment’s acceptance (zero signal too)

Directionality

Expected Signal

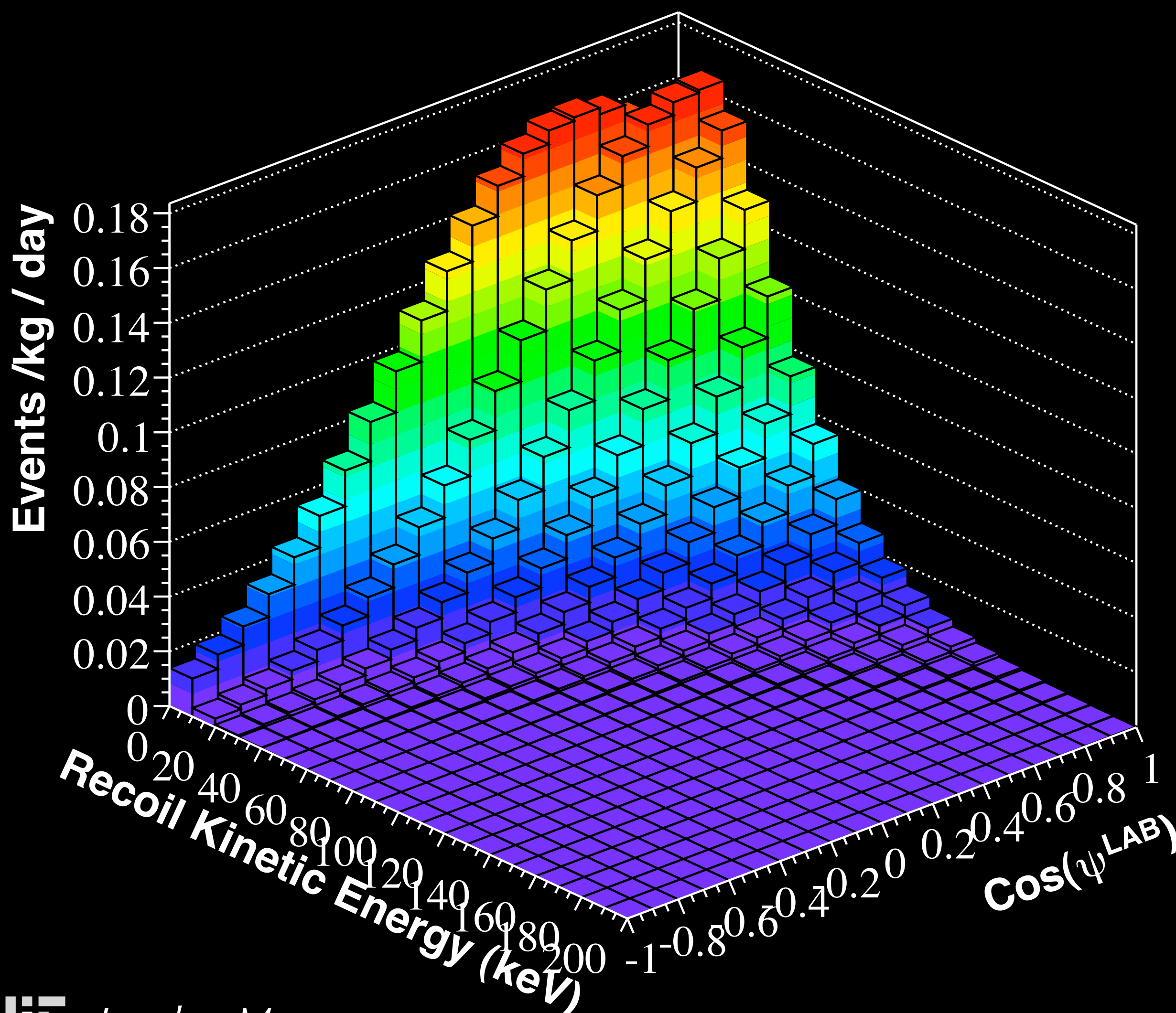
Limit Sensitivity

Discovery Potential

Directional Signal Expectation

$$\frac{d^2R}{dE_R d(cos\psi)} = \left(\frac{1}{2}\right)\left(\frac{R_0}{E_0 r}\right) exp\left[\frac{-(v_E cos\psi - v_{min})^2}{v_0^2}\right]$$

Cygnus



v_{th}/v_{halo}	Fraction of incident flux detected	Forward/back	July/January
0.00	1.00	4.00	1.04
0.20	0.97	4.17	1.04
0.40	0.90	4.66	1.05
0.60	0.78	5.44	1.07
0.80	0.65	6.56	1.08
1.00	0.50	8.10	1.11
1.20	0.37	10.18	1.13
1.40	0.25	12.98	1.16
1.60	0.16	16.73	1.20
1.80	0.10	21.77	1.24
2.00	0.06	28.54	1.28

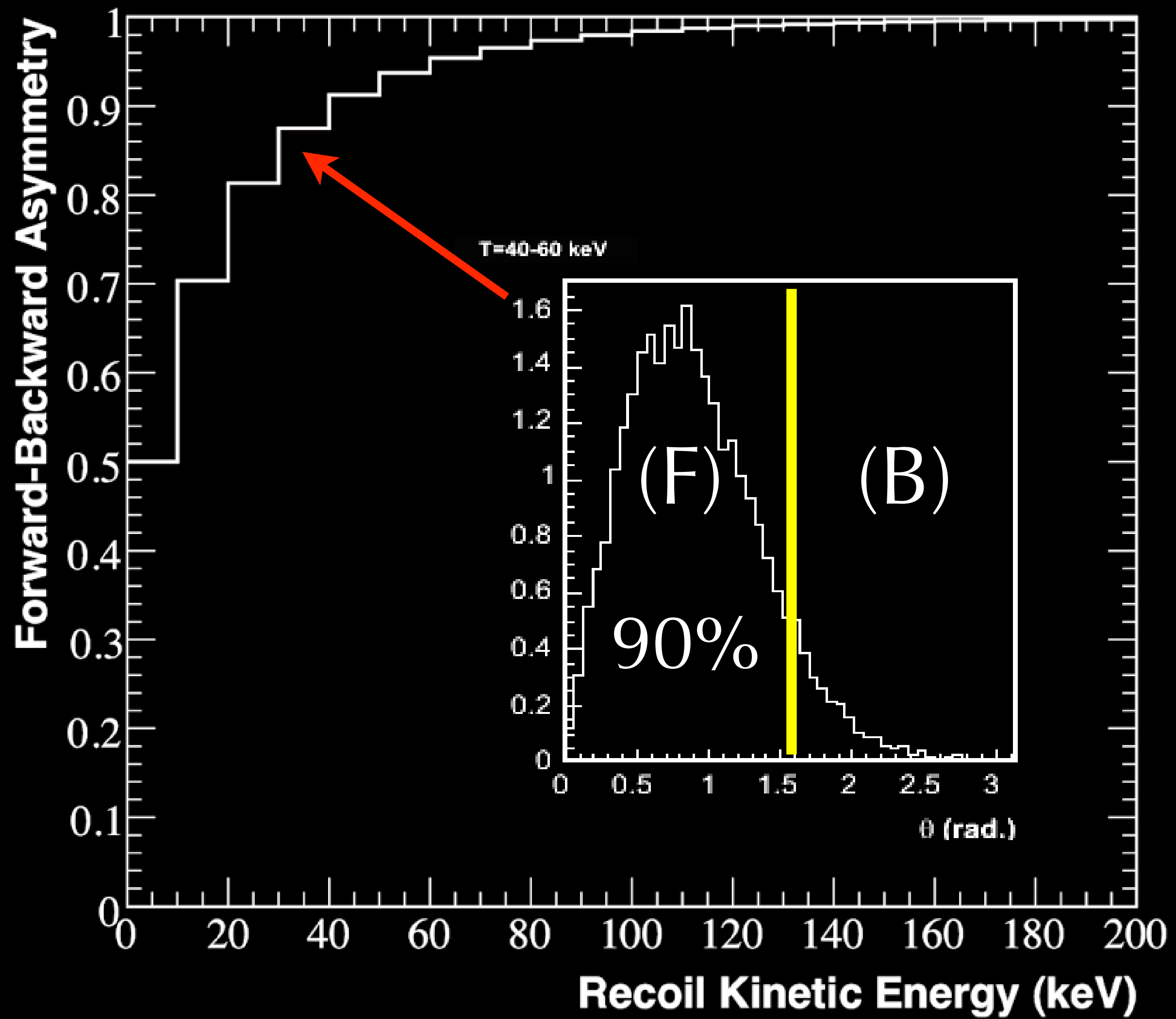
D. N. Spergel,
Phys. Rev. D37 1353 (1988)

Forward-Backward Asymmetry

Define coordinate system with respect to direction to Cygnus

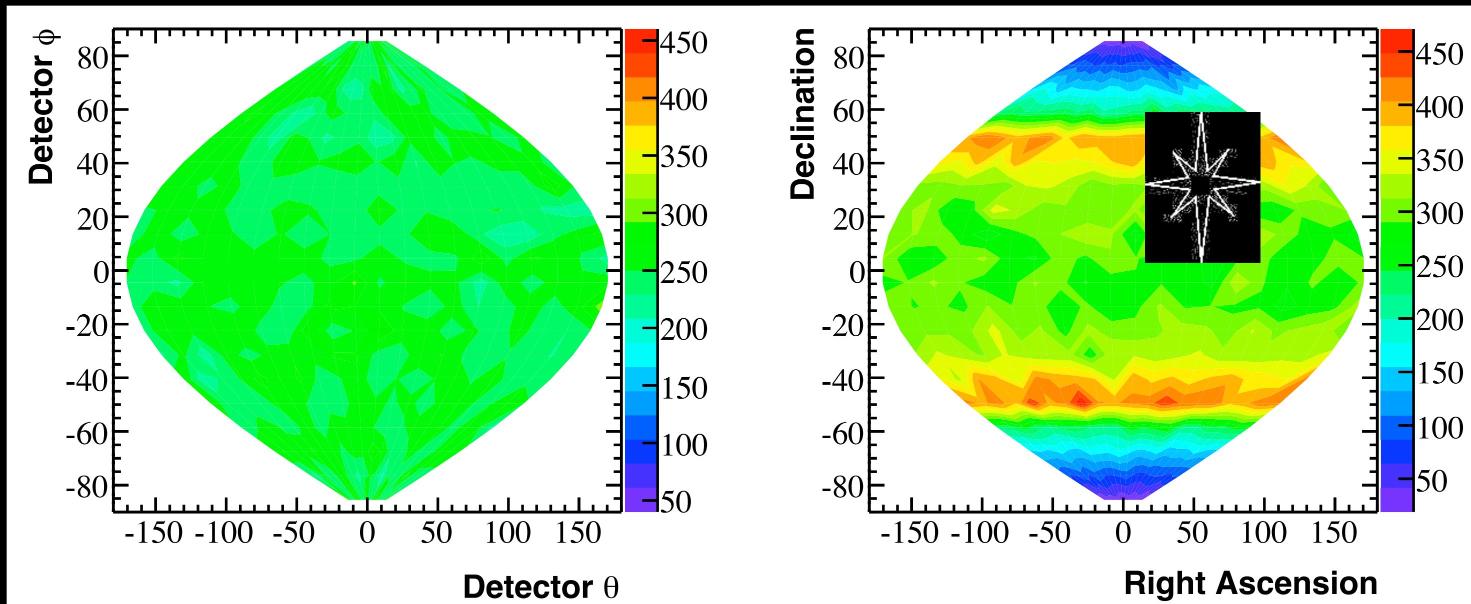
Compare integral of $\cos(\theta_{CYGNUS})$ above 90^o with below:

$$A = \frac{(forward - backward)}{(forward + backward)}$$



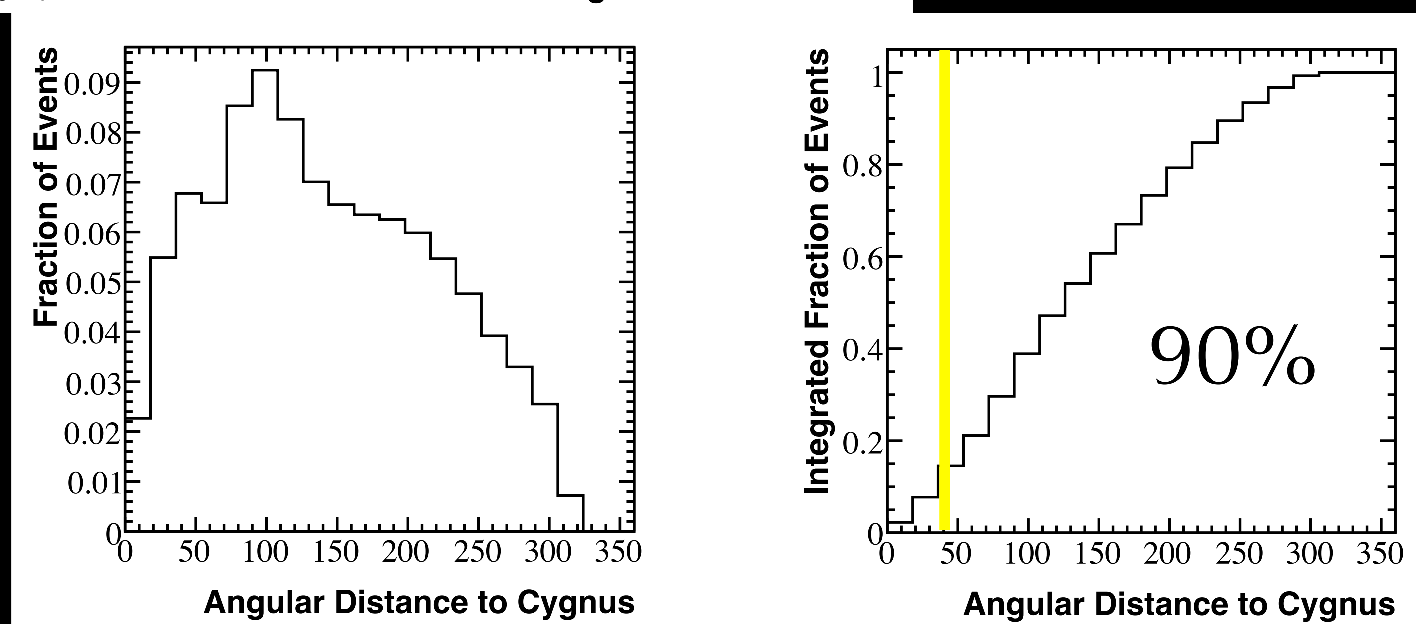
Asymmetry increases with increasing recoil kinetic energy, ~maximal by 100 keV

What Happens to Isotropic Backgrounds?



not isotropic in celestial coordinates

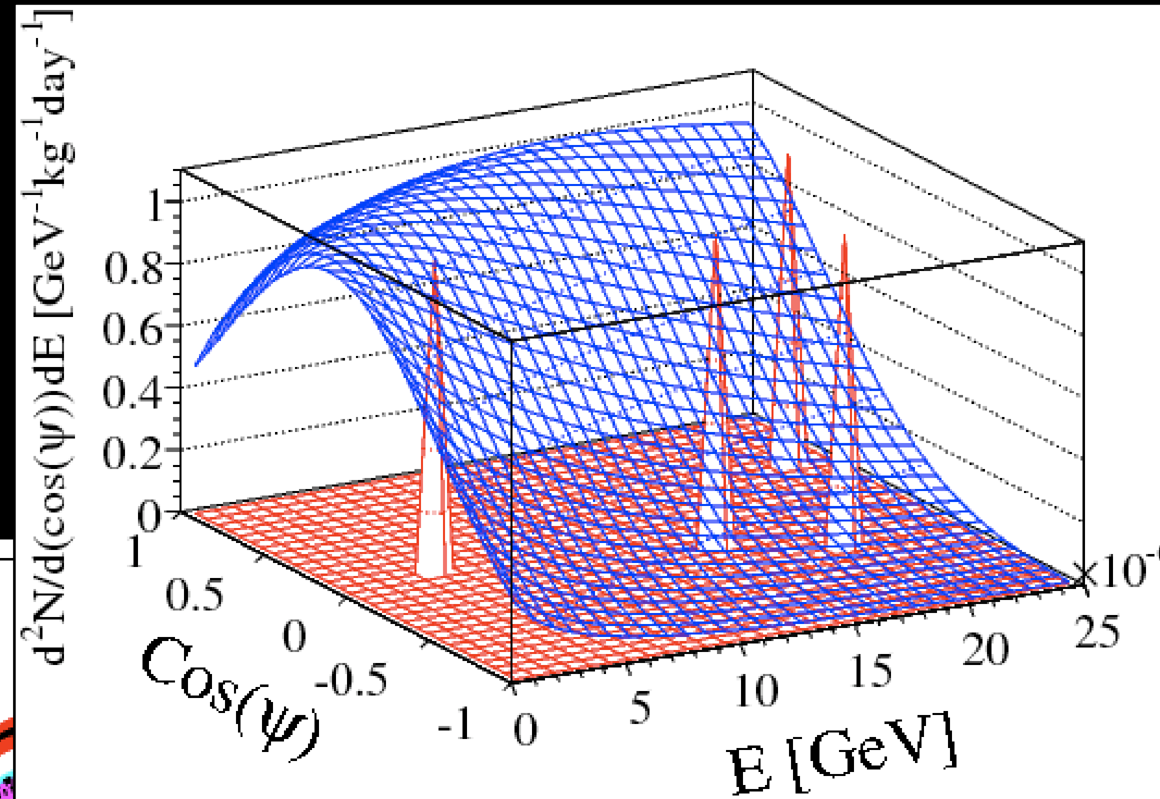
small fraction of locally isotropic events are near Cygnus

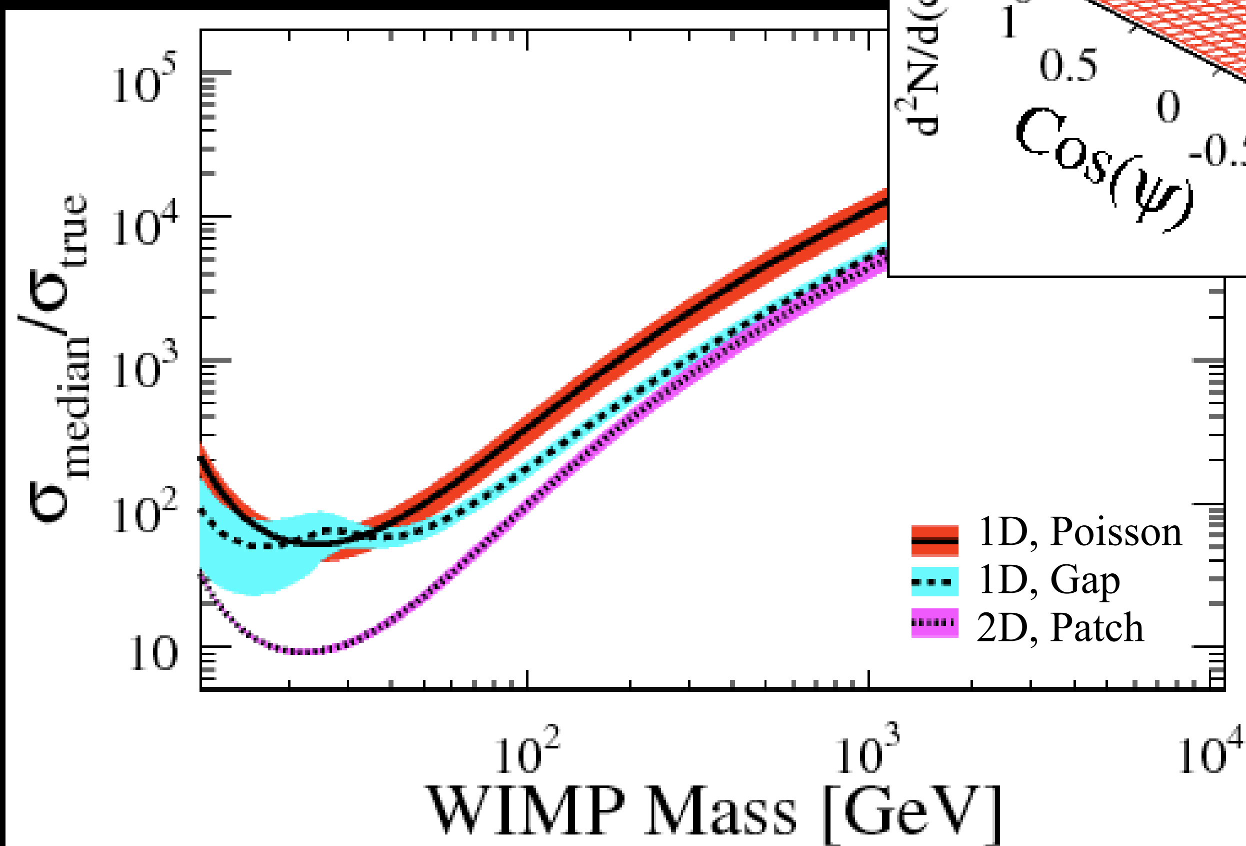


S. Henderson, JM, P. Fisher, arXiv:0801.1624

Sensitivity

even in the presence of backgrounds!



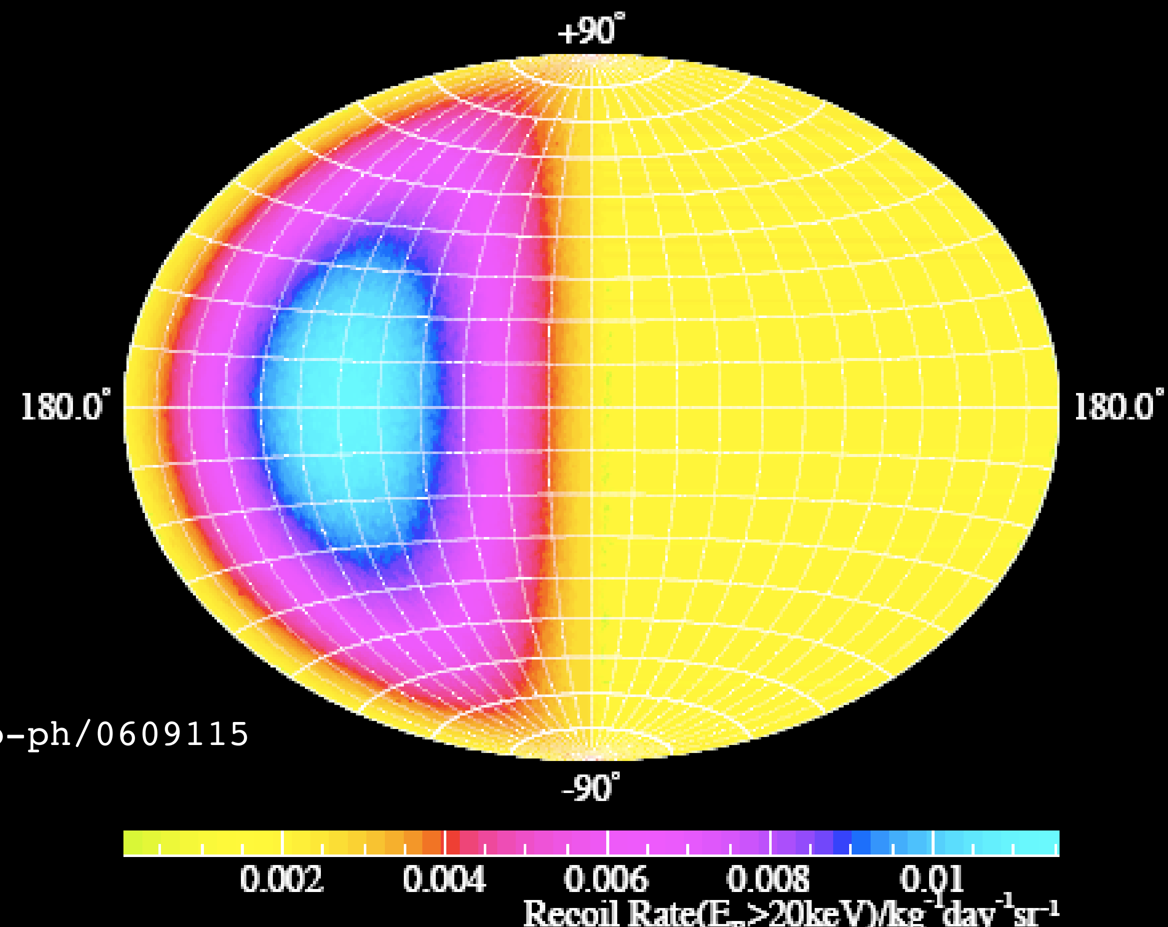


result:
2D dark matter direct detection beats 1D by ~10x

Discovery Potential

if you can reconstruct the energy and angle of the recoil nucleus,
you have **a dark matter telescope**

simulated reconstructed dark matter sky map: how many events are needed to reject isotropy?

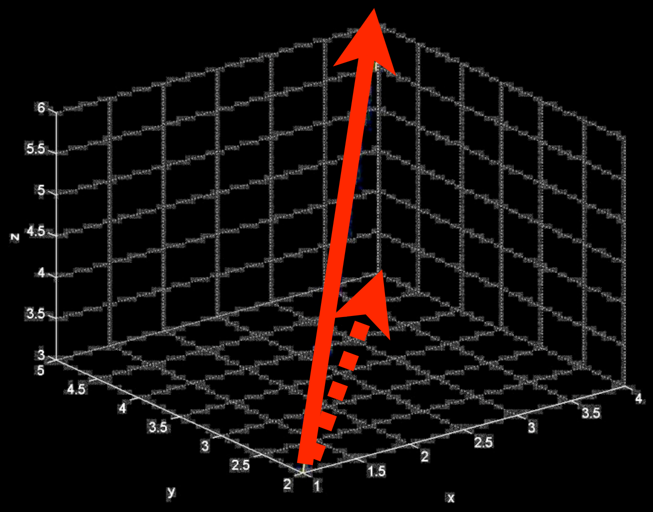


A. M. Green, B. Morgan, astro-ph/0609115

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

Optimization

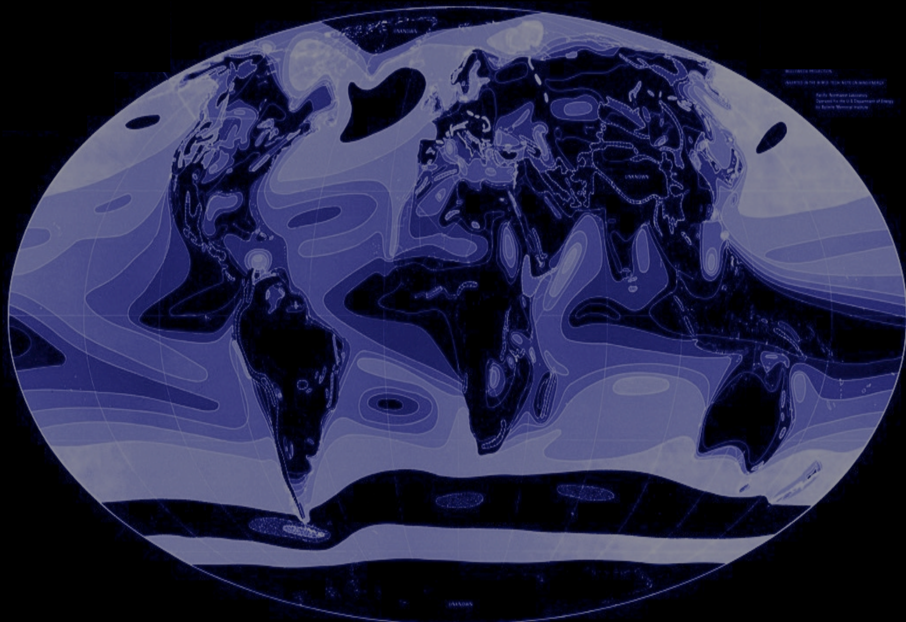
A. M. Green, B. Morgan, astro-ph/0609115



difference from baseline configuration	N_{90}	N_{95}
none	7	11
$E_{\mathrm{T}} = 0$ keV	13	21
no recoil reconstruction uncertainty	5	9
$E_{\mathrm{T}} = 50$ keV	5	7
$E_{\mathrm{T}} = 100$ keV	3	5
$S/N = 10$	8	14
$S/N = 1$	17	27
$S/N = 0.1$	99	170
3-d axial read-out	81	130
2-d vector read-out in optimal plane, raw angles	18	26
2-d axial read-out in optimal plane, raw angles	1100	1600
2-d vector read-out in optimal plane, reduced angles	12	18
2-d axial read-out in optimal plane, reduced angles	190	270

Table 1
The dependence of the number of events *above the energy threshold* required to reject isotropy for $A_c = R_c = 0.9$ and 0.95, N_{90} and N_{95}, on the detector configuration. The baseline configuration has 3-d vector read-out, energy threshold $E_{\mathrm{TH}} = 20$ keV, no background ($S/N = \infty$) and the uncertainty in reconstructing the recoil directions taken into account.

Detector Properties:
- energy threshold
- background
- reconstruction (2D vs. 3D)
- vector or axial
- angular resolution



Where We are Now

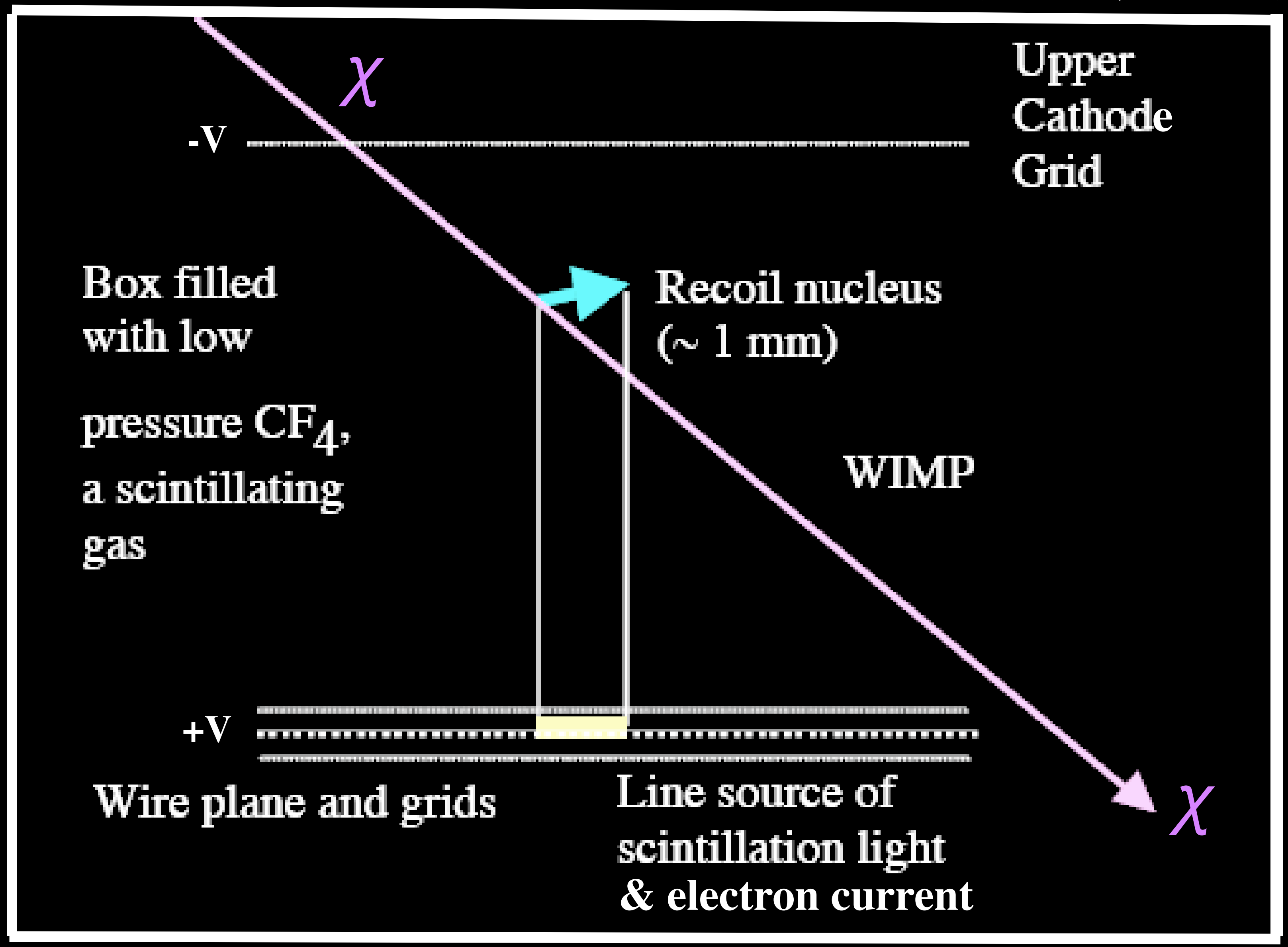
Measuring Directionality

Around the World

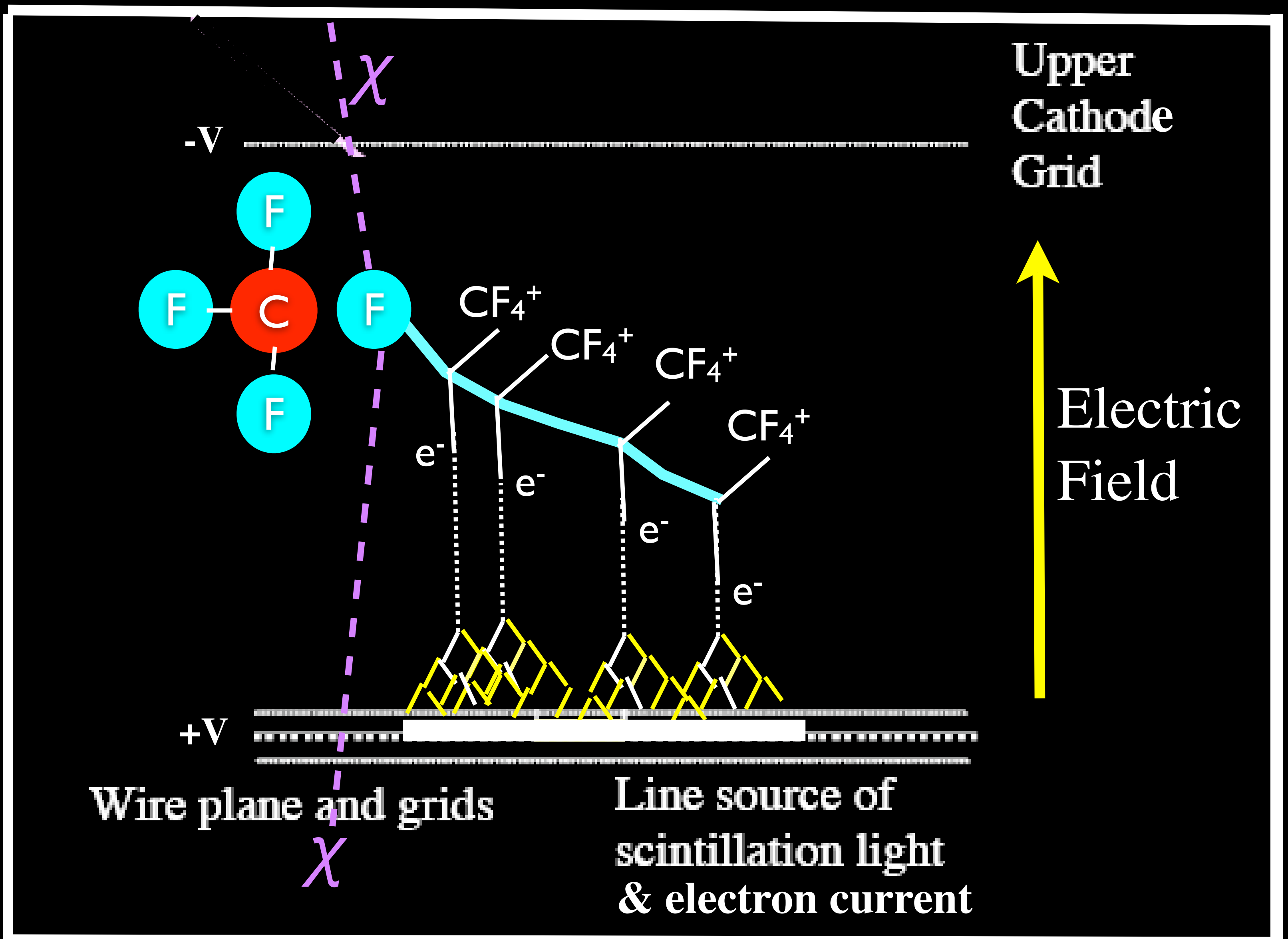
DMTPC Detector Development

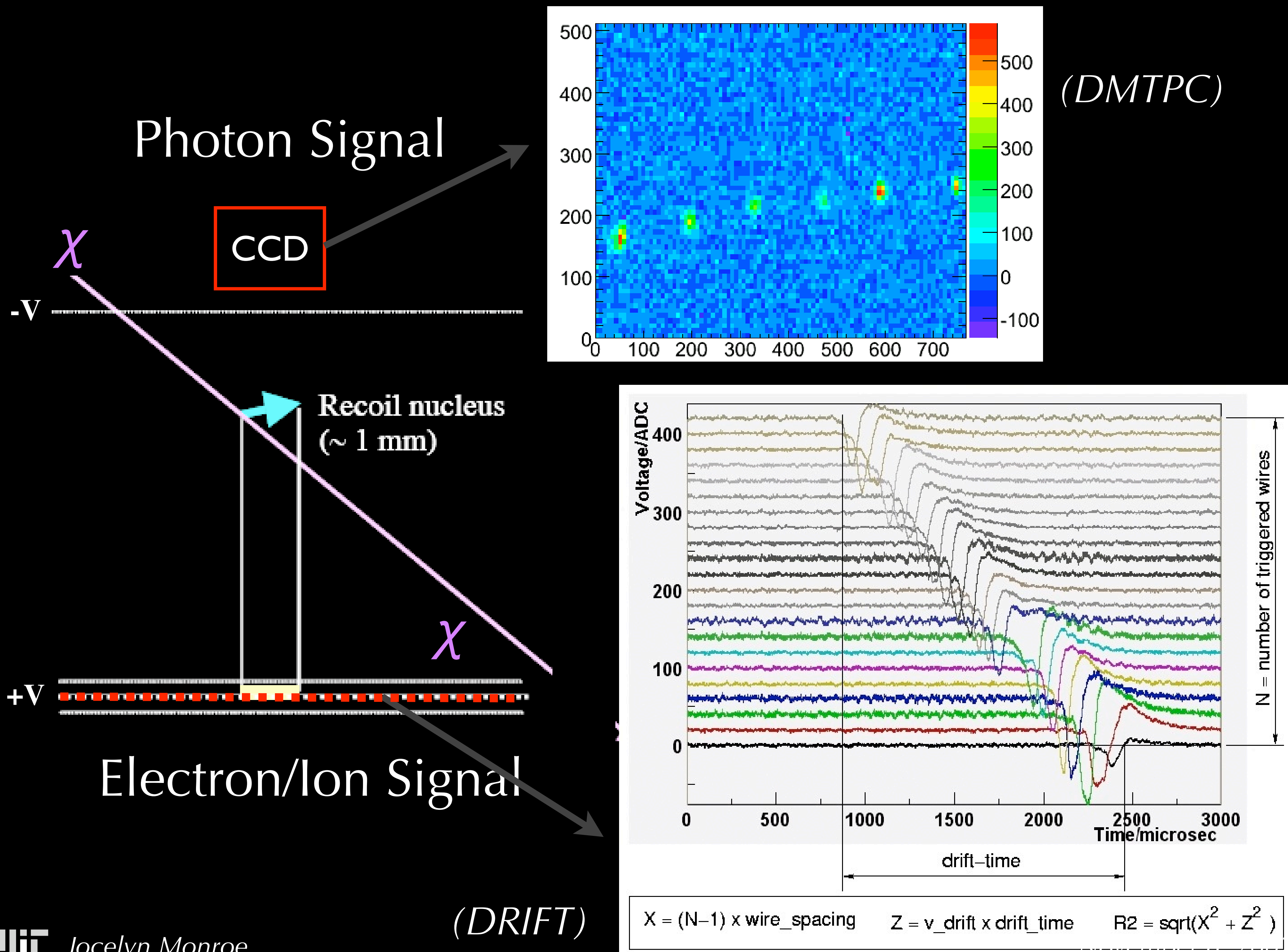
Directional Detection

(P. Fisher, S. Ahlen)



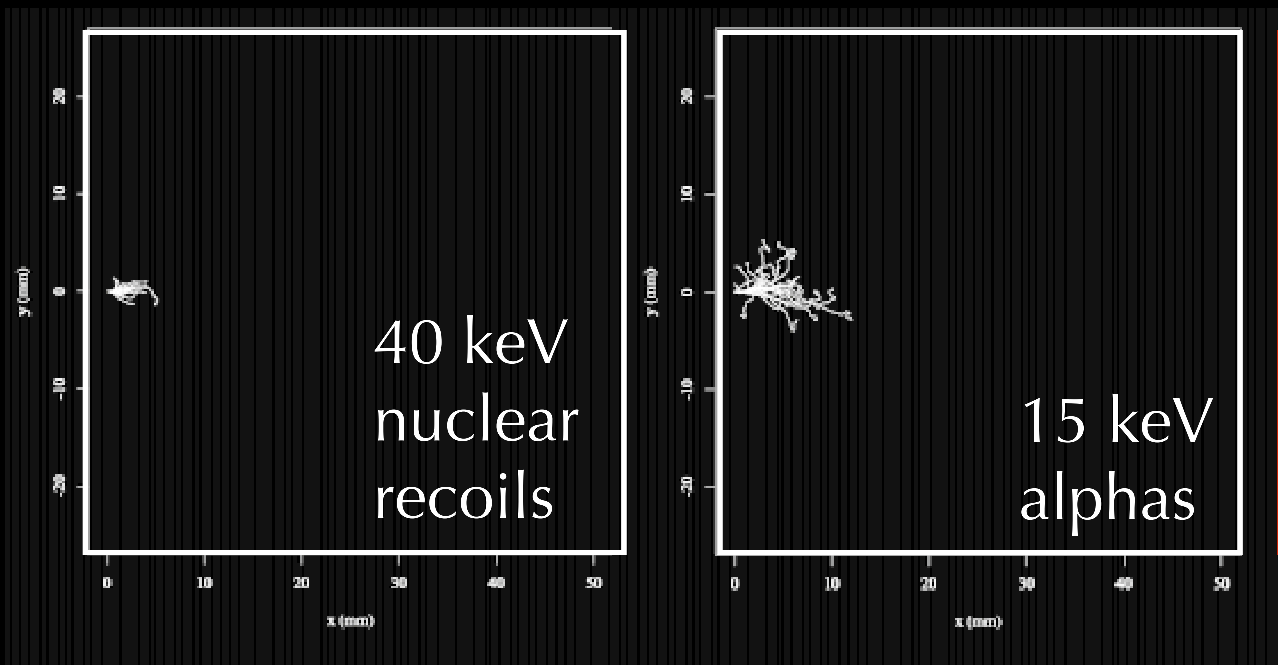
Directional Detection

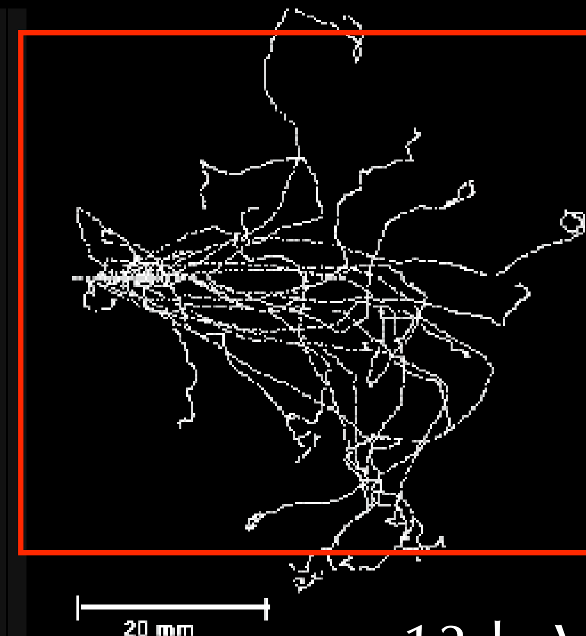



Photon Signal
CCD
(DMTPC)
χ
-V
Recoil nucleus
(~ 1 mm)
χ
+V
Electron/Ion Signal
(DRIFT)
Voltage/ADC
Time/microsec
N = number of triggered wires
drift–time
X = (N–1) x wire_spacing
Z = v_drift x drift_time
R2 = sqrt(X^2 + Z^2)

Backgrounds in Directional Detectors

1. electrons, photons, alphas: range vs. dE/dx

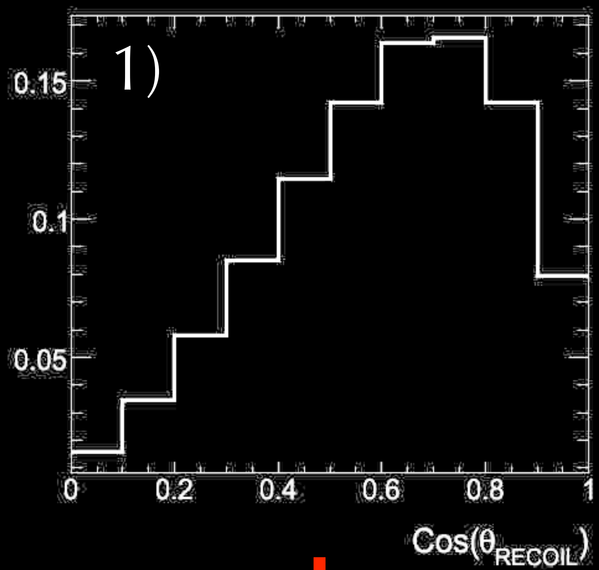




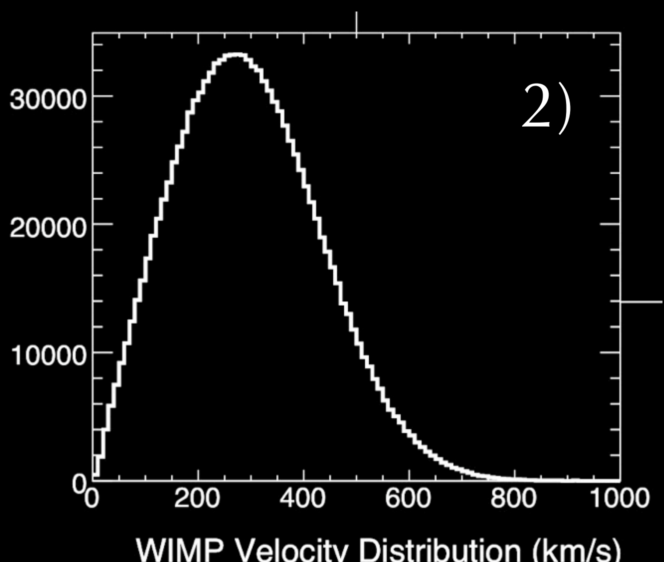
13 keV
electrons

2. neutrons: shielding
3. radon: high purity detector
4. solar neutrinos: cut with angular reconstruction

Signals in Directional Detectors



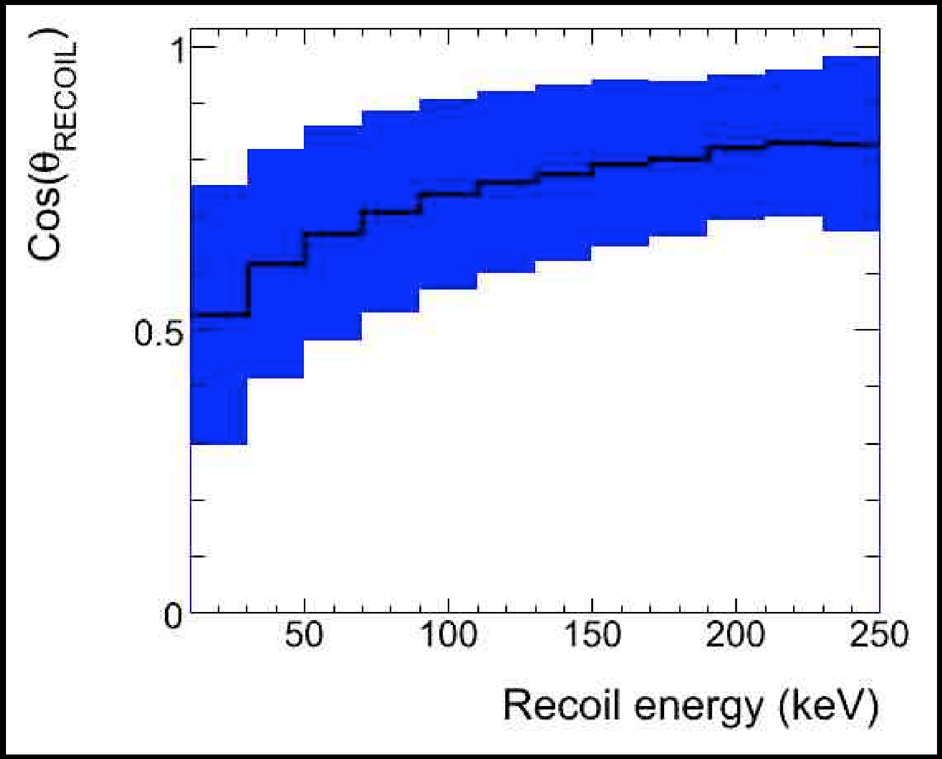
+



distribution of signal events determined by:

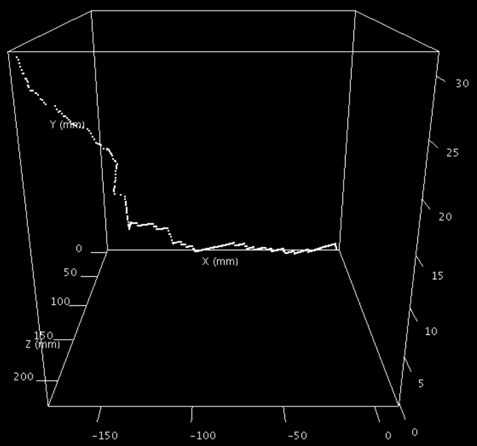
1. angular resolution of elastic scattering
2. dark matter velocity dispersion

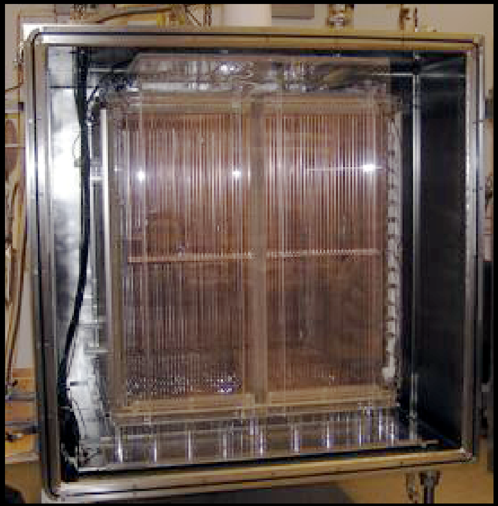
=

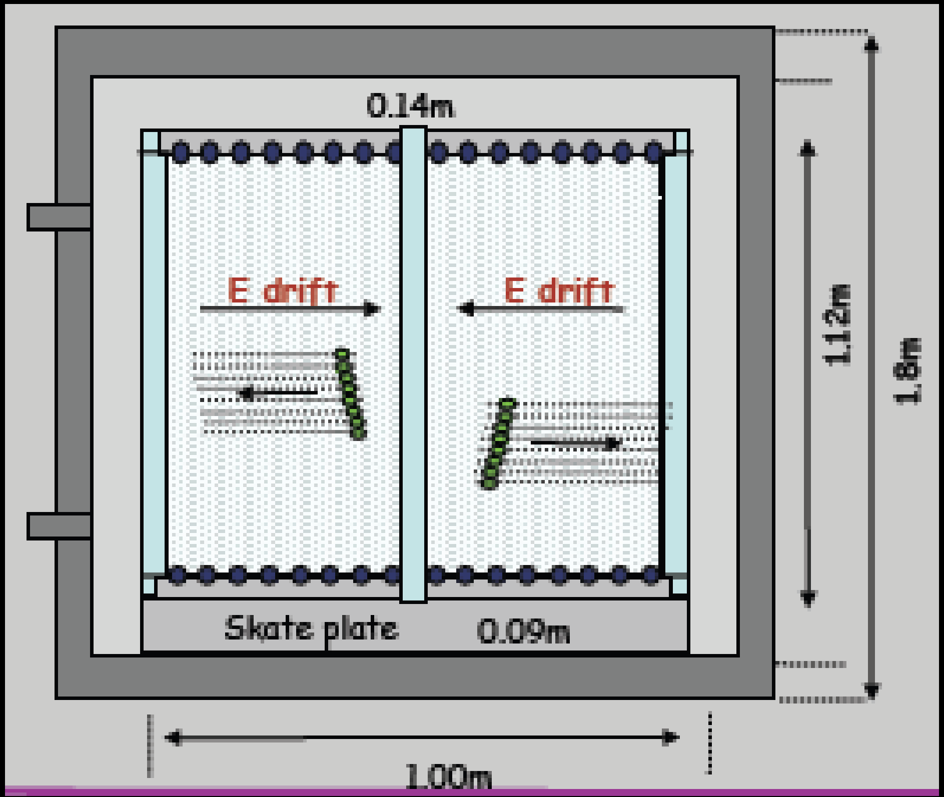


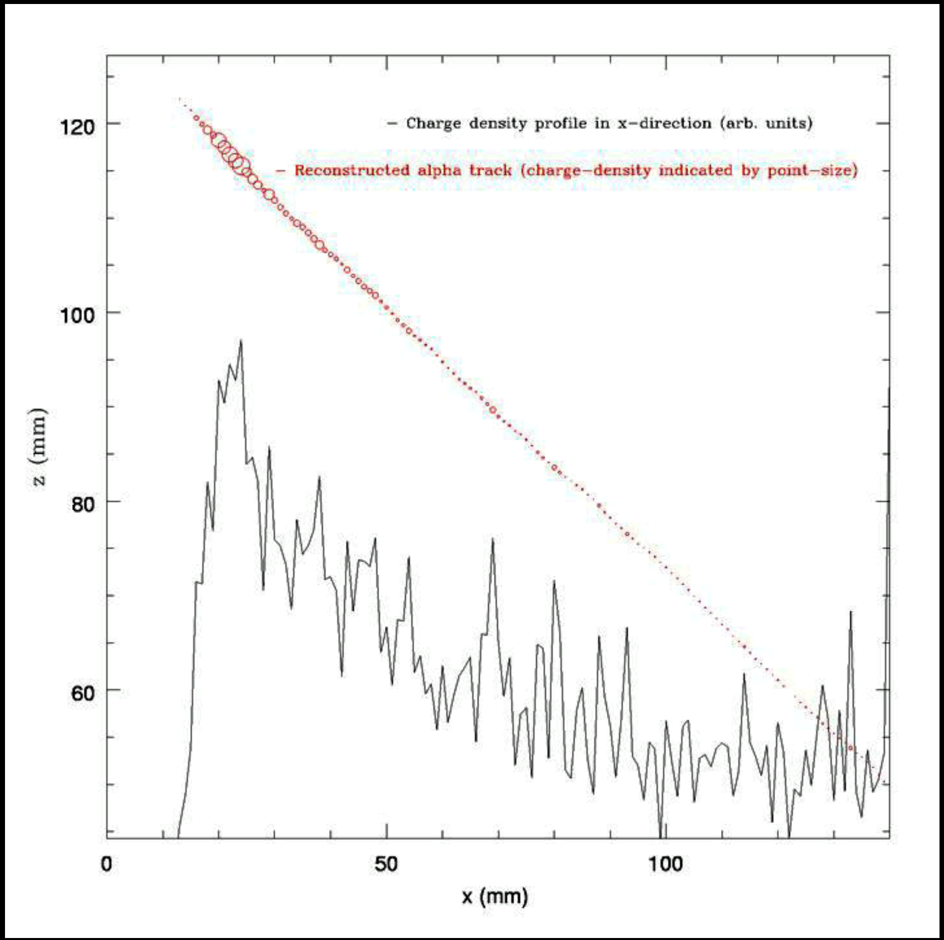
DRIFT

Operating in Boulby (UK), wire readout, 40 torr CS_2 gas, negative ion drift, 16 kg-day exposure









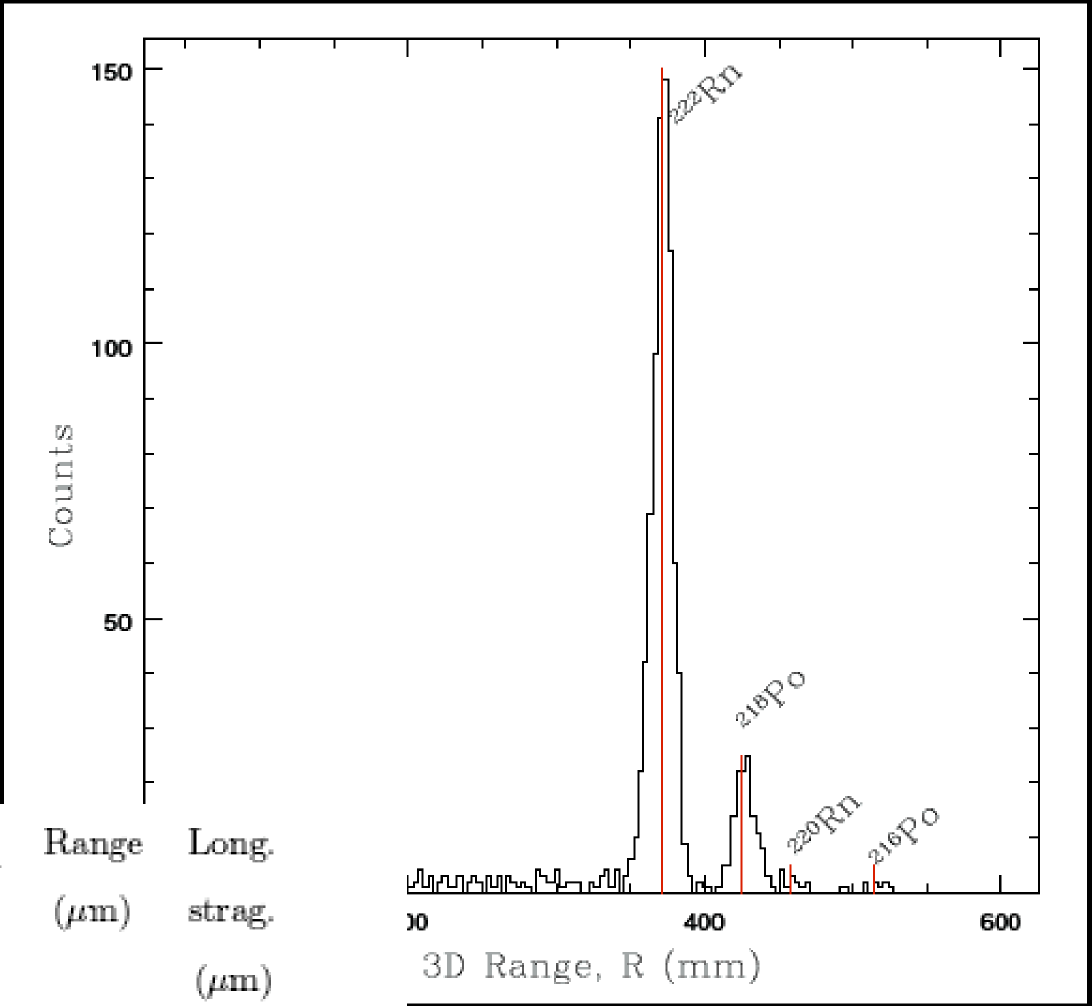
head-tail for ~5 MeV alphas

DRIFT

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

can distinguish different parts of the radon decay chain by range

Drift Collaboration, accepted for publication in AstroPart. Phys.

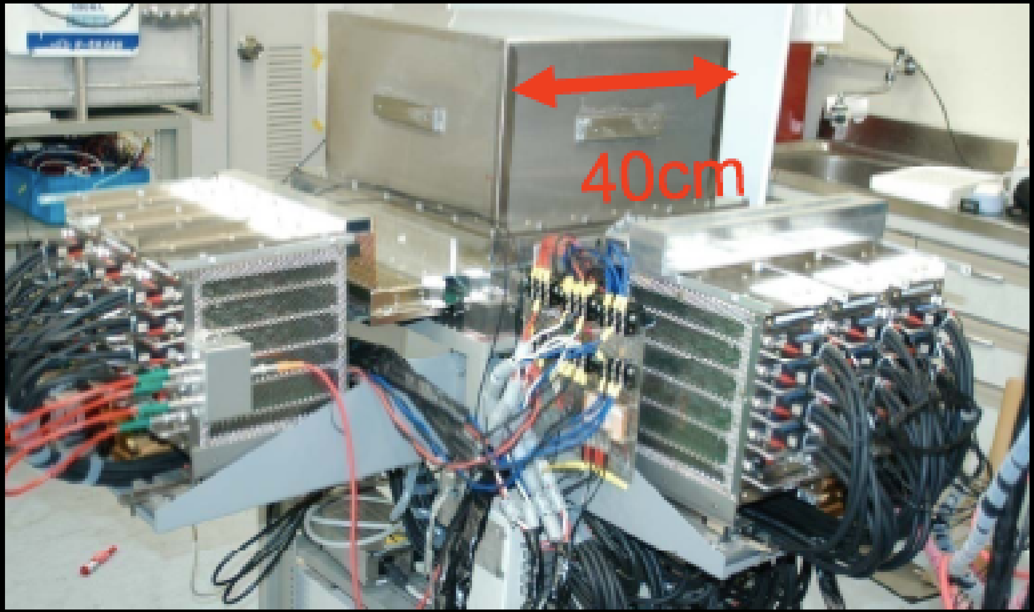


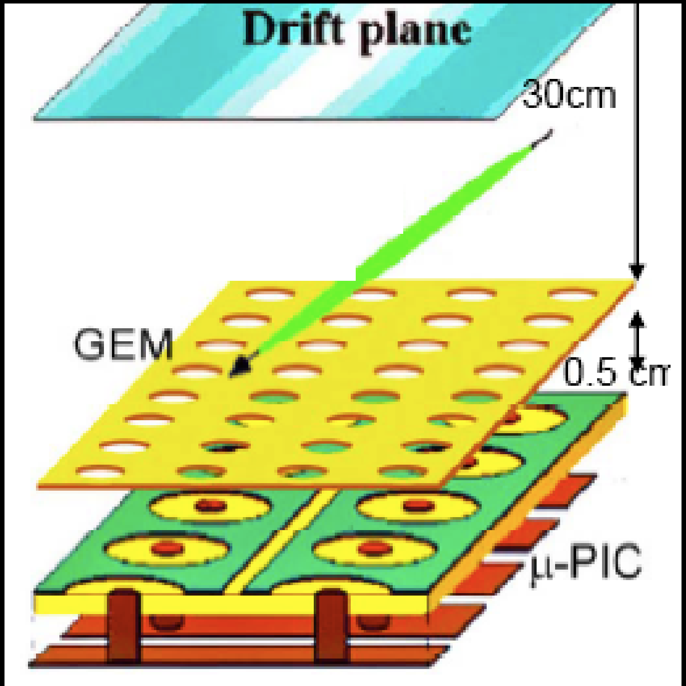
Isotope	E_α (MeV)	Range (mm)	Long. strag. (mm)	Recoil	E_{recoil} (keV)	Range (μm)	Long. strag. (μm)
^{222}Rn	5.48948	334	13.4	^{218}Po	100.82	577.91	119.61
^{218}Po	6.00235	383	15.3	^{214}Pb	112.33	628.54	129.62
^{214}Po	7.68682	567	23.3	^{210}Pb	146.64	745.25	149.99
^{220}Rn	6.288	413	16.3	^{216}Po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

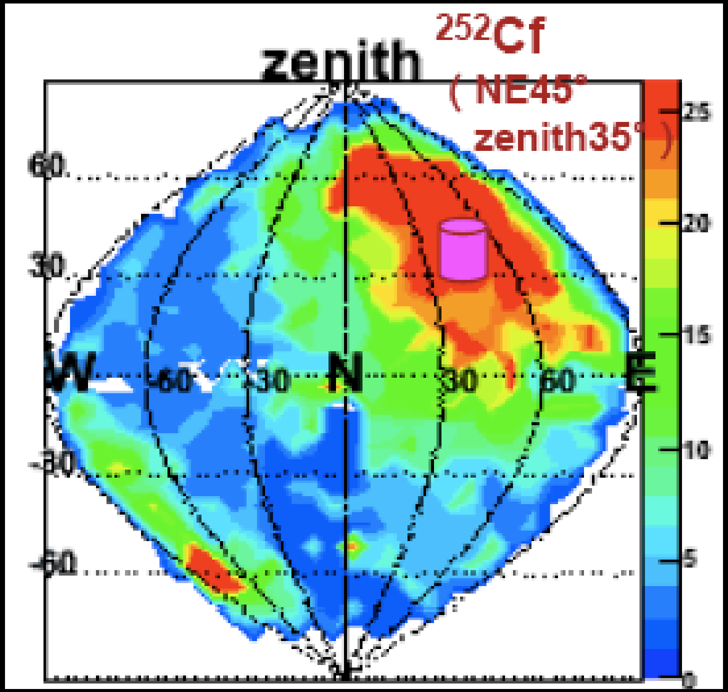
expected nuclear recoil signal range ~mm

NEWAGE

Operating in Kamioka (Japan),
μ−pattern gas detector readout,
100 torr CF_4 gas, e^- drift,
e- rejection: < 2E-4
100 keV recoil threshold





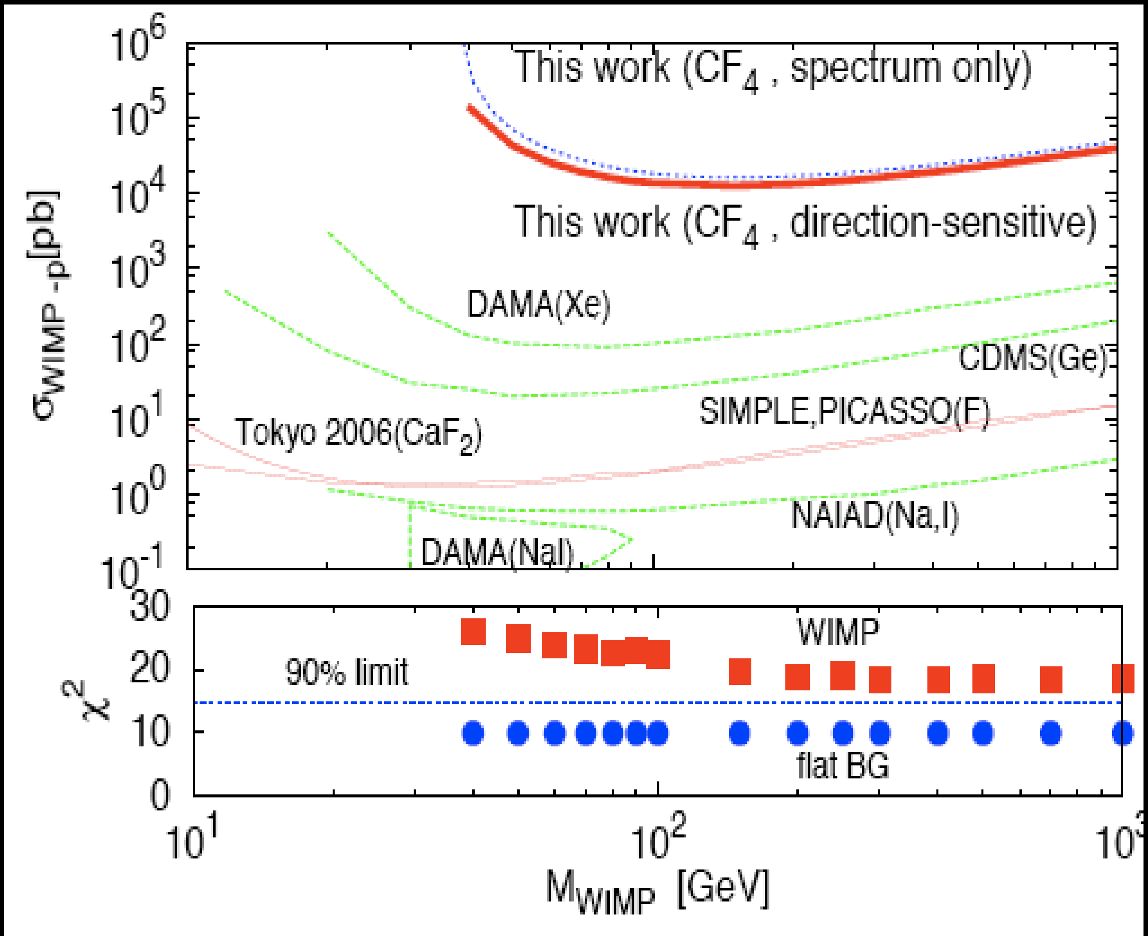


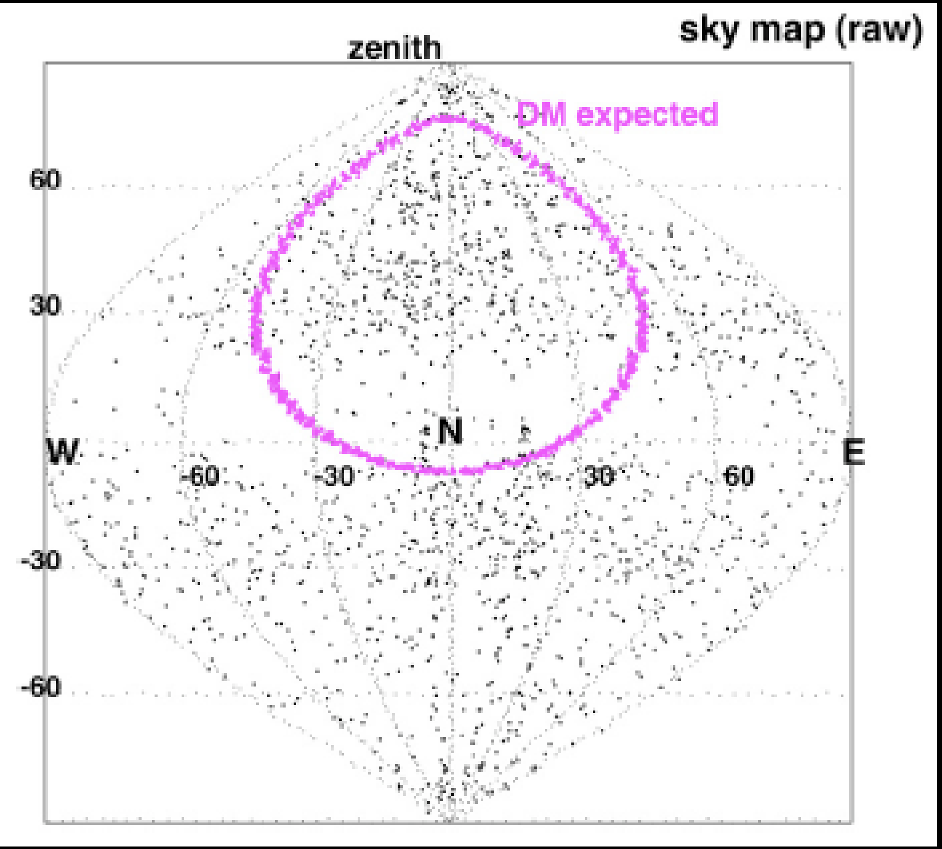
demonstrated axial 3D track reconstruction with ^{252}Cf source

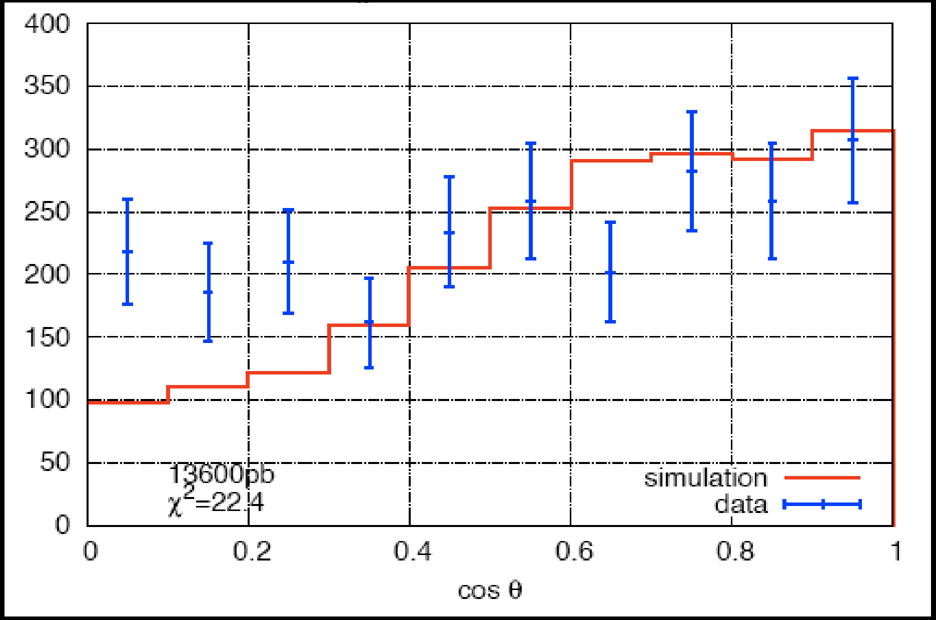
NEWAGE

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)







DM TPC

goal: directional dark matter detector with *vector* track reconstruction

<u>Boston University</u>
S. Ahlen, M. Lewandowska,
A. Roccaro, H. Tomita

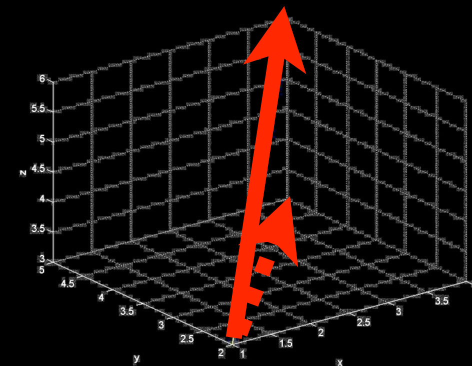
<u>MIT</u>
B.Cornell[* 1)], D.Dujmic, W.Fedus[*],
P.Fisher, A.Kaboth, G.Kohse,
R.Lanza, J.Monroe, A.Piso[*],
T.Sahin[*], G.Sciolla, R.Vanderspek,
R.Yamamoto, H.Yegoryan[*]

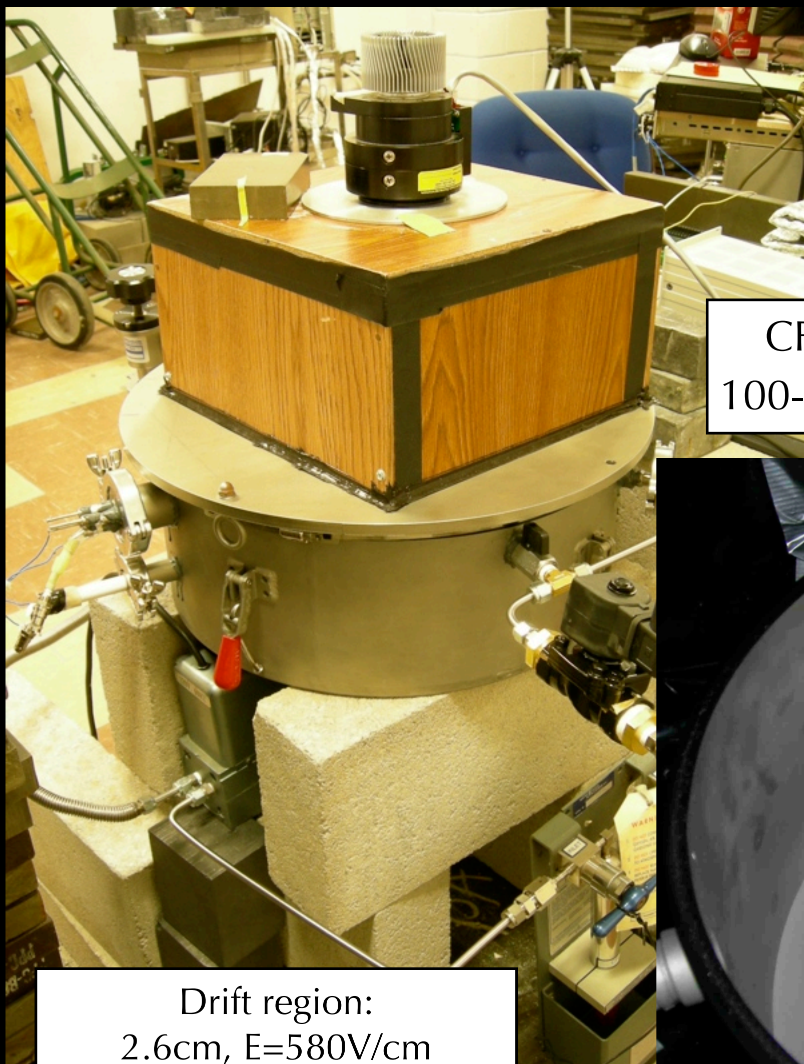
<u>Brandeis University</u>
H. Wellensten. N. Skvorodnev

*) undergraduate student, 1) Harvard U.

Detector

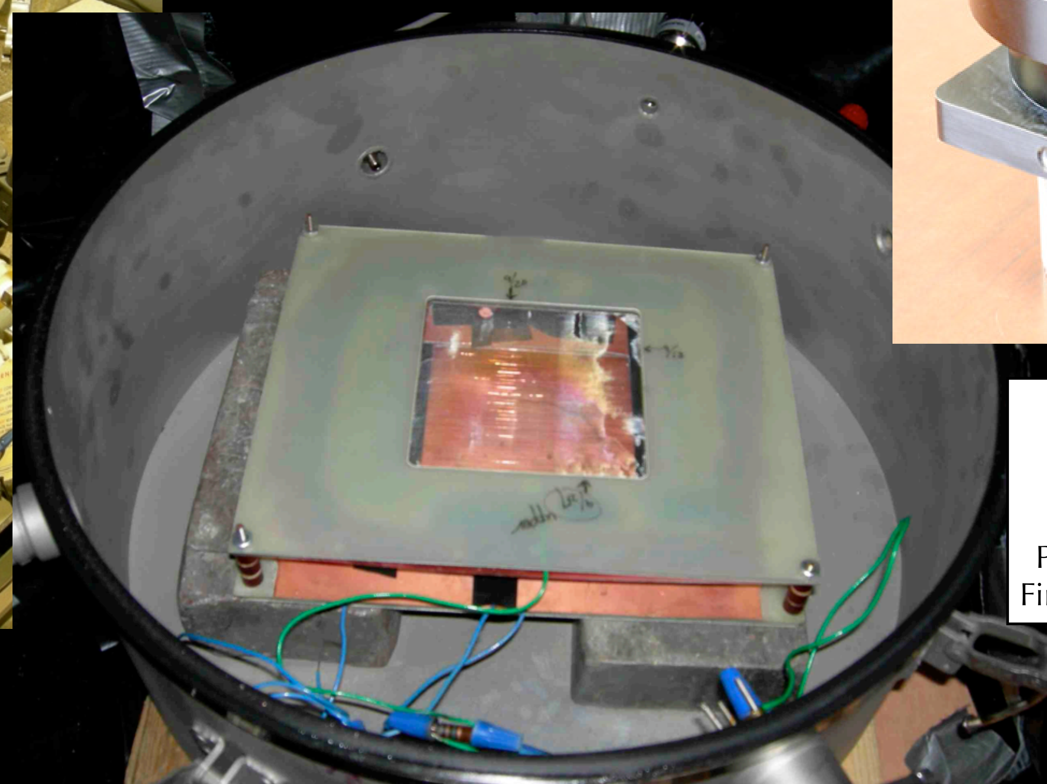
time projection chamber with CCD readout

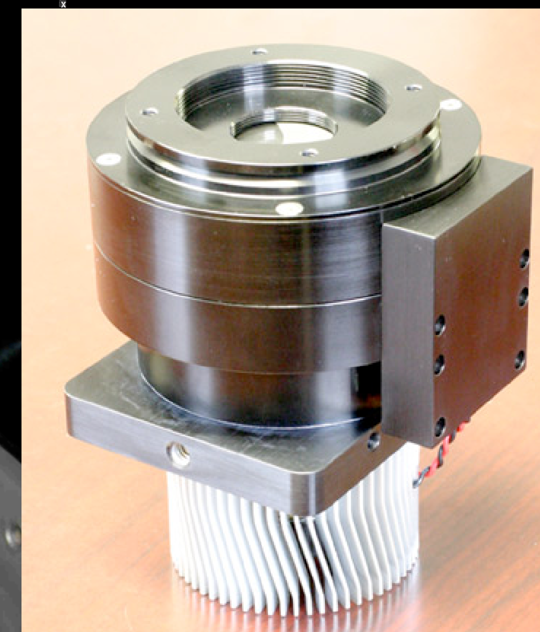




CF_4 gas
100-380Torr

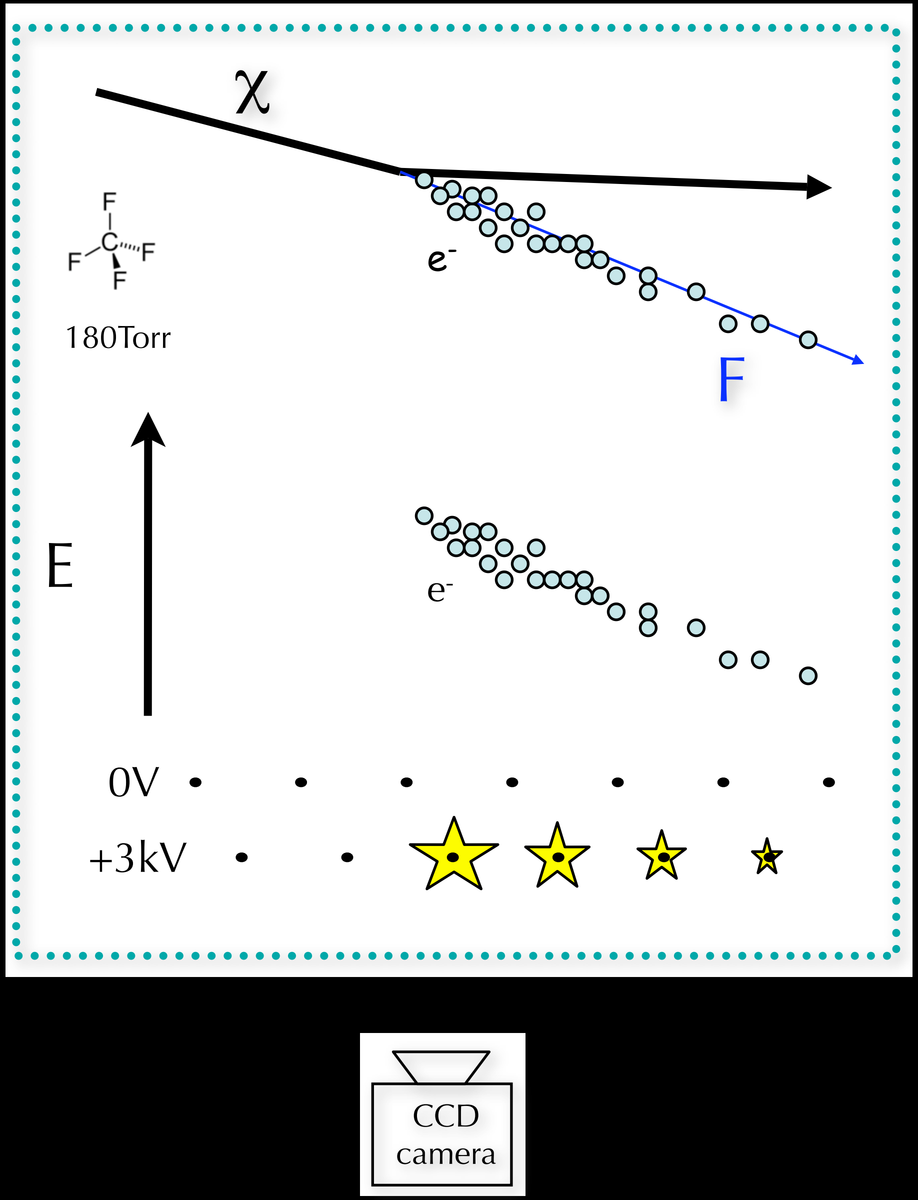
Drift region:
2.6cm, E=580V/cm
Amplification region:
Anode: 5mm pitch, 100µm
Ground: 2mm pitch, 50µm



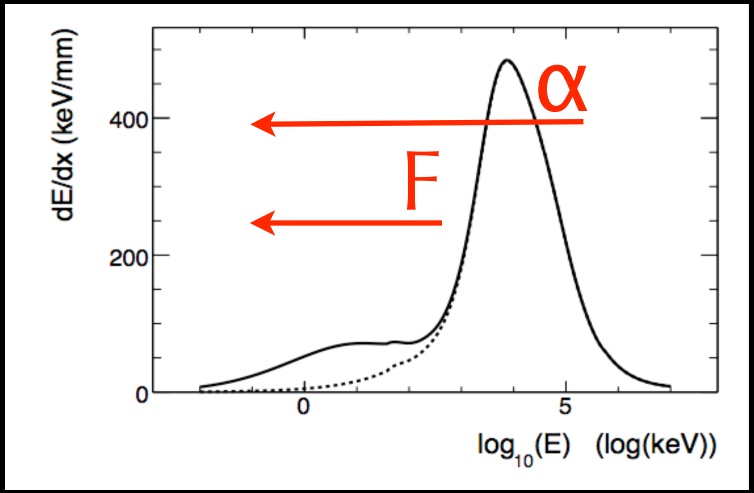


CCD Camera
Kodak KAF0401 chip
768x512 (9x9um)
Cooled (-20C)
Photographic lens (55mm)
Finger Lakes Instrumentation

Detection Principle



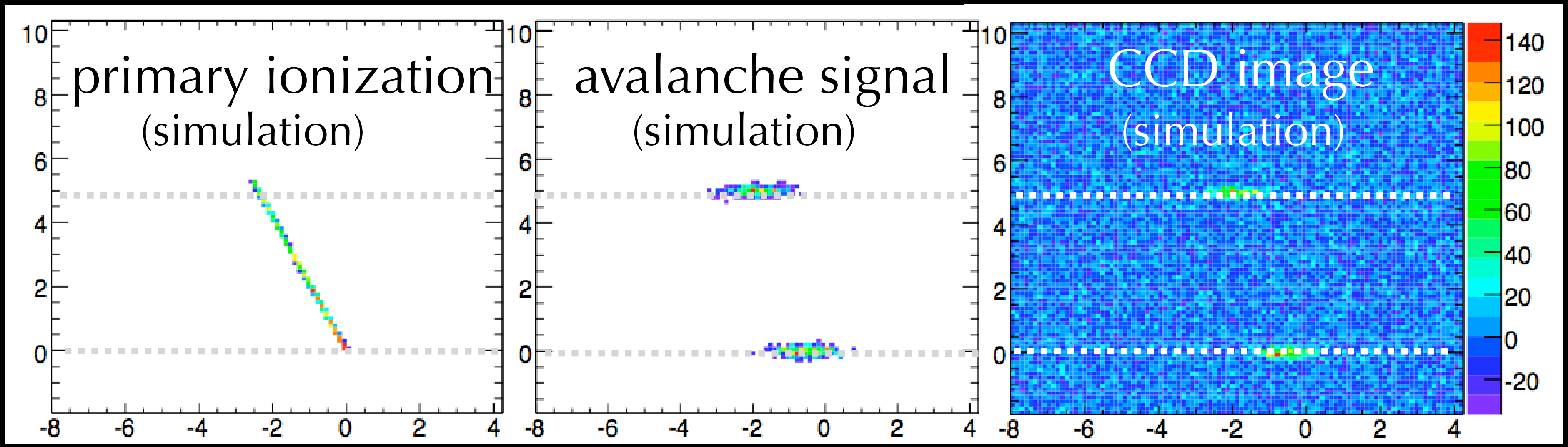
1. primary ionization encodes track direction via dE/dx profile

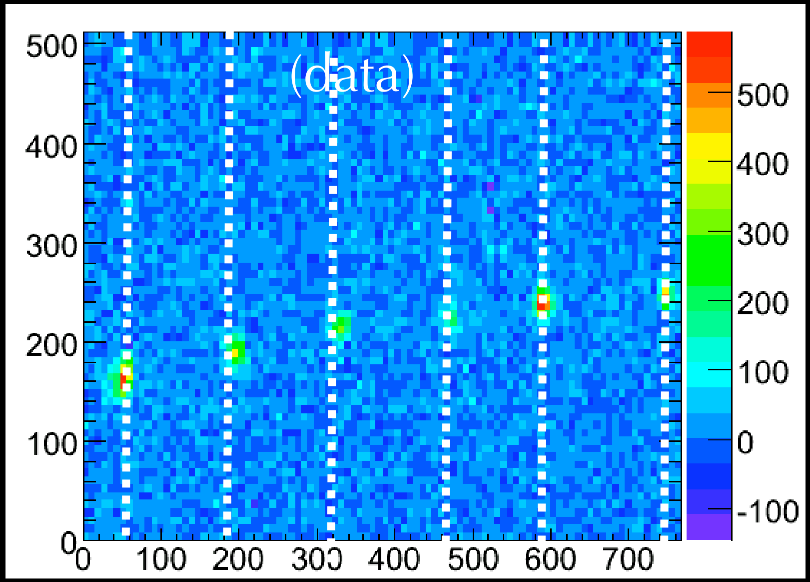


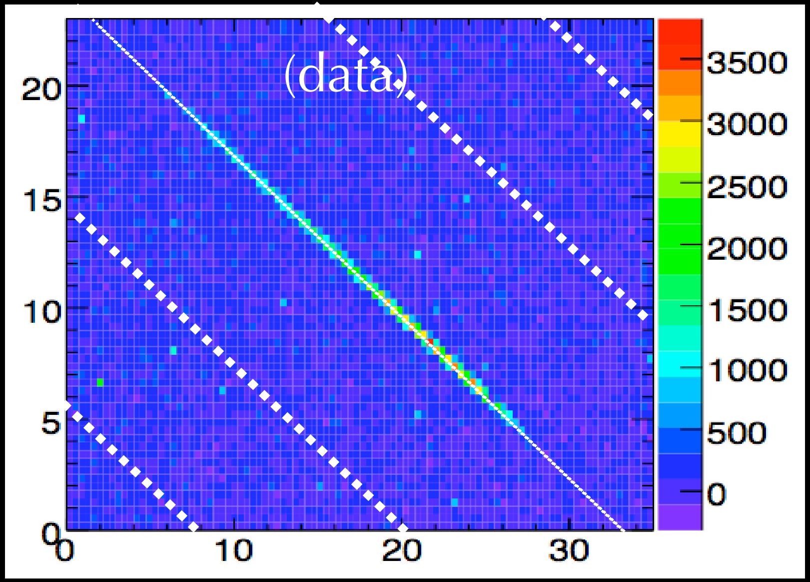
2. drifting electrons preserve dE/dx profile if diffusion is small

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

Event Displays



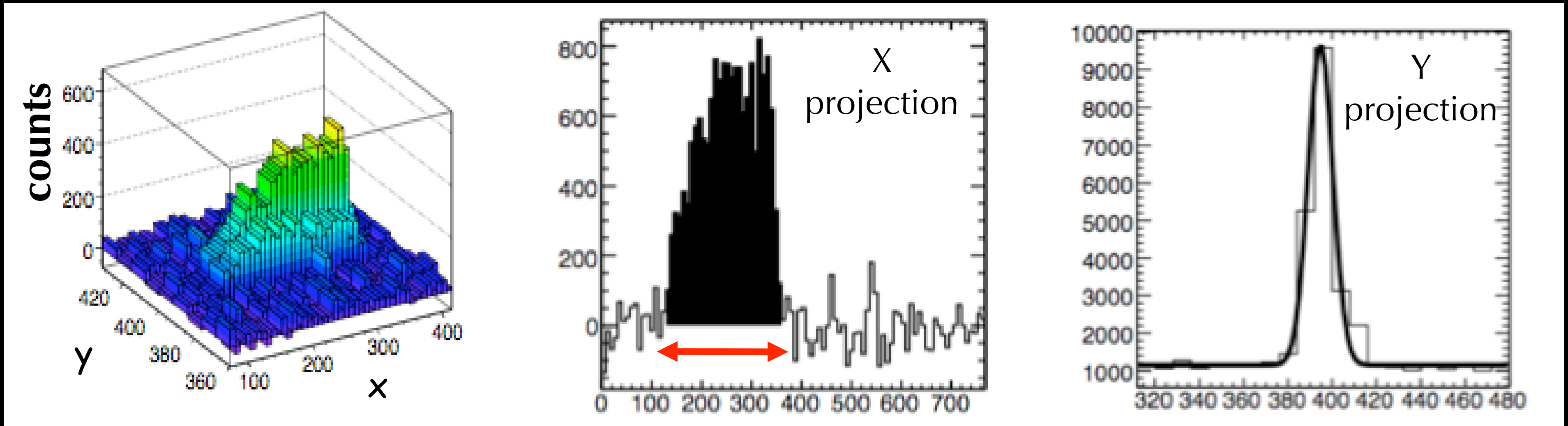




track perpendicular to wires

track parallel to wires

Track Analysis



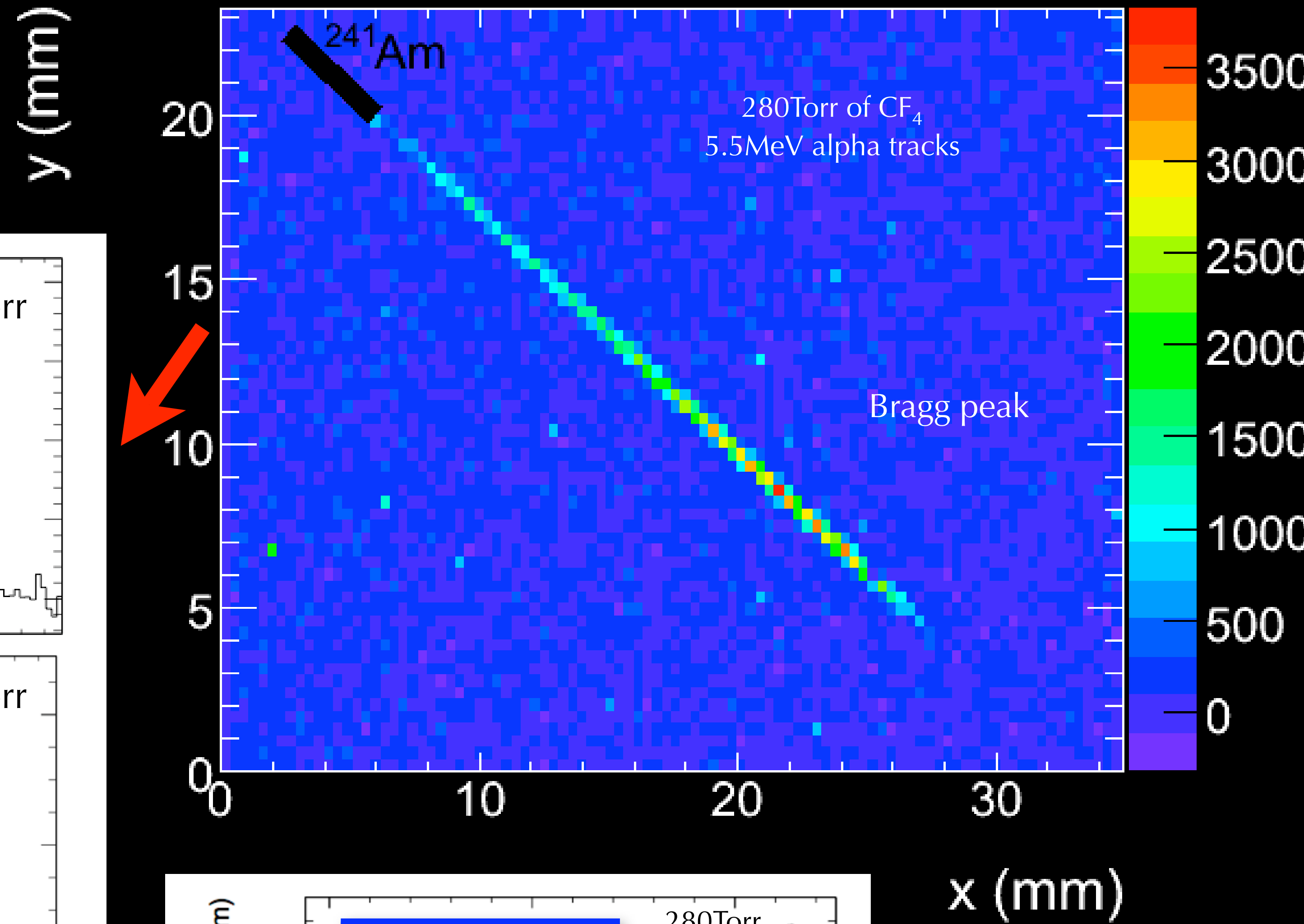
Range: count # of pixels above threshold

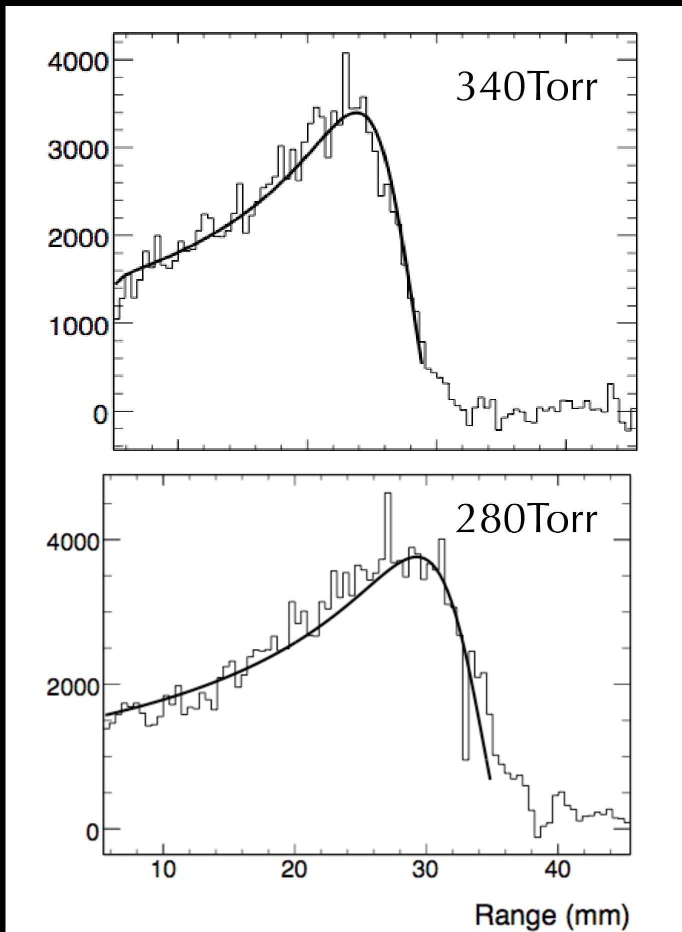
Measured along anode wires (+/- 3 pixels around wire), background estimate from pixels in between wires.

Energy: integral of light yield on the wire

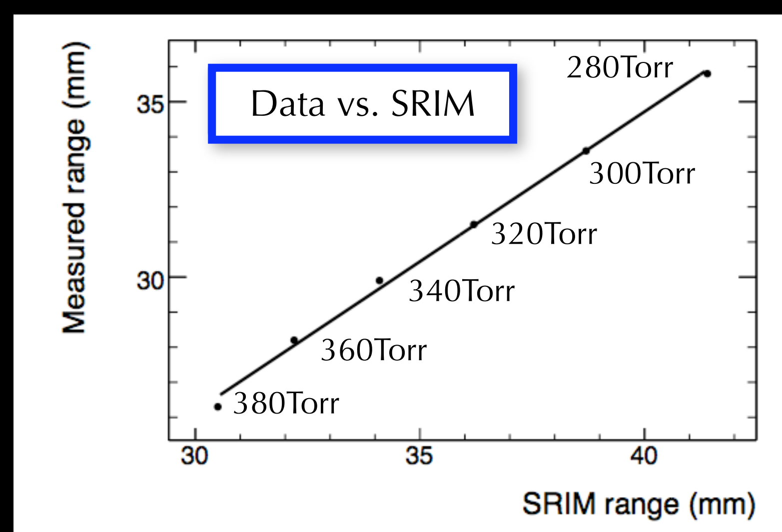
Measured in the y direction, perpendicular to anode wires, in +/- 5 pixels around segment, Gaussian fit above flat background.

α Scintillation Profile





fit for endpoint



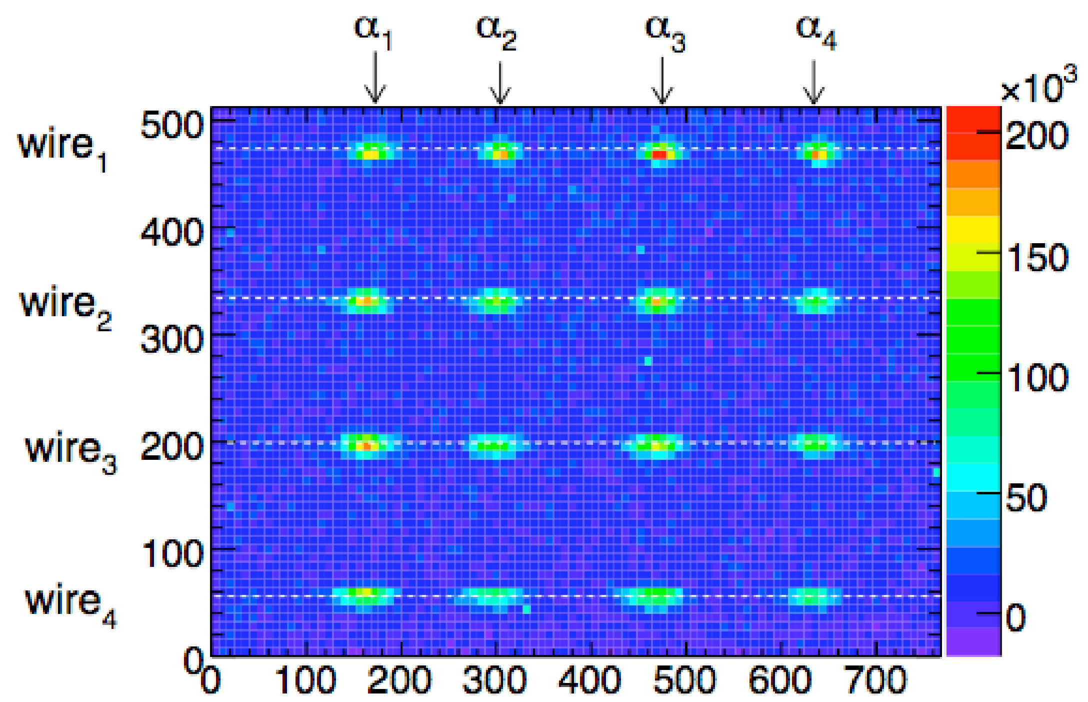
range calibration relative to SRIM simulation

Diffusion

Critical parameter:
nuclear recoil range ~ mm

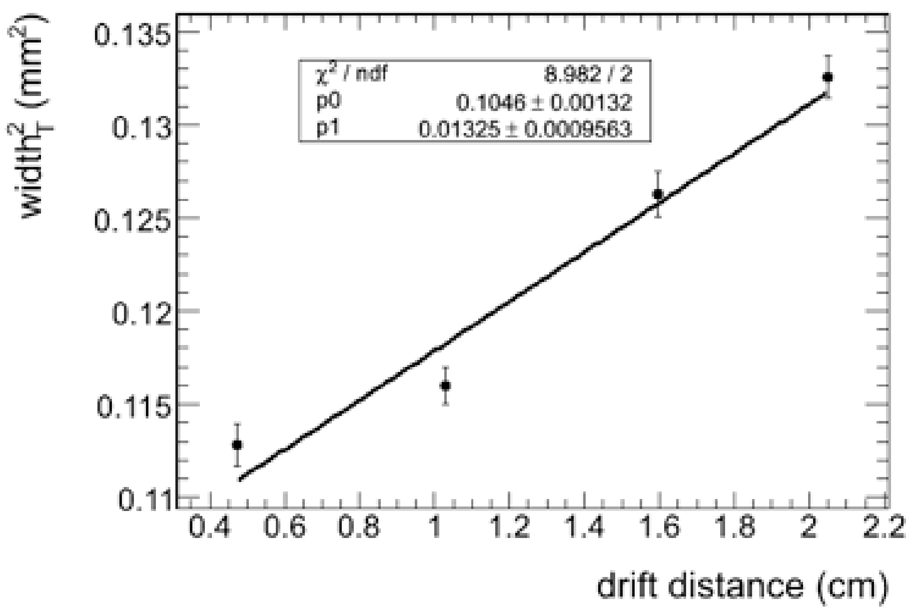
Measure with alpha sources at different heights in drift region (Δz)

0.5cm 1.05cm 1.6cm 2.05cm



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

200Torr

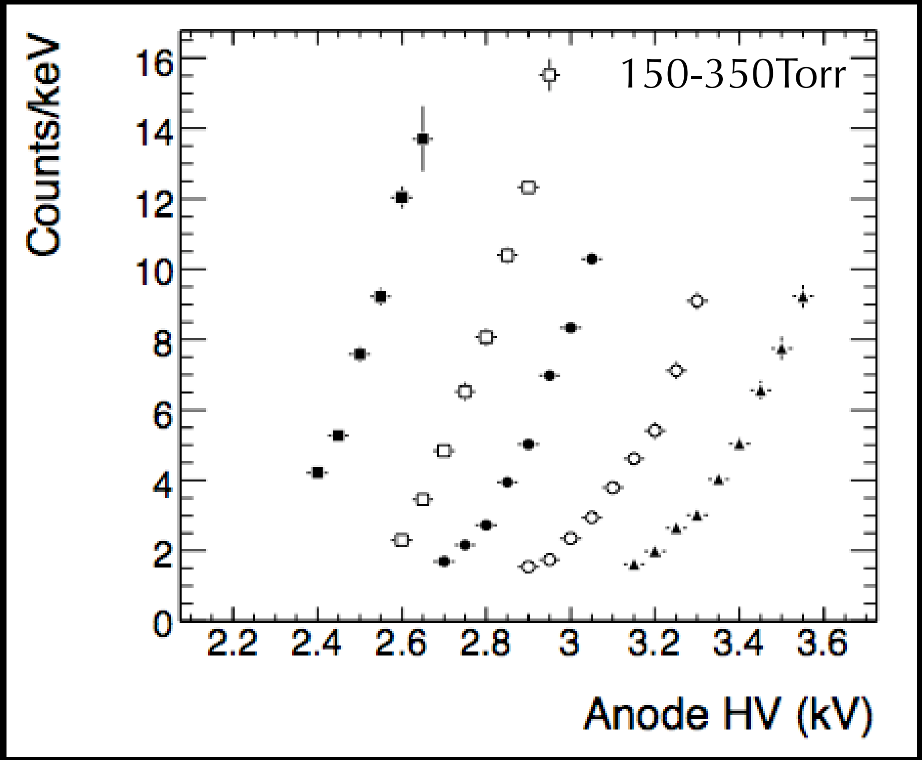


340μm for Δz=1cm
670μm for Δz=25cm

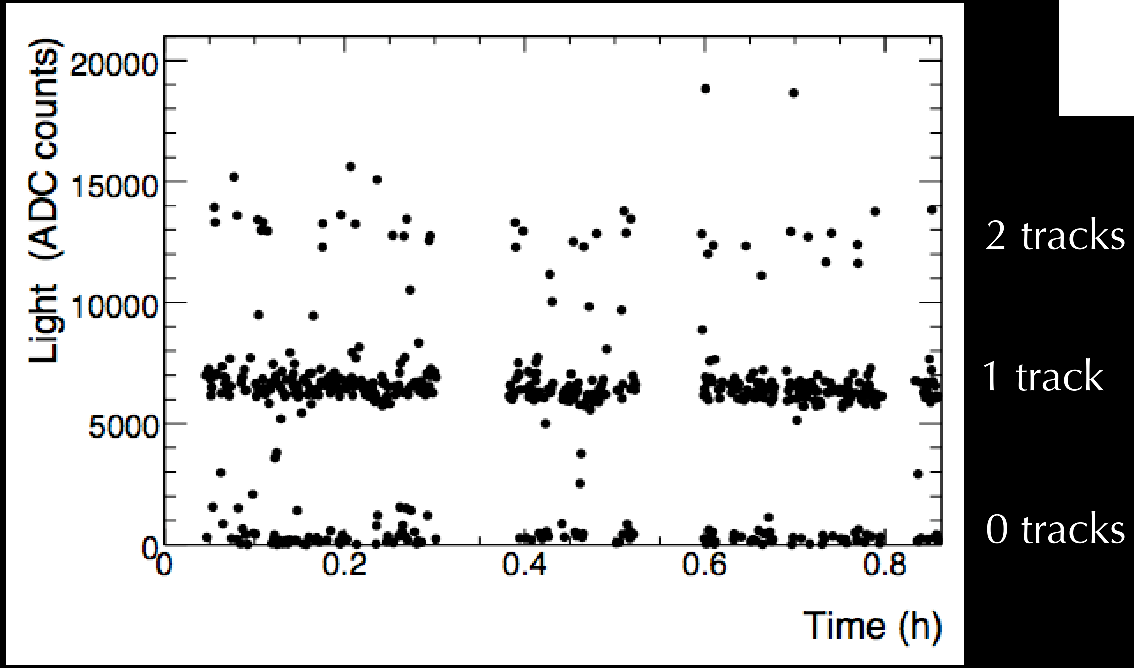
Maximum size of drift region

Gain, Energy Resolution

Calibrate gain, energy resolution with 5.5MeV α's from Am-241



Light intensity for alphas crossing a wire

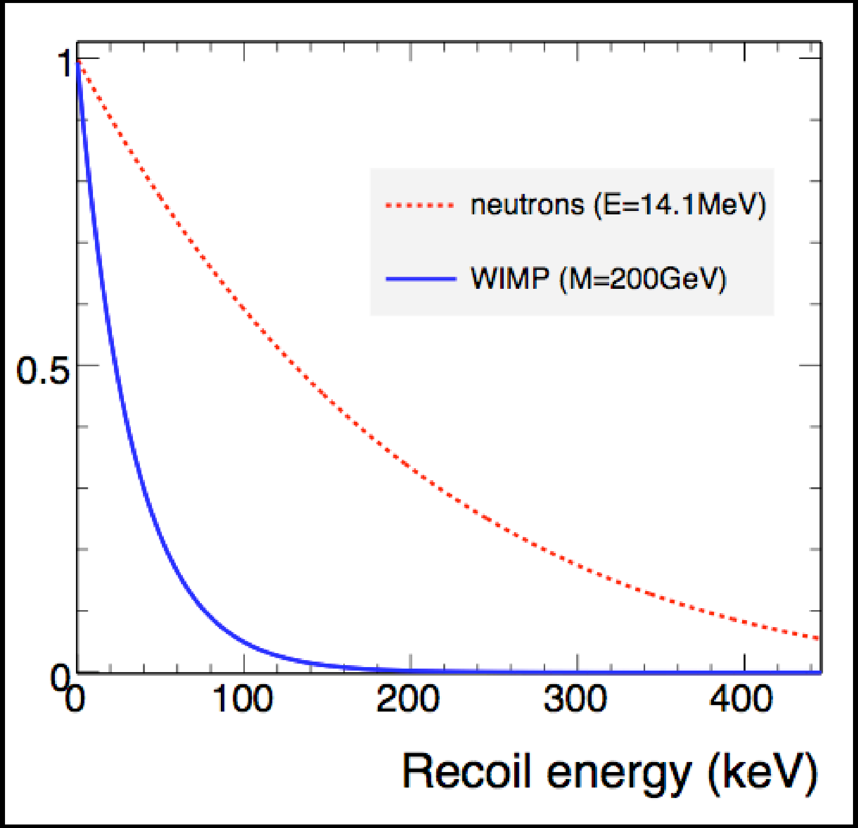


ΔE/E: ~9-15%
gain: ~8 counts/keV
stability: ~1/2 day
(without flowing gas)
100-400Torr

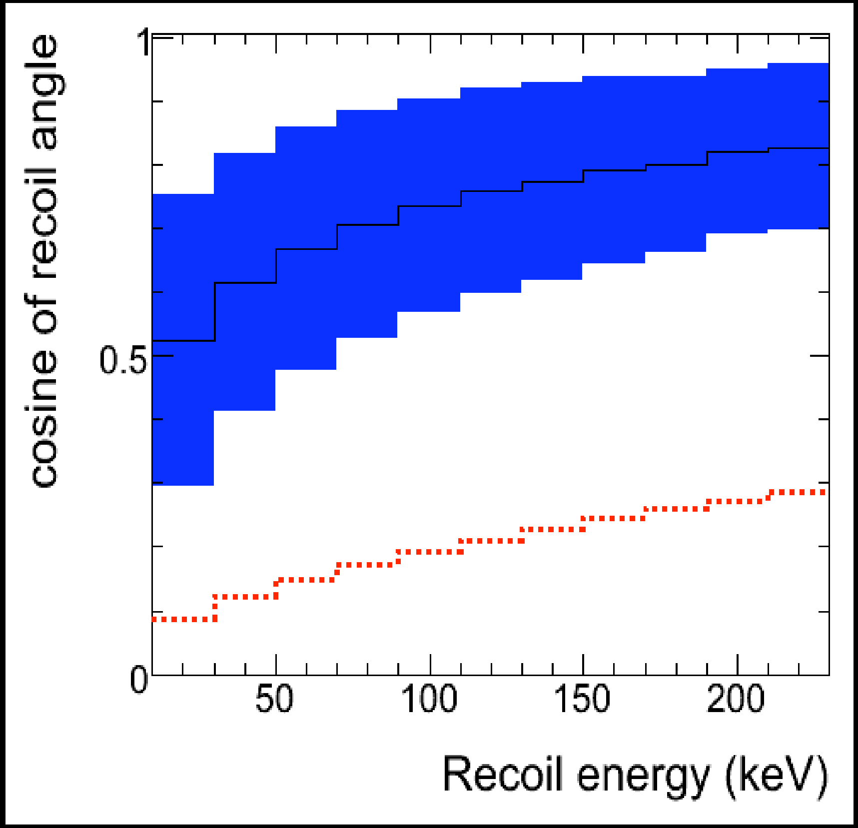
Neutron Beam Tests

Neutron elastic scattering mimics dark matter recoils

Fluorine recoil energy

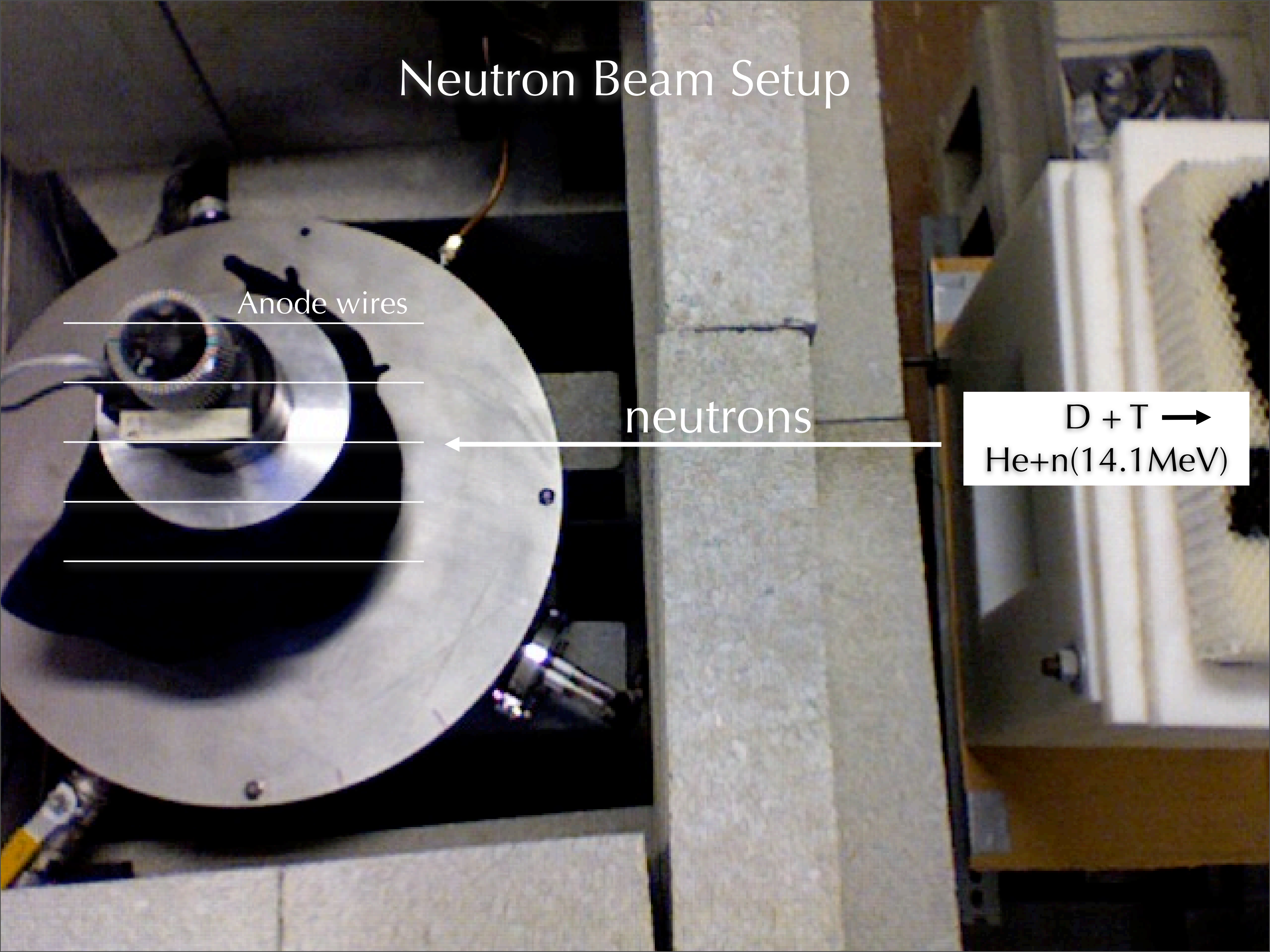


Fluorine recoil angle

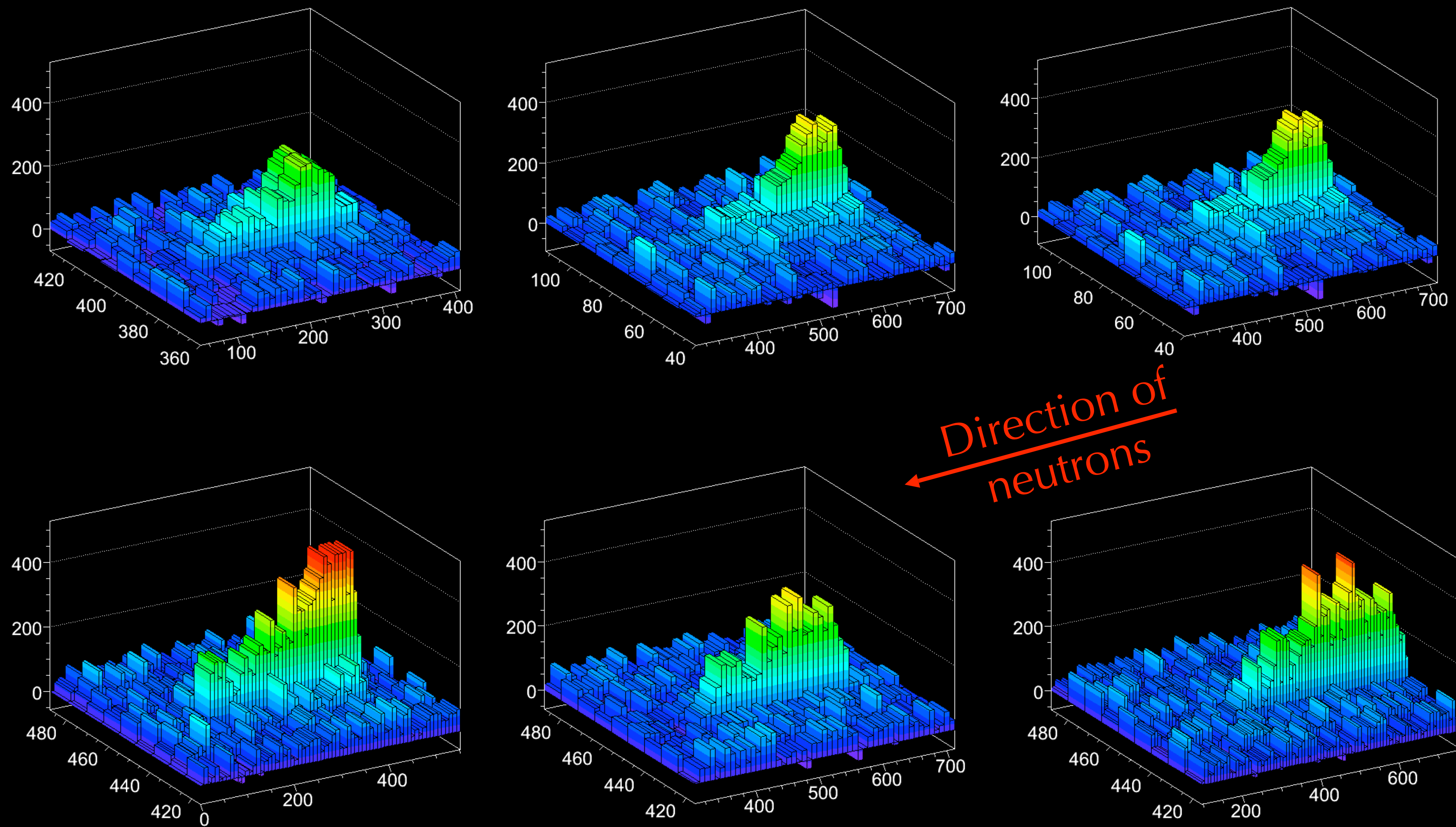


Fluorine recoil momentum better aligned with WIMP direction than neutron recoil

Neutron Beam Setup



Observation of Head-Tail



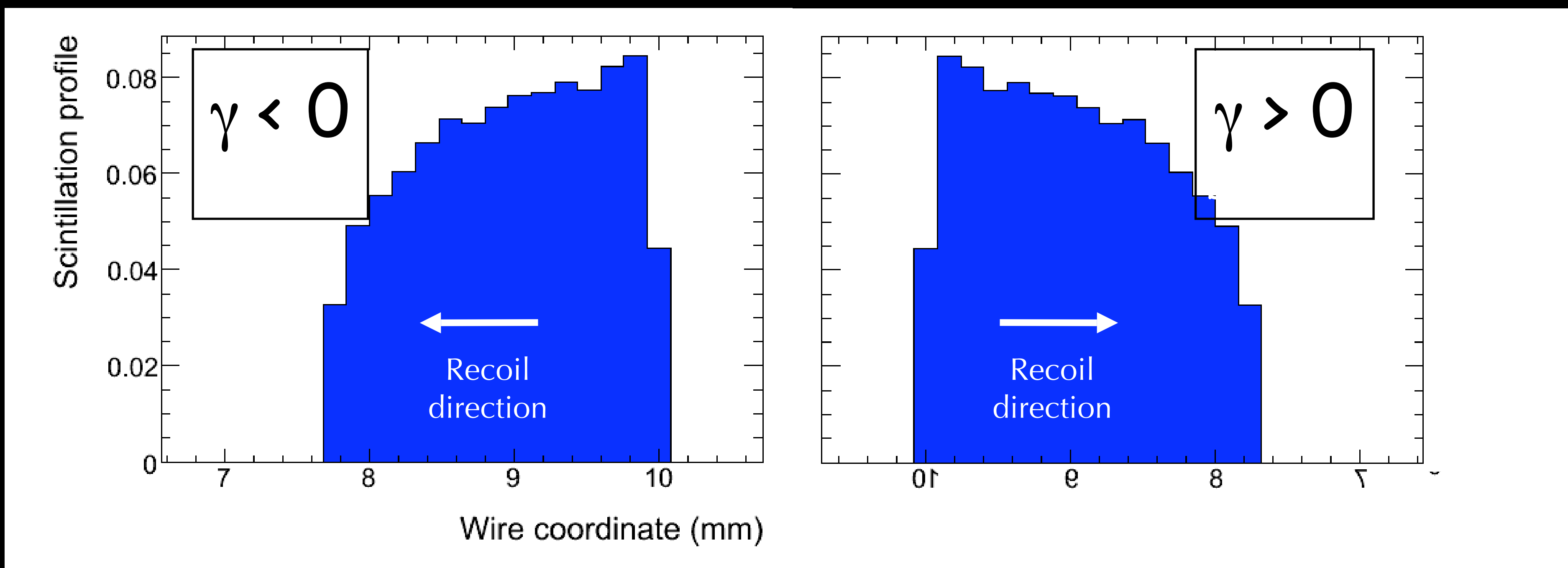
Wires at 0, 180 degrees (top, bottom row) with respect to neutron direction

Measure of Head-Tail Effect

Skewness of light asymmetry along segment:

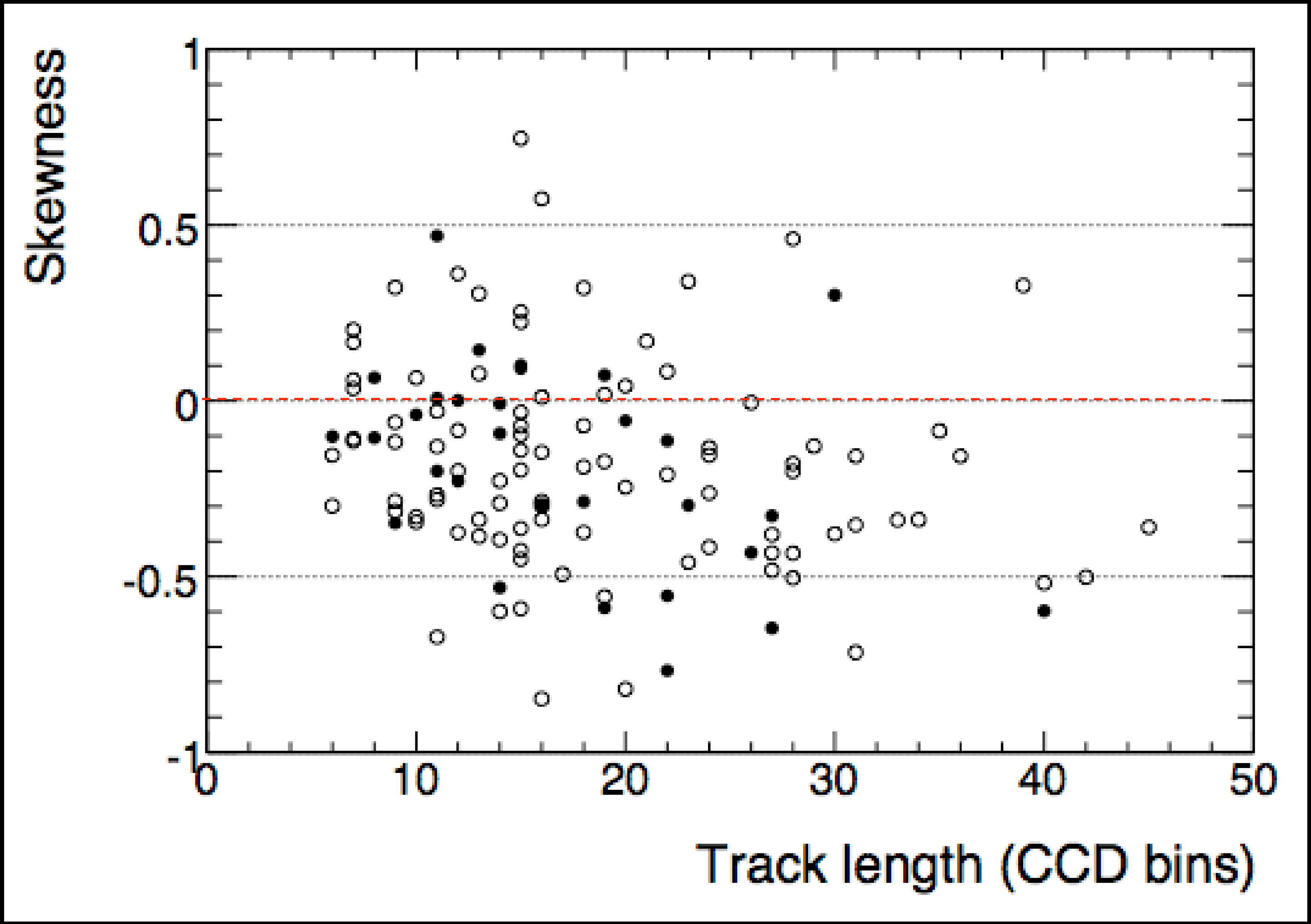
$$\gamma(x) = \frac{\mu_3}{\mu_2^{3/2}} = \frac{\langle (x - \langle x \rangle)^3 \rangle}{\langle (x - \langle x \rangle)^2 \rangle^{3/2}}$$ (dimensionless)

Direction tag:



Direction of neutrons

Head-Tail Results



backward
(26±4)%

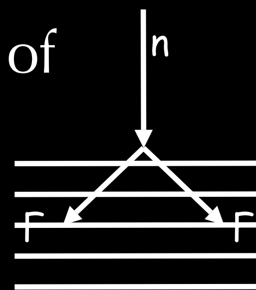
forward
(74±4)%

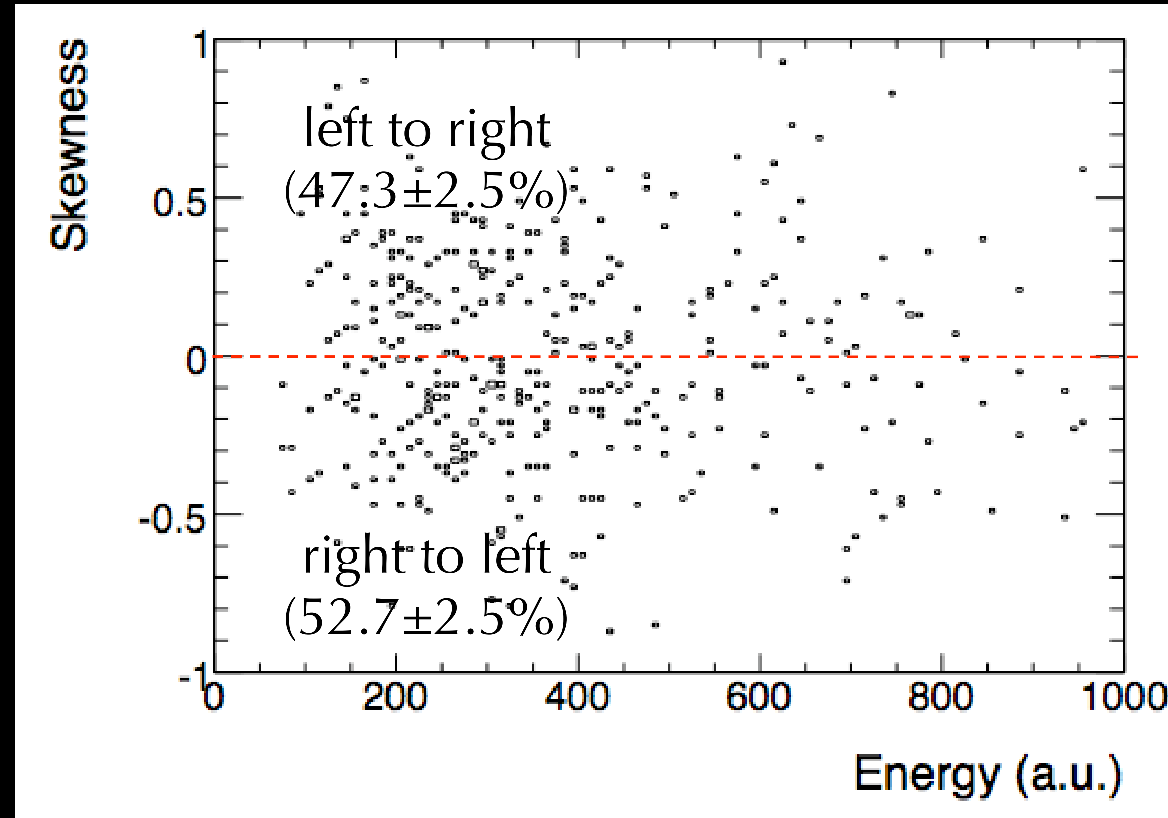
Filled - wires@0 deg, Hollow- wires@180 deg

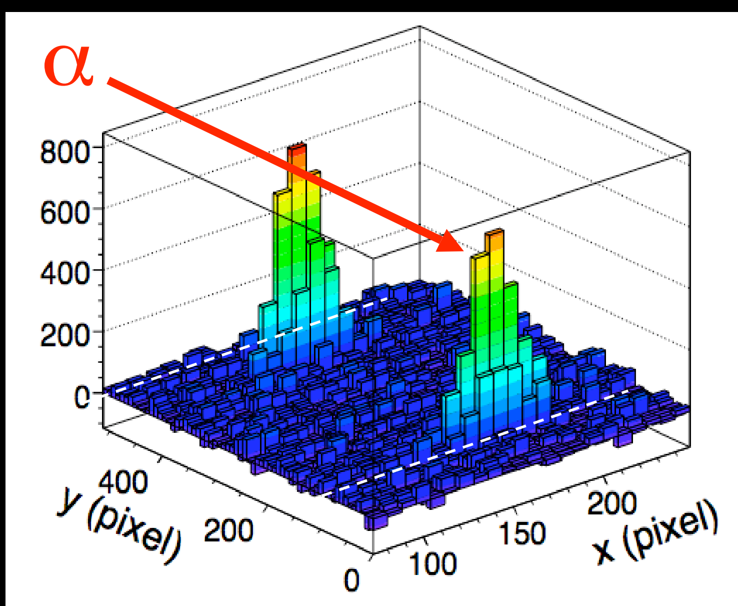
Control Samples

1. null test with neutrons perpendicular to wires

expect same number of (left,right) recoils







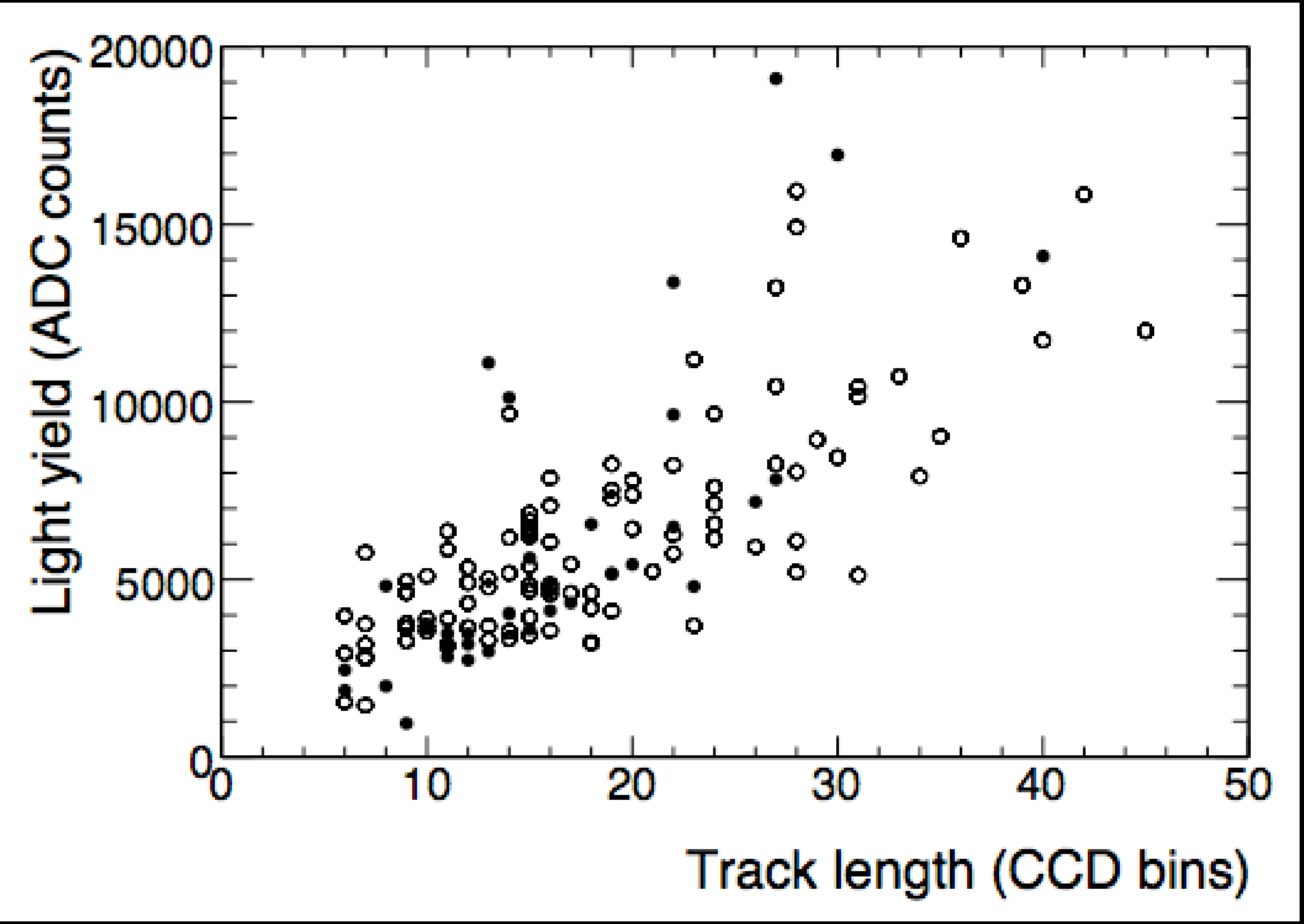
2. alpha track perpendicular to wires

expect symmetric signal (γ=0)

Skewness:
$\langle\gamma\rangle$=0.032+/- 0.024

Energy vs. Range

Correlation between energy (ADC counts) and range (CCD bins):

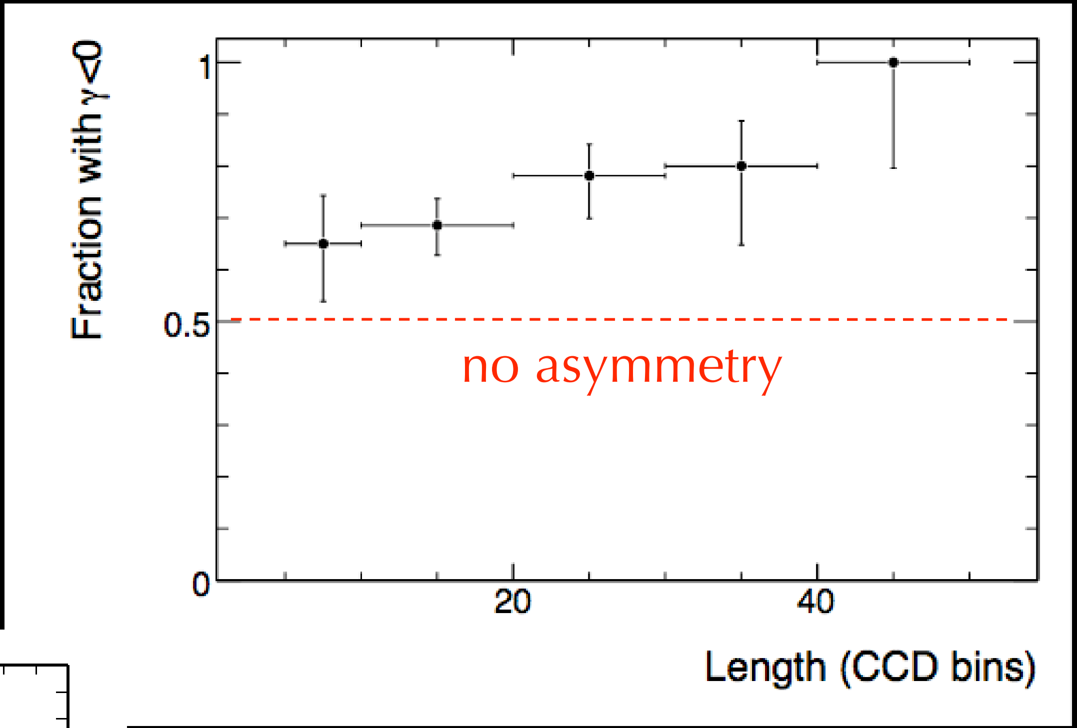


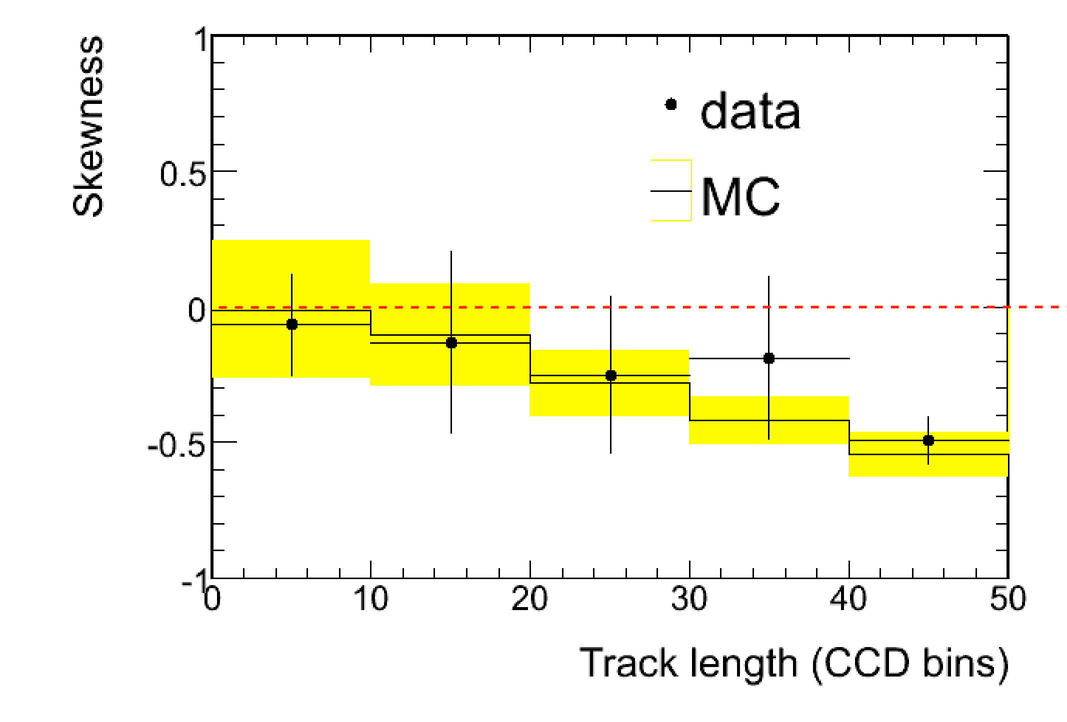
(Slope proportional to stopping power)

Filled - wires@0 deg, Hollow- wires@180 deg

Head-Tail Results

Fraction of recoils in direction of neutrons





backward

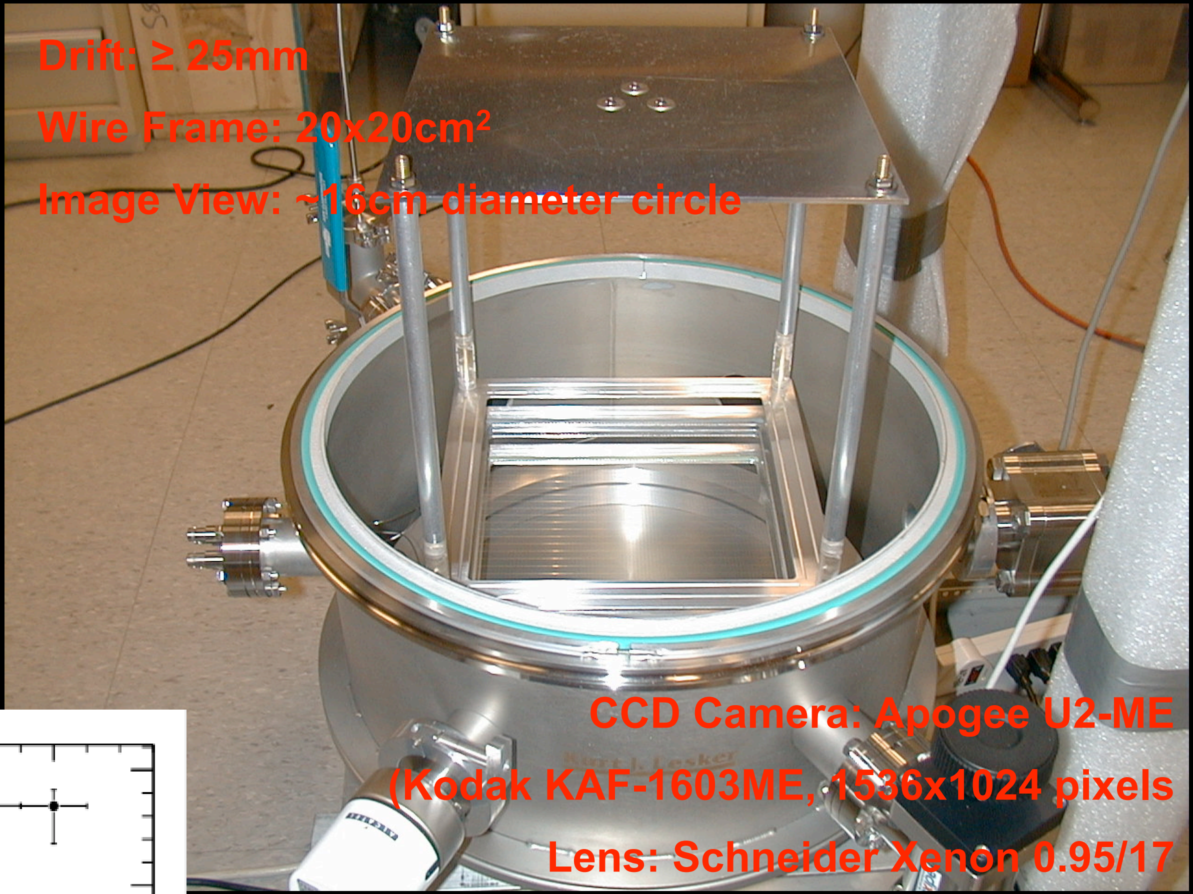
forward

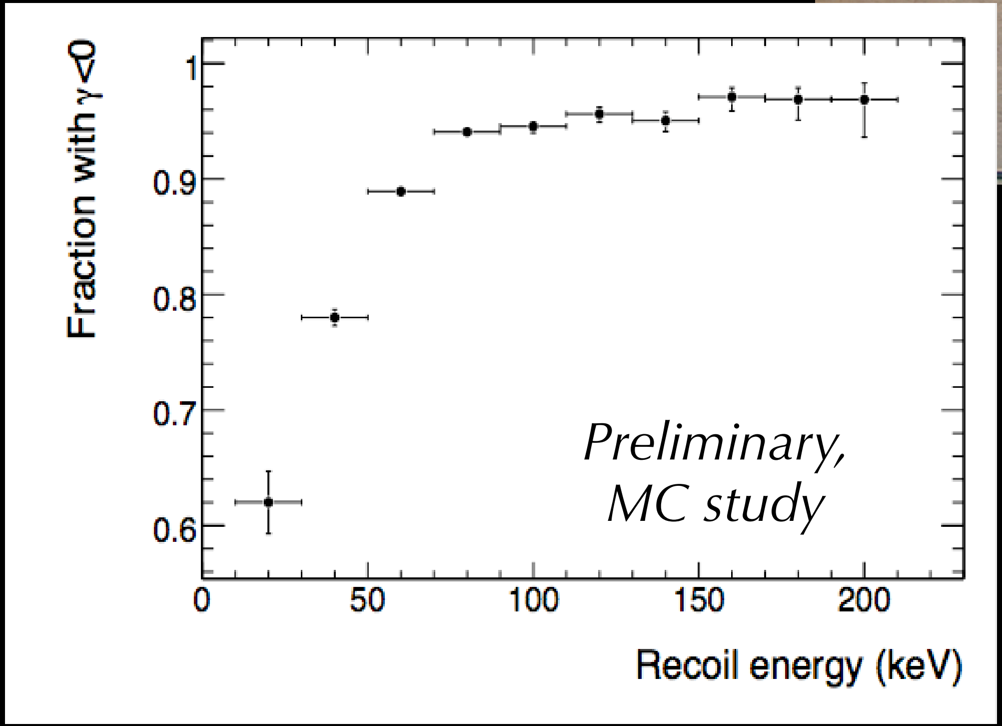
$\pm 1\sigma$ spread in data (points), MC (shaded)

D. Dujmic, et al., arXiV:0708.2370, accepted to NIM A

Next for DMTPC

Work on improvements:
- increase gain (x2),
- stability of operation,
- lower pressure,
- ^{252}Cf calibration;
- prototype #2 operating.



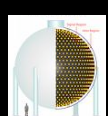


Next year: 1 m^3 chamber underground to study backgrounds, operating at 50 Torr.

DMTPC Future

Eventually: large detector, 10^{-46} cm^2 sensitivity

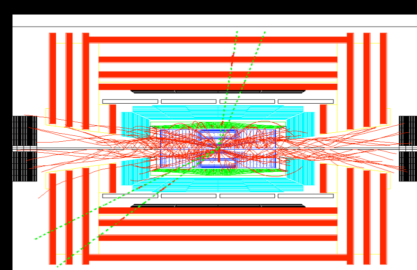
MiniBooNE:
$6 \times 6 \times 6$ m^3



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

1 ton of CF_4
@50Torr

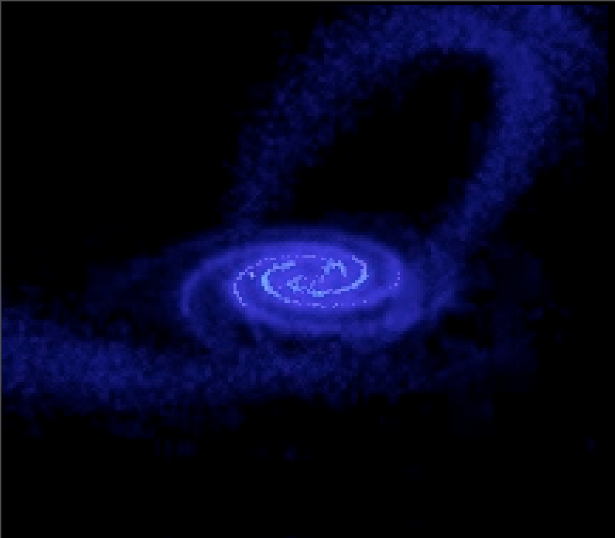
CMS:
$15 \times 15 \times 22$ m^3



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

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

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



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

Backgrounds make directional detection very attractive.

Huge progress experimentally in last few years:
- *first* directional experiment (DRIFT),
- *first* directional dark matter limit (NEWAGE),
- *first* observation of head-tail in low-energy nuclear recoils (DMTPC)

Dark matter telescope: transition from discovery to observatory.